2nd Workshop on Quantitative Challenges in SRC and EMC Research

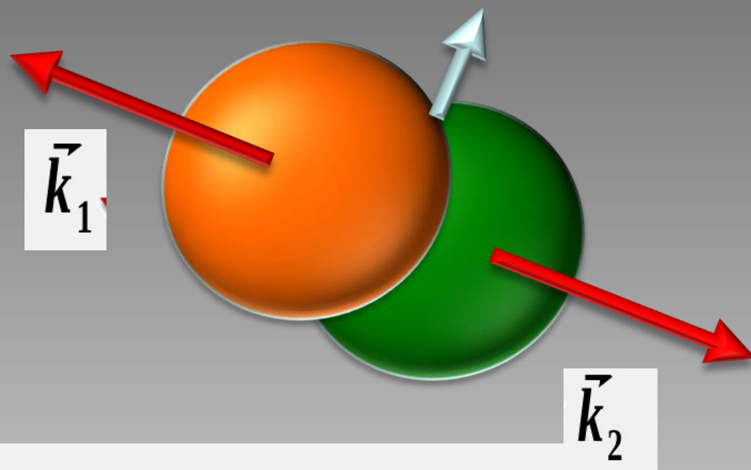
Massachusetts Institute of Technology
March 20-23, 2019

Eli Piasetzky, Tel Aviv University, Israel

Thursday, March 21: 2N and 3N SRCs

Time		Presenter	Title
9:00 - 9:30	25+5'	Eli Piasetzky	SRC in, FSI out?
9:30 - 9:50	17+3'	Mark Strikman	Interpreting SRCs: FSI in x>1, from (e,e') to (e,e'NN)
9:50 - 10:10	17+3'	Omar Benhar	Interpreting SRCs: FSI in x>1, from (e,e') to (e,e'NN)
10:10 - 10:30	30'	Discussion	
10:30 - 11:00		Morning Coffee Break	
11:00 - 11:20	17+3'	Wim Cosyn	Transparency: neutrons & two-nucleon
11:20 - 11:40	17+3'	Meytal Duer	p vs. n Transparency & SRC A-dependence from (e,e'Np)
11:40 - 12:00	17+3'	Douglas Higinbotham	Issues with theoretical description of polarized 3He (e,e'p) and 3He(e,e'd) data
12:00 - 12:30	30'	Discussion	

What Do We Mean by SRCs?



$$k_1 > k_F \quad k_2 > k_F \quad k_1 \simeq k_2$$

$$k_F \approx 250 \text{ MeV/c}$$

high relative and *low c.m. momentum,*

Part I: study properties of SRC pairs

(Part II: study NN interaction via SRC)

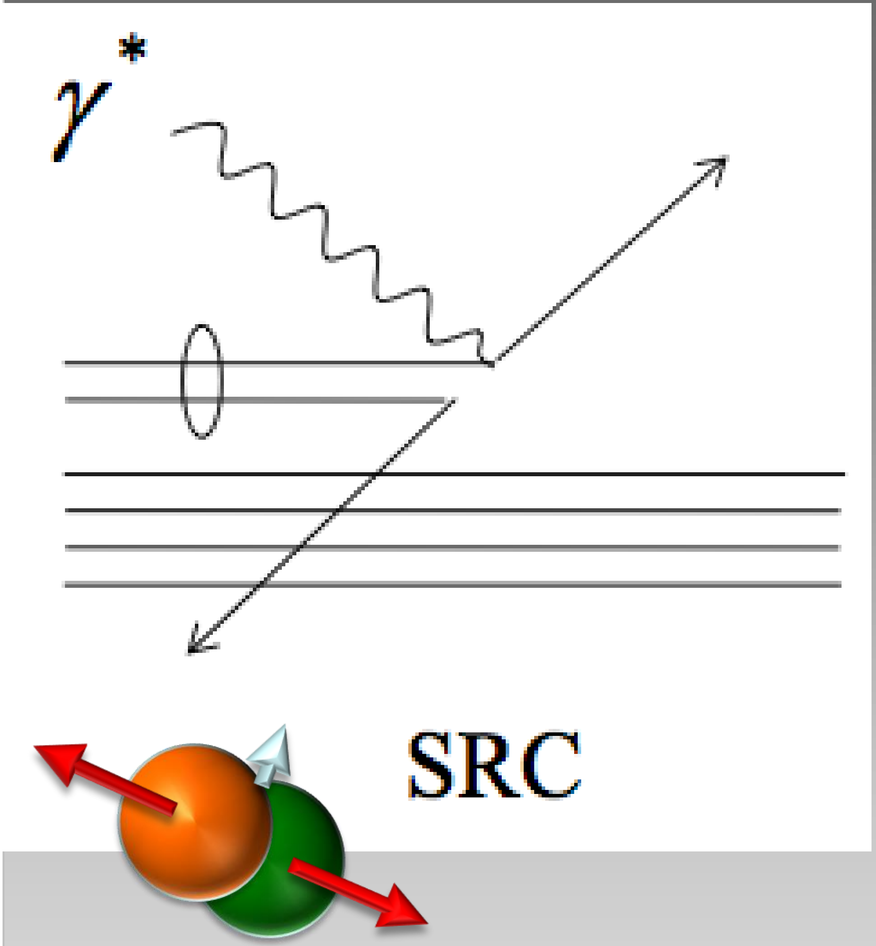
Friday, March 22: NN Interaction and Knock-out reactions

Saturday, March 23: EMC Effect

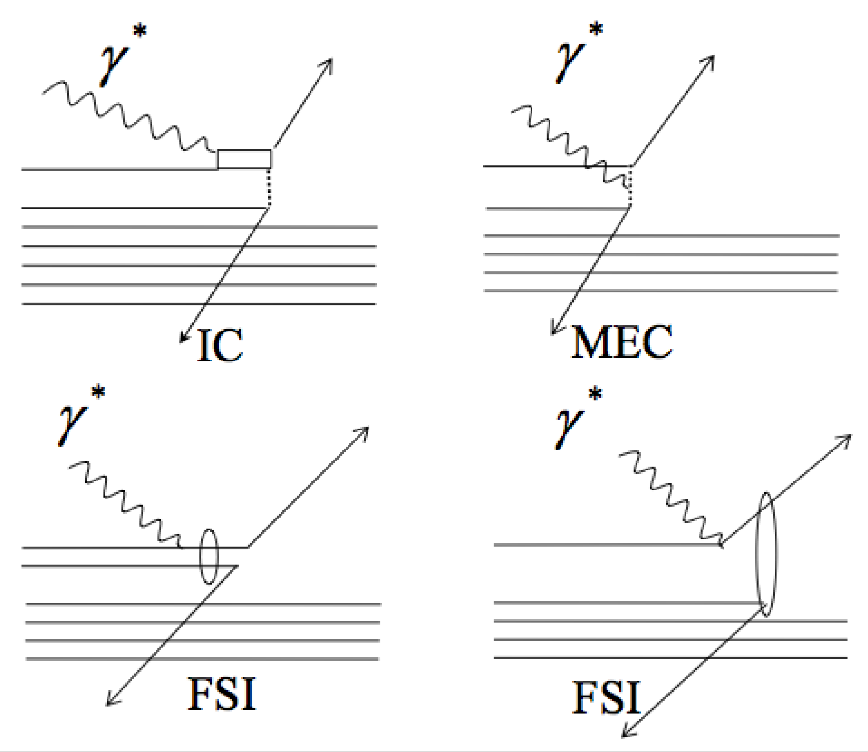
Time		Presenter	Title
9:00 - 9:30	25+5'	Gerald Miller	Short intro & new model
9:30 - 9:50	15+5'	Barak Schmookler	New 6 GeV results (CLAS)
9:50 - 10:15	20+5'	Mark Strikman	Quest for nonnucleonic degrees of freedom in nuclei
10:10 - 10:40	30'	Discussion: Understaning the dynamics behind the EMC Effect	

3N SRC

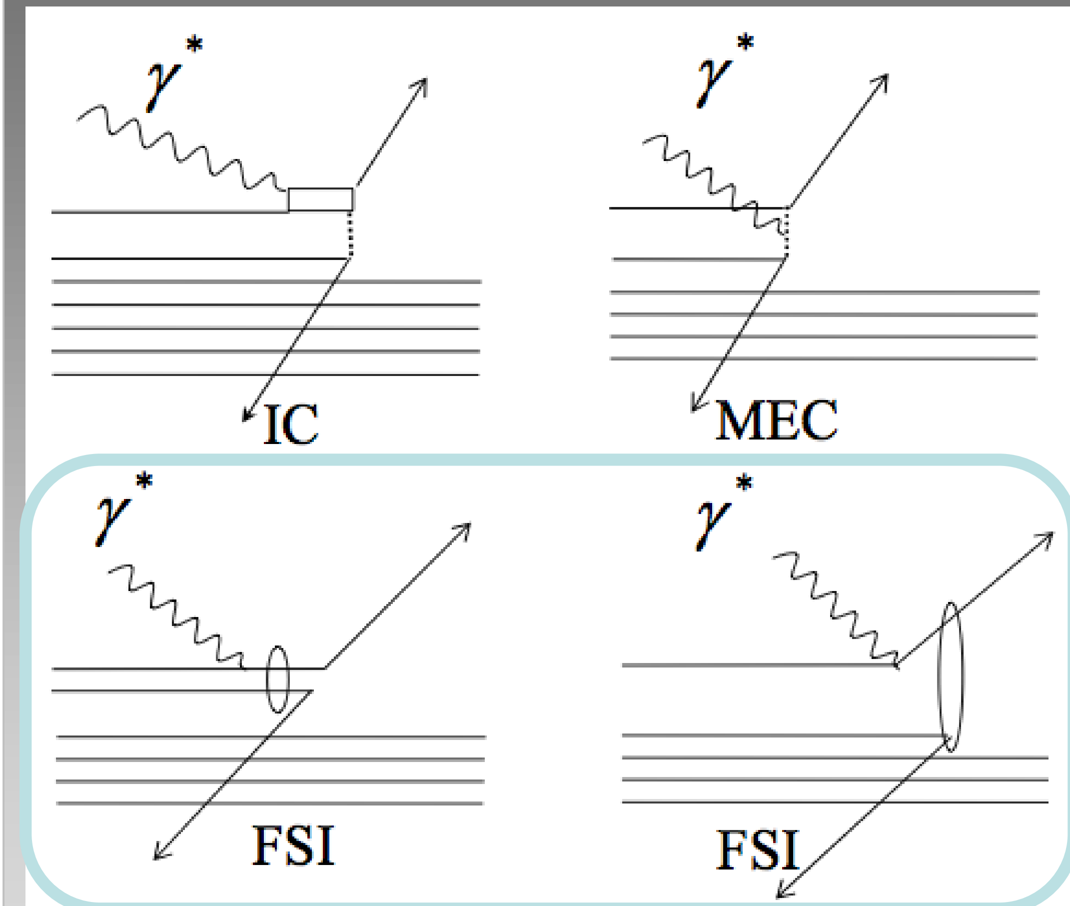
That is what we want



That is what we also get



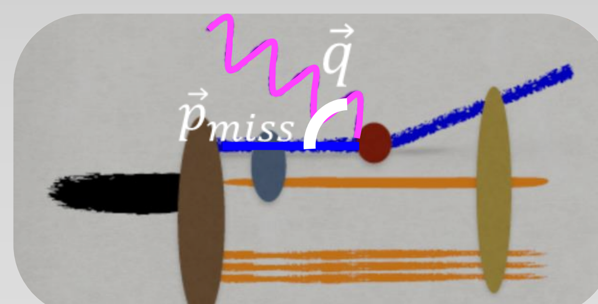
"SRC kinematics" "observables"



MEC suppressed @ **high-Q^2** ,
IC suppressed at
x_B > 1.

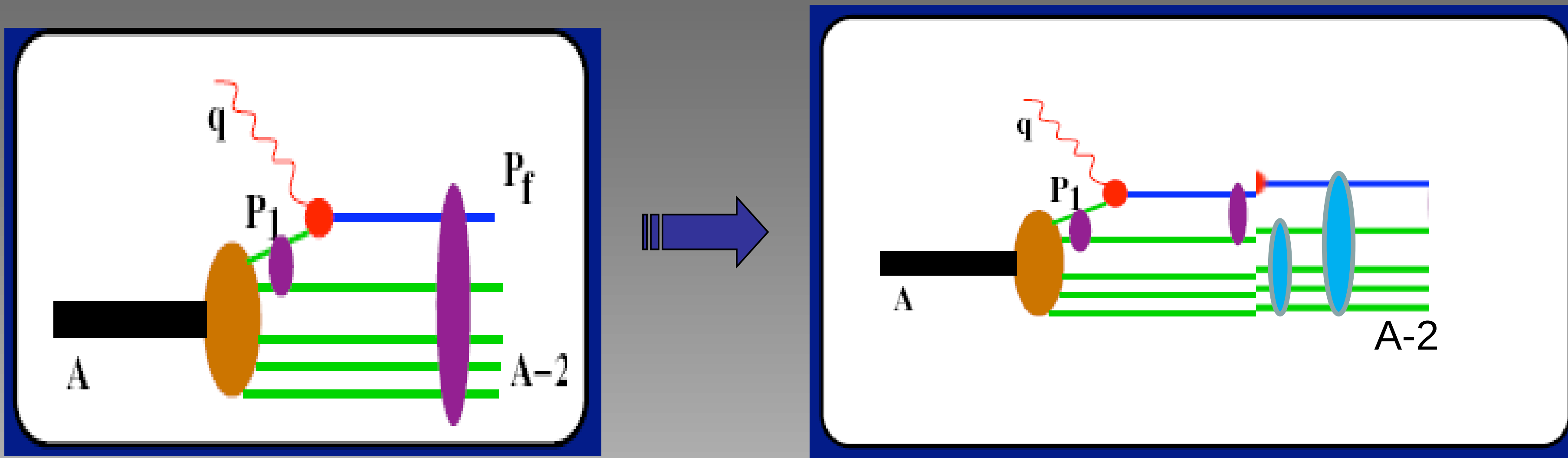
Large Pmiss

FSI suppressed in **anti-parallel** kinematics.
Treated using **Glauber** approximation.



Why FSI do not destroy the 2N-SRC signature ?

For large Q^2 and x>1 FSI is confined within the SRC
or can be factorize and approximate by Glauber calculations



distances that highly virtual struck nucleon propagates

$$\Delta E = -q_0 - M_A + \sqrt{m^2 + (p_i + q)^2} + \sqrt{M_{A-1}^2 + p_i^2}$$

$$r \approx \frac{1}{\Delta E v} \leq 1\,\mathrm{fm}$$

for $x > 1.3$

FSI in the SRC pair:

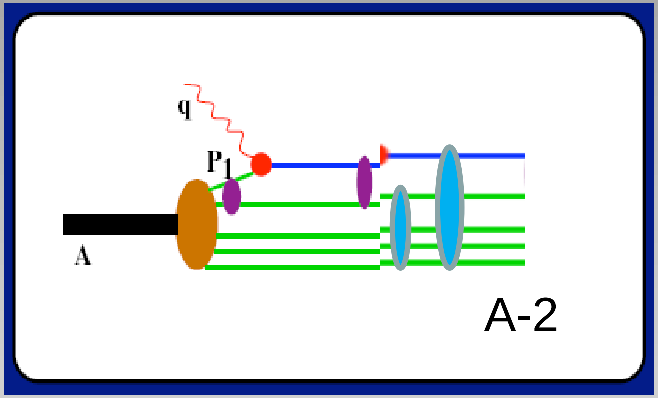
Conserve the isospin structure of the pair .

Conserve the CM momentum of the pair.

Kinematics optimized to minimize the competing processes

FSI with the A-2 system:

- ★ Geometry, (e, e'p) selects the surface.
- ★ Can be treated in Glauber approximation.
- ★ Can be tested experimentally.
- ★ Canceled in some of the measured ratios.

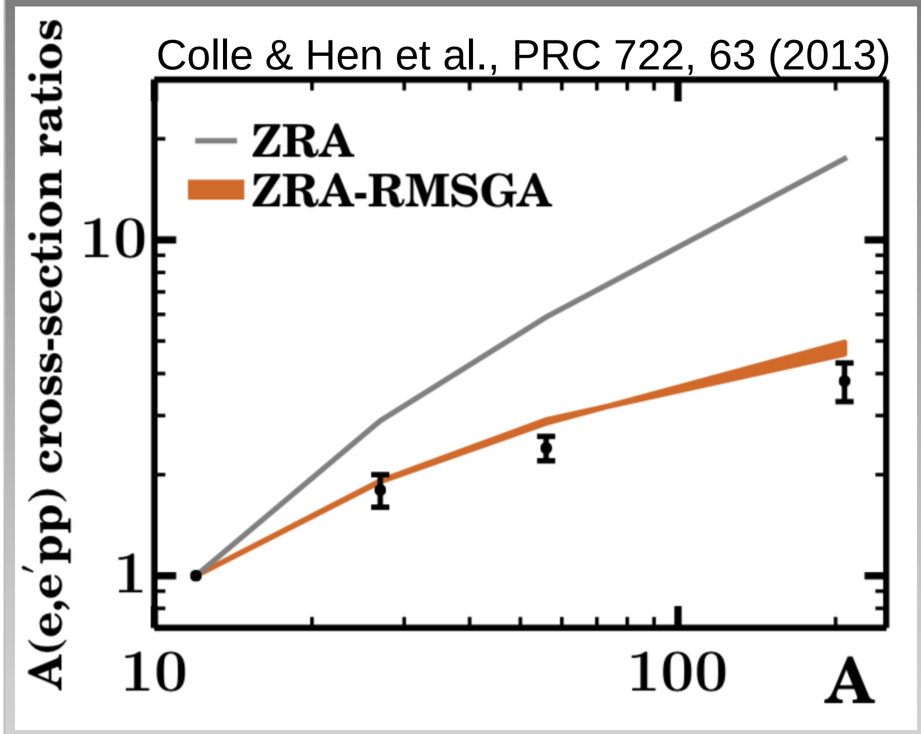


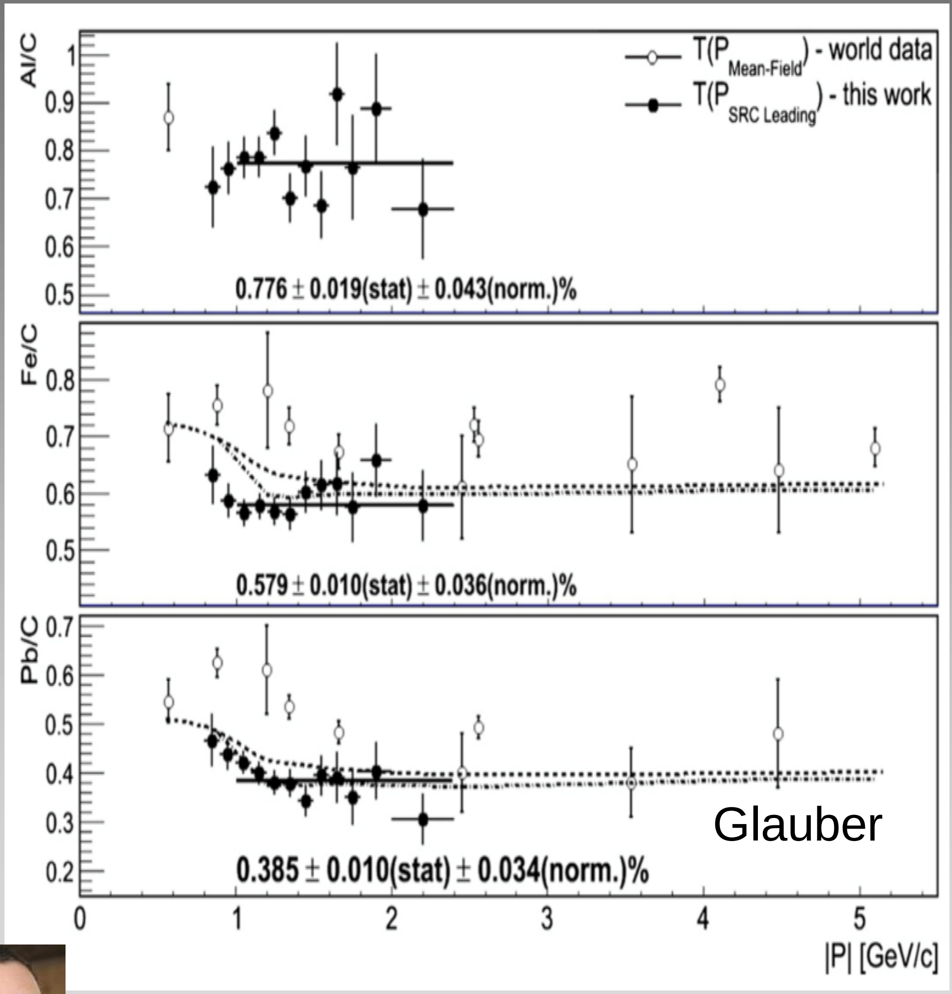
FSI in the SRC pair:

These are not necessarily small, BUT:

- ★ Conserve the isospin structure of the pair .
- ★ Conserve the CM momentum of the pair.

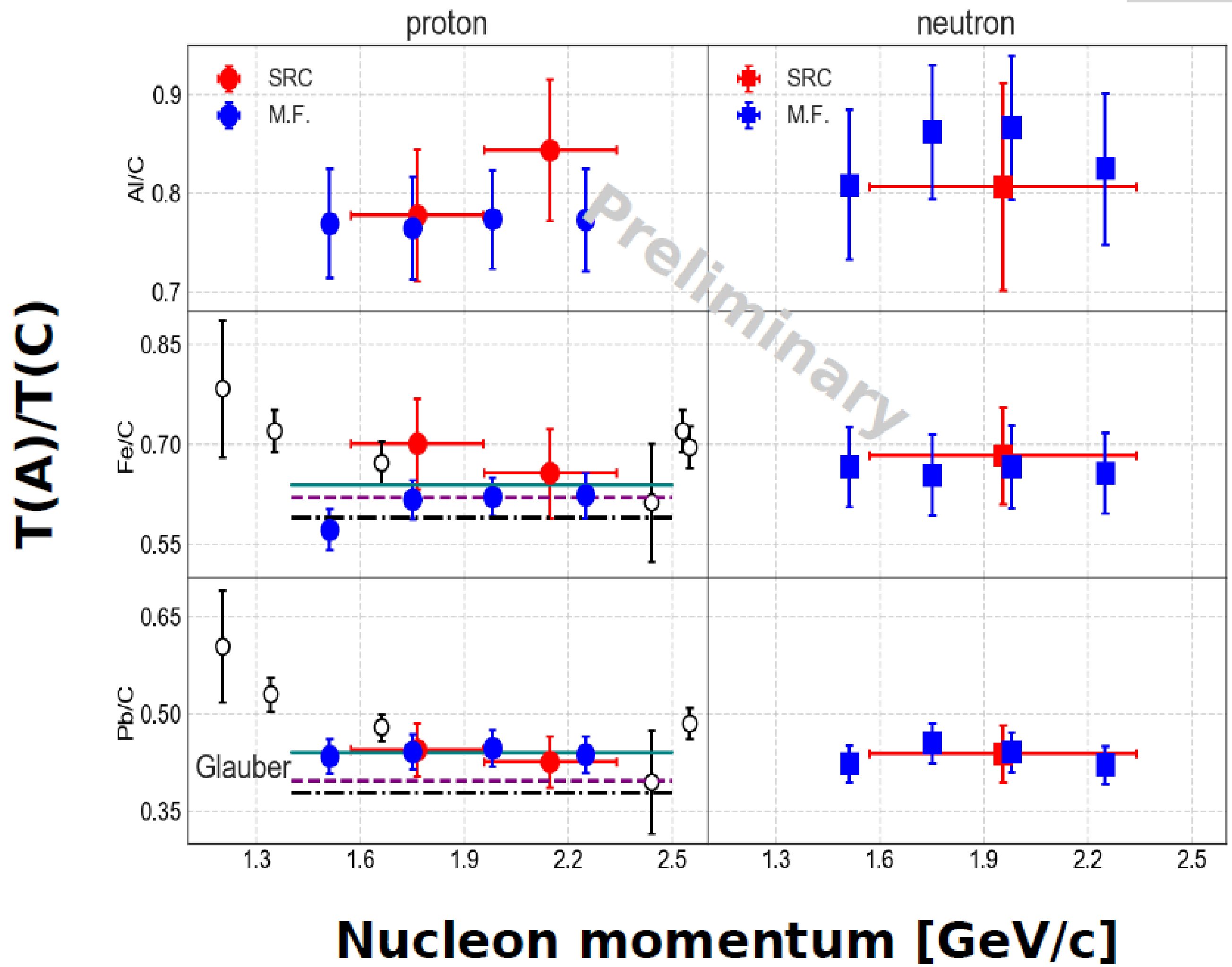
Glauber agrees with data!





Hen et al., Phys. Lett. B 722, 63 (2013)

Glauber agrees with data!

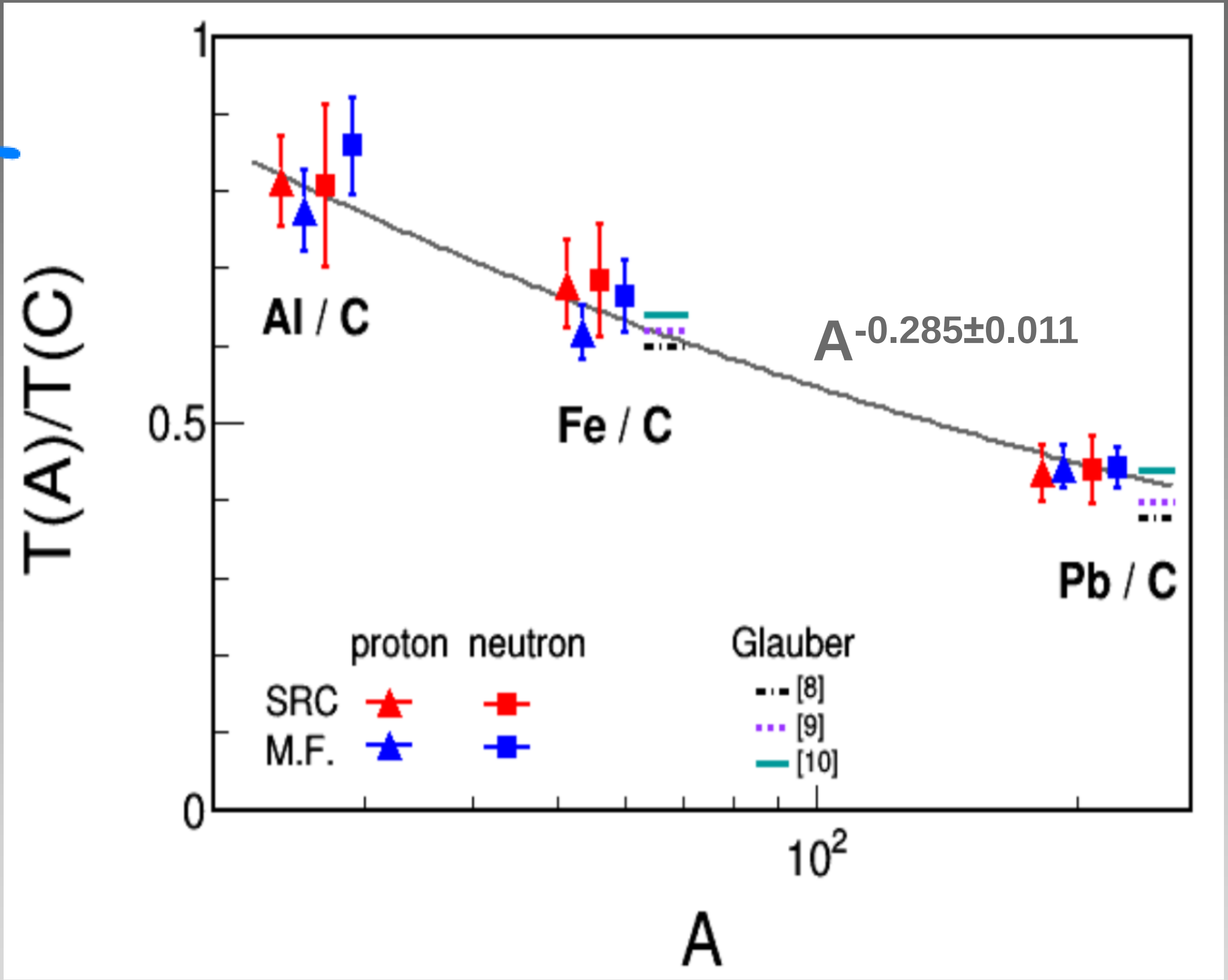


C. Colle, W. Cosyn, Phys. Rev. C 93, 034608 (2016).
L. L. Frankfurt, M. I. Strikman, and M. Zhalov, Phys. Lett. B. 503, 73 (2000).
V. I. Pandharipande, and S. C. Pieper, Phys. Rev. C 45, 791 (1992).

M. Duer et al.

Glauber agrees with data!

NEW! 2018-19



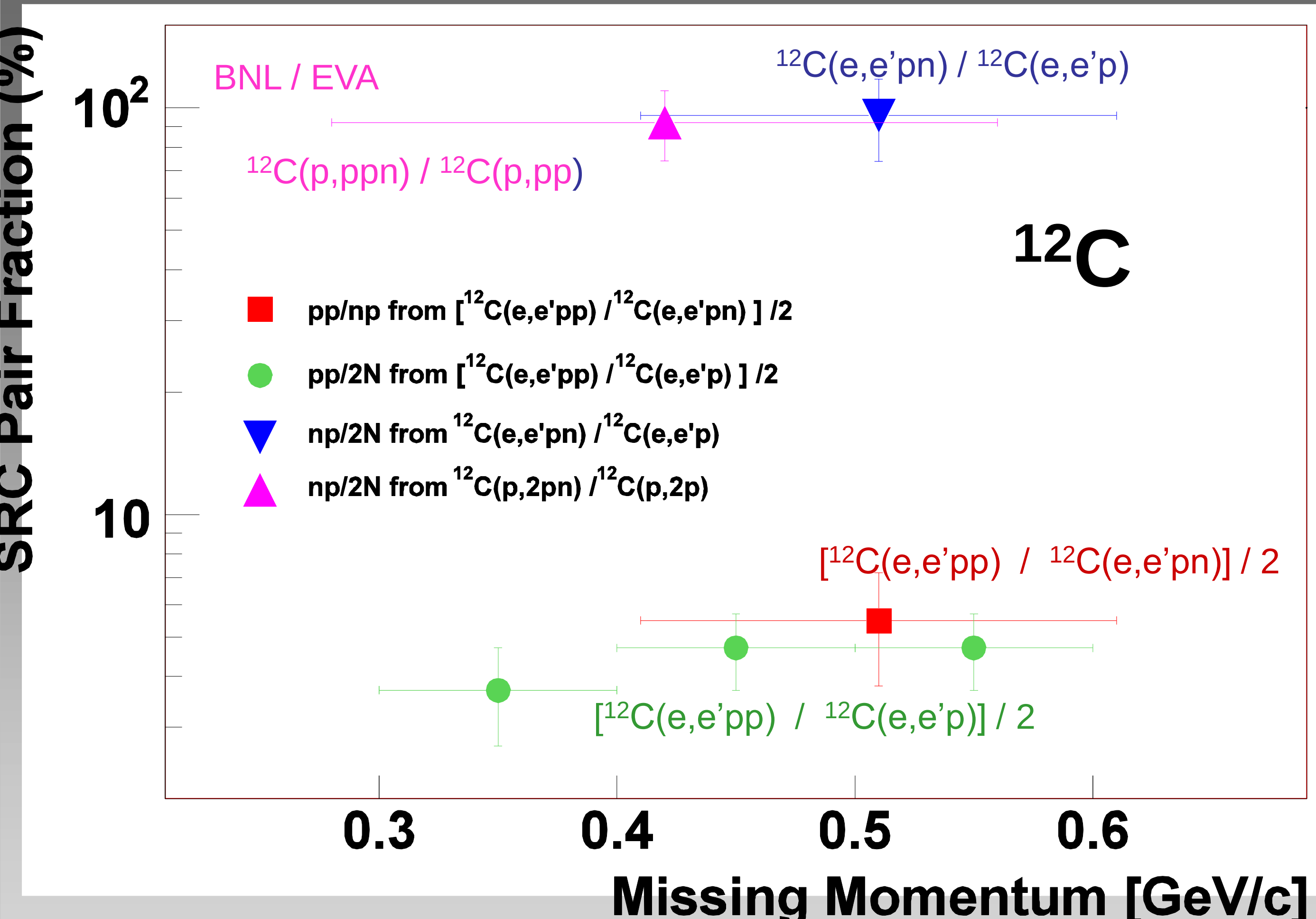
M. Duer et al.

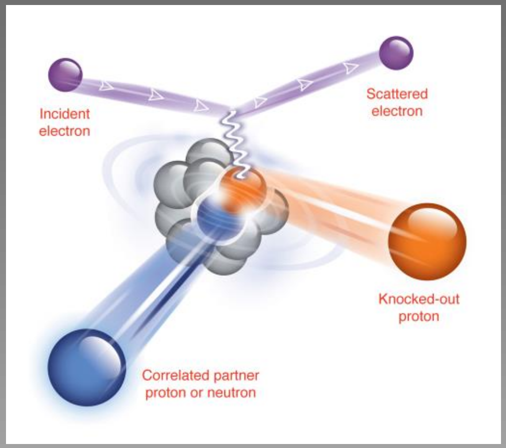
[8] C. Colle, W. Cosyn, Phys. Rev. C 93, 034608 (2016).
[9] L. L. Frankfurt, M. I. Strikman, and M. Zhalov, Phys. Lett. B. 503, 73 (2000)
[10] V. J. Pandharipande, and S. C. Pieper, Phys. Rev. C 45, 791 (1992)

Part I: study properties of SRC pairs

(Part II: study NN interaction via SRC)

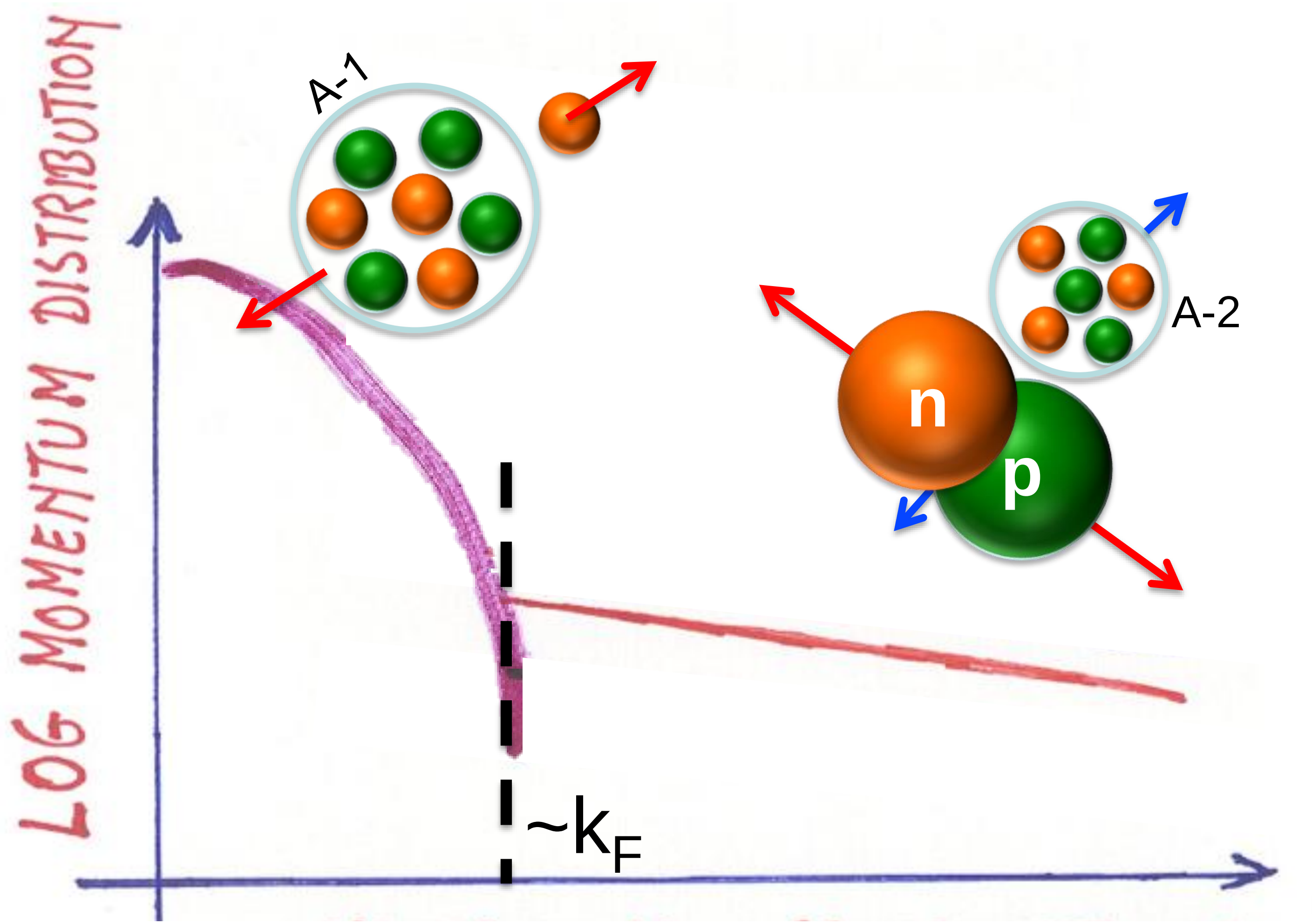
Piasetzky et al., PRL. 97 (2006) 162504.
R. Subedi et al., Science 320, 1476 (2008).





The high momentum tail in nuclei is dominated by SRC pairs

Most of the SRC pairs (90%) are np only 5% pp and 5% nn



$$S_{ab}^{\alpha} = \frac{1}{4\pi} \int \frac{d\boldsymbol{p}_2}{(2\pi)^3} \delta(f(\boldsymbol{p}_2)) \left|\tilde{\varphi}_{ab}^{\alpha}(|(\boldsymbol{p}_1 - \boldsymbol{p}_2)/2|)\right|^2 n_{ab}^{\alpha}(\boldsymbol{p}_1 + \boldsymbol{p}_2)$$

C.M. Motion of the SRC pairs

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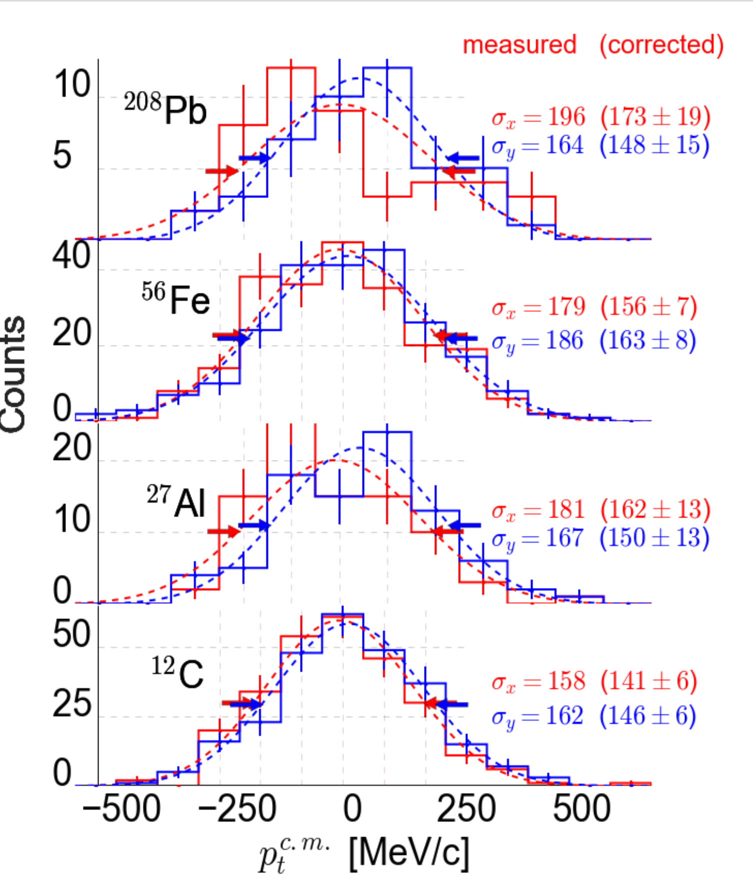
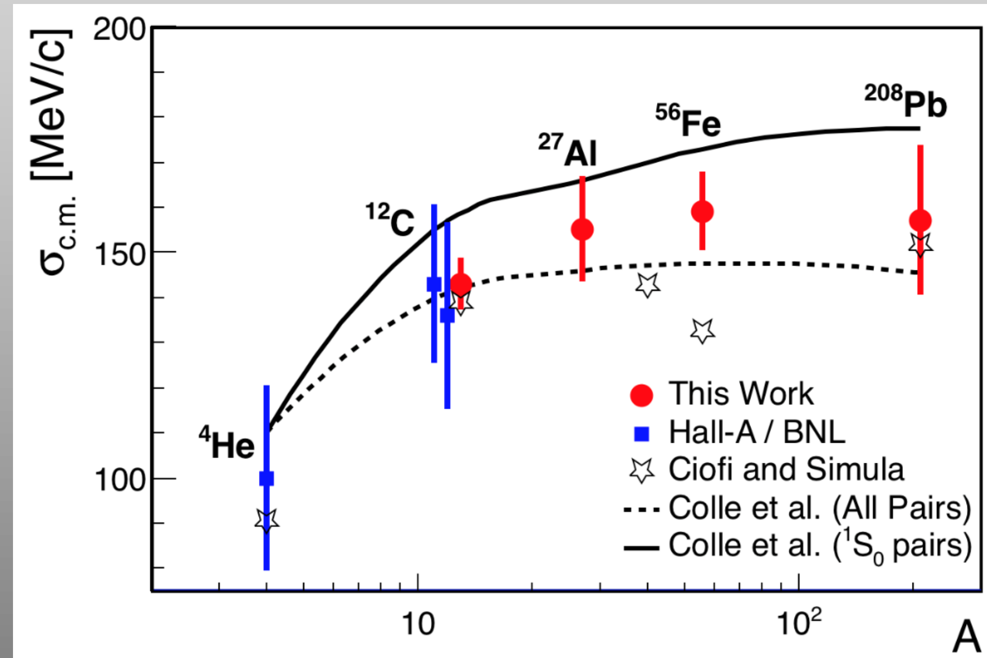
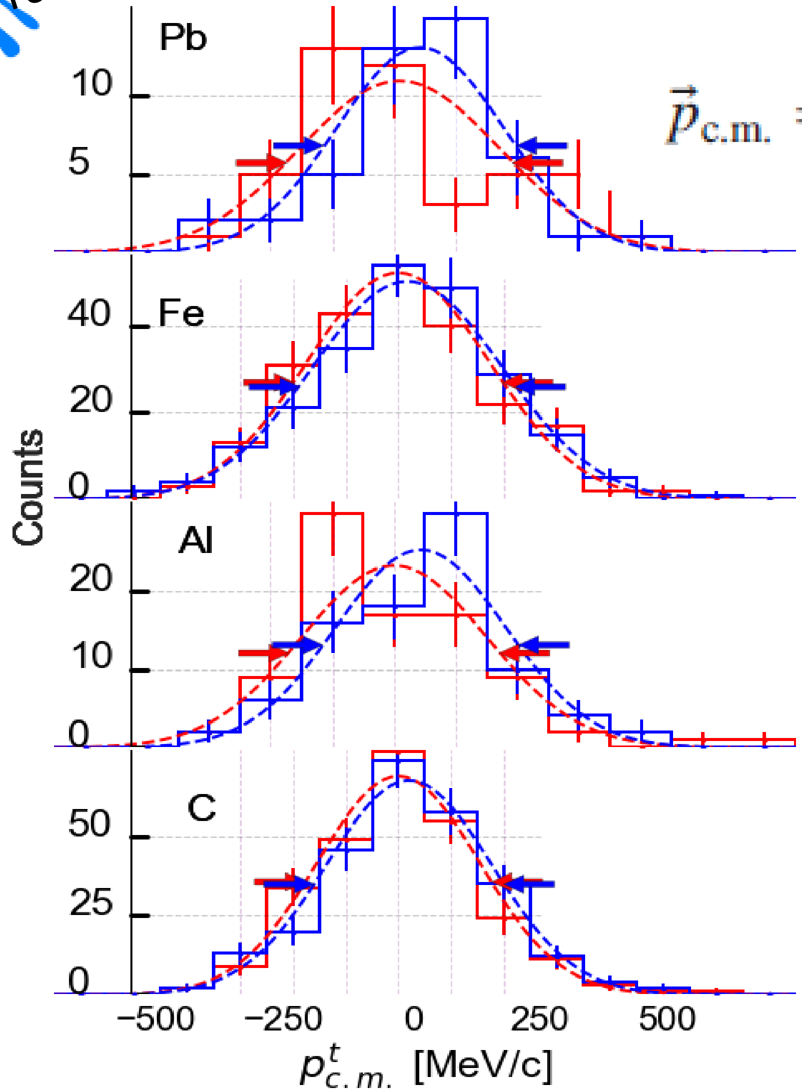
$A(e,e'pp)$



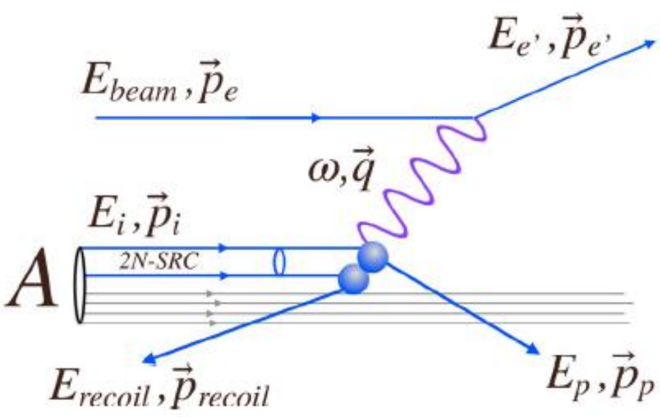


Erez Cohen (TAU), PRL. 121, 092501 (2018)., arXiv: 1805.01981

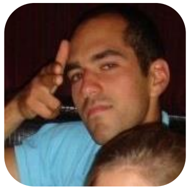
Low Pair C.M. Motion



$$\vec{p}_{\rm c.m.} = \vec{p}_{\rm miss} + \vec{p}_{\rm recoil} = \vec{p}_p - \vec{q} + \vec{p}_{\rm recoil}$$



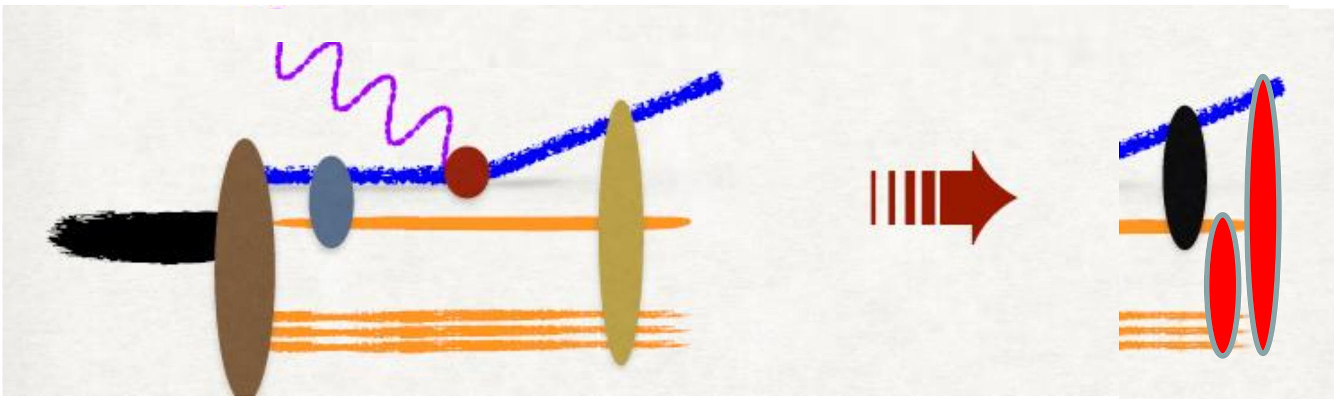
FSI permitted

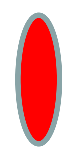


Erez Cohen (TAU), PRL. 121, 092501 (2018)., arXiv: 1805.01981

FSI

For SRC kinematics (large Q^2, $x>1$):

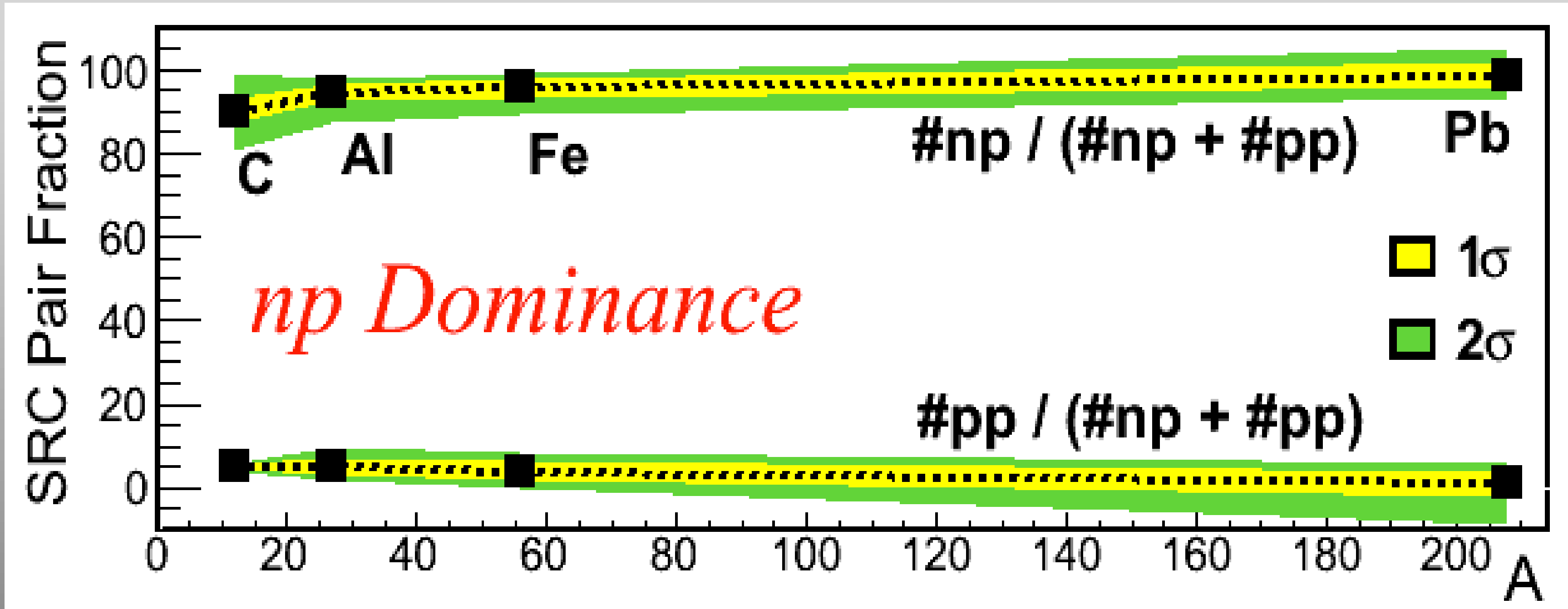




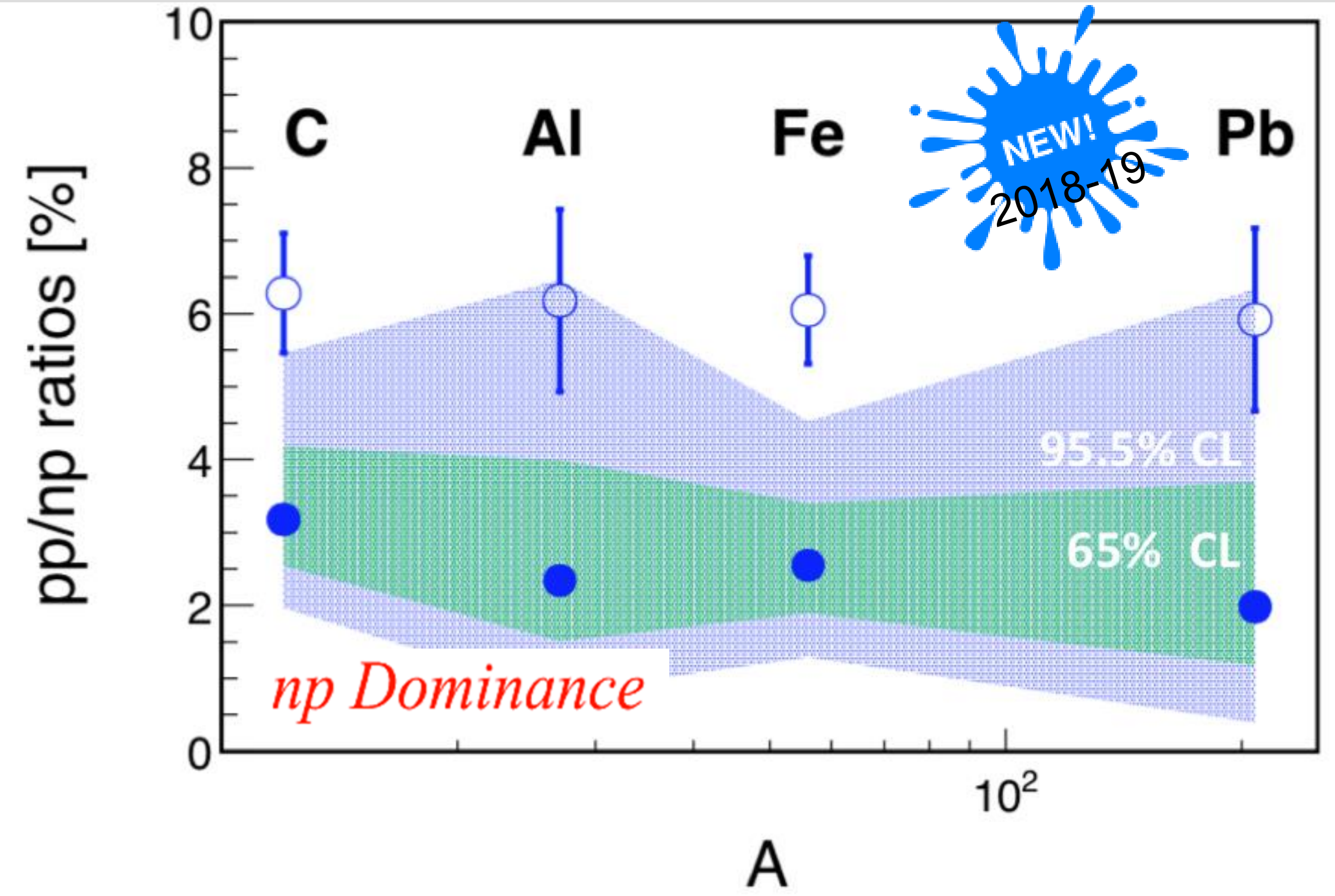
Attenuation SCX:
Calculate using Glauber.

Rescattering within the pair

Does not change the reconstructed CM momentum

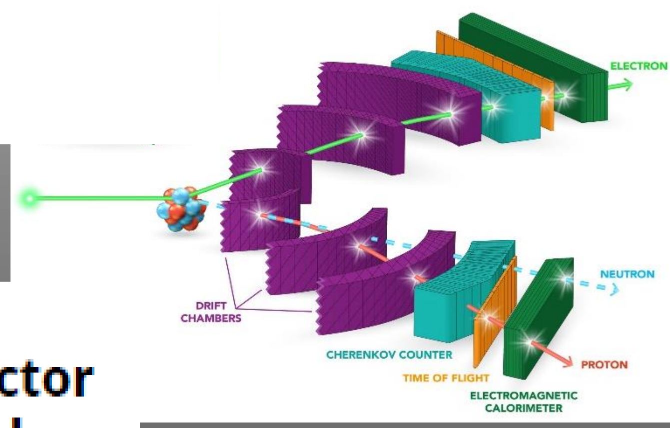


Hen et al., Science 346 (2014)



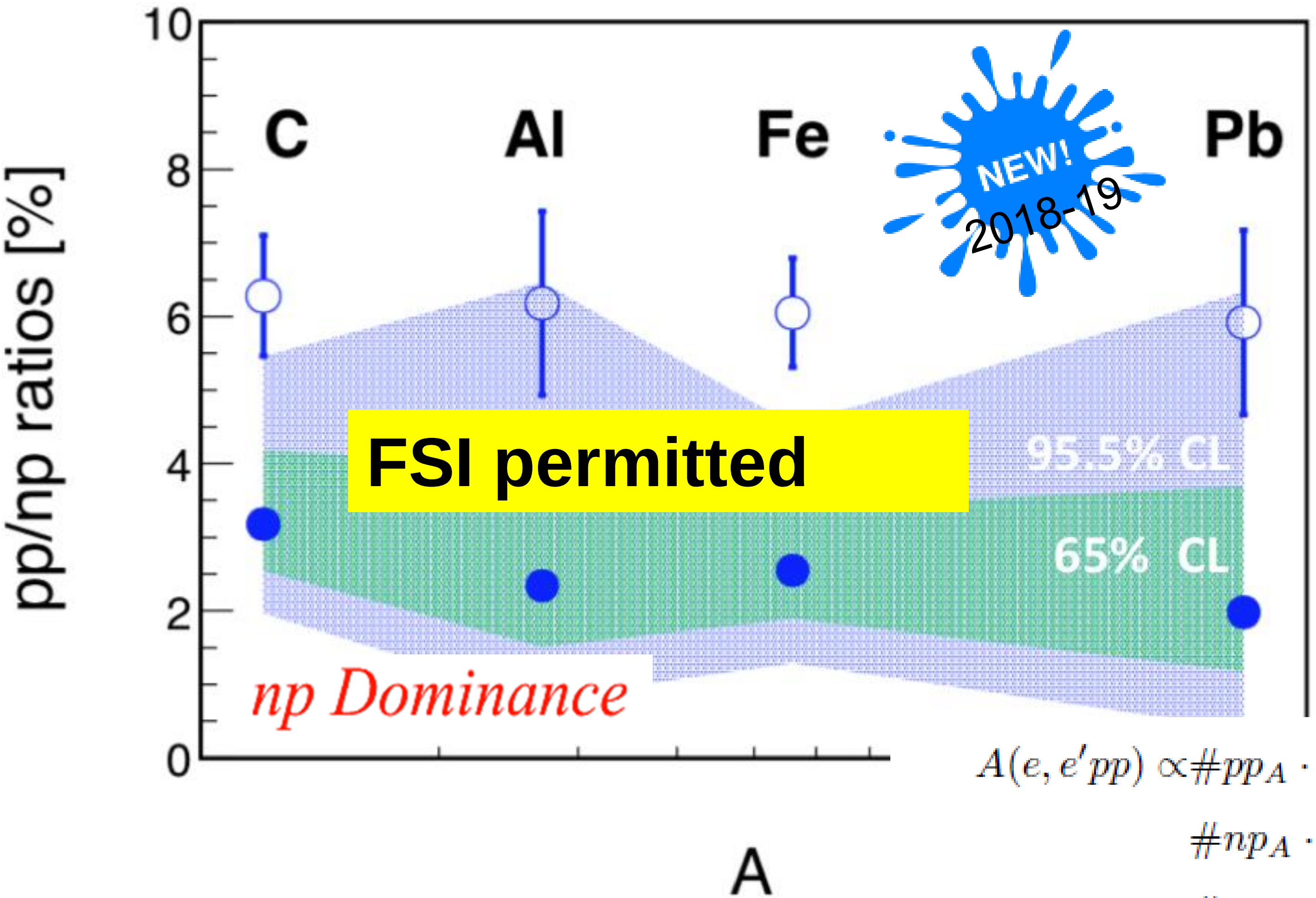
$$A(e,e'np)$$

$$A(e,e'pp)$$



CLAS Detector @ JLab

M. Duer (TAU) , Reviewed by PRL (2019)



$A(e,e'np)$

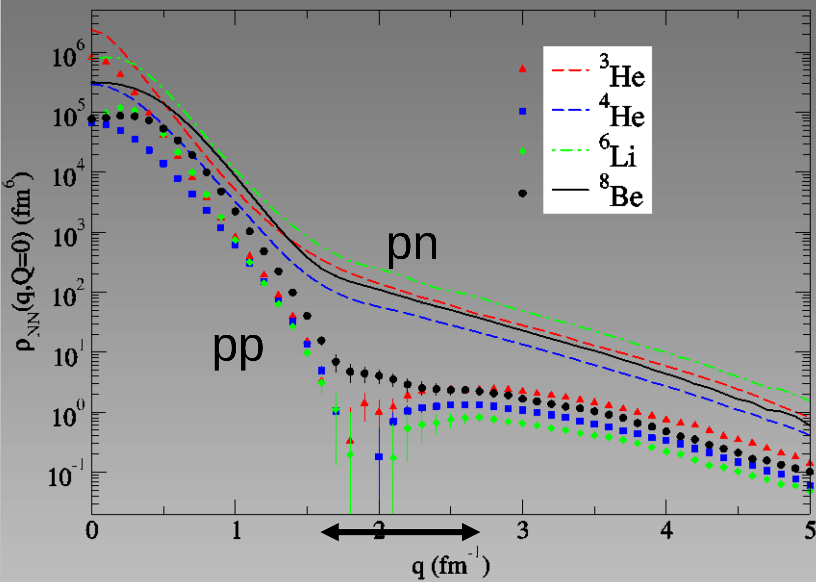
$A(e,e'pp)$

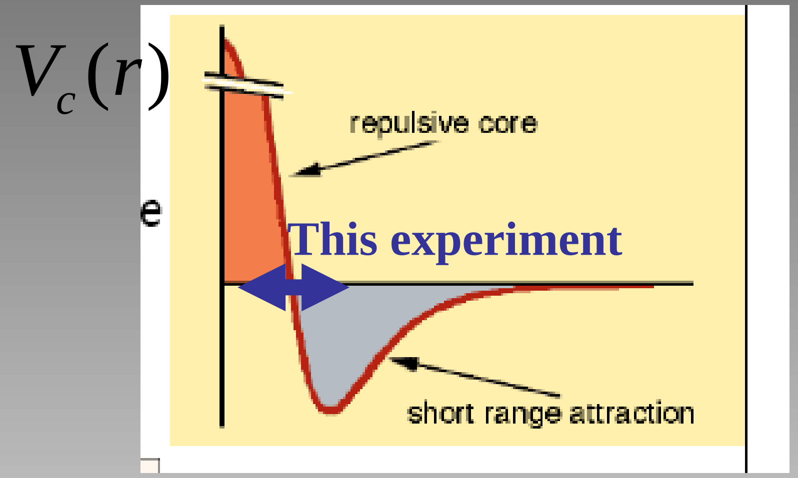
$$
\begin{aligned}
A(e,e'pp) \propto & \#pp_A \cdot 2\sigma_{ep} \cdot P_A^{pp} \cdot T_{A,pp} + \\
& \#np_A \cdot \sigma_{en} \cdot p_A^{[n]p} \cdot T_A^* + \\
& \#pn_A \cdot \sigma_{ep} \cdot P_A^{p[n]} \cdot T_A^*,
\end{aligned}
$$

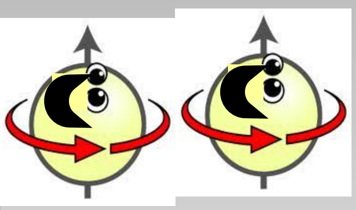
$$
\begin{aligned}
A(e,e'np) \propto & \#np_A \cdot \sigma_{en} \cdot P_A^{np} \cdot T_{A,np} + \\
& \#pp_A \cdot 2\sigma_{ep} \cdot P_A^{[p]p} \cdot T_A^* + \\
& \#nn_A \cdot 2\sigma_{en} \cdot P_A^{n[n]} \cdot T_A^*,
\end{aligned}
$$

M. Duer (TAU) , Reviewed by PRL (2019)

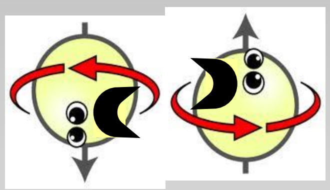
At 300-600 MeV/c there is an excess strength in the np momentum distribution due to the strong correlations induced by the tensor NN potential.







pp- nn- np- SRC



$$V_{NN}(r) = V_c(r) + V_T(r) S_{12}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \sigma_2$$

Only np-SRC

Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007).

Ciofi and Alvioli PRL 100, 162503 (2008).

Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005).

Generalized Nuclear Contact Formalism

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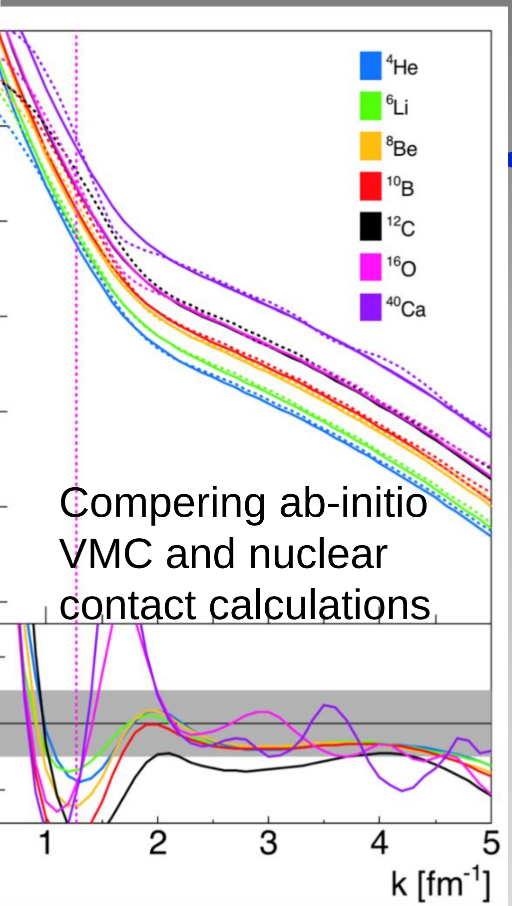
a factorized ansatz

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_\alpha(\boldsymbol{r}_{ij}) A^{\alpha}_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

- Universal function: the zero energy solution to the 2 body problem
- Nucleus (A-2) specific function

Momentum Distribution



Residual

The nuclear contacts and short range correlations in nuclei

R. Weiss,[1] R. Cruz-Torres,[2] N. Barnea,[1] E. Piasetzky,[3] and O. Hen[2]

Phys. Lett. B780 (2018) 211.

A universal description of SRC:

$$n_p(k) \xrightarrow[k\to\infty]{} C^d_{pn}\left|\varphi^d_{pn}(k)\right|^2 + C^0_{pn}\left|\varphi^0_{pn}(k)\right|^2 + 2C^0_{pp}\left|\varphi^0_{pp}(k)\right|^2$$

$l = 0,2\ s = 1\ j = 1$
np pairs

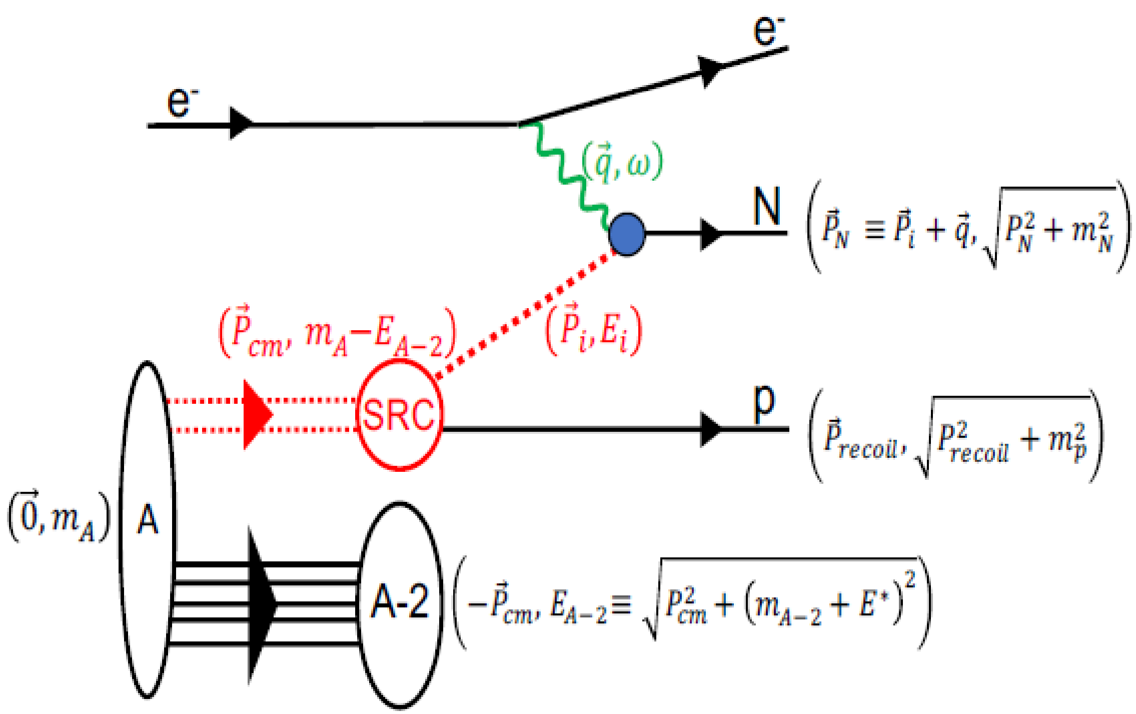
$l = s = j = 0$
pp, nn, np pairs

Friday, March 22: NN Interaction and Knock-out reactions

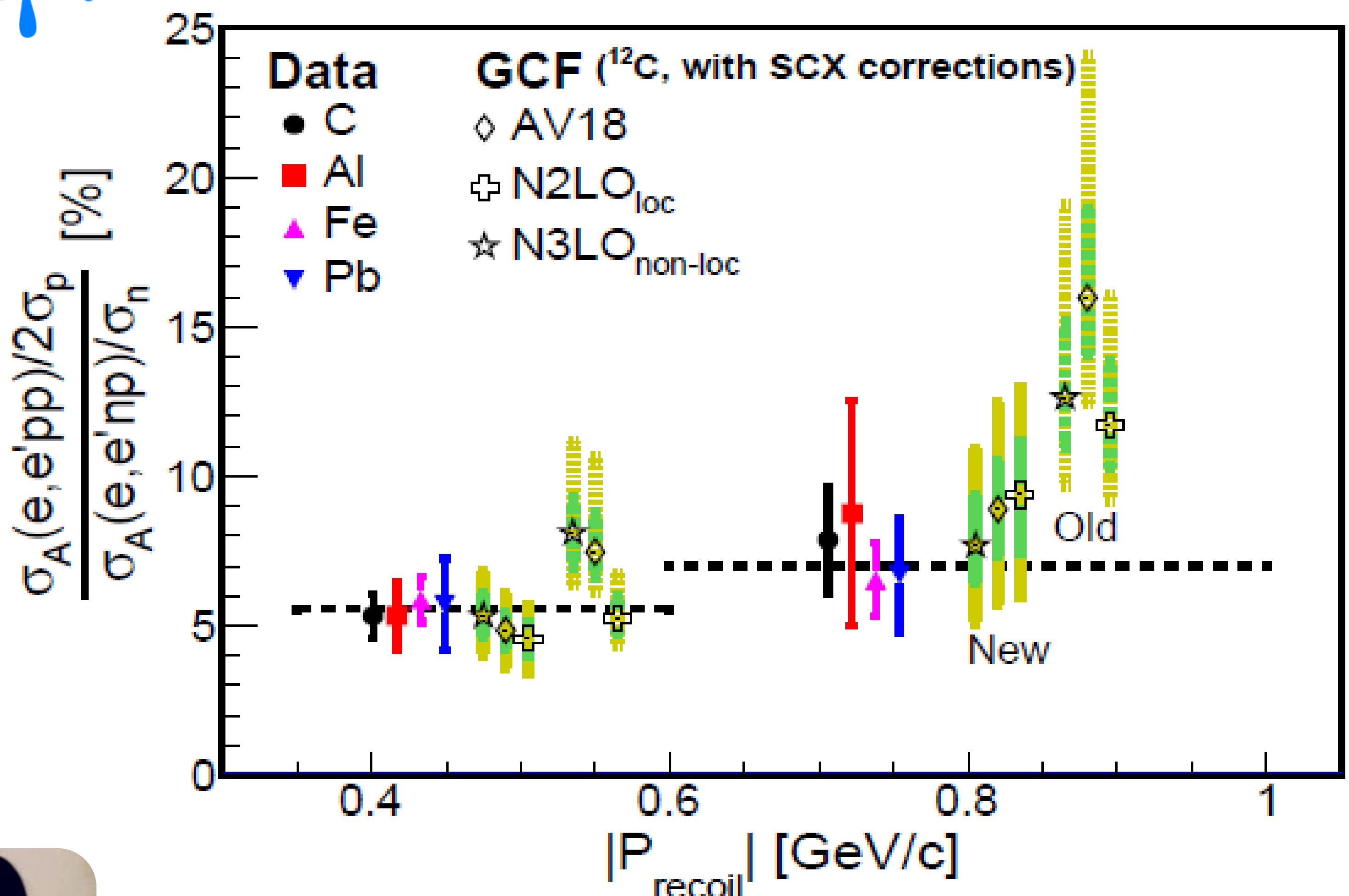
Ronen Weiss	Contact Formalism + Spectral Function

Friday, March 22: NN Interaction and Knock-out reactions

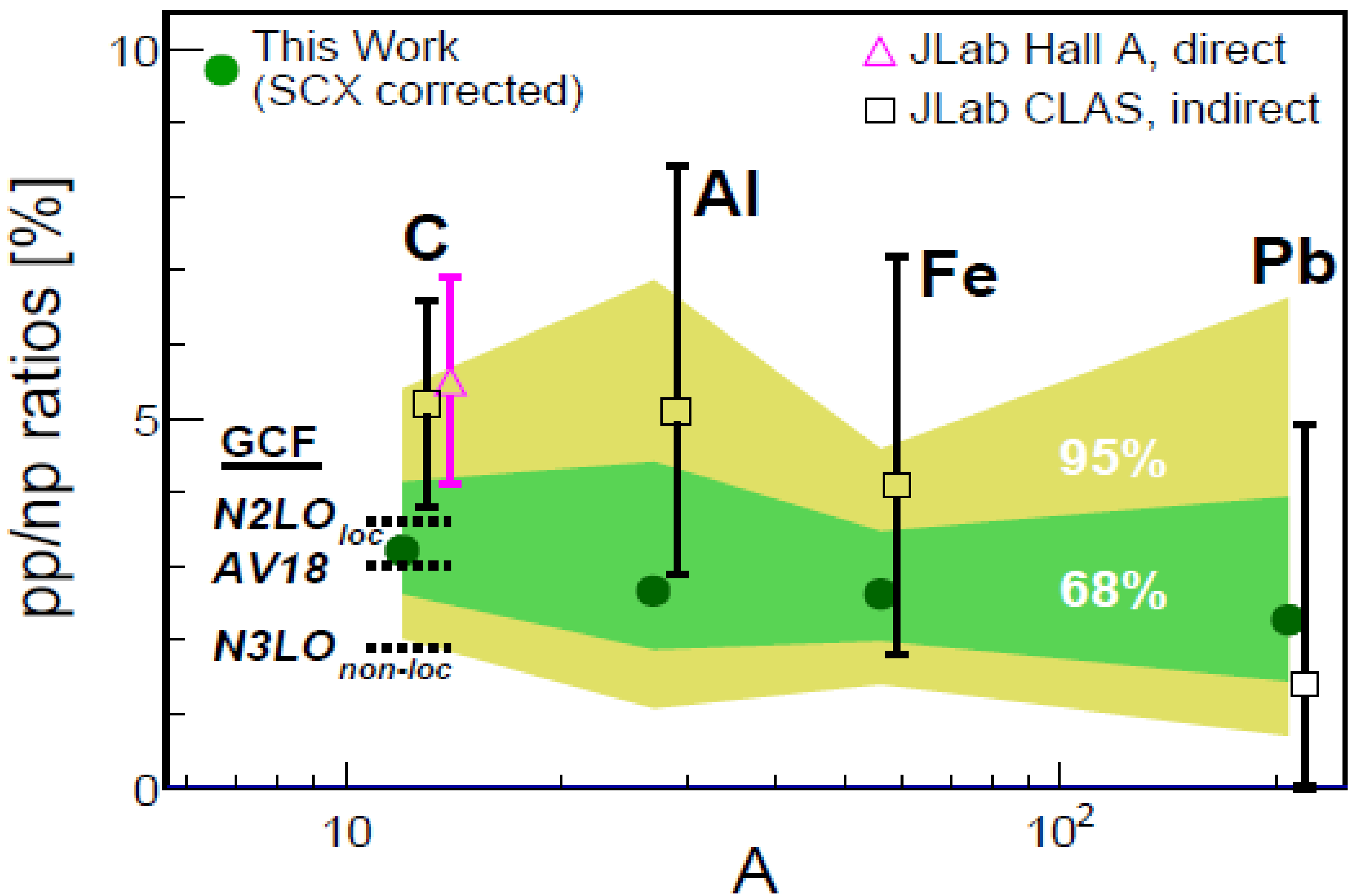
Axel Schmidt	GCF Generator



NEW!



M. Duer (TAU) , Reviewed by PRL (2019)



11:00 - 11:20	17+3'	Wim Cosyn	Transparency: neutrons & two-nucleon

Who are the parents of the 2N-SRC pairs ?

Asymmetric nuclei N>Z:

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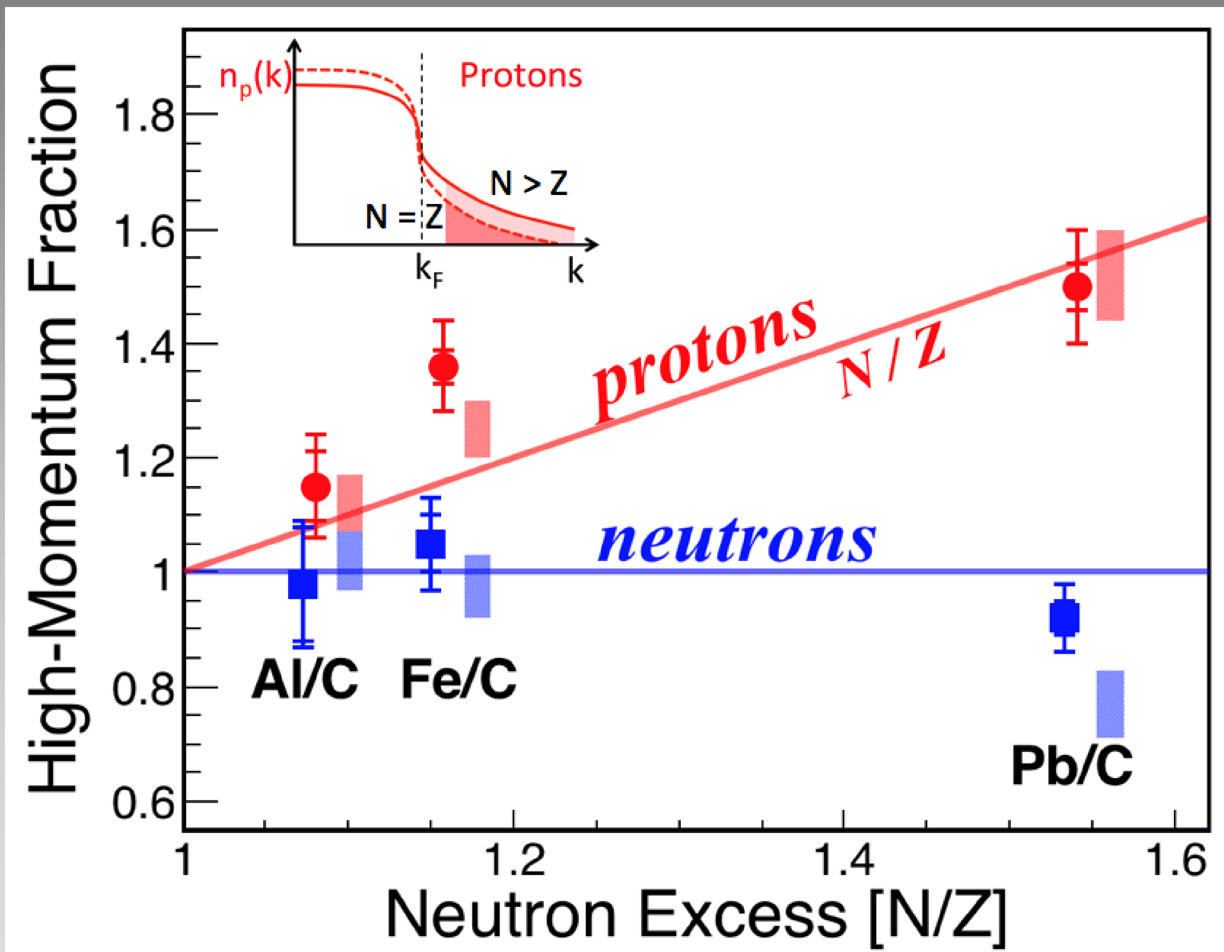
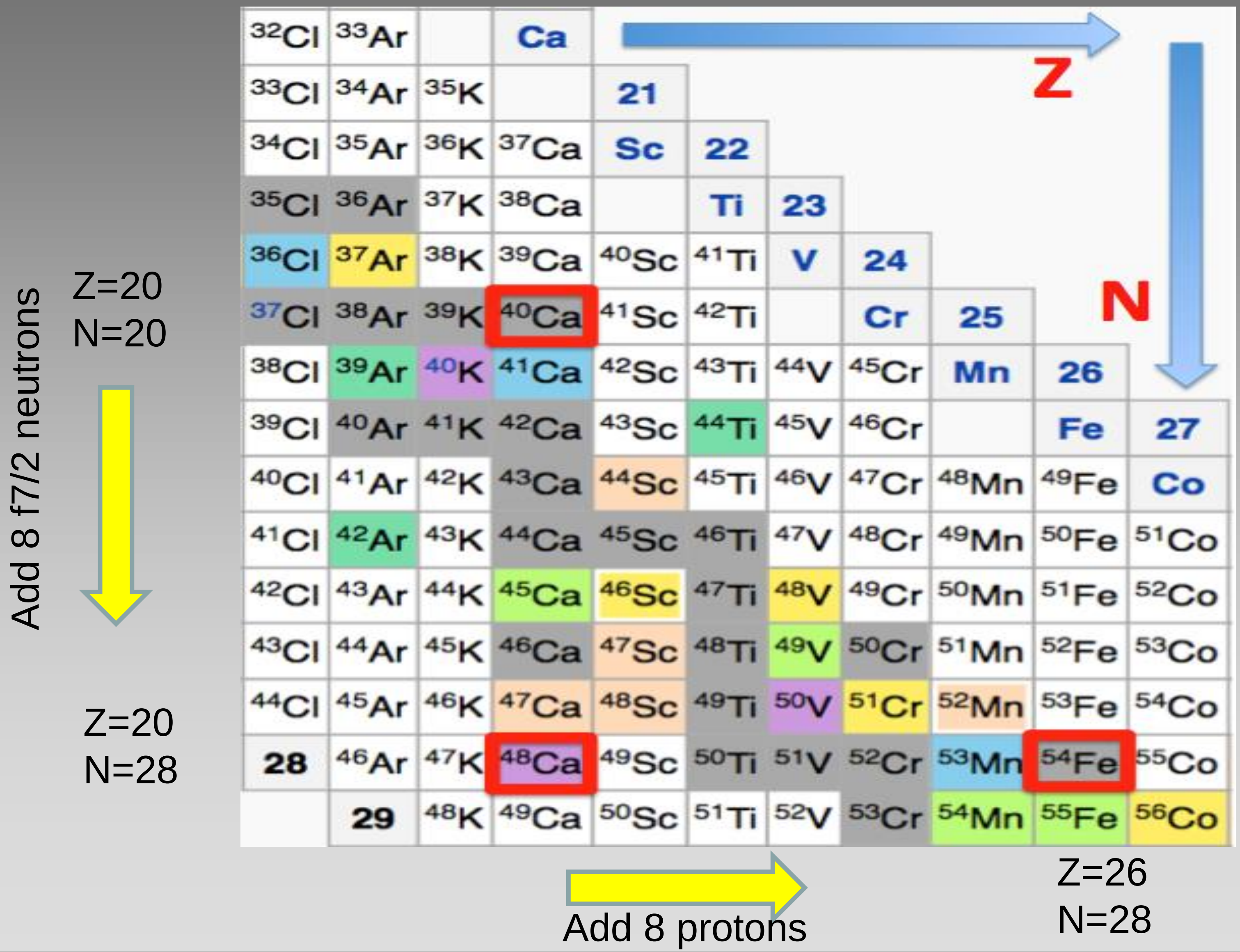
Correlation Probability:
Neutrons saturate Protons grow

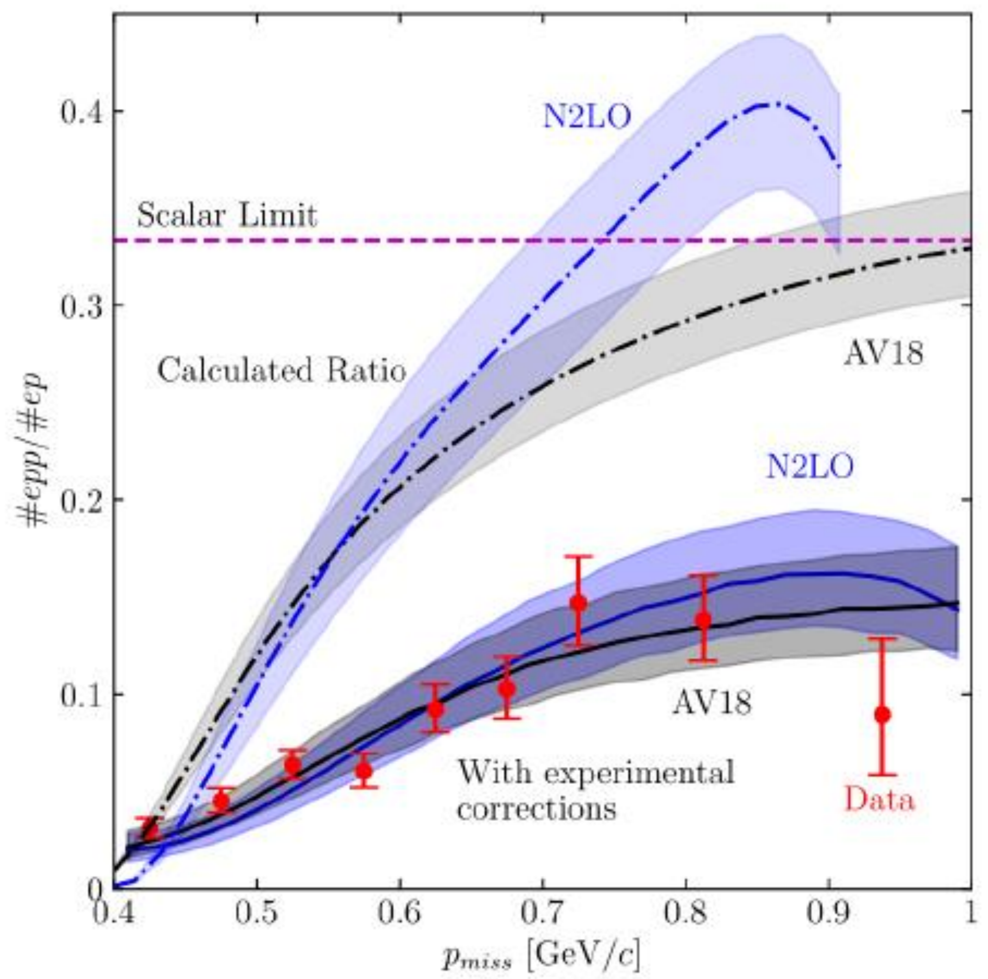


M. Duer et al. (CLAS Collaboration), Nature, 560 (2018) 617-621

Asymmetric nuclei N>Z:
Who are the parents of the 2N-SRC pairs ?



From tensor to scaler dominance

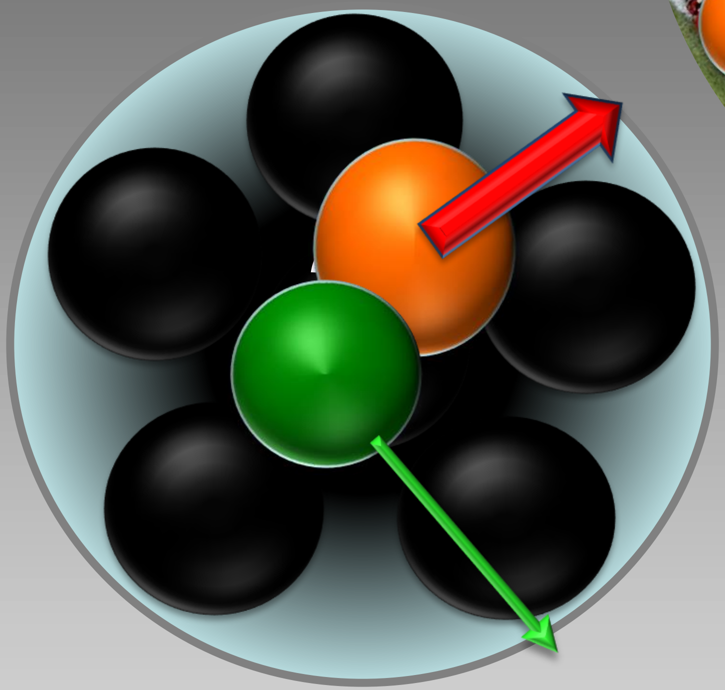


Probing the strong nuclear interaction at neutron-star densities

A. Schmidt et al. (CLAS Collaboration)

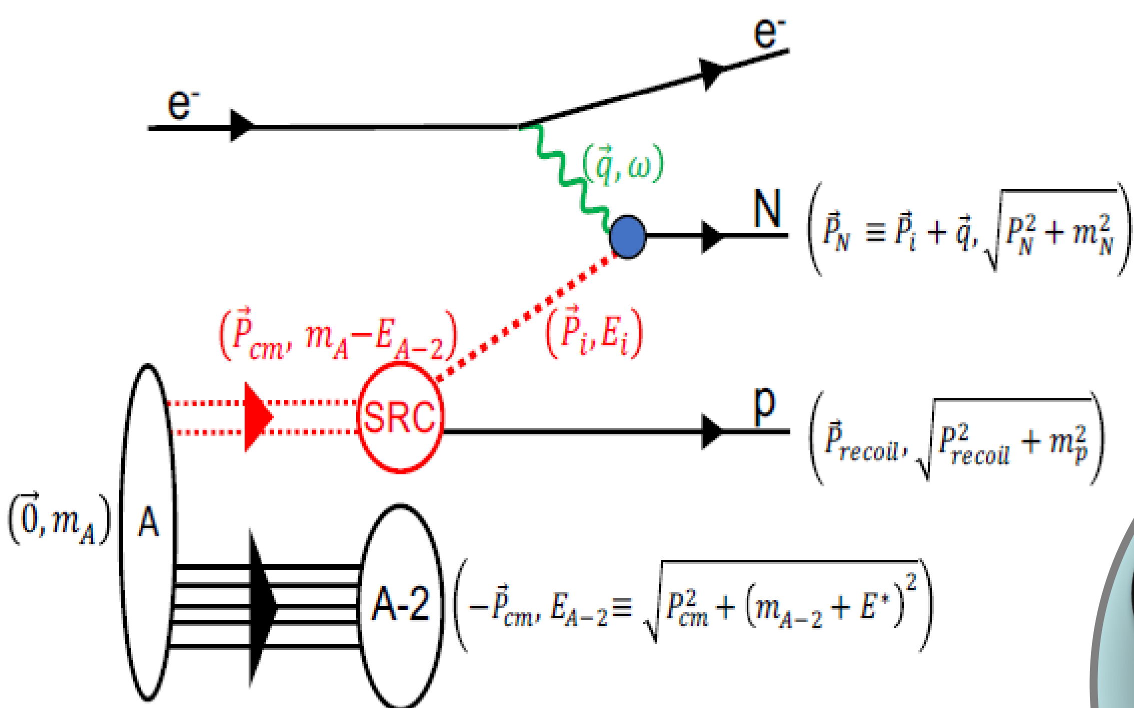
See a talk by Axel on Friday

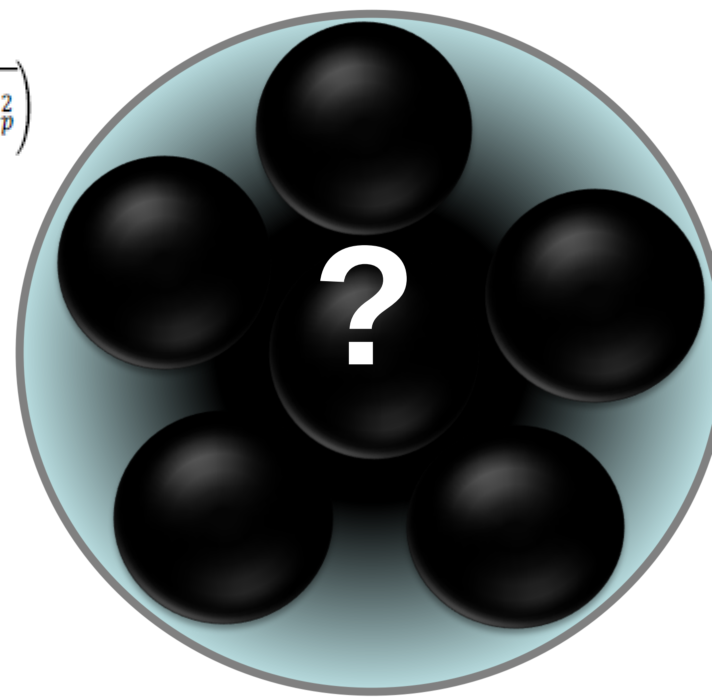
triple – coincidence measurements



Friday, March 22: NN Interaction and Knock-out reactions

Axel Schmidt	GCF Generator





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Inverse kinematics

leading protons

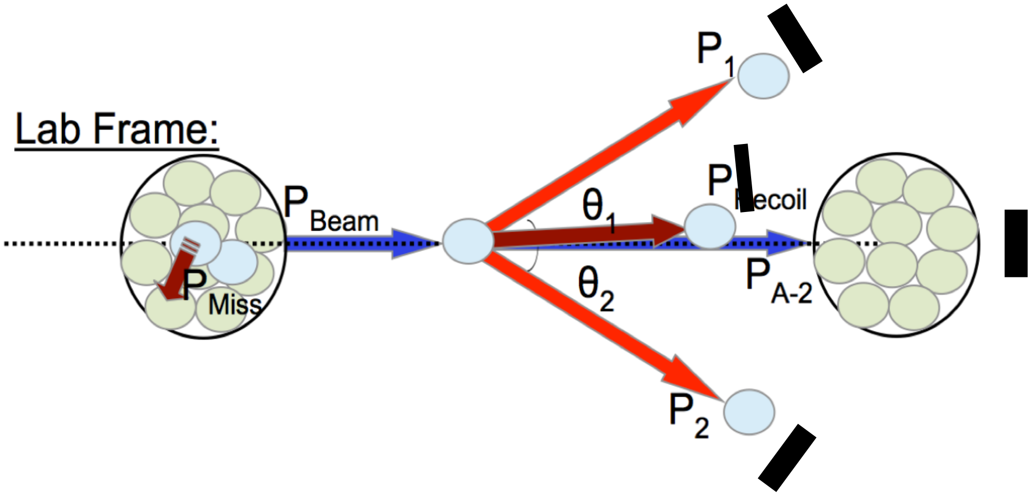
target proton

A-2

nuclear beam

recoil proton

SRC@JINR a



Inverse kinematics

Super exclusive measurement!

Detect (4 particles):

the scattered probe,

the knocked-out nucleon,

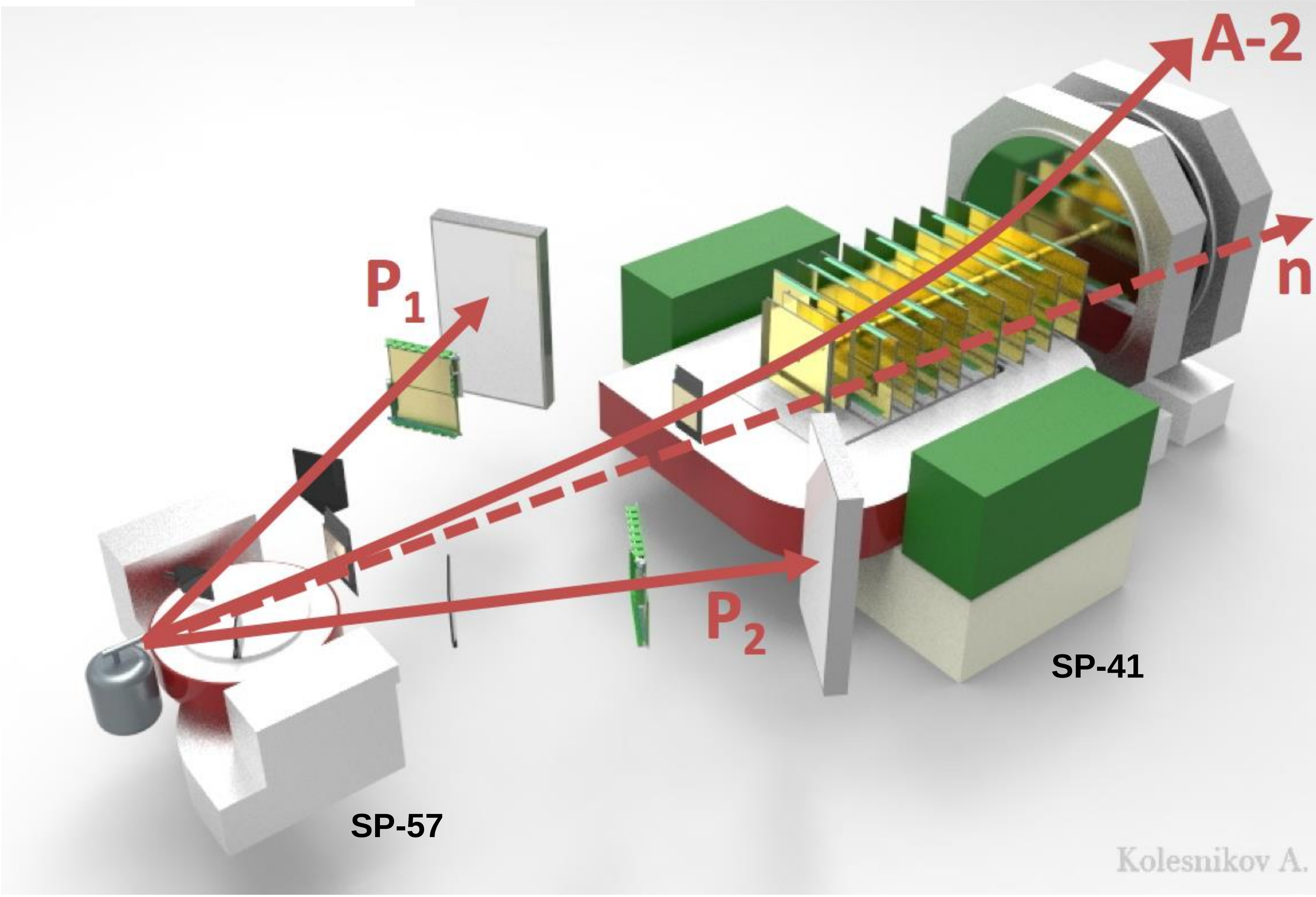
the recoil,

and the A-2 system!

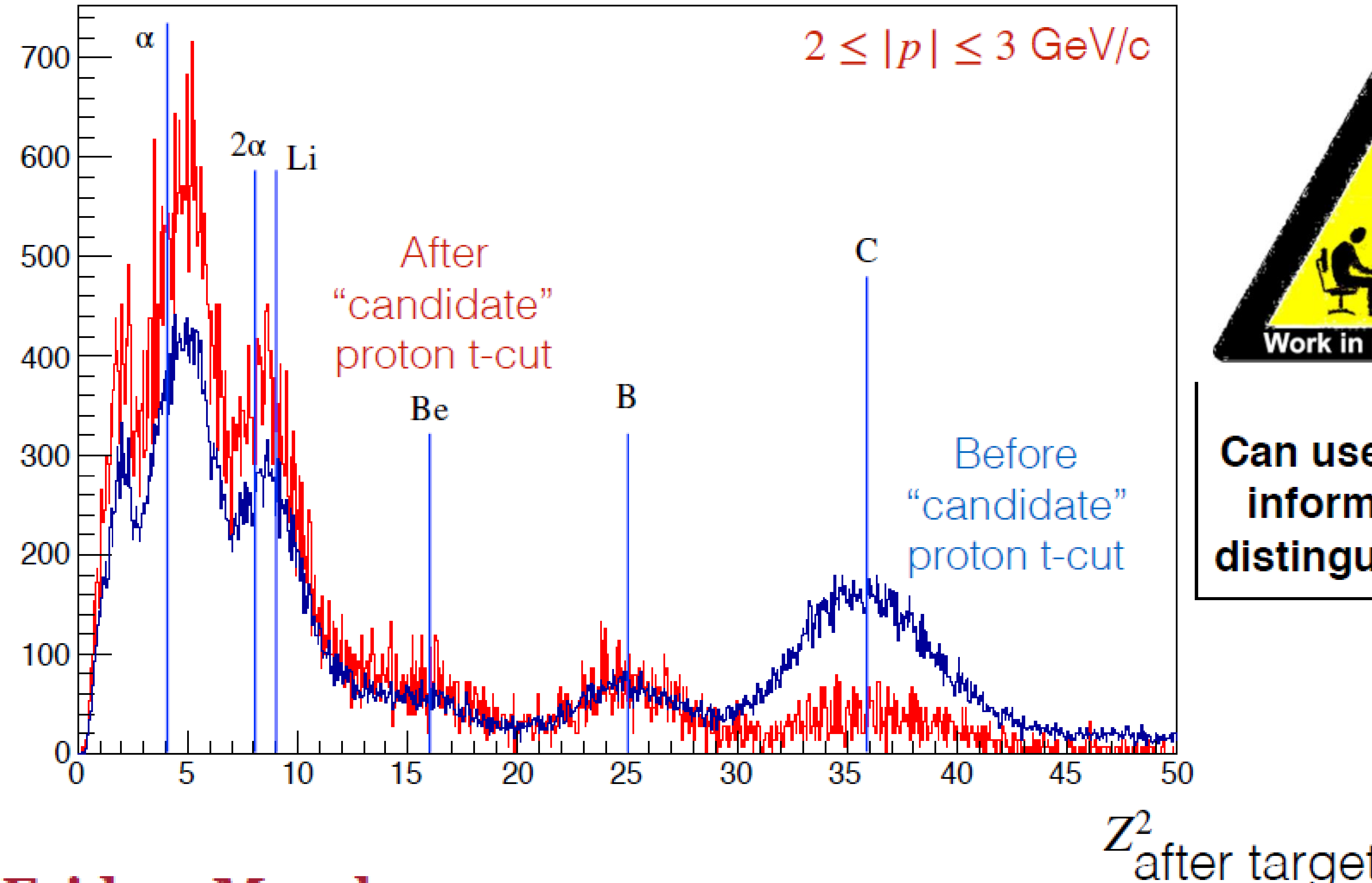
A(p, 2p n A-2) – Dubna

SRC@JINR a

Experimental setup



$$p + C \rightarrow p^{?} + p^{?} + X$$



Can use tracking information to distinguish Li, 2α

Friday, March 22

14:40 - 15:00	17+3'	Efrain Segarra	A-2 in SRC

Part II: SRC as a way to study NN interaction

Friday, March 22: NN Interaction and Knock-out reactions

Time		Presenter	Title
9:00 - 9:20	15+5'	Robert Wiringa	High-momentum in NN interactions
9:20 - 9:40	17+3'	Dick Furnstahl	EFT potentials above cutoff (2N truncation and effective 3N connstruction)
9:40-10:00	17+3'	Omar Benhar	Potentials
10:10 - 10:30	30'	Guided Discussion: high-resolutions high-momentum: the role and properties of 2N and 3N interactions	
10:30 - 11:00		Morning Coffee Break	
11:00 - 11:30	25+5'	Diego Lonardoni	QMC overview + two-body densities
11:30 - 11:50	17+3'	Alessandro Lovato	spectral function from two-body densities
11:50 - 12:10	17+3'	Ronen Weiss	Contact Formalism + Spectral Function
12:10 - 12:30	20'	Guided Discussion: High-momentum vs. short distances; Ab-initio vs. factorized theory	
12:30 - 14:00		Lunch Break	
14:00 - 14:25	20+5'	Speaker TBD	GCF Generator
14:25 - 14:40	12+3'	Igor Korover	(e,e'pn) in heavy nuclei
14:40 - 15:00	17+3'	Efrain Segarra	A-2 in SRC
15:00 - 15:30	30'	Discussion: probing the NN interaction with SRC data	

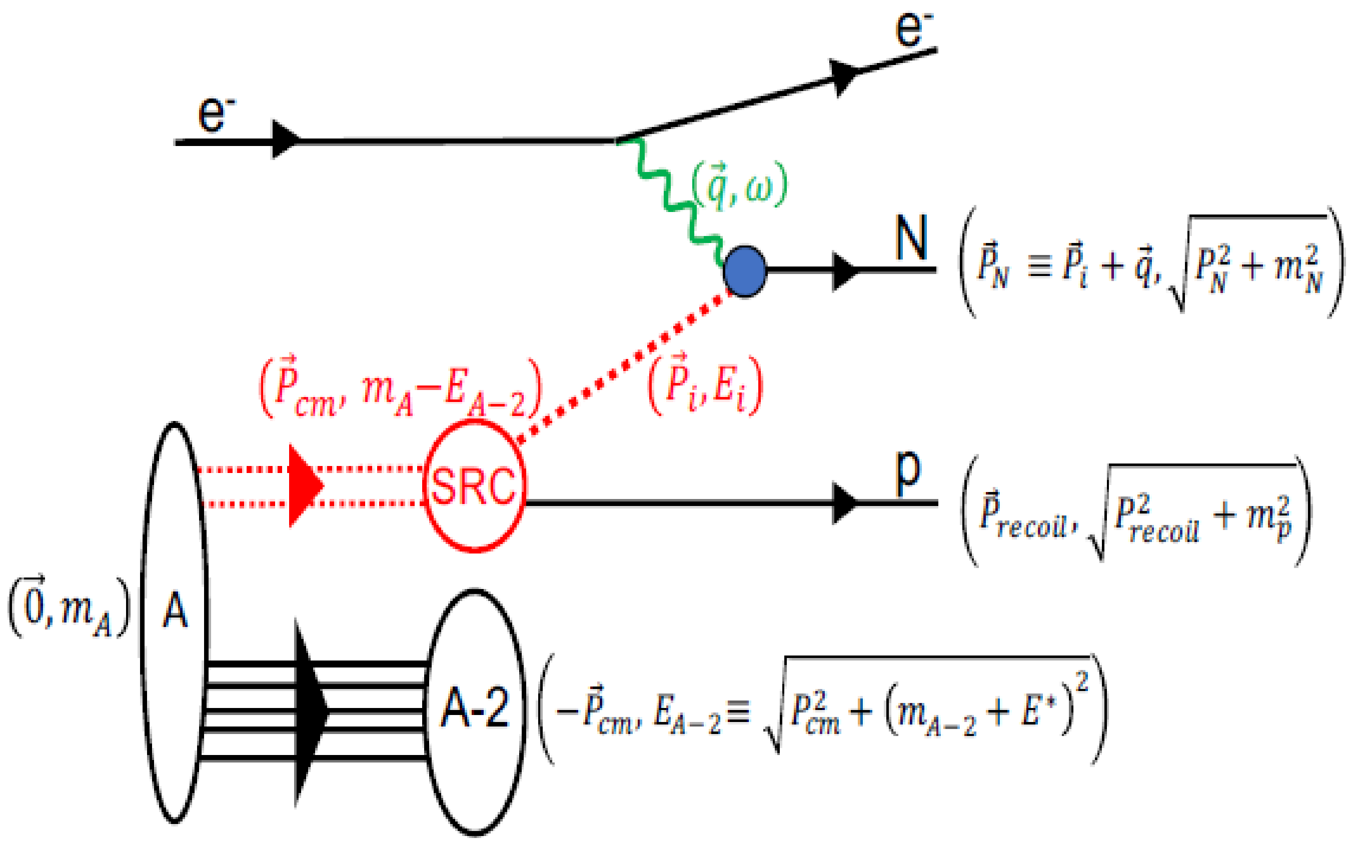
Study NN Interaction using SRC

What's needed?

