Institute for Nuclear Theory

Recent Results from Exclusive Studies of Two-Nucleon SRCs

Or Hen

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In Collaboration With:

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Nuclear Structure and Dynamics at Short Distances

2N-SRC 101

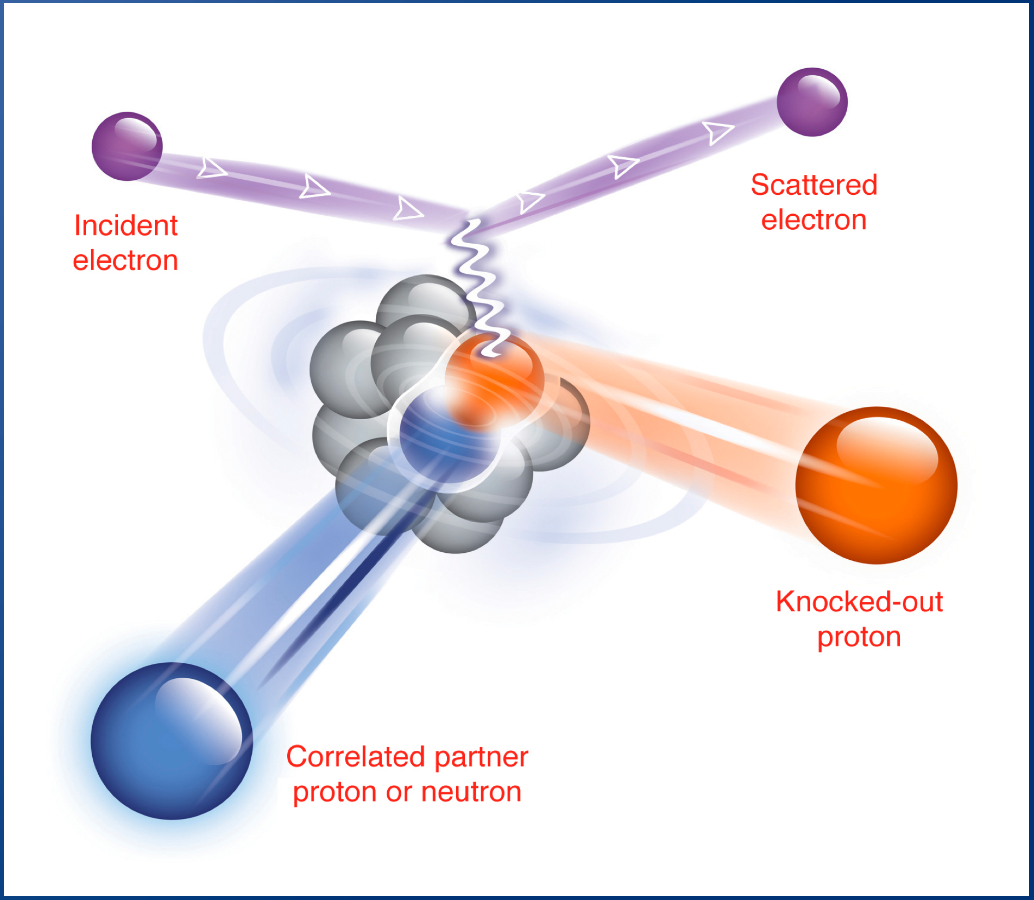
2N-SRC are pairs of nucleons that:

- Are close together (overlap) in the nucleus
- Have high relative momentum and low c.m. momentum, where high and low is compared to the Fermi momentum (k_F) of the nucleus

Exclusive pp-SRC Studies

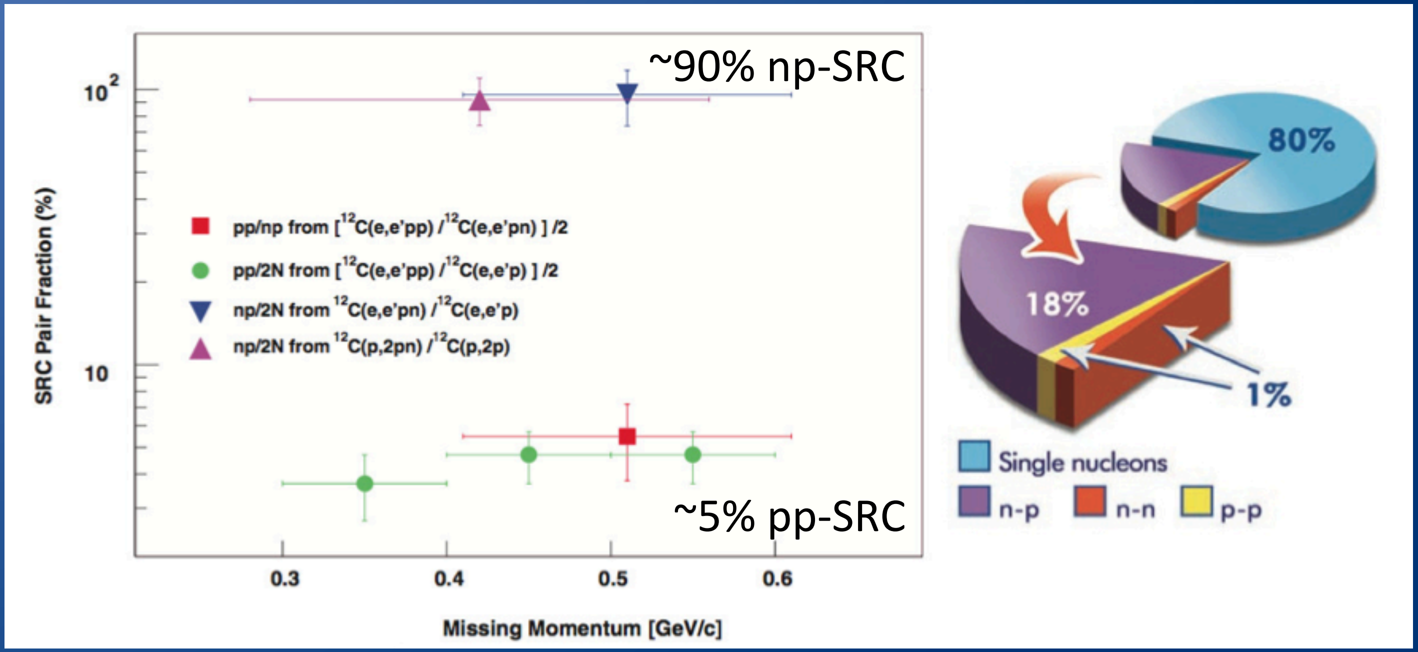
Measurement Concept:

1. Electron knockout of high momentum proton
2. Reconstruct the initial momentum of the knockout proton
3. Look for the emission of a recoil proton with momentum that balance that of the struck proton



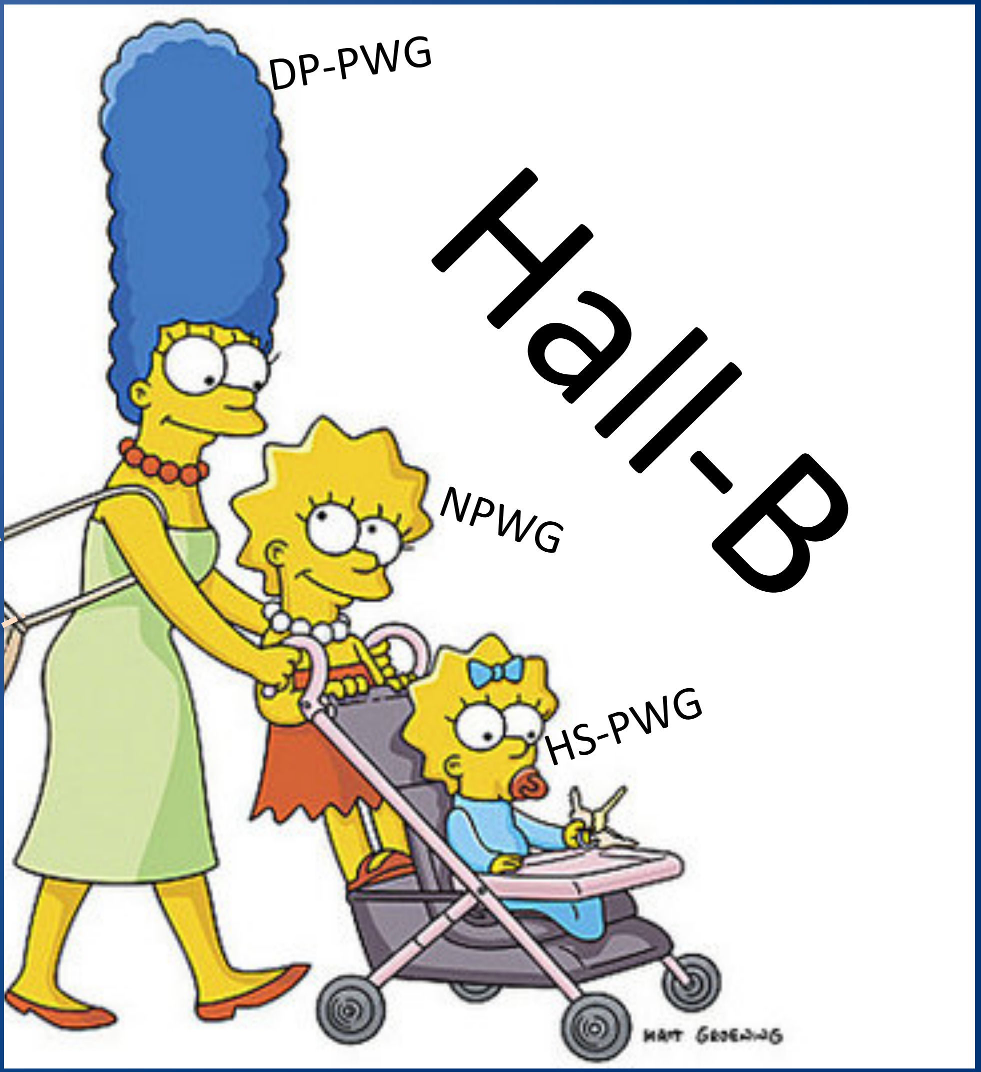
Previous Results – ^{12}C

- Exclusive $^{12}C(p,2pn)$ and $^{12}C(e,e'pN)$ measurements probe the structure of the high momentum tail of the nuclear wave function
- Results show that for $300<P_{miss}<600$ MeV/c all nucleons are part of 2N-SRC pairs



A. Tang et al., Phys.Rev.Lett. 90 (2003) 042301
E. Piasetzky et al., Phys.Rev.Lett. 97 (2006) 162504
R. Shneor et al., Phys.Rev.Lett. 99 (2007) 072501
R. Subedi et al., Science 320 (2008) 1476

Data-Mining Analysis

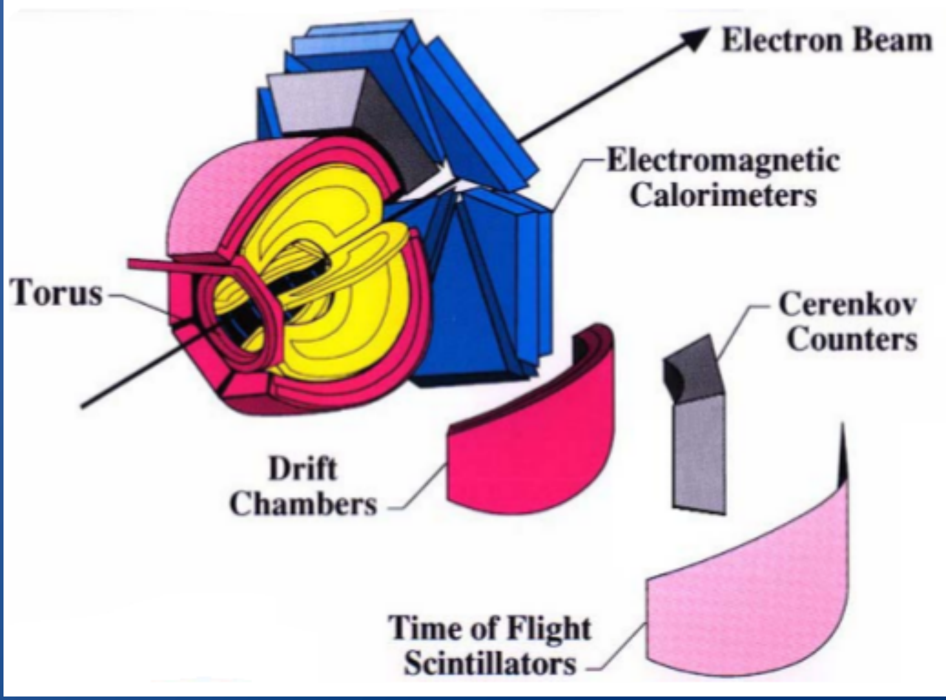


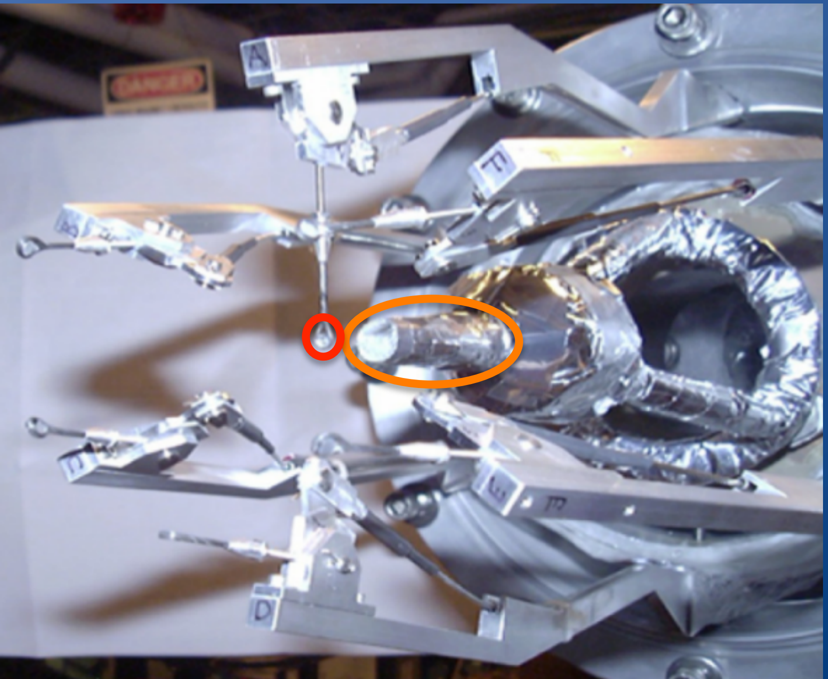
(main) Analysis Goals

1. pp-SRC universality in large A nuclei
   1. Existence
   2. Characteristics (c.m. and relative momentum dist.)
   3. Probabilities
2. Extend $|P_{miss}|$ coverage – transition to scalar force?
3. Nuclear Transparency - FSI in SRC kinematics
   [O. Hen et al., arXiv: 1212.5343]
4. Quantum Numbers Extraction?

EG2 Experiment

- Run at 2004 in Hall-B of Jefferson Lab
- 5 GeV electron beam
- **Deuterium**+**Solid** targets simultaneously





Data Collected for:

Deuterium + $^{12}C/^{56}Fe/^{208}Pb$

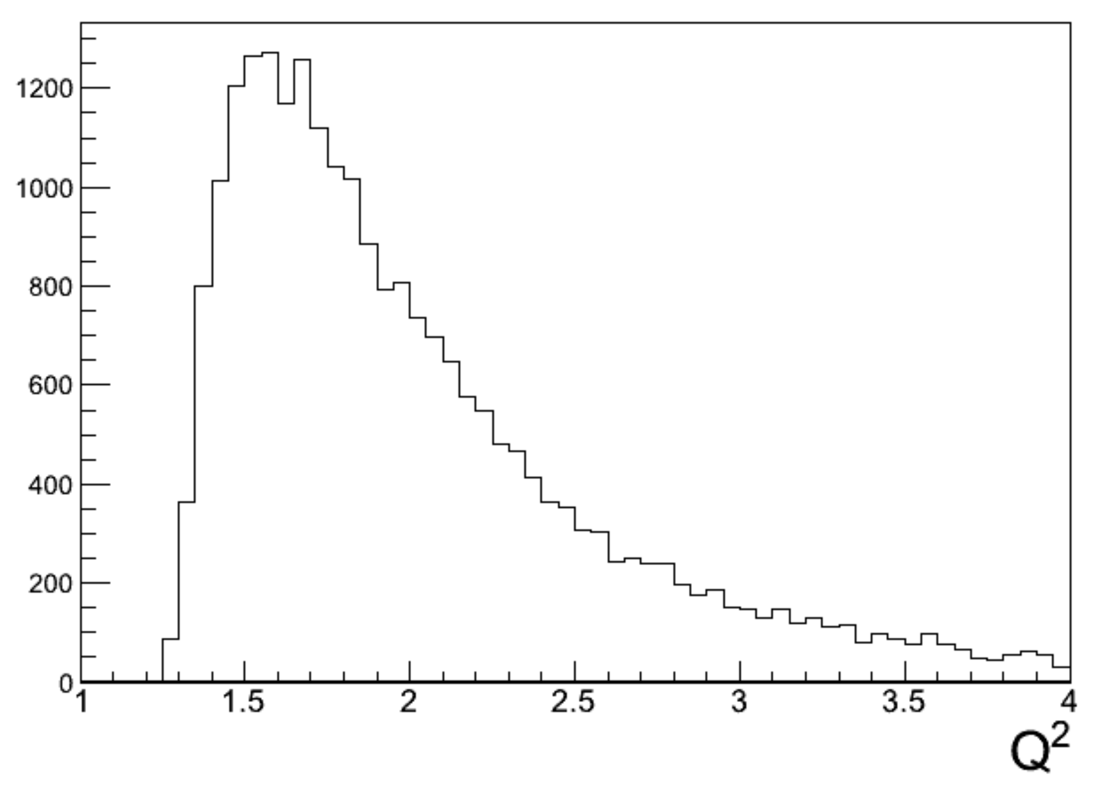
^{27}Al

Target Setup:
Deuterium + interchanging solid foils

(e,e'p) Event Selection

1. Kinematics
   - $x_B > 1.2$
   - $|P_{miss}| > 300$ MeV/c

   ➔ $Q^2 > 1.5$ GeV/c^2



(e,e'p) Event Selection

1. Kinematics
   – $x_B > 1.2$
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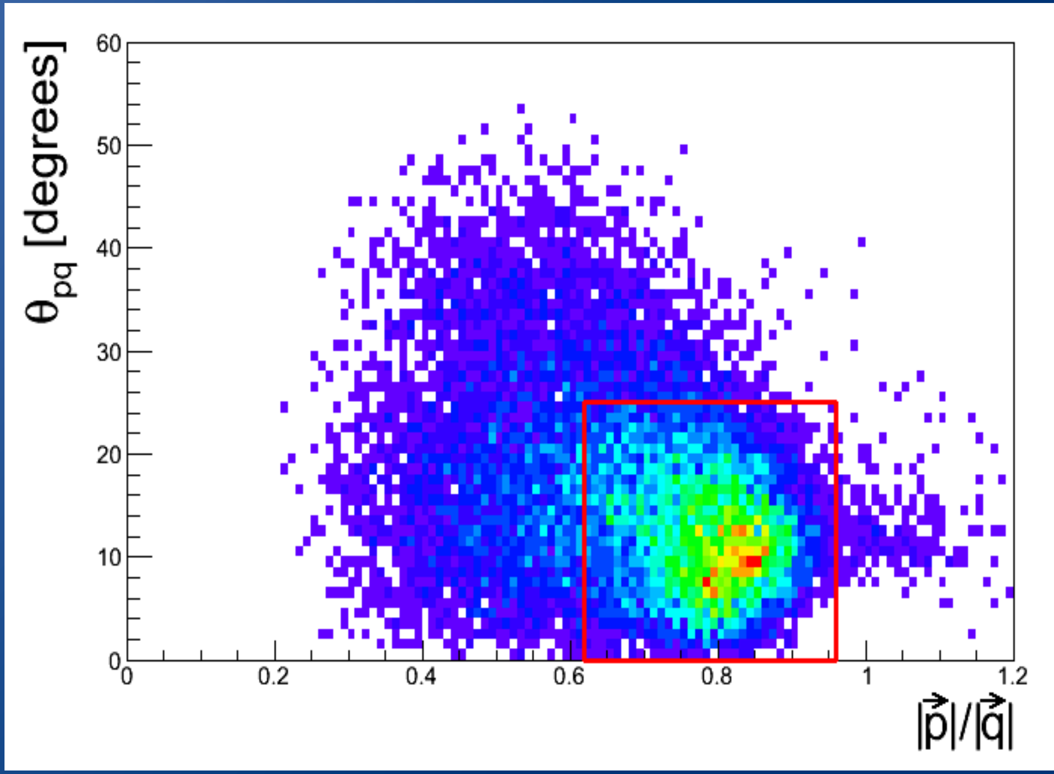
   → $Q^2 > 1.5$ GeV/c^2
2. Leading Proton
   – $\theta_{pq} > 25^o$
   – $0.62 < |P|/|q| < 0.96$



