INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

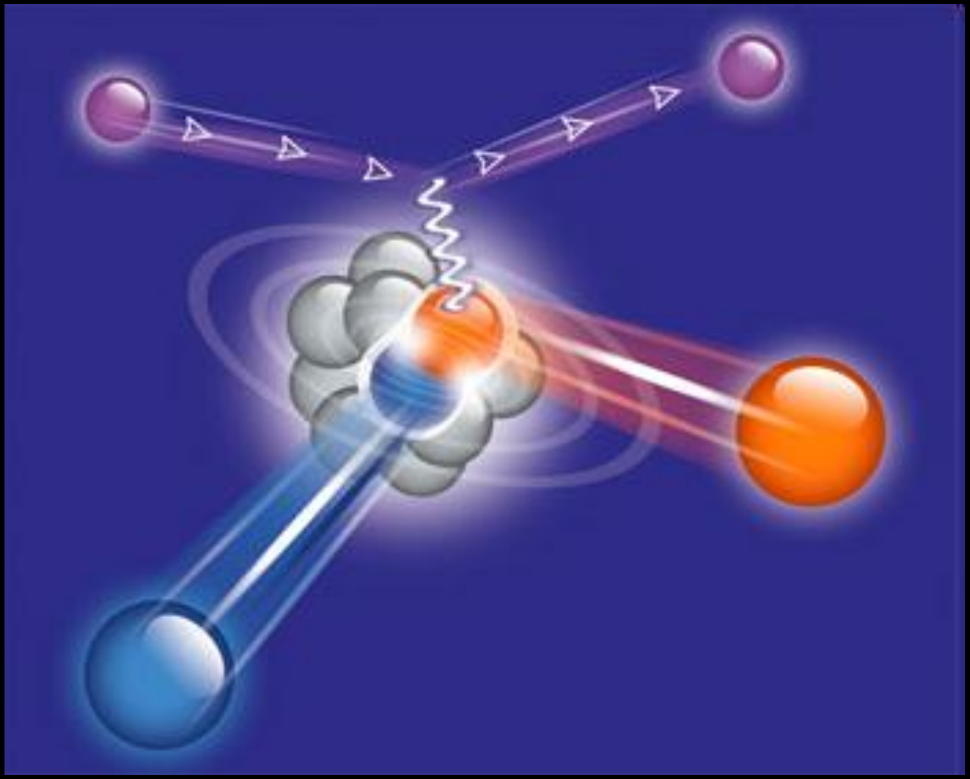
N-N Interaction & the Nuclear Many-Body Problem

November 18-27, 2010

TEL AVIV UNIVERSITY

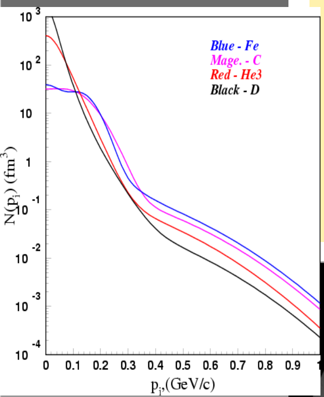
High-Momentum Components of the Nuclear Wave Function:

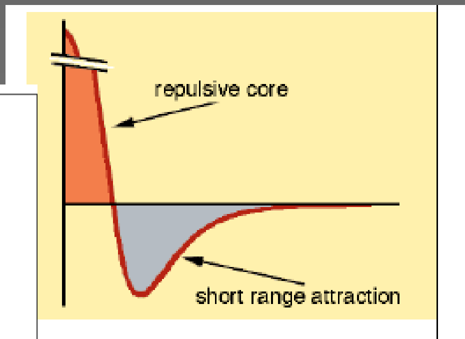
Short range correlation, the tensor N-N interaction, and the EMC effect

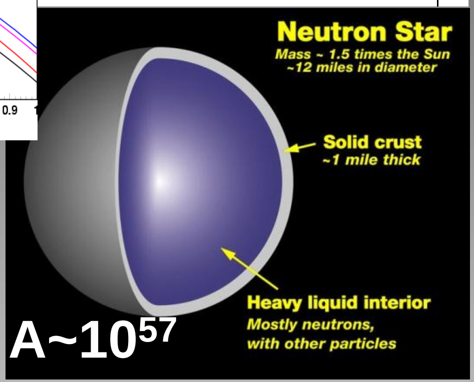


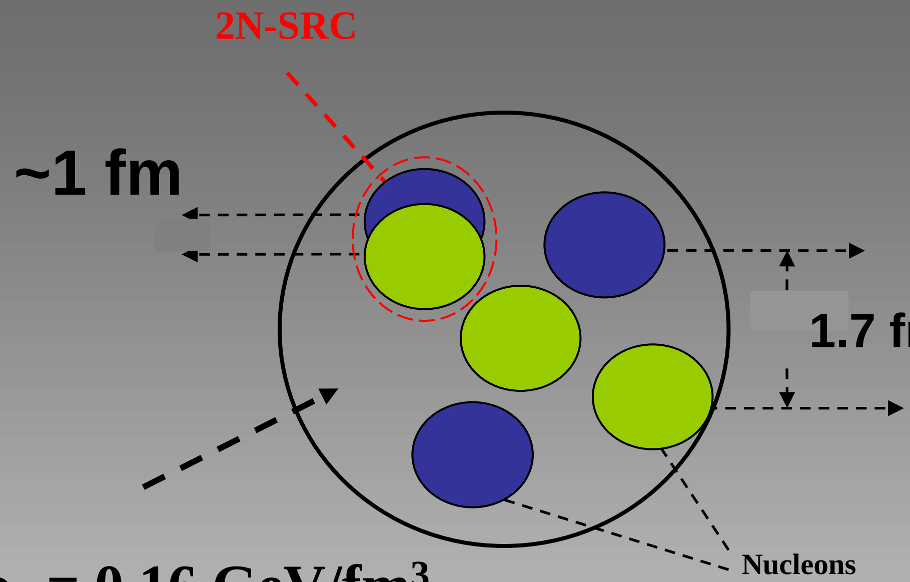
Eli Piasetzky Tel Aviv University, ISRAEL

Short /intermediate Range Correlations in nuclei









ρ_o = 0.16 GeV/fm^3

What SRC in nuclei can tell us about:

High – Momentum Component of the Nuclear Wave Function.

LRC ~R_A

SRC ~R_N

The Strong Short-Range Force Between Nucleons.

tensor force, repulsive core, 3N forces

Cold-Dense Nuclear Matter (from deuteron to neutron-stars).

Nucleon structure modification in the medium ?

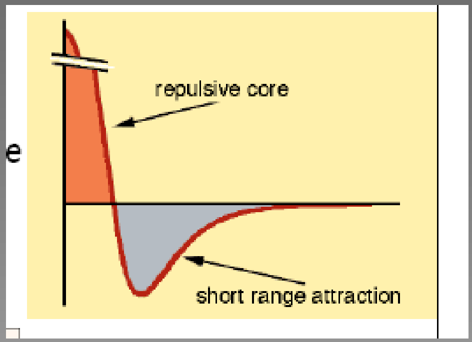
EMC and SRC

Short range correlations

“The structure of correlated many-body systems, particularly at distance scales small compared to the radius of the constituent nucleons, presents a formidable challenge to both experiment and theory”

(Nuclear Science: A Long Range Plan, The DOE/NSF Nuclear Science Advisory Committee, Feb. 1996 [1].)

A description of nuclei at distance scales small compared to the radius of the constituent nucleons is needed to take into account,



Short range repulsion

(common to many other systems)

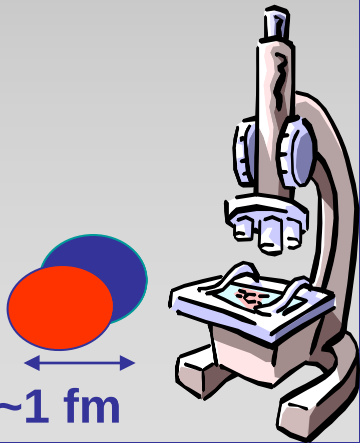
Intermediate- to long-range tensor attraction

(unique to nuclei)

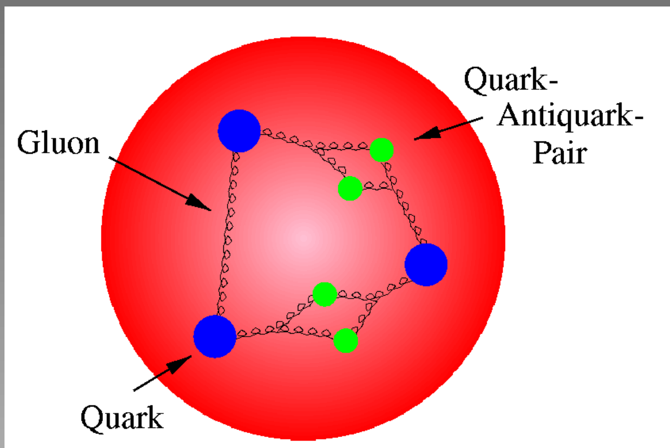
Very difficult many-body problem

presents a challenge to both experiment and theory

This long standing challenge for nuclear physics can experimentally be effectively addressed thanks to high momentum transfer reached by present facilities.



Hard processes are of particular interest because they have the resolving power required to probe the partonic structure of a complex target



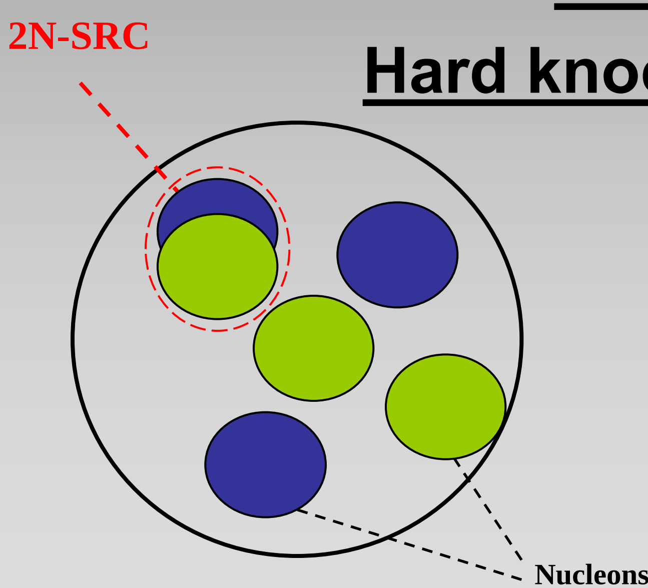
DIS

partonic structure of hadrons

Scale: several tens of GeV

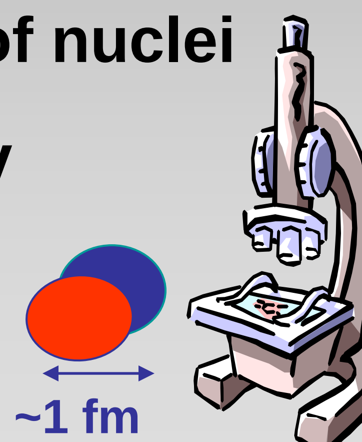
Inclusive electron scattering A(e,e')

Hard knockout reactions A(e,e'p) and A(e,e'pN)



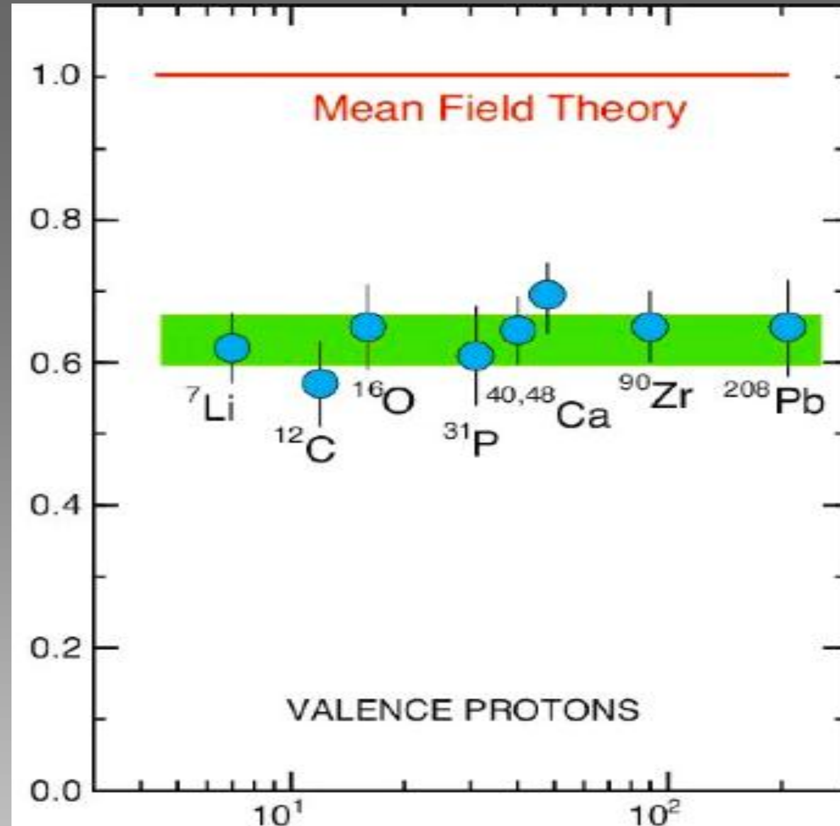
hadronic structure of nuclei

Scale: several GeV



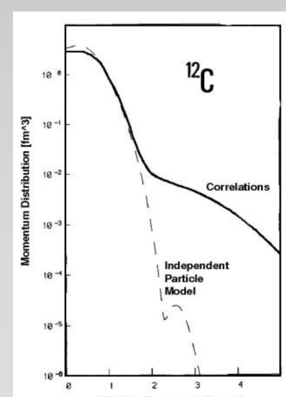
Spectroscopic factors for (e, e'p) reactions

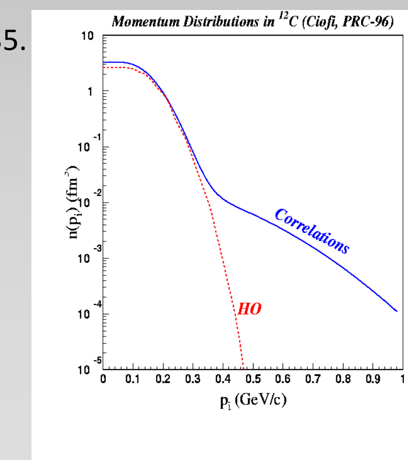
show only 60-70% of the expected single-particle strength.



L. Lapikas, Nucl. Phys. A553, 297c (1993)

Benhar et al., Phys. Lett. **B** 177 (1986) 135.



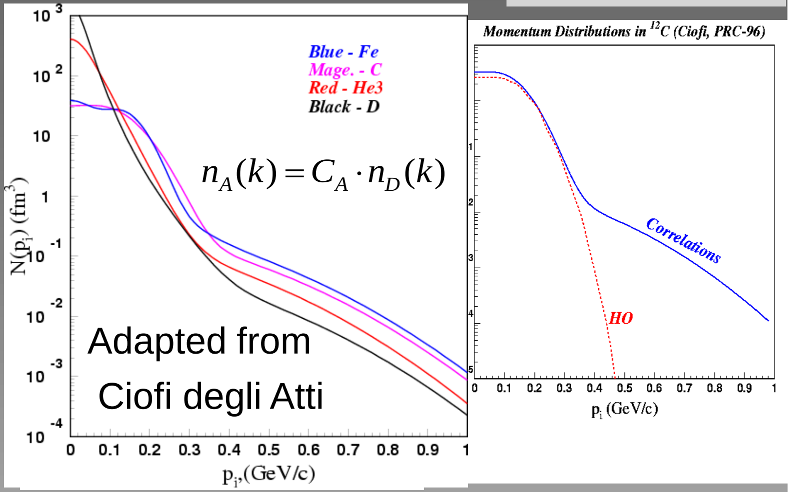


MISSING :

Correlations Between Nucleons SRC and LRC

The inclusive A(e,e') measurements

- At high nucleon momentum distributions are similar in shape for light and heavy nuclei: SCALING.

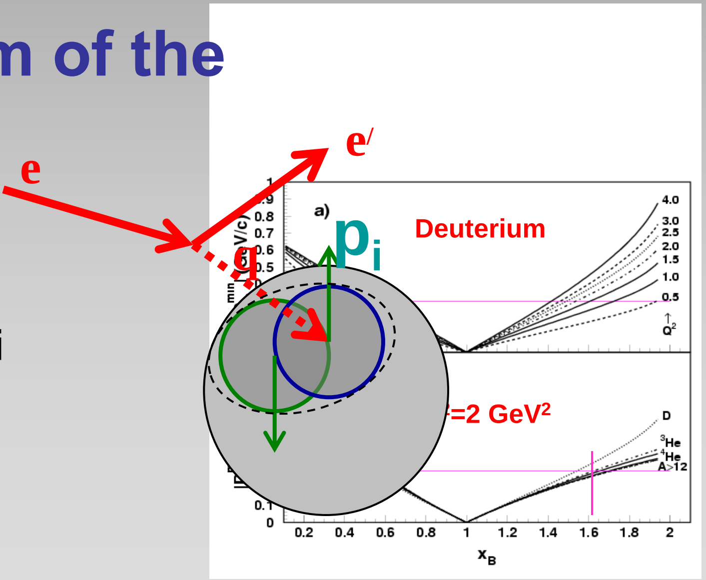


- Can be explained by 2N-SRC dominance.

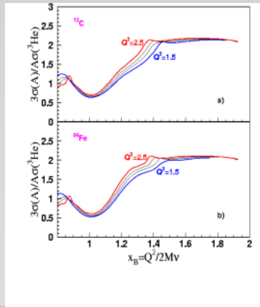
  - Within the 2N-SRC dominance picture one can get the probability of 2N-SRC in any nucleus, from the scaling factor.

Problem: In A(e,e') the momentum of the struck proton (p_i) is unknown.

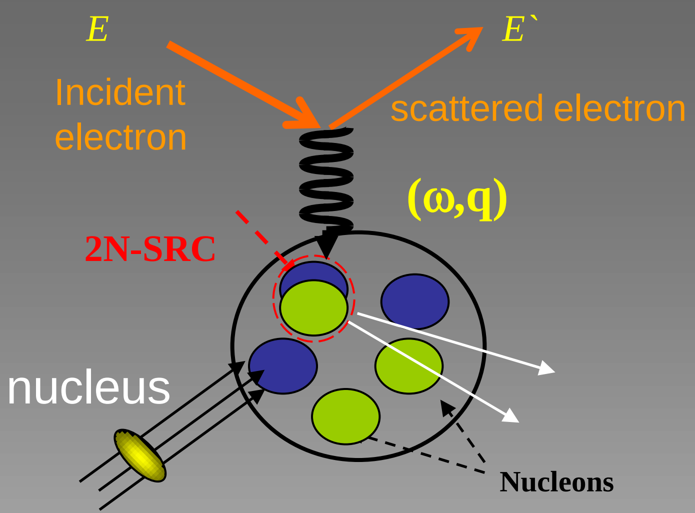
Solution: For fixed high Q^2 and $x_B>1$, x_B determines a minimum p_i



Prediction by Frankfurt, Sargsian, and Strikman:



A(e,e') Kinematics



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

$$\omega = E' - E$$

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

(just kinematics!)

DIS off a nucleon: $0 \le x_B \le 1$

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

HARD KNOCKOUT REACTIONS

$0 \le x_B \le A$

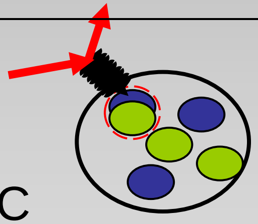
For large Q^2:

x_B counts the number of hadrons involved

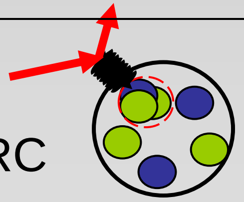
$x_B > j \;\Rightarrow$ at least $j+1$ nucleons

If exactly $j+1$ nucleons $\Rightarrow \frac{\sigma_A}{\sigma_{j+1}}$ scales

$x_B > 1$ 2N-SRC



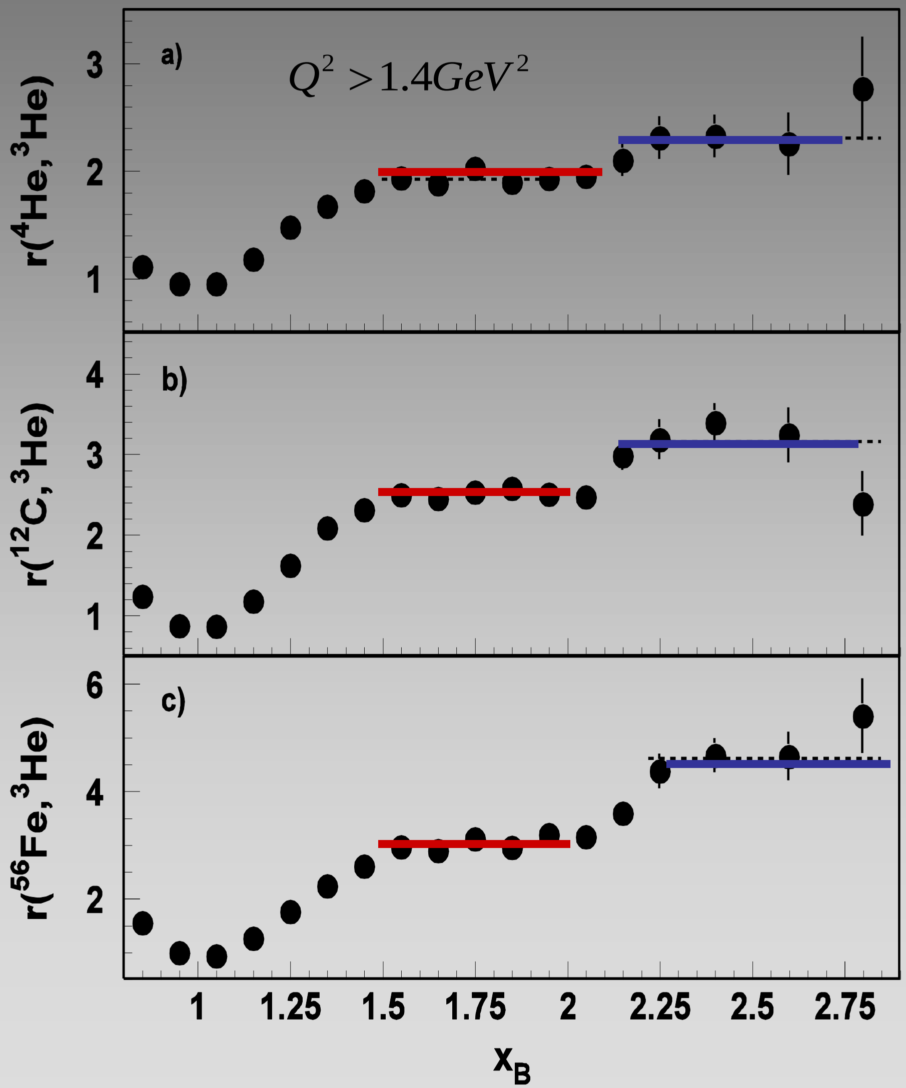
$x_B > 2$ 3N-SRC



JLab. CLAS A(e,e') Result

K. Sh. Egiyan et al. PRC 68, 014313 (2003)

K. Sh. Egiyan et al. PRL. 96, 082501 (2006)



The observed "scaling" means that the electrons probe the high-momentum nucleons in the 2(3) -nucleon phase, and the scaling factors determine the per-nucleon probability of the 2(3) N-SRC phase in nuclei with A>3 relative to ^3He.

For ^{12}C 2N-SRC (np, pp, nn) = 20 ± 4.5%.

The probabilities for 3-nucleon SRC are smaller by one order of magnitude relative to the 2N SRC.

More r(A,d) data:

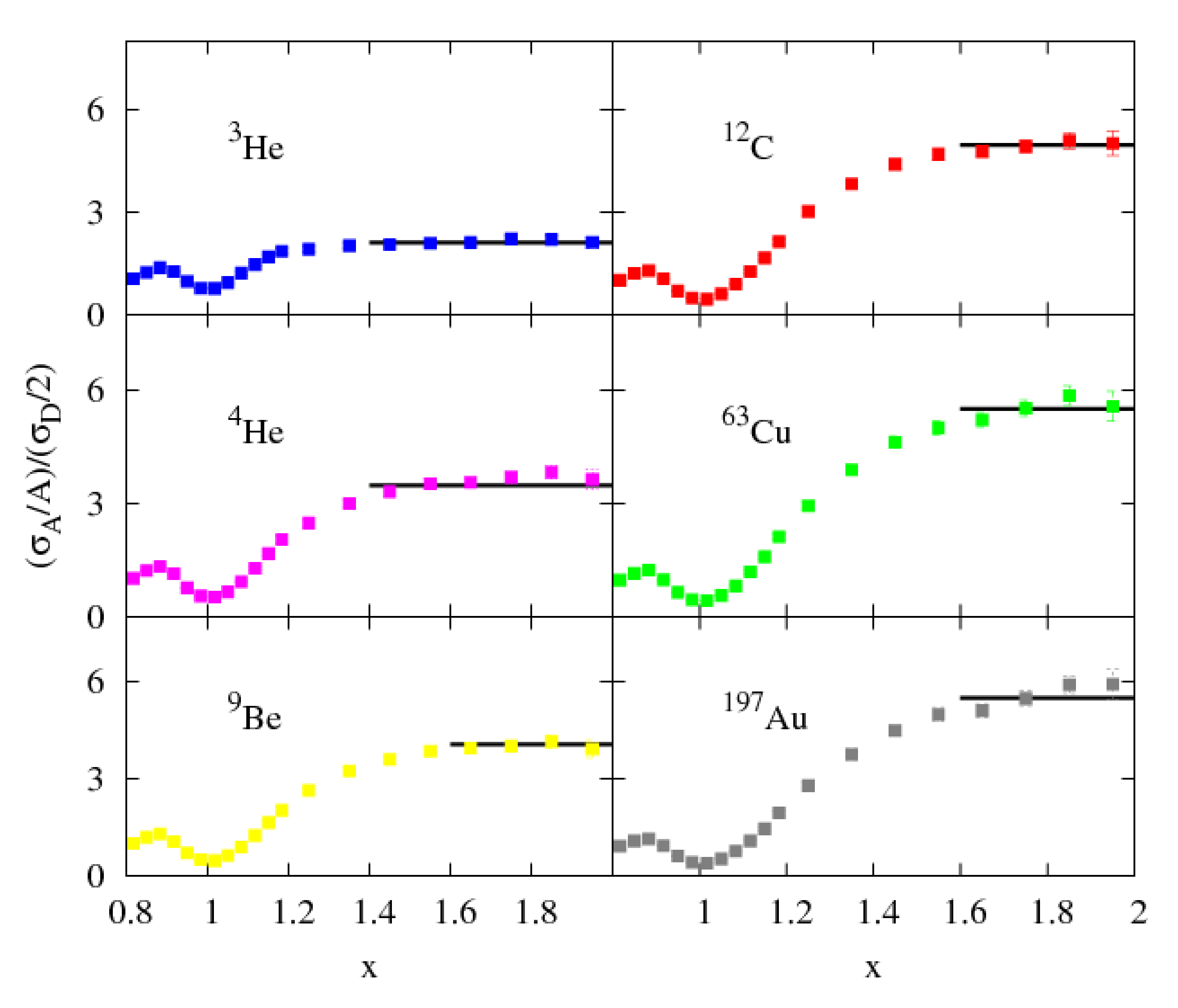
SLAC D. Day et al. PRL 59,427(1987)

JLab. Hall C E02-019

New Preliminary Results from JLab Hall C (E02-019)

Q^2=2.5GeV^2

a_{2N}(A/d)	
^{3}He	2.08±0.01
^{4}He	3.47±0.02
Be	4.03±0.04
C	4.95±0.05
Cu	5.48±0.05
Au	5.43±0.06

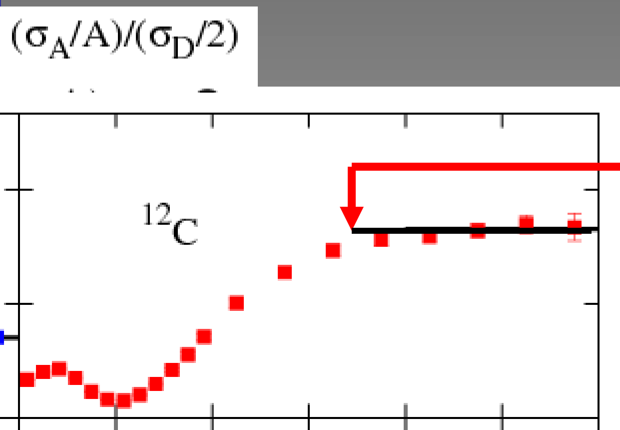


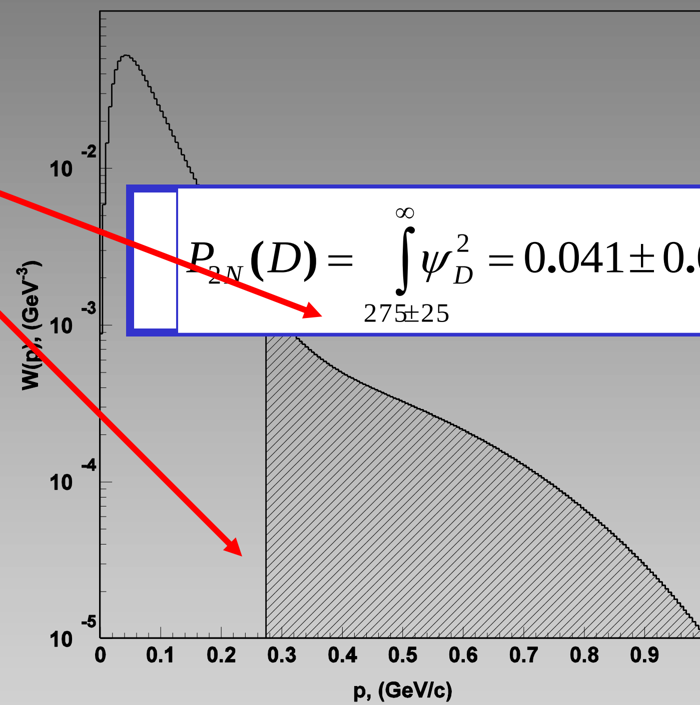
Estimate the amount of 2N-SRC in nuclei

This includes all three isotopic compositions (pn, pp, or nn) for the 2N-SRC phase in ^{12}C.

