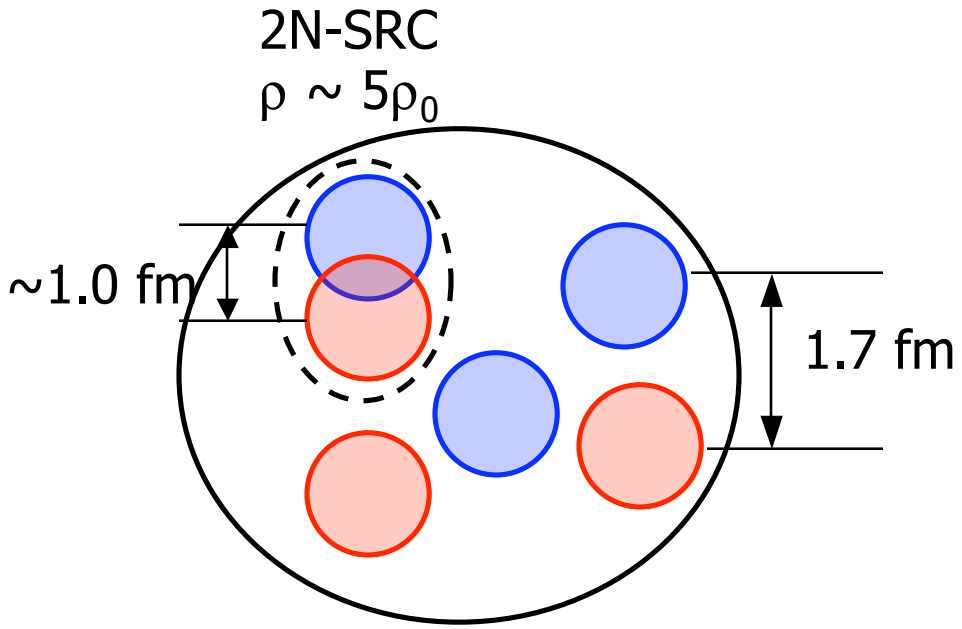
Nuclear Short Range Correlations

Larry Weinstein
Old Dominion University

- What are Correlations?
  - Neutron stars
  - EMC effect
- Hit the correlated pair
- Spectator correlated pairs
- np vs pp pairs
- Summary

Two nucleon short range correlations (NN-SRC)



Studying NN-SRC concerns:

- High momentum part of the nuclear wave function
- Short distance behavior of nucleons - overlapping??
- EMC Effect
- Neutron Stars

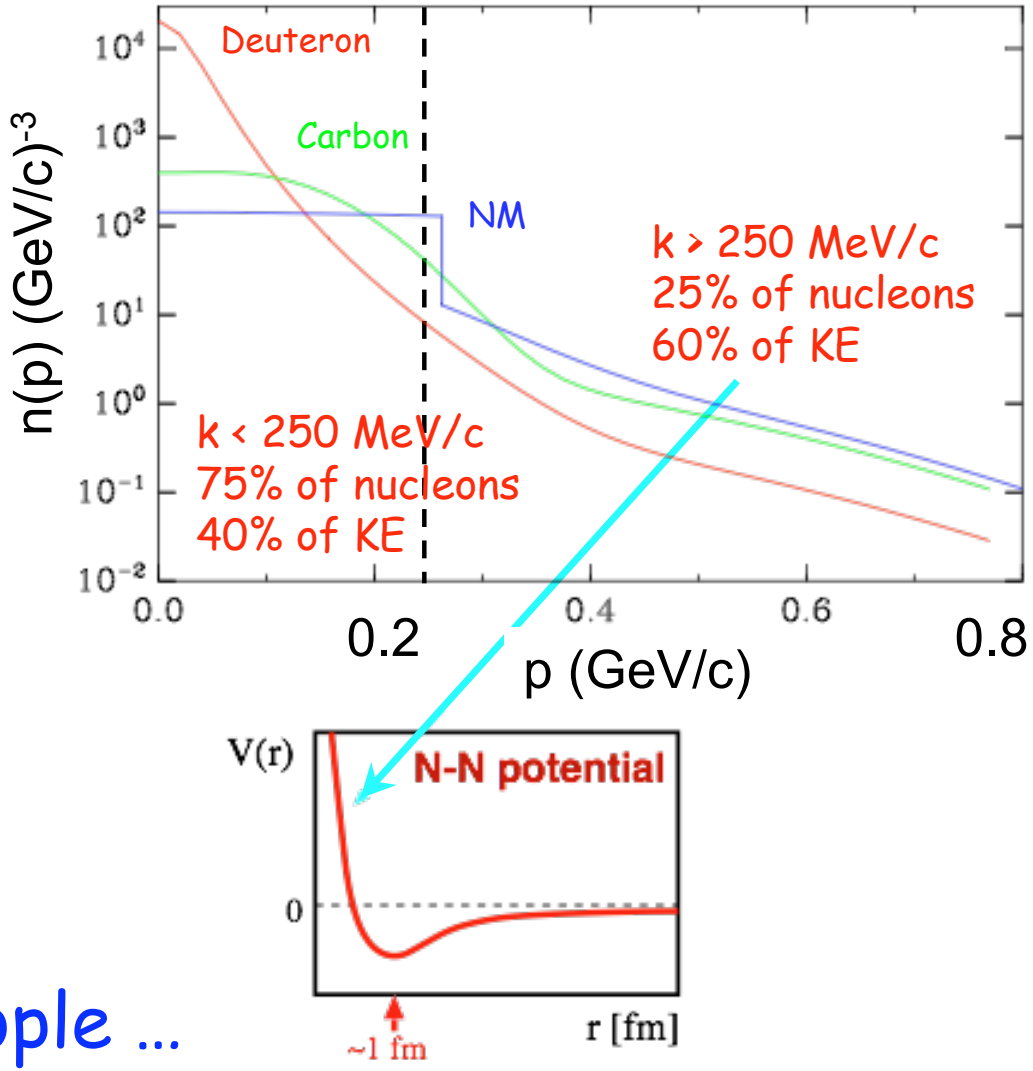
Short Range Correlations (SRCs)

High momentum tails: $k > k_F$
Calculable for few-body nuclei, nuclear matter.
Dominated by two-nucleon short range correlations

Poorly understood part of nuclear structure

NN potential models not applicable at $p > 350$ MeV/c

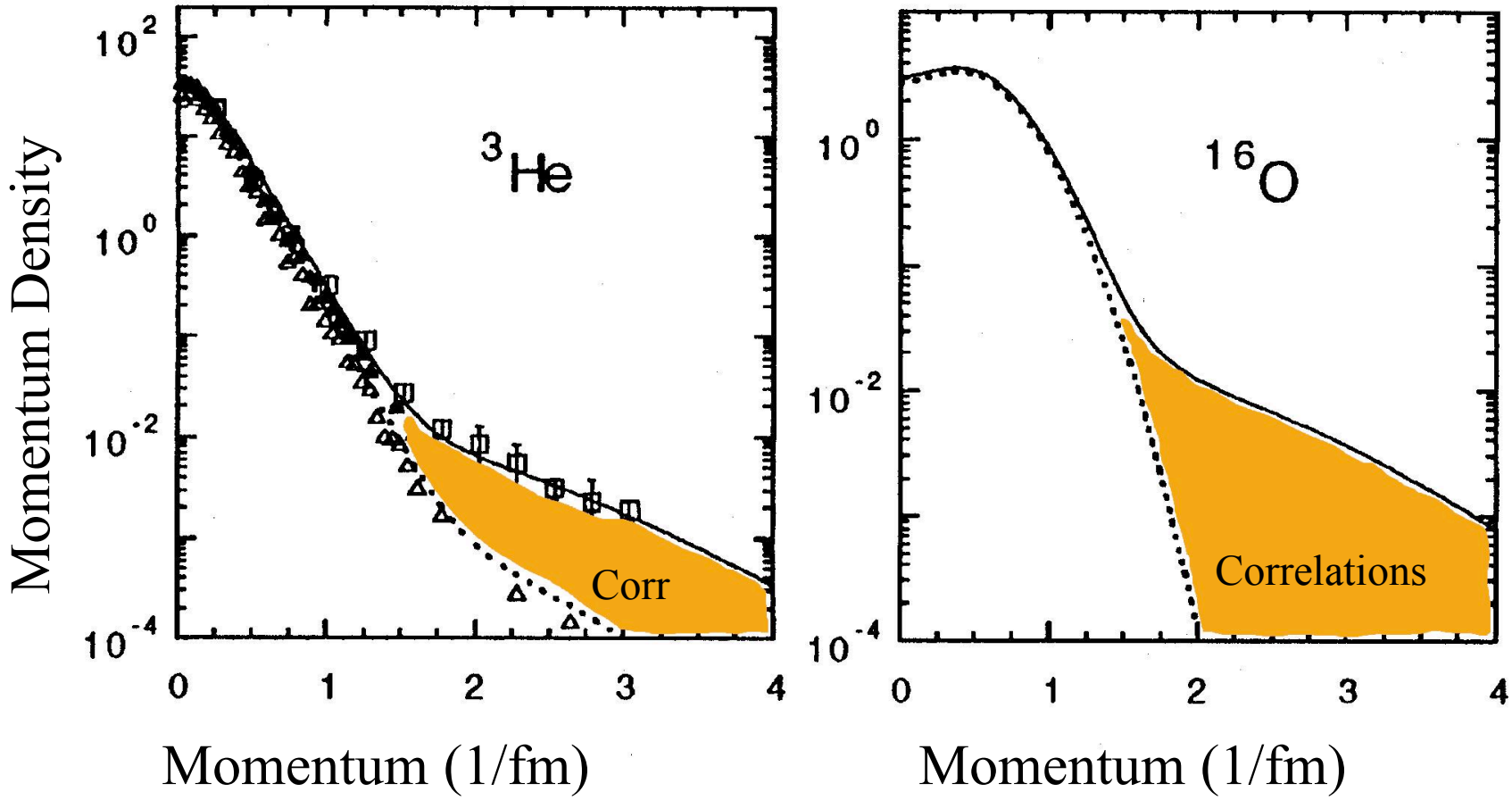
Uncertainty in SR interaction leads to uncertainty at $k \gg k_f$, even for simplest systems



Nucleons are like people …

Why are Correlations Interesting?

Responsible for high momentum part of Nuclear WF



Ciofi degli Atti, PRC 53 (1996) 1689

(See also Schiavilla, Van Orden, and many others)

Correlations and Neutron Stars

'Classical' neutron star: fermi gases of *e*, *p* and *n*
Low temperature ⇒ almost filled fermi spheres
⇒ limited ability of p⇔n decays (Urca process)

Correlations ⇒ high momentum tail and holes in the fermi spheres

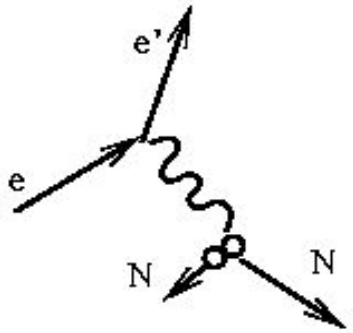
Why does this matter?

Cooling should be dominated by the Urca process:

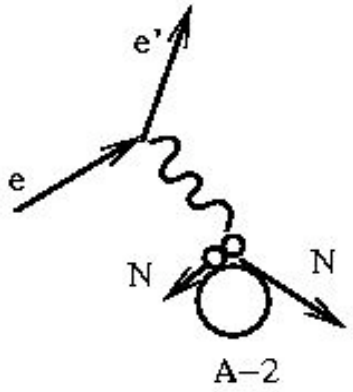
$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$p + e^- \rightarrow n + \nu_e$$

Correlations-caused holes in the proton fermi sphere should enhance this process by large factors and speed neutron star cooling.
(This is already included phenomenologically in the 'modified Urca process.)

