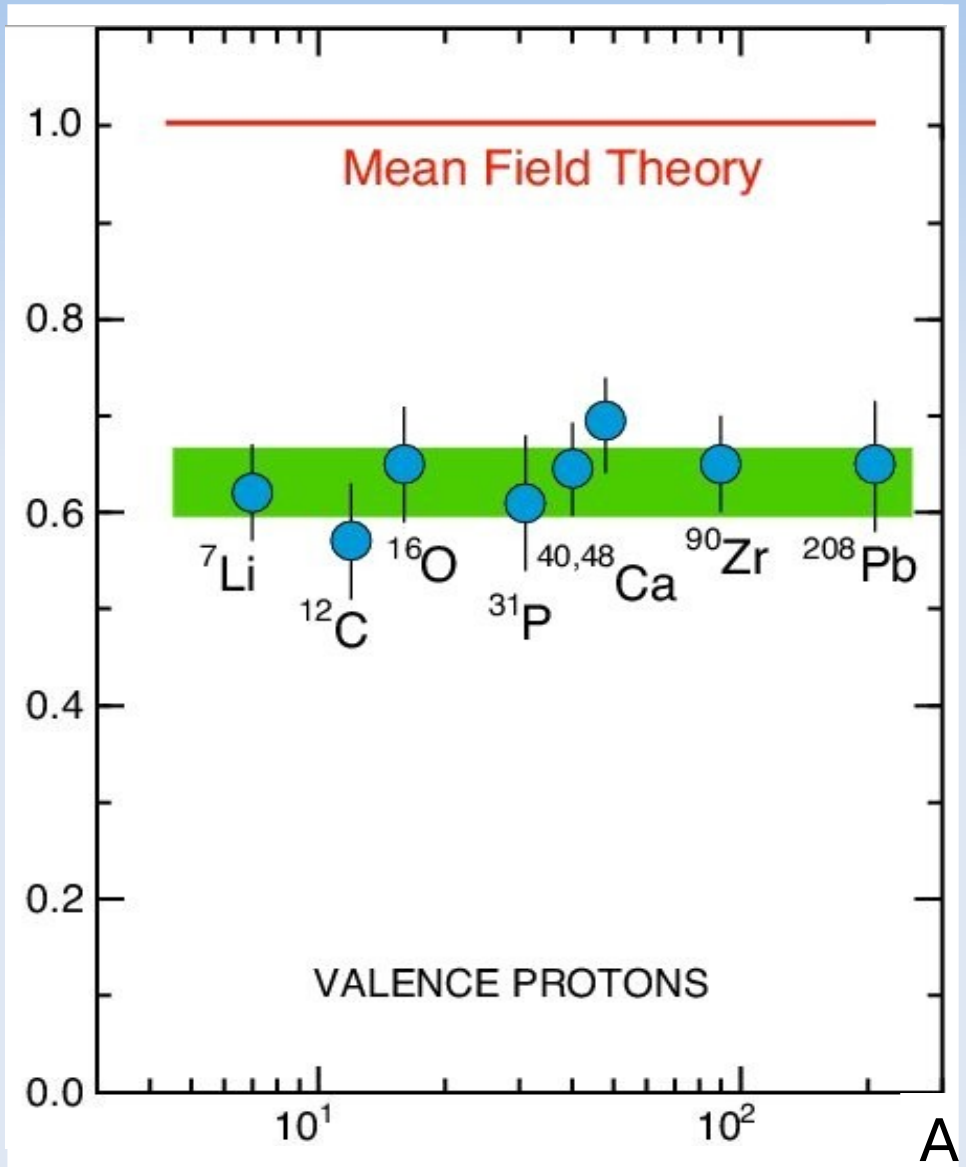
Short-Range Structure of Nuclei

Or Hen

Tel-Aviv University

Independent Particle Approximation

Spectroscopic factors from (e,e'p) measurements yield only 60-70% of the expected single particle strength



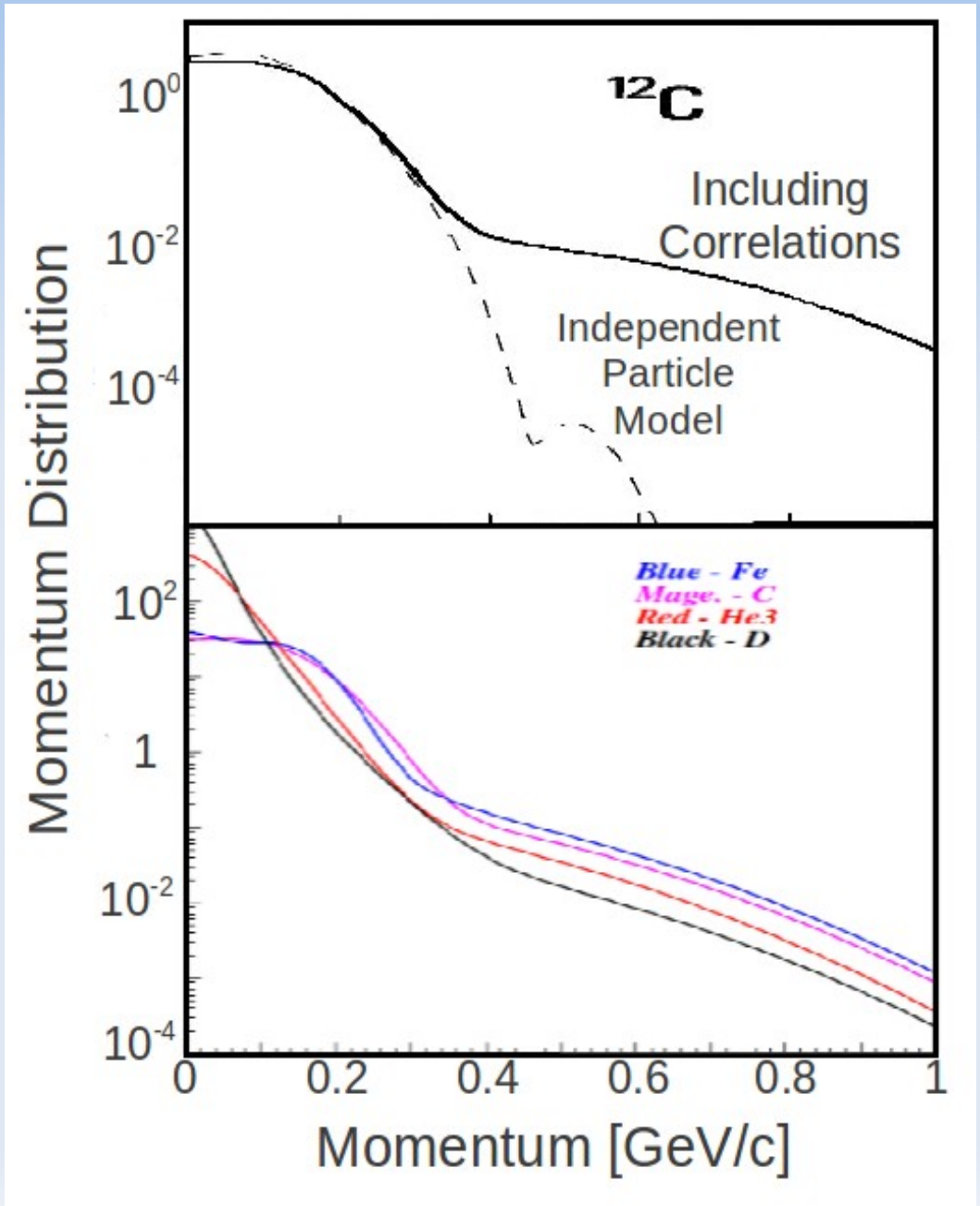
L. Lapikas, Nucl. Phys. A **553** (1993) 297.

<u>Missing:</u>

- Long Range Correlations (accounts for ~20%)
- High momentum nucleons

  (Short Range Correlations)

High Momentum Tail of the Nuclear Wave Function



- Independent particle models do not produce enough high momentum nucleons
- Many-body calculations predicts that the high momentum distribution for all nuclei has the same shape:

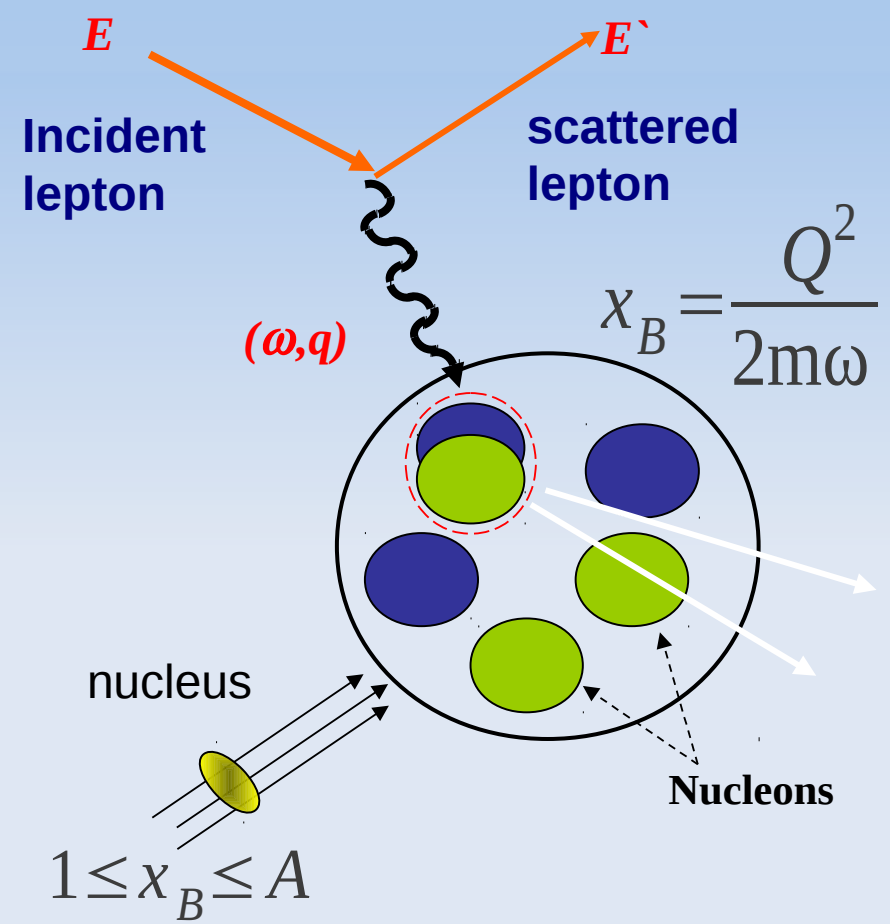
$$n_A(k)/n_d(k) = a_2(A/d)$$

O. Benhar et al., Phys. Lett. B **177** (1986) 135.
C. Ciofi degli et al. Phys. Rev. C **53** (1996) 1689

Inclusive Electron Scattering at x_B>1

- A hard process with the resolving power to probe the **<u>partonic structure of the nucleus</u>**
- x_B counts the number of nucleons involved in the reaction

  → for x_B>j, at least j nucleons are involved in the reaction



<u>Kinematics:</u>

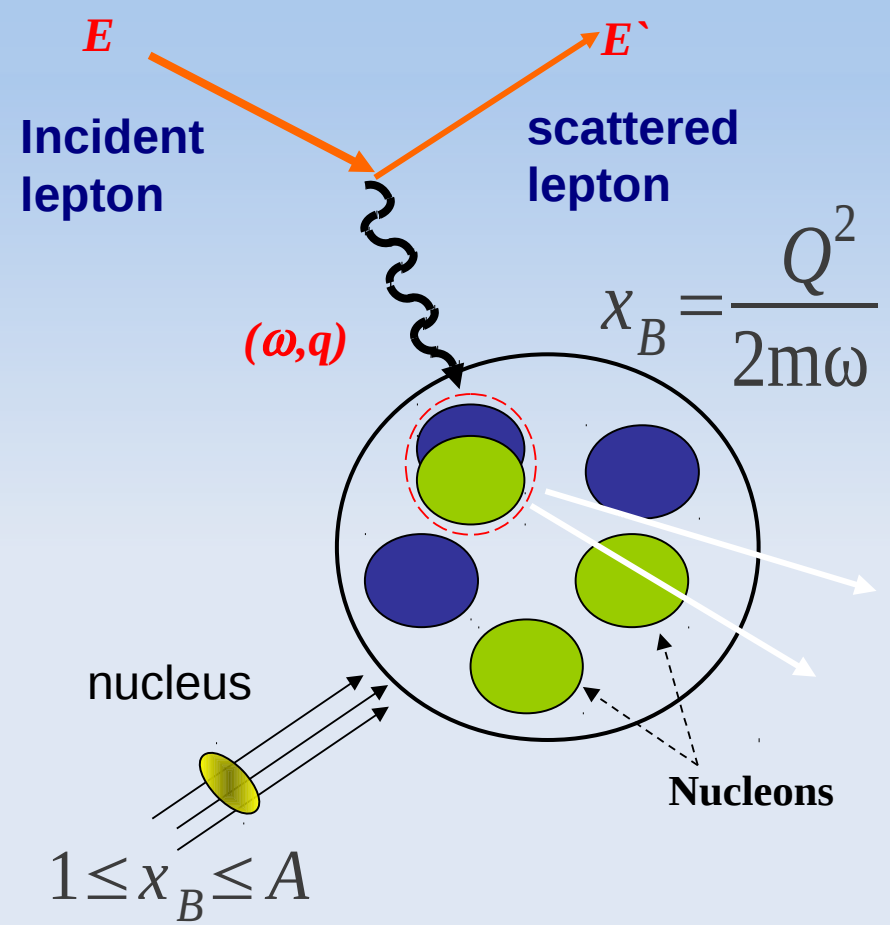
***E*, *E'* 3 - 5 GeV**

Q^2 2 - 3 [GeV/c]^2

$1 \le x_B \le A$

Inclusive Electron Scattering at x_B>1

- A hard process with the resolving power to probe the **<u>partonic structure of the nucleus</u>**
- x_B counts the number of nucleons involved in the reaction
- At high Q^2, x_B determines a minimum initial momentum for the scattered nucleon (y)

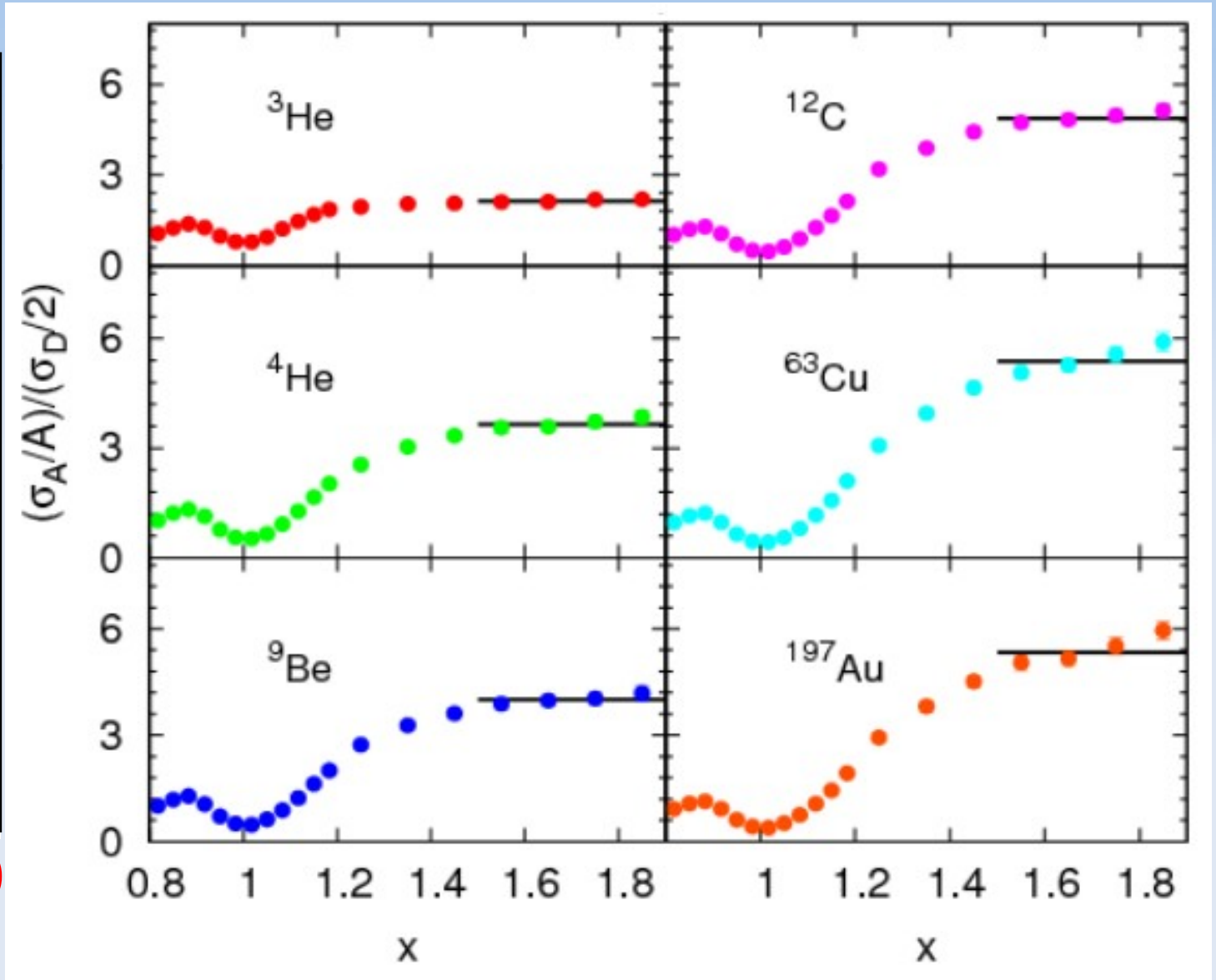


<u>momentum scaling ↔ x_B scaling</u>

High Precision Results from Hall-C

$a_2(A/d)$	
^{3}He	1.93±0.10
^{4}He	3.02±0.17
^{9}Be	3.37±0.17
^{12}C	4.00±0.24
^{63}Cu	4.33±0.28
^{197}Au	4.26±0.29

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

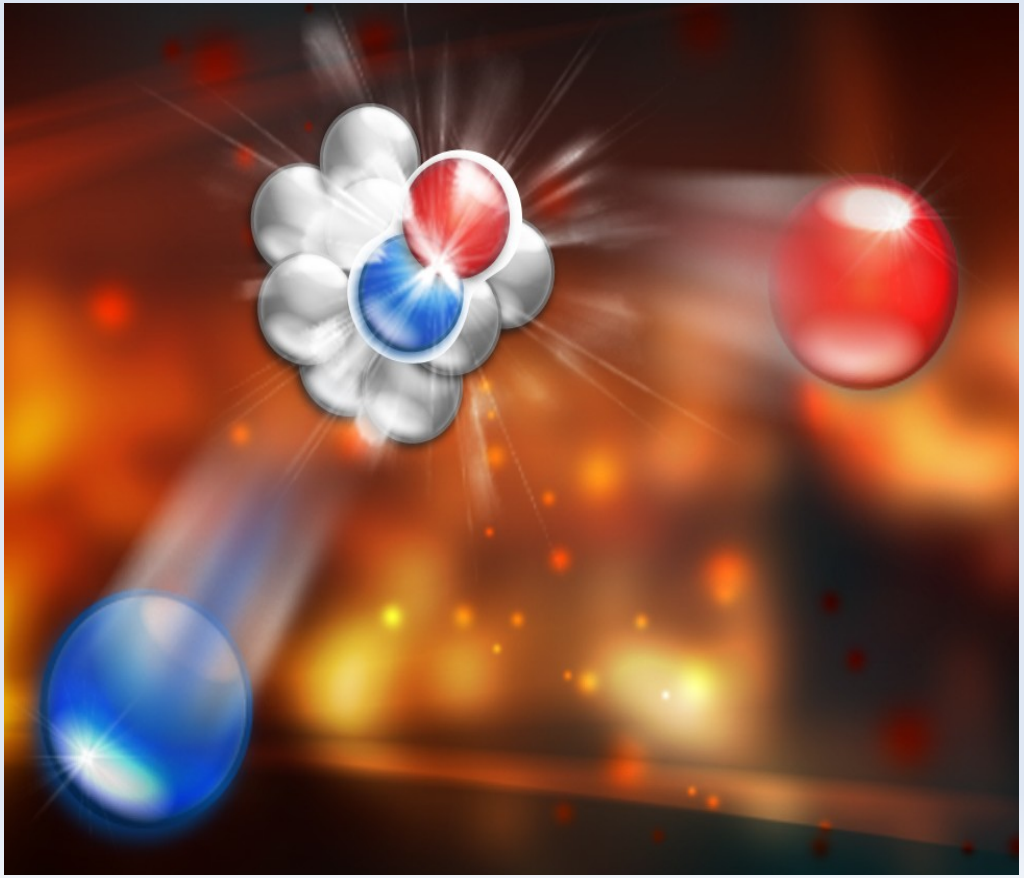


D. Day et al. Phys. Rev. Lett **59**, 427 (1987)
K. Sh. Egiyan et al. Phys. Rev. C **68**, 014313 (2003)
K. Sh. Egiyan et al. Phys. Rev. Lett **96**, 082501 (2006)
N. Fomin et al., Phys. Rev. Lett. 108, 092502 (2012)

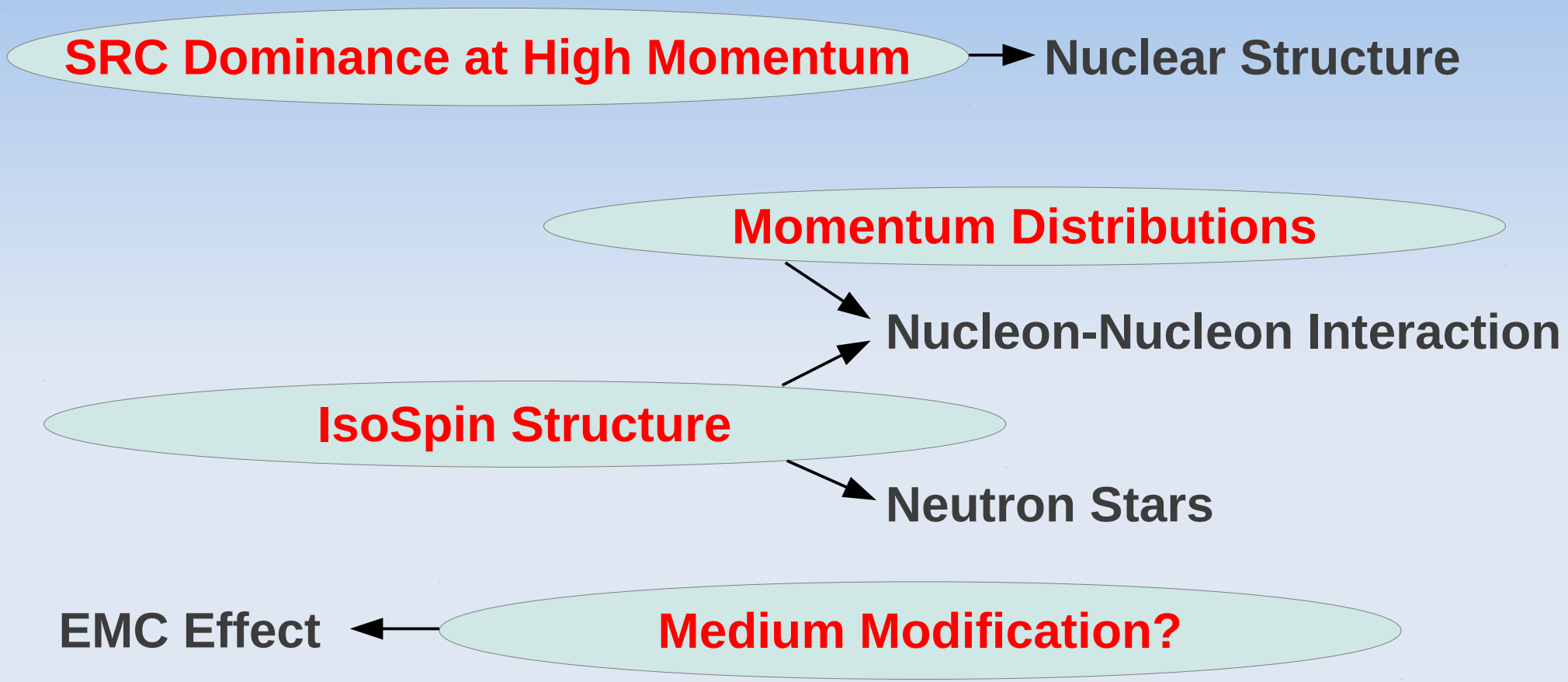
Theoretical Interpretation: L. L. Frankfurt et al. Phys. Rev. C **48**, 2415-2461 (1993)

Short Range Correlations (SRC)

- <u>2N-SRC are pairs of nucleons that:</u>
  - 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 of the nucleus



Short Range Correlations (SRC)

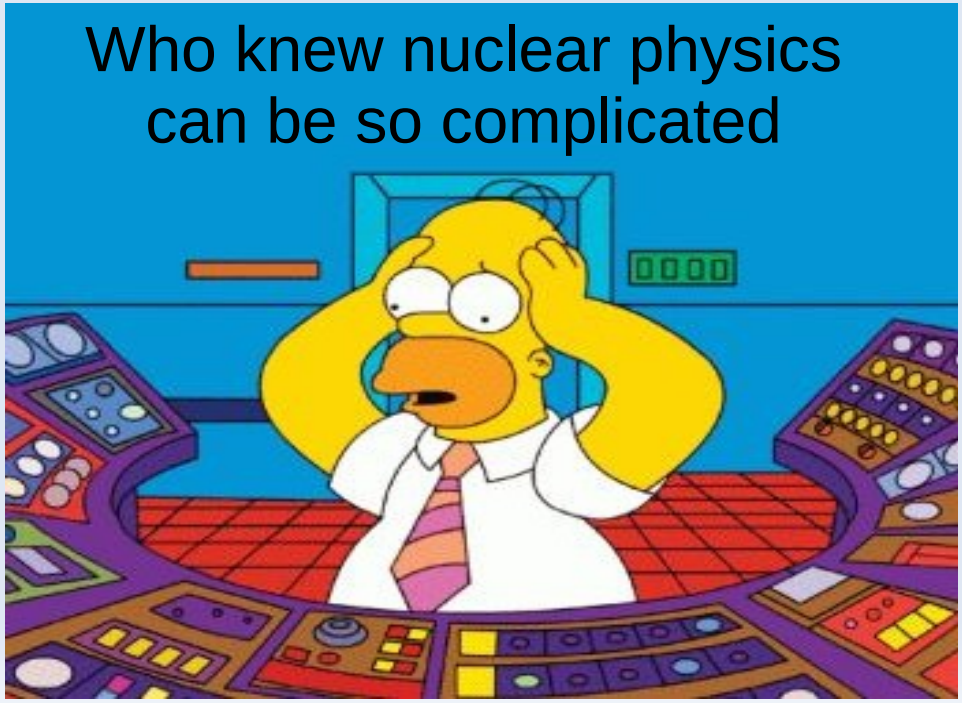


How? Using exclusive measurements

Exclusive SRC Studies

A(e,e'pN): detect electron + two nucleons

- Pros: Measure the “full” 2N final state to <u>characterize</u> the 2N-SRC pairs
- Cons:
  - <u>Interpretation difficulties:</u> Competing processes, FSI, Transparency.
  - <u>Experimental difficulties:</u> Large BG, Low statistics, Large Installation, Dedicated detectors



