Exclusive Reactions: Learning from experiment

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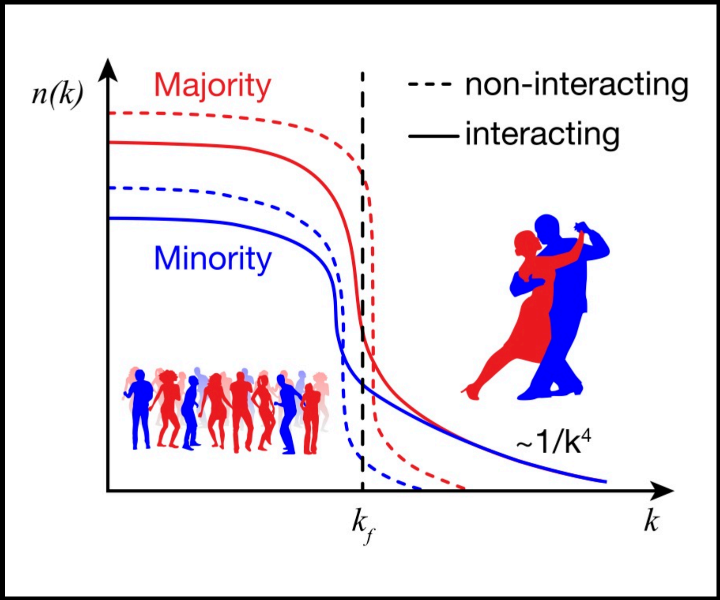
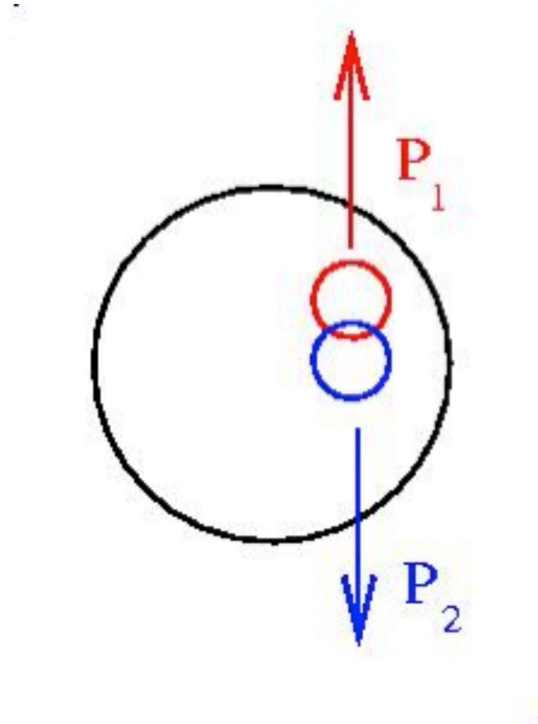
- What we have learned
- What we want to learn
- How can we learn it?



Signatures for Correlations

An Experimentalist's Definition:

- A high momentum nucleon whose momentum is balanced by **one** other nucleon
  - NN Pair with
    - Large Relative Momentum
    - Small Total Momentum



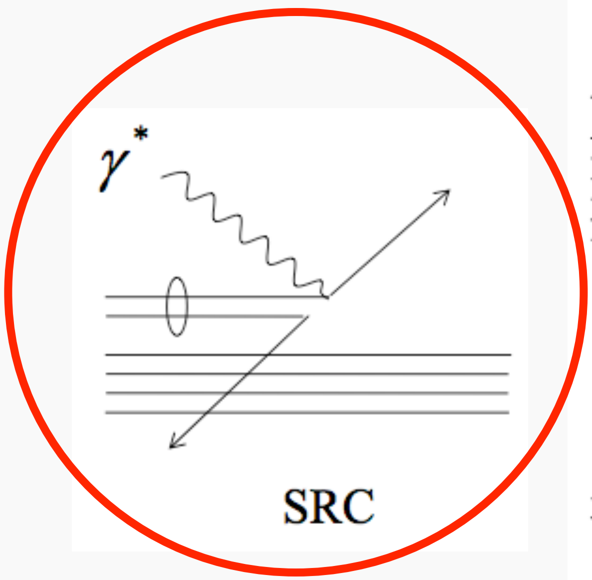
Be careful: this is also the signature of a struck nucleon rescattering from and knocking out a 2nd nucleon!

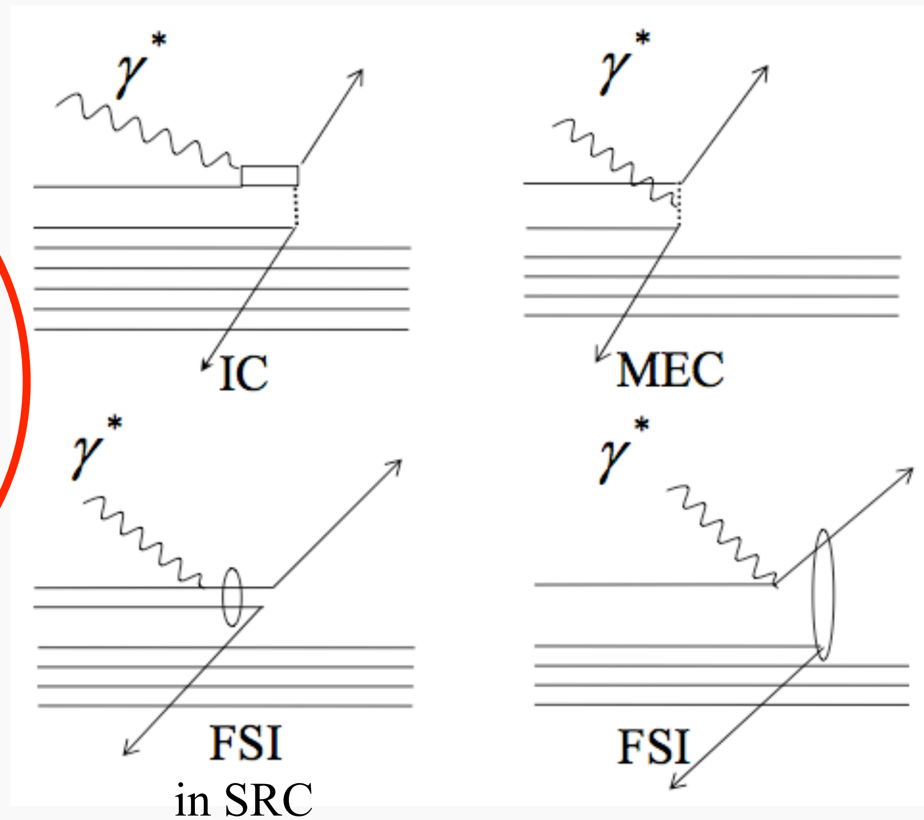
Glauber rescattering peaked at $\theta_{rq} \approx 70^\circ$