$a_{2N}(A/d)$

p_{min}





$$P_{2N}(D) = \int_{275\pm25}^{\infty} \psi_D^2 = 0.041 \pm 0.008$$

$a_{2N}(A/d)$	
^3He	2.08±0.01
^4He	3.47±0.02
Be	4.03±0.04
C	4.95±0.05
Cu	5.48±0.05
Au	5.43±0.06

$$P_{2N}(A) = a_{2N}(A/d) \cdot P_{2N}(D)$$

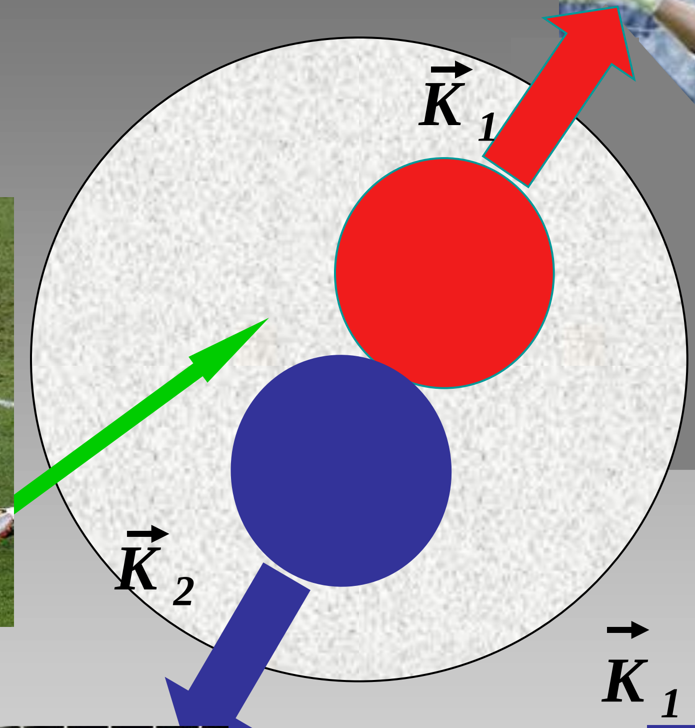
calculations

measurement

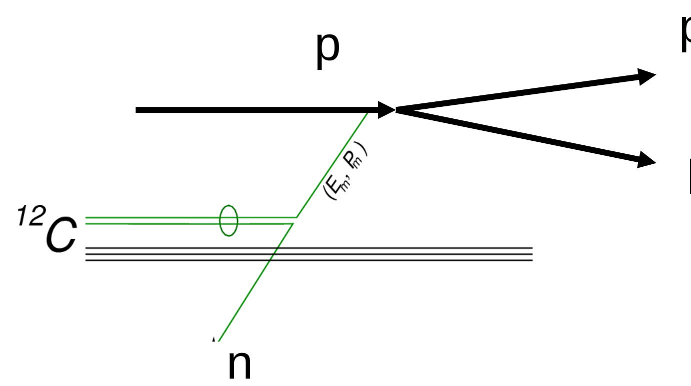
For Carbon:

$$P_{2N}(^{12}C) = 5 \cdot 4\% \approx 20\%$$

A triple – coincidence measurement
"Redefine" the problem in momentum space



EVA / BNL



$K_1 > K_F$,

$K_2 > K_F$

K_F ~250 MeV/c

$\vec{K}_1 \cong -\vec{K}_2$

E01-015 / Jlab (E07-006)

A pair with "large" relative momentum between the nucleons and small CM momentum.

Why several GeV and up protons are good probes of SRC ?

- They have small deBroglie wavelength:

$\lambda = h/p = hc/pc = 2\pi \bullet 0.197$ GeV-fm/(6 GeV) ≈ 0.2 fm.

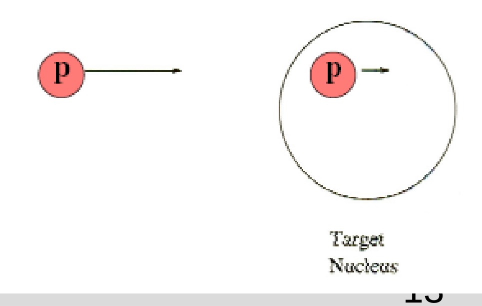
- Large momentum transfer is possible with wide angle scattering.

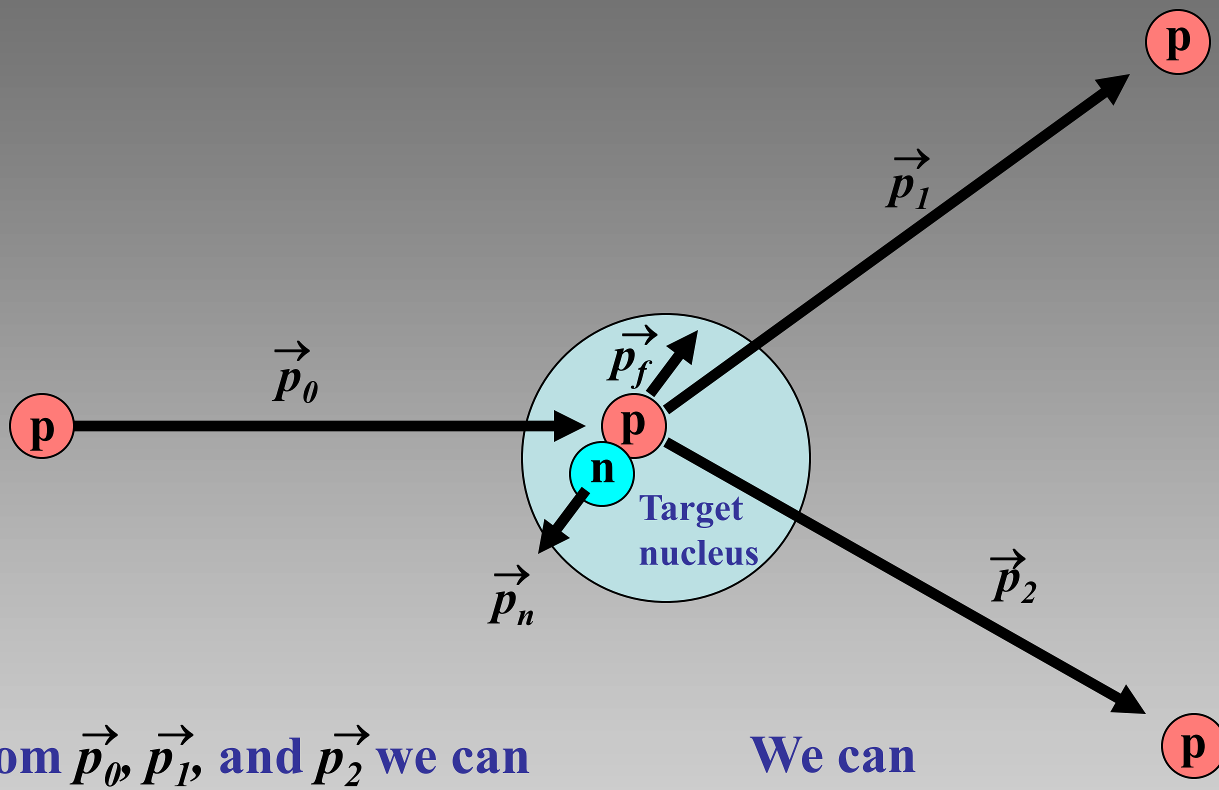
- The s^{-10} dependence of the p-p elastic scattering preferentially selects high momentum nuclear protons.

For pp elastic scattering near 90^0 cm

$$\frac{d\sigma}{dt} \propto s^{-10}$$

QE pp scattering near 90^0 has a very strong preference for reacting with forward going high momentum nuclear protons.





From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the binding energy of each knocked-out proton is.

We can then compare $\vec{p}_n$ with $\vec{p}_f$ and see if they are roughly "back to back."

$^{12}C(p, p'pn)$ measurements at EVA / BNL

A. Tang et al. Phys. Rev. Lett. 90 ,042301 (2003)

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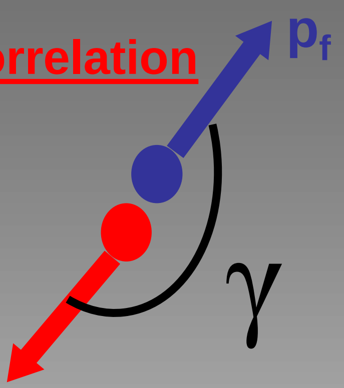
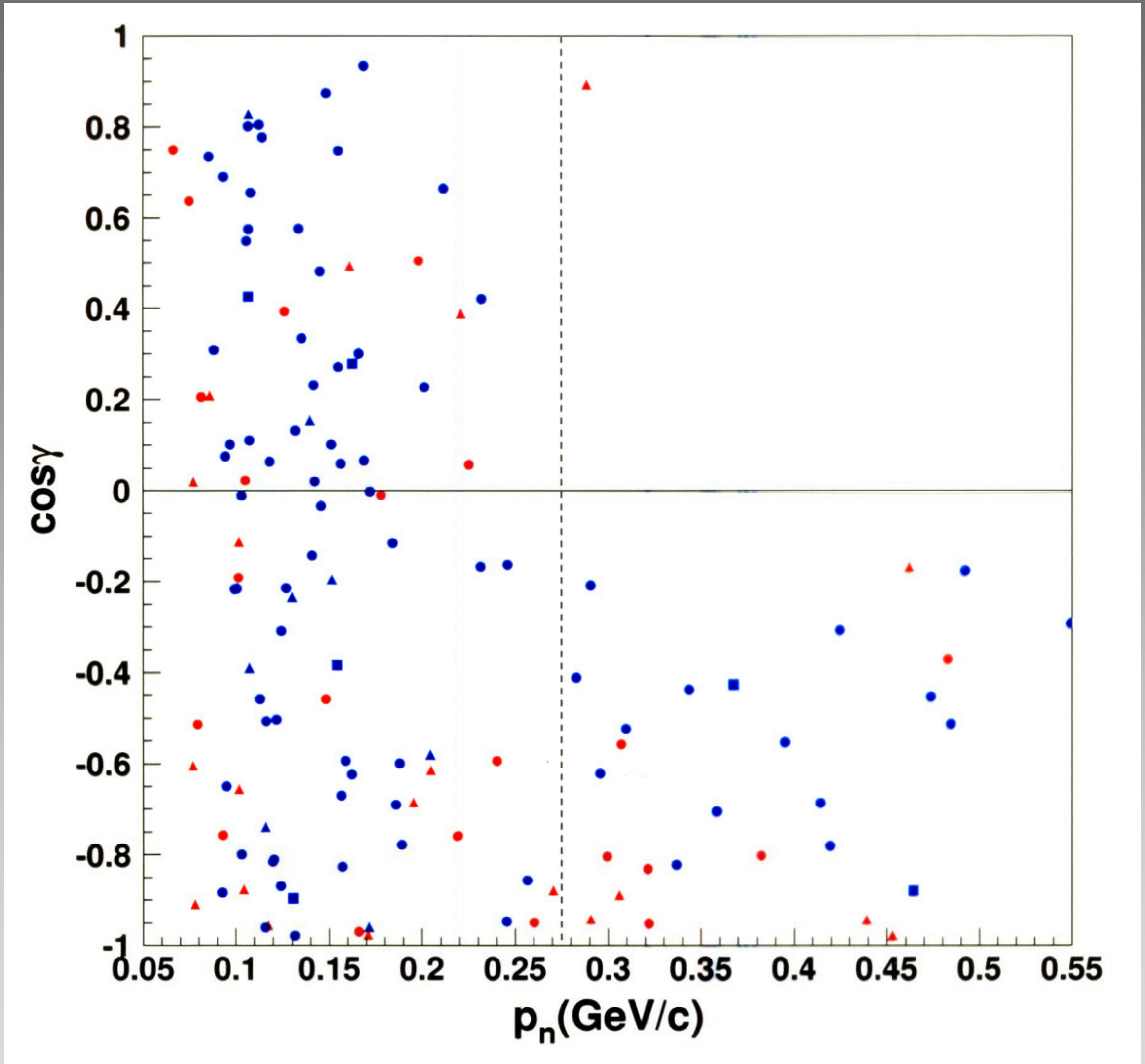


Piasetzky, Sargsian, Frankfurt, Strikman, Watson **PRL 162504(2006).**

Removal of a proton with momentum above 275 MeV/c from ^{12}C is **$92\pm^{8}_{18}$ %** accompanied by the emission of a neutron with momentum equal and opposite to the missing momentum.

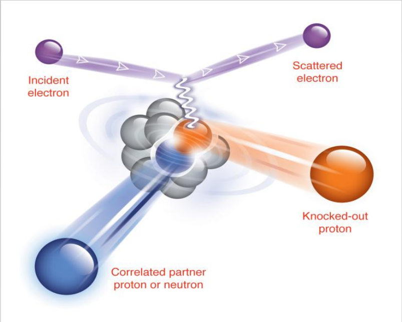


σ_{CM}=0.143±0.017 GeV/c

JLab Hall A EXP 01-015

- Identify pp-SRC pairs in nuclei. (e, e’ p p)
- Determine the abundance of pp-SRC pairs. (e, e’ p p) / (e, e’ p)
- Verify the abundance of np-SRC pairs as determined by the EVA / BNL experiment. (e, e’ p n) / (e, e’ p)
- Determine the pp-SRC / np-SRC ratio. (e, e’ p p) / (e, e’ p n)

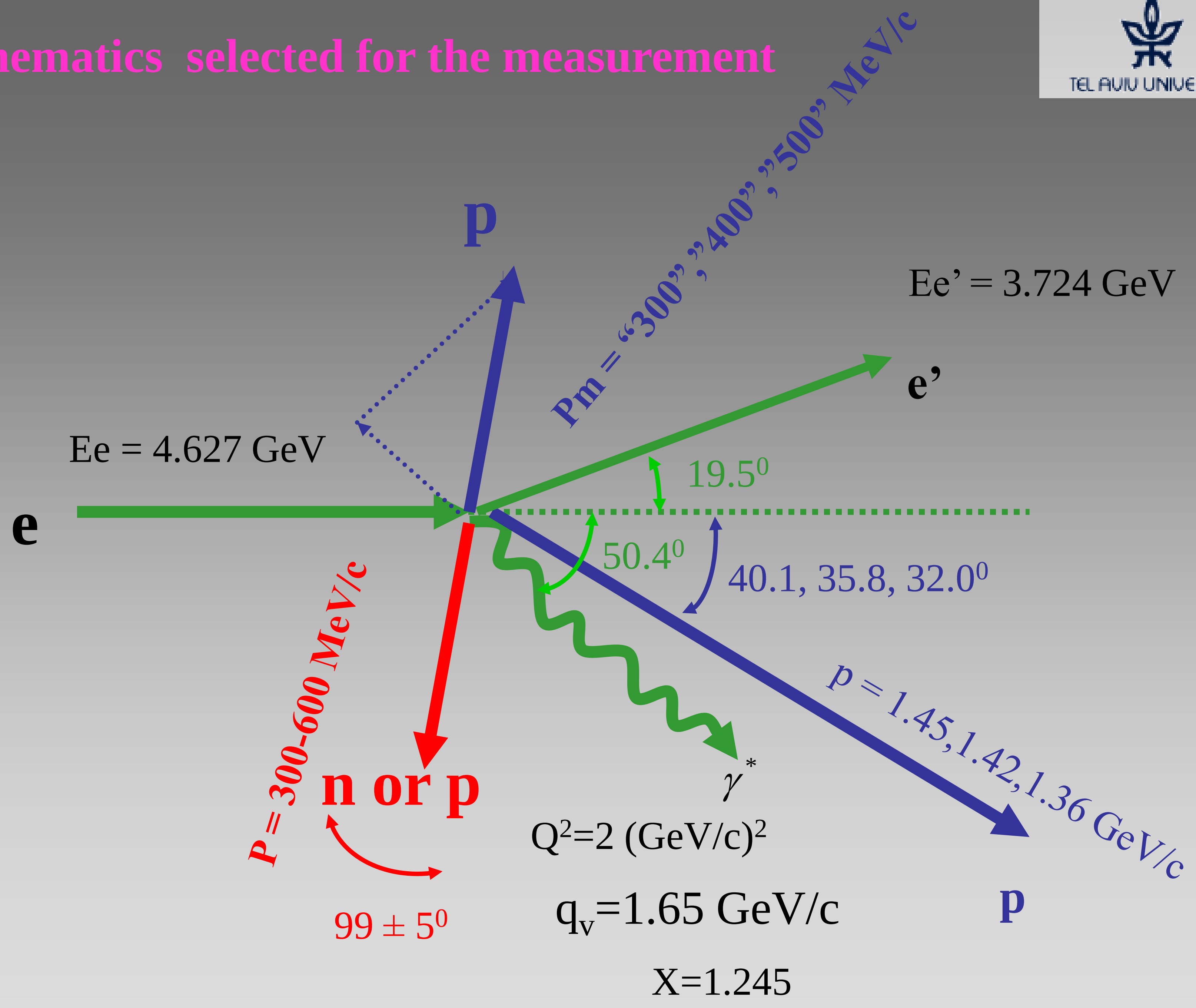
It is important to identify pp-SRC pairs and to determine the pp-SRC/np-SRC ratio since they can tell us about the isospin dependence of the strong interaction at short distance scale.



E01-015 ⇒

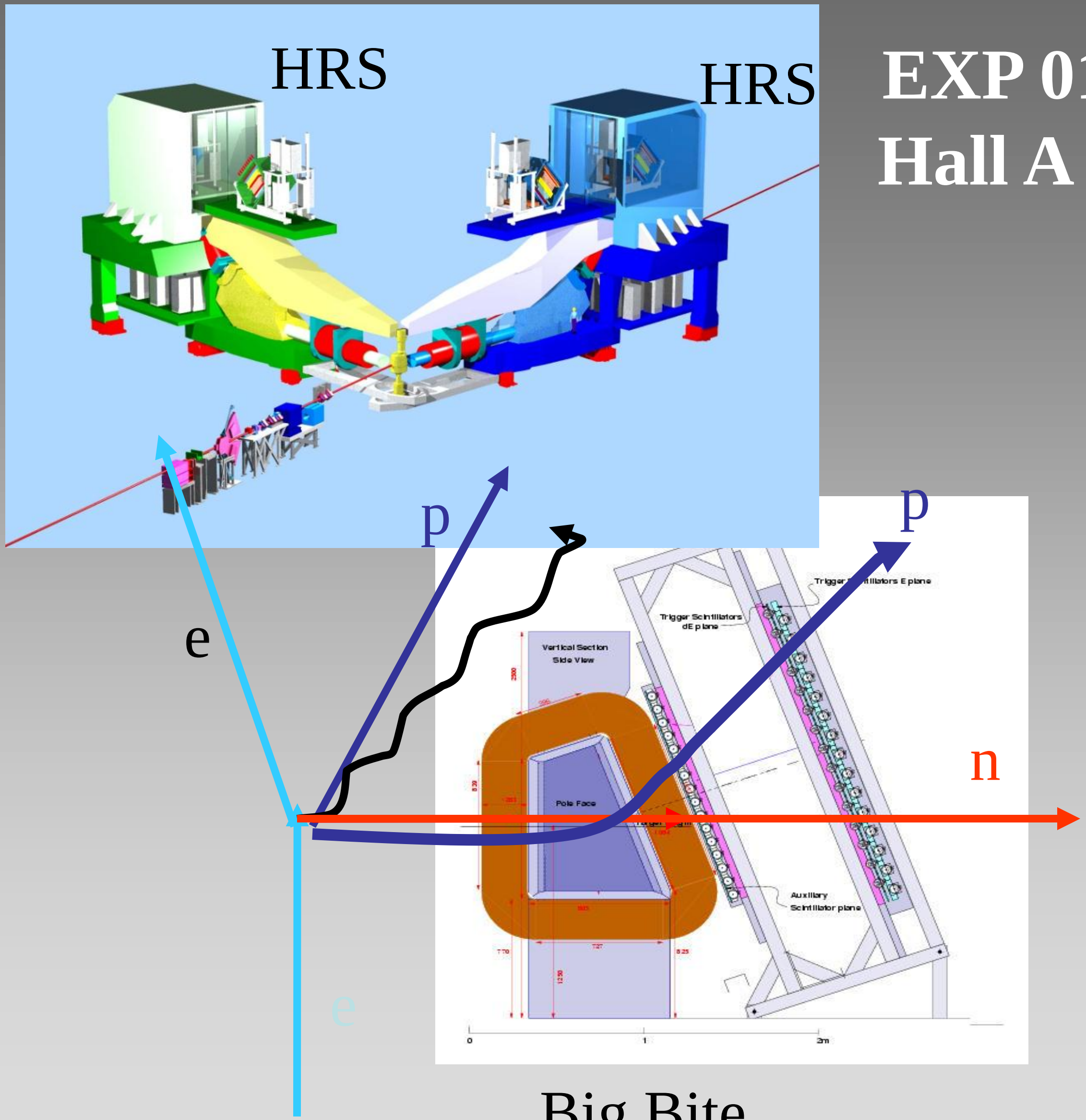
Simultaneous measurements of the .
(e,e’ p) , (e, e’ p p), and (e, e’ p n) reactions.

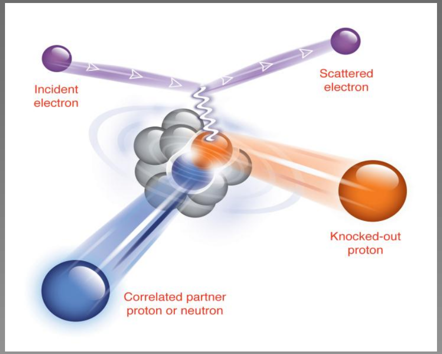
The kinematics selected for the measurement



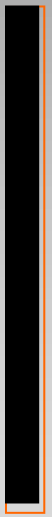
Simultaneous measurements of the . (e,e' p) , (e, e' p p), and (e, e' p n) reactions.