Exclusive SRC Studies

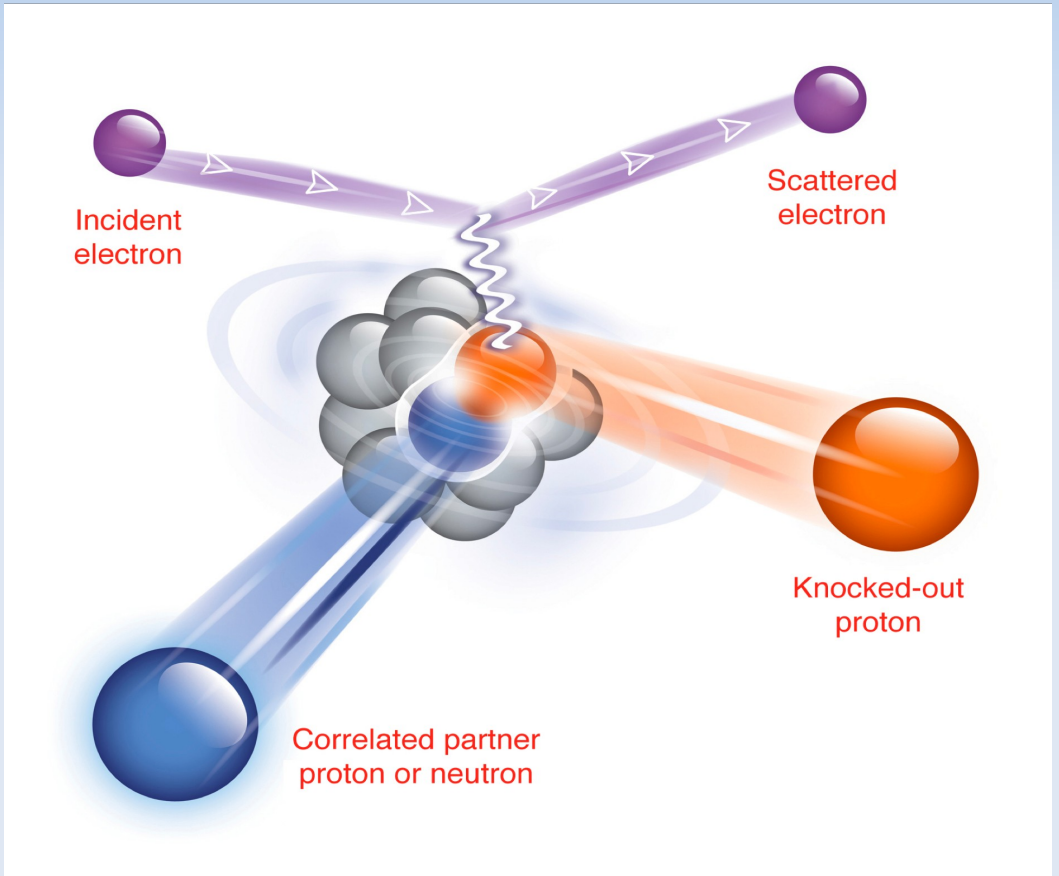
A(e,e'pN): detect electron + two nucleons

Measurement Concept:

1. Hard knock out of a high momentum proton

2. Reconstruct the initial (missing) momentum of the struck nucleon

3. Look for a recoil nucleon with momentum that balanced that of the struck proton

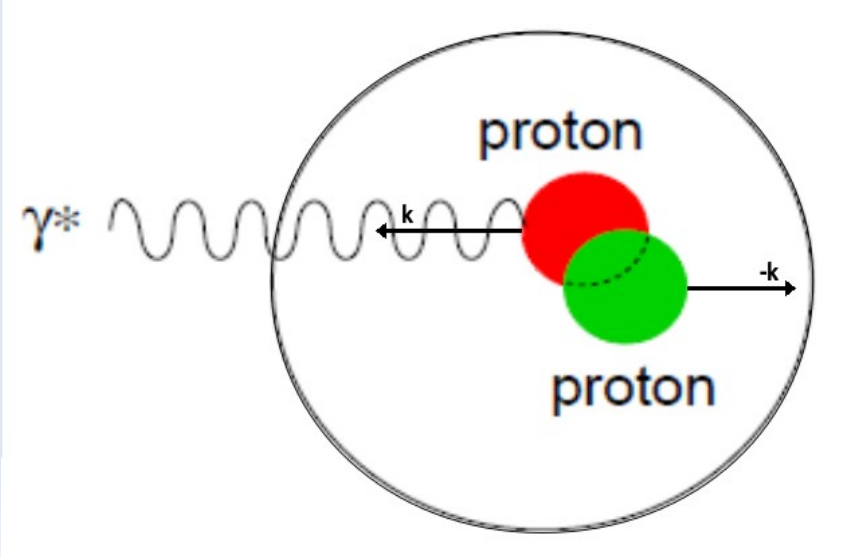


$$\vec{p}_{miss}\,\vec{q} - \vec{p}_{p} = -\vec{p}_{initial}$$

JLab Hall-A E01-015 (2004)

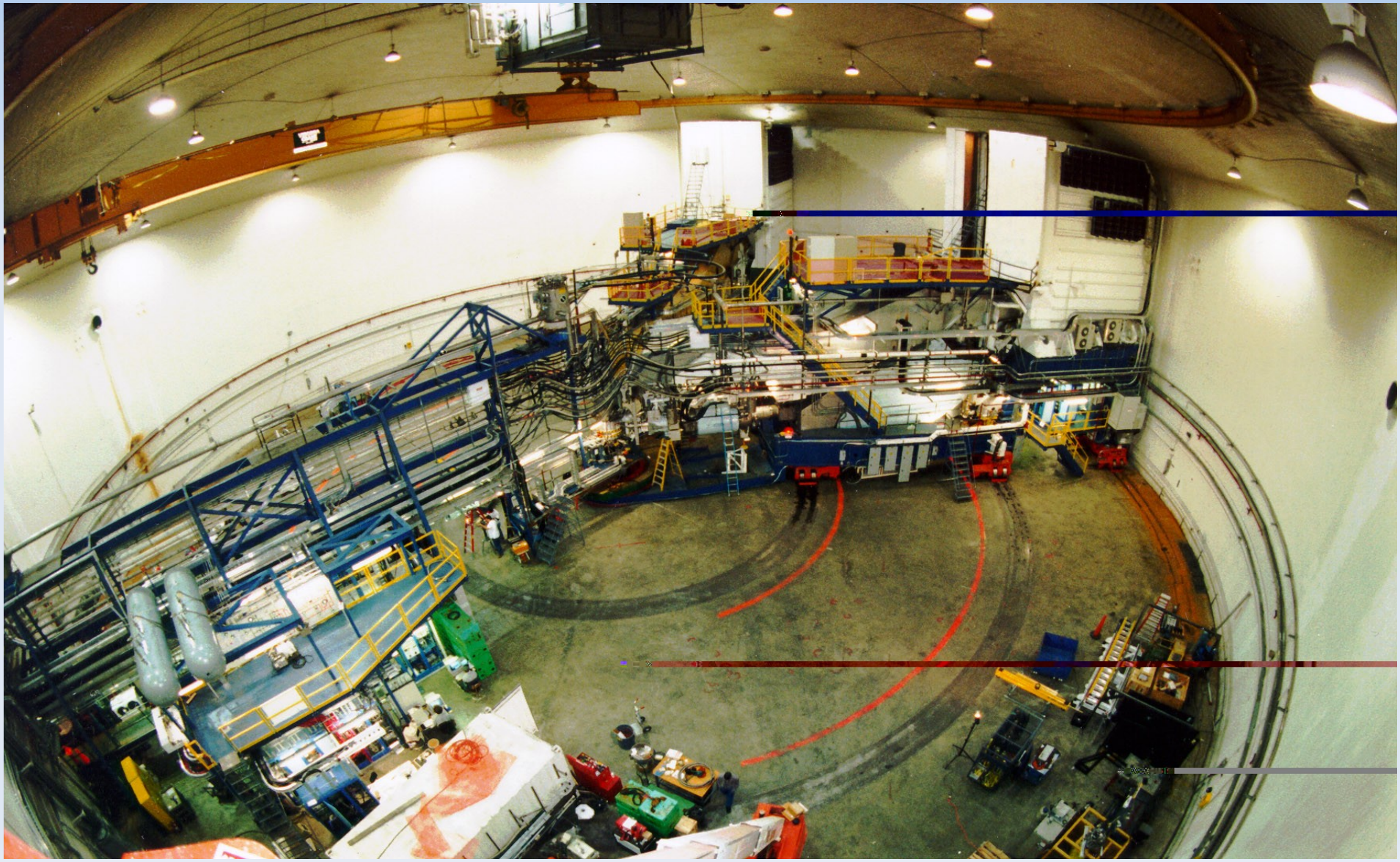
- Goal: Study both **pn and pp S**RC in ^{12}C over an (e,e'p) missing momentum range of 300-600 MeV/c

- Kinematics:
  - High Q^2 to minimize MEC
  - x_B>1 to suppress isobar contributions
  - Almost anti-parallel kinematics to confine FSI to within the 2N-SRC pair



JLab Hall-A

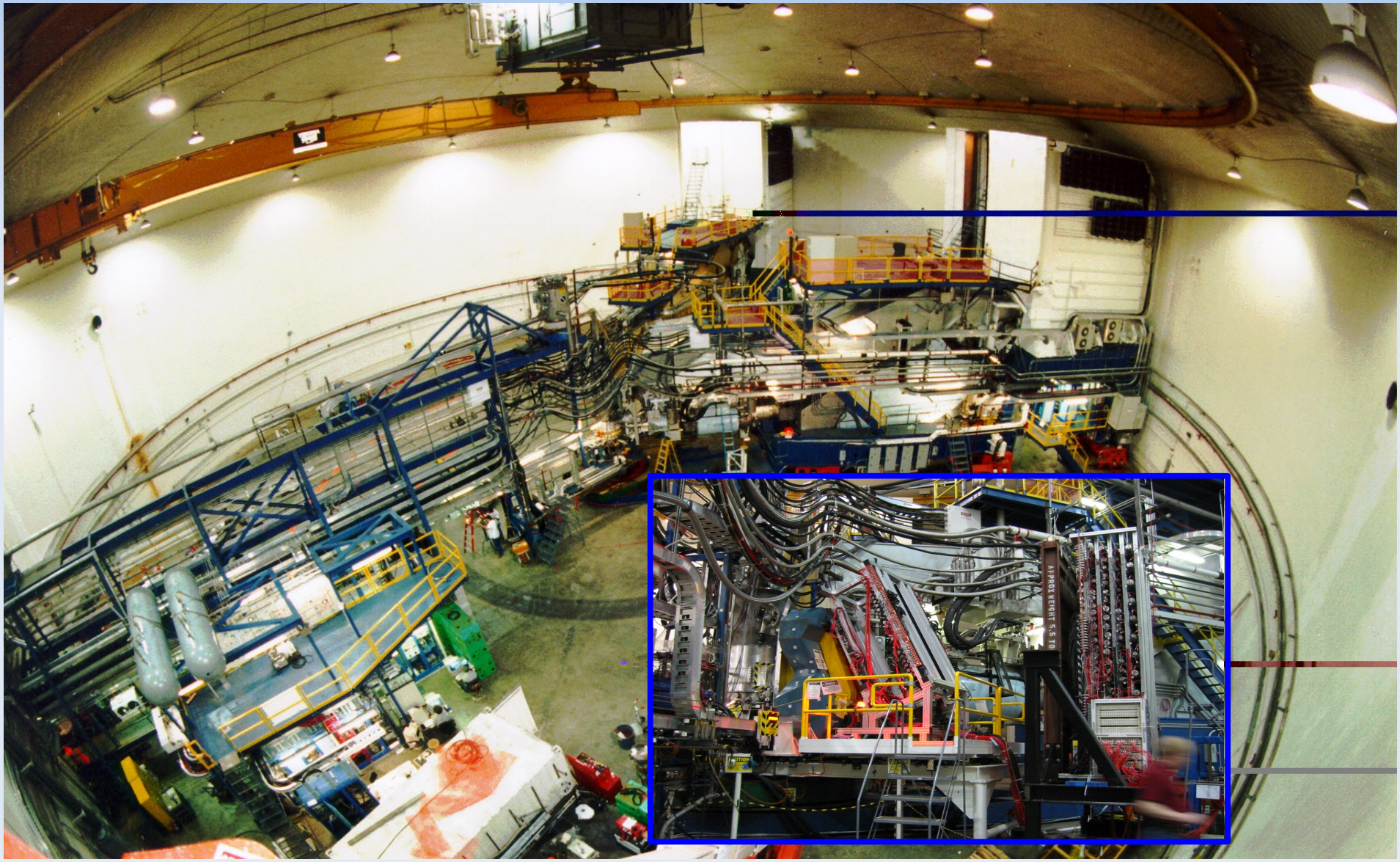
Physicists Tend To Fill Empty Space©



©D. Higinbotham

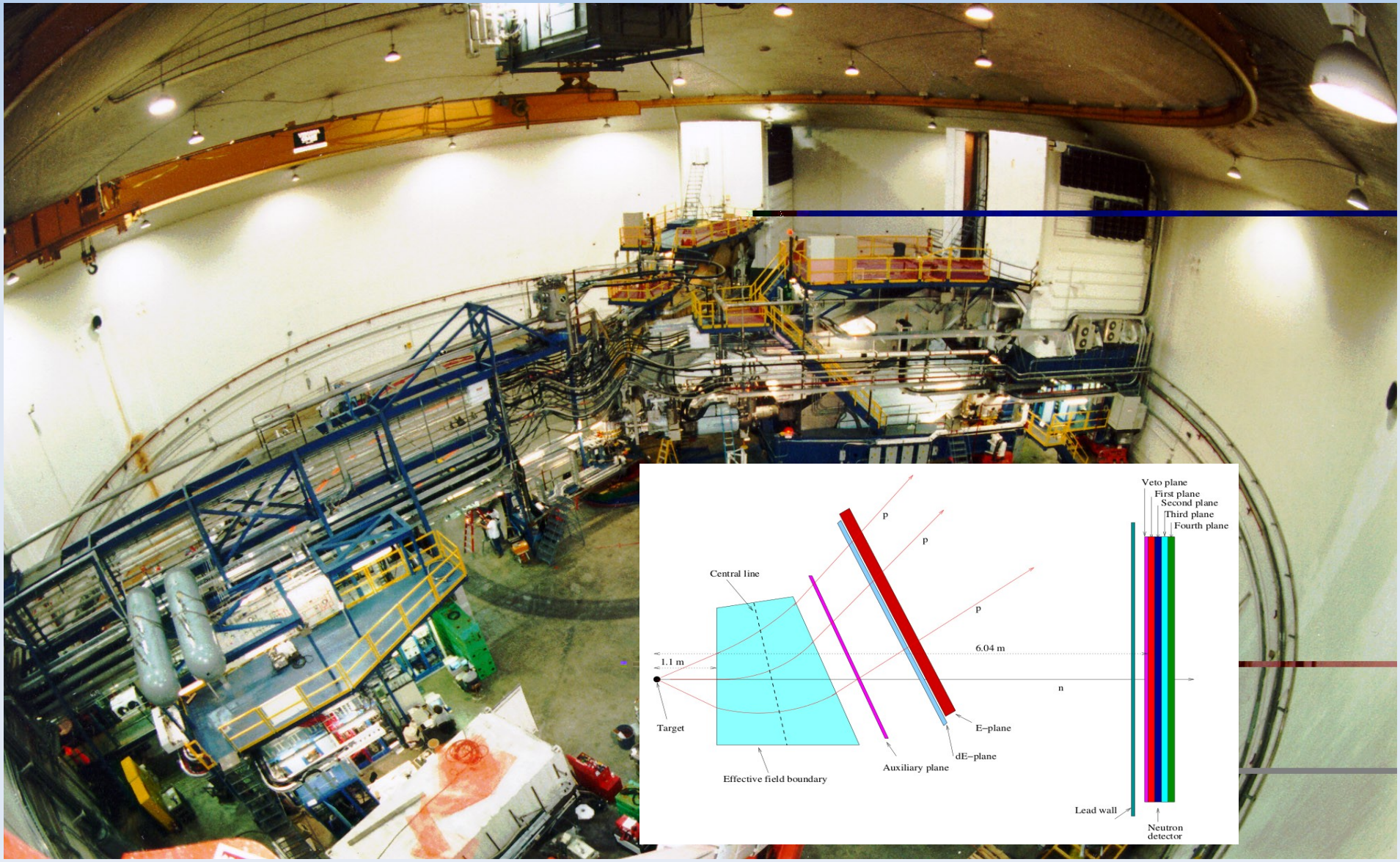
JLab Hall-A E01-015

Physicists Tend To Fill Empty Space©



JLab Hall-A E01-015

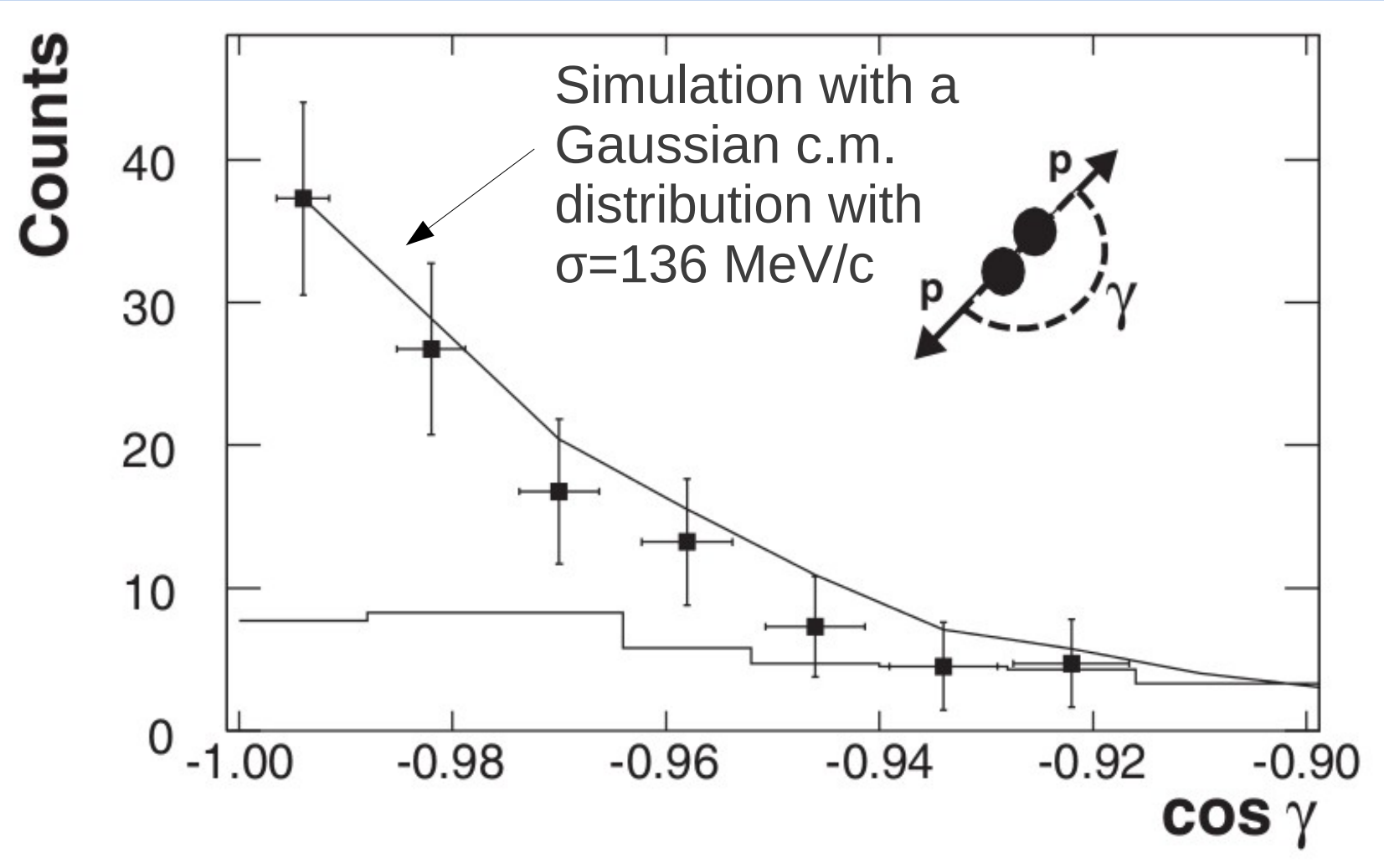
Physicists Tend To Fill Empty Space©



JLab Hall-A E01-015

[^{12}C(e,e'pp) Opening Angle]

Clear Back-to-Back correlation between $p_{initial}$ and p_{recoil}!



R. Shneor et al., Phys. Rev. Lett. **99**, 072501 (2007)

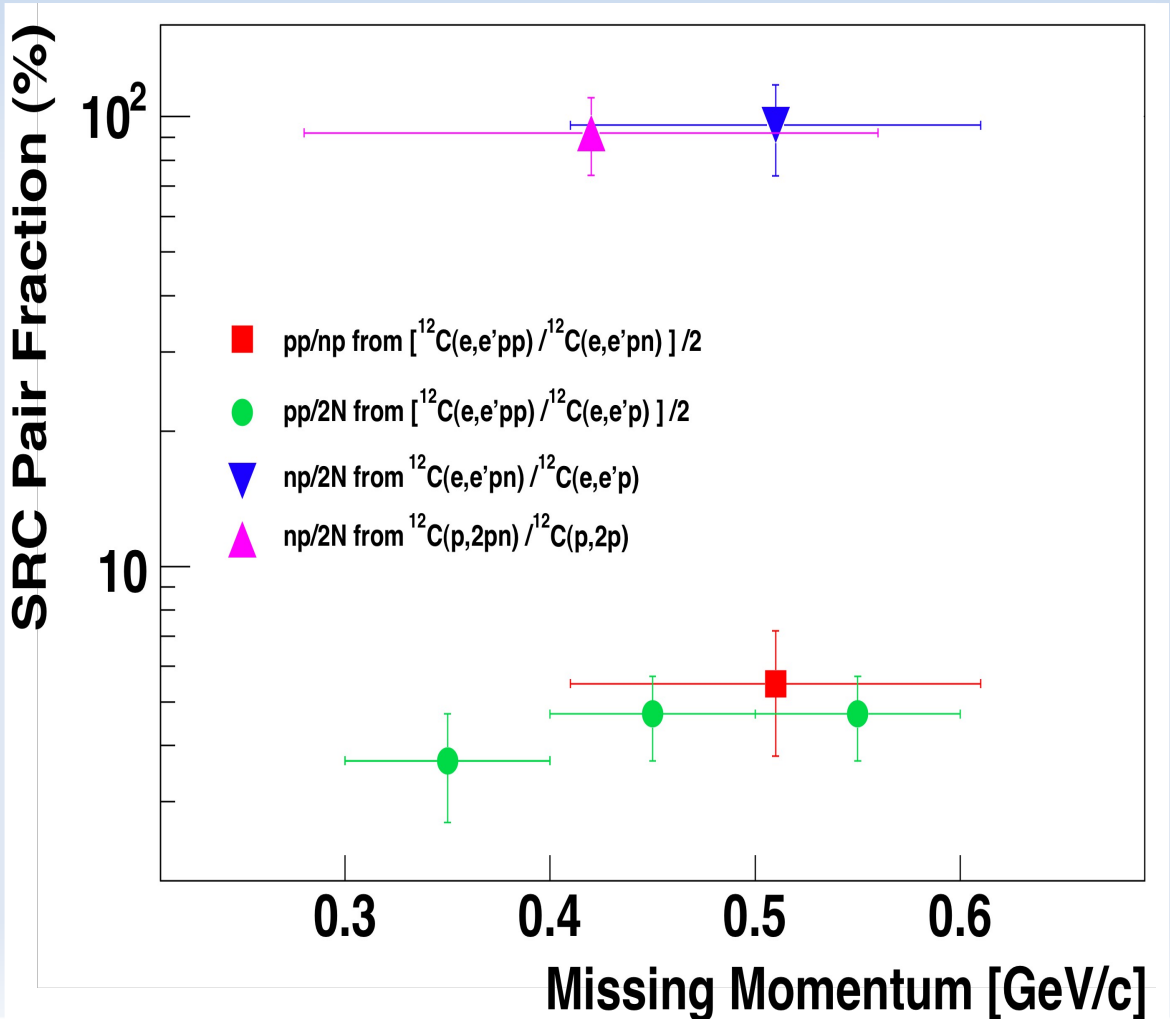
JLab Hall-A E01-015

[pn and pp SRC Probabilities and the pp/np ratio]

- The (e,e'pN)/(e,e'p) ratio gives the probability for a high momentum proton to be part of a pN-SRC pair.

- All high $p_{initial}$ protons have a correlated partner
- np pairs dominate

  Importance of tensor force at $0.3<p_{initial}<0.6$ GeV/c



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

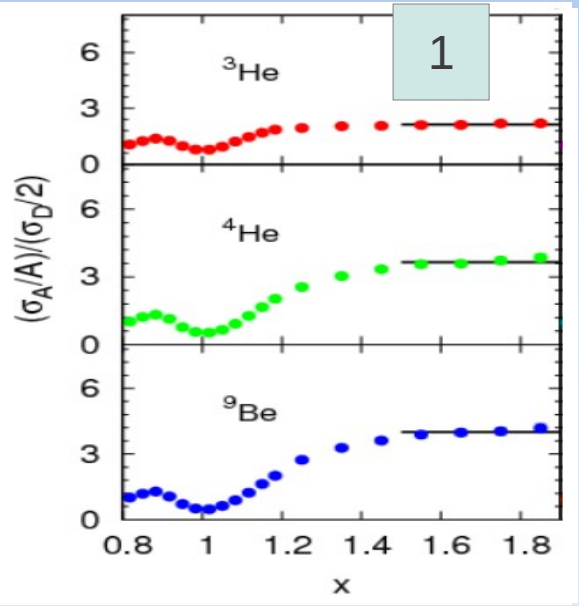
2N-SRC from inclusive and exclusive measurements

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

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

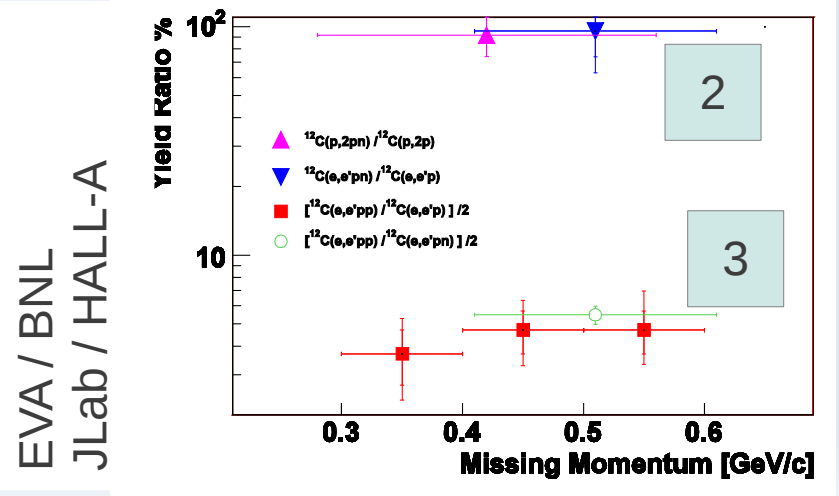
1 2N-SRC dominated by np pairs

→ **Tensor interaction**



1
2

~80% of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.