What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

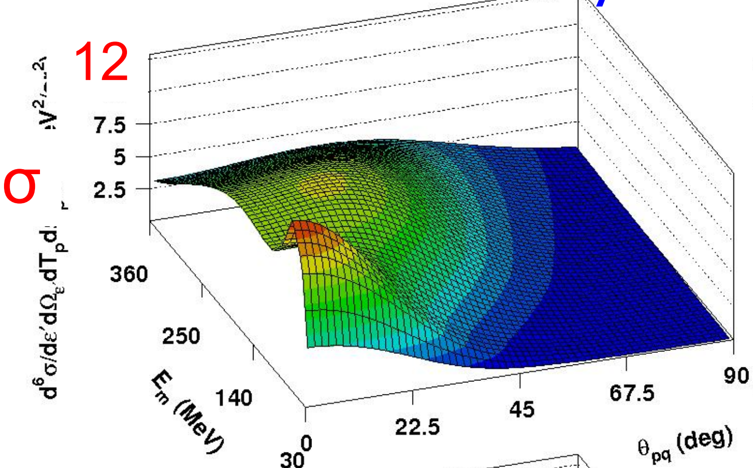
Two-body currents are not Correlations
(but add coherently)



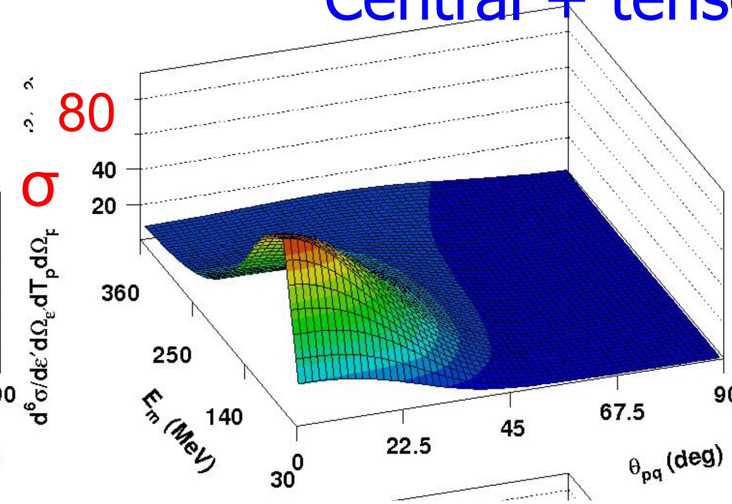


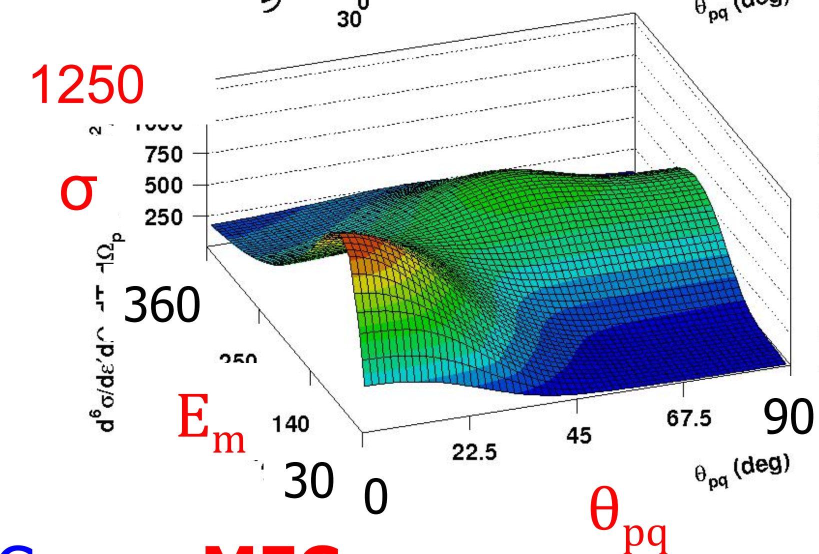
2N currents enhance correlations

Central correlations only



Central + tensor corr





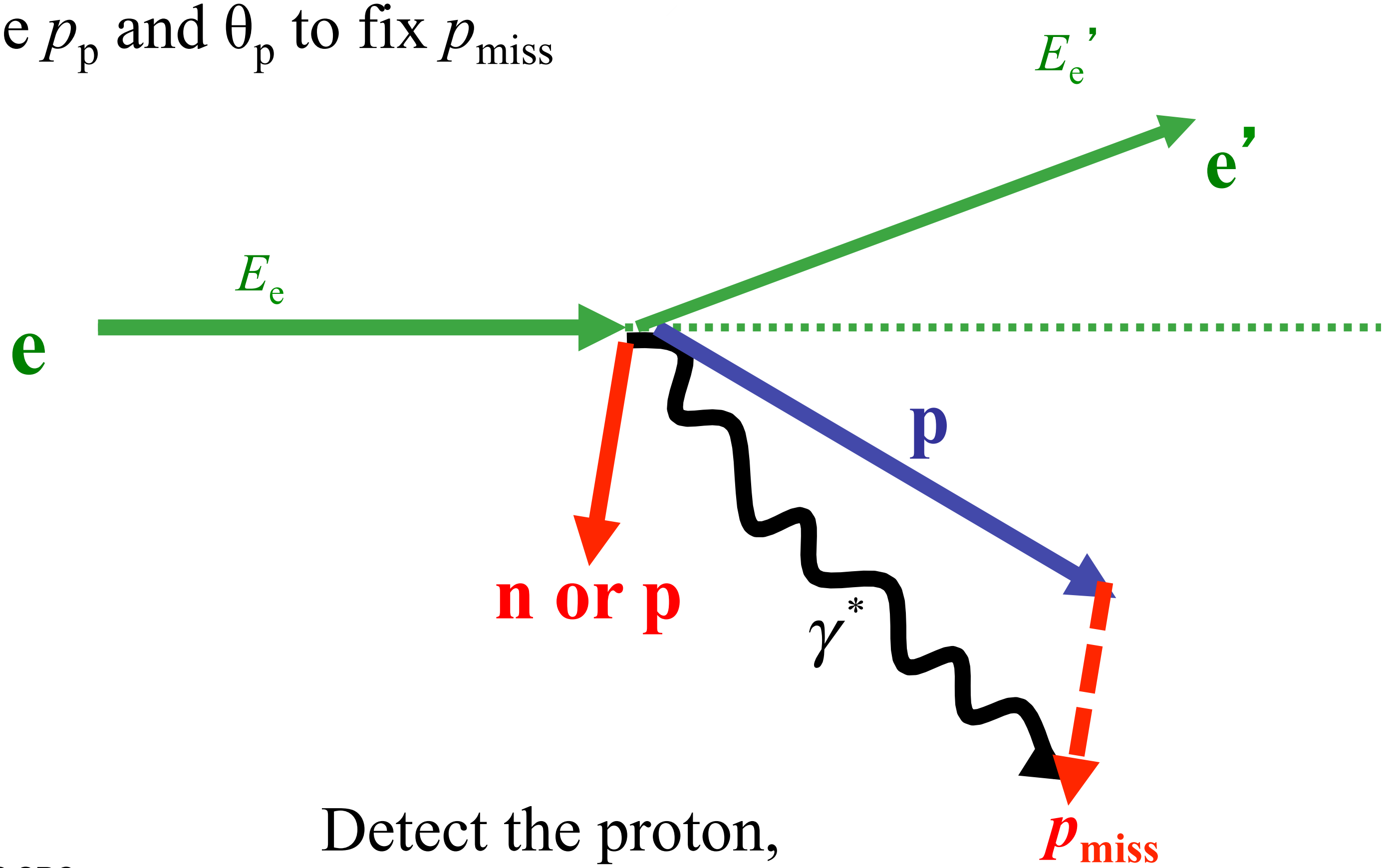
Corr + **MEC**

MEC changes the magnitude of the cross section, not the distribution in E_{miss} vs $Theta_{pq}$

O(e,e'p) Ryckebusch

(e,e'pN) - kinematics

Scatter e (or p) from nucleus
Detect knocked out proton and partner recoil nucleon (if any)
Choose E, E', θ_e to fix Q^2, ν and x
Choose p_p and θ_p to fix p_{miss}