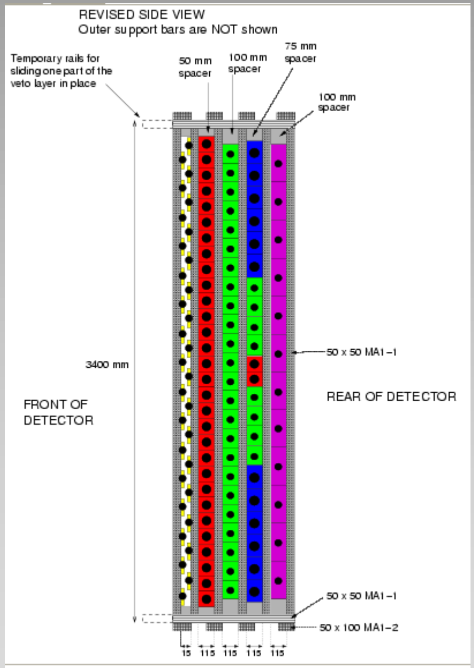
EXP 01-015
Hall A JLab





n array

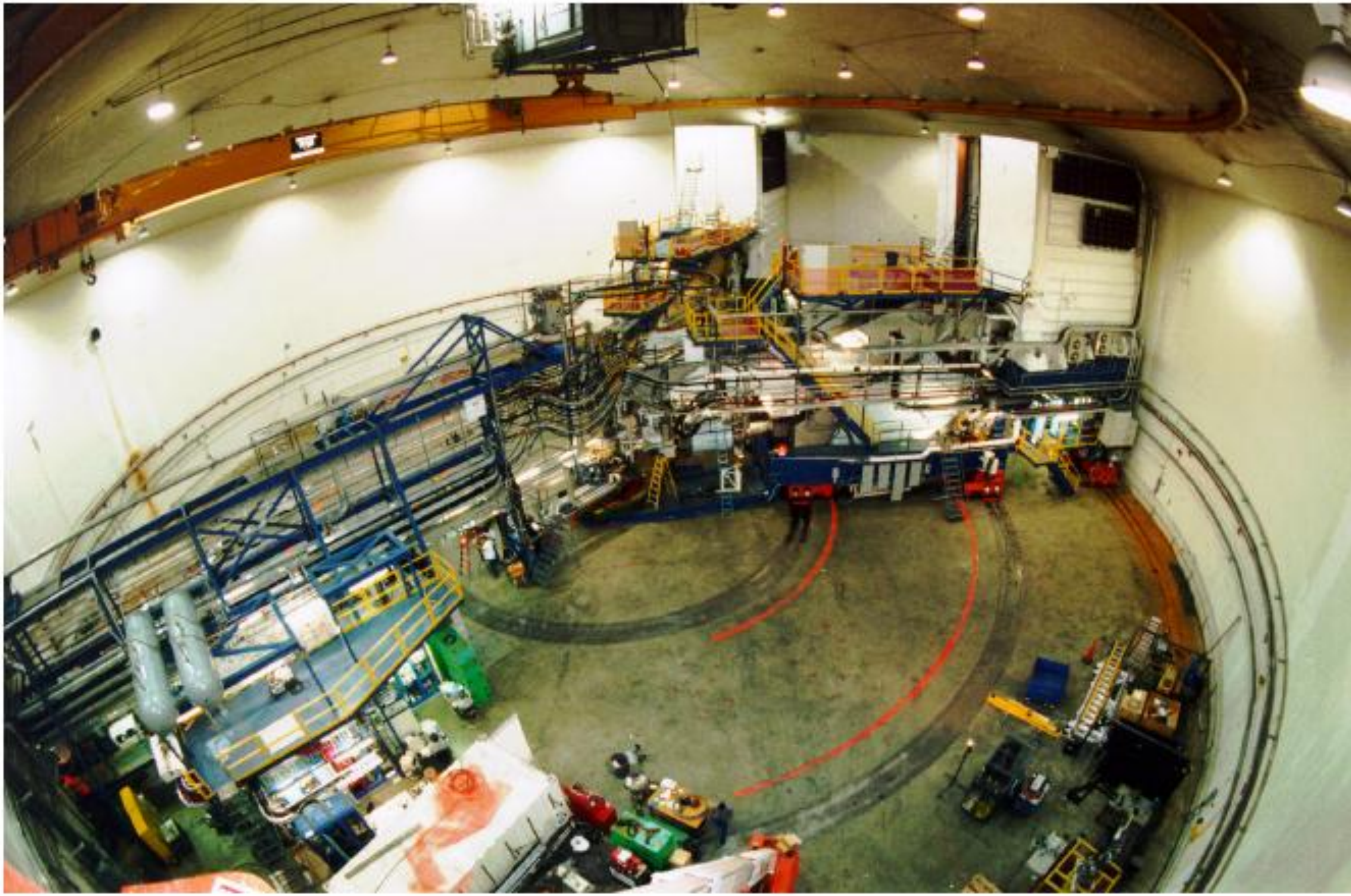




Big Bite

Lead wall

Jefferson Lab's Hall A



HAND -The Hall A neutron detector

The Big Bite spectrometer

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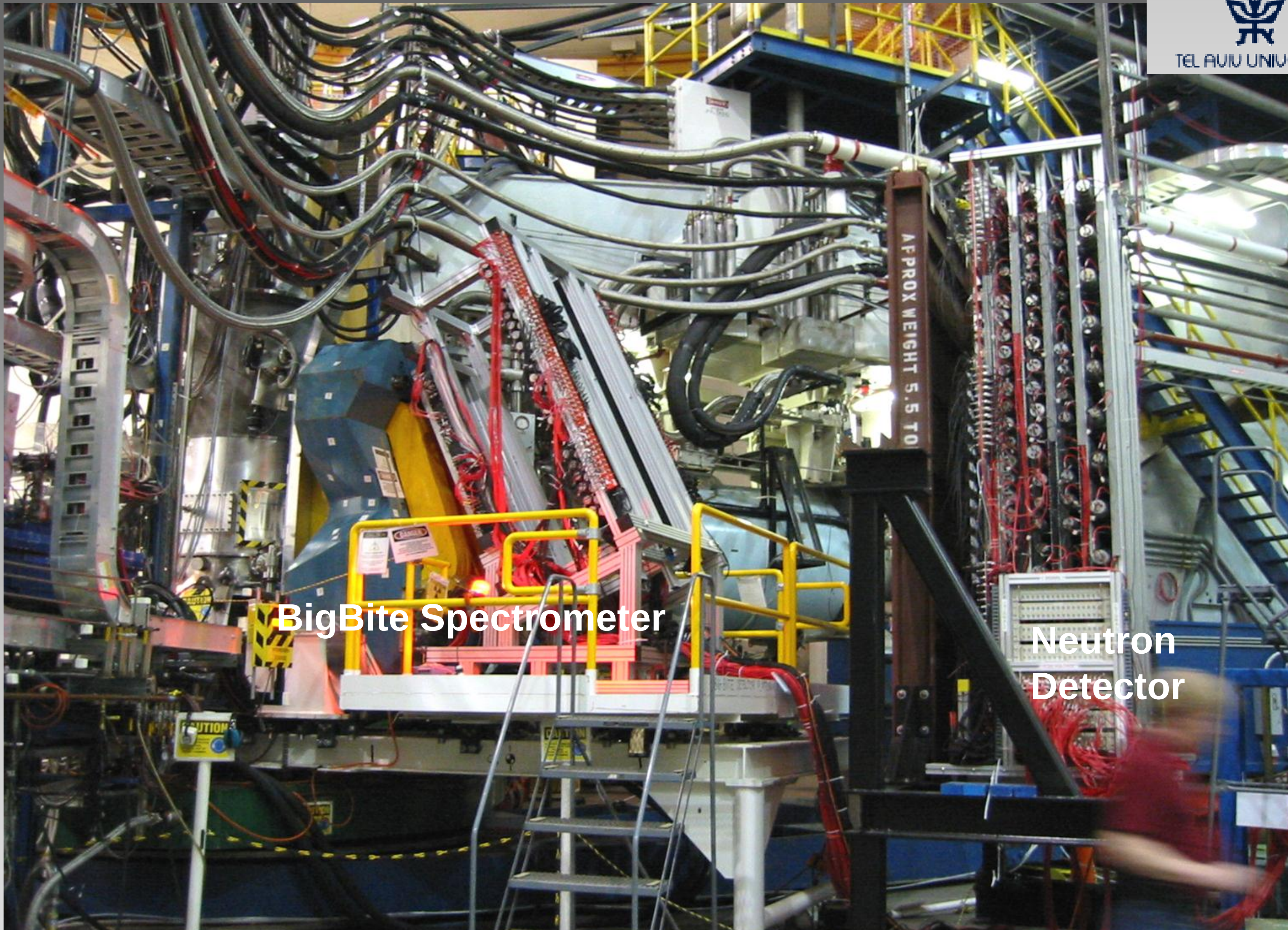

EXP 01-015 **Jlab / Hall A** Dec. 2004 – Apr. 2005

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

$x_B>1$

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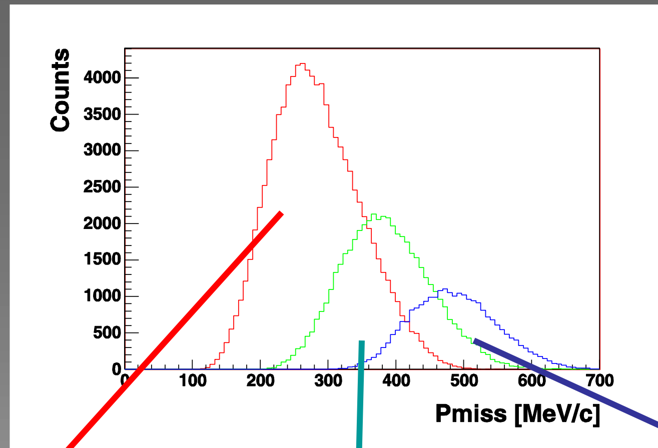
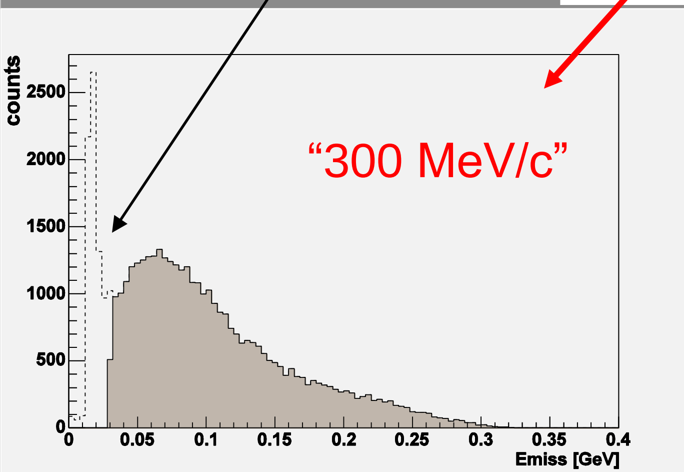


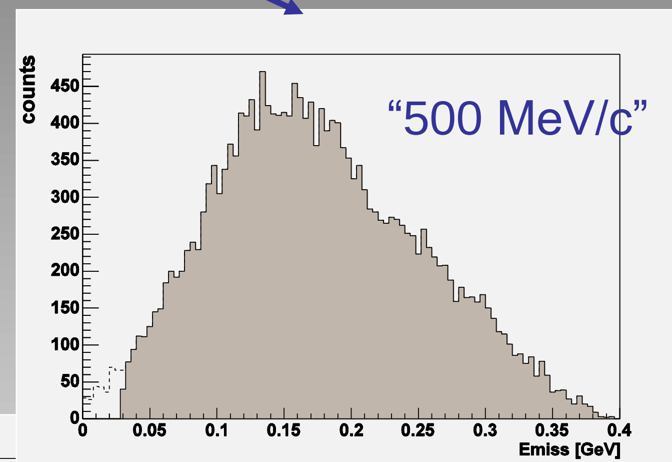
"300 MeV/c"

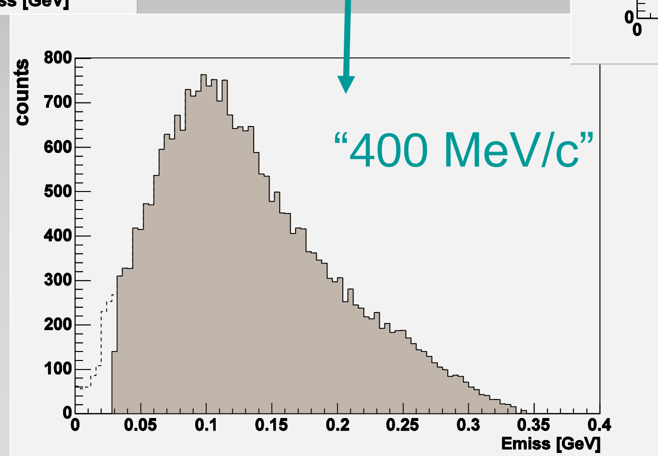
"400 MeV/c"

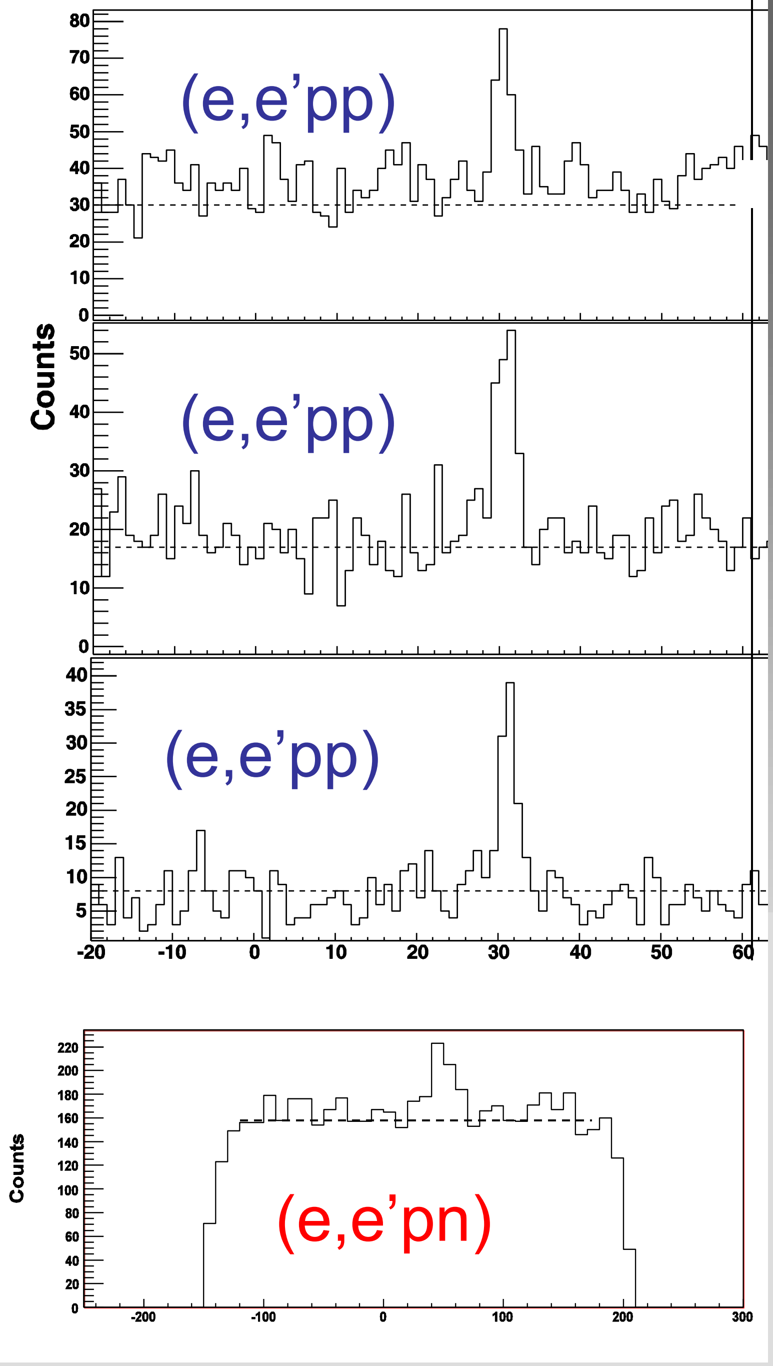
"500 MeV/c"

$^{12}C(e,e'p)^{11}B$









TOF [ns]

P_{mis}=“300” MeV/c

(Signal : BG= 1.5:1)

P_{mis}=“400” MeV/c

(Signal : BG= 2.3:1)

P_{mis}=“500” MeV/c

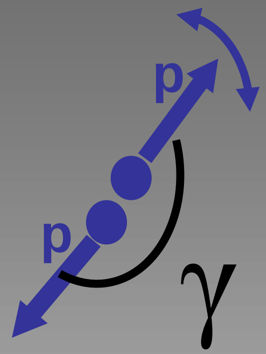
(Signal : BG= 4:1)

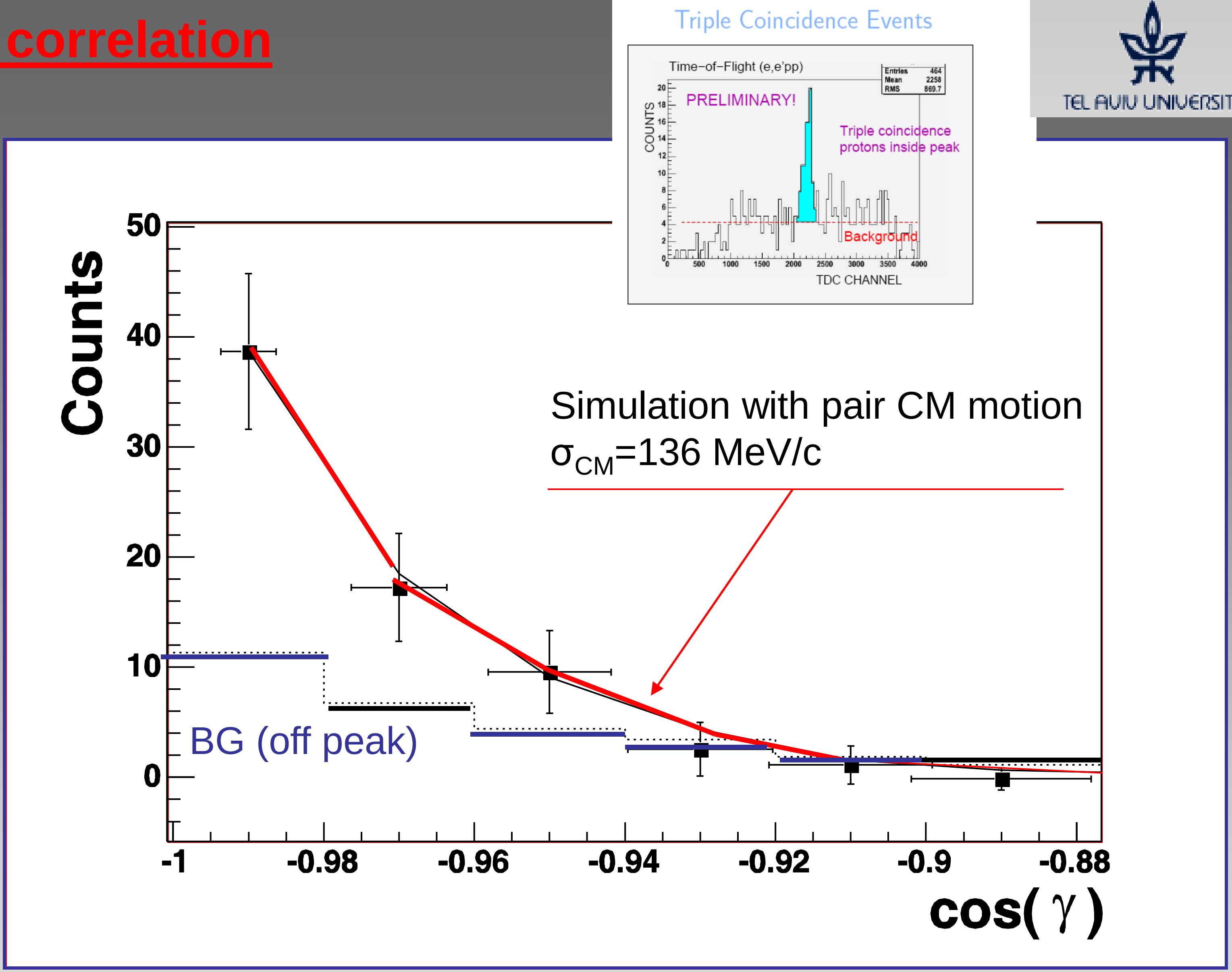
P_{mis}=“500” MeV/c

(Signal : BG= 1:7)

Directional correlation

$^{12}C(e,e'pp)$



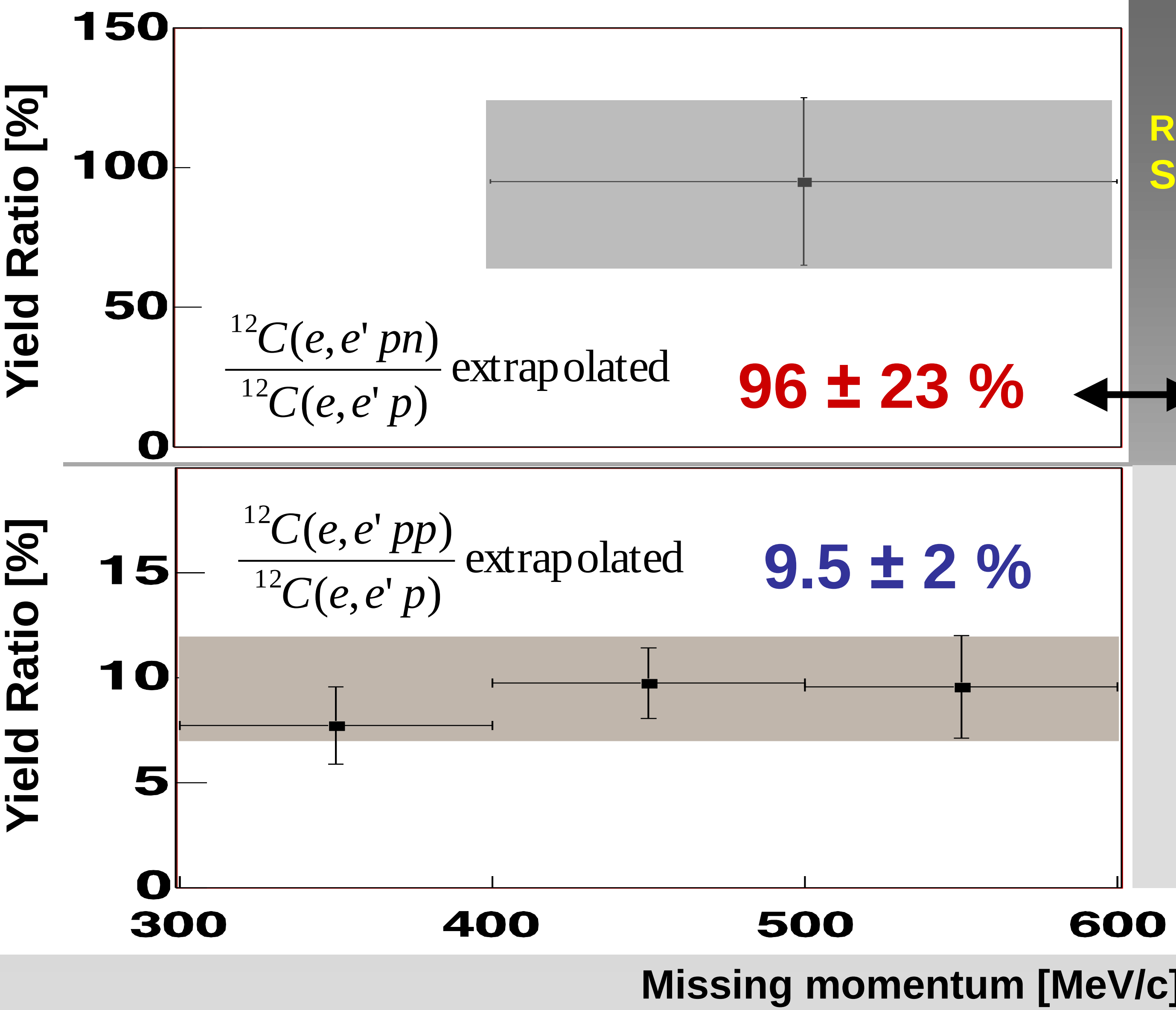


Measured 2 components of $\vec{p}_{c.m}$ and 3 kinematical setups => σ_{CM}=0.136 ± 0.020 GeV/c

(p,2pn) experiment at BNL : σ_{CM}=0.143±0.017 GeV/c

Theoretical prediction (Ciofi and Simula) : σ_{CM}=0.139 GeV/c

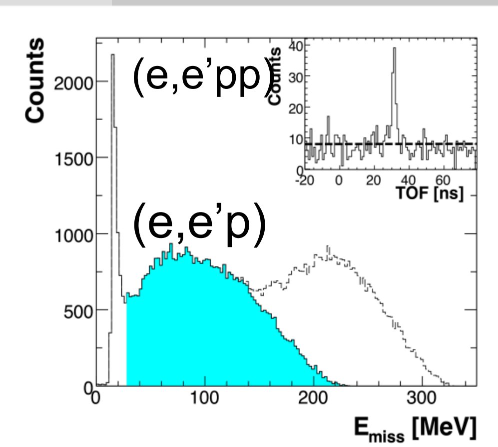
EXP 01-015 / Jlab



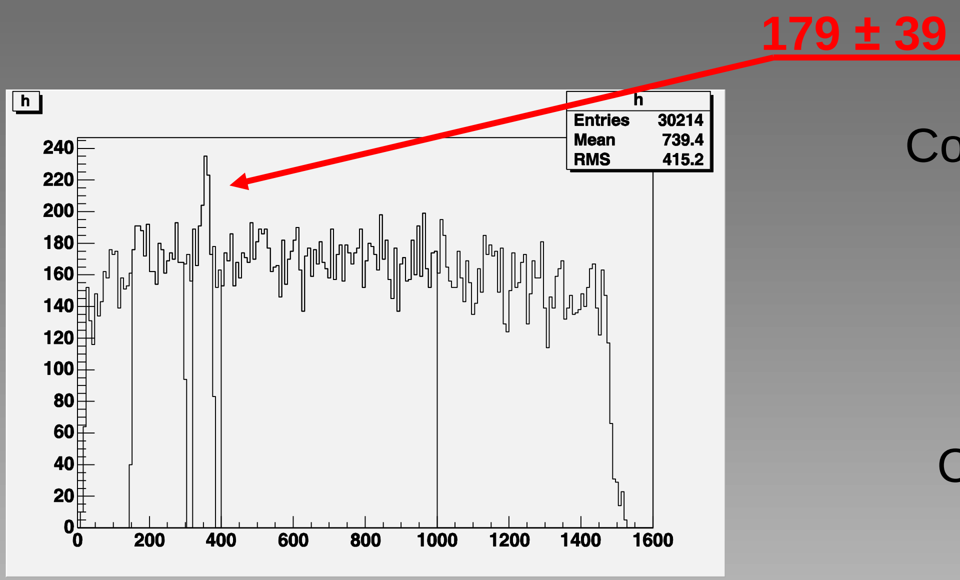
R. Subedi et al.,
Science 320 (2008) 1476

BNL Experiment measurment was $92^{+8}_{-18}\%$

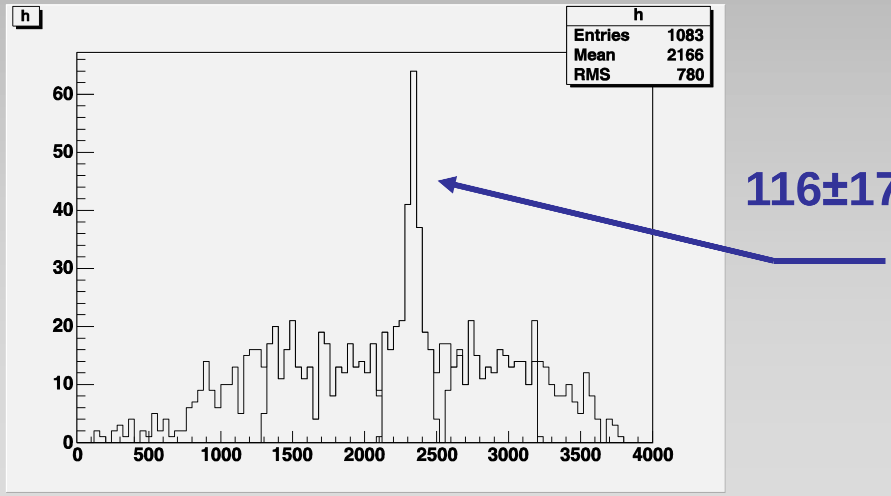
R. Shneor et al.,
PRL 99, 072501 (2007)



The (e, e'pn) / (e, e'pp) ratio



TOF for the neutrons [ns]



TOF for the protons [ns]