Ongoing Inclusive and Exclusive Analysis

Inclusive Analysis, E08-014 (Hall-A 2011):

1) Study the IsoSpin structure of 2N-SRC by comparing ^{40}Ca to ^{48}Ca
2) Study the Q^2 Dependence of the 3N-SRC plateau

Exclusive Analysis

1) E07-006 (2011): Second generation Hall-A measurements on ^{4}He.

   Pushing towards the repulsive core of the nucleon-nucleon interaction @ $400 \leq P_{miss} \leq 750$ MeV/c

2) Hall-B Data Mining Project

Ongoing Inclusive and Exclusive Analysis

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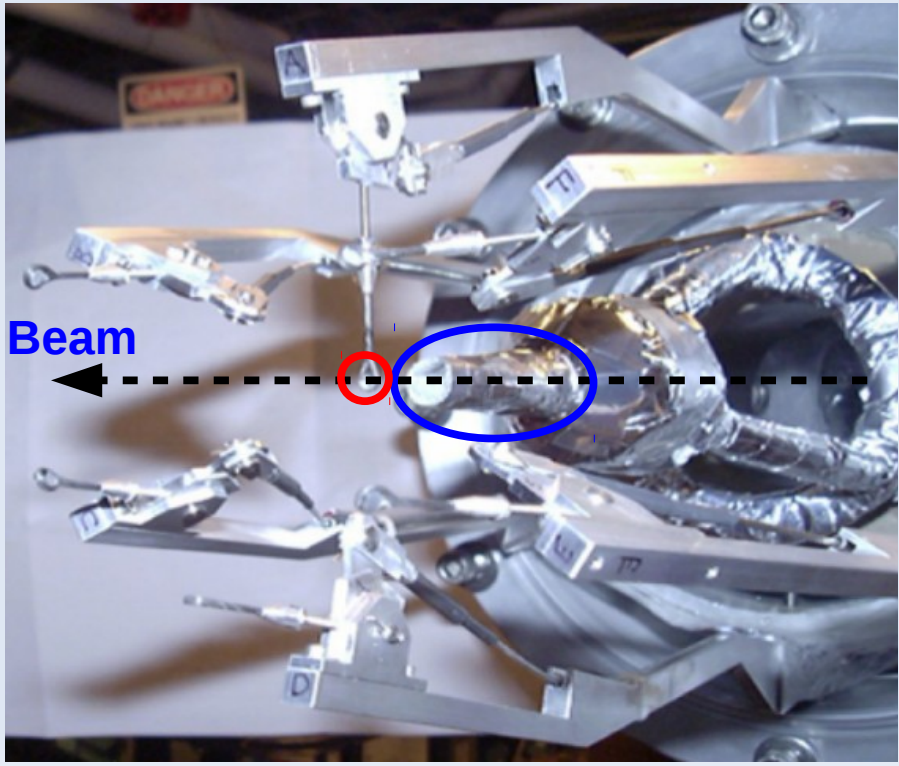
2) ***Hall-B Data Mining Project***

Hall-B Data Mining Project

“Short Distance Structure of Nuclei: Mining the Wealth of Existing Jefferson Lab Data”

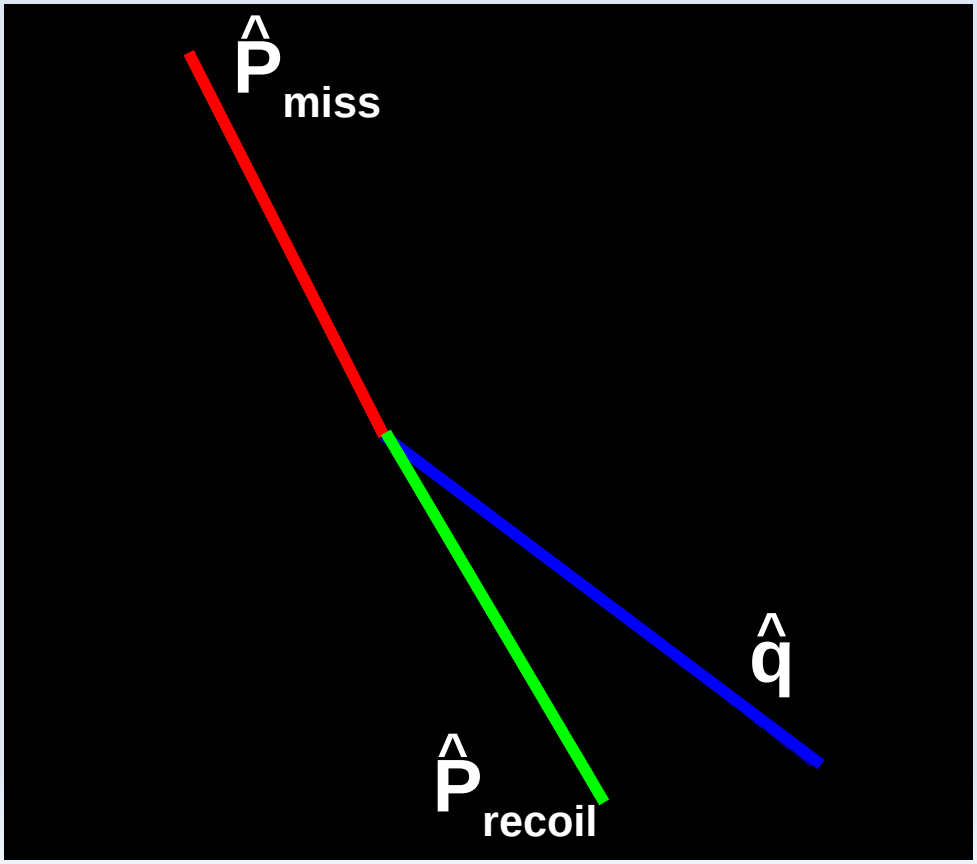
Current analysis focuses on the EG2 data-set:

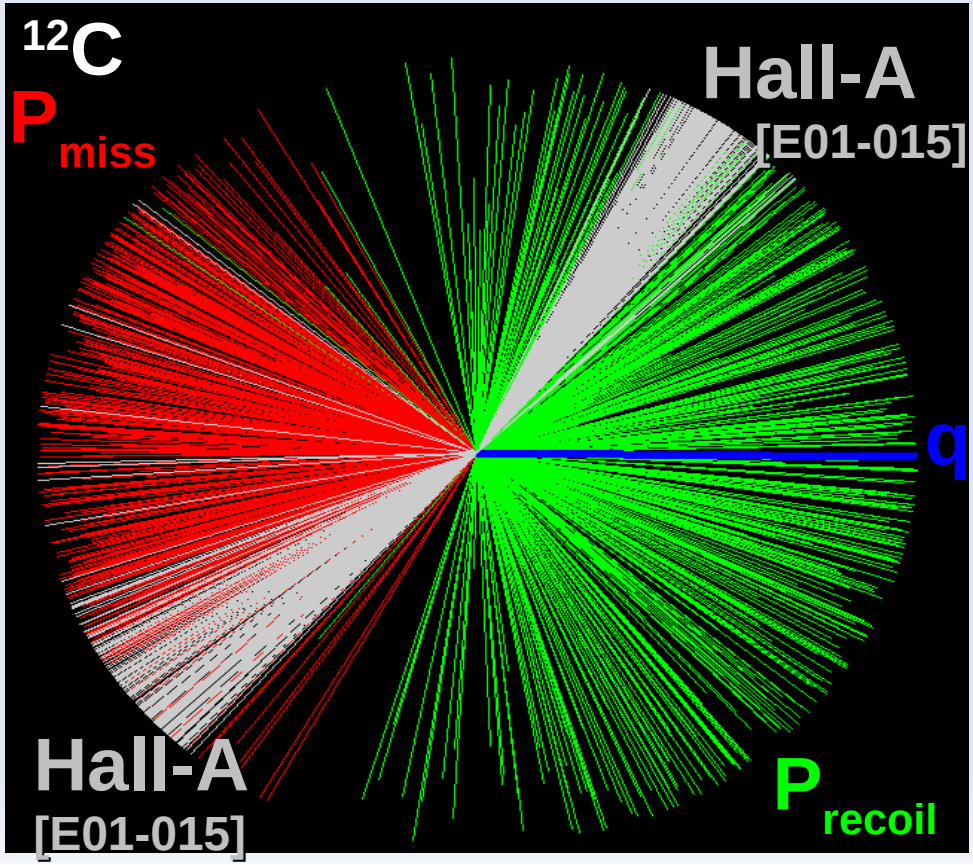
- A double solid+deuterium target set-up
- Open inclusive (e,e') trigger
- Run in 2004. Full CLAS calibration and PID schemes are available
- Previous analysis already passed the Hall-B publication committees



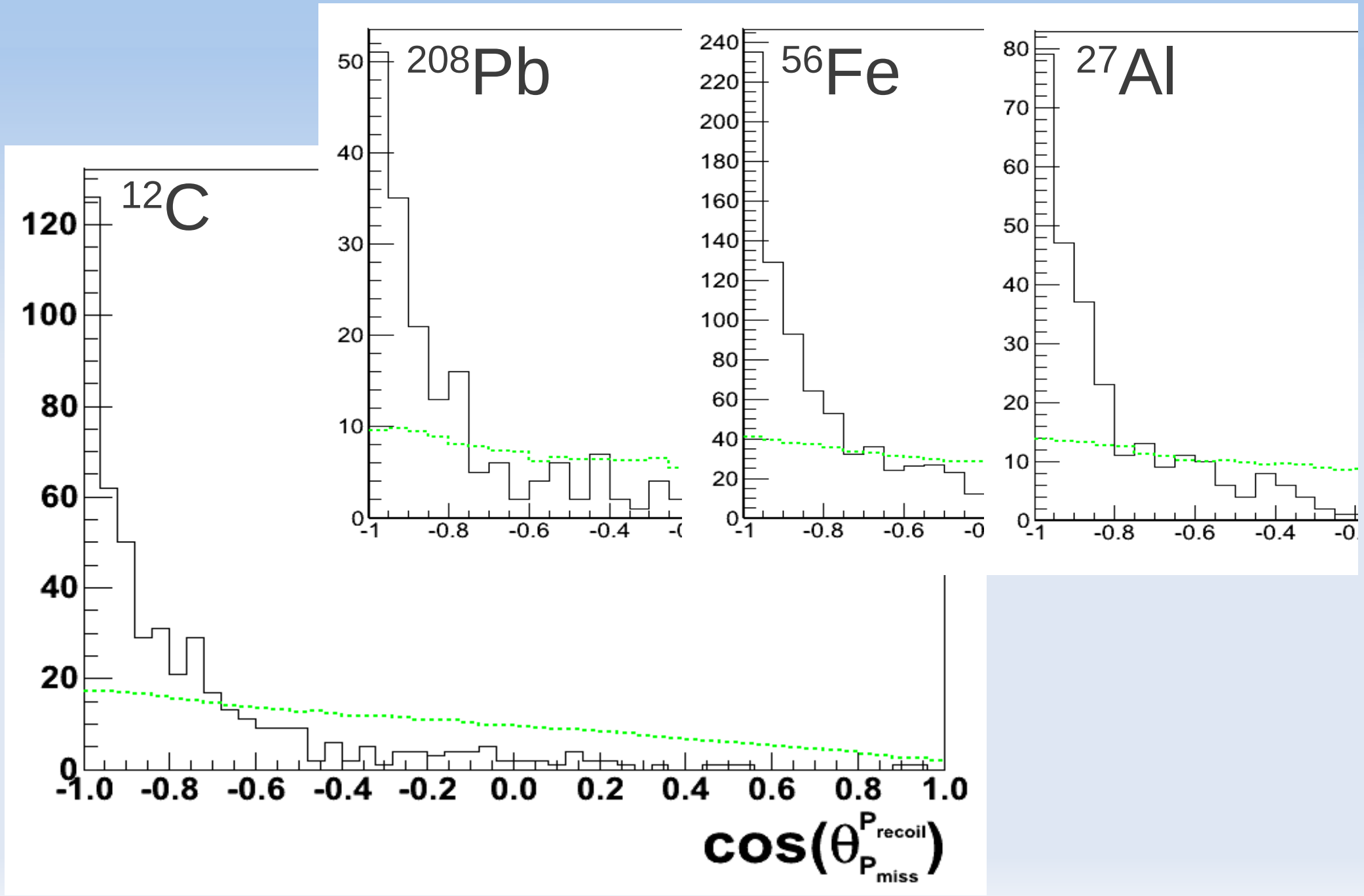
Data Mining: Exclusive pp-SRC

- Study pp-SRC in ^{12}C, ^{27}Al, ^{56}Fe, and ^{208}Pb nuclei
- EG2 data-set covers an (e,e'p) missing momentum range of 300~900 MeV/c
- Anti-Parallel, high Q^2, x_B>1.2 kinematics

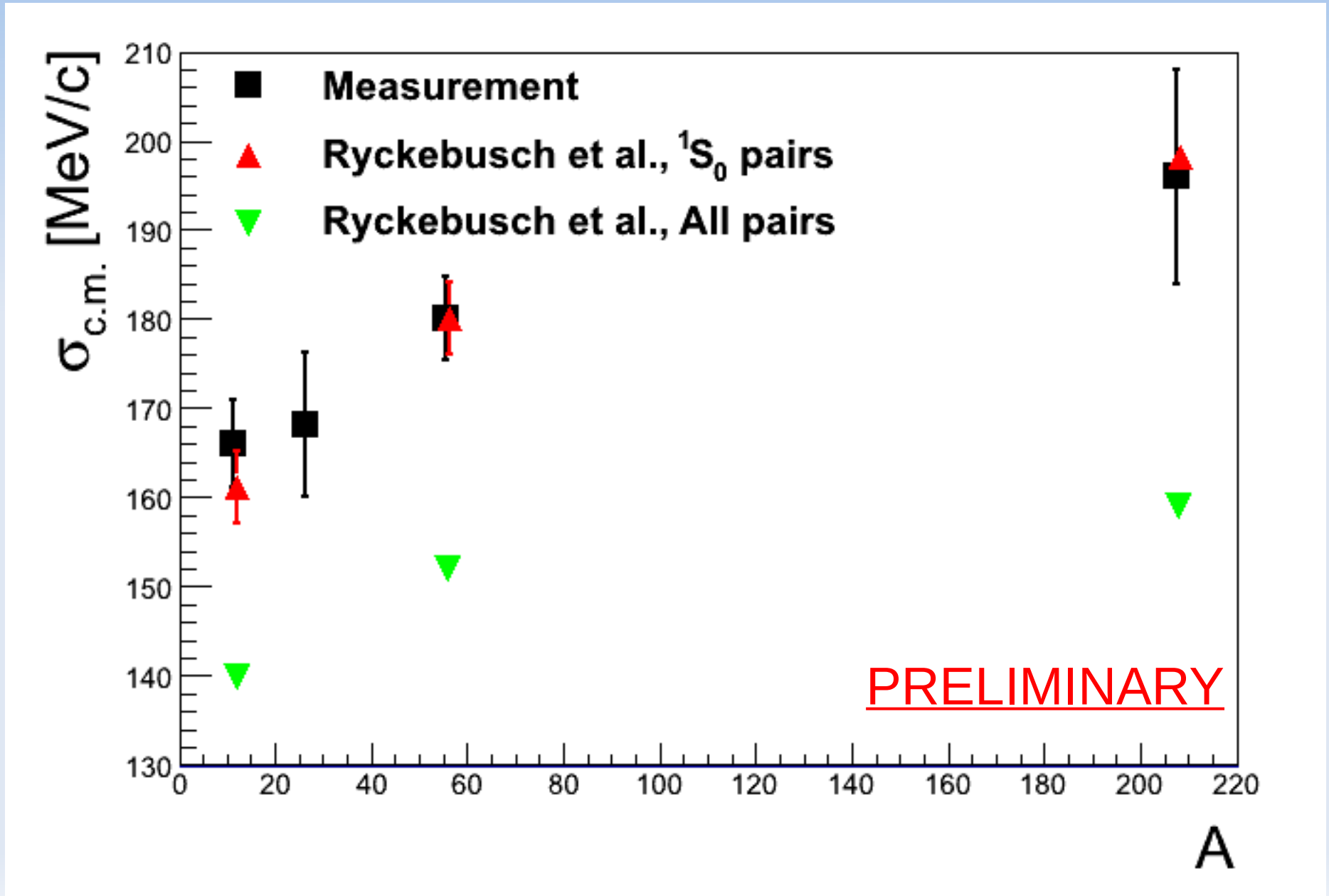




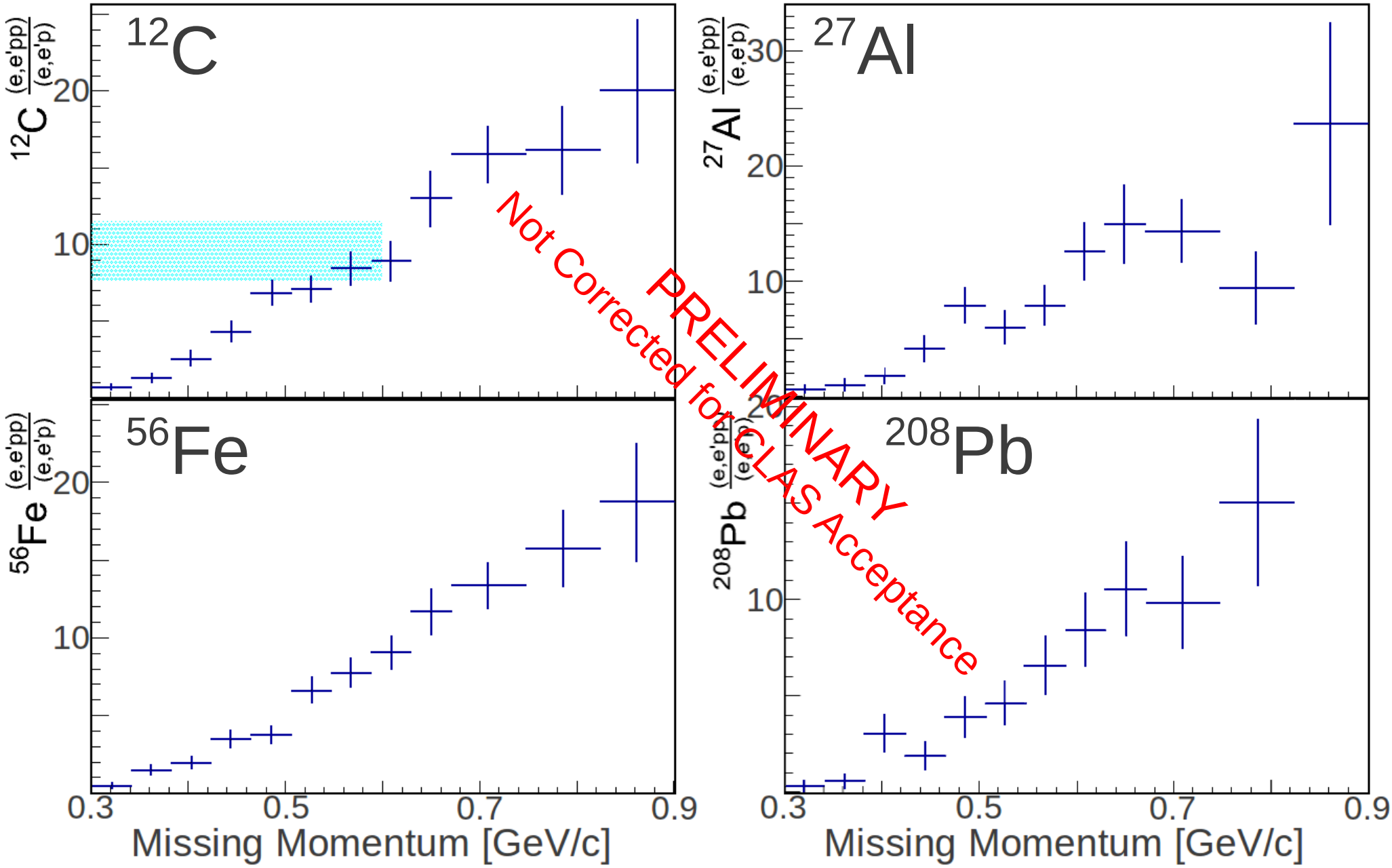
Opening angle Distribution



A dependence of the pp-SRC c.m. momentum distribution



pp-SRC Probabilities



2N-SRC (Even Before 12GeV)

IsoSpin Structure at high P_{miss}

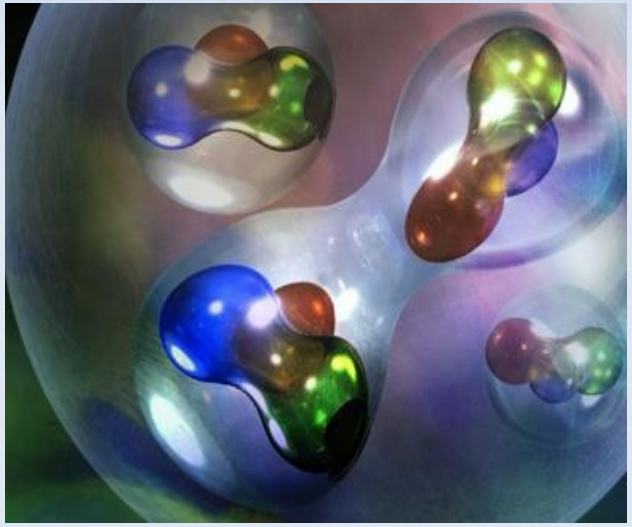
c.m. momentum distribution

SRC Universality

np-SRC Dominance ($^{40,48}Ca$)

High Precision 3N-SRC Probabilities

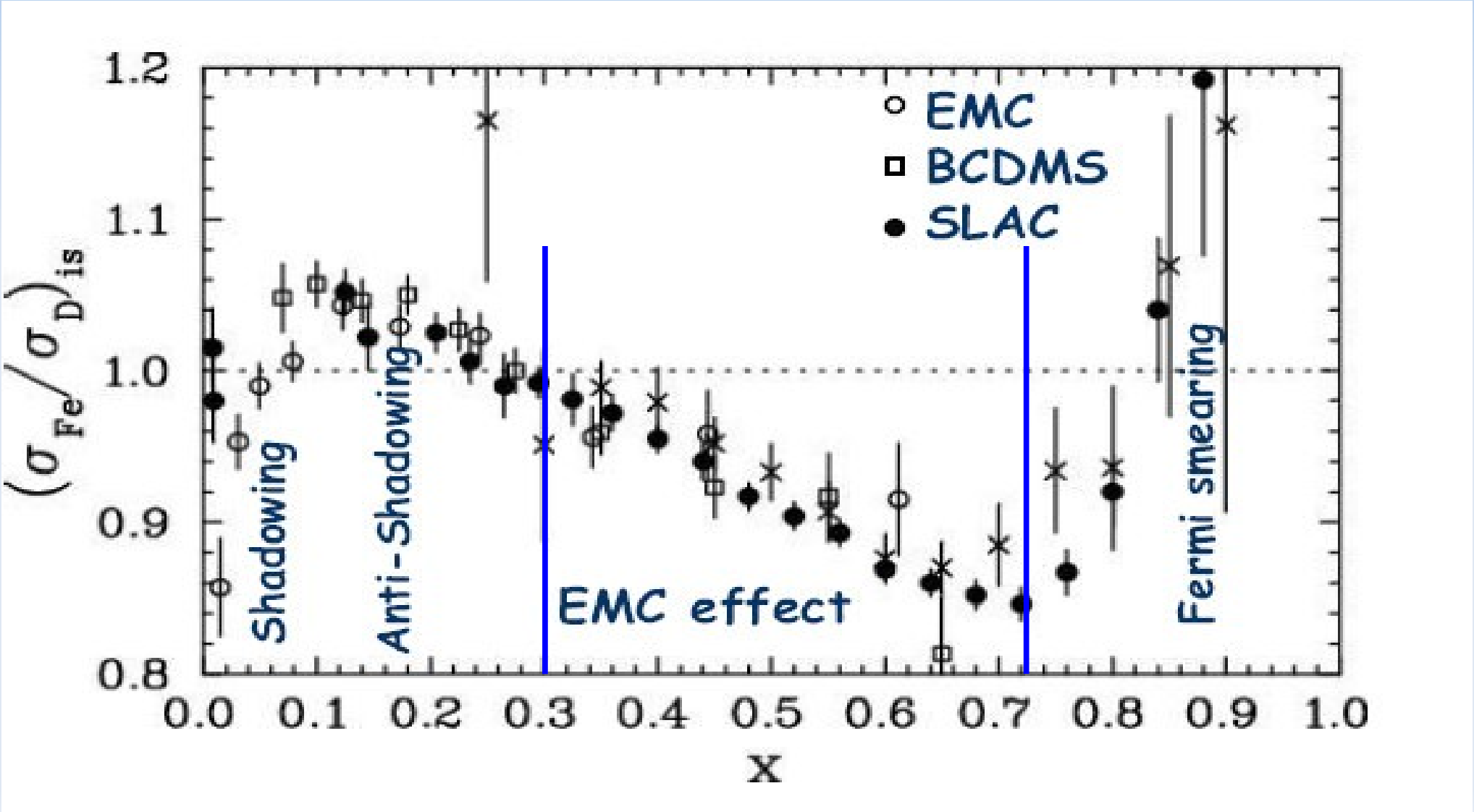
EMC Effect



DIS σ(e,e') A/d: The EMC Effect

Bound nucleon DIS ≠ Free nucleon DIS

30 years, ~1000 papers, no accepted explanation



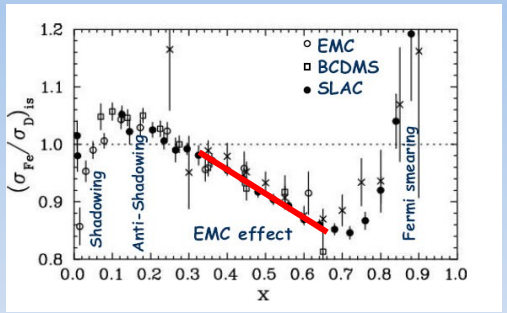
x is interpreted as momentum fraction of the struck quark

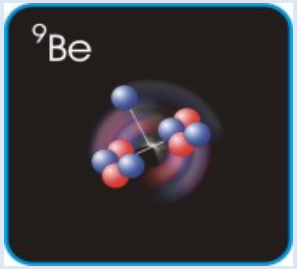
Hall-C Measurements in Light Nuclei

- Precise DIS measurements on light nuclei
- EMC does not scale as the average nuclear density