Detect the proton,
look for its partner nucleon

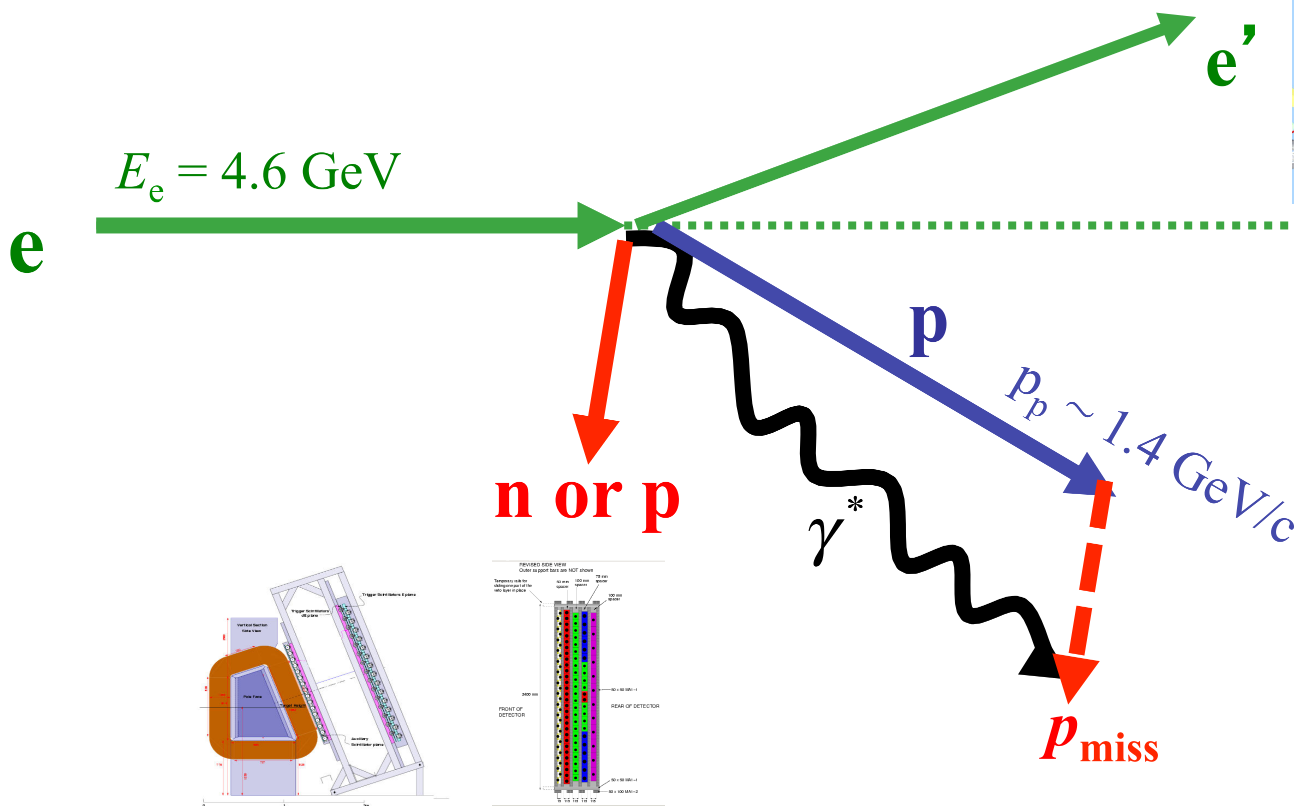
Kinematic tradeoffs for (e,e'pN)

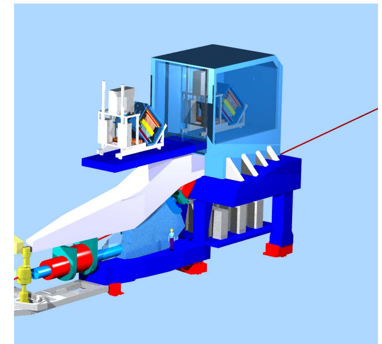
- $x > 1$
  - Reduces non-QE reaction mechanisms (pions [MEC] and deltas [IC]) for (e,e')
  - Struck nucleon has final momentum less than momentum transfer $p < q$
  - Recoil nucleon emitted forward (relative to $\vec{q}$)
  - More FSI
- $x < 1$
  - Increases non-QE reaction mechanisms (pions [MEC] and deltas [IC]) for (e,e')
  - Struck nucleon has final momentum more than momentum transfer $p > q$
  - Recoil nucleon emitted backward (relative to $\vec{q}$)
  - Less FSI

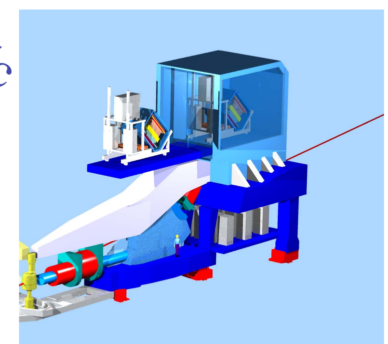
Phys. Rev. C 85, 064318 (2012)