- spectral function from NN interaction
- FSI under control
- Acceptance /efficiency under control

$$\frac{d^4\sigma}{d\Omega_{k'}\, d\epsilon'_k\, d\Omega_{p'_1}\, d\epsilon'_1} = p'_1 \epsilon'_1 \sigma_{eN} S^N(\boldsymbol{p}_1, \epsilon_1)$$

Similar expression for triple coincidence



Friday, March 22:

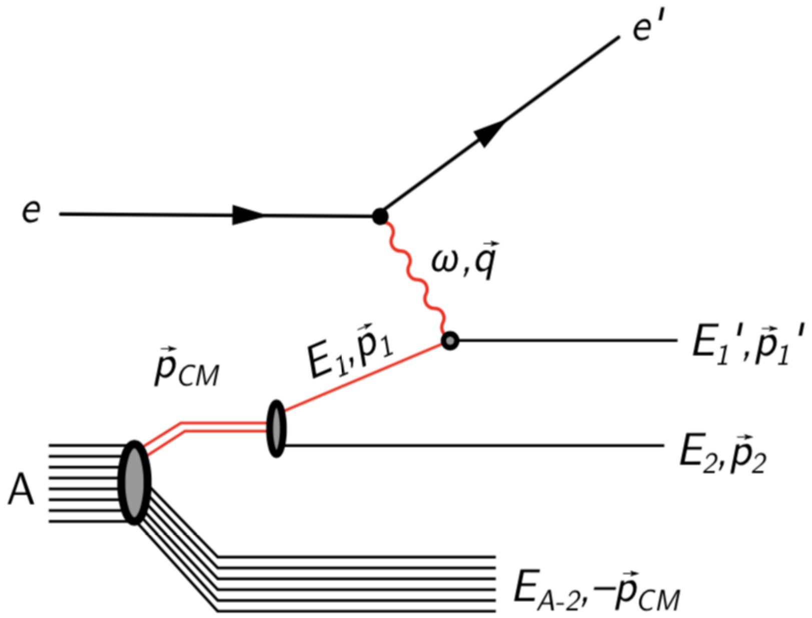
Axel Schmidt	GCF Generator

What's needed?

- Acceptance /efficiency under control

We bring the theory to the data:

- Generate A(e,e'NN) events following assumed reaction mechanism.
- Run through detector simulation.
  ⇒ Reject events outside the acceptance; weigh by detection efficiency.
- Weigh by calculated cross-sections and including reaction effects (transparency, single charge exchange)
- Apply event selection cuts and overlay on data distributions.



What's needed?

- spectral function from NN interaction

Sum of pairs:

$$\begin{aligned} S^p(p,\varepsilon) \quad = \quad & C_{pn}^{s=1} \cdot S_{pn}^{s=1}(p,\varepsilon) + \\ & C_{pn}^{s=0} \cdot S_{pn}^{s=0}(p,\varepsilon) + \\ & 2C_{pp}^{s=0} \cdot S_{pp}^{s=0}(p,\varepsilon) \end{aligned}$$

Each pair is convoluted with c.m. motion:

$$S_{ab}^{\alpha} = \frac{1}{4\pi}\int \frac{d\boldsymbol{p}_2}{(2\pi)^3}\delta(f(\boldsymbol{p}_2))\underbrace{\left|\tilde{\varphi}_{ab}^{\alpha}(|(\boldsymbol{p}_1-\boldsymbol{p}_2)/2|)\right|^2}_{\text{Relative}}\underbrace{n_{ab}^{\alpha}(\boldsymbol{p}_1+\boldsymbol{p}_2)}_{\text{c.m.}}$$

Relative
AV18
EFT

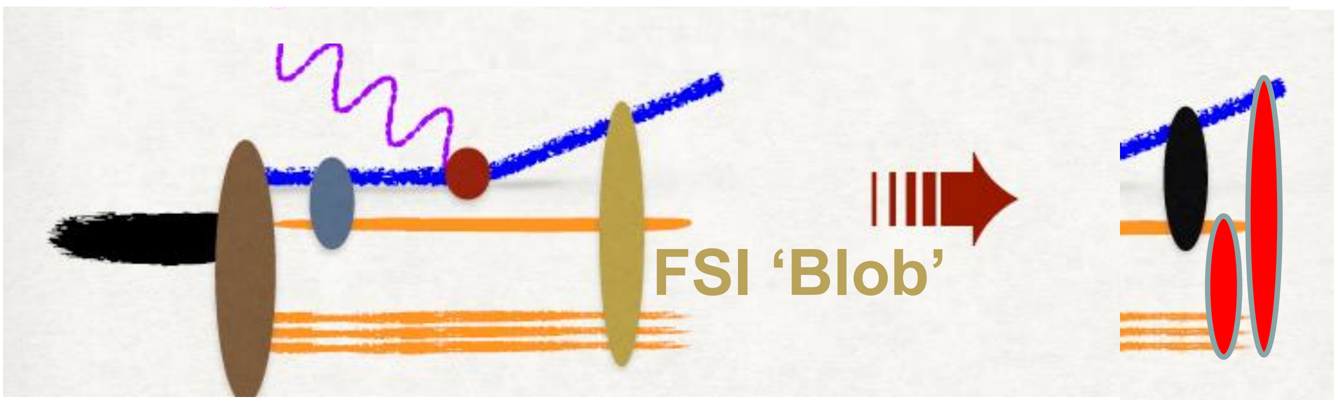
c.m.

Weiss, Phys. Lett. B (2018); Cruz Torres, Phys. Lett B (2018); Weiss arXiv: 1806.10217 (2

What's needed?

- FSI under control

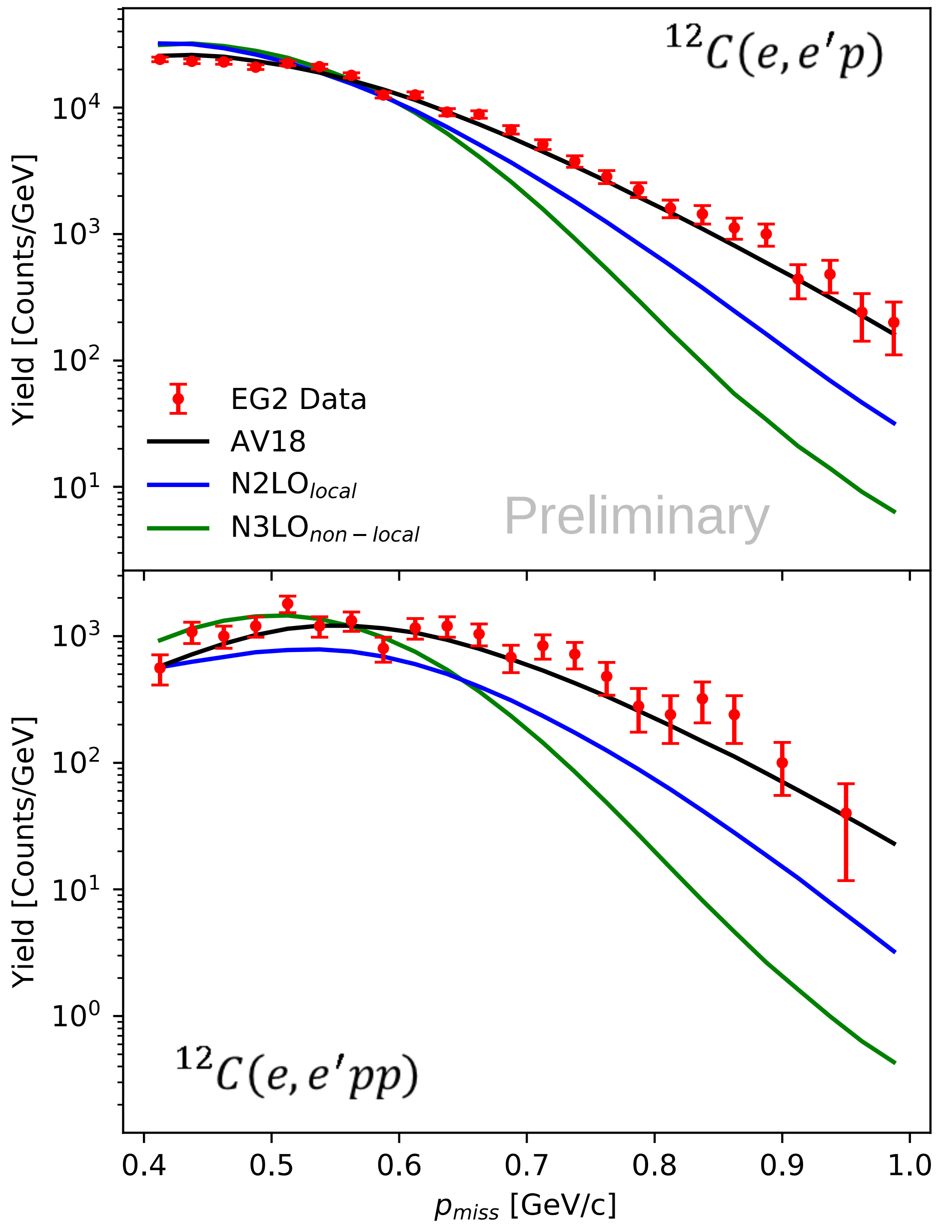
For SRC kinematics (large Q^2, $x>1$)



Pair rescattering:
Minimize by choosing correct kinematics

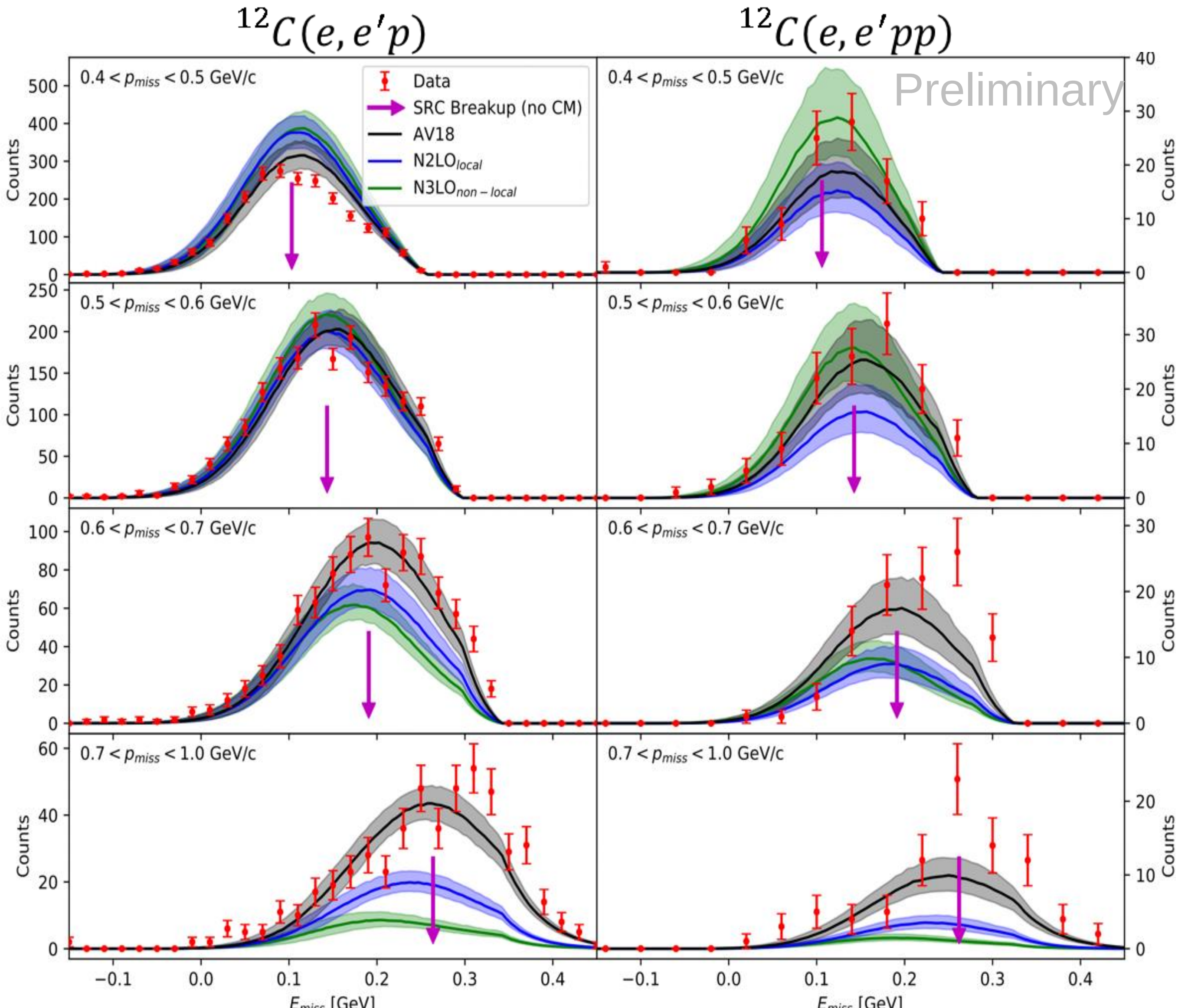
Attenuation:
Calculate using Glauber.

NEW!



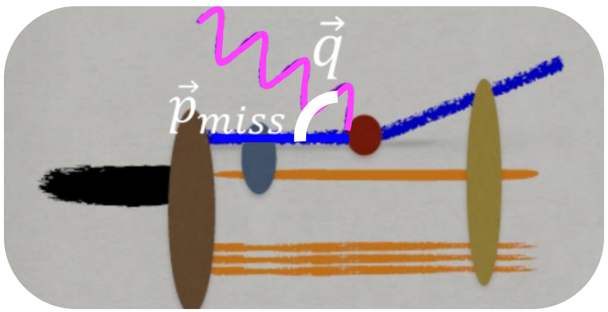
A. Schmidt

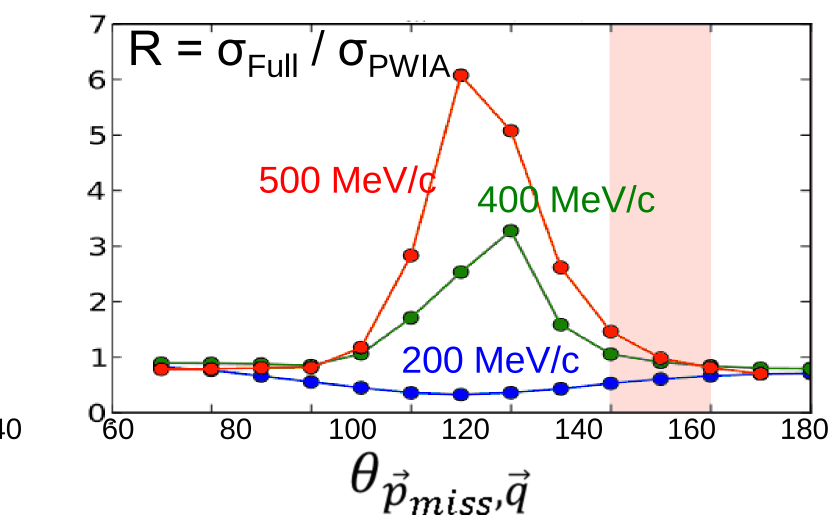
NEW!

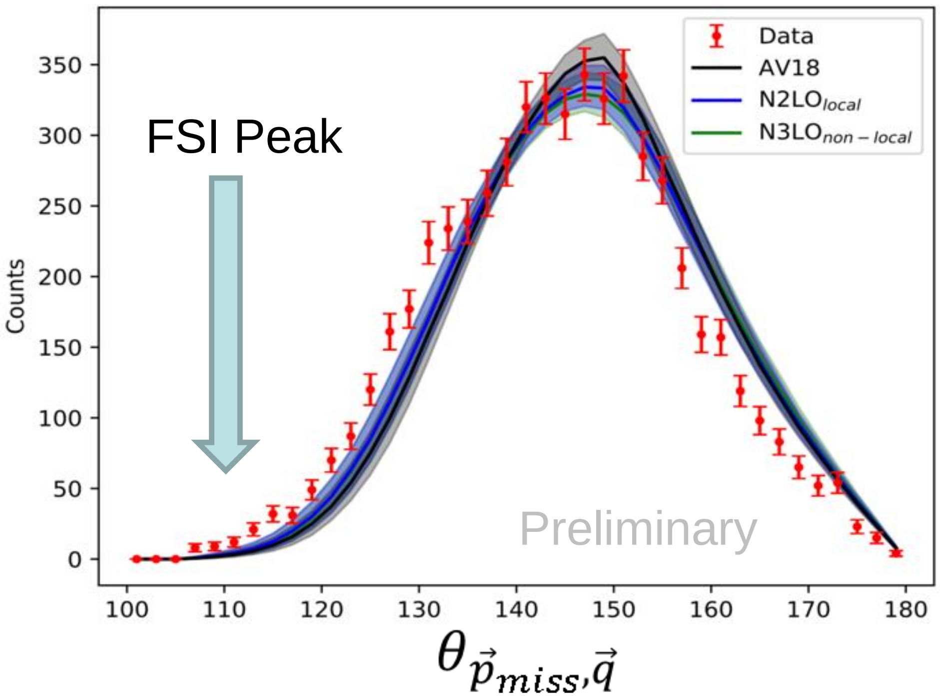


A. Schmidt

No evidence of FSI enhancements

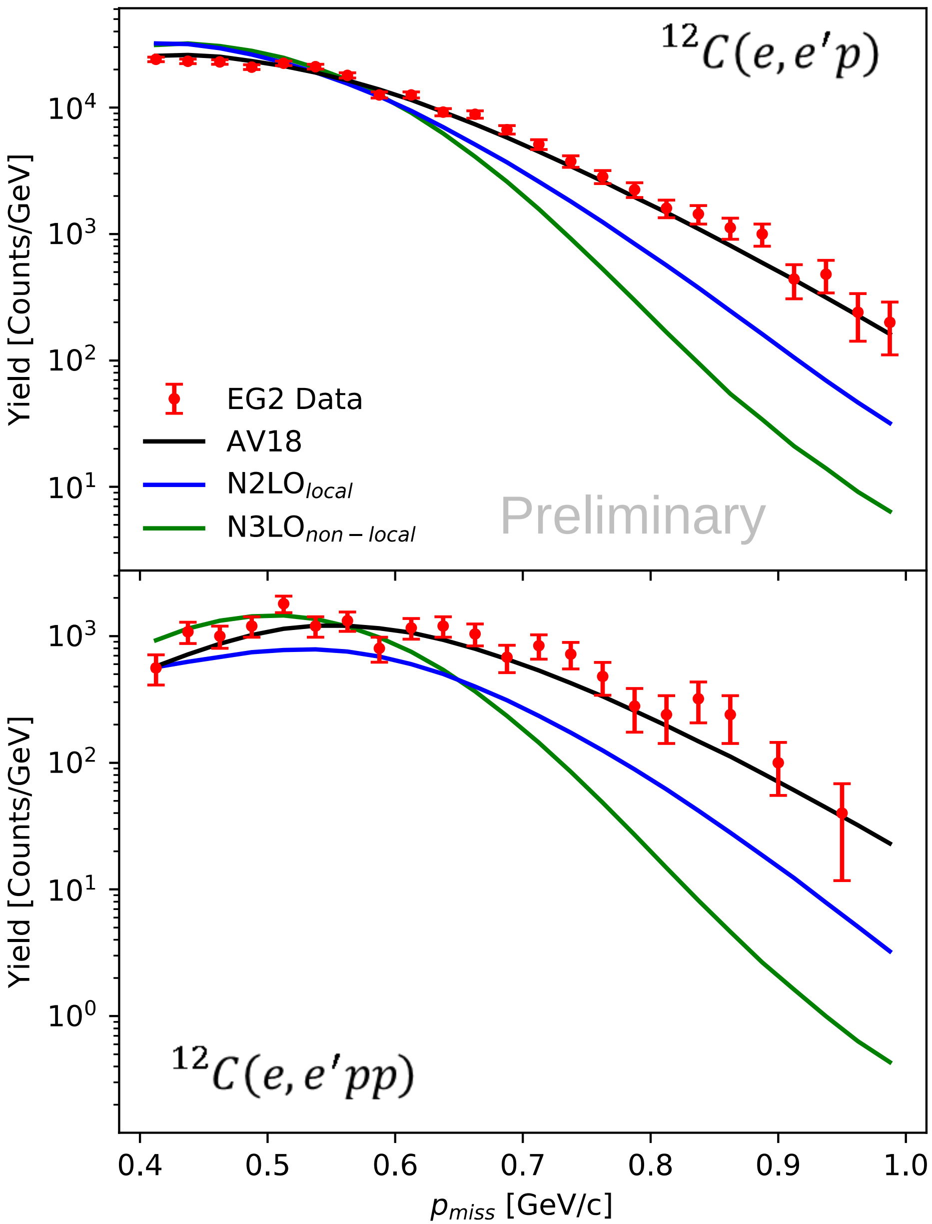






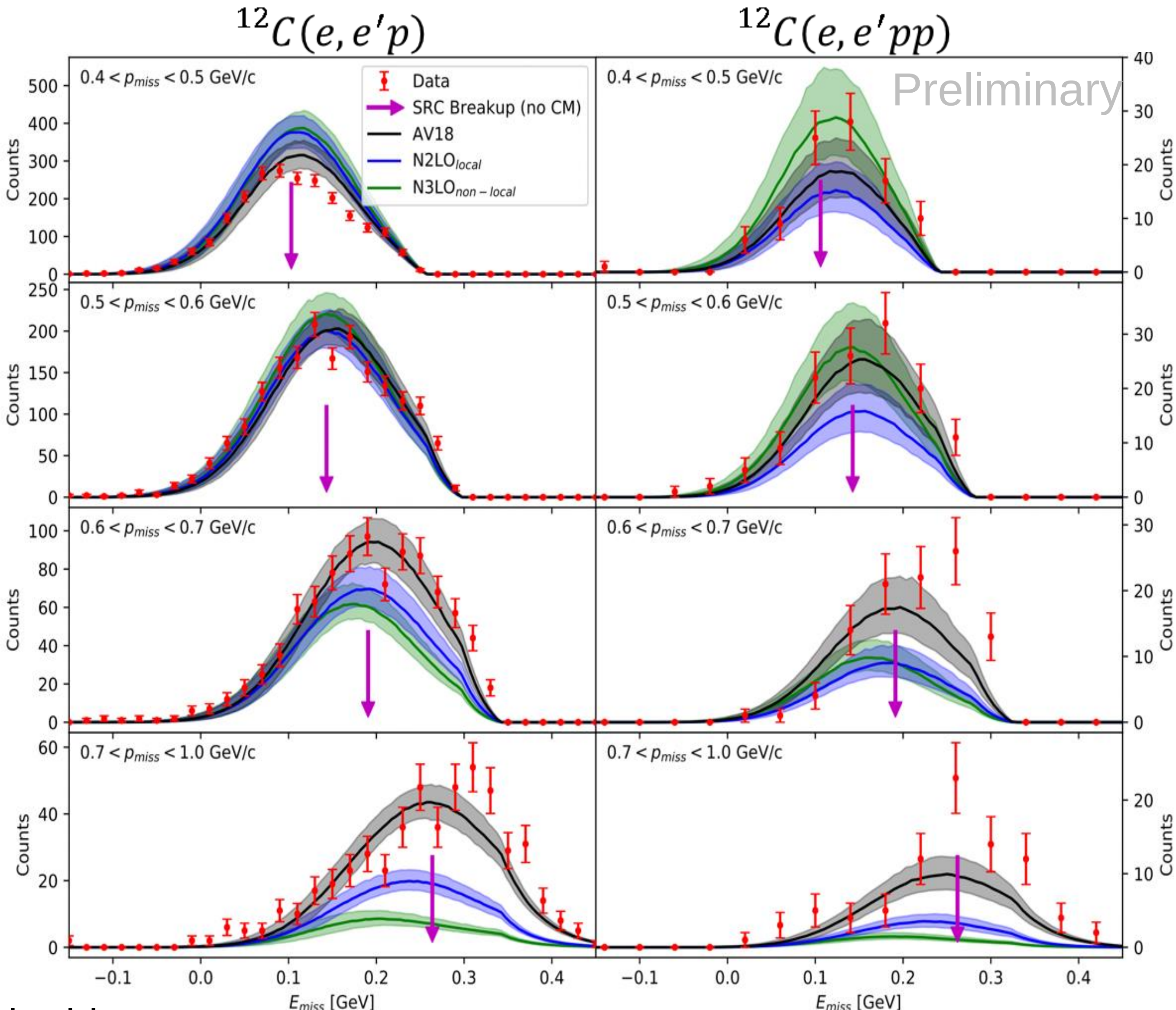

Landing in EWR

Reaching the Repulsive Core



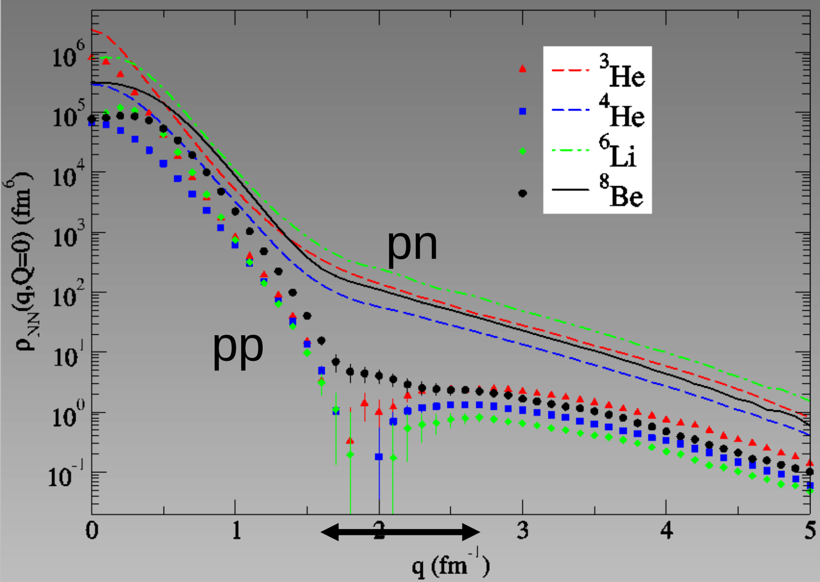
A. Schmidt

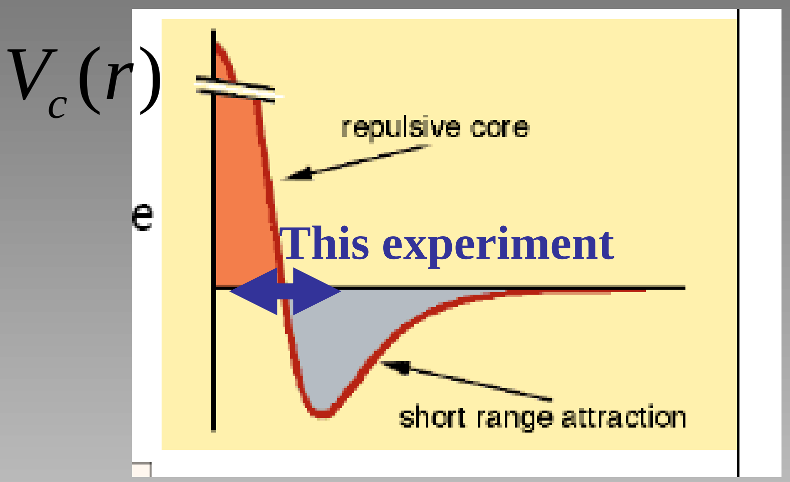
Reaching the Repulsive Core



A. Schmidt

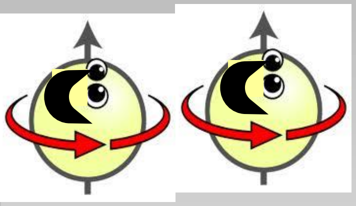
At 300-600 MeV/c there is an excess strength in the np momentum distribution due to the strong correlations induced by the tensor NN potential.



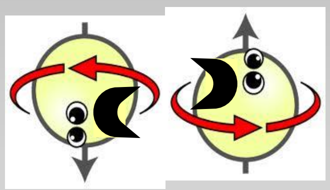


$$V_{NN}(r) = V_c(r) + V_T(r) S_{12}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \sigma_2$$



pp- nn- np- SRC



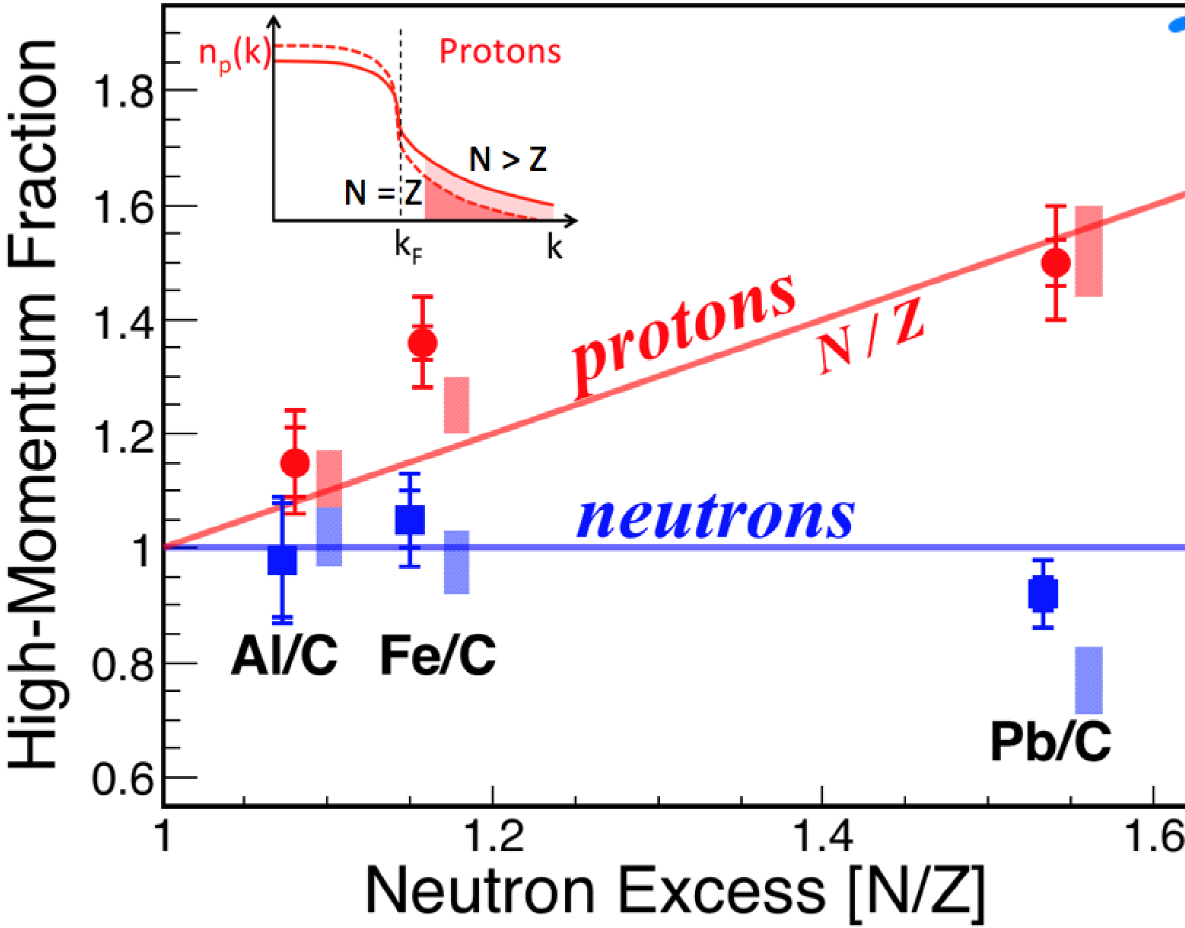
Only np-SRC

Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007).

Ciofi and Alvioli PRL 100, 162503 (2008).

Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005).

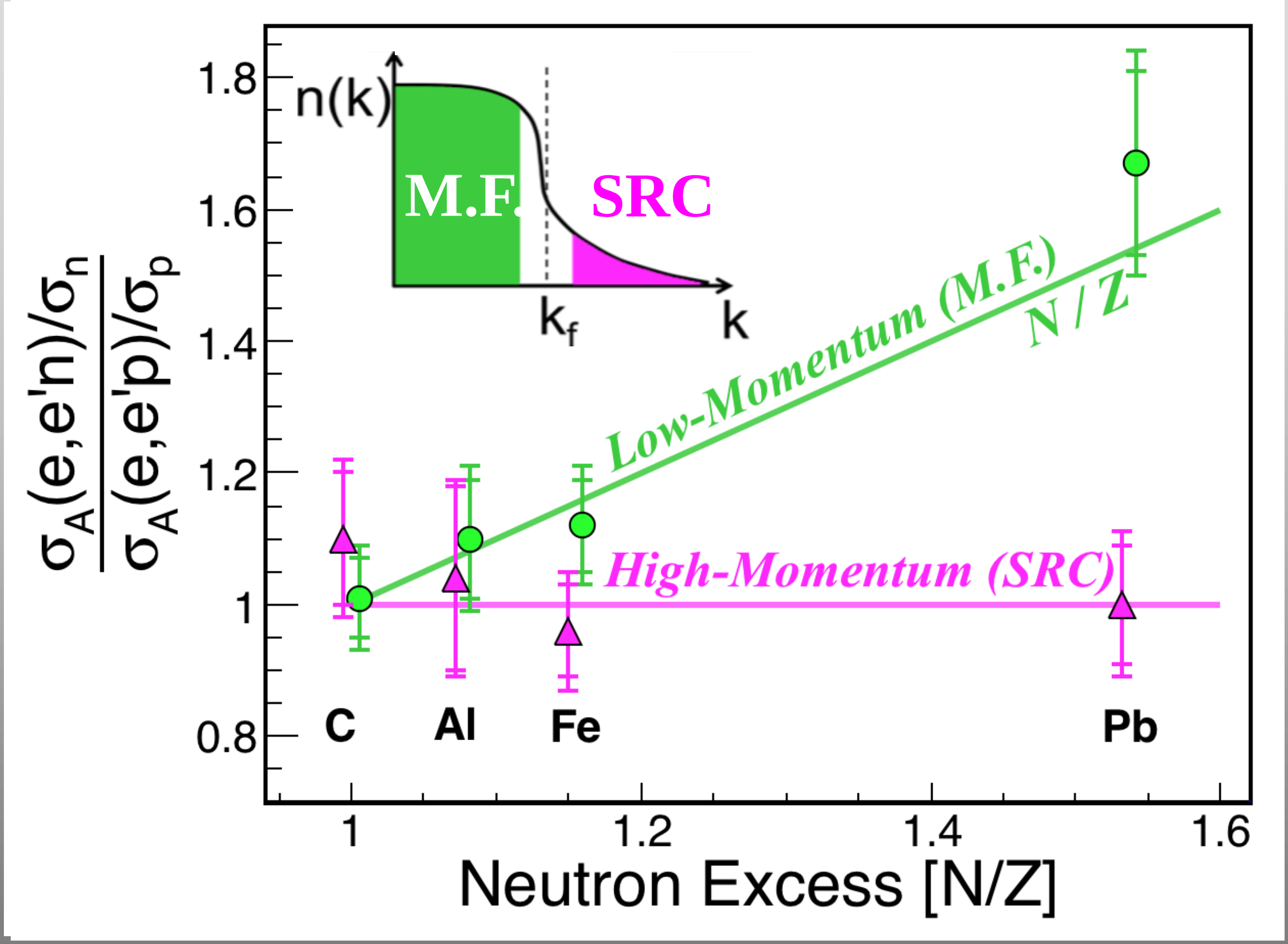
Correlation Probability:
Neutrons saturate Protons grow



M. Duer et al. (CLAS Collaboration), Nature, 560 (2018) 617-621

Asymmetric nuclei

$A(e,e'p)\ \ A(e,e'n)$



➔ **Same # of high-momentum protons and neutrons**

M. Duer et al. (CLAS Collaboration), Nature, 560 (2018) 617-621

Generalized Nuclear Contact Formalism

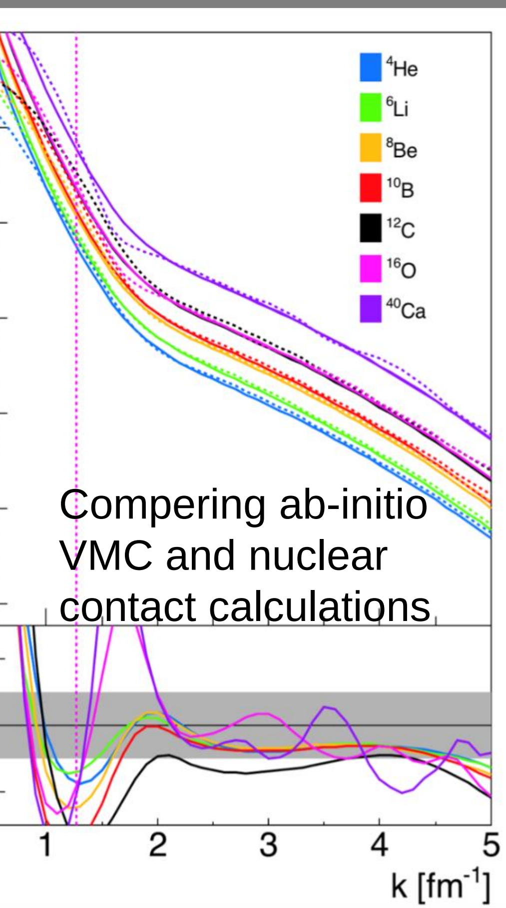
TEL AVIV UNIVERSITY

a factorized ansatz

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_\alpha(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

- Universal function: the zero energy solution to the 2 body problem
- Nucleus (A-2) specific function

Momentum Distribution



Compering ab-initio VMC and nuclear contact calculations

Residual

The nuclear contacts and short range correlations in nuclei

R. Weiss,[1] R. Cruz-Torres,[2] N. Barnea,[1] E. Piasetzky,[3] and O. Hen[2]

Phys. Lett. B780 (2018) 211.

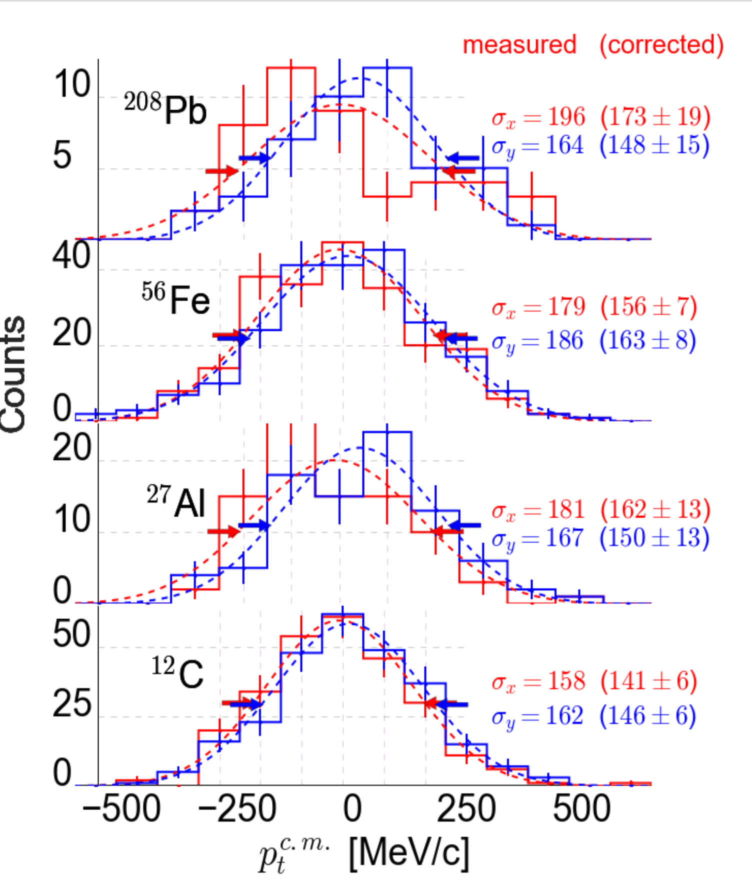
A universal description of SRC:

$$n_p(k) \xrightarrow[k\to\infty]{} C_{pn}^{d}\left|\varphi_{pn}^{d}(k)\right|^2 + C_{pn}^{0}\left|\varphi_{pn}^{0}(k)\right|^2 + 2C_{pp}^{0}\left|\varphi_{pp}^{0}(k)\right|^2$$

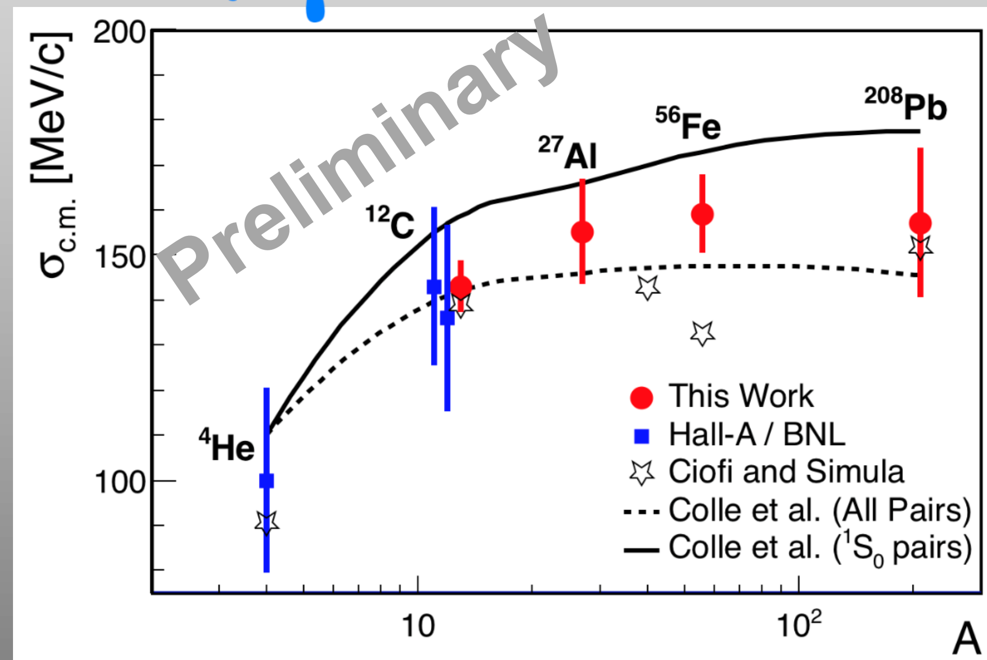
$l=0,2\; s=1\; j=1$
np pairs

$l=s=j=0$
pp, nn, np pairs

C.M. Motion of the SRC pairs



$A(e,e'pp)$



Erez Cohen (TAU), Submitted to PRL, arXiv: 1805.01981

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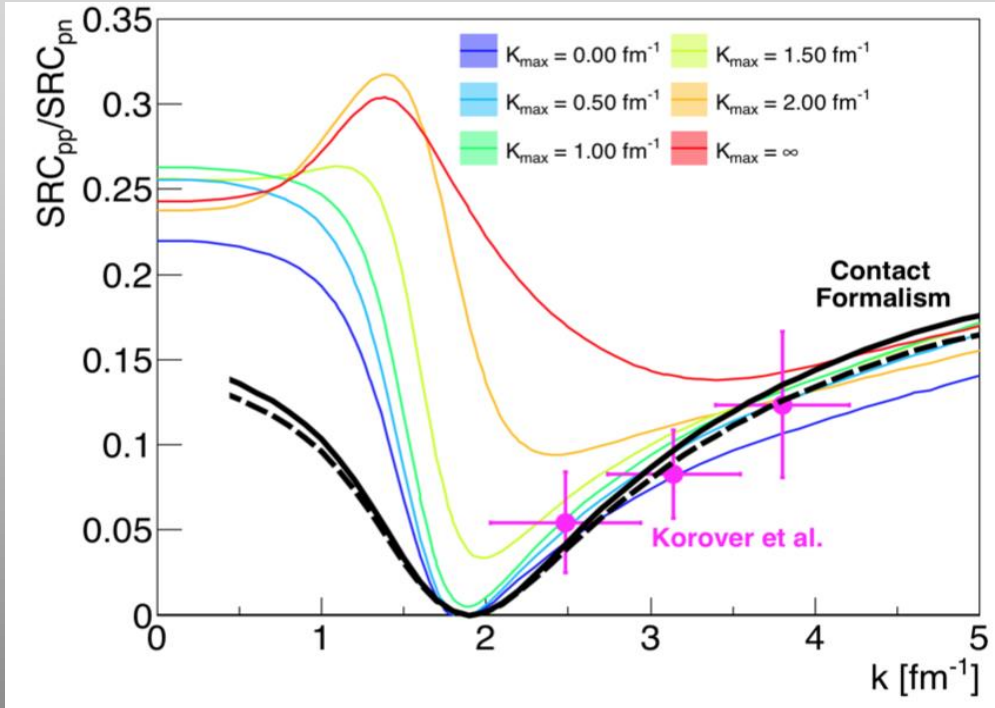


$$^4He(e,e'pp)$$

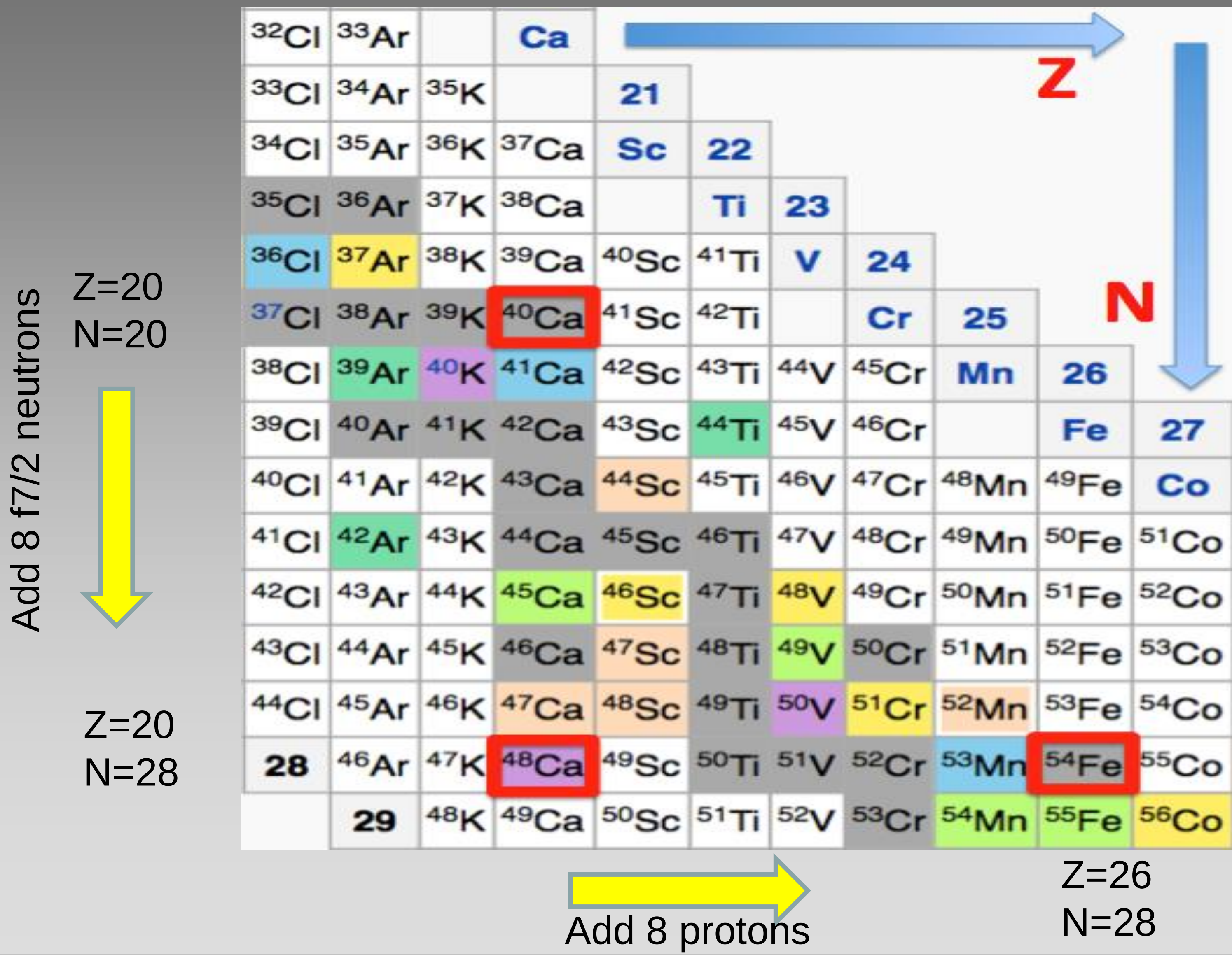
$$^4He(e,e'pn)$$

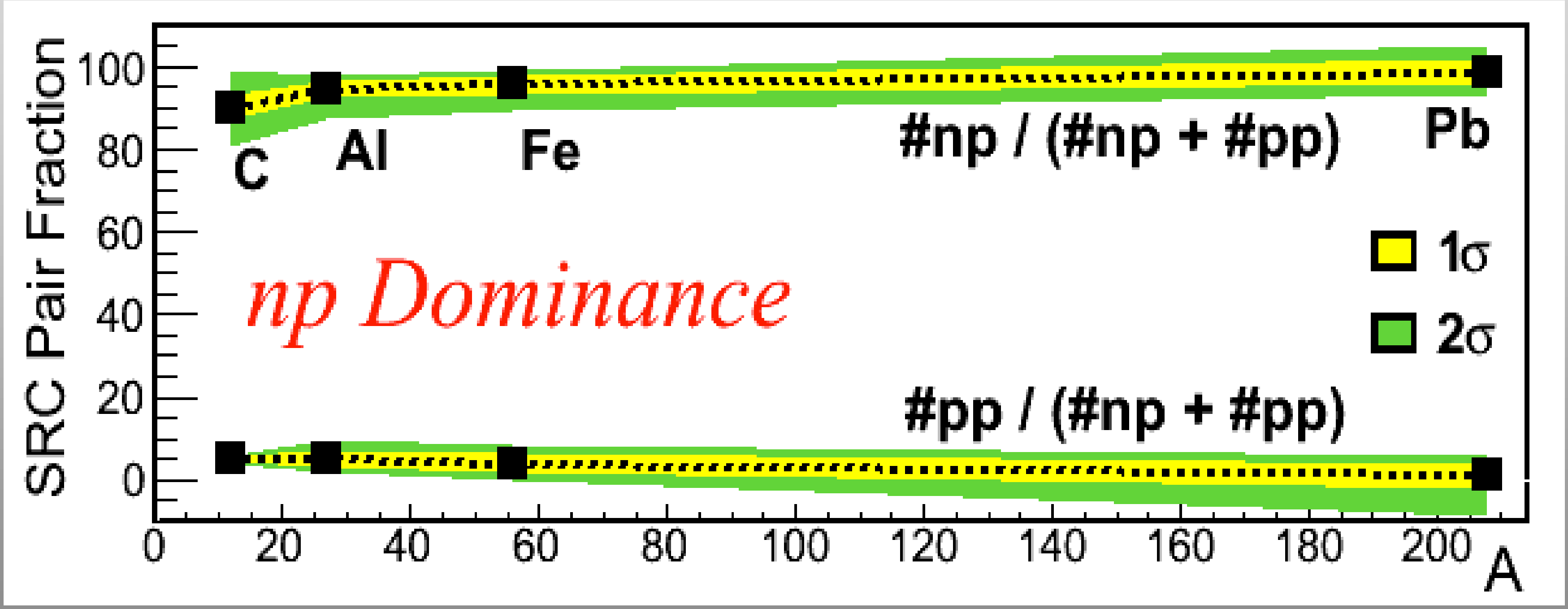
Igor Korover (TAU)

Korover et al. Phys. Rev. Lett. 113 (2014)

Asymmetric nuclei N>Z:

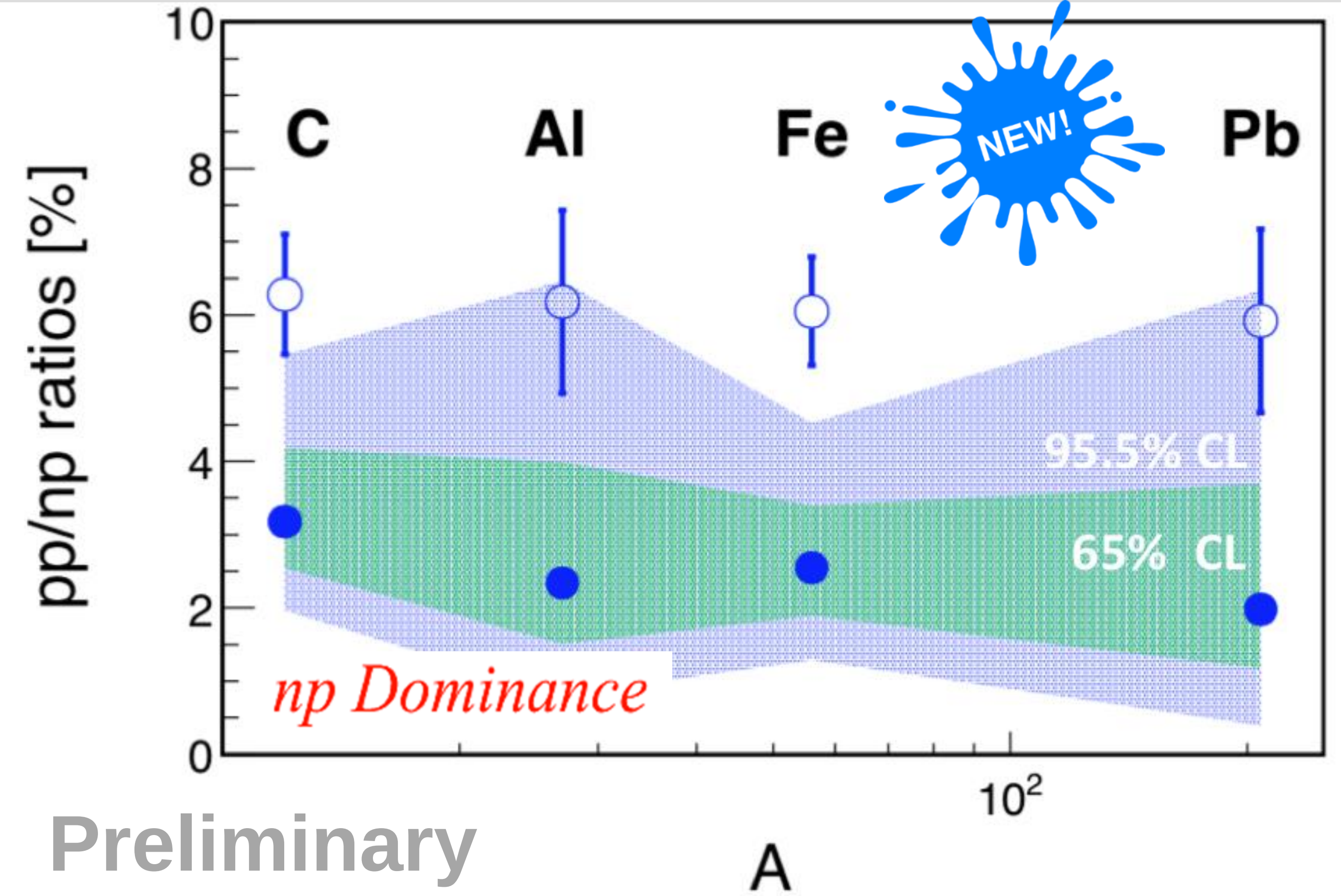
Who are the parents of the 2N-SRC pairs ?





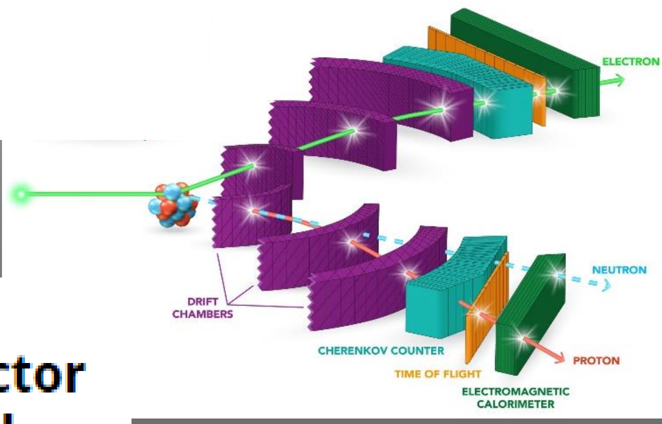
Hen et al., Science 346 (2014)

Or Hen (TAU)



$$A(e,e'np)$$

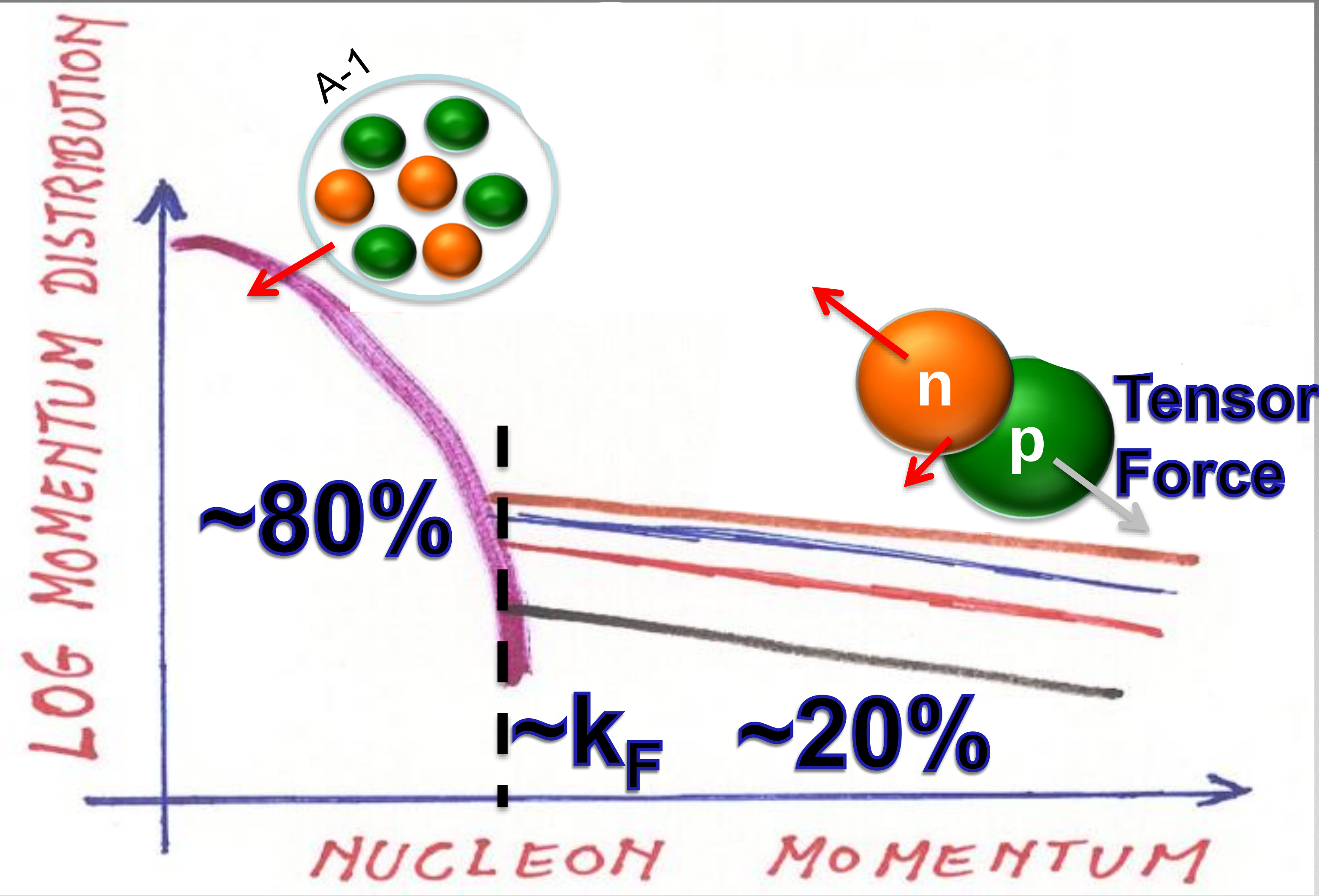
$$A(e,e'pp)$$



CLAS Detector @ JLab

M. Duer (TAU) , Reviewed by the collaboration (2018)

Nucleons has Isophobia (np – dominance)



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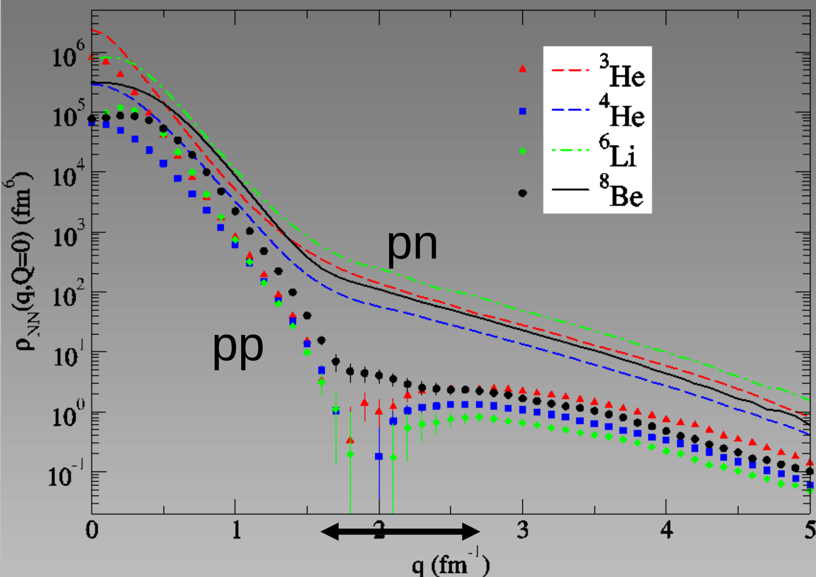

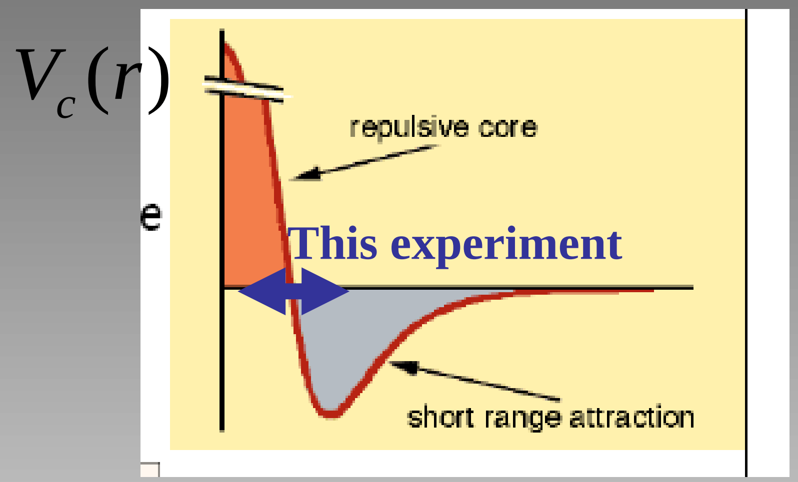

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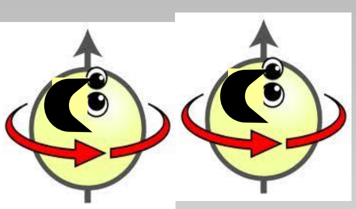
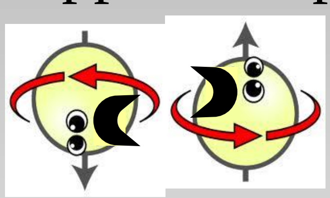


pp- nn- np- SRC



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Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007).

Ciofi and Alvioli PRL 100, 162503 (2008).

Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005).

Two-component interacting Fermi systems

For ulta-cold atomic gas systems of two different type of fermions with short-range interaction

$$a >> d >> r_{eff}$$

Adapted from Debora Jin (JILA).

Thermodynamics can be describe by a single parameter: ‘contact’

The contact measure the number of close different –fermions pairs

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

Generalized Nuclear Contact Formalism

TEL AVIV UNIVERSITY

a factorized ansatz

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_\alpha(\boldsymbol{r}_{ij}) A^\alpha_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

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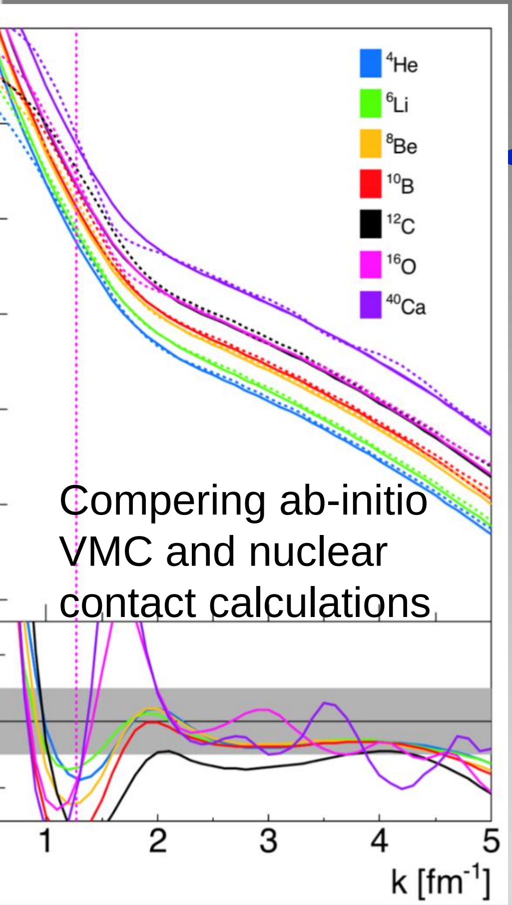
Momentum Distribution



Residual

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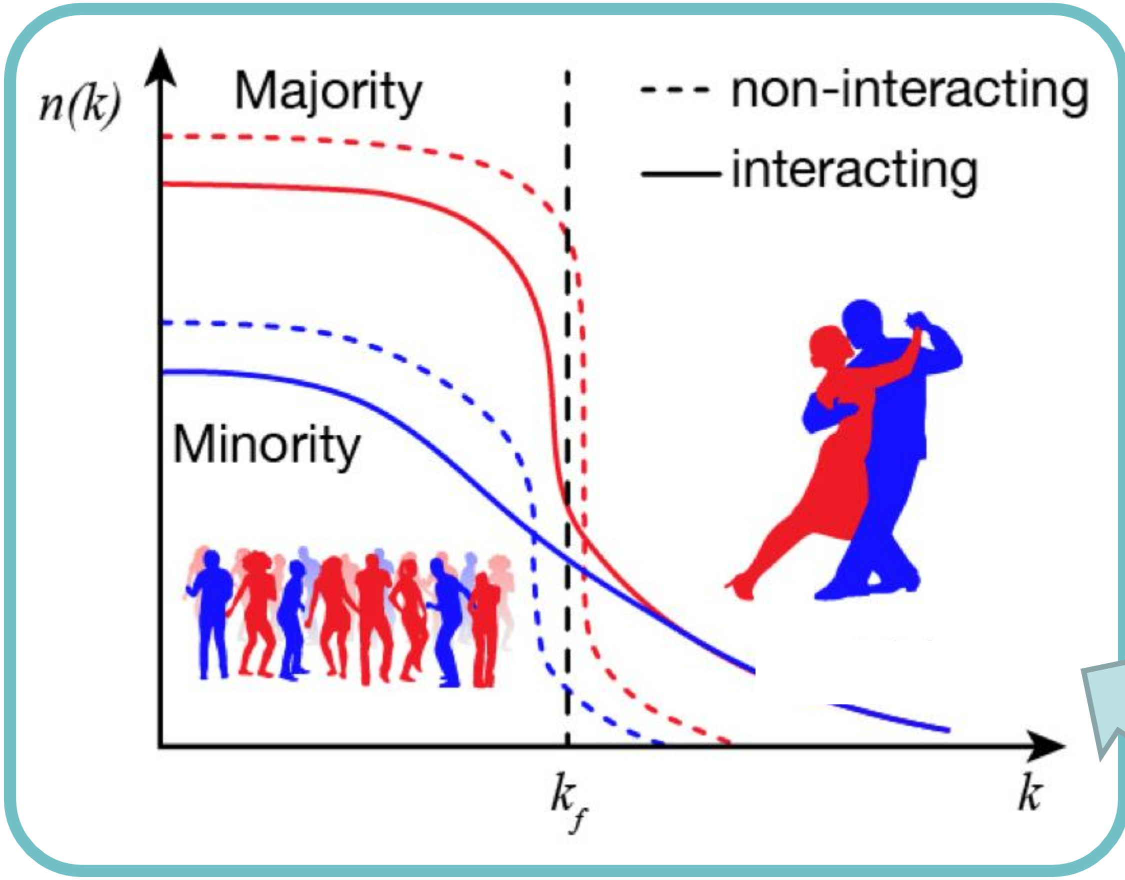
$l = 0, 2\ s = 1\ j = 1$

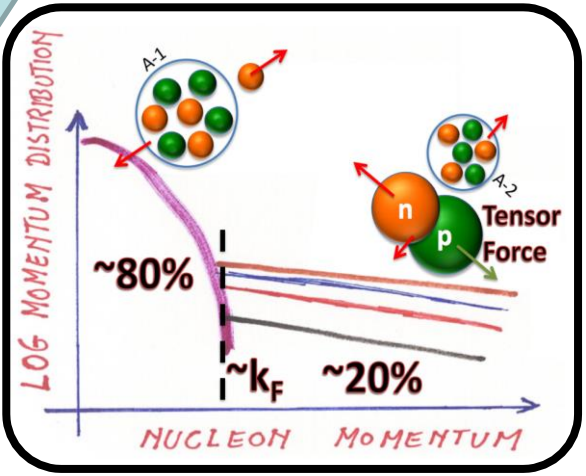
np pairs

$l = s = j = 0$

pp, nn, np pairs

np- dominance and Asymmetric Nuclei





For nuclei with N>Z:

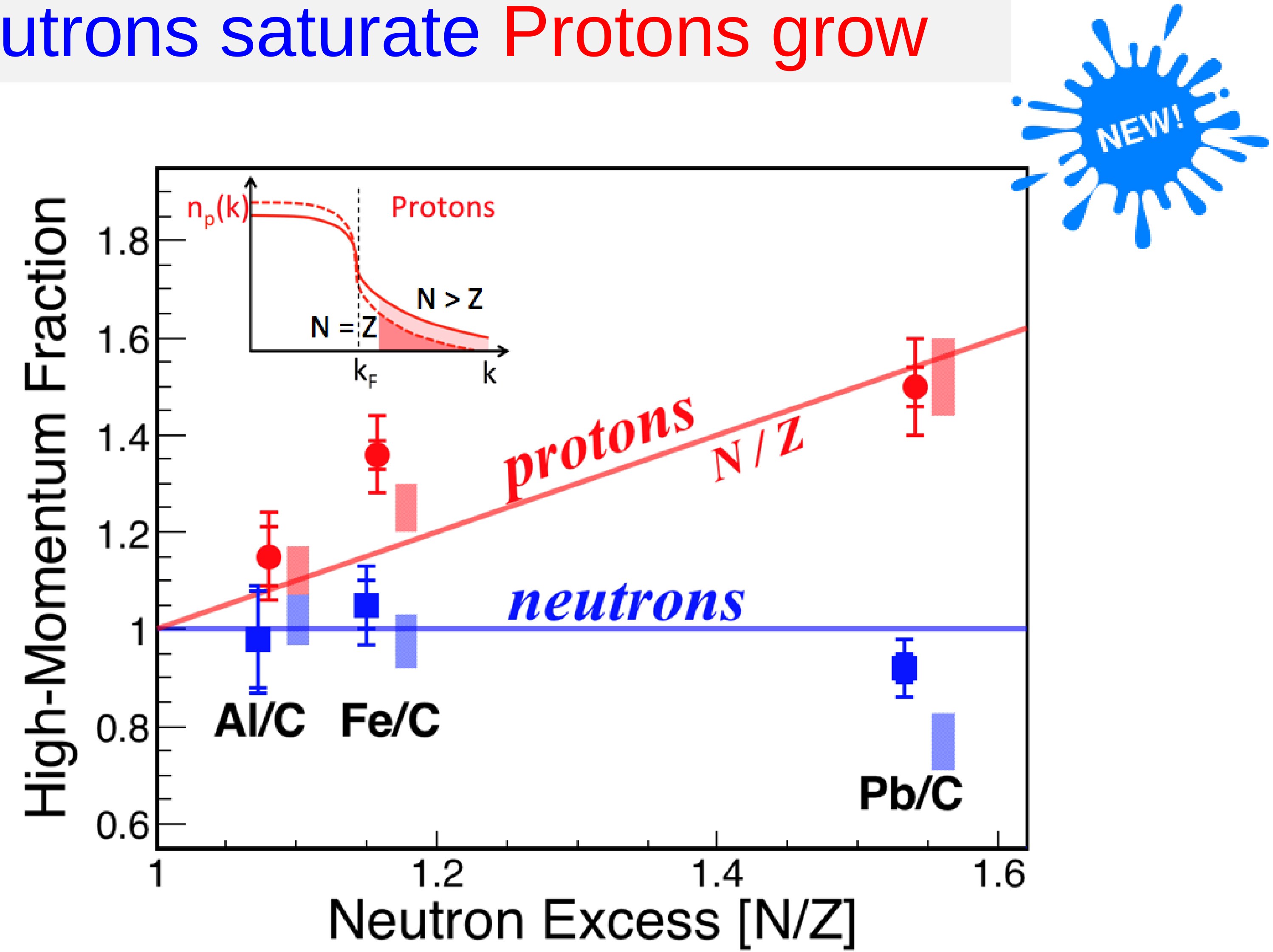
Protons have a greater probability than neutrons to be above the Fermi sea.

What do the outer shell neutrons do ?

Do they produce SRC pairs with the inner shells protons ?

M. Duer et al. (CLAS Collaboration), Nature, 560 (2018) 617-621

Correlation Probability:
Neutrons saturate Protons grow



M. Duer et al. (CLAS Collaboration), Nature, 560 (2018) 617-621

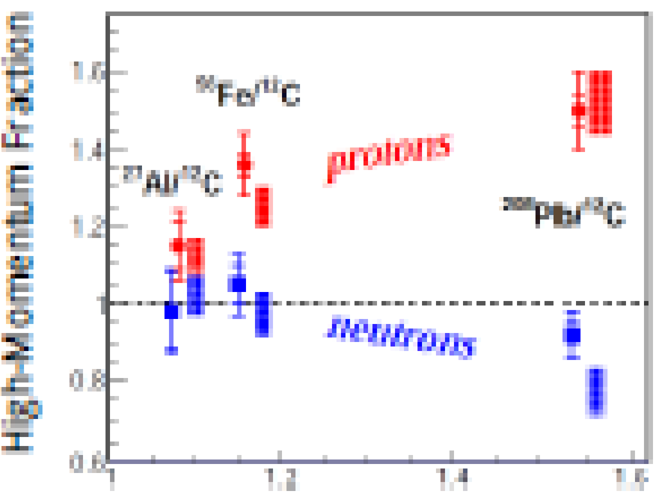
Kinetic energy sharing

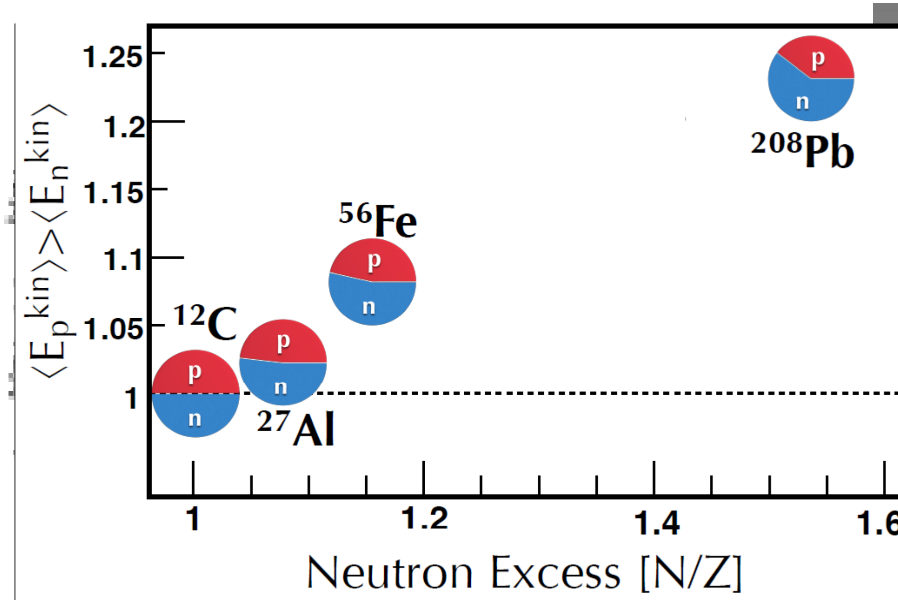
Simple np-dominance model

$$n_p(k) = \begin{cases} \eta \cdot n_p^{M.F.}(k) & k<k_0 \\ \frac{A}{2Z} \cdot a_2(A/d) \cdot n_d(k) & k>k_0 \end{cases}$$

(for neutrons: Z → N)

$$\frac{A(e,e'N)_{high}/A(e,e'N)_{low}}{{}^{12}C(e,e'N)_{high}/{}^{12}C(e,e'N)_{low}}$$

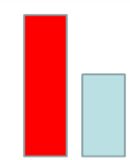




Neutron Excess [N/Z]

Protons move faster than neutrons in N>Z nuclei

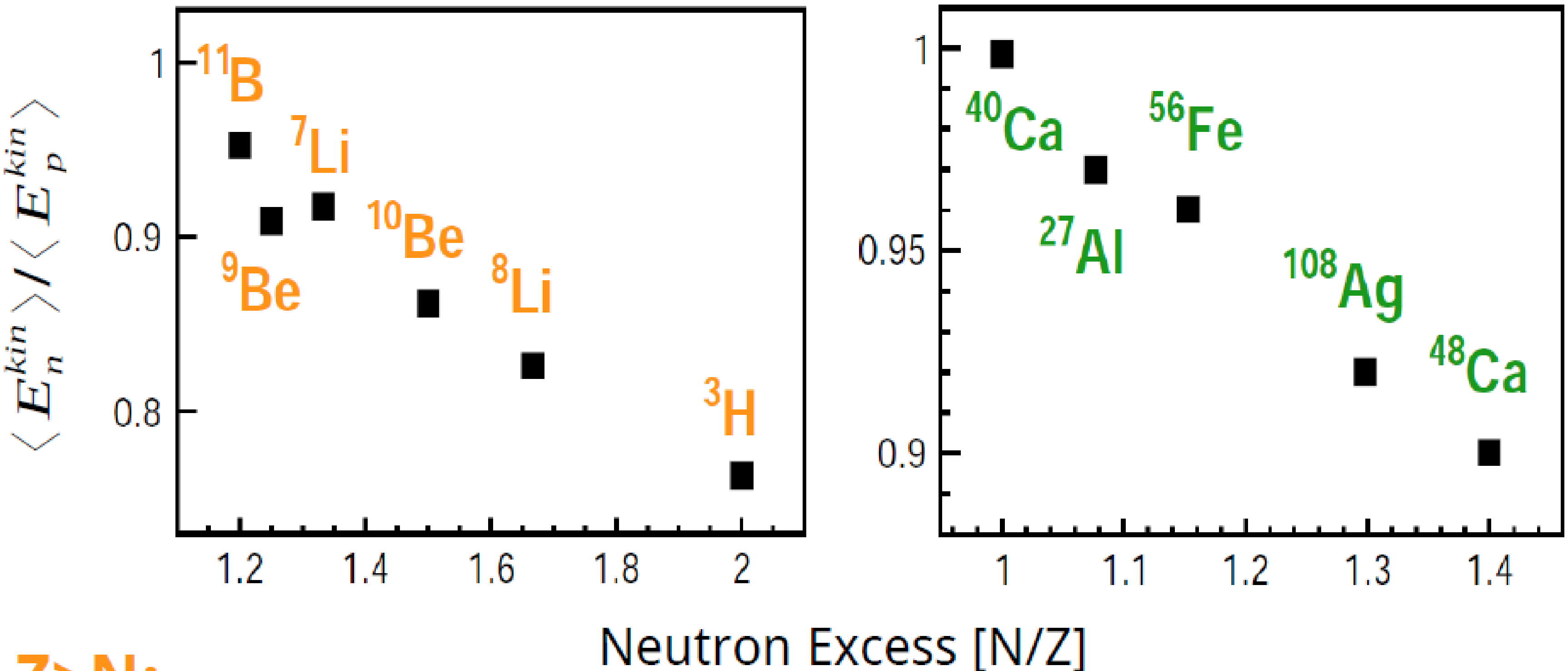
$$\langle E_p^{kin} \rangle > \langle E_n^{kin} \rangle$$



Pauli principle → $\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$

Theoretical predictions (N>Z)

Light nuclei (A<12) | **Heavy nuclei (A>12)**



Z>N:

^{3}He **N/Z =1/2** $\langle E_n^{kin} \rangle / \langle E_p^{kin} \rangle = 1.31$

Wiringa, Phys. Rev. C89, 024305 (2014)

Ryckebusch, J. Phys G42 (2015)

Summary

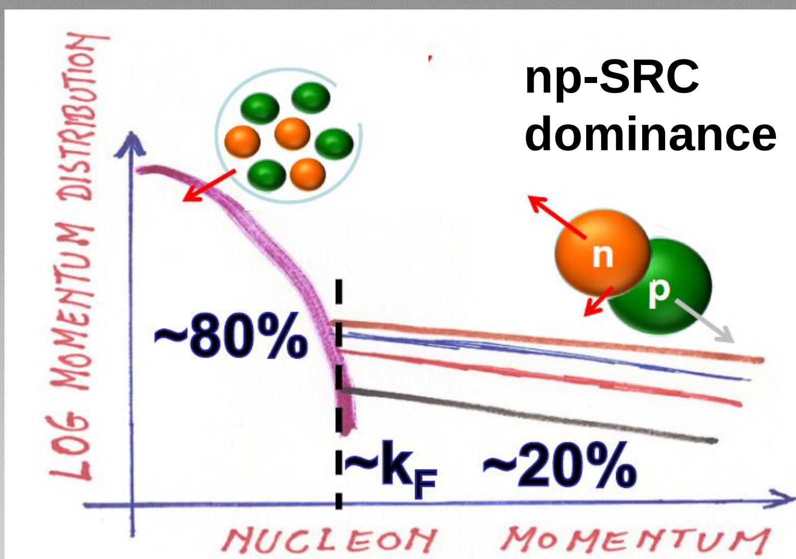
In nuclei the momentum distribution of nucleons can be divided into two distinct regions

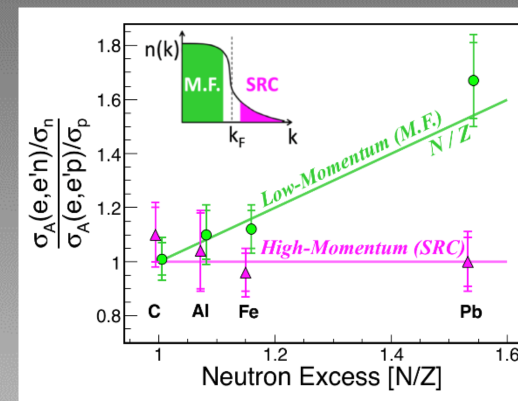
$k<k_F$

Mean field region

$k>k_F$

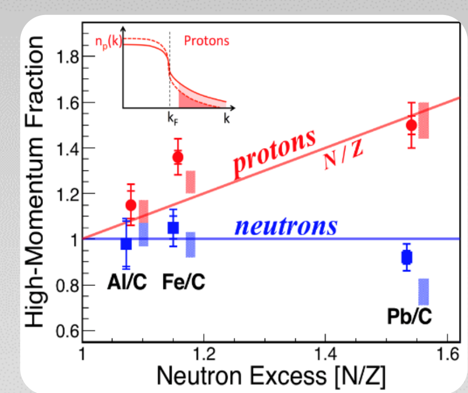
Correlated / high momentum region





#protons = #neutrons, irrespectively of the neutron excess

The fraction of correlated protons /neutrons is grow/constant , as a function of neutron excess,



Generalized Nuclear Contact Formalism

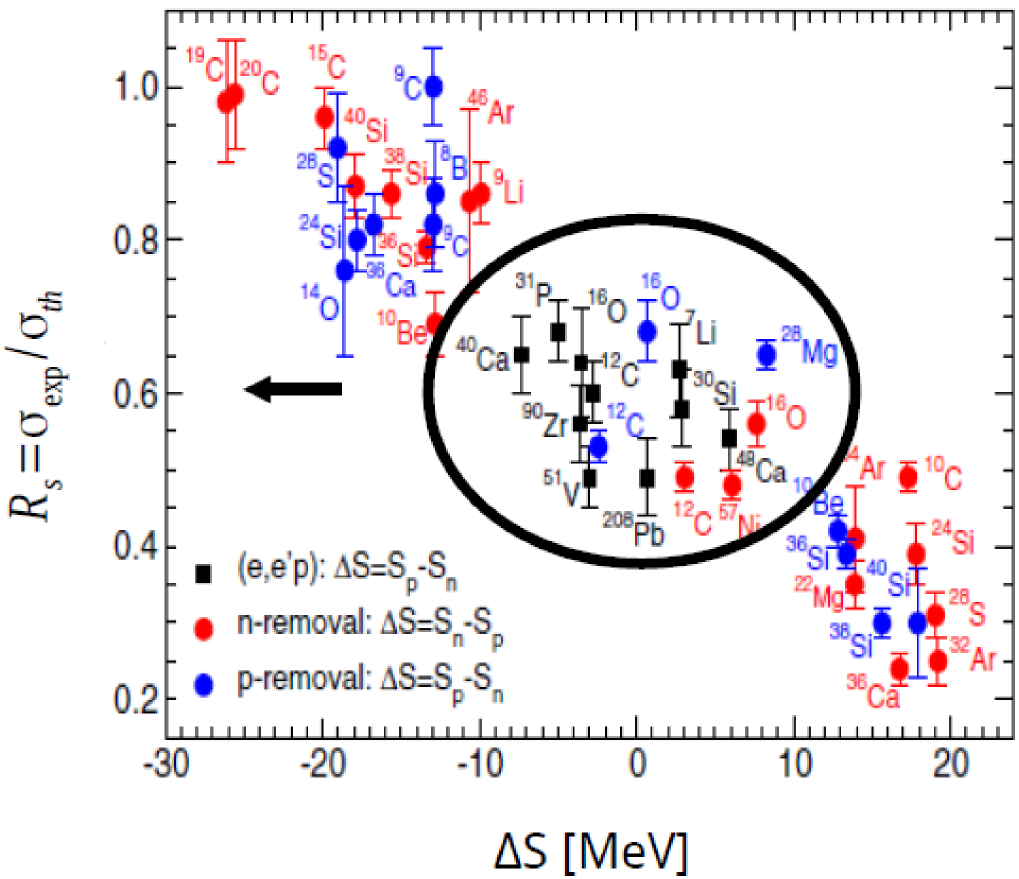
Reduction of single-particle strength

Spectroscopic factors
for (e,e'p) reactions

Only 60-70% of expected
single-particle strength

MISSING:

SRC **LRC**



J. A. Tostevin and A. Gade, PRC **90**, 057602 (2014)

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

High-Energy Reactions and the Evidence for Correlations in the Nuclear Ground-State Wave Function*

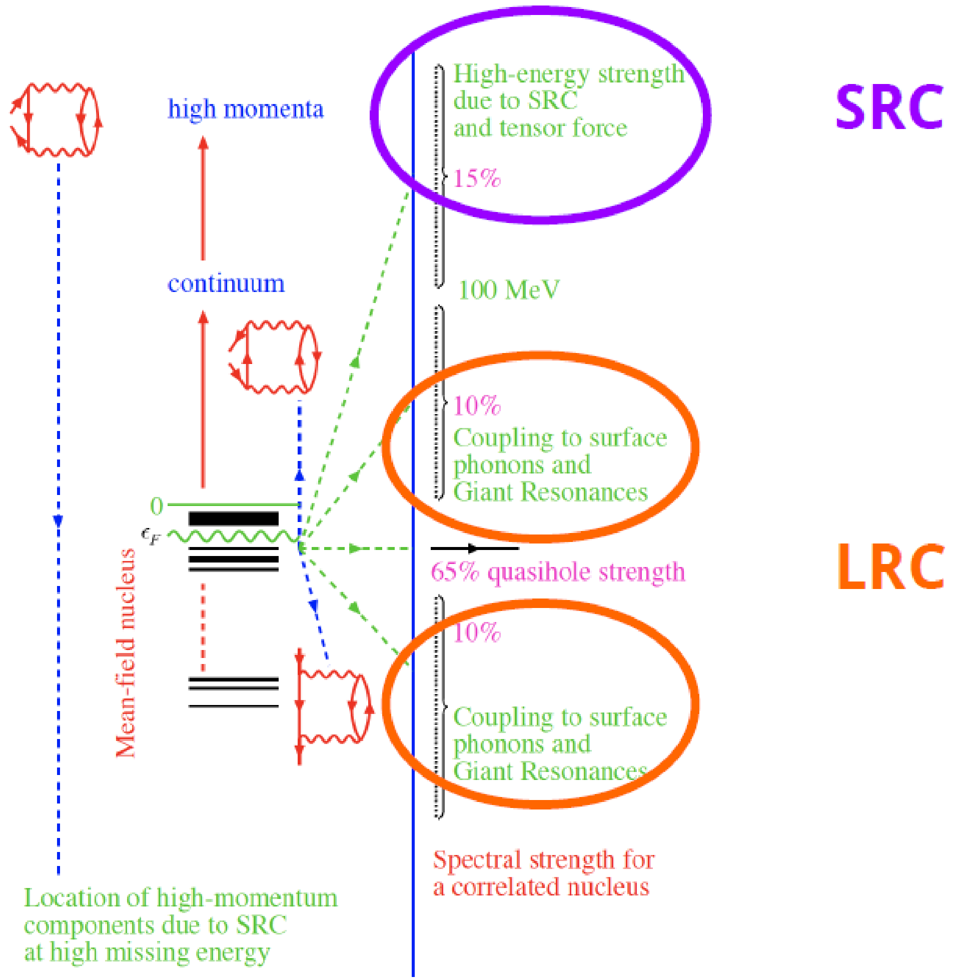
K. A. Brueckner, R. J. Eden,† and N. C. Francis
Indiana University, Bloomington, Indiana

(Received January 13, 1955)

V. CONCLUSIONS

We have analyzed evidence derived from a variety of high-energy experiments which has bearing on the problem of nuclear structure. This evidence is particularly significant since it is for these (or similar) processes that the possible departure of the nuclear ground-state wave function from an independent-particle wave function is most apparent. The result predicted uniformly by the group of quite diverse experiments which we have examined is that the nuclear ground-state wave function must have a very marked admixture of high-momentum components and hence must depart quite appreciably from an independent-particle-model wave function. Consequently it follows that the usual assumptions of the shell-model theory of the nucleus, that the particles move independently in a uniform potential, cannot be other than very approximately correct.

Single particle strength



W.H. Dickhoff, C. Barbieri, Progress in Particle and Nuclear Physics 52 (2004) 377–496

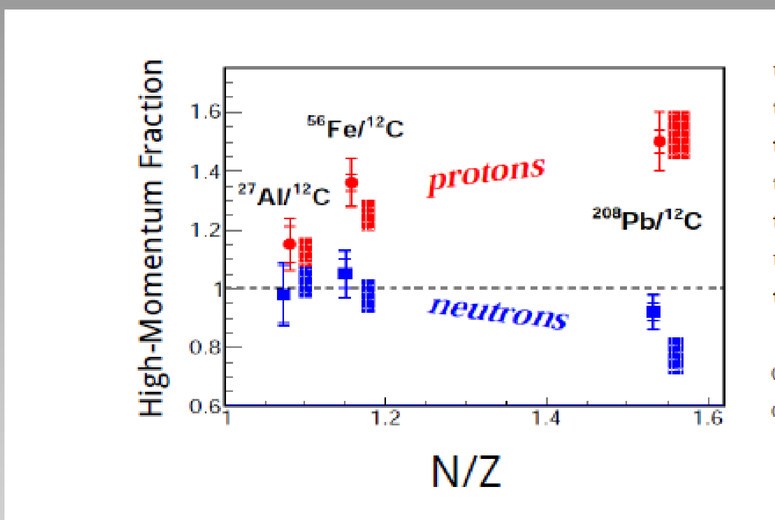
Isospin dependence of single-particle strength

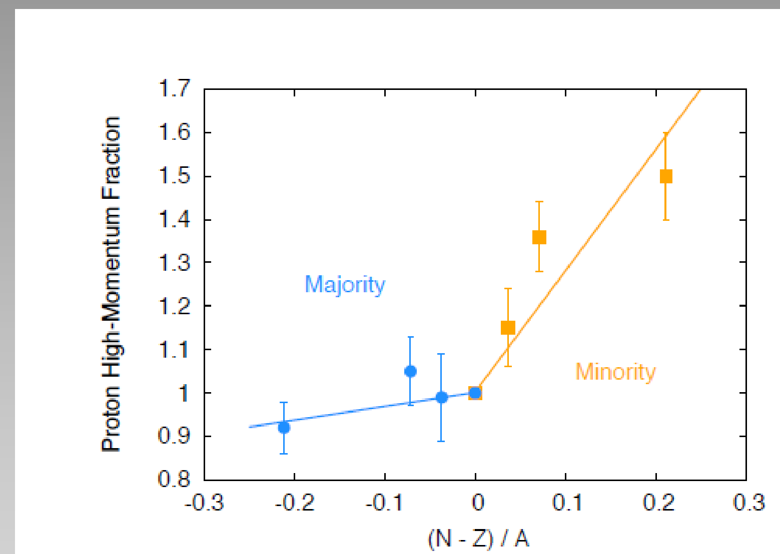
Single particle — Missing strength

$$QF = 1 - \text{LRC} - \text{SRC}$$

LRC: Weak Isospin dependence

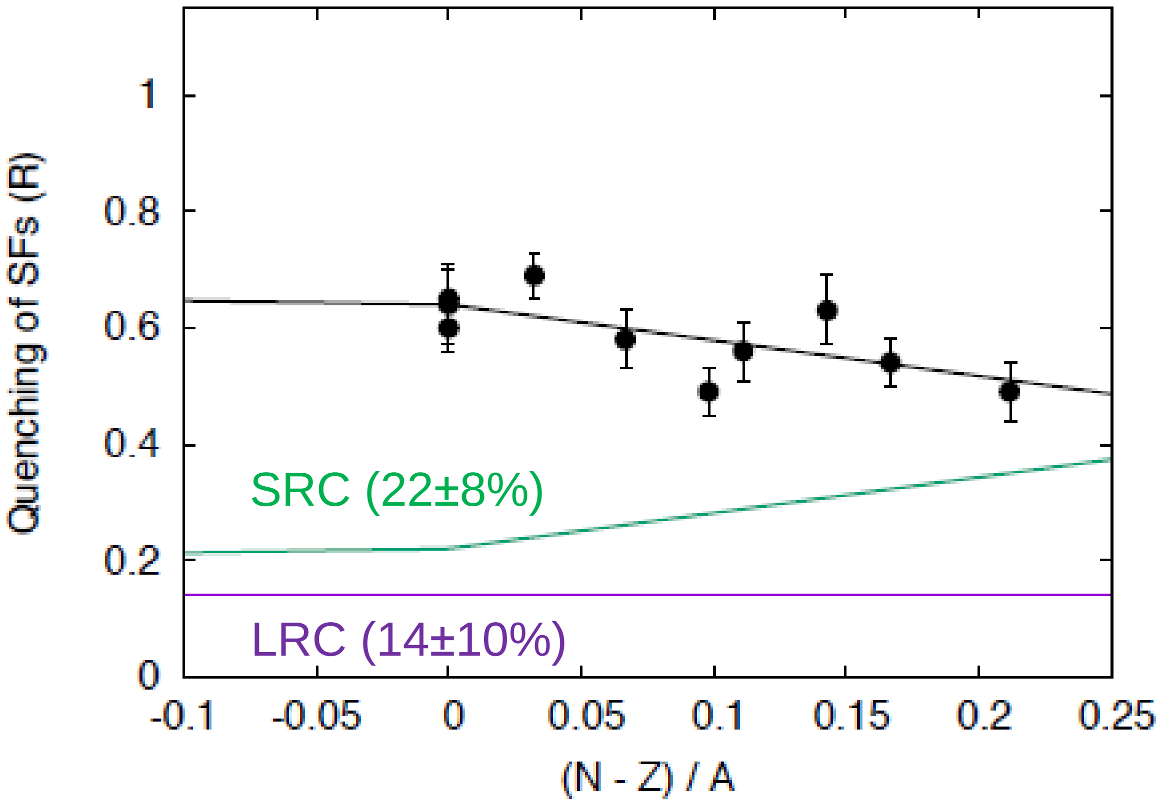
E. V. Litvinova and A. V. Afanasjev, Phys. Rev. C **84**, 014305 (2011).





$$N > Z: \quad QF_{SRC} = \gamma\left(1 + SL^{p}_{SRC}\frac{(N-Z)}{A}\right) \qquad N < Z: \quad QF_{SRC} = \gamma\left(1 + SL^{n}_{SRC}\frac{(N-Z)}{A}\right)$$

Paschalis, Macchiavelli, Petri, Hen, Piasetzky, arXiv 1812.08051 [nucl-exp]



Data

$R = SF_{exp}/SF,$

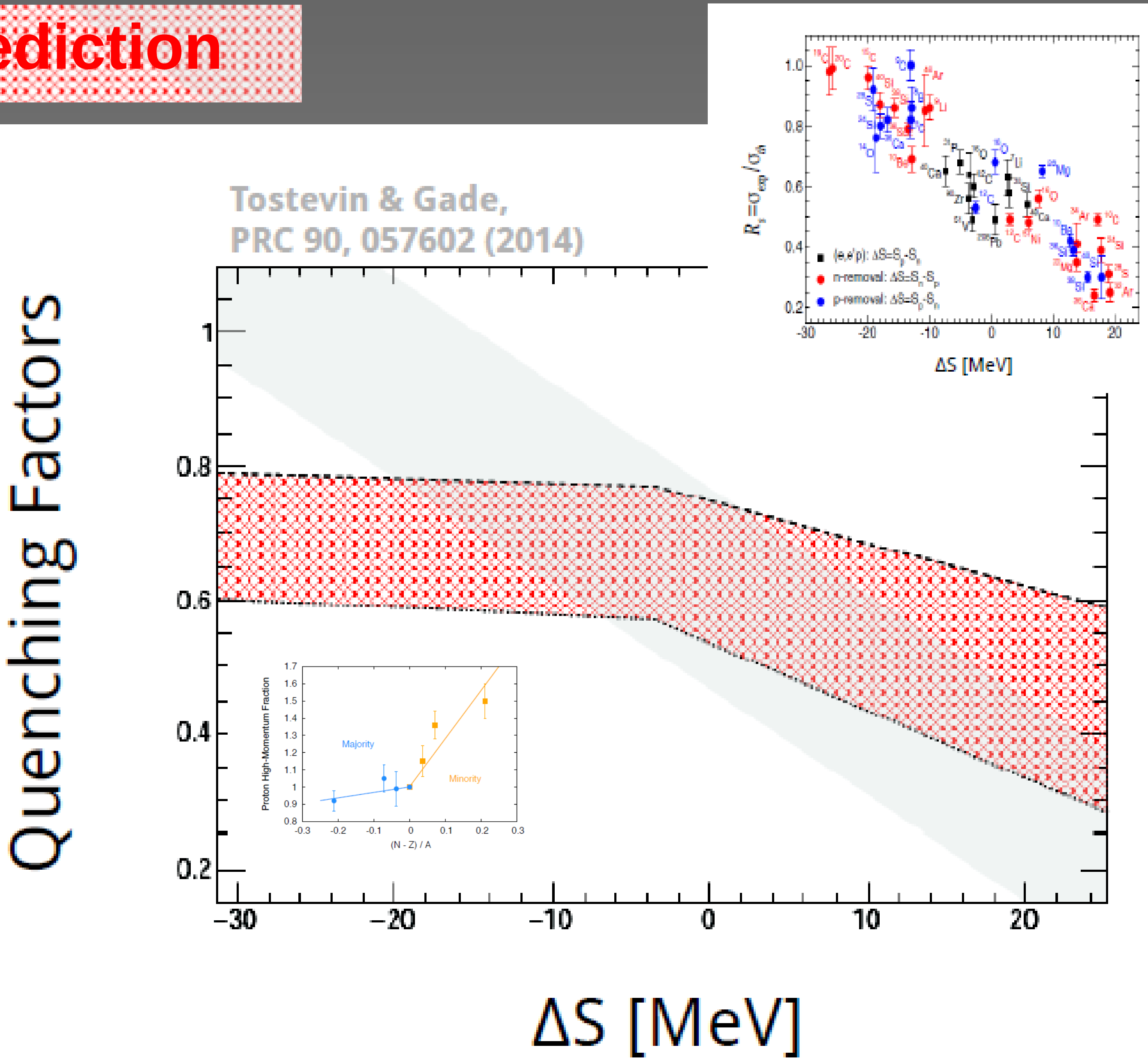
Nucleus	(N–Z)/A	SF_{exp}	R
^{7}Li	0.143	0.42 ± 0.04	0.63 ± 0.06
^{12}C	0	1.72 ± 0.11	0.60 ± 0.04
^{16}O	0	1.27 ± 0.13	0.64 ± 0.07 *
^{30}Si	0.067	2.21 ± 0.20	0.58 ± 0.05
^{31}P	0.032	0.40 ± 0.03	0.69 ± 0.04
^{40}Ca	0	2.58 ± 0.19	0.65 ± 0.05 *
^{48}Ca	0.167	1.07 ± 0.07	0.54 ± 0.04 *
^{51}V	0.098	0.37 ± 0.03	0.49 ± 0.04
^{90}Zr	0.111	0.72 ± 0.07	0.56 ± 0.05
^{208}Pb	0.212	0.98 ± 0.09	0.49 ± 0.05 *

G. Kramer, H. Blok, and L. Lapikas, Nucl. Phys. A **679**, 267 (2001).

A(e,e'p) g.s -> g.s

Paschalis, Macchiavelli ,Petri, Hen, Piasetzky, arXiv. 1812.08051 [nucl-exp]

Prediction



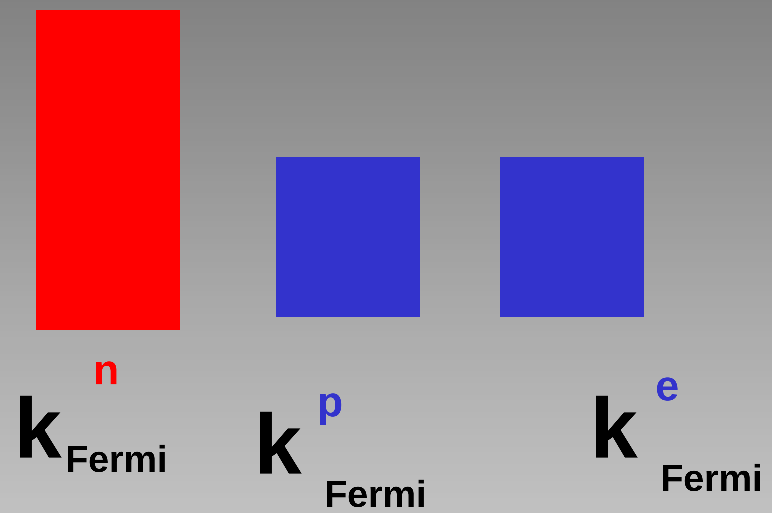
The difference) in proton and neutron separation energies,

Paschalis, Macchiavelli ,Petri, Hen, Piasetzky, arXiv. 1812.08051 [nucl-exp]

Implications for neutron stars

- ~95% neutrons, ~5% protons ~5% electrons (β-stability).
- three separate Fermi gases (n, p, e).