Correlations are Universal: A(e,e')

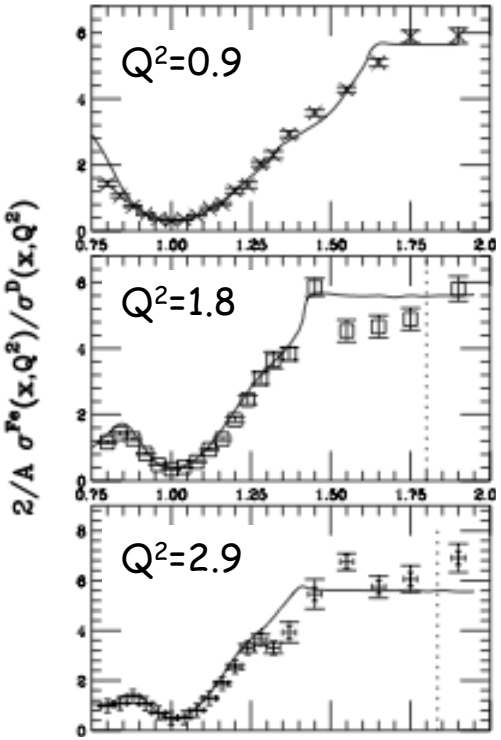


d(e,e')

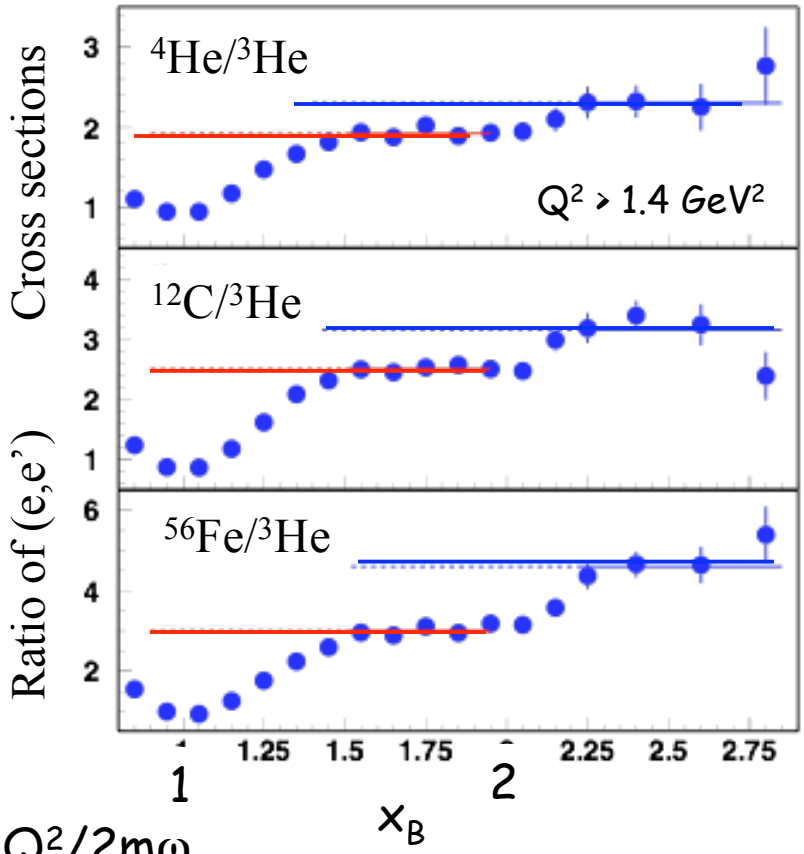


A(e,e')

Ratio (2/56) Fe/d



Ratios to ^{3}He (×3/A)



$x_B = Q^2/2m\omega$

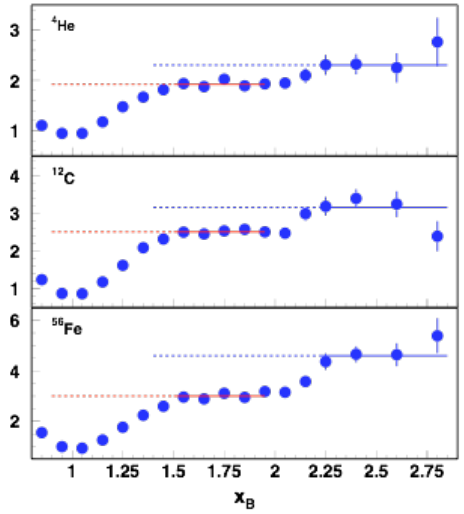
Scaling (flat ratios) indicates a common momentum distribution.
1 < x < 1.5: dominated by different mean field n(k)
1.5 < x < 2: dominated by 2N SRC
x > 2.3: dominated by 3N SRC

$\alpha_{2N} \approx 20\%$
$\alpha_{3N} \approx 1\%$

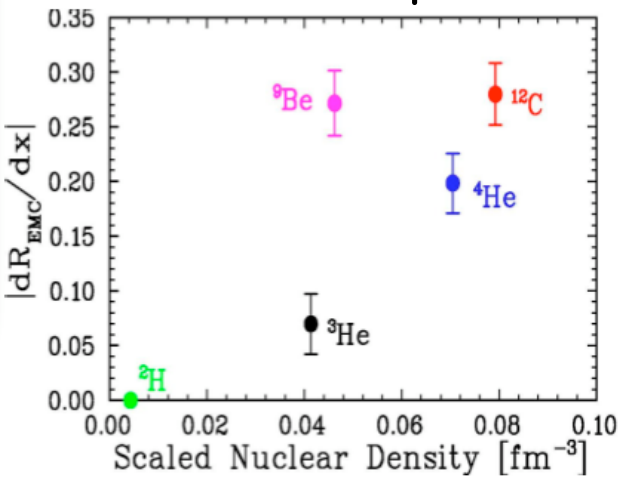
Frankfurt et al, PRC48 2451 (1993)
Egiyan et al., PRL 96, 082501 (2006)

EMC Effect and Correlations

Ratios to ^{3}He (×3/A)



EMC Slope



	Ratio to 3He	
	EMC	SRC a_{2n}
4He	3 (2-5)	1.9
12C	4 (3-7)	2.5

Not very good agreement

But: need to correct for d SRC

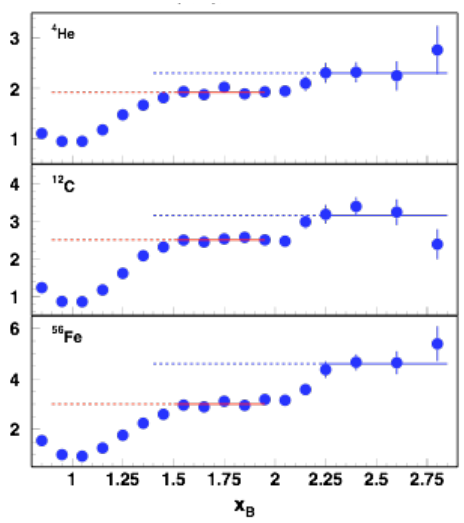
	Ratio to 3He		
	EMC	SRC a_{2n}^A	SRC $(a_{2n}^A - a_{2n}^d)$
4He	3 (2-5)	1.9	2.9
12C	4 (3-7)	2.5	4.0
Fe	???	3.0	5.1

(see earlier talk by P. Solvignon)

EMC Effect and SRC: Another Look

The deuteron is **not** a free np pair

Ratios to ^{3}He ($\times 3/A$)



SRC ratio 3He/d = 2.0

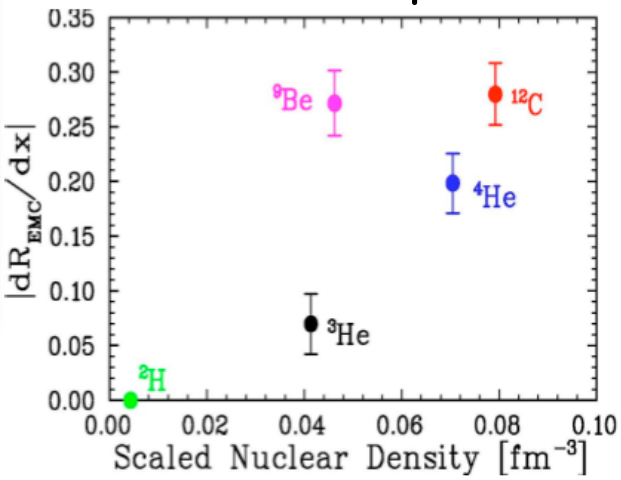
⇒If the EMC effect is due to SRC then the d EMC slope (relative to a free np pair) should be half of the 3He EMC slope

⇒ d EMC slope = 0.07

⇒ 3He corrected EMC slope = 0.14

⇒ add 0.07 to all measured EMC slopes

EMC Slope



	Ratio to 3He	
	EMC corrected	SRC
4He	2	1.9
12C	2.5	2.5

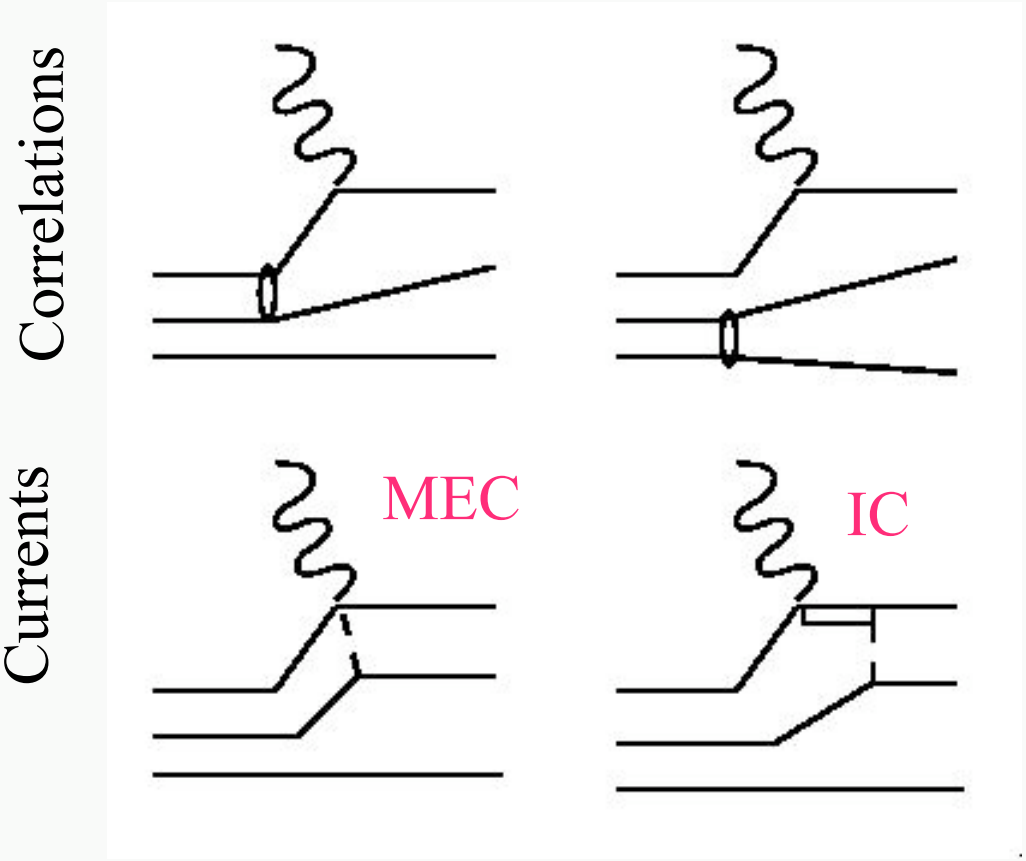
Wow! EMC is caused by SRC!

(Warning: large uncertainties)

What are correlations?

Average Two Nucleon Properties in the Nuclear Ground State

Two-body currents are not Correlations



Two body currents strongly enhance the effects of correlations

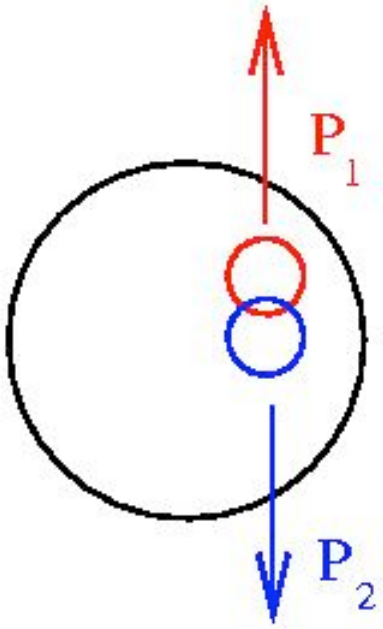
What are Correlations?