$(e,e'p)$ Event Selection

1. Kinematics
   - $x_B > 1.2$
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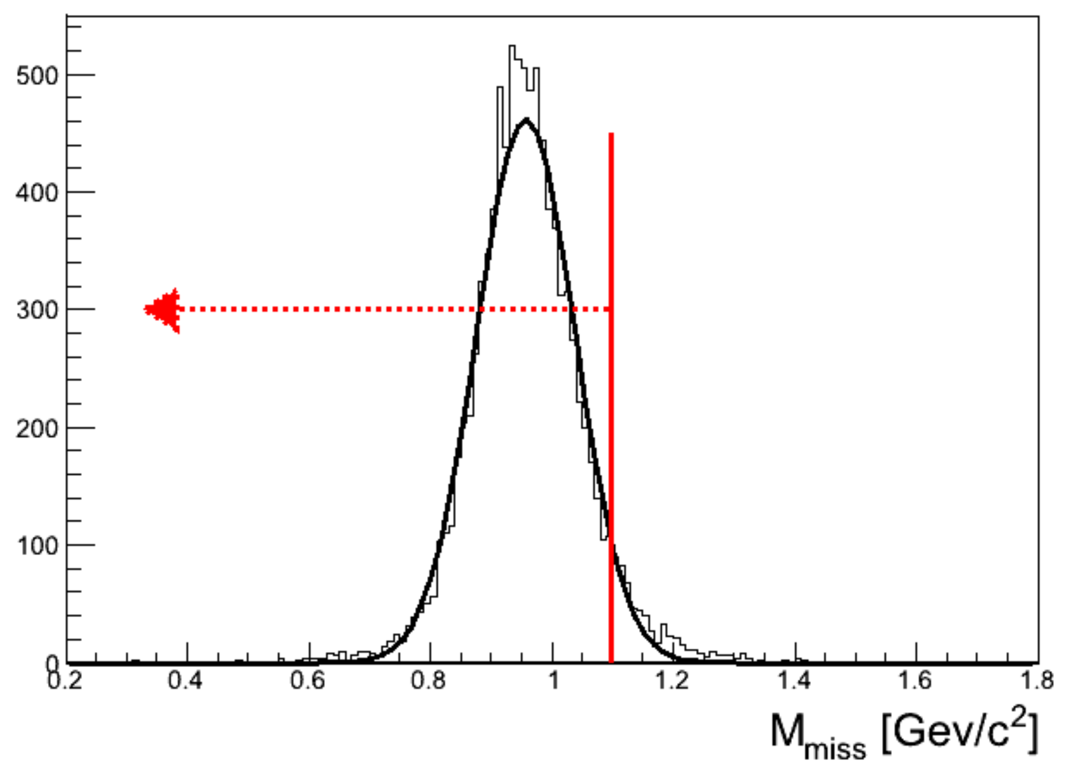
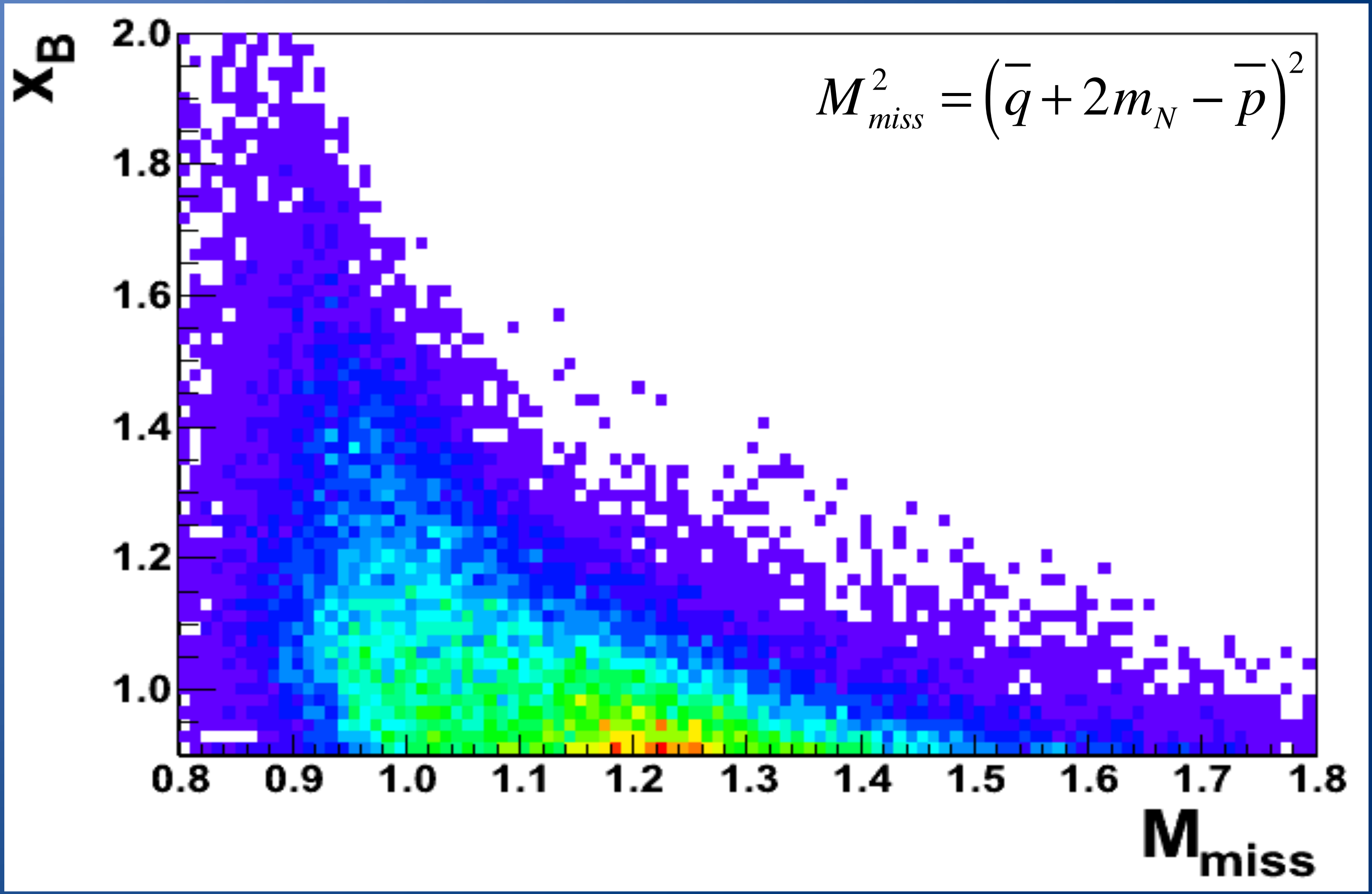
   ➔ $Q^2 > 1.5$ GeV/c^2
2. Leading Proton
   - $\theta_{pq} > 25^o$
   - $0.62 < |P|/|q| < 0.96$
3. Missing Mass
   - $M_{miss} < m_N + m_\pi$



x_B and Resonance Excitations



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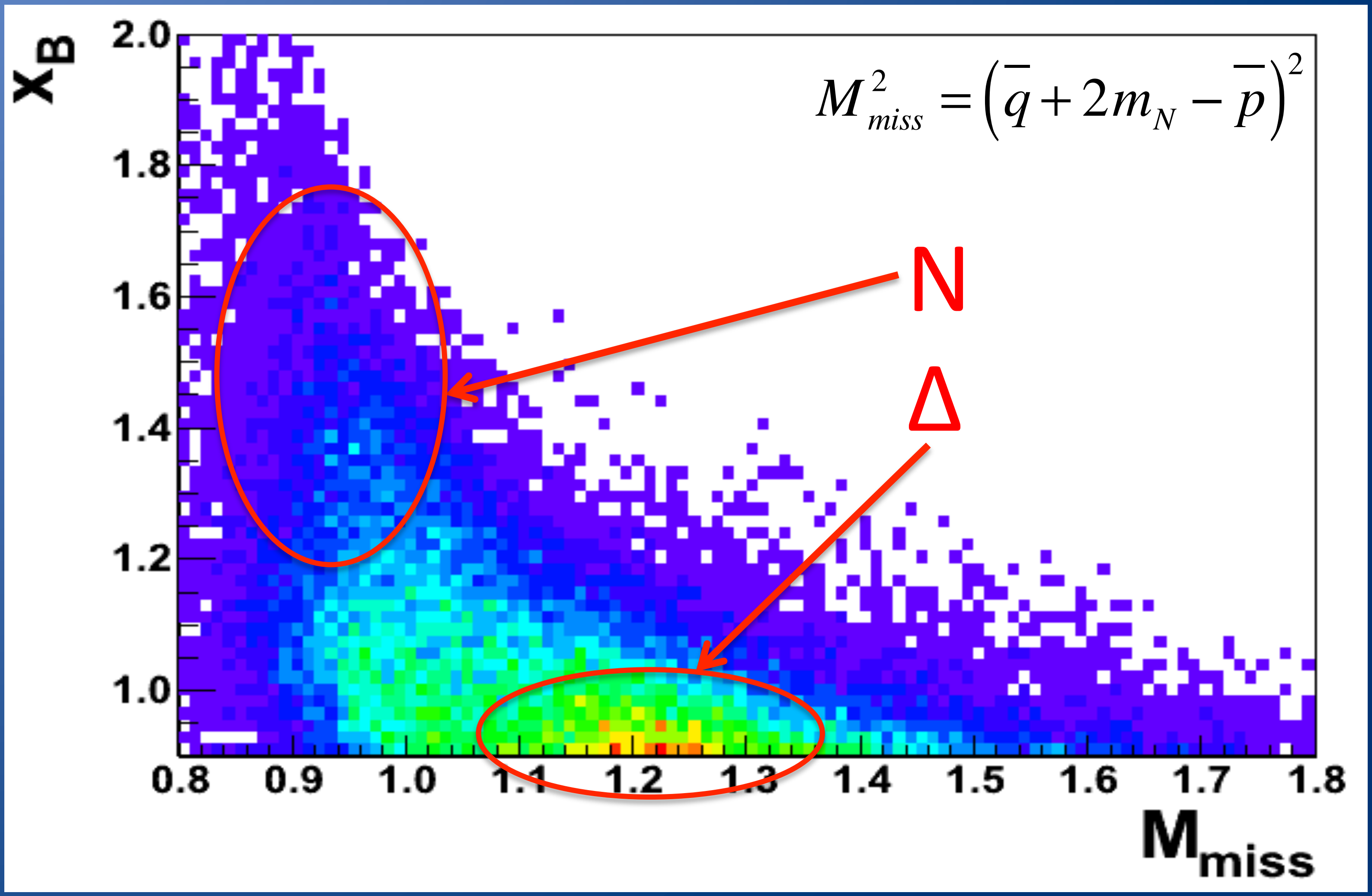

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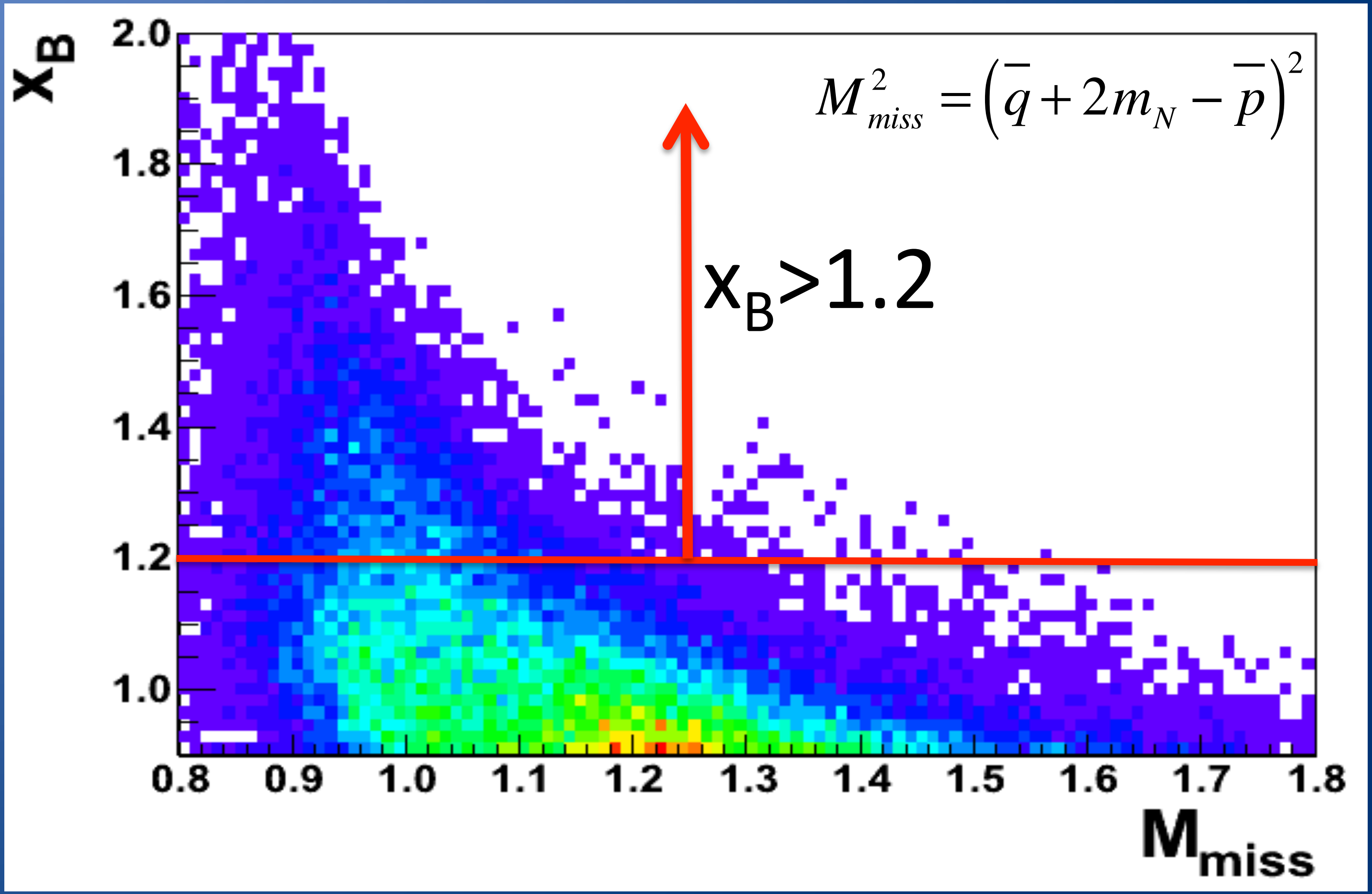
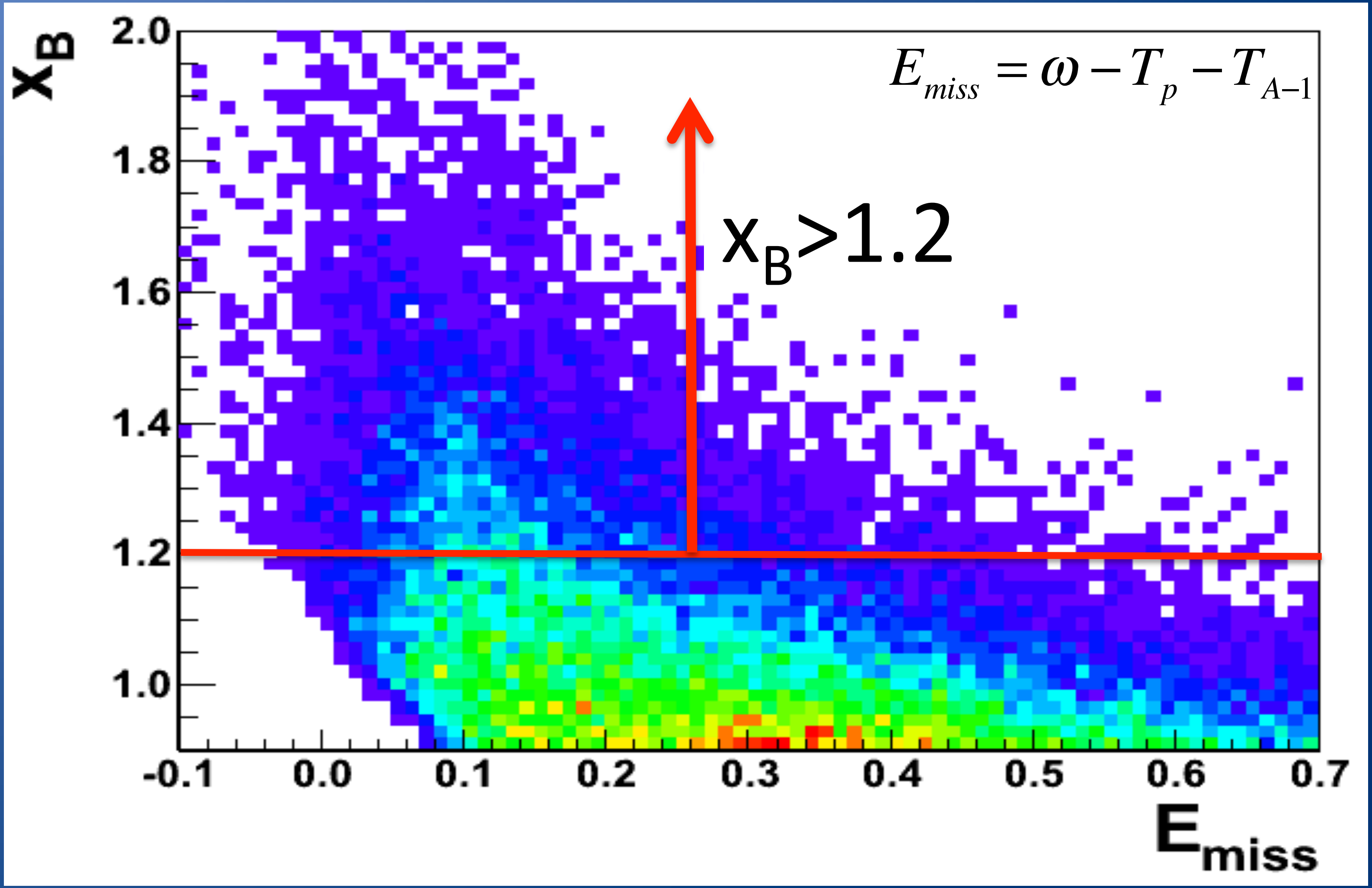


x_B and Resonance Excitations



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First Data-Mining Paper

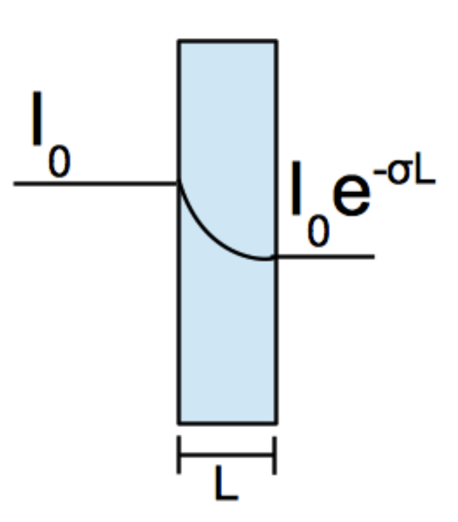
Measurement of transparency ratios for protons from short-range correlated pairs