  → Not a bulk property

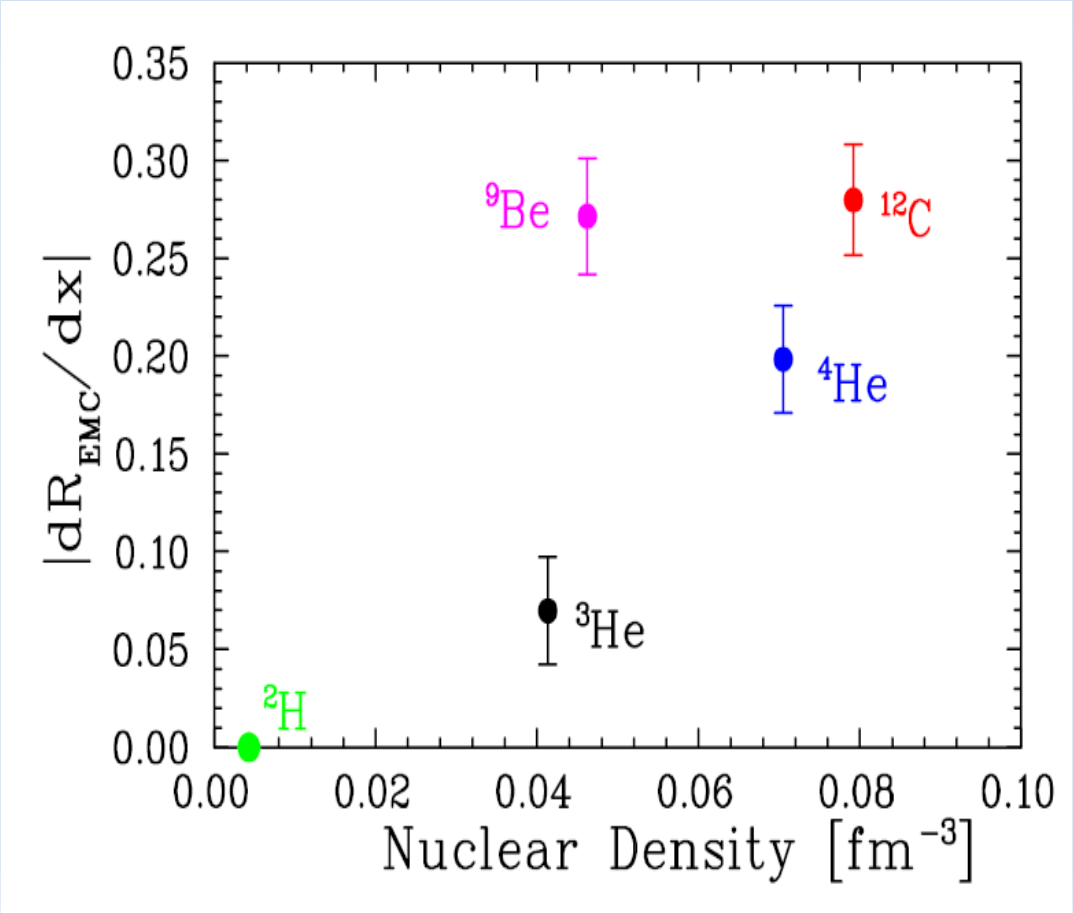
  of the nuclear medium





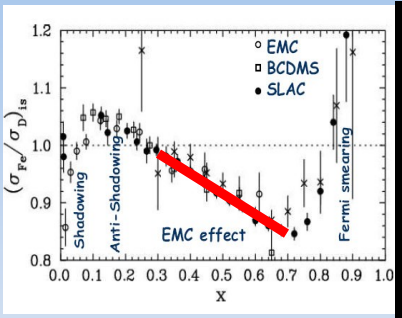
EMC IS A

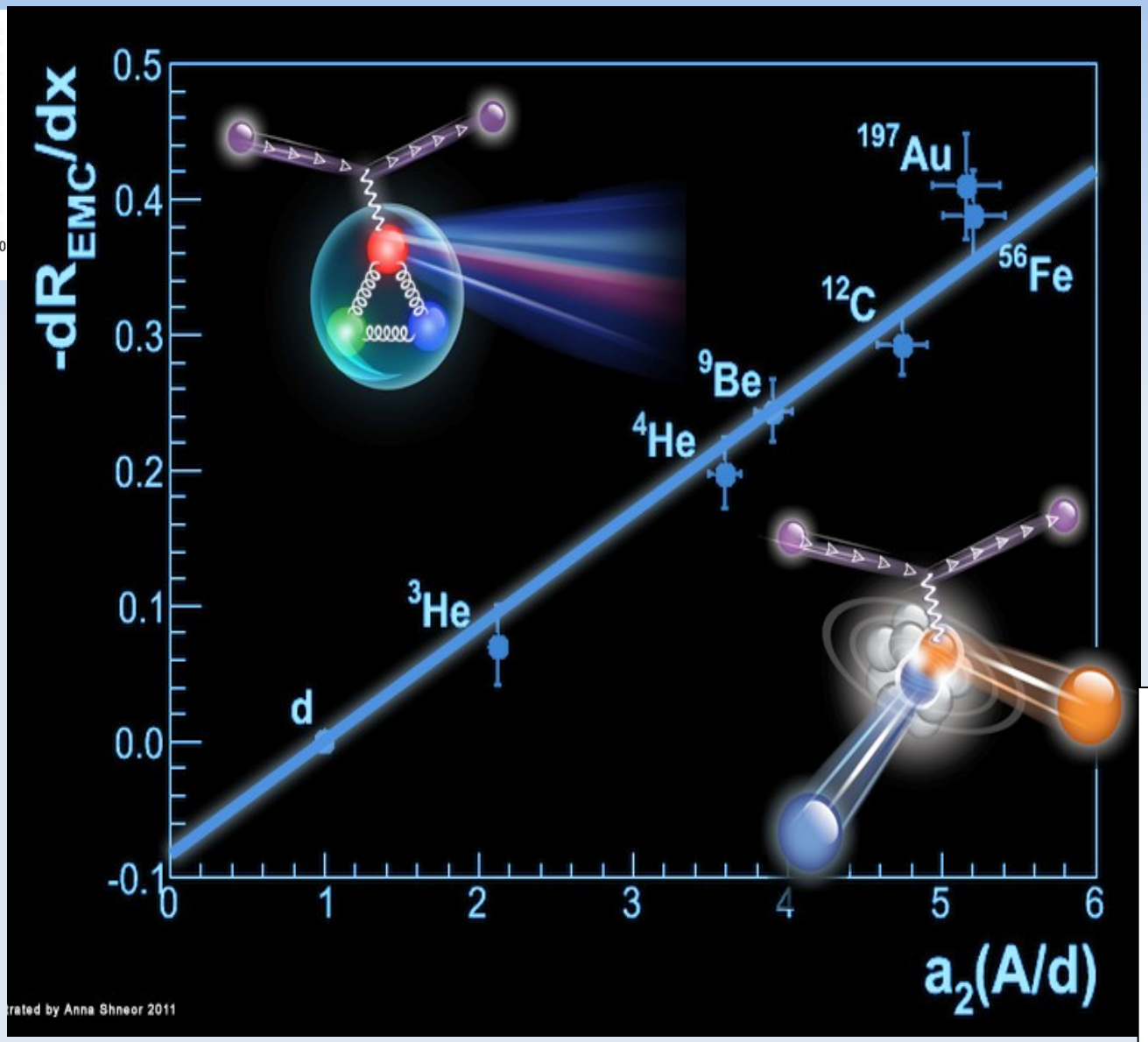
LOCAL EFFECT

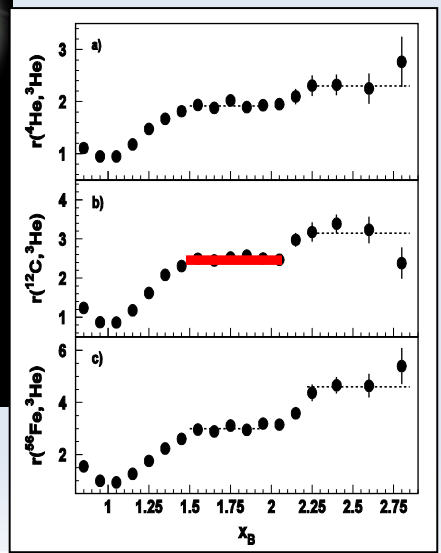


J. Seely et al. Phys. Rev. Lett. **103**, 202301 (2009)

EMC-SRC Correlation



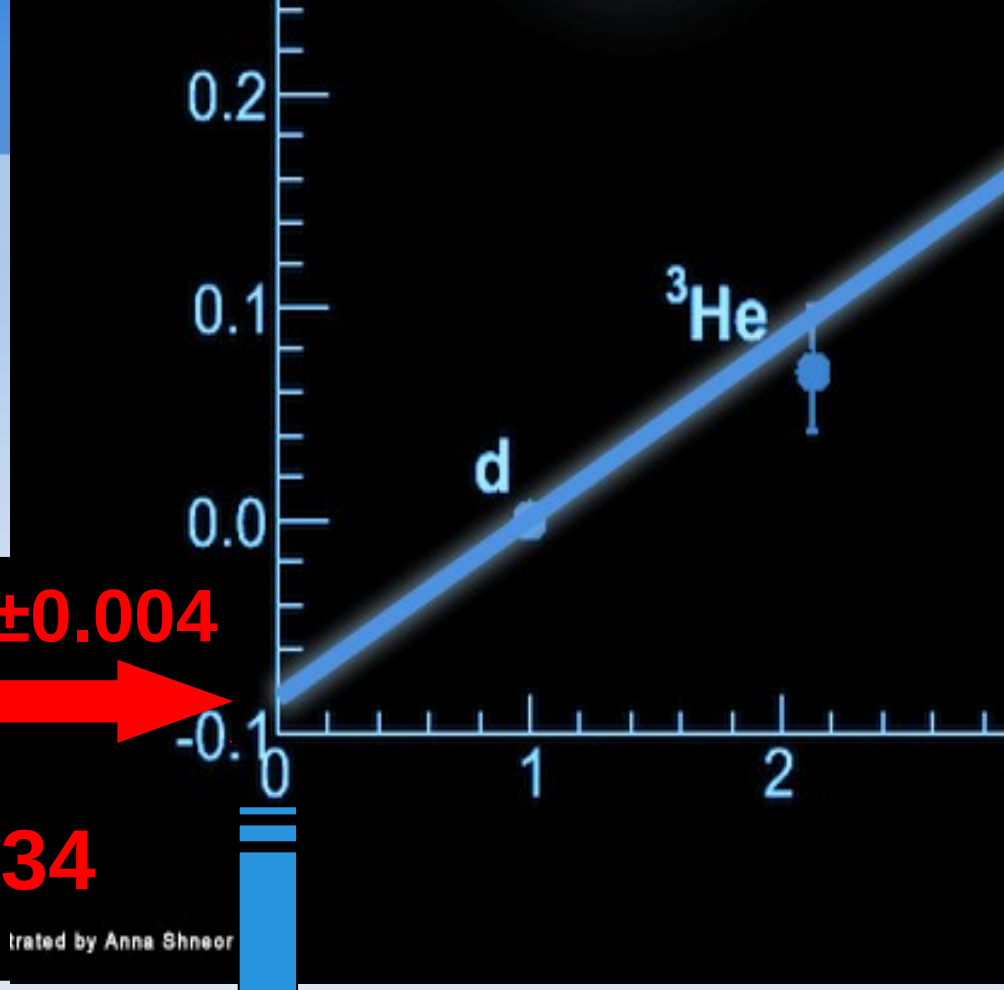




L. B. Weinstein et al., Phys. Rev. Lett. 106, 052301 (2011).
O. Hen, E. Piasetzky, and L. B. Weinstein, Phys. Rev. C **85**, 047301 (2012).

Deuteron IMC Effect:

$$\sigma_d \neq \sigma_n + \sigma_p$$



$$a = 0.084 \pm 0.004$$

$$\Downarrow$$

$$\frac{\sigma_n + \sigma_p}{\sigma_d}(x_B = 0.7) = 1.034$$

trated by Anna Shneor

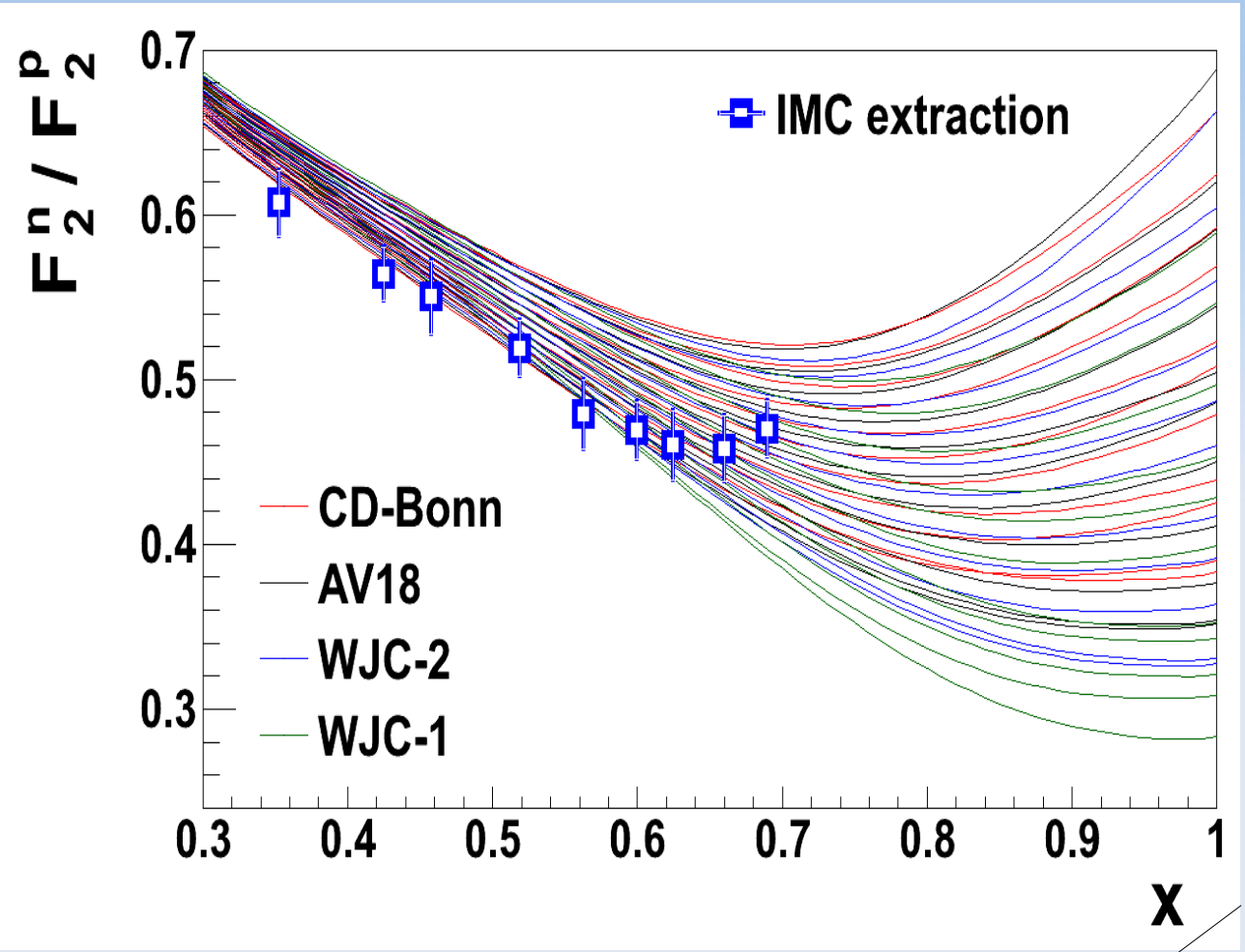
$$\Downarrow$$

SRC=0 → free nucleons

$$\Downarrow \quad \frac{F_2^n}{F_2^p} = \frac{2\,F_2^d / F_2^p}{1 - a(x_B - b)} - 1$$

L. B. Weinstein et al., Phys. Rev. Lett. 106, 052301 (2011).
O. Hen, E. Piasetzky, and L. B. Weinstein, Phys. Rev. C **85**, 047301 (2012).

IMC Constrain on d/u at $x_B \to 1$



$$\lambda = \left.\frac{\partial \Lambda^2}{\partial \log p^2}\right|_{p^2=M^2} = -2\frac{\delta R_N}{R_N}\frac{\delta p^2}{M^2},$$

Swelling Level

Average Nucleon Virtuality

Smearing Function

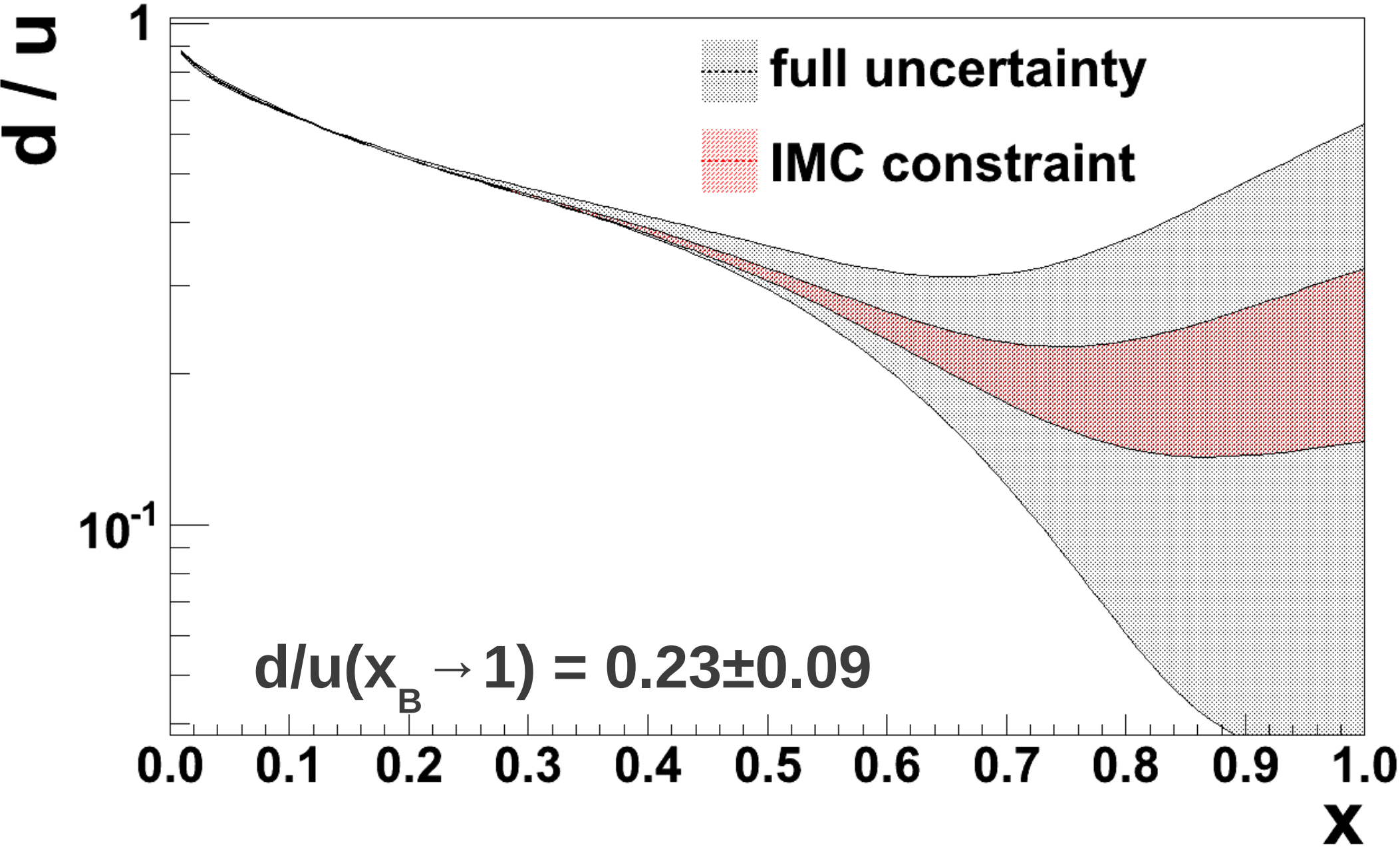
Free Nucleon S.F.

Off-Shell Correction

$$F_{2d}(x_B) = \int_{x_B}^{A} dy S_A(y,\gamma,x_B) F_2^{TMC+HT}(x_B/y, Q^2)\left(1 + \frac{\delta^{\text{off}} F_2(x)}{F_2(x)}\right)$$

O. Hen, A. Accardi, W. Melnitchouk, and E. Piasetzky, Phys. Rev. D **84**, 117501 (2011).

IMC Constrain on d/u at $x_B \rightarrow 1$



O. Hen, A. Accardi, W. Melnitchouk, and E. Piasetzky, Phys. Rev. D **84**, 117501 (2011).

SRC @ 12GeV

Inclusive measurements

- Hall-C program to study both EMC effect and SRC scaling plateaus is a wide verity of nuclei:

  ^{3,4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{12}C, ^{48,40}Ca, ^{63}Cu, ^{197}Au

  - Study the nuclear dependence of both the EMC effect and 2N-SRC and their correlation

- Hall-A measurements of both the EMC effect and SRC scaling plateaus in ^{3}He and ^{3}H

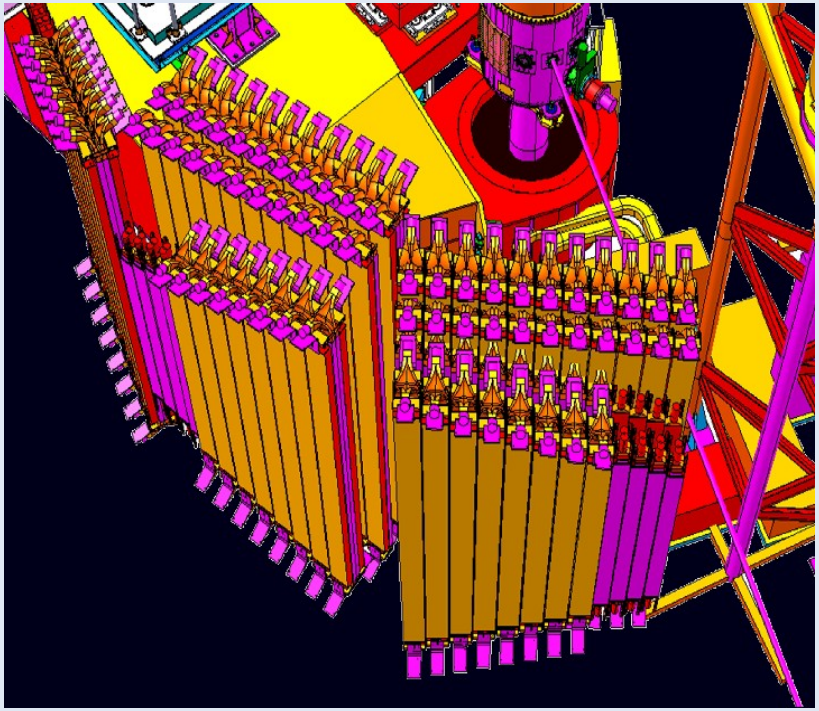
  - Study the IsoSpin dependence of 2N-SRC
  - ^{3}He/^{3}H DIS ratios will be used to extract F_2^n/F_2^p

J. Arrington and D. Day, Experiment No. **E12-06-105**
P. Solvignon-Slifer and J. Arrington, Experiment No. **E12-11-112**
J. Arrington, D. Gaskell, and A. Daniel, Experiment No. **E12-10-008**
G. G. Petratos, J. Gomez, R. J.Holt, and R. D. Ransome, Experiment Proposal No. **C12-10-103**

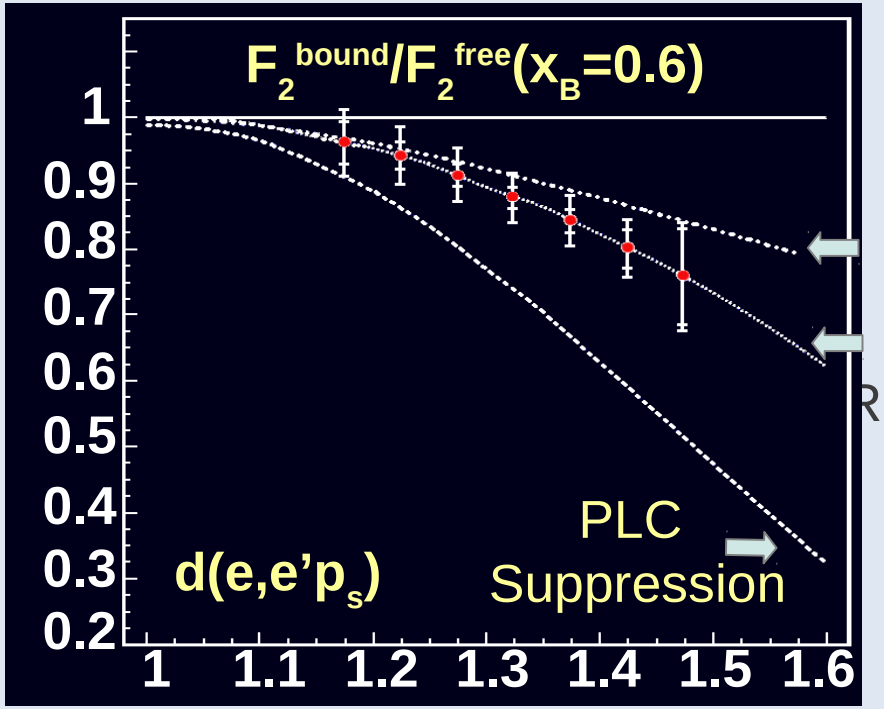
Semi-Inclusive Measurement

- Study the DIS d(e,e'N_{recoil}) reaction tagged by high momentum backwards recoil nucleons
  - Study the virtuality dependence of the proton and neutron structure functions

LAD Detector:



Projected Uncertainties:



Binding/
Off-Shell

Rescaling
Model

O. Hen, L. Weinstein, S. Wood, and S. Gilad, In medium nucleon structure functions, SRC, and the EMC effect, Experiment No. **E12-11-107**

Future SRC Studies @ 12GeV

Quark Distribution Modification in Nuclei

3N-SRC

Non-Nucleonic Degrees of Freedom

Momentum Distributions of SRC pairs

Why 12GeV?

High Statistics
High Nucleon Momentum
High Momentum Transfer

Thank You!