N/Z = 20



At T=0

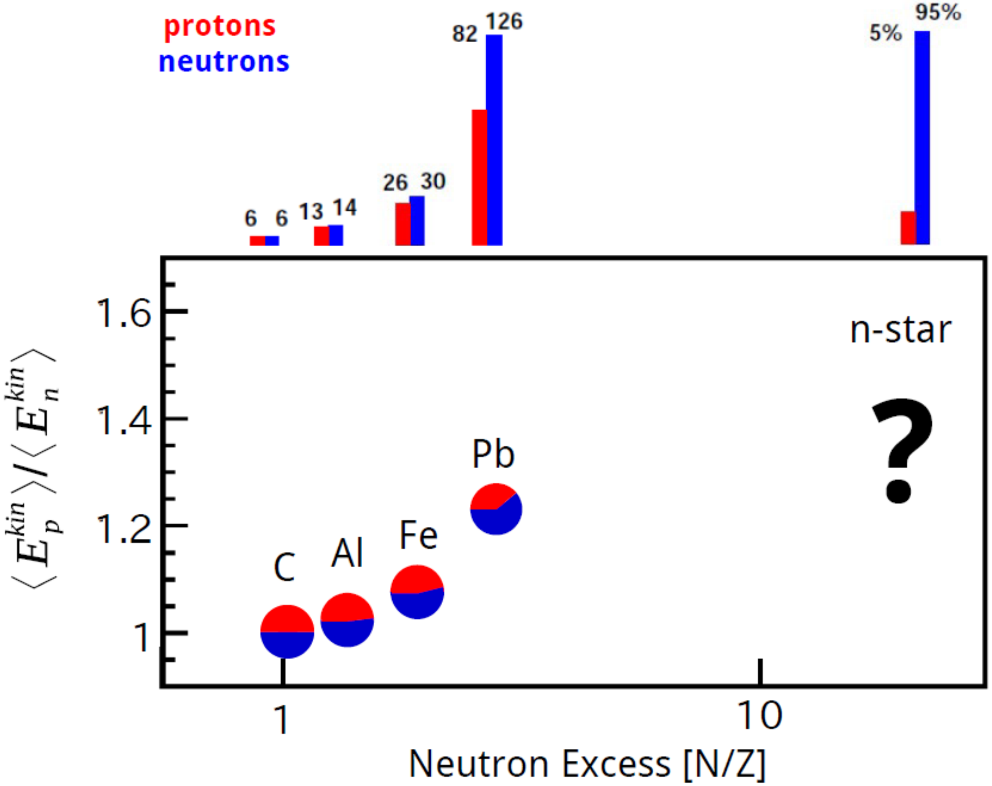
$$\frac{\langle E_k^p \rangle}{\langle E_k^n \rangle} = \left(\frac{k_F^p}{k_F^n}\right)^2 = \left(\frac{n_p}{n_n}\right)^{2/3} = \left(\frac{5-10\%}{90-95\%}\right)^{2/3} \approx \frac{1}{5-10}$$

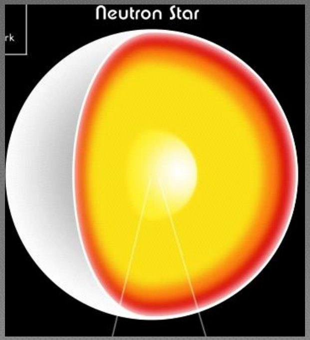
SRC in neutron rich nuclei →

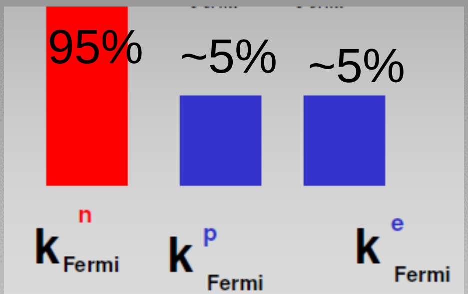
$$\frac{\langle E_k^p \rangle}{\langle E_k^n \rangle} > 1$$

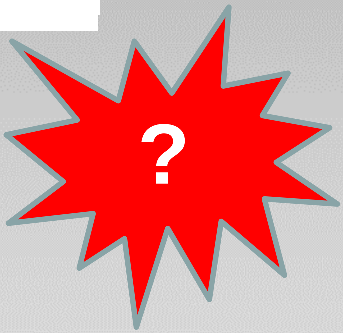
in neutron stars →

What happens in N>>Z?









Neglecting LRC assuming 0.2 np- SRC
With n(k)=1/k^4

$$\frac{\left\langle E_k^p \right\rangle_{SRC}}{\left\langle E_k^p \right\rangle_{SFG}} \approx 2.5$$

ν cooling

$$n \rightarrow p + e + \bar{\nu}_e$$

Magnetic field

Summary

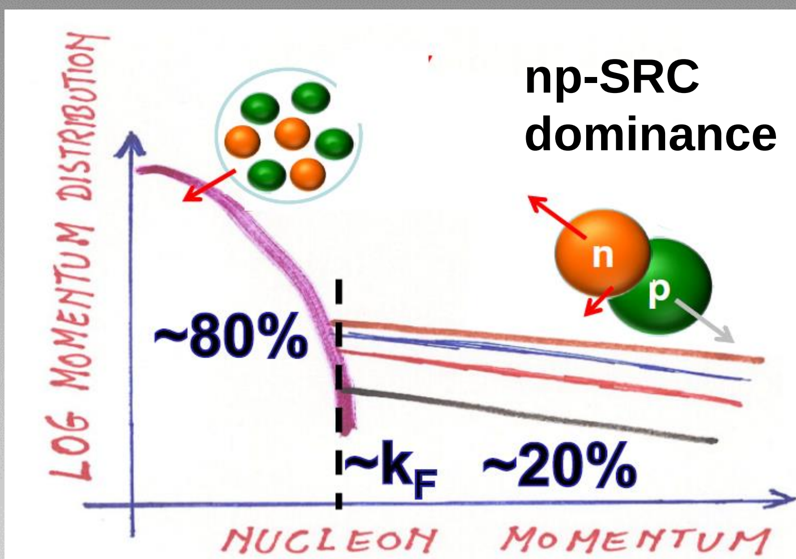
In nuclei the momentum distribution of nucleons can be divided into two distinct regions

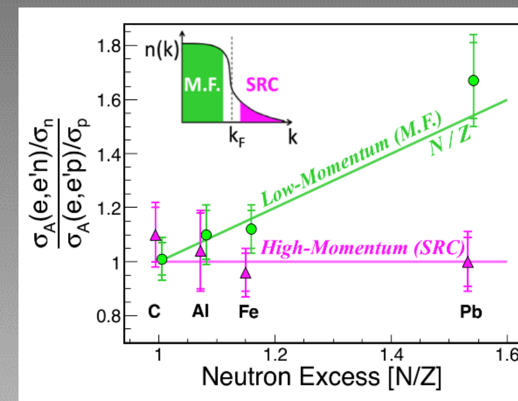
$k<k_F$

Mean field region

$k>k_F$

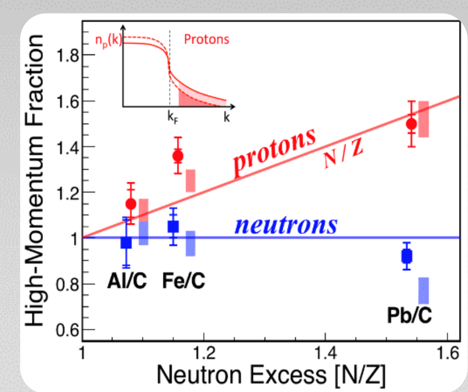
Correlated / high momentum region





#protons = #neutrons, irrespectively of the neutron excess

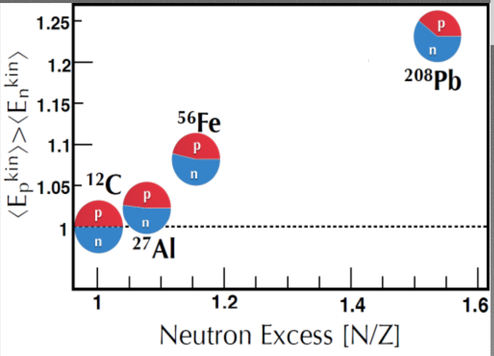
The fraction of correlated protons /neutrons is grow/constant , as a function of neutron excess,

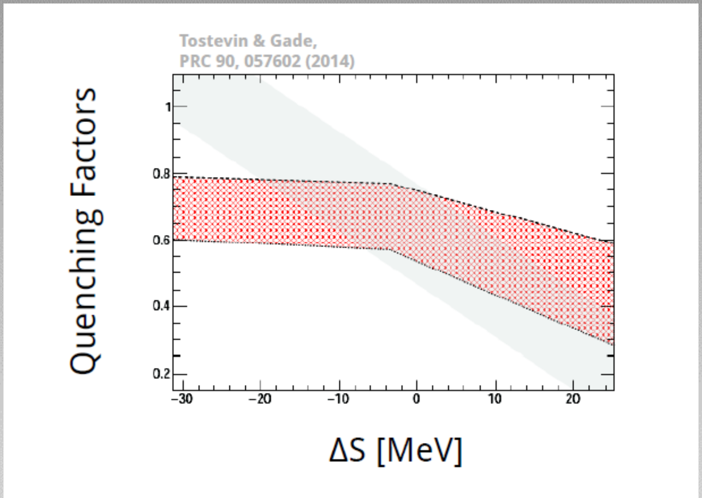


Generalized Nuclear Contact Formalism

Summary (II)

- **In neutron-rich nuclei:**
  - $\langle E^p{}_k \rangle > \langle E^n{}_k \rangle$
  - **Prediction for the isospin dependence of the single nucleon strength reduction.**





- **In neutron stars:**
  - **proton momentum > Simple Fermi Gas prediction.**
  - **consequences ?**

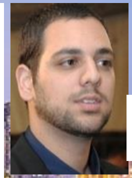
Acknowledgment

I thanks the organizers for the invitation

Tel Aviv University

Collaborators

Massachusetts Institute of Technology



Or Hen

Meytal Duer

NEW!

Old Dominion University

Larry Weinstein

Data-Mining collaboration

CLAS collaboration

Jefferson Lab

Isospin dependence of nucleon-nucleon correlations and the reduction of the single-particle strength in atomic nuclei

S. Paschalis,[1] A. O. Macchiavelli,[2] M. Petri,[1] O. Hen,[3] and E. Piasetzky[4]

arXiv. 1812.08051 [nucl-exp]

Single particle — Missing strength

$$QF = 1 - \left(QF_{PVC} + QF_{Pairing} + QF_{SRC} \right)$$

Long-Range Correlations — Short-Range Correlations

$$N > Z: \quad QF_{SRC} = \gamma \left(1 + SL^{p}_{SRC} \frac{(N-Z)}{A} \right) \qquad N < Z: \quad QF_{SRC} = \gamma \left(1 + SL^{n}_{SRC} \frac{(N-Z)}{A} \right)$$

$$QF_{PVC} = \alpha \left(1 + \frac{33}{51} \frac{(N-Z)}{A} \right)^2$$

Particle Vibration Coupling

$$QF_{Pairing} = 0.0324 \left(1 - 6.07 \left(\frac{(N-Z)}{A} \right)^2 \right)^2$$

Nuclear Physics **A431** (1984) 393-418

Isospin dependence of nucleon-nucleon correlations and the reduction of the single-particle strength in atomic nuclei

S. Paschalis,[1] A. O. Macchiavelli,[2] M. Petri,[1] O. Hen,[3] and E. Piasetzky[4]

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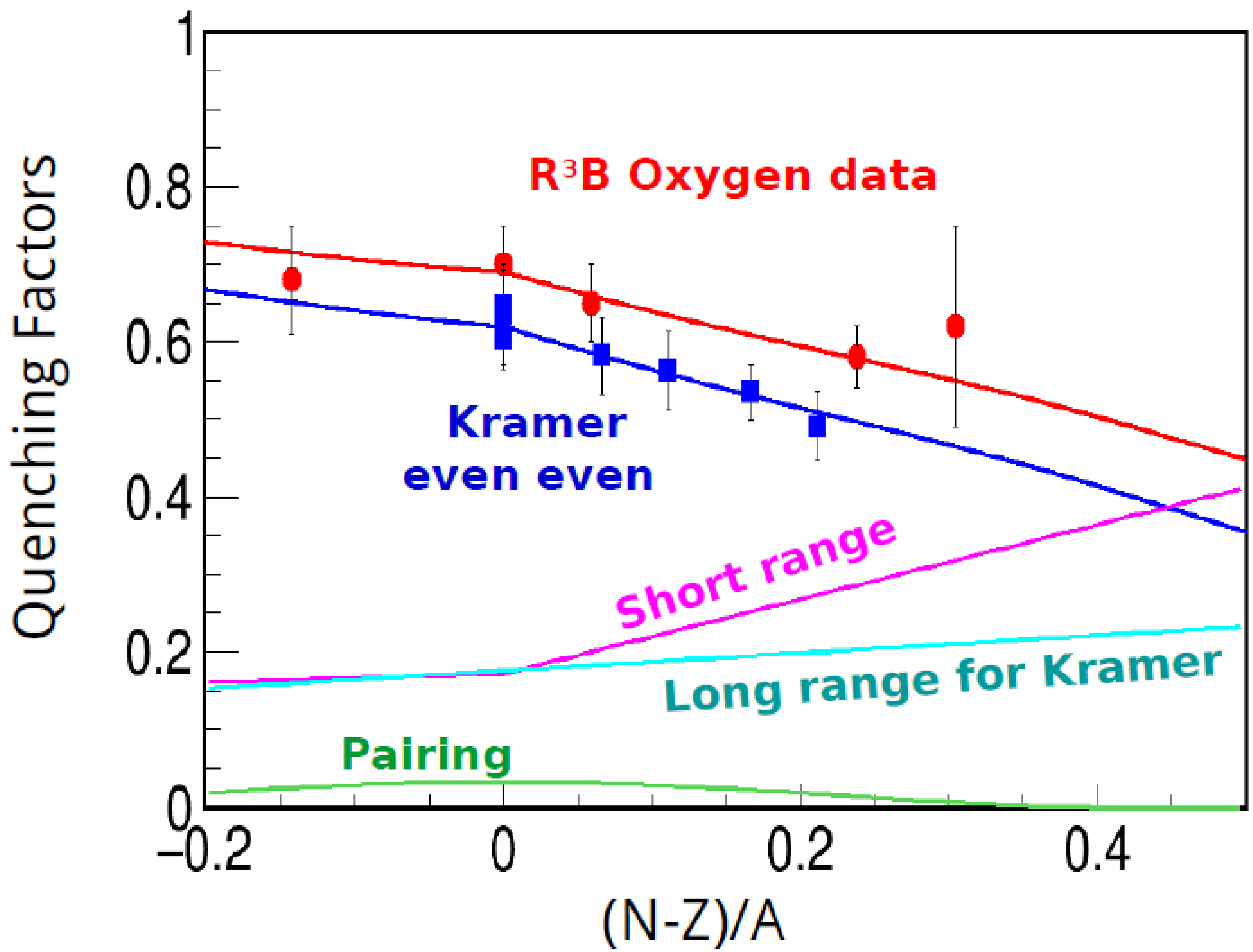
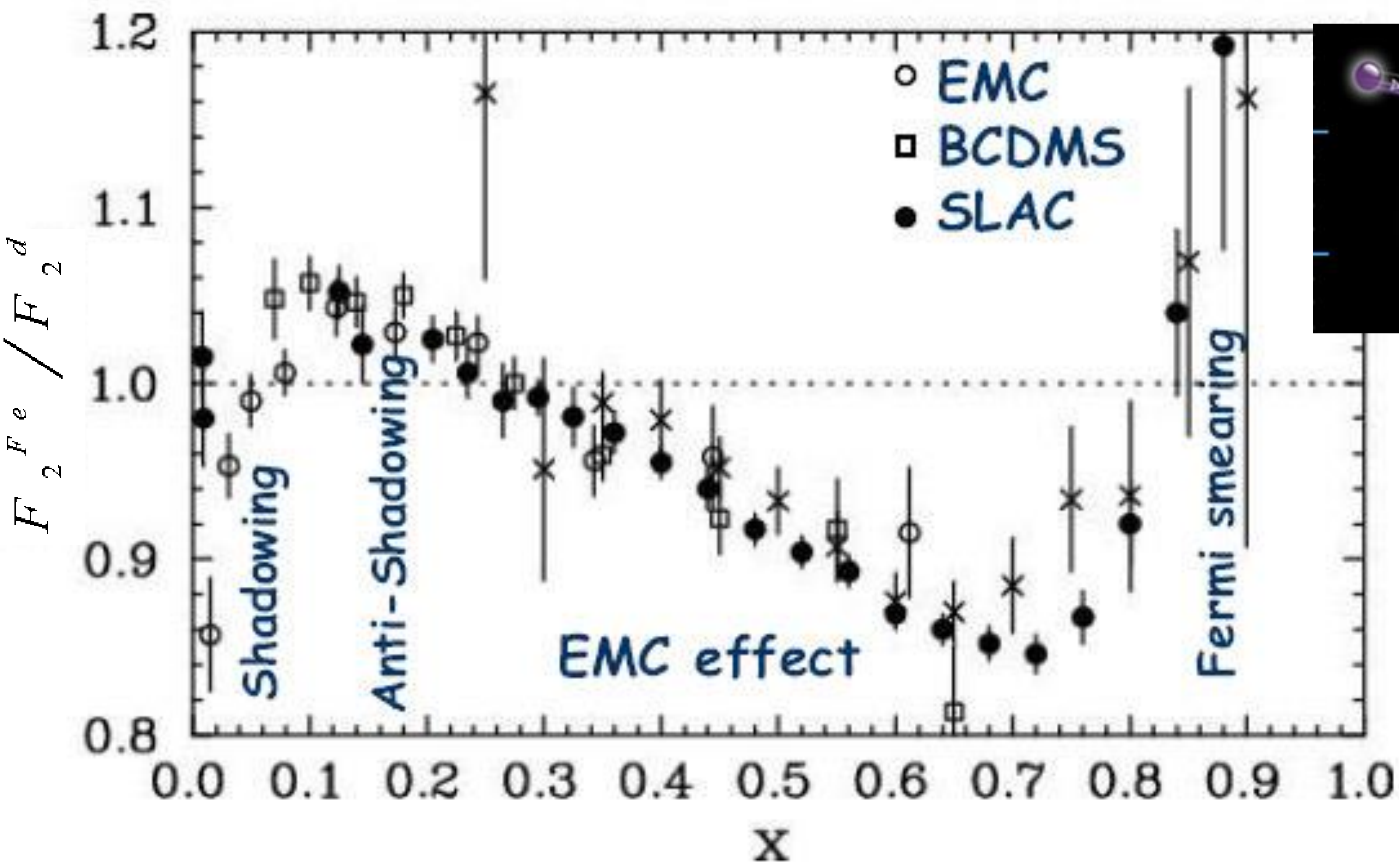


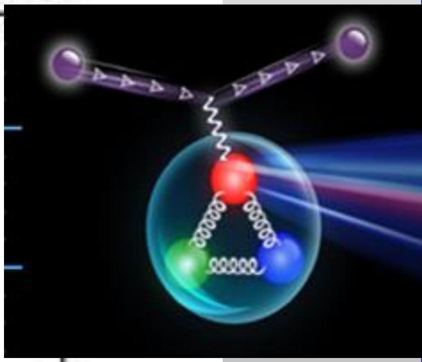
SRC fraction - 20%

gs → gs: G. Kramer, H. Blok, and L. Lapikas, NPA, 679, 267 (2001)

gs → all: Lee et al., PRC 73, 044608 (2006); L. Atar, Phys. Rev. Lett. 120 (5) (2018) 052501

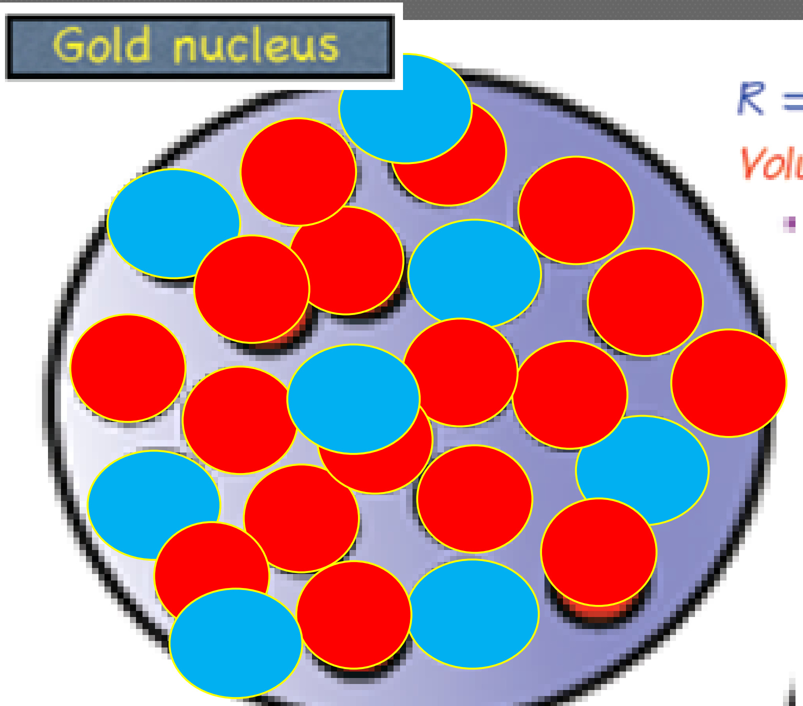
The European Muon Collaboration (EMC) effect





$$F_2^A \neq Z \cdot F_2^p + N \cdot F_2^n$$

After 30 years no consensus on cause of EMC effect



$R = 1.2A^{1/3}$

$Volume = \frac{4}{3}\pi R^3 \simeq 1400 fm^3$

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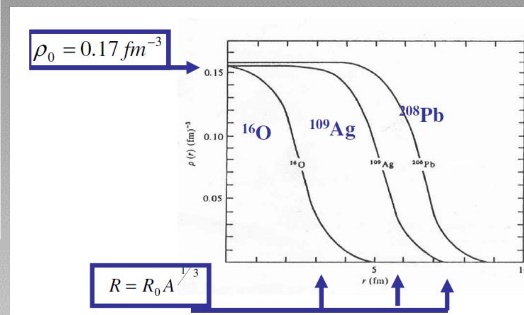
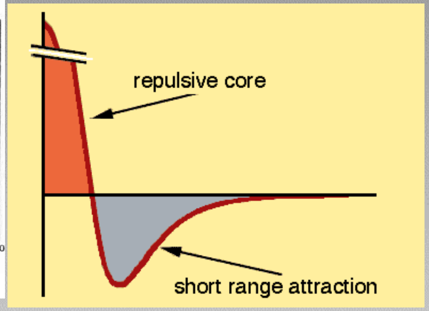
A single nucleon, r = 1 fm, has a volume of 4.2 fm^3:==>197 times 4.2 fm^3 ≈ 830 fm^3

60% of the volume is occupied

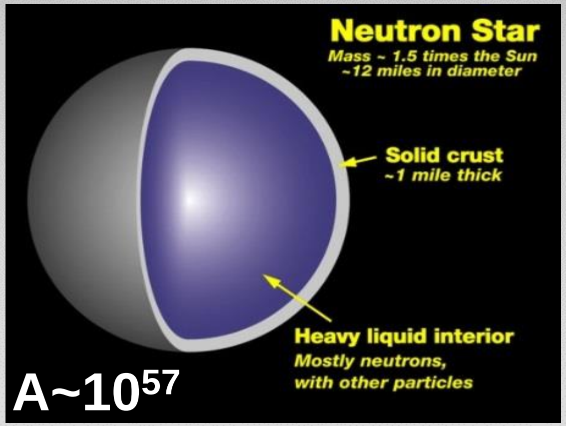
closely packed!

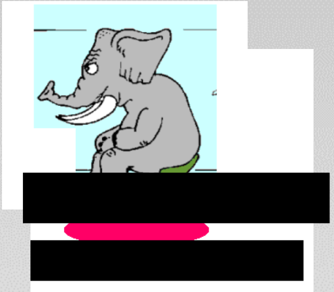
Nuclei are dense

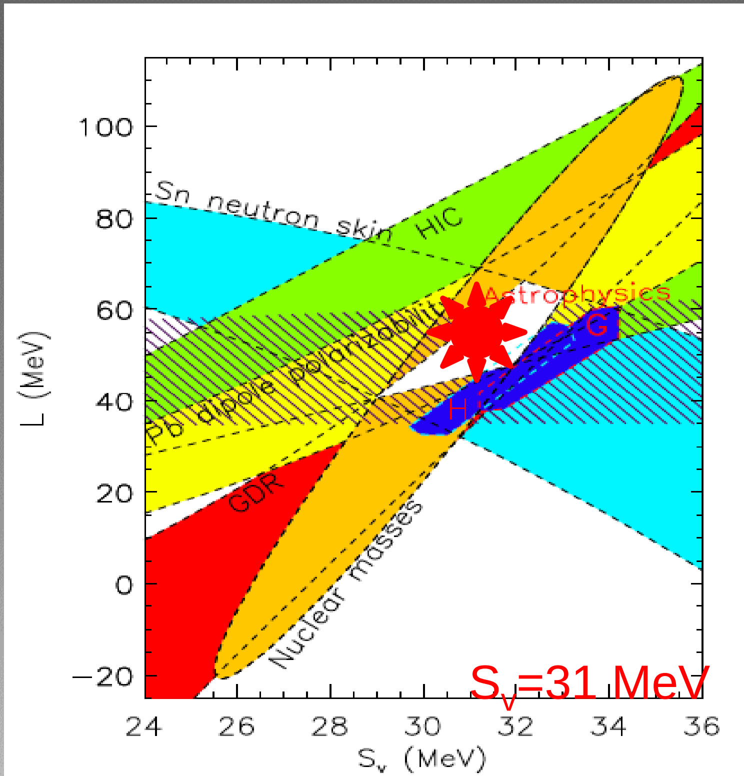


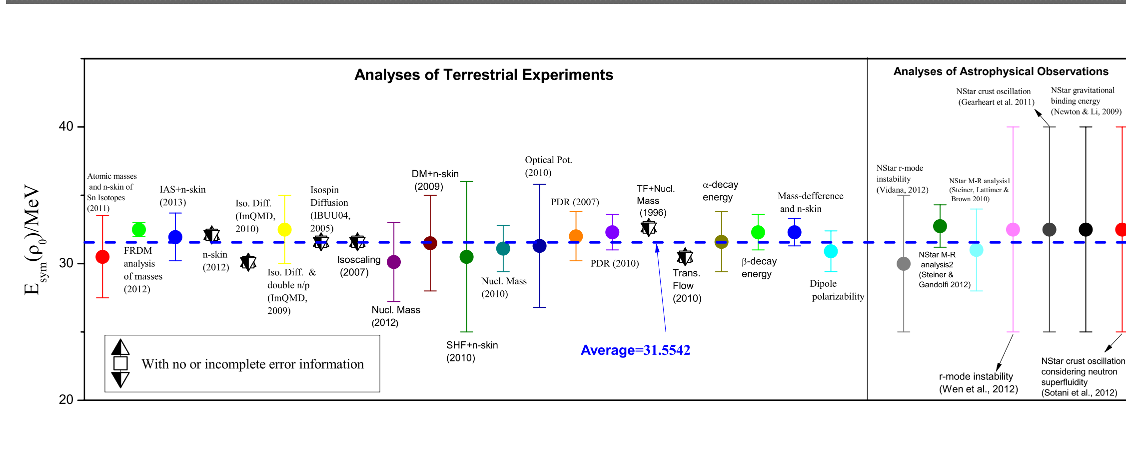


Even denser nuclear systems in nature:



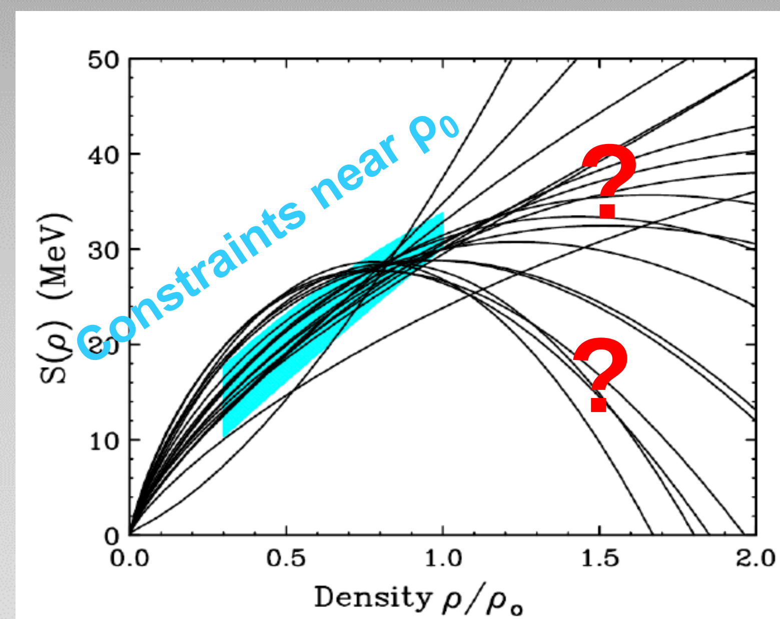






Bao-An Li and Xiao Han, Phys. Lett. B727, 276 (2013).

Lattimer and Steiner (6 out of 30 constraints)

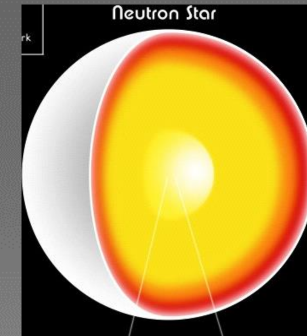


Adapted from Bao-An Li talk

M. B. Tsang et al., Phys. Rev. C86, 015803 (2012)

Nuclear density

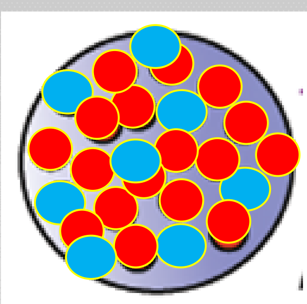
Asymetry



$$A \approx \frac{M_{\odot}}{M_p} \approx 10^{57}$$

$$N / Z \approx 95\% / 5\% = 20$$

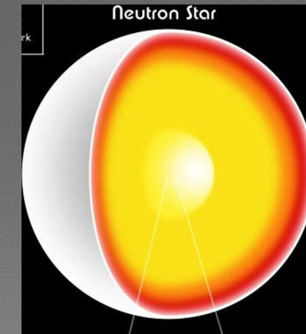
$$\rho_0 = 2 - 5\ \rho_0$$



$$A < 200\ (300)$$

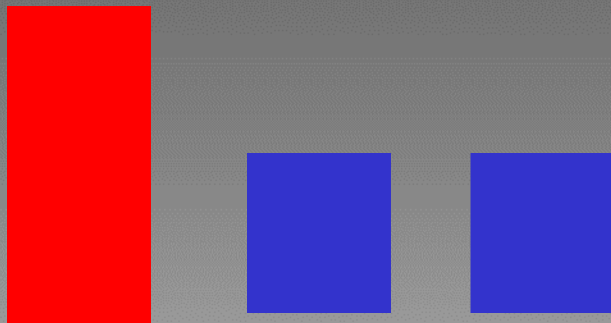
N/Z<1.5 (2.5)

$$\rho_0 = 0.17\ N / \ fm^3 = 0.16\ GeV / \ fm^3$$



•most accepted models assume :

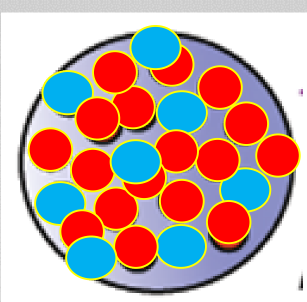
~95% neutrons, ~5% protons and ~5% electrons (β-stability).



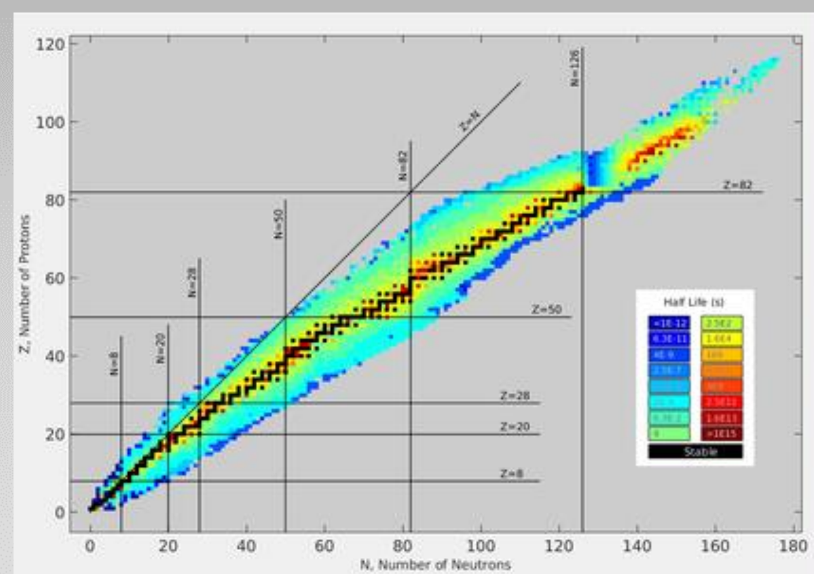
k^{n}_{Fermi} k^{p}_{Fermi} k^{e}_{Fermi}

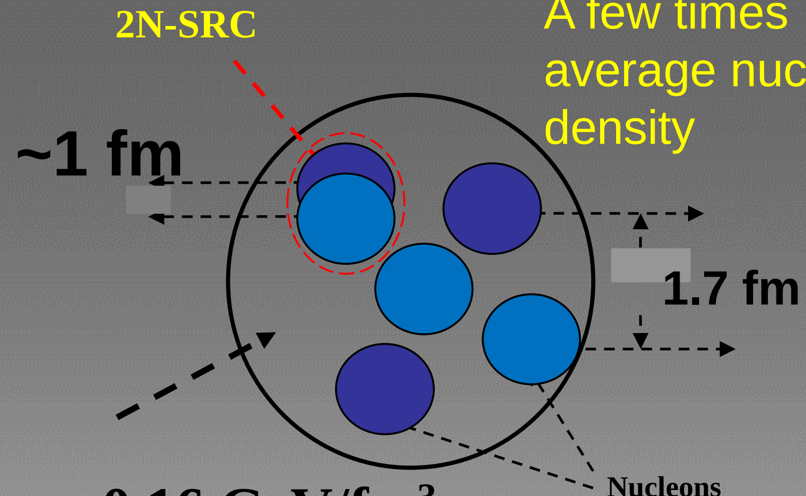
$$N / Z \approx 95\% / 5\% = 20$$

$$N/Z < 1.5\ (2.5)$$



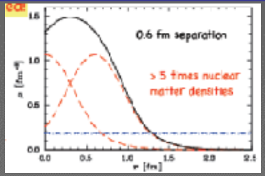
Had

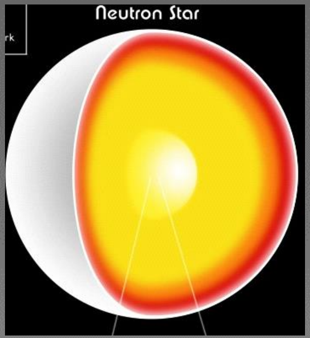




ρ_o = 0.16 GeV/fm^3

A few times average nuclear density



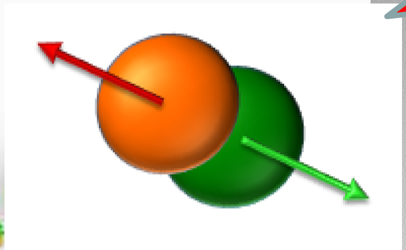


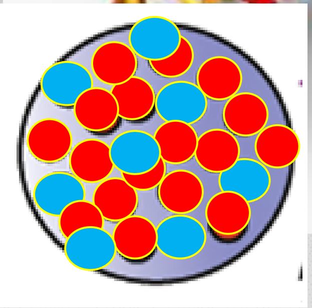
$$A \approx \frac{M_{\square}}{M_p} \approx 10^{57}$$

$$N / Z \approx 95\% / 5\% = 20$$

?

$$\rho_0 = 2 - 5\ \rho_0$$





$$A < 200\ (300)$$

N/Z<1.5 (2.5)

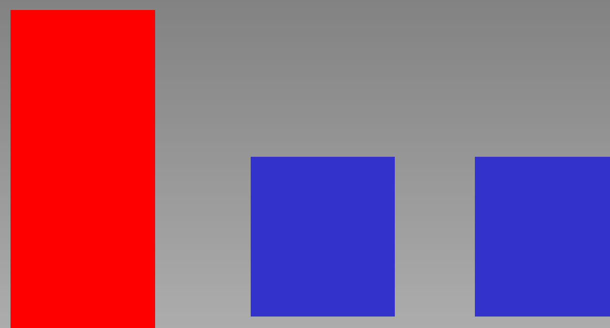
$$\rho_0 = 0.17\ N /\ fm^3$$

2N-SRCs: pairs of nucleons close together in the nucleus (wave functions overlap)

Had

•~95% neutrons, ~5% protons ~5% electrons (β-stability).

•three separate Fermi gases (n, p, e).



k^{n}_{Fermi} k^{p}_{Fermi} k^{e}_{Fermi} At T=0

$$\frac{\langle E_k^p \rangle}{\langle E_k^n \rangle} = \frac{k_F^p}{k_F^n} = \left(\frac{n_p}{n_n}\right)^{1/3} = \left(\frac{5-10\%}{90-95\%}\right)^{1/3} \approx \frac{1}{2-3}$$

SRC in neutron rich nuclei

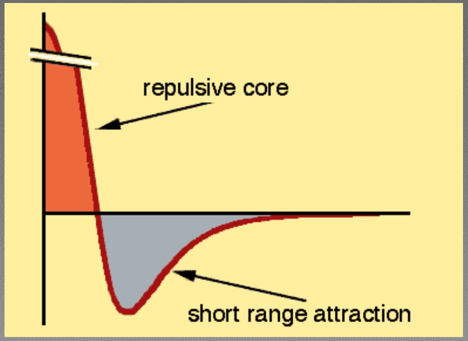
$$\frac{\langle E_k^p \rangle}{\langle E_k^n \rangle} > 1$$

in neutron stars

Nuclear Physics 101

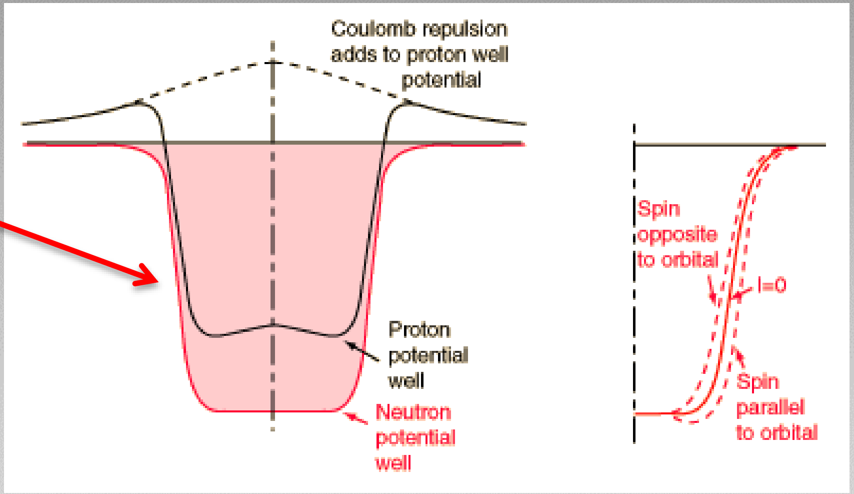
- Many-Body Hamiltonian:

$$H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i<j=1}^{A} V_{2N}(i,j) + \sum_{i<j<k=1}^{A} V_{3N}(i,j,k) + $$



- Mean-Field Approximation:

$$H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i=1}^{A} V(i)$$



Results in an "atom-like" shell model:

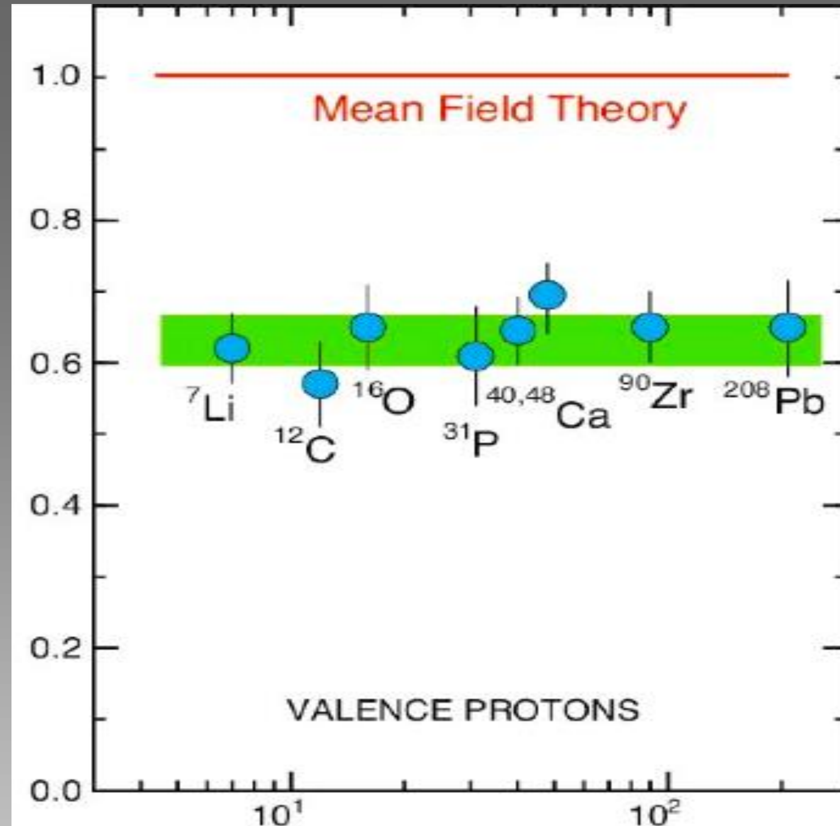
- Ground state energies
- Excitation Spectrum
- …

E. Wigner, M. Mayer, and J. Jenson, 1963 Nobel Prize

Beyond the Mean Field: NN Correlations

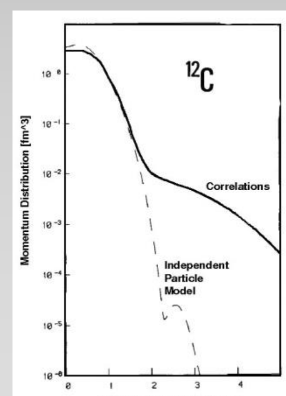
Spectroscopic factors for (e, e'p) reactions

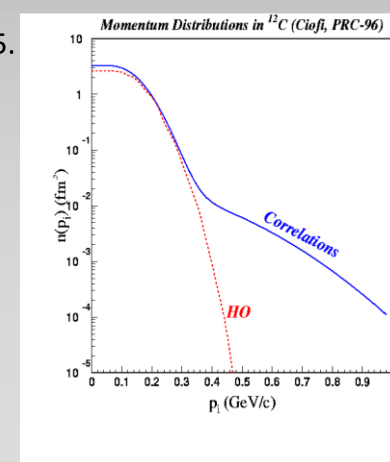
show only 60-70% of the expected single-particle strength.



L. Lapikas, Nucl. Phys. A553, 297c (1993)

Benhar et al., Phys. Lett. **B** 177 (1986) 135.





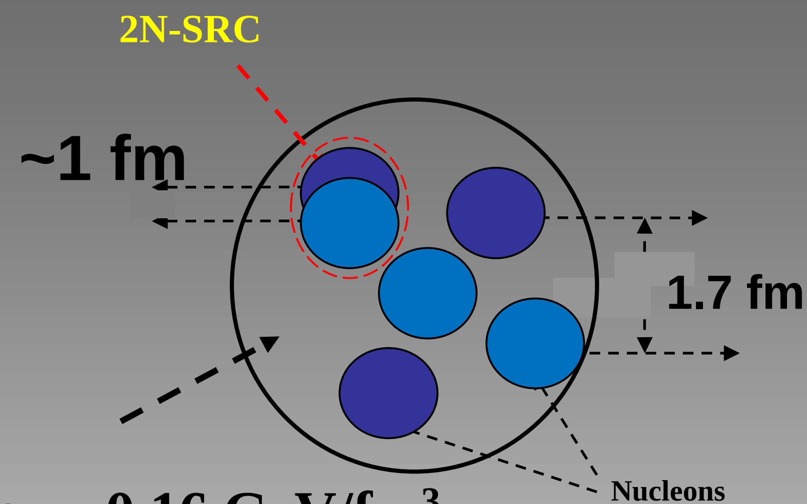
MISSING :

Correlations Between Nucleons

SRC ~R_N LRC ~R_A

What are Short Range Correlations in nuclei ?

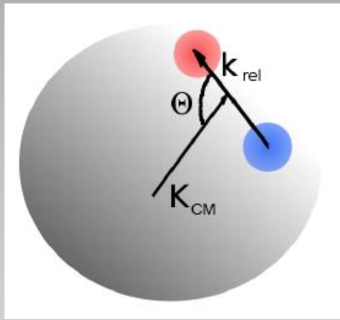
SRC ~R_N LRC ~R_A

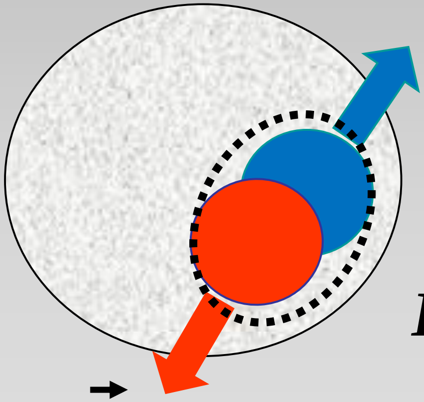


$\rho_o = 0.16\ GeV/fm^3$

In momentum space:

$$K_{rel} > K_F$$
$$K_{CM} < K_F$$





$\vec{K}_1$

$\vec{K}_2$

$$\vec{K}_1 \cong \vec{K}_2$$

$K_1 > K_F$,

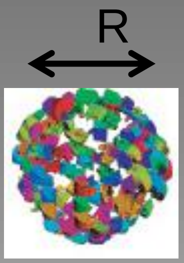
$K_2 > K_F$

A pair with large relative momentum between the nucleons and small CM momentum.

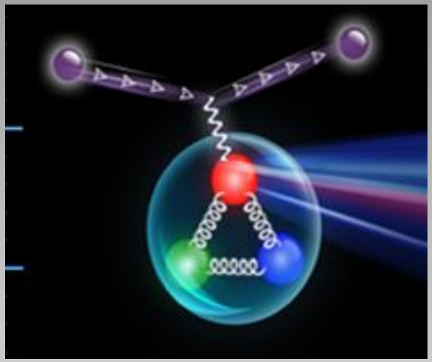
Hard scattering :

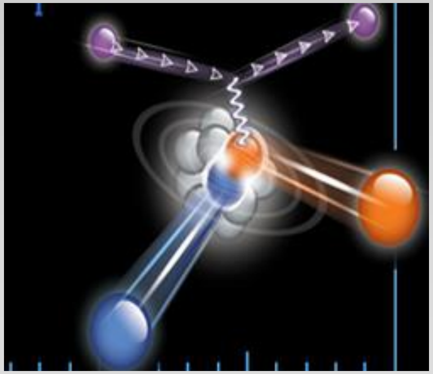
High-energy (small de Broglie wavelength λ) and large-momentum transfer q)

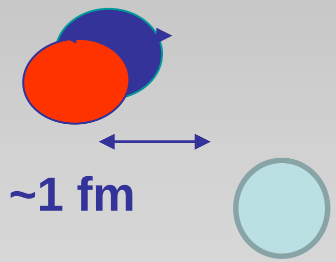
$$\lambda < R \qquad\qquad q \cdot R < 1$$

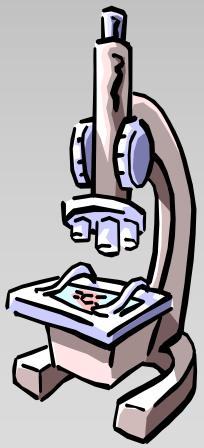


Hard scattering has the resolving power required to probe the internal (partonic) structure of a complex target



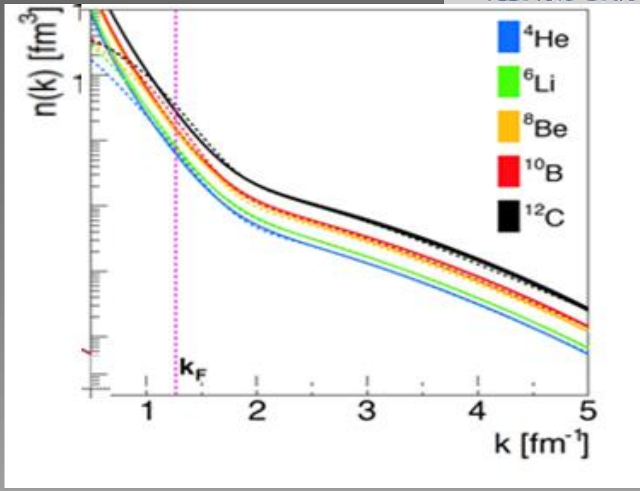




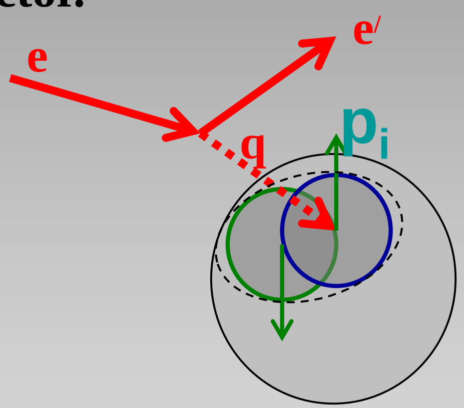


- At high nucleon momentum distributions are similar in shape for light and heavy nuclei: SCALING.

ab-initio VMC calculations



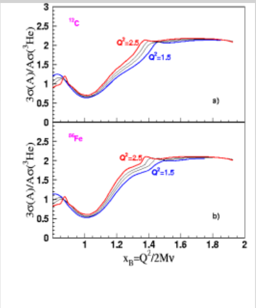
- Can be explained by 2N-SRC dominance.
- Within the 2N-SRC dominance picture one can get the probability of 2N-SRC in any nucleus, from the scaling factor.



In A(e,e') the momentum of the struck proton (p_i) is unknown.

But: For fixed high Q^2 and $x_B>1$, x_B determines a minimum p_i

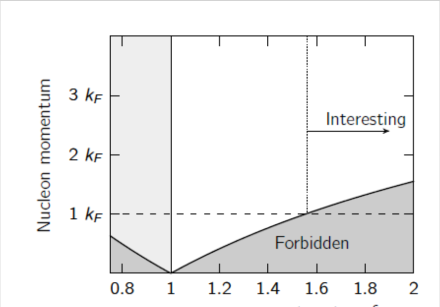
Prediction by Frankfurt, Sargsian, and Strikman:



$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega}$$



Inclusive scattering results from data mining (EG2c)

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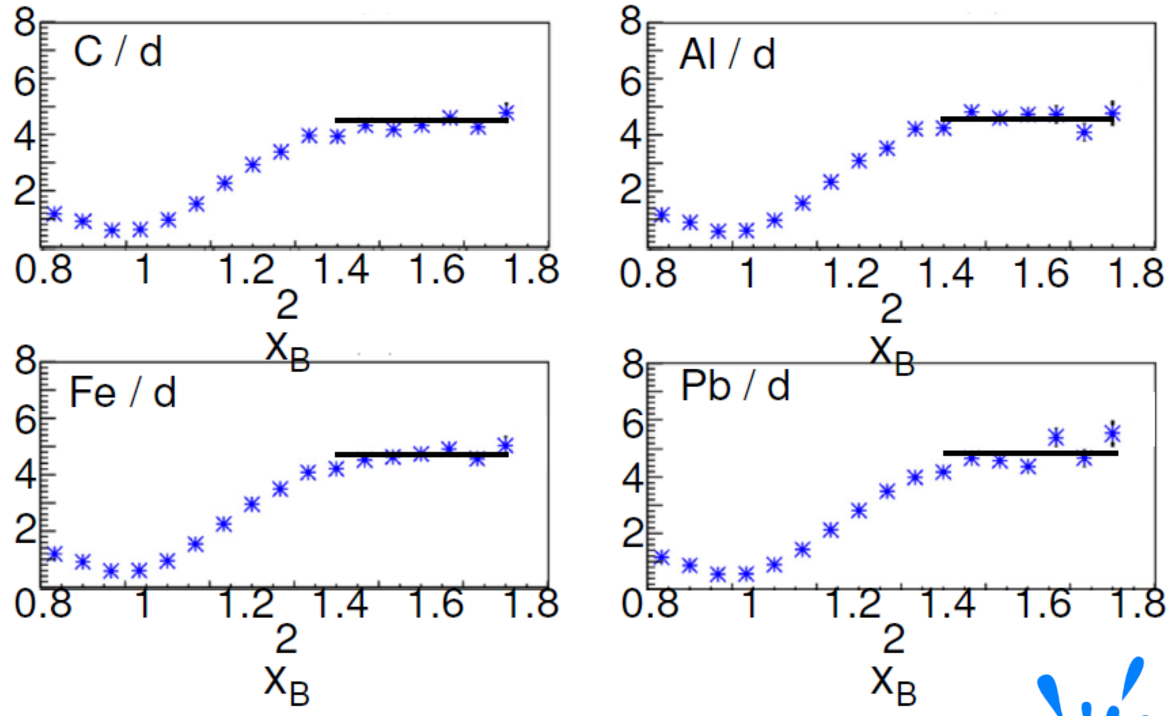
Q^2=1.55 GeV^2

a_{2N}(A/d)

	Fomin *et al.*	Fomin *et al.* [excluding the CM motion correction]
	5	6
^{3}He	1.93 ± 0.10	2.13 ± 0.04
^{4}He	3.02 ± 0.17	3.60 ± 0.09
^{9}Be	3.37 ± 0.17	3.91 ± 0.12
^{12}C	4.00 ± 0.24	4.75 ± 0.16
^{56}Fe	4.33 ± 0.28	5.21 ± 0.19
^{197}Au	4.26 ± 0.29	5.16 ± 0.21



Barak Schmookler (MIT)

NEW!

Jlab /Hall B: K. Sh. Egiyan et al. PRC 68, 014313 (2003)

K. Sh. Egiyan et al. PRL. 96, 082501 (2006)

Jlab/Hall C: N. Fomin et al. PRL. 108:092502, 2012.

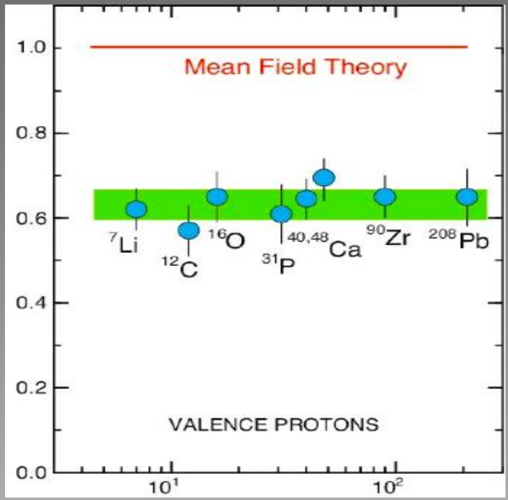
<u>More r(A,d) data:</u>

SLAC D. Day et al. PRL 59,427(1987)

Summary

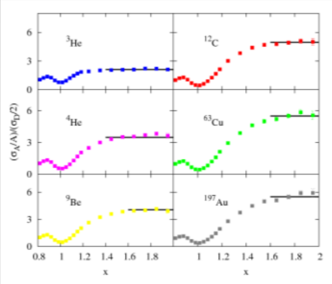
Hard Semi inclusive scattering
A(e, e'p)

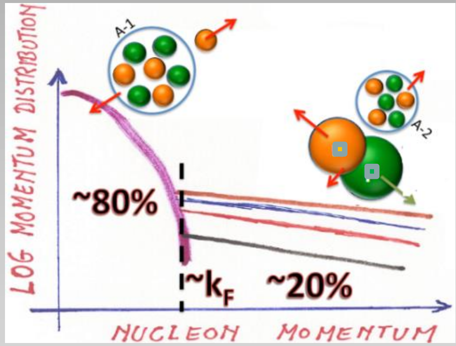
Only 60-70% of the expected single-particle strength.



SRC and LRC

Hard inclusive scattering
A(e, e')

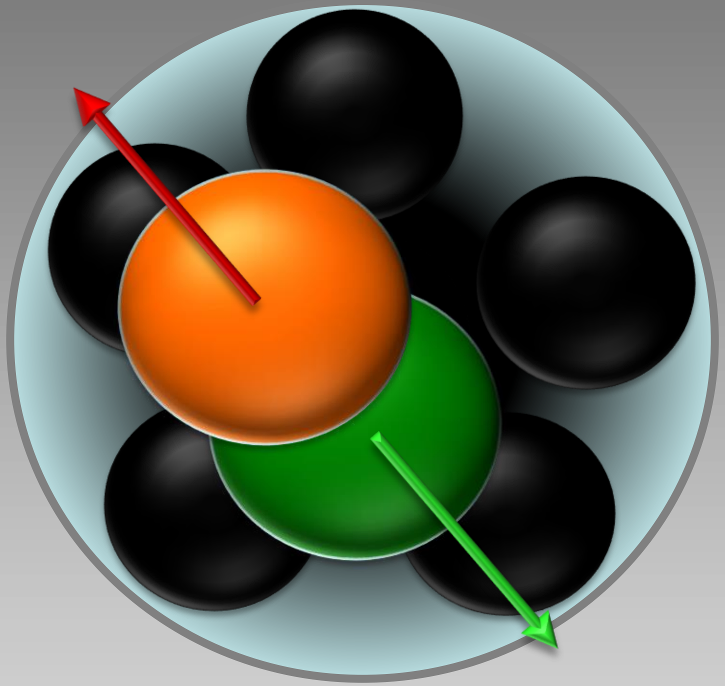




This ~20% includes all three isotopic compositions (pn, pp, or nn) for the 2N-SRC phase in ^{12}C.

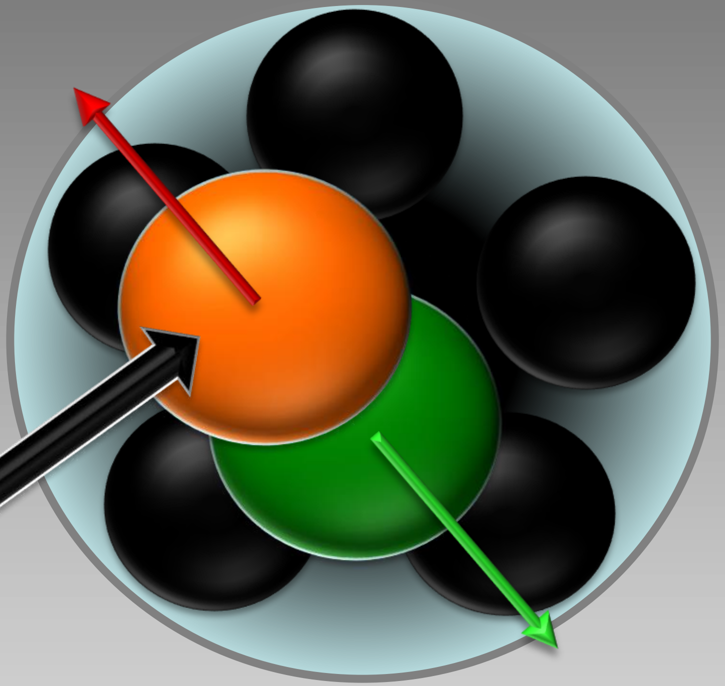
Hard exclusive scattering
A(e, e'pp) and A(e, e'pn)

Hard exclusive triple – coincidence measurements

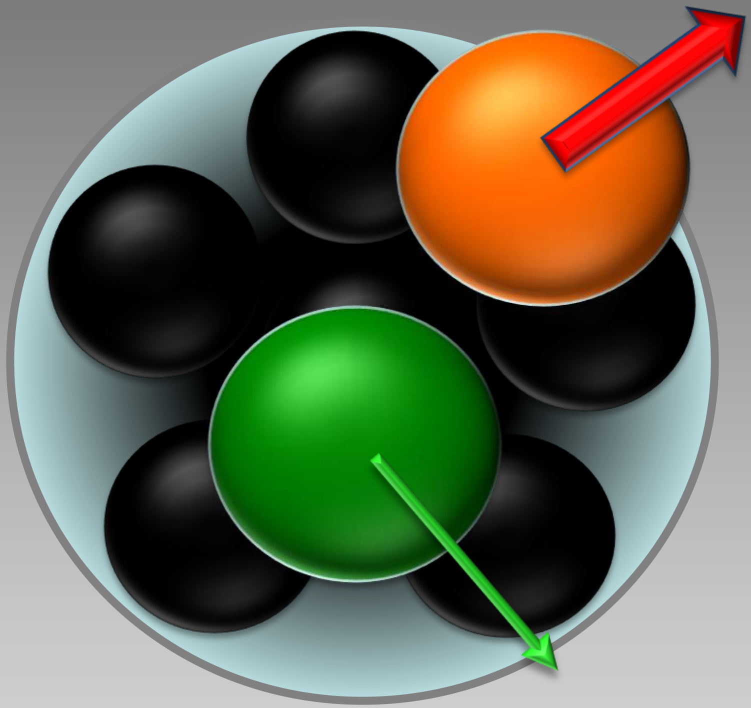


Quasi-Free scattering off a nucleon in a short range correlated pair

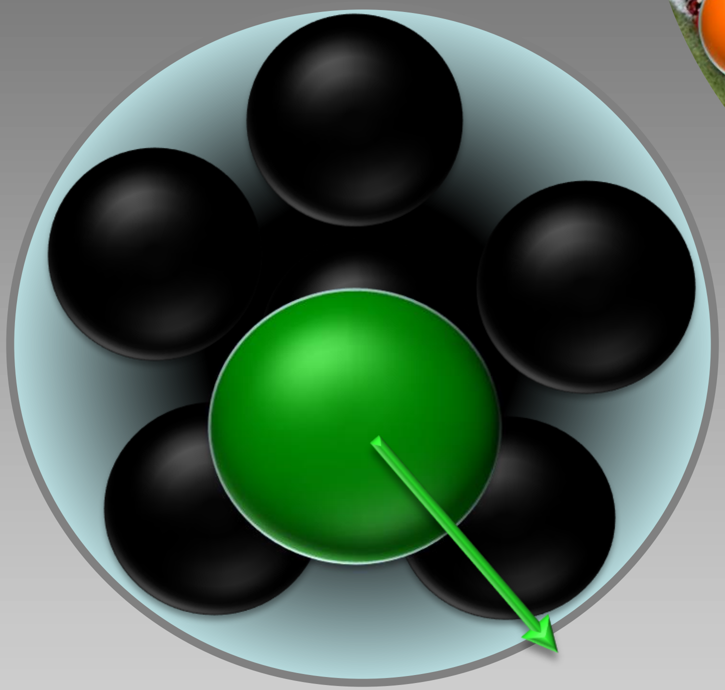
triple – coincidence measurements



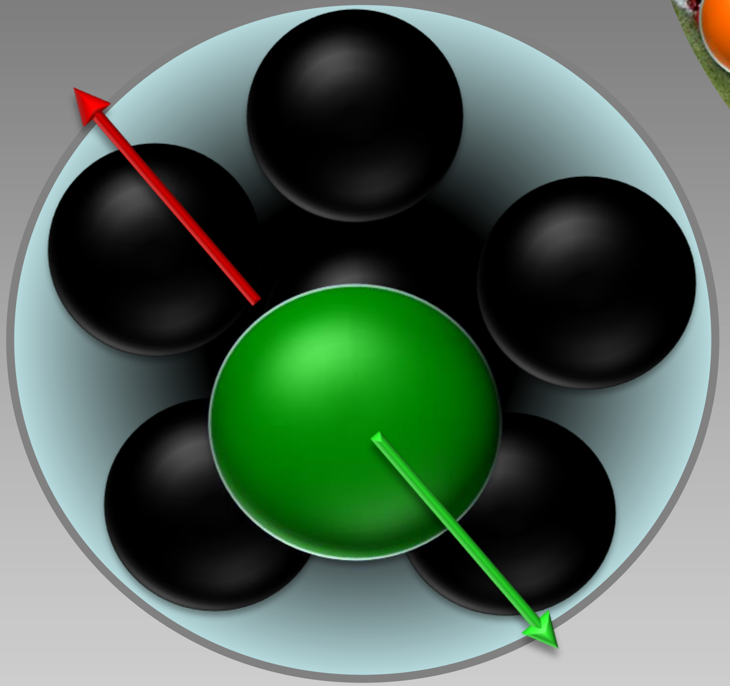
triple – coincidence measurements



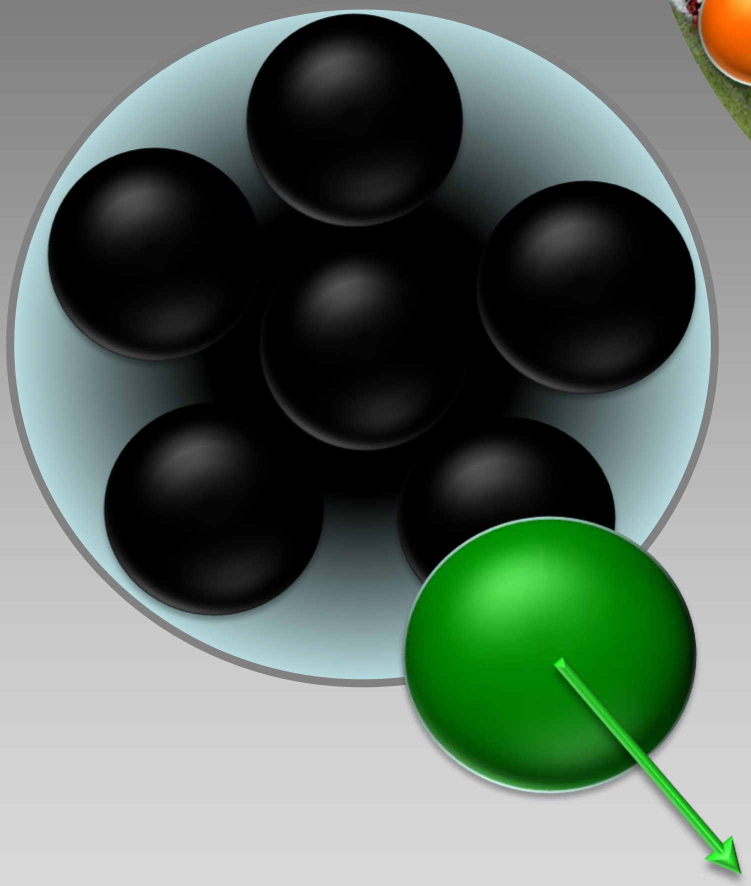
triple – coincidence measurements



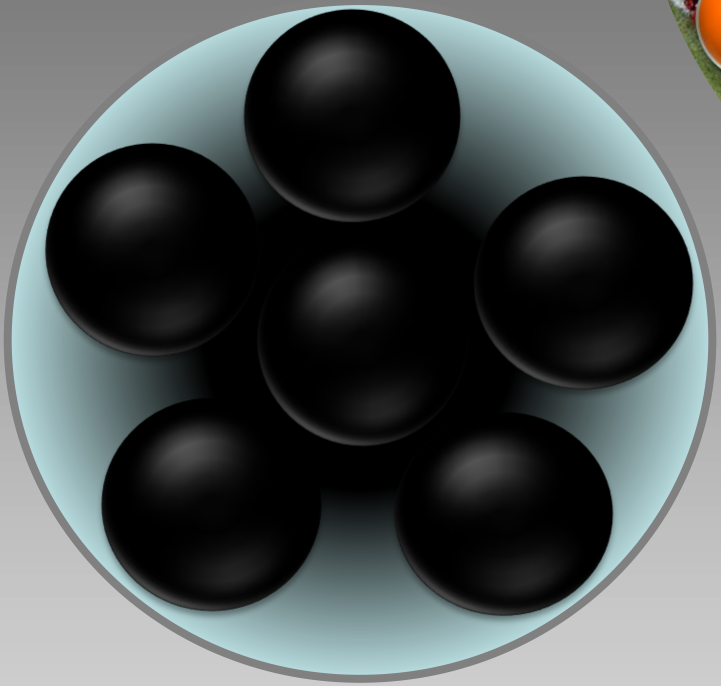
triple – coincidence measurements



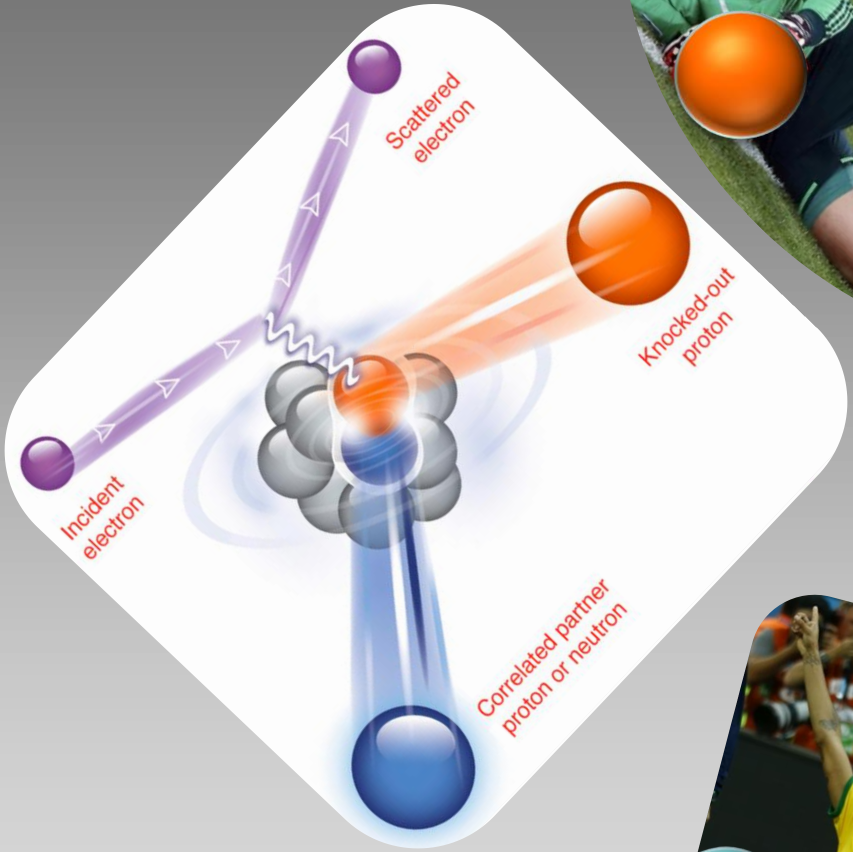
triple – coincidence measurements



triple – coincidence measurements

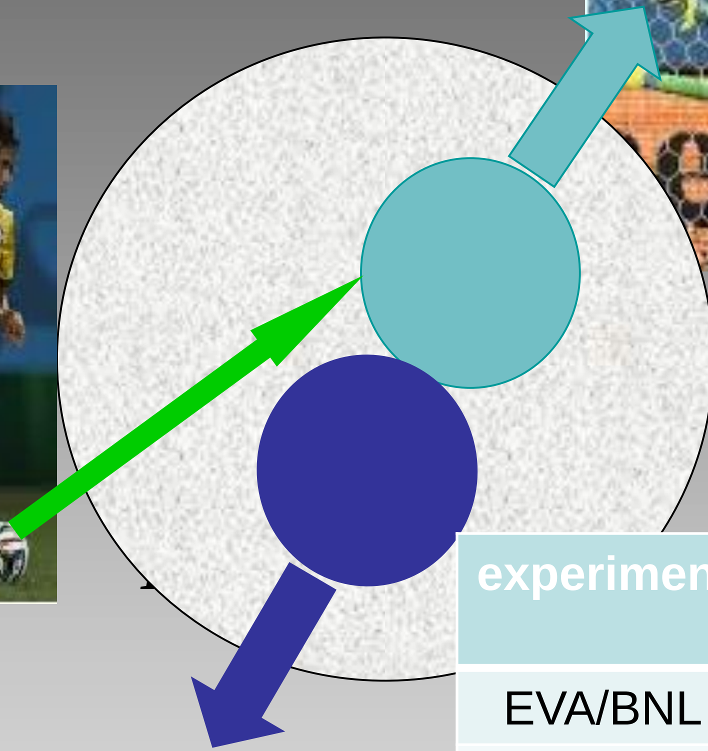


triple – coincidence measurements



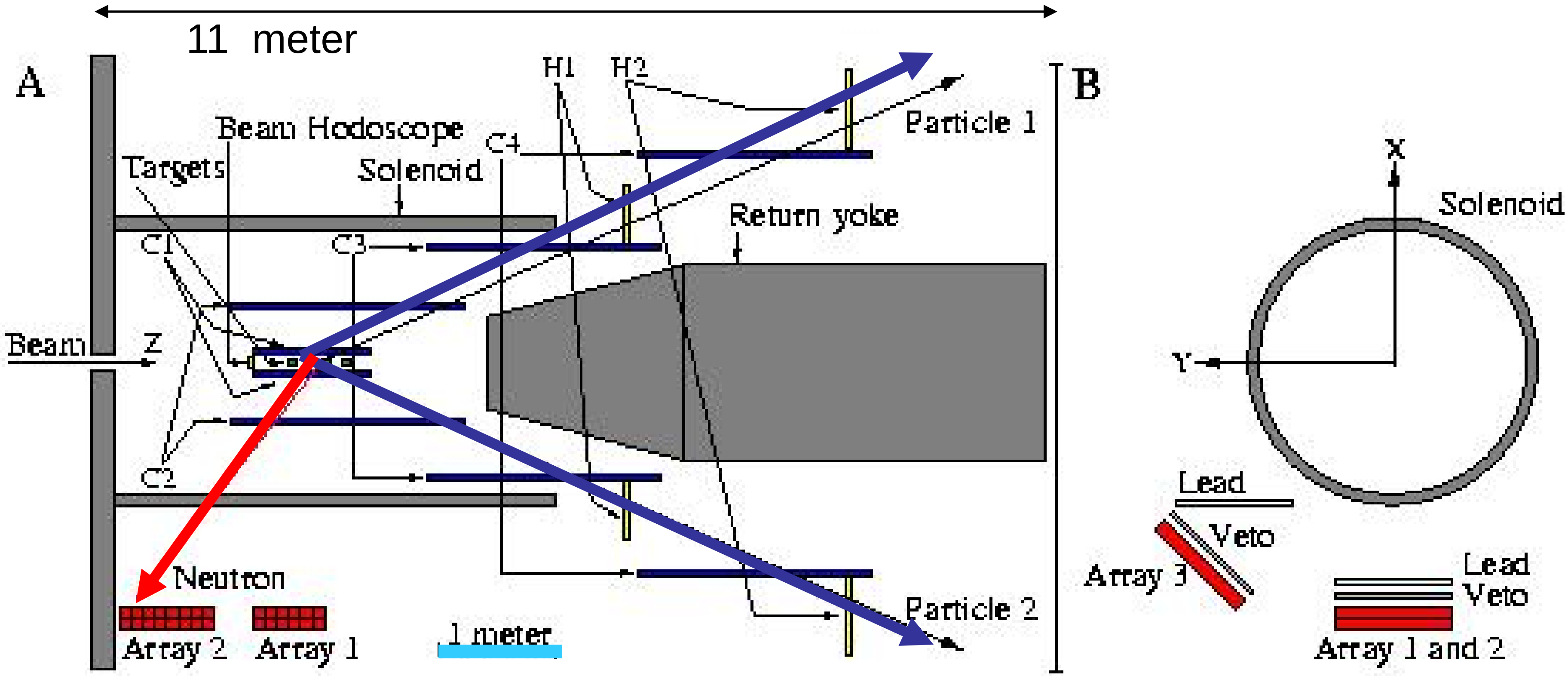
Quasi-Free scattering off a nucleon in a short range correlated pair

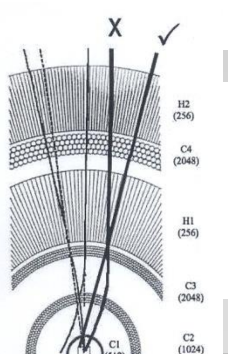
Hard exclusive triple – coincidence measurements

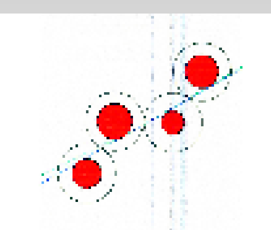


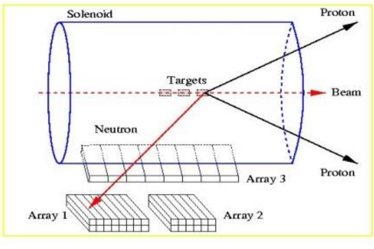
experiment	nuclei	pairs	Pmiss [MeV/c]
EVA/BNL	^{12}C	pn only	300-600
E01-015/ Jlab	^{12}C	pp and np	300-600
E07-006/ JLab	^{4}He	pp and np	400-850
CLAS/JLab	C, Al, Fe, Pb	pp and np	300-700

The EVA spectrometer and the n-counters at BNL



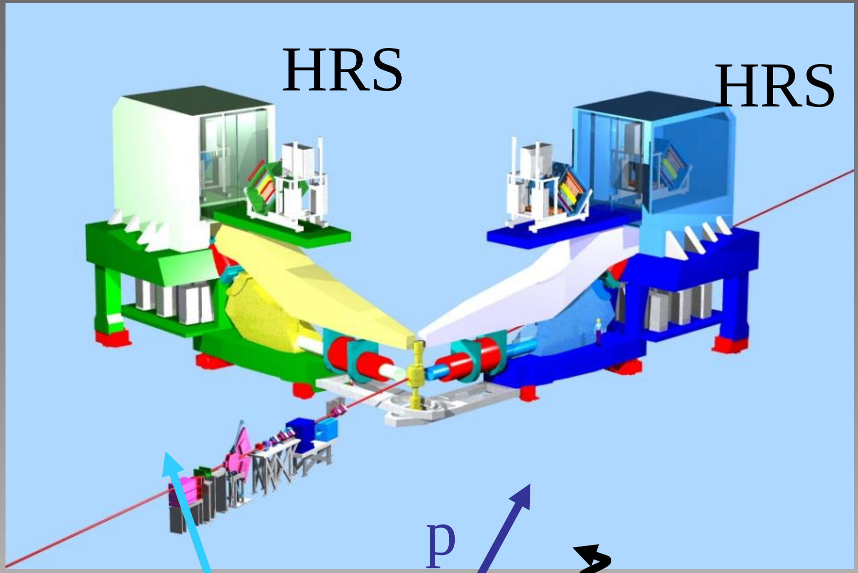




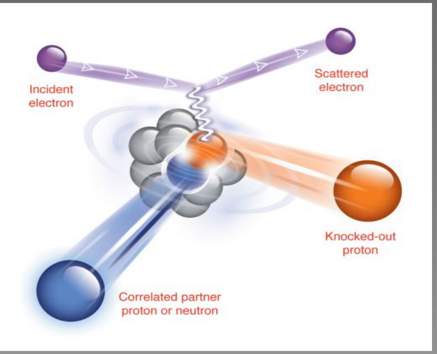


Array 1: total area 0.6×1.0 m^2, 12 counters, 2 layers 0.125 m

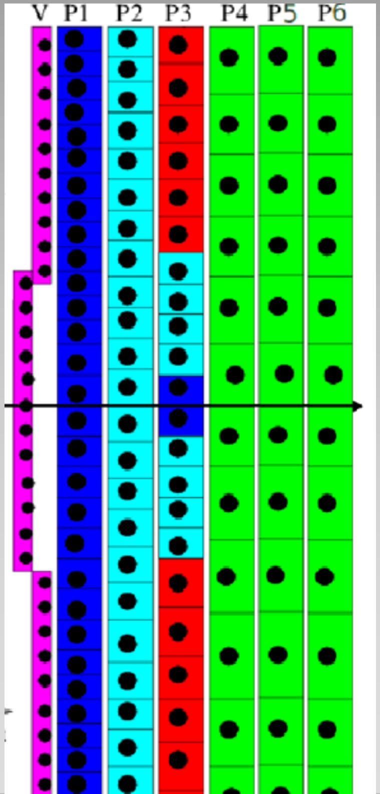
Simultaneous measurements of the .
(e,e' p) , (e, e' p p), and (e, e' p n) reactions.



EXP 01-015
and
EXP 07-006
Hall A JLab



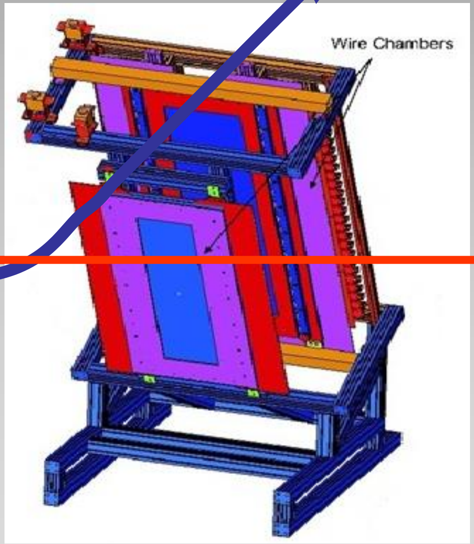
n array

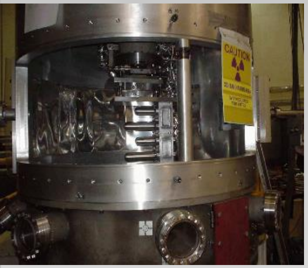


p

p

e



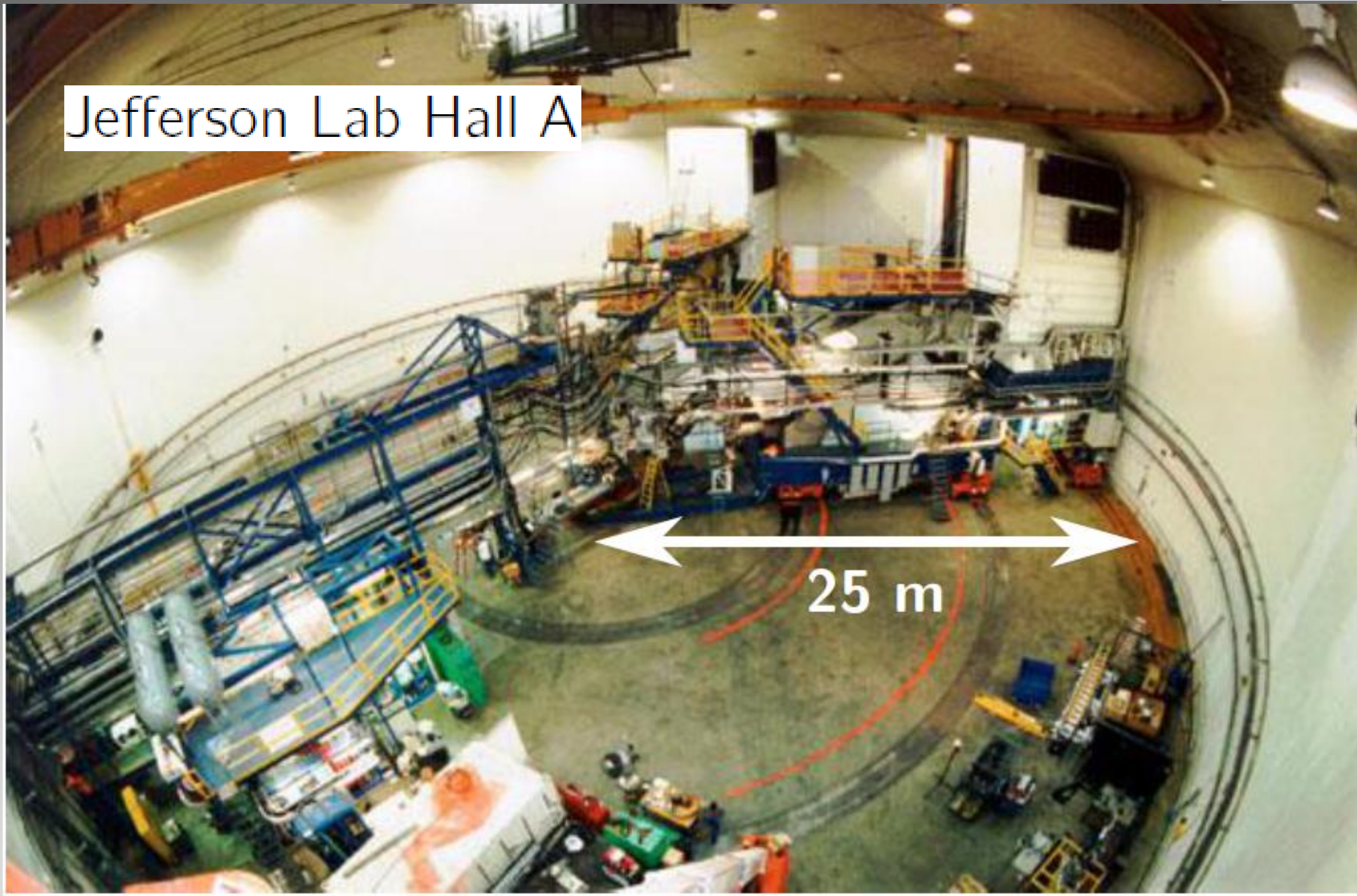


<u>Aluminum cylinder</u>

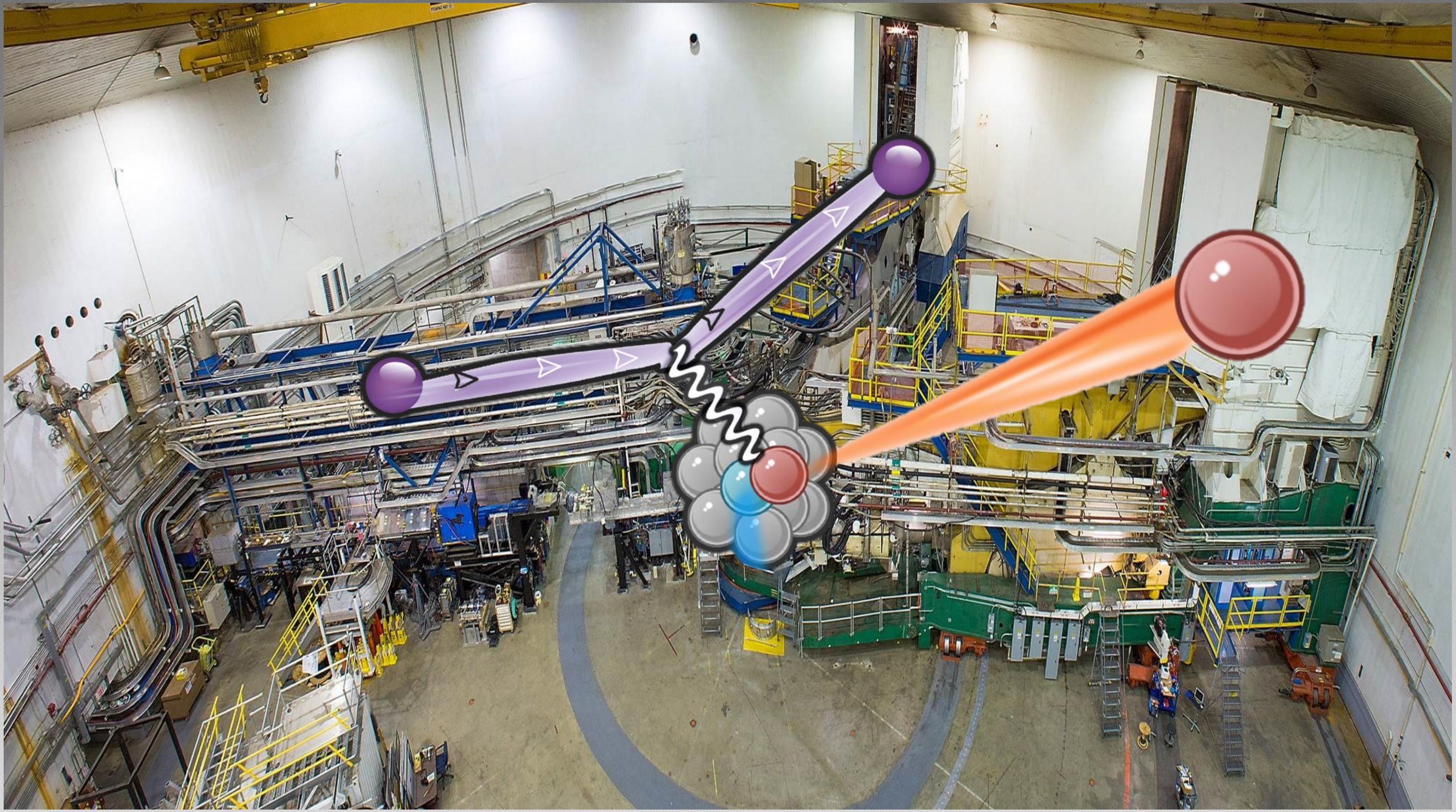
20 cm long
2.5 " diameter

Big Bite

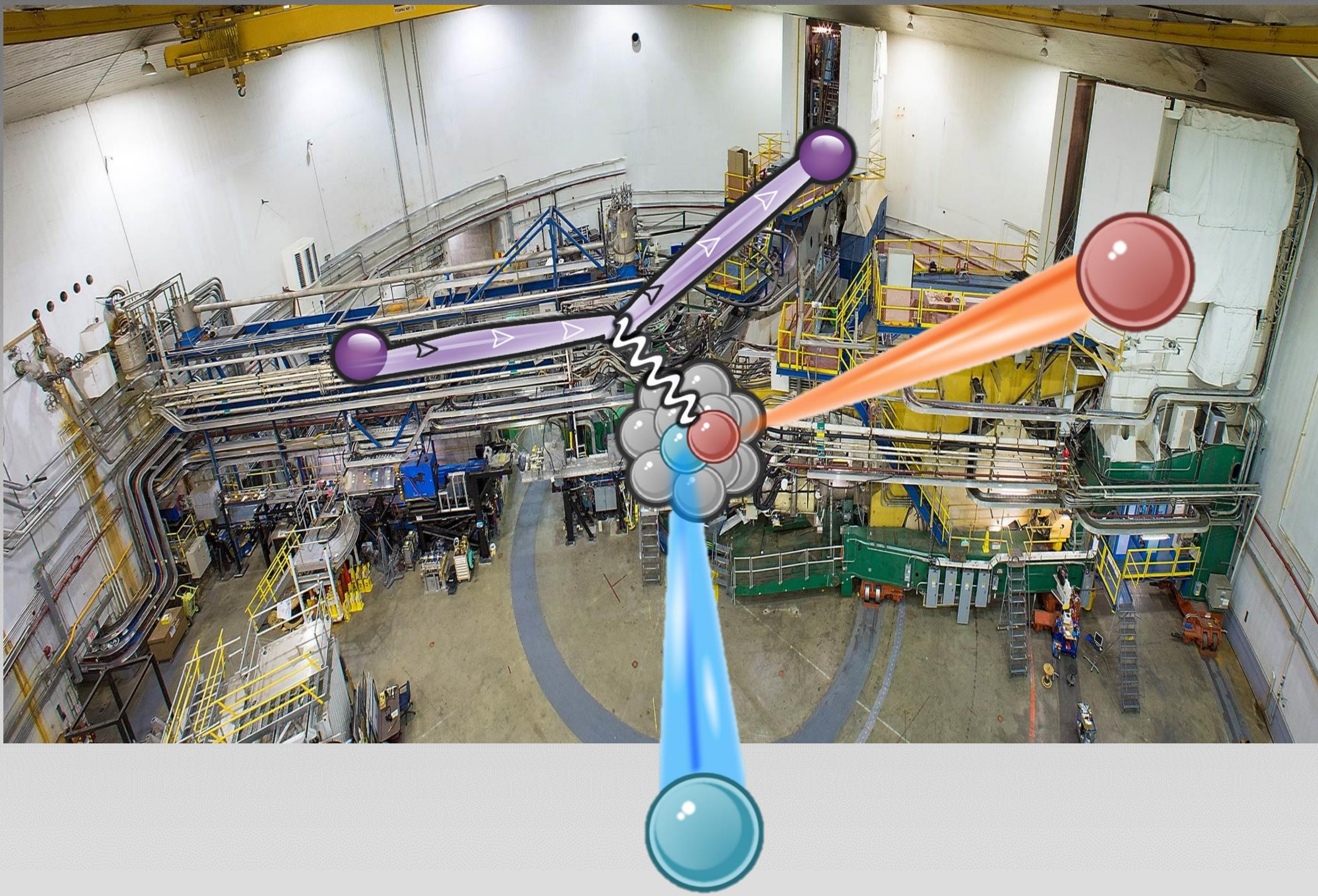
Lead wall


Jefferson Lab Hall A
25 m

Jefferson Lab Hall A



Jefferson Lab Hall A



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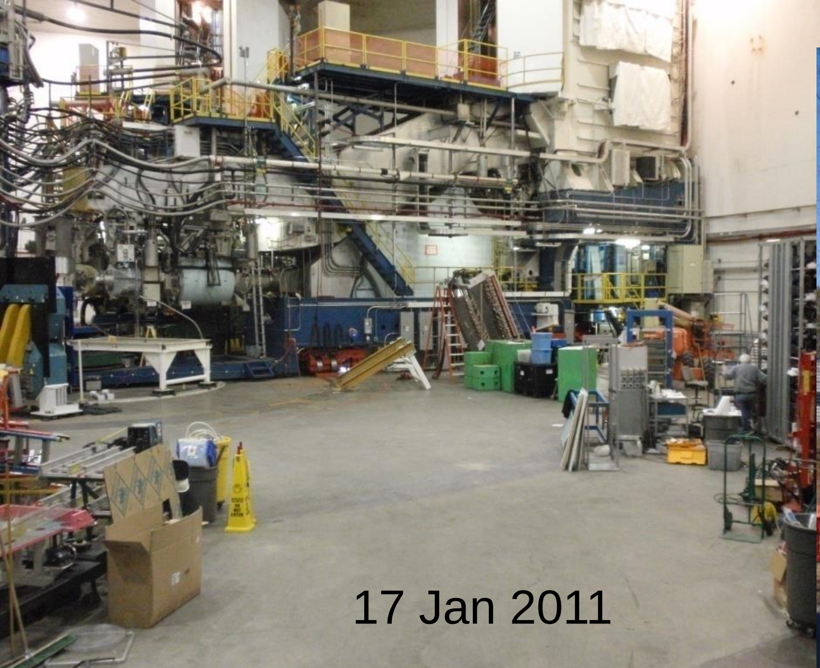

17 Jan 2011

12 Jan 2011

7 Jan 2011

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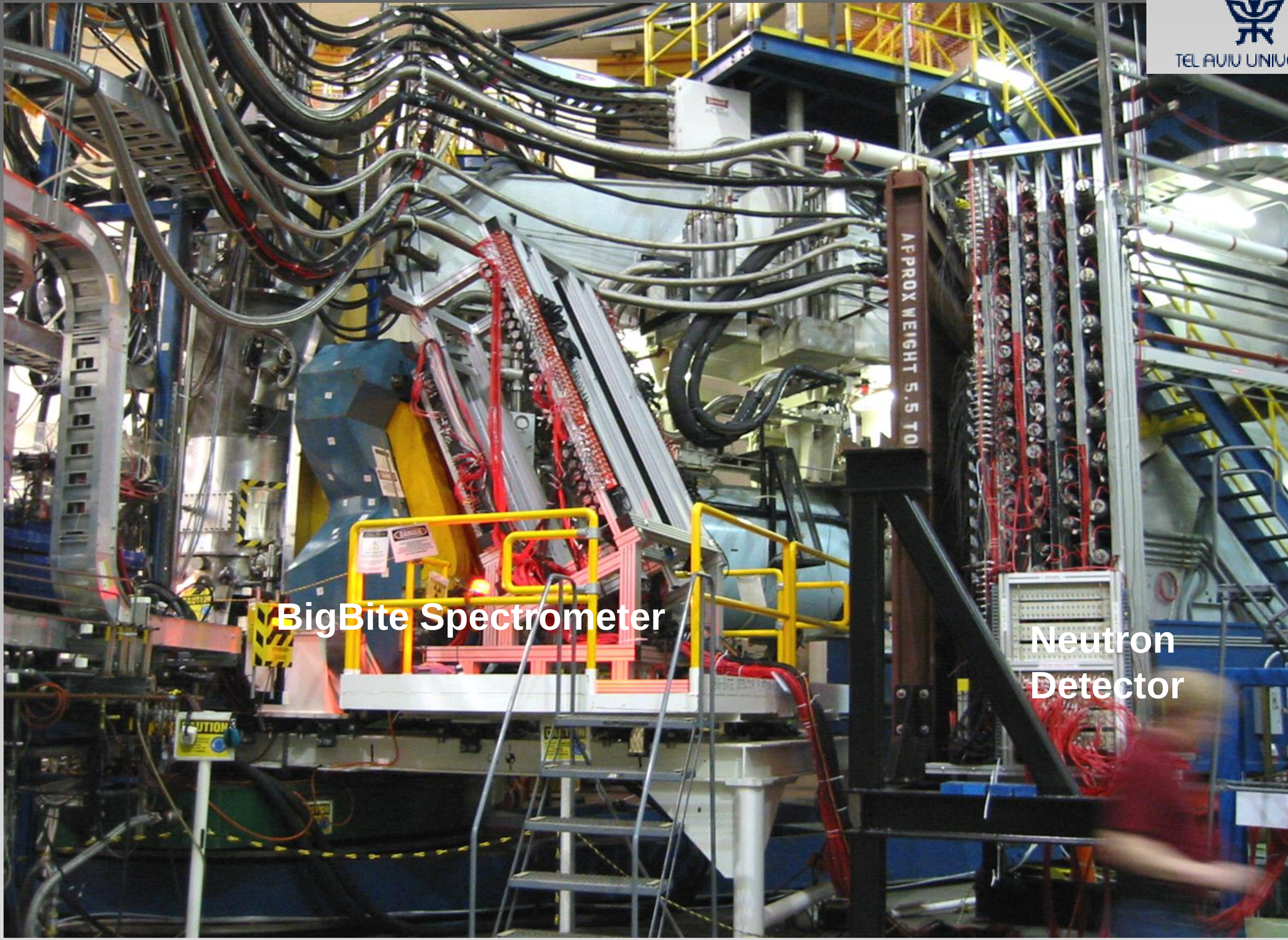
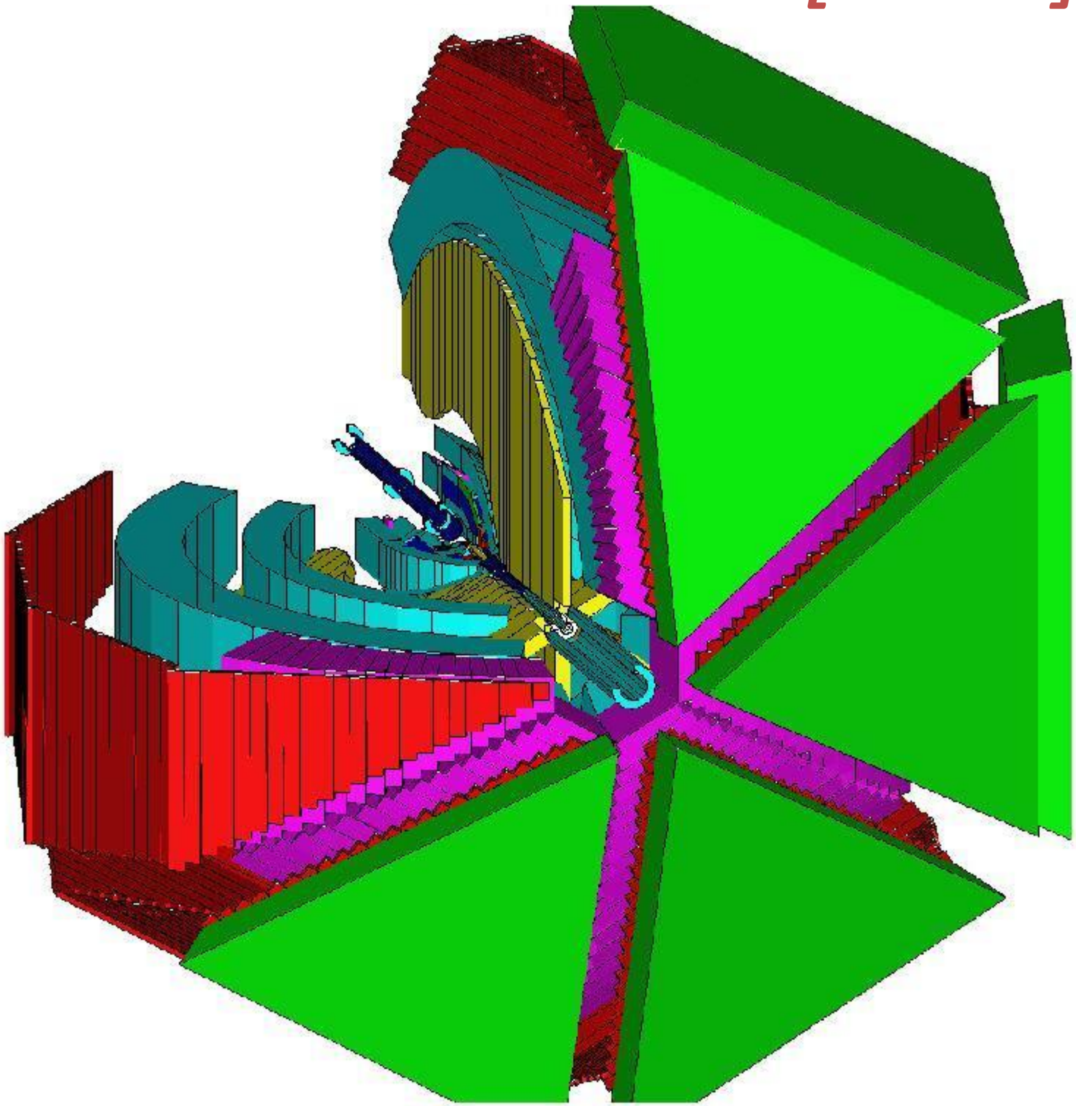
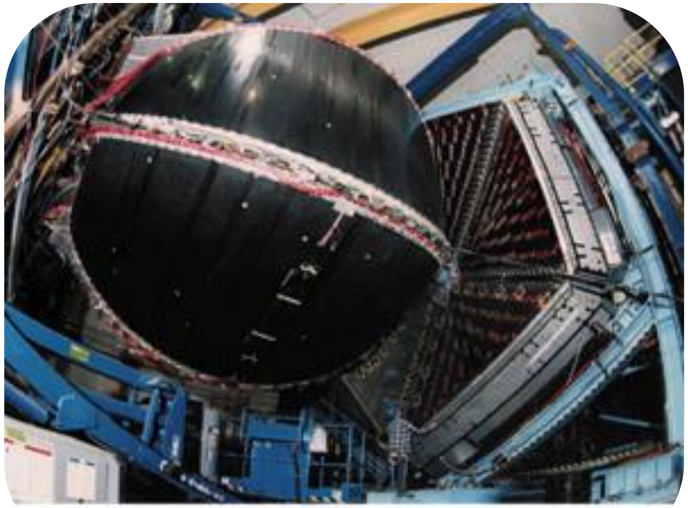


EXP 01-015 **Jlab / Hall A** Dec. 2004 – Apr. 2005

CEBAF Large Acceptance Spectrometer *[CLAS]*

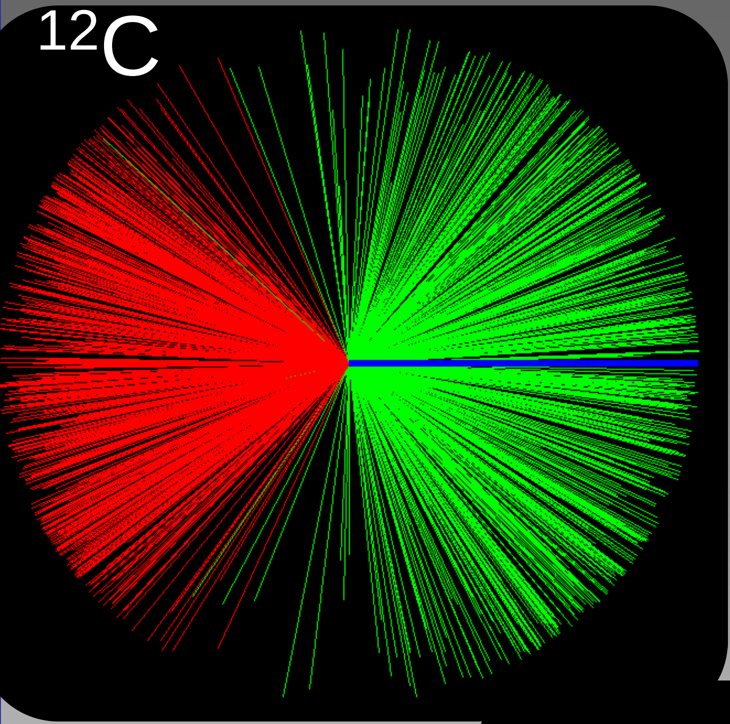




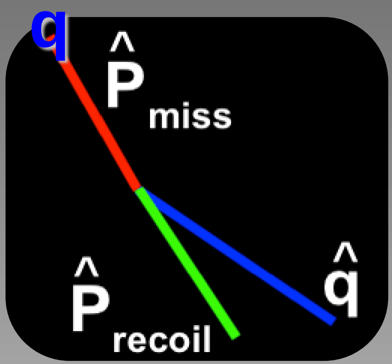
Hall B Large Acceptance Spectrometer

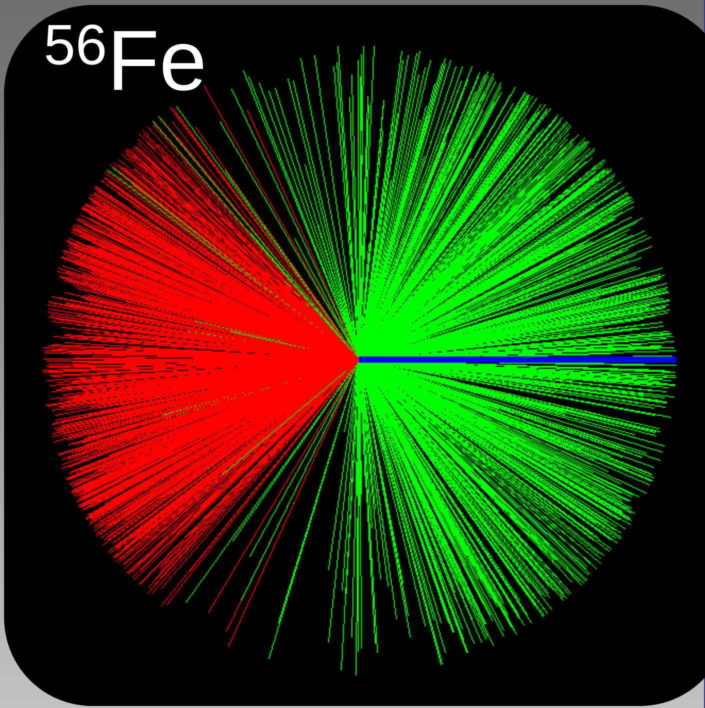
Open (e,e') trigger, Large-Acceptance, Low luminosity (~10^{34} cm^{-2}

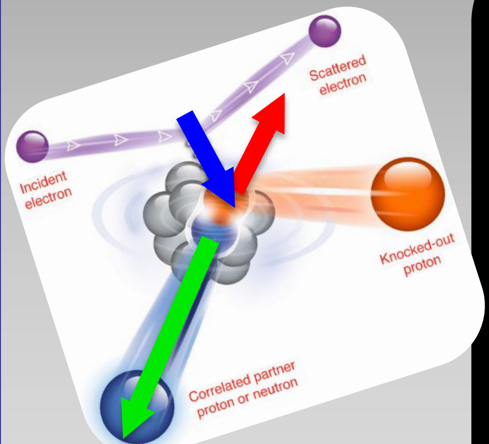
JLab / CLAS, Data Mining, EG2 data set

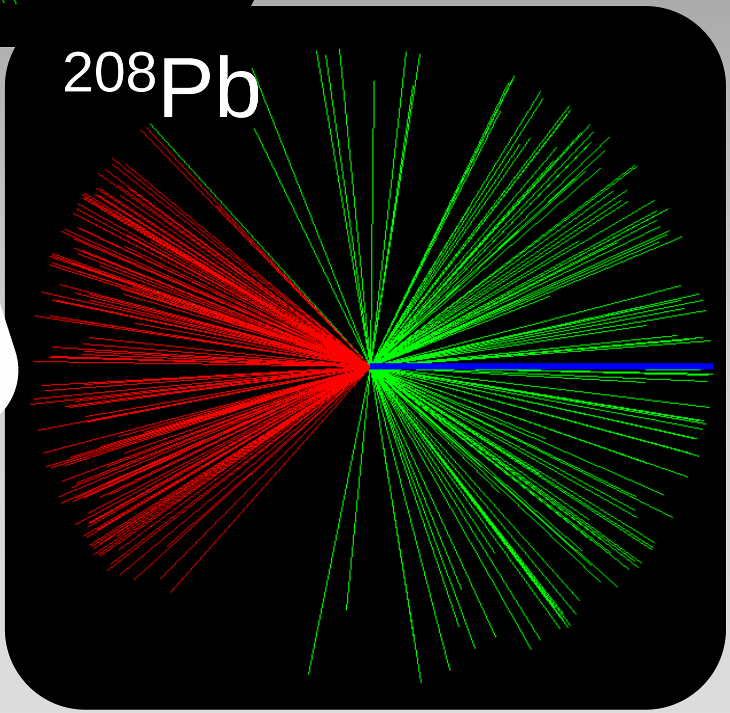


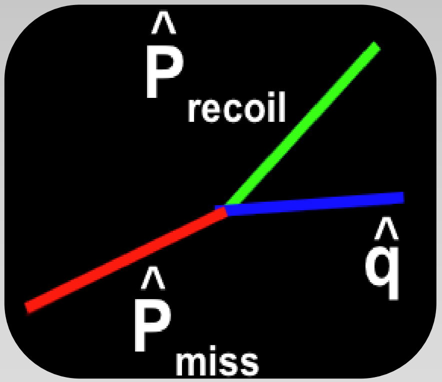
A(e.e’pp)







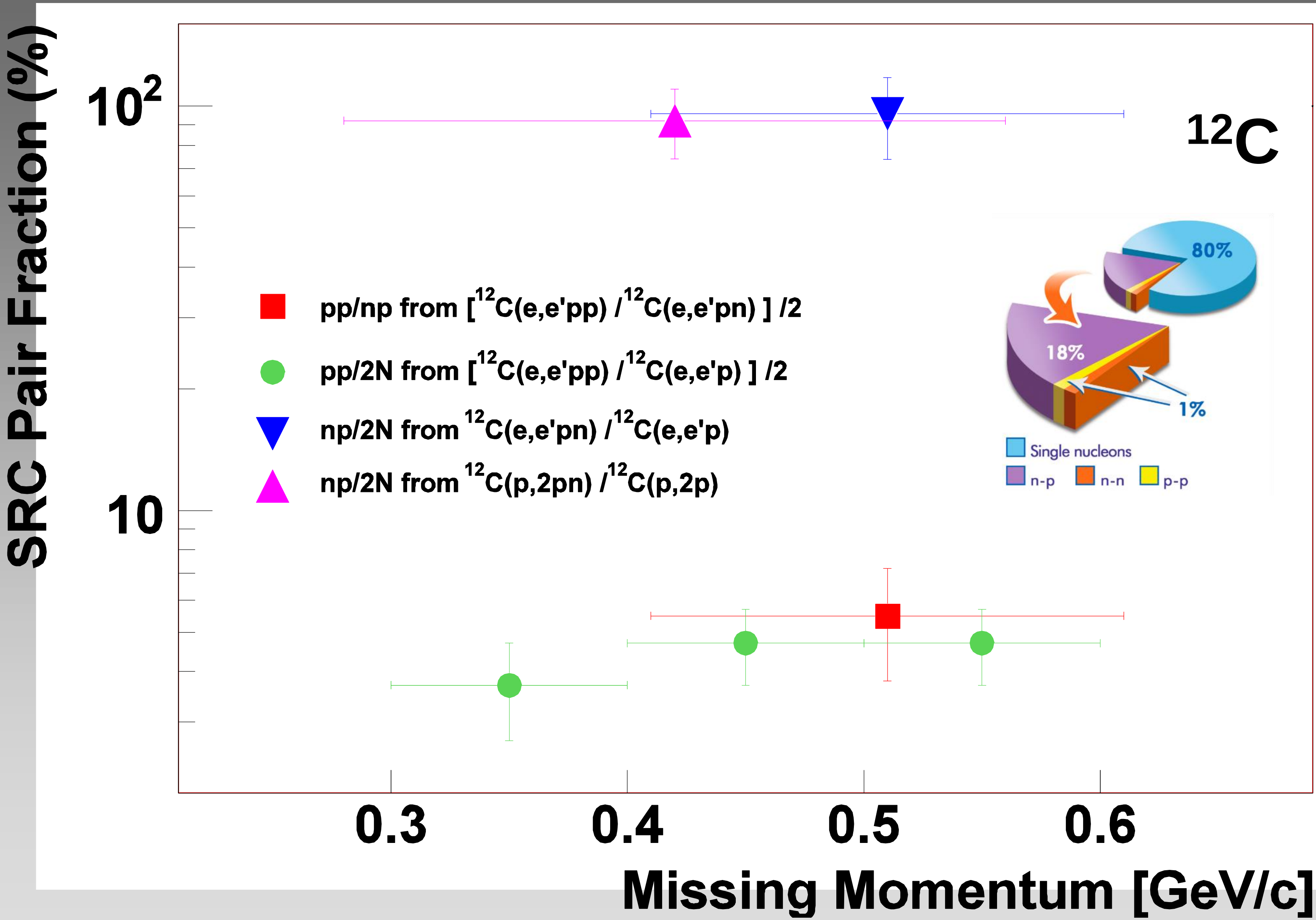




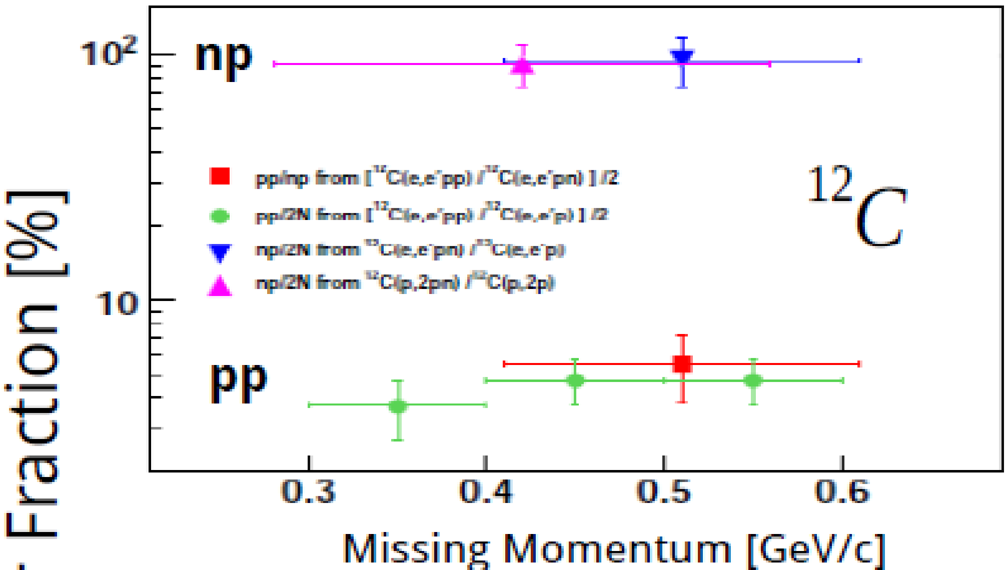
Back-to-back = SRC pairs!

