Future SRC Measurements

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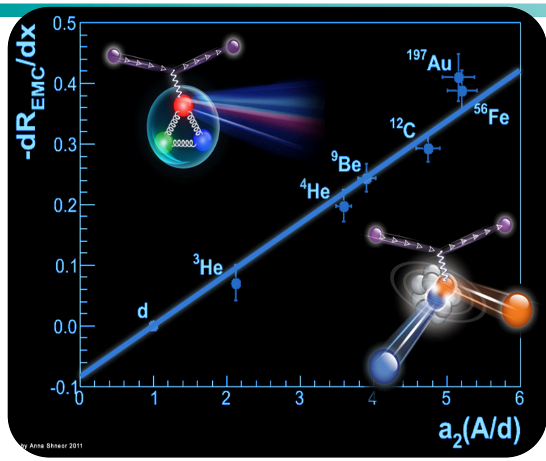
- Existing SRC data
- What we want to learn
- The CaFe experiment
- Tagged DIS
- Measuring everything with CLAS12
  - New physics
  - Old physics done better
- Questions for discussion

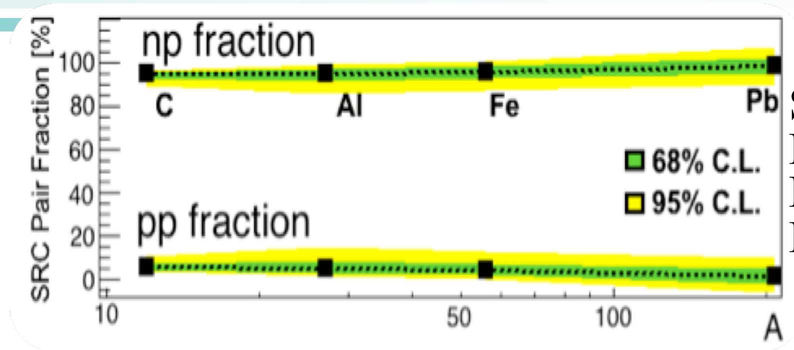
Status

What we know:

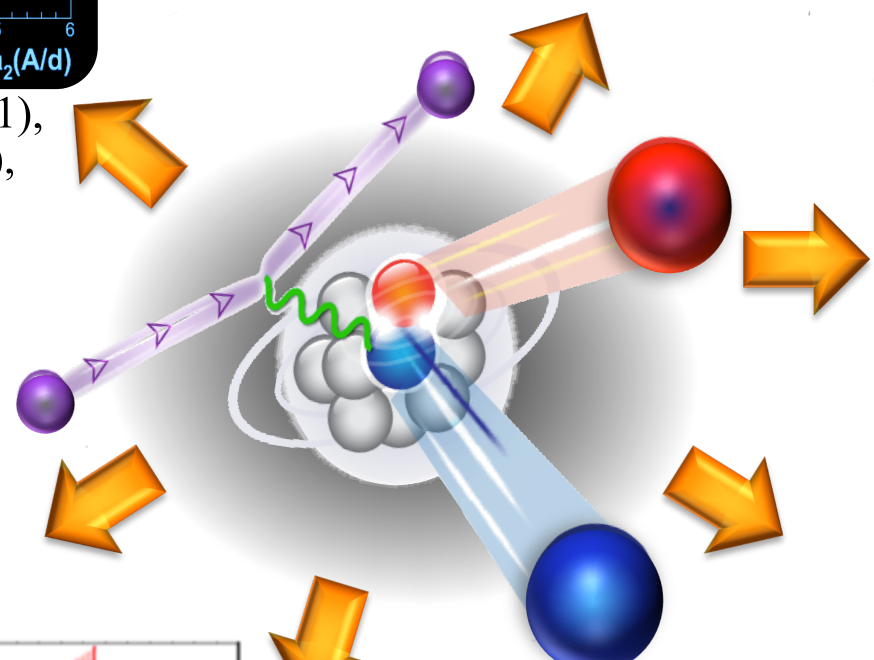
- Almost all protons with p > 300 MeV/c belong to SRC
  - $300 < p_{rel} < 500$ MeV/c: Almost all have a neutron partner
  - $p_{rel} > 500$ MeV/c: tensor → scalar transition
- P_{cm} consistent with adding two "mean field" nucleons
  - $\sigma_x = \sigma_y = \sigma_z \approx 150$ MeV/c
- pn pair dominance → protons move faster than neutrons in asymmetric nuclei
- The strength of the EMC effect is correlated with the probability of finding a nucleon in an SRC pair
  - The EMC effect can be explained by a universal modification of the structure of nucleons in pn SRC pairs

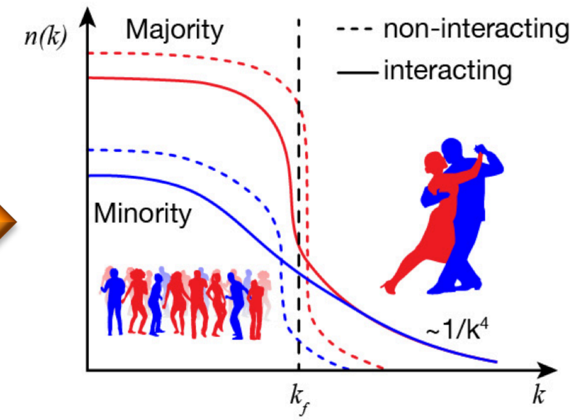


PRL **106**, 052301 (2011),
PRC **85**, 047301(2012),

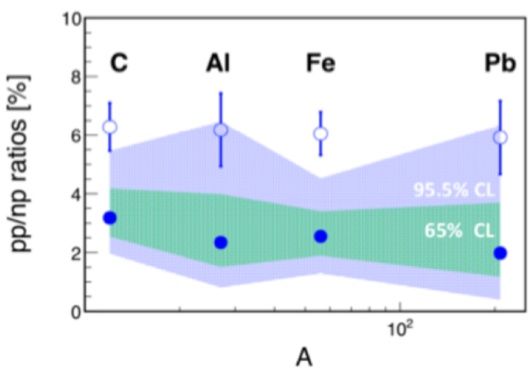


Science **320**, 1476 (2008),
PRL **108**, 092502 (2012),
PLB 772, **63** (2013),
PRC **92**, 024604 (2015).

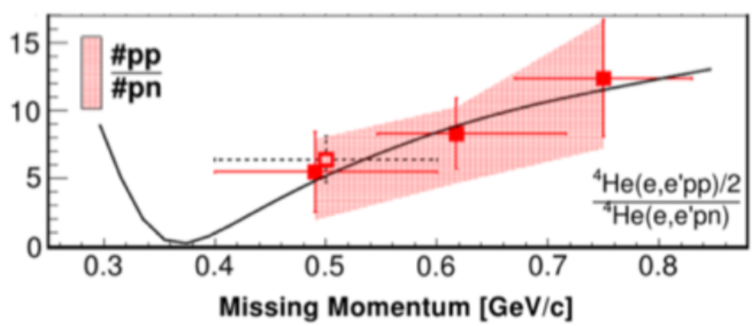




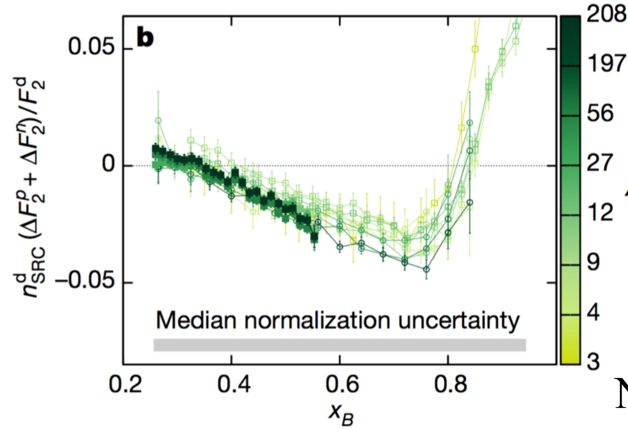
Science **346**, 614 (2014).