Robustness against different theoretical corrections

Correction "Bank":

1. Radiative Corrections
2. ISO Corrections
3. c.m. Corrections
4. Coulomb Corrections
5. Inelastic Subtraction

Nucleus	Egiyan *et al.* [12]	EMC-SRC prediction [8]	Fomin *et al.* [18] (analysis as in Ref. [12])	Fomin *et al.* [18]	Fomin *et al.* [18] (excluding the c.m. motion correction)	SLAC [10][a]	EMC slope [8] dR_{EMC}/dx
^{3}He	1.97 ± 0.10[b]		1.87 ± 0.06	1.93 ± 0.10	2.13 ± 0.04	1.7 ± 0.3	-0.070 ± 0.029
^{4}He	3.80 ± 0.34		3.64 ± 0.07	3.02 ± 0.17	3.60 ± 0.10	3.3 ± 0.5	-0.197 ± 0.026
^{9}Be		4.08 ± 0.60	4.15 ± 0.09	3.37 ± 0.17	3.91 ± 0.12		-0.243 ± 0.023
^{12}C	4.75 ± 0.41		4.81 ± 0.10	4.00 ± 0.24	4.75 ± 0.16	5.0 ± 0.5	-0.292 ± 0.023
^{56}Fe(^{63}Cu)	5.58 ± 0.45		5.29 ± 0.12	4.33 ± 0.28	5.21 ± 0.20	5.2 ± 0.9	-0.388 ± 0.032
^{197}Au		6.19 ± 0.65	5.29 ± 0.16	4.26 ± 0.29	5.16 ± 0.22	4.8 ± 0.7	-0.409 ± 0.039
EMC-SRC slope a	0.079 ± 0.006		0.082 ± 0.004	0.106 ± 0.006	0.084 ± 0.004		
$\frac{\sigma(n+p)}{\sigma_d}\|_{x_B=0.7}$	1.032 ± 0.004		1.033 ± 0.004	1.043 ± 0.005	1.034 ± 0.004		
χ^2/ndf	$0.7688/3$		$4.742/5$	$4.078/5$	$4.895/5$		
	1,2		1,2	1,3,4,5	1,4,5		

O. Hen, E. Piasetzky, and L. B. Weinstein, Phys. Rev. C **85**, 047301 (2012).

Robustness against different theoretical corrections

Correction "Bank":

1. Radiative Corrections
2. ISO Corrections
3. c.m. Corrections
4. Coulomb Corrections
5. Inelastic Subtraction

Nucleus	Egiyan *et al.* [12]	EMC-SRC prediction [8]	Fomin *et al.* [18] (analysis as in Ref. [12])	Fomin *et al.* [18]	Fomin *et al.* [18] (excluding the c.m. motion correction)	SLAC [10][a]	EMC slope [8] dR_{EMC}/dx
^{3}He	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	0.070 ± 0.029
^{4}He							[illegible]97 ± 0.026
^{9}Be							[illegible]43 ± 0.023
^{12}C	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]92 ± 0.023
^{56}Fe(^{63}Cu)	5.58 ± 0.45		[illegible] ± 0.12	4.33 ± 0.28	5.21 ± 0.20	5.2 ± 0.9	-0.388 ± 0.032
^{197}Au		6.19 ± 0.65	[illegible] ± 0.16	4.26 ± 0.29	5.16 ± 0.22	4.8 ± 0.7	-0.409 ± 0.039
EMC-SRC slope a	0.079 ± 0.006		[illegible]82 ± 0.004	0.106 ± 0.006	0.084 ± 0.004		
$\frac{\sigma(n+p)}{\sigma_d}\|_{x_B=0.7}$	1.032 ± 0.004		1.033 ± 0.004	1.043 ± 0.005	1.034 ± 0.004		
χ^2/ndf	$0.7688/3$		$4.742/5$	$4.078/5$	$4.895/5$		
	1,2		1,2	1,3,4,5	1,4,5		

χ^2/ndf 0.7688/3 4.742/5 4.078/5 4.895/5

O. Hen, E. Piasetzky, and L. B. Weinstein, Phys. Rev. C **85**, 047301 (2012).

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Nucleus	Egiyan *et al.* [12]	EMC-SRC prediction [8]	Fomin *et al.* [18] (analysis as in	Fomin *et al.* [18]	Fomin *et al.* [18] (excluding the c.m.	SLAC [10][a]	EMC slope [8] dR_{EMC}/dx
EMC-SRC slope a	0.079 ± 0.006			0.082 ± 0.004	0.106 ± 0.006	0.084 ± 0.004	
^{3}He							$.070 \pm 0.029$
^{4}He	3.80 ± 0.34		3.64 ± 0.07	3.02 ± 0.17	3.60 ± 0.10	3.3 ± 0.5	-0.197 ± 0.026
^{9}Be		4.08 ± 0.60	[illegible] ± 0.09	3.37 ± 0.17	3.91 ± 0.12		-0.243 ± 0.023
^{12}C	4.75 ± 0.41		[illegible] ± 0.10	4.00 ± 0.24	4.75 ± 0.16	5.0 ± 0.5	-0.292 ± 0.023
^{56}Fe(^{63}Cu)	5.58 ± 0.45		[illegible] ± 0.12	4.33 ± 0.28	5.21 ± 0.20	5.2 ± 0.9	-0.388 ± 0.032
^{197}Au		6.19 ± 0.65	5.29 ± 0.16	4.26 ± 0.29	5.16 ± 0.22	4.8 ± 0.7	-0.409 ± 0.039
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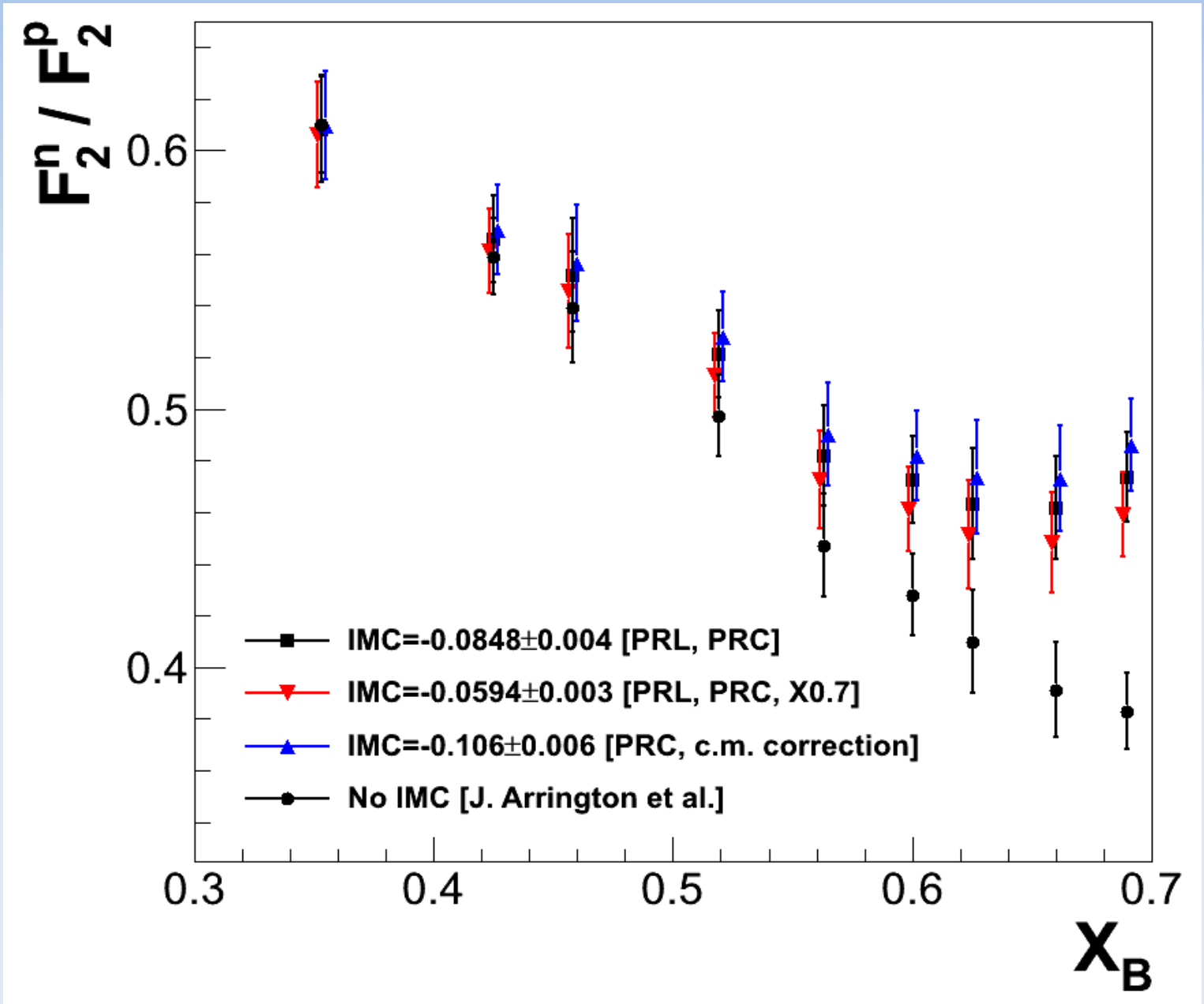
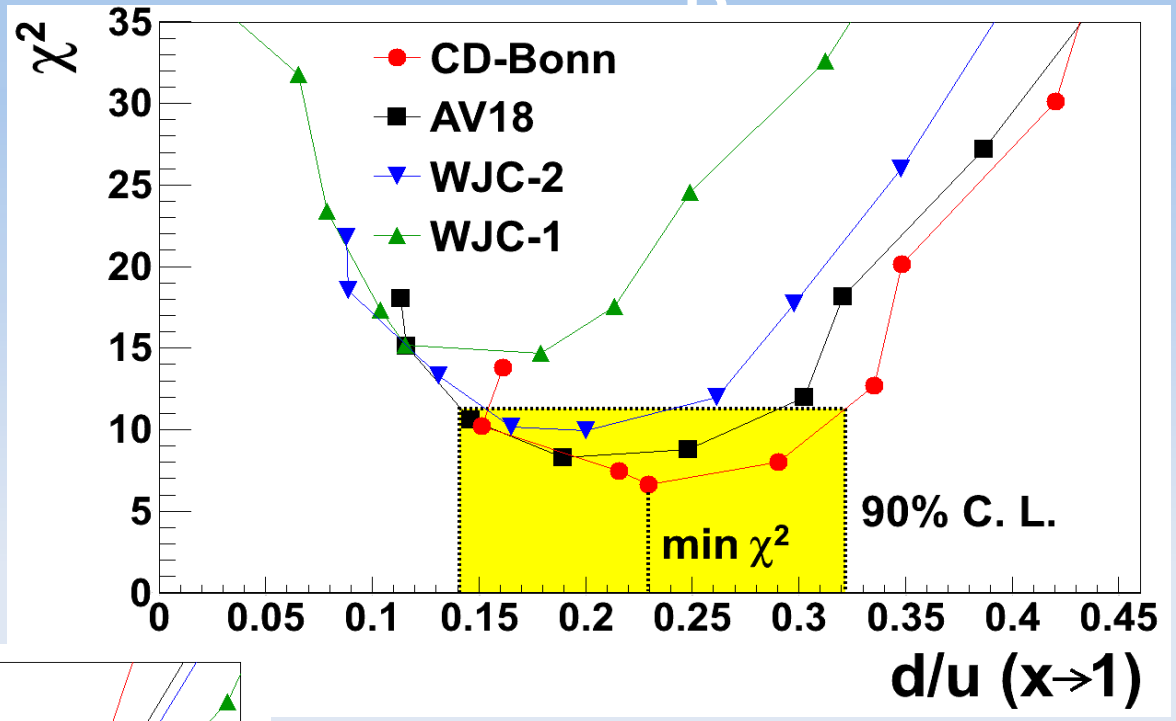
χ^2/ndf	$0.7688/3$		$4.742/5$	$4.078/5$	$4.895/5$		
	1,2		1,2	1,3,4,5	1,4,5		

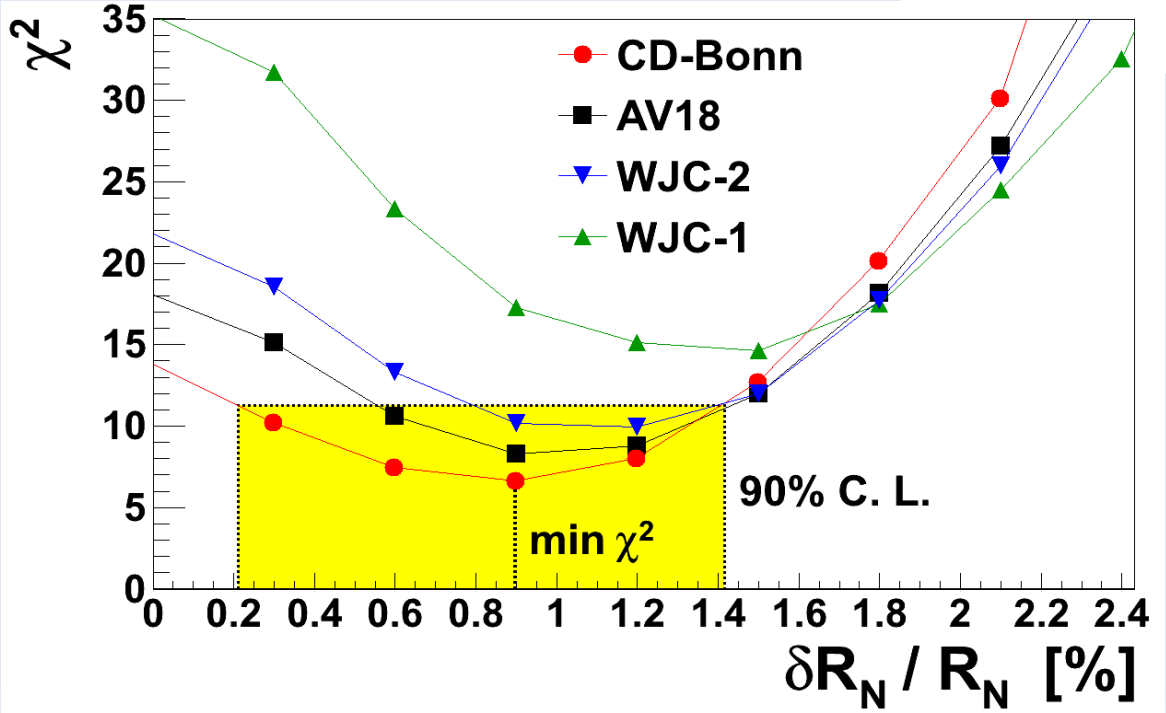
O. Hen, E. Piasetzky, and L. B. Weinstein, Phys. Rev. C **85**, 047301 (2012).

IMC Corrected F_2^n/F_2^p



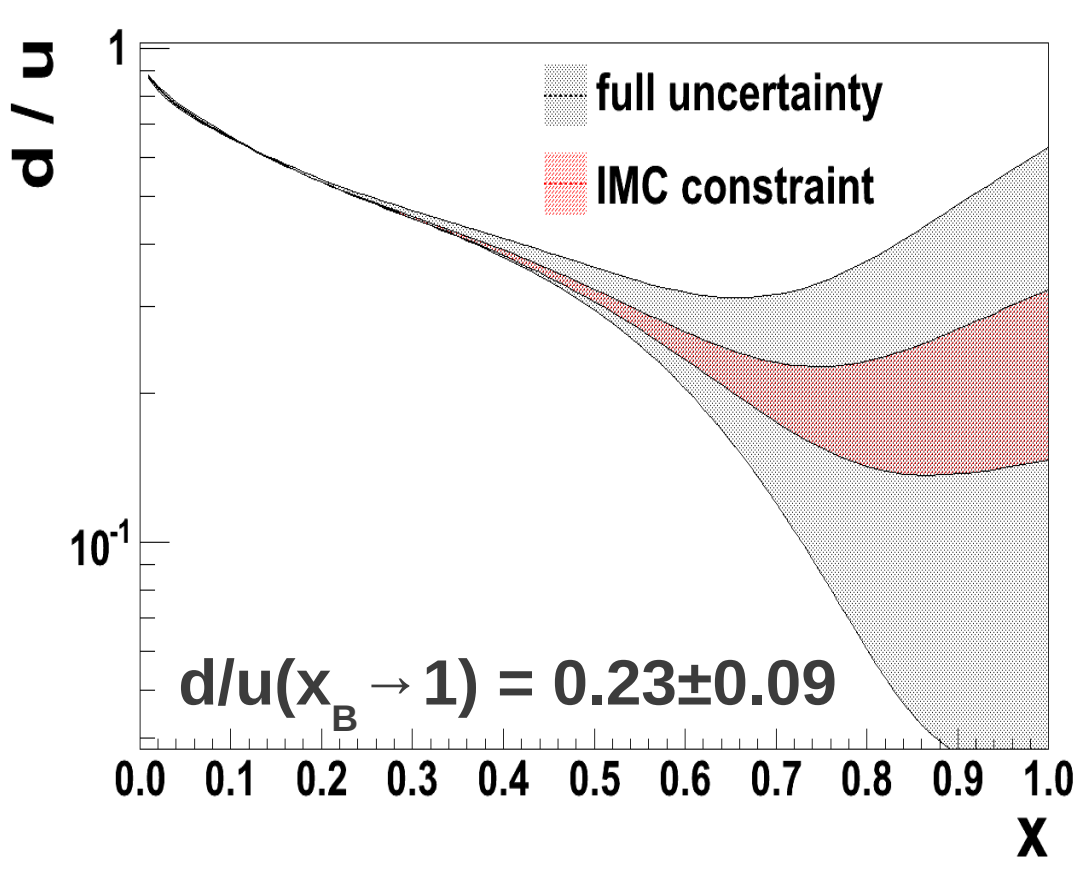
IMC Constrain on d/u at $x_B \rightarrow 1$

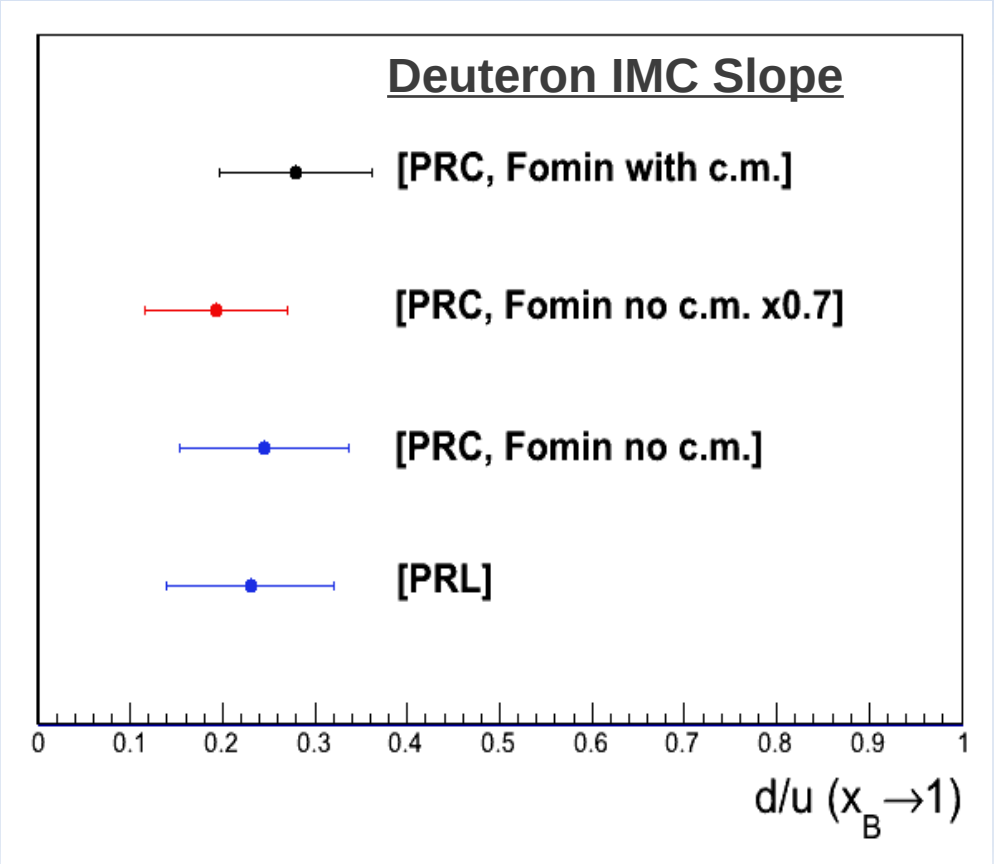




O. Hen, A. Accardi, W. Melnitchouk, and E. Piasetzky, Phys. Rev. D **84**, 117501 (2011).

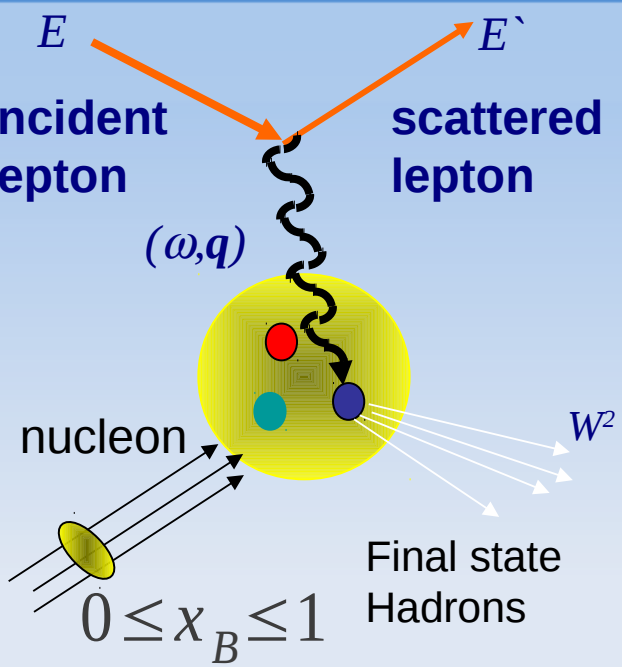
IMC Constrain on d/u at $x_B \rightarrow 1$





O. Hen, A. Accardi, W. Melnitchouk, and E. Piasetzky, Phys. Rev. D **84**, 117501 (2011).

Deep Inelastic Scattering (DIS)

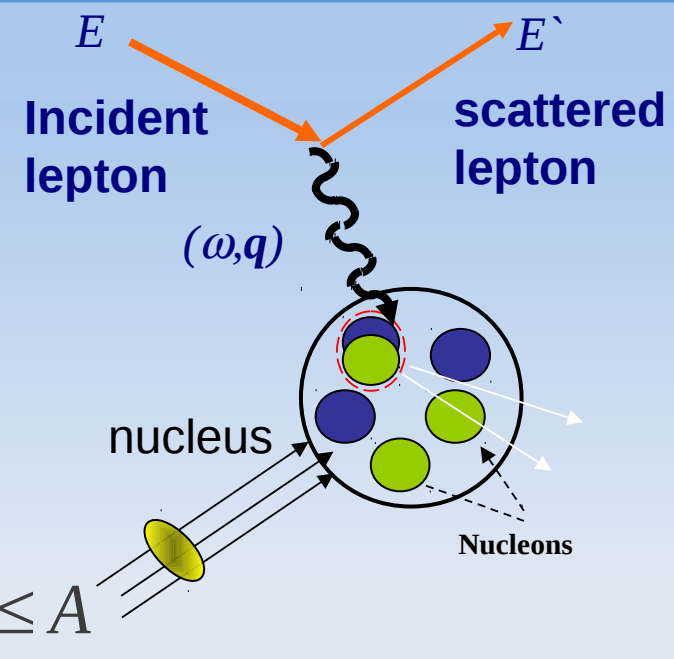


$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

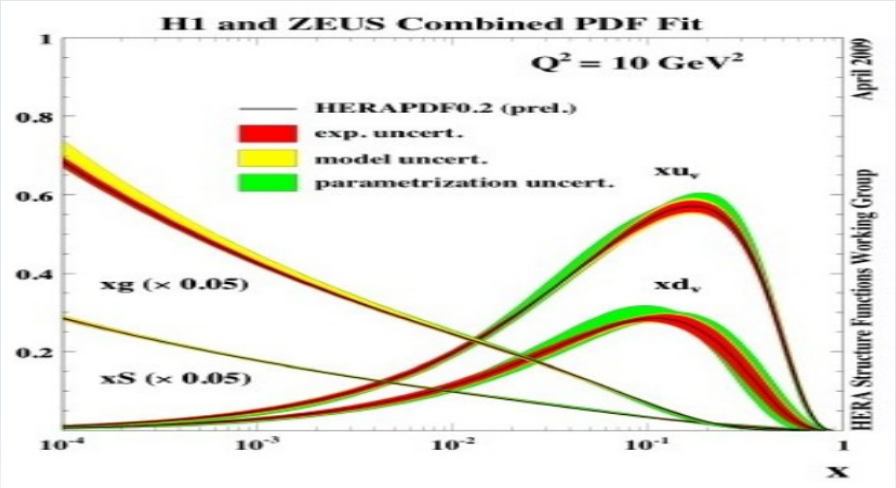
$$x_B = \frac{Q^2}{2m\omega}$$

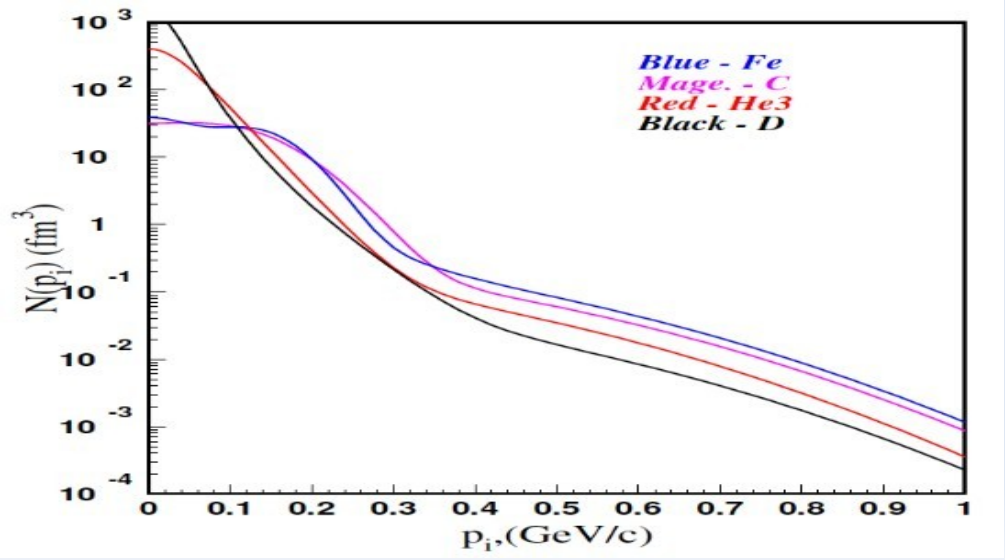
Inclusive electron scattering A(e,e')



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

x_B counts the minimum number of nucleons involved





EMC Effect

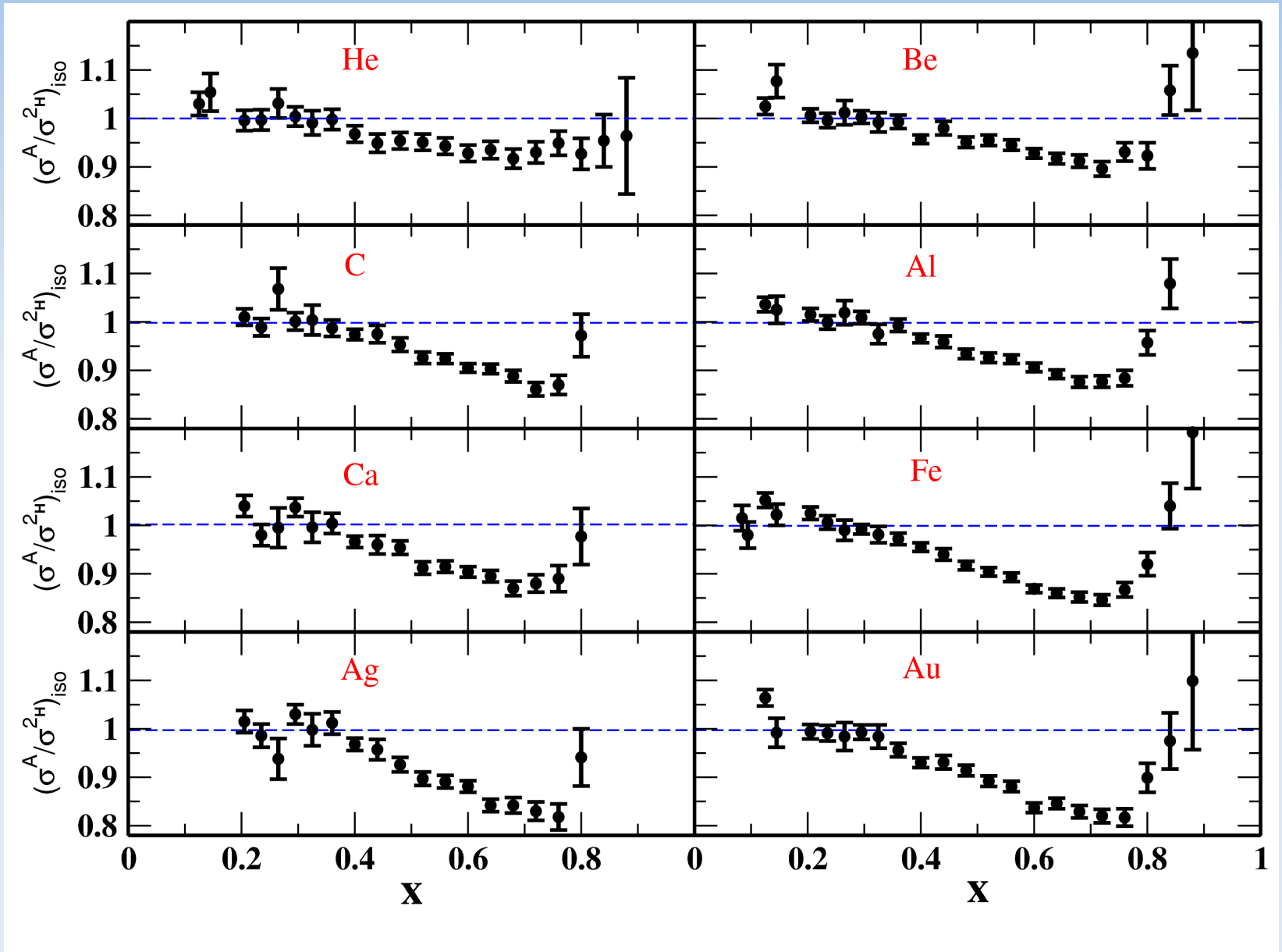
DIS off a bound nucleon ≠ DIS off a free nucleon

Hundreds of theoretical papers tried to explain the effect

- **Nuclear Effects:** binding effects, pion enhancement, 6-quark clusters, and many more...
- **Modification of the nucleon structure:** dynamical rescaling, point like configuration suppression, structure function modification in the mean field, and many more...