3D Reconstruction

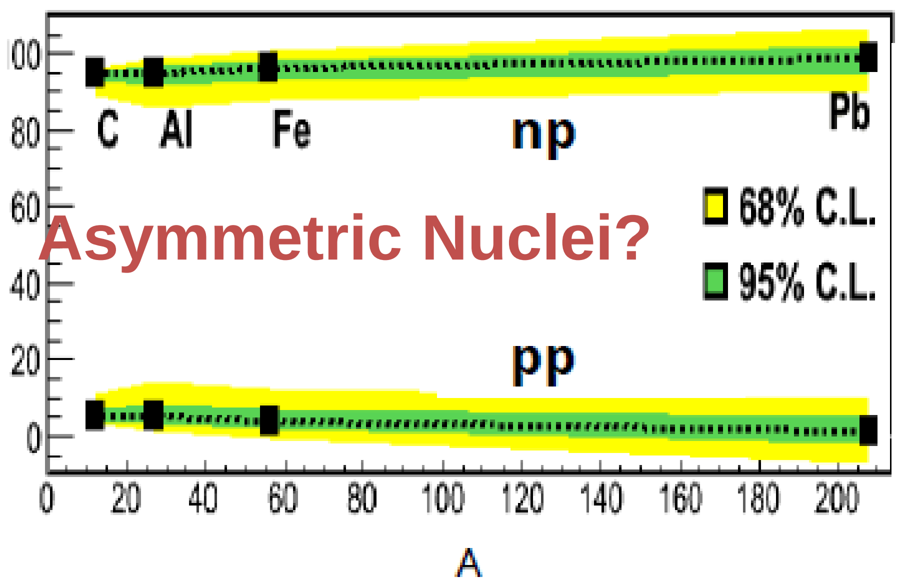
R. Subedi et al., Science 320, 1476 (2008).



np-dominance in 2N_SRC

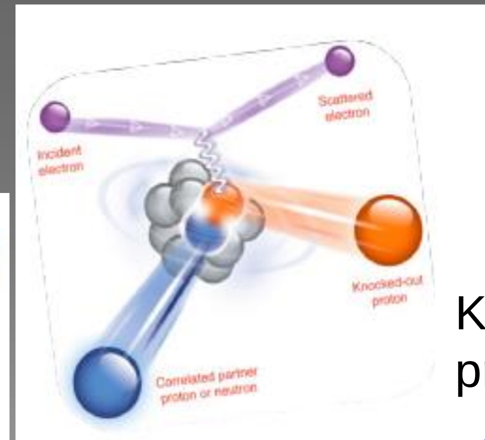


Subedi et al., Science 320 (2008)

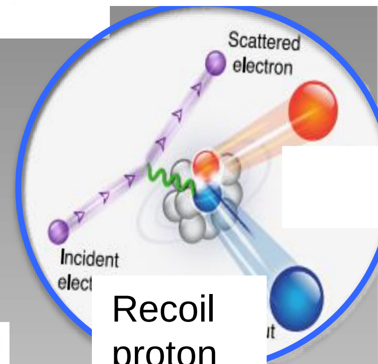


Asymmetric Nuclei?

Hen et al., Science 346 (2014)



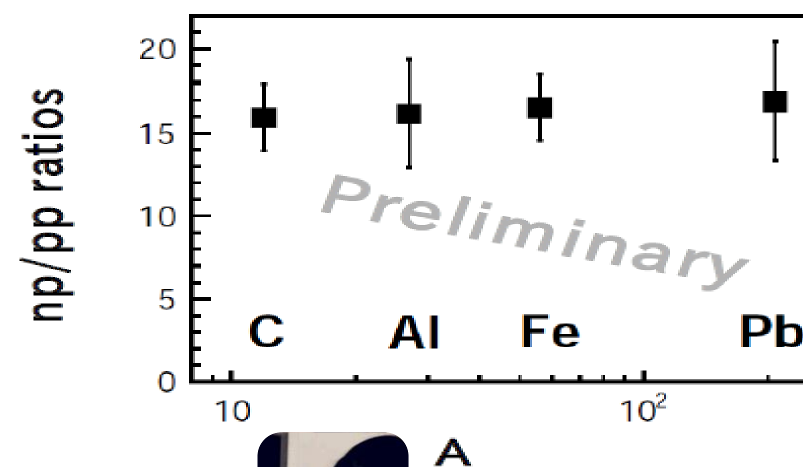
Knocked out proton/neutron

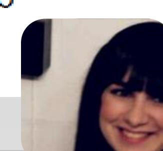


Recoil proton

NEW!

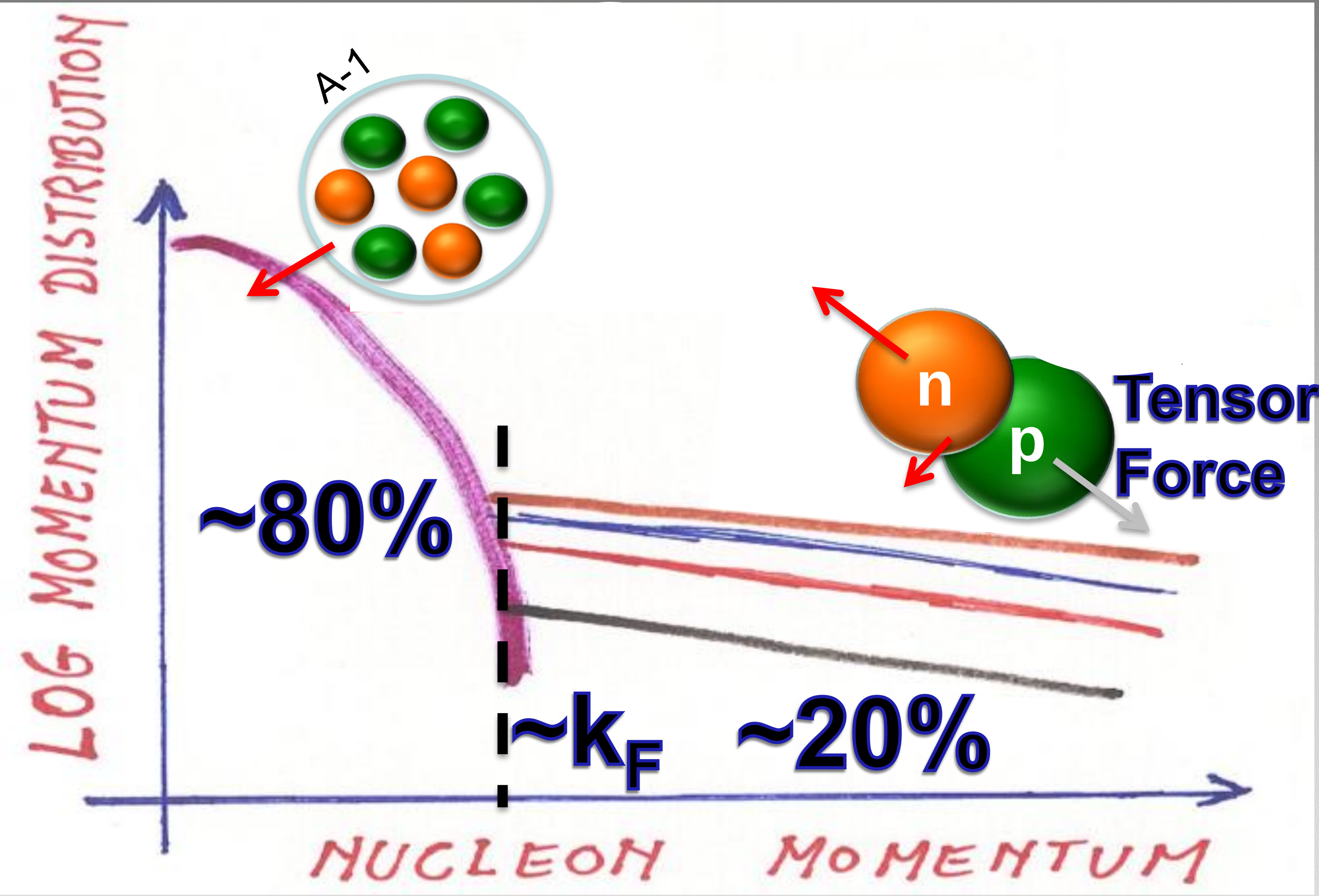
A(e,e'np)/A(e,e'pp)



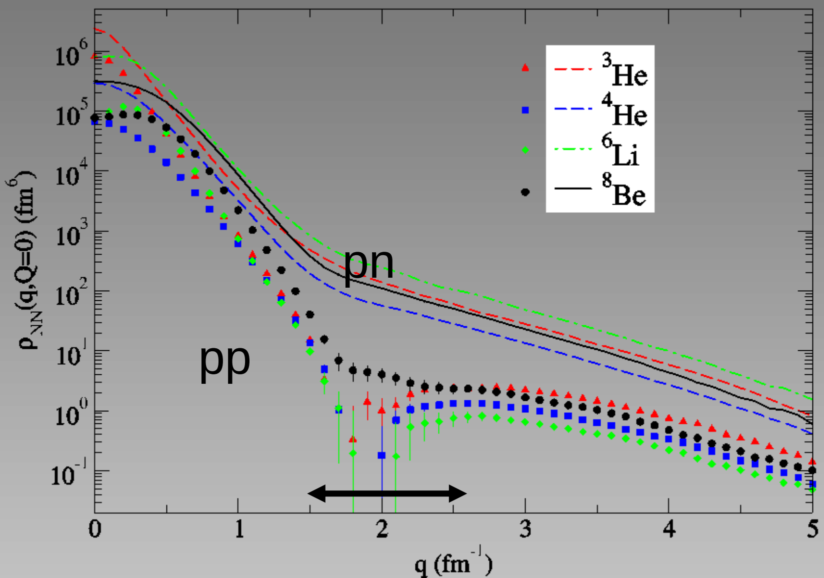


Meytal Duer (TAU)

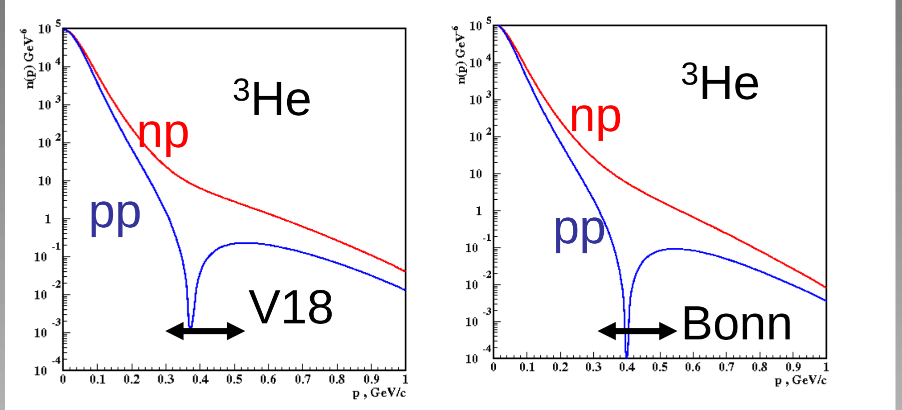
Nucleons has Isophobia (np – dominance)

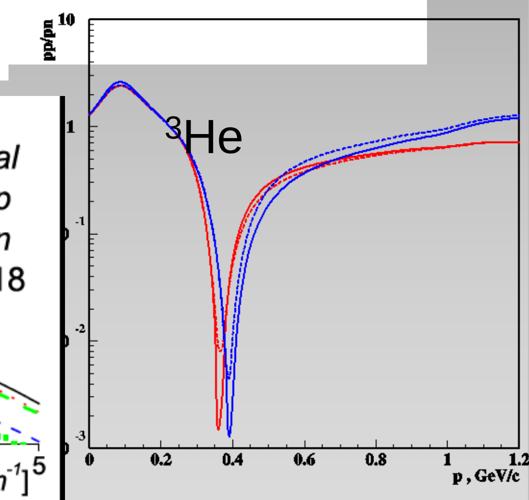


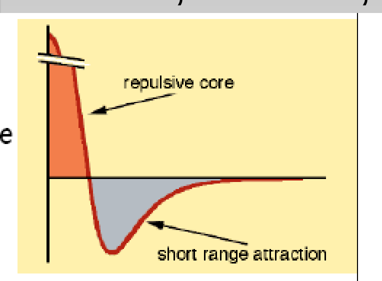
At 300-600 MeV/c there is an excess strength in the np momentum distribution due to the strong correlations induced by the tensor NN potential.



Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007).

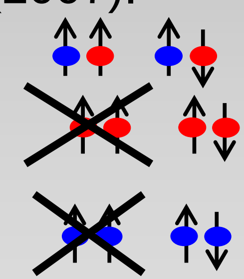


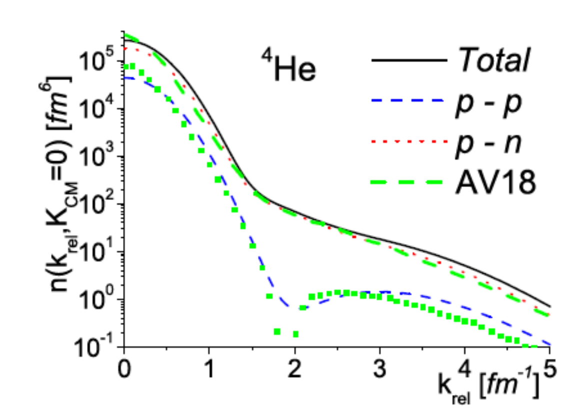




SRC

L = 0, 2





Ciofi and Alvioli PRL 100, 162503 (2008).

Sargsian, Abrahamyan, Strikman Frankfurt PR C71 044615 (2005

Generalized Nuclear Contact Formalism

A universal description of SRC without many-body calculations

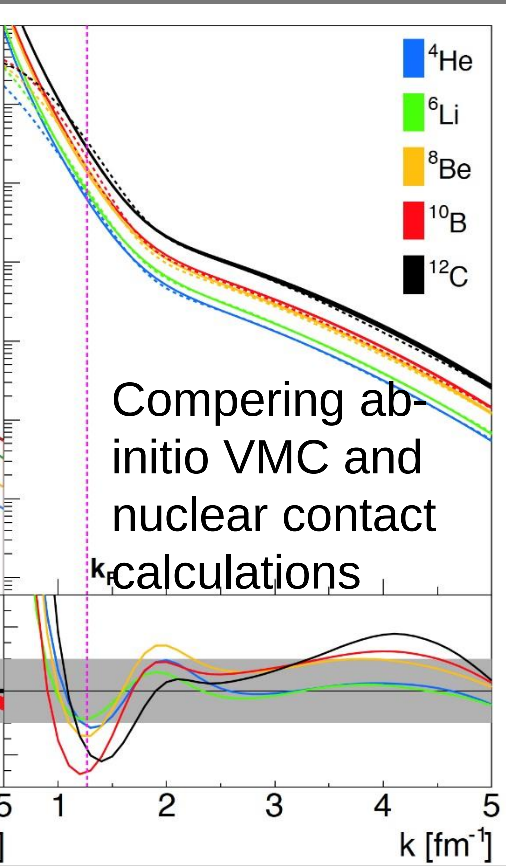
$$n_p(k) \xrightarrow[k\to\infty]{} C^d_{pn}\left|\varphi^d_{pn}(k)\right|^2 + C^0_{pn}\left|\varphi^0_{pn}(k)\right|^2 + 2C^0_{pp}\left|\varphi^0_{pp}(k)\right|^2$$

$l = 0,2\ s = 1\ j = 1$

np pairs

$l = s = j = 0$

pp, nn, np pairs



Compering ab-initio VMC and nuclear contact calculations

The nuclear contacts and short range correlations in nuclei

R. Weiss,[1] R. Cruz-Torres,[2] N. Barnea,[1] E. Piasetzky,[3] and O. Hen[2]

Phys. Lett., B 780, 211 (2018)

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_\alpha(\boldsymbol{r}_{ij}) A^\alpha_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

a factorized ansatz

- Nucleus (A-2) specific function

- Universal function: the zero energy solution to the 2 body problem

np-dominance in asymmetric nuclei

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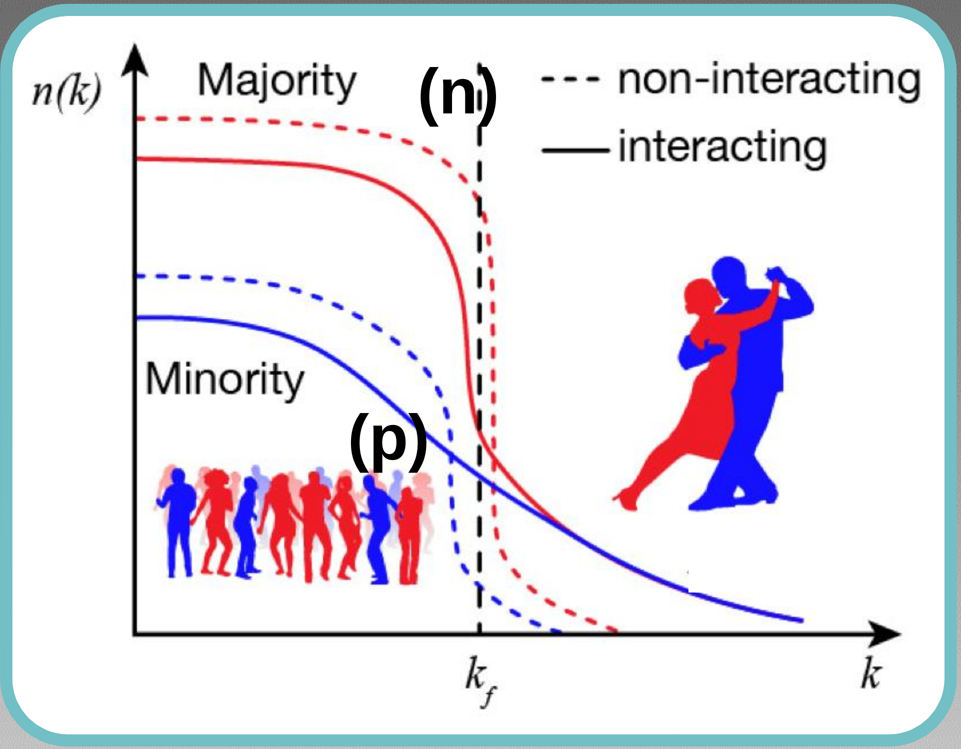
N>Z



Protons have a greater probability than neutrons to be above the Fermi sea

Protons probability increase (neutrons not) with increase N/Z.

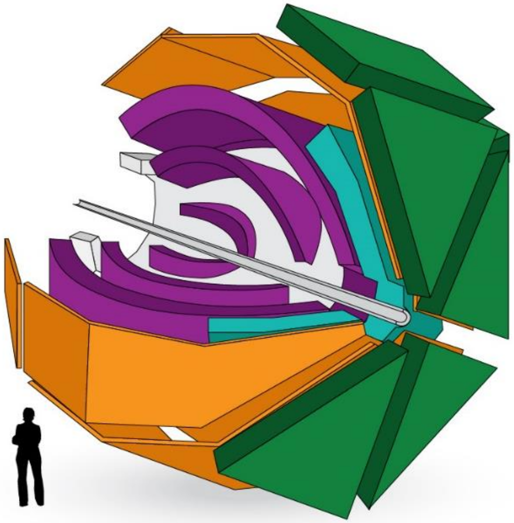
Protons move faster than neutrons

$$\langle E^p{}_k \rangle > \langle E^n{}_k \rangle$$

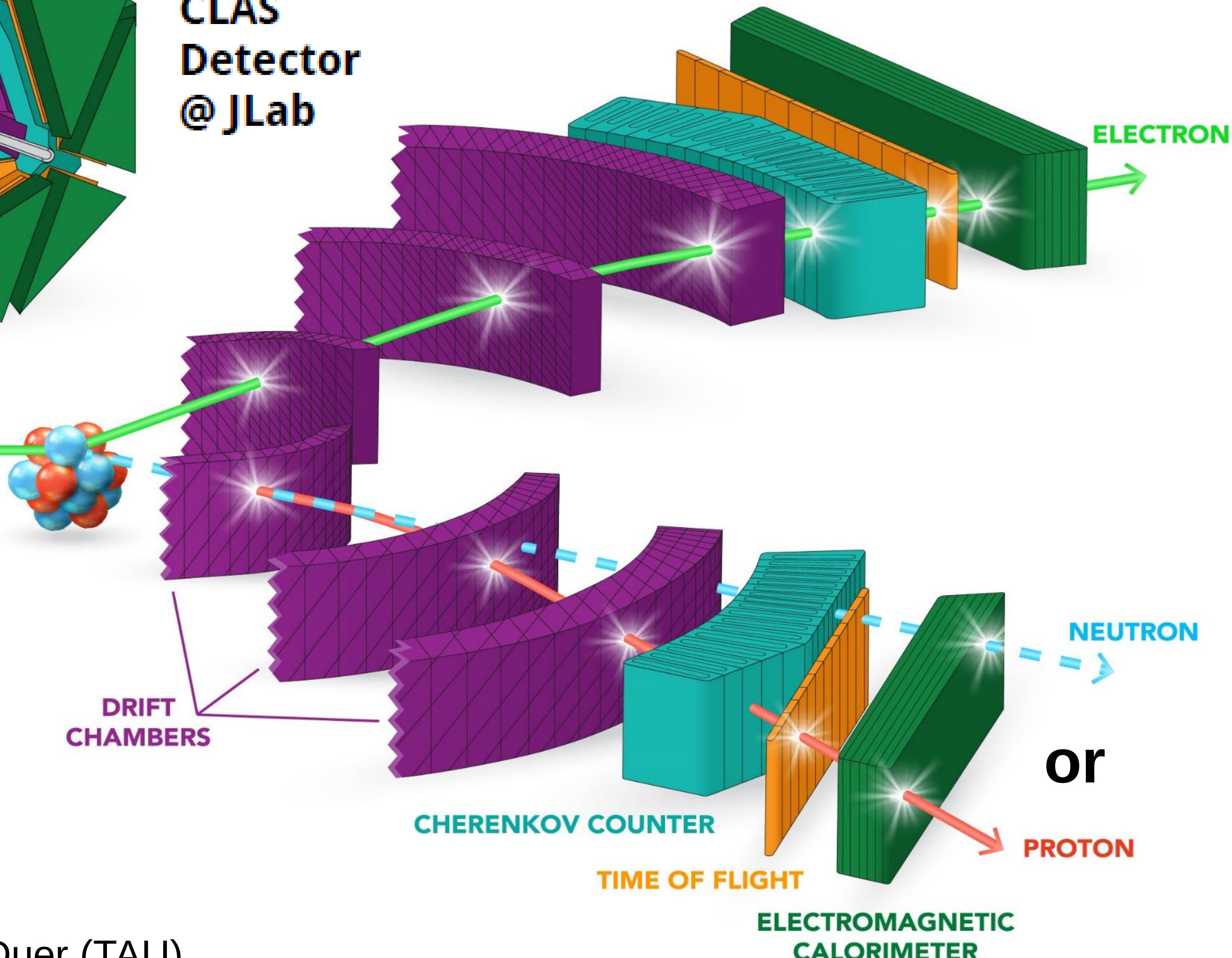
Impact on symmetry energy decomposition

Hard Neutron/proton Knockout

$$A(e,e'n)\ A(e,e'p)$$



CLAS Detector @ JLab

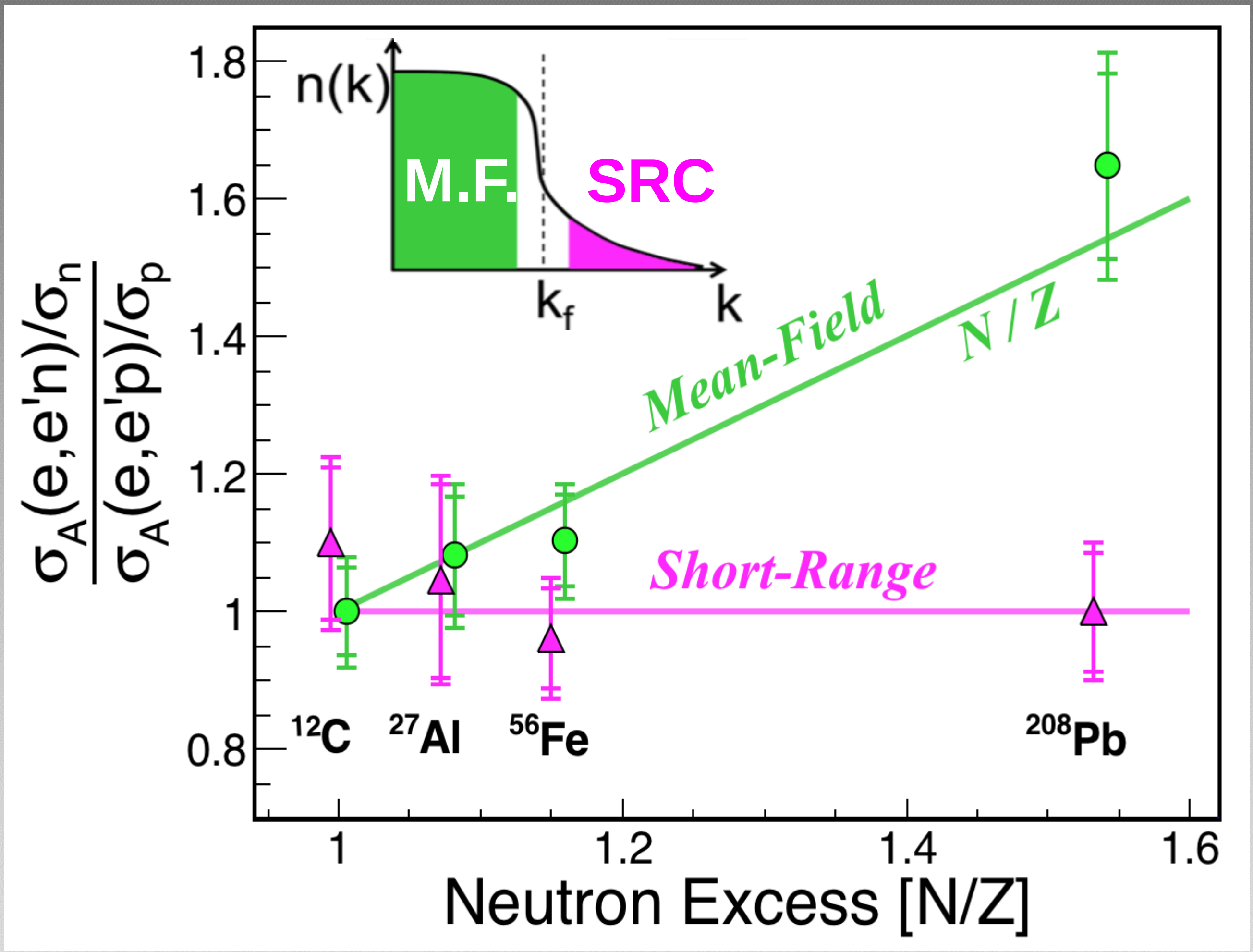


or

M. Duer (TAU)

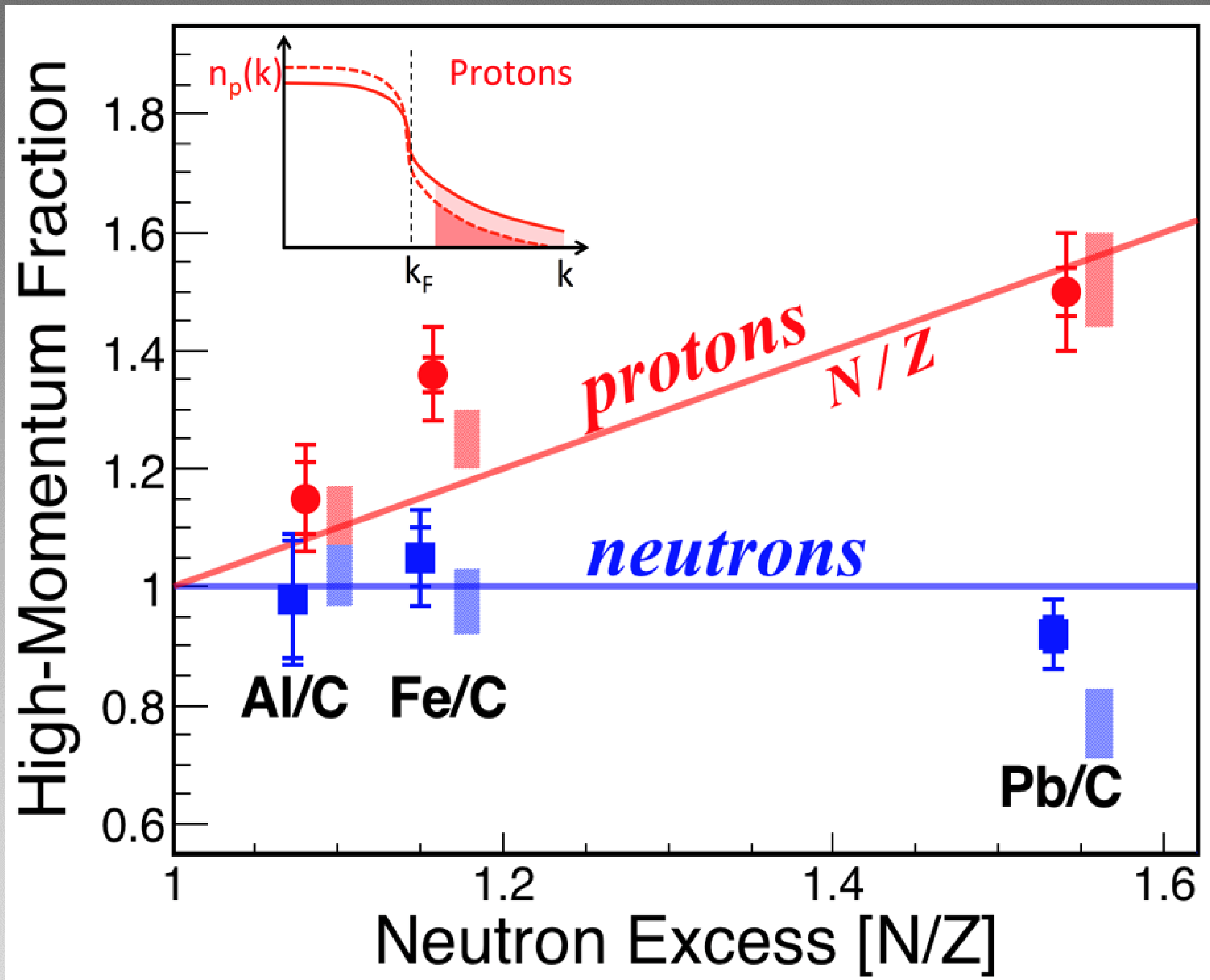
Equal Number of Correlated Protons and Neutrons!

NEW!



M. Duer et al. (CLAS Collaboration), send for publication (2018)

More Neutrons => More Correlated Protons



$$\frac{A(e,e'N)_{high} / A(e,e'N)_{low}}{{}^{12}C(e,e'N)_{high} / {}^{12}C(e,e'N)_{low}}$$

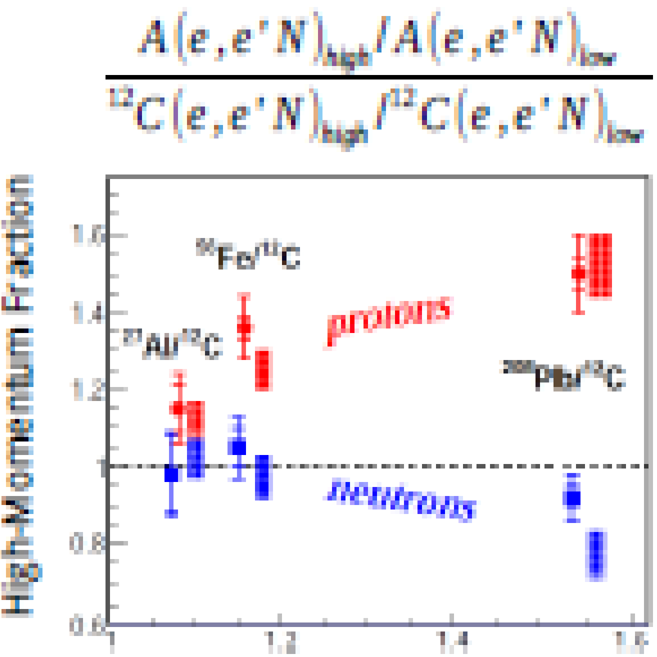
M. Duer et al. (CLAS Collaboration), send for publication (2018)

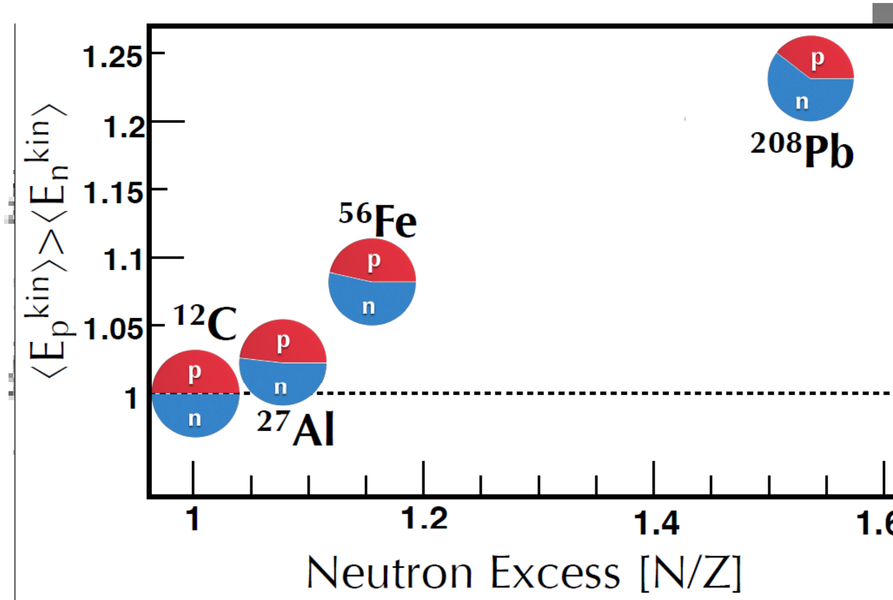
Kinetic energy sharing

Simple np-dominance model

$$n_p(k) = \begin{cases} \eta \cdot n_p^{M.F.}(k) & k < k_0 \\ \frac{A}{2Z} \cdot a_2(A/d) \cdot n_d(k) & k > k_0 \end{cases}$$

(for neutrons: Z → N)

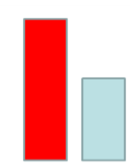




Neutron Excess [N/Z]

Protons move faster than neutrons in N>Z nuclei

$$\langle E_p^{kin} \rangle > \langle E_n^{kin} \rangle$$



Pauli principle → $\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$

Theoretical predictions (N>Z)

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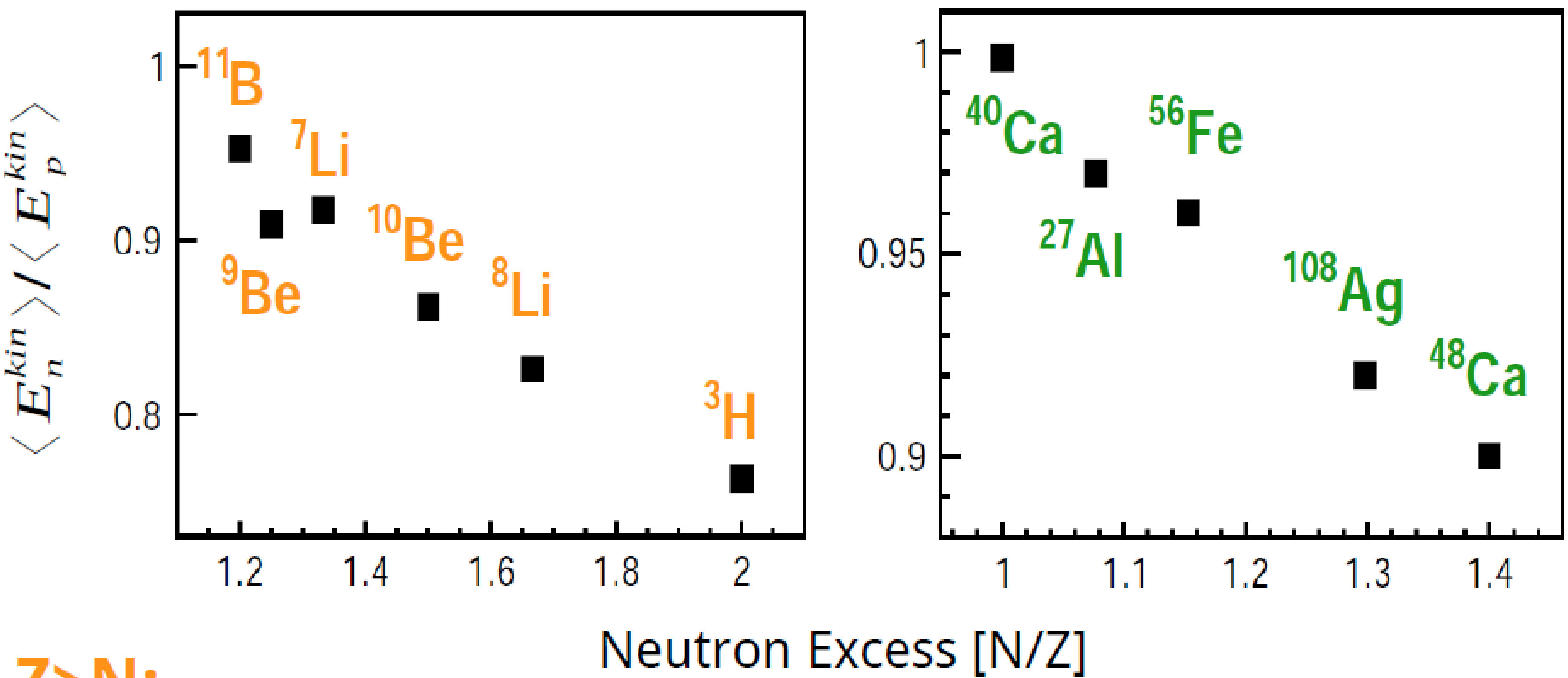
Light nuclei (A<12) **Heavy nuclei (A>12)**



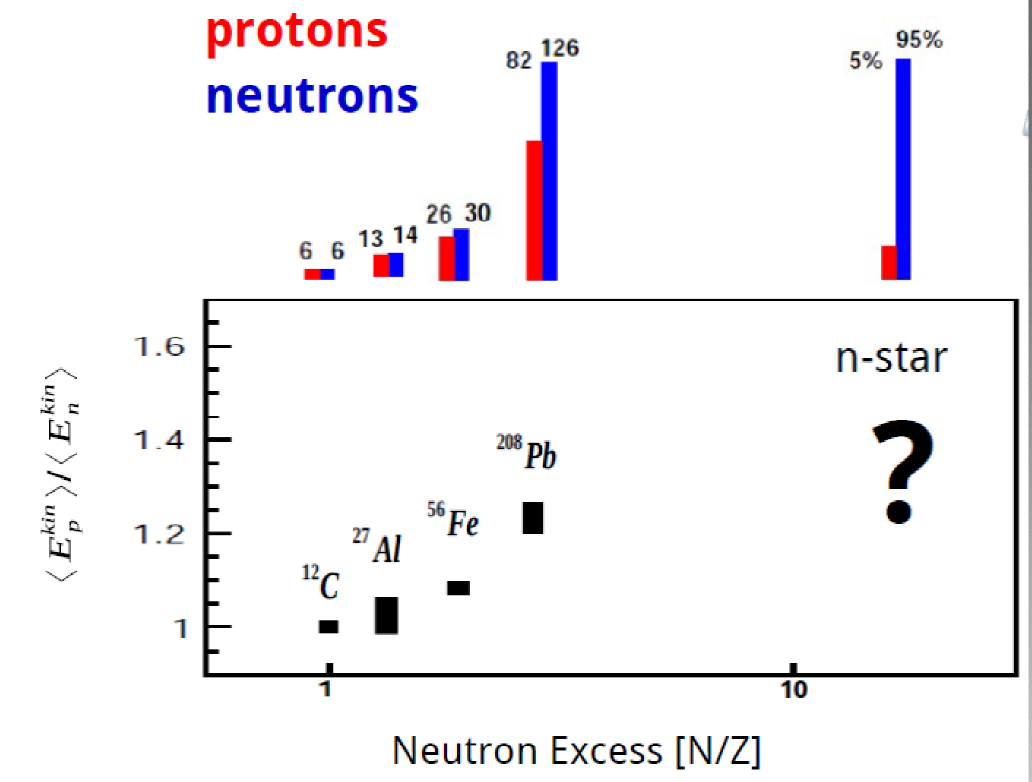
Z>N:

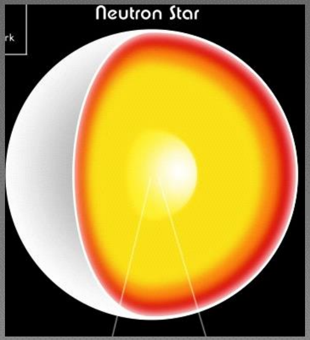
^{3}He **N/Z =1/2** $\langle E_n^{kin} \rangle / \langle E_p^{kin} \rangle = 1.31$

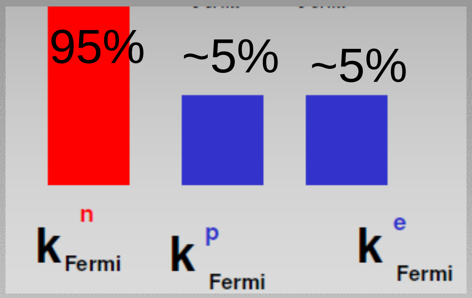
Wiringa, Phys. Rev. C89, 024305 (2014)

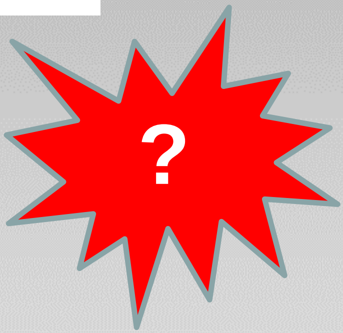
Ryckebusch, J. Phys G42 (2015)

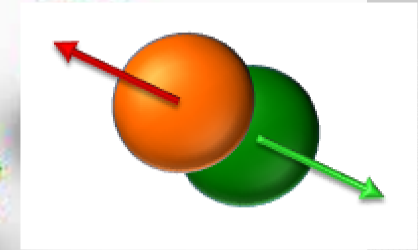
What happens in N>>Z?











ν cooling

$$n \to p + e + \bar{\nu}_e$$

Magnetic field

Nuclear Symmetry Energy

Energy of *asymmetric* nuclear matter:

$$E(\rho_n, \rho_p) = E_0(\rho_n = \rho_p) + E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + O(\delta^4)$$

symmetry energy

Only n 50% n 50% p

$$E_{sym}(\rho) \approx E(\rho)_{PNM} - E(\rho)_{SNM}$$

Relates to the energy change for n → p

- equation-of-state of neutron stars
- heavy-ion collisions
- r-process nucleosynthesi
- core-collapse supernova
- more…

with SRC :

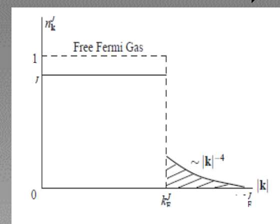
$$E_{sym}(\rho) \approx E(\rho)_{PNM} - E(\rho)_{SNM}$$

np-SRC dominance ➡

High momentum tail in SNM (np- pairs)

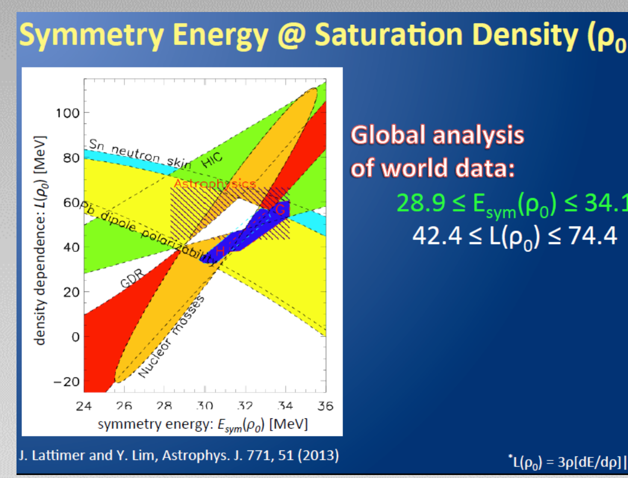
No high momentum tail in PNM

(nn- pairs)



➡ $$E^{kin}_{sym}(\text{with SRC}) < E^{kin}_{sym}(no\,\text{SRC})$$

$$E_{sym}(\rho) = E^{kin}_{sym}(\rho) + E^{pot}_{sym}(\rho)$$



$$E^{pot}_{sym}(\text{with SRC}) > E^{pot}_{sym}(no\,\text{SRC})$$

Density dependence of Symmetry Energy

$$E_{sym}(\rho) = E_{sym}^{kin}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha} + E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

FFG: $E_{sym}^{kin}(\rho_0) = 12.5\,\text{MeV}$ $\quad \alpha = 2/3 \quad \gamma = 0.48 \pm 0.1$

with Tensor Correlations (CFG):

$$E_{sym}^{kin}(\rho) = E_{sym}^{kin}(\rho)|_{FG} - \Delta E_{sym}^{kin}(\rho)$$

where the SRC correction term is:

$$\Delta E_{sym}^{kin} \equiv \frac{E_F^0}{\pi^2}c_0\left[\lambda\left(\frac{\rho}{\rho_0}\right)^{1/3} - \frac{8}{5}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{3}{5}\frac{1}{\lambda}\left(\frac{\rho}{\rho_0}\right)\right]$$

$$n(k) = \begin{cases} A_0 & k < k_F \\ C_0/k^4 & k_F < k < \lambda k_F \\ 0 & k > \lambda k_F \end{cases}$$

$E_{sym}^{kin}(\rho_0) = -10 \pm 3\,\text{MeV}$ $\quad \gamma = 0.25 \pm 0.05$

Density dependence of Symmetry Energy

Without Tensor Correlations (FFG) / with (CFG):

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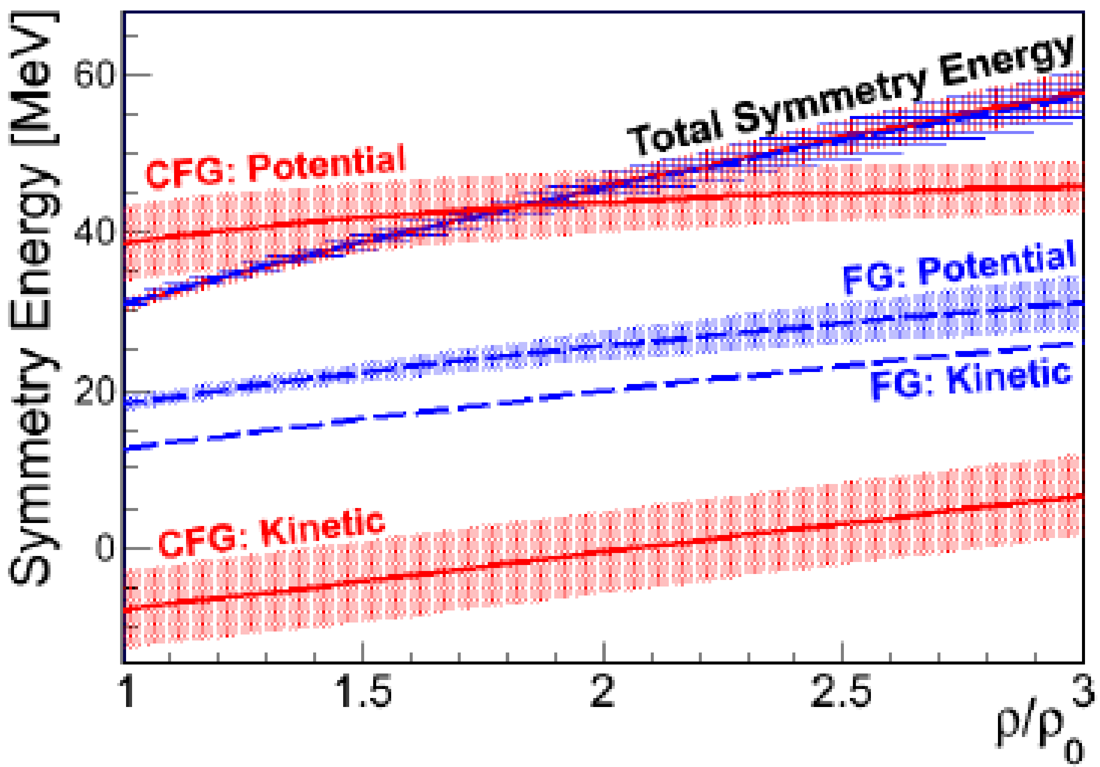


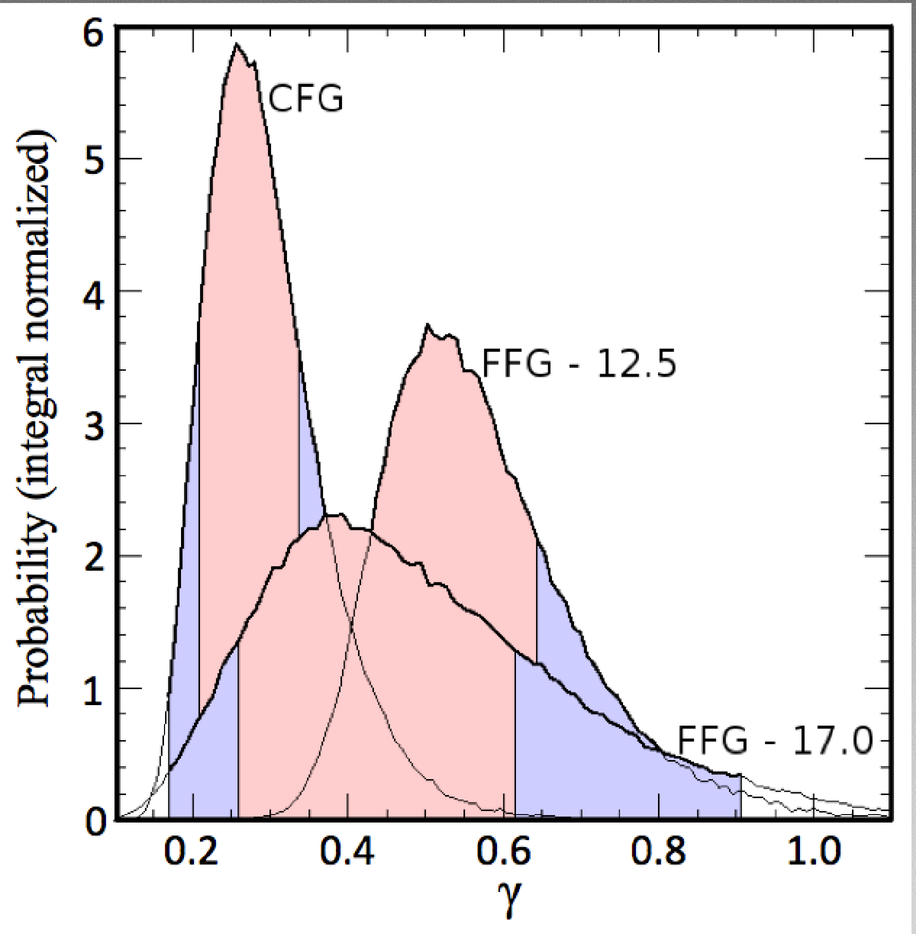
	$E_{sym}^{kin}(\rho_0)$ [MeV]	γ $\pm 1\sigma(2\sigma)$
CFG	-10 ± 3	0.25 ± 0.05
FG	-10 ± 3	0.58 ± 0.05
	0	0.55 ± 0.06
	12.5	0.48 ± 0.10
	17.0	0.41 ± 0.13

PHYSICAL REVIEW C 91, 025803 (2015)

Symmetry energy of nucleonic matter with tensor correlations

Or Hen,[1,*] Bao-An Li,[2] Wen-Jun Guo,[2,3] L. B. Weinstein,[4] and Eli Piasetzky[1]

Bayesian analysis of neutron stars observations lead to the same result



NS EOS

3 energy-density regions

A. W. Steiner, J. M. Lattimer, and E. F. Brown, Astrophys. J. **722**, 33 (2010), 1005.0811.

NS data include:

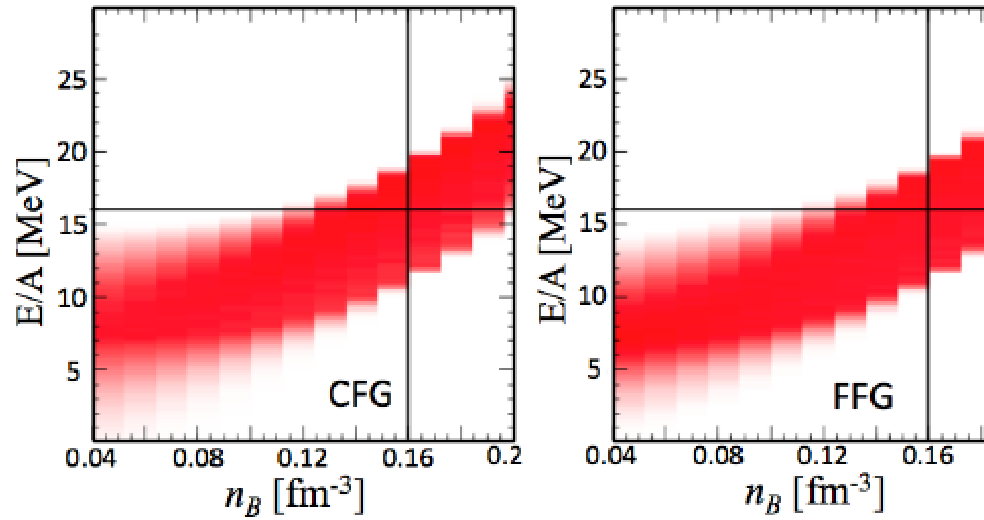
- high precision mass extractions from Pulsar-timing measurements
- simultaneous mass-radius extractions from photospheric radius expansion (PRE) X-ray burst measurements
- thermal spectra measurement of low-mass X-ray Binaries (LMXB

$$E^{pot}_{sym}(\rho/\rho_0) = S_{pot} \cdot (\rho/\rho_0)^{\gamma} = (S_v - S_{kin}) \cdot (\rho/\rho_0)^{\gamma},$$

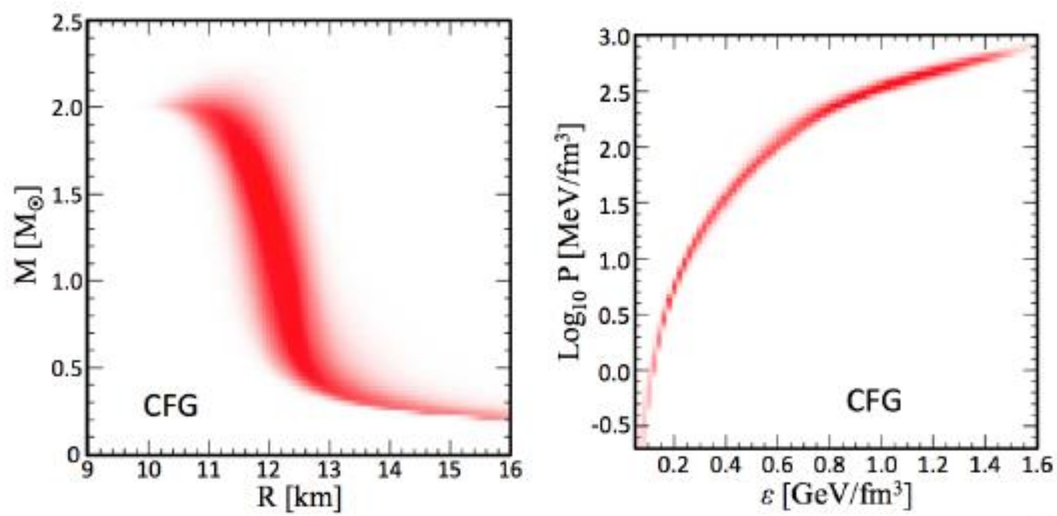
Analysis of Neutron Stars Observations Using a Correlated Fermi Gas Model

O. Hen,[1] A.W. Steiner,[2,3,4] E. Piasetzky,[1] and L.B. Weinstein[5]

Bayesian analysis of neutron stars observations



or online) The extracted energy per particle as a



Analysis of Neutron Stars Observations Using a Correlated Fermi Gas Model

O. Hen,[1] A.W. Steiner,[2,3,4] E. Piasetzky,[1] and L.B. Weinstein[5]

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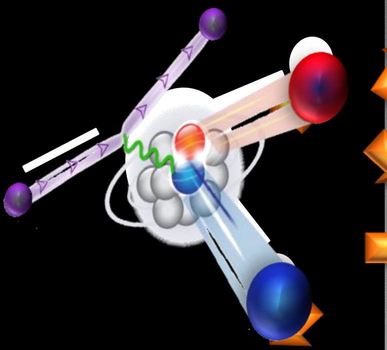
SRC correlations:



Breaks the Fermi Gas picture

Reduce the kinetic symmetry Energy (at ρ_0)

Enhance the potential symmetry Energy (at ρ_0)

Soften the potential symmetry density dependence

Impact on Compact Astronomical Systems ?

?

Short distance structure of nuclei

1 The probability for a nucleon to have momentum ≥ 300 MeV / c in medium nuclei is 20-25%

2 More than ~90% of all nucleons with momentum ≥ 300 MeV / c belong to 2N-SRC.

1 2 Most of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.

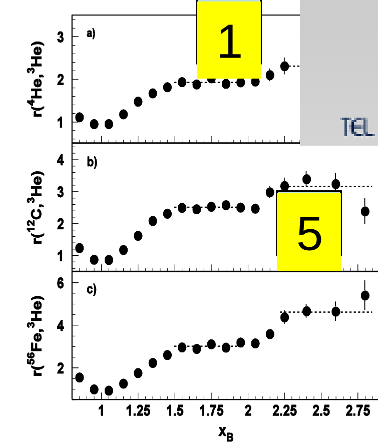
3 Probability for a nucleon with momentum 300-600 MeV / c to belong to np-SRC is ~18 times larger than to belong to pp-SRC.

1 2 3 In neutron - rich nuclei: **$<T_p> \; > \; <T_n>$**

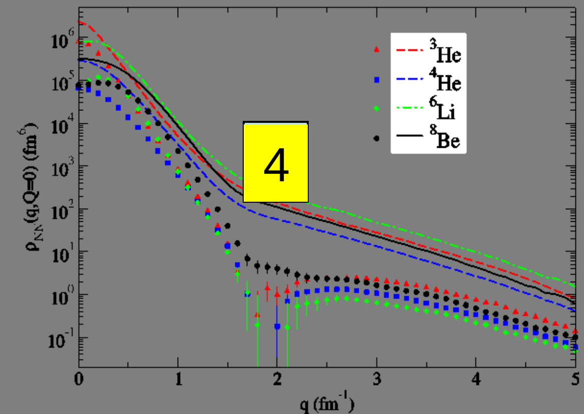
SRC probability for protons increase with N/Z

4 Dominant NN force in the 2N-SRC is tensor force.

CLAS / HALL B

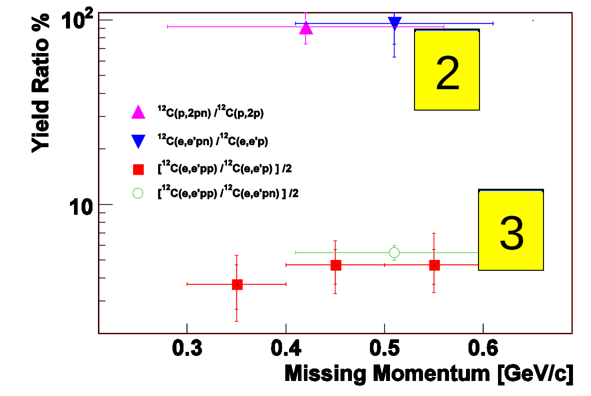


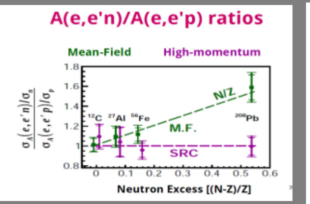
. PRL. 96, 082501 (2006)

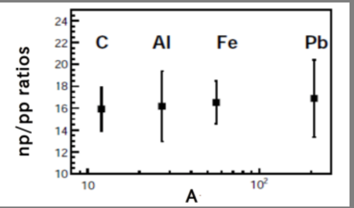


PRL 98,132501 (2007).

EVA / BNL and Jlab / HALL A







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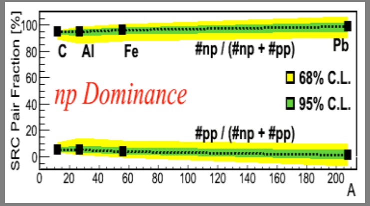


Duer et al.

Science 346, 614 (2014).

PRL 162504(2006); Science 320, 1476 (2008).

Impact on neutron star structure and properties

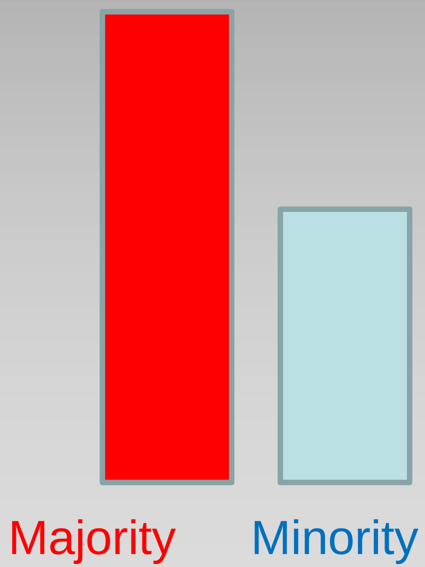
?

Our SRC Worldwide Program

Momentum sharing in Asymmetric (imbalanced) two components Fermi systems

non interacting Fermions

Pauli exclusion principle →

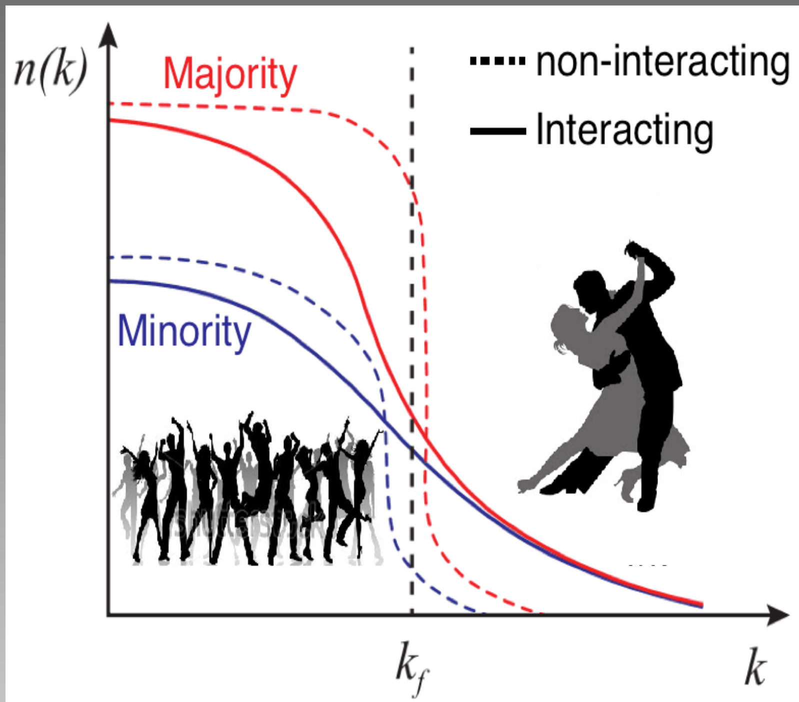


$$k_F^{Majority} > k_F^{Minority}$$

$$\left\langle E^{kin}{}_{Majotiry} \right\rangle > \left\langle E^{kin}{}_{Minority} \right\rangle$$

In a neutron-rich nuclei $\langle T_n \rangle > \langle T_p \rangle$

with short-range interaction : strong between unlike fermions, weak between same kind.



Universal property

A minority fermion have a greater probability than a majority fermion to be above the Fermi sea $k > k_F$

Possible inversion of the momentum sharing :

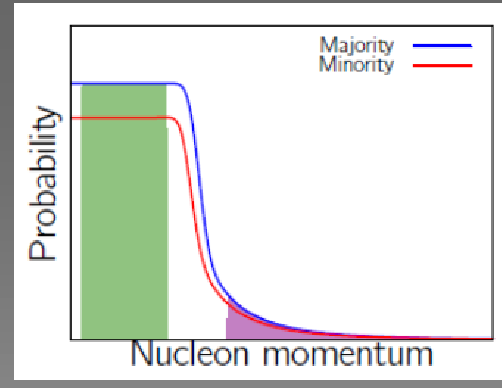
In a neutron-rich nuclei $\langle T_p \rangle > \langle T_n \rangle$

np-dominance in asymmetric nuclei

Simple np-dominance model

$$n_p(k) = \begin{cases} \eta \cdot n_p^{M.F.}(k) & k < k_0 \\ \frac{A}{2Z} \cdot a_2(A/d) \cdot n_d(k) & k > k_0 \end{cases}$$

(for neutrons: Z → N)



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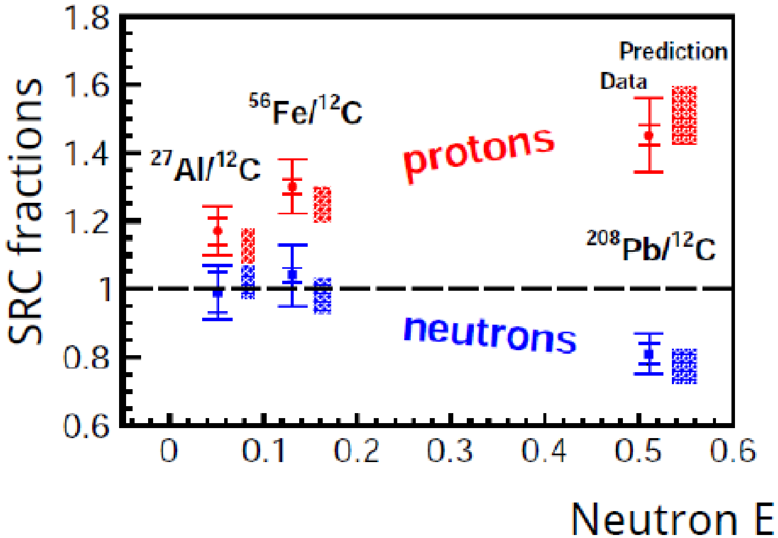
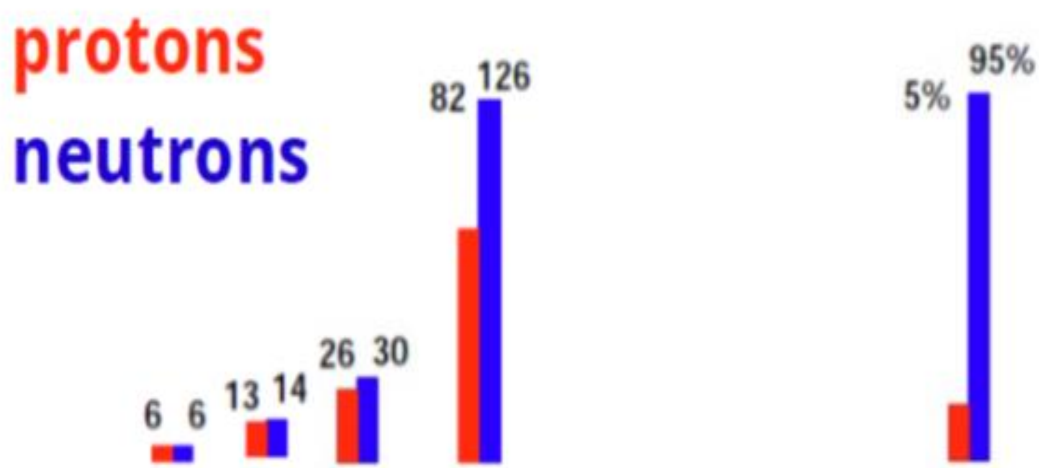
$$\frac{A(e,e'N)_{high} / A(e,e'N)_{low}}{{}^{12}C(e,e'N)_{high} / {}^{12}C(e,e'N)_{low}}$$



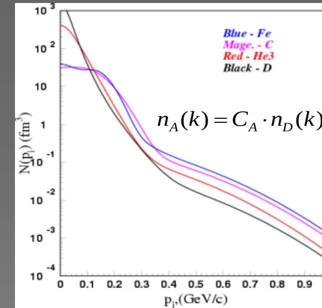
n stars ?



Protons move faster than neutrons in N>Z nuclei

$$\langle T_p \rangle > \langle T_n \rangle$$

- **At high nucleon momentum distributions are similar in shape for light and heavy nuclei: SCALING.**



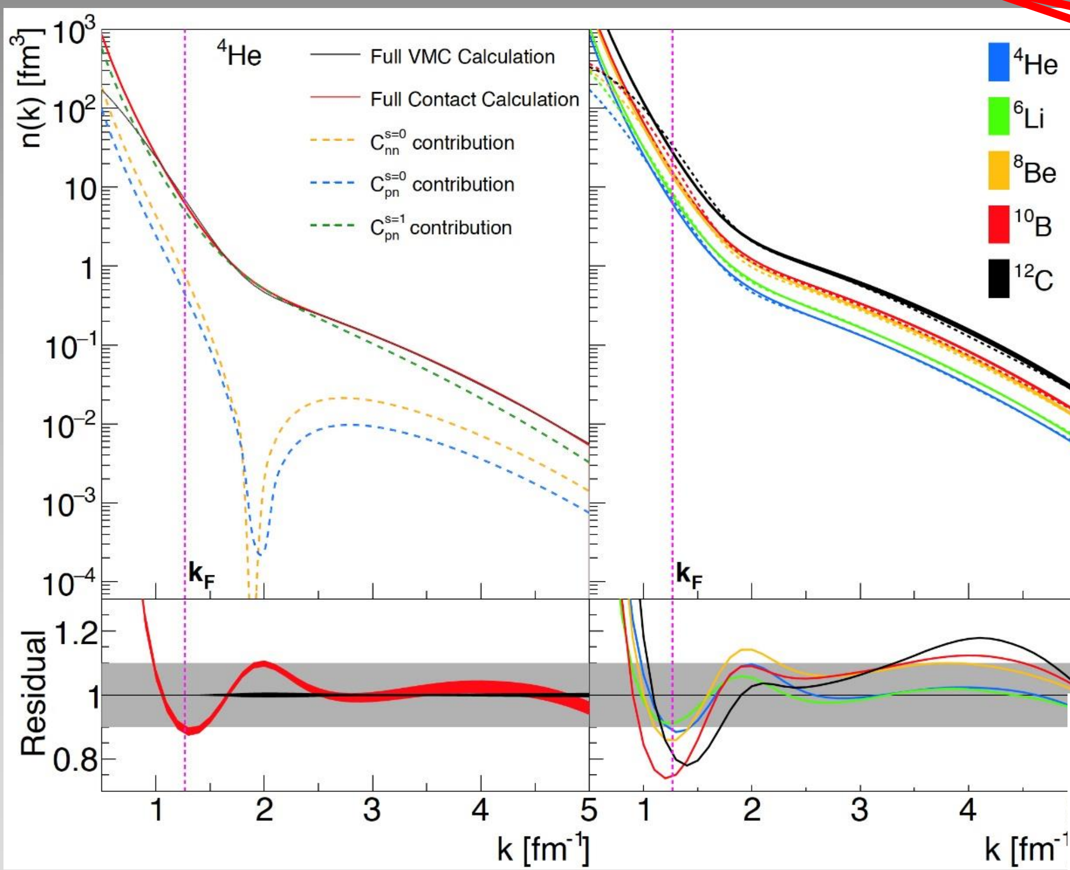
Adapted from
Ciofi degli Atti

Nuclear contact calculations

$$n_p(k) \xrightarrow[k\to\infty]{} C^d_{pn}\left|\varphi^d_{pn}(k)\right|^2 + C^0_{pn}\left|\varphi^0_{pn}(k)\right|^2 + 2C^0_{pp}\left|\varphi^0_{pp}(k)\right|^2$$

$l=0,2\ s=1\ j=1$
np pairs

$l=s=j=0$
pp, nn, np pairs



The nuclear contacts and short range correlations in nuclei

R. Weiss,[1] R. Cruz-Torres,[2] N. Barnea,[1] E. Piasetzky,[3] and O. Hen[2]

arXiv:1612.00923

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_\alpha(\boldsymbol{r}_{ij}) A^\alpha_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

a factorized ansatz

Nuclei (Athenaeum Ballroom)		Axel Schmidt
Session chair: Fabienne Kunne		
11:30-12:00	New Insights into Nucleon-Nucleon Correlations	Or Hen (MIT)

Compering ab-initio VMC and nuclear contact calculations

Scale-Separated Nuclear Structure

1. **Use a factorized ansatz for the short-distance (high-momentum) part of the many-body wave function**:

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_\alpha(\boldsymbol{r}_{ij}) A^{\alpha}_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

- Universal function of the NN interaction.
- Taken as the zero energy solution to the 2 body problem

- Nucleus (/ system) specific function
- Depends on all nucleons except the SRC pair (primarily mean-field)

2. Test by comparing to many-body calculations *and* data from hard knockout measurements

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, arXiv 1612.00923 (2017)

Short distance structure of nuclei

1 The probability for a nucleon to have momentum ≥ 300 MeV / c in medium nuclei is 20-25%

2 More than ~90% of all nucleons with momentum ≥ 300 MeV / c belong to 2N-SRC.

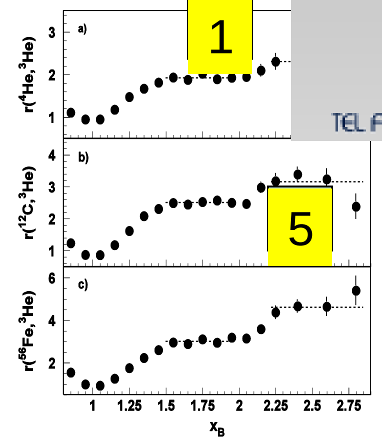
1
2 ⇒ Most of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.

3 Probability for a nucleon with momentum 300-600 MeV / c to belong to np-SRC is ~18 times larger than to belong to pp-SRC.

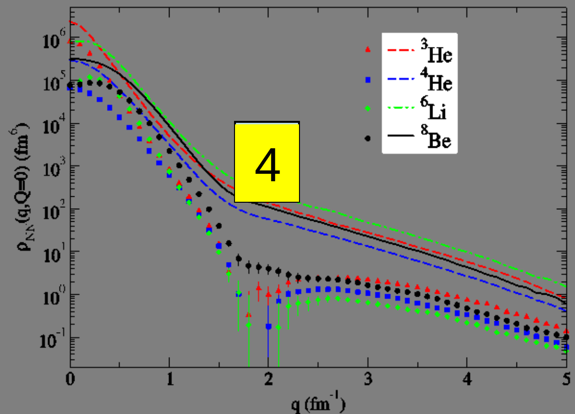
1
3
2 ⇒ In neutron - rich nuclei: **$\langle T_p \rangle > \langle T_n \rangle$**

4 Dominant NN force in the 2N-SRC is tensor force.

CLAS / HALL B

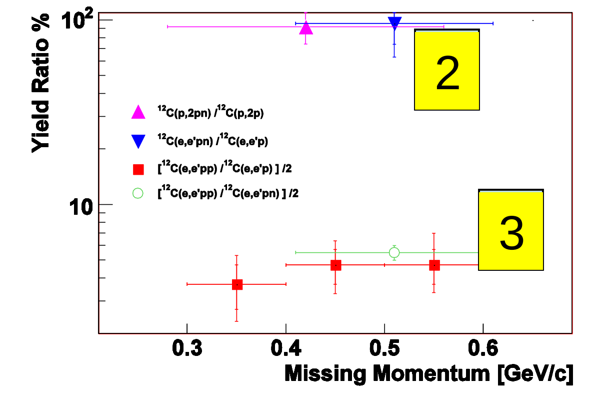


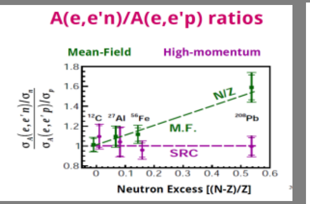
PRL. 96, 082501 (2006)

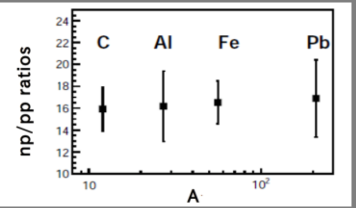


PRL 98,132501 (2007).

EVA / BNL and Jlab / HALL A







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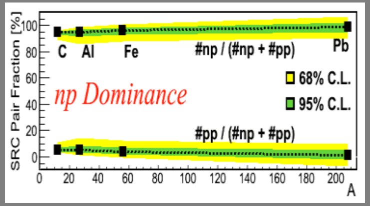


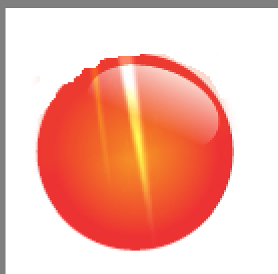
Duer et al.

Science 346, 614 (2014).

PRL 162504(2006); Science 320, 1476 (2008).

Are nucleons being modified in the nuclear medium ?

Free neutron



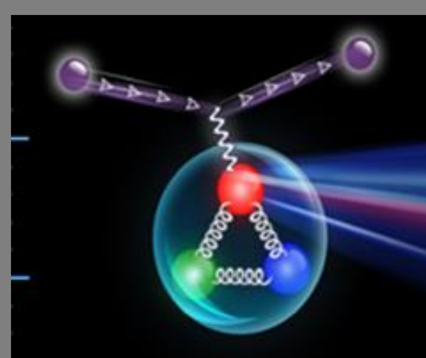
$\tau_n = 15\,\mathrm{min}$

Bound neutron

$\tau_{n^*} = \infty$

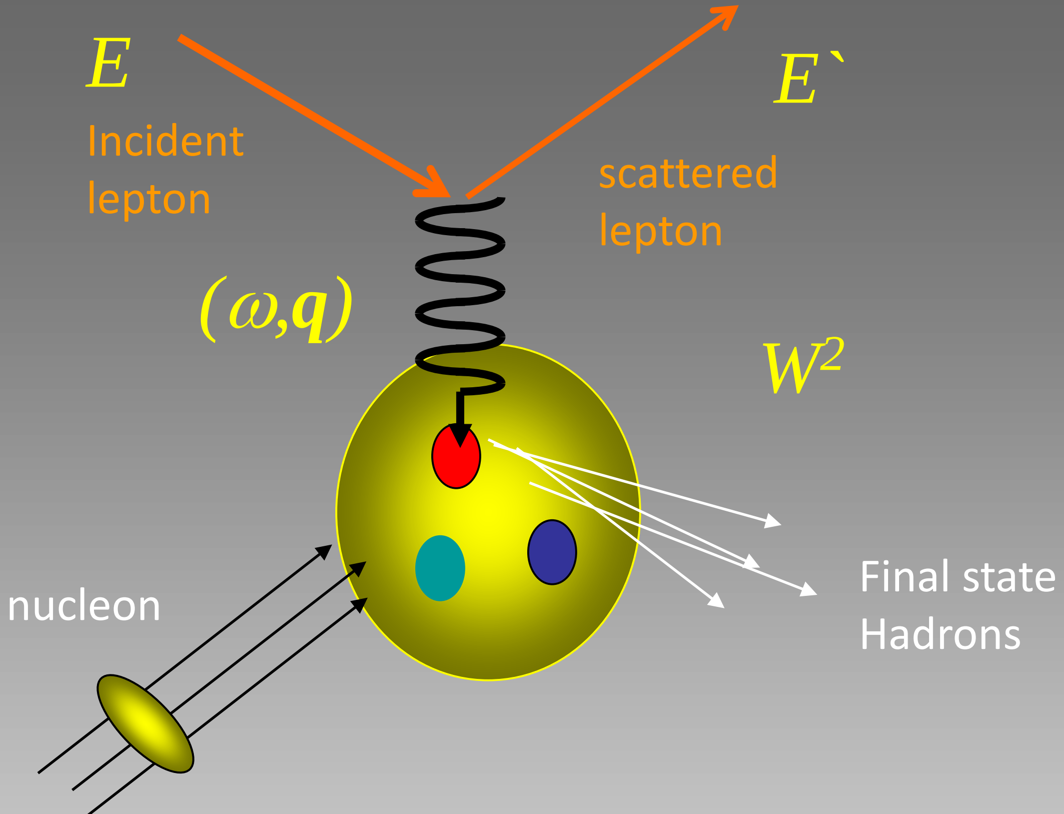
Do nucleons change their quark-gluon structure in the nuclear medium ?

➡ **Deep Inelastic Scattering (DIS)**



➡ **In-Medium vs. Free Structure Function**

Deep Inelastic Scattering (DIS)



Electrons, muons, neutrinos

SLAC, CERN, HERA, FNAL, JLAB

E, E' 5-500 GeV

Q^2 5-50 GeV^2

w^2 >4 GeV^2

$0 \le X_B \le 1$

$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

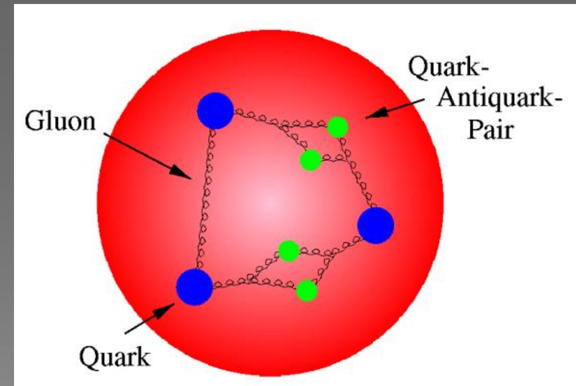
$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \qquad \left(= \frac{Q^2}{2(q \cdot p_T)}\right)$$

$$0 \le x_B \le 1$$

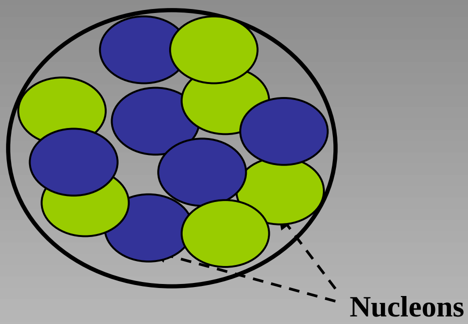
X_B gives the fraction of nucleon momentum carried by the struck parton

Information about nucleon vertex is contained in $F_1(x,Q^2)$ and $F_2(x,Q^2)$, the unpolarized structure functions



DIS scale: several tens of GeV

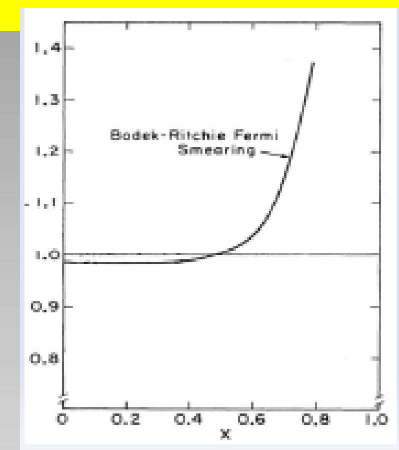
Nucleon in nuclei are bound by ~MeV

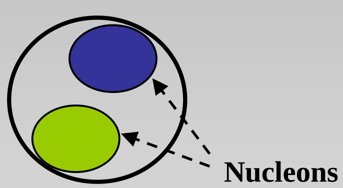


(My) Naive expectations :

DIS off a bound nucleon = DIS off a free nucleon

(Except for small Fermi momentum corrections)



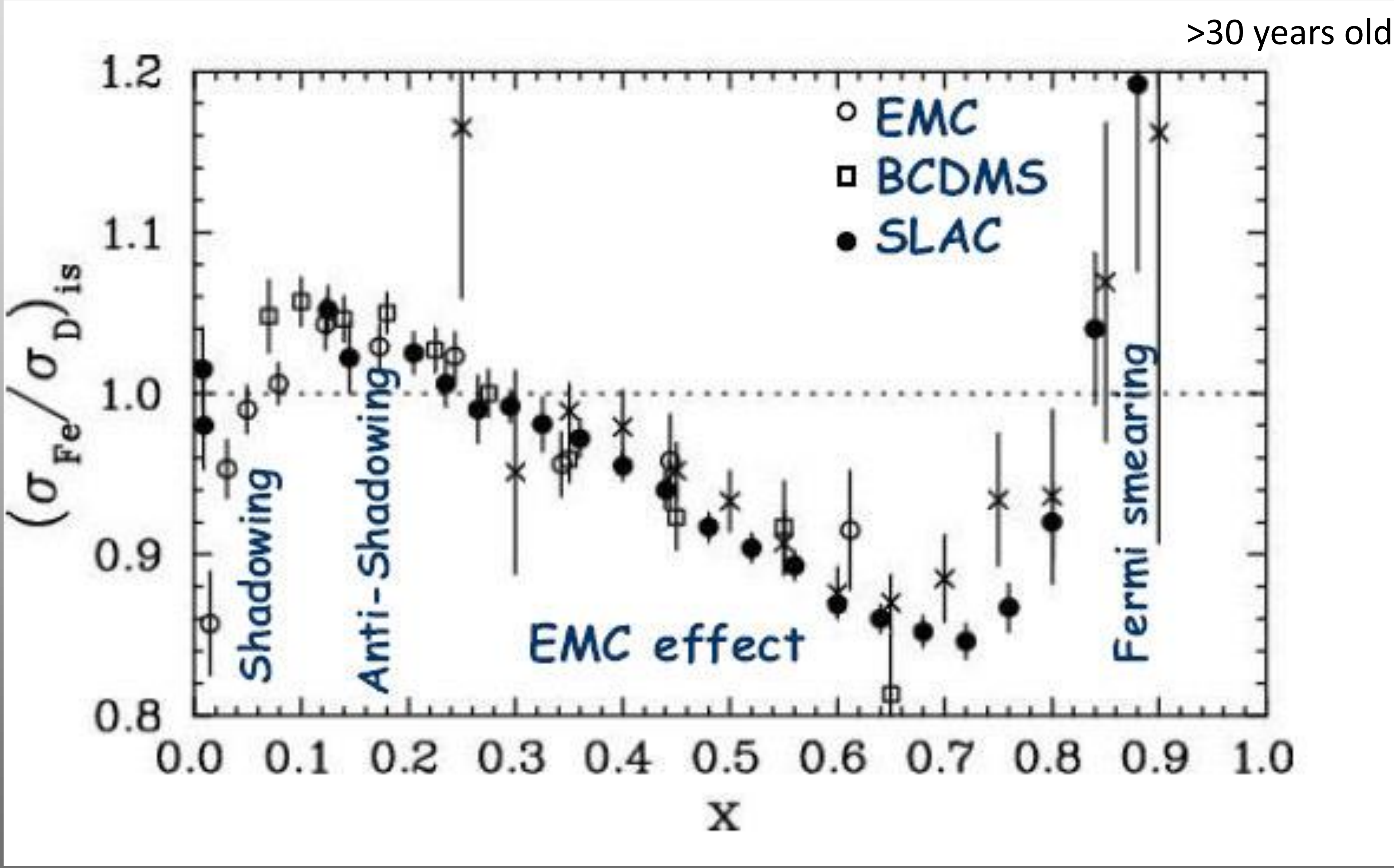


Deuteron: binding energy ~2 MeV

Average nucleons separation ~2 fm

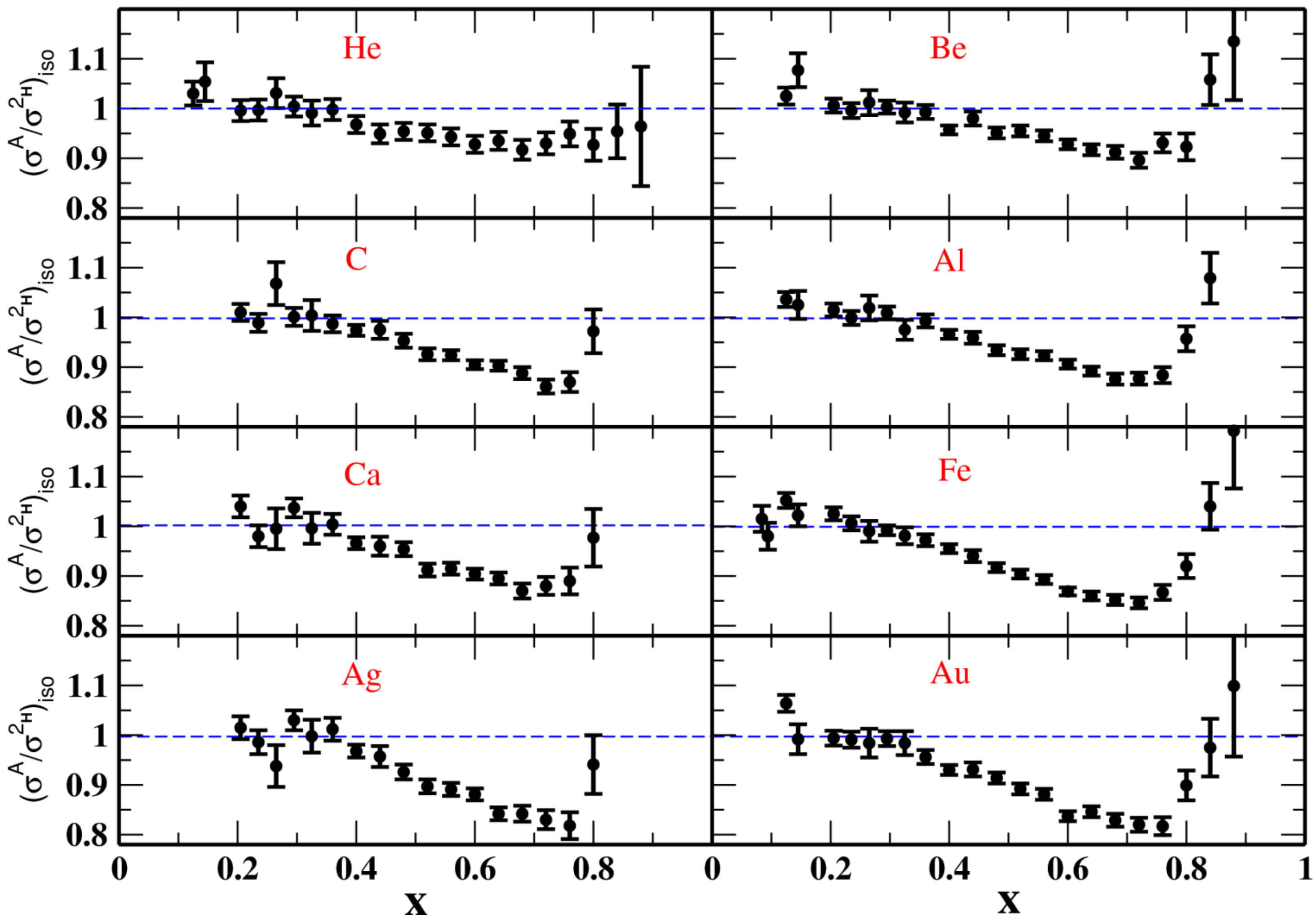
DIS off a deuteron = DIS off a free proton neutron pair

The European Muon Collaboration (EMC) effect



σ^{DIS} per nucleon in nuclei $\neq$ σ^{DIS} per nucleon in deuteron

SLAC E139

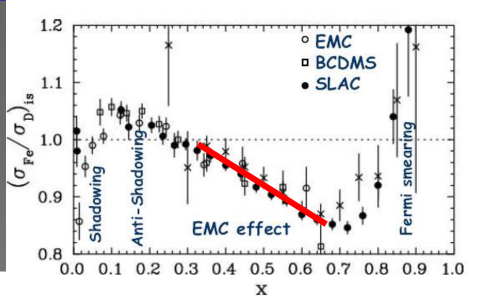


Data from CERN SLAC JLab
1983- 2009

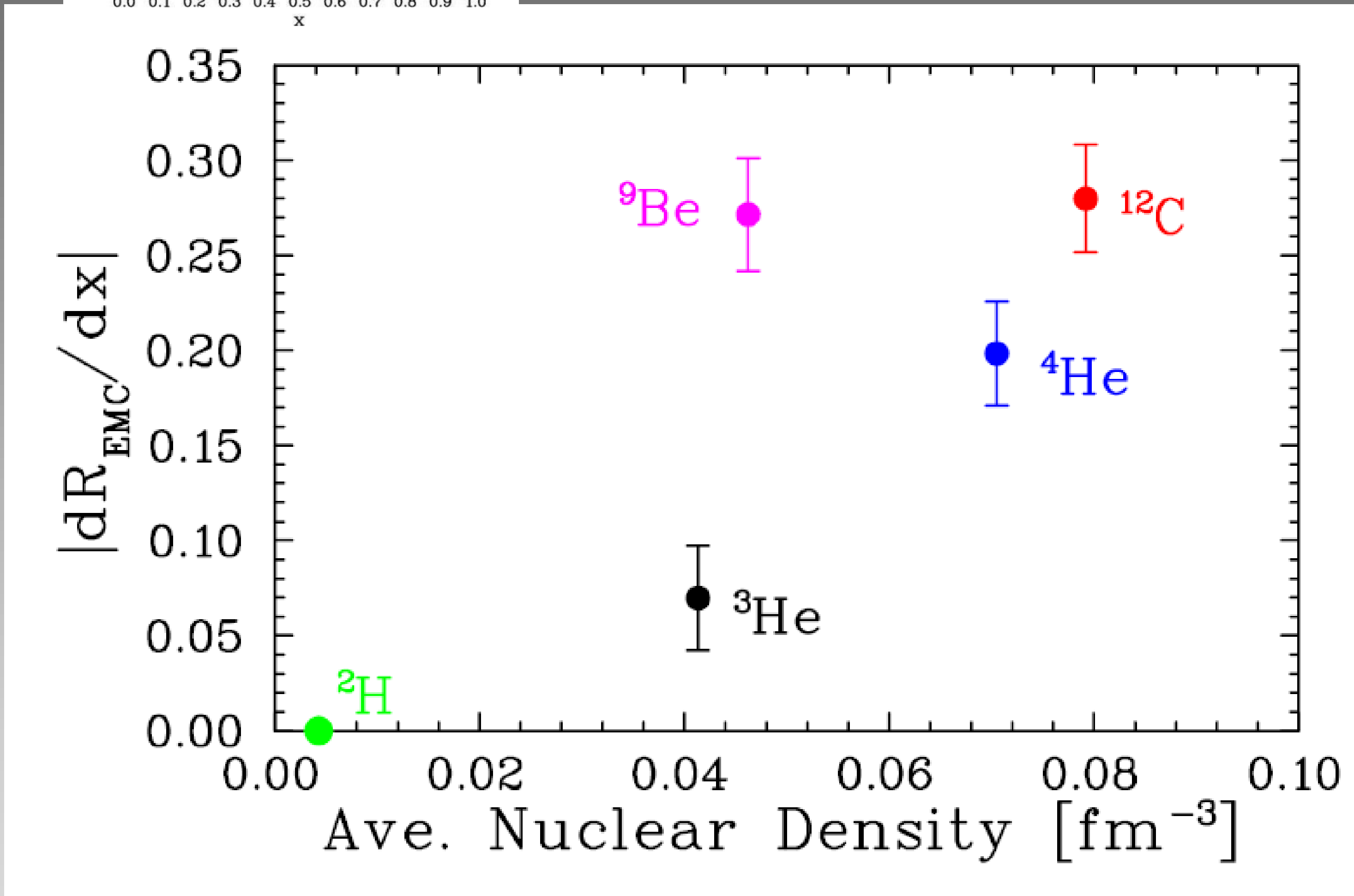
EMC collaboration, Aubert et al. PL B 123,275 (1983)

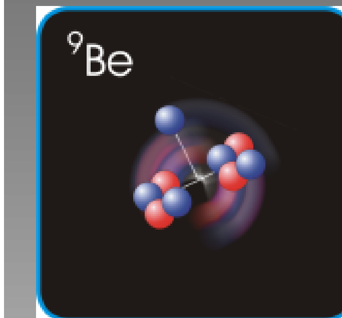
SLAC Gomez et al., Phys Rev. D49,4348 (1994)

A review of data collected during first decade, Arneodo, Phys. Rep. 240,301(1994)



EMC is a not a bulk property of nuclear medium





JLab / Hall C

. Seely et al. PRL 103, 202301 (2009)

Scaled nuclear density = *(A-1)/A <ρ>*
→ remove contribution from struck nucleon

<ρ> from ab initio few-body calculations
→ *[**S.C. Pieper and R.B. Wiringa**, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

The European Muon Collaboration (EMC) effect

30 years old

Well established measured effect with no consensus as to its origin

Models of the EMC effect

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Drell-Yan data

Nucleus ≠nucleons

bound N ≠ free N

Binding effects
Fermi motion
…

Pions
Vector mesons
Δs
Multiquak clusters
'Photons'
…

Global changes

Rare configurations

M*≠M
R*≠R
Dynamical rescaling
Confinement changes
Quark w,f. modification in mean field
…

Suppression of PLC
…

review papers:

Gessman, Saito,Thomas, Annu. Rev. Nucl. Part. Sci. 45:337(1995).