Average Two Nucleon Properties in the Nuclear Ground State

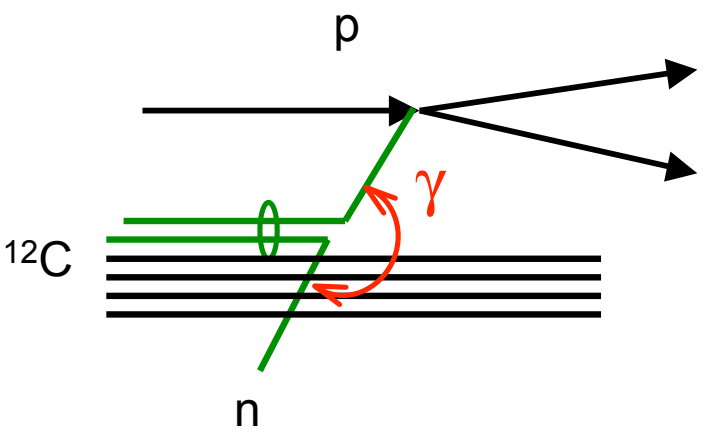
Not Two-Body Currents

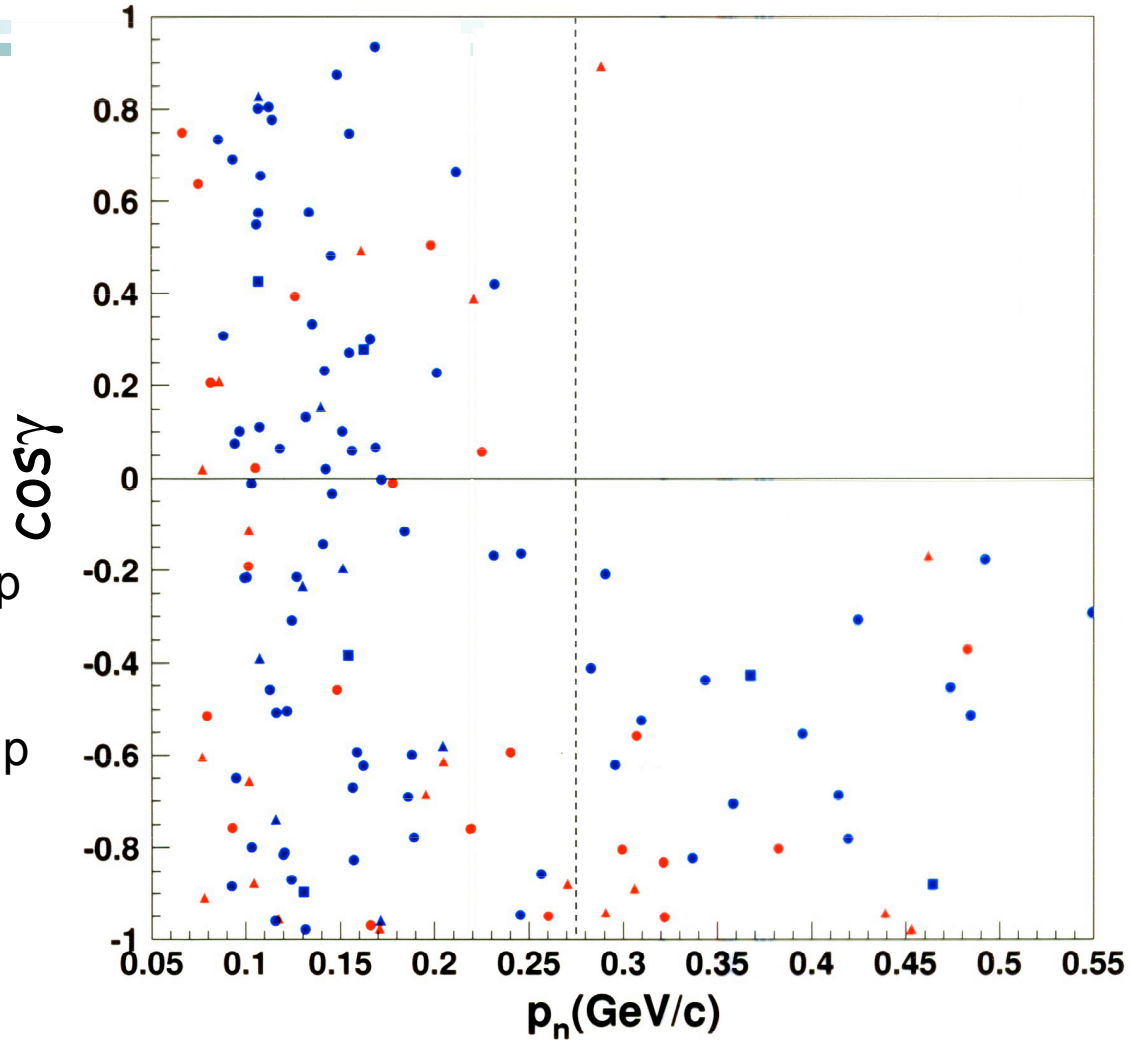
An Experimentalist's Definition:

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



$^{12}C(p,ppn)$ EVA/BNL





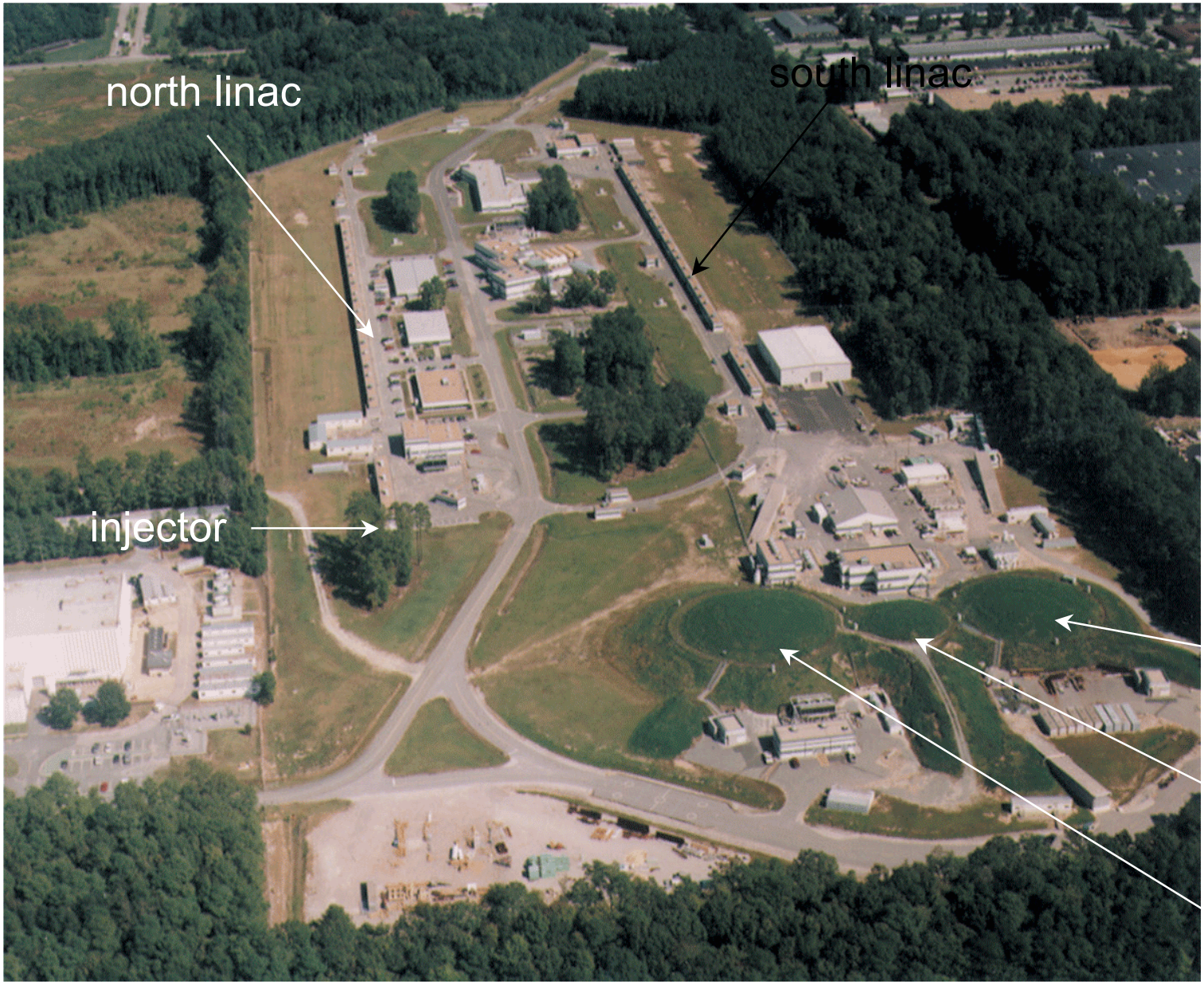
Large neutron momentum → *n* opposite p_{init}

Small neutron momentum → *n* isotropic

High momentum nucleons are paired

Tang et al, PRL 90, 042301 (2003)

Jefferson Lab Site

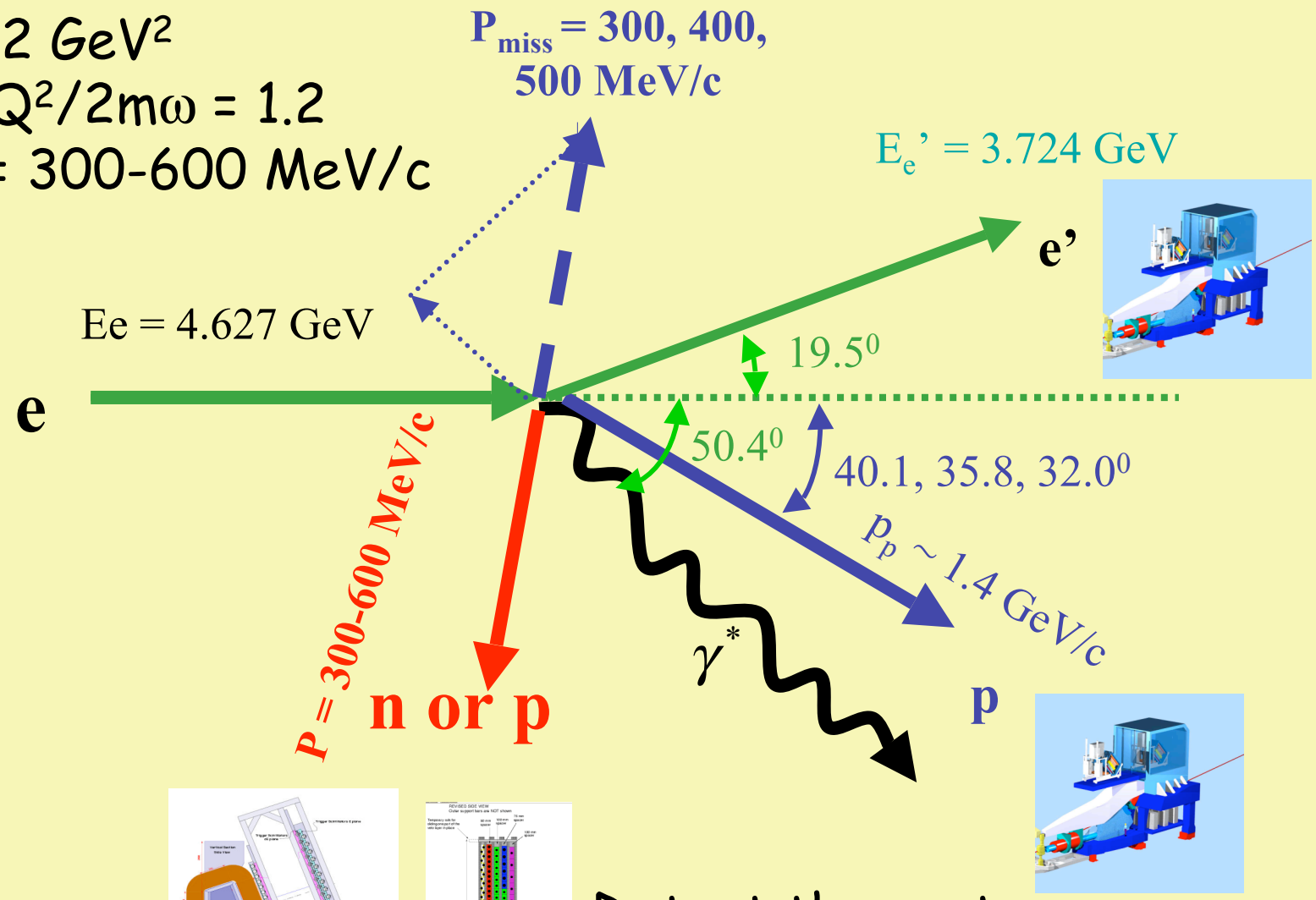


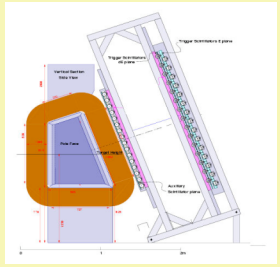
Knock out a correlated pair
JLab Hall A C(e,e'pN) - selected kinematics