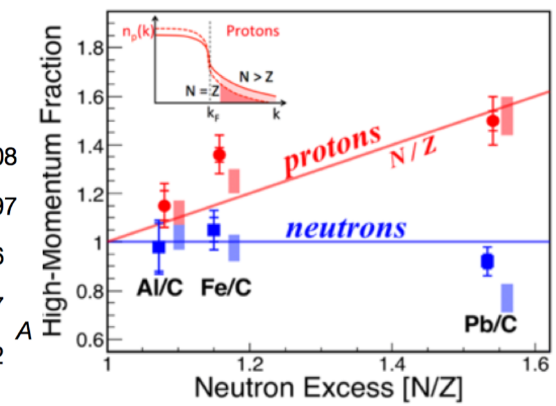


Submitted to PRL



PRL **113**, 022501 (2014),





Nature 560, 617 (2018)

Nature 566, 355 (2019)

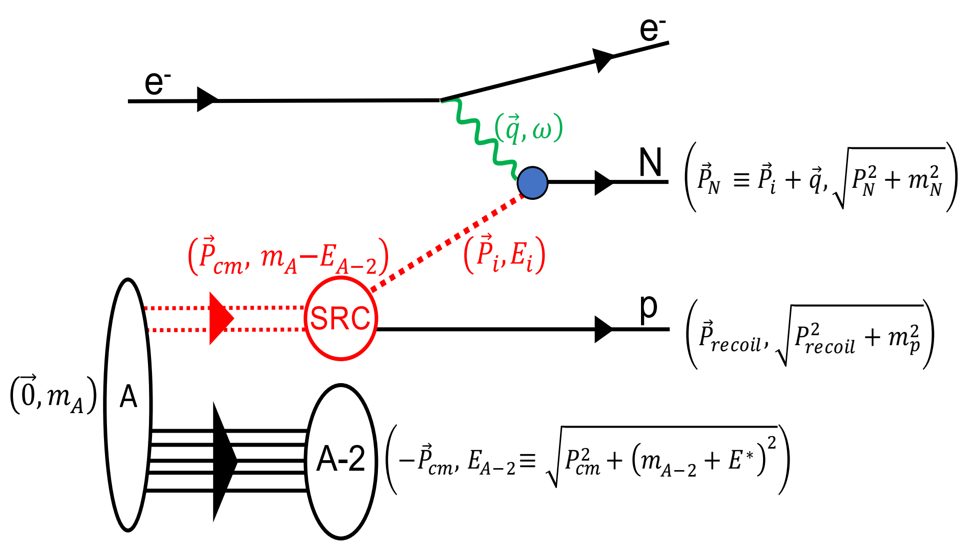
Existing data

How we know it:

→ a few hundred A(e,e'pp) and A(e,e'pn) events each at $x > 1.1$ and $Q^2 > 1.7$ GeV^2 on

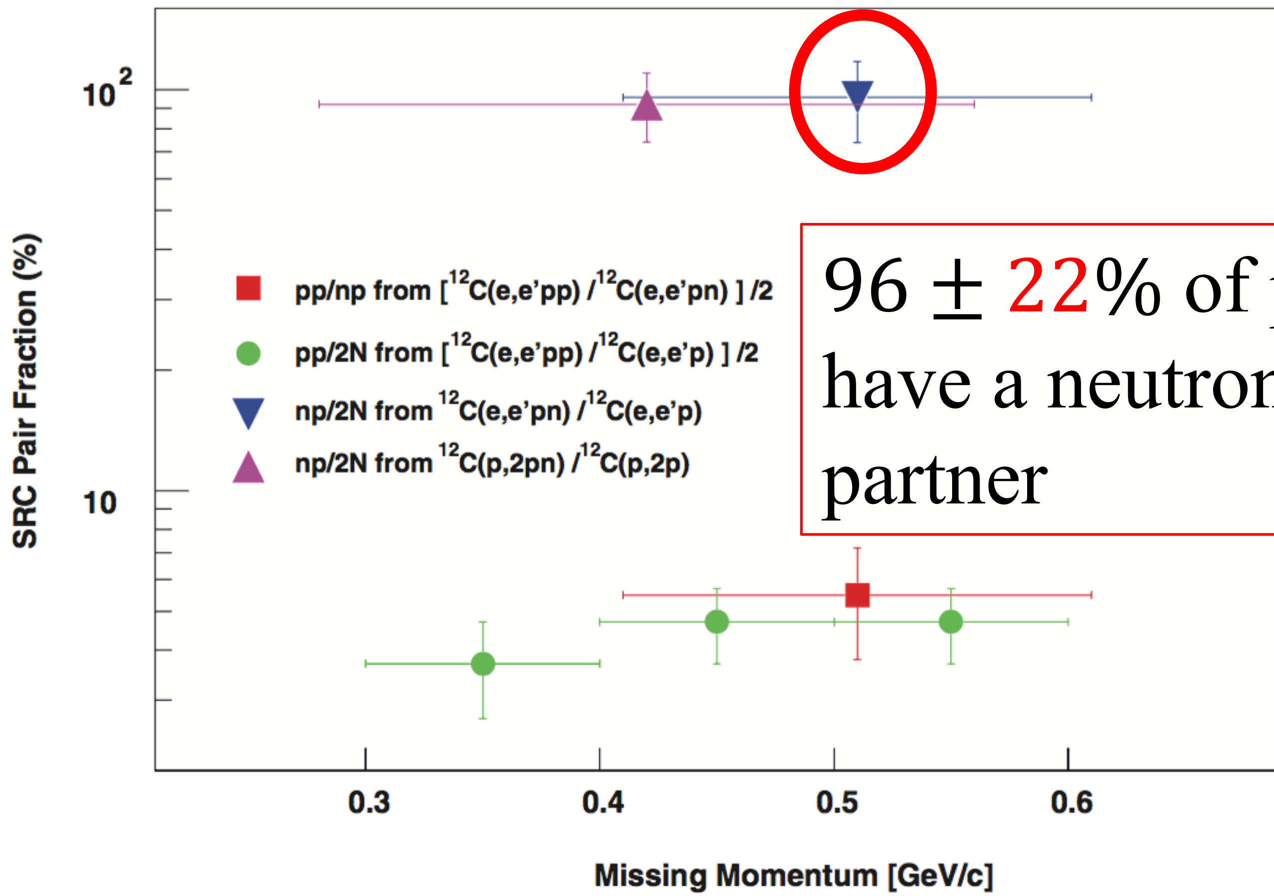
- ^{4}He and C (Hall A)
- C, Al, Fe and Pb (CLAS6 eg2)
- ^{3}He, ^{4}He, C and Fe (CLAS6 e2)

Simple reaction mechanism interpretation



What we want to learn

- More precision on existing measurements



96 ± 22% of protons have a neutron partner

What we really want to learn

- The NN interaction and the nuclear wave function* at short distances,
- SRC pair formation mechanisms,
- Nuclear asymmetry-dependence of SRCs,
- Three-Nucleon SRCs,
- The EMC Effect and its relation to SRCs