JLab Hall A ^{4}He, C(e,e'pN) - selected kinematics

$Q^2 = 2\ GeV^2$
$x_B = Q^2/2m\nu = 1.2$
$P_{miss} = 300\text{-}600\ MeV/c$







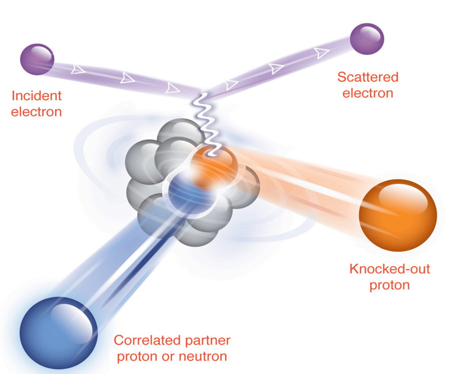
Detect the proton,
look for its partner nucleon

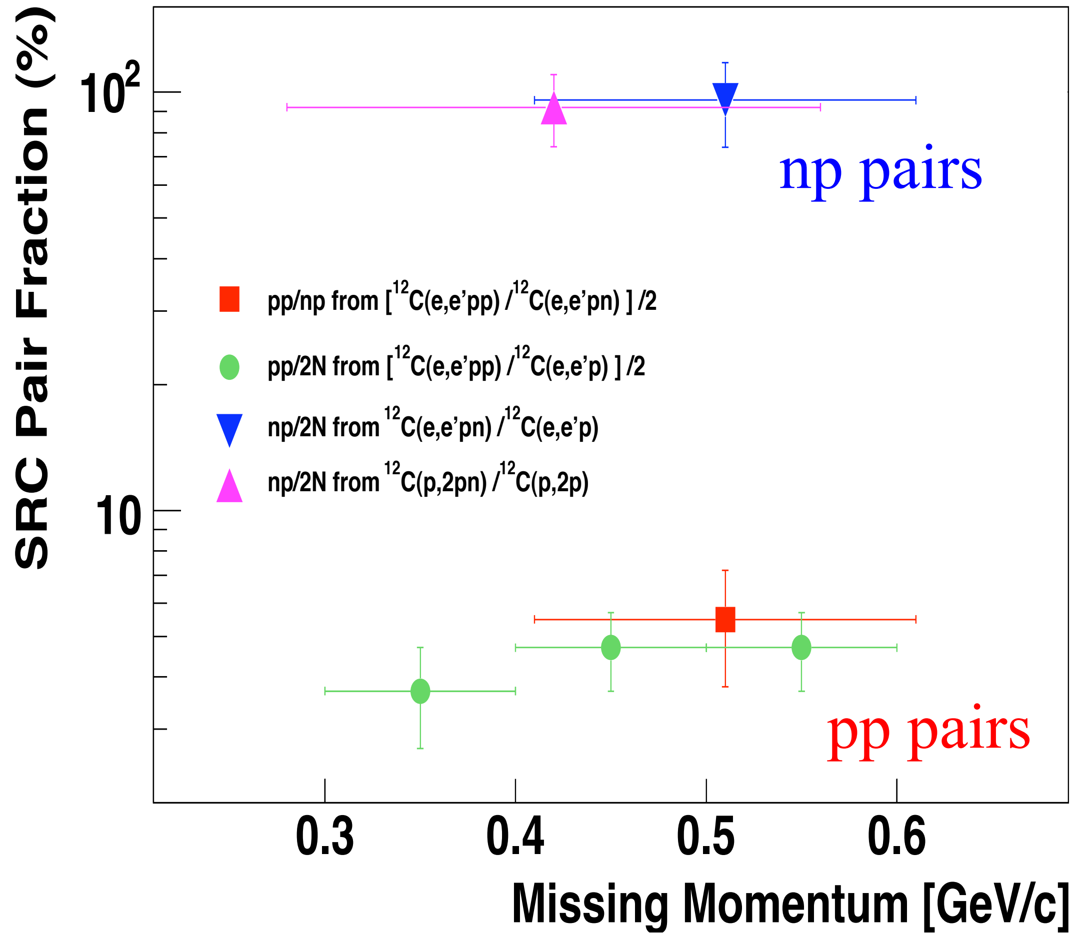
High momentum protons have partners
C(*e,e'pN*)

- Detect the knocked-out proton
- Look for its partner nucleon
- All high momentum protons have partners