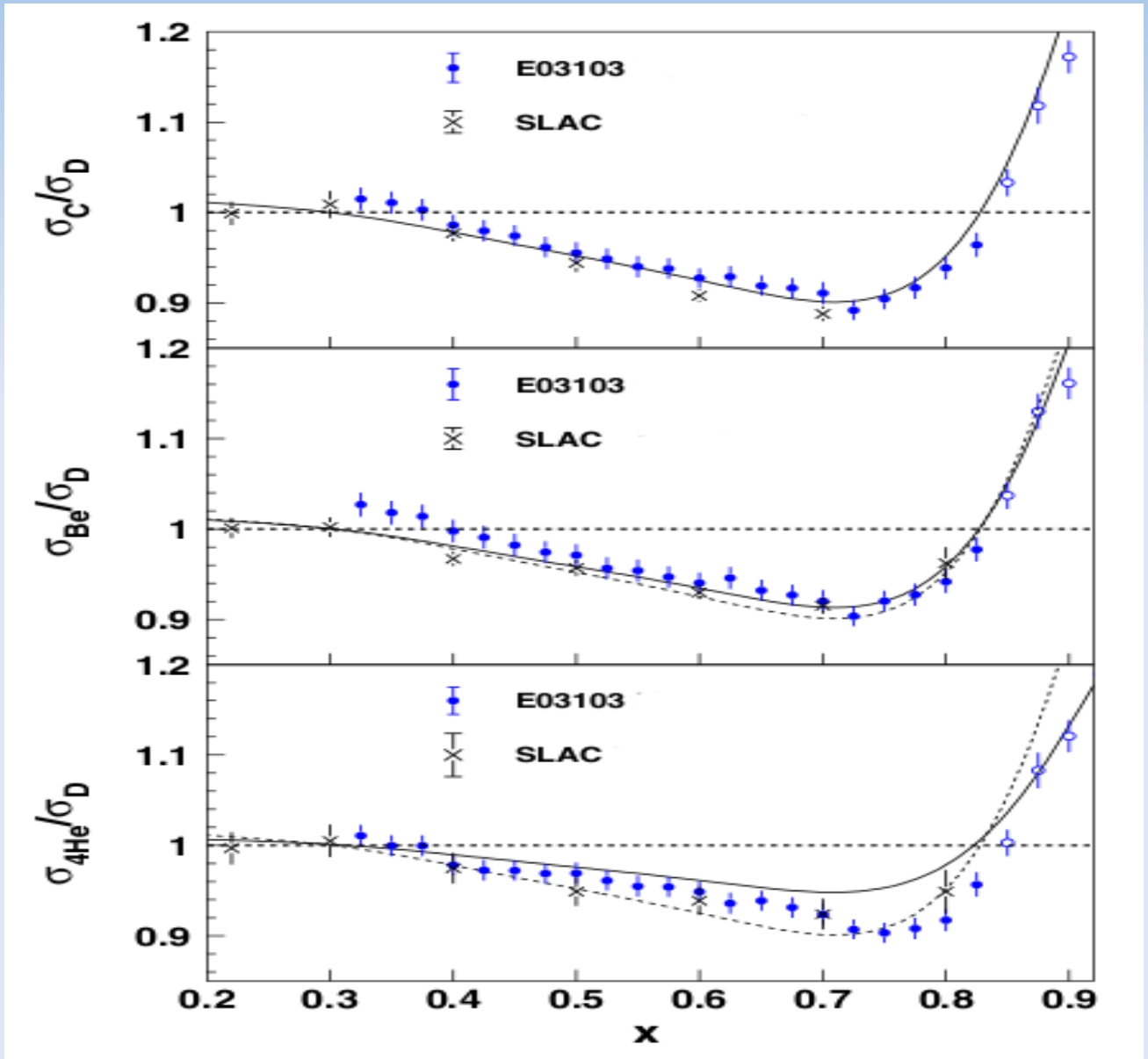
G. Miller: EMC = Every Model is Cool

SLAC E139



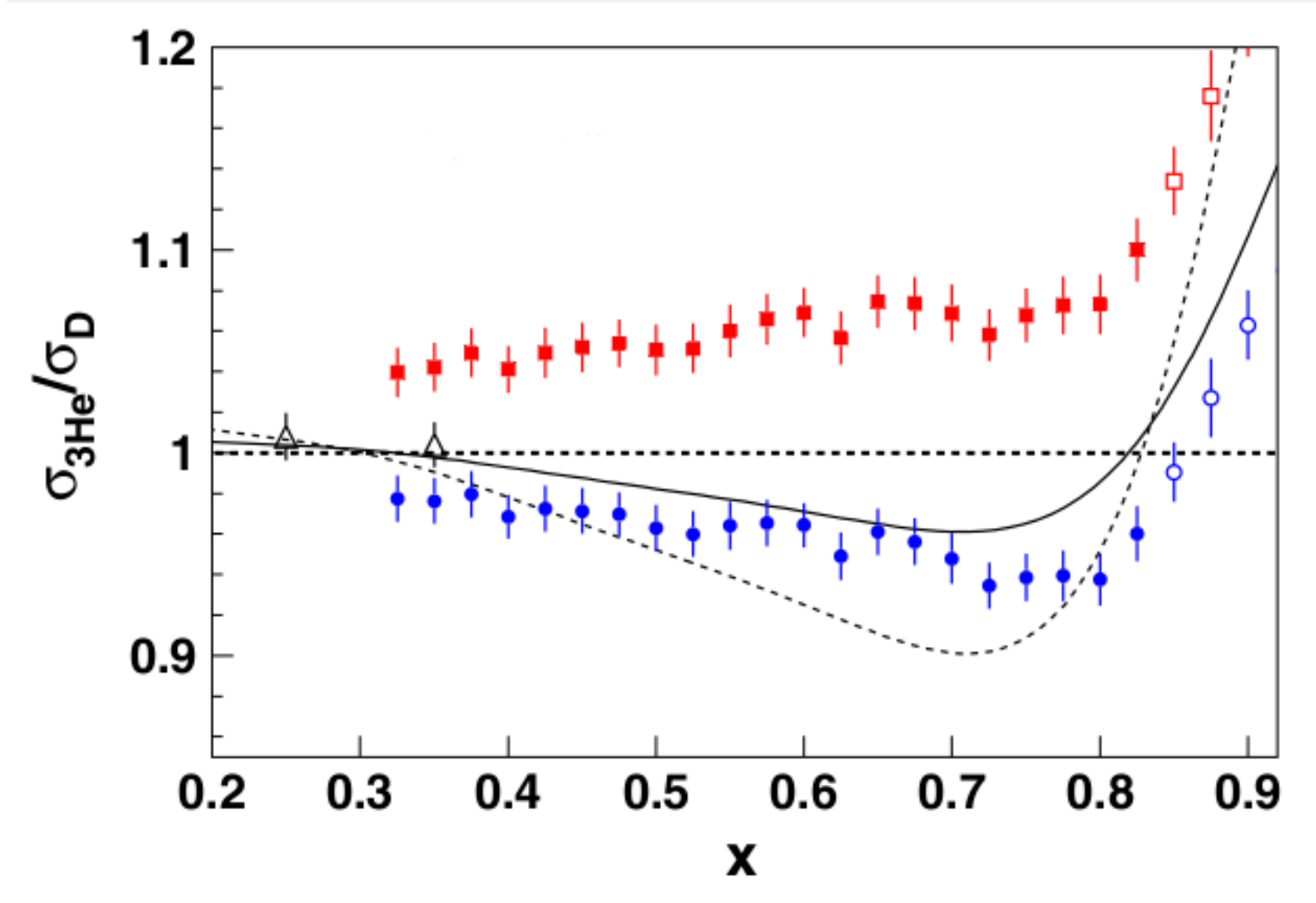
J. Gomez et al., Phys. Rev. D **49**, 4348 (1994)

EMC Effect in ^{4}He, ^{9}Be, and ^{12}C



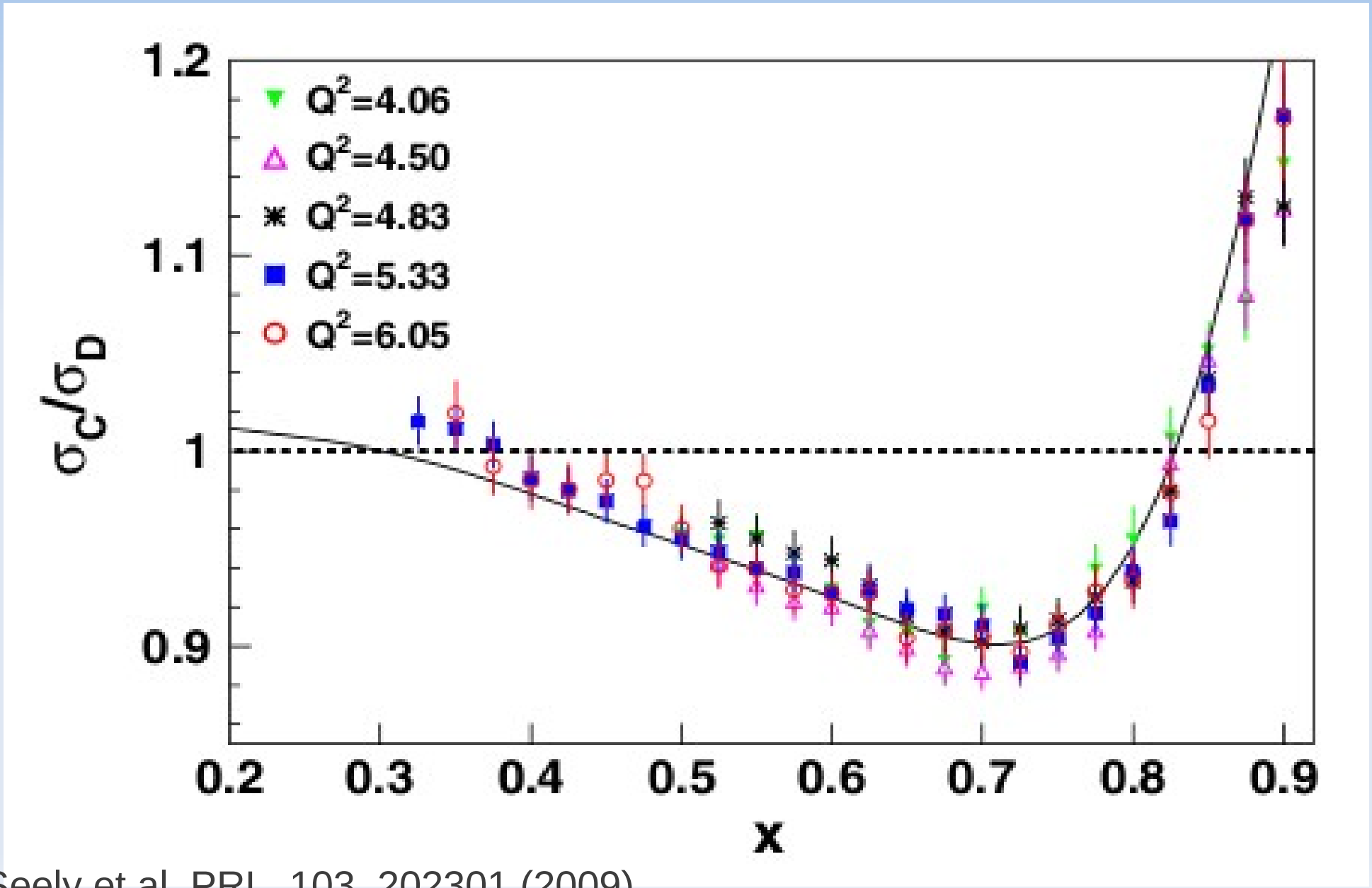
J. Seely et al. PRL 103, 202301 (2009)

EMC Effect in ^{3}He



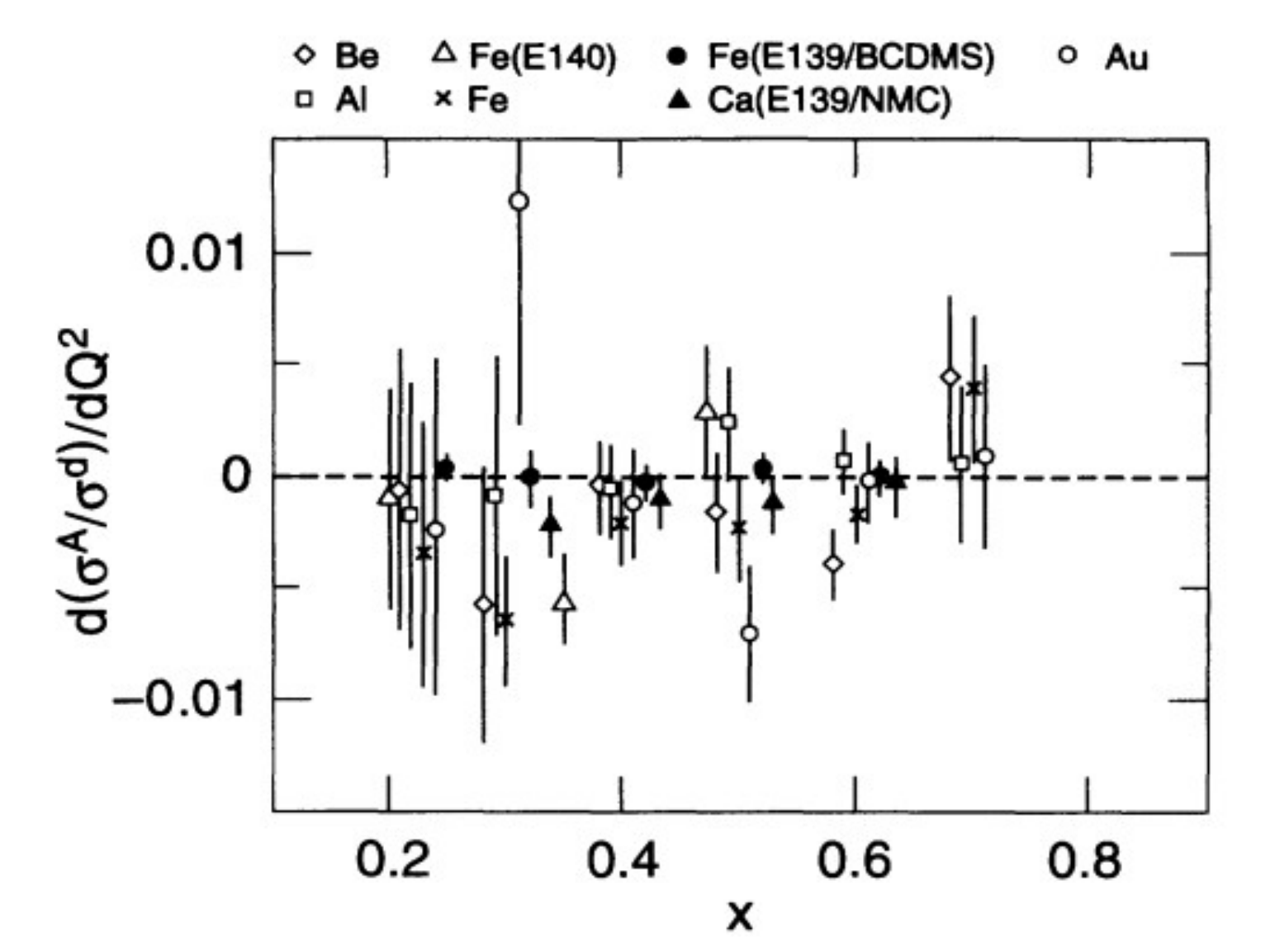
J. Seely et al. PRL 103, 202301 (2009)

$^{12}C/d$ for $4 < Q^2 < 6$ $[GeV/c]^2$



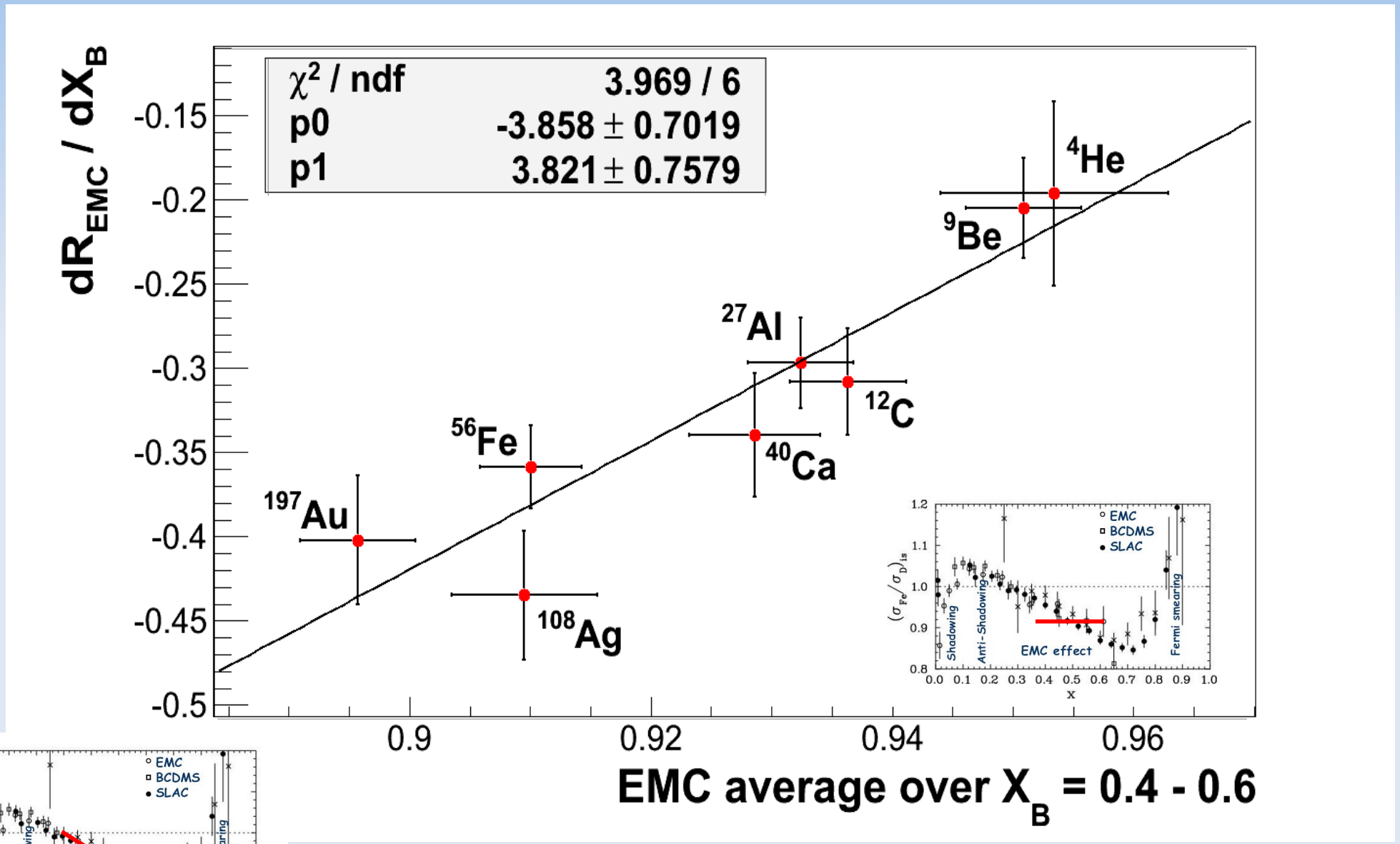
J. Seely et al. PRL 103, 202301 (2009)

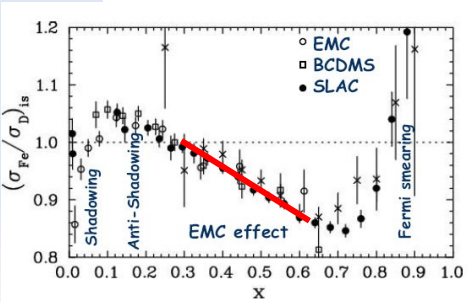
Q^2 independence



J. Gomez et al., Phys. Rev. D 49, 4348 (1994)

EMC slope vs. average of X_B=0.4-0.6





Based on data from J. Gomez et al., Phys. Rev. D 49, 4348 (1994)

BNL Measurements

[SRC Dominance at High Momentum]

Study the $^{12}C(p,2p+n)$ reaction in parallel kinematics

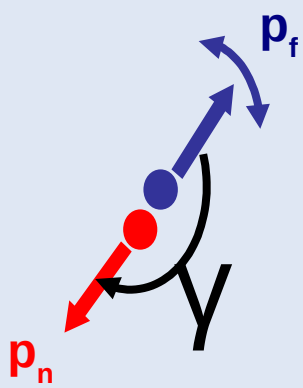
Results: SRC Dominance

92±18% of high momentum ($275<P_{miss}<550$ MeV/c) proton knockout events were accompanied by single neutron emission

$p_f = p_1 + p_2 - p_0$

p_0 = incident proton

p1 and p2 are detected



A. Tang et al., Phys. Rev. Lett. **90**, 042301 (2003)
E. Piasetzky et al., Phys. Rev. Lett. **97**, 162504 (2006)

BNL Measurements

[SRC Dominance at High Momentum]

Study the $^{12}C(p,2p+n)$ reaction in parallel kinematics

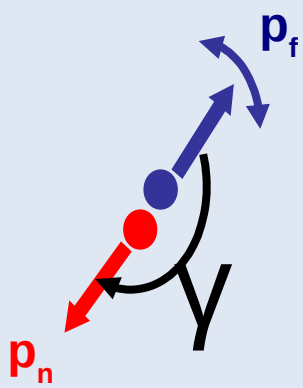
Results II: (SRC Threshold?)