O. Hen,[1] H. Hakobyan,[2,43] R. Shneor,[1] E. Piasetzky,[1] L.B. Weinstein,[3] W.K. Brooks,[2,39] S. May-Tal Beck,[1] S. Gilad,[4] I. Korover,[1] A. Beck,[1] K.P. Adhikari,[3] M. Aghasyan,[22] M.J. Amaryan,[3] S. Anefalos Pereira,[22] J. R. Arrington,[5] H. Baghdasaryan,[41,3] J. Ball,[11] M. Battaglieri,[23] V. Batourine,[39,28] I. Bedlinskiy,[26] A.S. Biselli,[15,9] J. Bono,[16] S. Boiarinov,[39] W.J. Briscoe,[19] V.D. Burkert,[39] D.S. Carman,[39] A. Celentano,[23] S. Chandavar,[32] P.L. Cole,[20,10,39] M. Contalbrigo,[21] V. Crede,[17] A. D'Angelo,[24,35] N. Dashyan,[43] R. De Vita,[23] E. De Sanctis,[22] A. Deur,[39] C. Djalali,[38] G.E. Dodge,[3] D. Doughty,[12,39] R. Dupre,[25] H. Egiyan,[39] A. El Alaoui,[5] L. El Fassi,[5] P. Eugenio,[17] G. Fedotov,[38,36] S. Fegan,[40,*] J.A. Fleming,[14] M.Y. Gabrielyan,[16] N. Gevorgyan,[43] G.P. Gilfoyle,[34] K.L. Giovanetti,[27] F.X. Girod,[39] J.T. Goetz,[32] W. Gohn,[13] E. Golovatch,[36] R.W. Gothe,[38] K.A. Griffioen,[42] L. Guo,[16,39] K. Hafidi,[5] N. Harrison,[13] D. Heddle,[12,39] K. Hicks,[32] M. Holtrop,[30] C.E. Hyde,[3] Y. Ilieva,[38,19] D.G. Ireland,[40] B.S. Ishkhanov,[36,37] E.L. Isupov,[36] H.S. Jo,[25] K. Joo,[13] D. Keller,[41] M. Khandaker,[31] P. Khetarpal,[16] A. Kim,[28] F.J. Klein,[10] S. Koirala,[3] A. Kubarovsky,[33,36] V. Kubarovsky,[39,33] S.E. Kuhn,[3] K. Livingston,[40] H.Y. Lu,[9] I. J. D. MacGregor,[40] D. Martinez,[20] M. Mayer,[3] B. McKinnon,[40] T. Mineeva,[13] V. Mokeev,[39,36] R.A. Montgomery,[40] H. Moutarde,[11] E. Munevar,[39] C. Munoz Camacho,[25] B. Mustapha,[5] P. Nadel-Turonski,[39] R. Nasseripour,[27,16] S. Niccolai,[25] G. Niculescu,[27] I. Niculescu,[27] M. Osipenko,[23] A.I. Ostrovidov,[17] L.L. Pappalardo,[21] R. Paremuzyan,[43,†] K. Park,[39,28] S. Park,[17] E. Pasyuk,[39,6] E. Phelps,[38] J.J. Phillips,[40] S. Pisano,[22] N. Pivnyuk,[44] O. Pogorelko,[26] S. Pozdniakov,[26] J.W. Price,[7] S. Procureur,[11] D. Protopopescu,[40] A.J.R. Puckett,[39] B.A. Raue,[16,39] D. Rimal,[16] M. Ripani,[23] B.G. Ritchie,[6] G. Rosner,[40] P. Rossi,[22] F. Sabatié,[11] M.S. Saini,[17] D. Schott,[19] R.A. Schumacher,[9] H. Seraydaryan,[3] Y.G. Sharabian,[39] G.D. Smith,[40] D.I. Sober,[10] S.S. Stepanyan,[28] S. Stepanyan,[39] S. Strauch,[38,19] M. Taiuti,[18,*] W. Tang,[32] C.E. Taylor,[20] Ye Tian,[38] S. Tkachenko,[41] M. Ungaro,[39,33] B. Vernarsky,[9] A. Vlassov,[44] H. Voskanyan,[43] E. Voutier,[29] N.K. Walford,[10] D.P. Watts,[14] M.H. Wood,[8,38] N. Zachariou,[38] L. Zana,[30] J. Zhang,[39] X. Zheng,[5,‡] and I. Zonta[24,§]
(The CLAS Collaboration)

O. Hen et al., arXiv: 1212.5343

Nuclear Transparency

- Definition (1):
  - Nuclear transparency is the average probability that a struck proton escapes from the nucleus without interaction



Nuclear Transparency

- Definition (1):
  - Nuclear transparency is the average probability that a struck proton escapes from the nucleus without interaction
- Definition (2):

$$T(A) = \frac{\sigma_{exp}(e, e'p)}{\sigma_{PWIA}(e, e'p)}$$

With:

$$\sigma_{PWIA} = \frac{d^6\sigma}{dE'_e d\Omega_{e'} dE'_p d\Omega_{p'}} = p' E'_p \sigma_1^{cc} S(p, E_s)$$

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Experiment

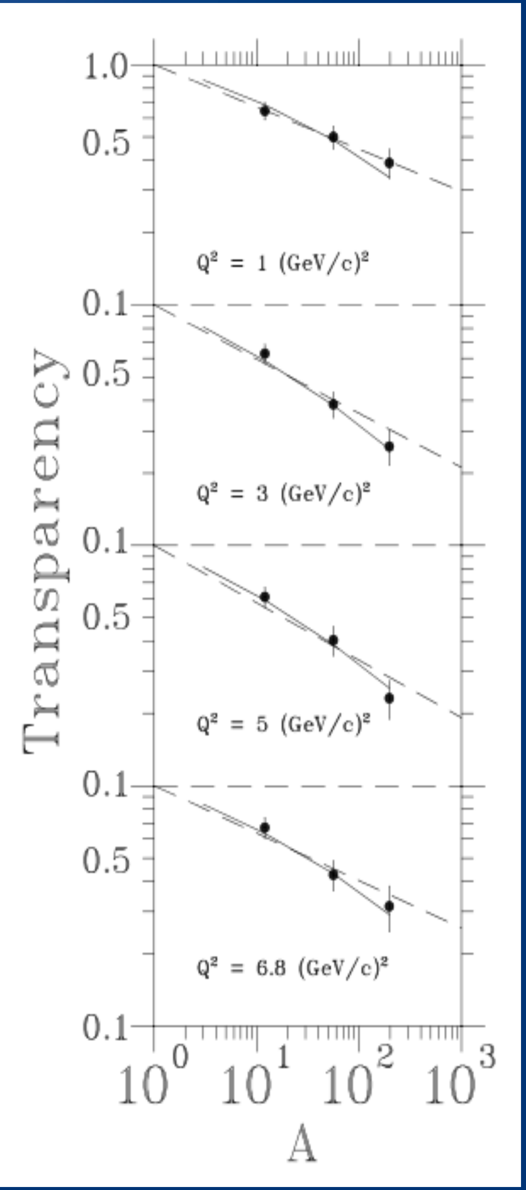
Theory

With:

$$\sigma_{PWIA} = \frac{d^6\sigma}{dE'_e d\Omega_{e'} dE'_p d\Omega_{p'}} = p' E'_p \sigma_1^{cc} S(p, E_s)$$

SLAC Results: Mean-Field Protons

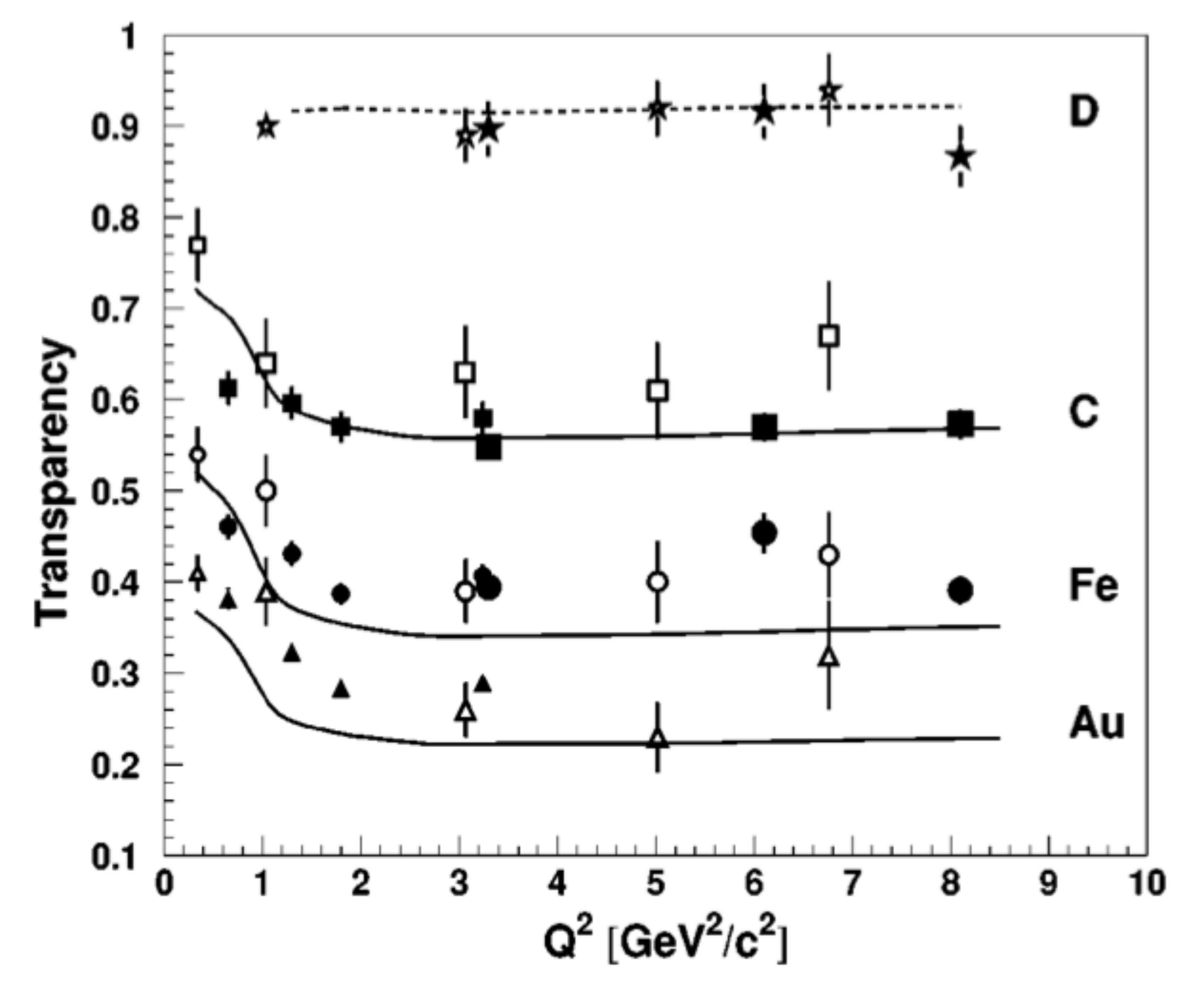
- SLAC extracted the transparency of protons from ^{12}C, ^{56}Fe, and ^{197}Au.
- Focused on mean-field (low momentum) protons, where the spectral function is well known
  - $-30 < E_{miss} < 100$ MeV
  - $0 < p_{miss} < 250$ MeV/c for ^{12}C and ^{56}Fe
  - $0 < p_{miss} < 210$ MeV/c for ^{197}Au



Q^2 $(GeV/c)^2$	T_C	T_{Fe}	T_{Au}
1.04	0.64±0.05	0.50±0.05	0.39±0.05
3.06	0.63±0.06	0.39±0.05	0.26±0.04
5.00	0.61±0.06	0.40±0.06	0.23±0.04
6.77	0.67±0.07	0.43±0.06	0.32±0.07

T. G. O'Neill et al. Phys. Lett. B 87, 351 (1995)

World Data: Mean-Field



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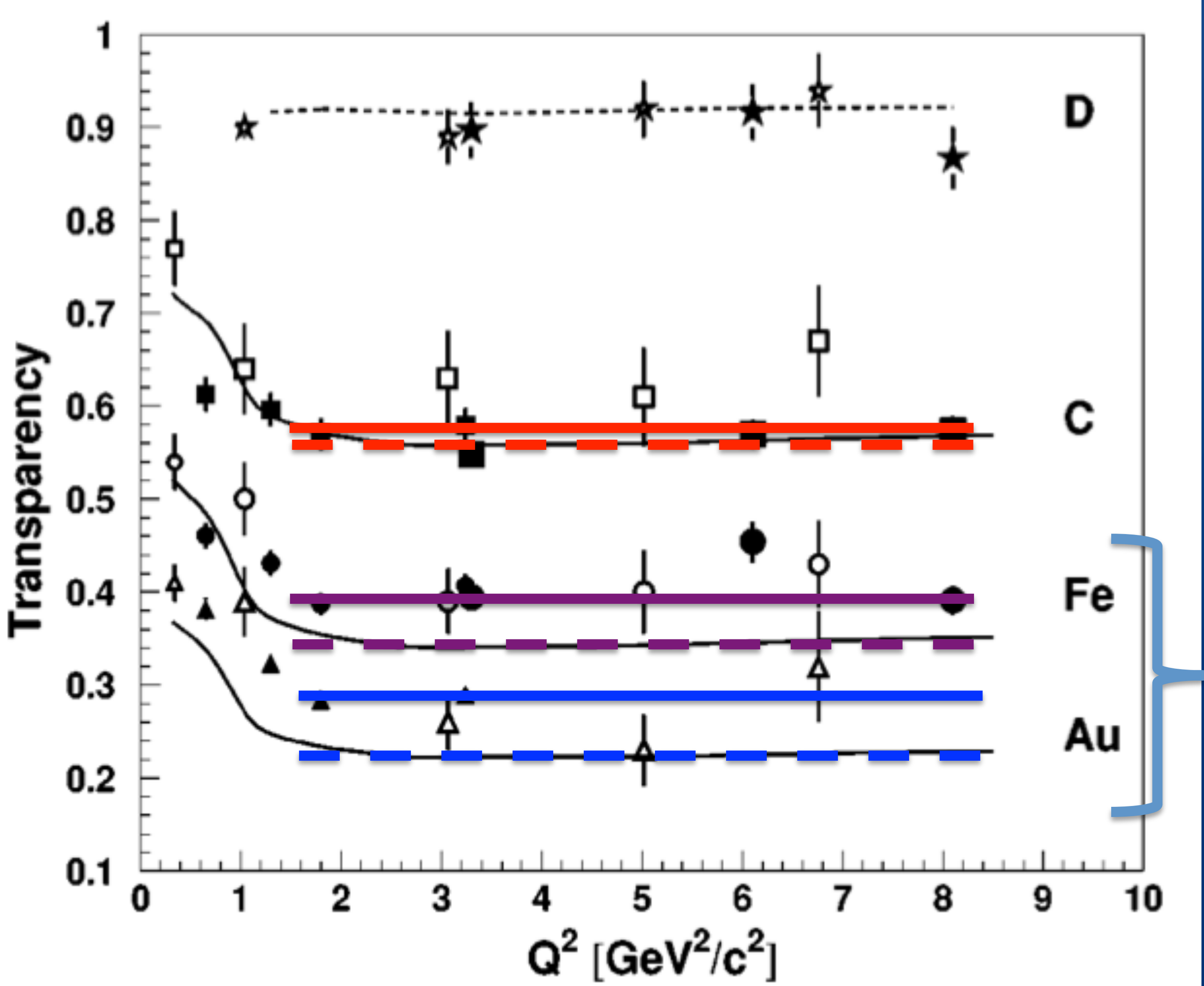
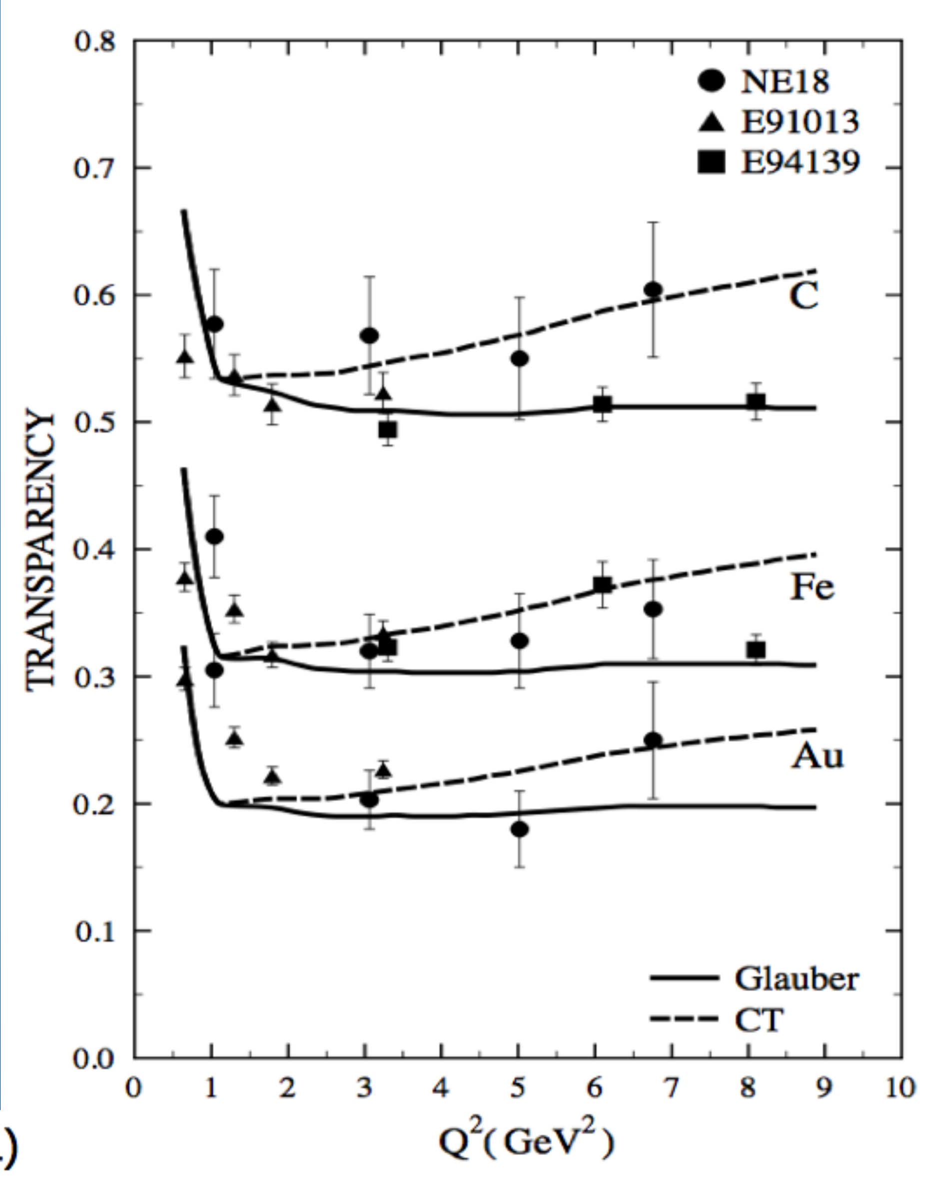