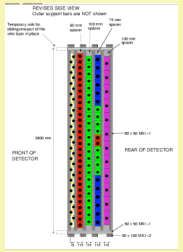
$Q^2 = 2\ GeV^2$

$x_B = Q^2/2m\omega = 1.2$

$P_{miss} = 300\text{-}600\ MeV/c$

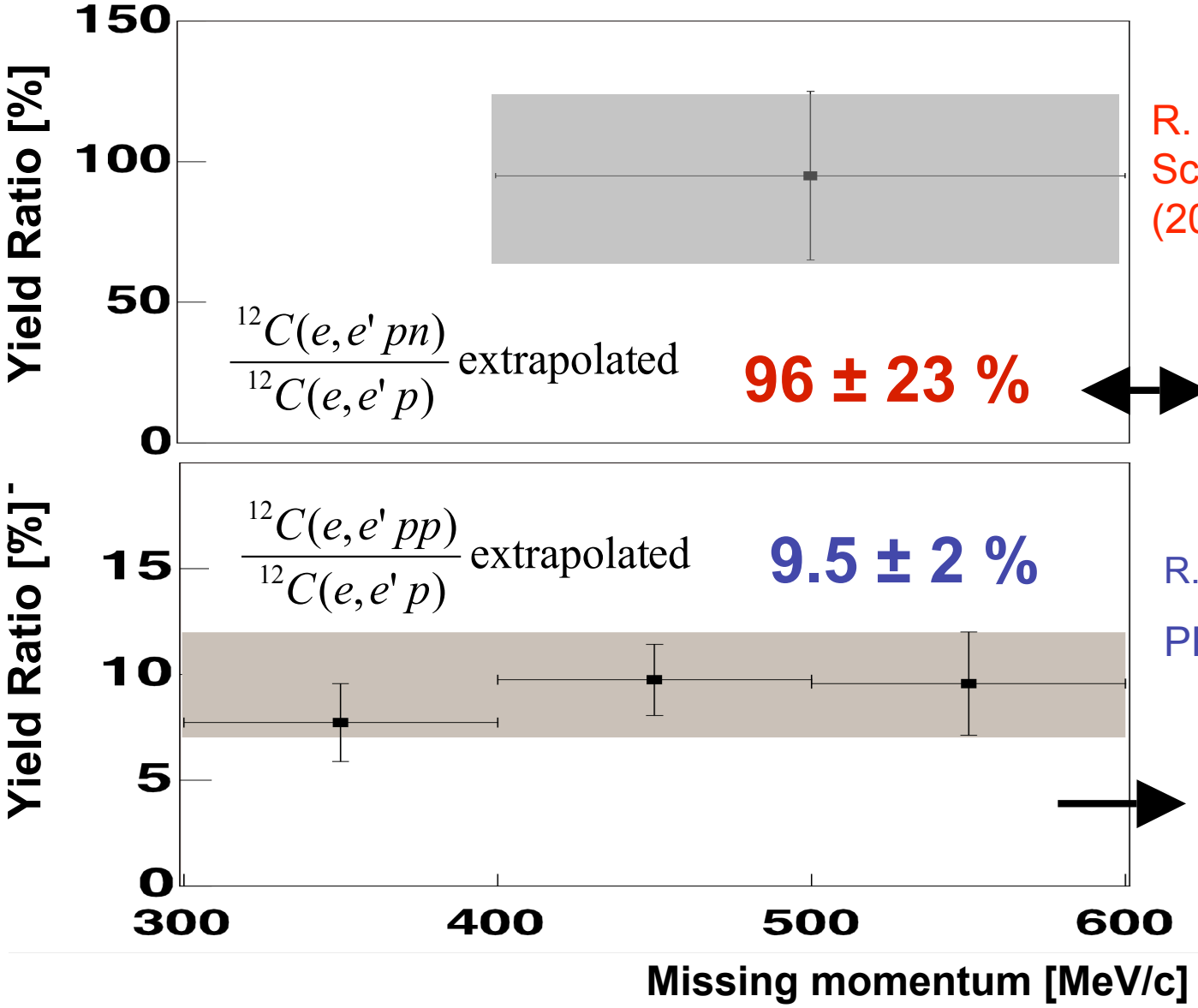






Detect the proton,
look for its partner nucleon

High momentum protons have partners



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

BNL Experiment measurement was 92^{+8}_{-18}%

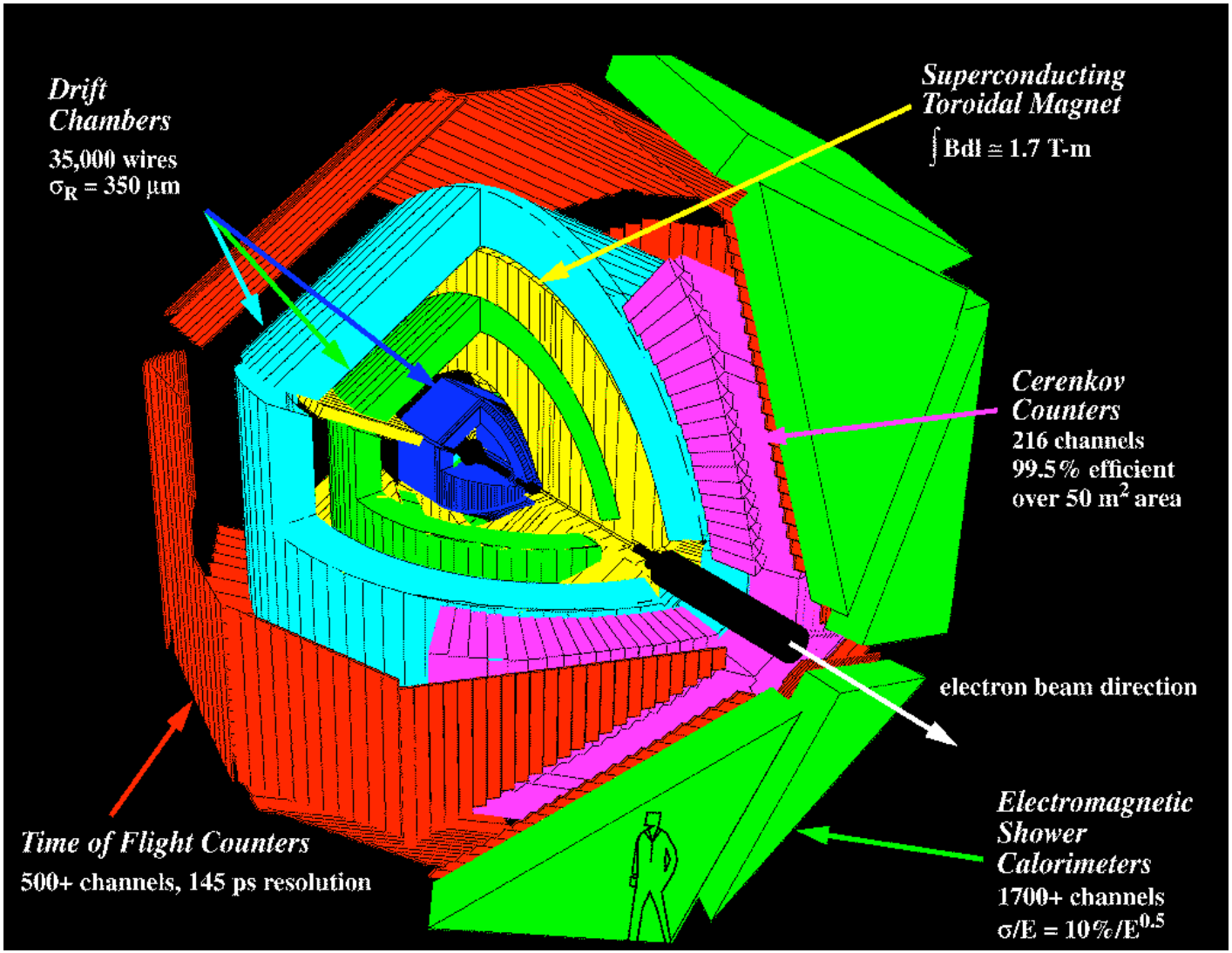
R. Shneor et al., PRL **99**, 072501 (2007)