P.R. Norton , Rep Prog. 66 (2003).

Frankfurt and Strikman (2012)

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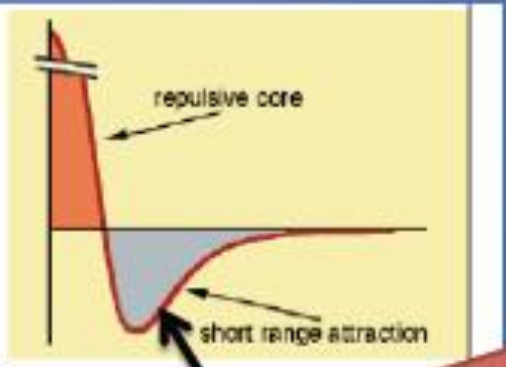
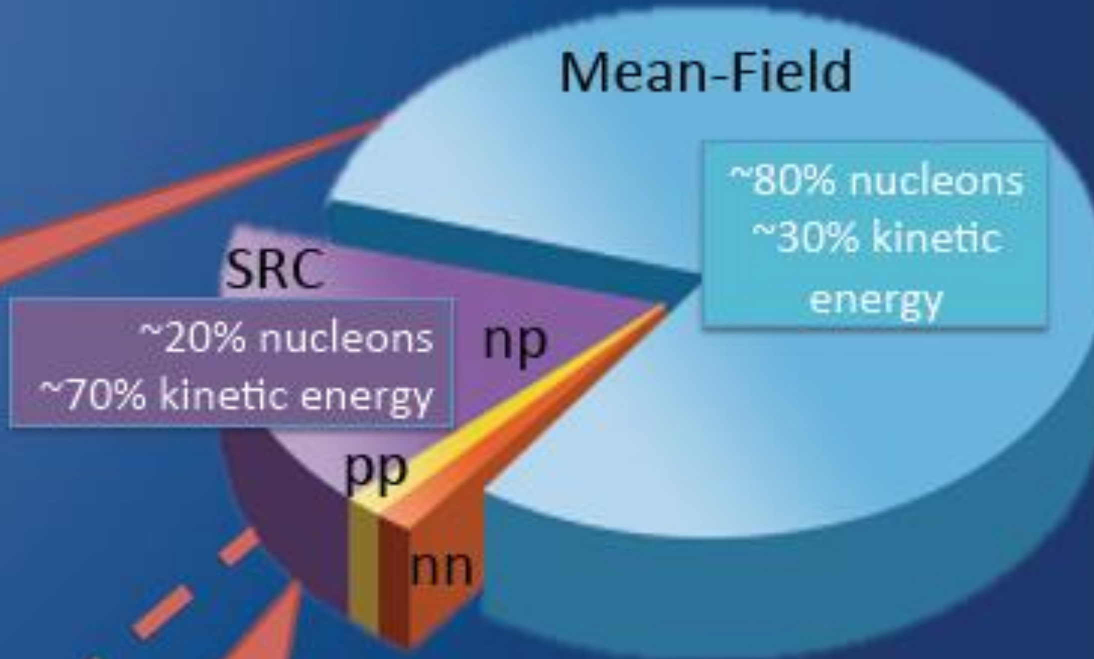
Where is the EMC Effect?



Largest attractive force



Mean-Field

SRC

High local nuclear matter density, large momentum, large off shell, large virtuality

$$\upsilon = p^2 - m^2$$

Inclusive electron scattering A(e,e')

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Deep Inelastic Scattering

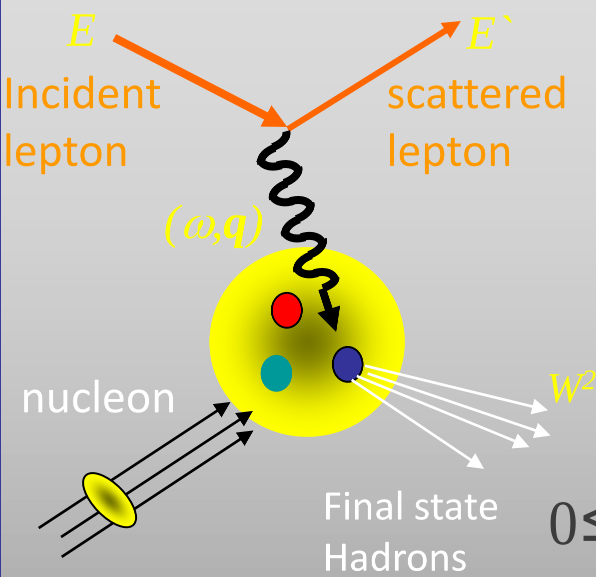
→ Partonic (quark) Structure of **Hadrons**

Inclusive Scattering at $X_B>1$ A(e,e')

→ Partonic (nucleon) Structure of **Nucleus**

Inclusive electron scattering A(e,e')

DIS off nucleons



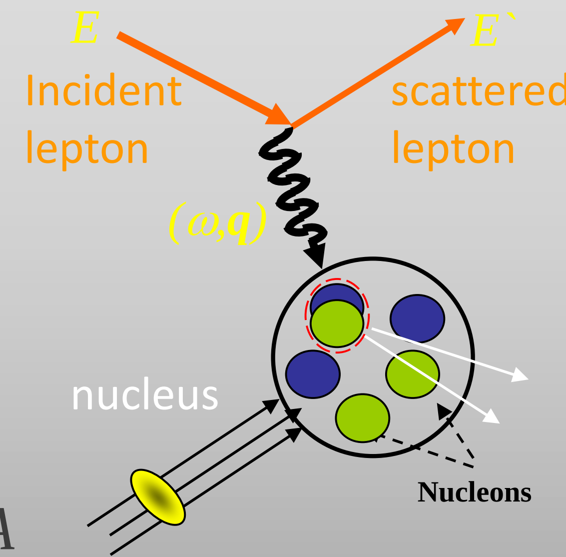
$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \qquad \left(x_B' = \frac{Q^2}{2(q \cdot p_T)}\right)$$

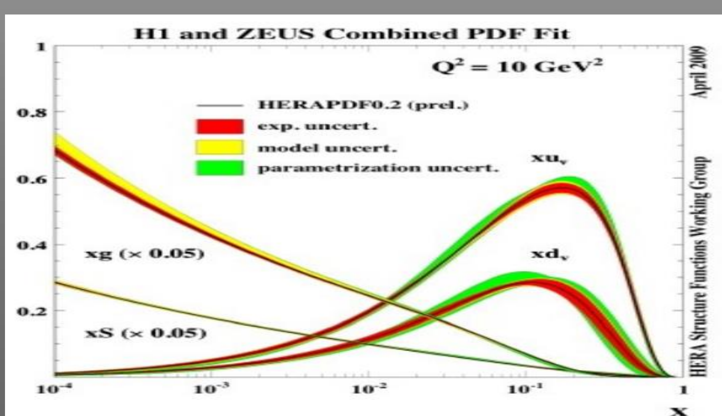
$0 \leq x_B \leq 1$

DIS off nuclei

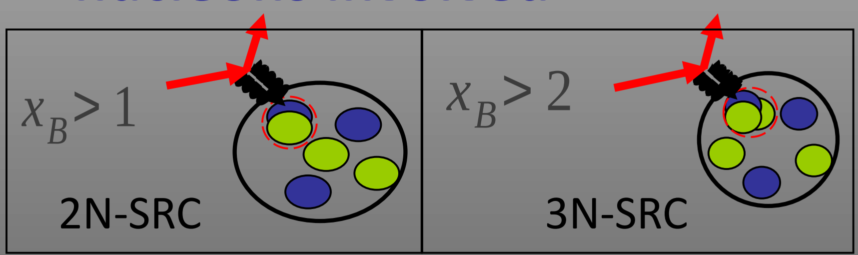


$0 \leq x_B \leq A$

x_B gives the fraction of nucleon momentum carried by the struck parton



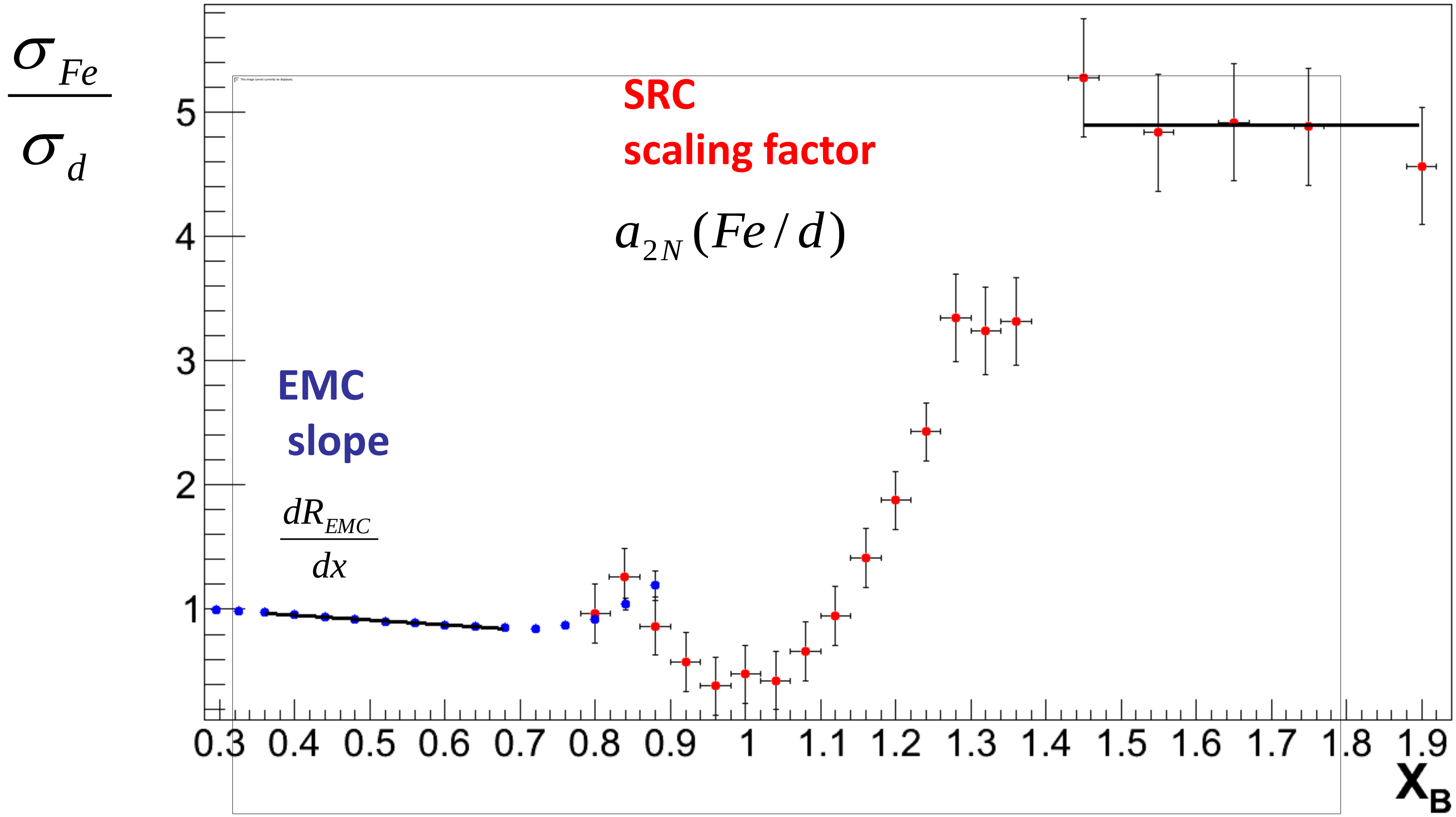
x_B counts the number of nucleons involved



--> scaling

--> Counting the number of SRC clusters in nuclei

Comparing magnitude of EMC effect and SRC scaling factors



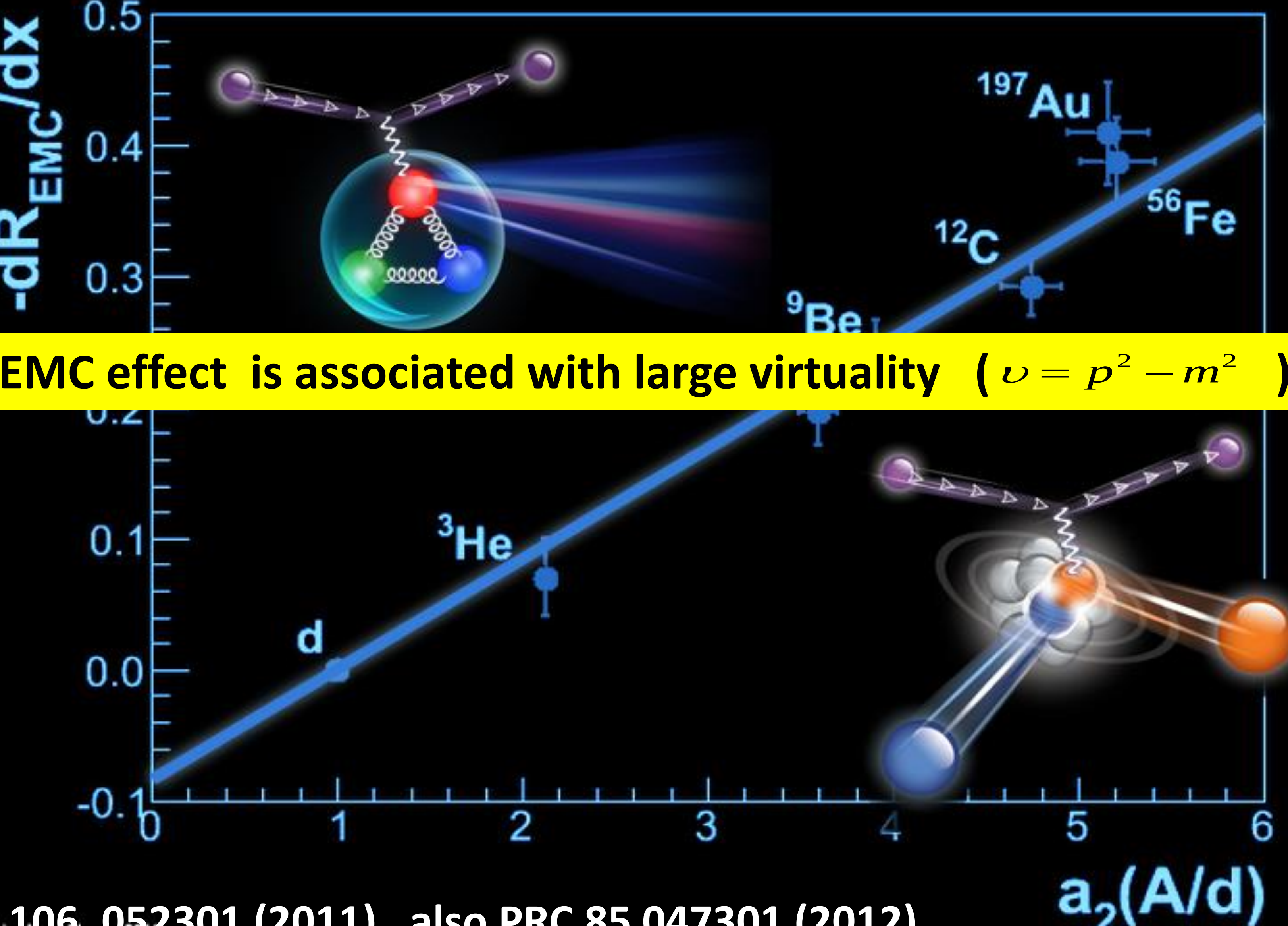
SLAC data:

Gomez et al., Phys. Rev. D49, 4348 (1983).

Q^2=2, 5, 10, 15 GeV/c^2 (averaged)

Frankfurt, Strikman, Day, Sargsyan, Phys. Rev. C48 (1993) 2451.

Q^2=2.3 GeV/c^2



the EMC effect is associated with large virtuality ($\upsilon = p^2 - m^2$)

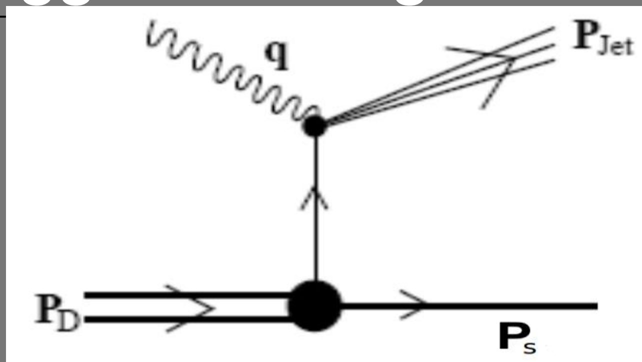
EMC

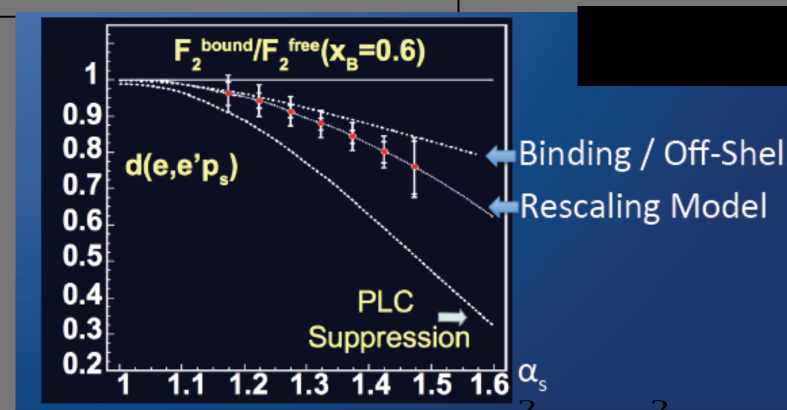
SRC

PRL 106, 052301 (2011), also PRC 85 047301 (2012)

Is the EMC effect associated with large virtuality ?

Hypothesis can be verified by measuring DIS off Deuteron tagged with high momentum recoil nucleon





$$v = p^2 - m^2$$

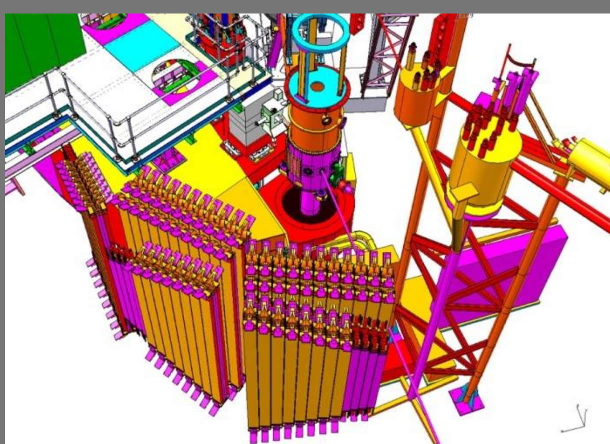
12 GeV JLab/ Hall C approved experiment **E 12-11-107**

Tagged recoil proton measure neutron structure function

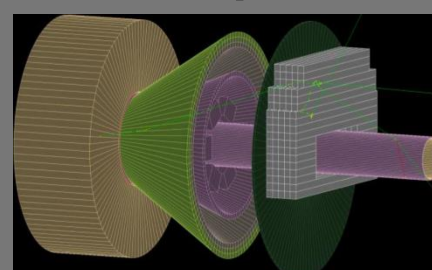
12 GeV JLab/ Hall B approved experiment

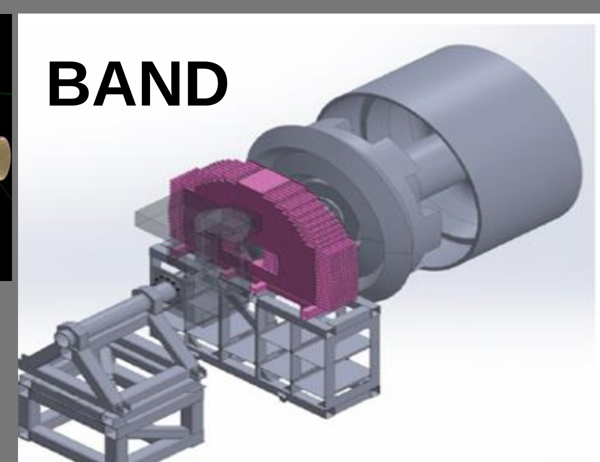
E12-11-003a

Tagged recoil neutron measure in the proton structure function

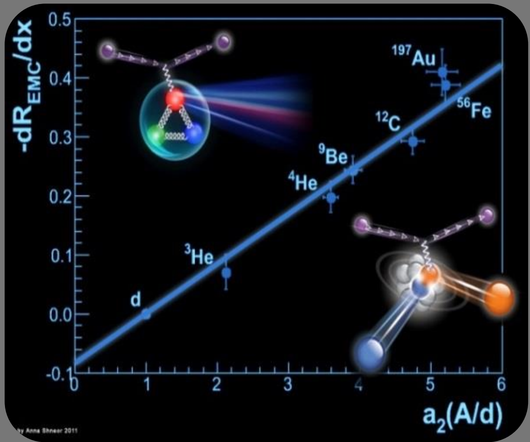


LAND

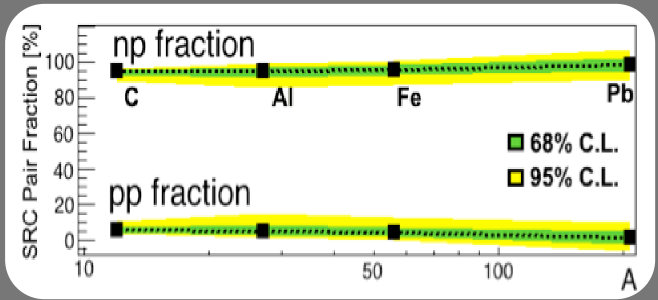




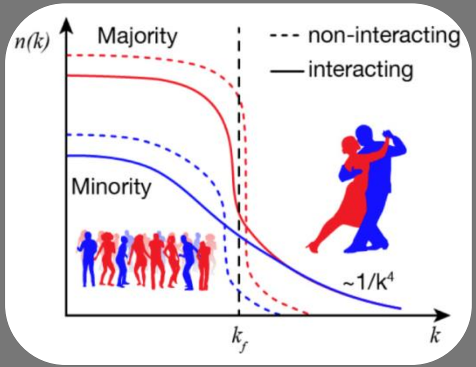
Summary – relevant of Correlations

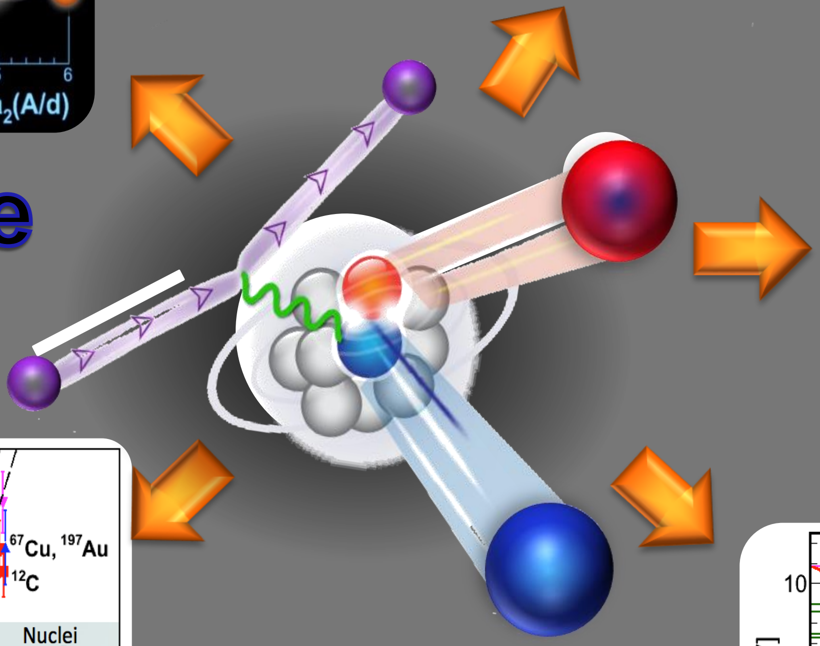


Particle



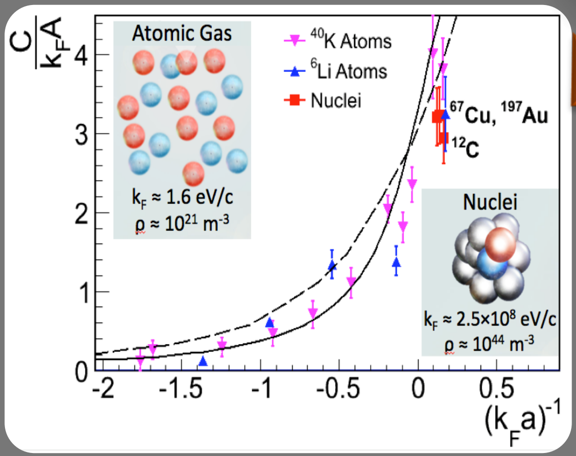
Nuclear





3N-SRC

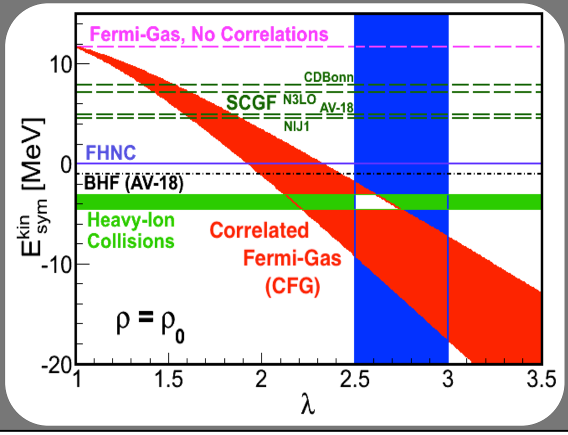
Atomic



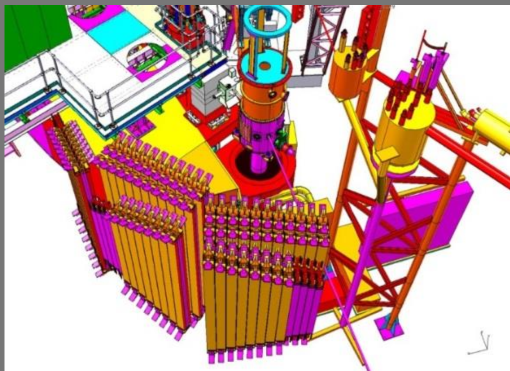
Contact term

Astro

Symmetry energy

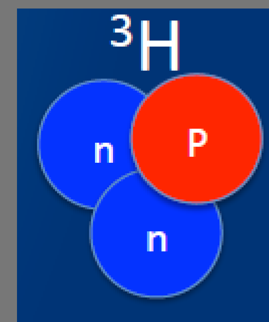


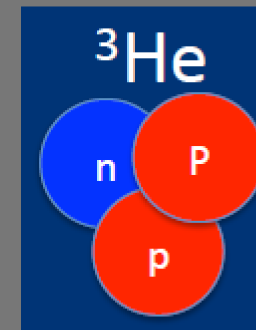
Summary – proposed experiments

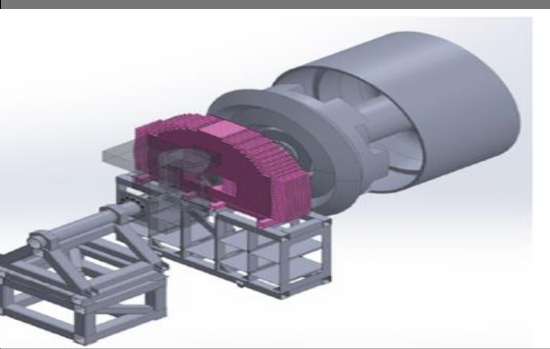


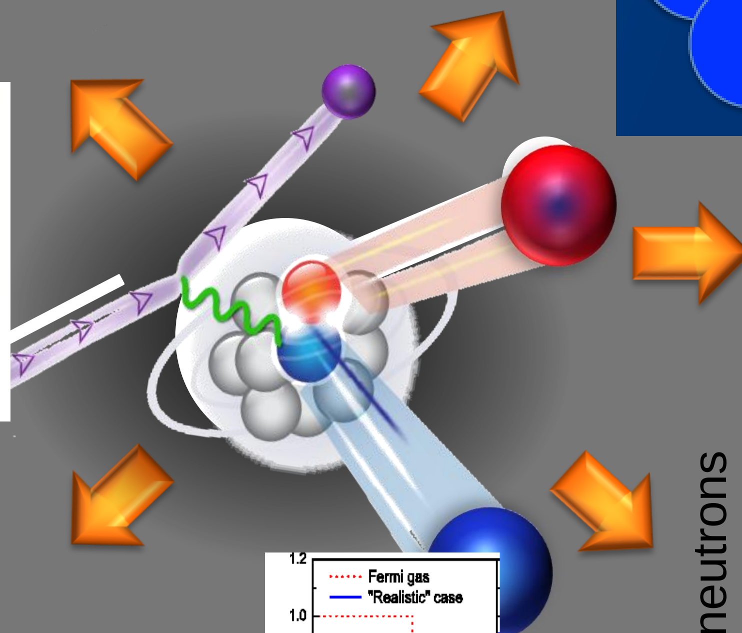
JLab Hall C: E12-11-107

JLab









JLab Hall A: E12-14-011

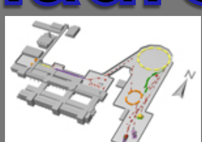
JLab Hall B: E12-11-003a

^{32}Cl	^{33}Ar		Ca							
^{33}Cl	^{34}Ar	^{35}K		21					Z	
^{34}Cl	^{35}Ar	^{36}K	^{37}Ca	Sc	22					
^{35}Cl	^{36}Ar	^{37}K	^{38}Ca		Ti	23				
^{36}Cl	^{37}Ar	^{38}K	^{39}Ca	^{40}Sc	^{41}Ti	V	24			
^{37}Cl	^{38}Ar	^{39}K	^{40}Ca	^{41}Sc	^{42}Ti		Cr	25		N
^{38}Cl	^{39}Ar	^{40}K	^{41}Ca	^{42}Sc	^{43}Ti	^{44}V	^{45}Cr	Mn	26	
^{39}Cl	^{40}Ar	^{41}K	^{42}Ca	^{43}Sc	^{44}Ti	^{45}V	^{46}Cr		Fe	27
^{40}Cl	^{41}Ar	^{42}K	^{43}Ca	^{44}Sc	^{45}Ti	^{46}V	^{47}Cr	^{48}Mn	^{49}Fe	Co
^{41}Cl	^{42}Ar	^{43}K	^{44}Ca	^{45}Sc	^{46}Ti	^{47}V	^{48}Cr	^{49}Mn	^{50}Fe	^{51}Co
^{42}Cl	^{43}Ar	^{44}K	^{45}Ca	^{46}Sc	^{47}Ti	^{48}V	^{49}Cr	^{50}Mn	^{51}Fe	^{52}Co
^{43}Cl	^{44}Ar	^{45}K	^{46}Ca	^{47}Sc	^{48}Ti	^{49}V	^{50}Cr	^{51}Mn	^{52}Fe	^{53}Co
^{44}Cl	^{45}Ar	^{46}K	^{47}Ca	^{48}Sc	^{49}Ti	^{50}V	^{51}Cr	^{52}Mn	^{53}Fe	^{54}Co
28	^{46}Ar	^{47}K	^{48}Ca	^{49}Sc	^{50}Ti	^{51}V	^{52}Cr	^{53}Mn	^{54}Fe	^{55}Co
	29	^{48}K	^{49}Ca	^{50}Sc	^{51}Ti	^{52}V	^{53}Cr	^{54}Mn	^{55}Fe	^{56}Co

Add 8 f7/2 neutrons

Add 8 protons

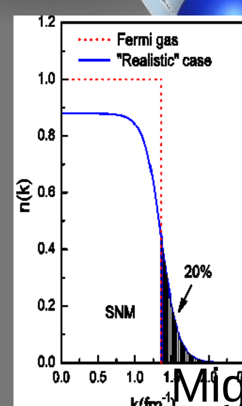
Hadron facilities



GSI / FAIR

Dubna

Nuclotron



Migdal jump

SRC talks

TEL AVIV UNIVERSITY

Thursday, November 02

Nuclei (Athenaeum Ballroom)

Session chair: **Fabienne Kunne**

11:30-12:00	New Insights into Nucleon-Nucleon Correlations	Axel Schmidt (MIT)

Parallel Workshops | Wednesday, November 01 | 15:00-15:30

2\. New Avenues in Lepton Scattering

Session I: Nuclear & Nucleon Structure

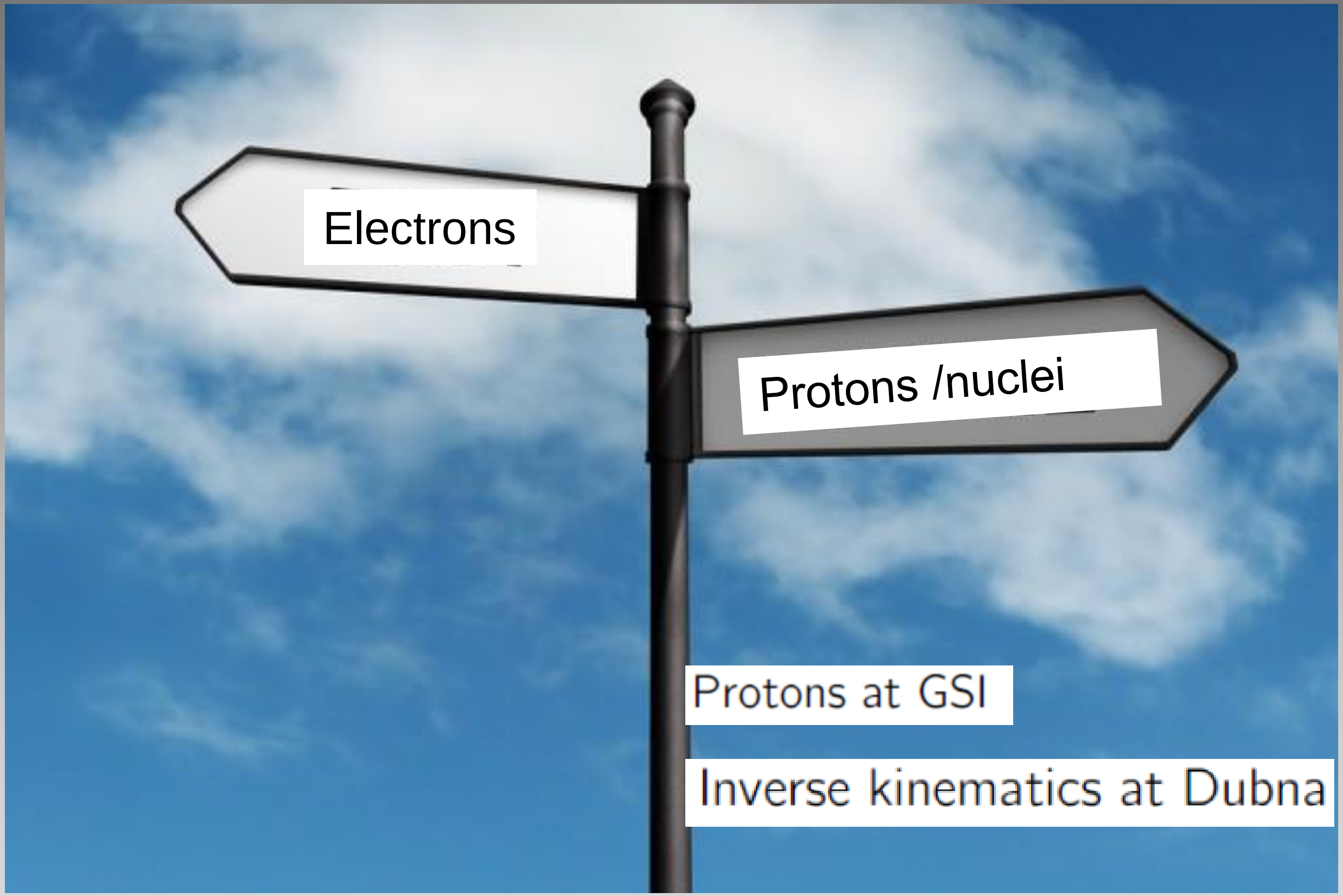
N-N correlations in nuclei	Meytal Duer (Tel-Aviv)

Acknowledgment

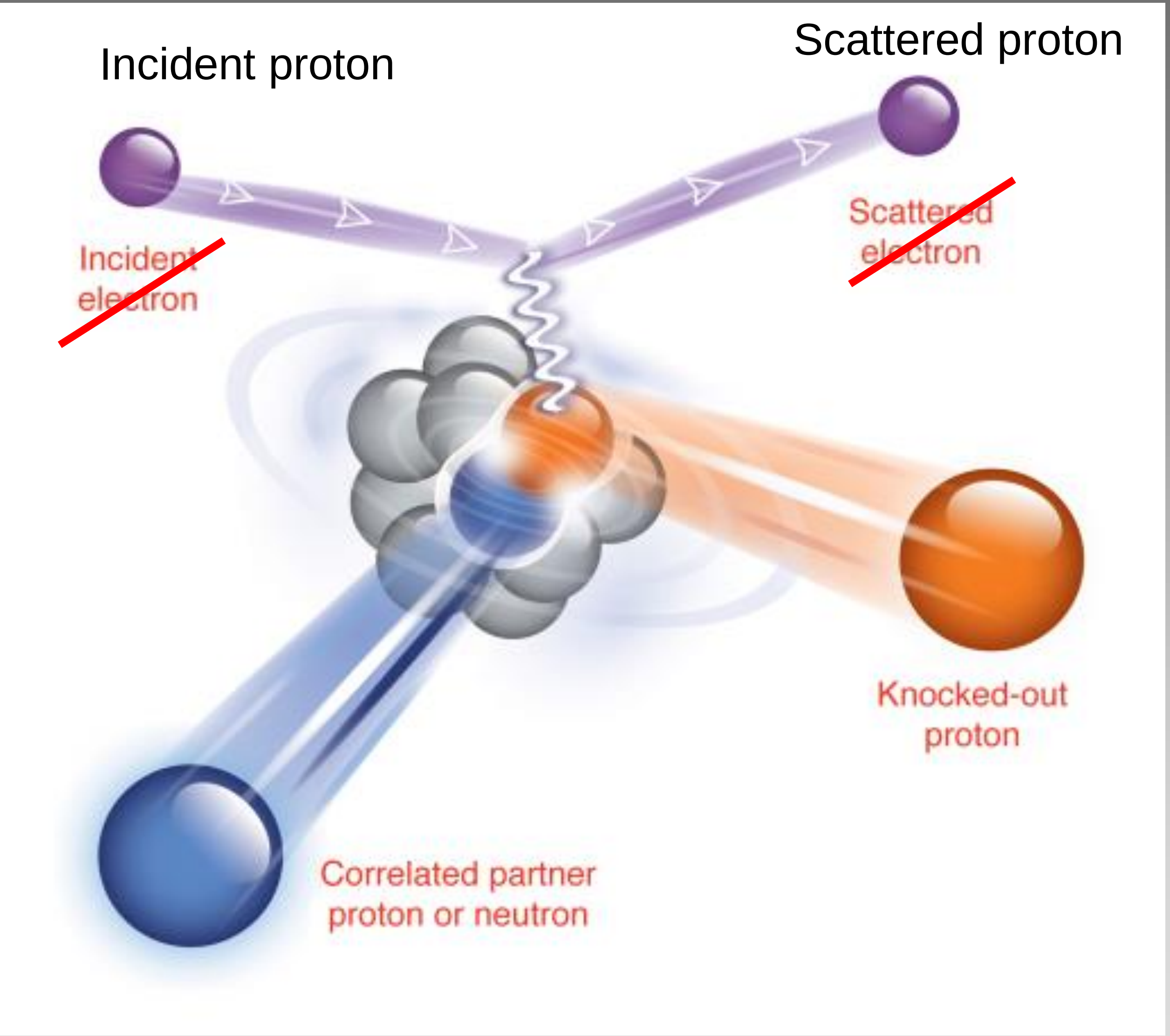
I would like to thank the organizers for the invitation.

Erez Cohen

Axel Schmidt


Electrons
Protons /nuclei
Protons at GSI
Inverse kinematics at Dubna

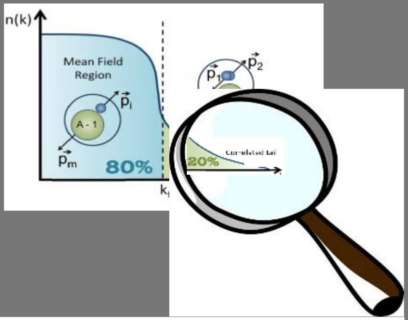
Triple coincidence A (p, p p N) measurements complementary to JLab



Complementary to JLab study with electrons

Why H.E. protons are good probes of SRC ?

selective attention to SRC



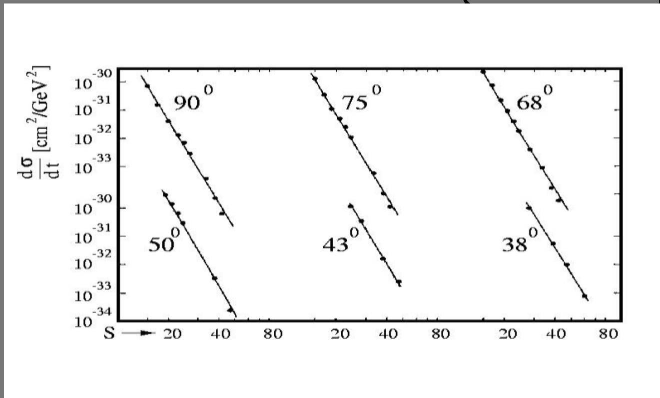
Psychology Wiki

Selective attention. A type of attention which involves focusing on a specific aspect of a scene while ignoring other aspects.

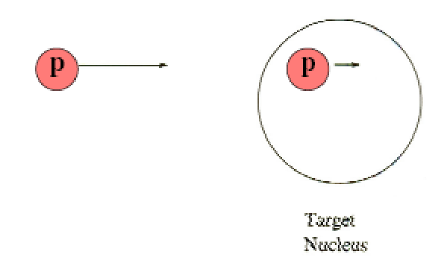
p p → pp elastic scattering near 90^0 c.m

$$\frac{d\sigma}{dt} \propto s^{-10}$$

Constituent Counting Rules

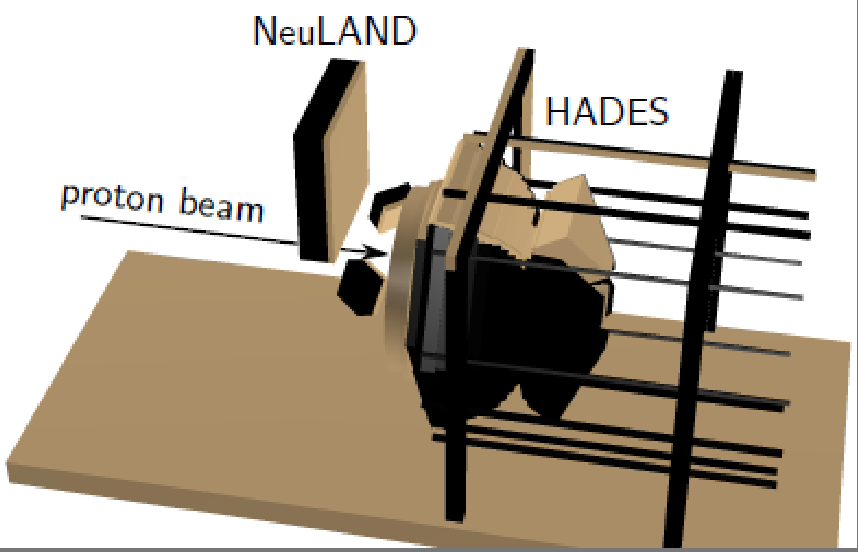


QE pp scattering have a very strong preference for reacting with forward going high momentum nuclear protons

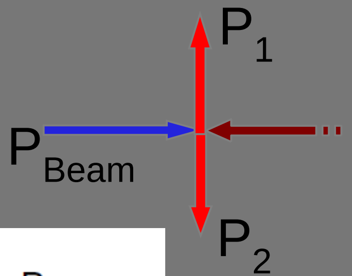


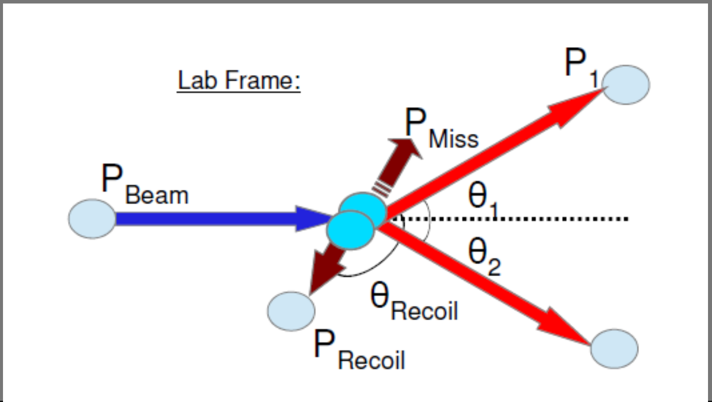
A new proton scattering experiment at GSI can yield

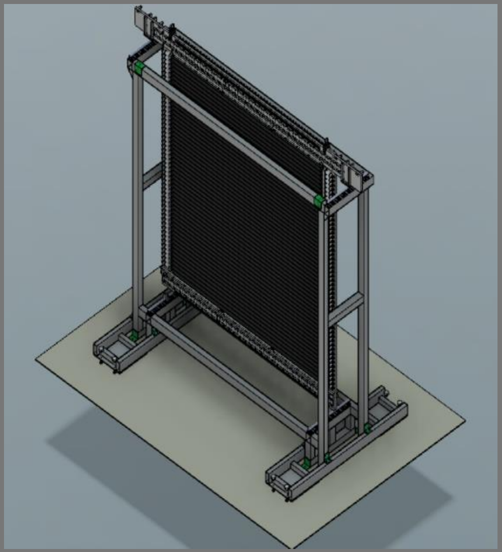
- Proton scattering enhances SRC cross section
- Use existing HADES, NeuLAND detectors
- Chance to look at 3-nucleon correlations

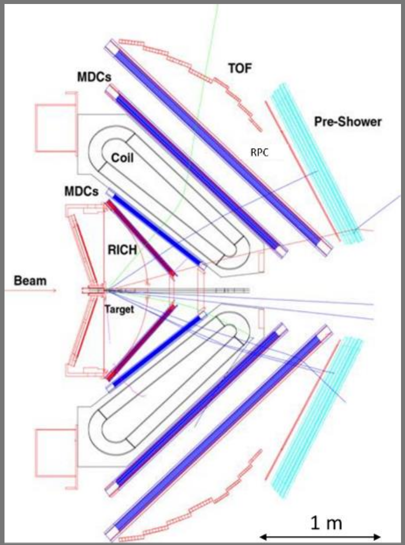


C.M. Frame :

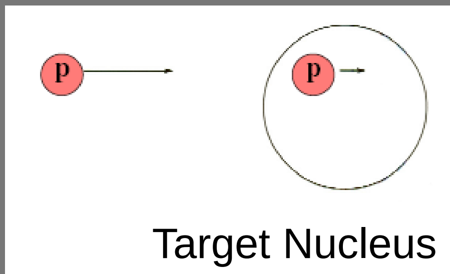


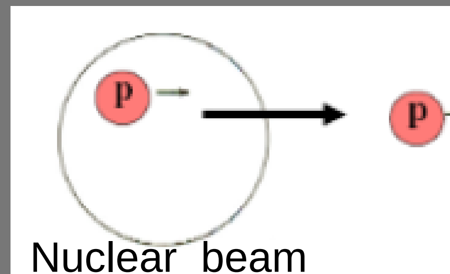


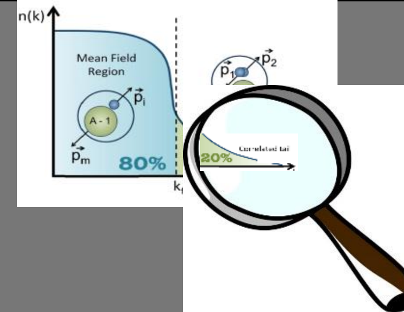




Inverse kinematics at Dubna







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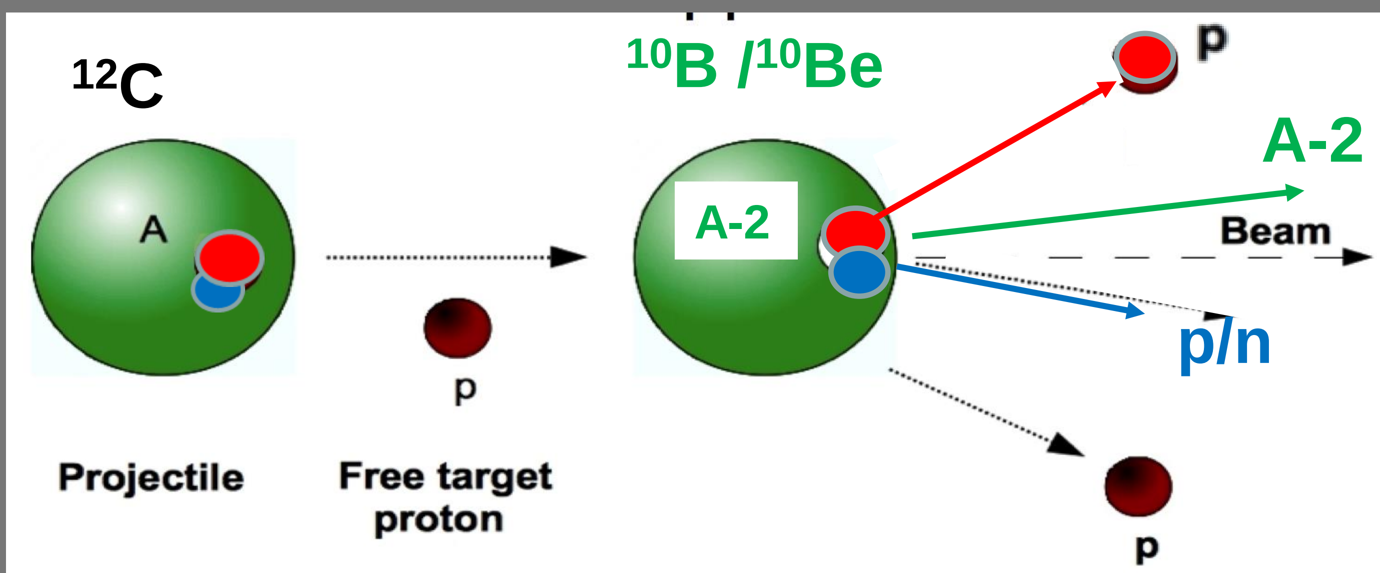
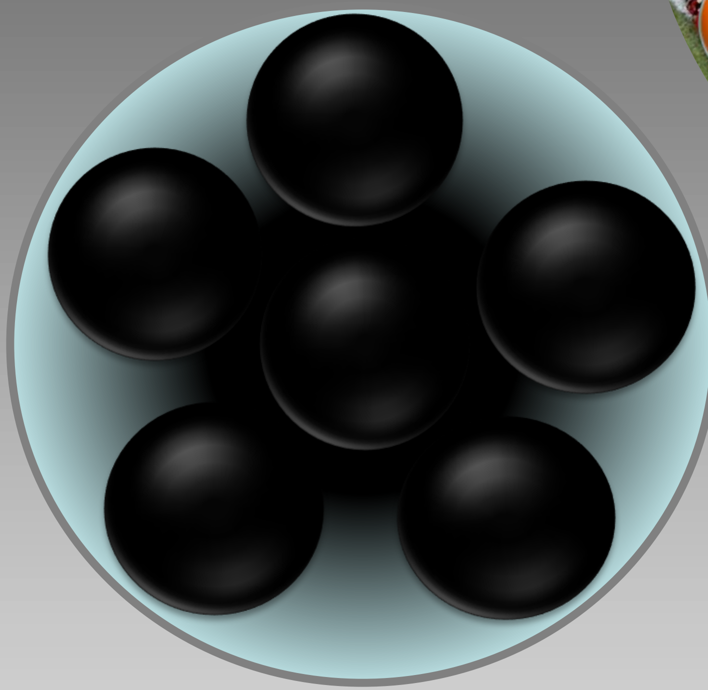
Same selective attention to SRC

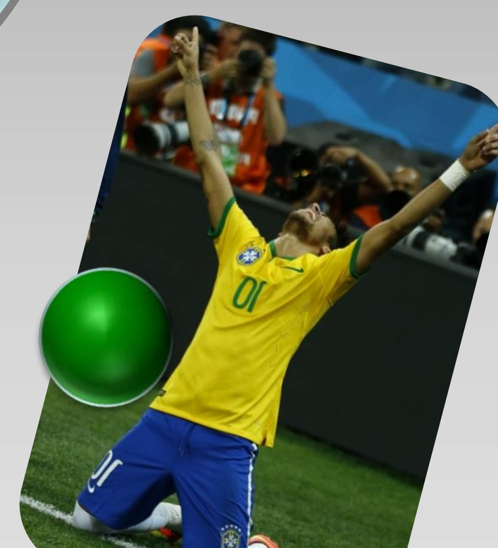
A proposal for a BM@N experiment

To study the NN Repulsive Core with Hard inverse kinematic reactions

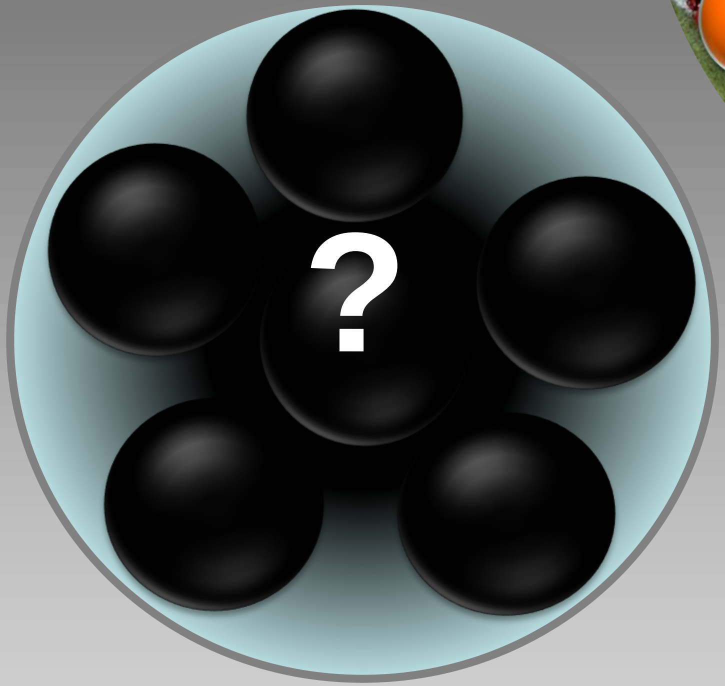


triple – coincidence measurements

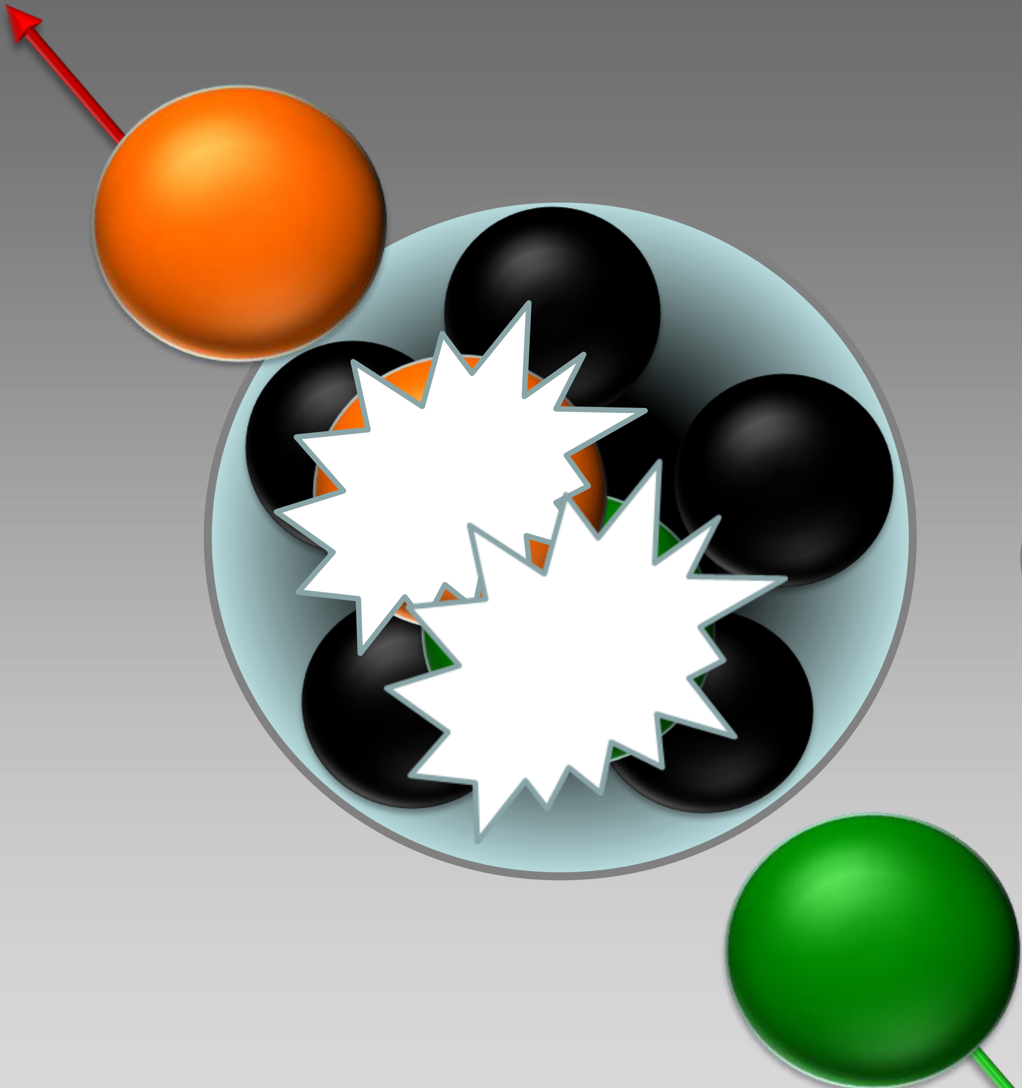


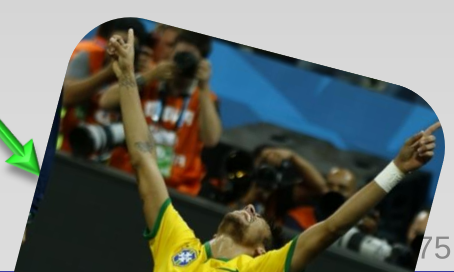


triple – coincidence measurements

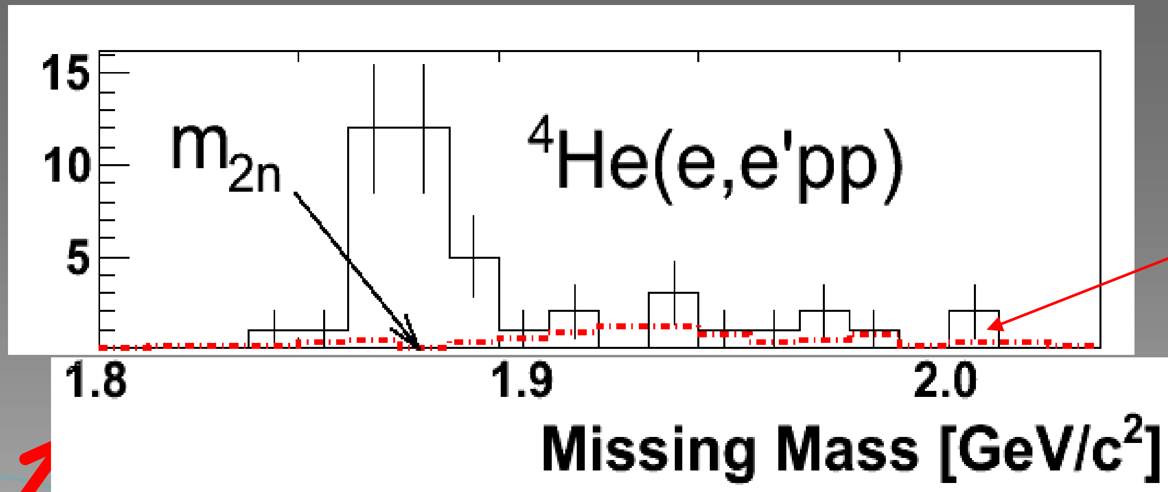


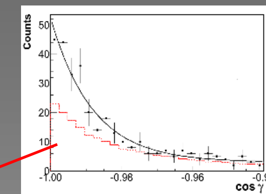
Inverse kinematics





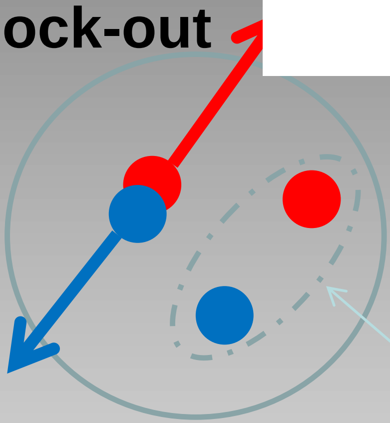
E07-006 (2011) ^{4}He (^{12} C)



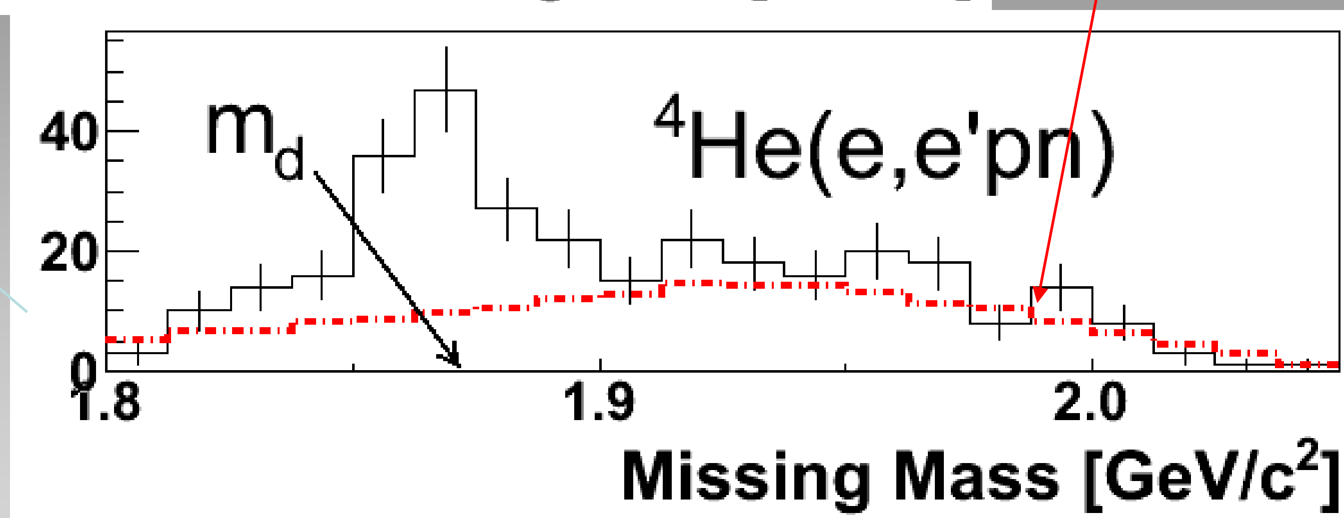


background

Knock-out



Recoil

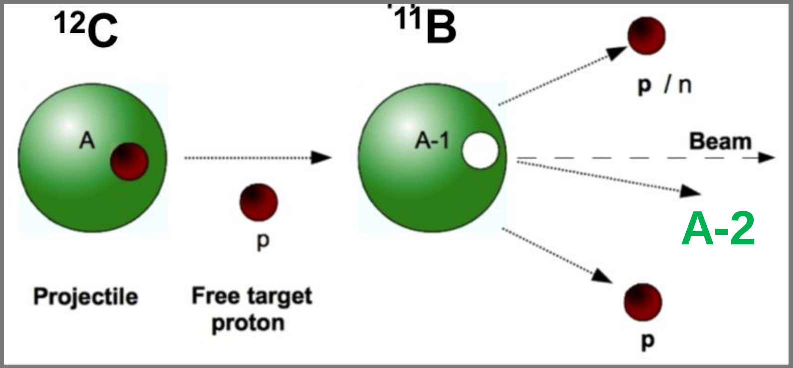


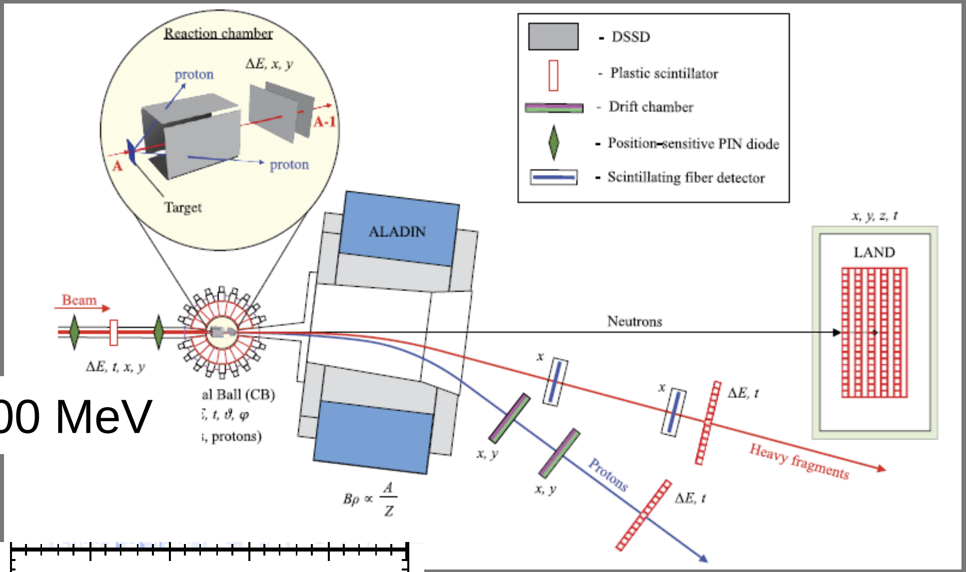
Jlab Hall A experiment

I. Korover et al. Phys. Rev. Let. 113, 022501 (2014).

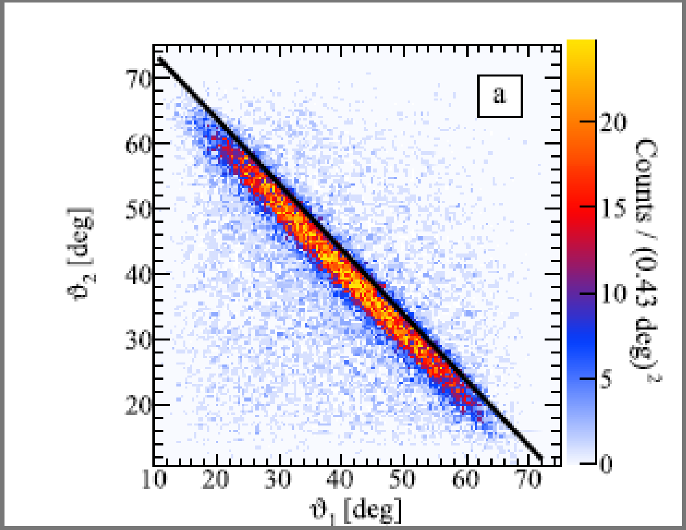
QE measurement with LAND/R3B@GSI

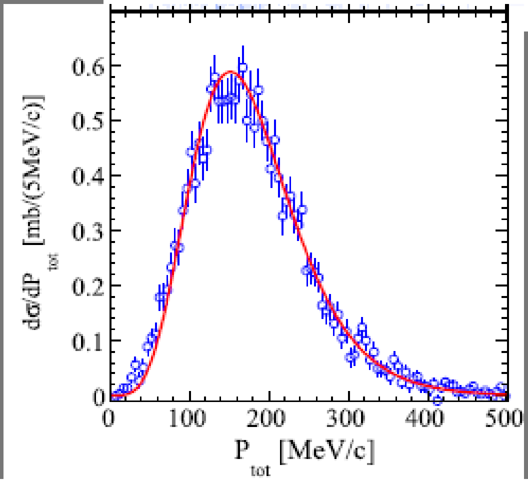
V. Panin et al. PLB 753 (2016) 204.





~400 MeV



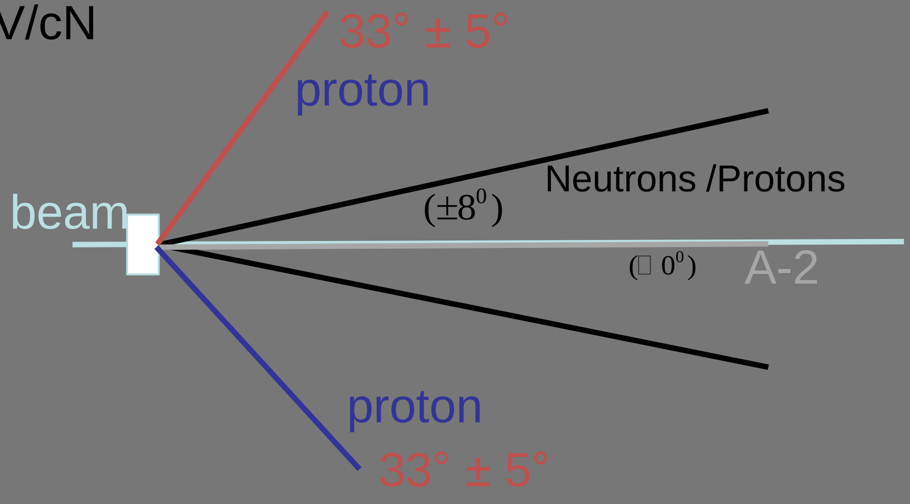


Energy limit at R3B around 1 GeV/nucleon
due to maximum rigidity of Super-FRS of 20 Tm

SRC @ Dubna

Carbon beam with momentum of 4 GeV/cN

$^{12}C + p \rightarrow 2p + {}^{11}_{5}B$	QE
$^{12}C + p \rightarrow 2p + {}^{10}_{5}B + n$	np SRC
$^{12}C + p \rightarrow 2p + {}^{10}_{4}Be + p$	pp SRC



Get the ratios:

$$np-SRC \Big/ pp-SRC$$

$$\#({}^{10}_{5}B+n) \Big/ \#({}^{10}_{4}Be+p)$$

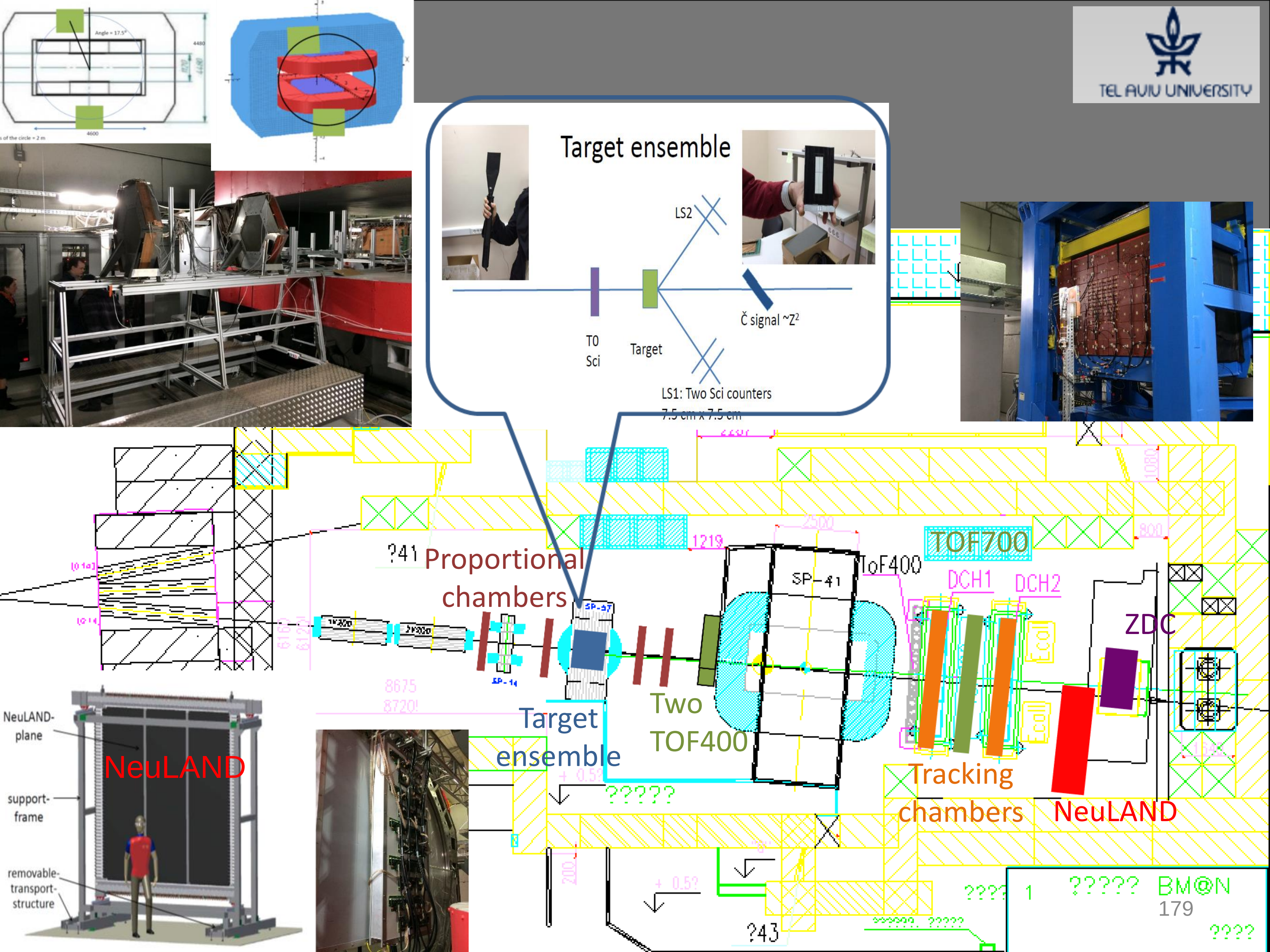
$$np-SRC \Big/ p$$

$$\#({}^{10}_{5}B+n) \Big/ \#(p,2p)$$

$$pp-SRC \Big/ p$$

$$\#({}^{10}_{4}Be+p) \Big/ \#(p,2p)$$

$$\#({}^{11}_{5}B) \Big/ \#(p,2p)$$



Target ensemble
LS2
Č signal ~Z²
T0
Sci
Target
LS1: Two Sci counters
7.5 cm x 7.5 cm
Proportional
chambers
TOF700
ToF400
SP-41
DCH1
DCH2
ZDC
Target
ensemble
Two
TOF400
Tracking
chambers
NeuLAND
NeuLAND-
plane
NeuLAND
support-
frame
removable-
transport-
structure
BM@N

LH_2 Vs. CH_2

LH_2:

- Length: 15 cm
- Interaction probability: ~3%

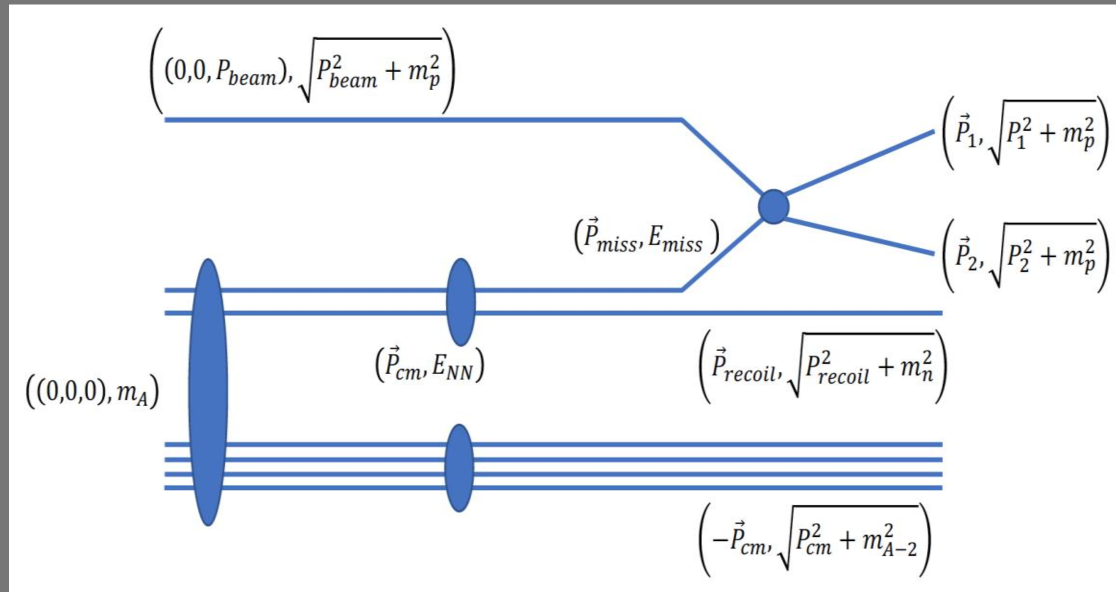
CH_2:

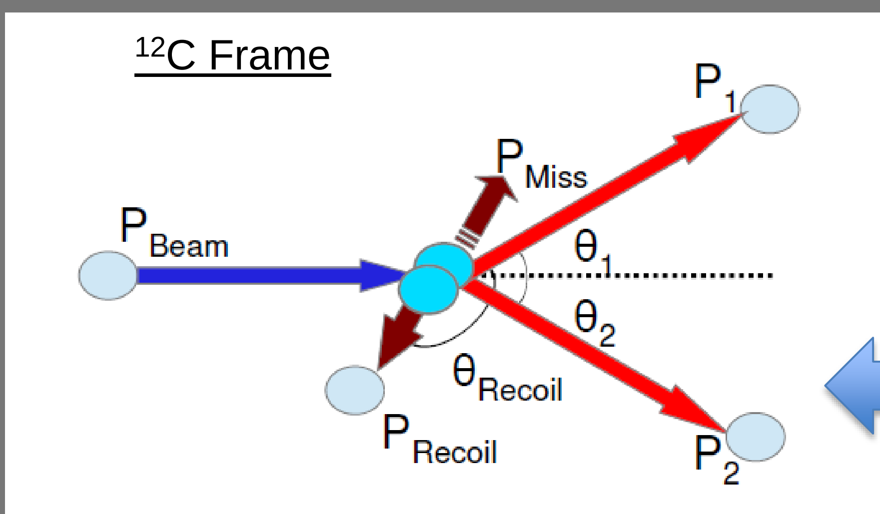
- Length: ~9 cm [equal hydrogen areal density]
- Interaction probability: ~10% [7% with C, 3% with H_2]

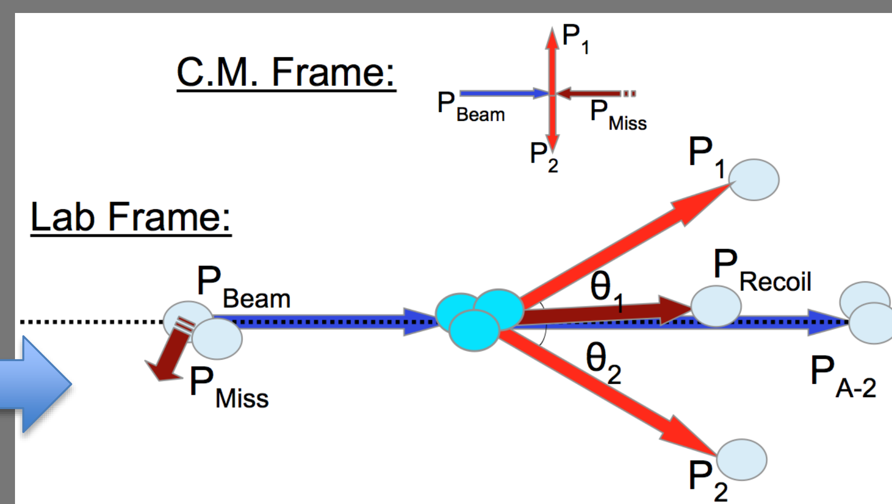
Other considerations:

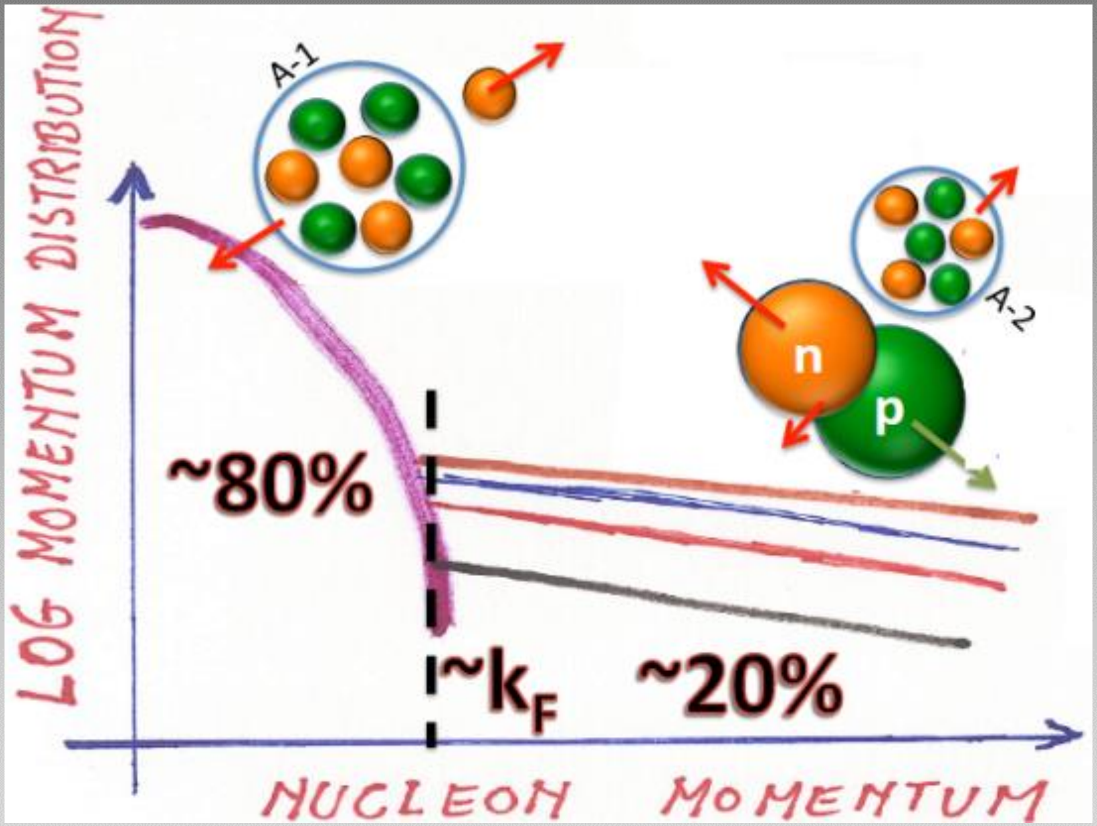
- CH_2 has increased BG from C-C interactions.
- CH_2 requires extra time for C subtraction.
- CH_2 maintenance free.
- LH_2 requires safety approval for used in BM@N area.

simulation


$\left((0,0,P_{beam}), \sqrt{P_{beam}^2 + m_p^2}\right)$
$\left(\vec{P}_1, \sqrt{P_1^2 + m_p^2}\right)$
$\left(\vec{P}_{miss}, E_{miss}\right)$
$\left(\vec{P}_2, \sqrt{P_2^2 + m_p^2}\right)$
$\left((0,0,0), m_A\right)$
$\left(\vec{P}_{cm}, E_{NN}\right)$
$\left(\vec{P}_{recoil}, \sqrt{P_{recoil}^2 + m_n^2}\right)$
$\left(-\vec{P}_{cm}, \sqrt{P_{cm}^2 + m_{A-2}^2}\right)$


^{12}C Frame
P_1
P_{Miss}
P_{Beam}
θ_1
θ_2
θ_{Recoil}
P_{Recoil}
P_2


C.M. Frame:
P_1
P_{Beam}
P_{Miss}
P_2
Lab Frame:
P_1
P_{Recoil}
P_{Beam}
θ_1
θ_2
P_{Miss}
P_{A-2}
P_2



LOG MOMENTUM DISTRIBUTION
A-1
A-2
n
p
~80%
~k_F
~20%
NUCLEON MOMENTUM

$$\psi_{2N}^{SRC}(\vec{k}_{rel}, \vec{K}_{c.m.}) \rightarrow \sum_{\alpha} \varphi_{2N}(\vec{k}_{rel}) \cdot A_{2N}(\vec{K}_{c.m.}, \{k_\alpha\}_{\alpha \neq 2N})$$

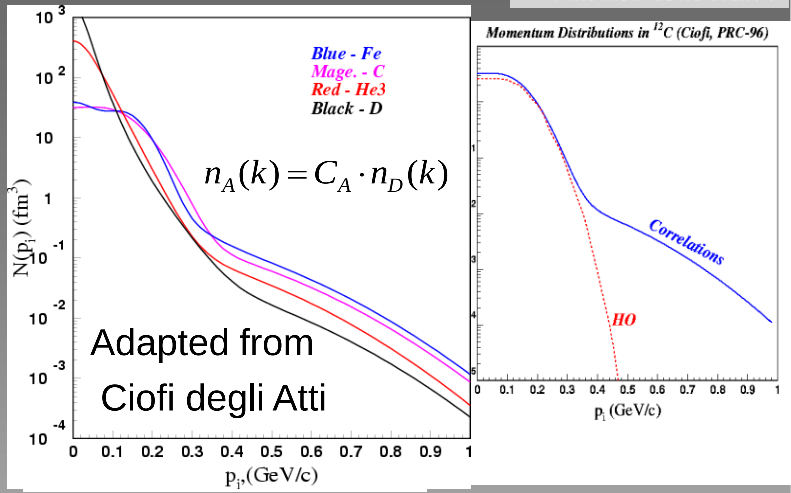
(Factorization) [R. Weiss et al. arXiv:1612.00923]

In this work we will consider only the main channels contributing to SRCs, namely, the pn deuteron channel ($\ell = 0, 2$ and $s = 1$ coupled to $j = 1$) and the singlet pp, pn, and nn s-wave channel ($\ell = s = j = 0$). Using Eq. (2), asymptotic expressions for the one- and two-body momentum densities can be derived [38]:

$$\begin{aligned} n_p(\boldsymbol{k}) =& 2C_{pp}^{s=0}|\tilde{\varphi}_{pp}^{s=0}(\boldsymbol{k})|^2 + C_{pn}^{s=0}|\tilde{\varphi}_{pn}^{s=0}(\boldsymbol{k})|^2 \\ &+ C_{pn}^{s=1}|\tilde{\varphi}_{pn}^{s=1}(\boldsymbol{k})|^2 \end{aligned} \tag{3}$$

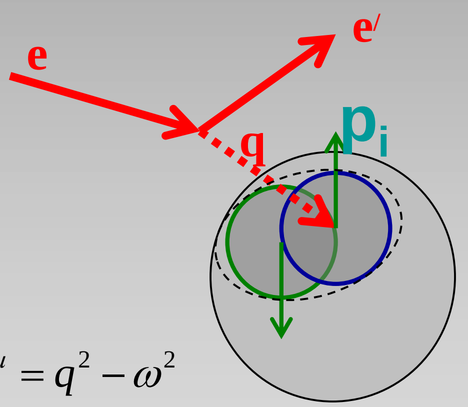
The inclusive A(e,e') measurements

- At high nucleon momentum distributions are similar in shape for light and heavy nuclei: SCALING.
- Can be explained by 2N-SRC dominance.



- Within the 2N-SRC dominance picture one can get the probability of 2N-SRC in any nucleus, from the scaling factor.

In A(e,e') the momentum of the struck proton (p_i) is unknown.



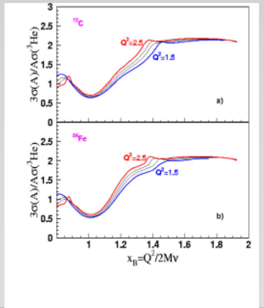
But: For fixed high Q^2 and $x_B>1$, x_B determines a minimum p_i

$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega}$$

Prediction by Frankfurt, Sargsian, and Strikman:



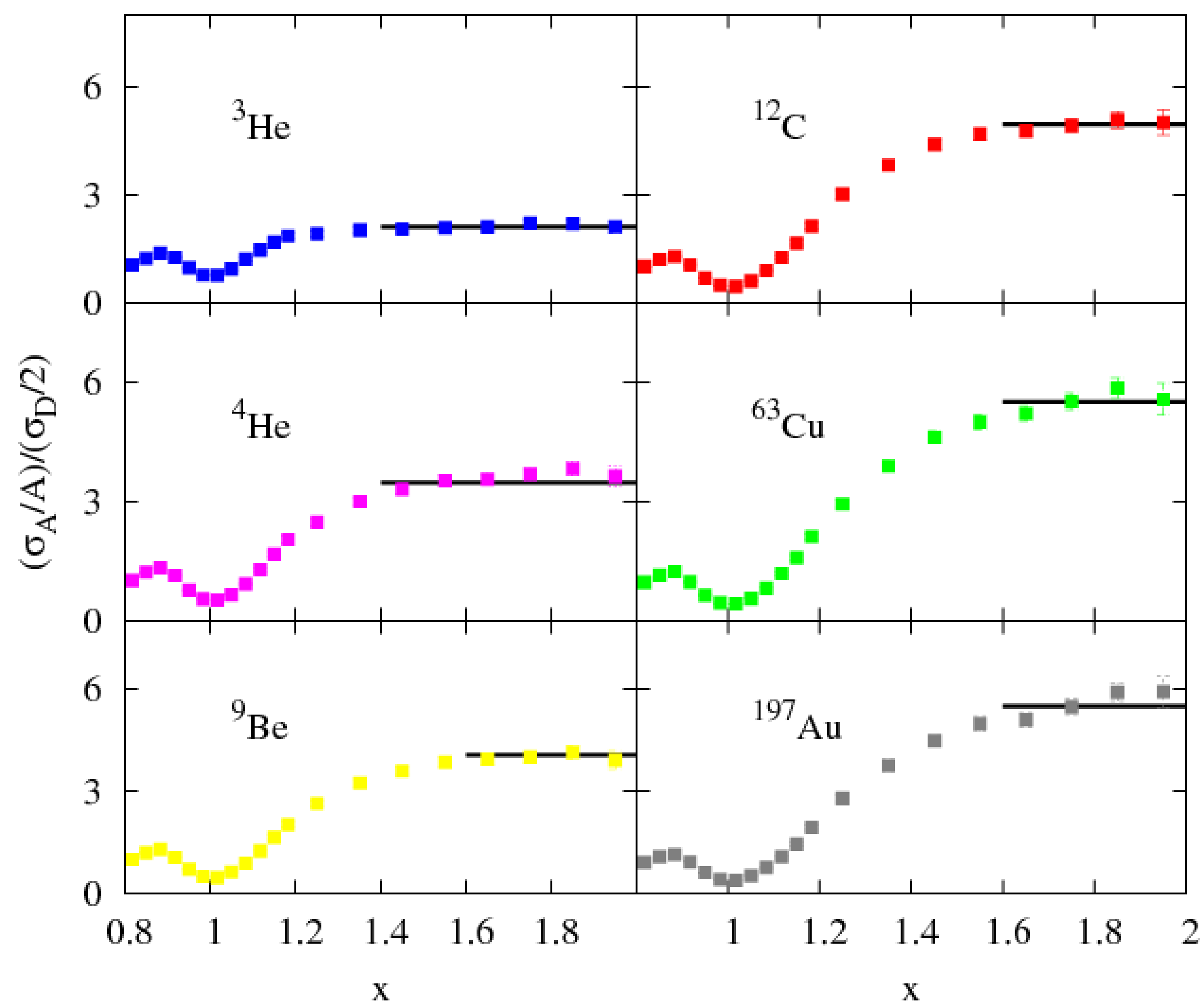
Results from JLab Hall C (E02-019)

N. Fomin et al. Phys. Rev. Lett. 108:092502, 2012.

$Q^2 = 2.5 GeV^2$

$a_{2N}(A/d)$

	Fomin *et al.*	Fomin *et al.* [excluding the CM motion correction]
	5	6
^{3}He	1.93 ± 0.10	2.13 ± 0.04
^{4}He	3.02 ± 0.17	3.60 ± 0.09
^{9}Be	3.37 ± 0.17	3.91 ± 0.12
^{12}C	4.00 ± 0.24	4.75 ± 0.16
^{56}Fe(	4.33 ± 0.28	5.21 ± 0.19
^{197}Au	4.26 ± 0.29	5.16 ± 0.21



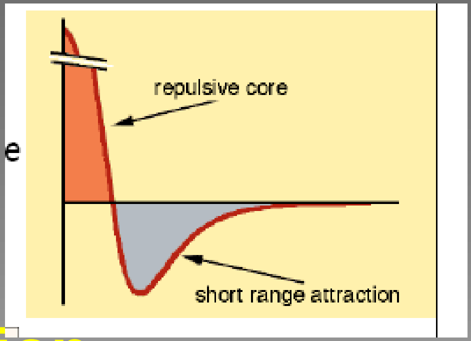
More r(A,d) data:

SLAC D. Day et al. PRL 59,427(1987)

Jlab /Hall B: K. Sh. Egiyan et al. PRC 68, 014313 (2003)

K. Sh. Egiyan et al. PRL. 96, 082501 (2006)

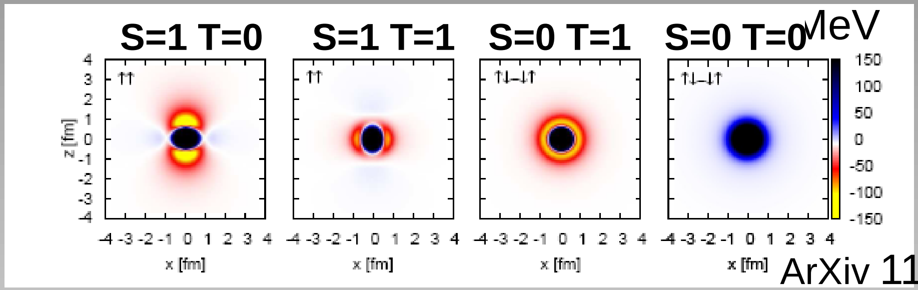
A description of bound nucleons and nuclei at distance scales small compared to the radius of the constituent nucleons needs to take into account:



complicated nucleon-nucleon interaction

Short range repulsion
(common to many other systems)

Intermediate- to long-range tensor attraction
(unique to nuclei)



Argonne V8 potential

ArXiv 1107.4956

**Large density of the nucleus =>
all relevant scales (nucleon size, average distance, and interaction range) are comparable,**

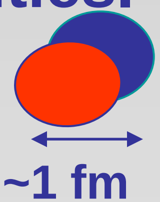
**Very difficult many-body problem
presents a challenge to both experiment and theory**

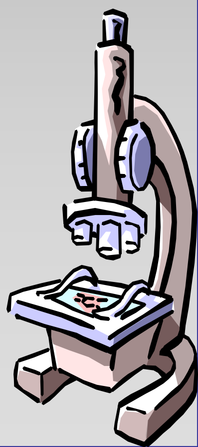
Short range correlations

"The structure of correlated many-body systems, particularly at distance scales small compared to the radius of the constituent nucleons, presents a formidable challenge to both experiment and theory"

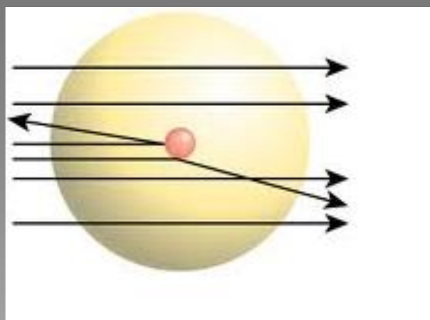
(Nuclear Science: A Long Range Plan, The DOE/NSF Nuclear Science Advisory Committee, Feb. 1996 [1].)

This challenge for nuclear physics can experimentally be effectively addressed thanks to high energy and large momentum transfer reached by present facilities.