~20% difference between data and Glauber calculation

SRC Renormalization

Discrepancy between data and calculation can be explained by an 'over-correction' applied due to the contribution of SRC in the Mean-Field kinematics



D. Dutta et al., arXiv: 1121.2826 (2012)
P. Lava et al., Phys. Lett. B. **595**, 117 (2004)
L. L. Frankfurt et al., Phys. Lett. B. **503**, 73 (2001)

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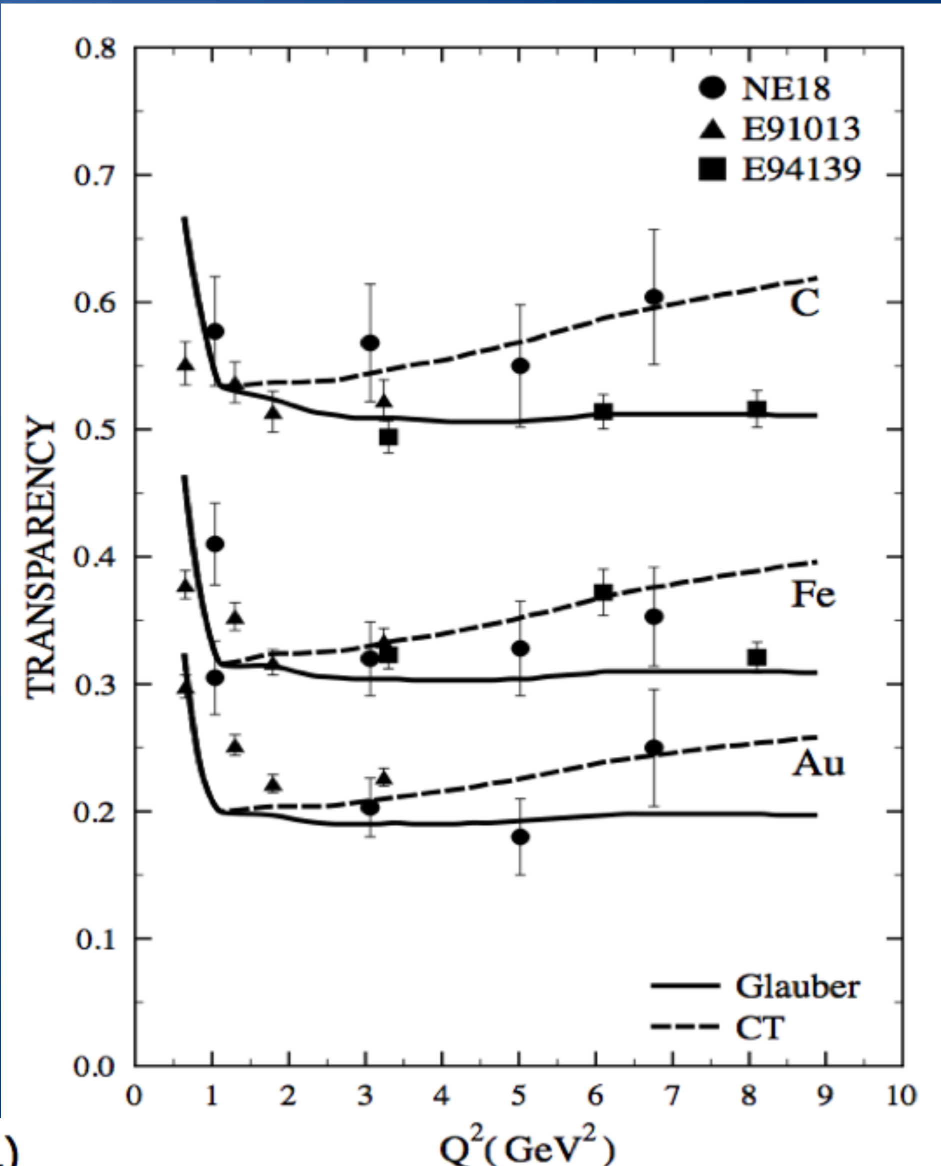

Our Approach – Focus on the Correlations!

D. Dutta et al., arXiv: 1121.2826 (2012)
P. Lava et al., Phys. Lett. B. **595**, 117 (2004)
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Transparency in SRC Dominated kinematics

- Large Q^2, $x_B>1$ region dominated by 2N-SRC pairs
- Spectral function scales according to the number of 2N-SRC pairs.

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- Spectral function scales according to the number of 2N-SRC pairs.

Transparency ratio of SRC protons in nuclei can be expressed as:

$$\frac{T(A_1)}{T(A_2)} = \frac{\sigma_{A_1(e,e'p)}/(\#np \cdot \sigma_{ep} + 2\#pp \cdot \sigma_{ep})_{A_1}}{\sigma_{A_2(e,e'p)}/(\#np \cdot \sigma_{ep} + 2\#pp \cdot \sigma_{ep})_{A_2}}$$

Number of np-SRC pairs

ep->ep off-shell cross section

Number of pp-SRC pairs

Counting the Relative Number of 2N-SRC Pairs in Nuclei

- From inclusive (e,e') cross section ratios we know that:

$$\frac{a_2(A_1/d)}{a_2(A_2/d)} = \frac{(\#np\cdot(\sigma_{ep}+\sigma_{en})+2\#pp\cdot\sigma_{ep}+2\#nn\cdot\sigma_{en})_{A_1}/A_1}{(\#np\cdot(\sigma_{ep}+\sigma_{en})+2\#pp\cdot\sigma_{ep}+2\#nn\cdot\sigma_{en})_{A_2}/A_2}$$

$$\frac{T(A_1)}{T(A_2)} = \frac{\sigma_{A_1(e,e'p)}/(\#np\cdot\sigma_{ep}+2\#pp\cdot\sigma_{ep})_{A_1}}{\sigma_{A_2(e,e'p)}/(\#np\cdot\sigma_{ep}+2\#pp\cdot\sigma_{ep})_{A_2}}$$

Counting the Relative Number of 2N-SRC Pairs in Nuclei

- Assuming np-SRC Dominance

$$\frac{a_2(A_1/d)}{a_2(A_2/d)} = \frac{(\#np\cdot(\sigma_{ep}+\sigma_{en}) + \cancel{2\#pp\cdot\sigma_{ep} + 2\#nn\cdot\sigma_{en}})_{A_1}/A_1}{(\#np\cdot(\sigma_{ep}+\sigma_{en}) + \cancel{2\#pp\cdot\sigma_{ep} + 2\#nn\cdot\sigma_{en}})_{A_2}/A_2}$$

$$\frac{T(A_1)}{T(A_2)} = \frac{\sigma_{A_1(e,e'p)}/(\#np\cdot\sigma_{ep} + \cancel{2\#pp\cdot\sigma_{ep}})_{A_1}}{\sigma_{A_2(e,e'p)}/(\#np\cdot\sigma_{ep} + \cancel{2\#pp\cdot\sigma_{ep}})_{A_2}}$$

Counting the Relative Number of 2N-SRC Pairs in Nuclei

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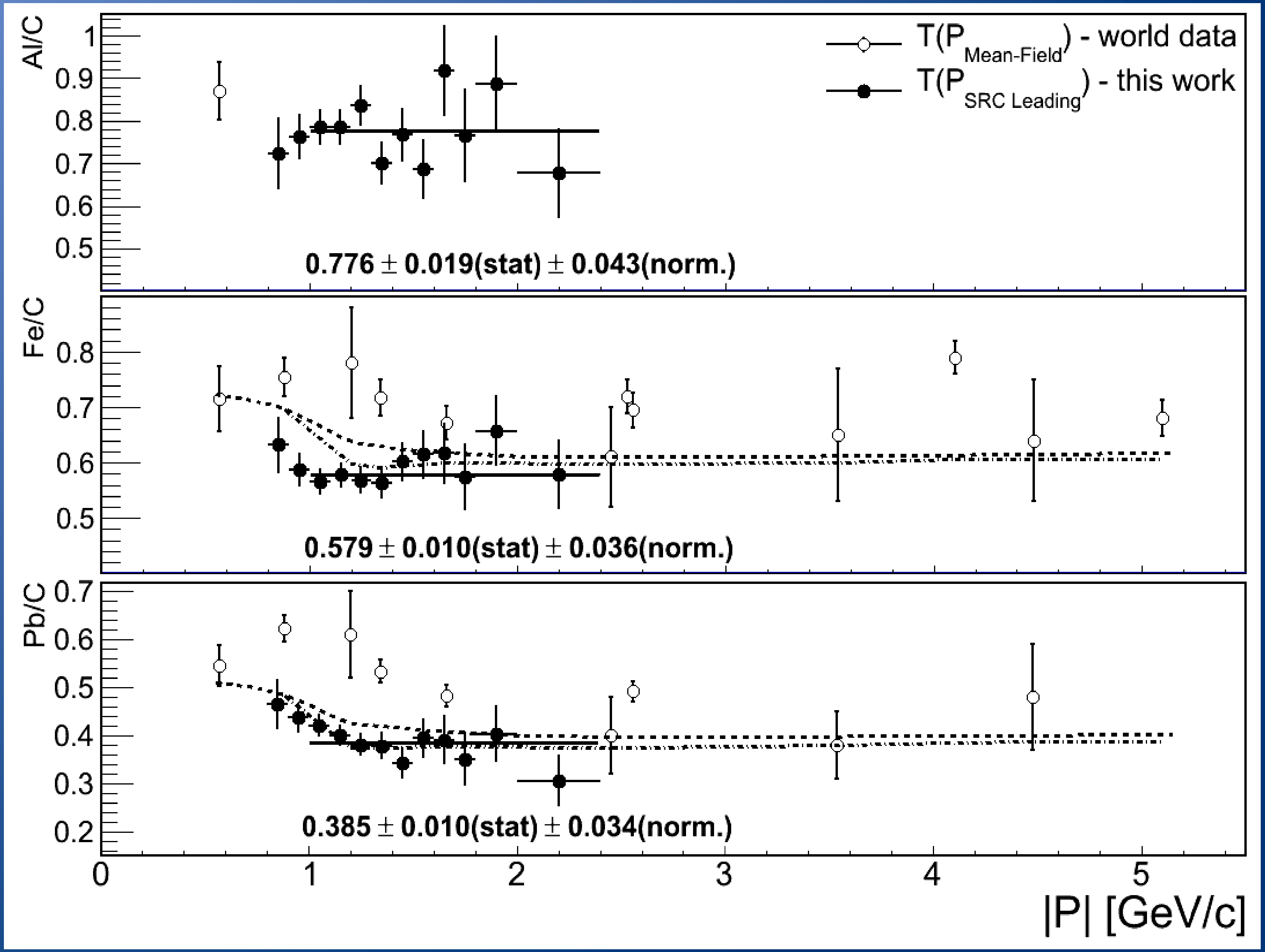
Which Gives:

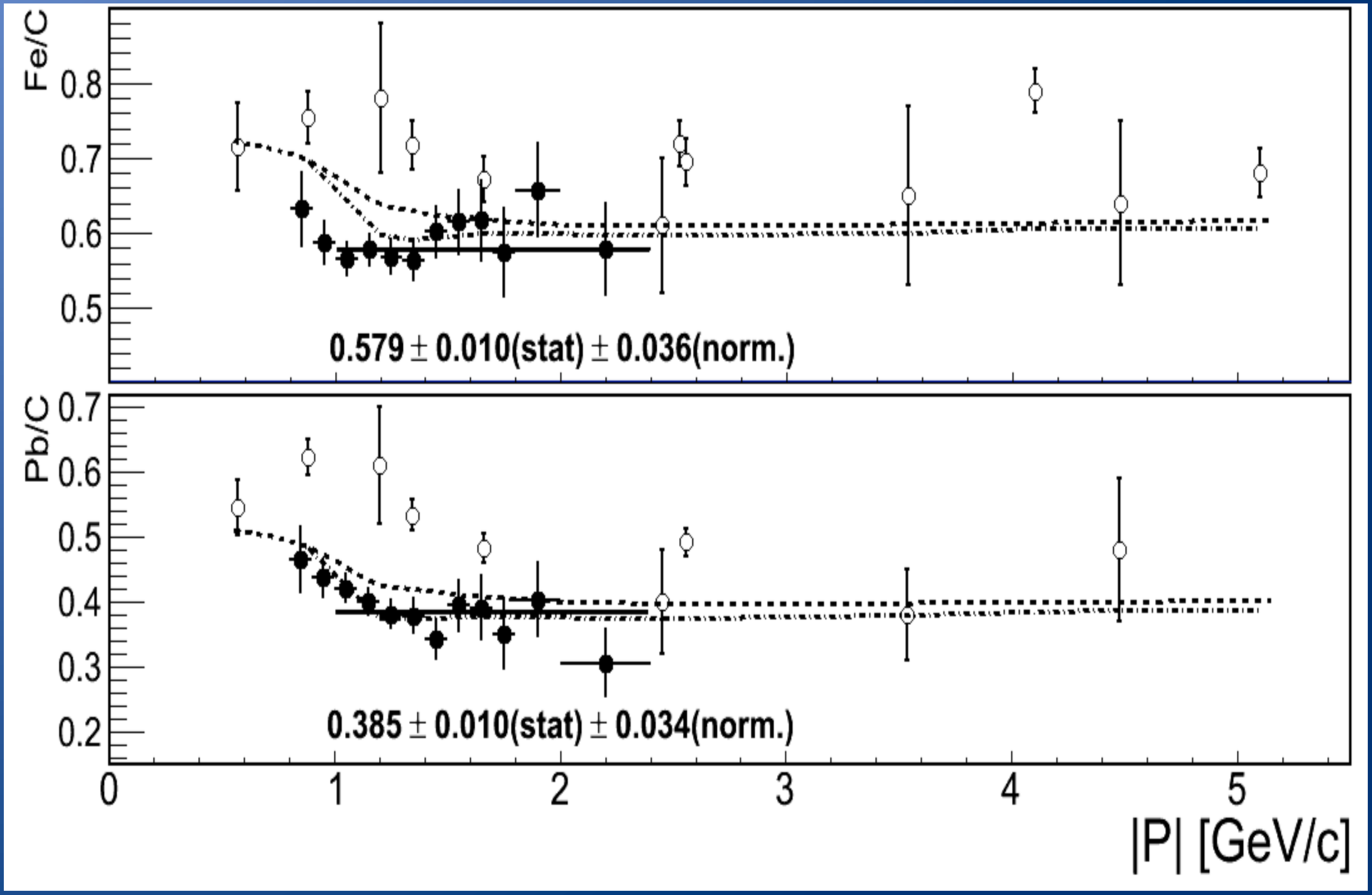
$$\frac{T(A_1)}{T(A_2)} = \frac{\sigma_{A_1(e,e'p)}/(A_1 \cdot a_2(A_1))}{\sigma_{A_2(e,e'p)}/(A_2 \cdot a_2(A_2))} = a_2(A_2/A_1) \cdot \frac{\sigma_{A_1(e,e'p)}/A_1}{\sigma_{A_2(e,e'p)}/A_2}$$

Theory Independent Observable!

Results I - |P| Dependence



Results I - |P| Dependence



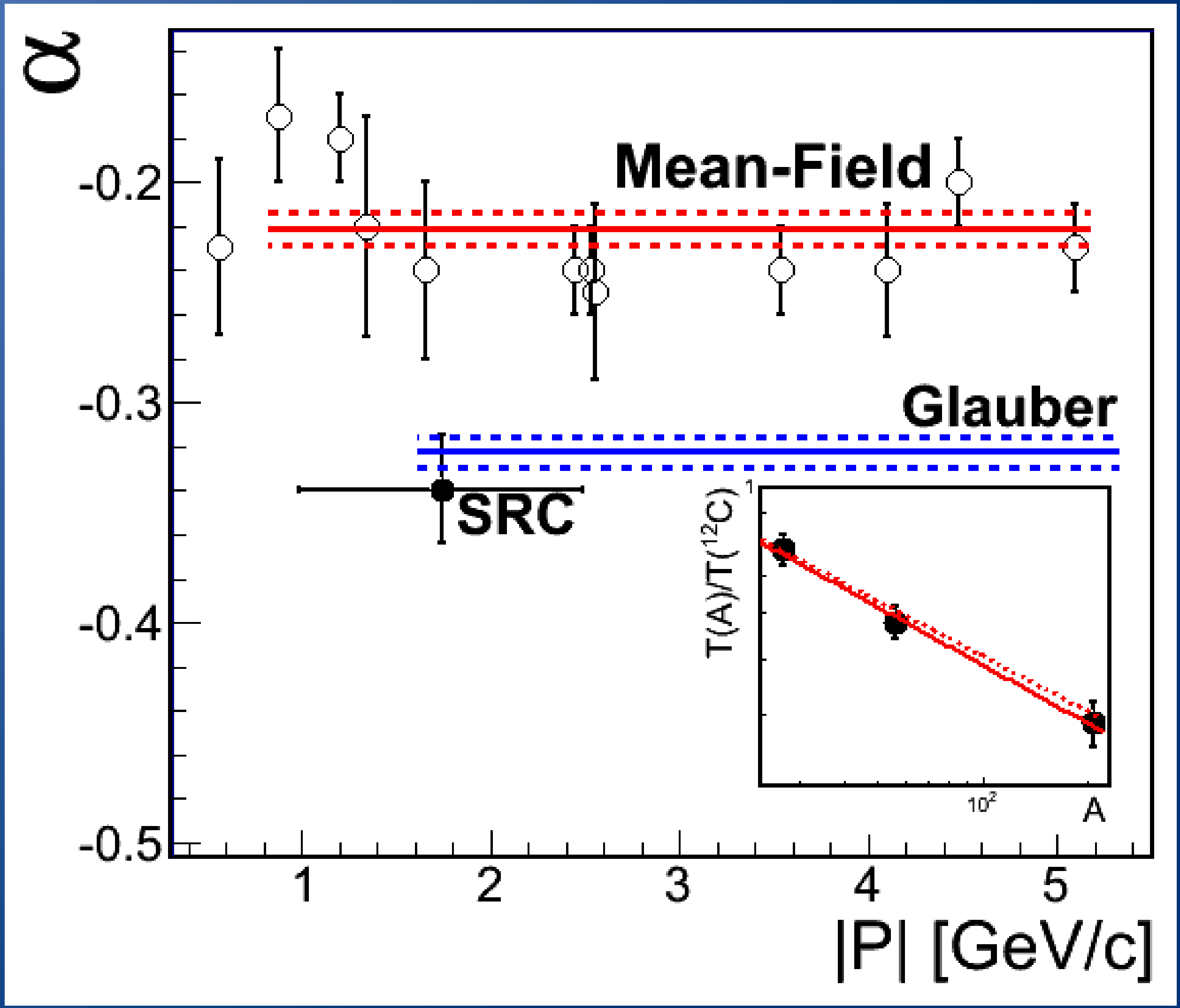
Results II – A dependence

Assume

$T(A)=A^{\alpha}$

$\alpha \approx -1/3$

Consistent with scattering from the nucleus surface



Next Step - ***NEUTRONS***

Goal:

Study the A(e,e'n) and A(e,e'np) reactions in SRC kinematics

[compare to the A(e,e'p) and A(e,e'pp) reactions]

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Next Step - *NEUTRONS*

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Study the A(e,e'n) and A(e,e'np) reactions in SRC kinematics

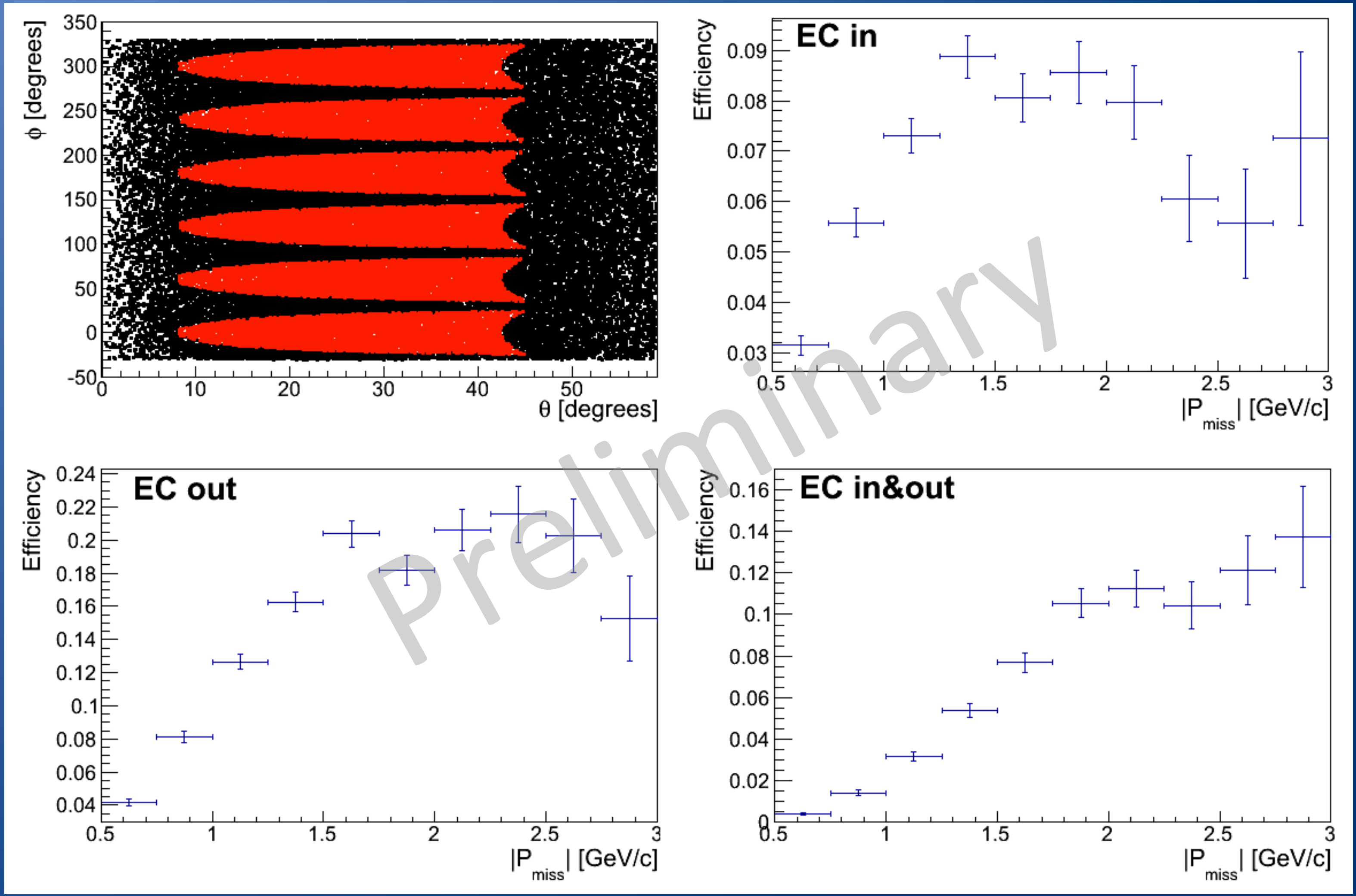
[compare to the A(e,e'p) and A(e,e'pp) reactions]

First steps in EG2 Neutrons analysis (Done☺) :

- Identify neutrons using exclusive d(e,e'p$\pi^+\pi^-$n) events
- Determine path-length and momentum corrections
- Extract detection efficiency and momentum resolution

Neutron Detection Efficiency

$d(e,e'\pi^+\pi^-n) / d(e,e'\pi^+\pi^-)n$



Neutron Detection Efficiency

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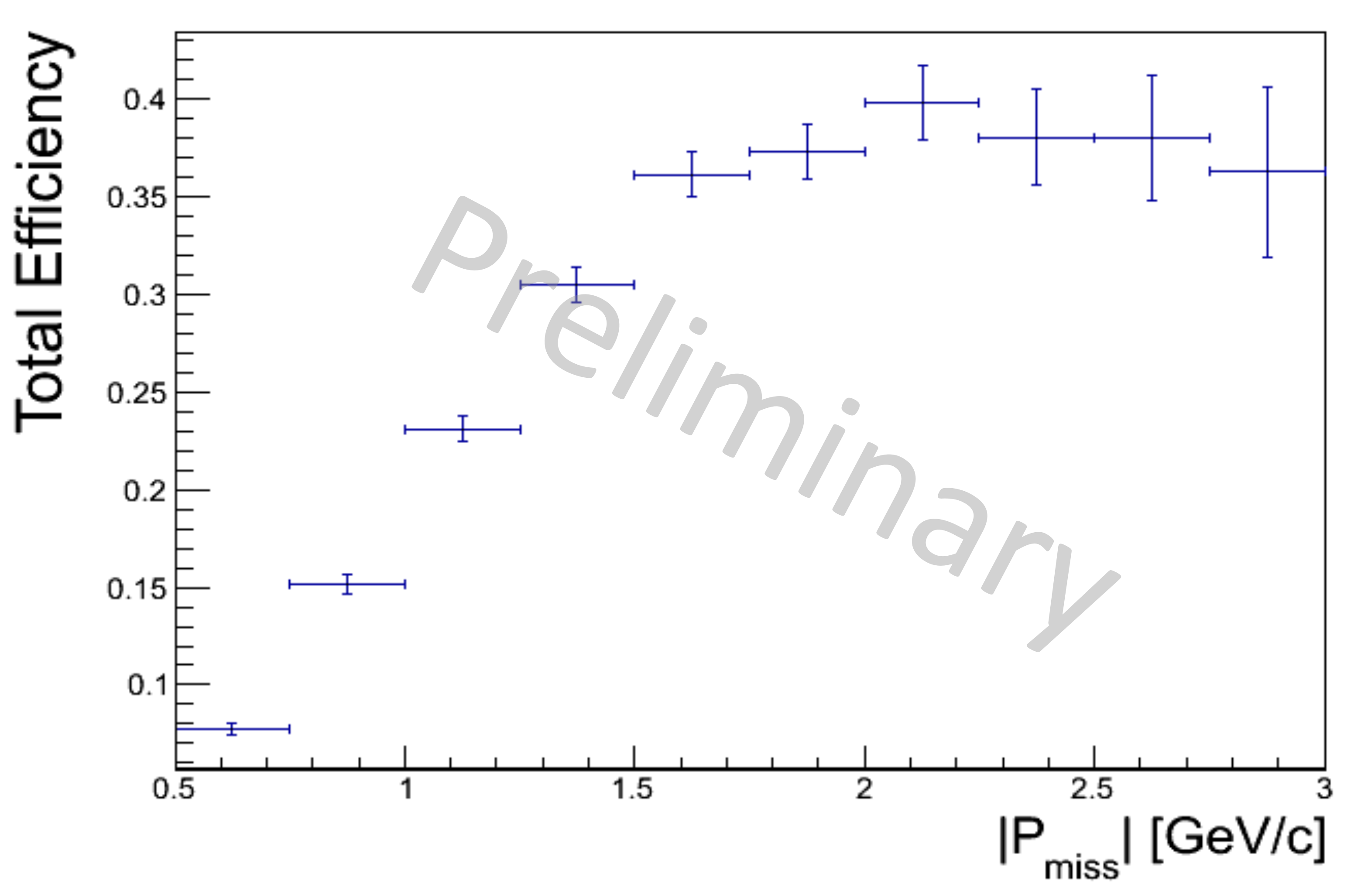
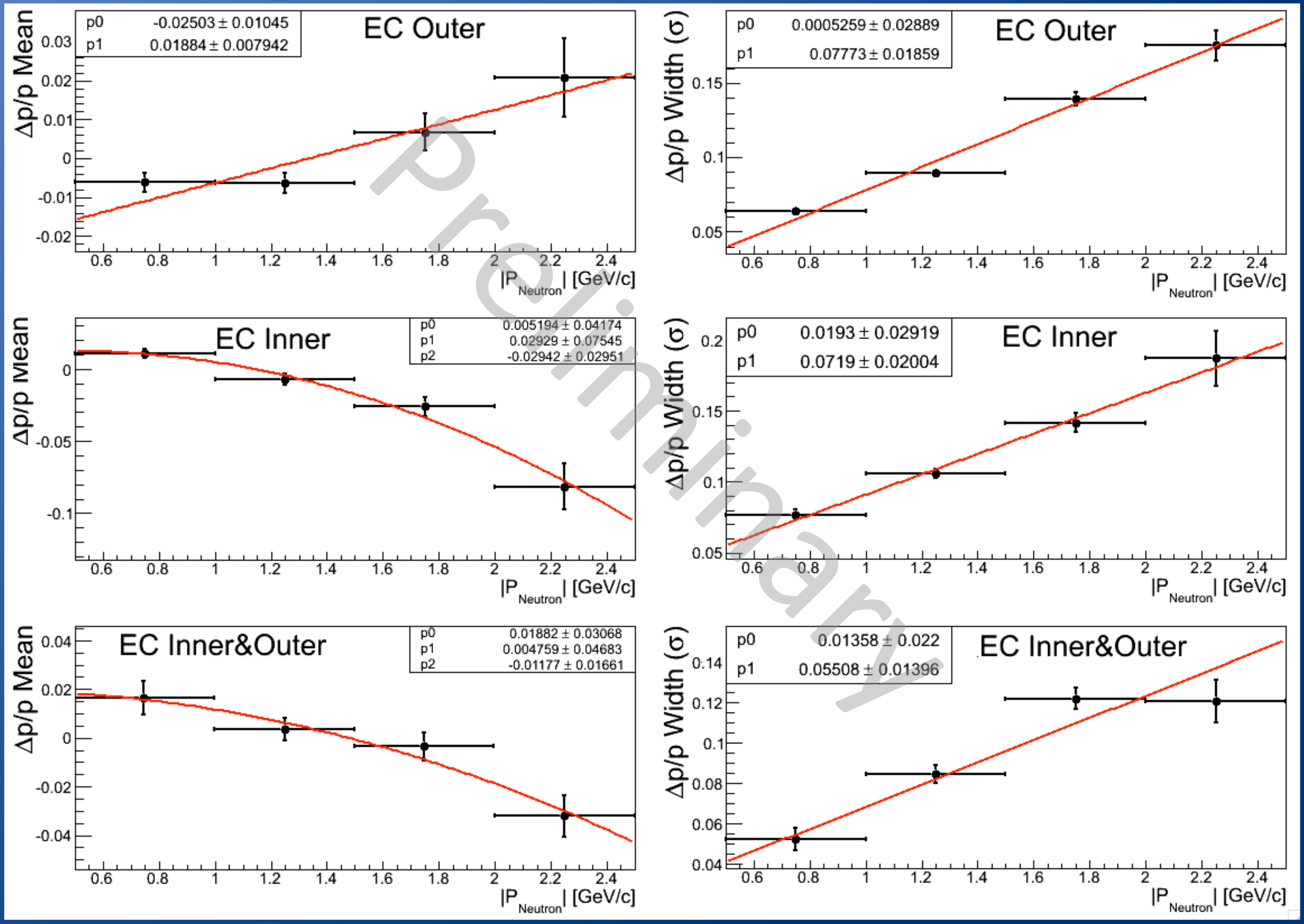


Momentum Resolution

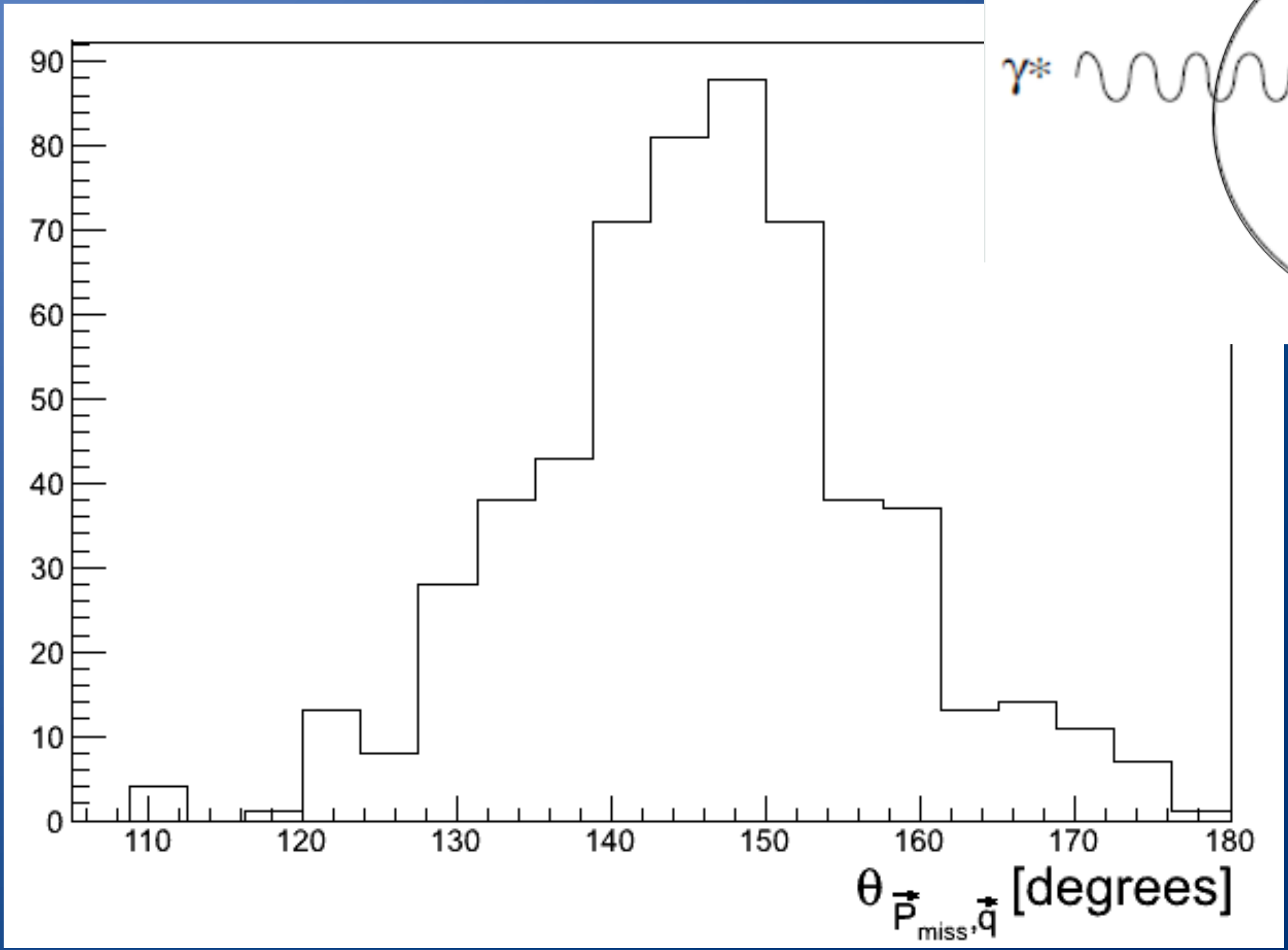
$d(e,e'\pi^+\pi^-n)$

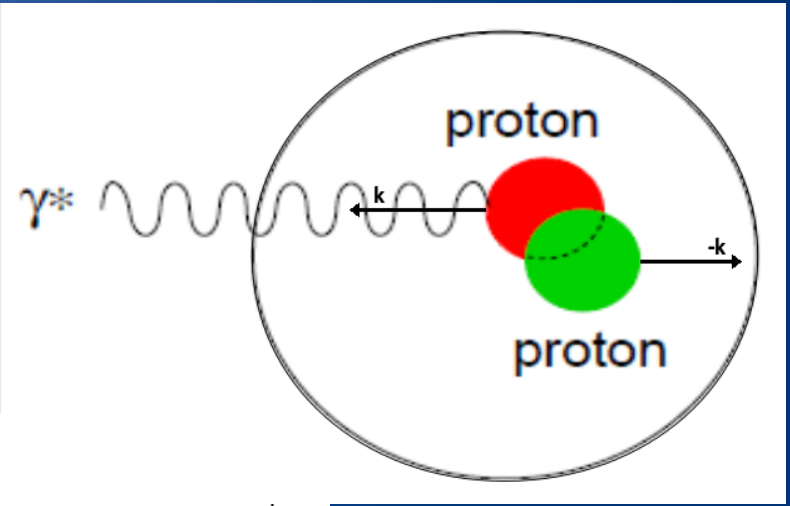


(e,e'pp) Event Selection

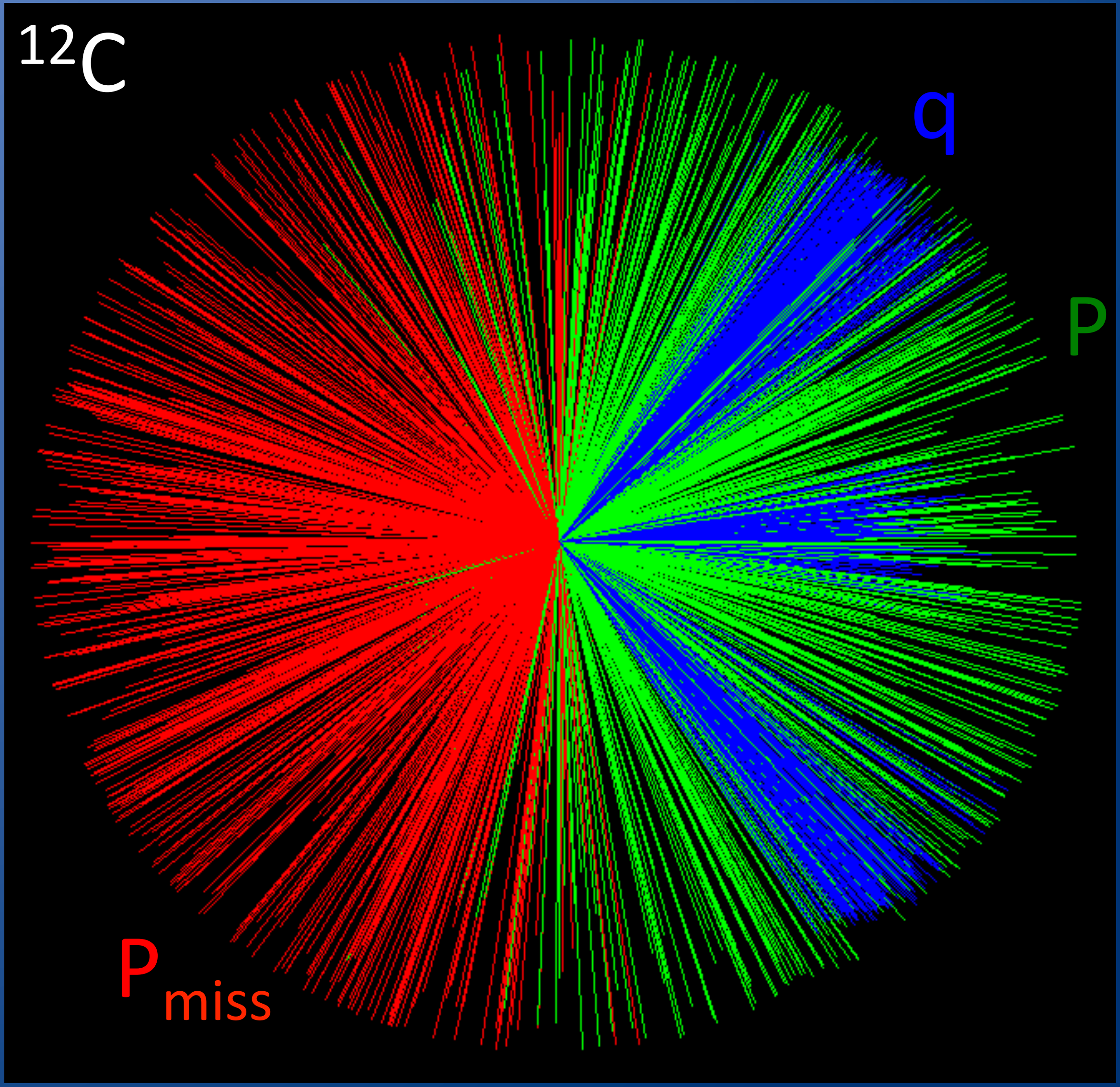
- Select events with exactly two identified protons in the final state
- Apply electron kinematical cuts
  - $x_B > 1.2$
- Identify a leading proton:
  - $\theta_{pq} > 25^o$, $0.62 < |P|/|q| < 0.96$
    [No events with two leading protons]
- Apply all A(e,e'p) cuts on the leading proton
  - $|P_{miss}| > 300$ MeV/c
  - $M_{miss} < m_N + m_\pi$