pp/pN = 5%

Since the electron can hit either proton

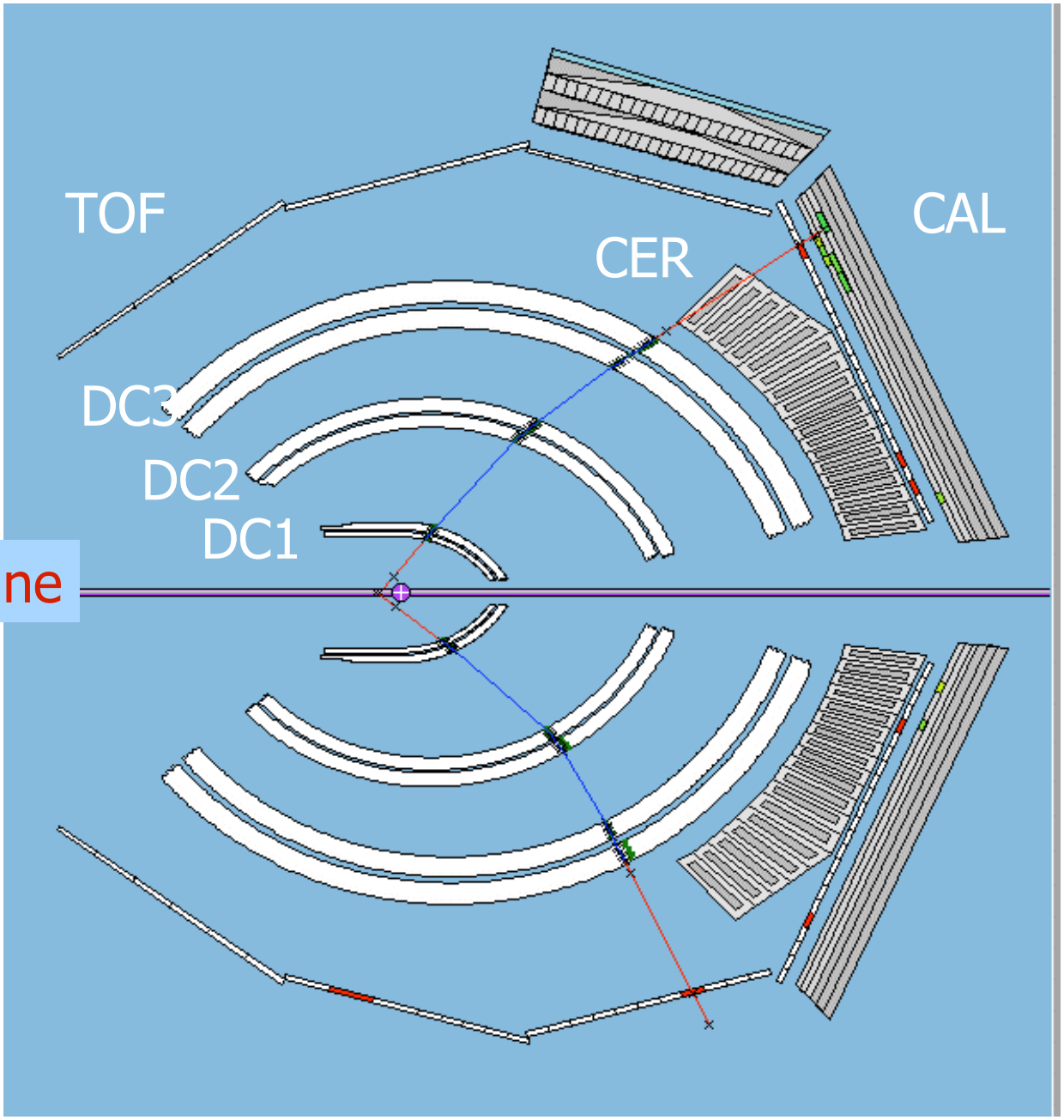
^{3}He(e,eX) in CLAS

- e2a and e2b
- 2.2 and 4.7 GeV electrons
- Inclusive trigger



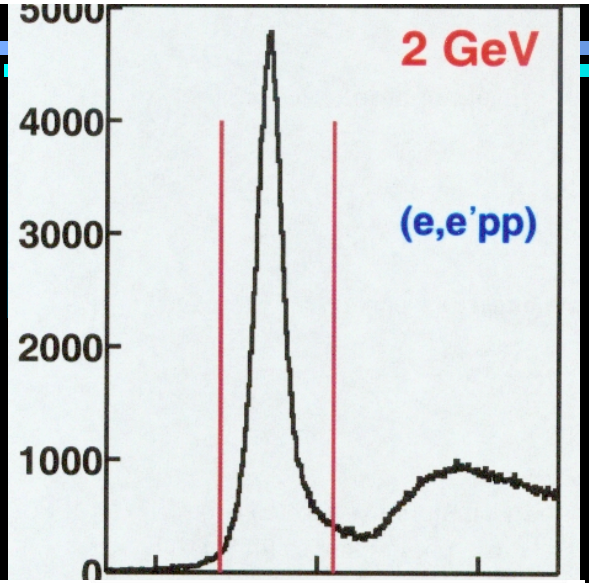
CLAS Event Display

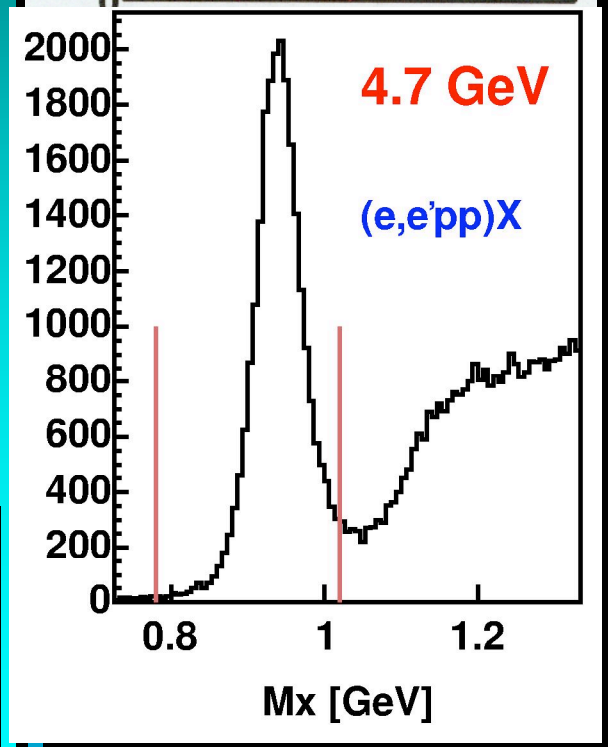
Sectors 1 and 4



CLAS in Maintenance Position

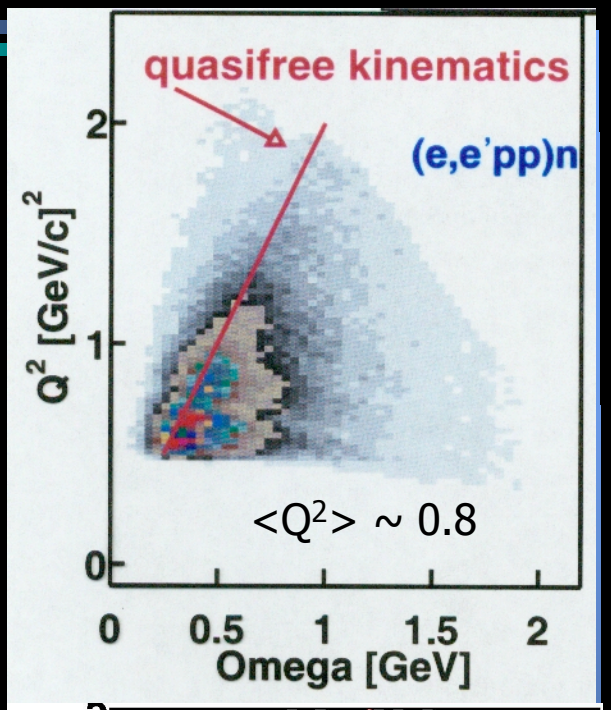
CLAS
^{3}He(e,e'pp)

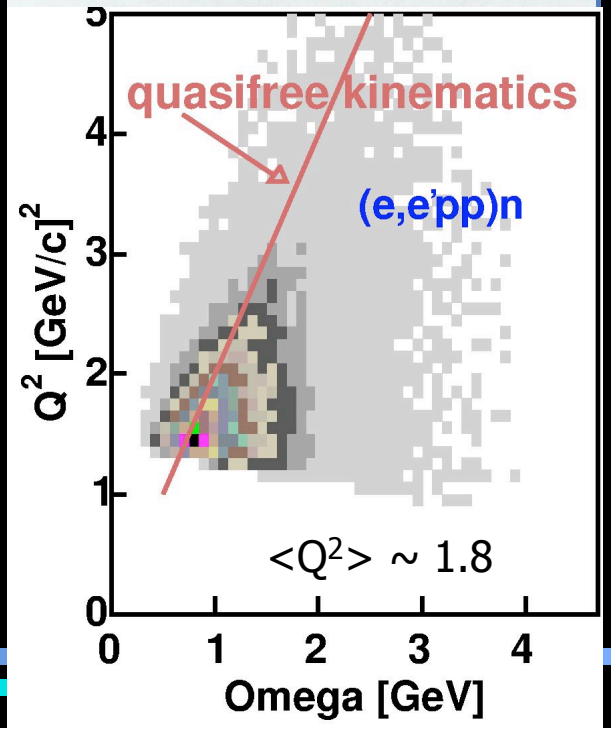




Detect 2 protons, reconstruct the neutron

Huge electron acceptance



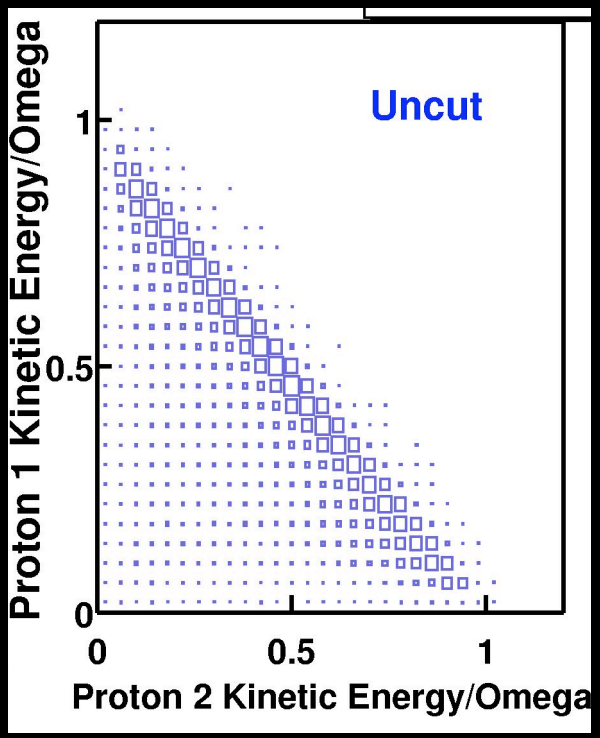


^{3}He(e,e'pp)n nucleon energy balance:

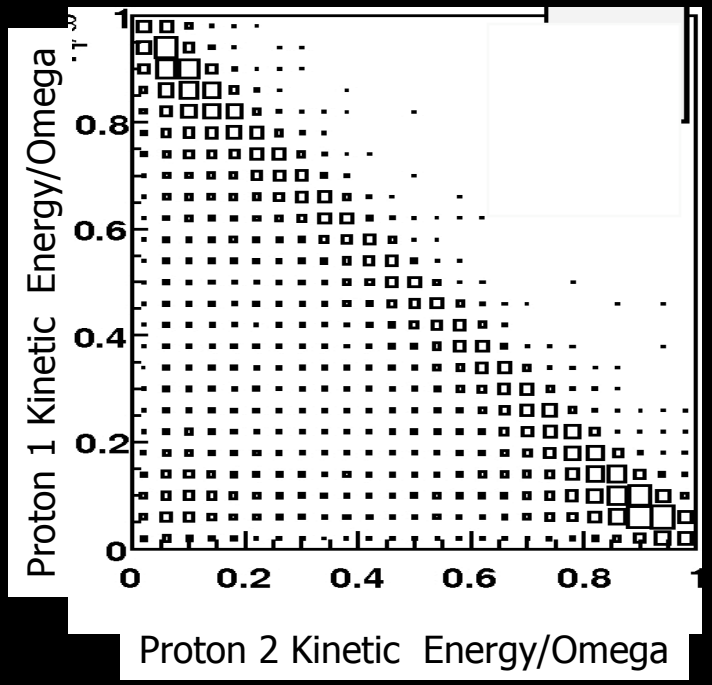
Lab frame Dalitz plots

Proton threshold 250 MeV/c

2.2 GeV

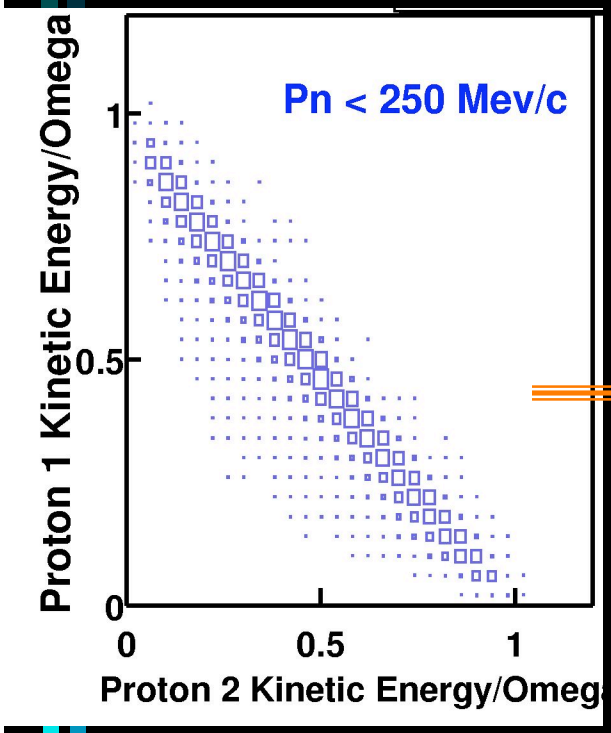


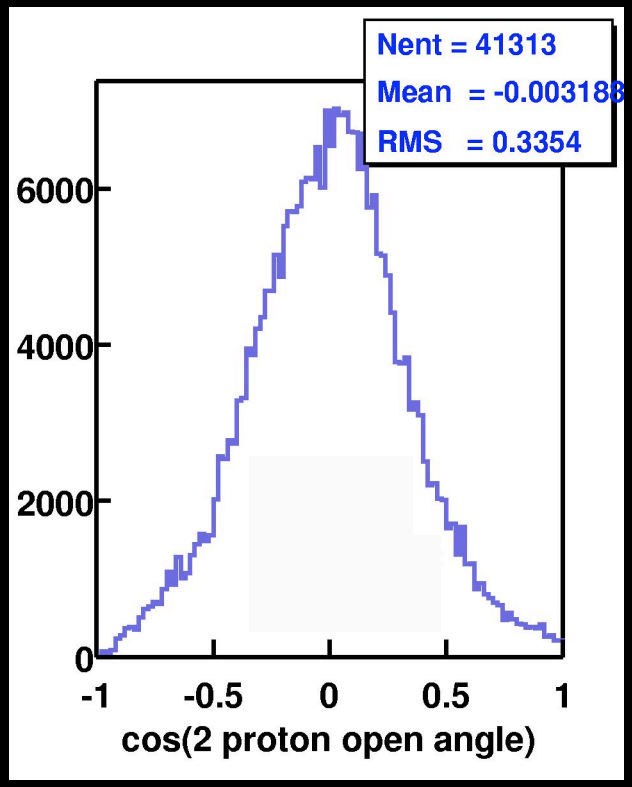
4.7 GeV



Mostly pp knockout with a low energy neutron

pp knockout dominated by rescattering

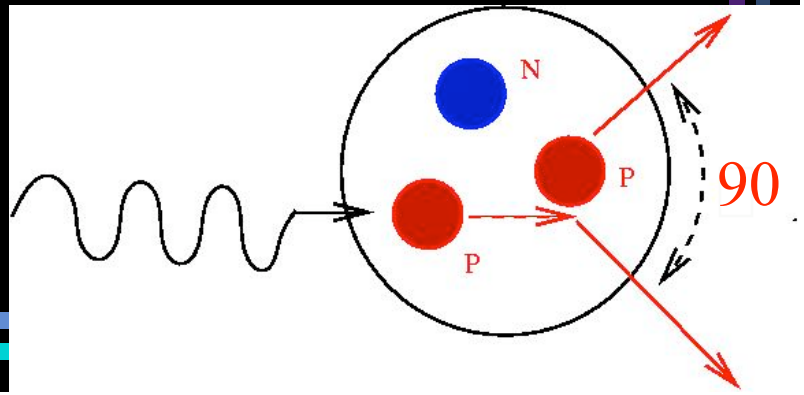




90 degree
pp opening angle

Rescattering!

Energy balance (Dalitz plot):
^{3}He(e,e'pp)n events
with spectator neutron



But let's look more closely ...