And finally

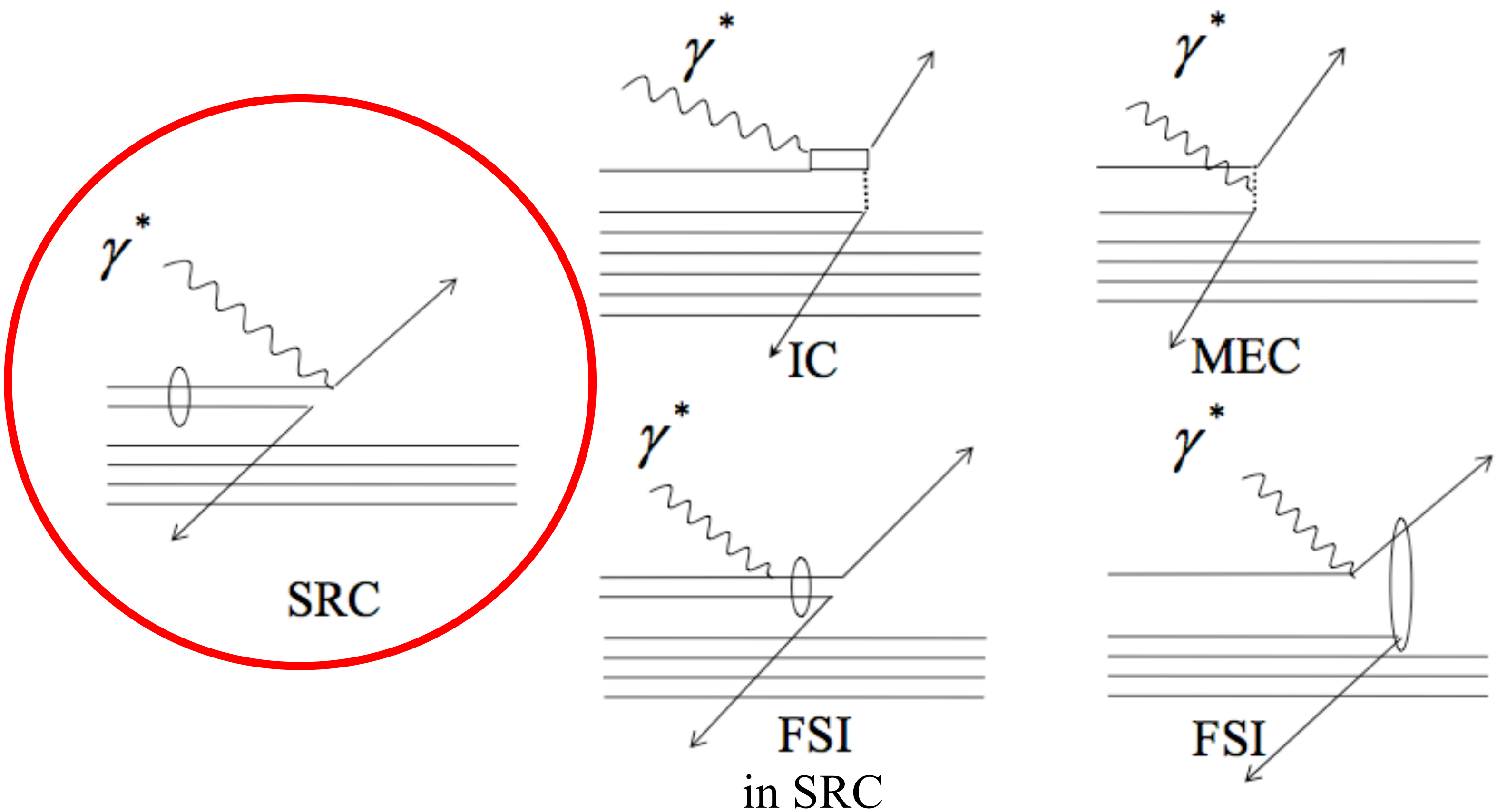
- More precision on existing measurements

* The wave function is not an observable. This assumes the one-body operator, high momentum wave function picture.

What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

Two-body currents are not Correlations
(but add coherently)



Need to calculate or minimize the effect of 2-body currents
to make quantitative statements about SRC

Upcoming experiments: (1) CaFe

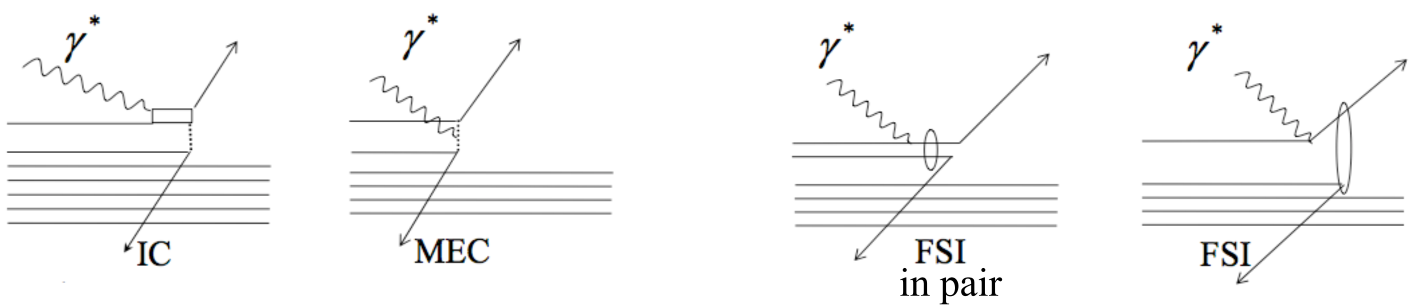
- How do 8 extra *neutrons* change the fraction of high-momentum *protons*?
- How do $1f_{7/2}$ neutrons pair with s, p, d core protons?
- A(e,e'p) on ^{40}Ca, ^{48}Ca and ^{54}Fe
  - $Q^2 \approx 2\ \mathrm{GeV}^2$,
  - $\theta_{pr} < 40°$
  - $x > 1$
  - Low and hi $\vec{p}_{miss} = \vec{q} - \vec{p}_p$

E_{Beam} GeV	E'_e GeV	θ_e	$\lvert\mathbf{p}_p\rvert$ GeV/c	θ_p	p_{miss} GeV/c	Q^2 GeV^2
11	9.85	8.0°	1.43	63.0°	0.40	2.1
11	9.85	8.0°	2.01	44.5°	0.15	1.8

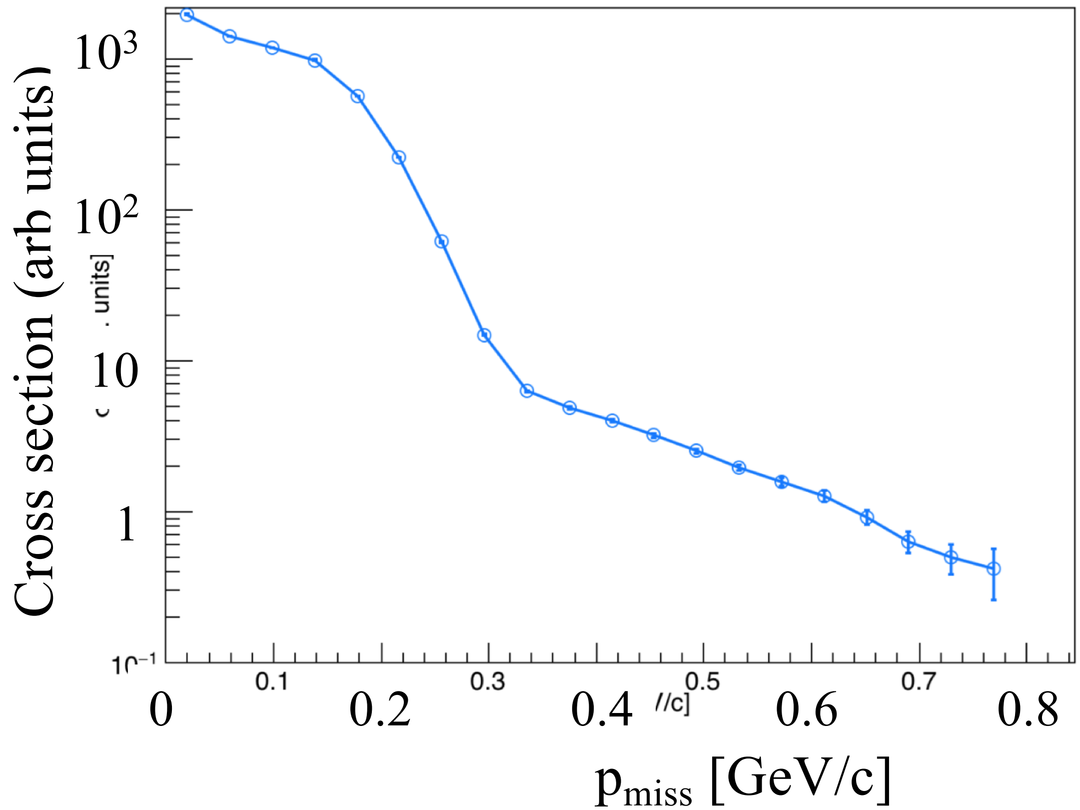
- Take double ratios of hi $\vec{p}_{miss}$ to low $\vec{p}_{miss}$ cross sections for ^{48}Ca relative to ^{40}Ca (and ^{54}Fe)