(e,e'pp) Kinematics

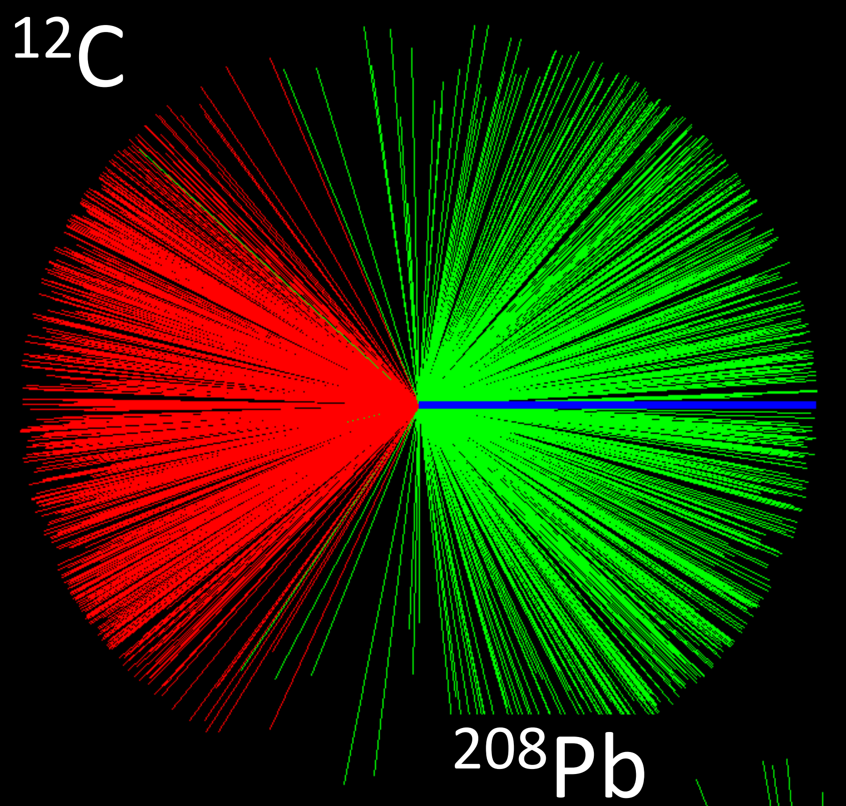


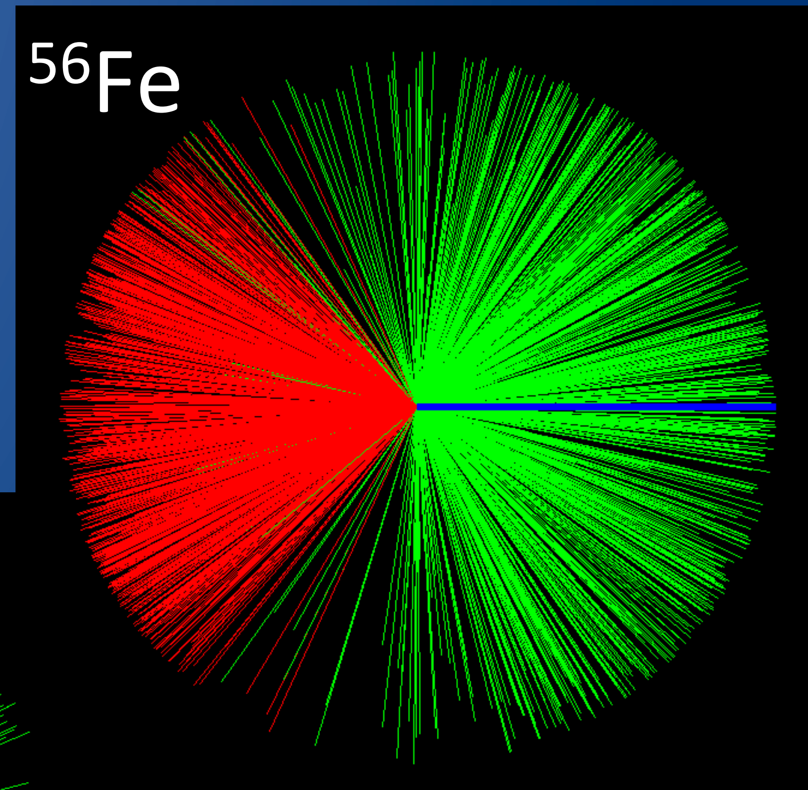


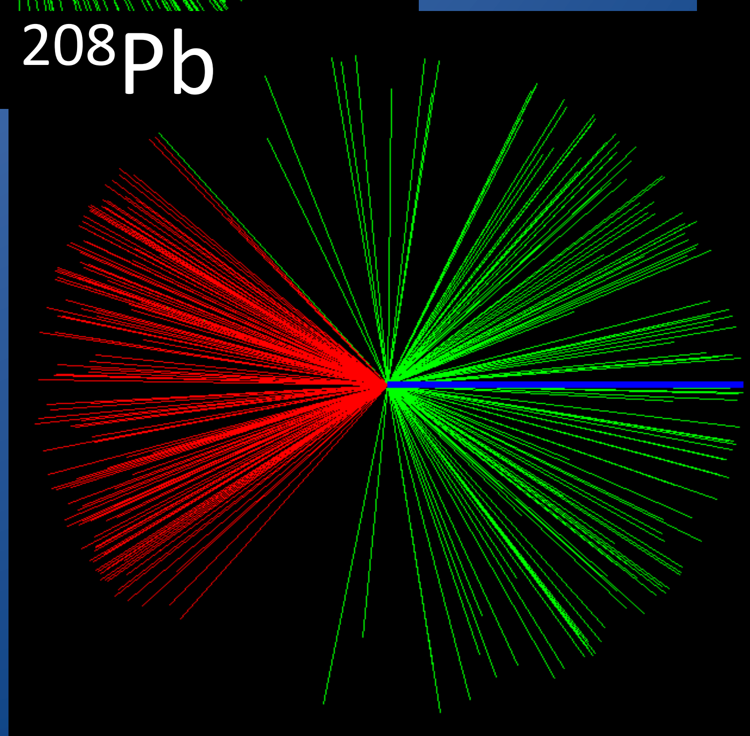
(e,e'pp) Kinematics



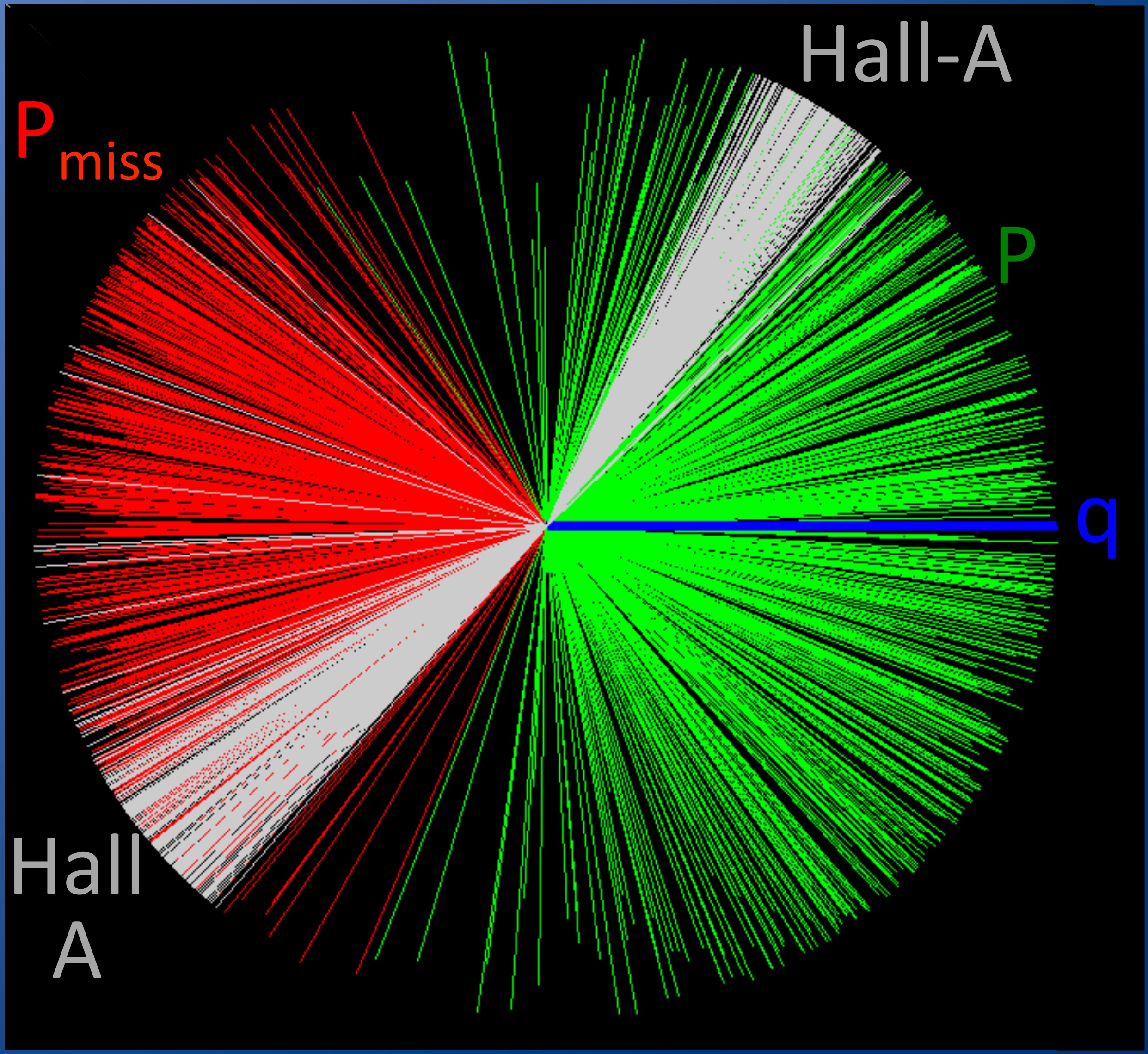
(e,e’pp) Kinematics



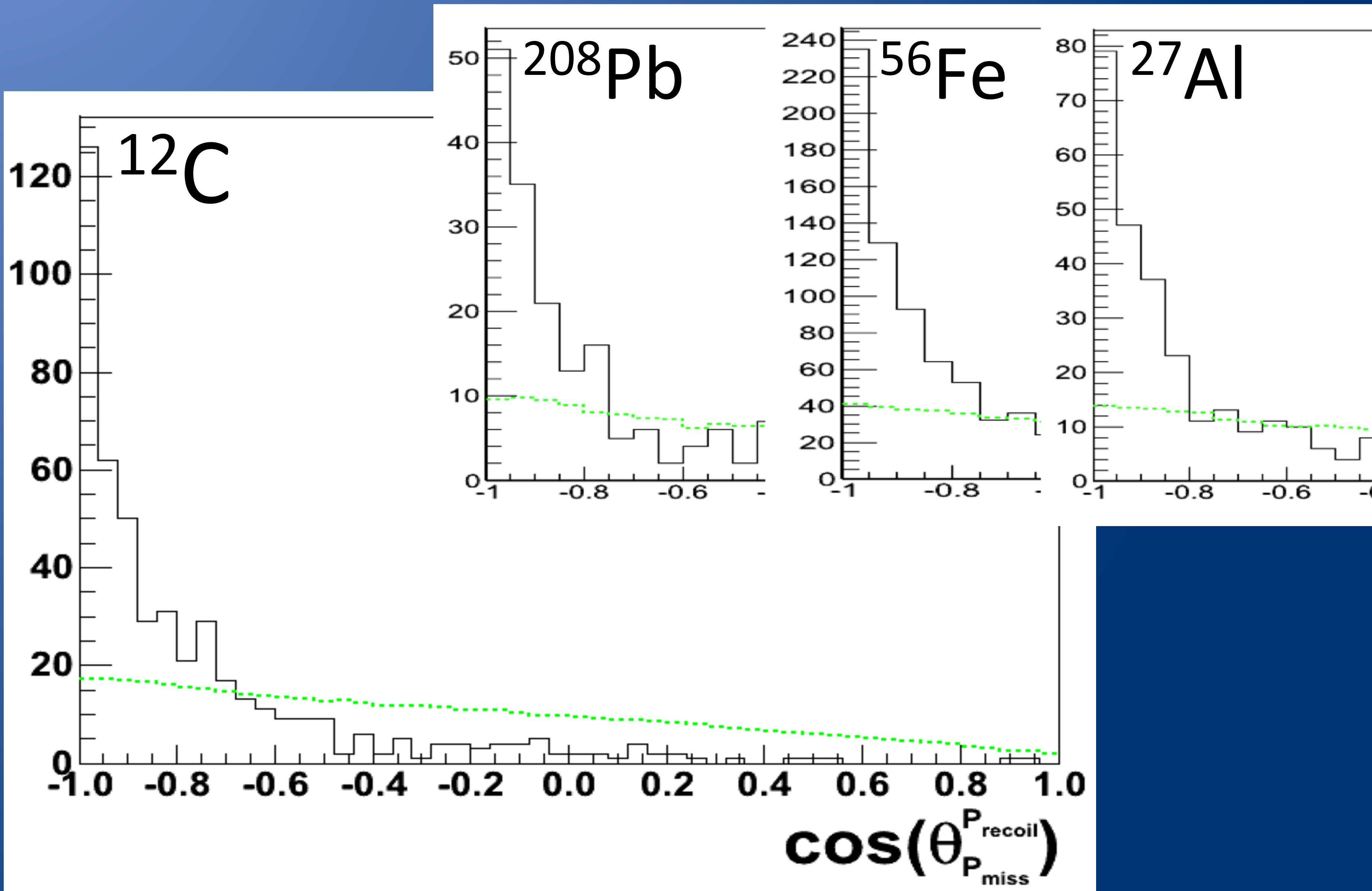




(e,e'pp) Kinematics

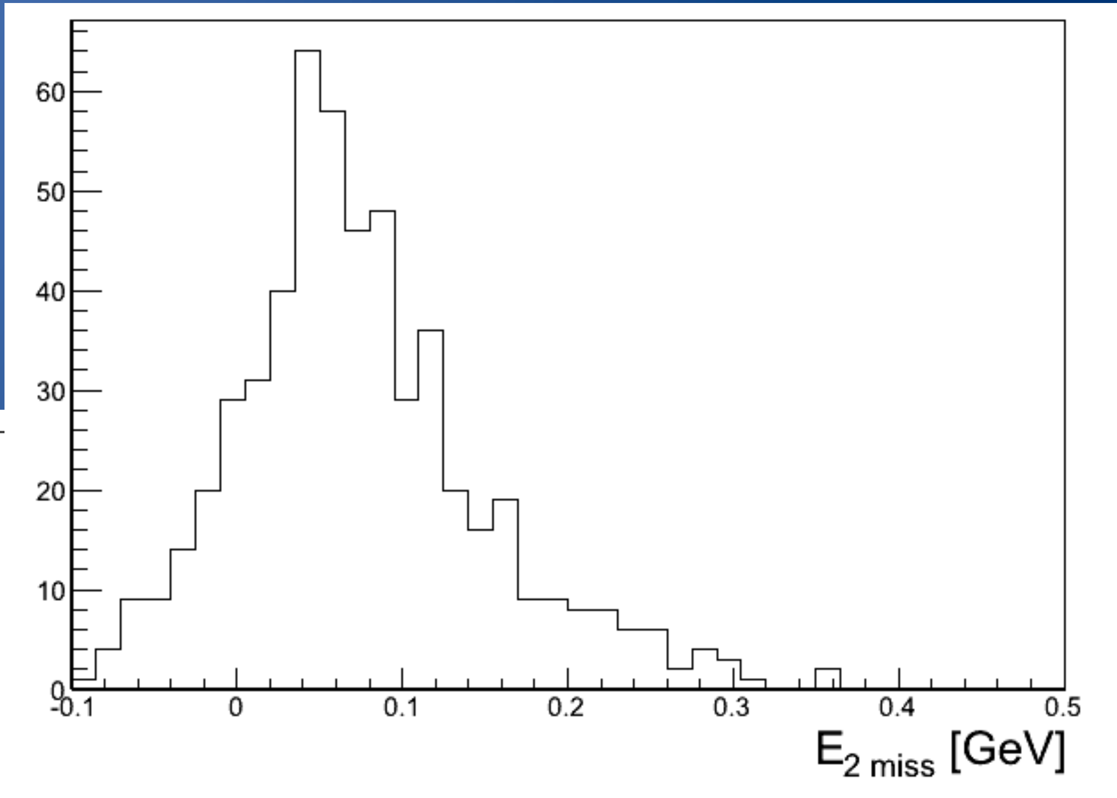


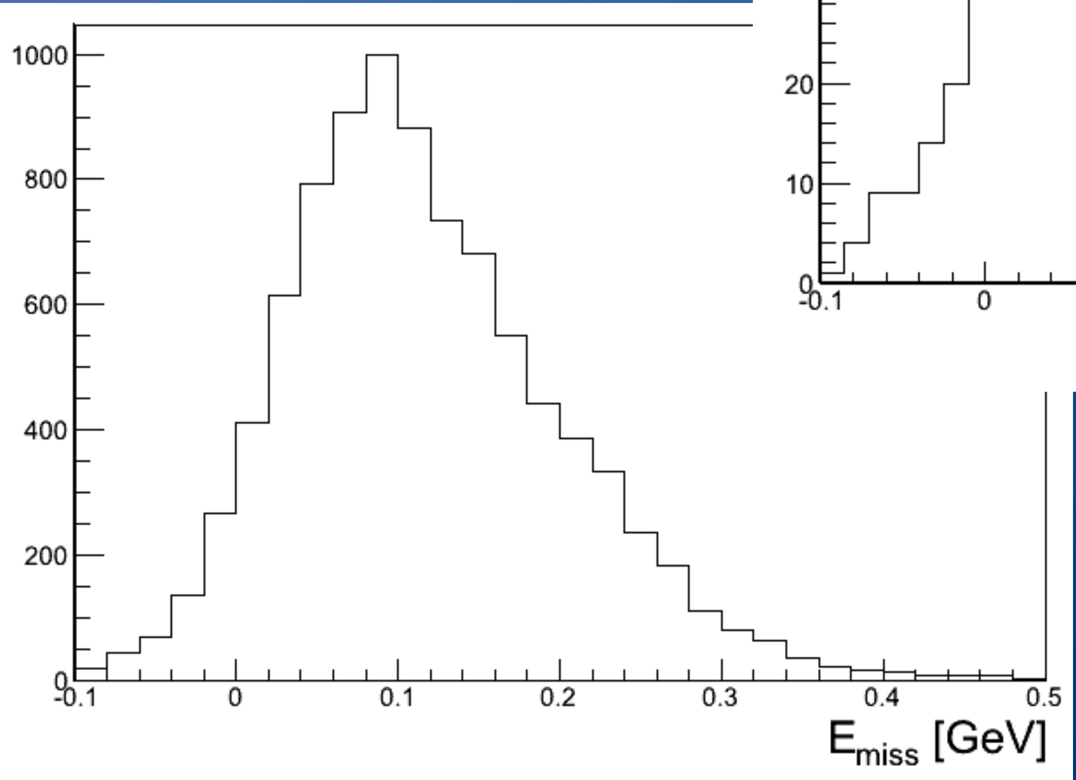
Opening angle



excitation Energies

(e,e'pp)