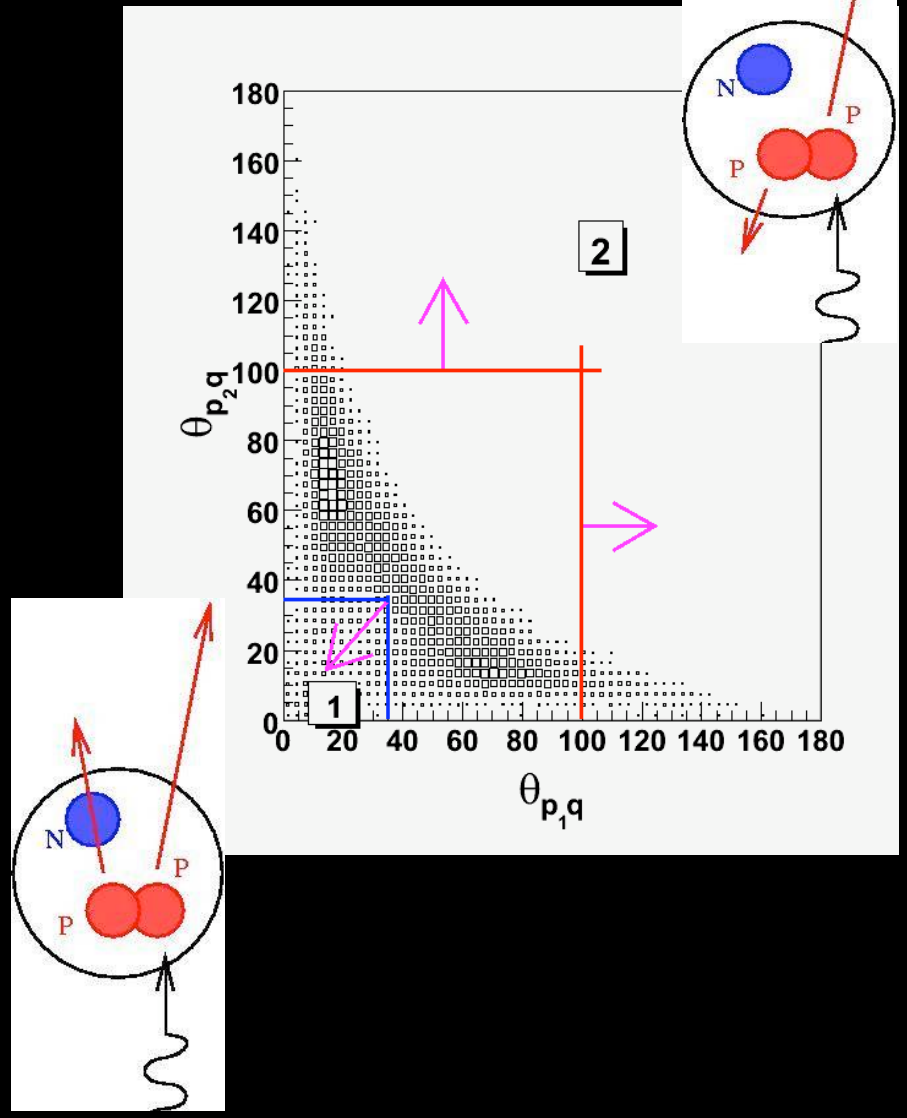
pp knockout: a closer look

Two active nucleons:
$p_{neutron} < 200$ MeV/c

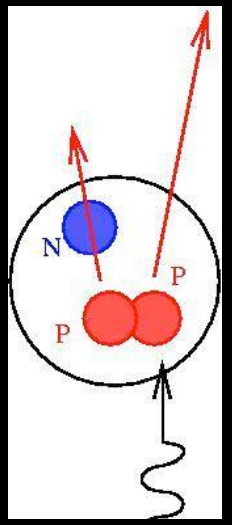
Try to minimize FSI:

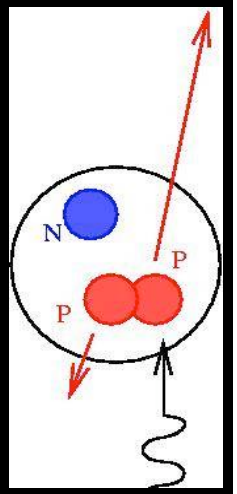
1. Two forward protons $X_B>1$
   $\theta(pq) < 35^o$
2. Slower backward proton
   $X_B<1$, $\theta(p_{slow}q) > 100^o$

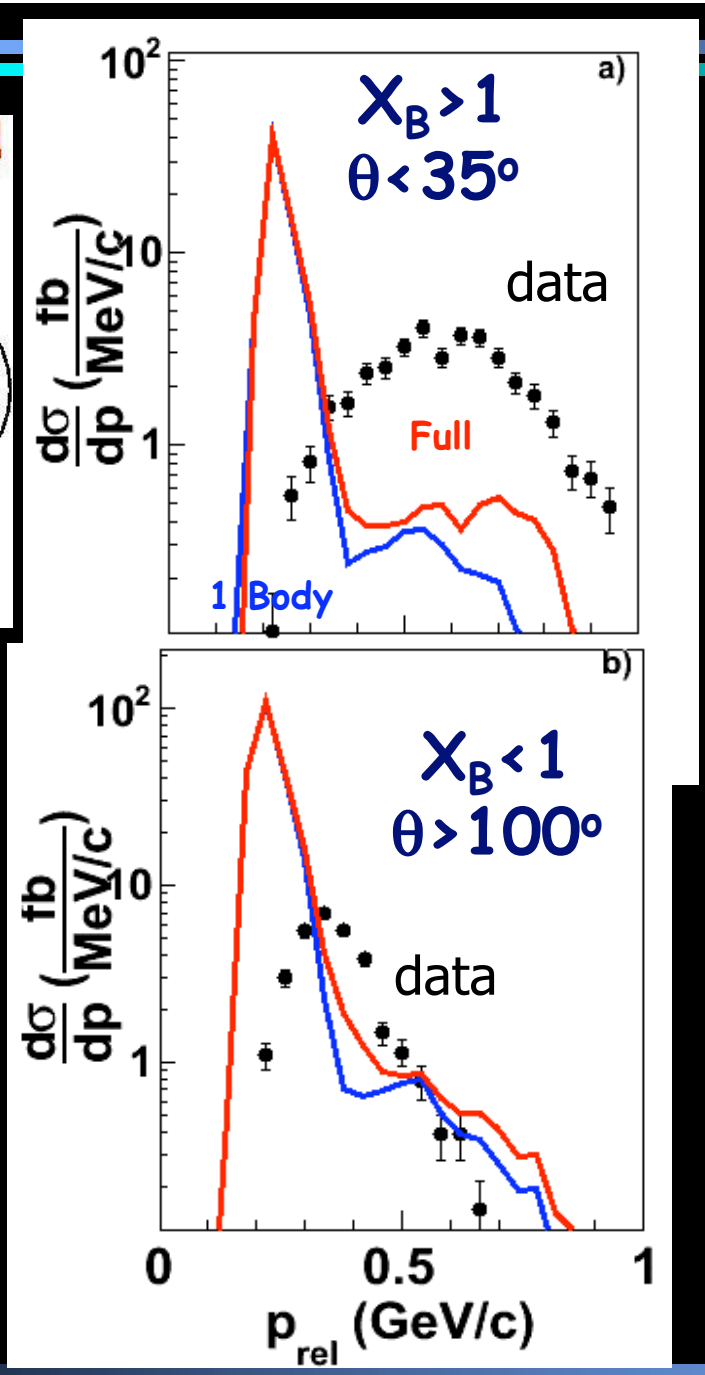
Plot vs $P_{rel}=(P_{fast}-q-P_{slow})/2$



pp knockout: correlations?





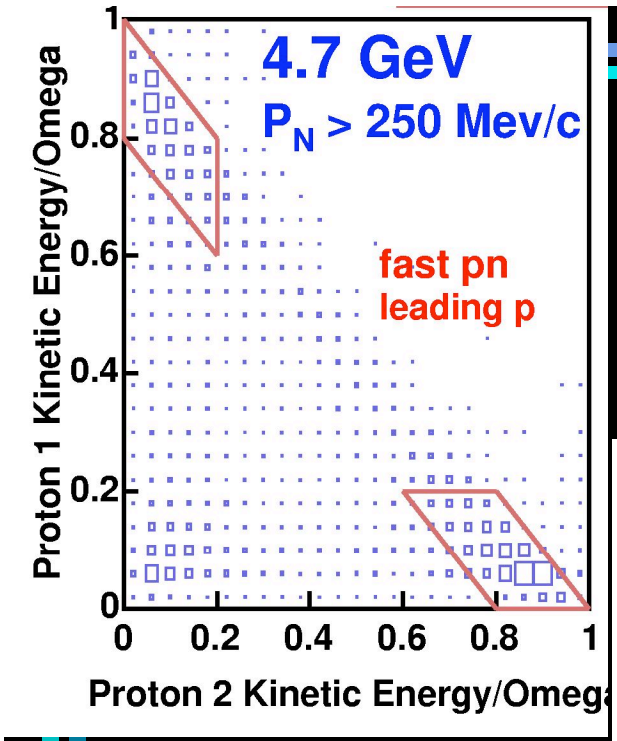


Avoiding FSI:

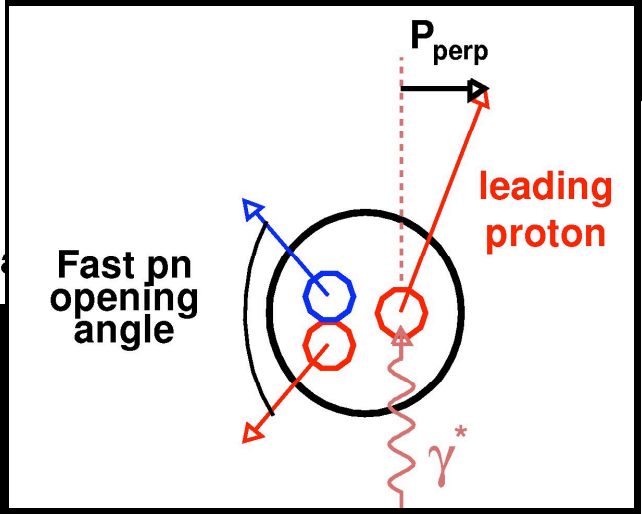
1. x<1 and x>1 data completely disagree
2. Laget calculation does not describe data
   1. Little FSI or MEC predicted
3. Backward (x<1) data matches calculation better

No obvious sensitivity to the bound state wf

3He(e,e'pp)n: p_N > 250 MeV/c Spectator pairs

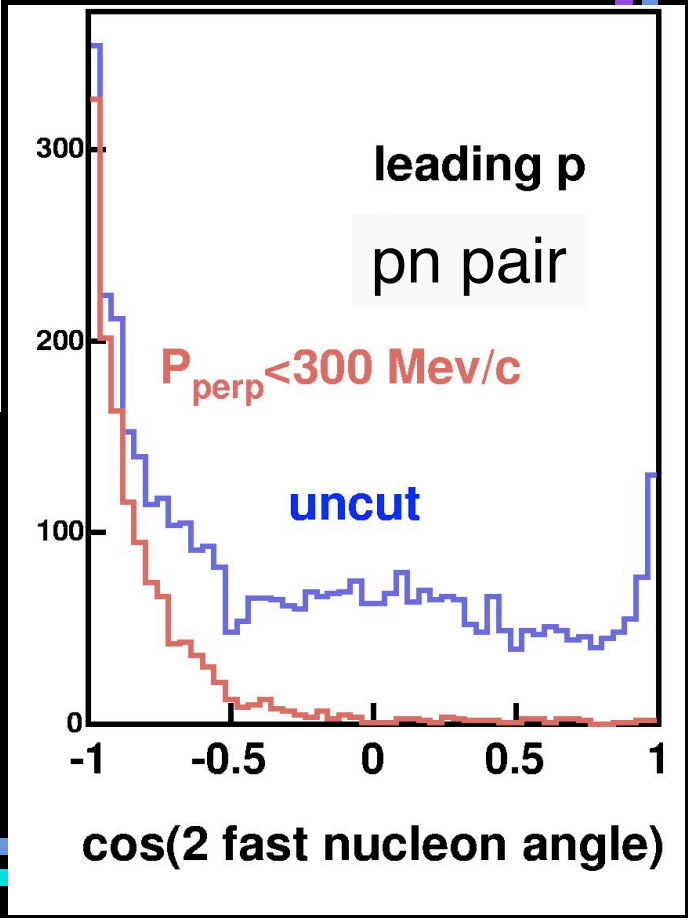


Select peaks in Dalitz plot



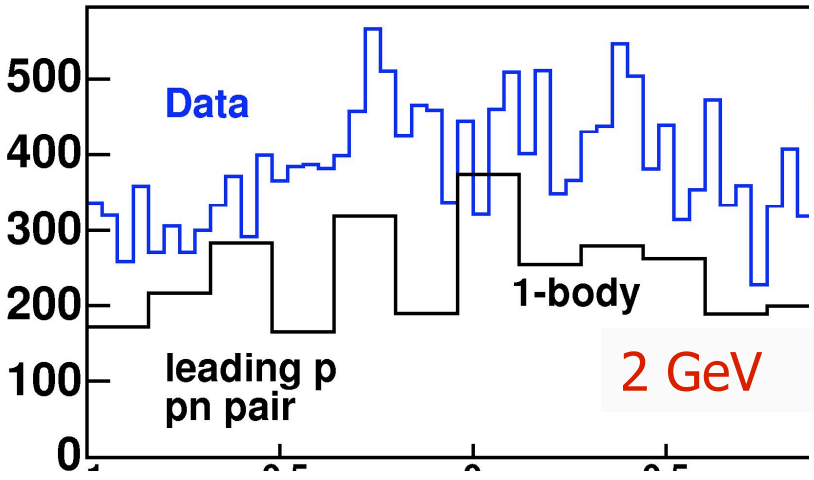
Cut on leading nucleon perpendicular momentum