How to do interpretable expts
(in the absence of a comprehensive theory)

- Minimize unwanted reaction mechanisms
  - $Q^2 \approx 2$ GeV^2: reduces MEC and Δ contributions
  - $\theta_{pr} < 40°$: reduces FSI
  - $x > 1$: reduces MEC and Δ contributions
  - Take ratios of cross sections: further reduces FSI
  - Take ratios of ratios of cross sections …



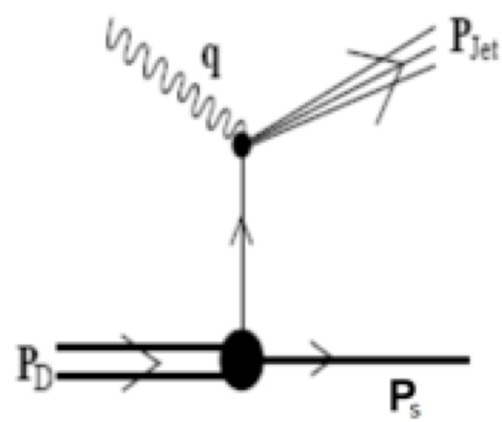
Expected CaFe uncertainties



E12-17-005, approved for four(!) ***entire*** days of beam time

Upcoming experiments: (2) Tagged DIS

- Measure DIS from a nucleon in deuterium
- “Tag” that nucleon by measuring the other “spectator” backward nucleon
- How do bound nucleon structure functions vary with nucleon momentum or virtuality $v = p^2 - m^2$?
  - Mean field vs SRC pairs
- Tag backward neutrons: BAND + CLAS12 (running now)
- Tag backward protons: LAD + HMS and SHMS in Hall C



Experimental Method

$d(e,e'N_S)$ cross section **Factorizes** into the cross section $(\sigma \propto F_2)$ times the distorted spectral function $S^D(p,E)$.

Cross section **ratio** at fixed nucleon momentum
➔ distorted spectral function cancels:

$$F_2^*(x_1',\alpha_S,p_T,Q_1^2)\Big/F_2^*(x_2',\alpha_S,p_T,Q_1^2)=\left(\frac{d^4\sigma}{dx_1'dQ^2d\vec{p}_S}/K_1\right)\Big/\left(\frac{d^4\sigma}{dx_2'dQ^2d\vec{p}_S}/K_2\right)$$

Measure α_s dependence at $\theta_{pq} > 107^\circ$ (small FSI)

$$x'=\frac{Q^2}{2p_\mu q^\mu}=\frac{Q^2}{2[(M_d-E_S)\omega+\vec{p}_S\cdot\vec{q}]}$$

x' is x-Bjorken in the moving struck-nucleon frame

$$\alpha_s=(E_s-p_s^z)/m_s$$

$\vec{p}_s$ maps to (α_s,p_T)

Experimental Method (cont.)

- Minimize experimental and theoretical uncertainties by measuring cross-section ratios

$$\frac{\sigma_{DIS}(x'_{high}, Q_1^2, \vec{p}_s)}{\sigma_{DIS}(x'_{low}, Q_2^2, \vec{p}_s)} \cdot \frac{\sigma_{DIS}^{free}(x_{low}, Q_2^2)}{\sigma_{DIS}^{free}(x_{high}, Q_1^2)} \cdot R_{FSI} = \frac{F_2^{bound}(x'_{high}, Q_1^2, \vec{p}_s)}{F_2^{free}(x_{high}, Q_1^2)}$$