Hard scattering has the resolving power required to probe the internal (partonic) structure of a complex target

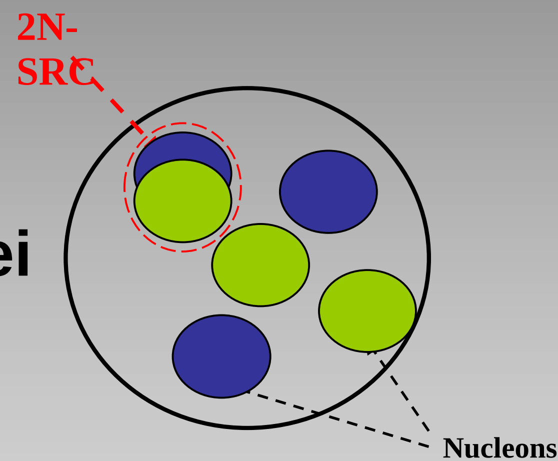


Rutherford scattering

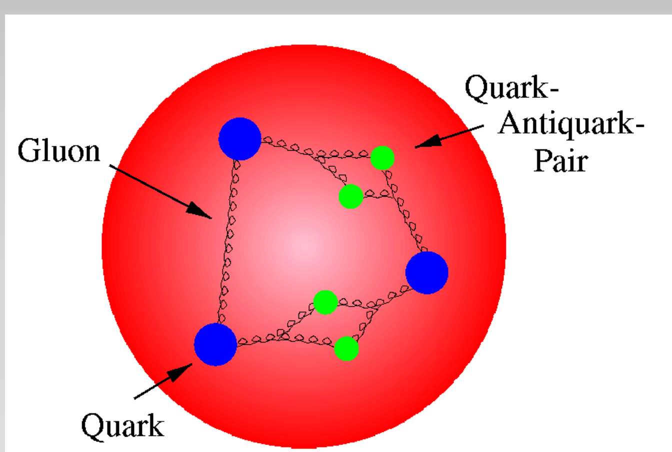
structure of atoms

Hard nuclear reactions

hadronic structure of nuclei



Scale:
several GeV

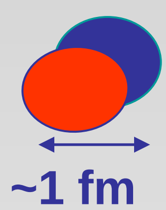


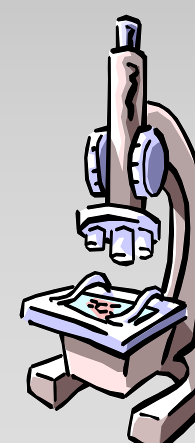
DIS

Scale:
several tens of GeV

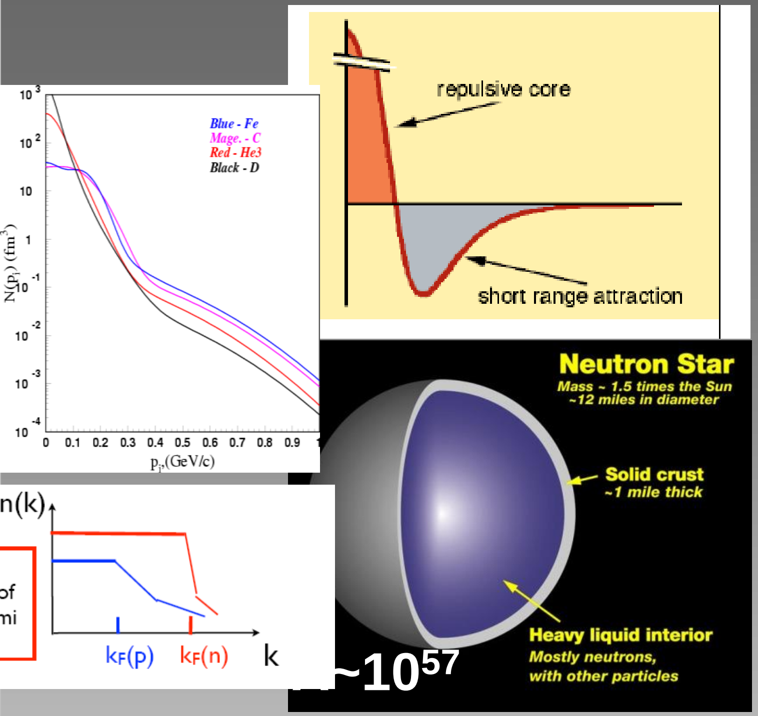
partonic structure of hadrons

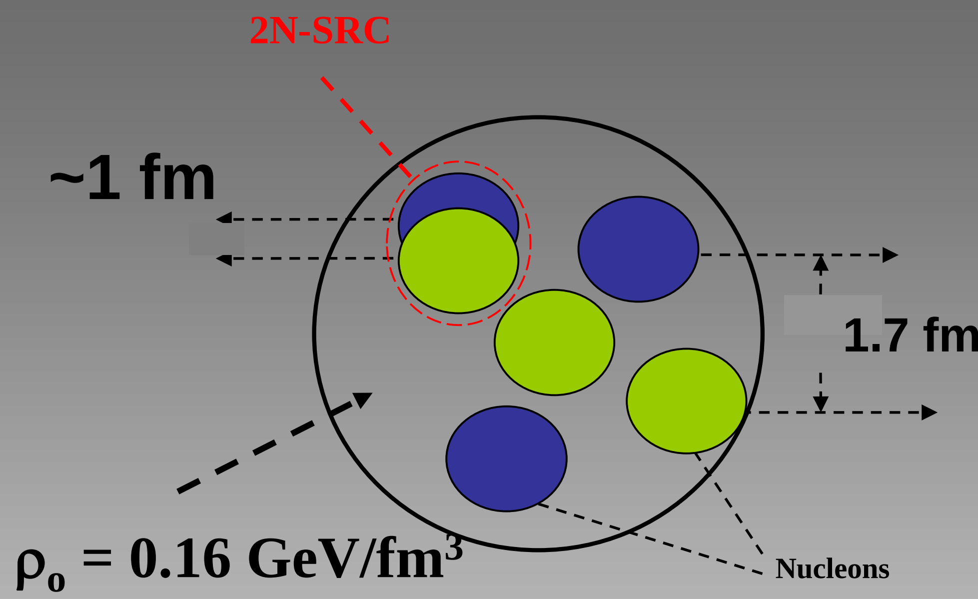
Fluctons





Short /intermediate Range Correlations in nuclei





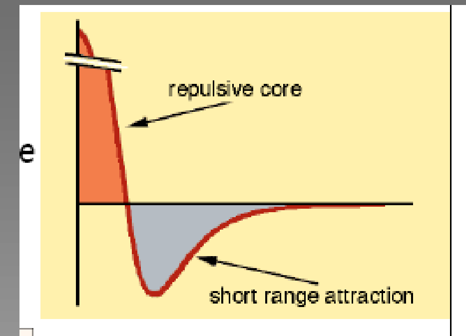
What SRC in nuclei can tell us about:

- **High – Momentum Component of the Nuclear Wave Function.**
- **The Strong Short-Range Force Between Nucleons.**

  tensor force, repulsive core, 3N forces
- **Cold-Dense Nuclear Matter (from deuteron to neutron-stars).**
- **Nucleon structure modification in the medium ?**

  EMC and SRC

A description of nuclei at distance scales small compared to the radius of the constituent nucleons needs to take into account,

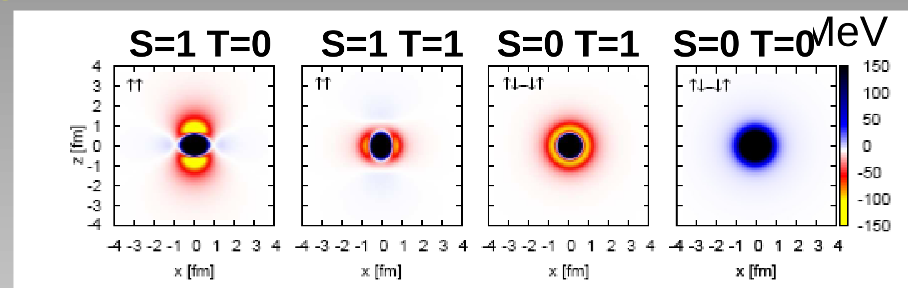


Short range repulsion

(common to many other systems)

Intermediate- to long-range tensor attraction

(unique to nuclei)



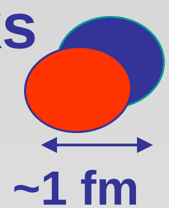
Argonne V8 potential

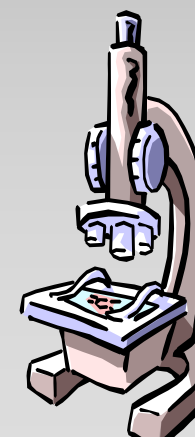
ArXiv 1107.4956

Very difficult many-body problem

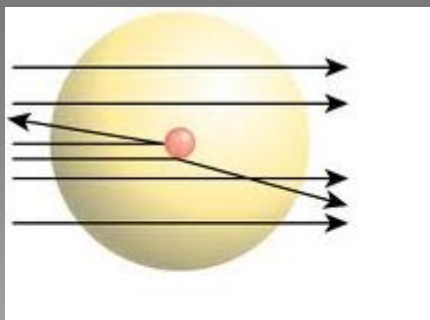
presents a challenge to both experiment and theory

This long standing challenge for nuclear physics can experimentally be effectively addressed thanks to high energy and large momentum transfer reached by present facilities.



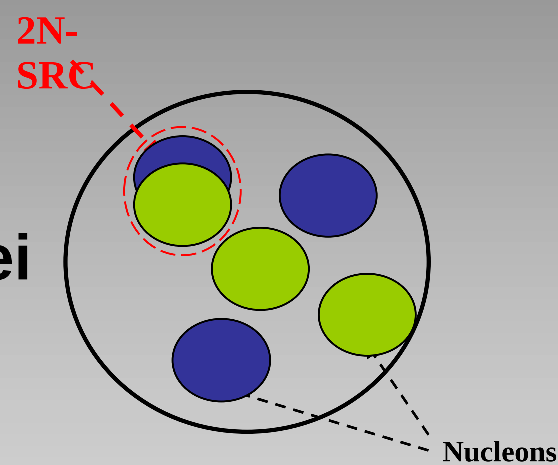


Hard scattering has the resolving power required to probe the internal (partonic) structure of a complex target



Rutherford scattering

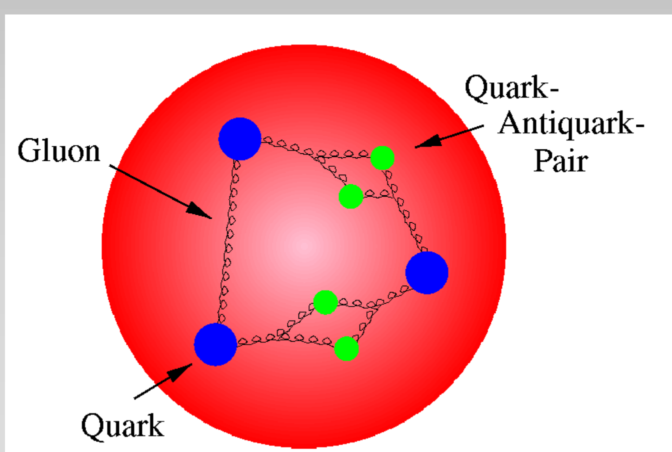
structure of atoms



Hard nuclear reactions

hadronic structure of nuclei

Scale:
several GeV

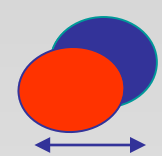


DIS

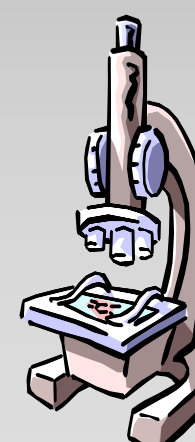
Scale:
several tens of GeV

partonic structure of hadrons

Fluctons

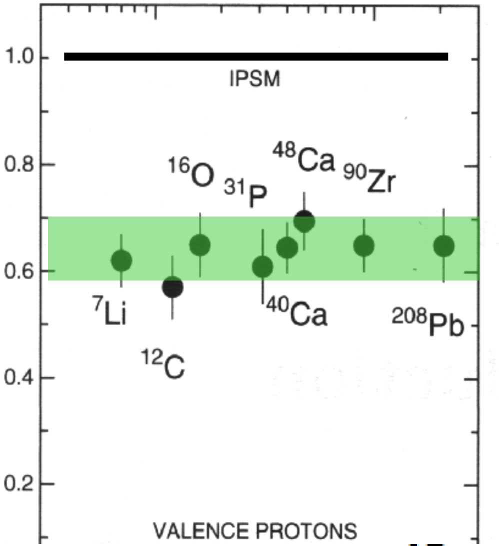


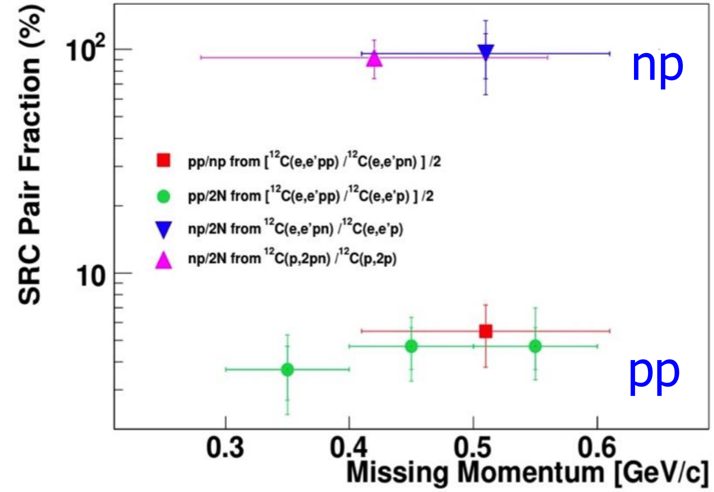
~1 fm

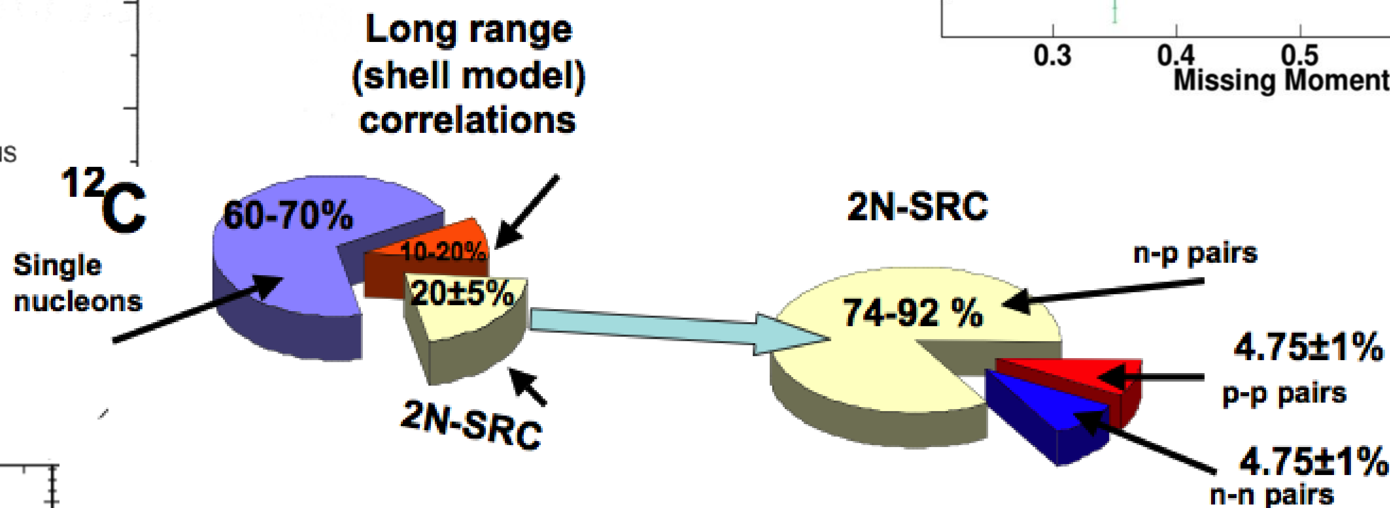


Summary

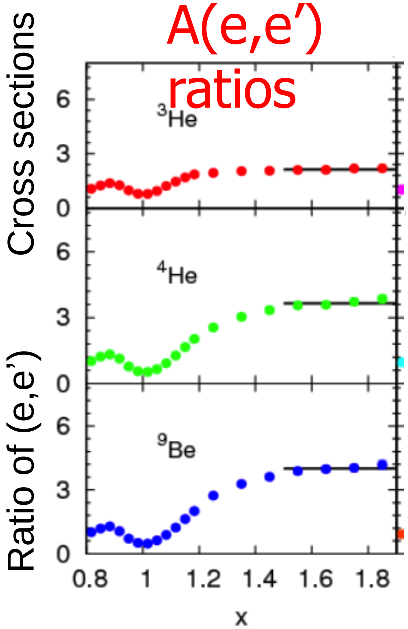
(e,e'p)
Shell
occ

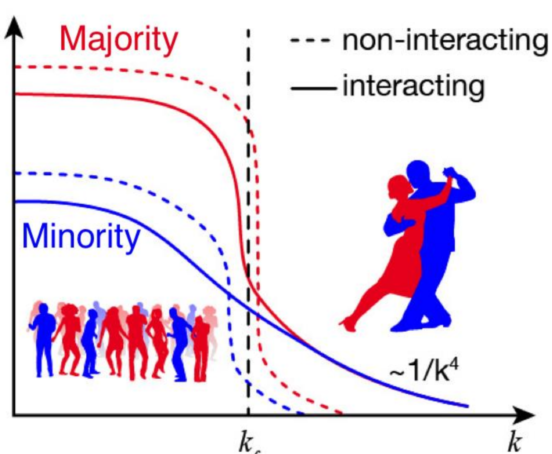


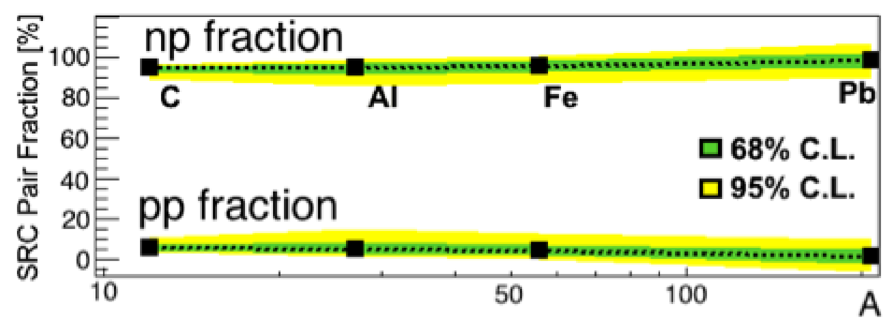




A(e,e')
ratios



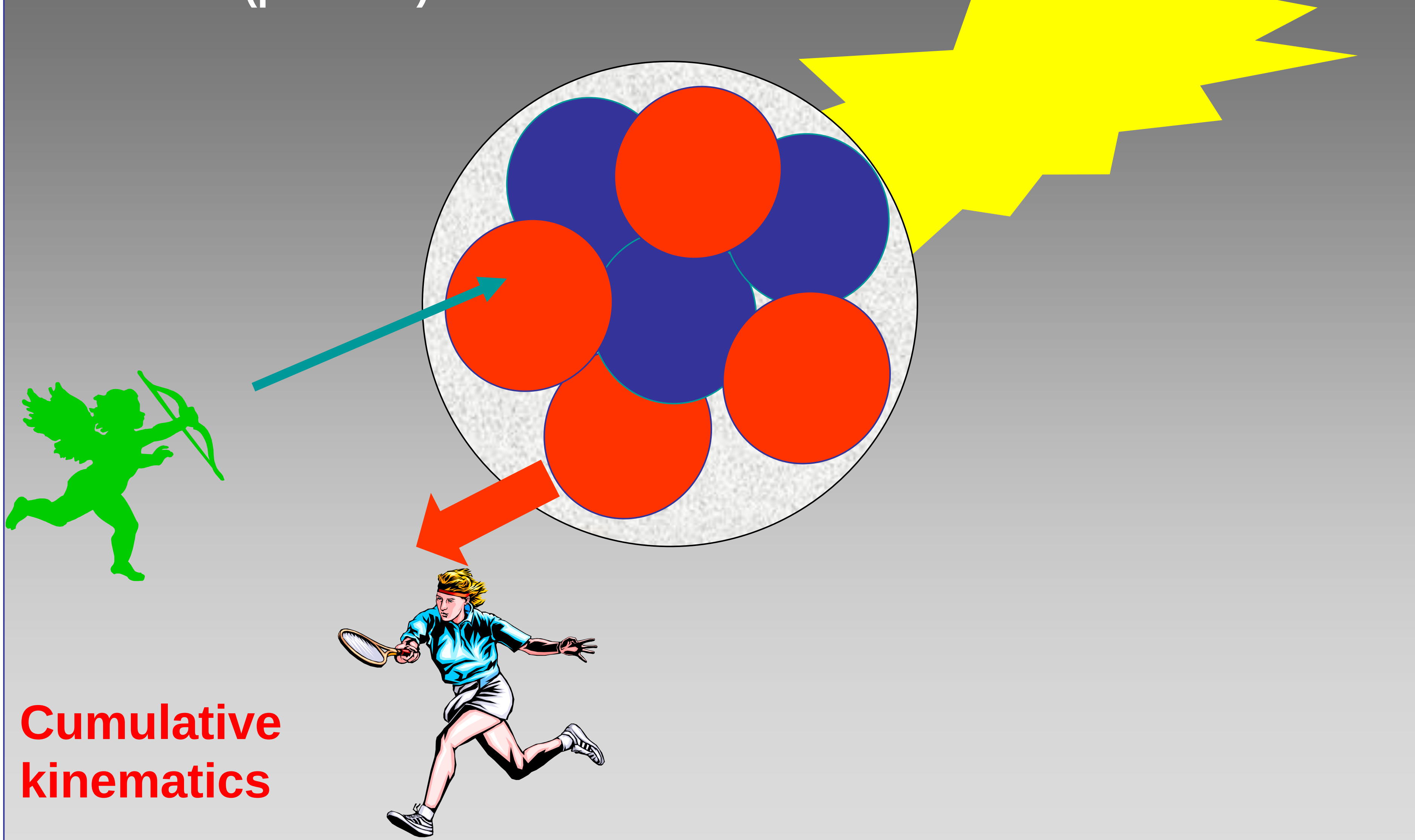




~25% SRC pairs

- ~90% tensor correlated np pairs

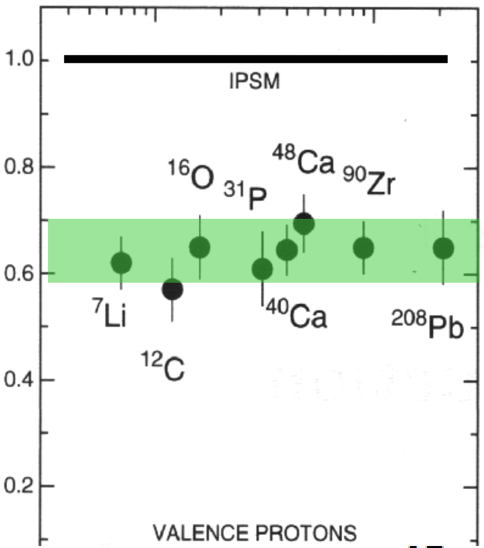
The story of studying cold dense nuclear matter using high energy probes started here (70s) with the measurements of Fast Backward Production at JINR and ITEP Moscow (p,π) and YerPhi (photons) .

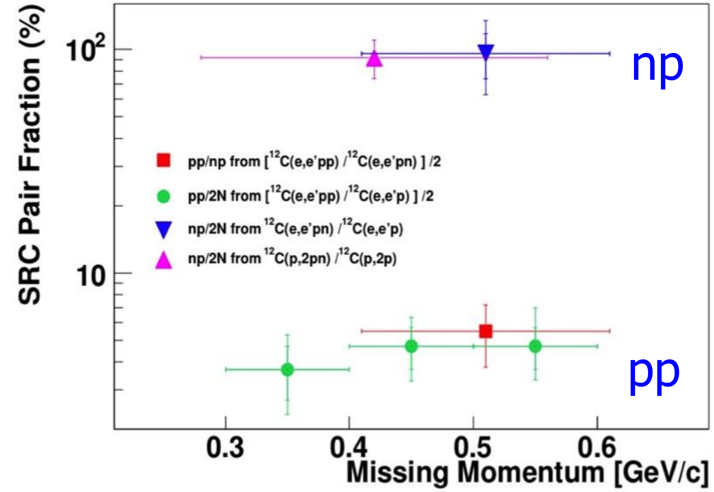


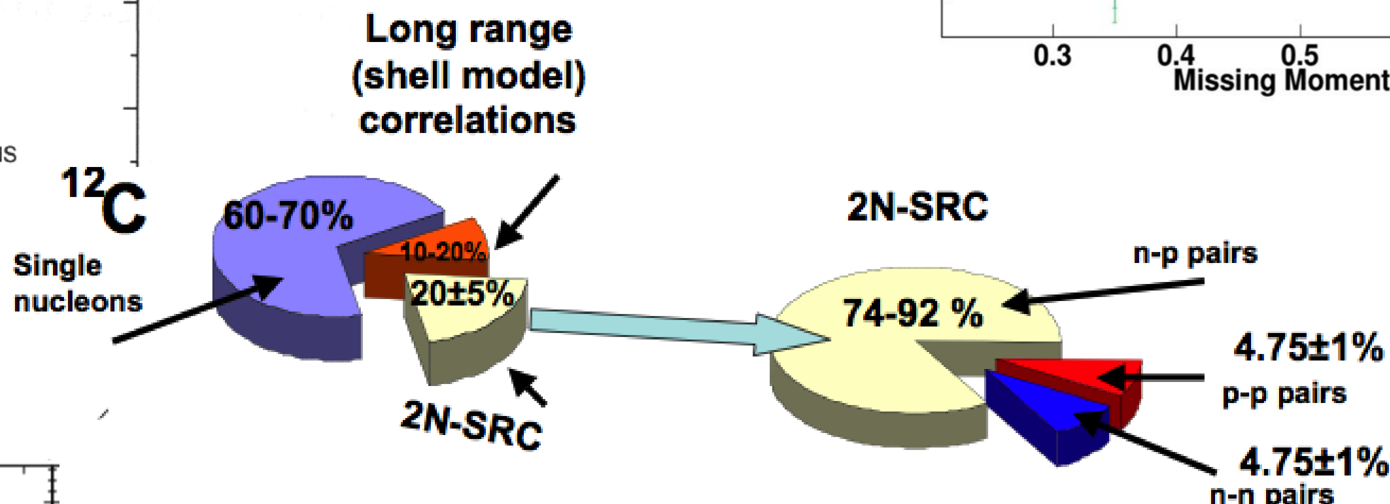
Cumulative kinematics

Summary

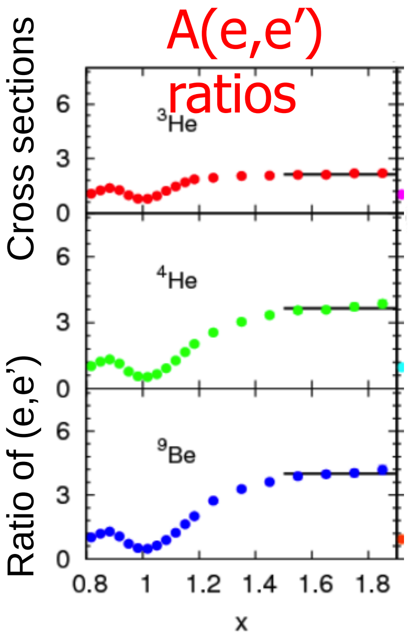
(e,e'p)
Shell
occ

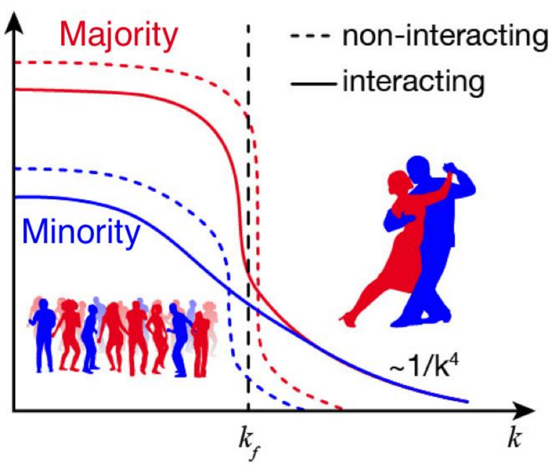


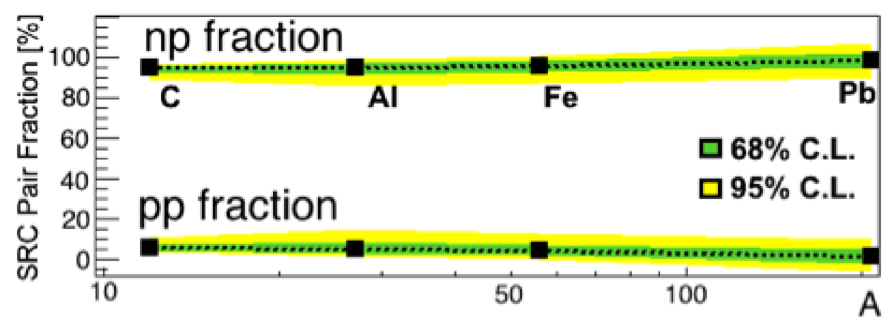




A(e,e')
ratios



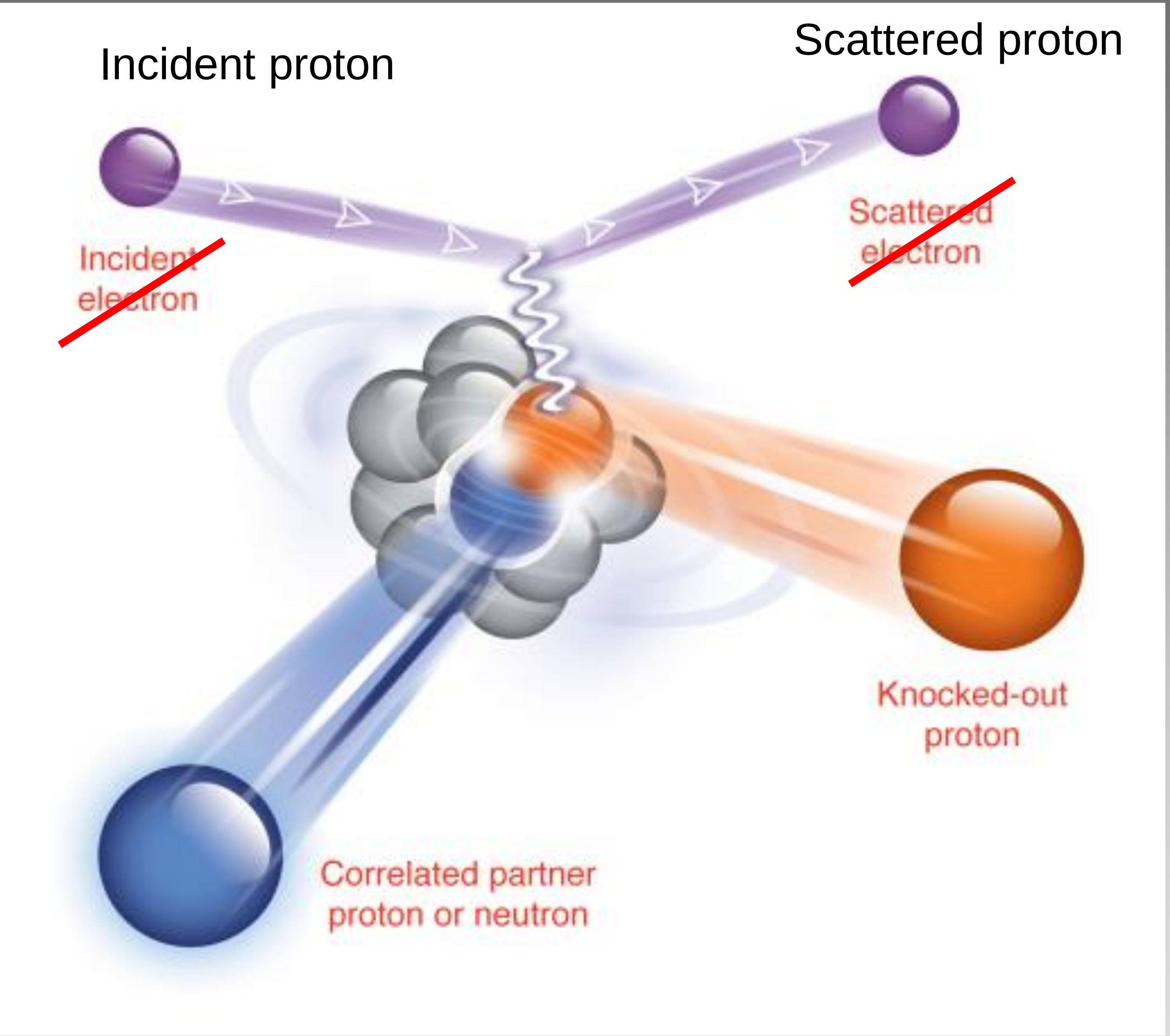




~25% SRC pairs

- ~90% tensor correlated np pairs

Triple coincidence A (p, p p n) measurements complementary to JLab



Complementary to JLab study with electrons

Why H.E. protons are good probes of SRC ?

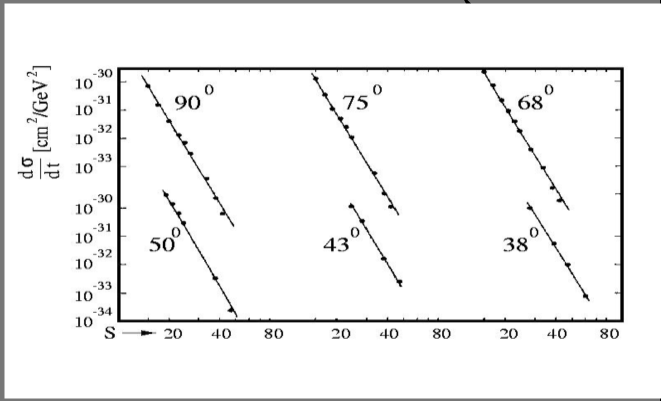
selective attention to SRC

Psychology Wiki

Selective attention. A type of attention which involves focusing on a specific aspect of a scene while ignoring other aspects.

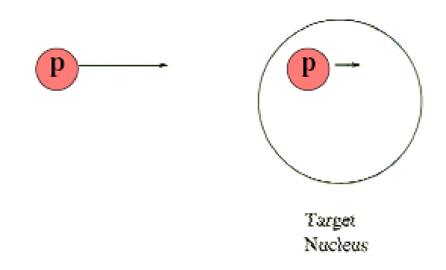
p p → pp elastic scattering near 90^0 c.m

$$\frac{d\sigma}{dt} \propto s^{-10}$$



Constituent Counting Rules

QE pp scattering have a very strong preference for reacting with forward going high momentum nuclear protons



Other reasons Why several GeV and up protons are good probes of SRC ?

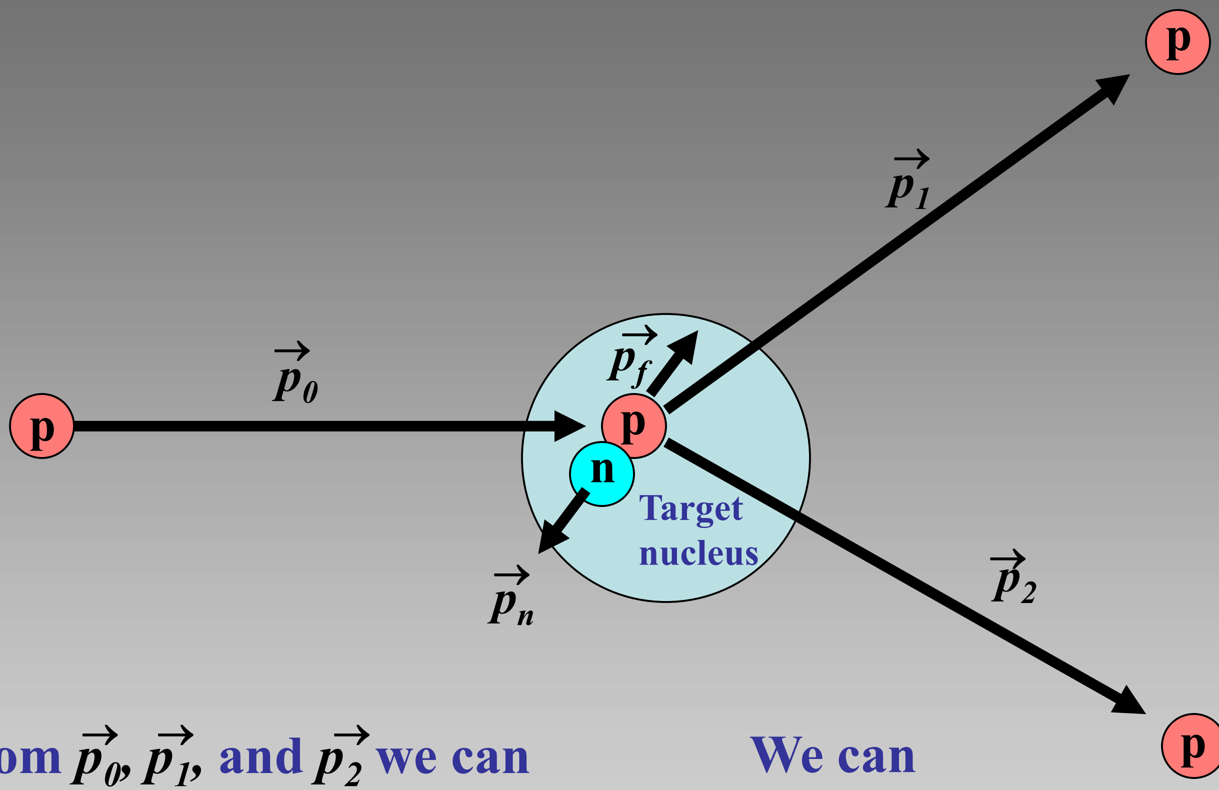
They have Small deBroglie wavelength:

λ = h/p = hc/pc = 2π • 0.197 GeV-fm/(6 GeV) ≈ 0.2 fm.

Large momentum transfer is possible with wide angle scattering

Cross section is large

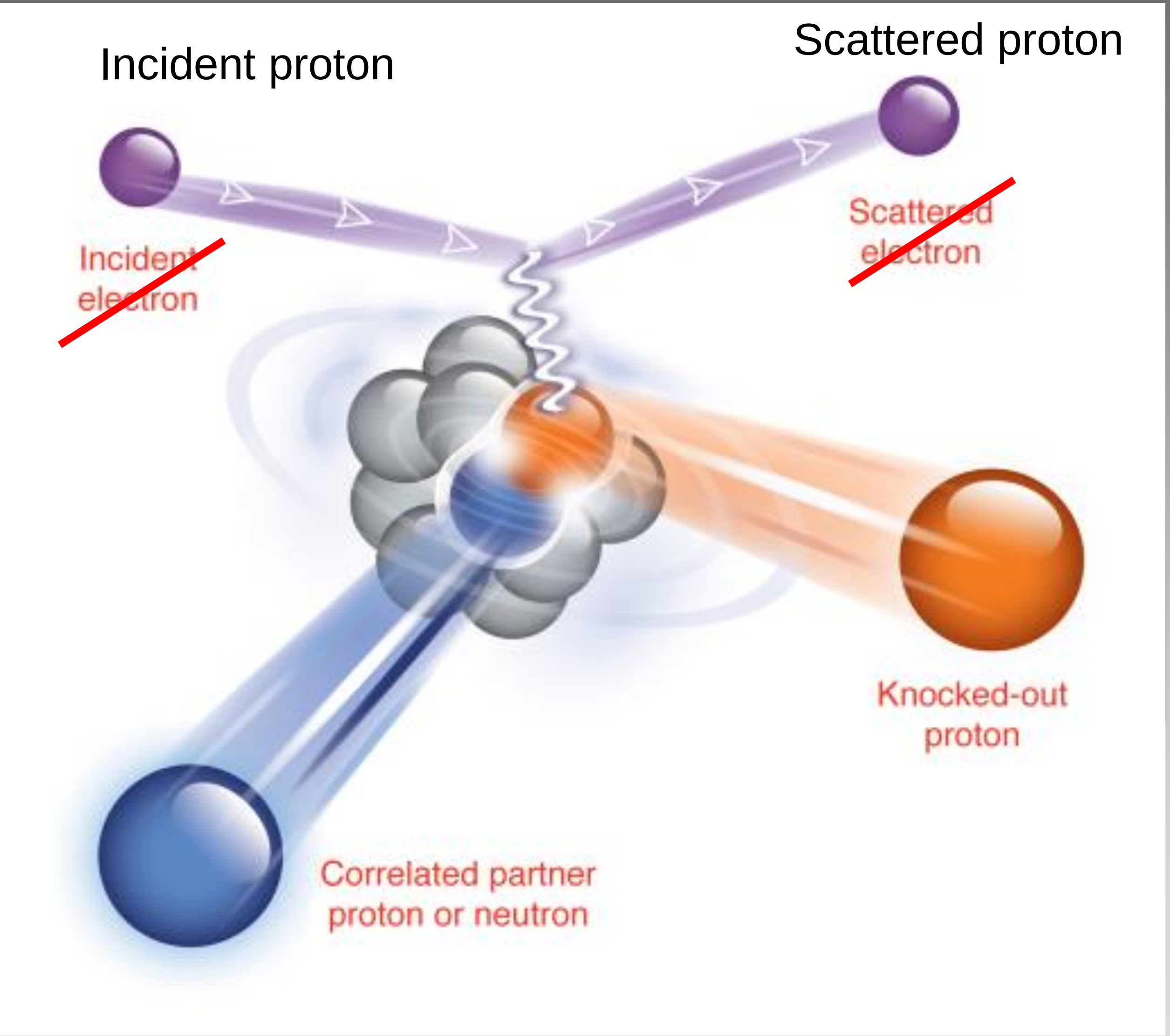
TEL AVIV UNIVERSITY



From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the binding energy of each knocked-out proton is.

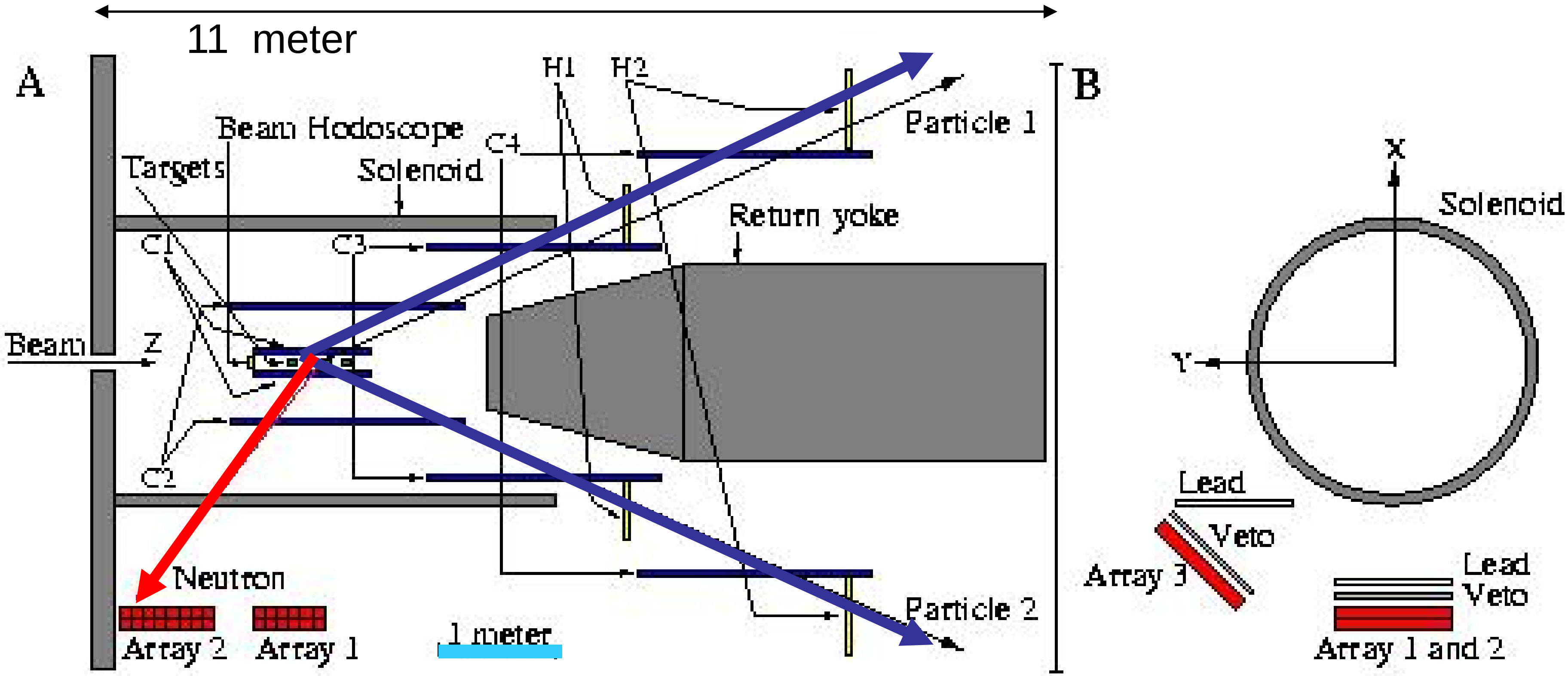
We can then compare $\vec{p}_n$ with $\vec{p}_f$ and see if they are roughly "back to back."

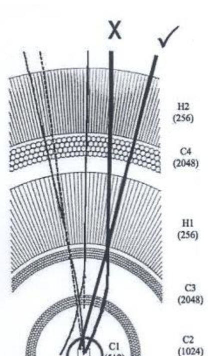
First Triple coincidence ^{12}C (p, p p n) measurements at EVA / BNL

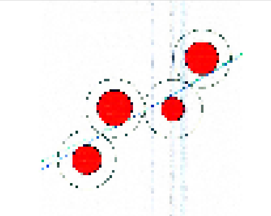


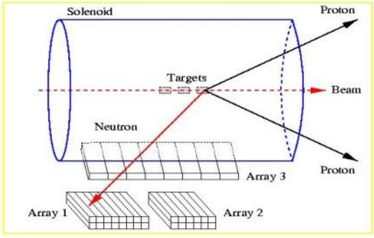
Complementary to JLab study with electrons

The EVA spectrometer and the n-counters at BNL







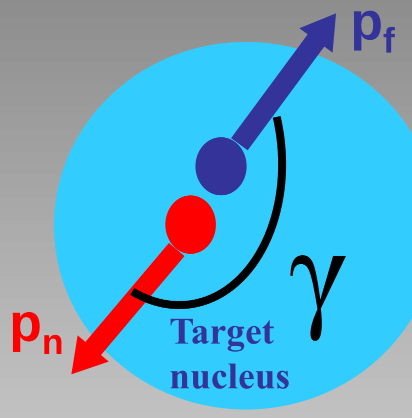


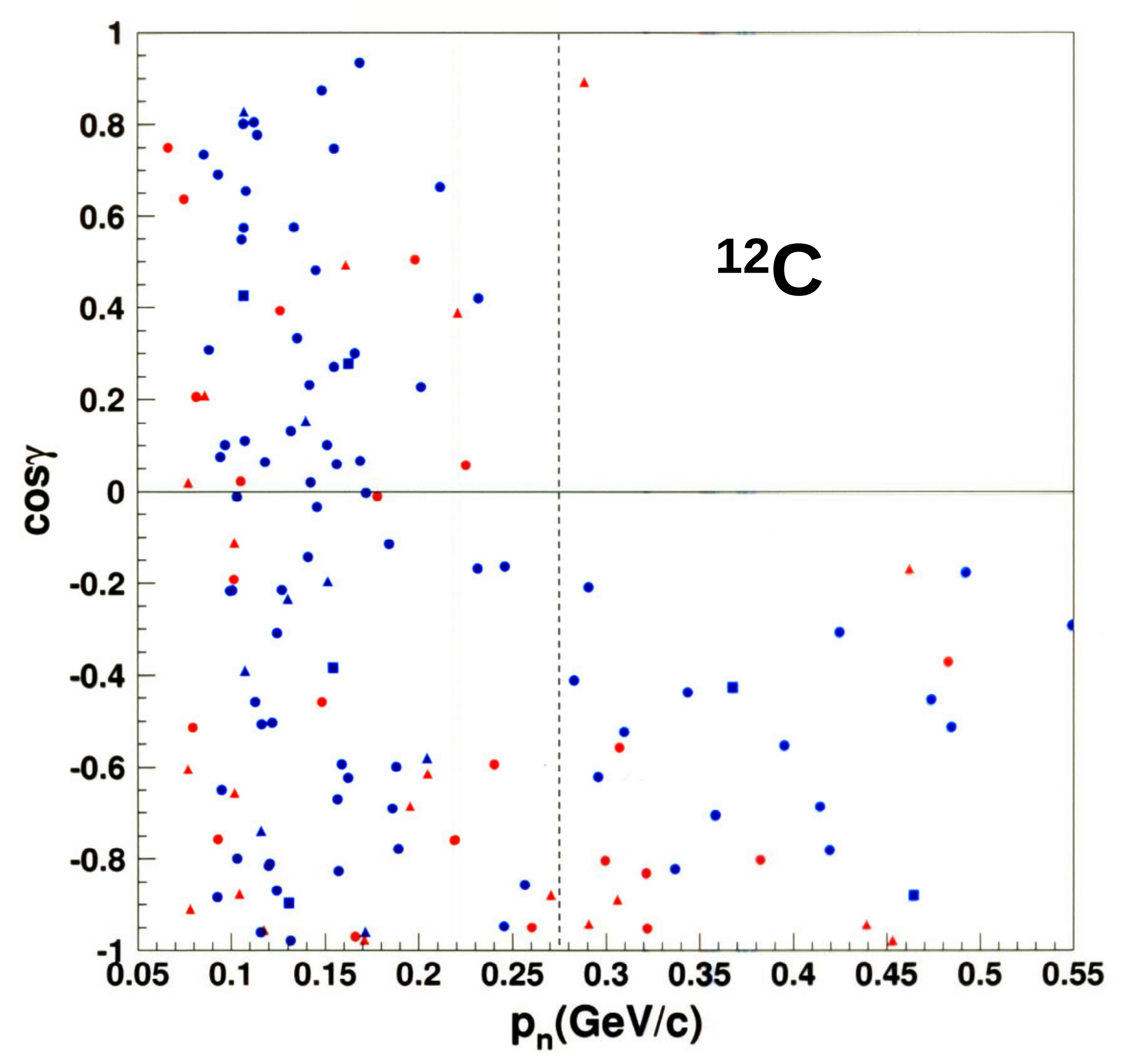
Array 1: total area 0.6×1.0 m², 12 counters, 2 layers 0.125 m

Triple coincidence $^{12}C(p, p\ pn)$ measurements at EVA / BNL

A. Tang et al. Phys. Rev. Lett. 90 ,042301 (2003)

Directional correlation





p_0 – incident proton

p_1 and p_2 are detected

$$\vec{p}_f = \vec{p}_1 + \vec{p}_2 - \vec{p}_0$$

Triple coincidence $^{12}C(p, p\ pn)$ measurements at EVA / BNL

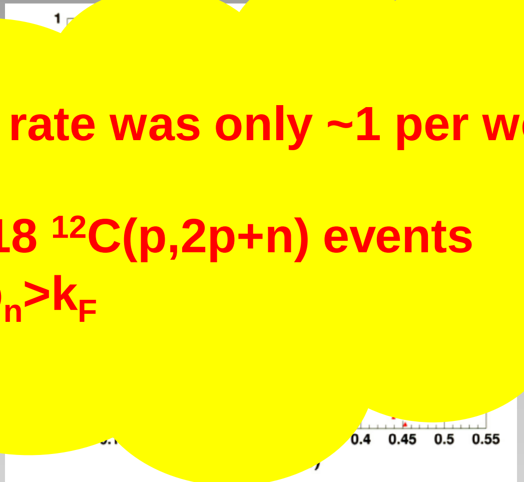
Piasetzky, Sargsian, Frankfurt, Strikman, Watson PRL 162504(2006).

Removal of a proton with momentum above 275 MeV/c from ^{12}C is **$92\pm^{8}_{18}$ %** accompanied by the emission of a neutron with momentum equal and opposite to the missing momentum.

* **2N-SRC dominance**

(74-100% are partners in 2N-SRC).

* **np-SRC dominance**:



count rate was only ~1 per week

Only 18 $^{12}C(p,2p+n)$ events with $p_n > k_F$

Did not observe pp-SRC. Upper limit of 13% for pp-SRC contribution to protons with momentum above 275 MeV/c in ^{12}C.

motion of the pair

The Relative and c.m. Motion of Correlated n-p Pairs:

$$p_z^{cm} = 2m(1 - \frac{\alpha_p + \alpha_n}{2}),$$

$$p_z^{rel} = m|\alpha_p - \alpha_n|.$$

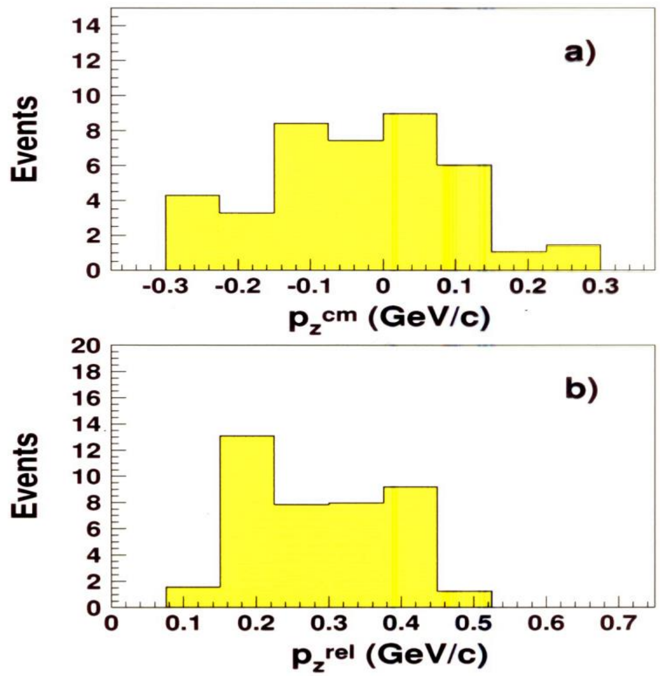


Figure 23: Plots of (a) p_z^{cm} and (b) p_z^{rel} for correlated n-p pairs in ^{12}C, for $^{12}C(p,2p{+}n)$ events. Each event has been "s-weighted".

$^{12}C(p,2pn)$ at BNL

$\sigma_{CM}=0.143\pm0.017$ GeV/c

A. Tang et al. Phys. Rev. Lett. 90 ,042301 (2003)

Theoretical prediction (Ciofi and Simula) : $\sigma_{CM}=0.139$ GeV/c PRC 53 (1996) 1689.

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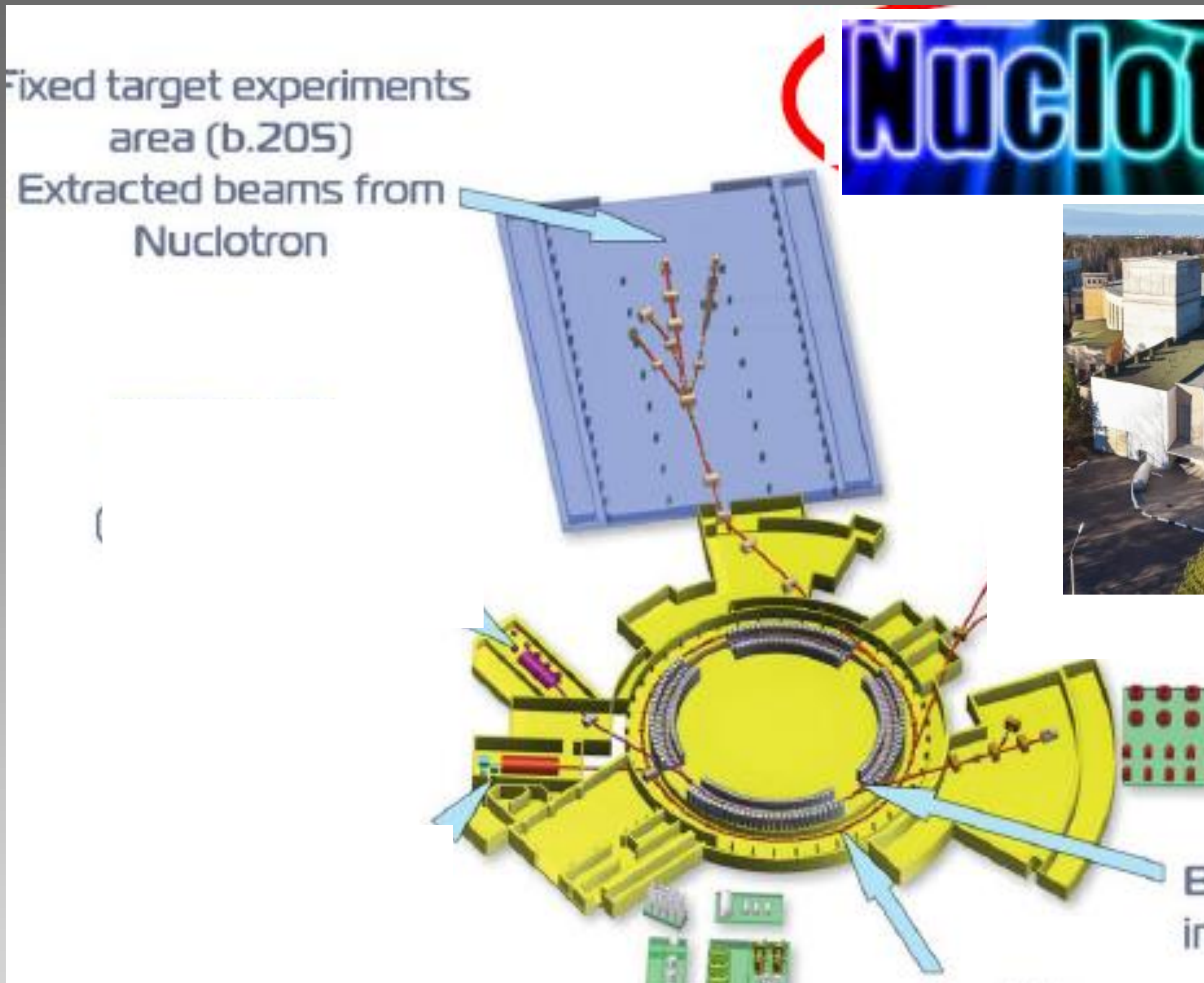
Study of SRC at JINR



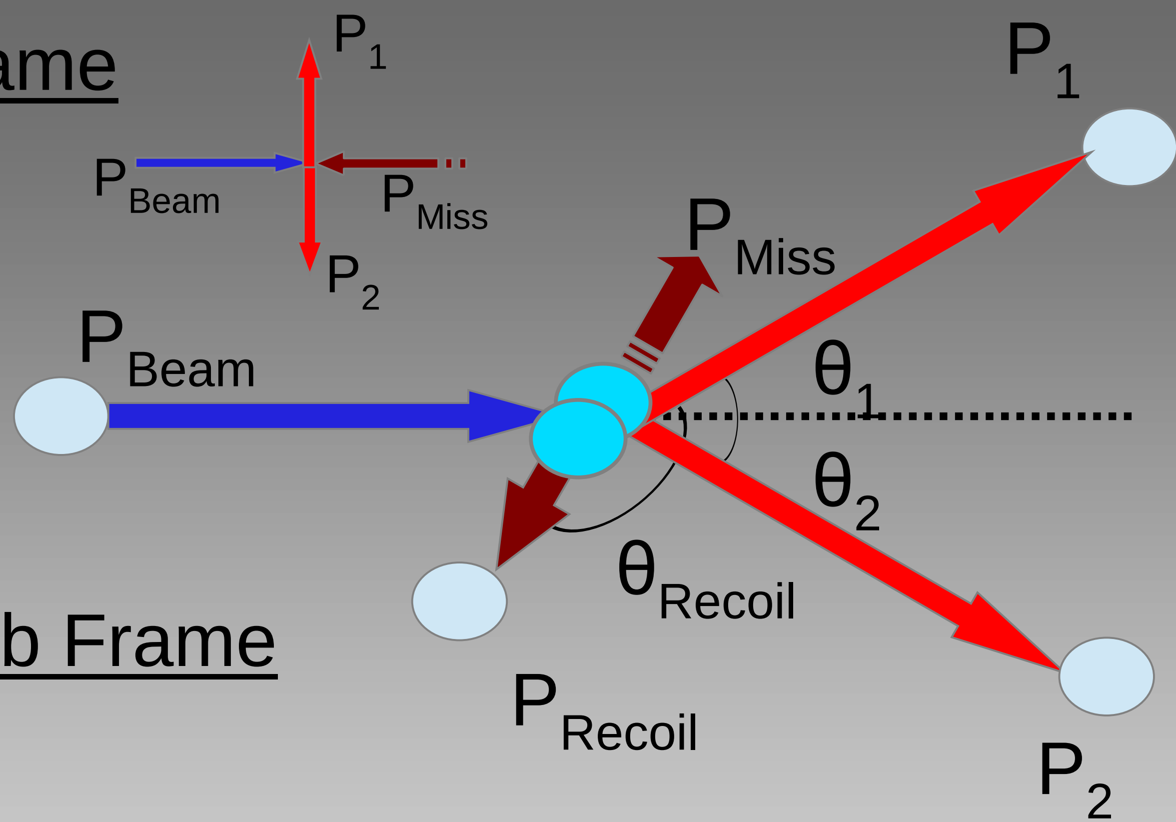
Nuclotron

Beam	Nuclotron beam intensity (particle per cycle)		
	Current	Ion source type	New ion source + booster
p	$3 \cdot 10^{10}$	Duoplasmotron	$5 \cdot 10^{12}$

•Selecting events

C.M. Frame

Lab Frame



•SRC dominance

$$|p_{recoil}| \geq 250 MeV/c$$

$$\theta_{recoil} \geq 90^0$$

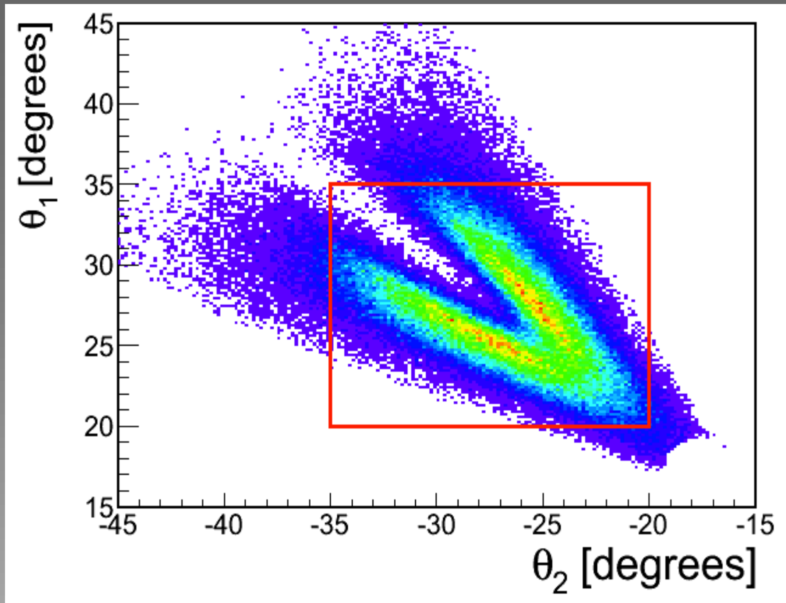
•Hard process

$$-t = -(p1 - p3)^2 > 2(GeV/c)^2$$

$$-u = -(p1 - p2)^2 > 2(GeV/.c)^2$$

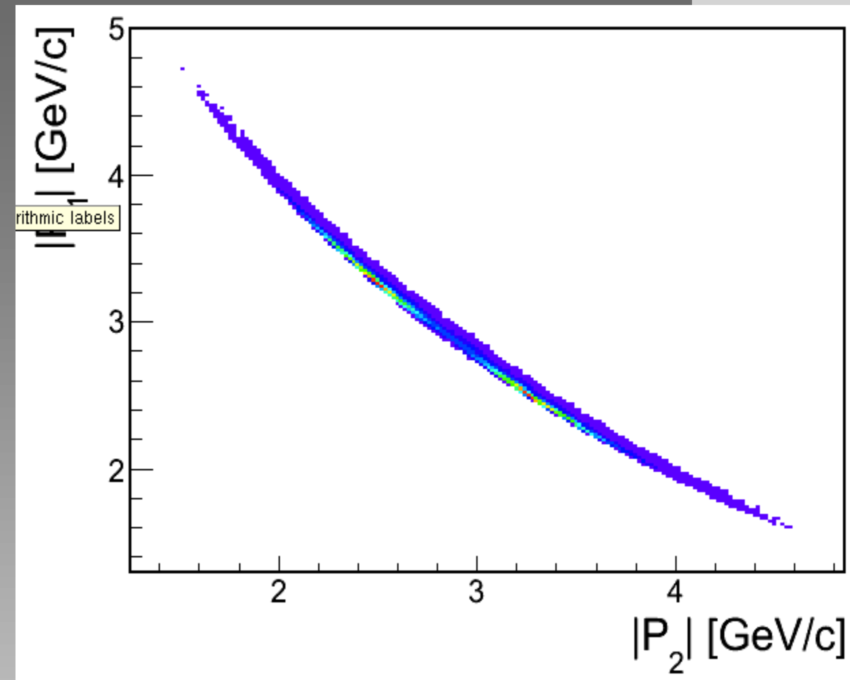
$$s > 7(GeV/c)^2$$

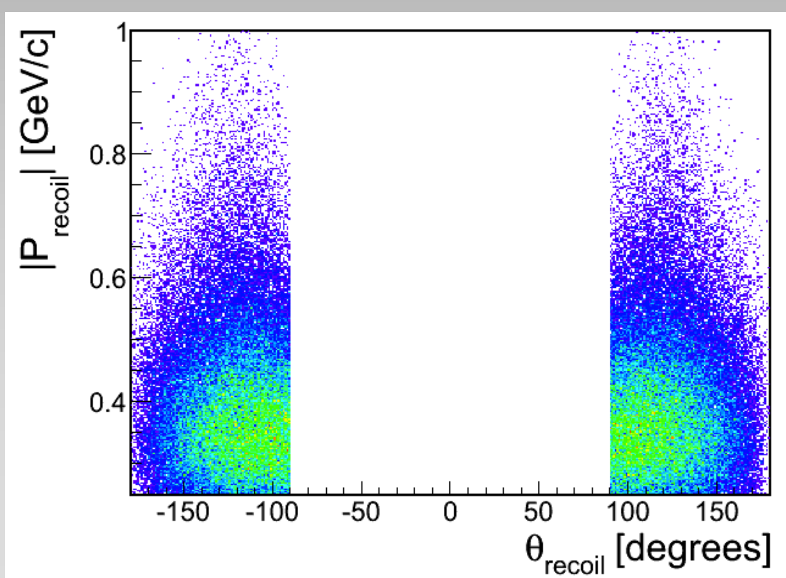
$$\theta_1 = 27.5^0 \pm 7.5^0, \theta_2 = -27.5^0 \pm 7.5^0 \quad (\vartheta_{cm} \approx 90^0)$$



simulated 90^0 cm scattering off a SRC pair

$$\theta_1 = 27.5^0 \pm 7.5^0, \theta_2 = -27.5^0 \pm 7.5^0$$

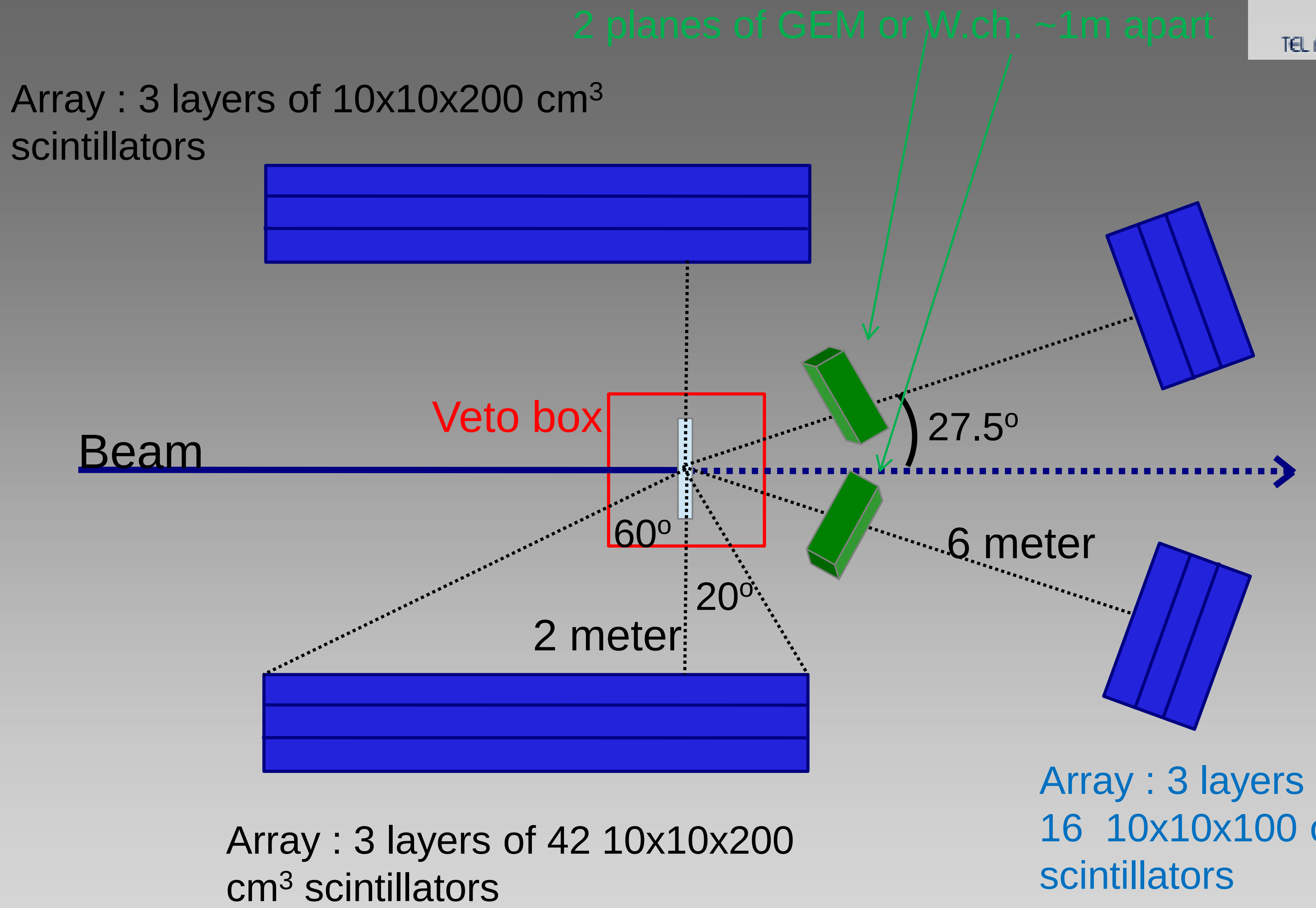




Simulated θ_{cm}~90^0 scattering of a pair

$$\sigma_{cm} = 140 MeV/c$$

$$n(p_{rel}) = e^{-7 p_{rel}}$$ $0.25 < P_{rel} < 1$ GeV/c



'start' signal for TOF ?

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The CLAS12 Scintillator Setup

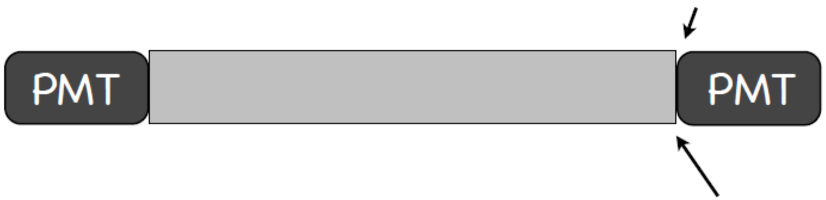
Scintillators:

BC-404; 6 cm x 6 cm x (50 - 200) cm and

BC-408 for the longer bars

PMT: Hamamatsu ~~R9779~~ R13089

(2) No Light guides
PMT directly glued to SC



(3) Scintillator wrapped in **Aluminized Mylar**

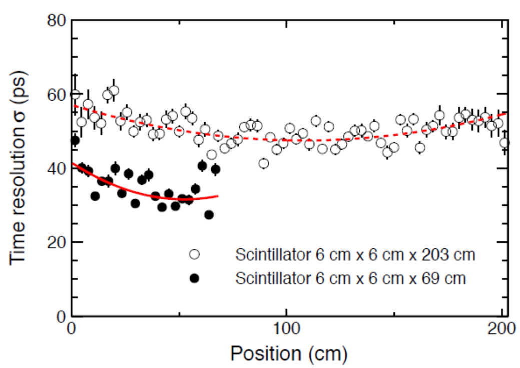
(4) Light tight **DuPont Tedlar** encases entire counter

(1) Corners masked with black tape

Approximate Cost

- The average scintillator costs for the JLab project was about **$600** per scintillator. This is the per scintillator cost for the FTOF project with an average scintillator length of 2 m.
- The cost for the Hamamatsu PMT is about **$800** per PMT.

Achieved Time Resolutions



- Time resolution after calibration, event selection, time-walk correction:

– σ_{avg} = 51 ps for 203-cm bar

– σ_{avg} = 34 ps for 69-cm bar

R. Gothe and Y. Tian, private communication.

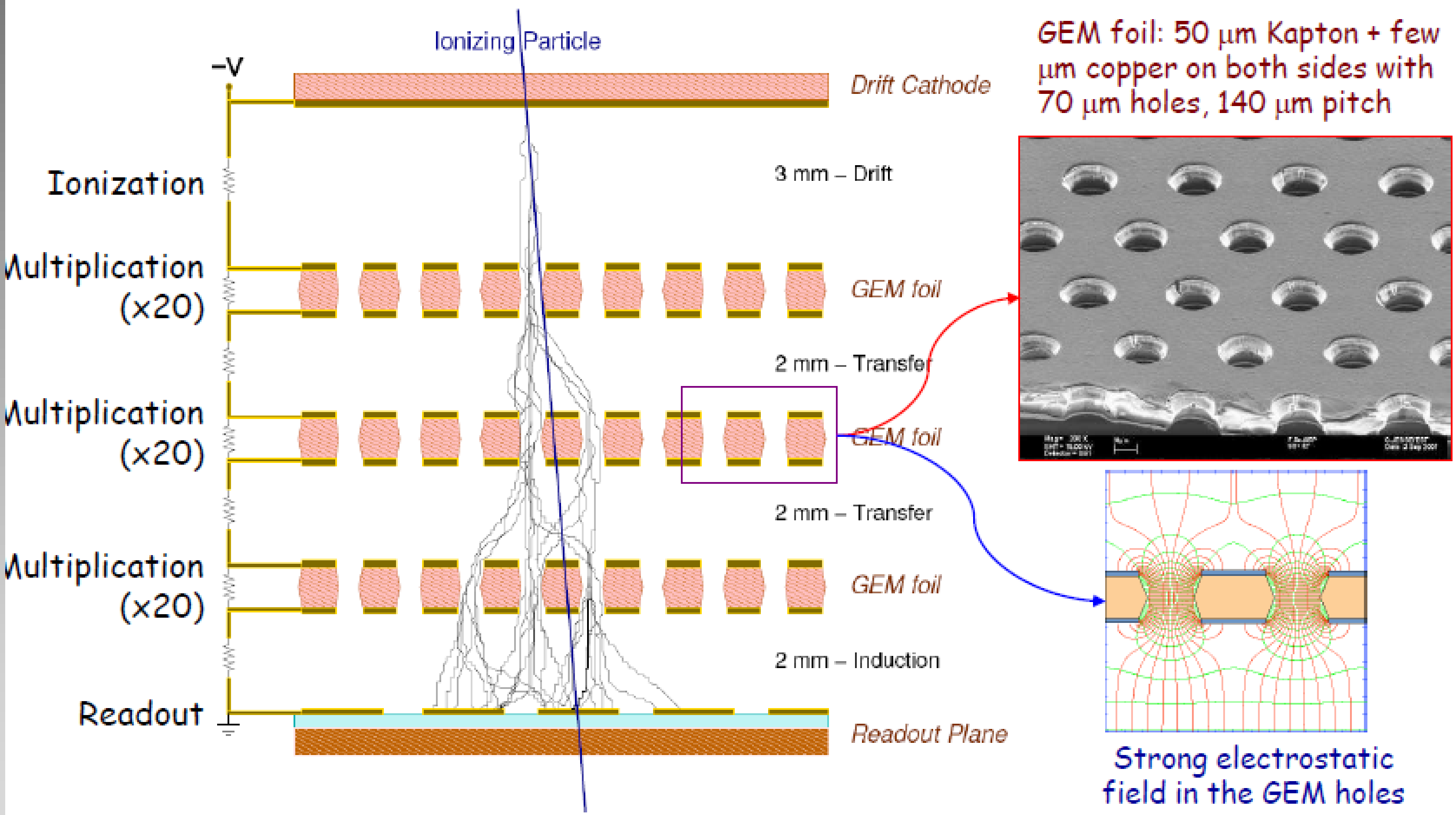
Total 96 1m long and 252 2m long
(350 counters are needed

PMs 700x800$=550k$
Sci (96+2x252)x600=360k$
~1M$

Adapted from a talk by Steffen Strauch
University of South Carolina

GEM = Gas Electron Multiplier

GEM working principle



Recent technology: F. Sauli, Nucl. Instrum. Methods A386(1997)531

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Rates - (For a 10^9 protons/sec beam)

Triple coincidence $^{12}C(p,2pn)$ **np pairs**

100 events/hour

In 30 days (50% beam availability) 35,000 events

Triple coincidence $^{12}C(p,pnn)$ **nn pairs**

2 events/hour

In 30 days (50% beam availability) 700 events

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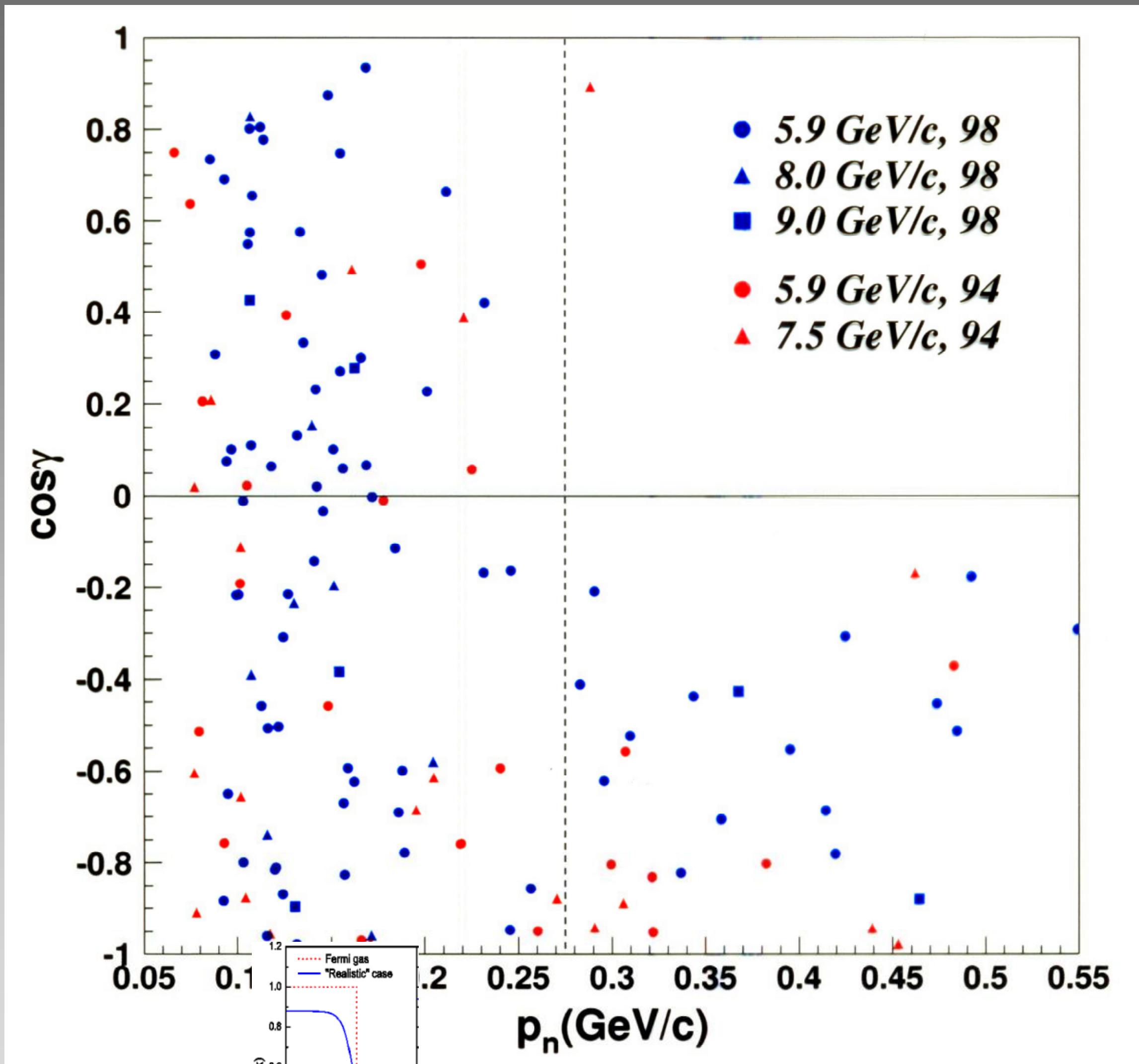
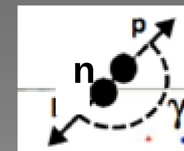
Mapping the transition from mean field to SRC





EVA / BNL:

Only 18 $^{12}C(p,2p+n)$ events with $p_n > k_F$

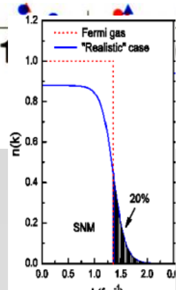
Nuclotron

Expecting 35,000 $^{12}C(p,2p+n)$ events with $p_n > k_F$

With 100ps TOF resolution:

$$\Delta p_{miss} \approx 15 MeV / c$$

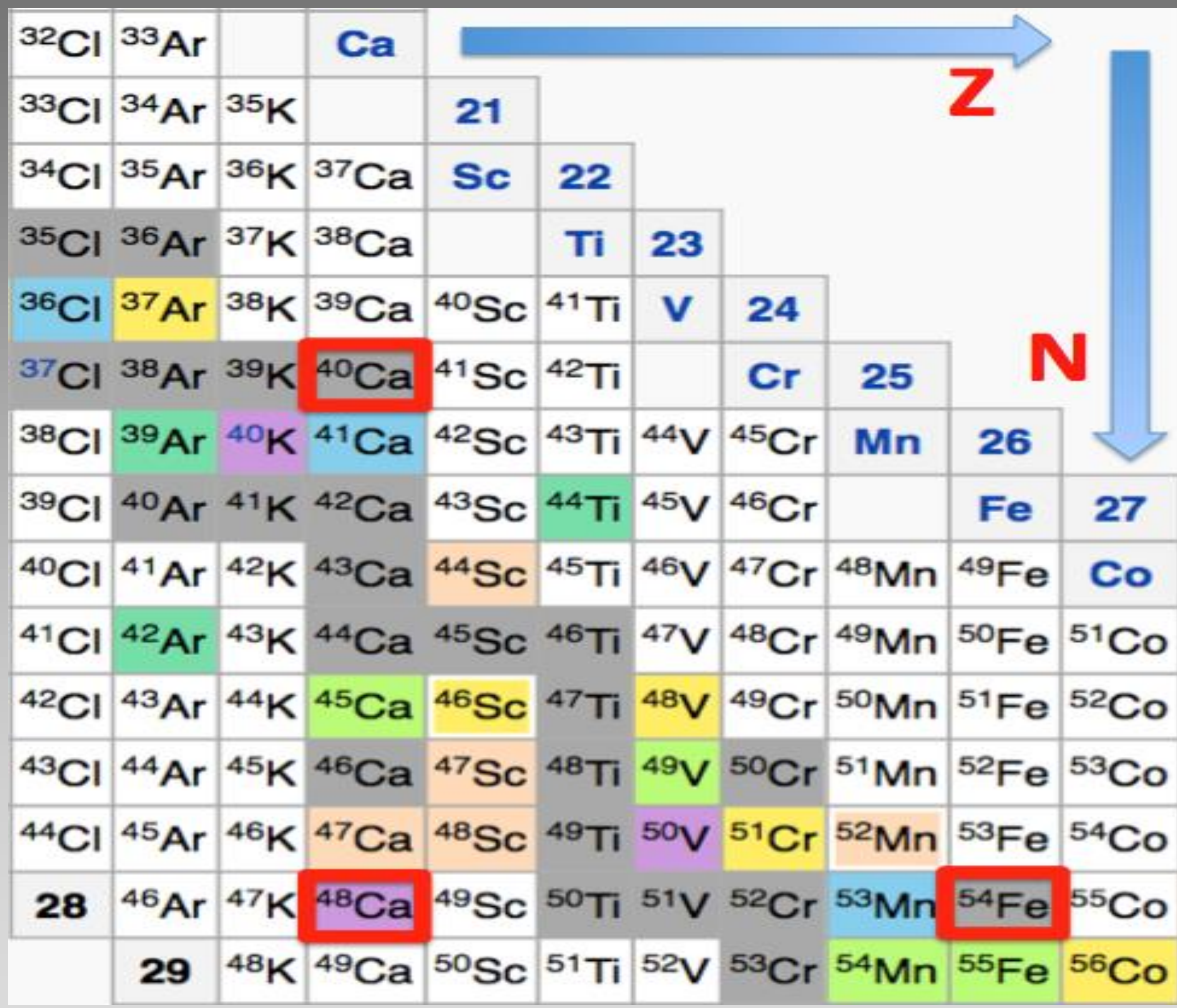
Migdal jump



Asymmetric nuclei N>Z:
Who are the parents of the 2N-SRC pairs ?

Z=20
N=20

Add 8 f7/2 neutrons

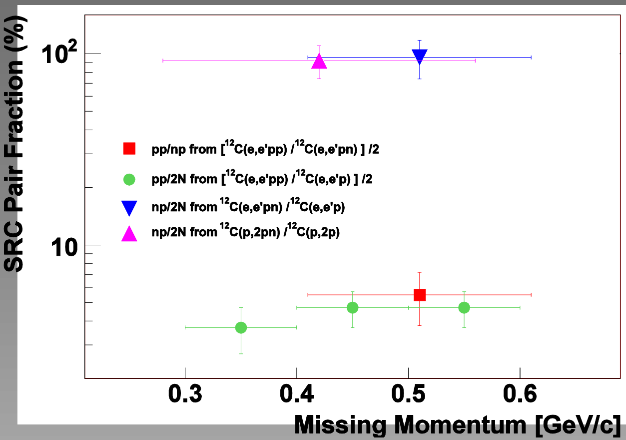


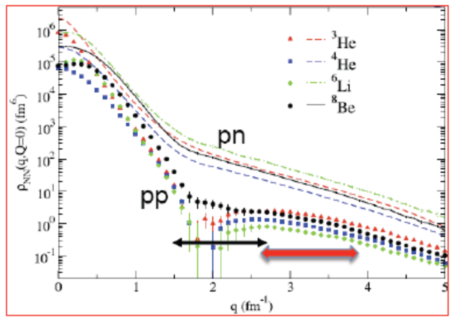
Z=20
N=28

Add 8 protons

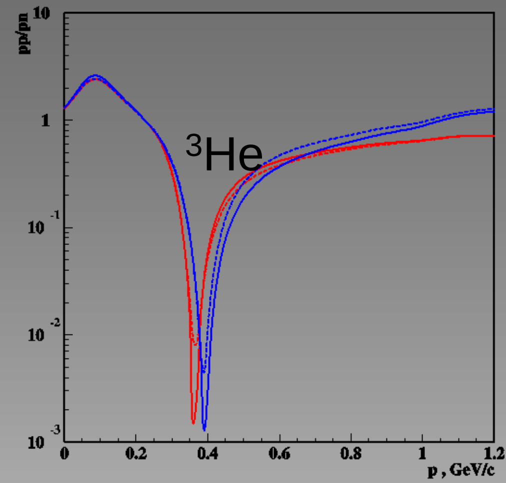
Z=26
N=28

SRC Isospin Structure and the Tensor Force





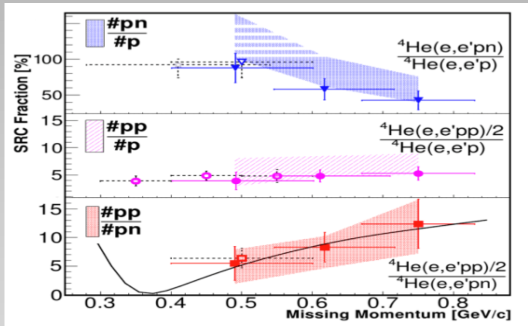
R. Schiavilla, R. B. Wiringa, S. C. Pieper, J. Carlson, Phys. Rev. Lett. **98** (2007) 132501



At 400-600 MeV/c.

np SRC is ~18 times pp (nn) SRC!!!

Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005).



I. Korover, et al. Phys. Rev. Lett 113, 022501 (2014).

. **At Nuclotron we propose :**
First measurement below 400 MeV/c
Better statistics above 600 MeV/c

C.M. and Relative Momenta Distributions:

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The Relative and c.m. Motion of Correlated n-p Pairs:

$$p_z^{cm} = 2m(1 - \frac{\alpha_p + \alpha_n}{2}),$$

$$p_z^{rel} = m|\alpha_p - \alpha_n|.$$

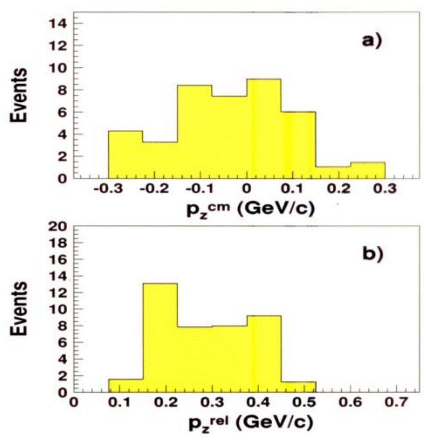


Figure 23: Plots of (a) p_z^{cm} and (b) p_z^{rel} for correlated n-p pairs in ^{12}C, for $^{12}C(p,2p+n)$ events. Each event has been "s-weighted".

EVA / BNL:
Only 18 $^{12}C(p,2p+n)$ events with $p_n>k_F$

Nuclotron

Expecting 35,000 $^{12}C(p,2p+n)$ events with $p_n>k_F$

~1000 $^{12}C(p,np+n)$ events with $p_n>k_F$

Can compare nn-SRC to np-SRC

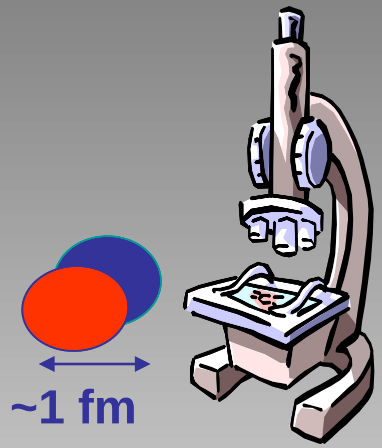
Reaction Mechanism

Hard processes

high energy and large momentum-transfer

Important practical question:

How low in t, u, Q2 … can we still use the advantages of hard scattering ?



Questions for Next Generation

Properties of SRC Pairs

Quantum numbers?
Central vs. tensor correlations?
Mean-field to SRC transition (Migdal jump)?
c.m. and relative motion?
Nuclei far from stability?

Structure of SRC nucleons

Structure of SRC nucleons?
Explaining the EMC effect?

Imbalanced systems

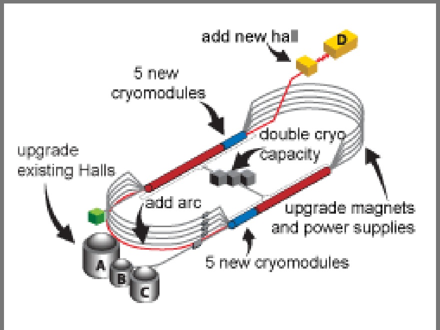
Minority move faster?
Minority have larger pairing probability?
Dynamics of pairing with symmetry?

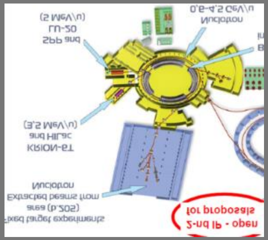
Connection of SRC to…

Neutrino-nucleus interactions?
Neutron stars structure and cooling rate?
Universality of contact interactions?
Atomic traps studies of asymmetric systems?
Fluctons

The new facilities:

12 GeV JLab



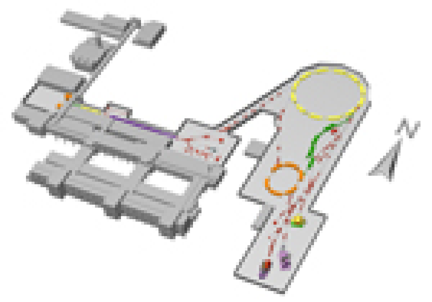


NICA

Nuclotron ->NICA

JINR, Dubna

J-PARC
Japan Proton Acce



GSI ->FAIR

CSR, Lanzhou ?

Acknowledgment

We would like to thank
A. Sorin for the invitation.

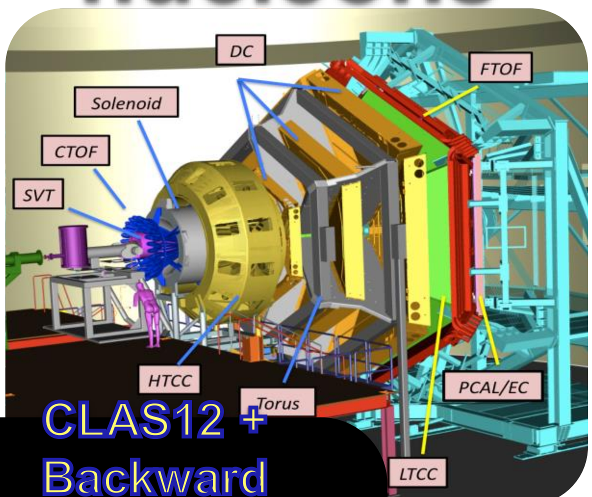
We will be here Thu /Fri and hope to come back with
a proposal to study 2N - SRC @ Dubna

Questions for Next Generation

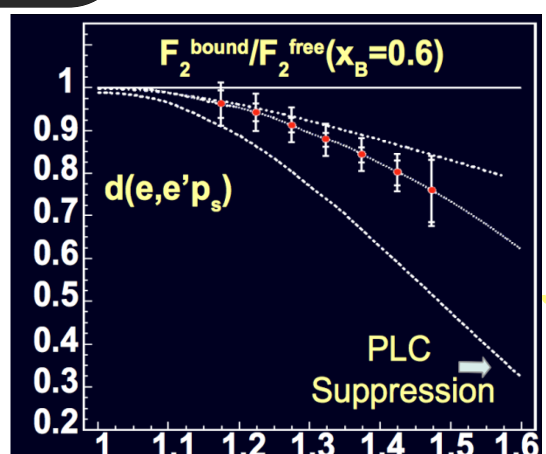
Structure of SRC nucleons

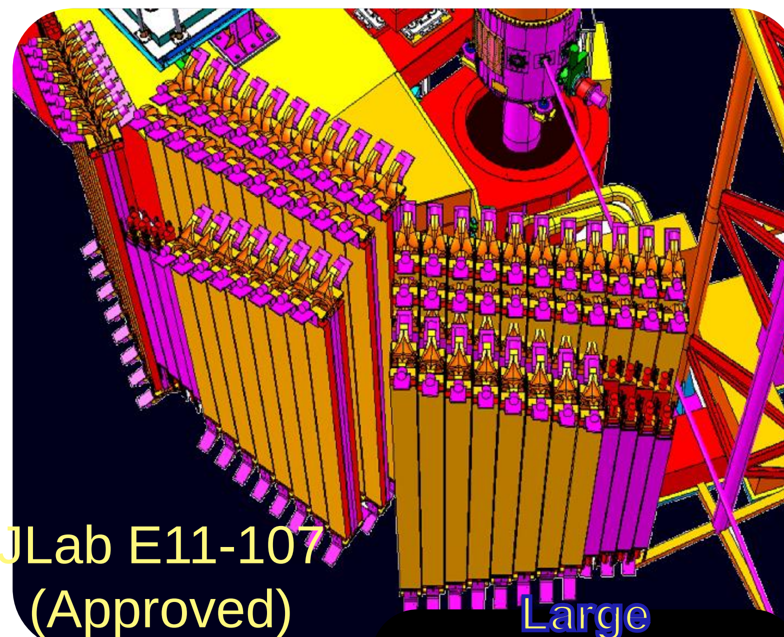
Tagged structure function measurements allows accessing the internal structure functions of SRC nucleons. [JLab 12GeV / EIC]

Structure of SRC nucleons?
Proton vs. neutron modification?
Explaining the EMC effect?



CLAS12 + Backward Neutron Detector (BND)





JLab E11-107 (Approved)

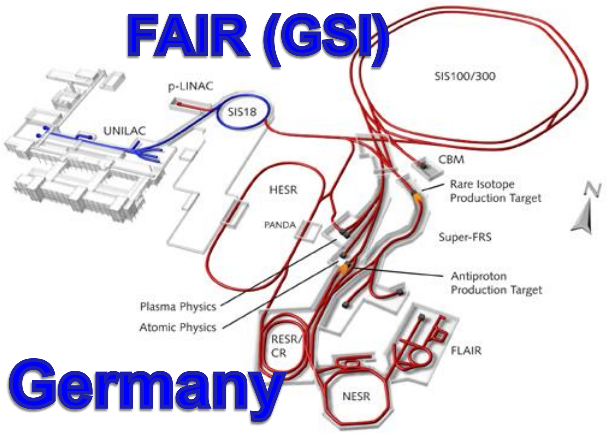
Large Acceptance Detector (LAD)

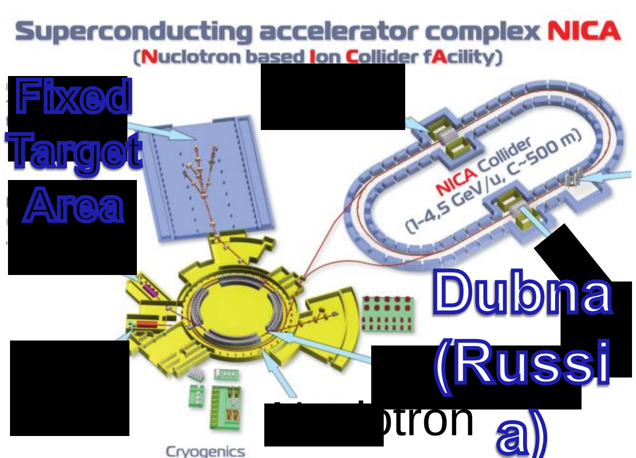
Questions for Next Generation

Properties of SRC Pairs

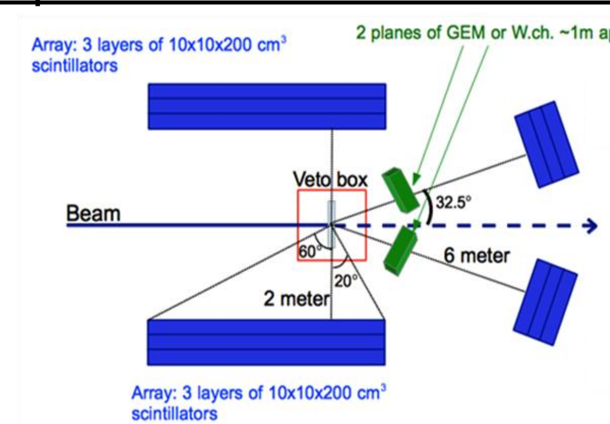
New high-intensity, few-GeV, Hadron beams allow high-statistics exclusive 2N-SRC measurements. [GSI / Dubna / Lanzhou]

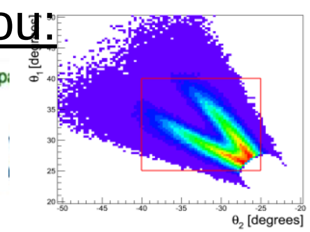
Quantum numbers?
Central vs. tensor correlations?
Mean-field to SRC transition (Migdal jump)?
c.m. and relative motion?
Nuclei far from stability? (FRIB)

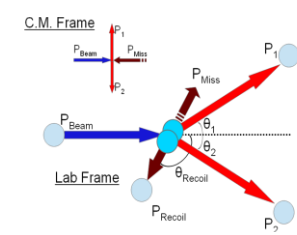




<u>Proposal submitted to Lanzhou:</u>



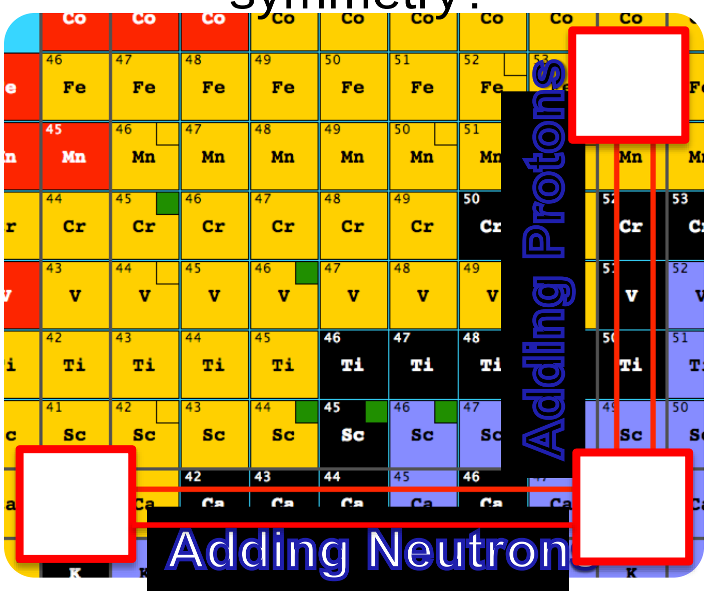




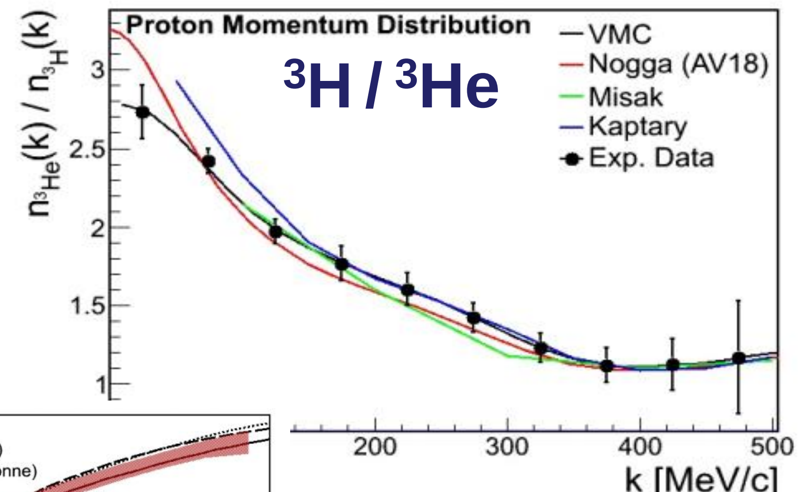
Questions for Next Generation

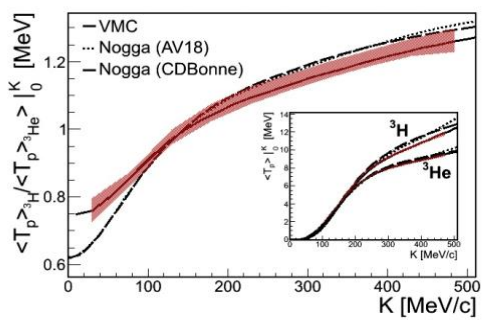
Imbalanced Systems

Minority move faster?
Minority have larger pairing probability?
Dynamics of pairing with symmetry?