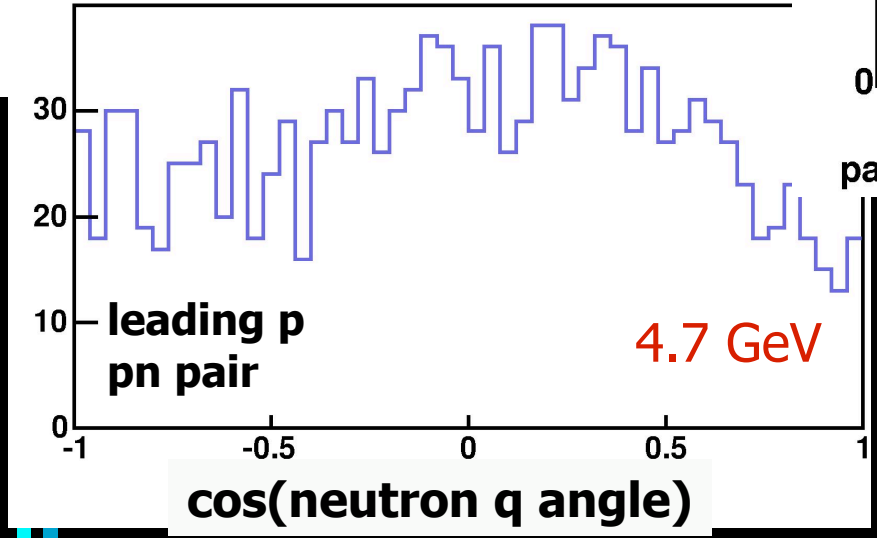
Pair has back-to-back peak!

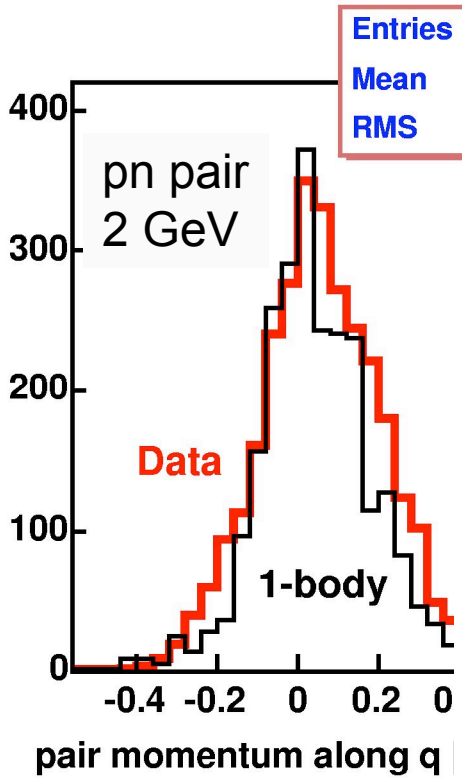


I don't want to get involved: spectator correlated pairs

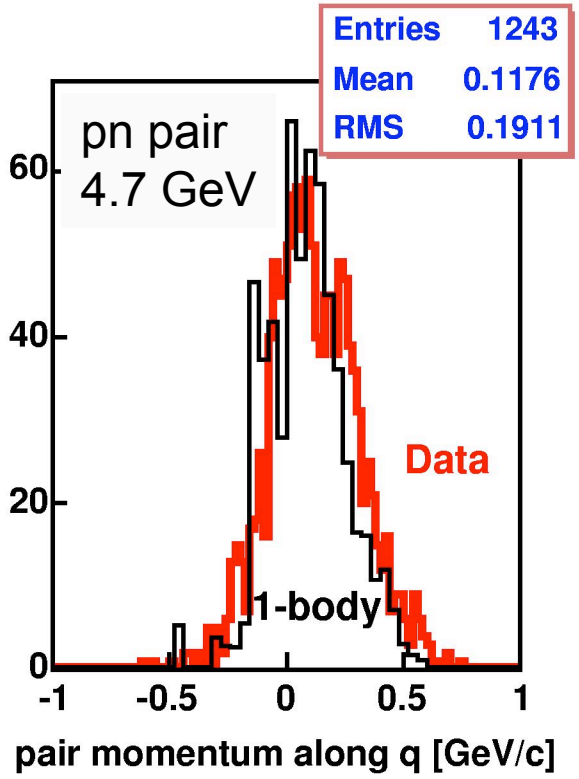
Isotropic!







Small forward momentum (described by theory)



Results:

2.2 GeV ($Q^2 \approx 0.8$ GeV^2)

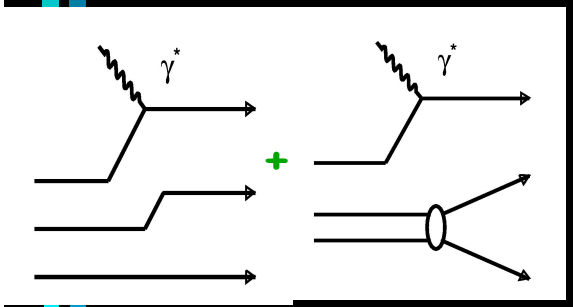
4.7 GeV ($Q^2 \approx 1.5$ GeV^2)

4.7 GeV scaled by 5.3

Similar momentum distributions

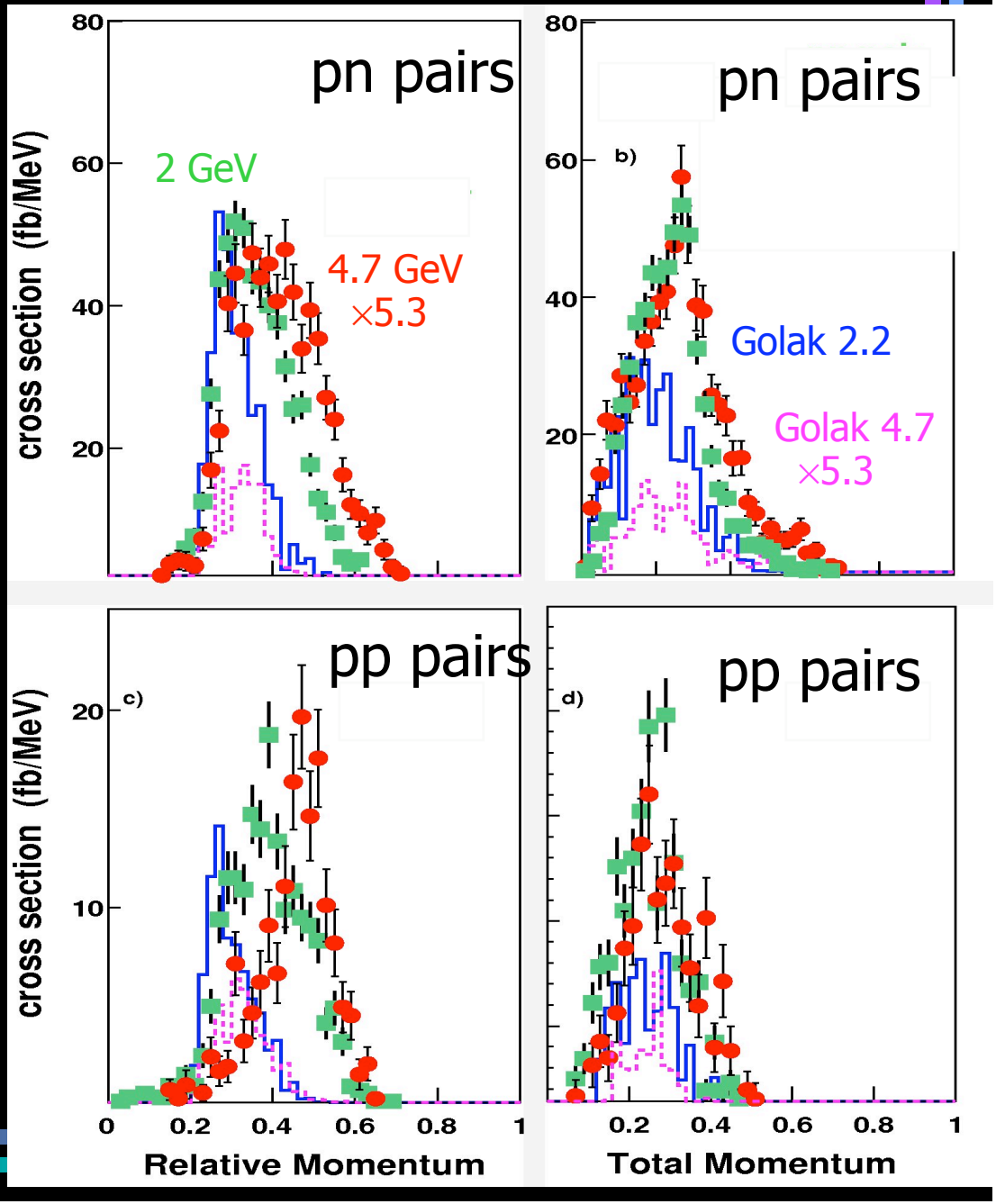
- Relative
- Total

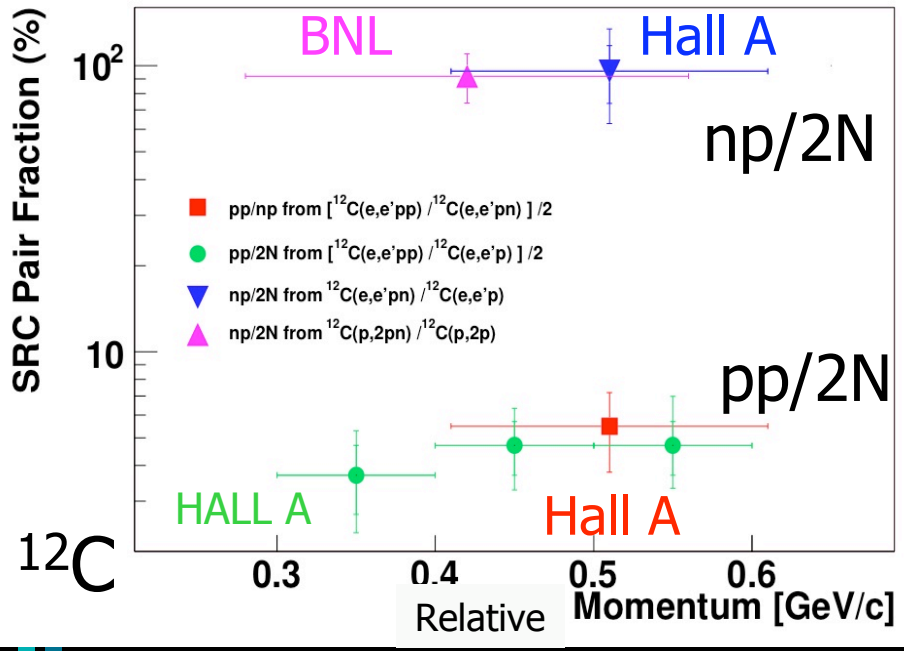
pn:pp ratio ~ 4



Theory (Golak)