FSI correction factor

x' = x from a moving nucleon

$$x'_{high} \geq 0.45$$

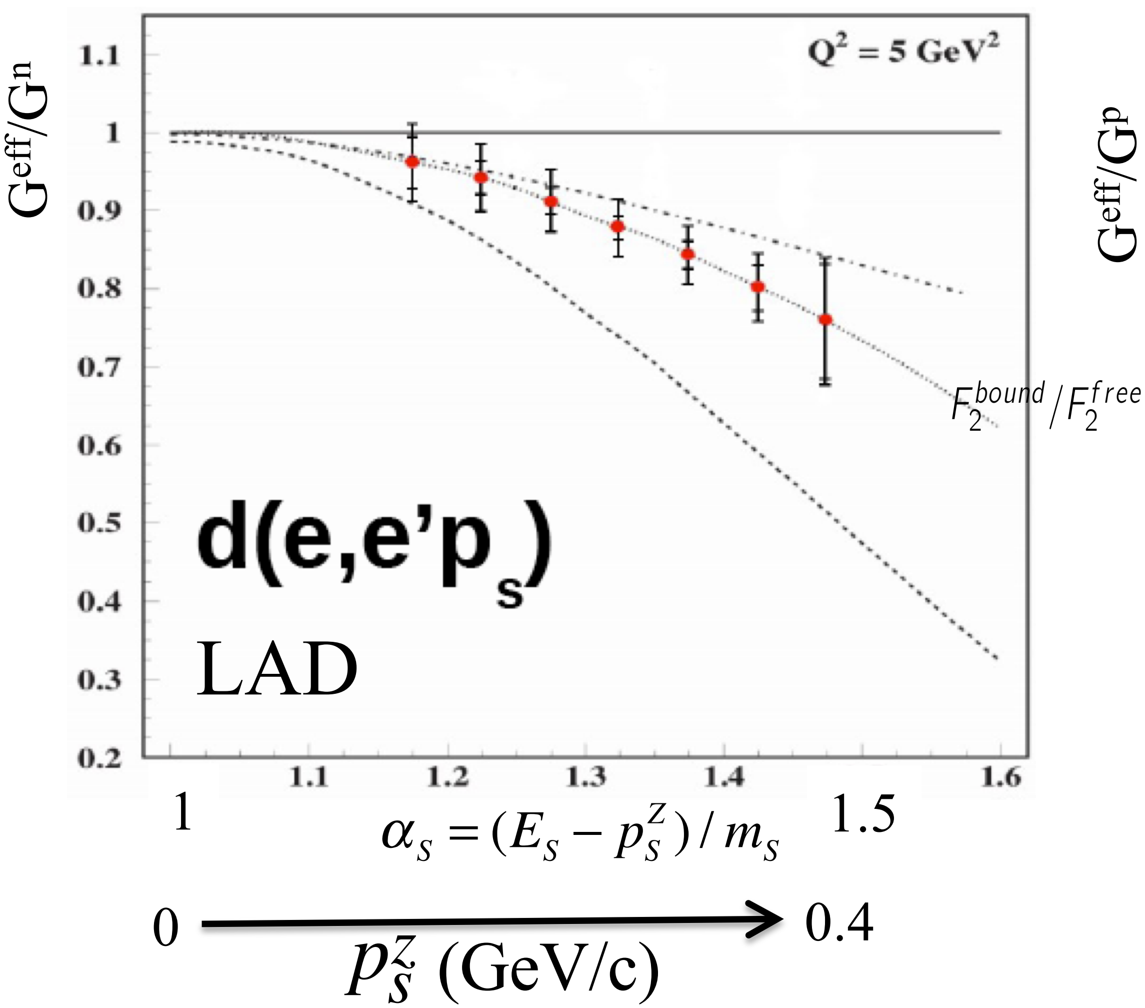
$$0.25 \geq x'_{low} \geq 0.35$$

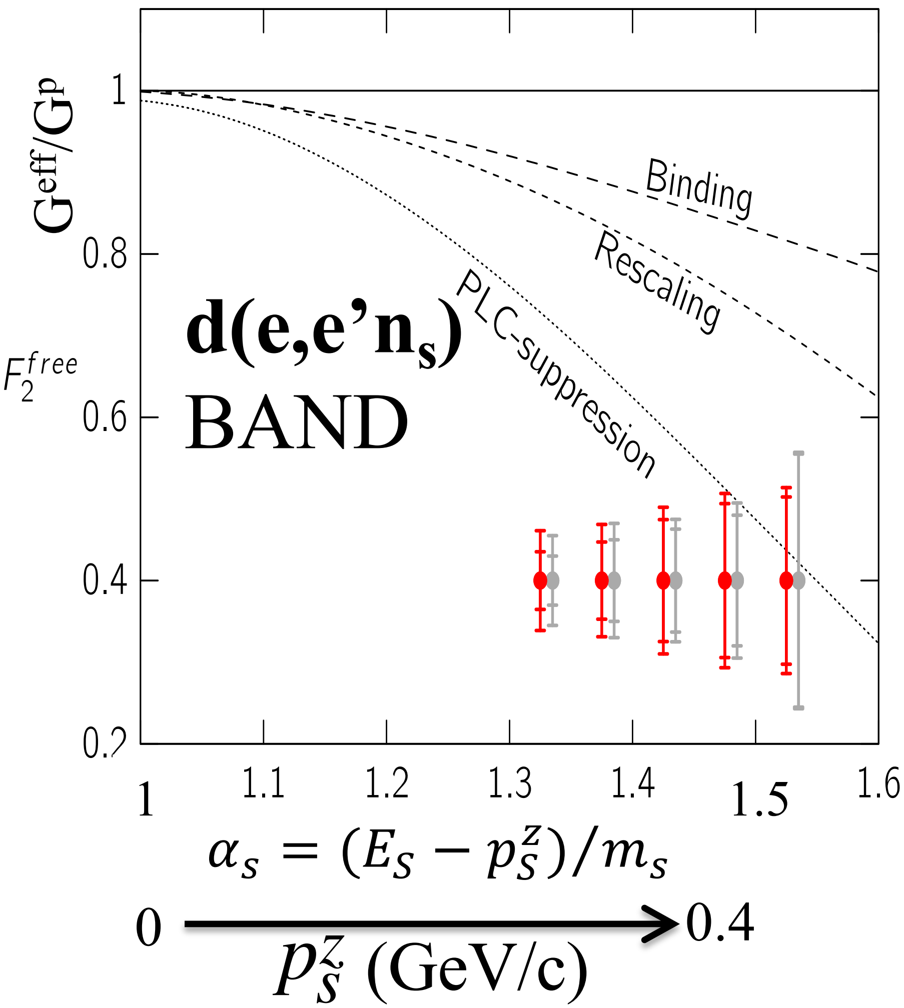
No EMC effect is expected

$$x'_B = \frac{Q^2}{2p_\mu q^\mu} \overset{\text{(For d)}}{=} \frac{Q^2}{2[(M_d - E_S)\omega + \vec{p}_S \cdot \vec{q}]}$$