➔ np pairs dominate at

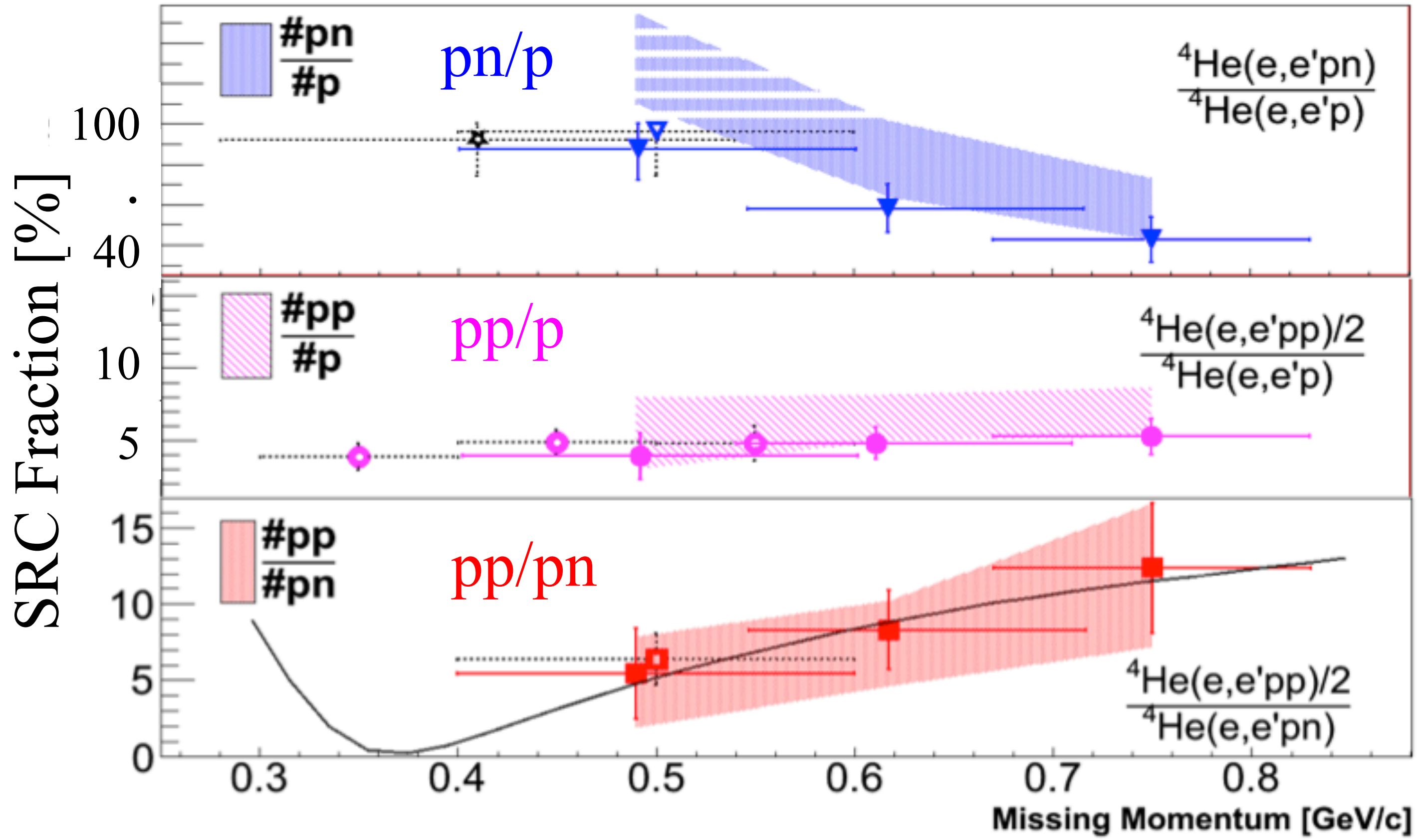
$0.3 < p_i < 0.6$





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

Higher momentum protons? $^{4}He(e,e'pN)$

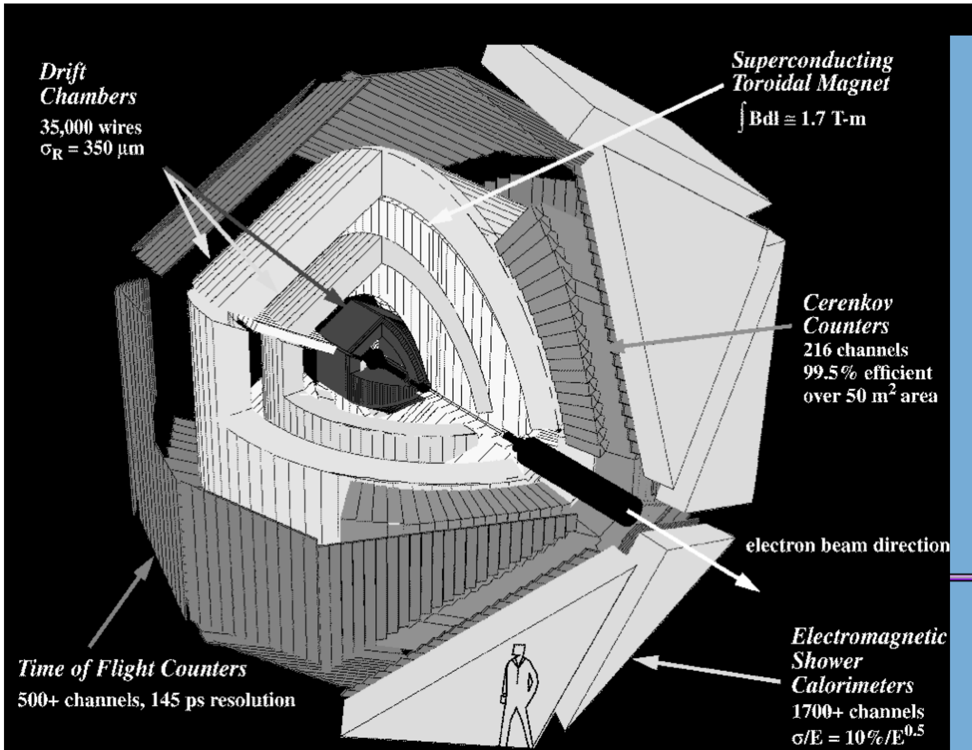


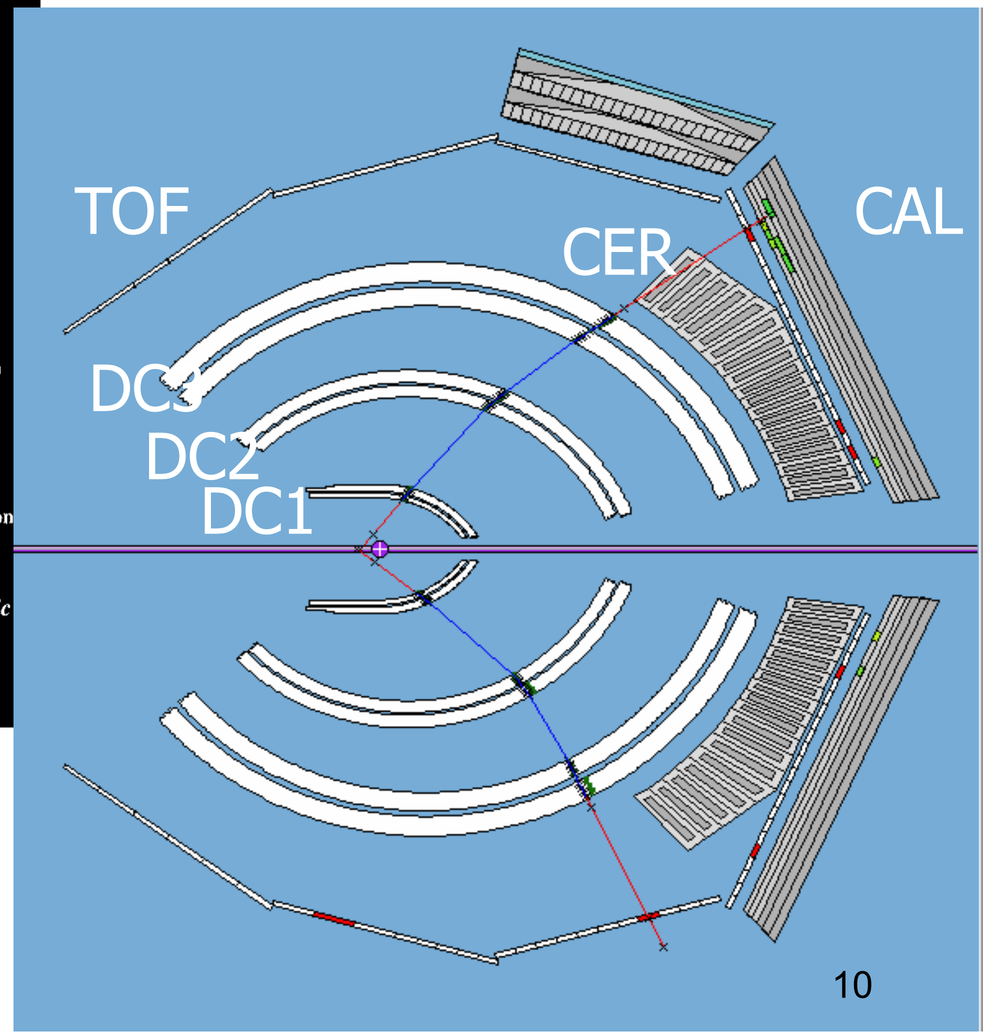
- pp pairs still only 5% of high momentum protons
- np pairs decrease with missing momentum
- Three nucleon correlations???