- Describes 2 GeV OK
  - P_{rel} too low
- Too low at 4.7 GeV

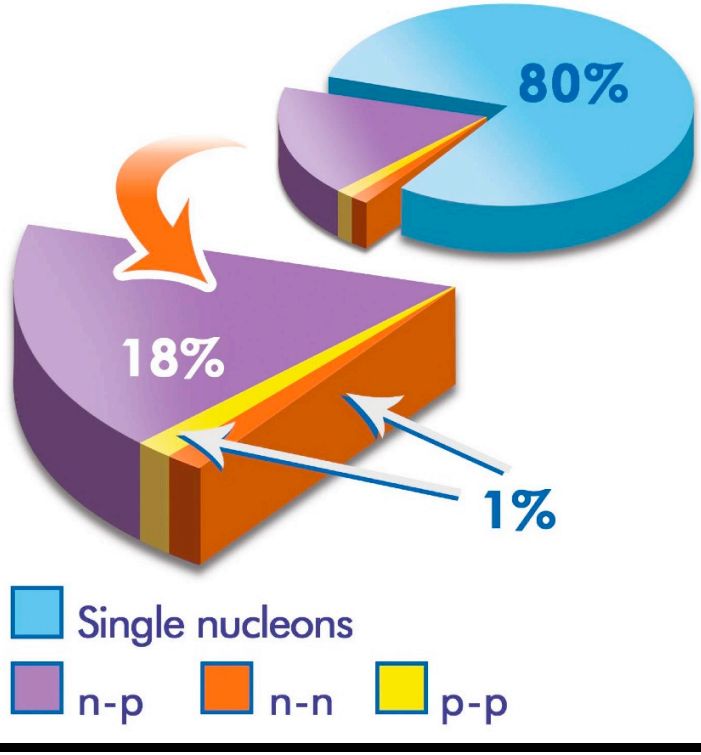




pp to pn comparison

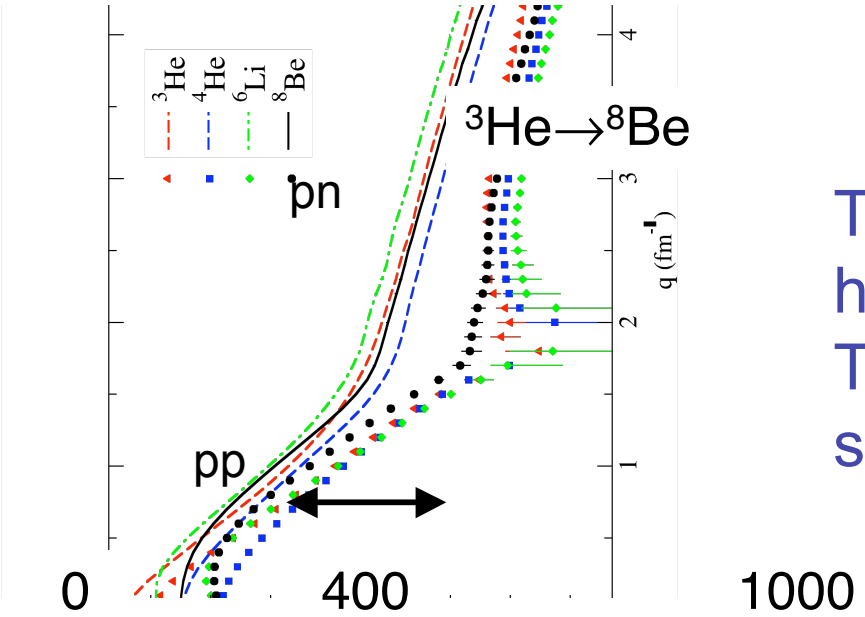
Subedi et al, Science (2008)

	<Q^2> (GeV^2)	pp to pn ratio
Hall A / BNL	2 / ??	1/18
CLAS	1-2	1/4

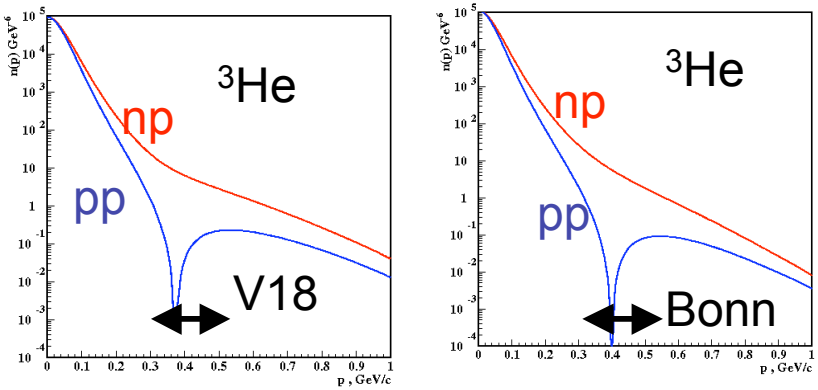


Contradiction???

Why is pp/np so small at p_{rel}=300-500 MeV/c?



The s-wave momentum distribution has a minimum
The *np* minimum is filled in by strong tensor correlations



Pair relative momentum

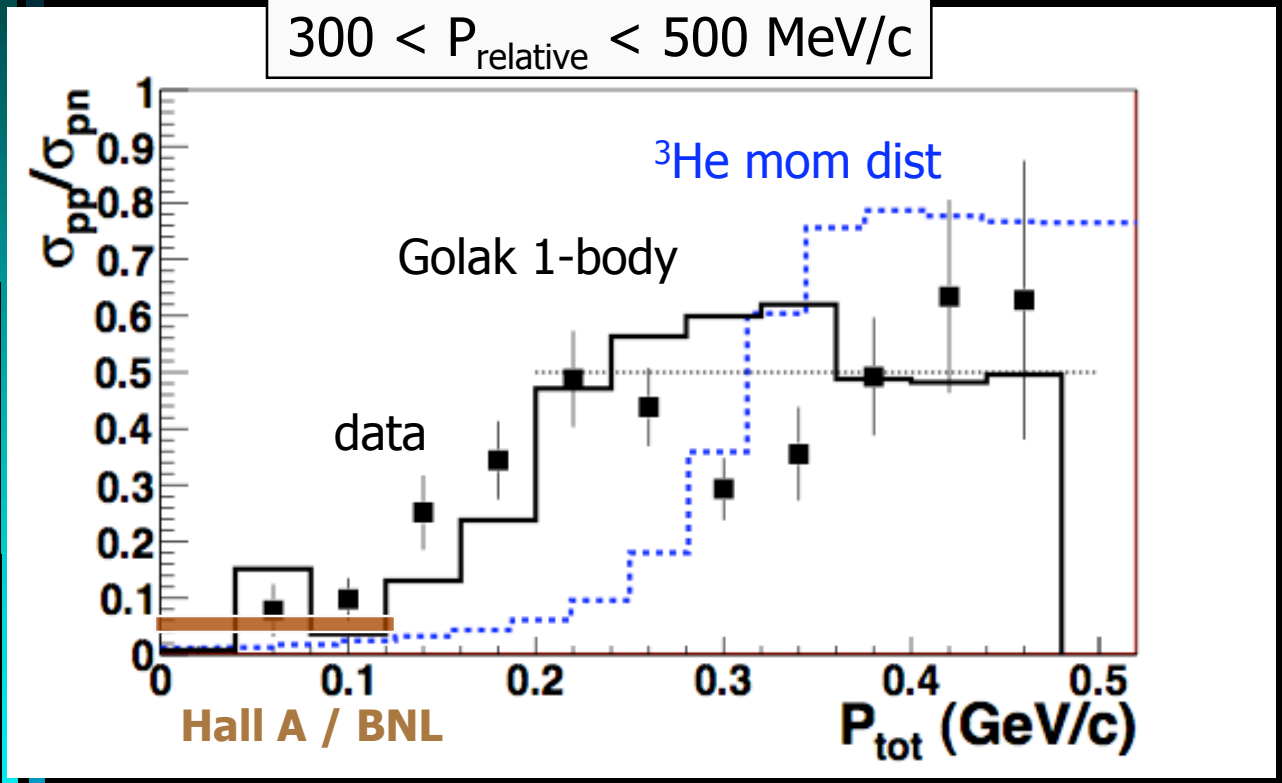
Ciofi degli Atti, Alvioli;

Schiavilla, Wiringa, Pieper, Carlson

Sargsian, Abrahamyan, Strikman, Frankfurt

pp to pn resolution:

pp/pn ratio increases with pair total momentum P_{tot}



Tensor Correlations!

Small $P_{tot} \Rightarrow$ pp pair in s-wave (no tensor)
$\Rightarrow$ wave fn minimum at p_{rel}=400 MeV/c

Hall A: small $P_{tot} \Rightarrow$ less pp
Hall B: large $P_{tot} \Rightarrow$ more pp

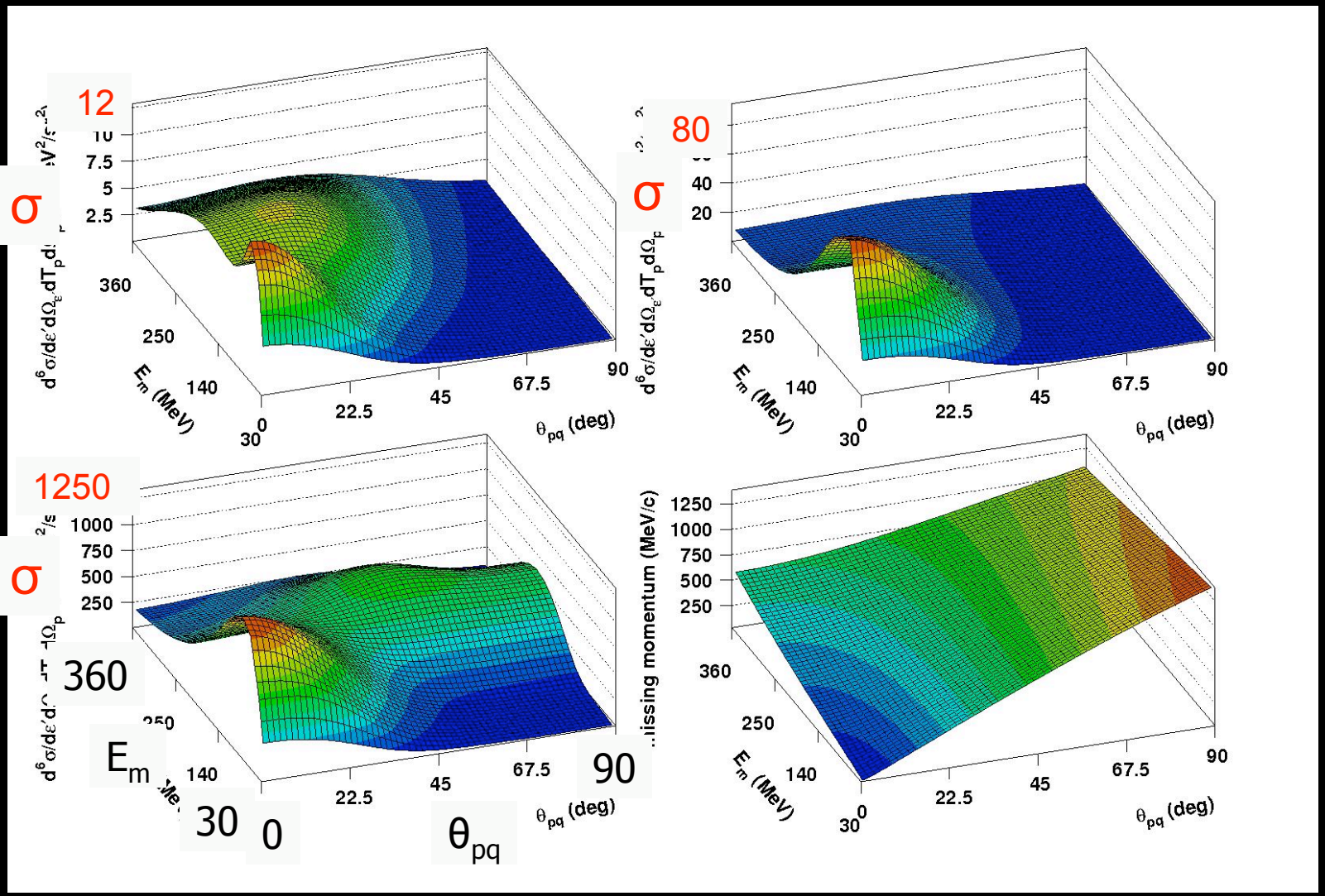
Summary

- *NN* Correlations are universal in nuclei
  - Dominate the nuclear wave function for $p > 0.25$ GeV/c
  - 25% in heavy nuclei
  - SRC and new EMC Ratios agree
- High momentum nucleons are emitted opposite their knocked-out correlated partner
- Momentum distributions from two-forward and forward-backward *pp* pairs strongly disagree
  - other processes?
  - which one is sensitive to the initial state?
- Two-nucleon correlated pairs are predominantly *pn*
  - The *pp*/*pn* ratio increases with increasing p_{tot}
  - Tensor correlations dominant at $0.3 < p_{rel} < 0.5$ GeV/c
- Measurements at higher relative momentum coming soon …

2N currents enhance correlations

Central correlations only

Central + tensor corr



Corr + MEC — O(e,e'p) Ryckebusch — kinematics