Corrected for detection efficiency:

$$\frac{^{12}C(e,e'pn)}{^{12}C(e,e'pp)} = 8.1 \pm 2.2$$

Corrected for SCX (using Glauber):

$$\frac{^{12}C(e,e'pn)}{^{12}C(e,e'pp)} = 9.0 \pm 2.5$$

In Carbon:

$$\frac{np-SRC}{pp-SRC} = 18.0 \pm 5$$

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

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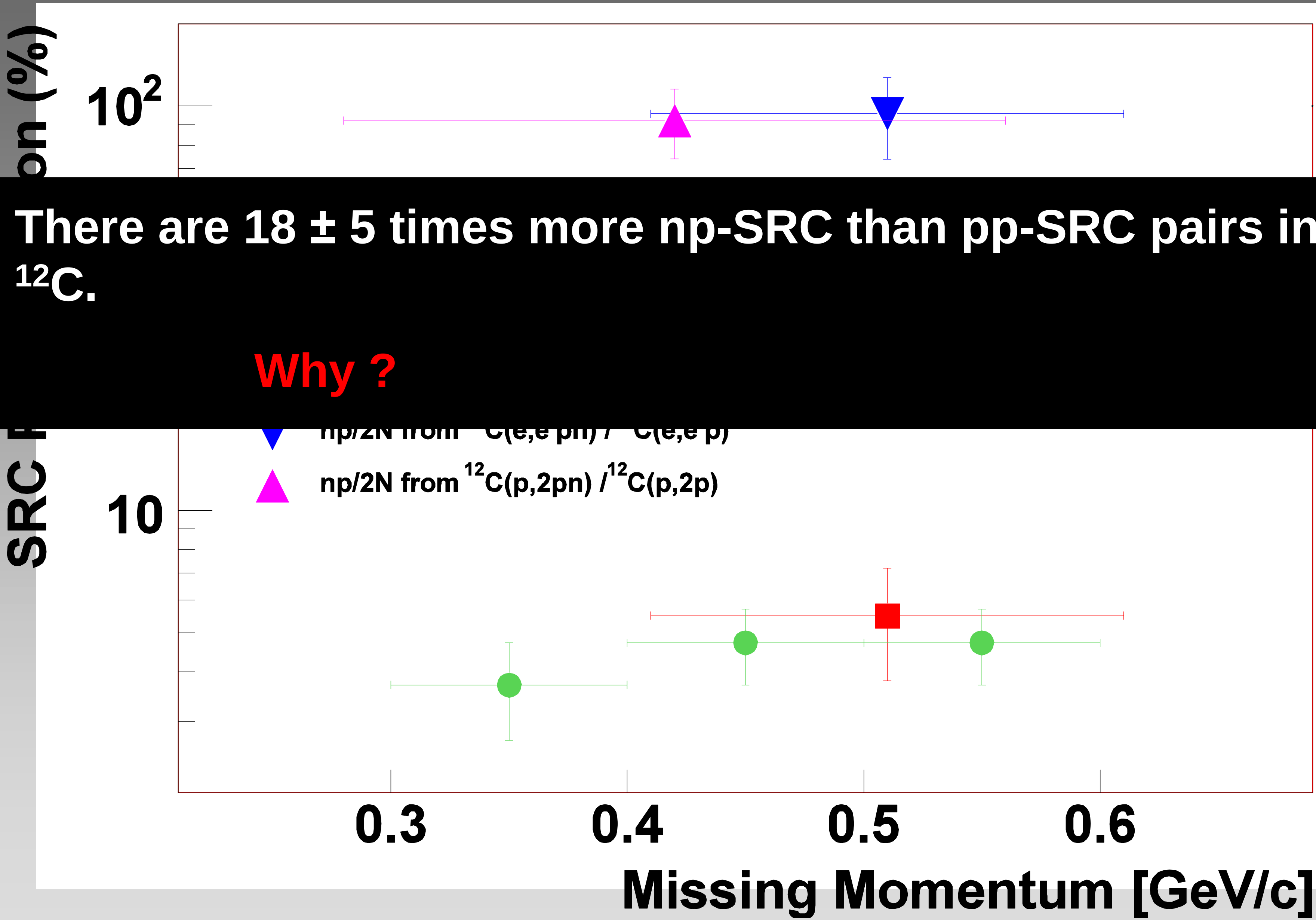
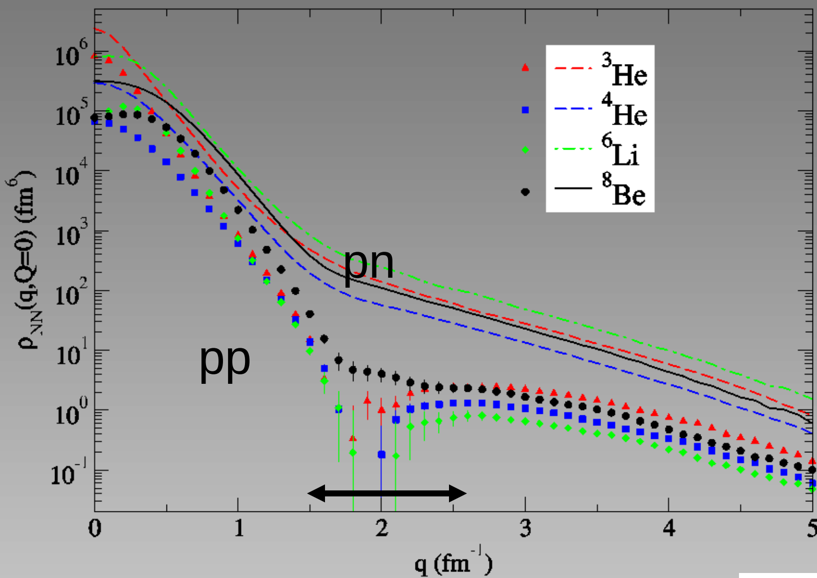


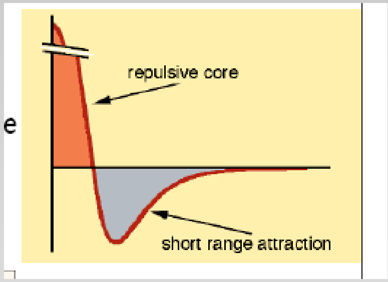
There are 18 ± 5 times more np-SRC than pp-SRC pairs in ^{12}C.

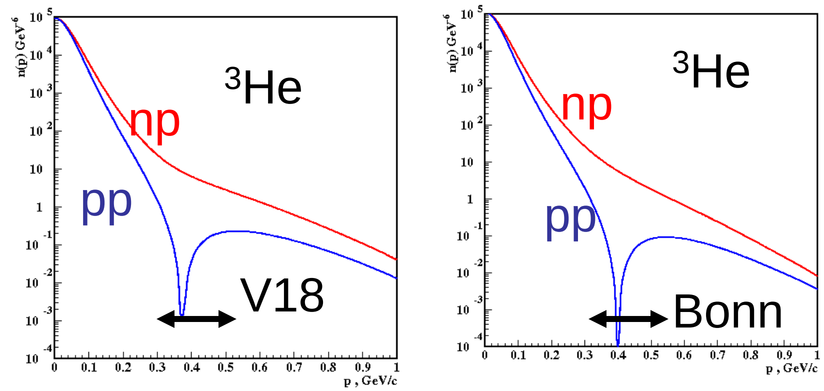
Why ?

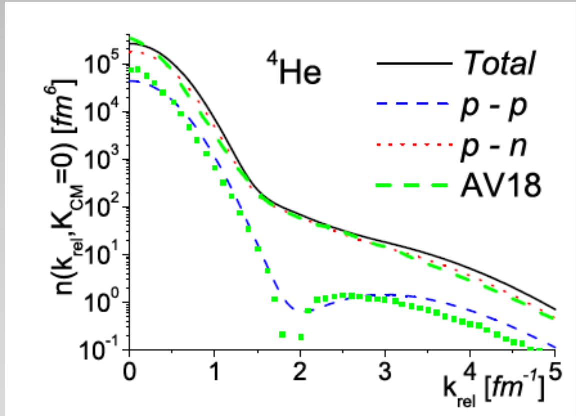
At 300-500 MeV/c there is an excess strength in the np momentum distribution due to the strong correlations induced by the tensor NN potential.



Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007).

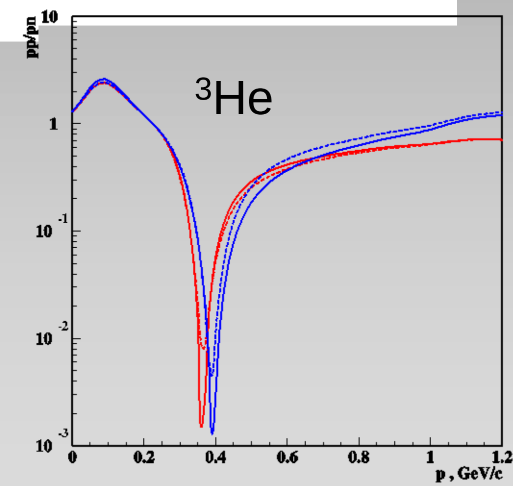






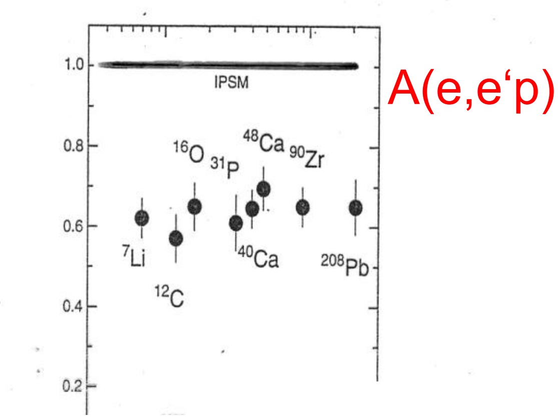
Ciofi and Alvioli PRL 100, 162503 (2008).

pp/np



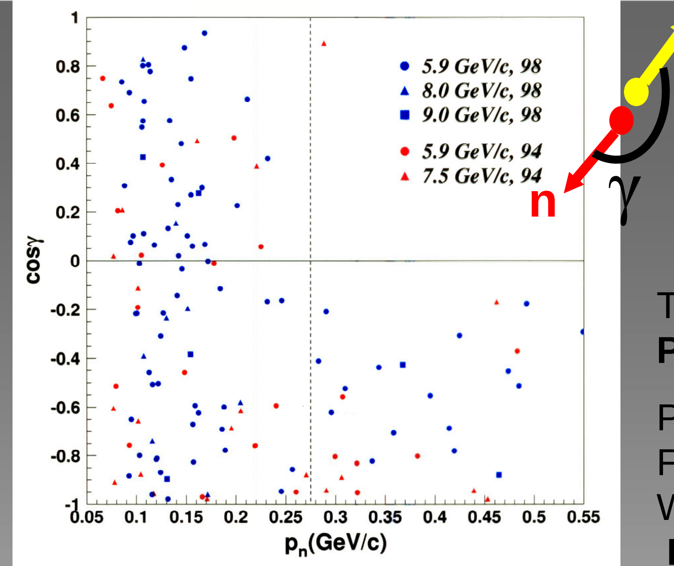
Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005).

Summary of Results



A(e,e'p)

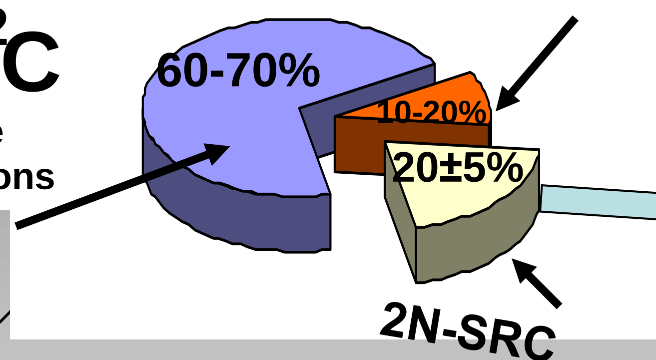
Long range (shell model) correlations

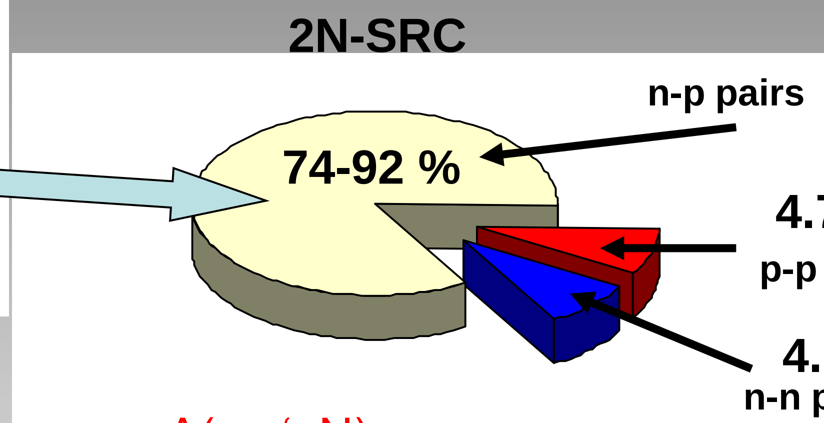


^{12}C(p,2p n)

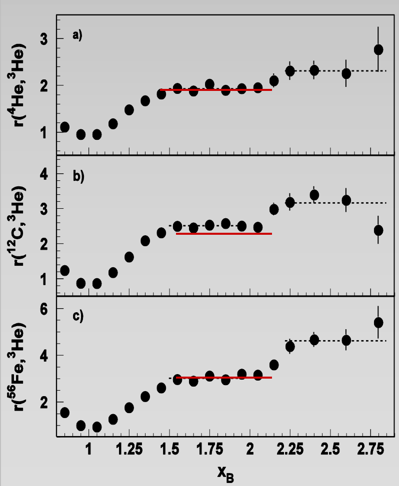
Tang et al.
PRL 042301 (2003)

Piasetzky, Sargsian, Frankfurt, Strikman, Watson
PRL 162504(2006).



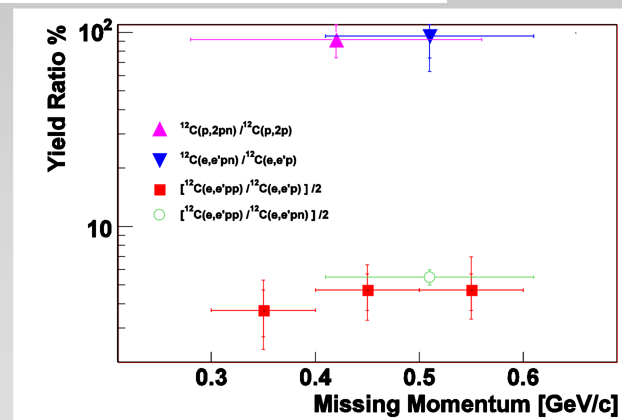


A(e,e'pN)



A(e,e')

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



Egiyan et al. **PRC 68, 014313.**
Egiyan et al. **PRL. 96, 082501 (2006)**

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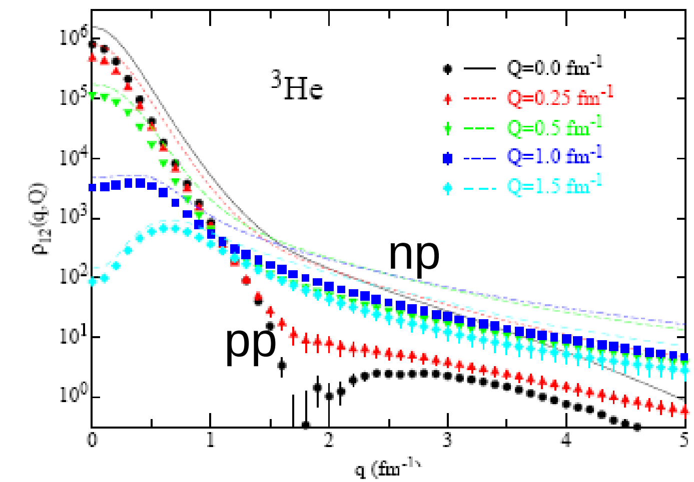
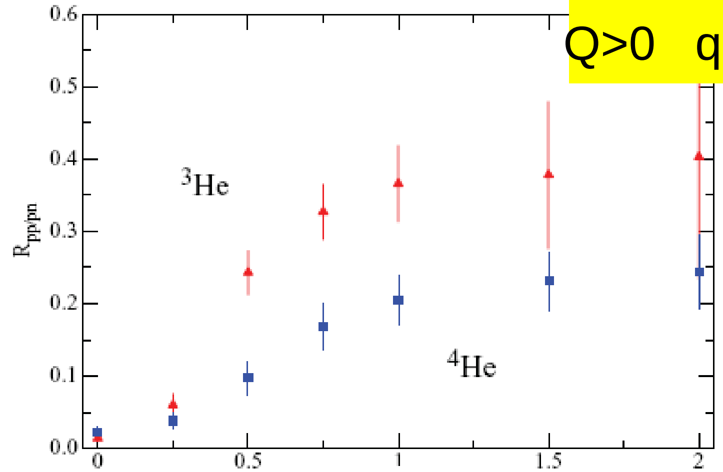
pp/pn ratio as a function of pair CM momentum

Q>0 q=300-500 MeV/c



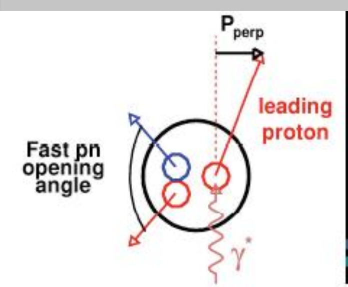
q (fm^{-1})

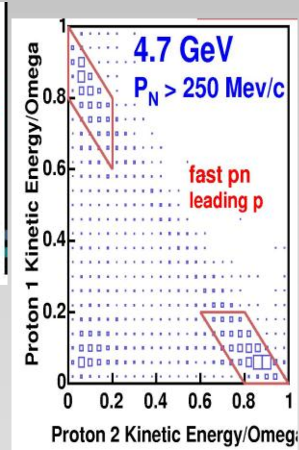


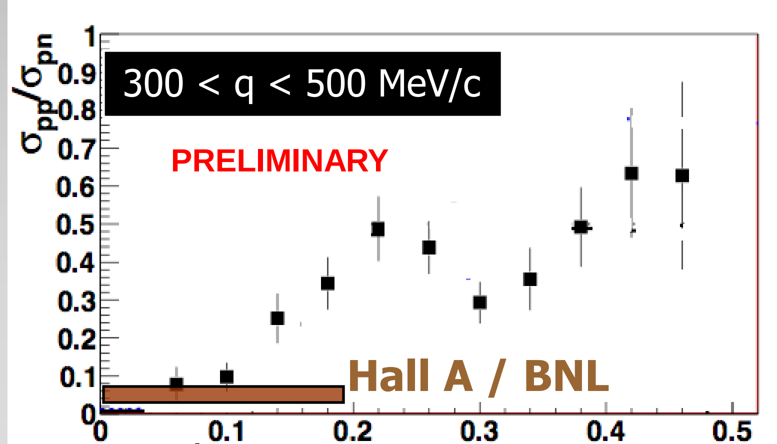
Q (fm^{-1})

Wiringa, Schiavilla, Pieper, Carlson **PRC** 78 021001 (2008)

Small Q ⇒ pp pair in s-wave ⇒ large tensor contribution ⇒ small pp/np ratio







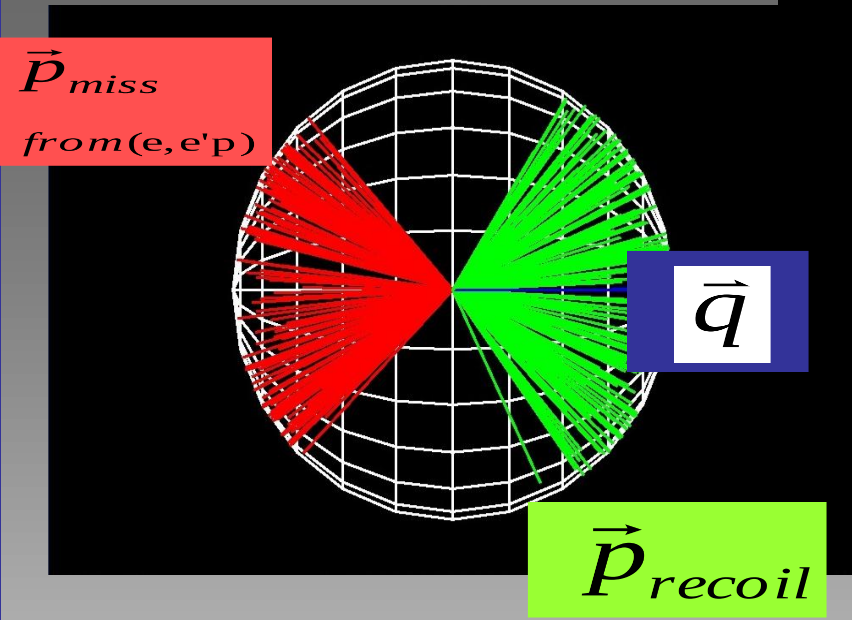
JLab / Hall B preliminary data

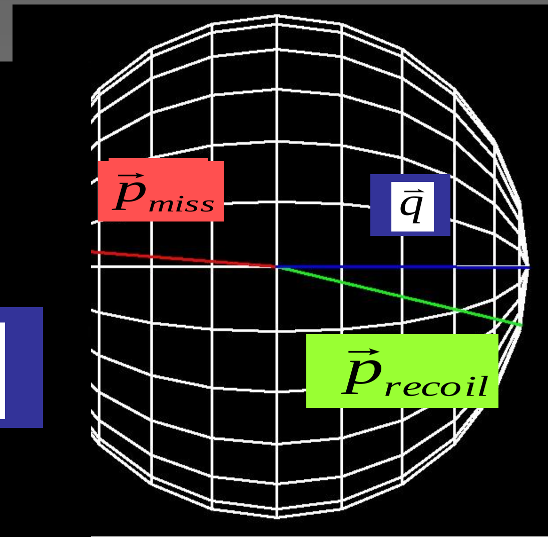
Thanks to

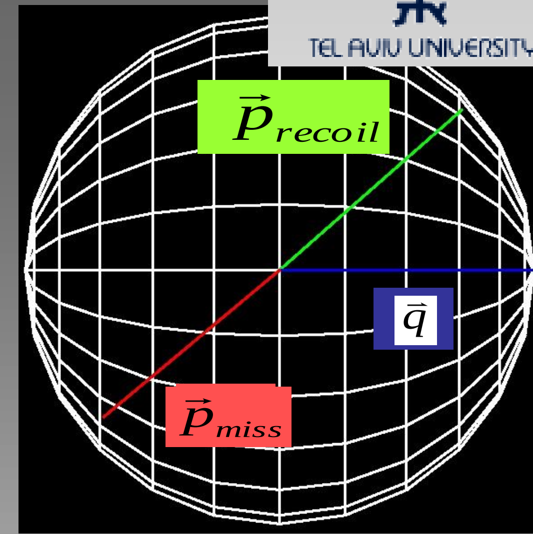
L. Weinstein

$$\frac{pp}{np} \approx \frac{1}{4}$$

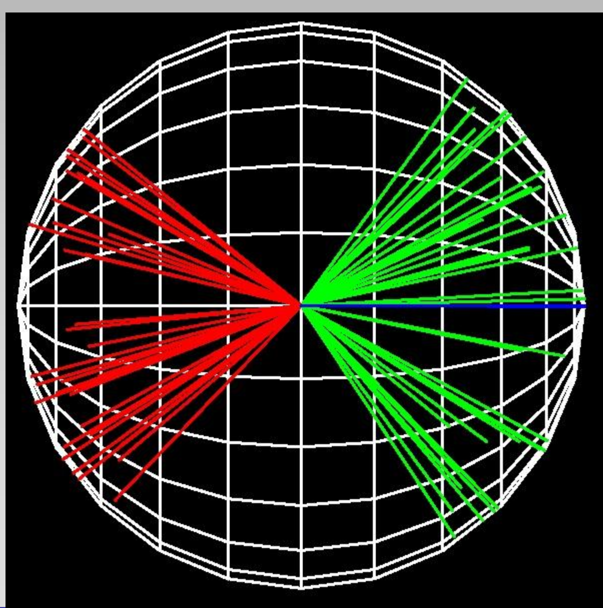
F_e(e,e'pp)

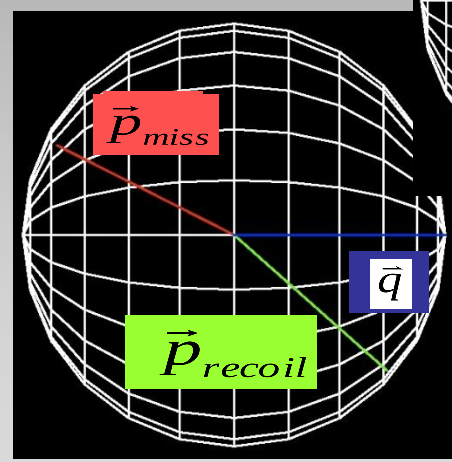


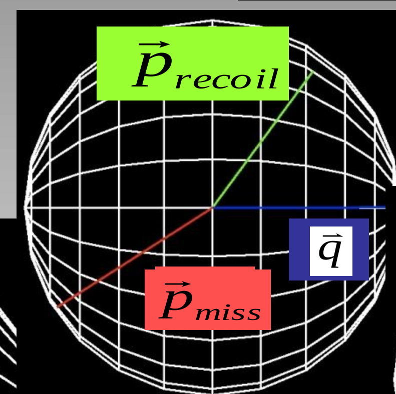


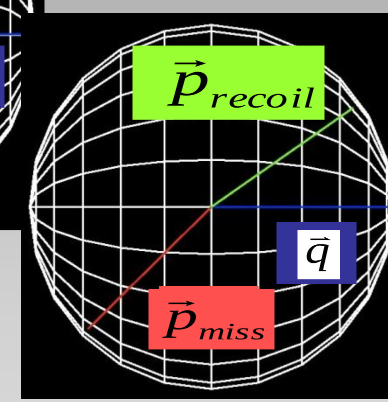


P_b(e,e'pp)