Recoil neutrons above ~275 Mev/c have back to back angular correlation with the $^{12}C(p,2p)$ missing momentum vector

$\mathbf{p_f = p_1 + p_2 - p_0}$

p_0 = incident proton

p1 and p2 are detected



A. Tang et al., Phys. Rev. Lett. **90**, 042301 (2003)
E. Piasetzky et al., Phys. Rev. Lett. **97**, 162504 (2006)

BNL Measurements

[SRC Dominance at High Momentum]

Study the $^{12}C(p,2p+n)$ reaction in parallel kinematics

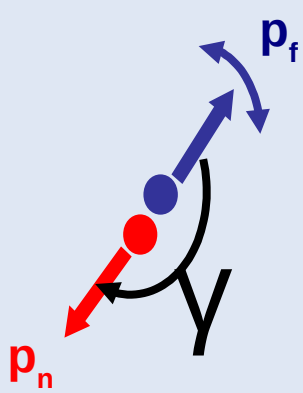
Results III: (c.m. Momentum)

The c.m. momentum distribution was measured to be Gaussian with $\sigma = 143 \pm 17$ MeV/c

$\mathbf{p_f = p_1 + p_2 - p_0}$

p_0 = incident proton

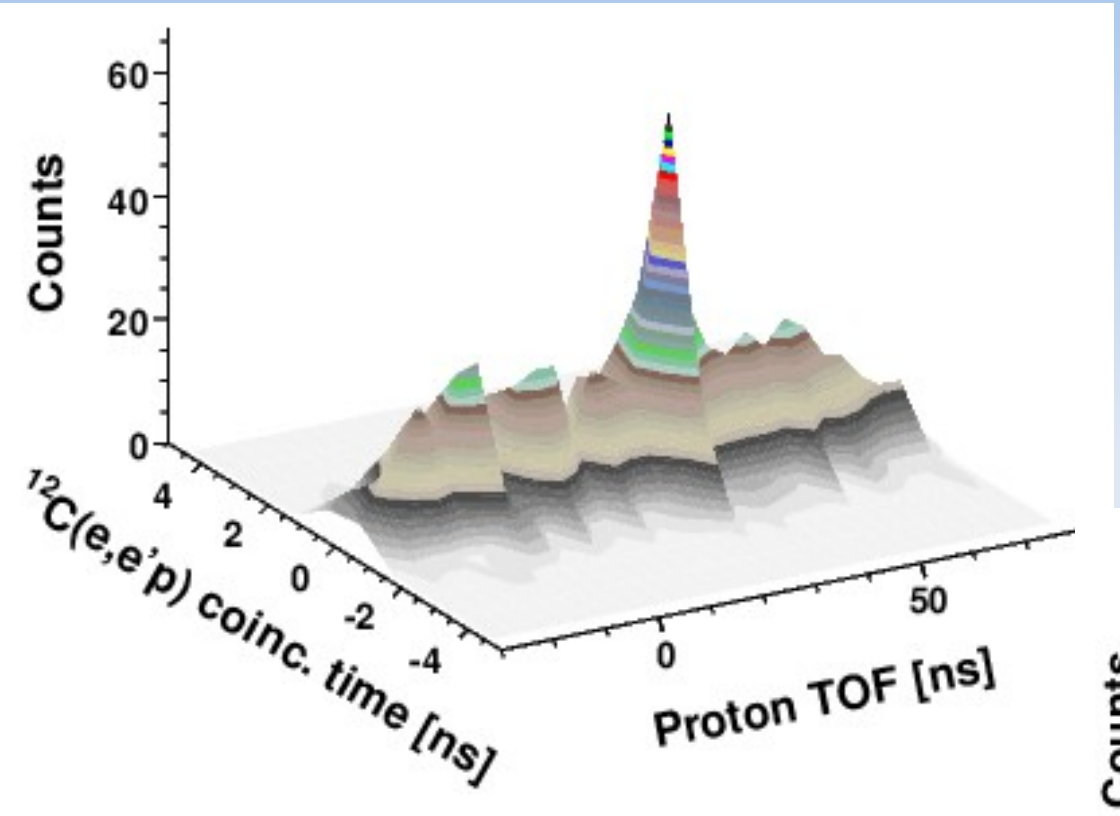
p1 and p2 are detected



A. Tang et al., Phys. Rev. Lett. **90**, 042301 (2003)
E. Piasetzky et al., Phys. Rev. Lett. **97**, 162504 (2006)

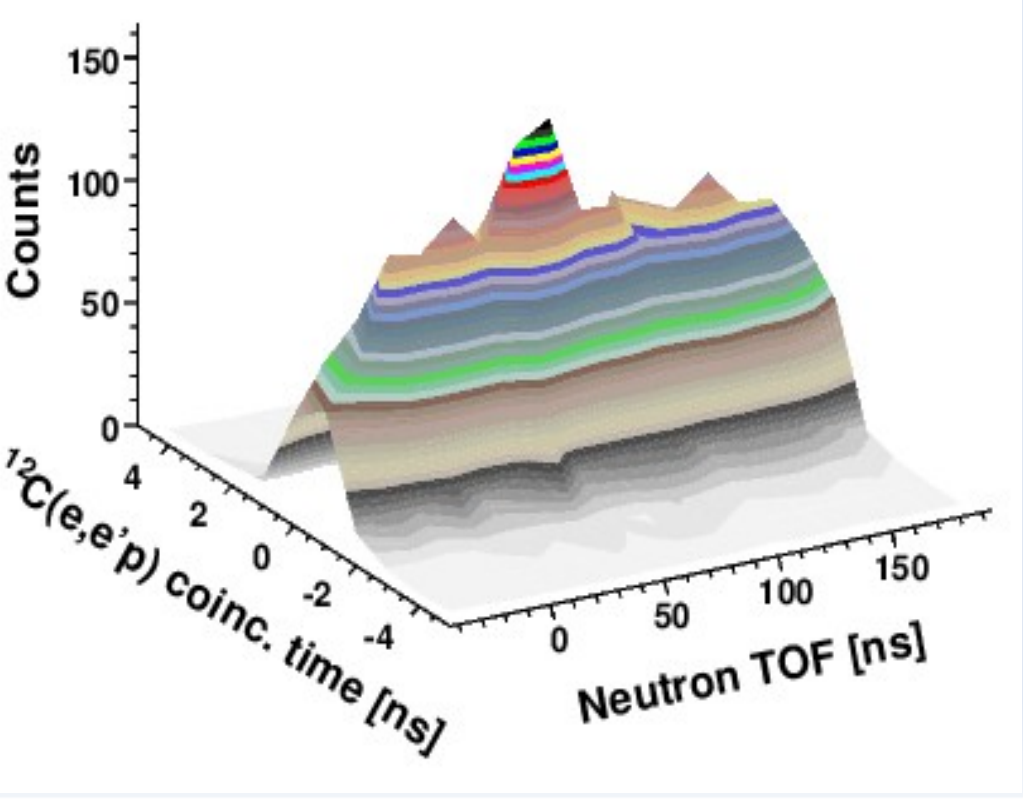
Jlab Hall-A E01-015

[Triple Coincidence (e,e'pp) and (e,e'pn) TOF Spectra]



^{12}C(e,e'pp)
S:BG ≈ 2:1

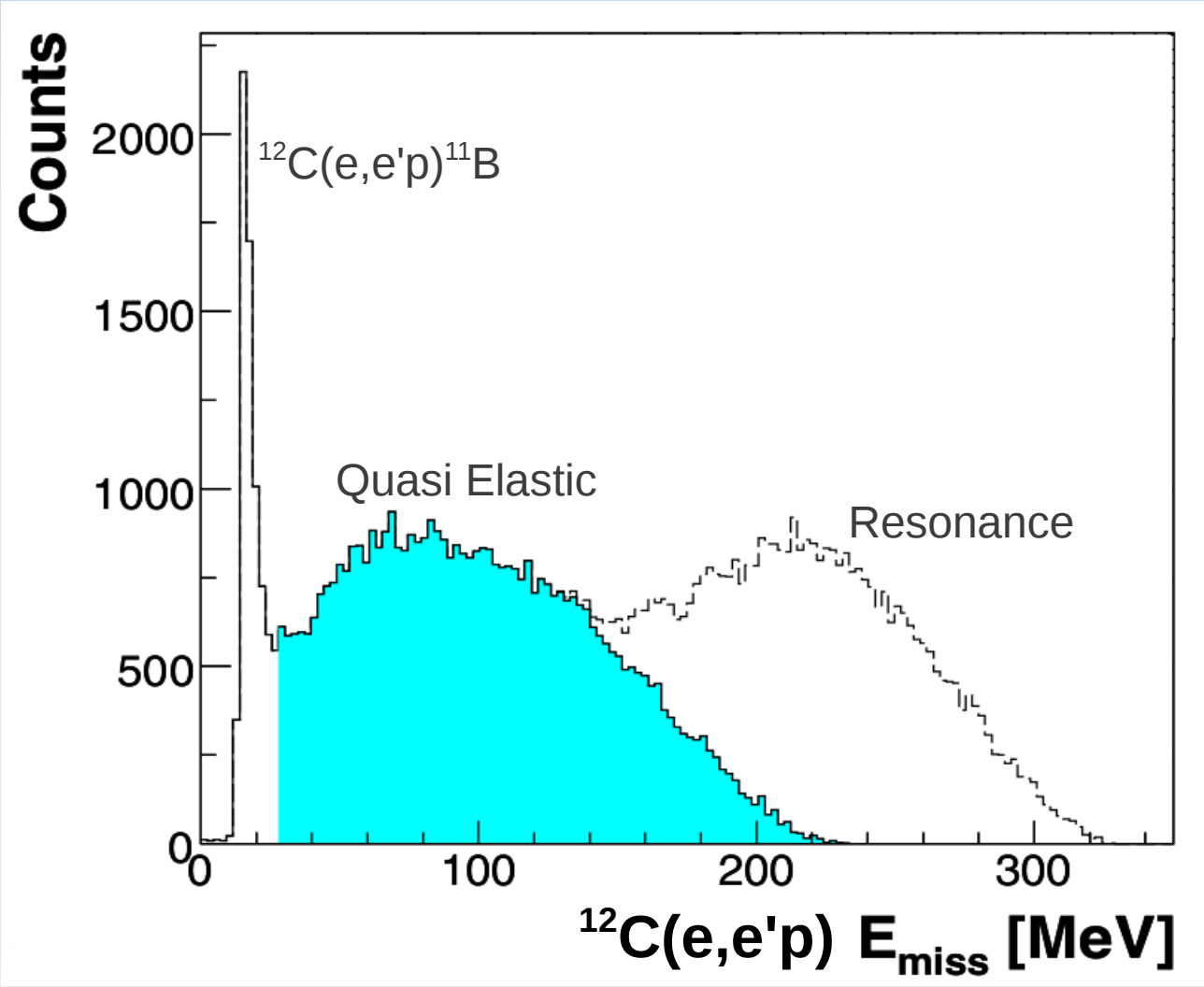
^{12}C(e,e'pn)
S:BG ≈ 1:3



Jlab Hall-A E01-015

[QE Events Selection]

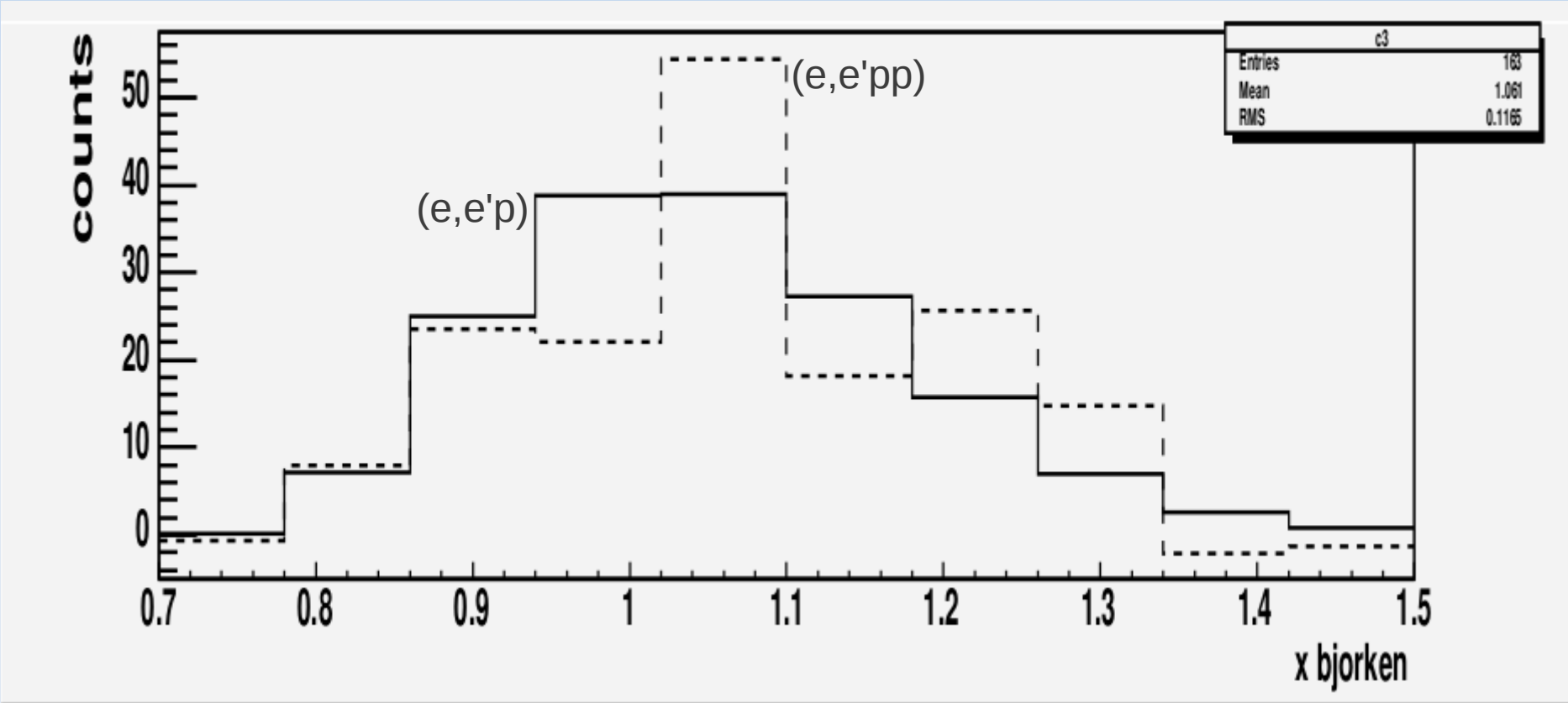
Missing energy spectrum from $^{12}C(e,e'p)$ at P_{miss}=300 MeV/c kinematics