New targets (e.g ^{3}H, ^{48}Ca) allow studying the momentum distribution of protons and neutrons and Isospin dynamics of SRC with change of nuclear asymm





JLab E14-011 (Approved)

Acknowledgment

EVA collaboration **/ BNL**

A. Carroll, S. Heppelman, J. Alster,

B. J. Aclander, A. Malki, A. Tang

Exp 01 – 015 collaboration **Hall A / JLab**

S. Gilad , S. Wood, J. Watson, W. Bertozzi,
D. Higinbotham, R. Shneor, P. Monaghan, R. Subedi

Exp 07 – 006 collaboration **Hall A / JLab**

O. Hen, I. Korover, M. Navaphon

Hall B/JLab K. Egiyan‡
L. Weinstien Or Hen

M. Sargsian, L. Frankfurt, M. Strikman:
For their theoretical support and guidance.

Number of hard Triple coincidence events (World data)

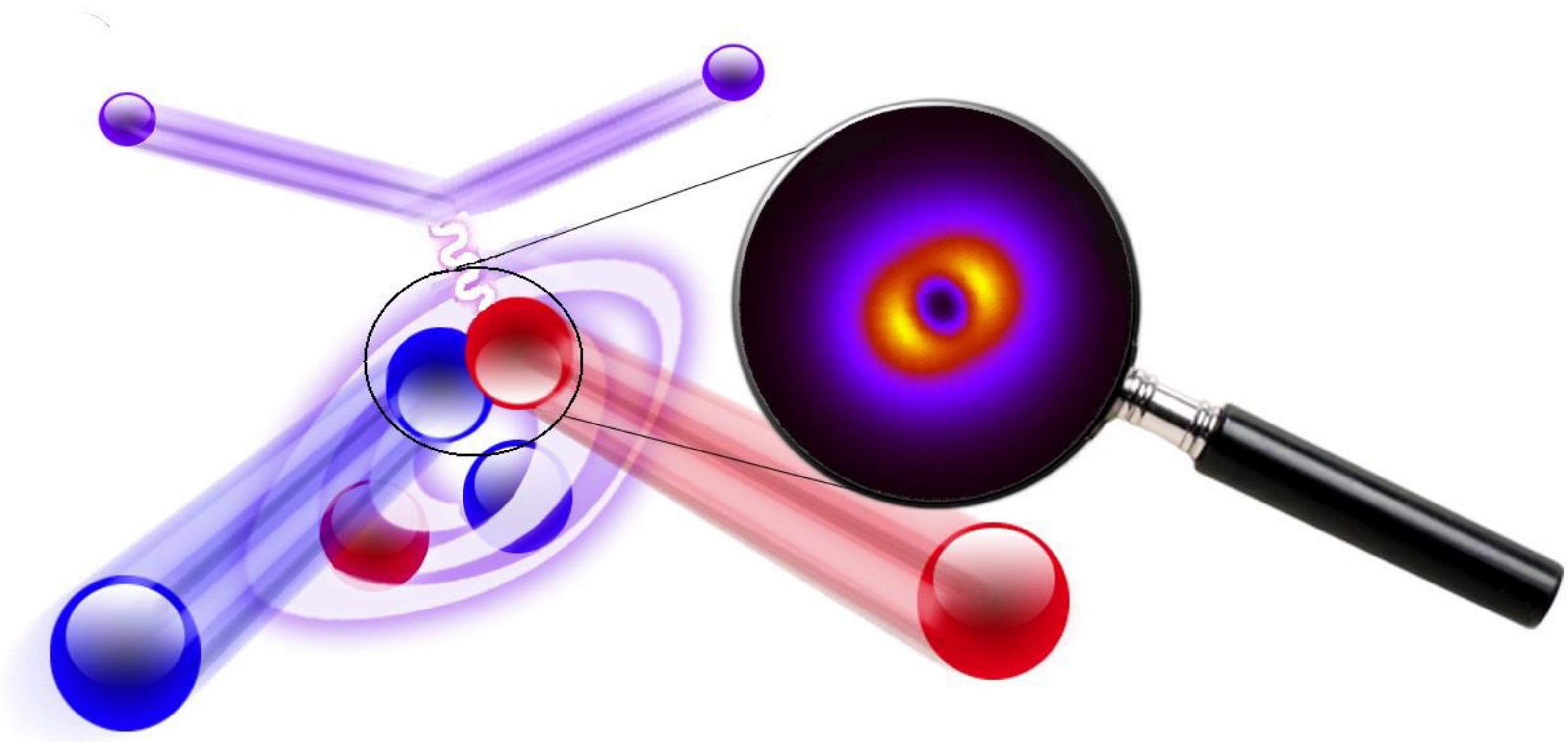
experiment	pp pairs	np pairs	nn pairs
EVA/BNL	-	<30	-
E01-015/JLab	263	179	-
E07-006/JLab	50	223	-
CLAS/JLab	1600	-	-
Total	<2000	<450	0

Why are we here ?

NICA

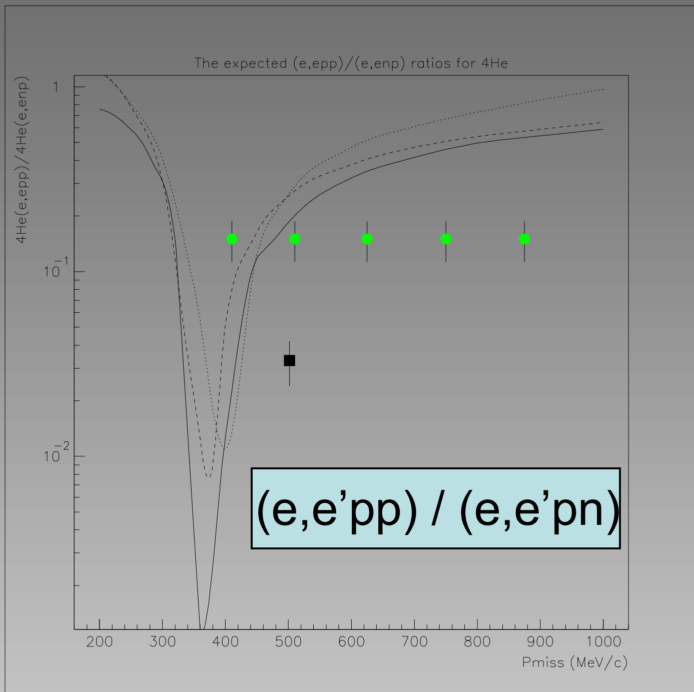
➔ **>10k events**

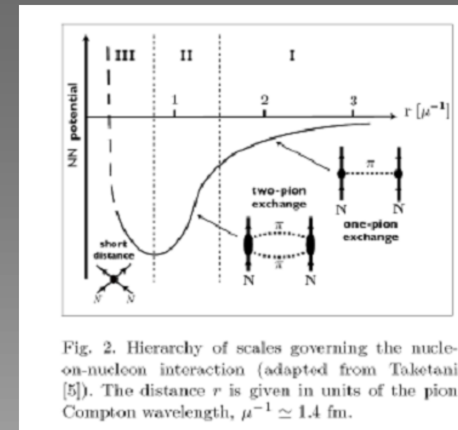
5GeV 10^9 protons/sec



A new experiment scheduled to run 2011 at JLab (E 07-006)

Measurement over missing momentum range from 400 to 875 MeV/c.





QMC

(Thomas)

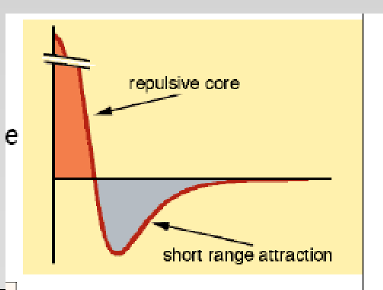
Taketani, Nakamura, Saaki
Prog. Theor. Phys. 6 (1951) 581.

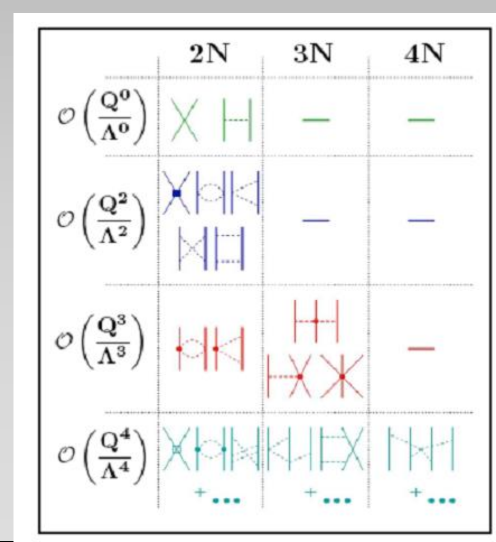
Chiral effective field

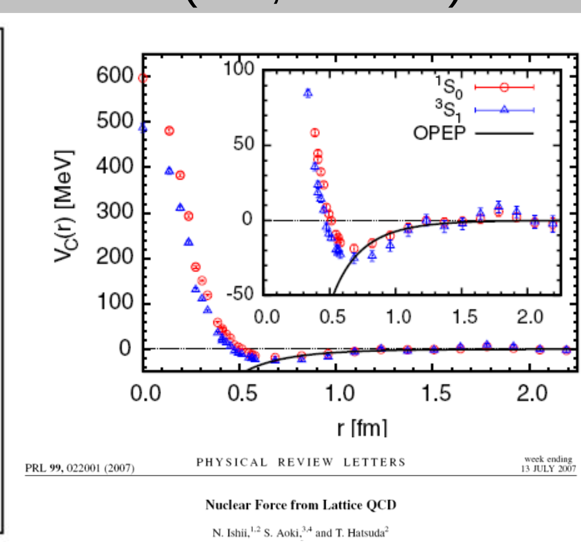
(Machleidt)

Lattice QCD
(Doi, Beane)

The data are expected to be sensitive to the NN tensor force and the NN short range repulsive force.







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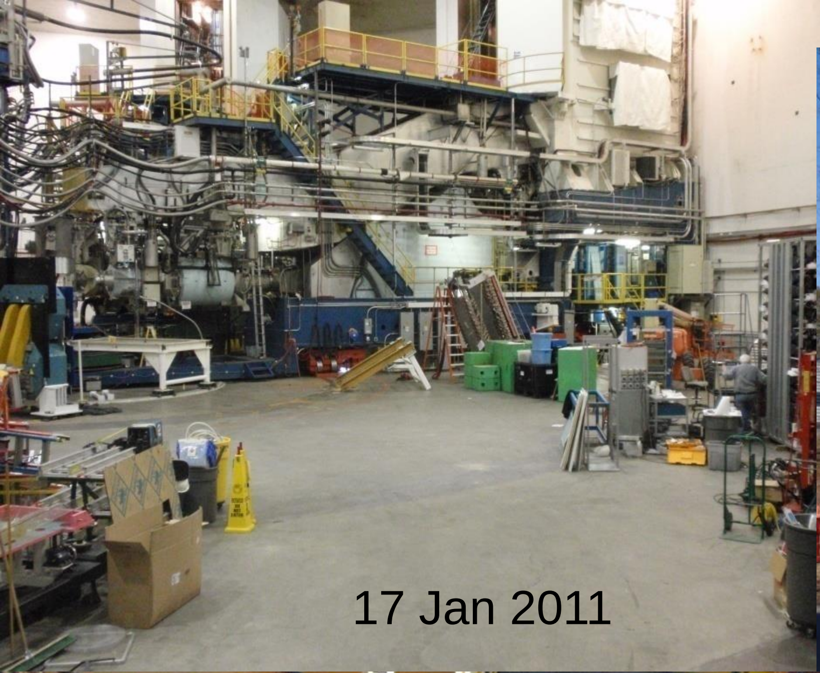
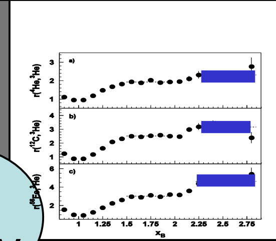
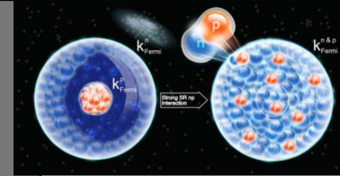

17 Jan 2011

12 Jan 2011

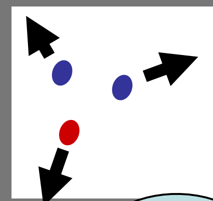

7 Jan 2011

outlook



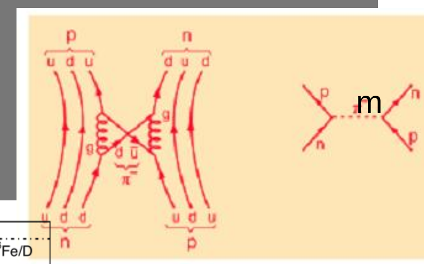


What is the role played by short range correlation of more than two nucleons ?

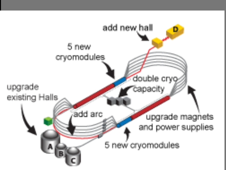


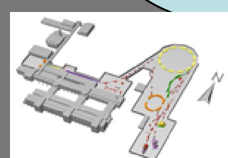
How to relate what we learned about SRC in nuclei to the dynamics of neutron star formation and structure ?

What is the role played by non nucleonic degrees of freedom in SRC ?

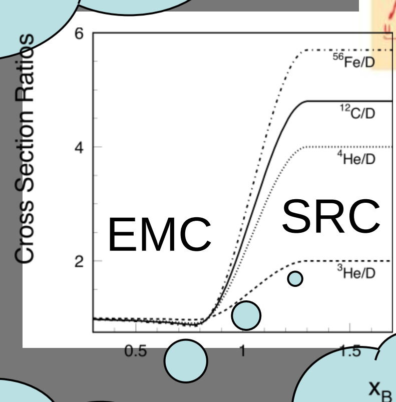


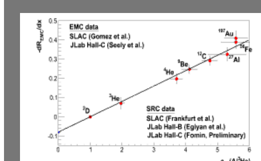
12 GeV JLab





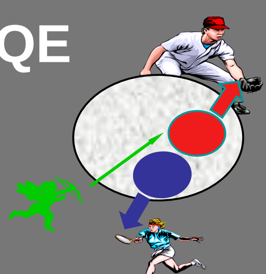
GSI

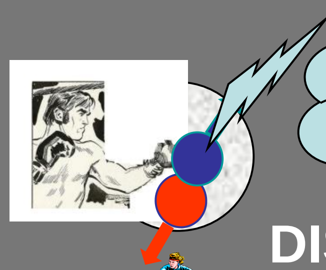




The new facilities will allow even harder knockout reactions

QE





DIS

What are the observables ?

Optimized kinematics ?

Is theory well enough established to interpret the data?

E01-015: A customized Experiment to study 2N-SRC

$Q^2 = 2$ GeV/c , $x_B \sim 1.2$, P_m=300-600 MeV/c, E_{2m}<140 MeV

Luminosity ~ $10^{37\text{-}38}$ $cm^{-2}s^{-1}$

Kinematics optimized to minimize the competing processes

High energy, Large Q^2

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MEC are reduced as $1/Q^2$.

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FSI can treated in Glauber approximation.

x_B>1

Reduced contribution from isobar currents.

Large p_{miss}, and $E_{miss} \sim p^2_{miss}/2M$

Large P_{miss_z}

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  - Pauli blocking for the recoil particle.
  - Geometry, (e, e'p) selects the surface.
- ★ Can be treated in Glauber approximation.
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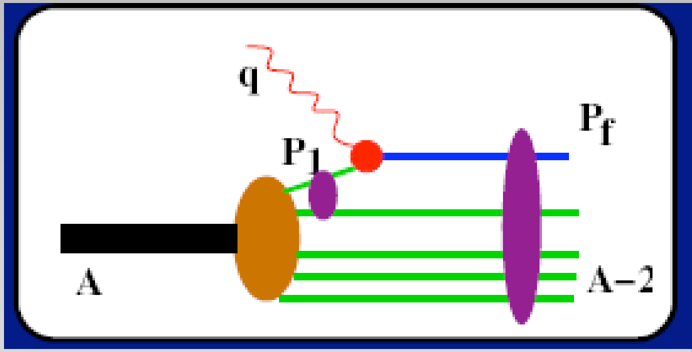

Why FSI do not destroy the 2N-SRC signature ?

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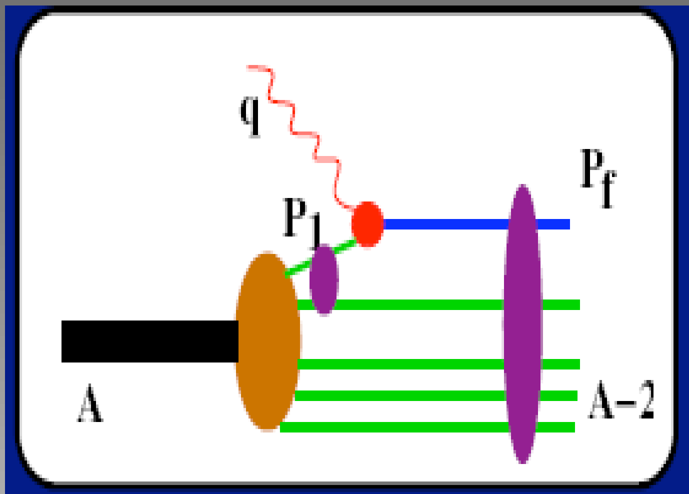
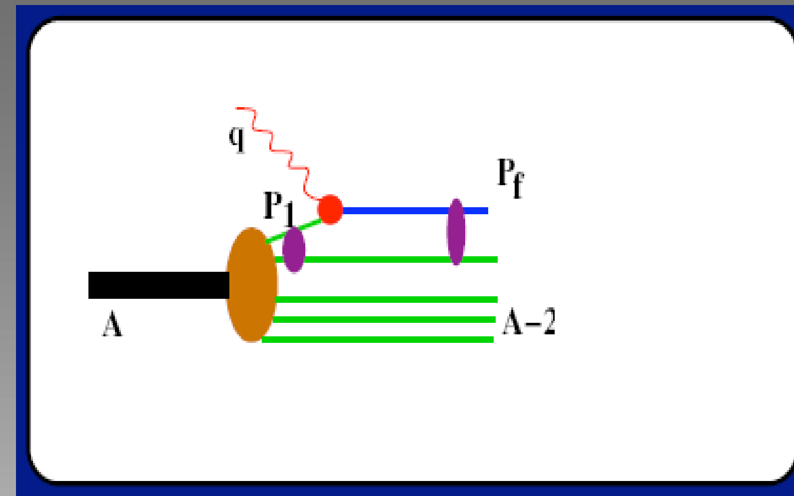
For large Q^2 and x>1 FSI is confined within the SRC





distances that highly virtual struck nucleon propagates

$$\Delta E = -q_0 - M_A + \sqrt{m^2 + (p_i + q)^2} + \sqrt{M_{A-1}^2 + p_i^2}$$

$$r \approx \frac{1}{\Delta E v} \leq 1\,\mathrm{fm}$$

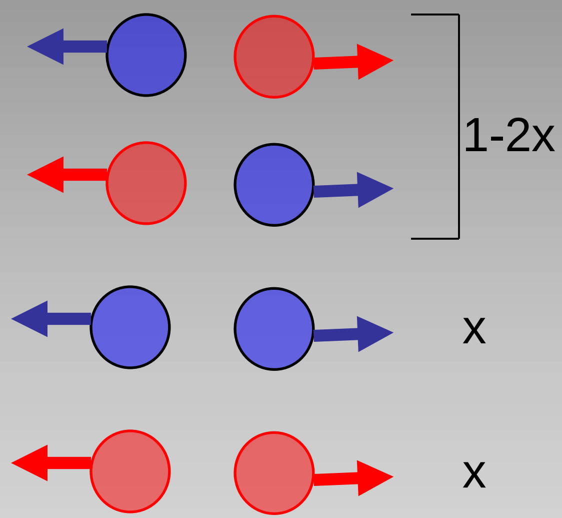
for $x > 1.3$

FSI in the SRC pair:

- Conserve the isospin structure of the pair .
- Conserve the CM momentum of the pair.

$$\frac{(e,e'pp)}{(e,e'p)} = 9.5 \pm 2\% \quad \Rightarrow \quad \frac{\text{pp-SRC}}{2N-SRC} = 4.75 \pm 1\%$$

Assuming in ^{12}C nn-SRC = pp-SRC and 2N-SRC=100%



A virtual photon with $x_B > 1$ "sees" all the pp pairs but only 50% of the np pairs.

$$\frac{(e,e'pp)}{(e,e'p)} = \frac{x}{x+(1-2x)/2} = 2x$$

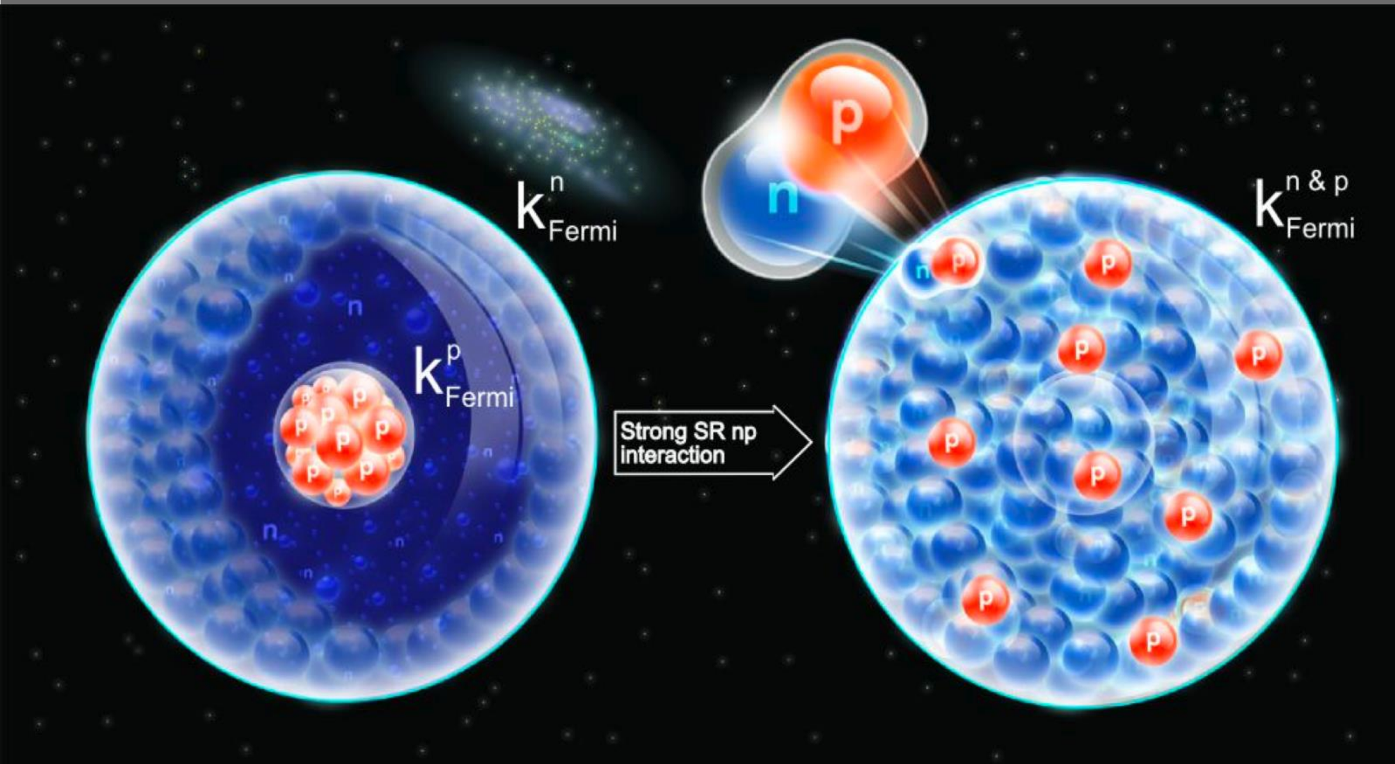
$$BNL \qquad \frac{(\mathrm{p,2pn})}{(\mathrm{p,2p})} = \frac{\mathrm{np - SRC}}{\mathrm{np - SRC + 2\,(pp - SRC)}} = \frac{\mathrm{np - SRC}}{\mathrm{2N - SRC}} = (74\text{-}100)\ \%$$

$$Jlab \quad \frac{(\mathrm{e,e'pn})}{(\mathrm{e,e'p})} = \frac{np - SRC}{2N - SRC} = (84 - 100)\%$$

$$Jlab \quad \frac{(\mathrm{e,e'pp})}{(\mathrm{e,e'p})} = (9.5 \pm 2)\ \% \quad \text{i.e} \quad \frac{\mathrm{pp\text{-}SRC}}{\mathrm{2N\text{-}SRC}} = \frac{nn - SRC}{2N - SRC} = (5 \pm 1)\%$$

$$\frac{np - SRC}{2N - SRC} = (84 - 92)\%$$

Implications for Neutron Stars



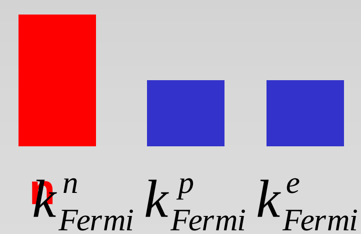
Adapted from: D.Higinbotham, E. Piasetzky, M. Strikman CERN Courier 49N1 (2009) 22

•**At the core of neutron stars, most accepted models assume :**

~95% neutrons, ~5% protons and ~5% electrons (β-stability).

•**Neglecting the np-SRC interactions, one can assume three separate Fermi gases (n p and e).**

• **strong np interaction** → **the n-gas heats the p-gas.**



See estimates in Frankfurt and Strikman **: Int.J.Mod.Phys.A23:2991-3055,2008.**

SRC in nuclei: implication for neutron stars

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 ~95% neutrons, ~5% protons and ~5% electrons (β-stability).

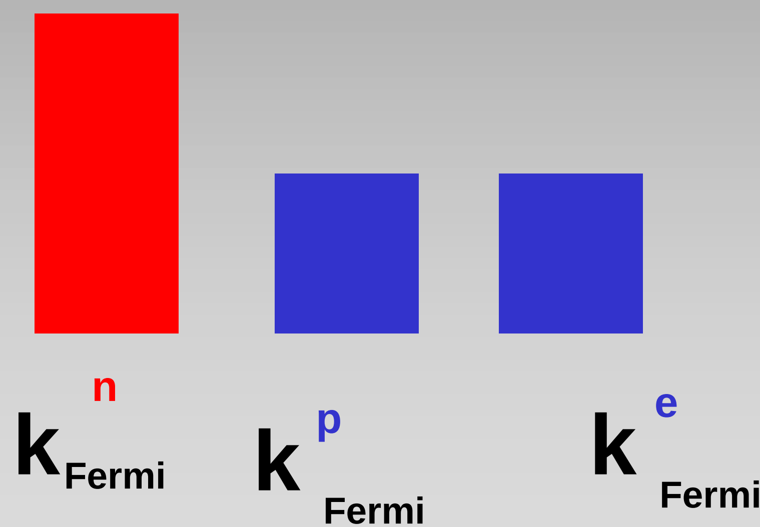
- **Neglecting the np-SRC interactions, one can assume three separate Fermi gases (n p and e).**

At T=0 $$k^n_{Fermi} = k^p_{Fermi} + k^e_{Fermi}$$ $$k^p_{Fermi} = k^e_{Fermi} = (\frac{N_p}{N_n})^{1/3} k^n_{Fermi}$$

For $$\rho = 5\rho_{0,}\ \ k^n_{Fermi} \approx 500\ \mathrm{MeV/c},\ \ k^p_{Fermi} = k^e_{Fermi} \approx 250\ \mathrm{MeV/c}$$

Pauli blocking prevent direct n decay

$$n \rightarrow p + \mathrm{e} + \bar{\nu}_\mathrm{e}$$



Strong SR np interaction

THE MEAN FIELD APPROXIMATION

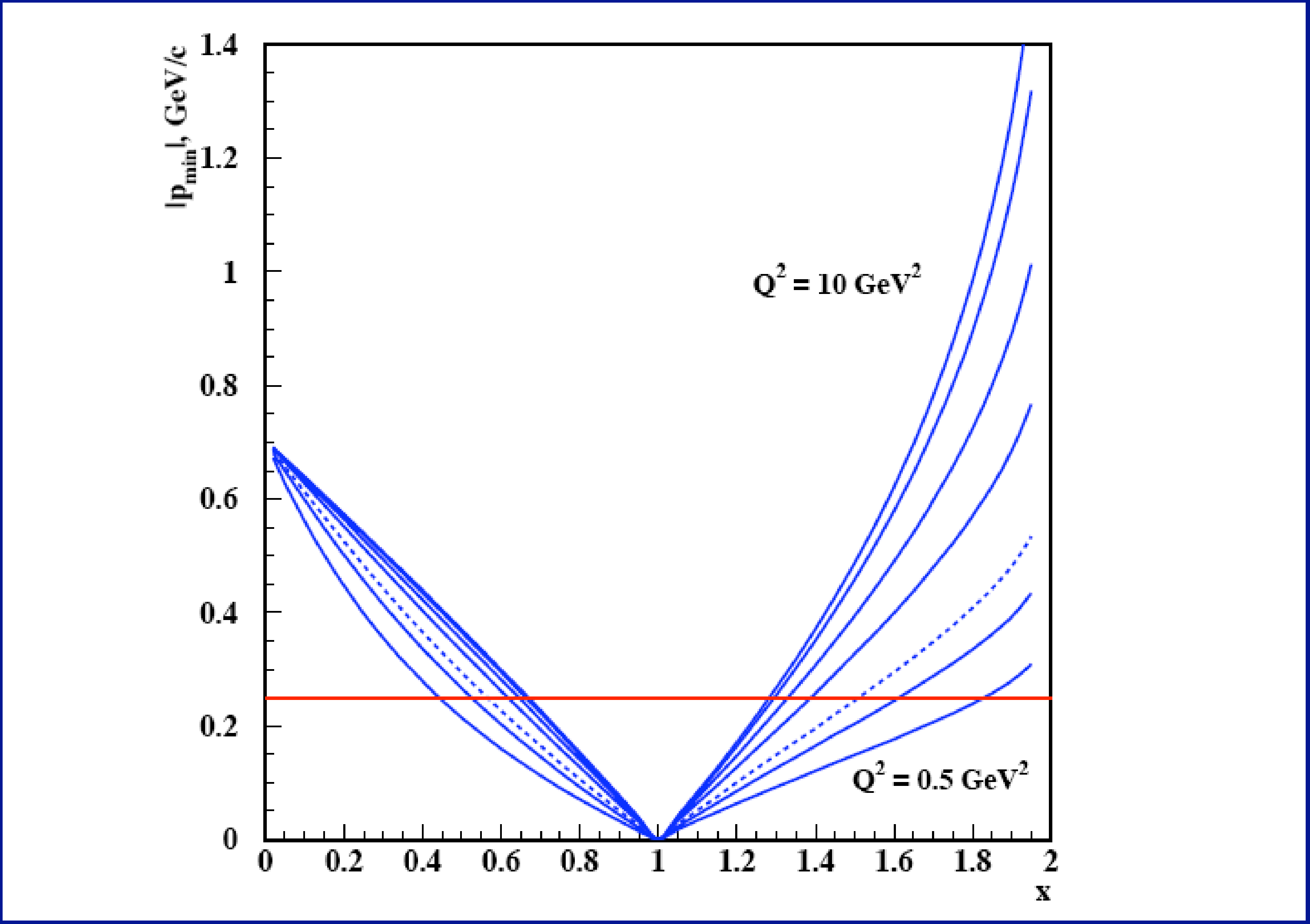
$$\left[-\frac{\hbar^2}{2m}\sum_i \hat{\nabla}_i^2 + \sum_{i<j} \hat{v}_{ij}\right]\Psi_o = E_o\,\Psi_o$$

$$\Downarrow$$

$$\left[-\frac{\hbar^2}{2m}\sum_i \hat{\nabla}_i^2 + \sum_i V(r_i)\right]\Phi_o = \epsilon_o\,\Phi_o$$

Variational monte carlo (Urbana Group)
Cluster expansion techniques (Ciofi, Alvioli, Cda, Morita)

x> 1 is not automatically means 2N SRC one needs also large Q2



$Q^2 \uparrow$

$q_+ \gg$

Brookhaven Experiment

A. Tang et al, PRL 2003

$$F = \frac{\text{Number of (p,ppn) events } (p_i, p_n > k_F)}{\text{Number of (p,pp) events } (p_i > k_F)},$$

$$F = 0.43^{+0.11}_{-0.07} \qquad \text{for } 275 \le p_i, p_n \le 550 \text{ MeV/c}$$

Theoretical Analysis

Piasetzky, MS, Frankfurt, Strikman, Watson PRL 2007

$$P_{pn/pX} = \frac{F}{T_n R}$$

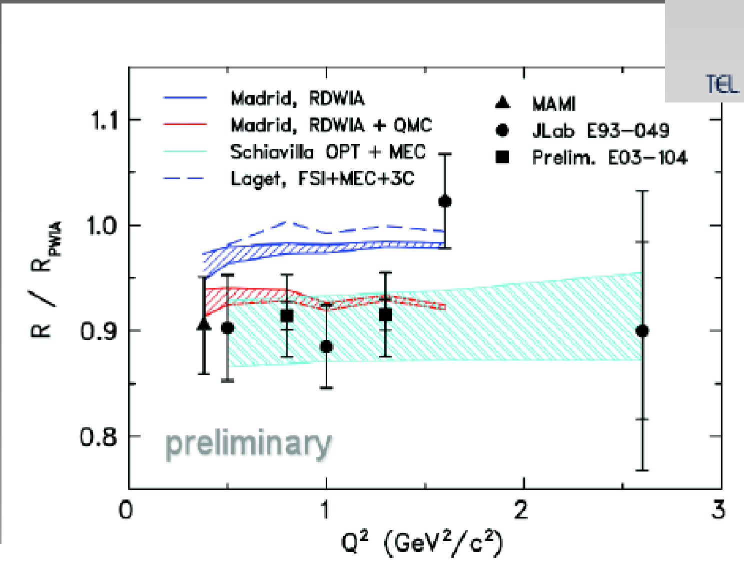
relative probability of finding pn SRC in the "pX" configuration that contains a proton with $p_i > k_F$.

$$R \equiv \frac{\int_{\alpha_i^{min}}^{\alpha_i^{max}} \int_{p_{ti}^{min}}^{p_{ti}^{max}} \int_{\alpha_n^{min}}^{\alpha_n^{max}} \int_{p_{tn}^{min}}^{p_{tn}^{max}} D^{pn}(\alpha_i, p_{ti}, \alpha_n, p_{nt}, P_{R+}) \frac{d\alpha}{\alpha} d^2 p_t \frac{d\alpha_n}{\alpha_n} d^2 p_{tn} dP_{R+}}{\int_{\alpha_i^{min}}^{\alpha_i^{max}} \int_{p_{ti}^{min}}^{p_{ti}^{max}} S^{pn}((\alpha_i, p_{ti}, P_{R+}) \frac{d\alpha}{\alpha} d^2 p_t dP_{R+}}.$$

$^{4}He(\vec{e},e'\vec{p})$

Polariztion Transfer

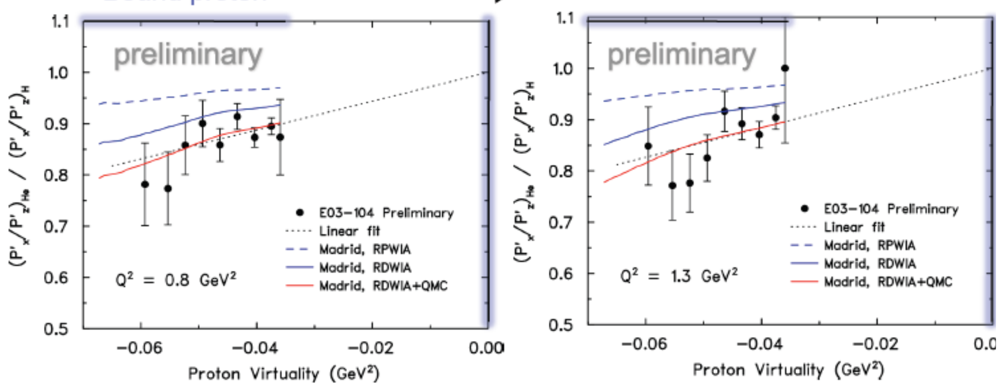
Copied from S. Strauch talk



Proton Virtuality: $v = p^2 - m_P^2$

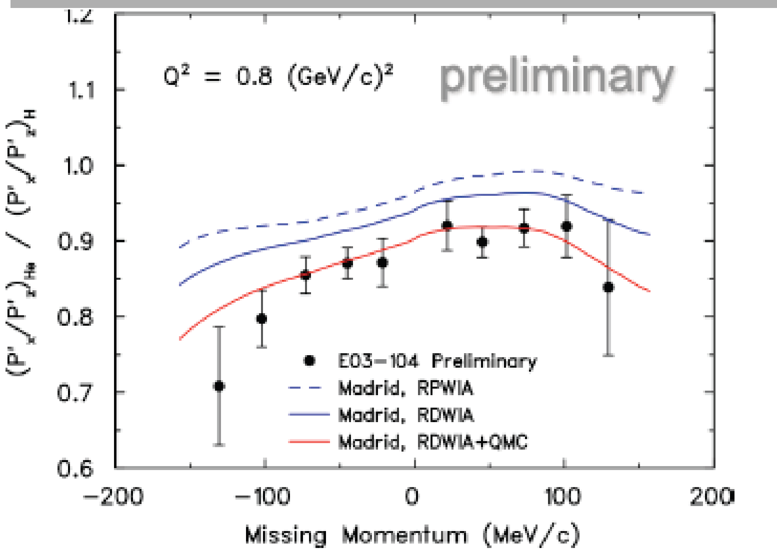
Free proton

Bound proton

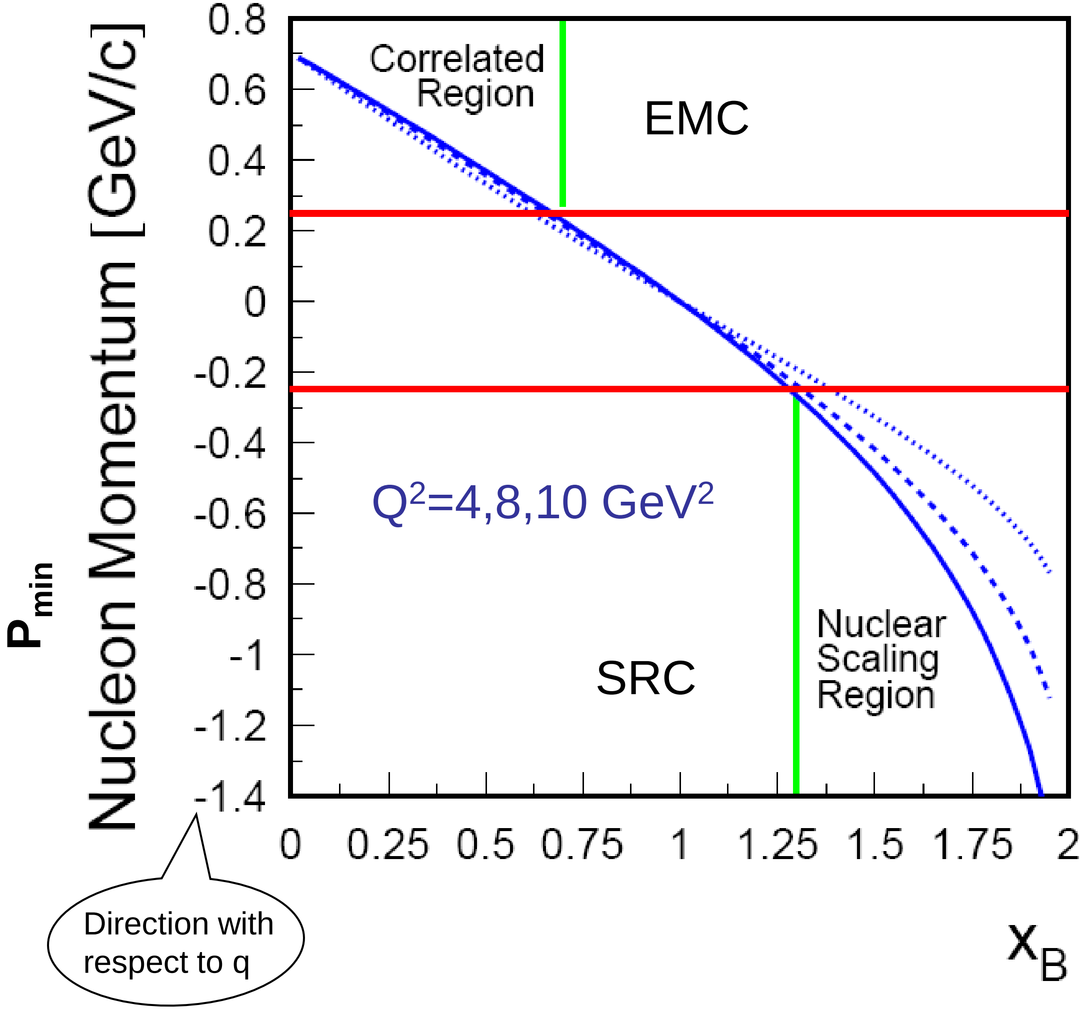


- Polarization-transfer double-ratio data and calculations show dependence on proton virtuality with the trend of R ≈ 1 for $p^2 = m_P^2$; as it should be.
- Excellent description of preliminary E03-104 data with the RDWIA + QMC (in-medium form factors) model.

see: C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)



M. Paolone at al. PRL 105,072001,(1020)



The minimum missing momentum of the D(e,e')pn reaction from

conservation of energy and momentum for quasi-elestic scattering

$$(q + p_d - p_n)^2 = m_p^2$$

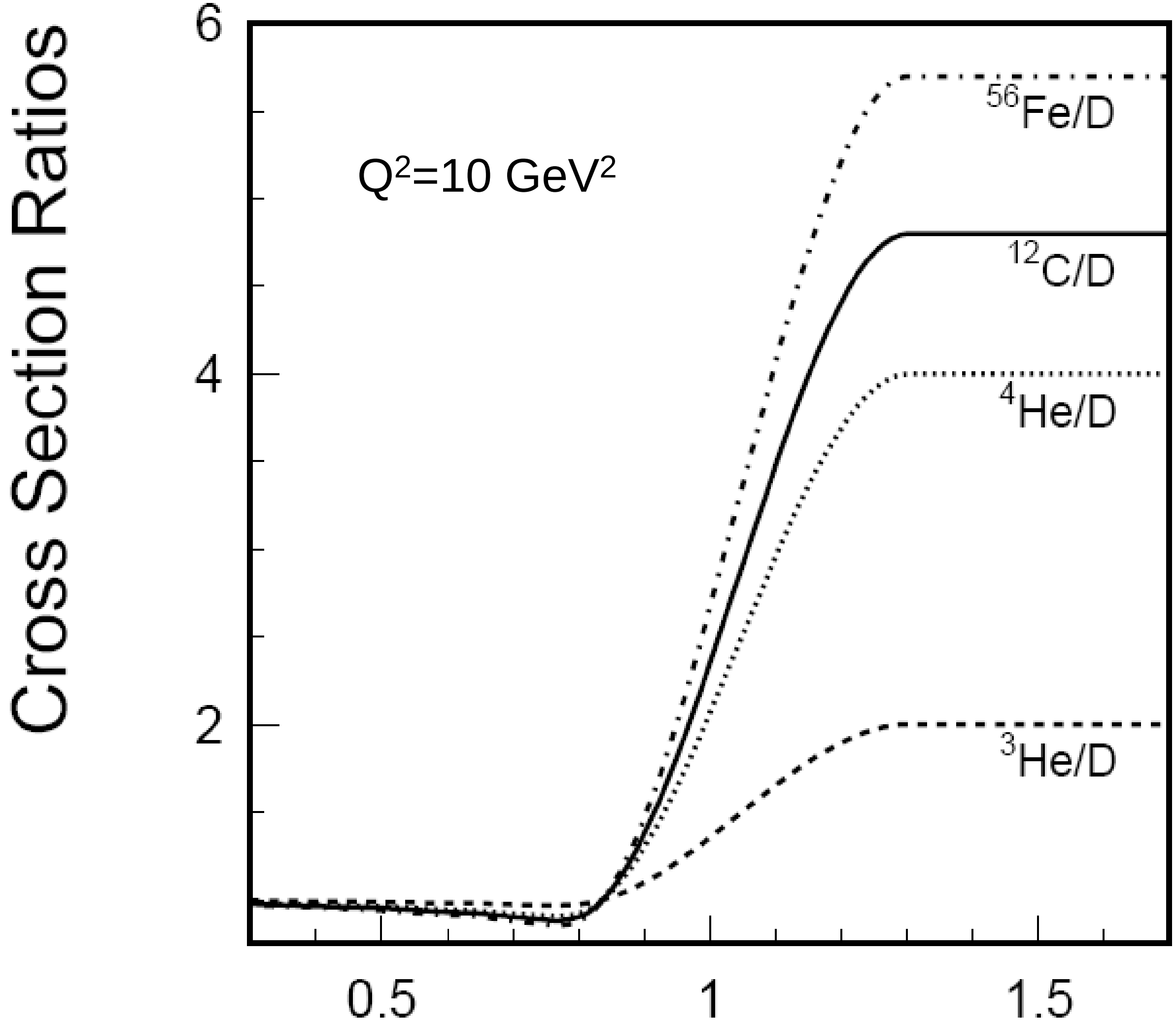
$$P_d(x_B) = 2\pi \cdot \int_{P\min}^{\infty} p^2 \cdot n_d(p) \cdot dp$$

$$n_A(p) = n_d(p) \cdot a_2(A/d)$$

$$P_A(x_B) = 2\pi \cdot \int_{P\min}^{\infty} p^2 \cdot n_A(p) \cdot dp$$

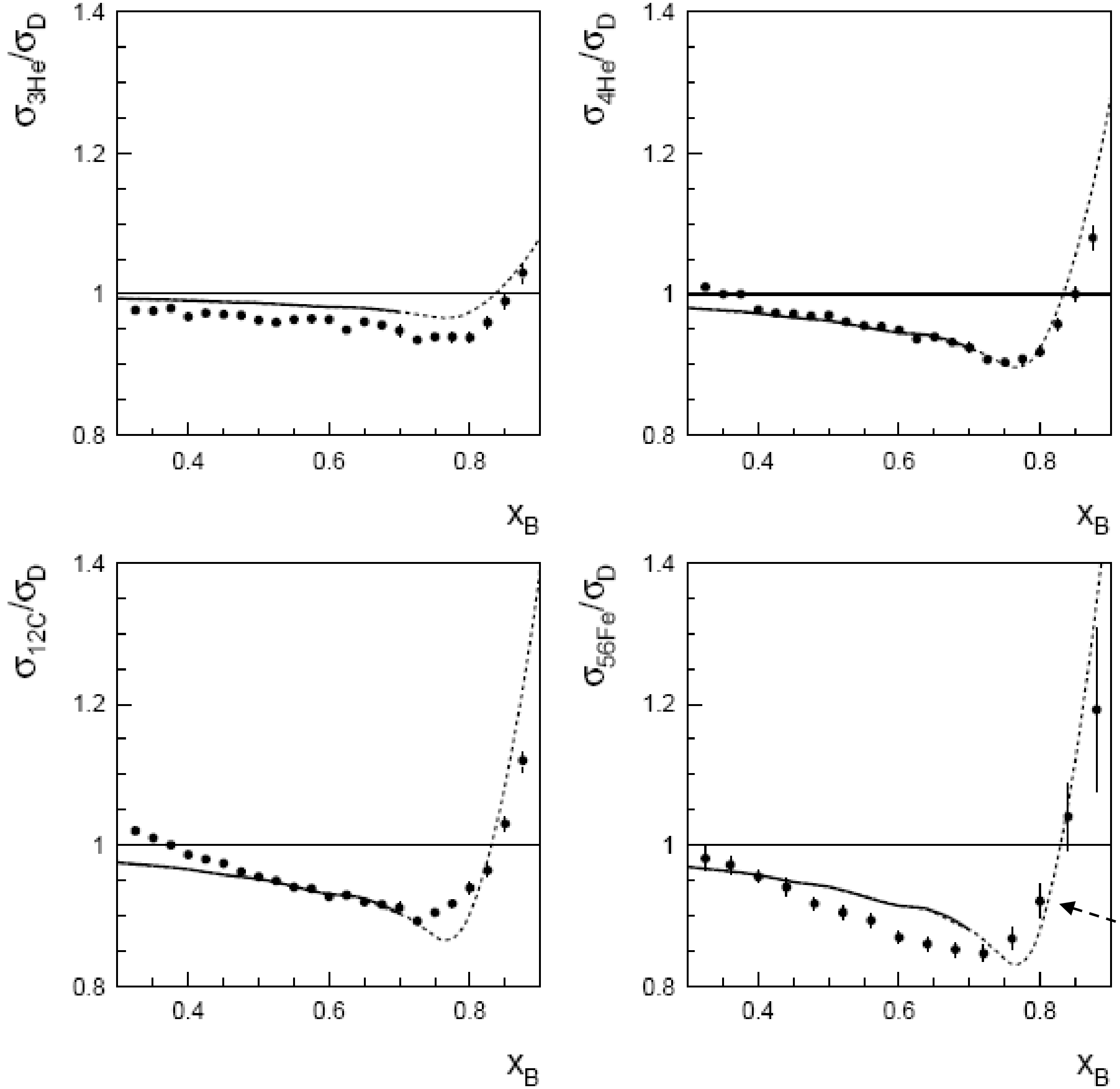
$$\frac{\sigma_A}{\sigma_d} = \frac{1 - P_A(x_B)}{1 - P_d(x_B)}$$

Higinbotham, Gomez, Piasetzky arXiv:1003.4497 [hep-ph]



$$\frac{\sigma_A}{\sigma_d} = \frac{1-P_A(x_B)}{1-P_d(x_B)}$$ interpolation $a_2(A/d)$ x_B

Higinbotham, Gomez, Piasetzky arXiv:1003.4497 [hep-ph]



Data:

$^{3}He, ^{4}He, ^{12}C$

J. Seely et al.
PRL 103, 202301 (2009).

^{56}Fe

J. Gomez et al.
PR D49, 4348 (1994).

interpolation

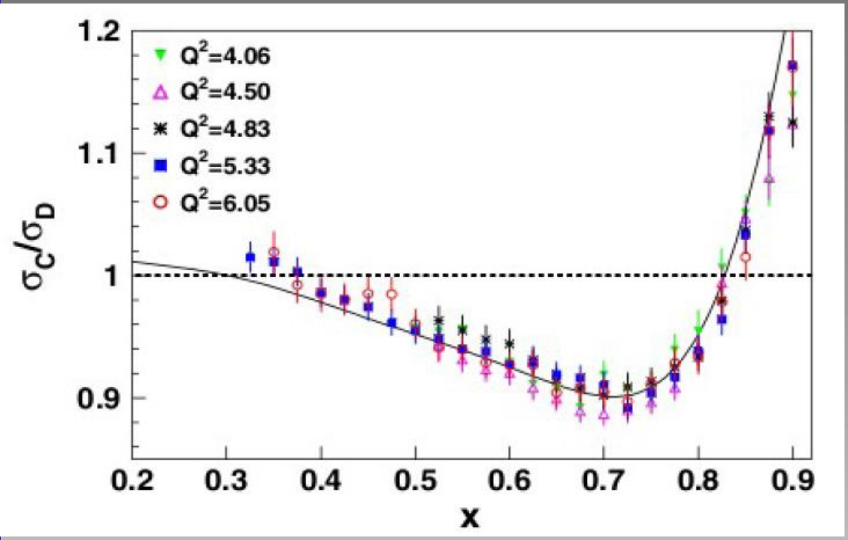
Higinbotham, Gomez, Piasetzky arXiv:1003.4497 [hep-ph]

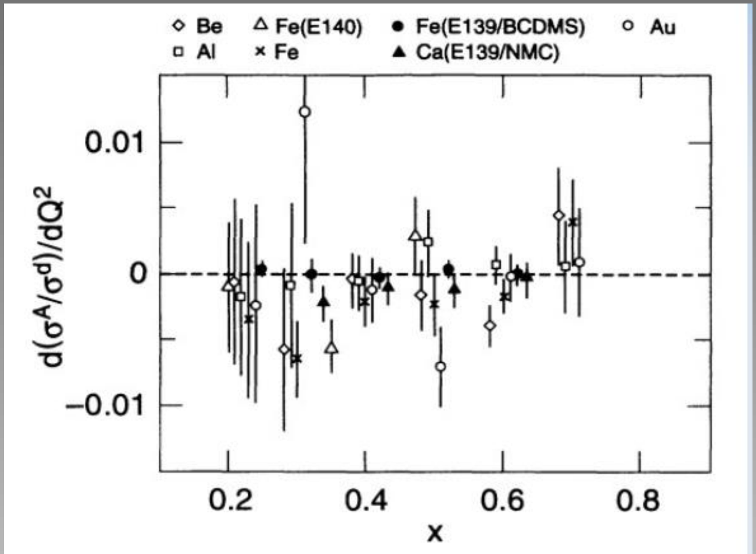
Very weak Q^2 dependence

EMC

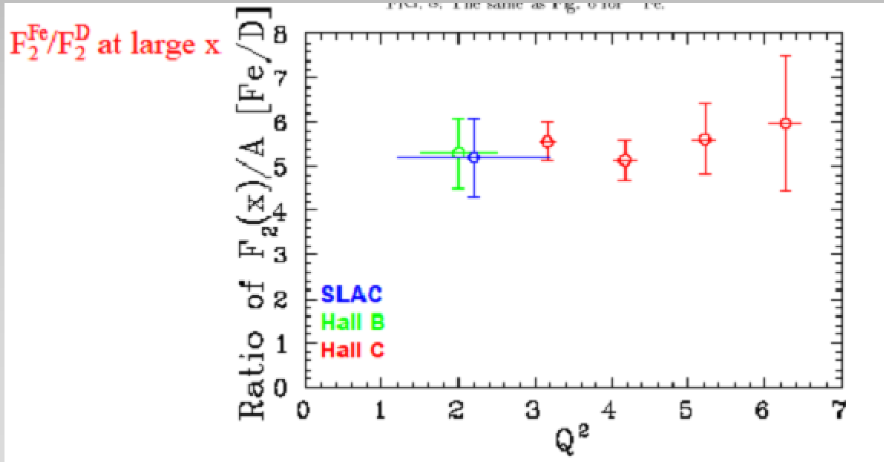
JLab J. Seely et al.

SLAC J. Gomez et al.





SRC



J. Arrington talk, Minami 2010.

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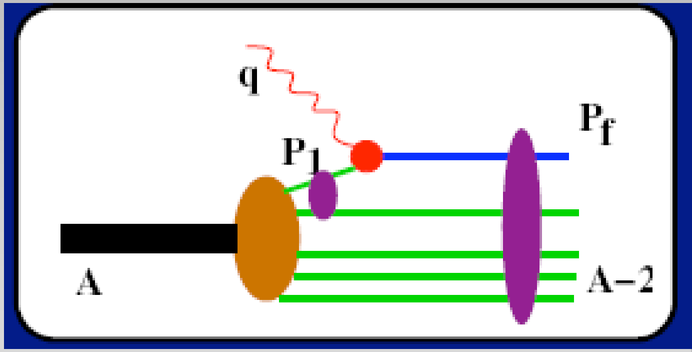
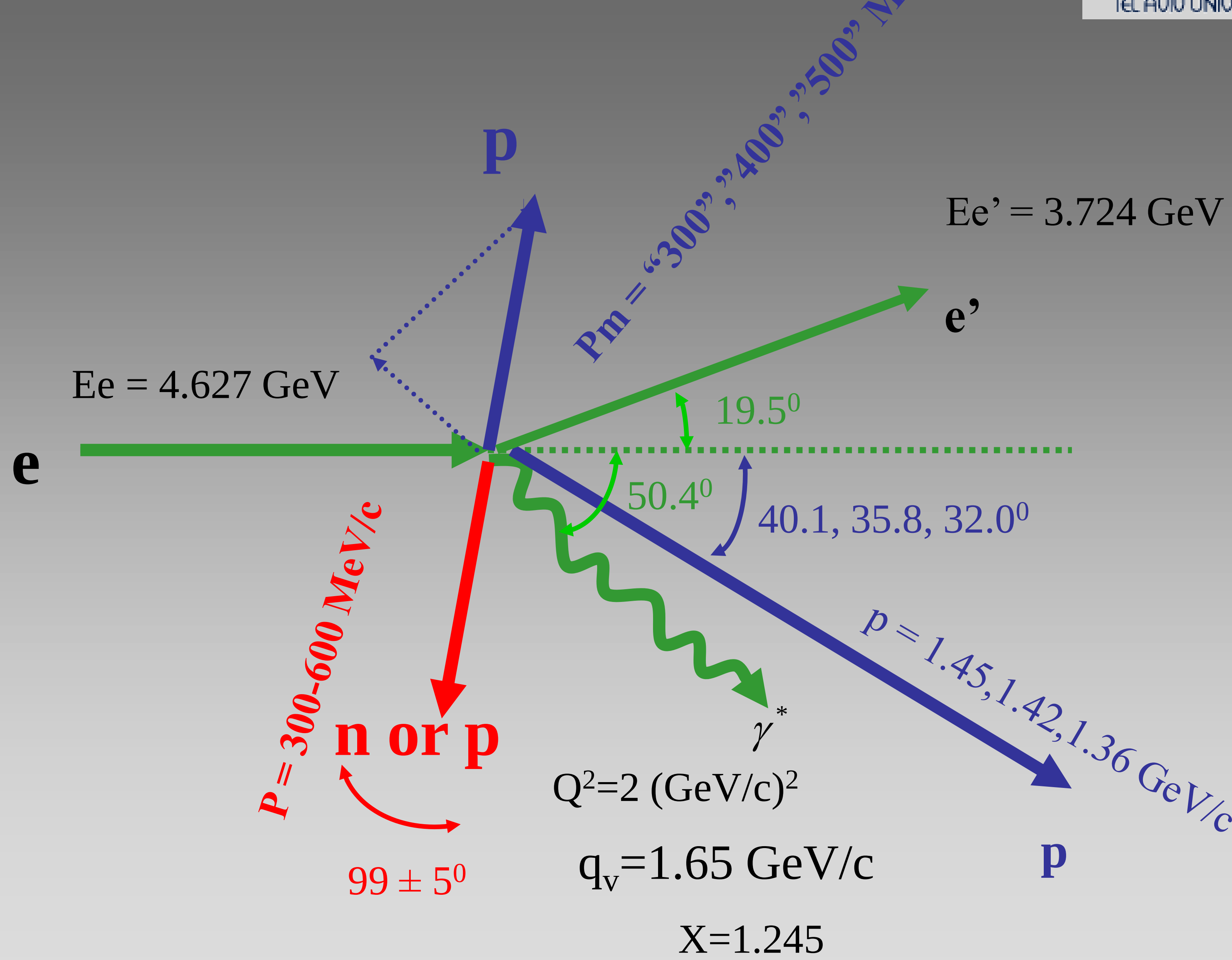
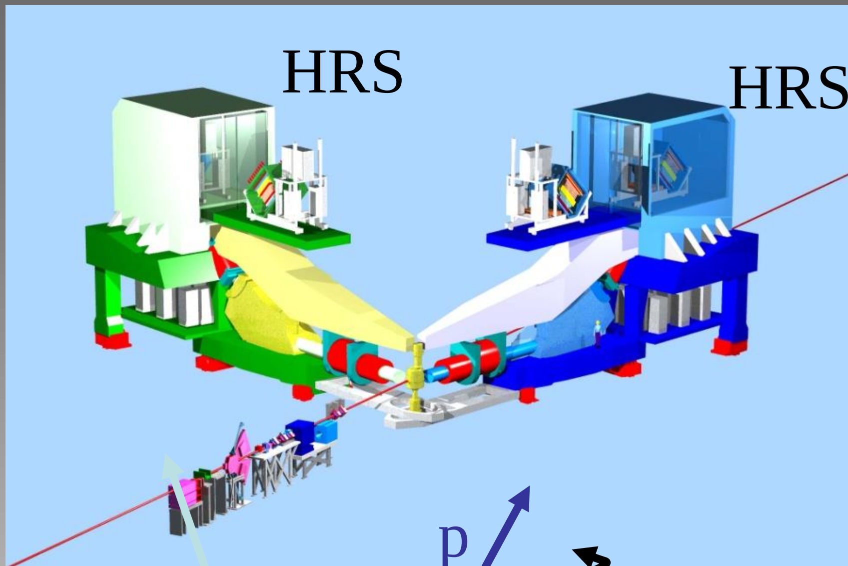


The kinematics selected for the measurement



Experimental setup

EXP 01-015 / Jlab

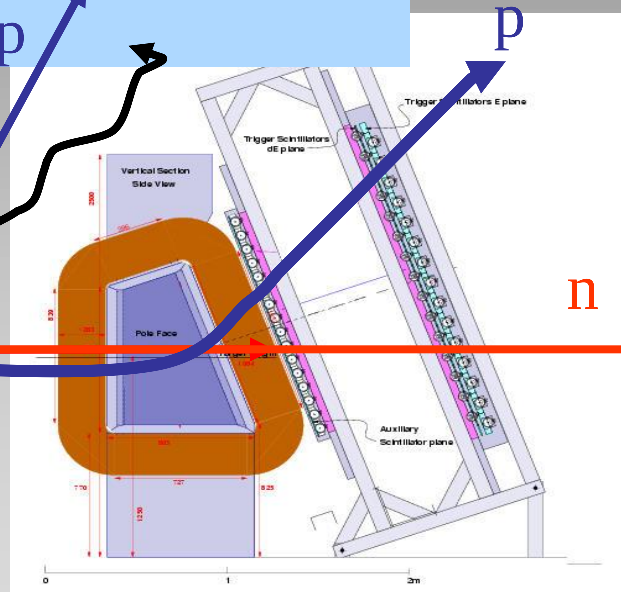


e

p

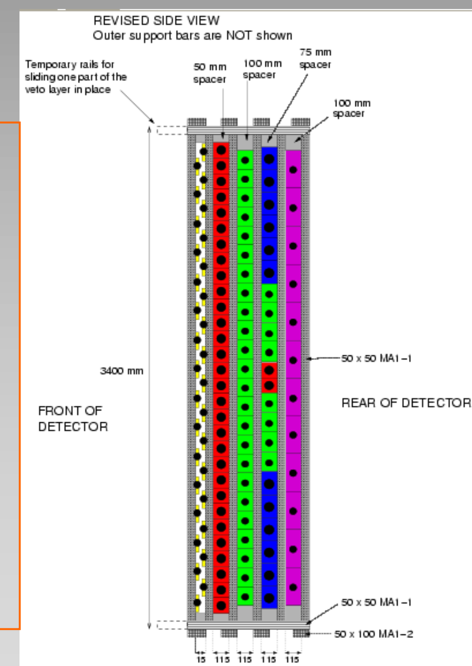
n

e



Big Bite

n array



Lead wall

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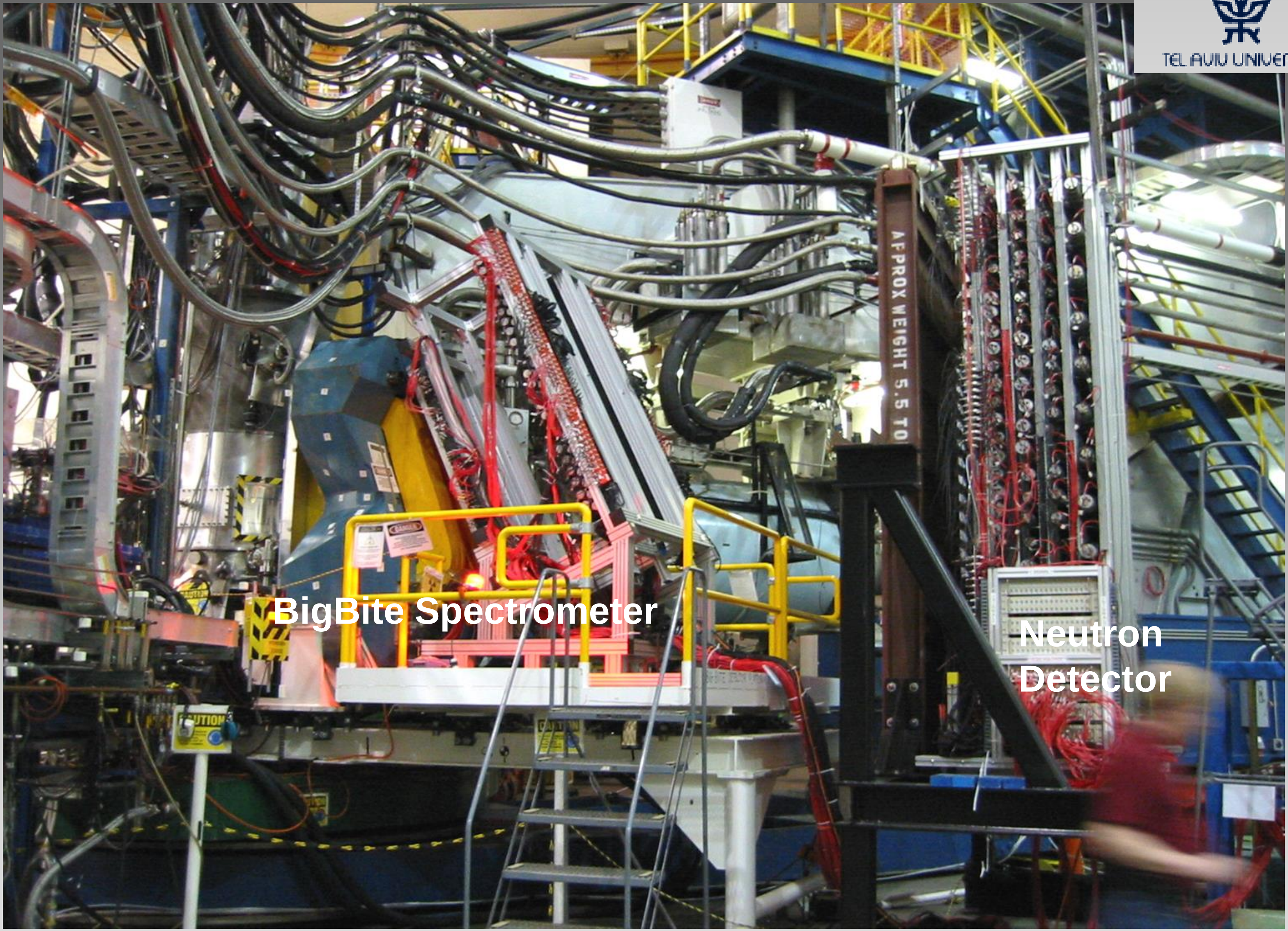
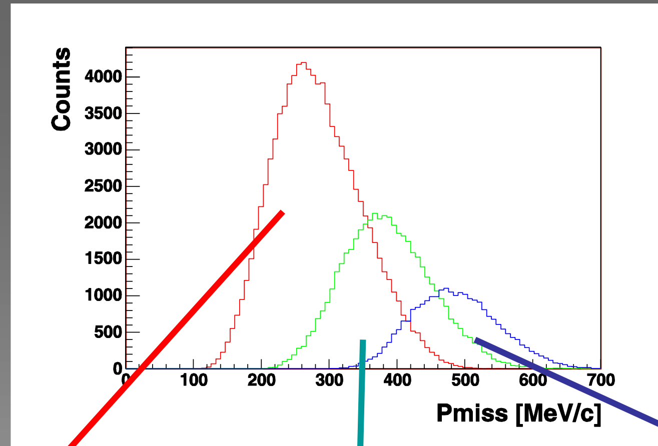


EXP 01-015 **Jlab / Hall A** Dec. 2004 – Apr. 2005

$^{12}C(e,e'p)$

$x_B>1$

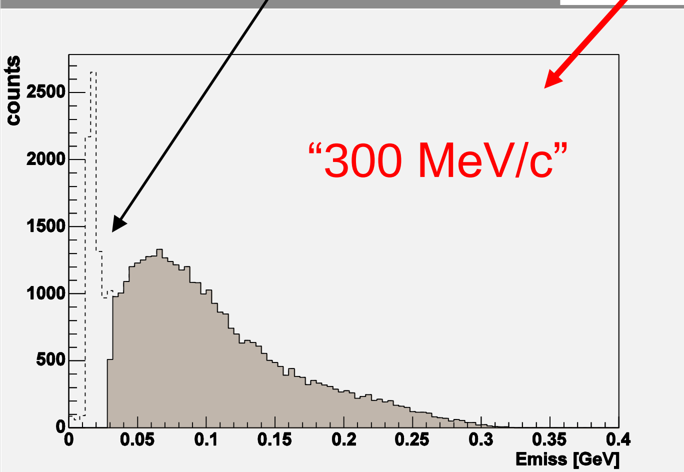


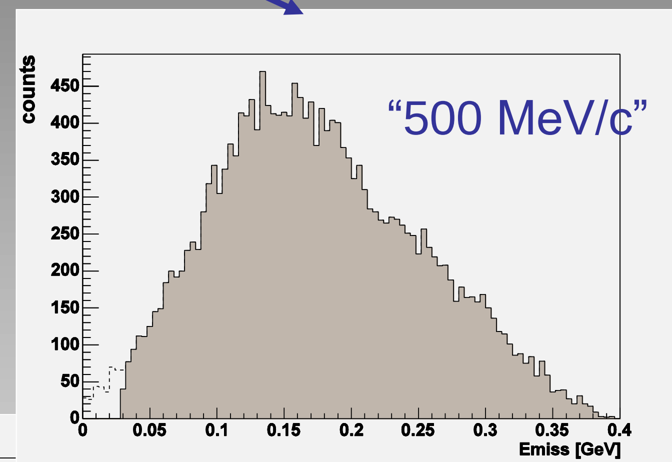
"300 MeV/c"

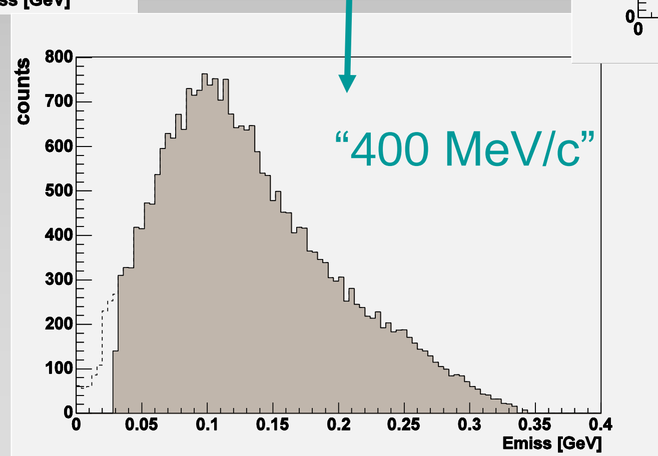
"400 MeV/c"

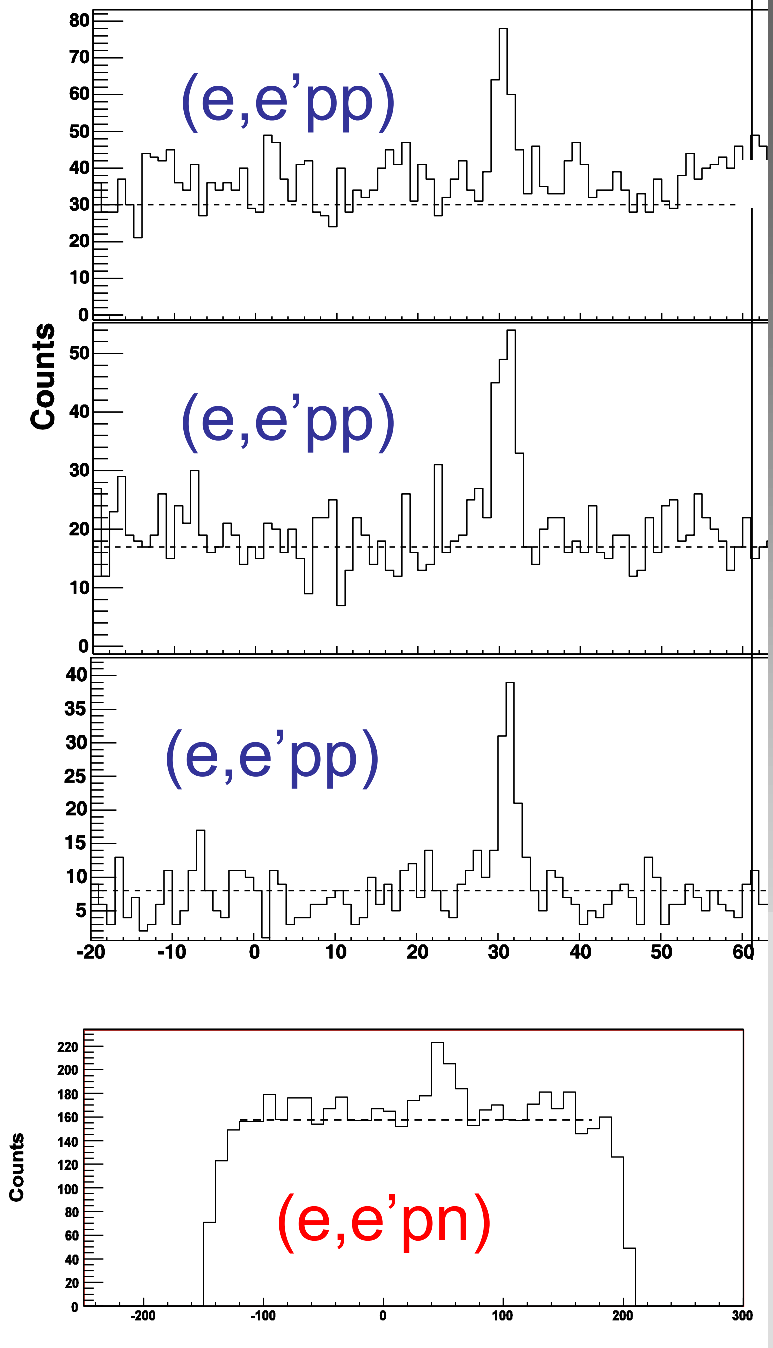
"500 MeV/c"

$^{12}C(e,e'p)^{11}B$









TOF [ns]

P_{mis}="300" MeV/c

(Signal : BG= 1.5:1)

P_{mis}="400" MeV/c

(Signal : BG= 2.3:1)

P_{mis}="500" MeV/c

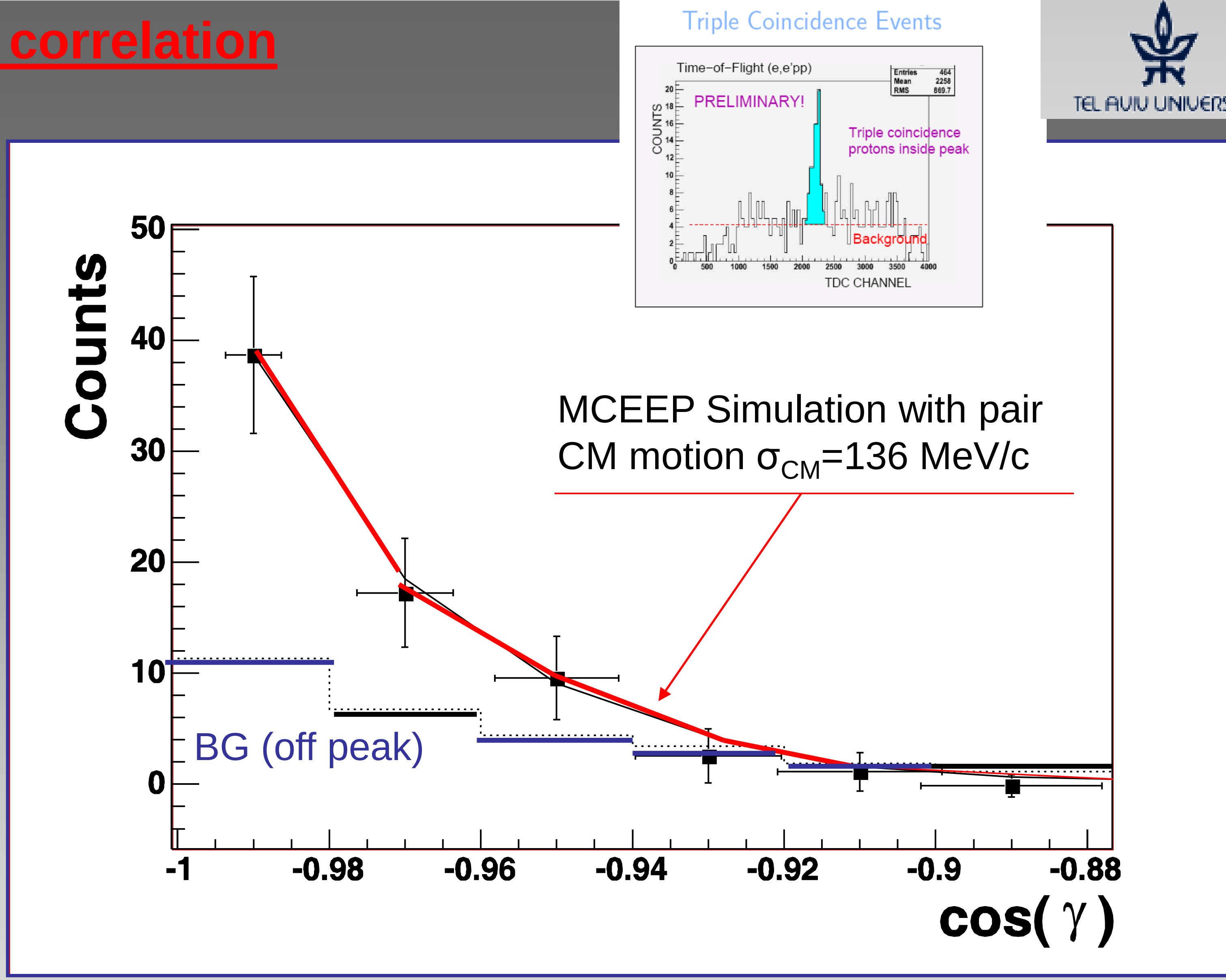
(Signal : BG= 4:1)

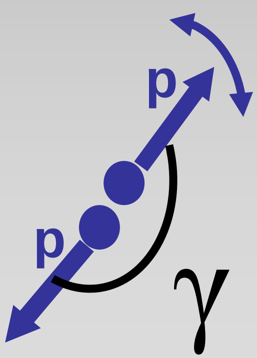
P_{mis}="500" MeV/c

(Signal : BG= 1:7)

Directional correlation

$^{12}C(e,e'pp)$





Directional correlation

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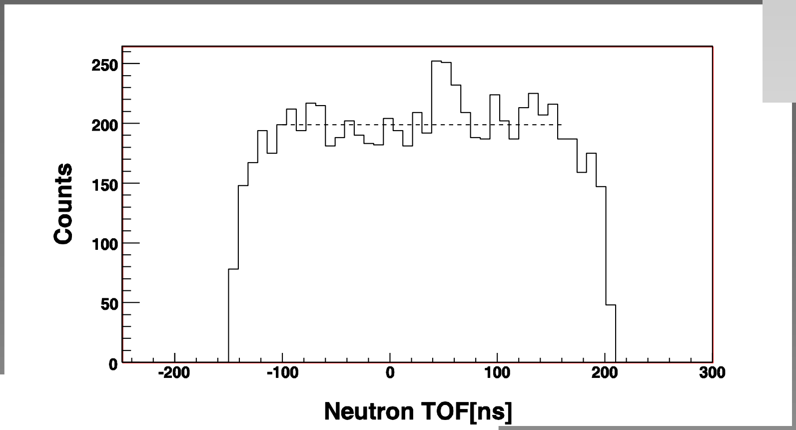
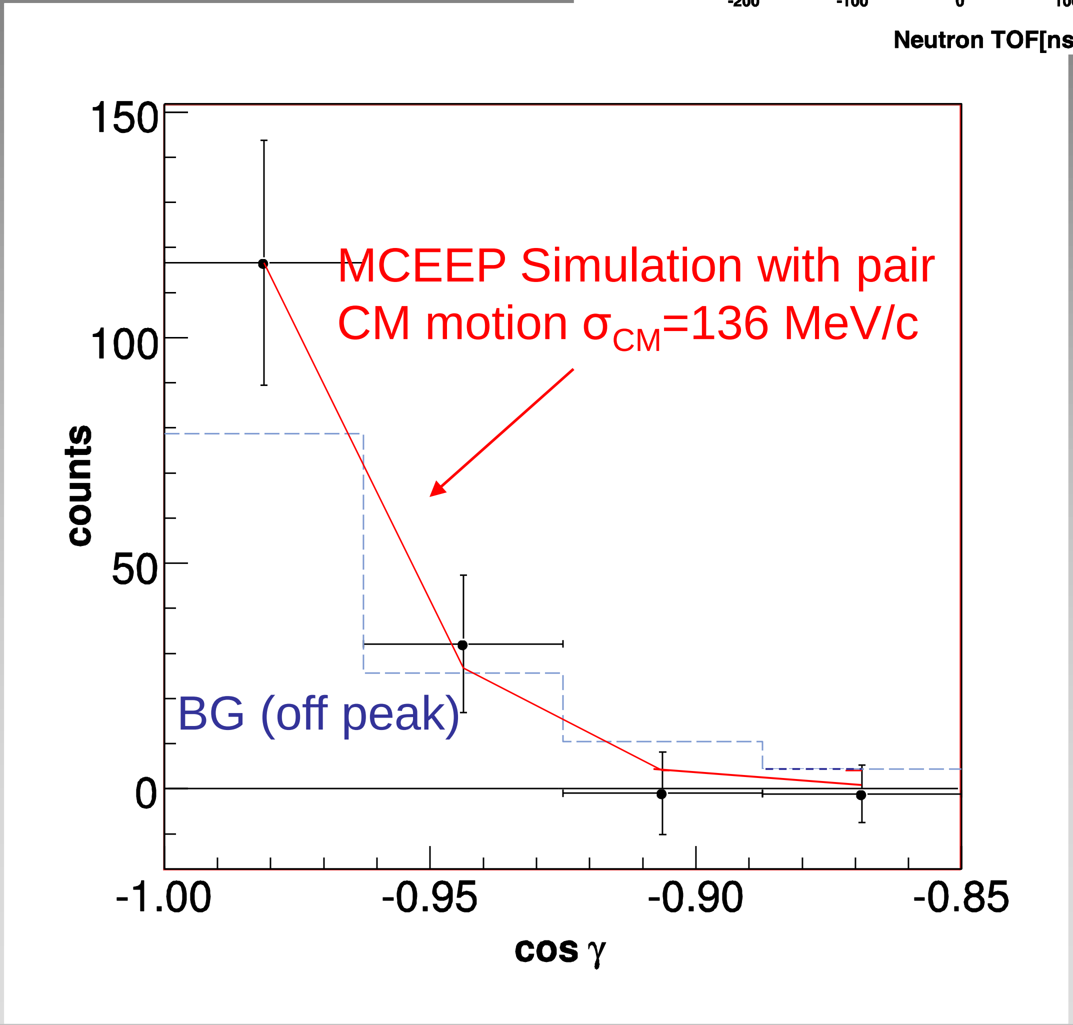
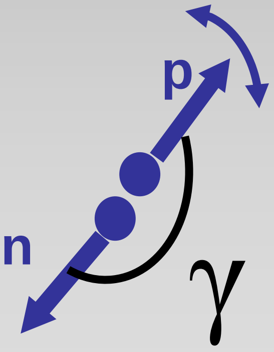
$^{12}C(e,e'pn)$

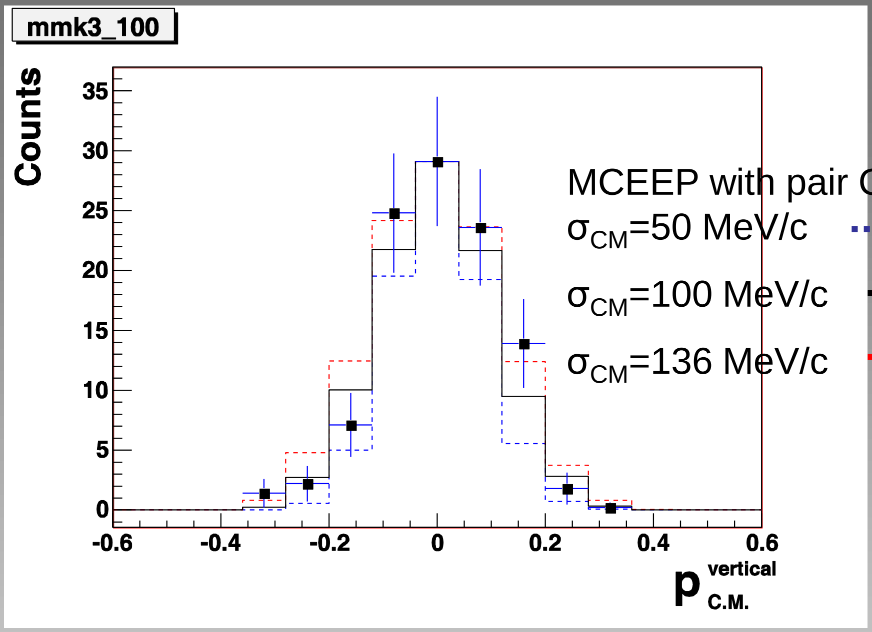


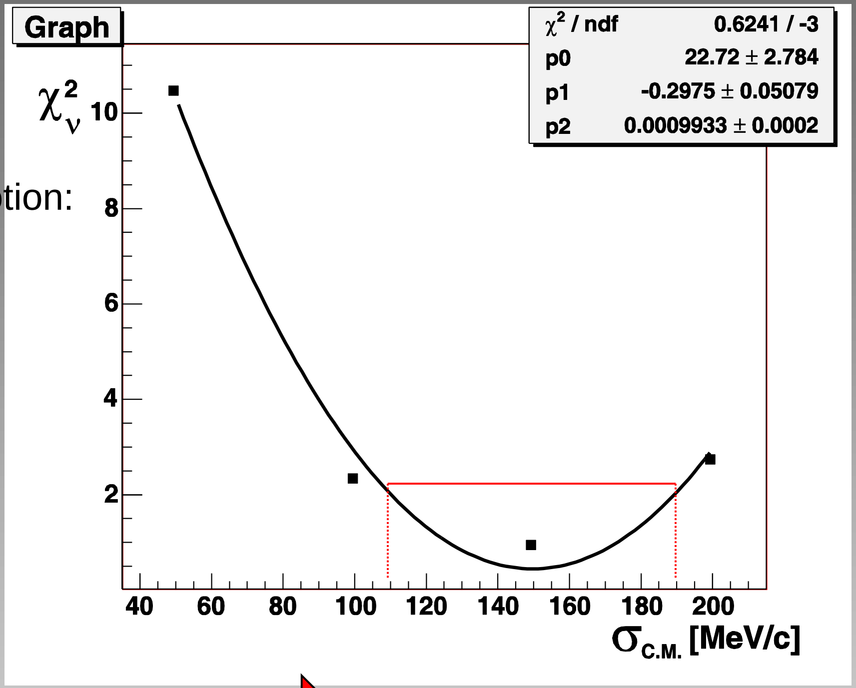




CM motion of the pair:

$P_{c.m}^{vertical}$, “500 MeV/c “ setup





2 components of $\vec{p}_{c.m}$ and 3 kinematical setups

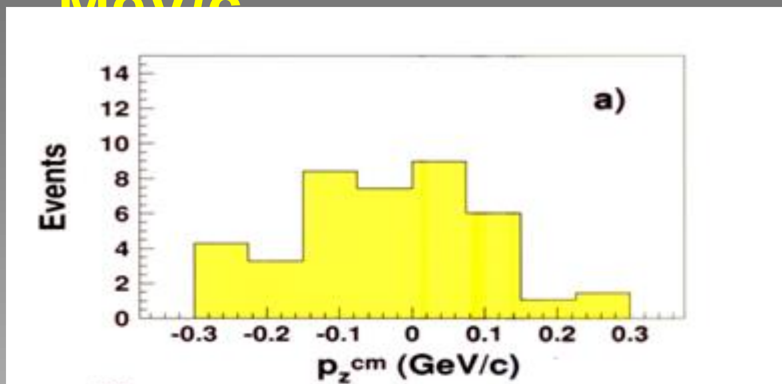
This experiment : σ_{CM}=0.136 ± 0.020 GeV/c

(p,2pn) experiment at BNL : σ_{CM}=0.143±0.017 GeV/c

Theoretical prediction (Ciofi and Simula) : σ_{CM}=0.139 GeV/c

CM motion of the pair (“old” data)

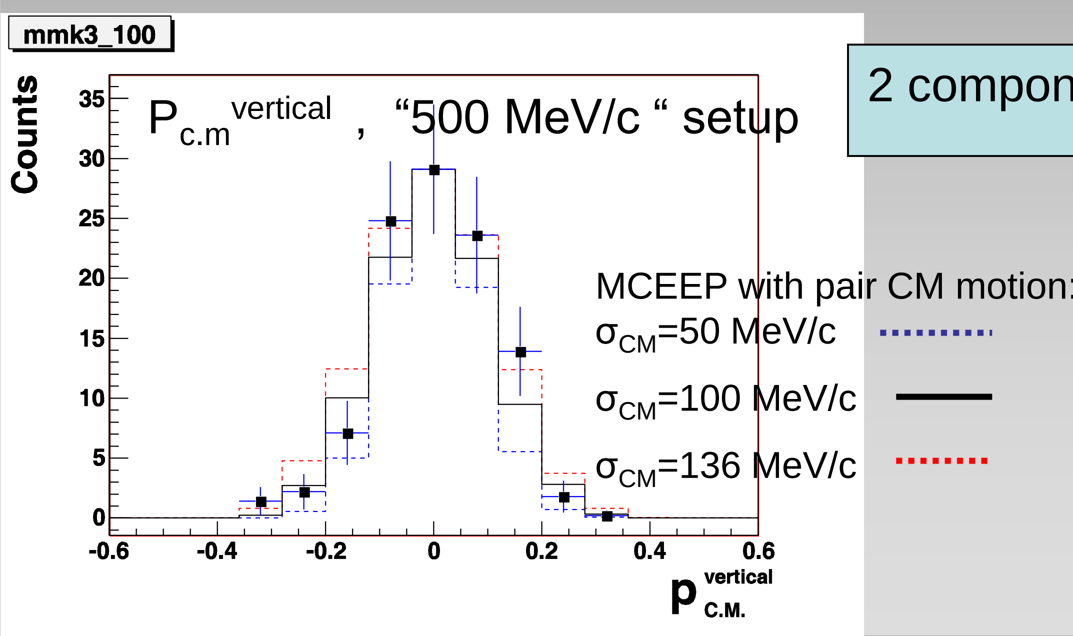
(p,2pn) experiment at BNL : σ_{CM}=143 ± 17 MeV/c



$$p_z^{cm} = 2m(1 - \frac{\alpha_p + \alpha_n}{2}),$$

A. Tang et al.
B. Phys. Rev. Lett. 90 ,042301 (2003)

(e,e’pp) JLab/E01-15 : σ_{CM}=136 ± 20 MeV/c



2 components of $\vec{p}_{c.m}$ and 3 kinematical setups

R. Shneor et al.,

PRL 99, 072501 (2007)

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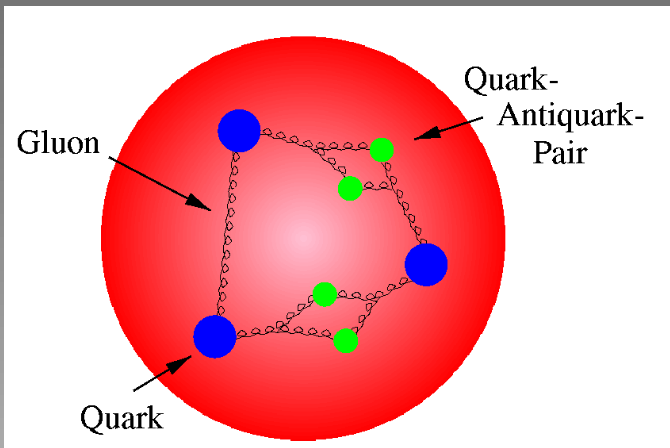
Hard processes are of particular interest because they have the resolving power required to probe the partonic structure of a complex target



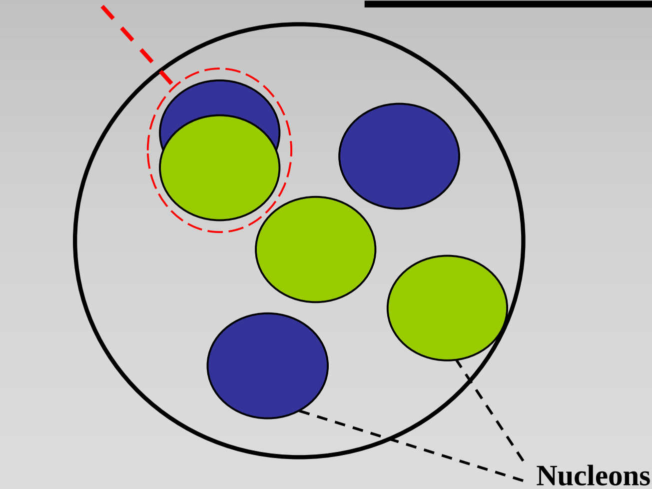
DIS

partonic structure of hadrons

Scale: several tens of GeV

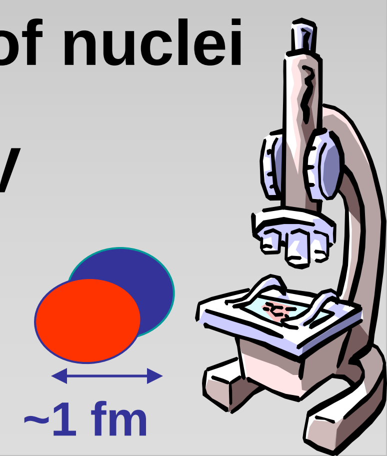
Inclusive electron scattering A(e,e')

Hard knockout reactions A(e,e'p) and A(e,e'pN)

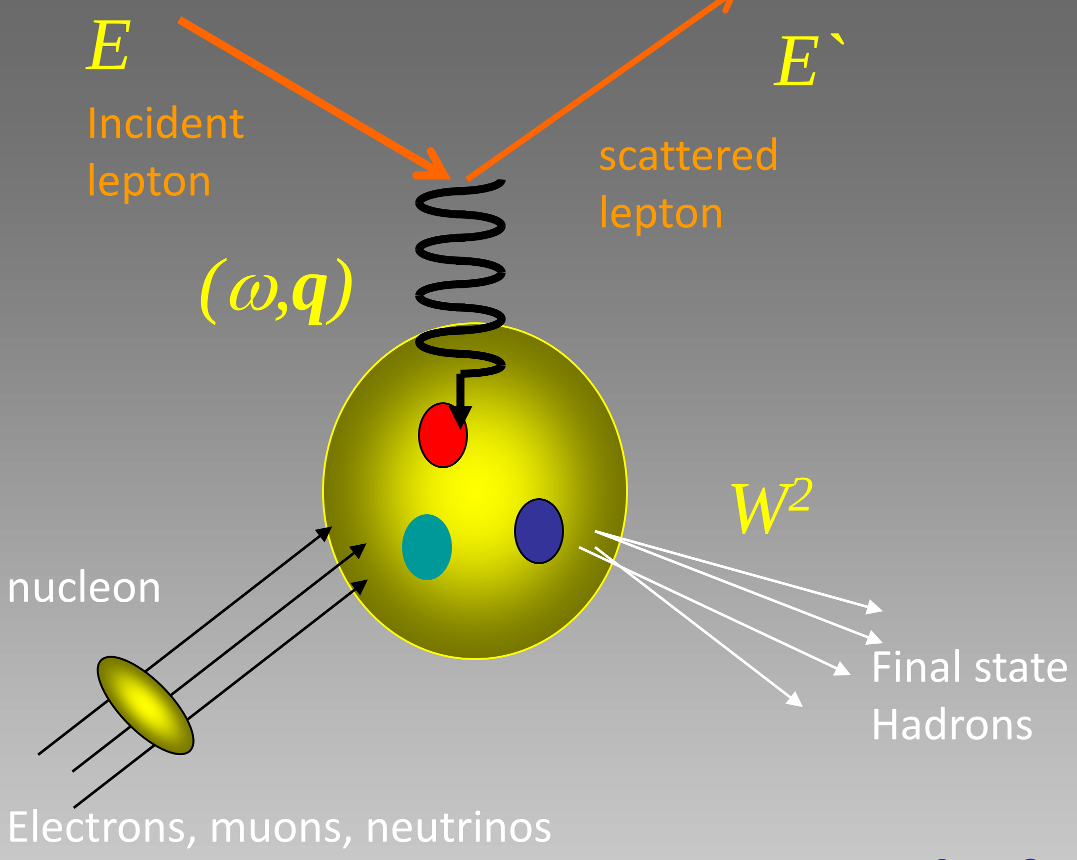


hadronic structure of nuclei

Scale: several GeV



Deep Inelastic Scattering (DIS)



$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \qquad (= \frac{Q^2}{2(q \cdot p_T)})$$

SLAC, CERN, HERA, FNAL, JLAB

E, E' 5-500 GeV

Q^2 5-50 GeV^2

w^2 >4 GeV^2

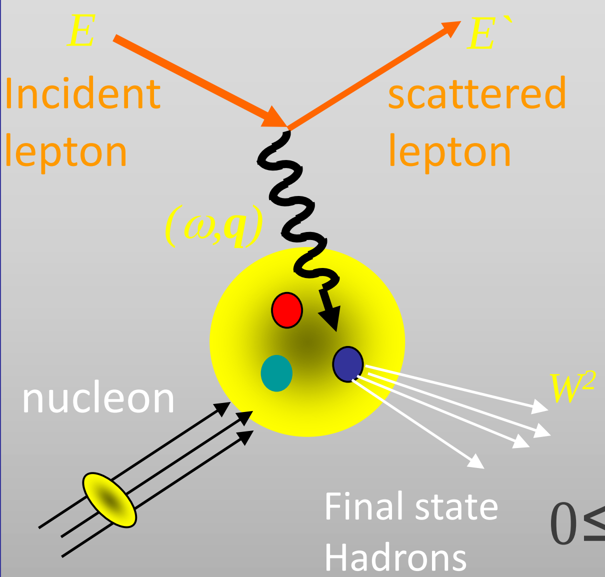
$0 \le X_B \le 1$

X_B gives the fraction of nucleon momentum carried by the struck parton

Information about nucleon vertex is contained in $F_1(x,Q^2)$ and $F_2(x,Q^2)$, the unpolarized structure functions

Inclusive electron scattering A(e,e')

Deep Inelastic Scattering (DIS)



$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

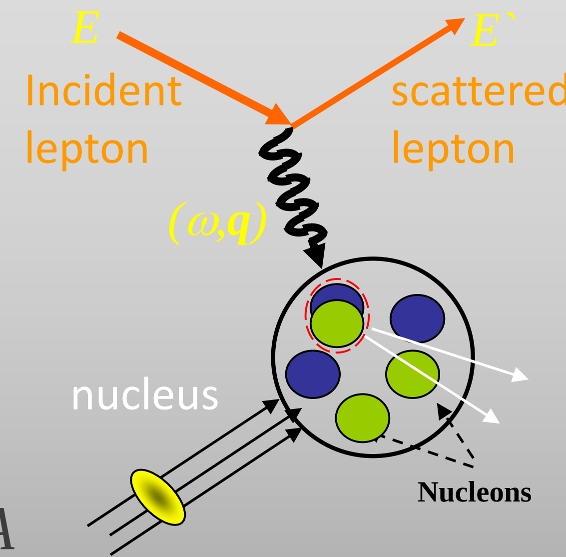
$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \qquad \left(x_B^{'} = \frac{Q^2}{2(q \cdot p_T)}\right)$$

$0 \leq x_B \leq 1$

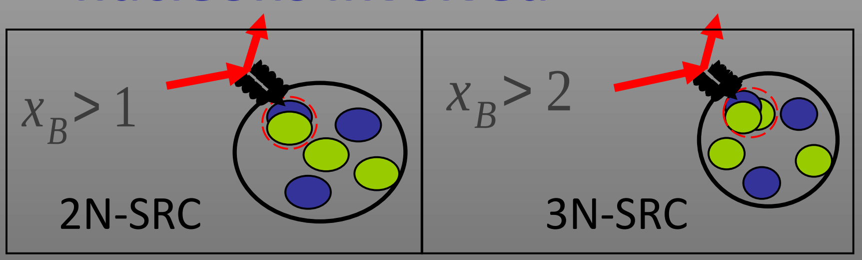
$0 \leq x_B \leq A$

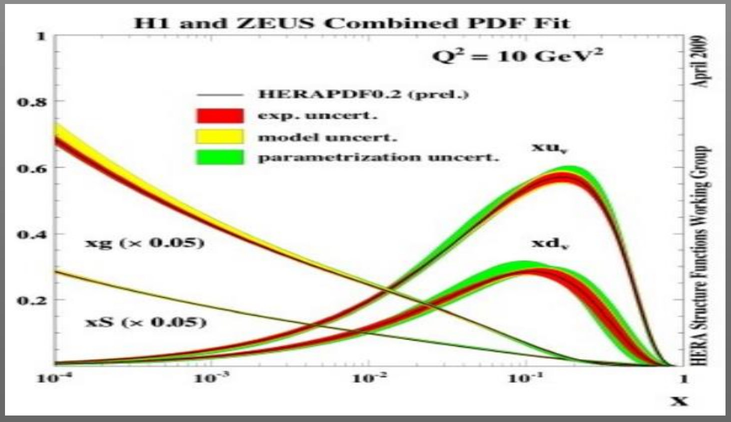
Hard knockout reaction



x_B gives the fraction of nucleon momentum carried by the struck parton

x_B counts the number of nucleons involved





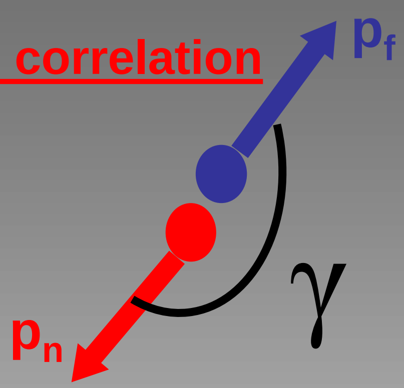
--> scaling

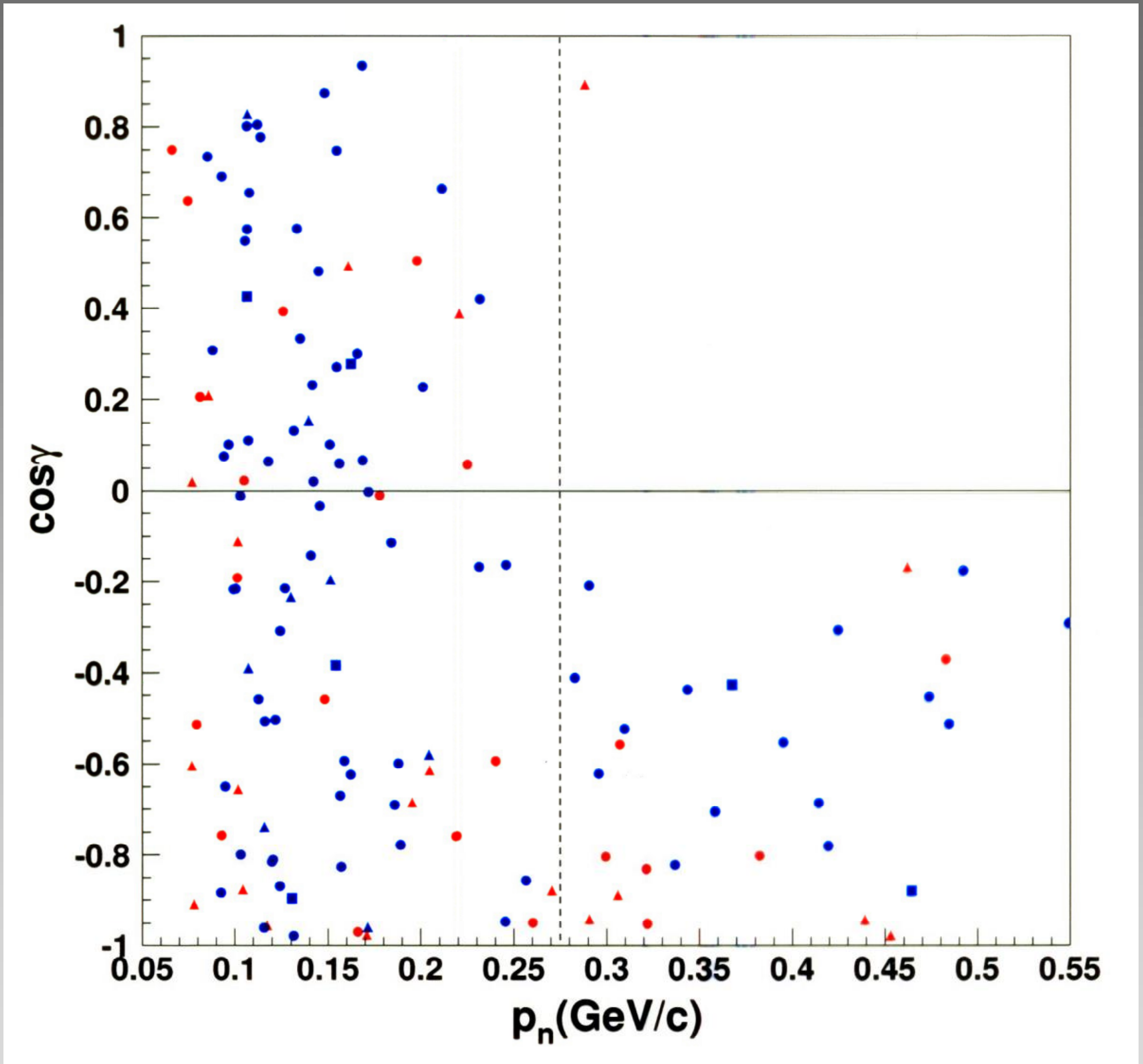
--> Counting the number of SRC clusters in nuclei

$^{12}C(p, p'pn)$ measurements at EVA / BNL

A. Tang et al. Phys. Rev. Lett. 90 ,042301 (2003)

Directional correlation





Piasetzky, Sargsian, Frankfurt, Strikman, Watson **PRL 162504(2006).**

Removal of a proton with momentum above 275 MeV/c from ^{12}C is **$92\pm^{8}_{18}$ %** accompanied by the emission of a neutron with momentum equal and opposite to the missing momentum.