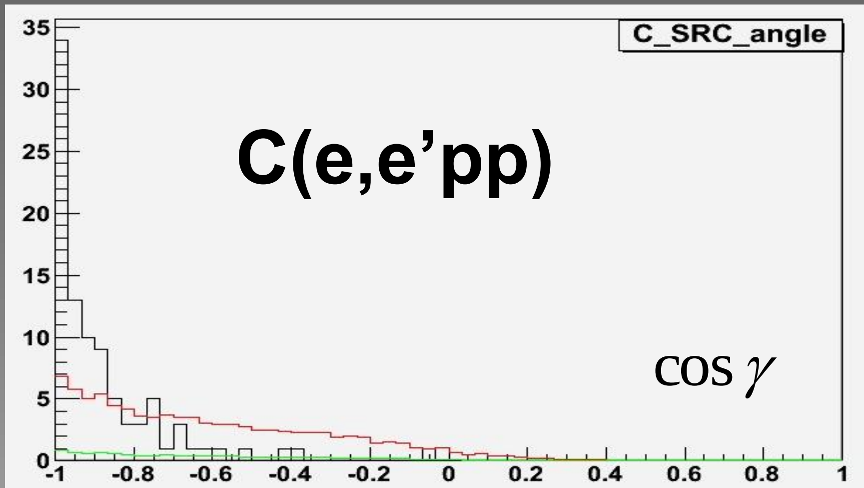


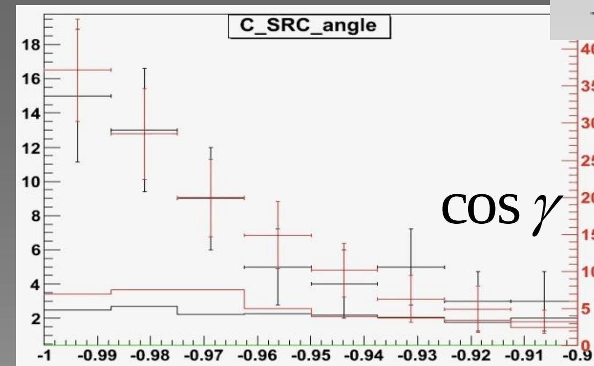
Ein =5.014 GeV

Q^2=2GeV/c^2 X>1.2

JLab / CLAS Data Mining, EG2 data set, Or Chen et al

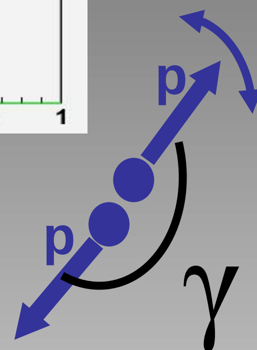
Directional correlation





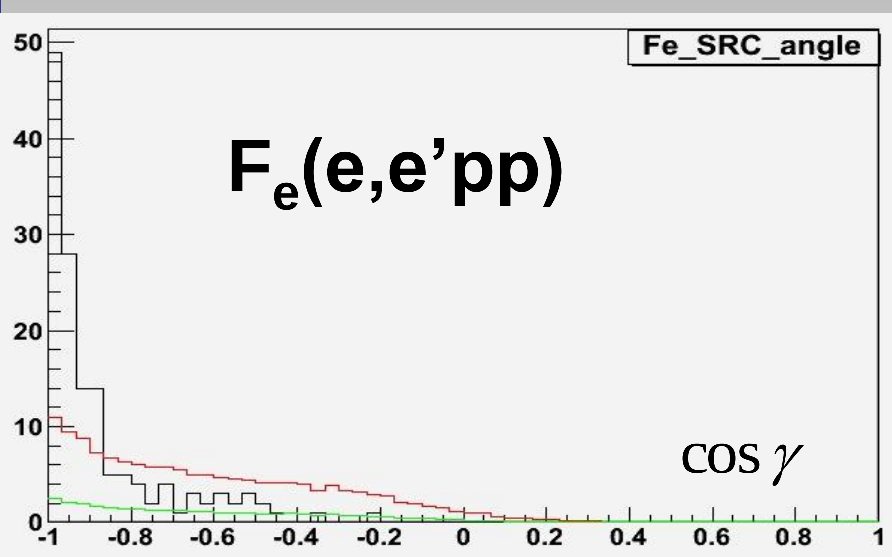
Hall A data PRL 99(2007)072501

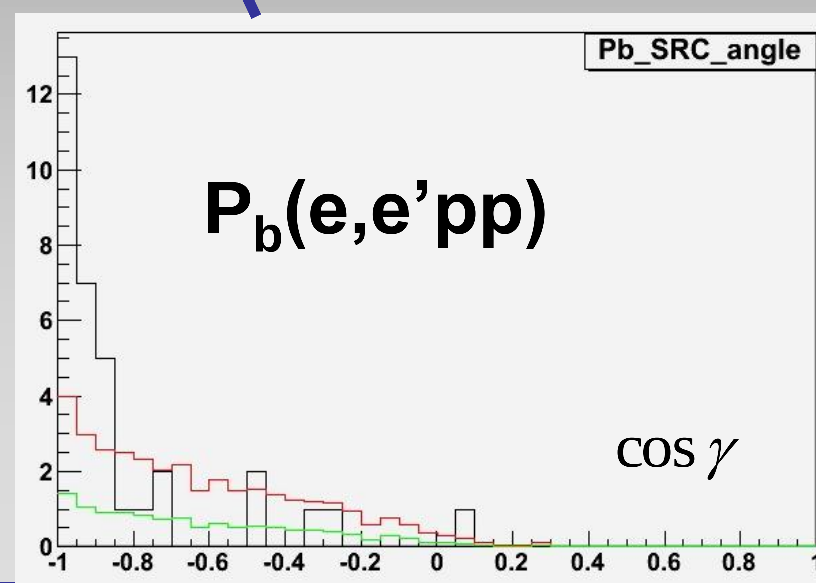
Hall B



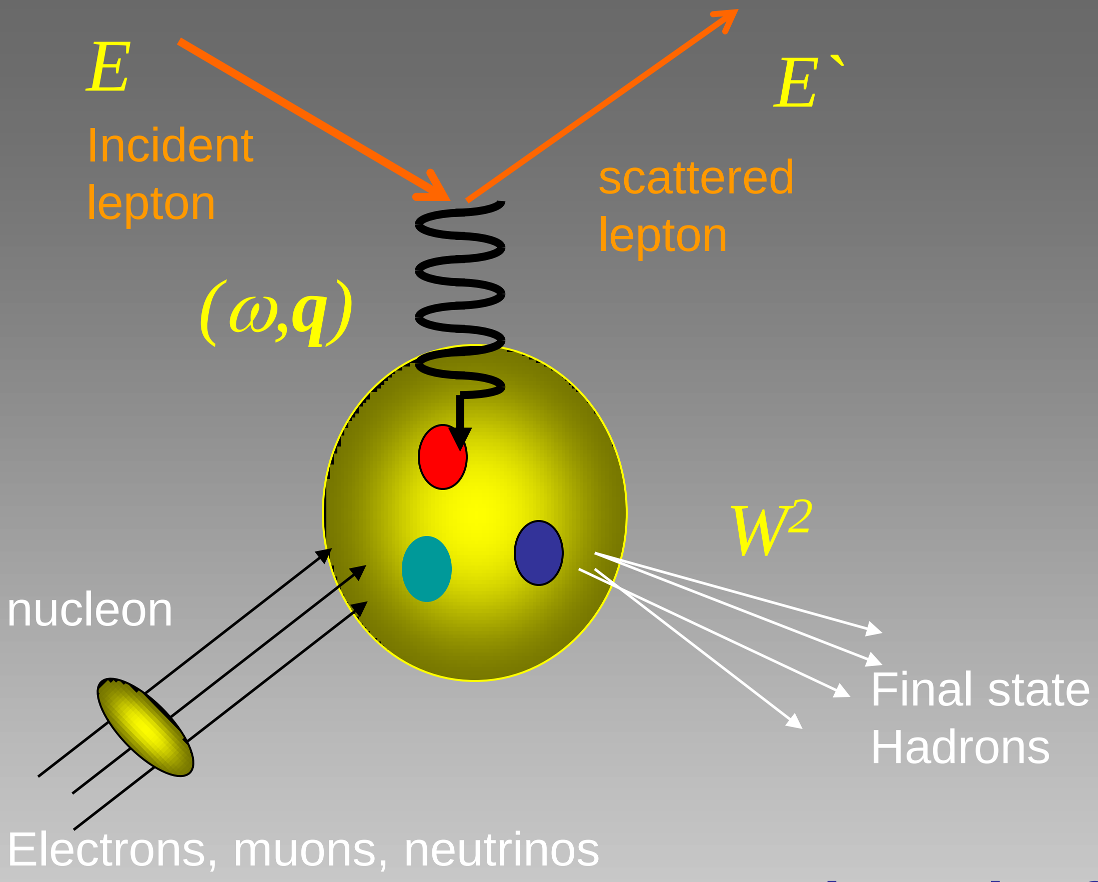
JLab / CLAS Data Mining,
EG2 data set, Or Chen et al.

PRELIMINARY





Deep Inelastic Scattering (DIS)



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

$$\omega = E' - E$$

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

SLAC, CERN, HERA, FNAL, JLAB

E, E' 5-500 GeV

Q^2 5-50 GeV^2

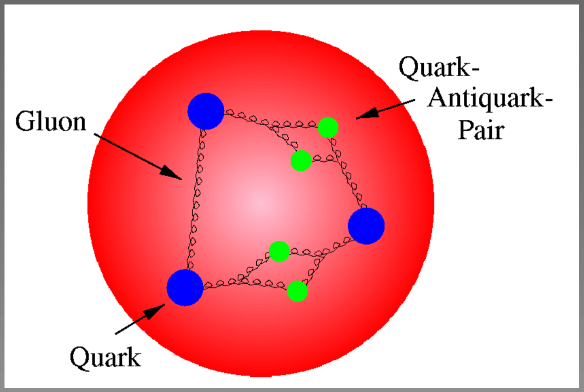
w^2 >4 GeV^2

$0 \leq X_B \leq 1$

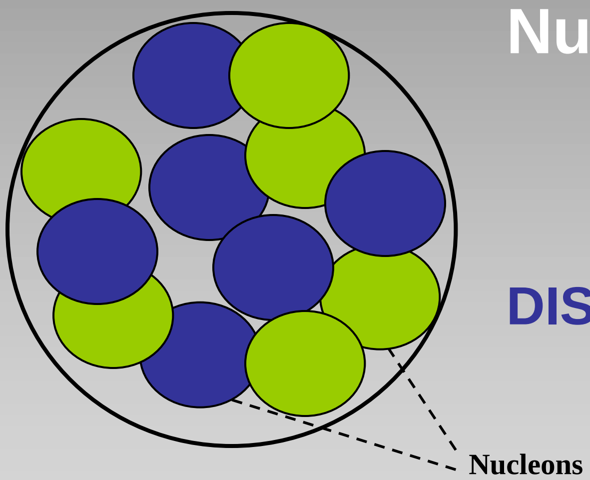
X_B gives the fraction of nucleon momentum carried by the struck parton

Information about nucleon vertex is contained in $F_1(x,Q^2)$ and $F_2(x,Q^2)$, the unpolarized structure functions

DIS



Scale: several tens of GeV

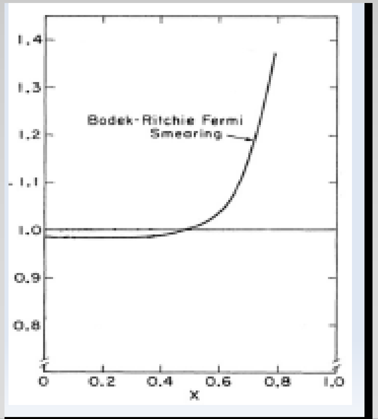


Nucleon in nuclei are bound by ~MeV

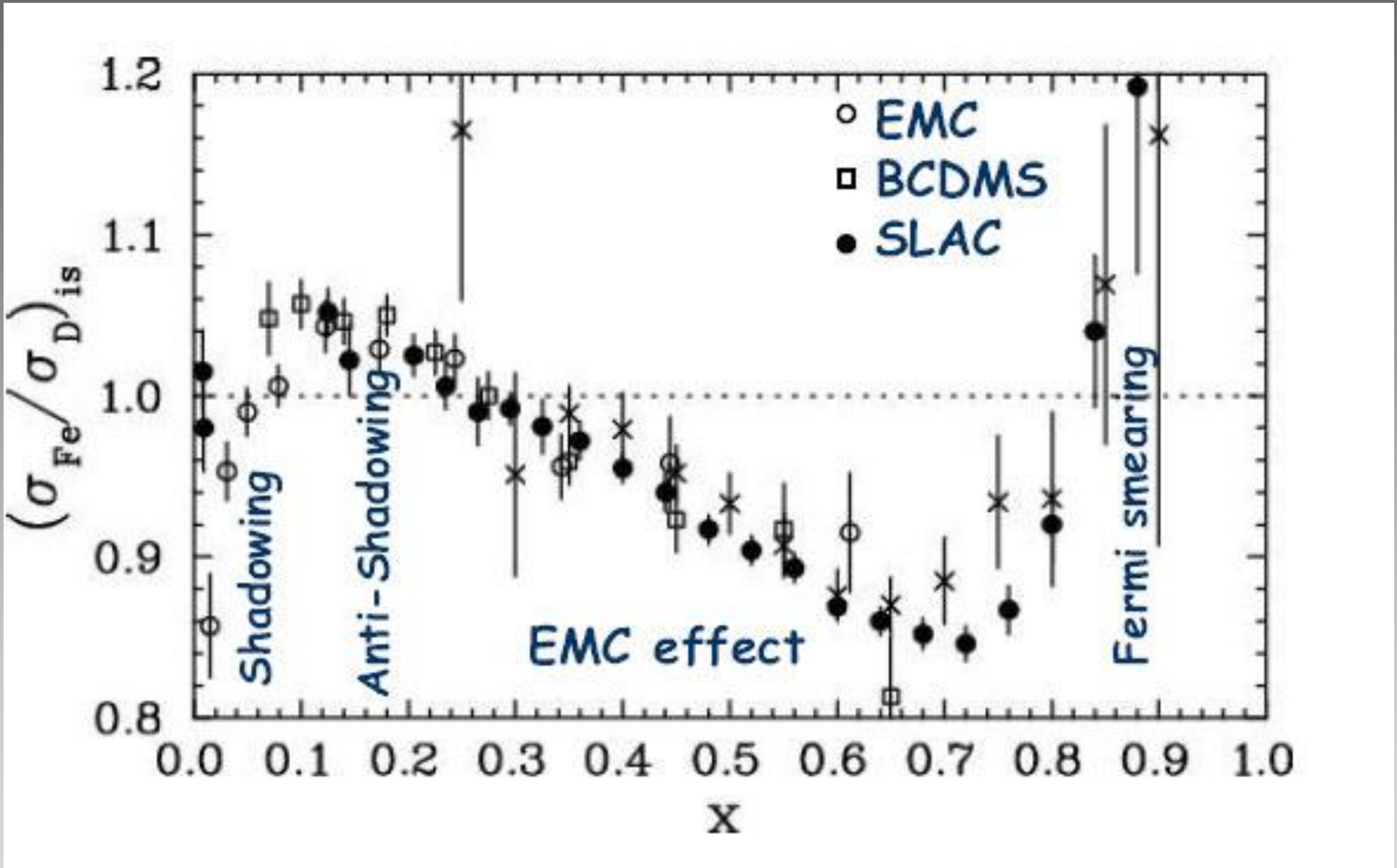
Naive expectation :

DIS off a bound nucleon = DIS off a free nucleon

(Except some small Fermi momentum correction)



The European Muon Collaboration (EMC) effect



DIS cross section per nucleon in nuclei ≠ DIS off a free nucleon

SLAC E139

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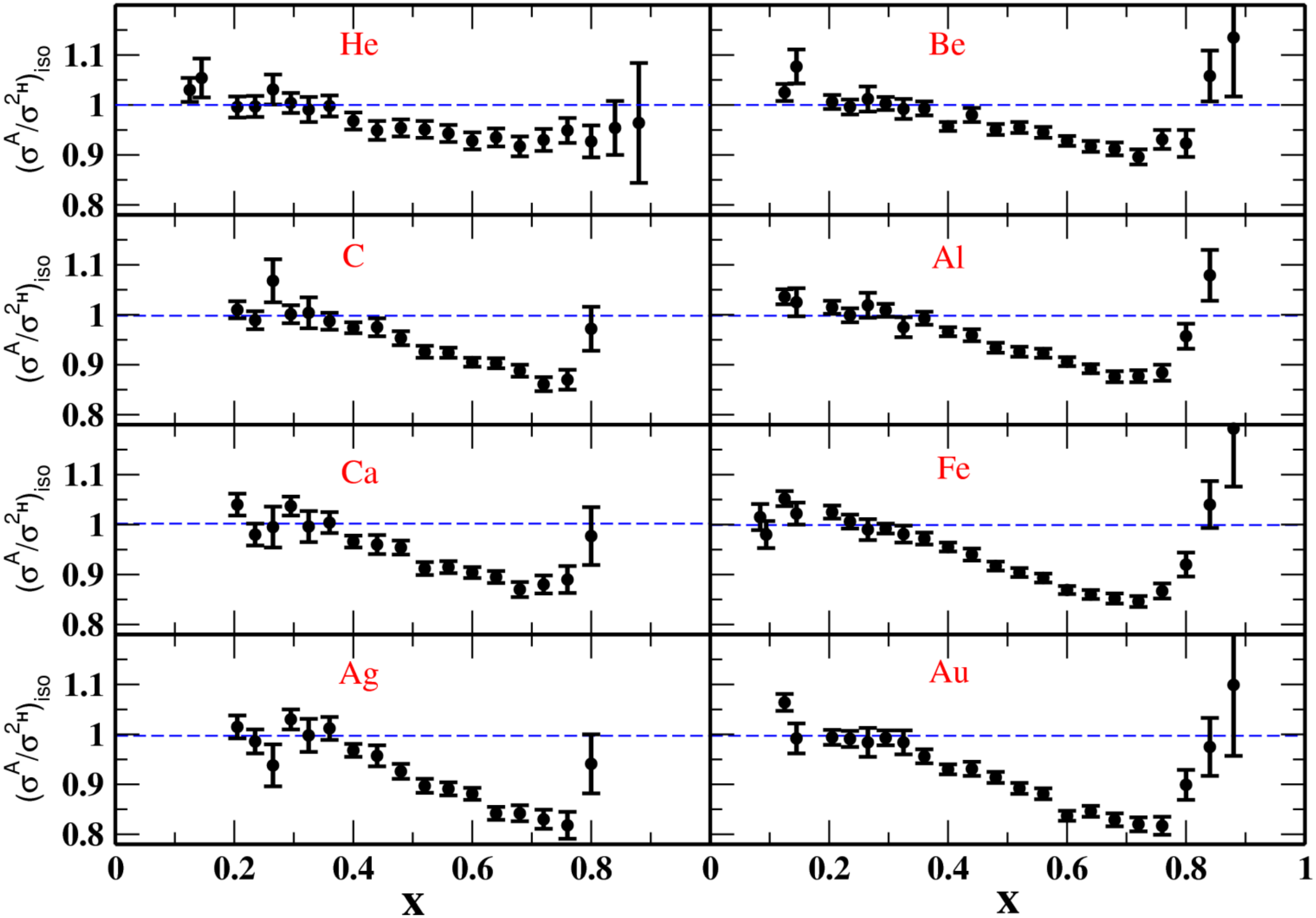
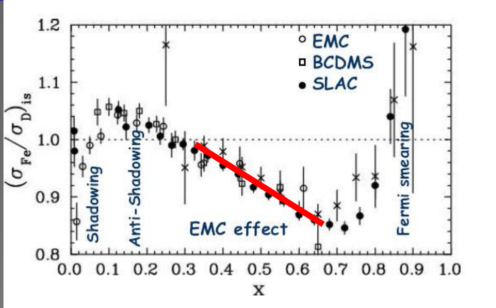
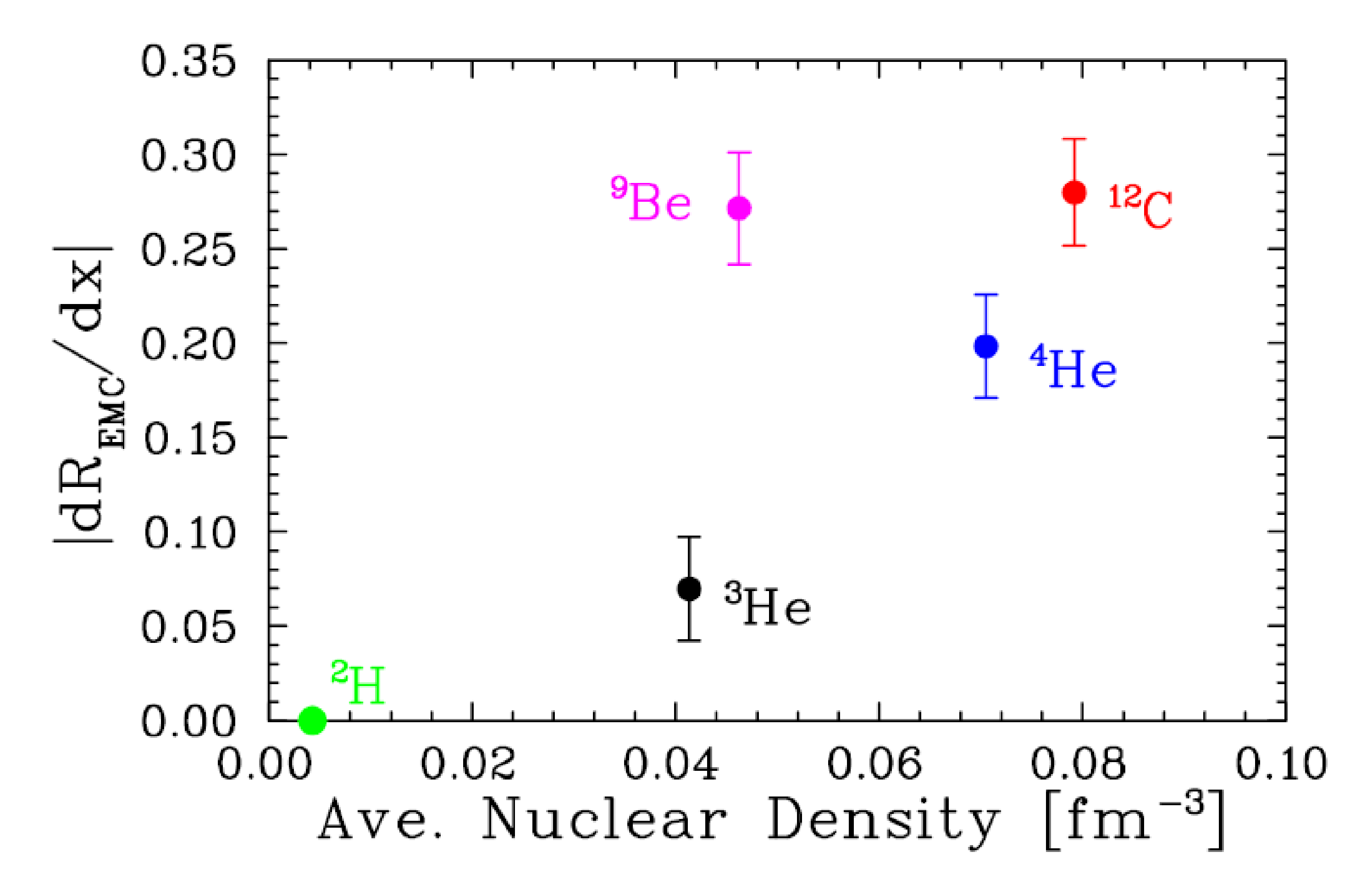
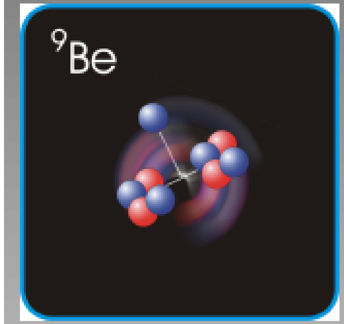


Data from CERN SLAC JLab 1983- 2009



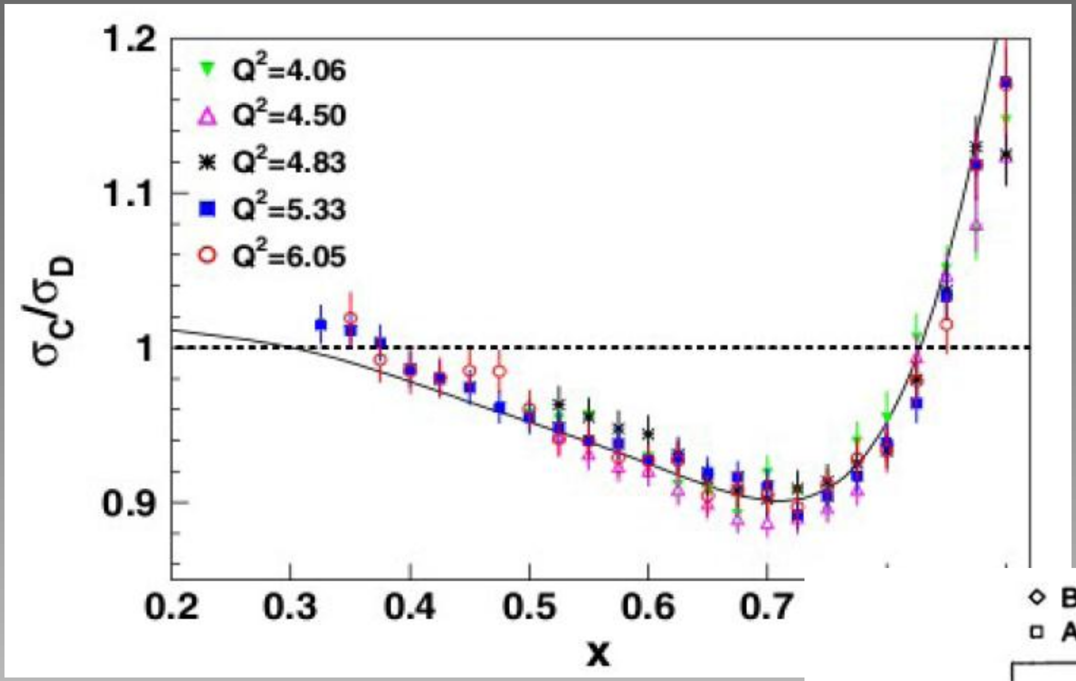
EMC is a local density or nucleon momentum dependence effect,
not a bulk property of nuclear medium





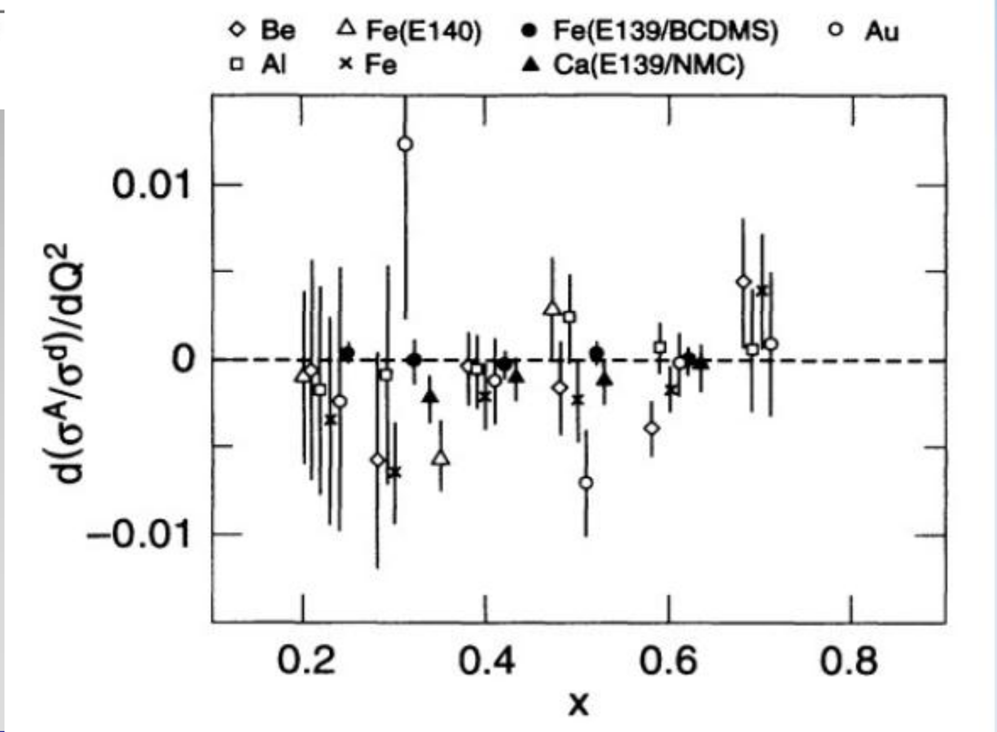
JLab / Hall C J. Seely et al. PRL 103, 202301 (2009)

Very weak Q^2 dependence



JLab

J. Seely et al.



SLAC

J. Gomez et al.

Theoretical interpretations: ~1000 of papers

- **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...

EMC recent review papers:

Gessman, Saito,Thomas, Annu. Rev. Nucl. Part. Sci. 45:337(1995).