R. Shneor et al., Phys. Rev. Lett. **99**, 072501 (2007)

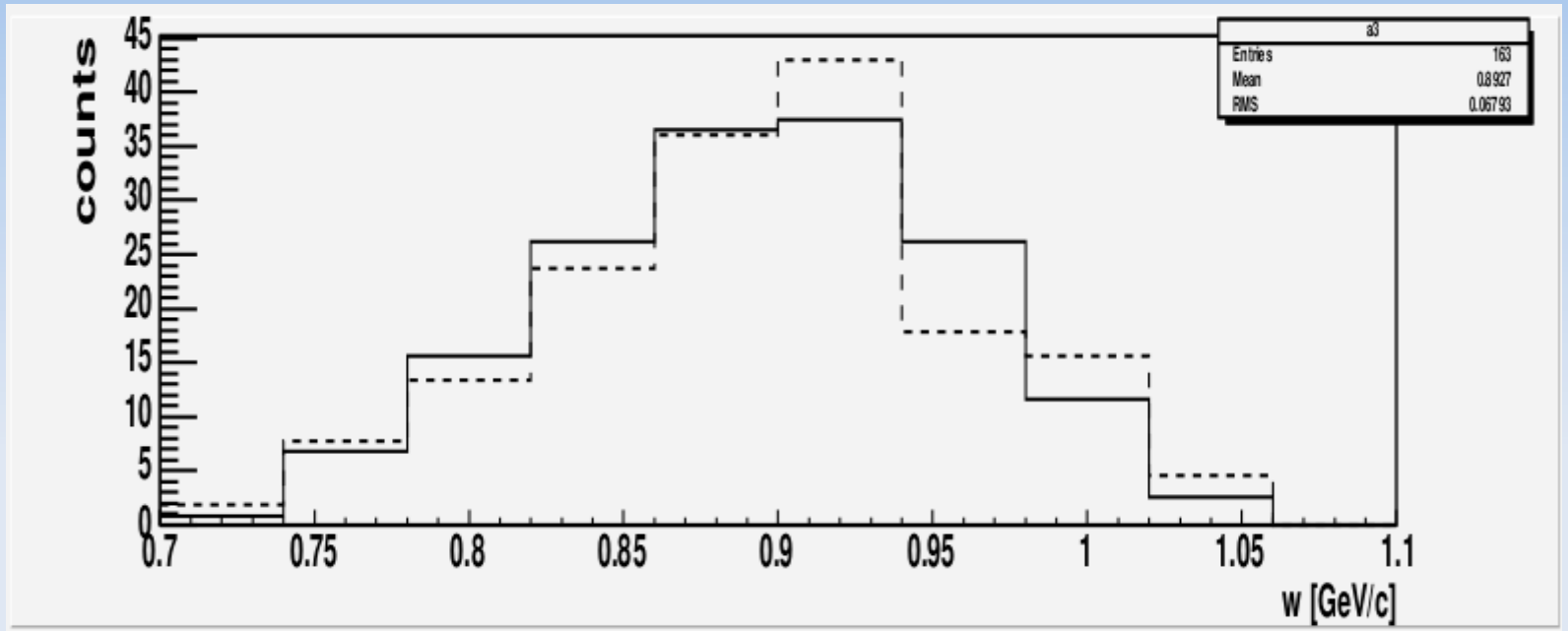
Hall-A E01-015 kinematics

x_B Distribution

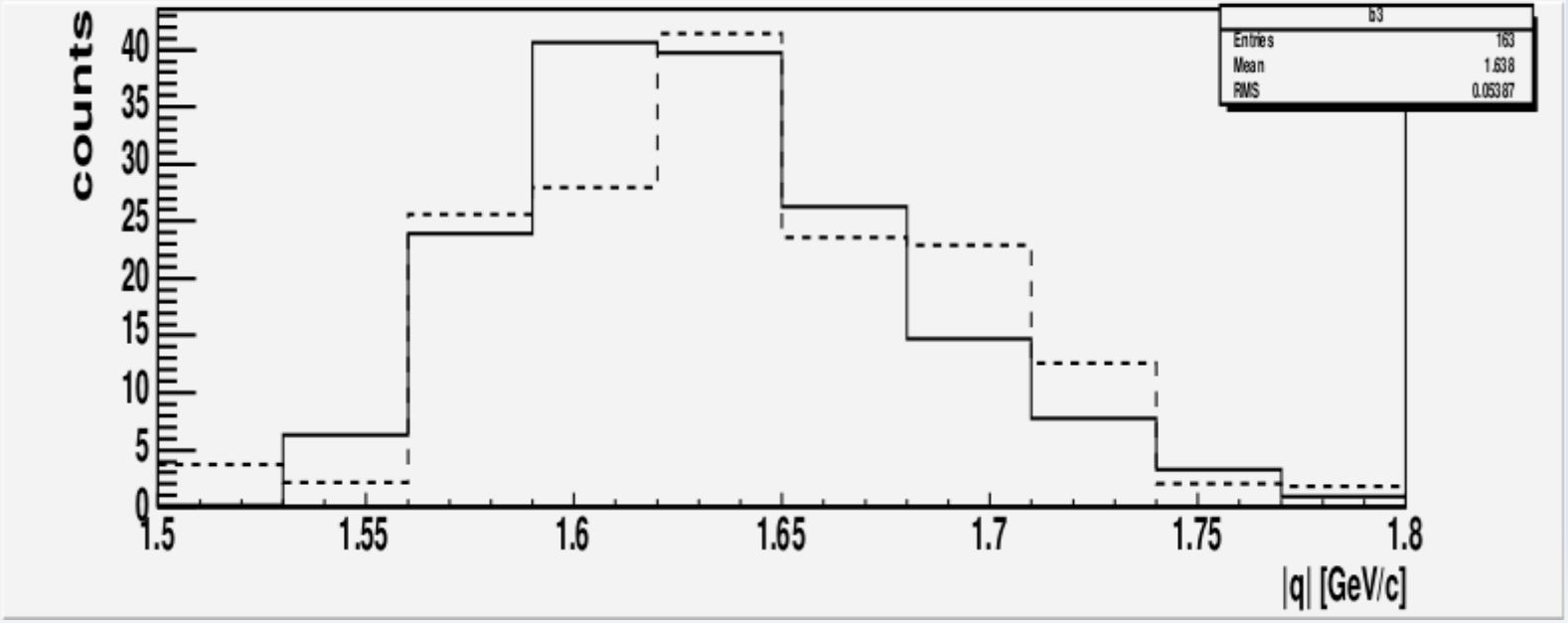


Hall-A E01-015 kinematics

Q^2 Distribution

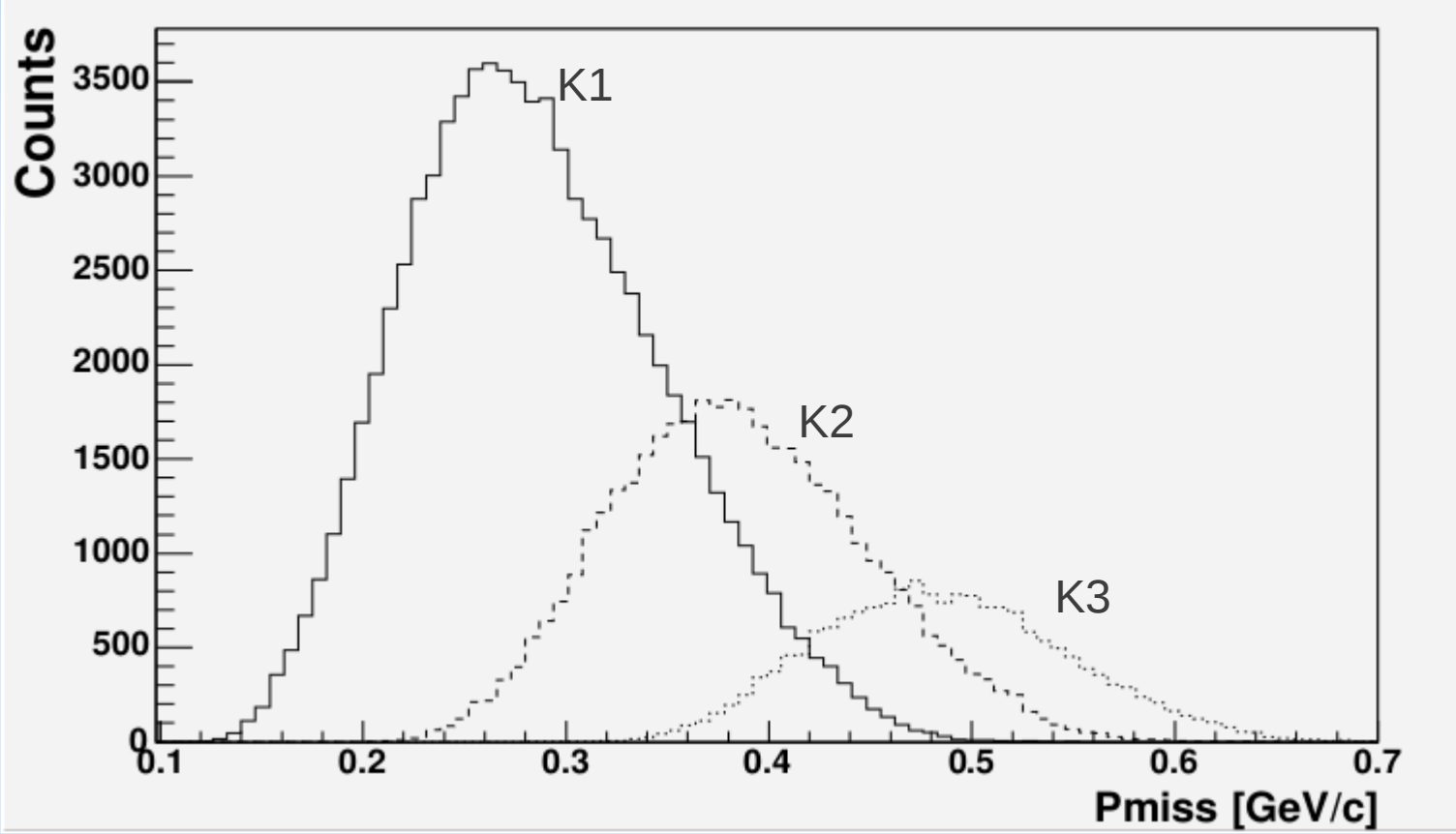


$Q^2 \approx 1.8$



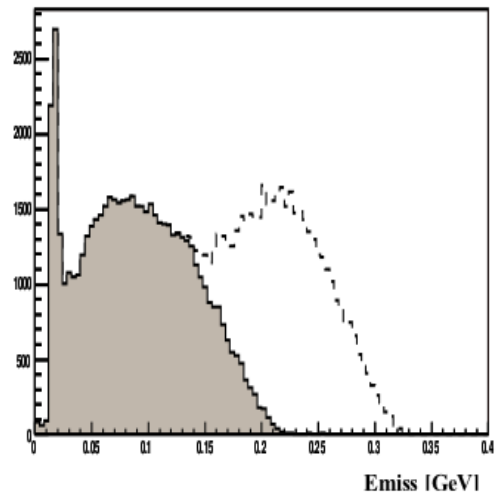
Hall-A E01-015 kinematics

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

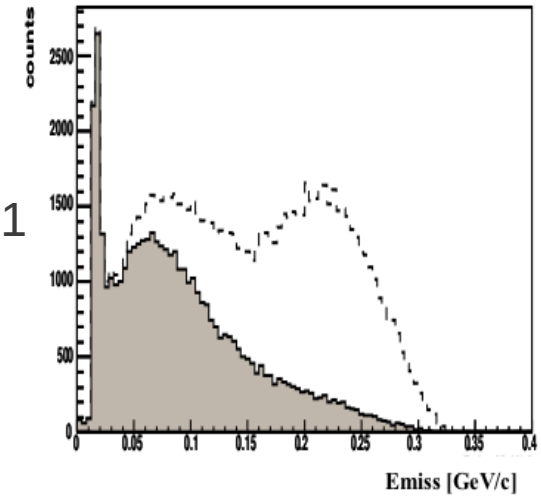


Hall-A E01-015 Delta Contamination

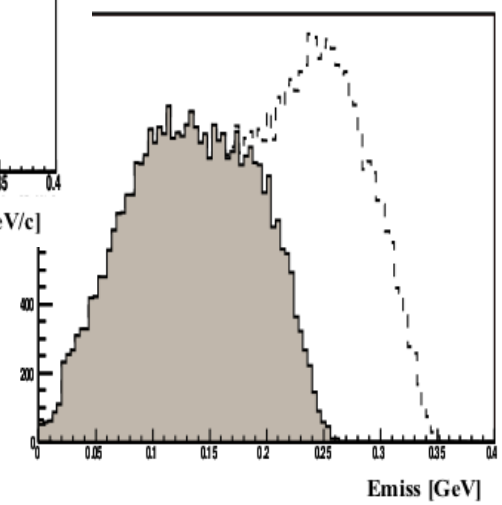
$^{12}C(e,e'p)$ E_{miss} Distribution



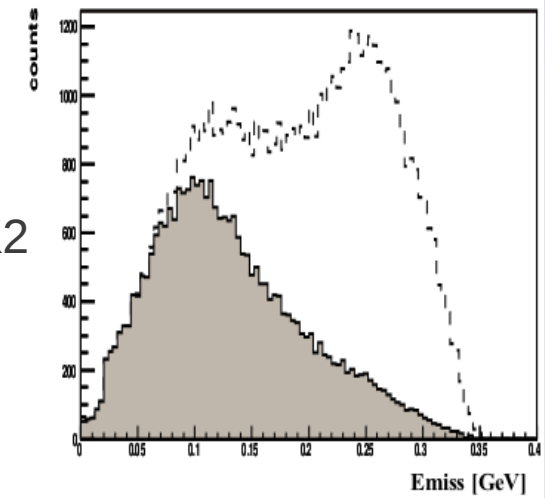
K1

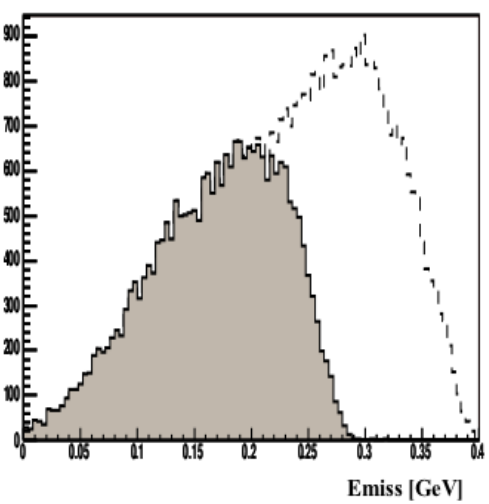


Large E_{miss} is associated with Delta production

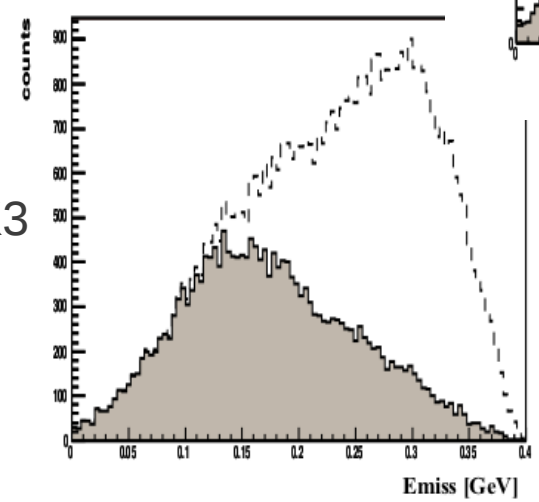


K2





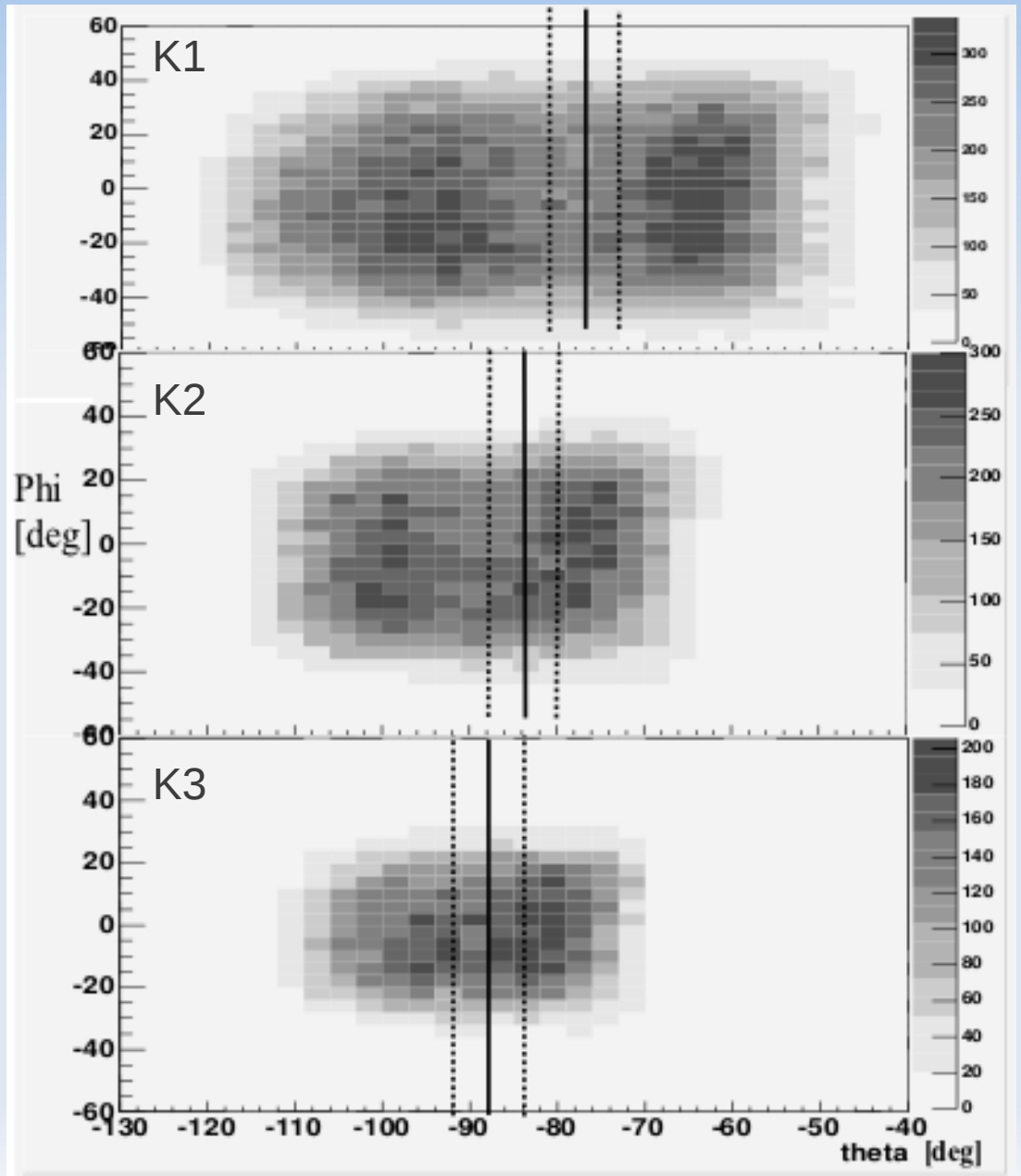
K3



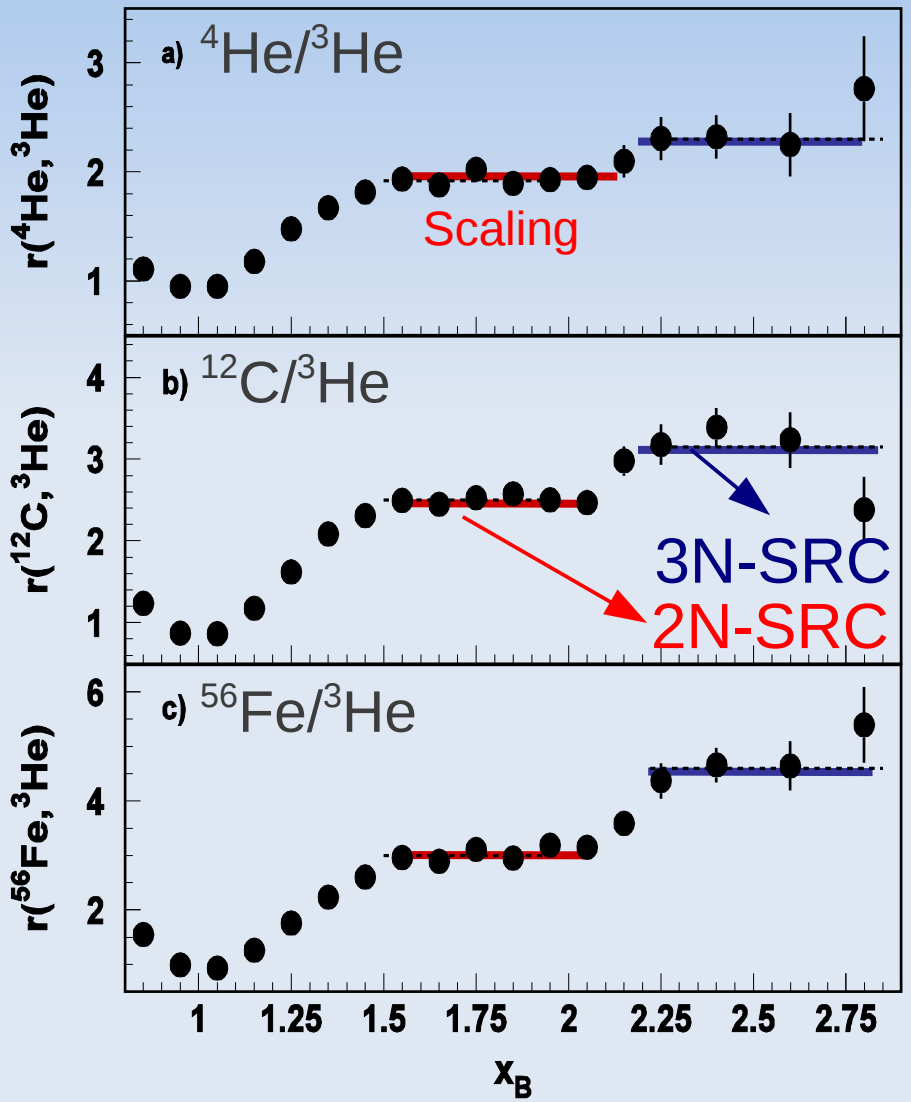
Delta events are killed by cutting on: $\boldsymbol{\theta_{Pmiss}}$**>77-88º** (left) or x_B>1 (right)

Hall-A E01-015 Delta Contamination

θ_{Pmiss} Cut



Scaling of Inclusive A(e,e') Cross Section Ratios

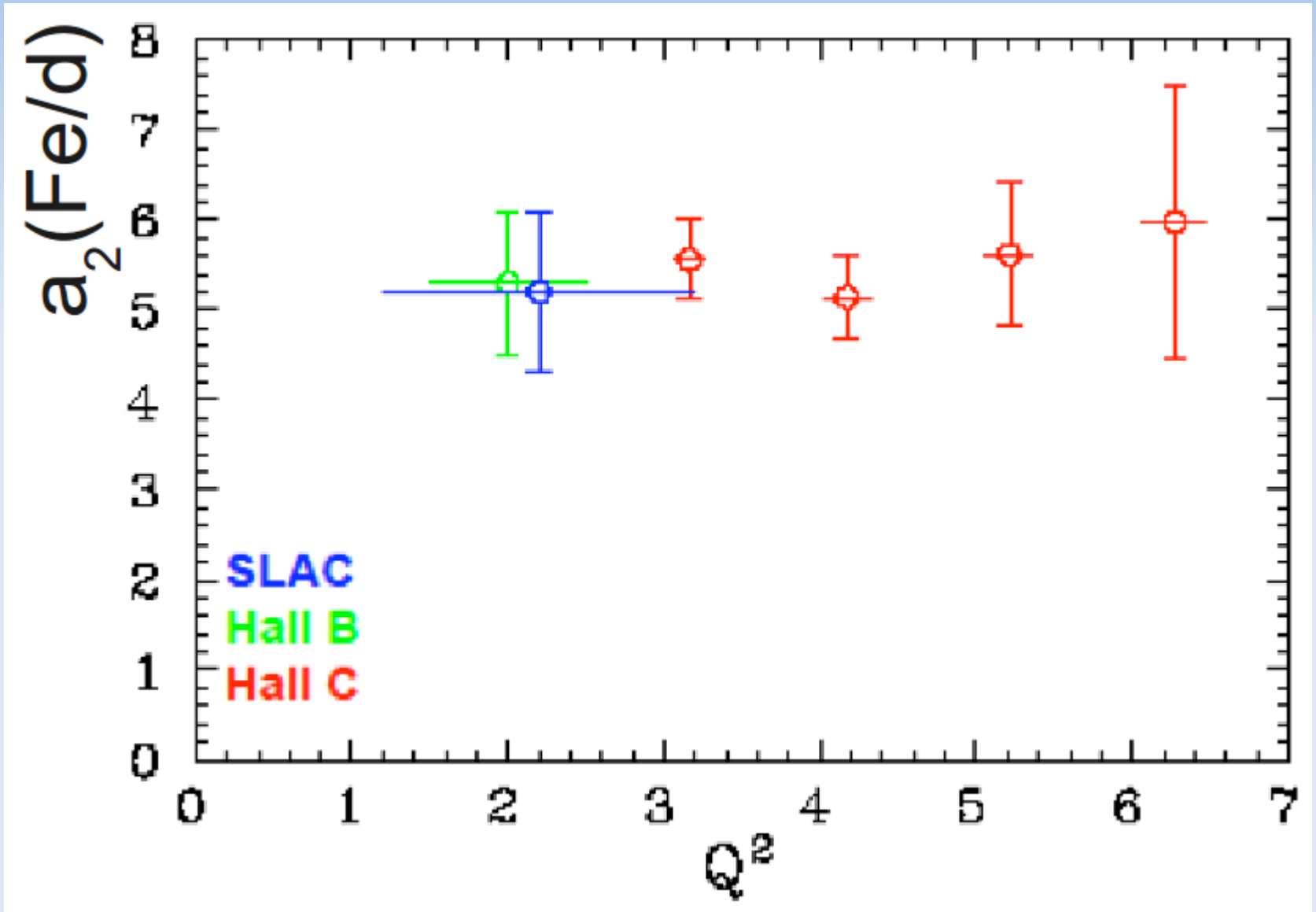


- First observed in SLAC by D. Day et al.
- Validates the expected momentum scaling
- Interpreted using the 2N-SRC model
- Extract the relative number of 2N(3N) SRC pairs in nuclei

D. Day et al. Phys. Rev. Lett **59**, 427 (1987)
K. Sh. Egiyan et al. Phys. Rev. C **68**, 014313 (2003)
K. Sh. Egiyan et al. Phys. Rev. Lett **96**, 082501 (2006)

Theoretical Interpretation: L. L. Frankfurt et al. Phys. Rev. C **48**, 2415-2461 (1993)

a_2(Fe/d) Q^2 independence



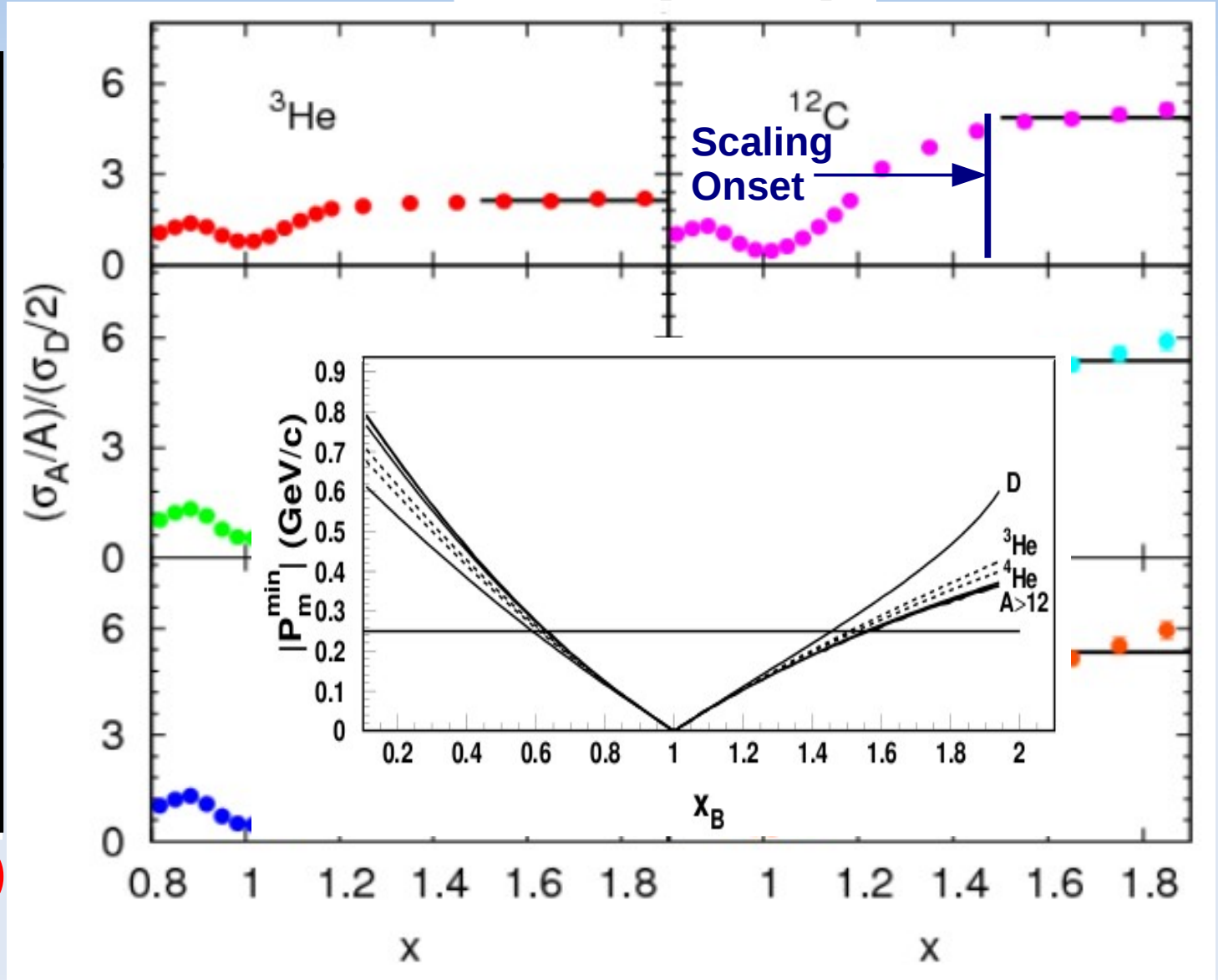
From J. Arrington talk in “High Energy Nuclear Physics and QCD” meeting, FIU, Miami,

High Precision Results from Hall-C

$a_2(A/d)$	
^{3}He	1.93±0.10
^{4}He	3.02±0.17
^{9}Be	3.37±0.17
^{12}C	4.00±0.24
^{63}Cu	4.33±0.28
^{197}Au	4.26±0.29

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

Q^2=2.5 [GeV/c]^2



N. Fomin et al., Phys. Rev. Lett. **108**.

Short Range Correlations From Inclusive Measurements

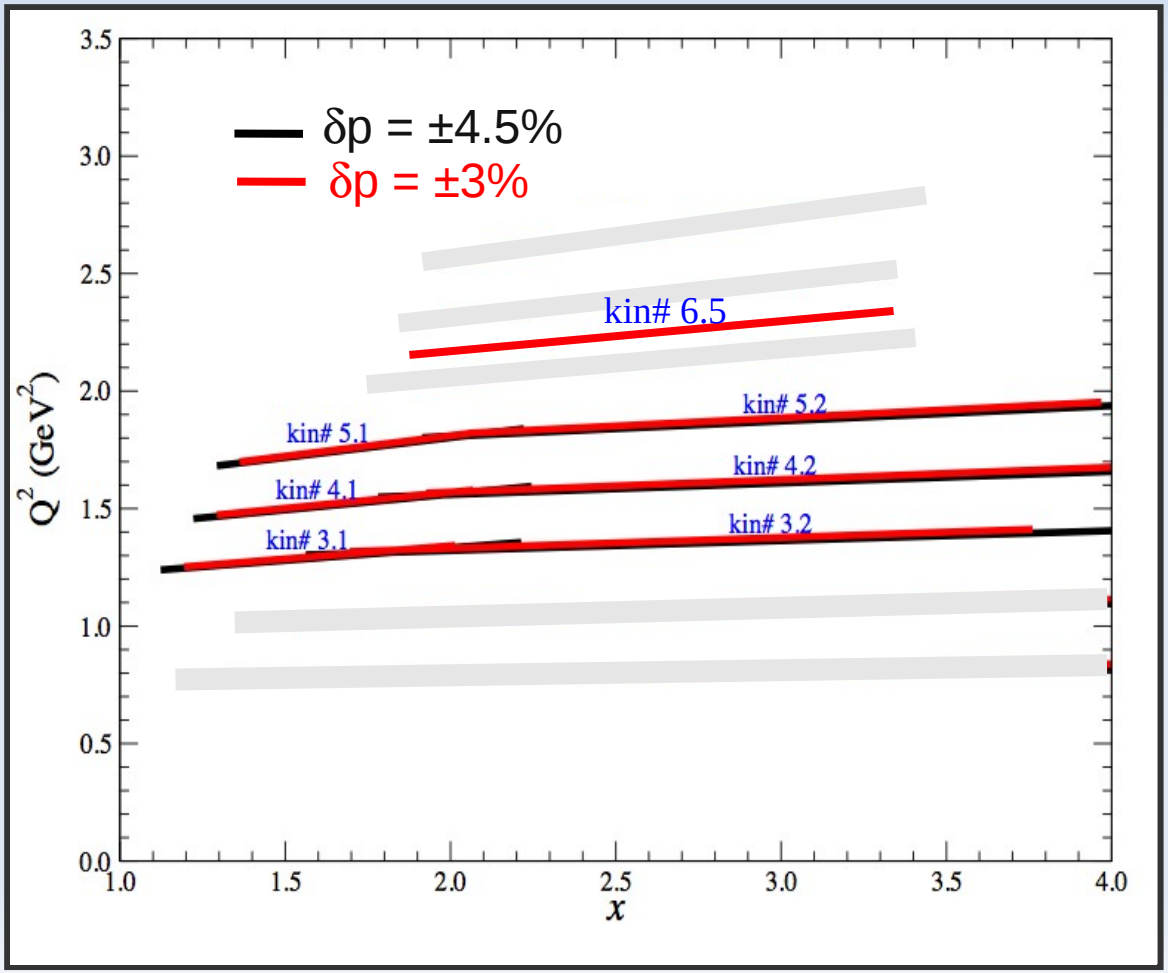
- Scaling onset corresponds to $P_{min} \approx 275$ MeV/c

$$\int_0^\infty n_d(k)k^2 dk = 100\% \implies \int_{P_{min}}^\infty n_d(k)k^2 dk = 4\%$$

- In nuclei with A > 12, 2N-SRC account for:
  - ~20% of the nucleons in the nuclei
  - ~80% of the kinetic energy carried by the nucleons
- 3N-SRC are an order of magnitude less abundant then 2N-SRC

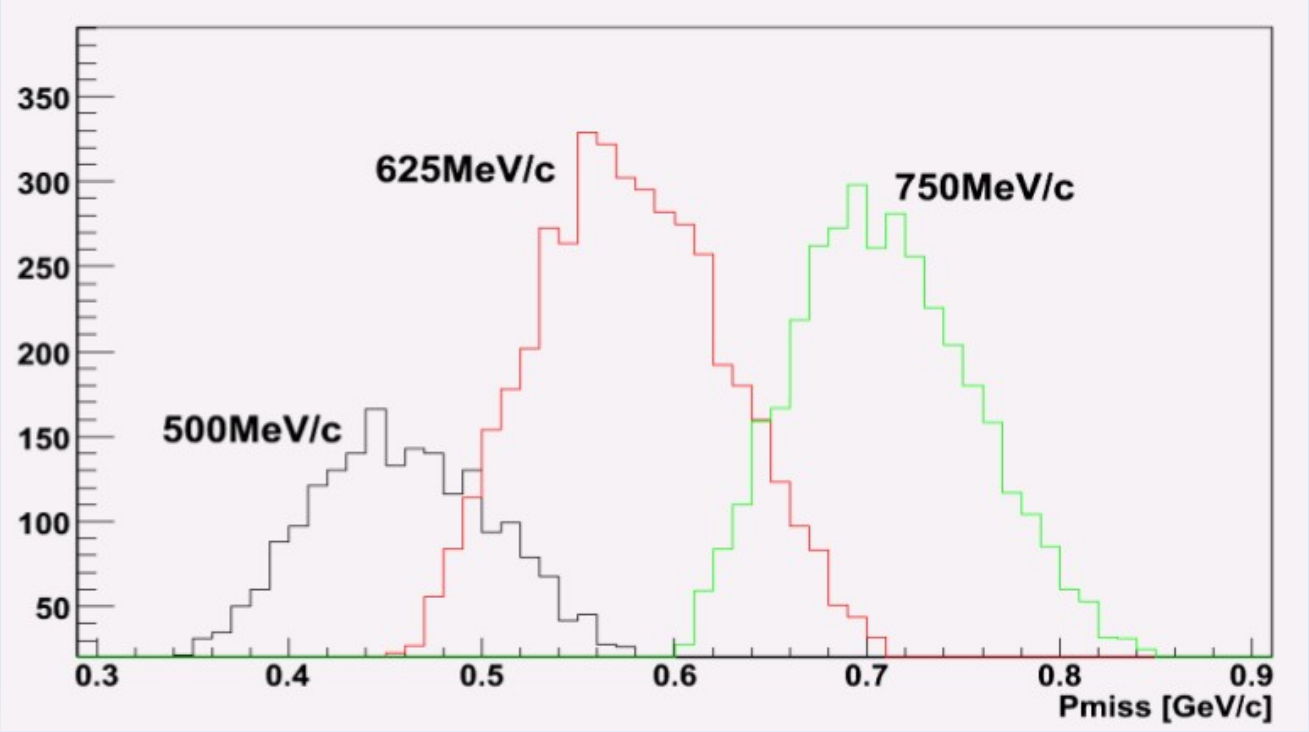
Hall-A E08-014 (2011)

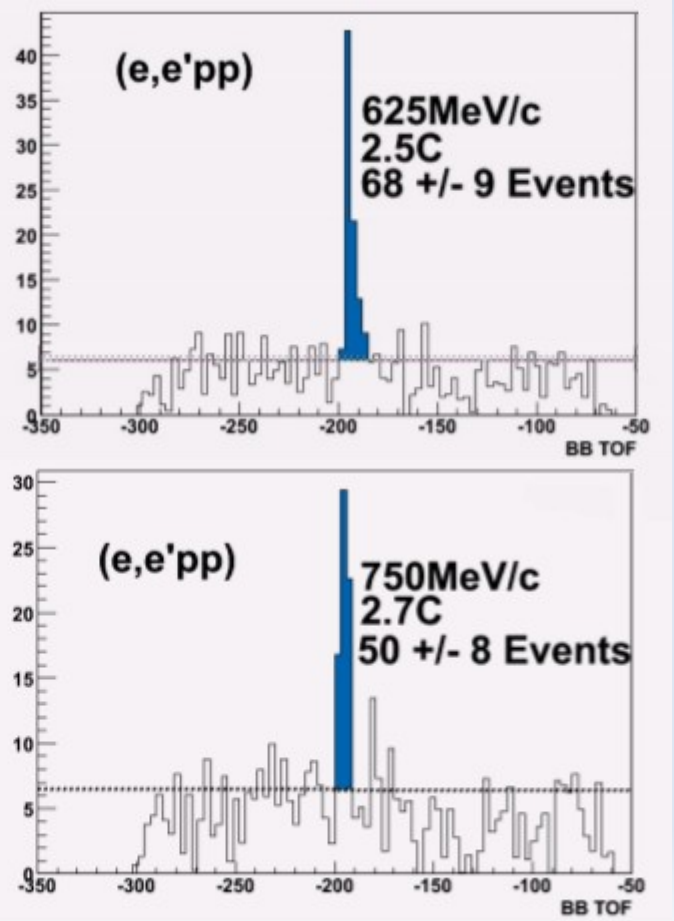
- E08-014 (main objectives):
  1) Inclusive study of the 3N-SRC plateau at $x_B>2$
  2) Study on IsoSpin structure of 2N-SRC by comparing ^{40}Ca to ^{48}Ca
- Studies the Q^2 dependence of the 3N-SRC plateau over a range of $Q^2=1.4\text{-}2.4\ [GeV/c]^2$



Hall-A E07-006 (2011)

- E07-006: Second generation Hall-A experiment, pushing towards the repulsive core of the NN interaction
- Covered a ^{4}He(e,e'p) missing momentum range of 400-750 MeV/c





2N-SRC (Even Before 12GeV)

1) The probability for a nucleon to have p ≥ 300 MeV/c in medium nuclei is 20-25%
2) More than ~90% of all nucleons with p ≥ 300 MeV/c belong to 2N-SRC.
3) 2N-SRC dominated by np pairs **(for P_{miss}<600 MeV/c)**
4) 2N-SRC probabilities, c.m. motion and IsoSpin structure at high P_{miss} in a wide verity of nuclei
5) Quantum numbers of pp(np?)-SRC pairs
6) np dominance from inclusive measurements (^{48,40}Ca)
7) Three nucleon SRC are present in nuclei
8) High precession extraction of the 3N(4N?)-SRC plateau and it's Q^2 dependence