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

LAD and BAND expected results

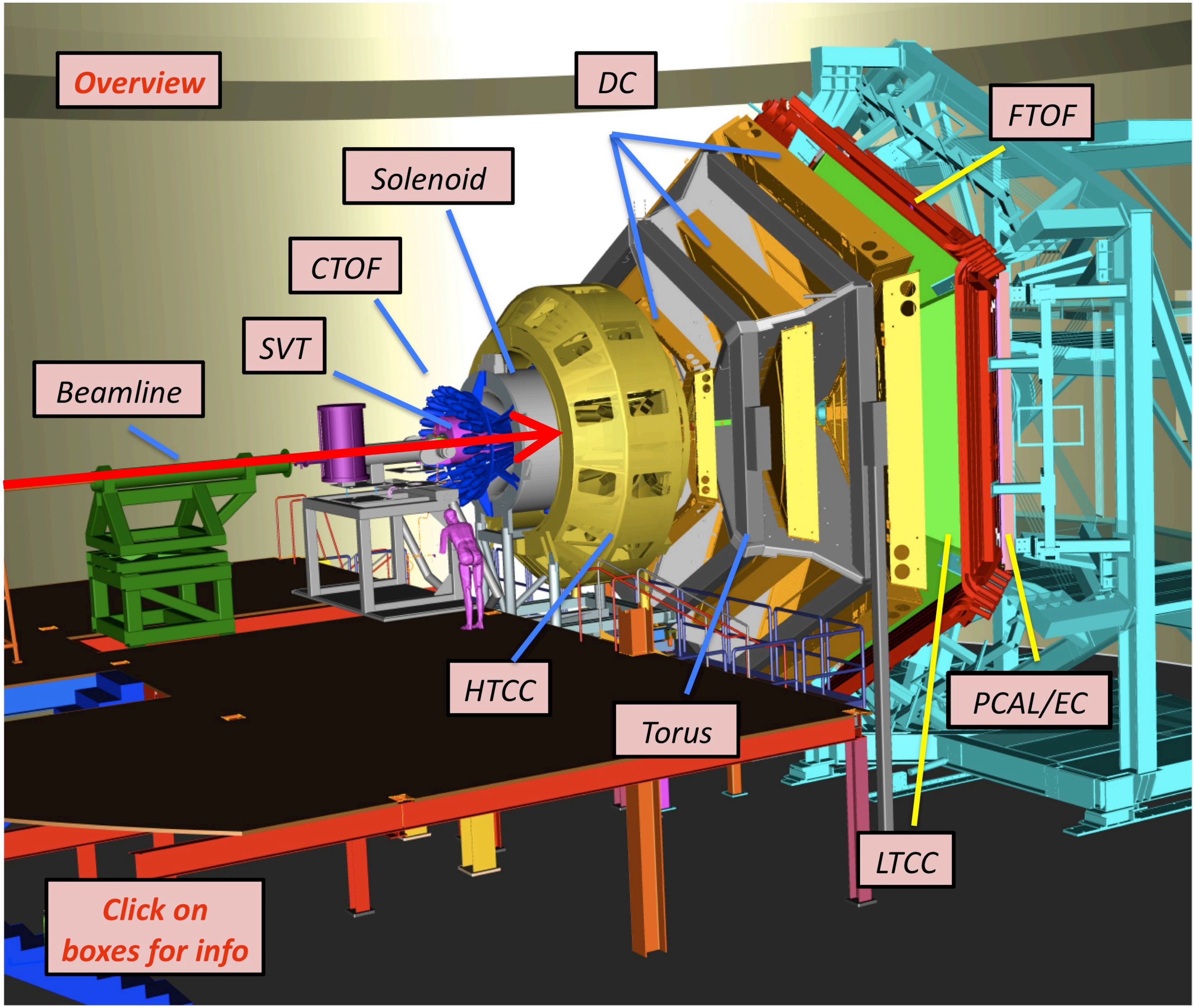




See Florian's talk Saturday for details

Upcoming experiments: (3) CLAS12 SRC/$e4\nu$

Beam



Upcoming experiments: (3) CLAS12 SRC/$e4\nu$

E	d	^{4}He	C	O	^{28}Si	^{40}Ar	^{40}Ca	^{48}Ca	Sn	Pb	Total
1.1	X	X	0.5	0.5	X	0.5	X	X	X	X	1.5
2.2	X	X	1	X	X	1	X	X	X	X	2
4.4	2	1	1	X	X	1	X	X	1	1	7
6.6	5	3	2	X	2	2	3	3	4	5	29
Total days	7	4	4.5	0.5	2	4.5	3	3	5	5	<u>39.5</u>

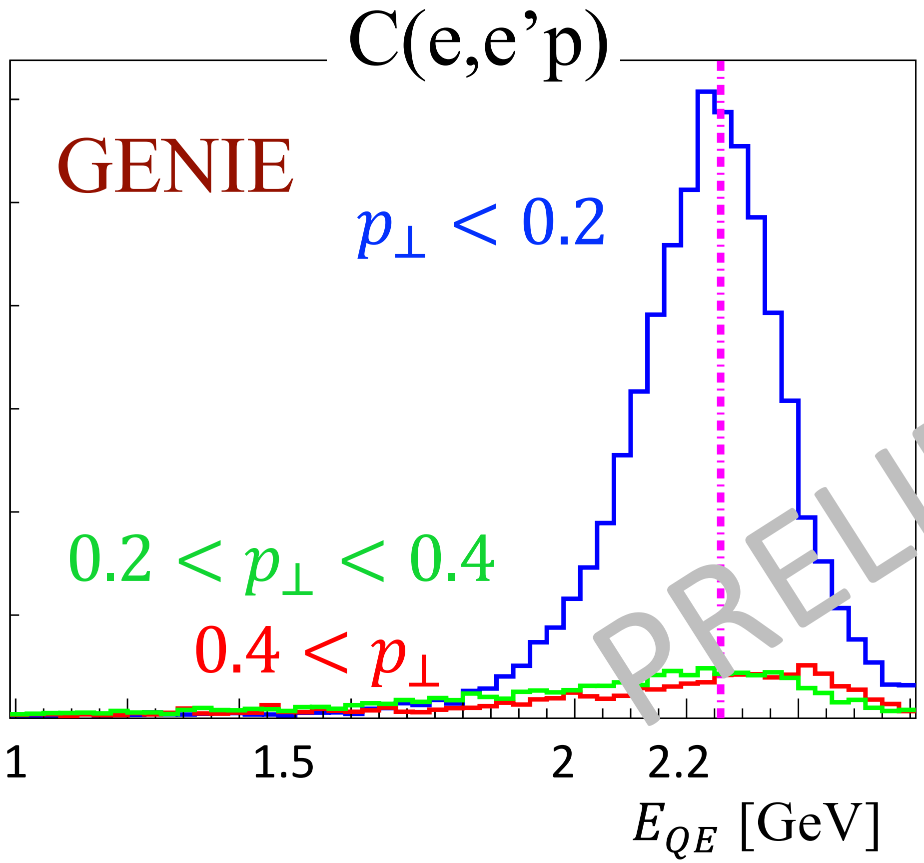
- Increase statistics by ~10 (per nucleus) over CLAS6 data
- Expand range of nuclei
  - Separate A and asymmetry effects
  - ^{48}Ca and Sn have the same asymmetry

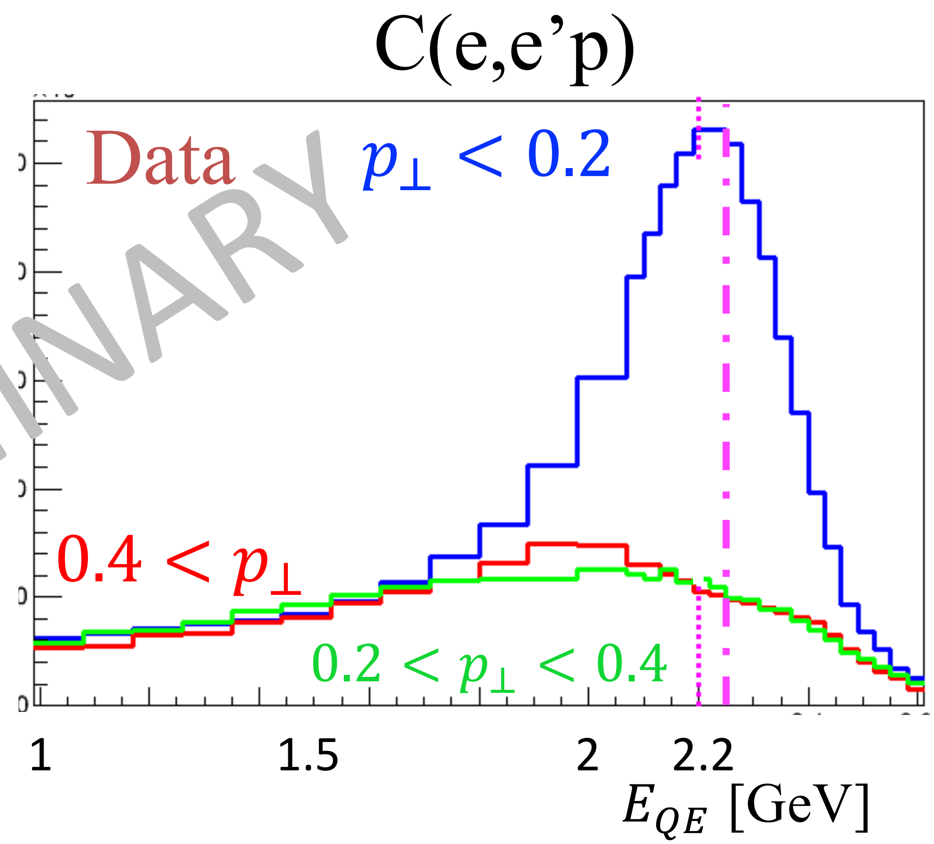
$e4\nu$: Electrons for neutrinos

- Use electron scattering data to constrain neutrino event generators
  - Cross sections
  - Incident energy reconstruction