σ_{CM}=0.143±0.017 GeV/c

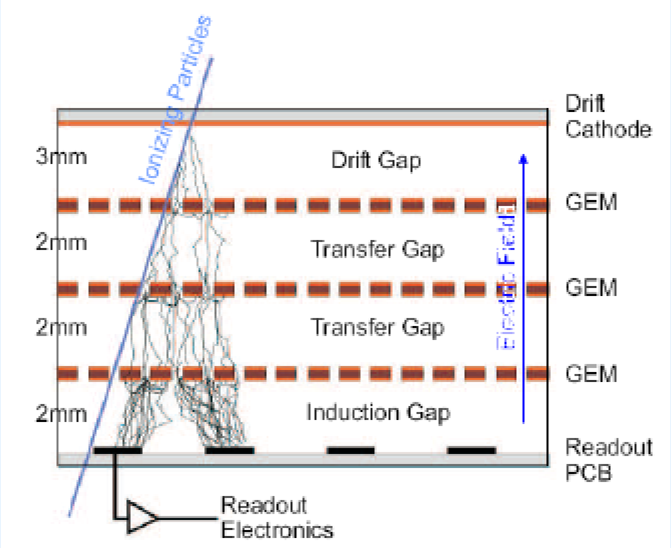
Principle of GEM Detectors

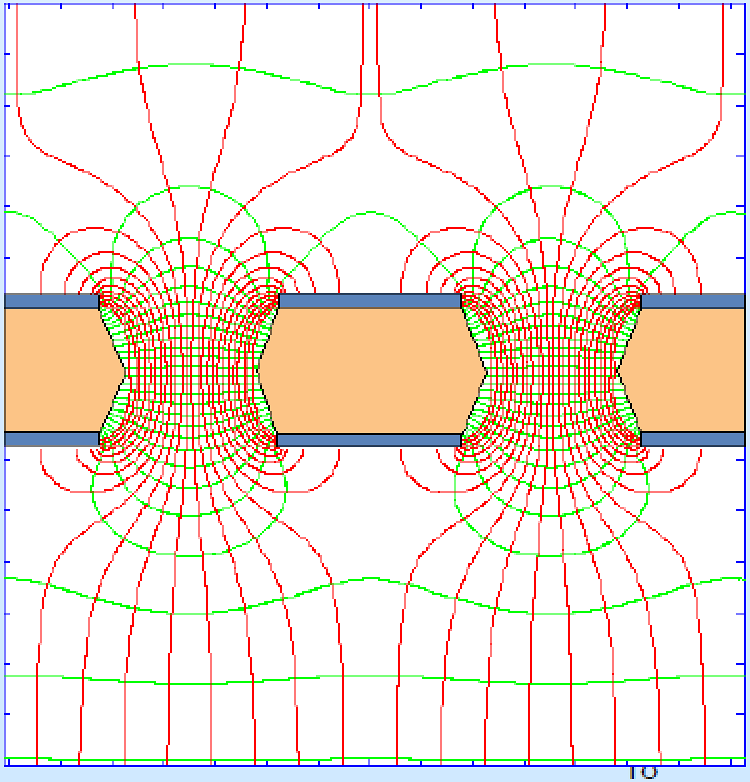
- GEM = Gas Electron Multiplier

  introduced by F. Sauli in mid 90's, F. Sauli et al., NIMA 386 (1997) 531

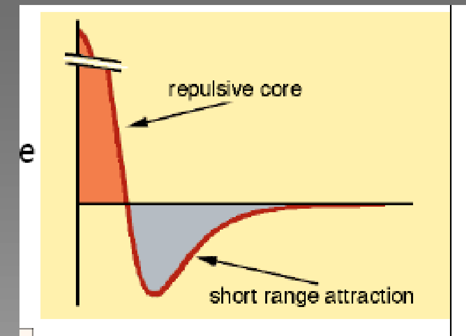
- Copper layer-sandwiched kapton foil with chemically etched micro-hole pattern

⇒ gas amplification in the hole





A description of nuclei at distance scales small compared to the radius of the constituent nucleons is needed to take into account,



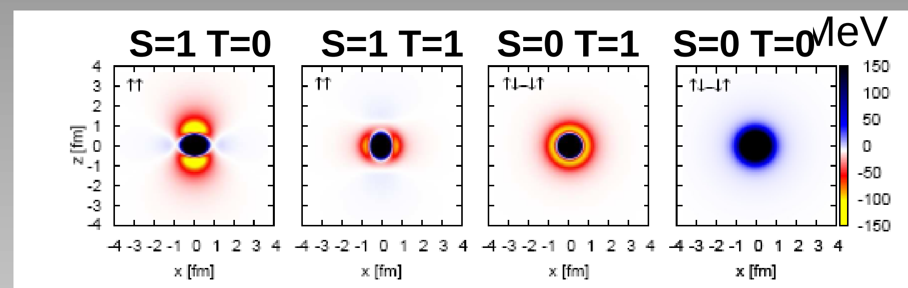
Short- range repulsion

(common to many other systems)

Intermediate-range tensor attraction

(unique to nuclei)

Argonne V8 potential



ArXiv 1107.4956

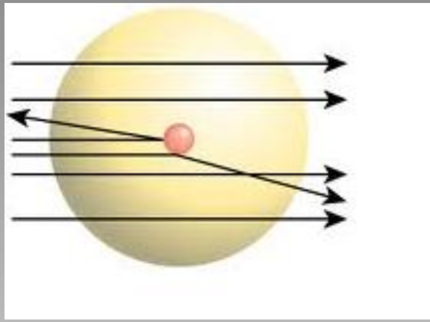
long- range attraction

Very difficult many-body problem

presents a challenge to both experiment and theory

This long standing challenge for nuclear physics can experimentally be effectively addressed thanks to high energy and large momentum-transfer (hard scattering) reached by present facilities.

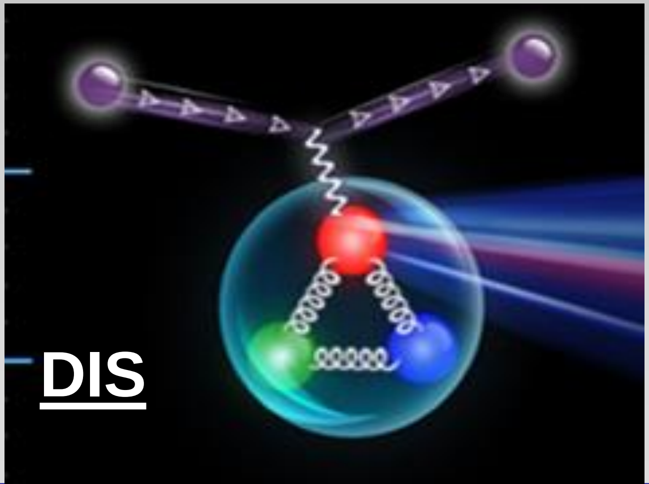
Hard processes



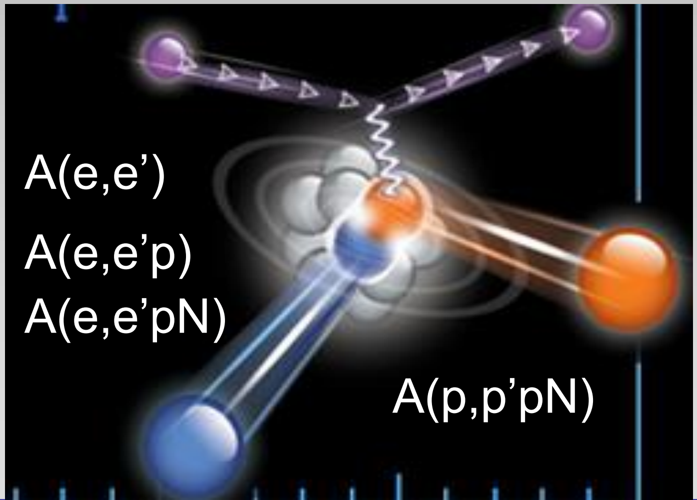
structure of atoms

Rutherford scattering

structure of nucleons



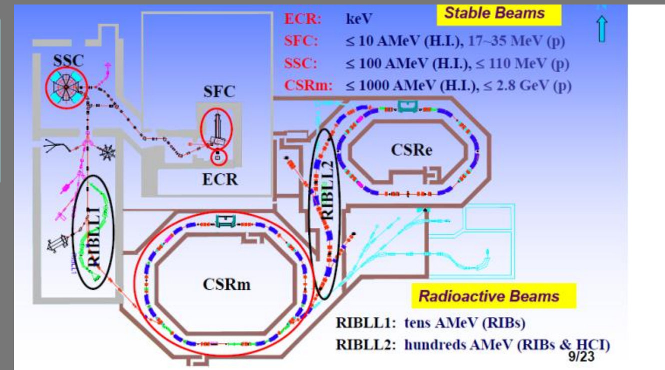
structure of nuclei

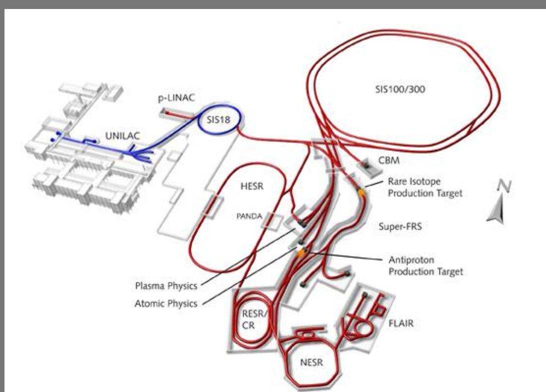


The new facilities:

CSR, Lanzhou

up to 3.6 GeV/c





GSI ->FAIR / PANDA

1.5-15 GeV/c

30 GeV/c

J-PARC
Japan Proton Acce

pA@RICH BNL

100 GeV protons on
100 GeV/nucleon heavy ions

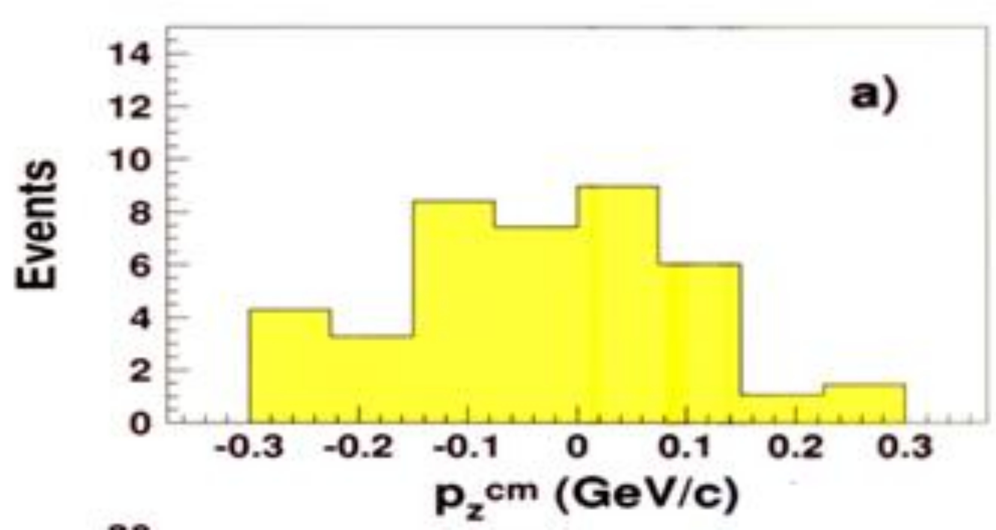
CM motion of the pair ("old" data)

$^{12}C(p,2pn)$ experiment at BNL : σ_{CM}=143 ± 17 MeV/c

$$p_z^{cm} = 2m\left(1 - \frac{\alpha_p + \alpha_n}{2}\right),$$

A. Tang et al.
B. Phys. Rev. Lett. 90 ,042301 (2003)

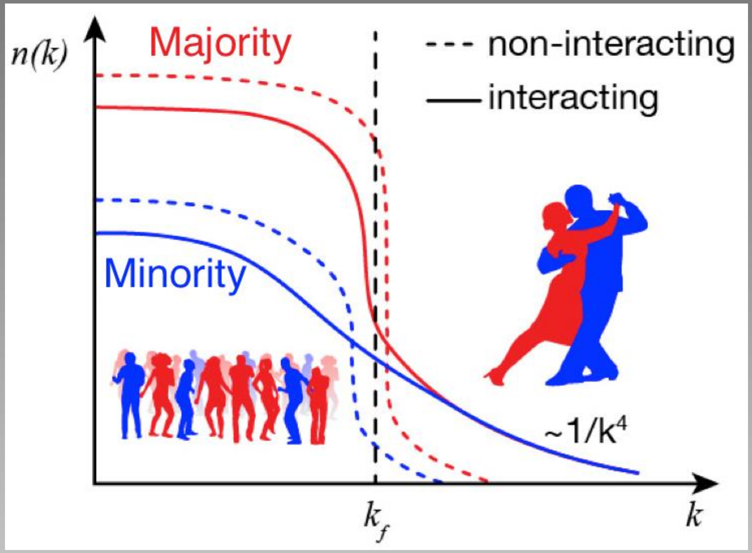
Theoretical prediction (Ciofi and Simula) :
σ_{CM}=0.139 GeV/c PRC 53 (1996) 1689.



Only ~20 $^{12}C(p,2p+n)$ events with $p_n > k_F$

Asymmetric nuclei N>Z:

np-SRC dominance



Equal number of protons and neutrons above k_F

The probability for a proton to be with momentum above k_F is higher than for a neutron

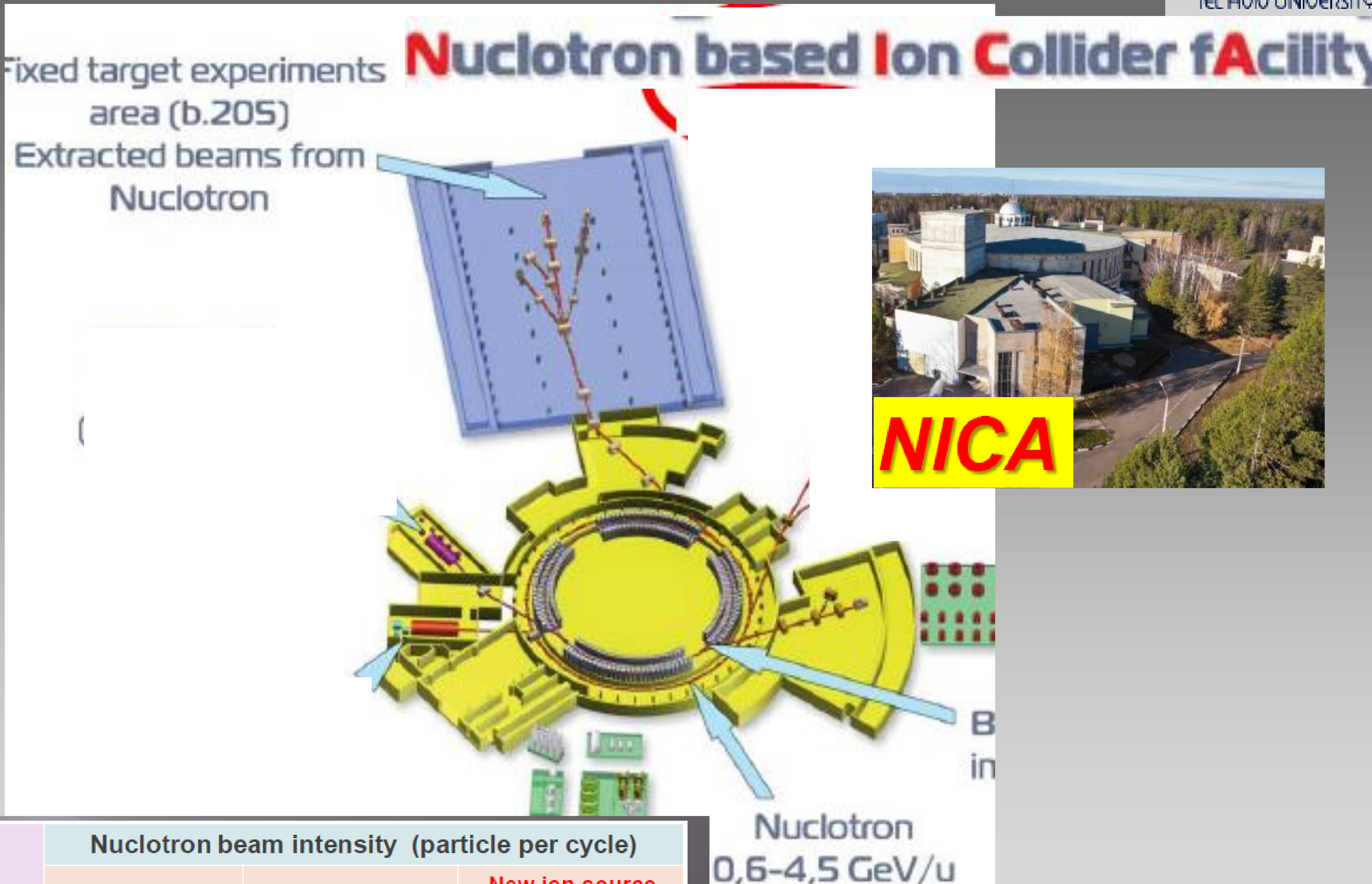
SRC @

at Nuclotron

at Nuclotron

SRC @

Study of SRC at JINR



Beam	Nuclotron beam intensity (particle per cycle)		
	Current	Ion source type	New ion source + booster
p	$3{\cdot}10^{10}$	Duoplasmotron	$5{\cdot}10^{12}$

Or Hen

אוניברסיטת תל-אביב
TEL AVIV UNIVERSITY → **MIT**

Guy Ron

האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

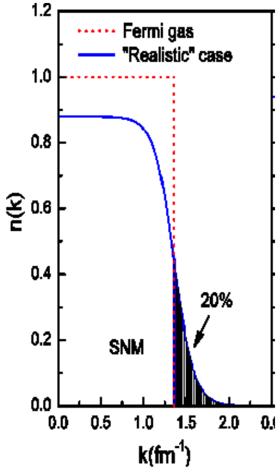
Eli Piasetzky

אוניברסיטת תל-אביב
TEL AVIV UNIVERSITY

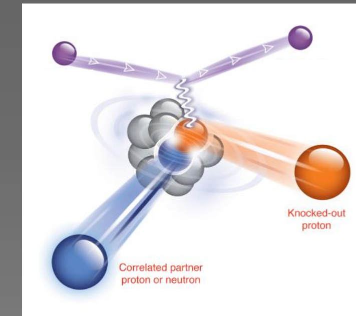
SRC @

at Nuclotron

?


Fermi gas
"Realistic" case
n(k)
SNM
20%
k(fm^{-1})

Number of hard triple coincidence events (World data)



experiment	pp pairs	np pairs	nn pairs
EVA/BNL	-	18	-
E01-015/JLab	263	179	-
E07-006/JLab	50	223	-
CLAS/JLab	1533	-	-
Total	<2000	<450	0

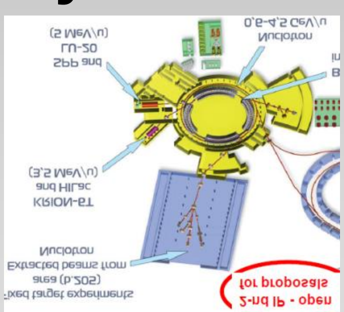
$^{12}C(p,2pn)$

$^{12}C(e,e'pn)$ $^{12}C(e,e'pp)$

$^{4}He(e,e'pn)$ $^{4}He(e,e'pp)$

$\mathrm{C, Al, Fe, Pb}\,(e,e'pp)$

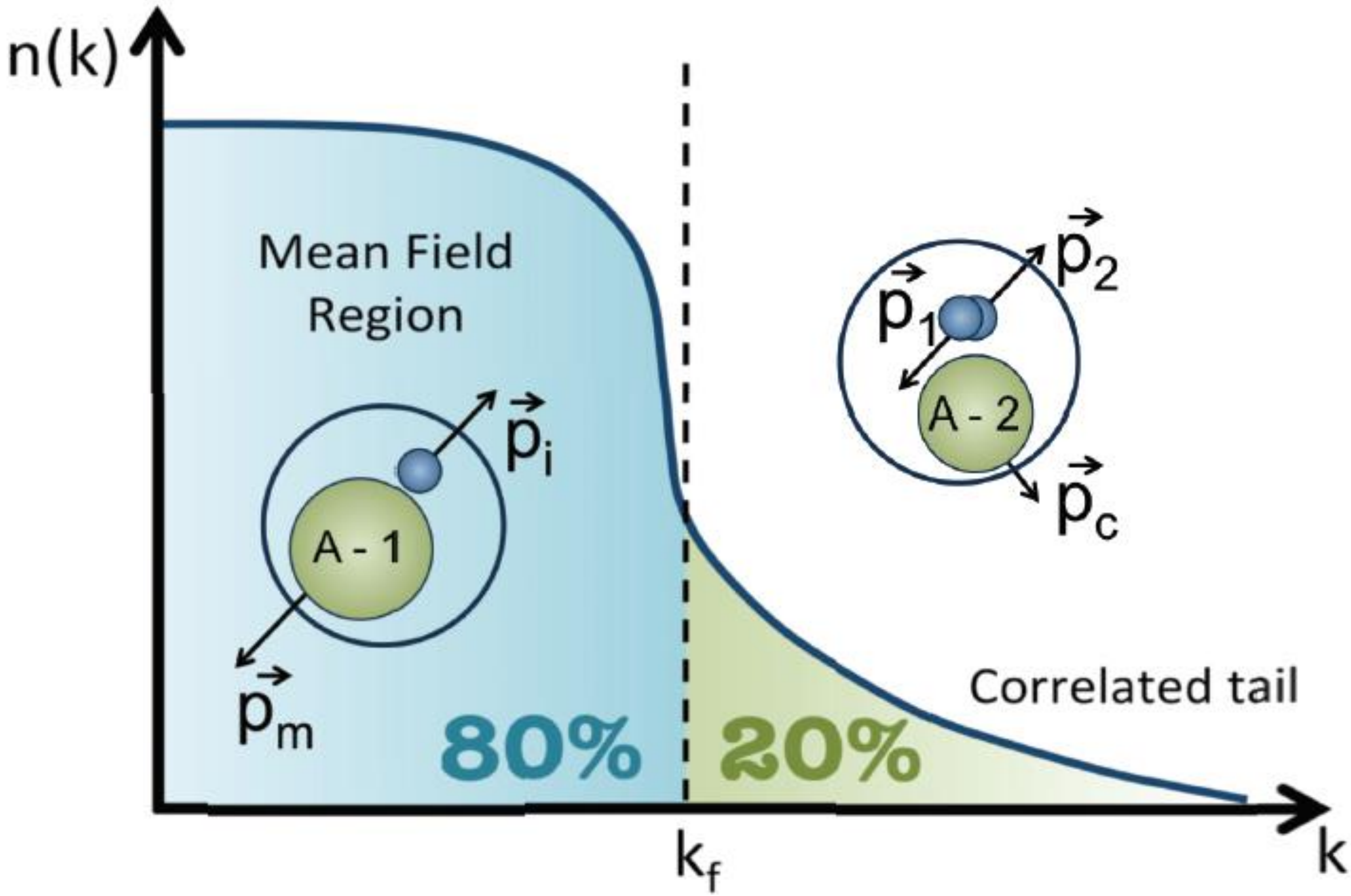
Why are we here ?



Nuclotron

➔ >10k events Before 2018

5 GeV/c 10^9 protons/sec fixed target


n(k)
Mean Field
Region
$\vec{p}_i$
A - 1
$\vec{p}_m$
80%
$\vec{p}_2$
$\vec{p}_1$
A - 2
$\vec{p}_c$
Correlated tail
20%
k_f
k

We want to investigate SRCs with new probes.

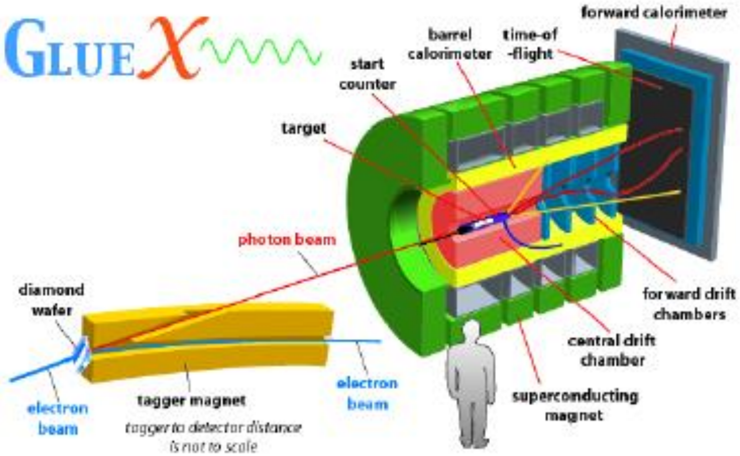
Proposals:

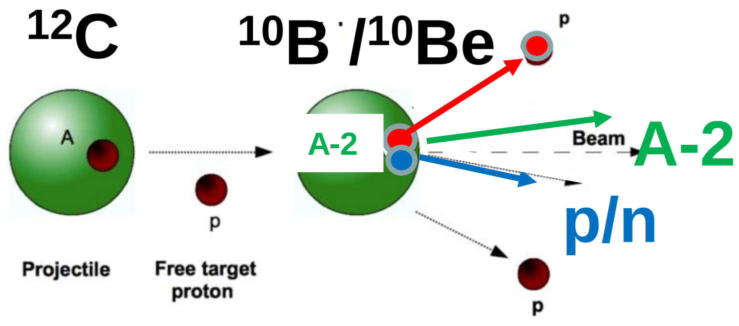
1. Inverse kinematics at Dubna
2. Protons at GSI
3. Photons at GlueX

Glue-X: study SRC pairs with real photons.

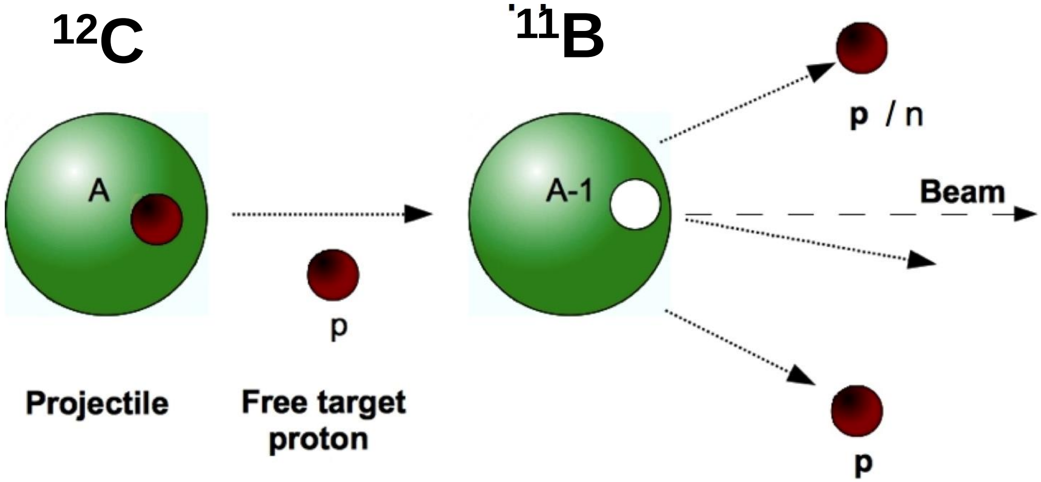
- Glue-X detector at JLab Hall D
- Study neutrons with charged final states:
  - $\gamma n \longrightarrow \pi^- p$
- Tests of vector meson dominance and transparency

For details talk with Maria Patsyuk





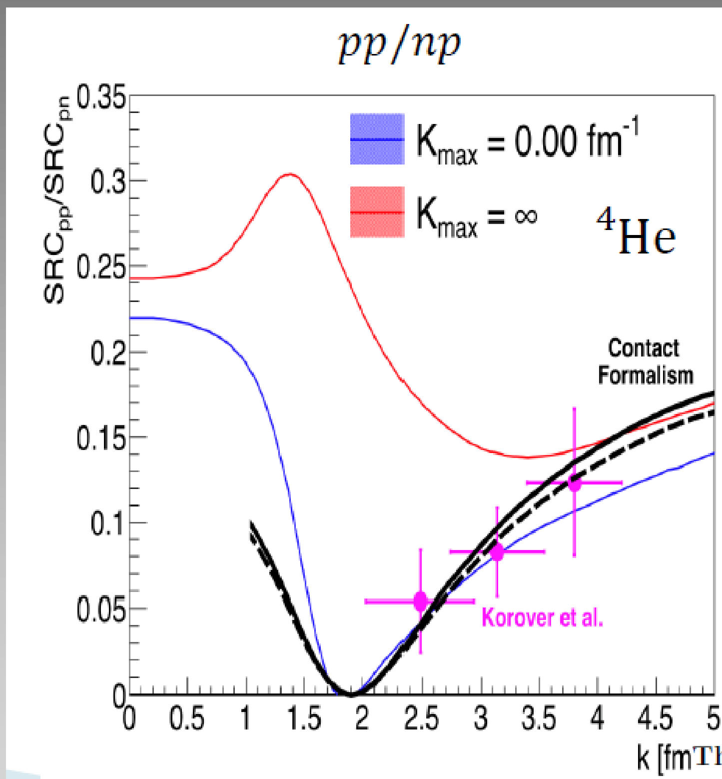
12C
10B /10Be
p
A
A-2
Beam
A-2
p/n
p
Projectile
Free target proton
p

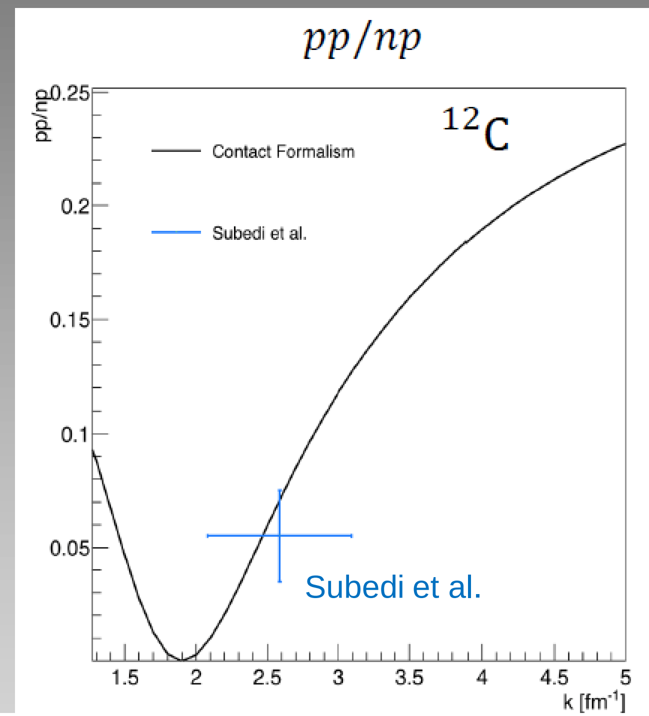


12C
11B
p / n
A
A-1
Beam
p
Projectile
Free target proton
p

Nuclear contact calculations

(Weiss, Cruz-Torres, Barnea, Piasetzky, Hen)



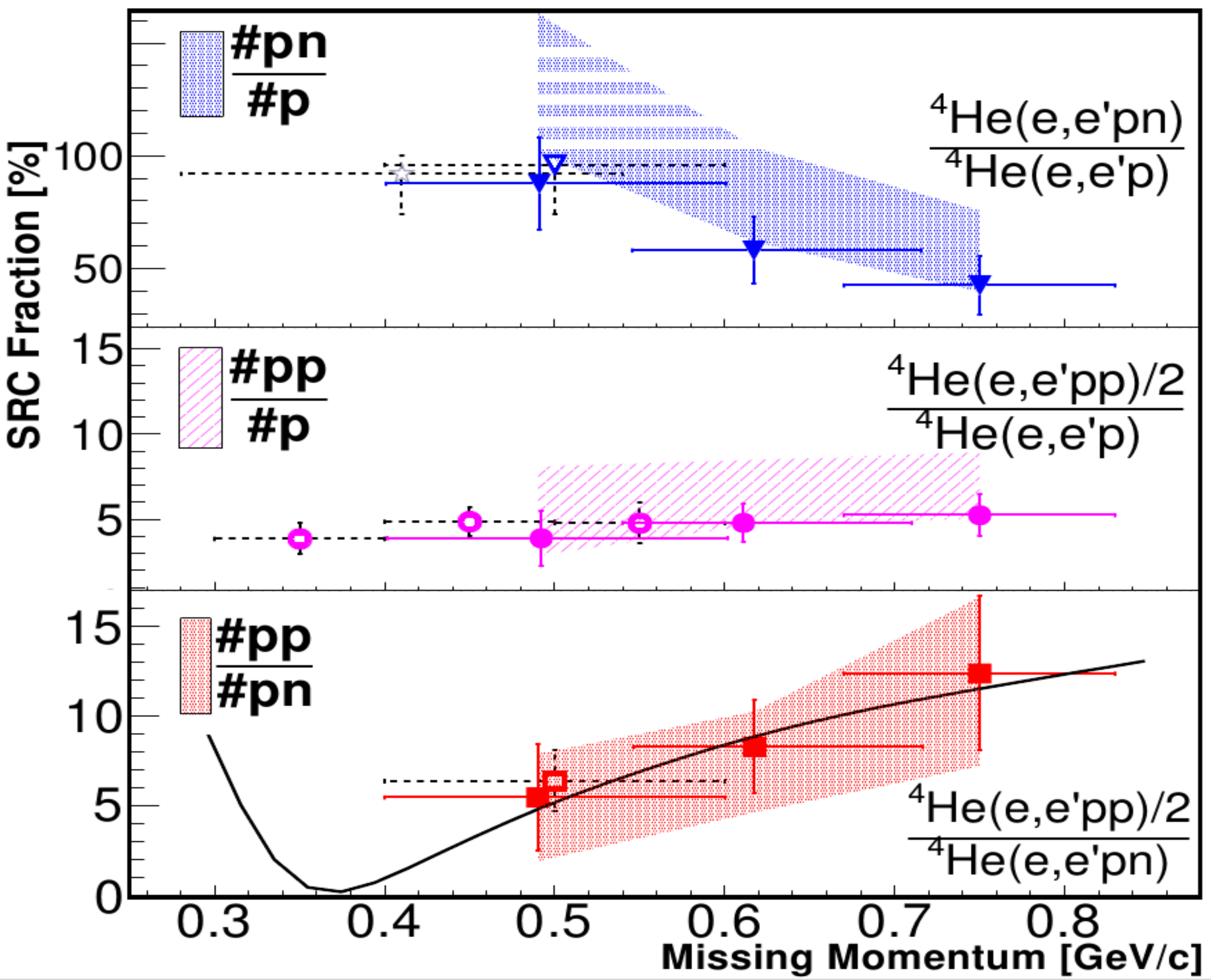


The nuclear contacts and short range correlations in nuclei

R. Weiss,[1] R. Cruz-Torres,[2] N. Barnea,[1] E. Piasetzky,[3] and O. Hen[2]

E07-006 (2011) ^{4}He (^{12} C)

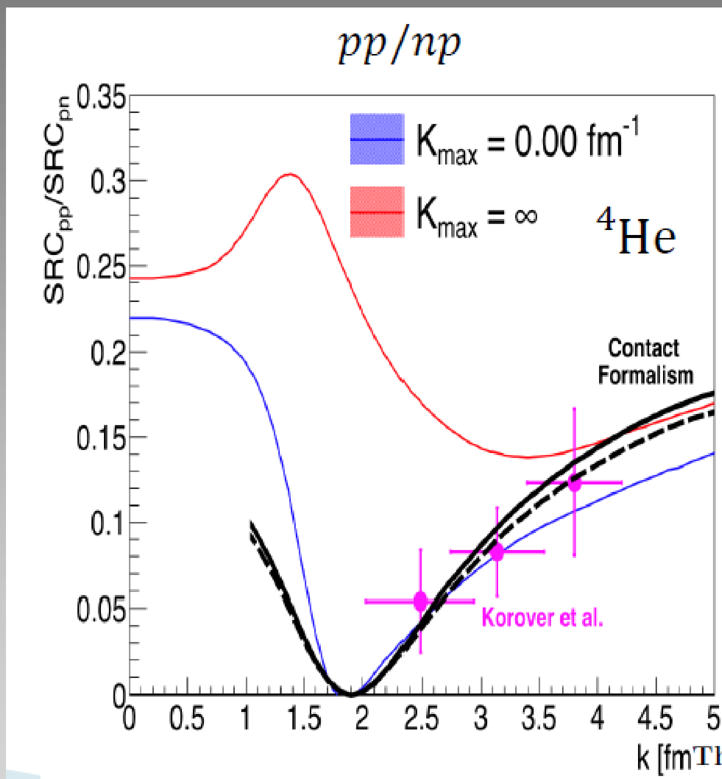
New Jlab experiment extend the SRC measurement to **P_{miss}=850 MeV/c**

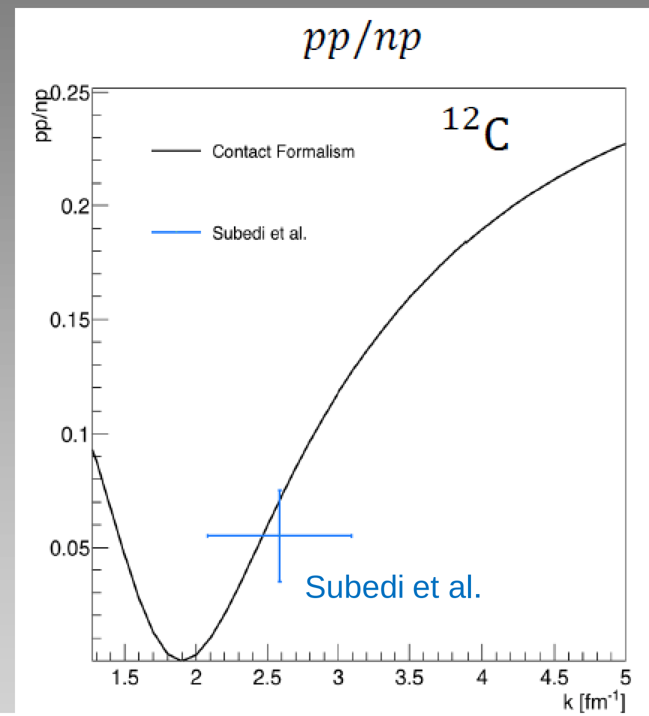


I. Korover et al. Phys. Rev. Let. 113, 022501 (201

Nuclear contact calculations

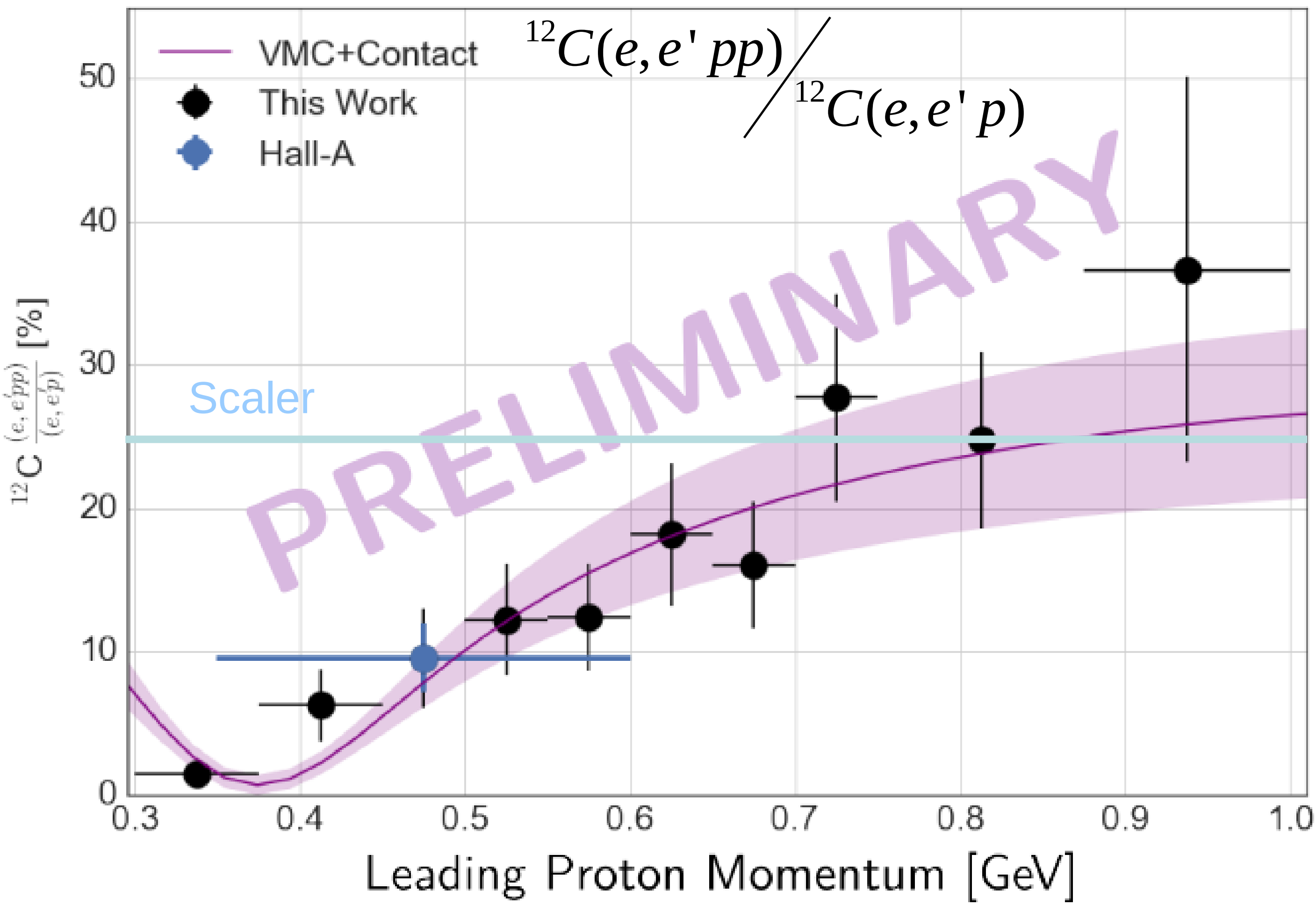
(Weiss, Cruz-Torres, Barnea, Piasetzky, Hen)



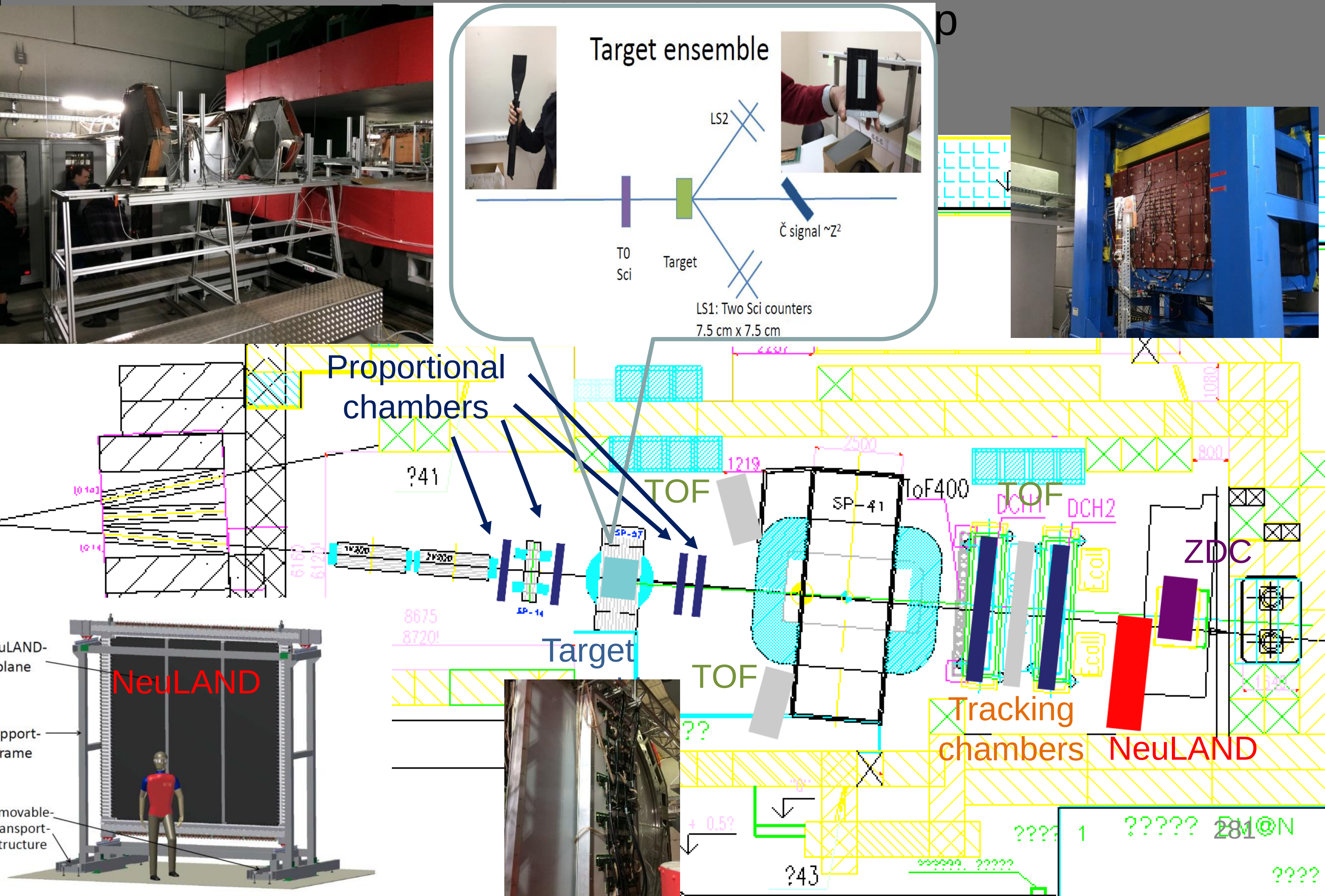


The nuclear contacts and short range correlations in nuclei

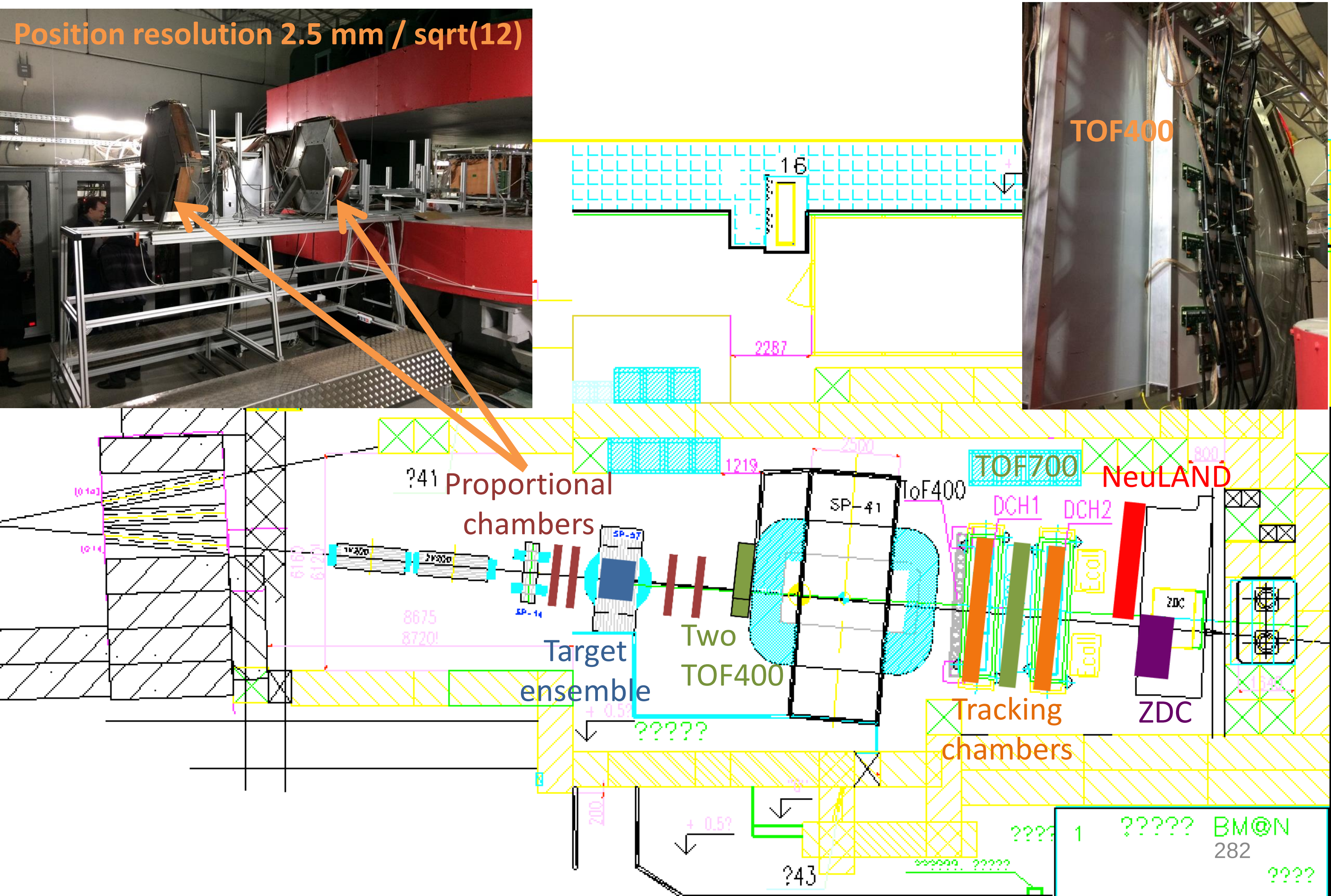
R. Weiss,[1] R. Cruz-Torres,[2] N. Barnea,[1] E. Piasetzky,[3] and O. Hen[2]

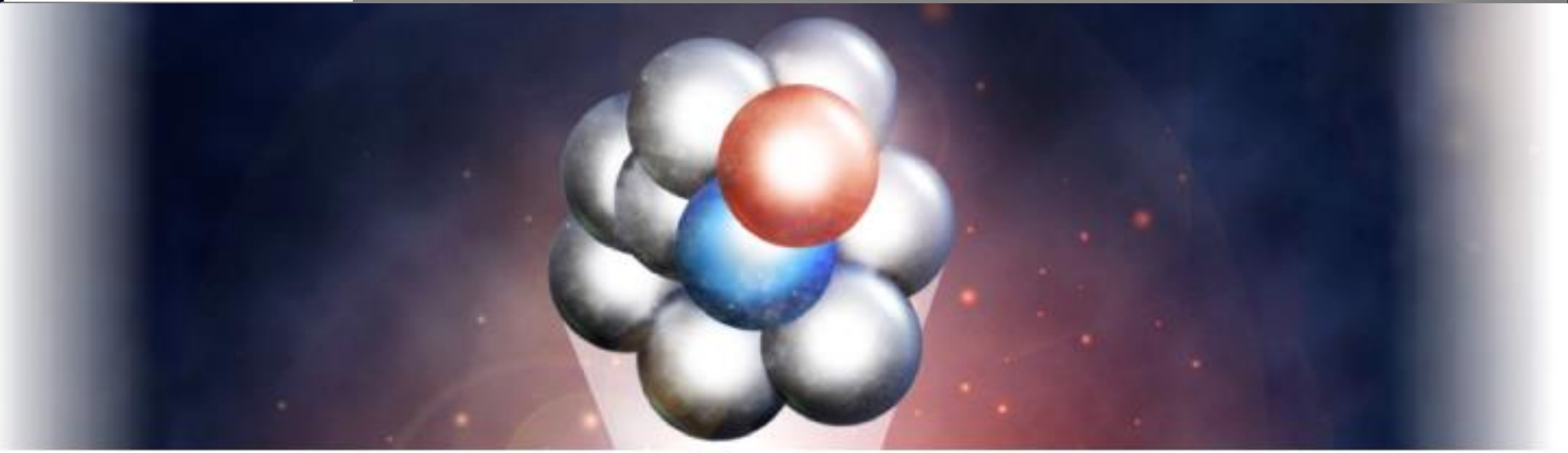


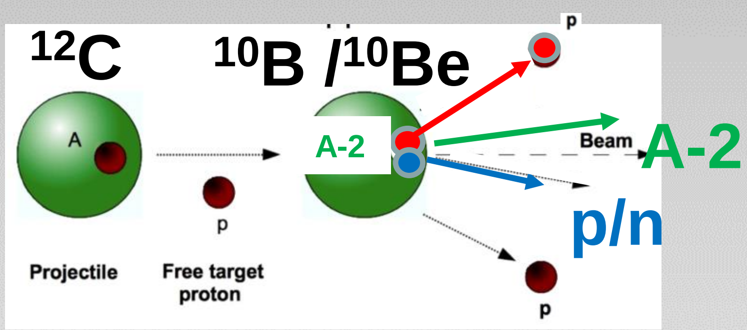
Data mining , CLAS/Jlab, analysis by Erez Cohen (TAU)


Target ensemble
LS2
T0
Sci
Target
Č signal ~Z²
LS1: Two Sci counters
7.5 cm x 7.5 cm
Proportional
chambers
Target
TOF
TOF
TOF
ToF400
SP-41
DCH1
DCH2
ZDC
Tracking
chambers
NeuLAND
NeuLAND
BM@N

Proposed experimental layout



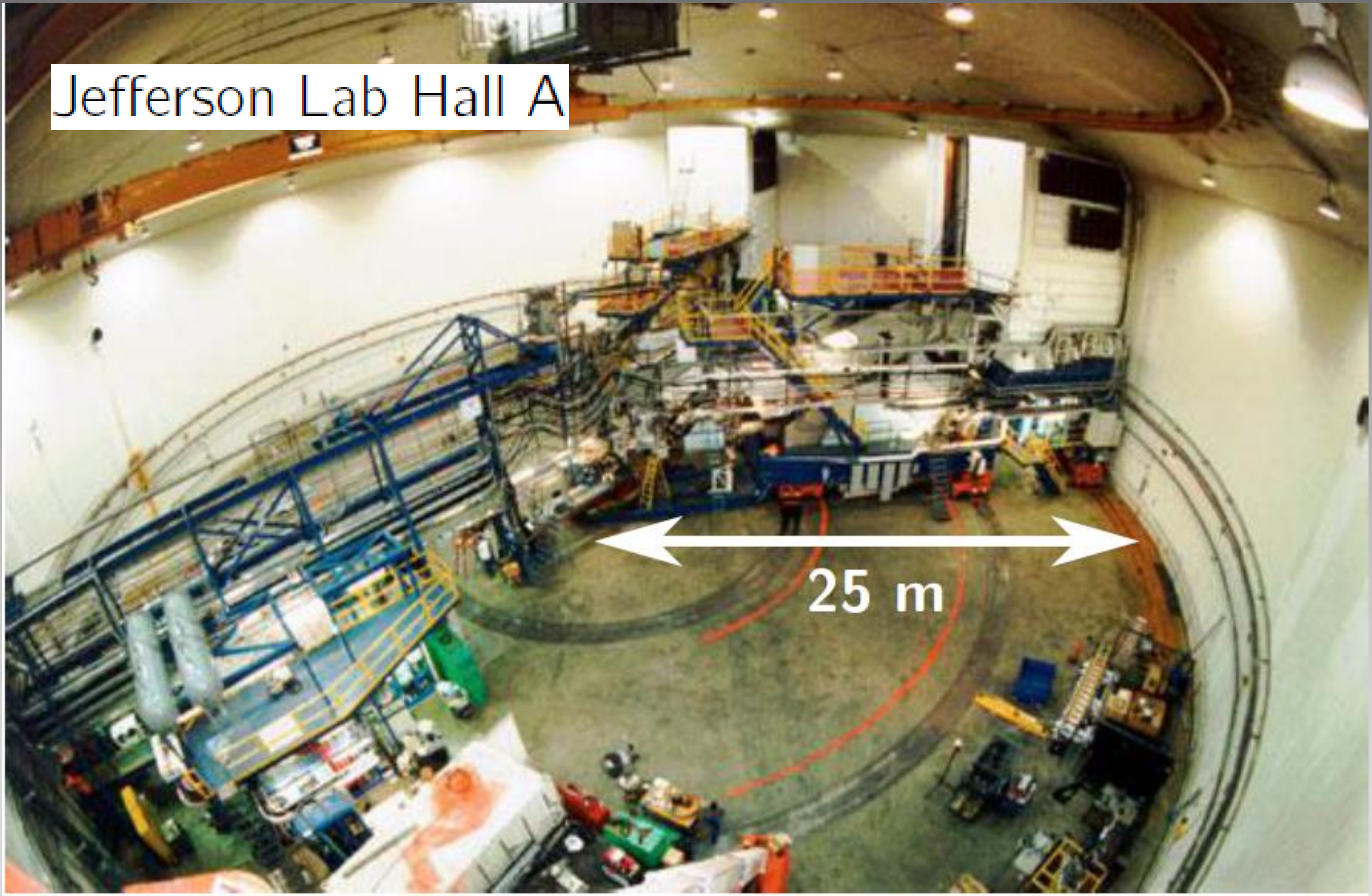


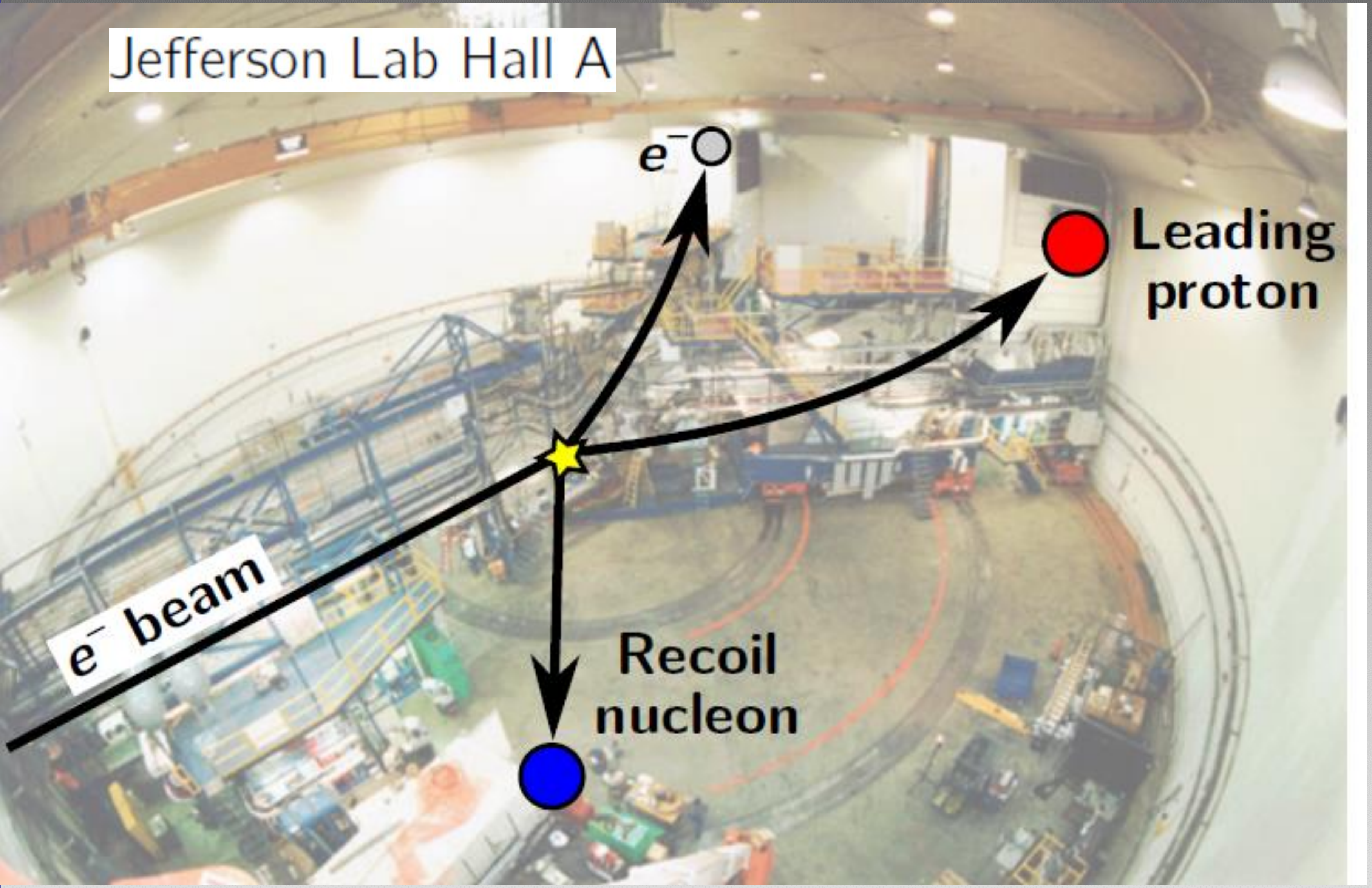


SRC @ JINR Dubna

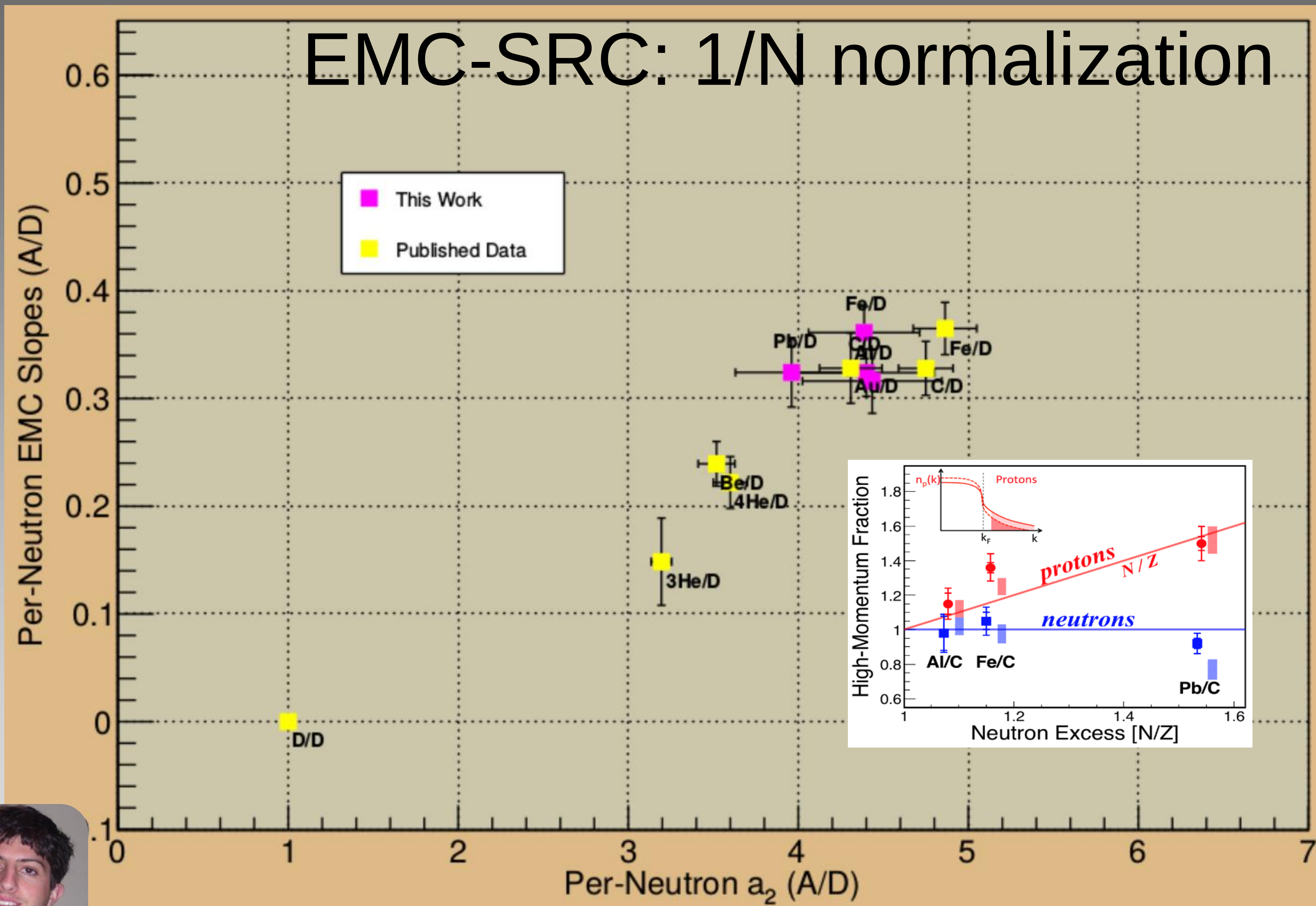
Eli Piasetzky Tel Aviv University, Israel

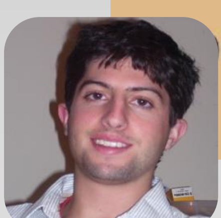
April 2017


Jefferson Lab Hall A
25 m


Jefferson Lab Hall A
e⁻
Leading proton
Recoil nucleon
e⁻ beam

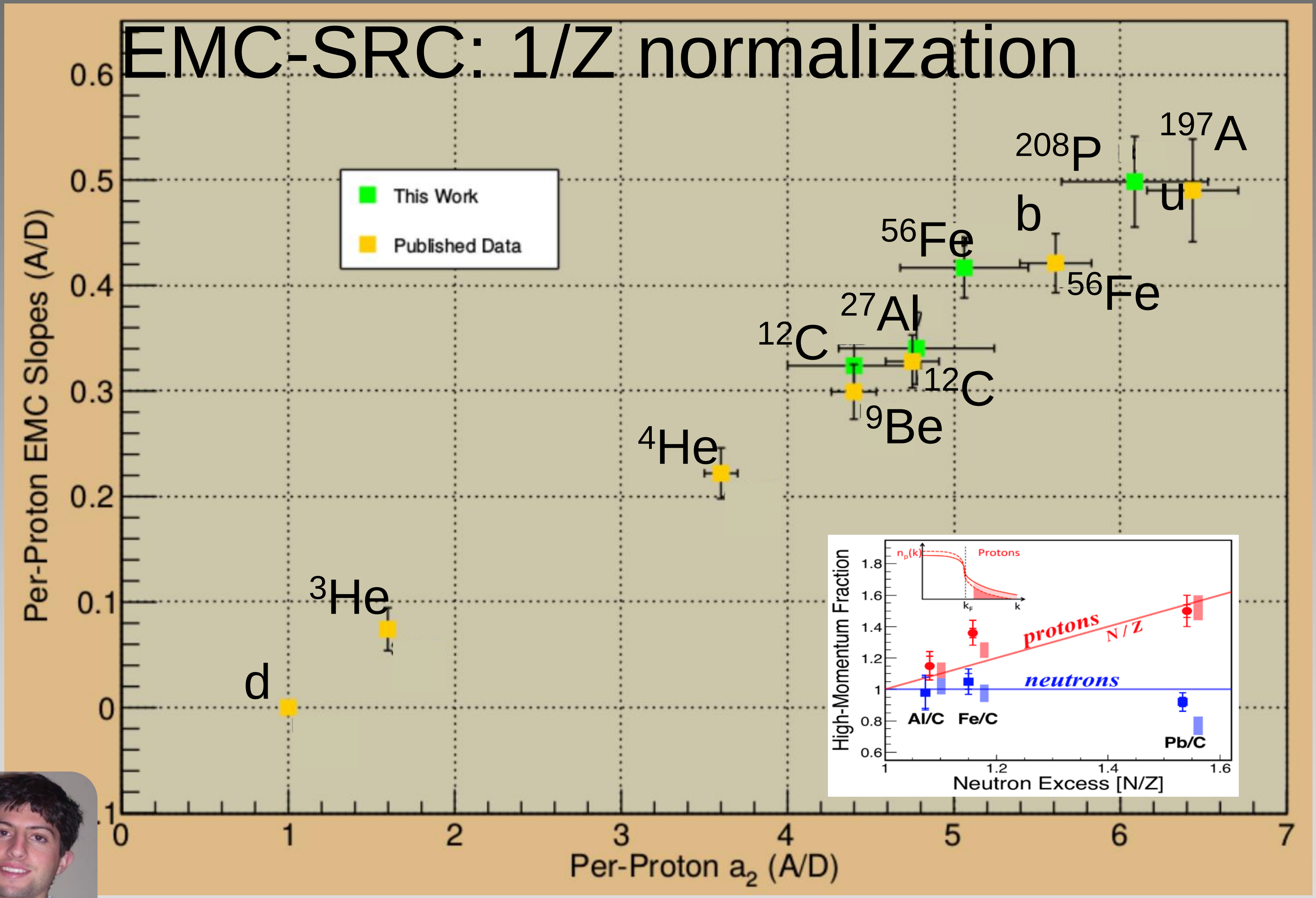
Preliminary results from data mining (EG2c)





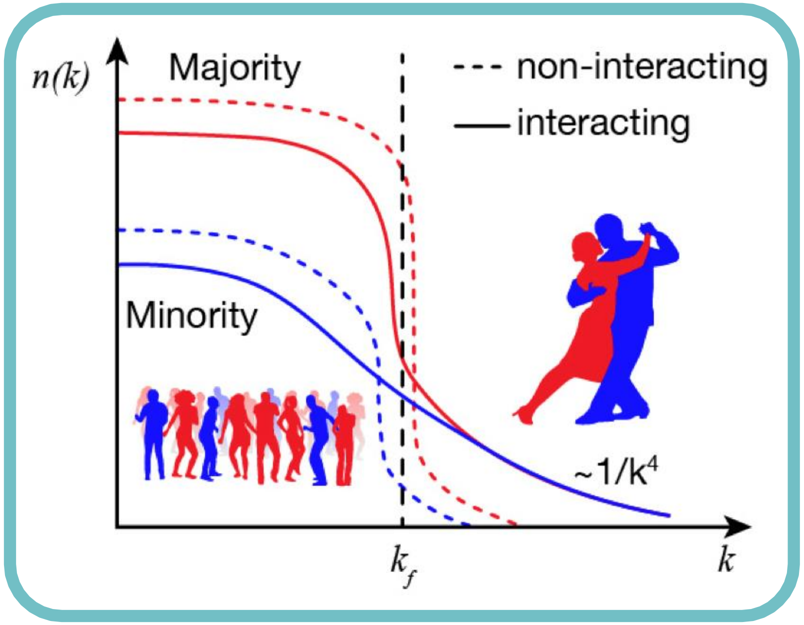
Barak Schmookler / MIT

Preliminary results from data mining (EG2c)



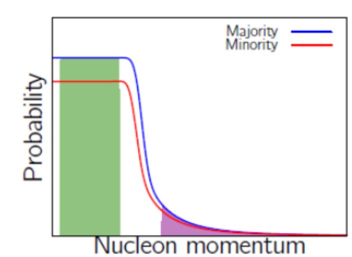
Barak Schmookler / MIT

np-dominance in asymmetric nuclei



M. Sargsian Phys. Rev. C89(2014)3, 034305

O. Hen et al., Science 346, 614 (2014)



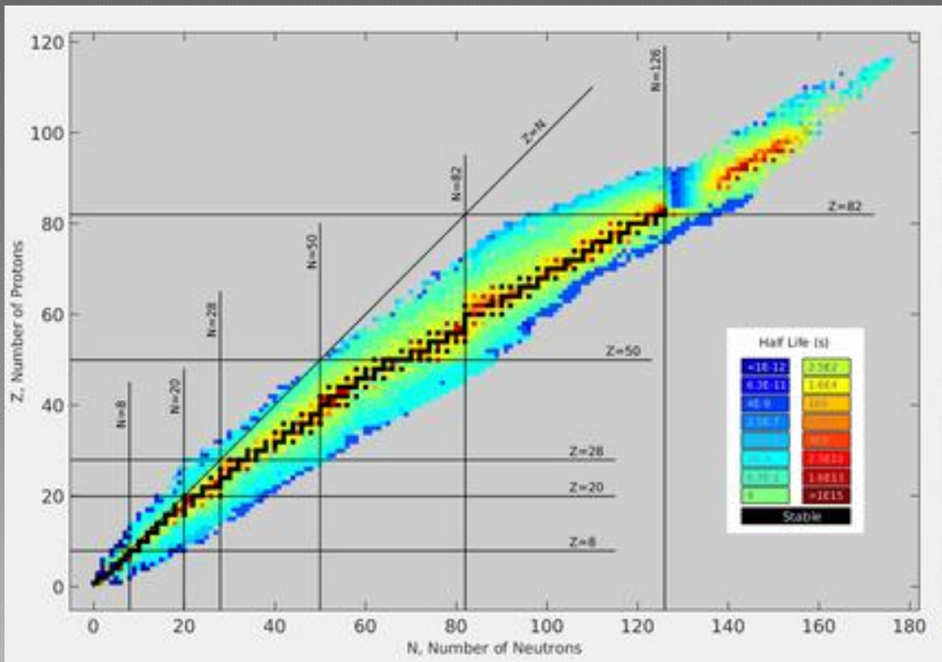
N>Z

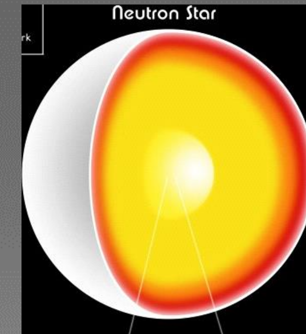
$$\langle T_{p(n)}\rangle = \int n_{p(n)} \cdot \frac{k^2}{2m} \cdot d^3k$$

Pauli principle → $\langle T_n\rangle > \langle T_p\rangle$

SRC → $\langle T_p\rangle \overset{?}{>} \langle T_n\rangle$

Possible inversion of the momentum sharing

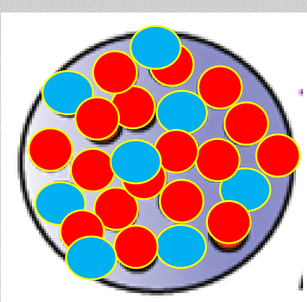




$$A \approx \frac{M_{\odot}}{M_p} \approx 10^{57}$$

$$N / Z \approx 95\% / 5\% = 20$$

$$\rho_0 = 2 - 5\ \rho_0$$

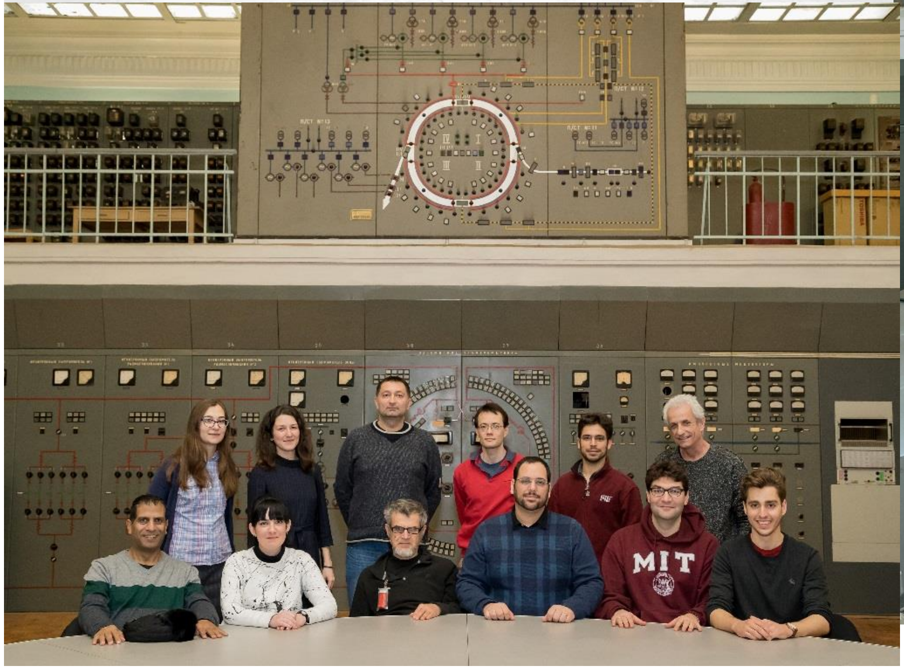


$$A < 200\ (300)$$

N/Z<1.5 (2.5)

$$\rho_0 = 0.17\ N / \ fm^3$$

Had


MIT

•~95% neutrons, ~5% protons ~5% electrons (β-stability).

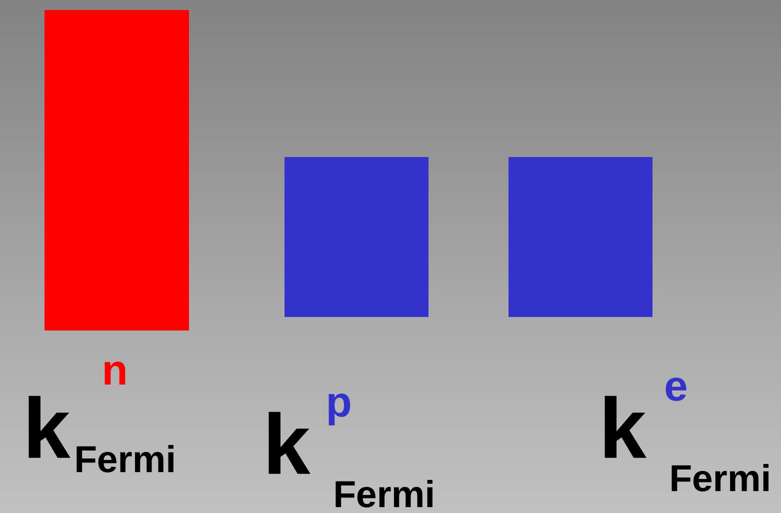
•three separate Fermi gases (n, p, e).

Pauli blocking prevent direct n decay

$$n \rightarrow p + \mathrm{e} + \bar{\nu}_{\mathrm{e}}$$

?

Magnetic field



At T=0

$$\frac{\langle E_k^p \rangle}{\langle E_k^n \rangle} = \frac{k_F^p}{k_F^n} = \left(\frac{n_p}{n_n}\right)^{1/3} = \left(\frac{5-10\%}{90-95\%}\right)^{1/3} \approx \frac{1}{2-3}$$

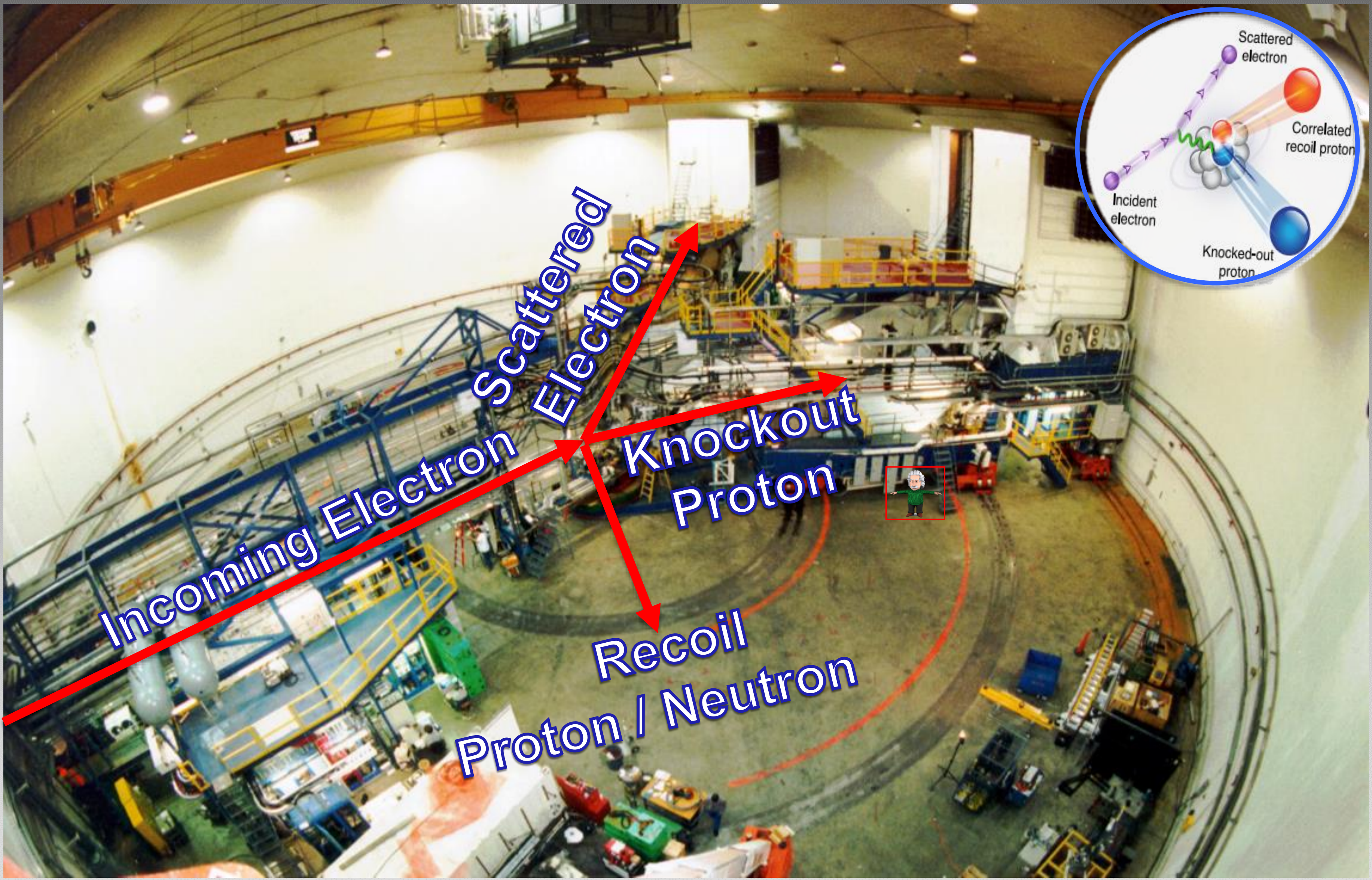
SRC in neutron rich nuclei

$$\frac{\langle E_k^p \rangle}{\langle E_k^n \rangle} > 1$$

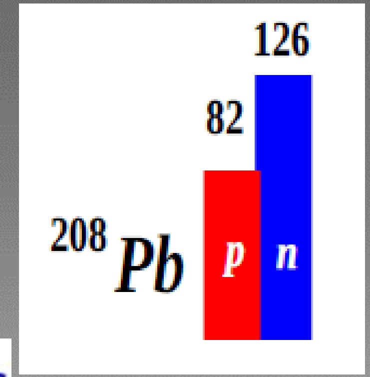
in neutron stars

?

Jefferson Lab Hall A



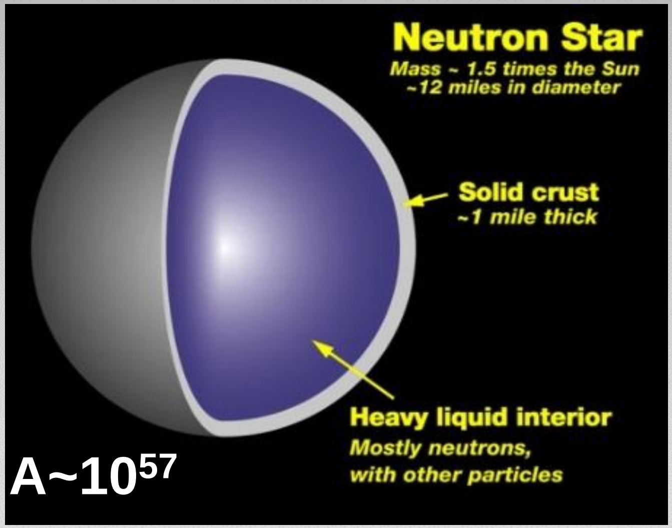
Pauli principle → ~~$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$~~



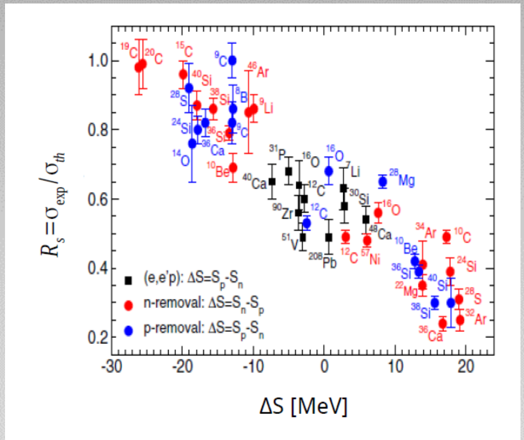
In neutron-rich nuclei (N>Z)

$\langle E_p^{kin} \rangle > \langle E_n^{kin} \rangle$

Protons move faster than neutrons



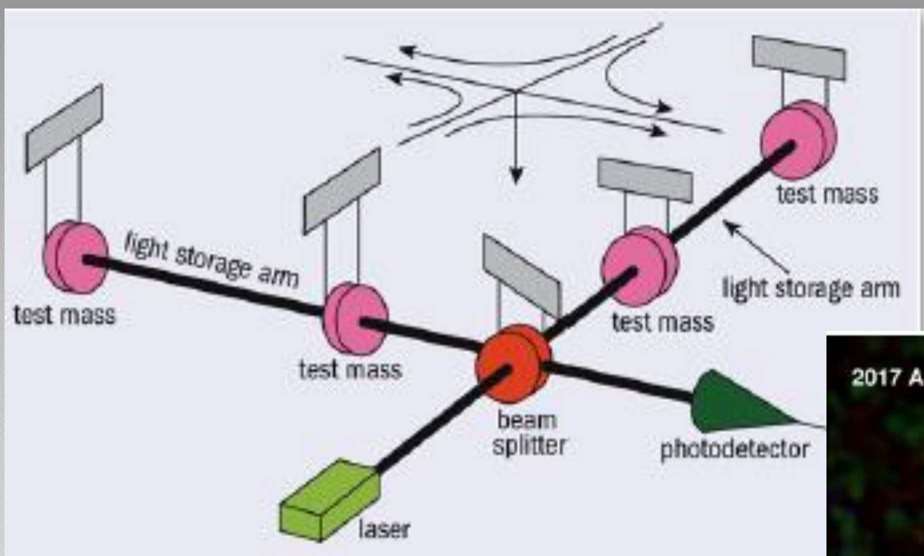
Neutron Stars

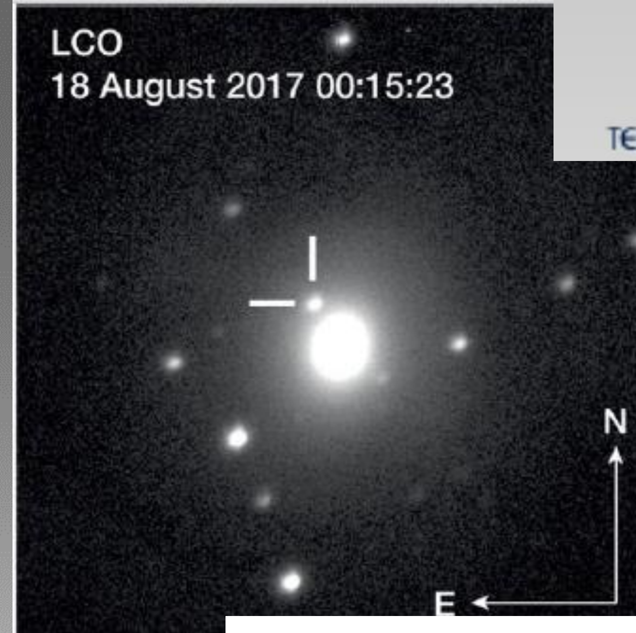


J. A. Tostevin and A. Gade, PRC **90**, 057602 (2014)

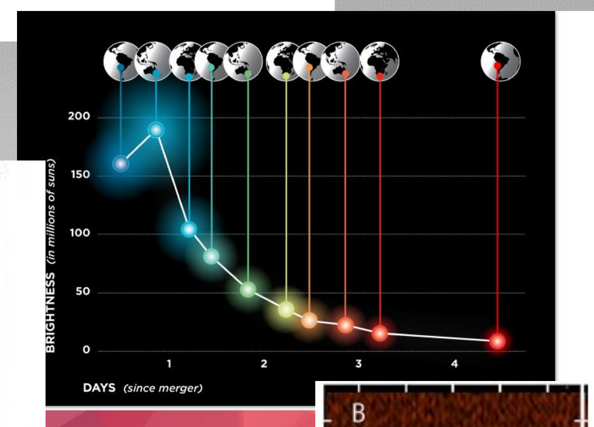
Reduction of the single particle strength

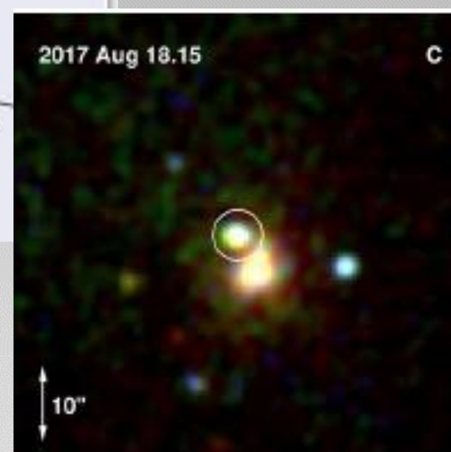
Binary neutron star merge



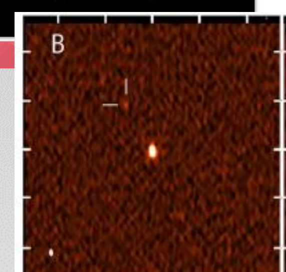


NGC 4993





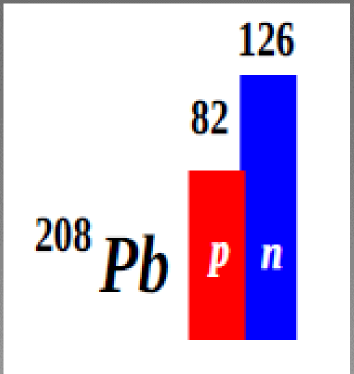
UV (Evans+)



Radio (Hallinan+)

High Momentum Protons Neutron Stars

Pauli principle → ~~$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$~~



In neutron-rich nuclei (N>Z)

$\langle E_p^{kin} \rangle > \langle E_n^{kin} \rangle$

At the core of neutron stars, most accepted models assume:

~95% neutrons, ~5% protons, and ~5% electrons.

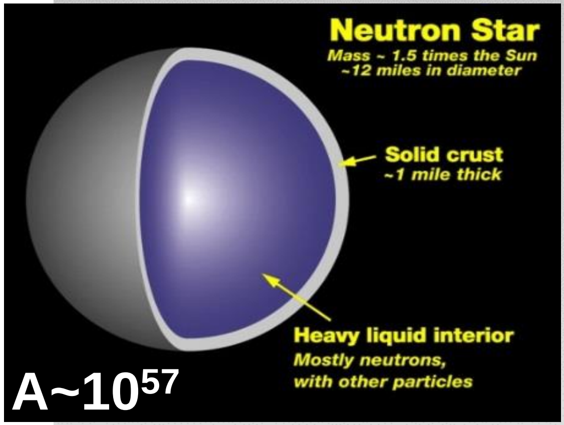
Neglecting np-SRC interaction, one can assume 3 separate Fermi gases.

~500 MeV/c

~250 MeV/c

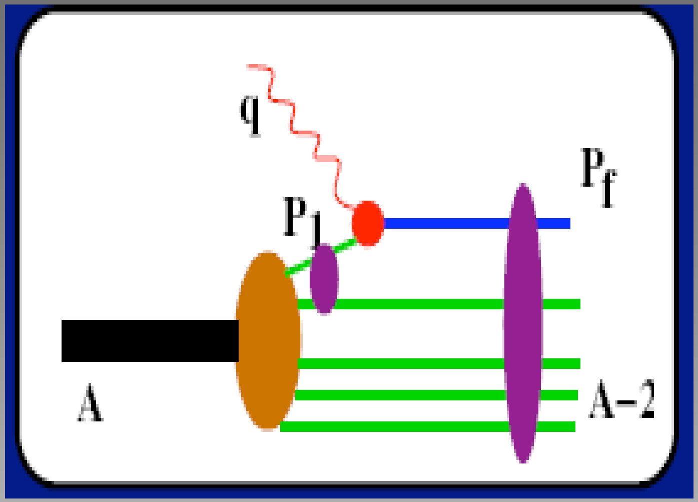
k^n_{Fermi} k^p_{Fermi} k^e_{Fermi}

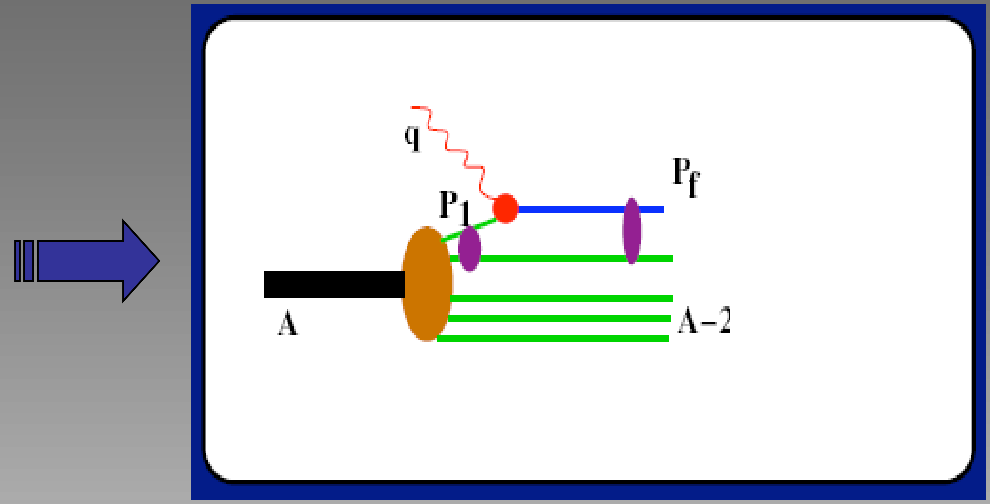
$\langle E_p^{kin} \rangle$? $\langle E_n^{kin} \rangle$



Why FSI do not destroy the 2N-SRC signature ?

For large Q^2 and x>1 FSI is confined within the SRC





distances that highly virtual struck nucleon propagates

$$\Delta E = -q_0 - M_A + \sqrt{m^2 + (p_i + q)^2} + \sqrt{M^2_{A-1} + p_i^2}$$

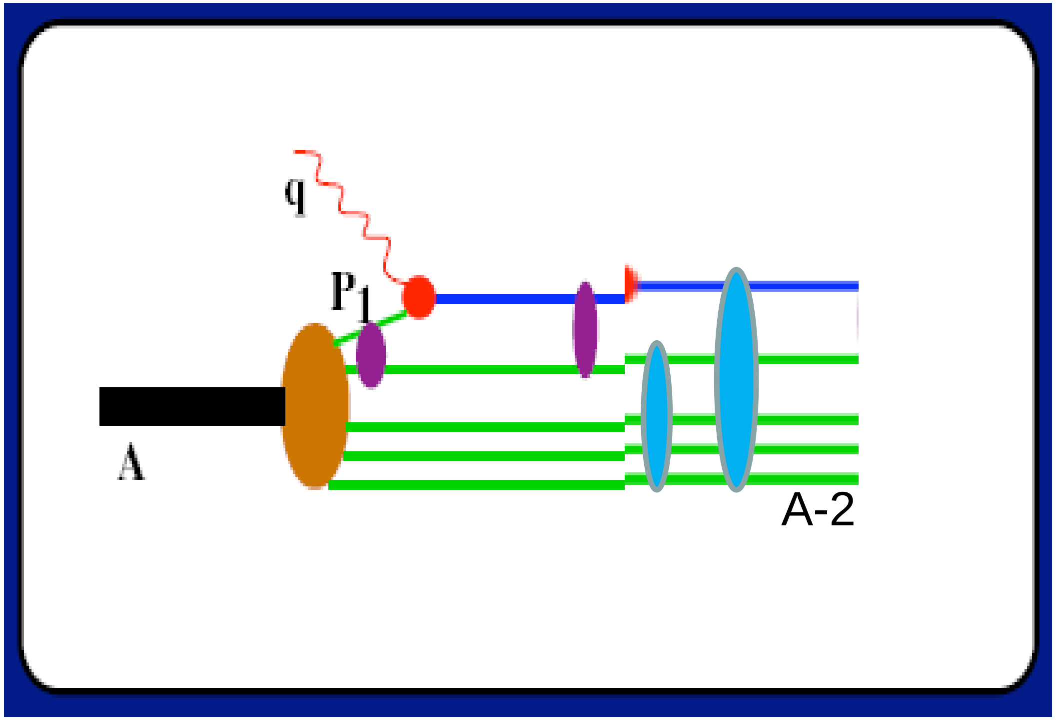
$$r \approx \frac{1}{\Delta E v} \leq 1\,\text{fm}$$

for x > 1.3

FSI in the SRC pair:

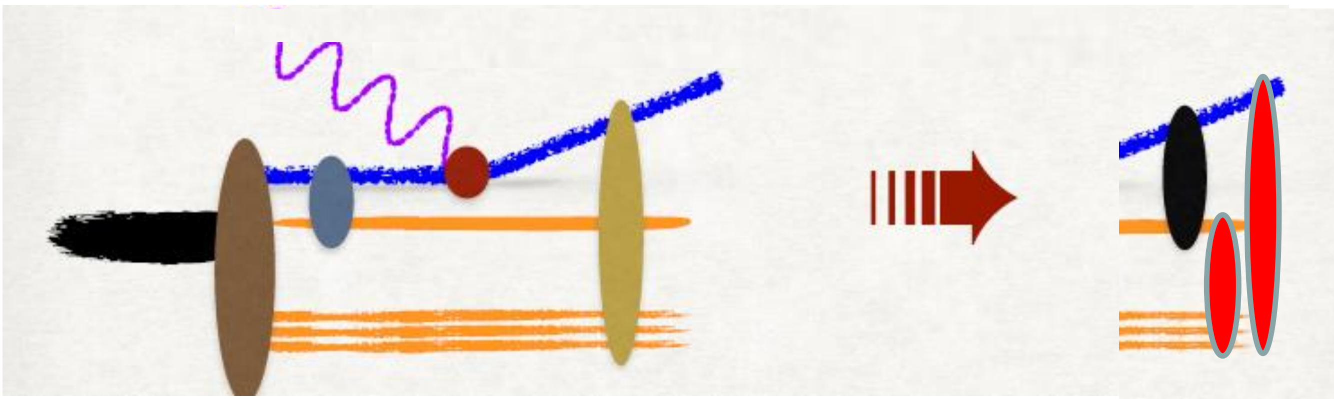
Conserve the isospin structure of the pair .

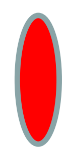
Conserve the CM momentum of the pair.


q
p1
A
A-2

FSI

For SRC kinematics (large Q^2, $x>1$):





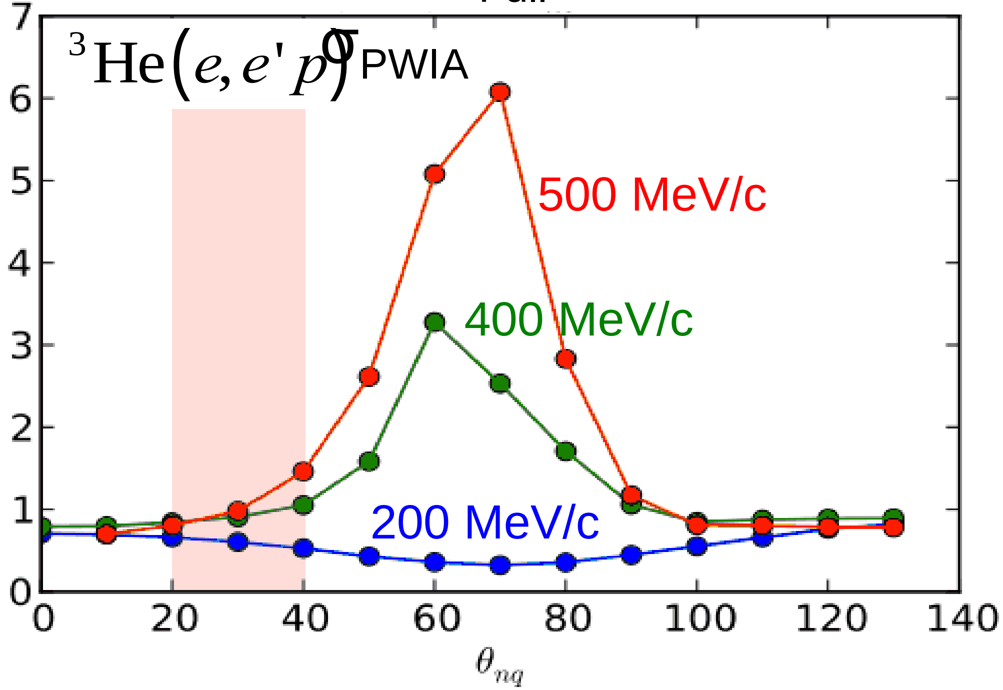
Attenuation SCX:
Calculate using Glauber.

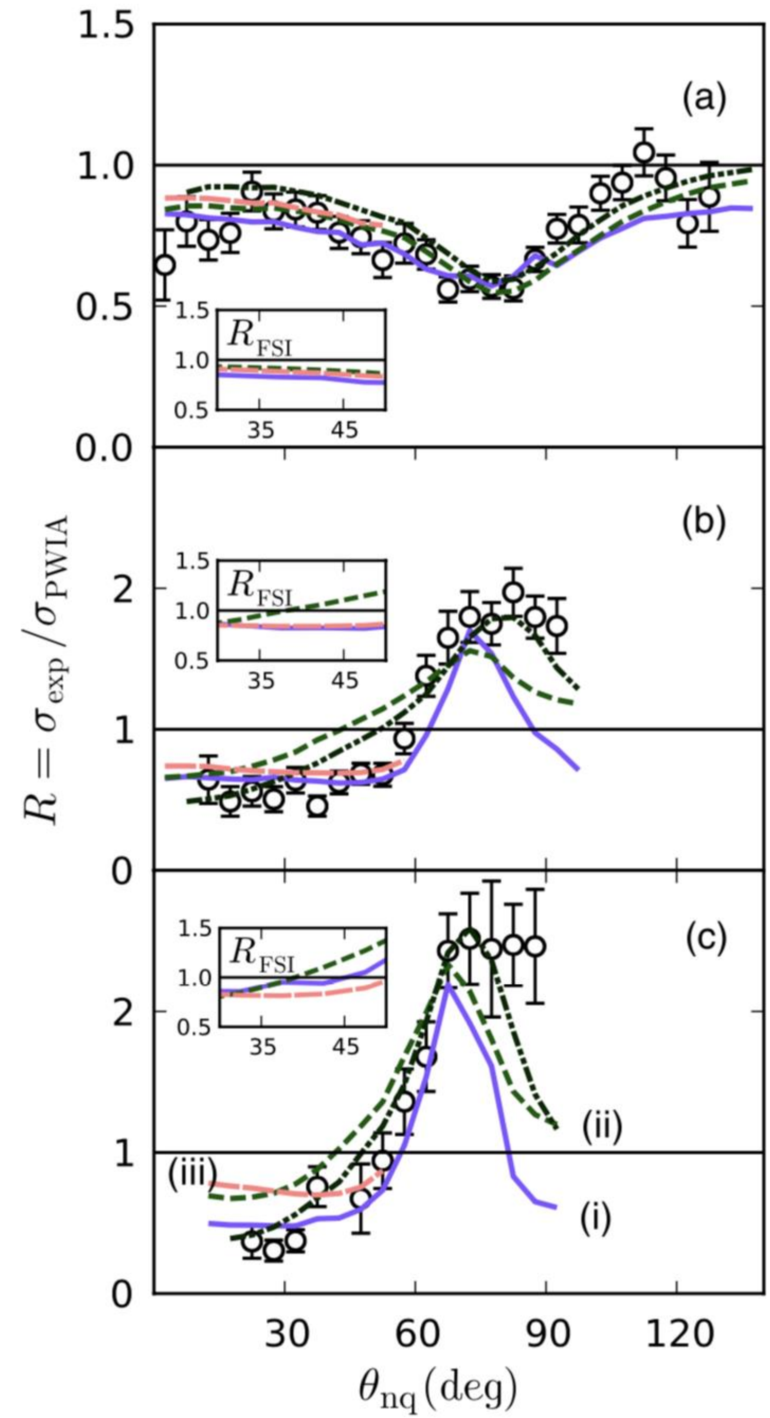
Rescattering within the pair

Does not change the reconstructed
CM momentum

Pair Rescattering

$R = \sigma_{Full} / \sigma_{PWIA}$





M. Sargsian; Boeglin PRL (2011).