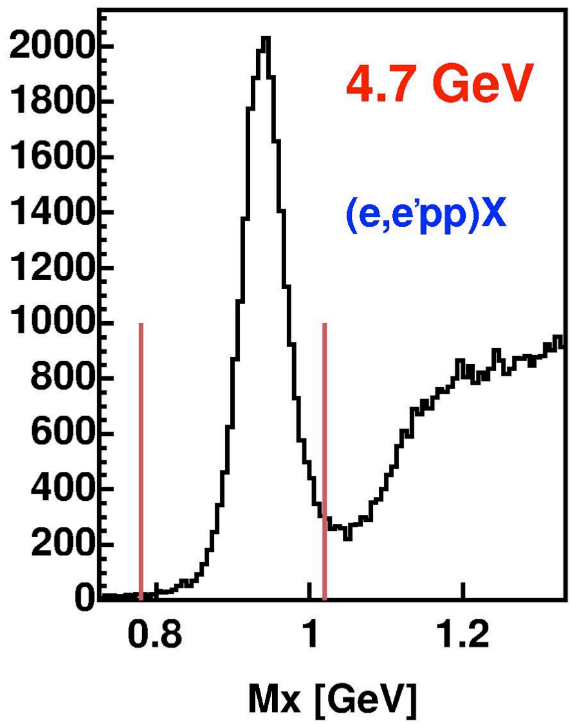
I. Korover et al., PRL 113, 022501 (2014)

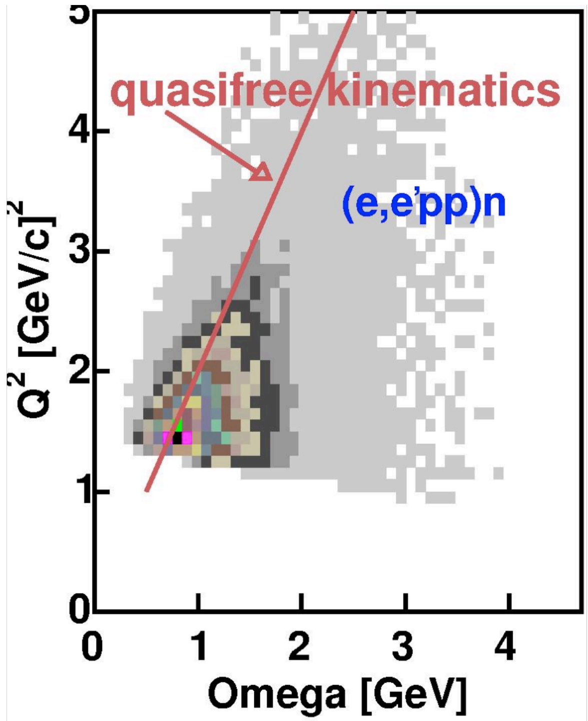
^{3}He(e,epp)n in CLAS

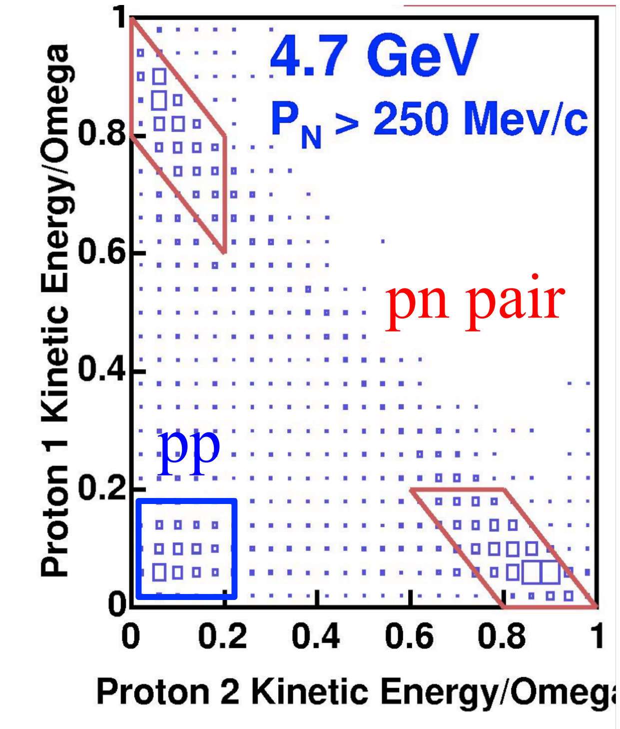
- 2 and 4 GeV electrons
- Inclusive trigger
- Almost 4π detector