P.R. Norton Rep Prog. 66 (2003).

G. Miller: EMC = Every Model is Cool

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Deep Inelastic Scattering

$\rightarrow$ Partonic (quark) Structure of **Hadrons**

Inclusive Scattering at X_B>1 **A(e,e')**

$\rightarrow$ Partonic (nucleon) Structure of **Nucleus**

Comparing the magnitude of the EMC effect and the SRC scaling factors

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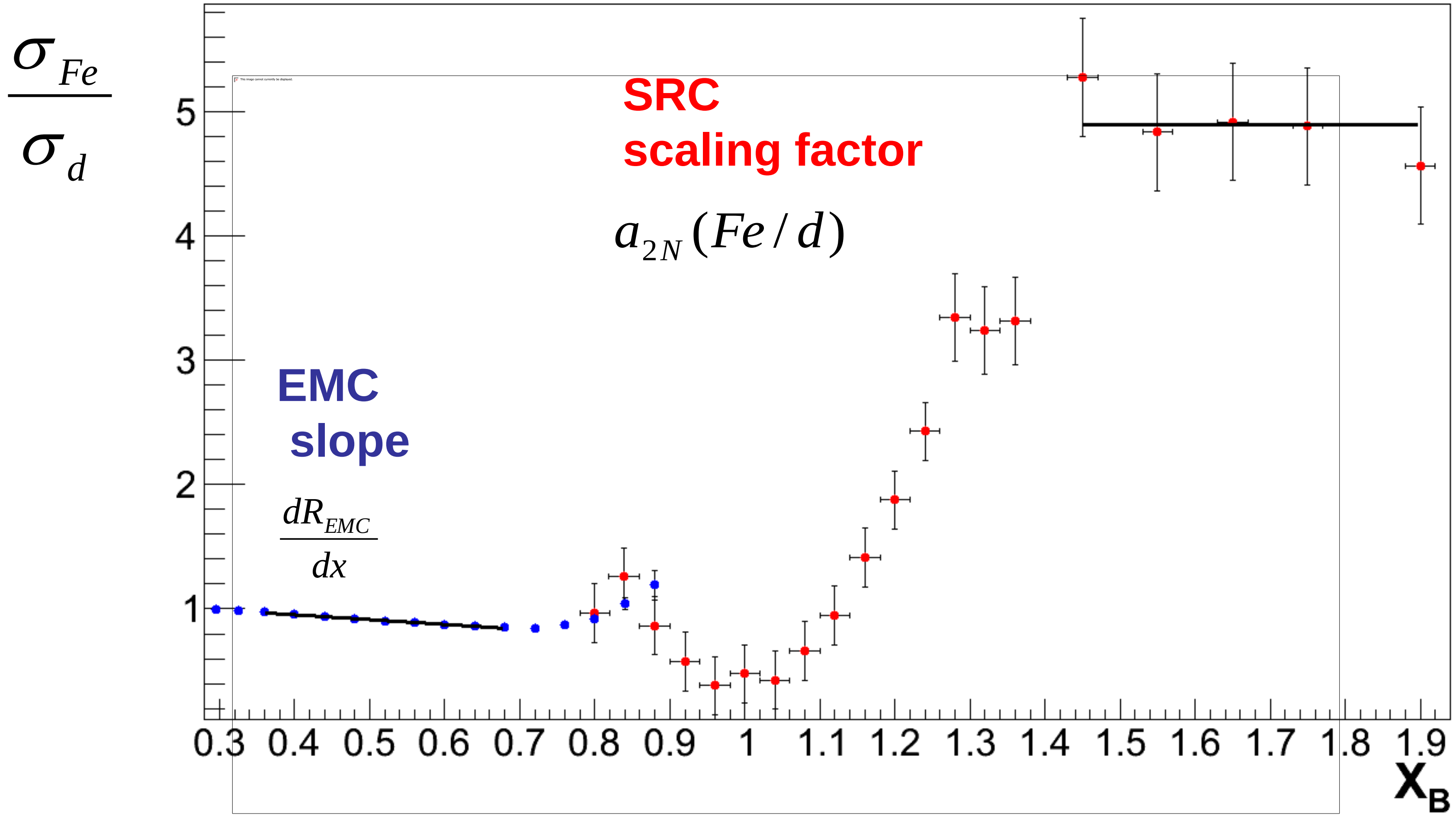
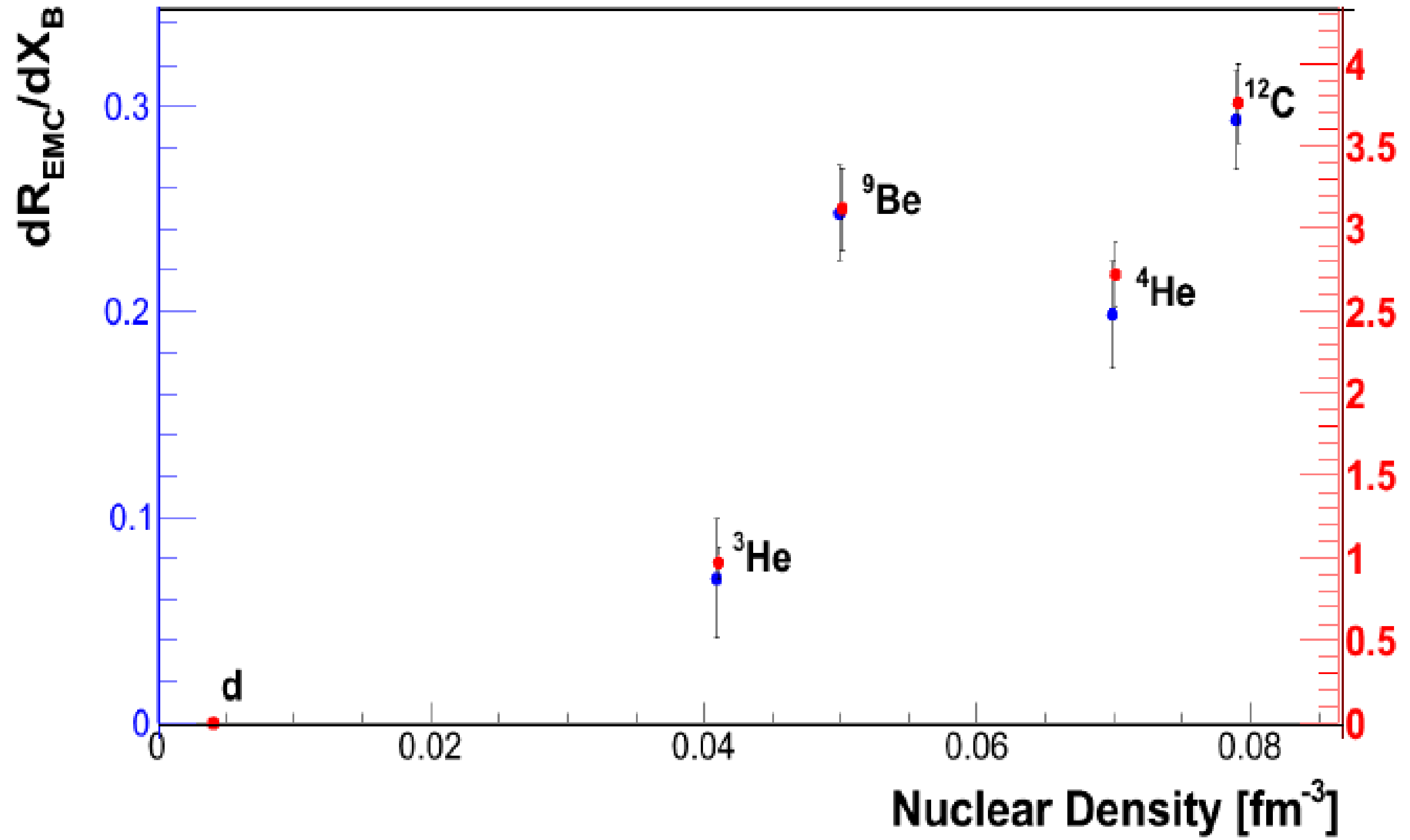
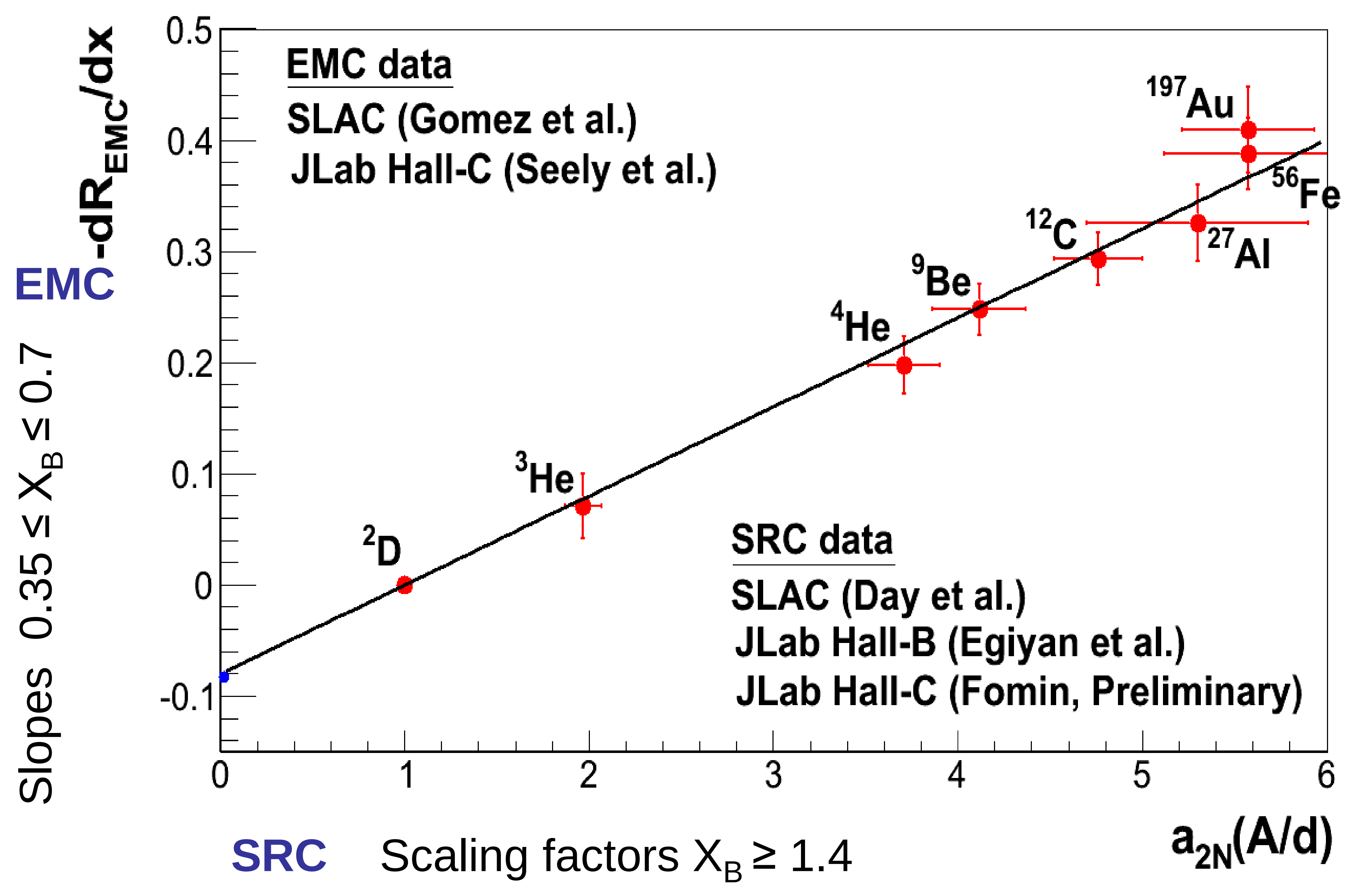


SLAC data:

Frankfurt, Strikman, Day, Sargsyan, Phys. Rev. C48 (1993) 2451. **Q^2=2.3 GeV/c^2**

Gomez et al., Phys. Rev. D49, 4348 (1983). **Q^2=2, 5, 10, 15 GeV/c^2 (averaged)**


dREMC/dXB
0.3
0.2
0.1
0
0
0.02
0.04
0.06
0.08
Nuclear Density [fm-3]
a2(A/d)-1
4
3.5
3
2.5
2
1.5
1
0.5
0
12C
9Be
4He
3He
d



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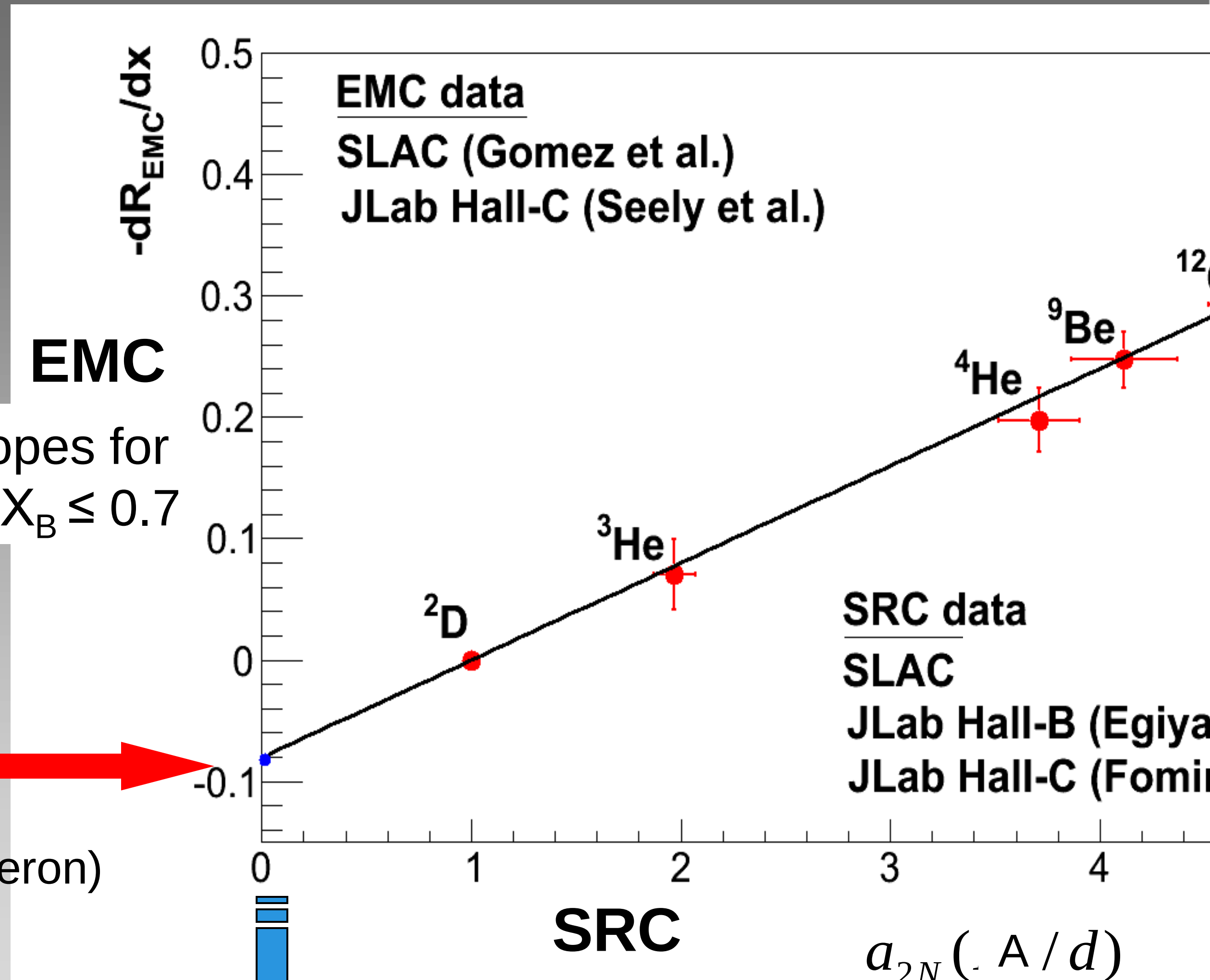
EMC
Slopes 0.35 ≤ X_B ≤ 0.7
-dR_EMC/dx
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
1
2
3
4
5
6
a_2N(A/d)
EMC data
SLAC (Gomez et al.)
JLab Hall-C (Seely et al.)
197Au
56Fe
12C
27Al
9Be
4He
3He
2D
SRC data
SLAC (Day et al.)
JLab Hall-B (Egiyan et al.)
JLab Hall-C (Fomin, Preliminary)
SRC
Scaling factors X_B ≥ 1.4

Deuteron is not a free np pair

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

$$\sigma_d \big/ \sigma_p + \sigma_n \approx \sigma_{^3He} \big/ \sigma_d$$

The slopes for $0.35 \le X_B \le 0.7$



0.079±0.06

bound to free n p pairs
(as opposed to bound to deuteron)

SRC=0 free nucleons

In Medium Correction effect

Due to a lack of a free neutron target the EMC measurements used the deuteron as an approximation to free proton and neutron

IMC: Ratio of bound to free n p pairs
(as opposed to bound to deuteron)

For deuteron:

$$\left|\frac{dR}{dx}\right|_d = 0.078 \pm 0.006$$

For any nuclei:

$$\left|\frac{dR}{dx}\right|_A = \left|\frac{dR}{dx}\right|_{measured} + (0.078 \pm 0.006)$$

Virtual free neutron target

The free neutron DIS cross section

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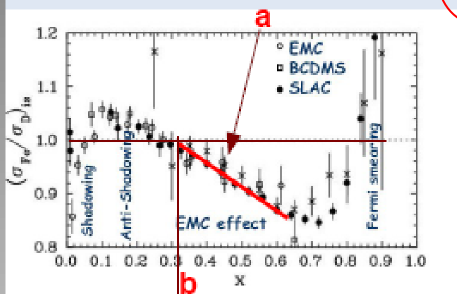
- Assuming linear dependence for $0.3 < X_B < 0.7$:

$$\frac{\sigma_d}{\sigma_n + \sigma_p} = 1 - a\left(X_B - b\right)$$



$$a = \left|\frac{dR_{EMC}}{dX_B}\right| = 0.079 \pm 0.006$$

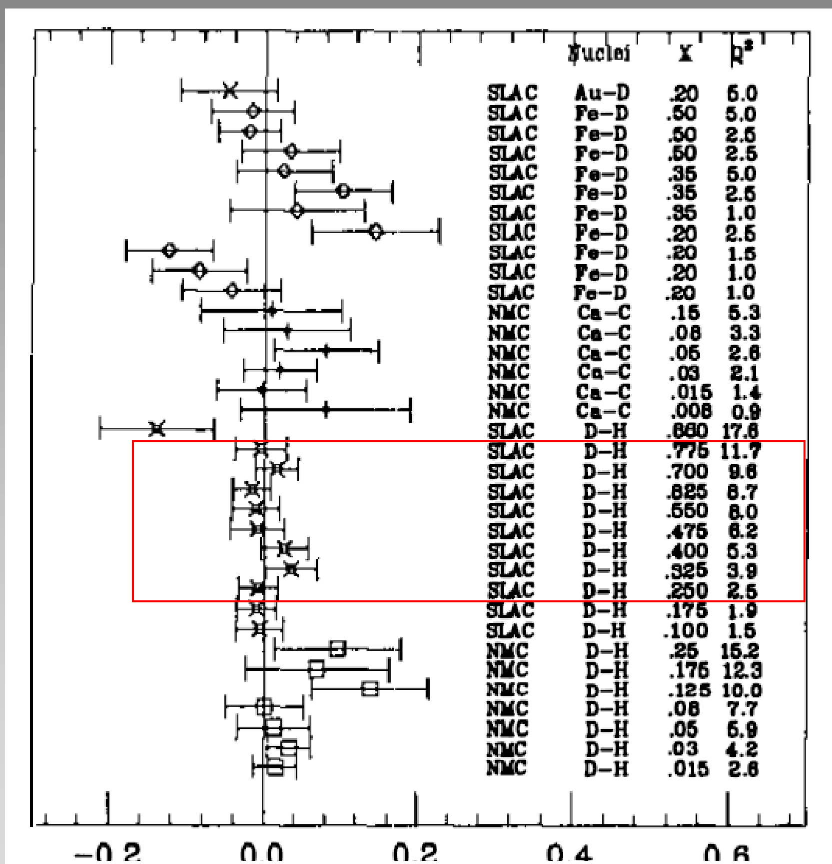
$$b = 0.31 \pm 0.04 \quad \rightarrow \quad \textit{the intersect of EMC ratio} = 1$$

$$\sigma_n = \frac{\sigma_d}{1 - a\left(X_B - b\right)} - \sigma_p$$

$$\frac{\sigma_n}{\sigma_p} = \frac{\sigma_d / \sigma_p}{1 - a\left(X_B - b\right)} - 1$$

$$F_2 = 2 \cdot x \cdot F_1 \cdot \frac{1+R}{1+2 \cdot M \cdot \omega}$$

Where $R = \sigma_L / \sigma_R$ is the ratio of cross sections for absorbing a longitudinal to that for a transverse photon.



Measurements of the difference in $R = \sigma_L/\sigma_T$ for a variety of targets

Asuming that $R=\sigma_L/\sigma_T$ is the same for n, p, d, the cross section ration equals the structure function ratio:

$$\frac{F_2^n(X_B,Q^2)}{F_2^p(X_B,Q^2)} = \frac{2F_2^d(X_B,Q^2) \;/\; F_2^p(X_B,Q^2)}{1-a(X_B-b)} - 1$$

Gessman, Saito,Thomas,Annu. Rev. Nucl. Part. Sci. 1995. 45:337

The free neutron structure function

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

For

$0.35 \le X_B \le 0.7$

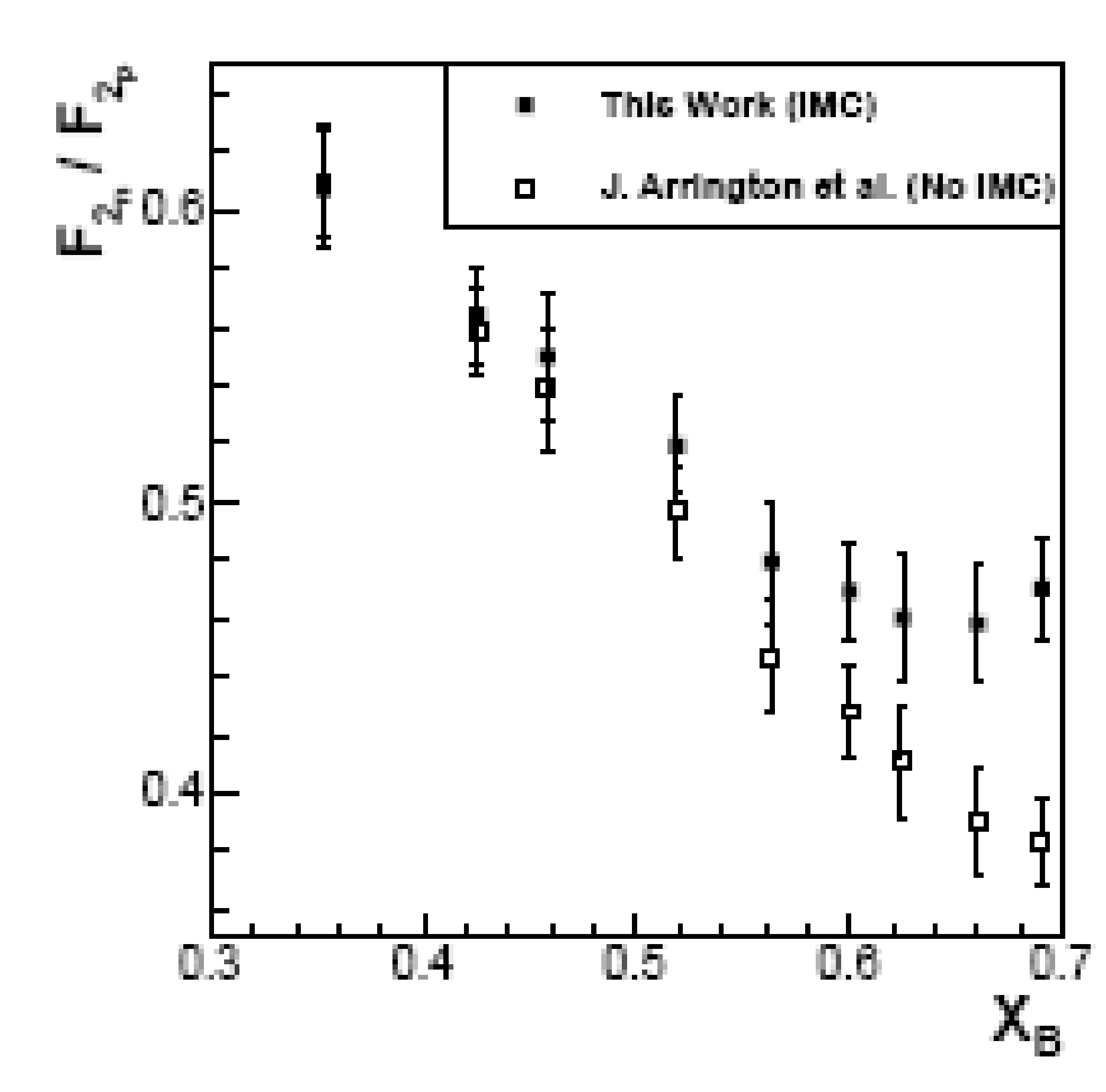
$$\frac{\sigma_d}{\sigma_p+\sigma_n} = 1 - a(x_B - b)$$

□ SLAC Data, J. Arrington et al. JPG 36(2009)205005.