$e4\nu$: E_{beam} Reconstruction

$$E_{QE} = \frac{2ME_l + 2M\varepsilon - m_l^2}{2(M - E_l + |k_l|\cos\theta)}$$



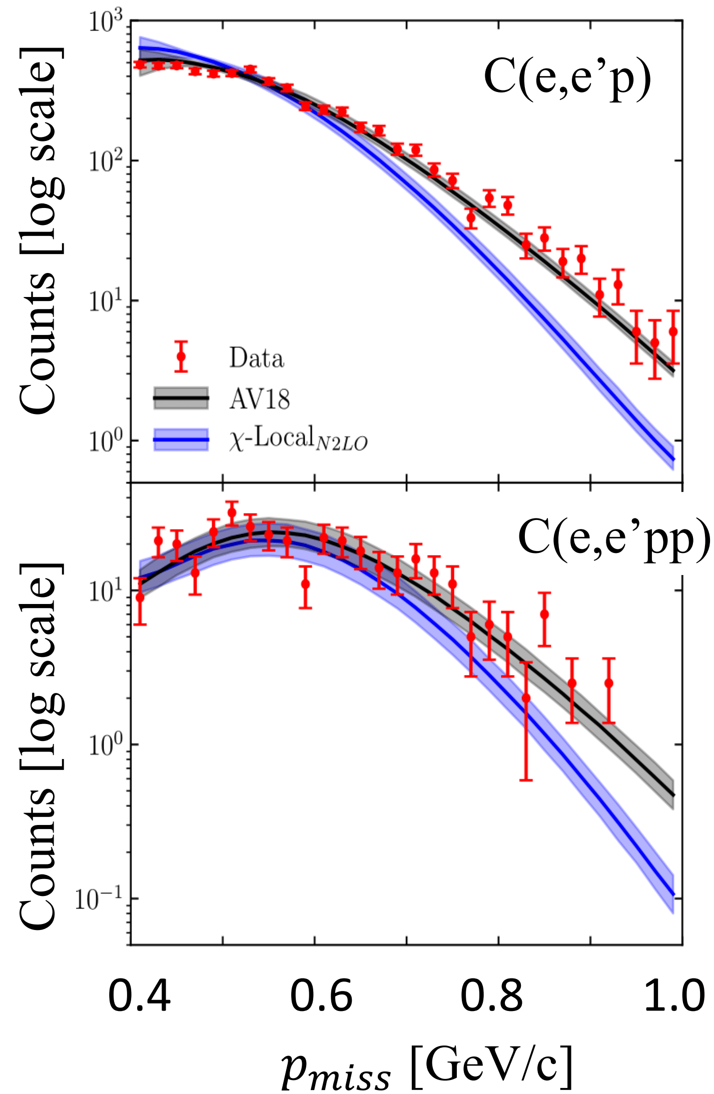


$e4\nu$: Electrons for neutrinos

- Use electron scattering data to constrain neutrino event generators
  - GENIE has both electron and neutrino modes
- Cross sections
- Incident energy reconstruction
- C, O, Ar targets
- Range of energies

New Expt, New and New-ish Physics

- Do 3N SRC exist?
  - Low abundance, hard to find
  - Important for neutron stars and NNN interactions
  - Expect few-100 (e,e'ppn) events at most
- NN interaction and nuclear wave fn at short distances
  - Study d and 4He, compare to heavier nuclei to prove A independence



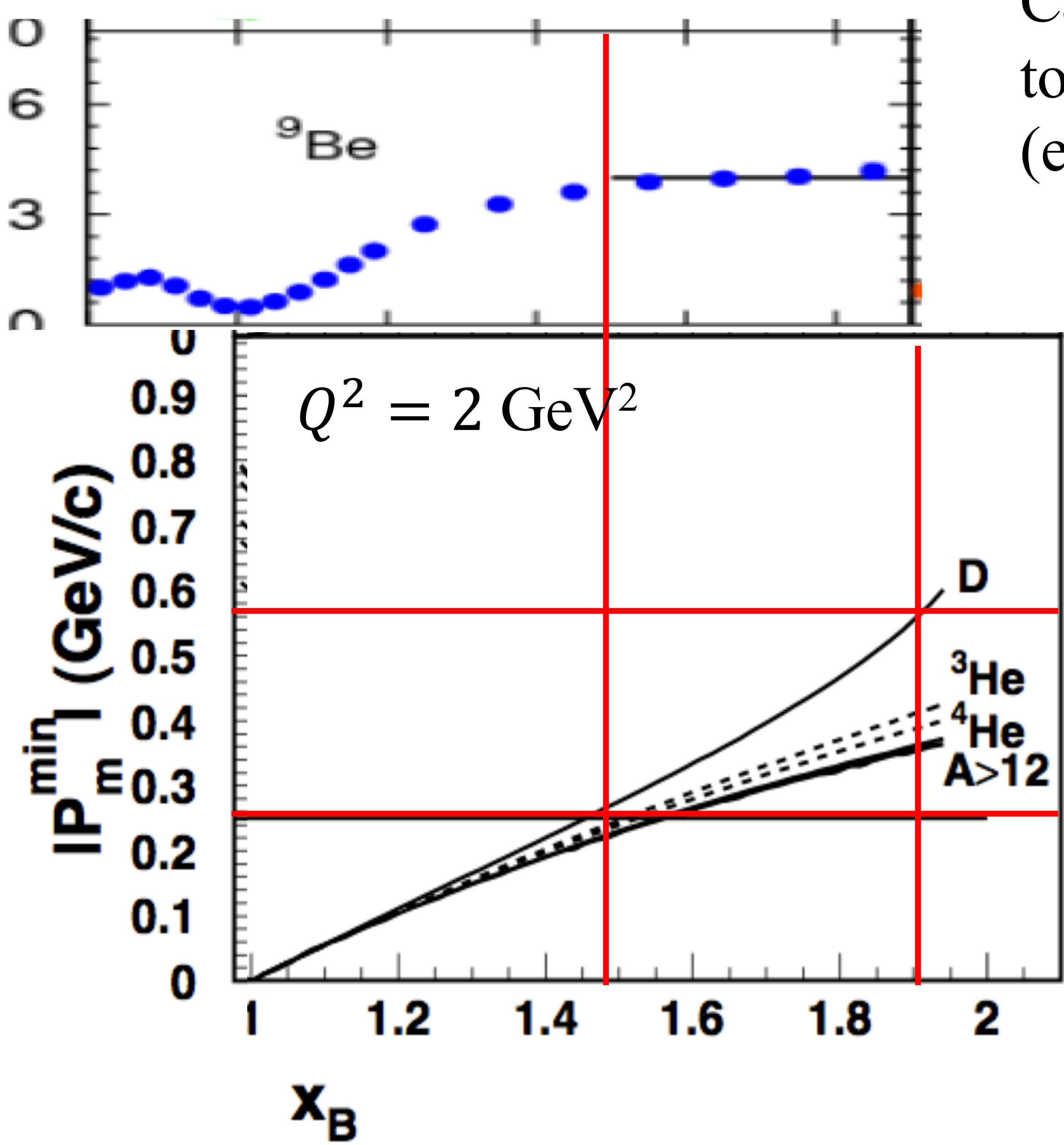
New Expt, New and New-ish Physics

- SRC pair formation mechanisms
- Nuclear asymmetry dependence
  - Compare nn and pp pairs in symmetric and neutron-rich nuclei
  - Separate A and asymmetry dependence
    - Previous nuclei were C, Al, Fe, and Pb
    - Now: (4He, C, 28Si, 40Ca), (48Ca, Sn), (Pb)
- EMC-SRC studies
  - Many nuclei
  - Tagged (new) and inclusive (new-ish)
- Reaction mechanism studies
  - Need much better theory support to become quantitative

All the new experiments

- New physics (30%)
  - 3N SRC
  - Tagged DIS
  - Superfast quarks in nuclei
  - x>2 inclusive measurements
- New-ish physics (70%)
  - More nuclei
  - More statistics
  - Need more theory support to fully exploit the increased precision