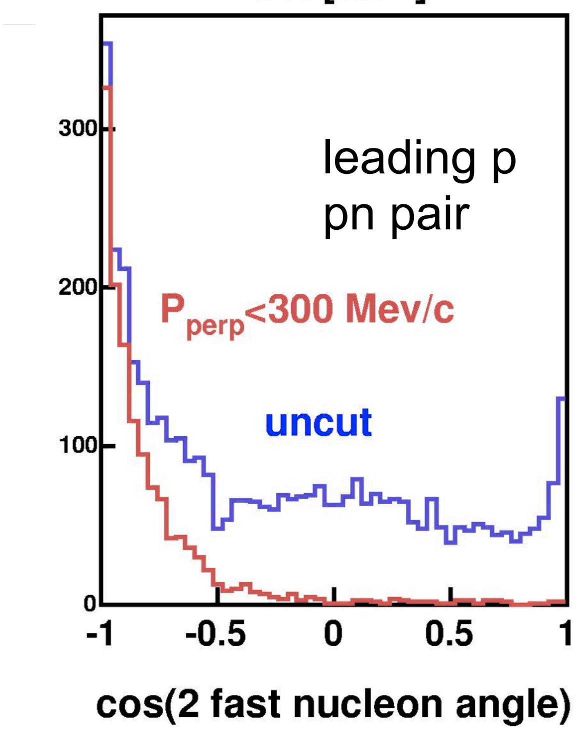




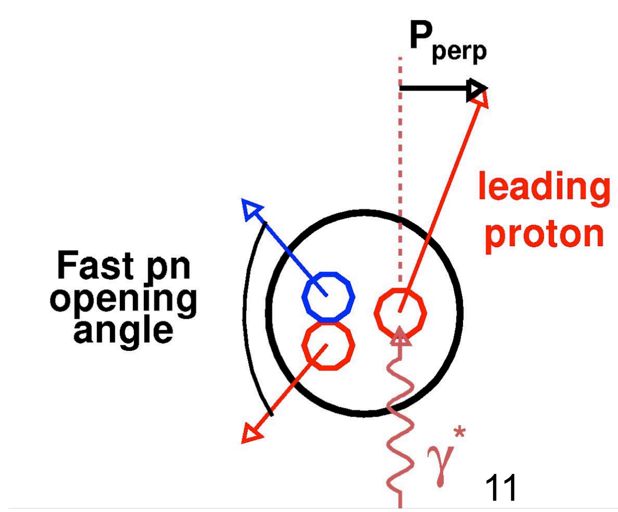




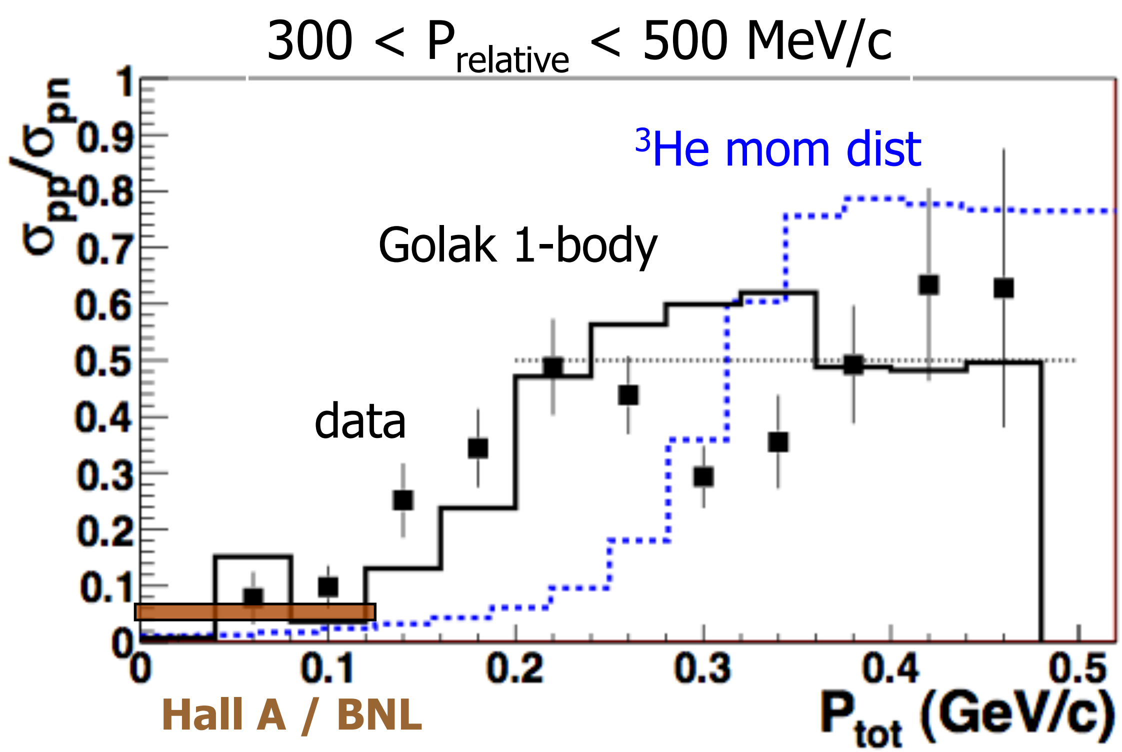




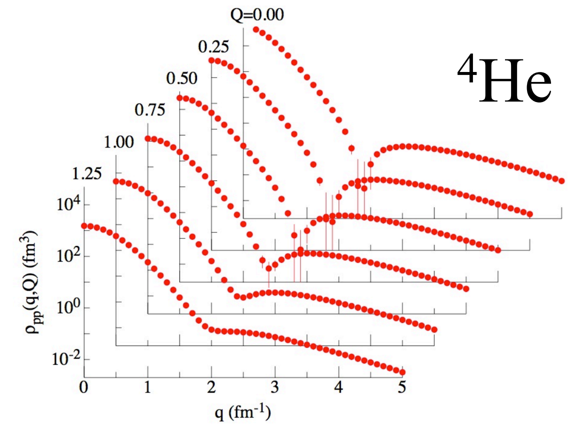
- Detect two protons
- Reconstruct the neutron
- Select peaks in Dalitz plot
- Remaining *NN* pair is back to back



pp/*pn* ratio and pair total momentum



Wiringa, PRC 89 (2014) 024305



Increasing P_{tot} fills in *pp* minimum

Small P_{tot} ➔ *pp* pair in s-wave (no tensor)
➔ wave fn minimum at $P_{relative}$=400 MeV/c

Increase in *pp*/*pn* ratio with P_{tot} ➔tensor correlations

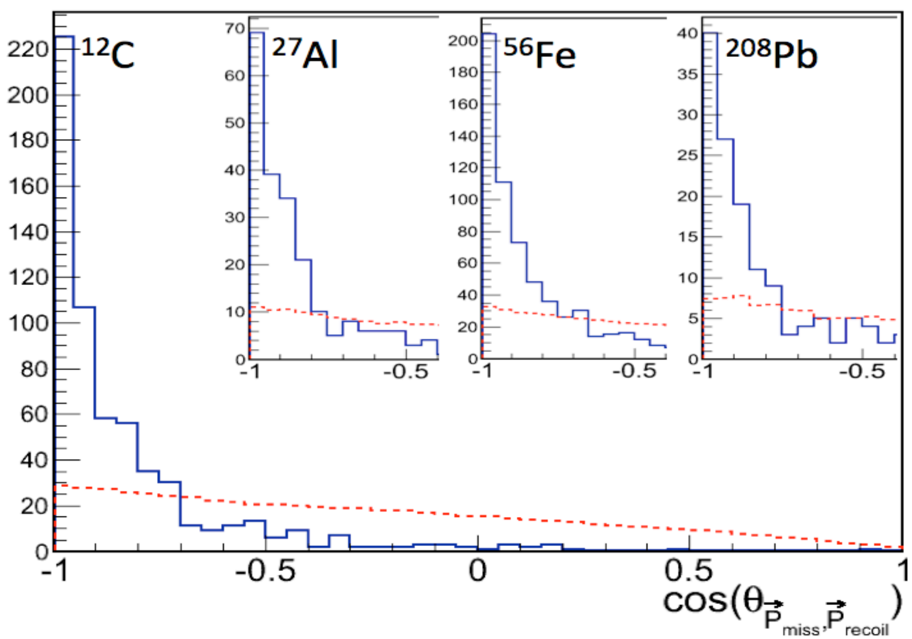
Baghdasaryan, PRL 105, 222501 (2010)