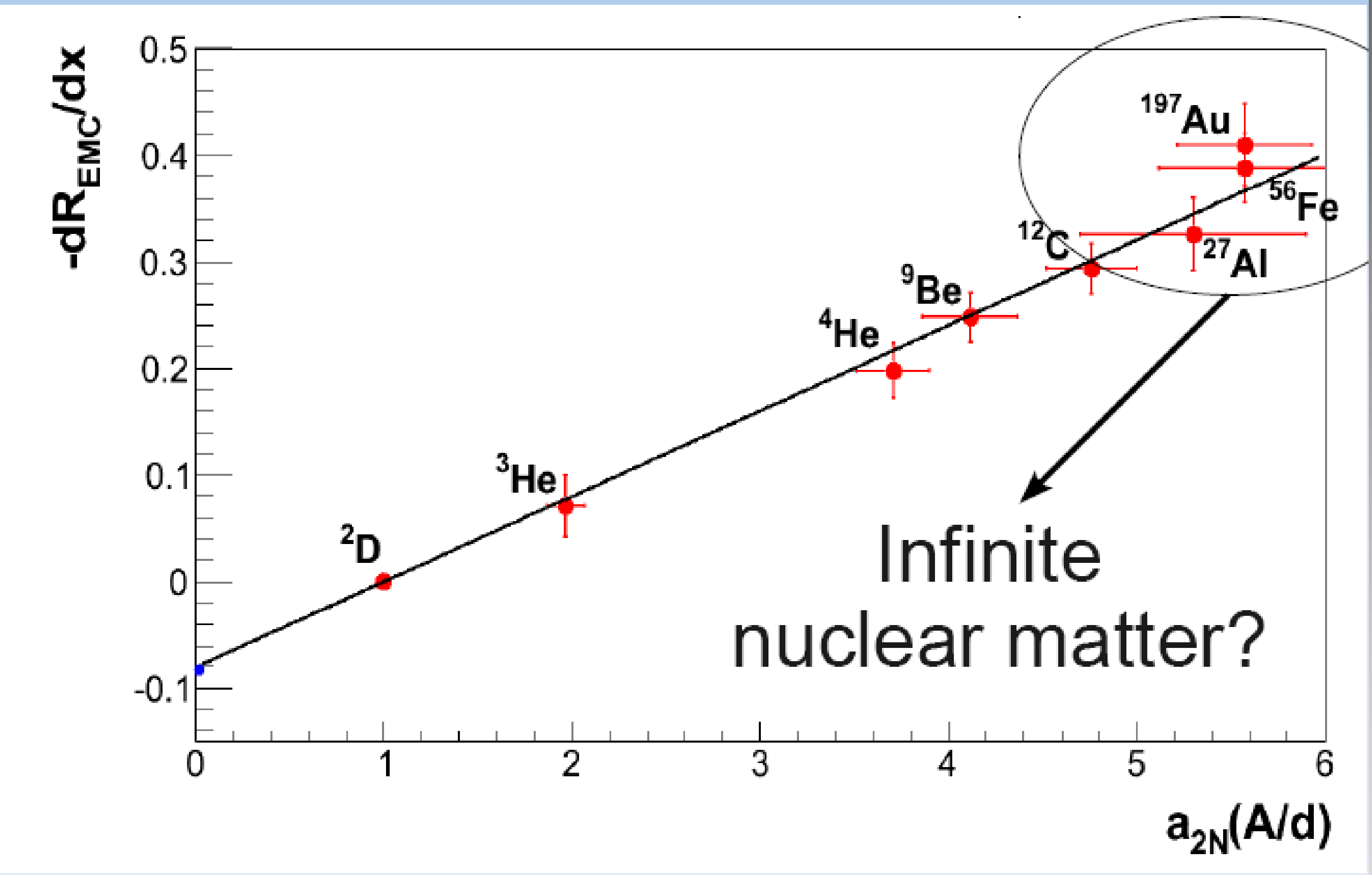
Fermi smearing using relativistic deuteron momentum density

■ Extracted from this work

With medium correction



Approaching the infinite nuclear matter limit



Approaching the infinite nuclear matter limit

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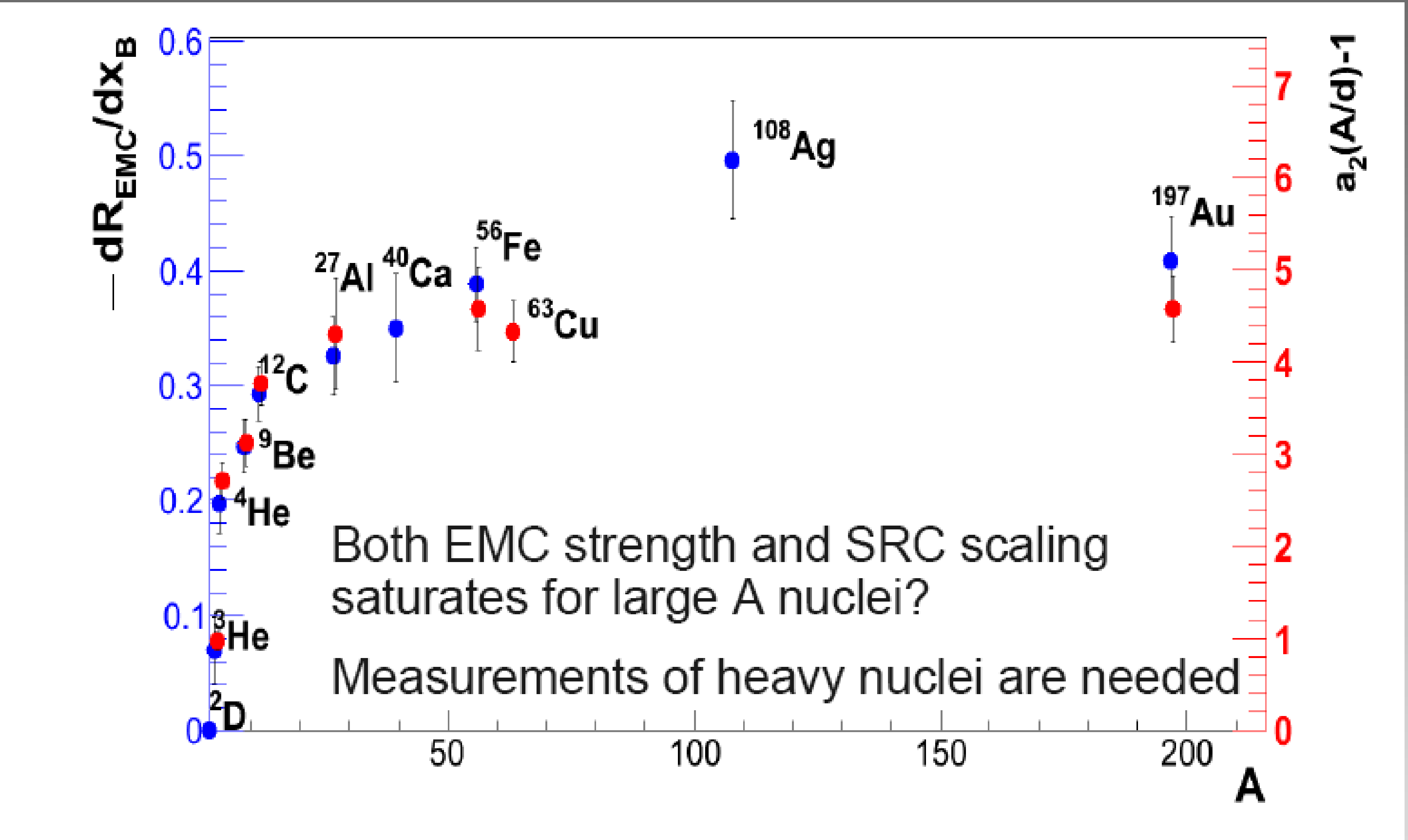
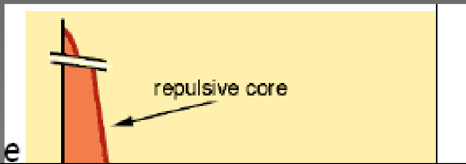
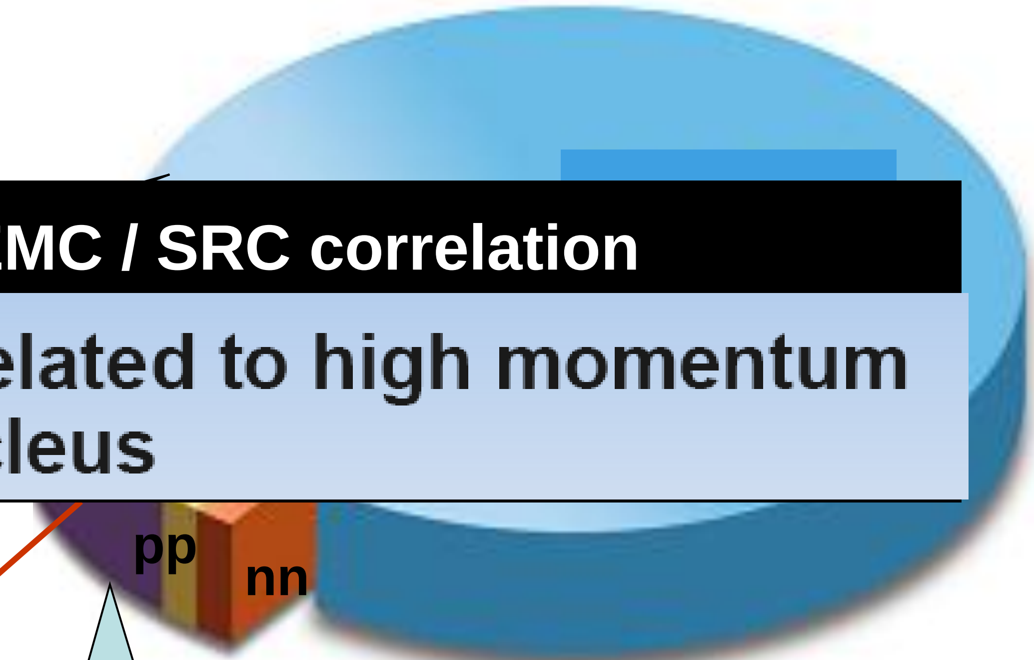


Need more data on heavy nuclei to study the A dependence for large A

Where is the EMC effect ?



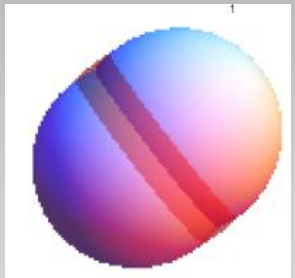


Possible explanation for EMC / SRC correlation

- The EMC effect is related to high momentum nucleons in the nucleus

20% nucleons
(80% kinetic energy)

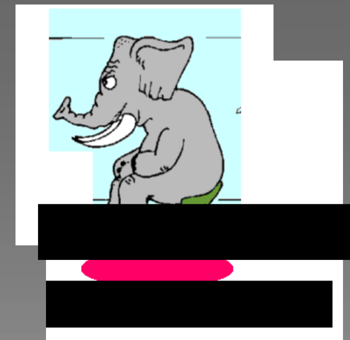
Nuclei are optimized to yield the strongest EMC effect possible



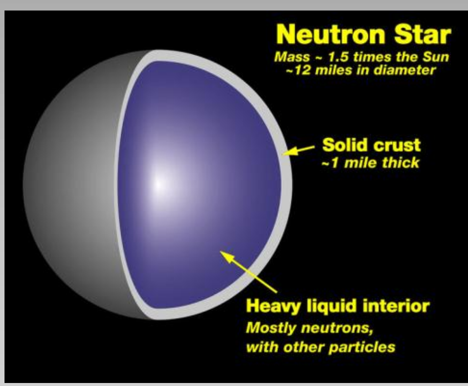
OR

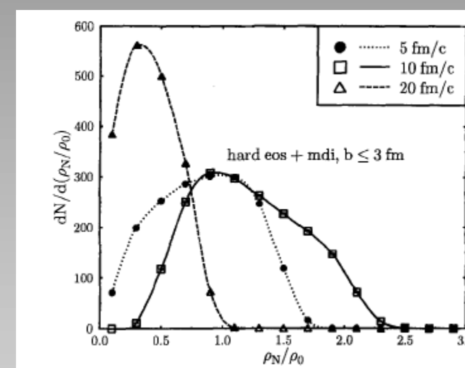
High local nuclear matter density,
large momentum, large off shell.
large virtuality ($\nu = p^2 - m^2$)

How large is EMC effect in dense nuclear systems?



What are the consequences of a large EMC in these systems?





Nucleon and baryon densities in heavy ion collisions at 1 GeV/nucl

S.A. Bass[1,2], C. Hartnack[2,3], H. Stöcker[1], W. Greiner[1] Z. Phys. A 351, 359–360 (1995)

n stars

Central HI collisions

Summary I

Standard model for short distance structure of nuclei

1 The probability for a nucleon to have momentum ≥ 300 MeV / c in medium nuclei is ~25%

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

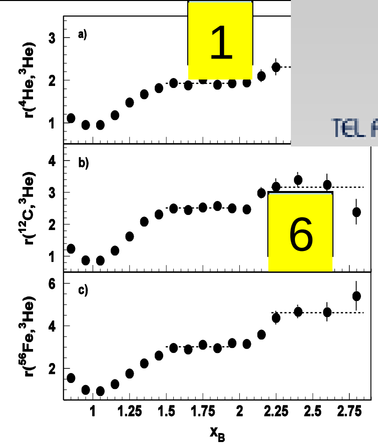
1 2 ~80% of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.

3 Probability for a nucleon with momentum 300-600 MeV / c to belong to np-SRC is ~18 times larger than to belong to pp-SRC.

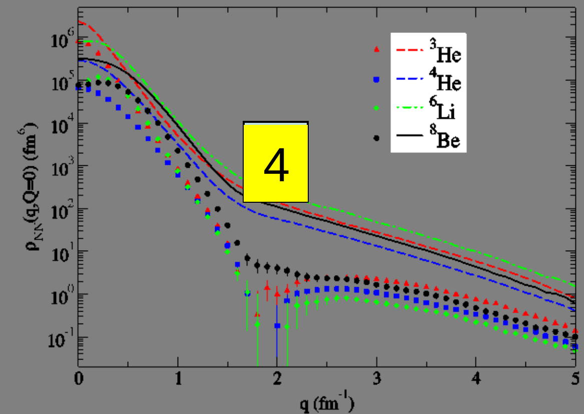
4 Dominant NN force in the 2N-SRC is tensor force.

6 Three nucleon SRC are present in nuclei.

CLAS / HALL B

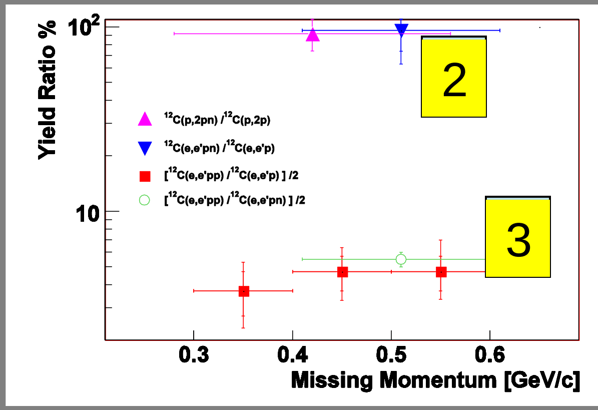


. PRL. 96, 082501 (2006)



PRL 98,132501 (2007).

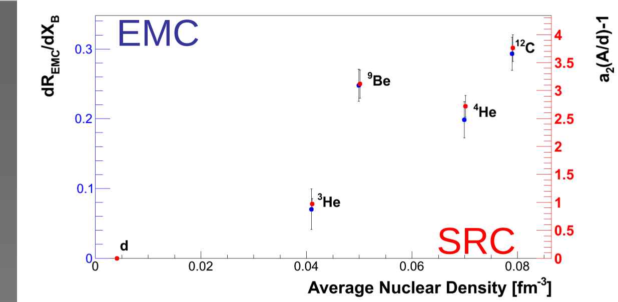
EVA / BNL and Jlab / HALL A



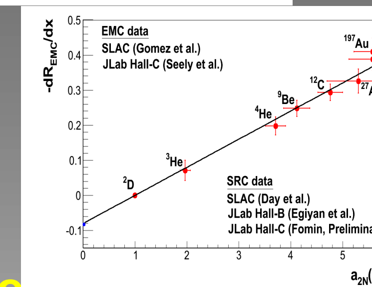
PRL 162504(2006); Science 320, 1476 (2008).

Summary II

- The EMC is a local density and / or momentum dependent effect not a bulk property of the nuclear medium.



- The magnitude of the EMC effect and SRC scaling factor are linearly related.



- We speculate that observed correlation arises because <u>both EMC and SRC are dominated by high momentum</u> (large virtuality) <u>nucleons in nuclei</u>.

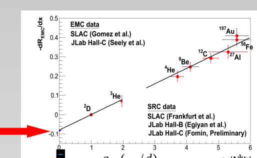
<u>The observed phenomenological relationship is used to extract:</u>

(For $0.35 < X_B < 0.7$)

ratio of deuteron to free n p pair cross sections.

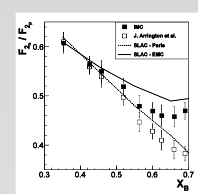
DIS cross section for a free neutron.

0.079±0.06



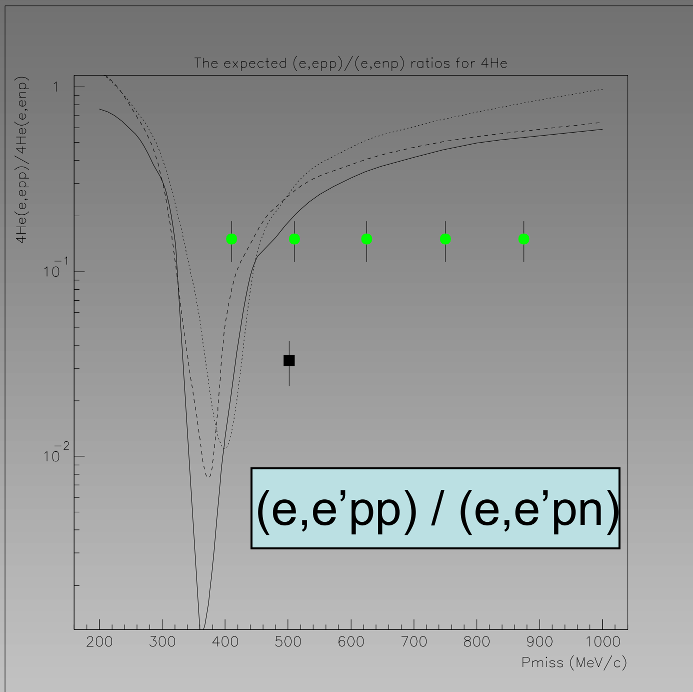
SRC=0

$F_2^n(x,Q2)$, the free neutron structure function.



A new experiment scheduled to run 2011 at JLab (E 07-006)

Measurement over missing momentum range from 400 to 875 MeV/c.



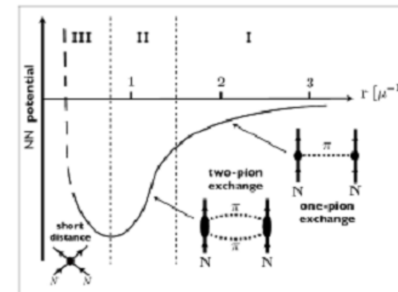


Fig. 2. Hierarchy of scales governing the nucleon-nucleon interaction (adapted from Taketani [5]). The distance r is given in units of the pion Compton wavelength, $\mu^{-1} \simeq 1.4$ fm.

QMC

(Thomas)

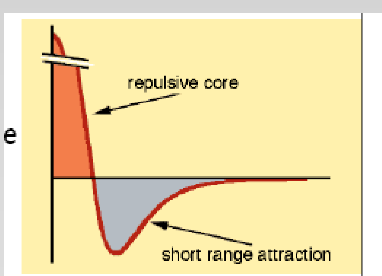
Taketani,Nakamura,Saaki
Prog. Theor. Phys. 6 (1951) 581.

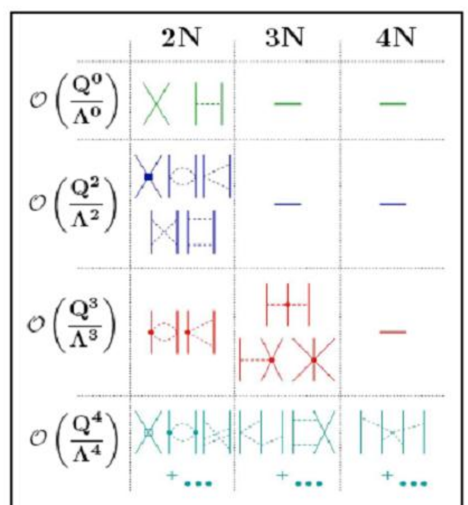
Chiral effective field

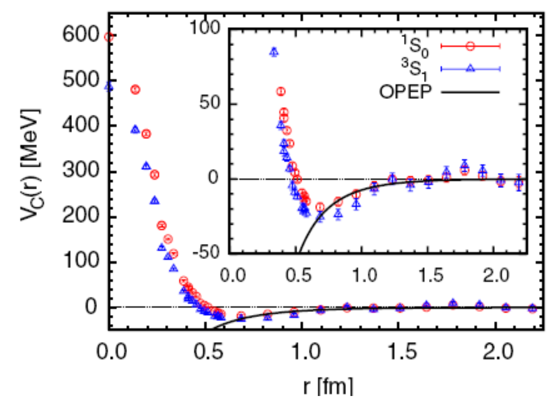
(Machleidt)

Lattice QCD
(Doi, Beane)

The data are expected to be sensitive to the NN tensor force and the NN short range repulsive force.





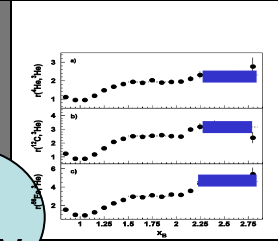


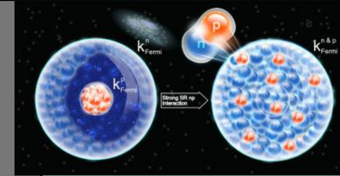
PRL 99, 022001 (2007) PHYSICAL REVIEW LETTERS week ending 13 JULY 2007

Nuclear Force from Lattice QCD

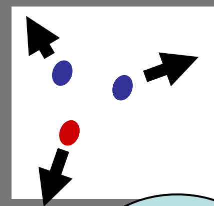
N. Ishii,[1,2] S. Aoki,[3,4] and T. Hatsuda[2]

outlook



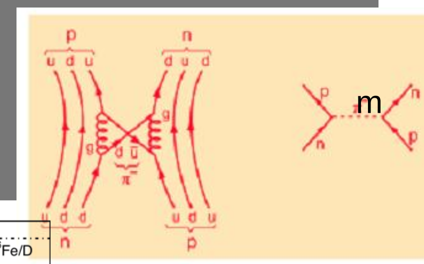


What is the role played by short range correlation of more than two nucleons ?

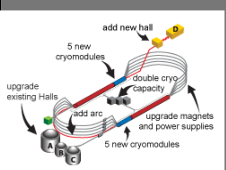


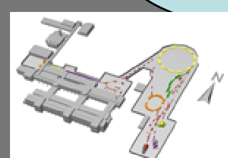
How to relate what we learned about SRC in nuclei to the dynamics of neutron star formation and structure ?

What is the role played by non nucleonic degrees of freedom in SRC ?

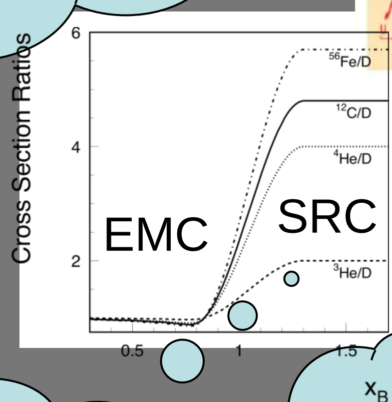


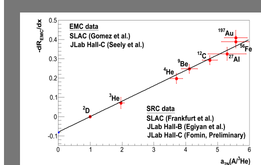
12 GeV JLab





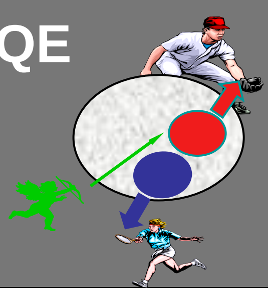
GSI





The new facilities will allow even harder knockout reactions

QE



DIS

What are the observables ?

Optimized kinematics ?

Is theory well enough established to interpret the data?

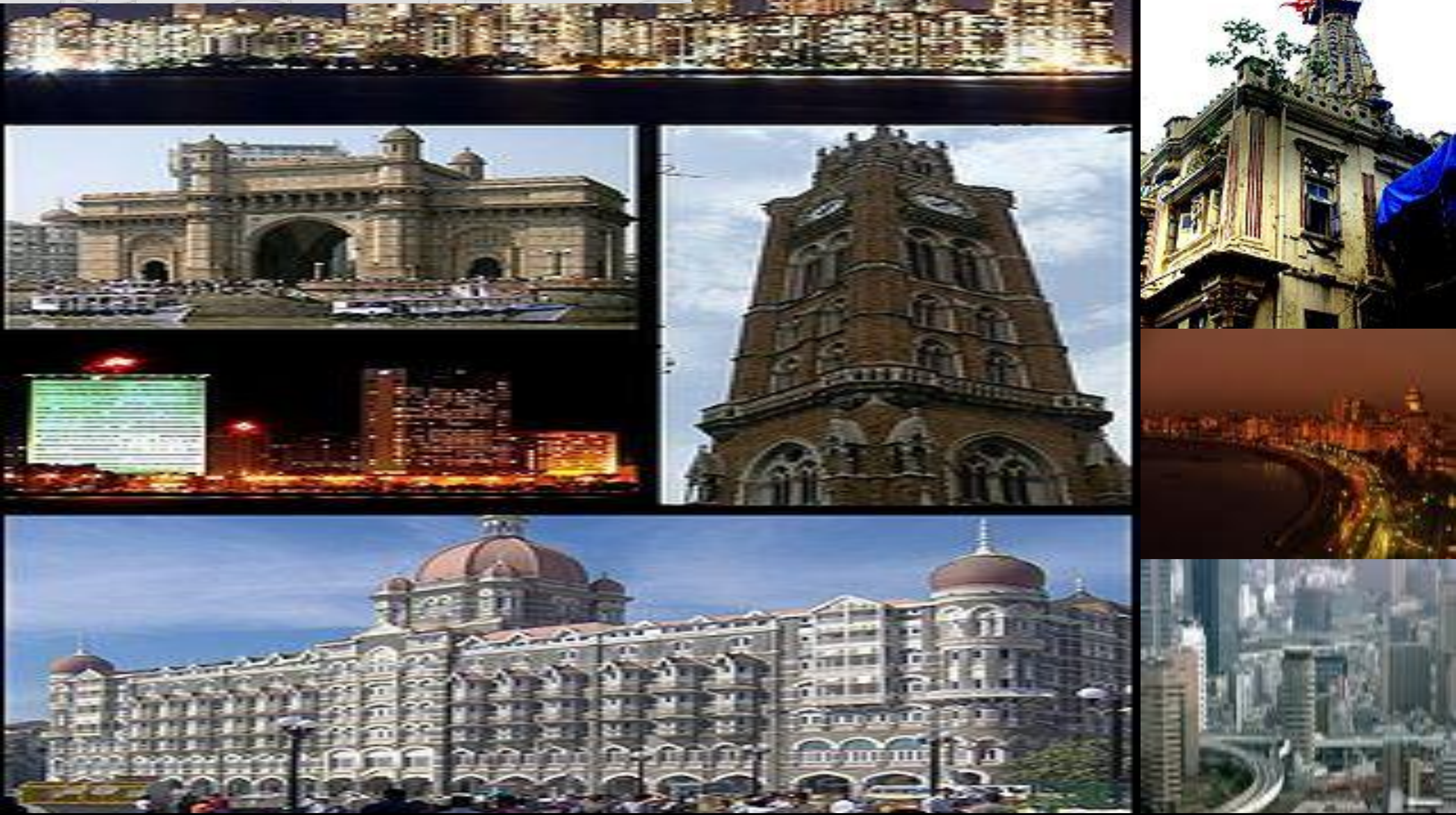
INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

TEL AVIV UNIVERSITY

N-N Interaction & the Nuclear Many-Body Problem

November 18-27, 2010



I would like to thank the organizers for the invitation

E01-015: A customized Experiment to study 2N-SRC

$Q^2 = 2$ GeV/c , $x_B \sim 1.2$, P_m=300-600 MeV/c, E_{2m}<140 MeV

Luminosity ~ 10^{37-38} $cm^{-2}s^{-1}$

Kinematics optimized to minimize the competing processes

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The large Q^2 is required to probe the small size SRC configuration.

MEC are reduced as $1/Q^2$.

Large Q^2 is required to probe high P_{miss} with x_B>1.

FSI can treated in Glauber approximation.

x_B>1

Reduced contribution from isobar currents.