But …



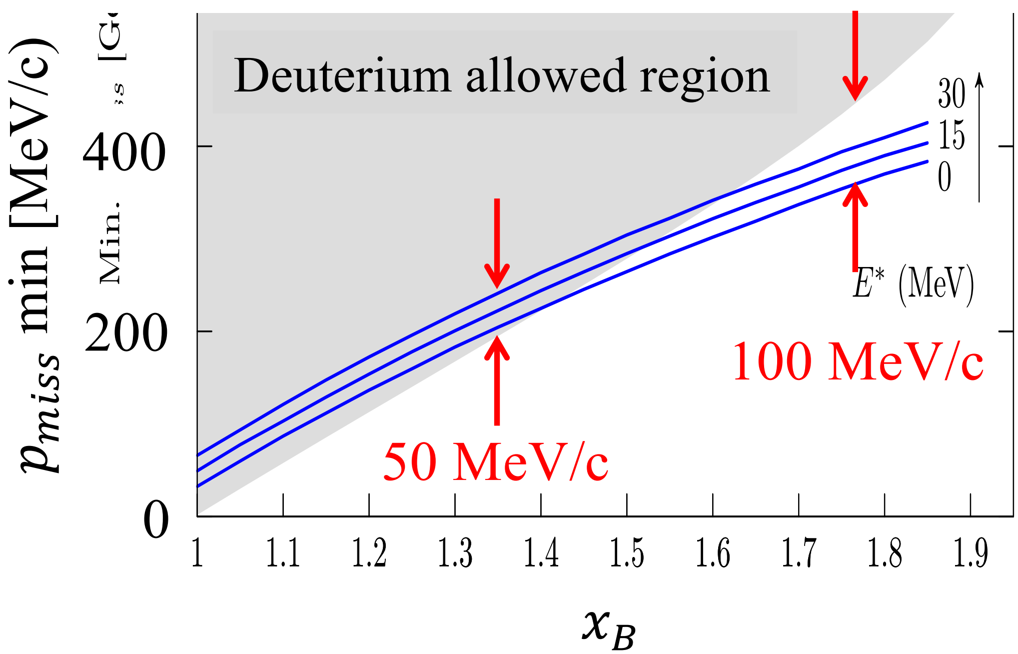
Can we relate (Q^2, x_B) to minimum p_{miss} in (e,e')?

275 to 600 MeV/c assuming d target

No binding energy, no A-2 excitation, no pair motion

But ...

- Can we relate (Q^2, x_B) to minimum p_{miss} in (e,e')?

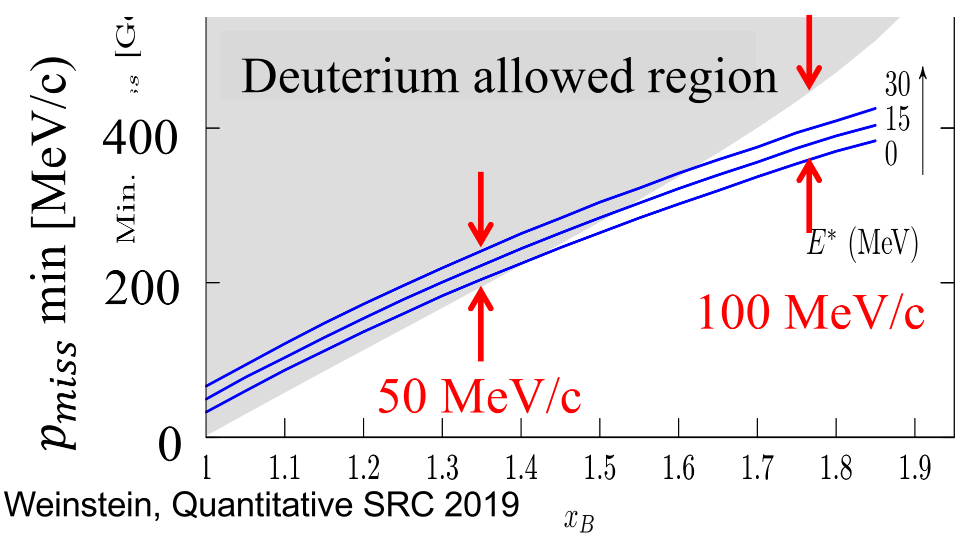


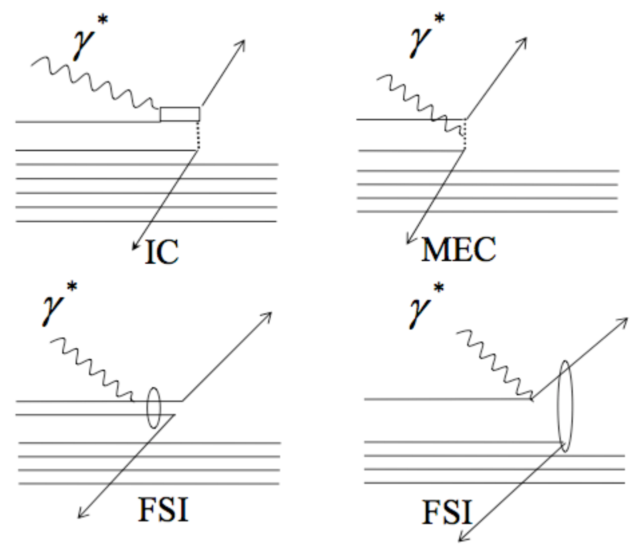
C(e,e') including pair motion, A-2 excitation energy (E*) and binding energy

  - Different A-2 excitation energies → 50 MeV/c variation in p_{miss} min
  - C and d curves are non-parallel due to C binding energy and pair motion

Statements for discussion

- We can't relate (Q^2, x_B) to minimum p_{miss} in (e,e')
  - How can we interpret a2?
  - How can we relate (e,e') cross sections to momentum distributions?
- We don't have complete reaction mechanism calculations for (e,e'p) and (e,e'pN)
  - How can we interpret (e,e'p) and (e,e'pN) cross sections and ratios?





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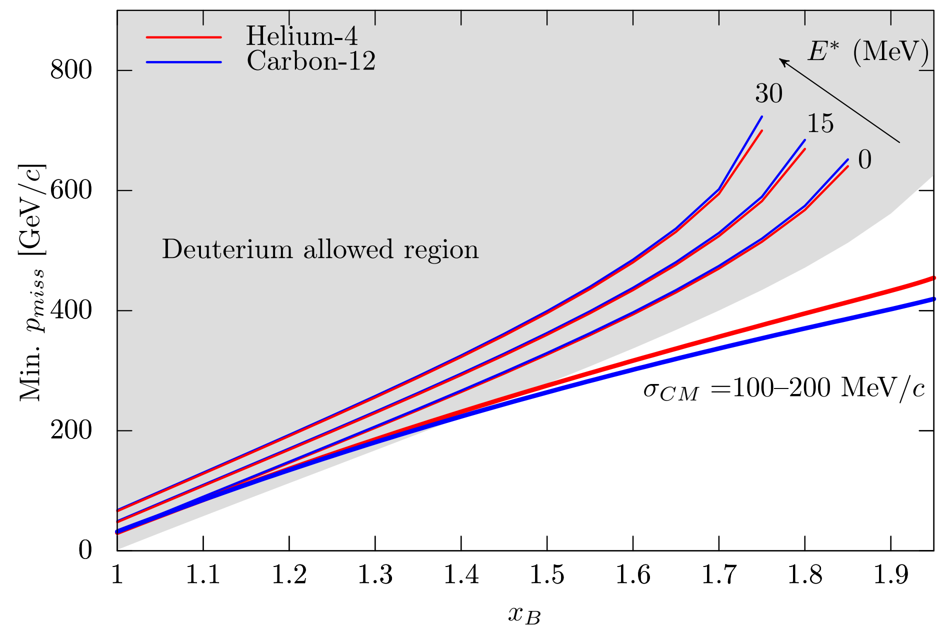

Helium-4
Carbon-12
E^* (MeV)
30
15
0
Deuterium allowed region
σ_{CM} =100–200 MeV/c
Min. p_{miss} [GeV/c]
800
600
400
200
0
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
x_B