(e,e'p)

Kinematic Coverage and *(Current)* Observables

- Cross section ratios:
  - $A(e,e'p)_{M.F.} / {}^{12}C(e,e'p)_{M.F.}$
  - $A(e,e'p)_{SRC} / {}^{12}C(e,e'p)_{SRC}$
  - $A(e,e'pp)_{SRC} / {}^{12}C(e,e'pp)_{SRC}$
- pp-SRC characteristics:
  - Pairs opening angle
  - Center-of-mass momentum distribution
- pp-SRC probabilities

Kinematic Coverage and *(Current)* Observables

- Cross section ratios:
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  - $A(e,e'p)_{SRC}$ / $^{12}C(e,e'p)_{SRC}$
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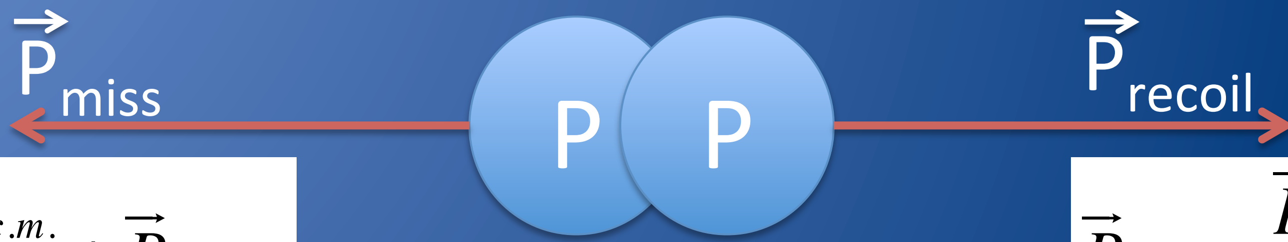
  - Pairs opening angle
  - Center-of-mass momentum distribution
- pp-SRC probabilities

See talk by E. Piasetzky for (e,e'p) results

Ground-State Picture of SRCs



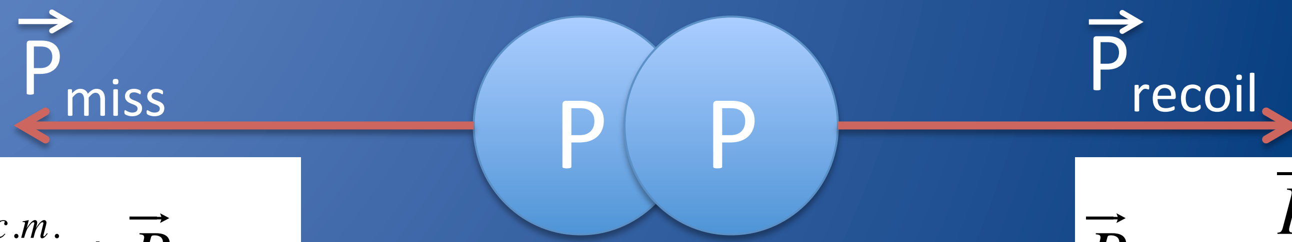
$$\vec{P}_{miss} = \frac{\vec{P}_{c.m.}}{2} + \vec{P}_{relative}$$

$$\vec{P}_{miss} = \frac{\vec{P}_{c.m.}}{2} - \vec{P}_{relative}$$

$$|P_{miss}| \neq |P_{recoil}|$$

[Due to c.m. motion of the pair]

Ground-State Picture of SRCs



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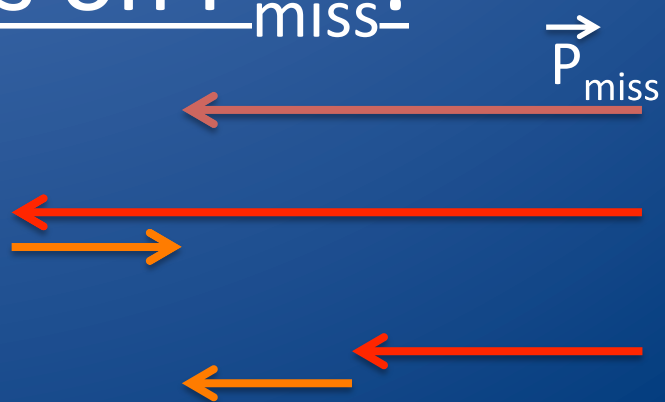
[Due to c.m. motion of the pair]

<u>Focus on $\vec{P}_{miss}$:</u>

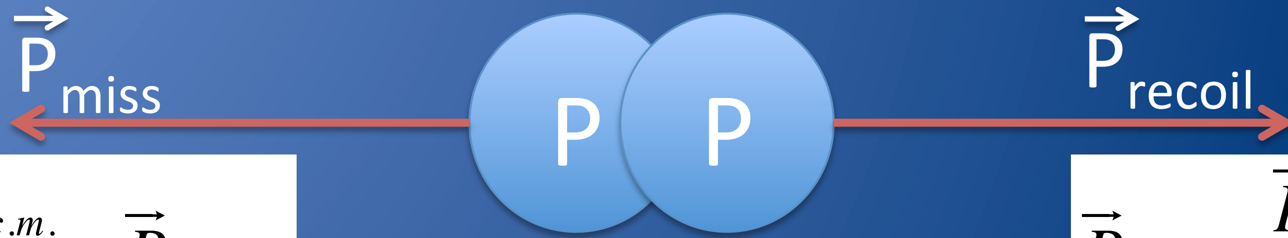
$$\vec{P}_{miss} = \frac{\vec{P}_{c.m.}}{2} + \vec{P}_{relative}$$

Case I:

Case II:



Ground-State Picture of SRCs



$$\vec{P}_{miss} = \frac{\vec{P}_{c.m.}}{2} + \vec{P}_{relative}$$

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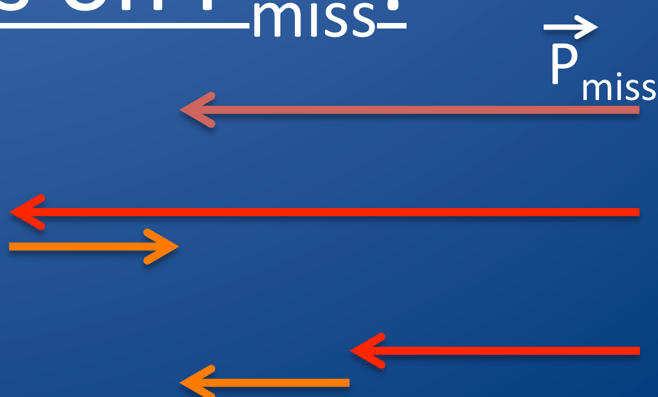
[Due to c.m. motion of the pair]

Focus on $\vec{P}_{miss}$:

Case I:

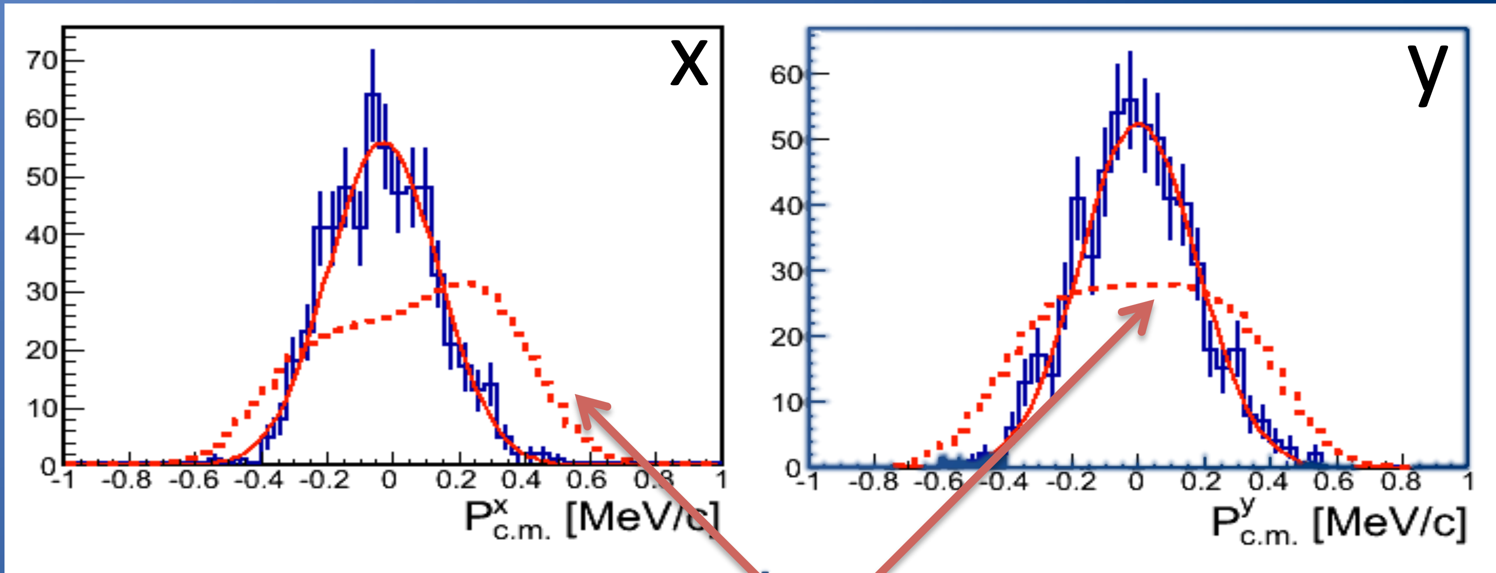
Case II:

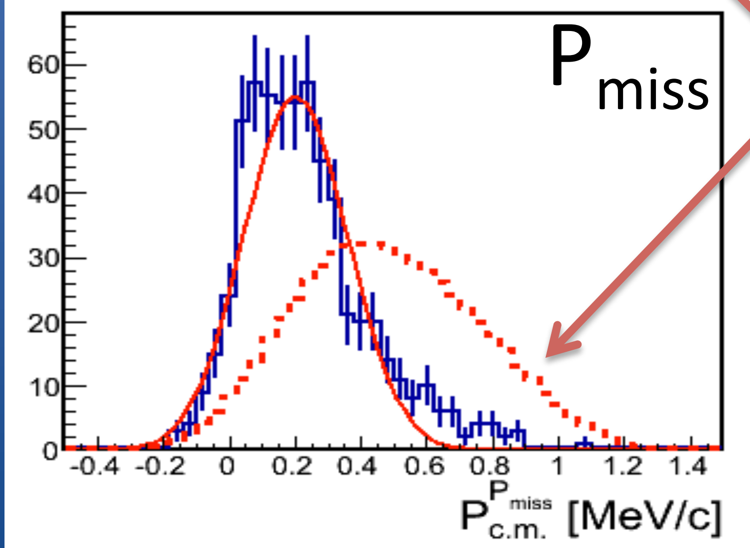


It is more likely to find a high P_{miss} nucleon that comes from a *low $P_{relative}$ and a $P_{c.m.}$ that points in its direction* (i.e. case II)

Event-Mixing Acceptance Corrections

^{56}Fe





Mixed events:

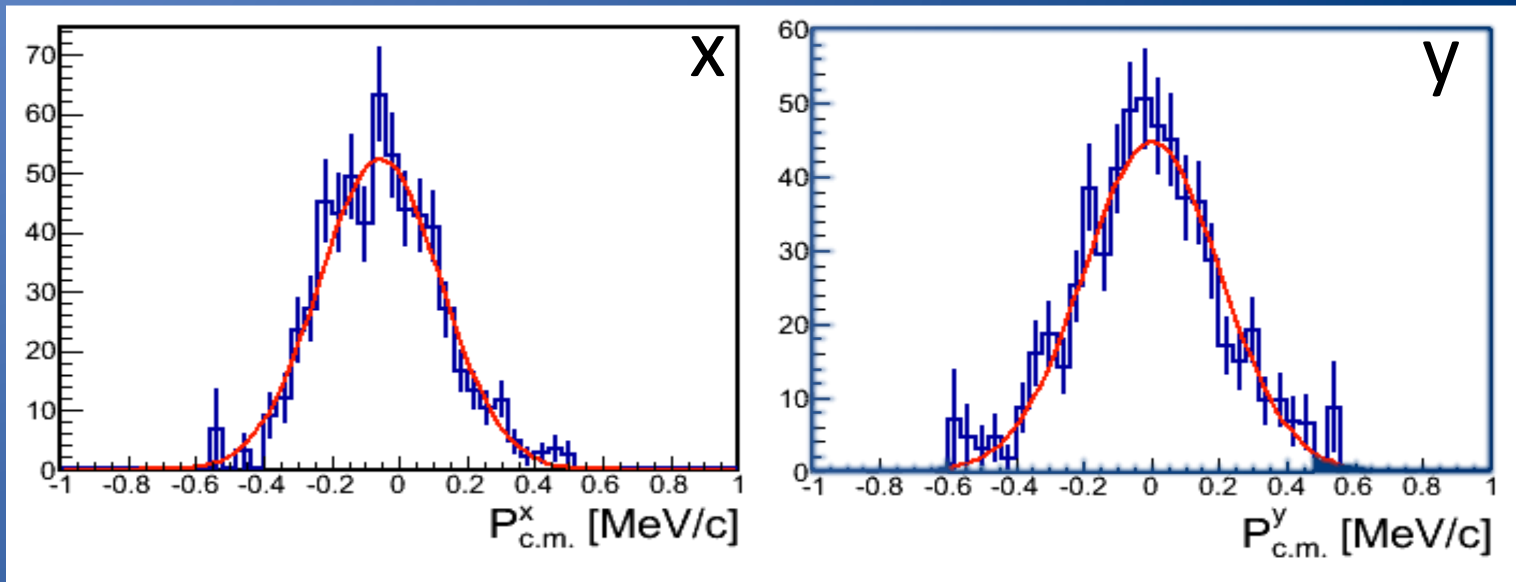
(e,e’p) – event one

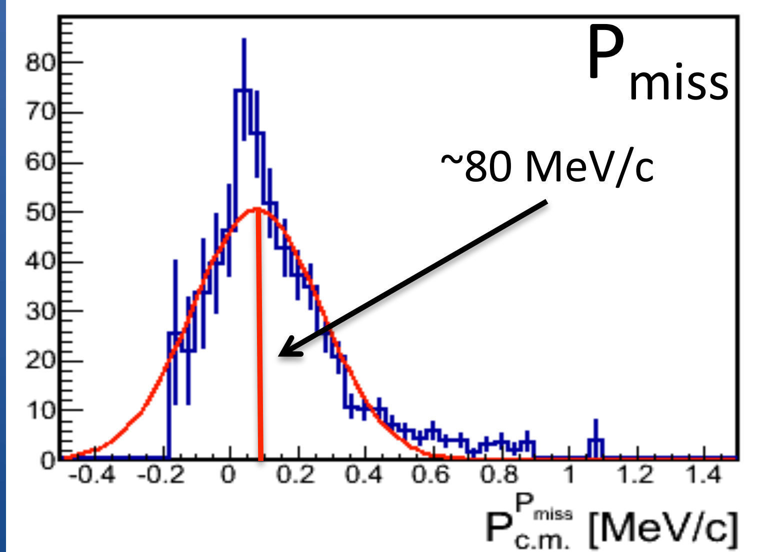
P_{recoil} – event two

Represents the acceptance of the detector for a random sample that pass our selection cuts