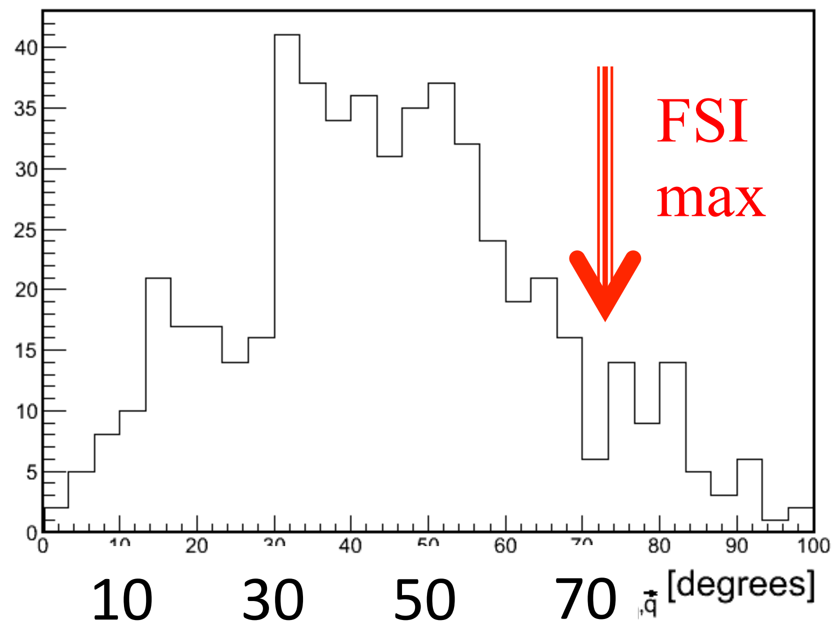
$A(e,e'p)$ and $(e,e'pp)$ in heavy nuclei
(a data mining analysis)

- 5 GeV CLAS data
- C, Al, Fe, Pb targets
- Select leading (knocked-out) proton
- How many high p_{miss} leading protons have a correlated proton partner?

$E_{beam}=5$ GeV
$x_B>1.2$
$\rightarrow Q^2>1.5$ GeV^2
$300<p_{miss}<600$ MeV/c
$\theta_{pq}<25^\circ$
$p_p/q\geq 0.6$

(*e,e'pp*) angular distributions





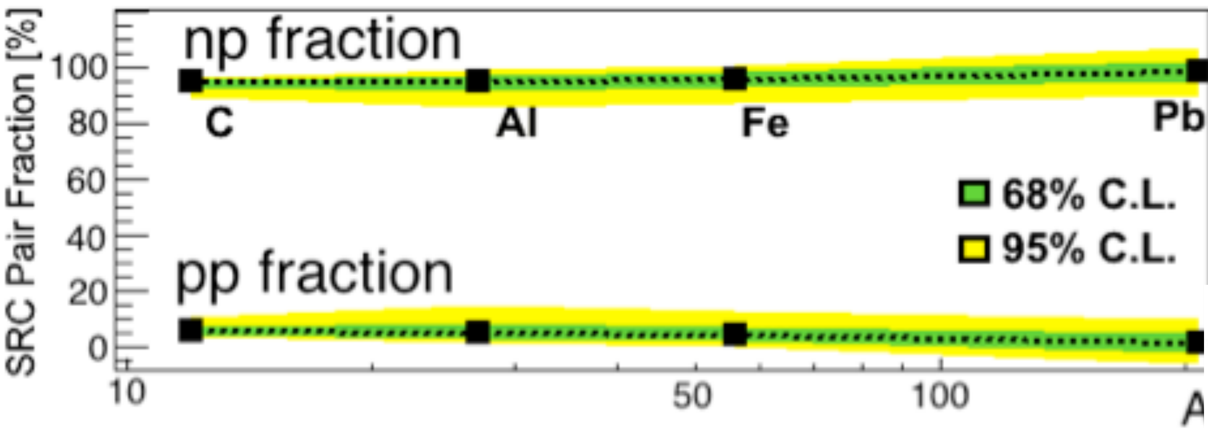
Angle between the (e,e'p) missing momentum and the recoil proton momentum

Angle between *q* and the recoil proton momentum

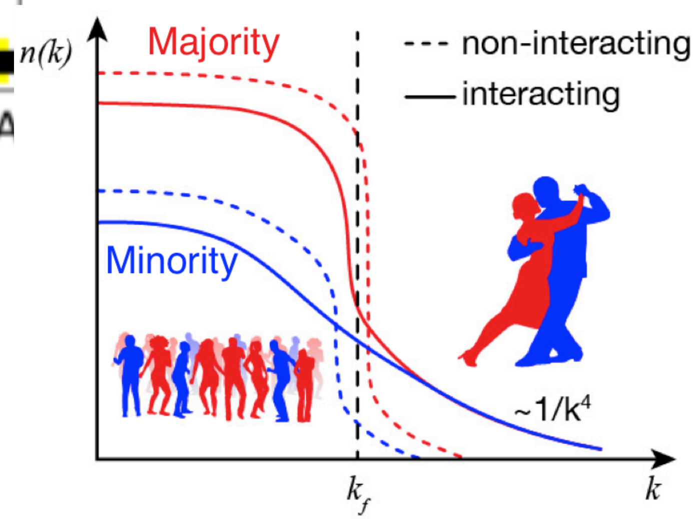
np and *pp* pairs

- Correct for proton rescattering via Glauber
- Assume all high-p_{miss} protons have a correlated partner
  - Use double ratio to get pp pair fraction
- ➔ High momentum tail still predominantly *np*

$$R = \frac{\dfrac{\sigma_A(e,e'pp)}{\sigma_A(e,e'p)}}{\dfrac{\sigma_C(e,e'pp)}{\sigma_C(e,e'p)}}$$



Momentum inversion?



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

L. Weinstein, EMC SRC MIT 2016

What we learned so far

- Onset of correlations (BNL)
- Fraction of high-p protons with partner
  - n
  - p
  - Momentum dependence
- cm momentum distribution of pairs (see Erez' talk)

Not much, but enough for two Science papers!

But very low statistics so far

<table>
<tr><th>Experiment</th><th>pp pairs</th><th>np pairs</th><th>nn pairs</th></tr>
<tr><td>C(p,2pN) BNL</td><td></td><td>18</td><td></td></tr>
<tr><td>C(e,e'pN) Hall A</td><td>263</td><td>179</td><td></td></tr>
<tr><td>He(e,e'pN) Hall A</td><td>50</td><td>223</td><td></td></tr>
<tr><td>A(e,e'pp) CLAS</td><td>1500</td><td></td><td></td></tr>
<tr><td>3He(e,e'pp)n CLAS</td><td colspan="2">~4000</td><td></td></tr>
</table>

Need a LOT more data to answer the big questions

Higher cross sections at 11 GeV

What we want to learn:

- Pairing: pn vs pp vs nn
- Mean-field➔correlations transition (Migdal jump)
- CM (Q) vs relative (q) momentum distributions
- *A* dependence
- central vs tensor correlations
- 3NF / 3N SRC ???

What we need:

- A LOT more data
- More theory support
  - Nuclear models
  - Reaction theory
    - Must: Where is factorization valid?
    - Should: Exact cross section calculations for light nuclei in restricted kinematics
    - Want: Exact cross section calculations for heavy nuclei in all kinematics