Event-Mixing Acceptance Corrections

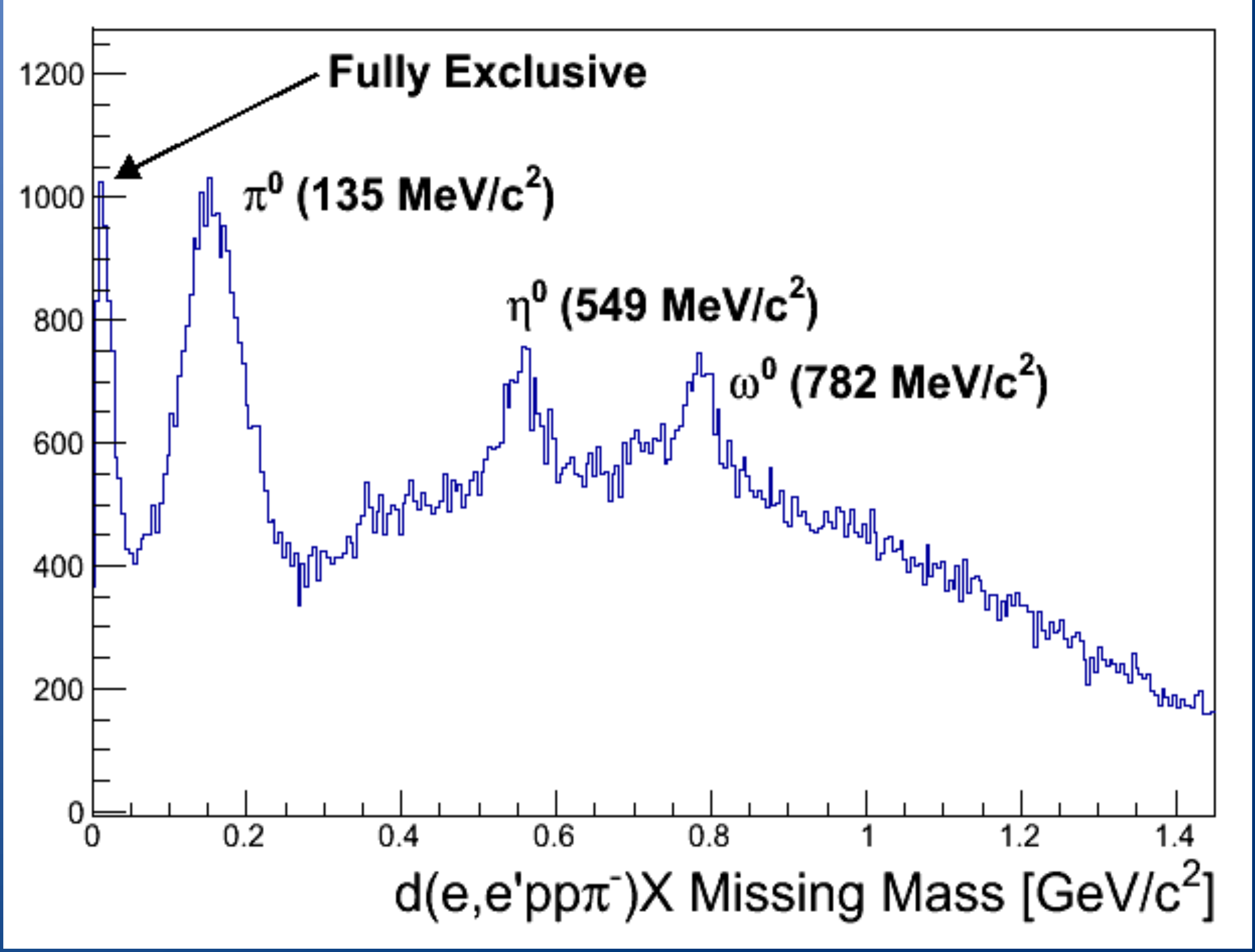
^{56}Fe



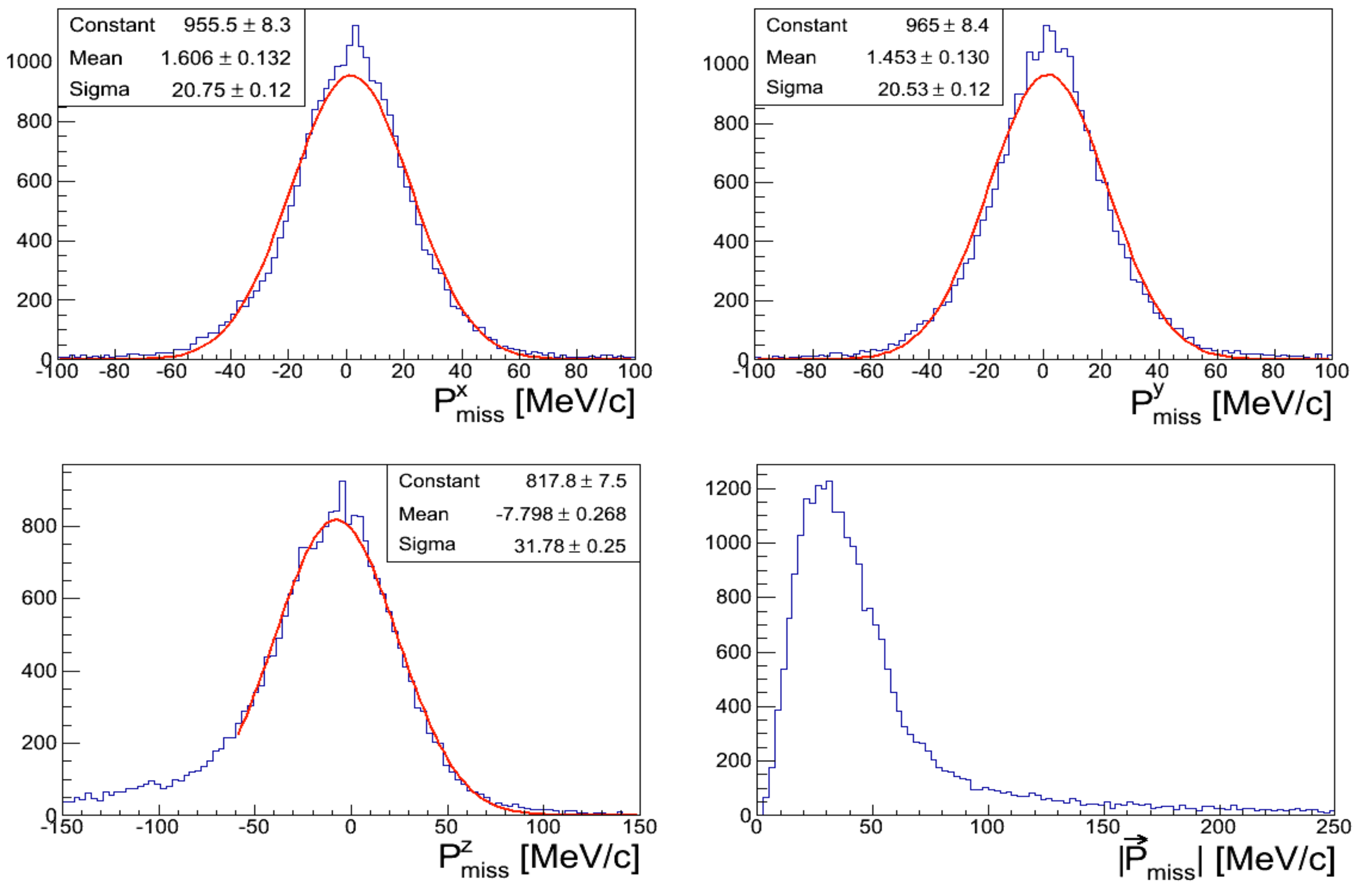


Acceptance corrected c.m. momentum distributions – after dividing by the mixed events phase-space

$|P_{c.m.}|$ Reconstruction Resolution



$|P_{c.m.}|$ Reconstruction Resolution



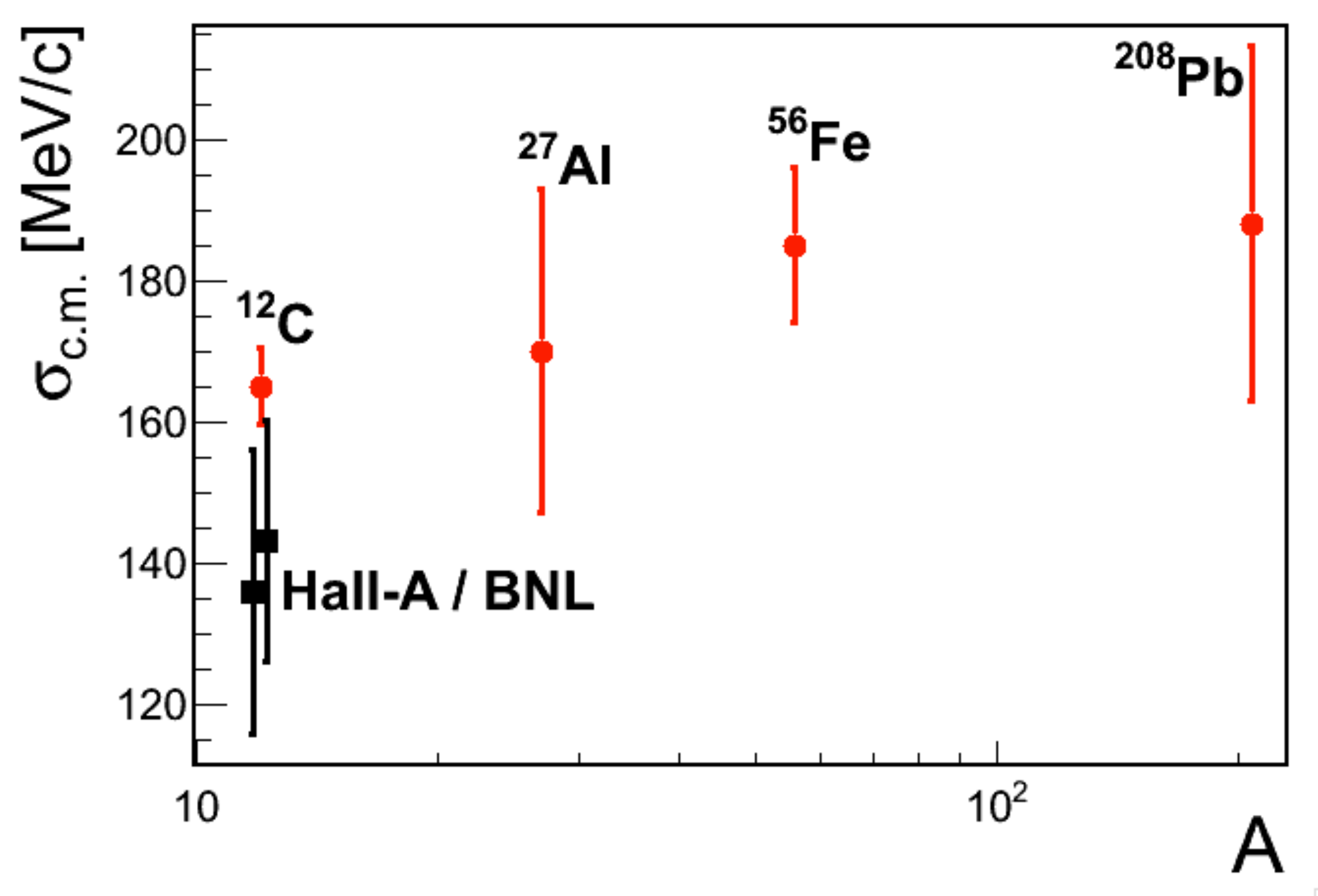
$d(e,e'pp\pi^-)$

$\sigma_{res} \cong 20$ MeV/c

$$\sigma_{c.m.} = \sqrt{\sigma_{exp}^2 - \sigma_{res}^2} \quad \Rightarrow$$

Correction of ≈3 MeV/c for $\sigma_{c.m.}$ ≈160 MeV/c

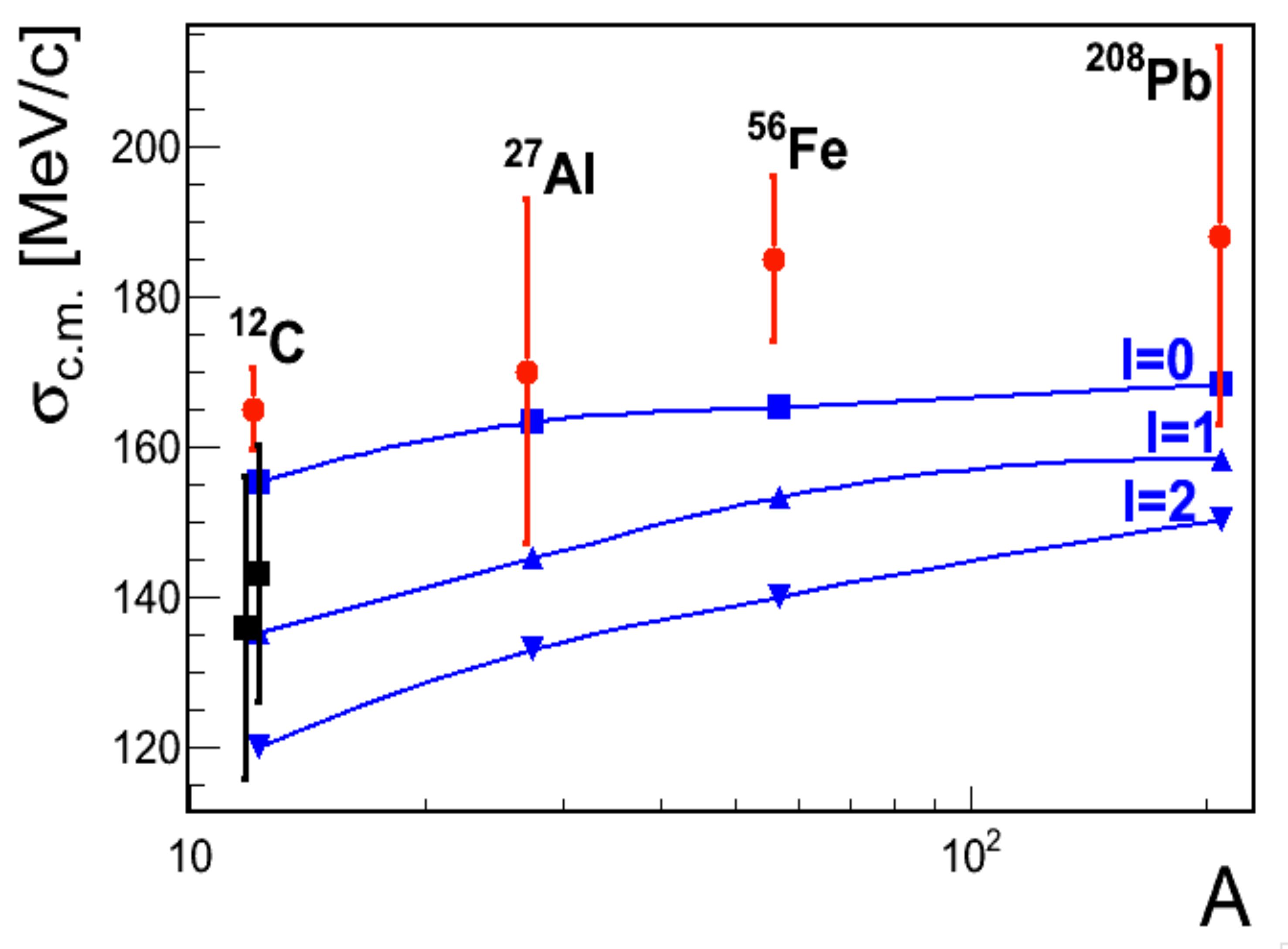
(weak) A-dependence of the c.m. momentum distribution



VERY week A dependence

Indicate small contribution form FSI?

(weak) A-dependence of the c.m. momentum distribution



A-dependence of $\sigma_{A(e,e'pp)}$

- Very week A-dependence of the A(e,e'pp) cross section:

	Z(Z-1)
– ^{27}Al / ^{12}C = 1.9 ± 0.16	5
– ^{56}Fe / ^{12}C = 2.5 ± 0.14	21
– ^{208}Pb / ^{12}C = 4.4 ± 0.35	221

A-dependence of $\sigma_{A(e,e'pp)}$

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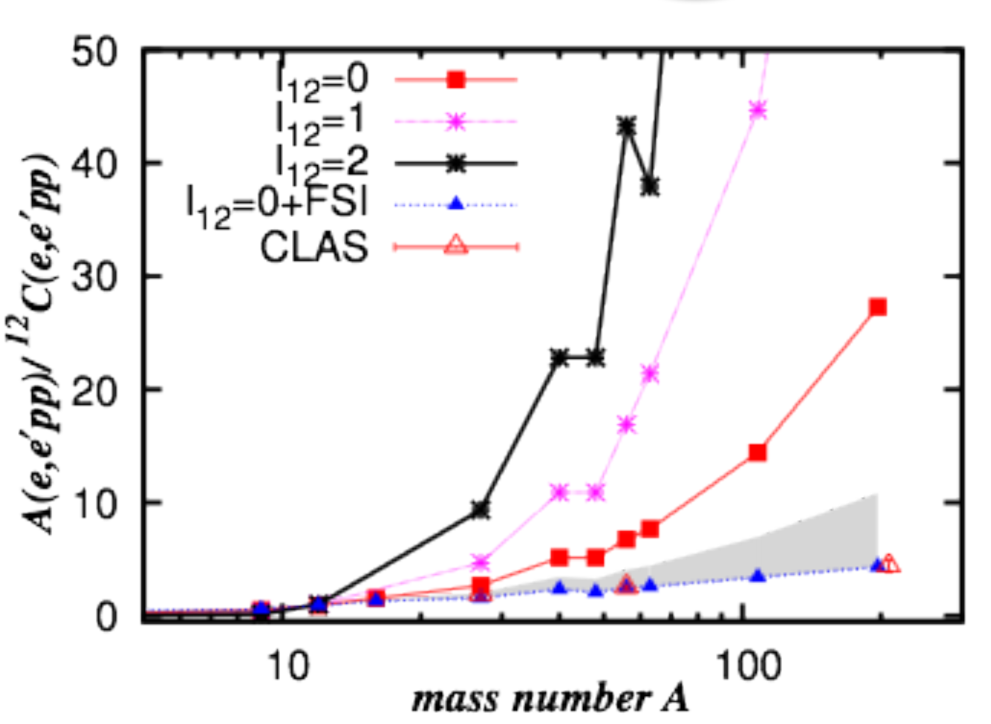
See talk by J. Ryckebusch

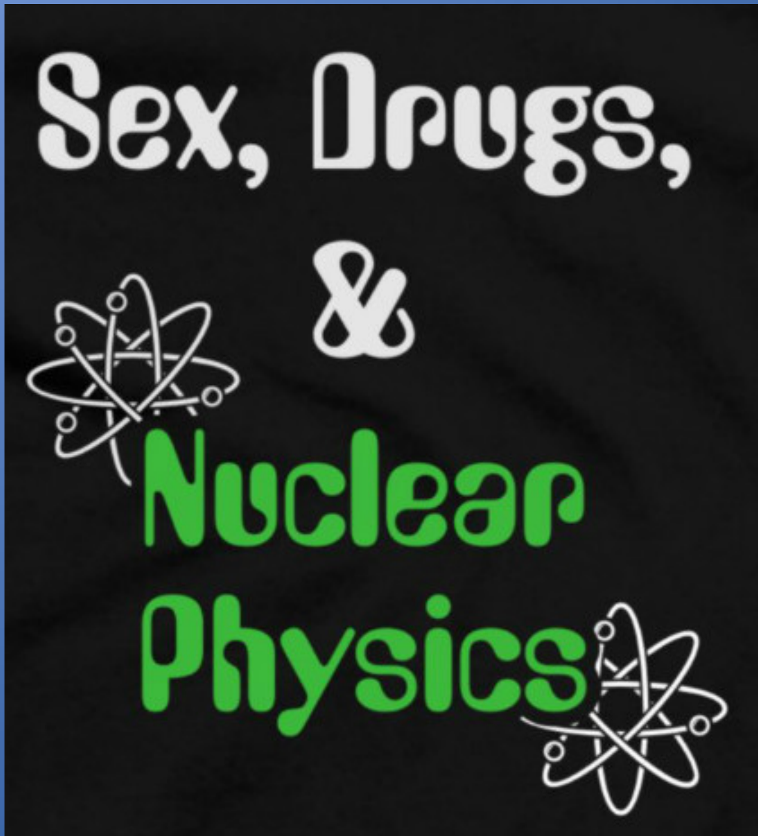
- Calculations by the GENT group show consistency with l=0 SRC pairs



Results and conclusions

- (e,e'p) and (e,e'n)
  - First paper on SRC protons transparency ratios under review for publication in Physics Letters B
  - Neutron analysis in progress
- (e,e'pp) - pp-SRC universality
  - Extracted c.m. momentum distributions
  - width are 160~180 MeV/c for ^{12}C - ^{208}Pb
  - A(e,e'pp) cross section increase slowly with A (^{208}Pb/ ^{12}C = 4.4)

  [Consistent with l=0 calculation by the GENT group]
- Analysis of (e,e'pp)/(e,e'p) as a function of P_{miss} in progress



Thank You !

Questions?