Large p_{miss}, and $E_{miss} \sim p^2_{miss}/2M$

Large P_{miss_z}

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TEL AVIV UNIVERSITY

FSI

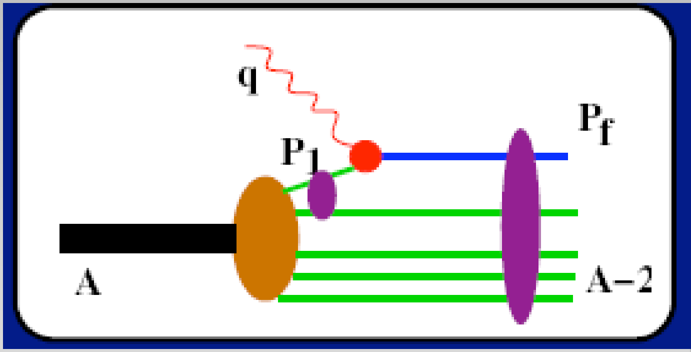
FSI with the A-2 system:

- ★ Small (10-20%) .
  - Kinematics with a large component of p_{miss} in the virtual photon direction.
  - Pauli blocking for the recoil particle.
  - Geometry, (e, e'p) selects the surface.
- ★ Can be treated in Glauber approximation.
- ★ Canceled in some of the measured ratios.

FSI in the SRC pair:

These are not necessarily small, BUT:

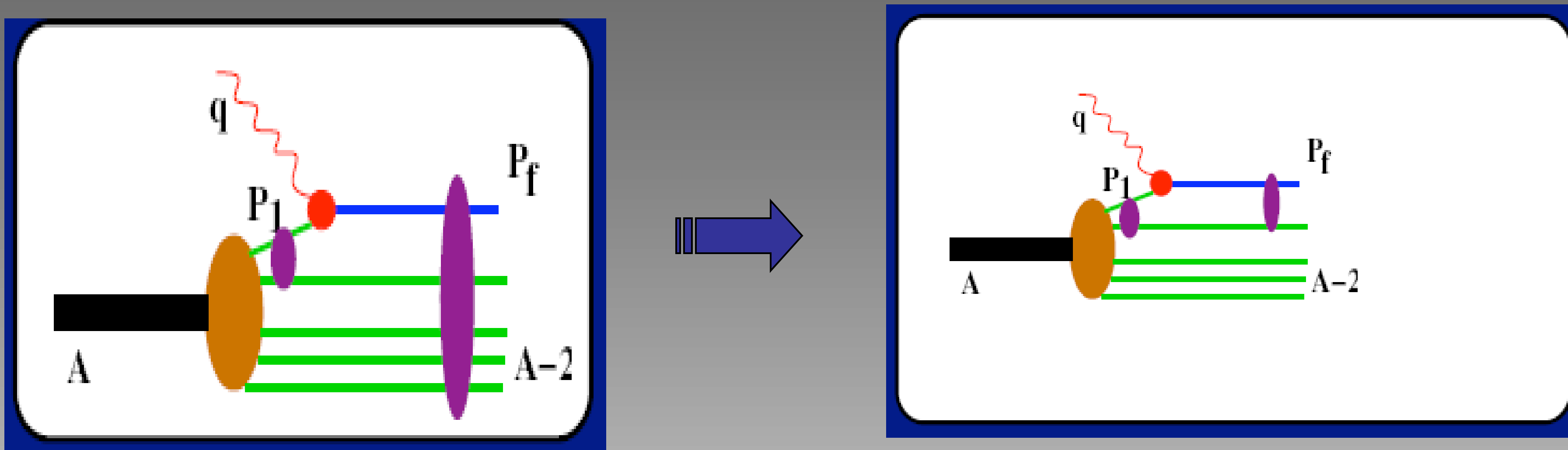
- ★ Conserve the isospin structure of the pair .
- ★ Conserve the CM momentum of the pair.



Why FSI do not destroy the 2N-SRC signature ?

TEL AVIV UNIVERSITY

For large Q^2 and x>1 FSI is confined within the SRC



distances that highly virtual struck nucleon propagates

$$\Delta E = -q_0 - M_A + \sqrt{m^2 + (p_i + q)^2} + \sqrt{M_{A-1}^2 + p_i^2}$$

$$r \approx \frac{1}{\Delta E v} \leq 1\,\text{fm}$$

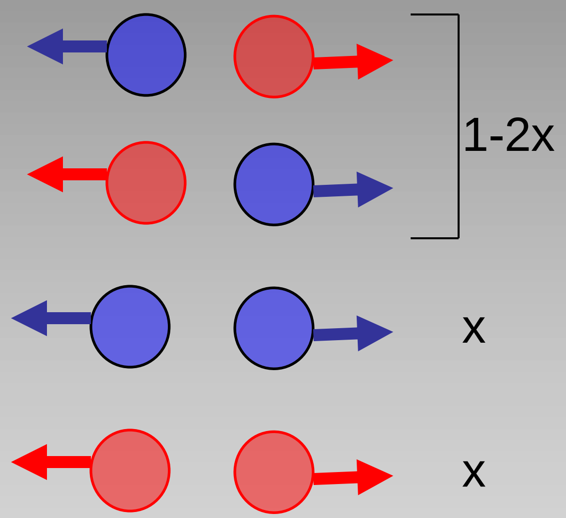
for x > 1.3

FSI in the SRC pair:

- Conserve the isospin structure of the pair .
- Conserve the CM momentum of the pair.

$$\frac{(e,e'pp)}{(e,e'p)} = 9.5 \pm 2\% \quad \Rightarrow \quad \frac{\text{pp-SRC}}{2N-SRC} = 4.75 \pm 1\%$$

Assuming in ^{12}C nn-SRC = pp-SRC and 2N-SRC=100%



A virtual photon with $x_B > 1$ "sees" all the pp pairs but only 50% of the np pairs.

$$\frac{(e,e'pp)}{(e,e'p)} = \frac{x}{x + (1-2x)/2} = 2x$$

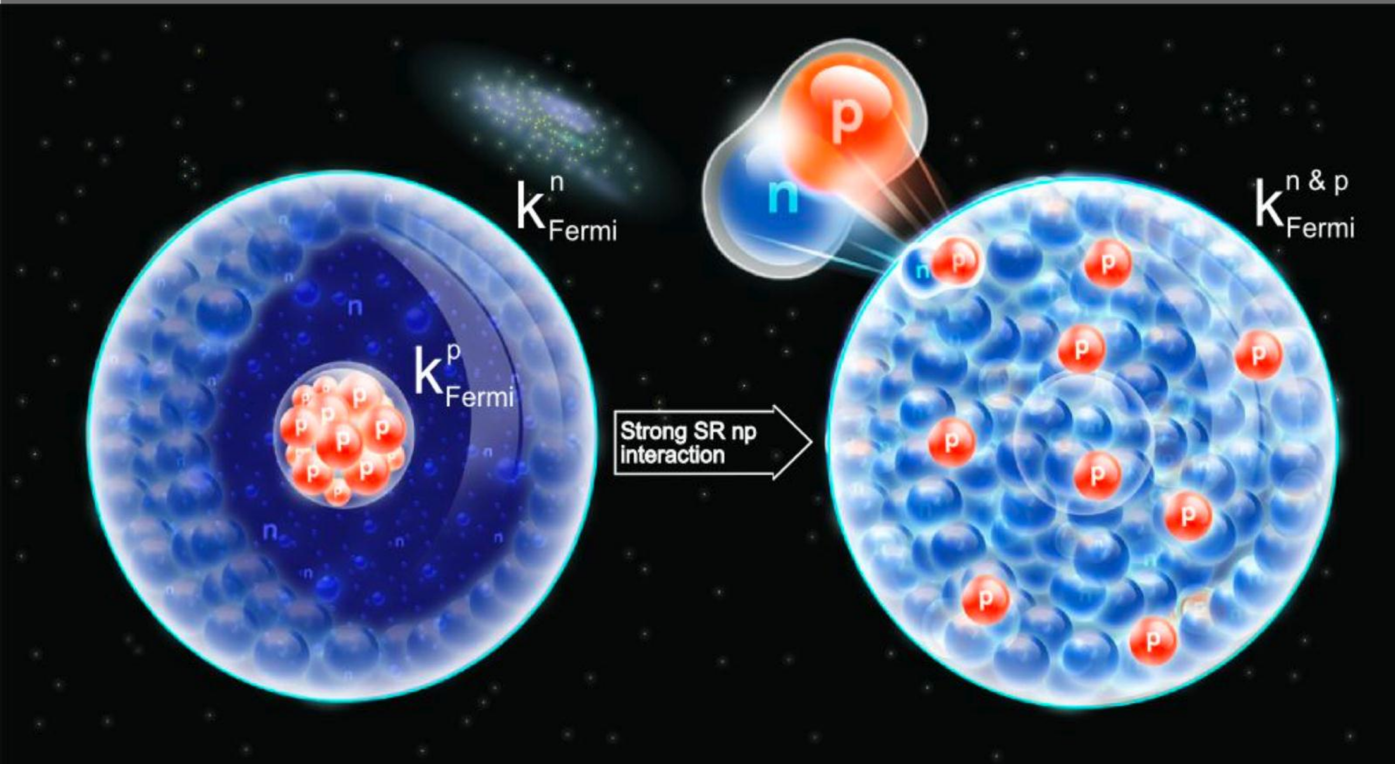
$$BNL \qquad \frac{(p,2pn)}{(p,2p)} = \frac{np\text{ - }SRC}{np\text{ - }SRC+2\,(pp\text{ - }SRC)} = \frac{np\text{ - }SRC}{2N\text{ - }SRC} = (74\text{-}100)\ \%$$

$$Jlab \quad \frac{(e,e'pn)}{(e,e'p)} = \frac{np - SRC}{2N - SRC} = (84\text{ - }100)\%$$

$$Jlab \quad \frac{(e,e'pp)}{(e,e'p)} = (9.5 \pm 2)\ \% \ \text{ i.e } \frac{pp\text{-}SRC}{2N\text{-}SRC} = \frac{nn - SRC}{2N - SRC} = (5 \pm 1)\%$$

$$\frac{np - SRC}{2N - SRC} = (84\text{ - }92)\%$$

Implications for Neutron Stars



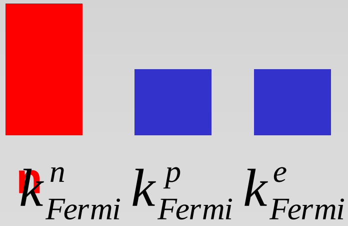
Adapted from: D.Higinbotham, E. Piasetzky, M. Strikman CERN Courier 49N1 (2009) 22

- **At the core of neutron stars, most accepted models assume :**

 ~95% neutrons, **~5% protons** **and ~5% electrons (β-stability).**

- **Neglecting the np-SRC interactions, one can assume three separate Fermi gases (n p and e).**

- **strong np interaction** → **the n-gas heats the p-gas.**



See estimates in Frankfurt and Strikman **: Int.J.Mod.Phys.A23:2991-3055,2008.**

SRC in nuclei: implication for neutron stars

•**At the core of neutron stars, most accepted models assume :**

~95% neutrons, ~5% protons and ~5% electrons (β-stability).

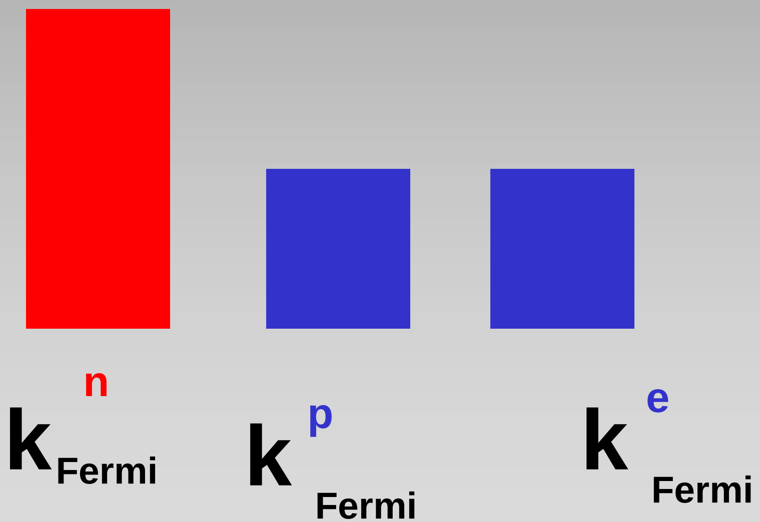
•**Neglecting the np-SRC interactions, one can assume three separate Fermi gases (n p and e).**

At T=0
$$k^n_{Fermi} = k^p_{Fermi} + k^e_{Fermi}$$
$$k^p_{Fermi} = k^e_{Fermi} = (\frac{N_p}{N_n})^{1/3} k^n_{Fermi}$$

For $\rho = 5\rho_{0,}\ \ k^n_{Fermi} \approx 500\,\mathrm{MeV/c},\ \ k^p_{Fermi} = k^e_{Fermi} \approx 250\,\mathrm{MeV/c}$

Pauli blocking prevent direct n decay

$$n \rightarrow p + \mathrm{e} + \overline{\nu}_{\mathrm{e}}$$



Strong SR np interaction

THE MEAN FIELD APPROXIMATION

$$\left[-\frac{\hbar^2}{2m}\sum_i \hat{\nabla}_i^2 + \sum_{i<j} \hat{v}_{ij}\right]\Psi_o = E_o\Psi_o$$

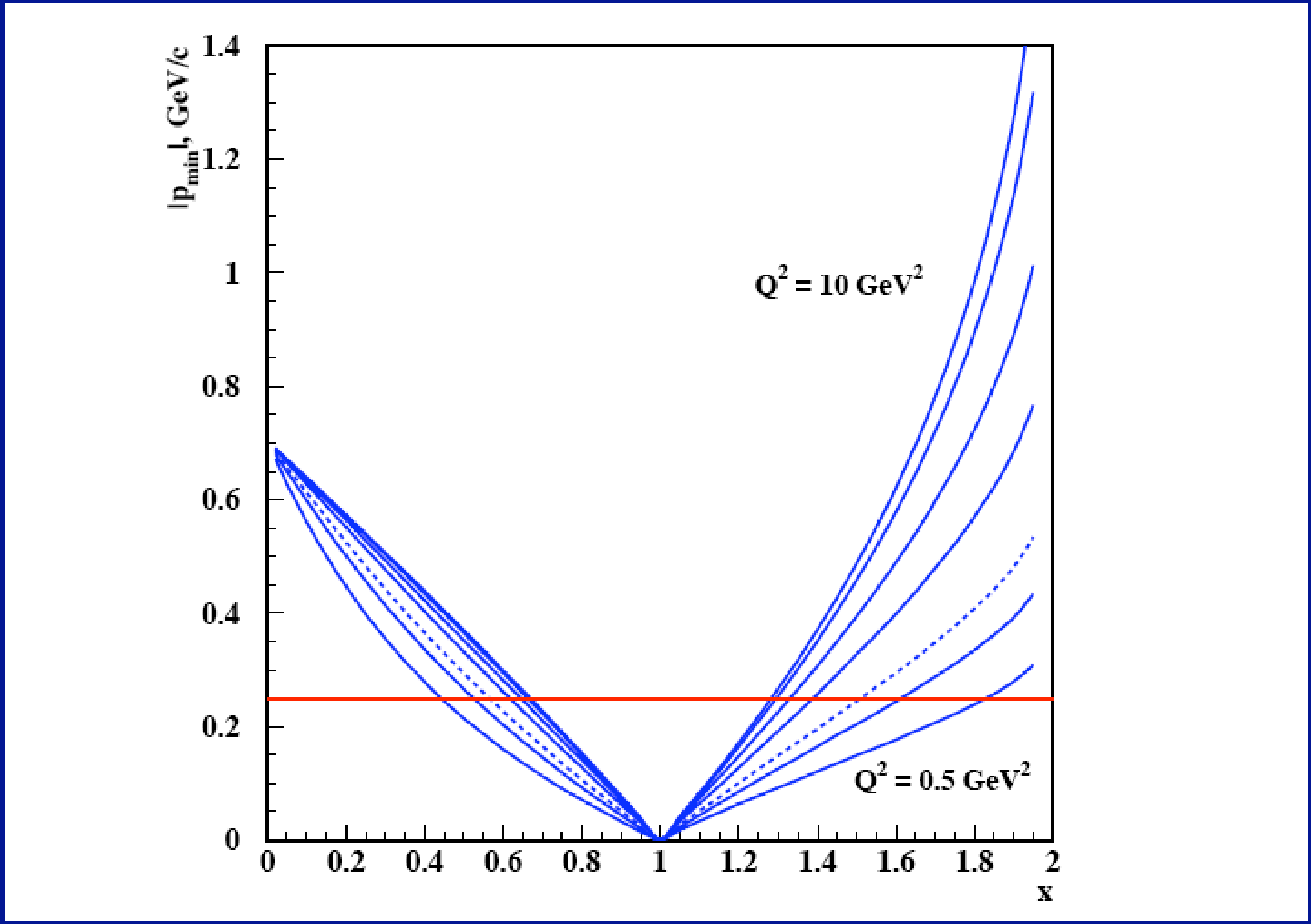
$$\Downarrow$$

$$\left[-\frac{\hbar^2}{2m}\sum_i \hat{\nabla}_i^2 + \sum_i V(r_i)\right]\Phi_o = \epsilon_o\Phi_o$$

Variational monte carlo (Urbana Group)

Cluster expansion techniques (Ciofi, Alvioli, Cda, Morita)

x> 1 is not automatically means 2N SRC one needs also large Q2



Q^2 ↑

$q_+ \gg$

Brookhaven Experiment

A. Tang et al, PRL 2003

$$F = \frac{\text{Number of (p,ppn) events } (p_i, p_n > k_F)}{\text{Number of (p,pp) events } (p_i > k_F)},$$

$$F = 0.43^{+0.11}_{-0.07} \qquad \text{for } 275 \le p_i, p_n \le 550 \text{ MeV/c}$$

Theoretical Analysis

Piasetzky, MS, Frankfurt, Strikman, Watson PRL 2007

$$P_{pn/pX} = \frac{F}{T_n R}$$

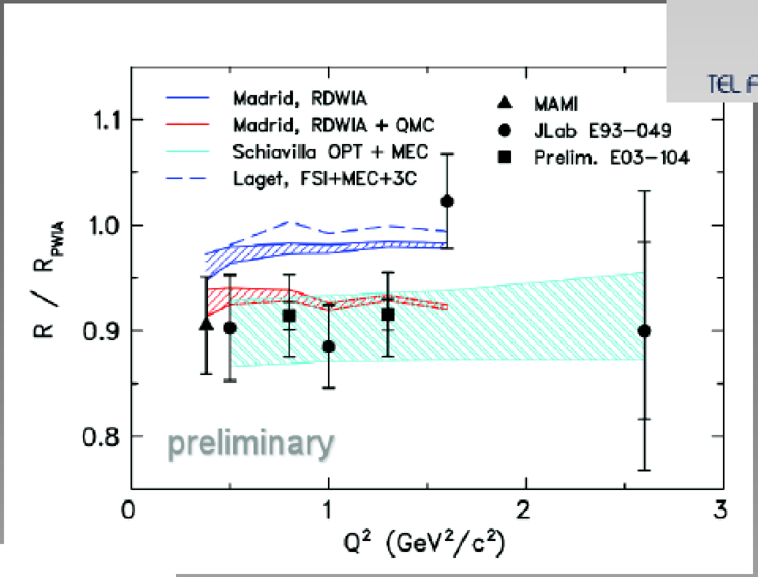
relative probability of finding pn SRC in the "pX" configuration that contains a proton with $p_i > k_F$.

$$R \equiv \frac{\int\limits_{\alpha_i^{min}}^{\alpha_i^{max}} \int\limits_{p_{ti}^{min}}^{p_{ti}^{max}} \int\limits_{\alpha_n^{min}}^{\alpha_n^{max}} \int\limits_{p_{tn}^{min}}^{p_{tn}^{max}} D^{pn}(\alpha_i, p_{ti}, \alpha_n, p_{nt}, P_{R+}) \frac{d\alpha}{\alpha} d^2p_t \frac{d\alpha_n}{\alpha_n} d^2p_{tn} dP_{R+}}{\int\limits_{\alpha_i^{min}}^{\alpha_i^{max}} \int\limits_{p_{ti}^{min}}^{p_{ti}^{max}} S^{pn}((\alpha_i, p_{ti}, P_{R+}) \frac{d\alpha}{\alpha} d^2p_t dP_{R+}}.$$

$^4He(\vec{e},e'\vec{p})$

Polariztion Transfer

Copied from S. Strauch talk



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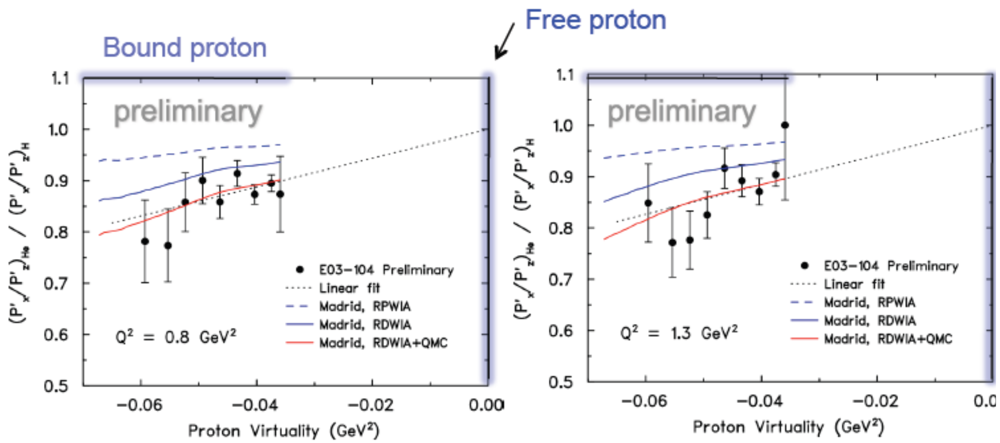
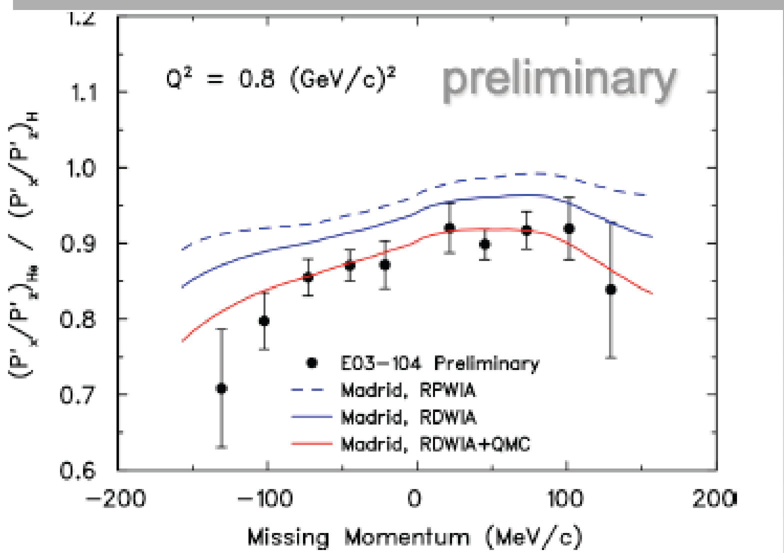
Proton Virtuality: $v = p^2 - m_P^2$

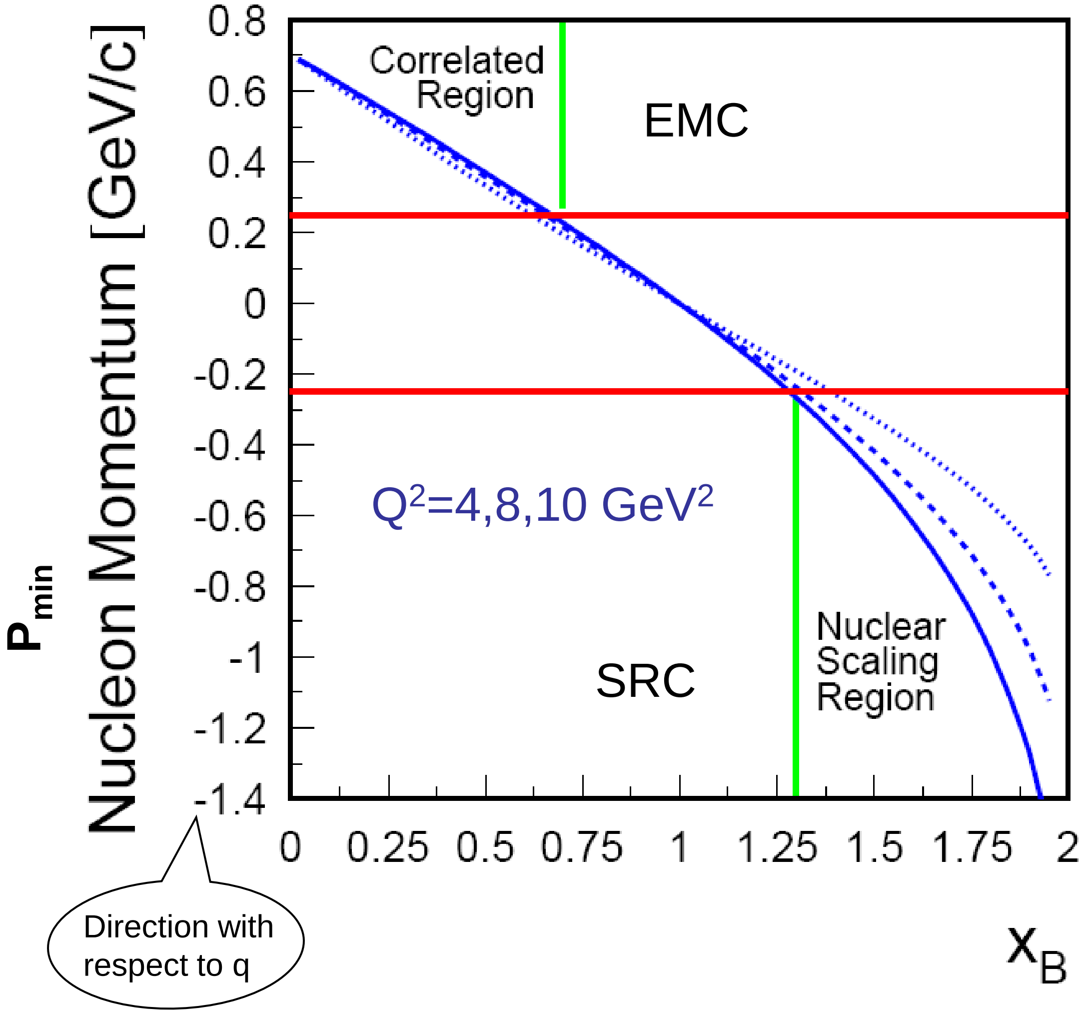


- Polarization-transfer double-ratio data and calculations show dependence on proton virtuality with the trend of R ≈ 1 for $p^2 = m_P^2$; as it should be.
- Excellent description of preliminary E03-104 data with the RDWIA + QMC (in-medium form factors) model.

see: C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)



M. Paolone at al. PRL 105,072001,(1020)



The minimum missing momentum of the D(e,e')pn reaction from

conservation of energy and momentum for quasi-elestic scattering

$$(q + p_d - p_n)^2 = m_p^2$$

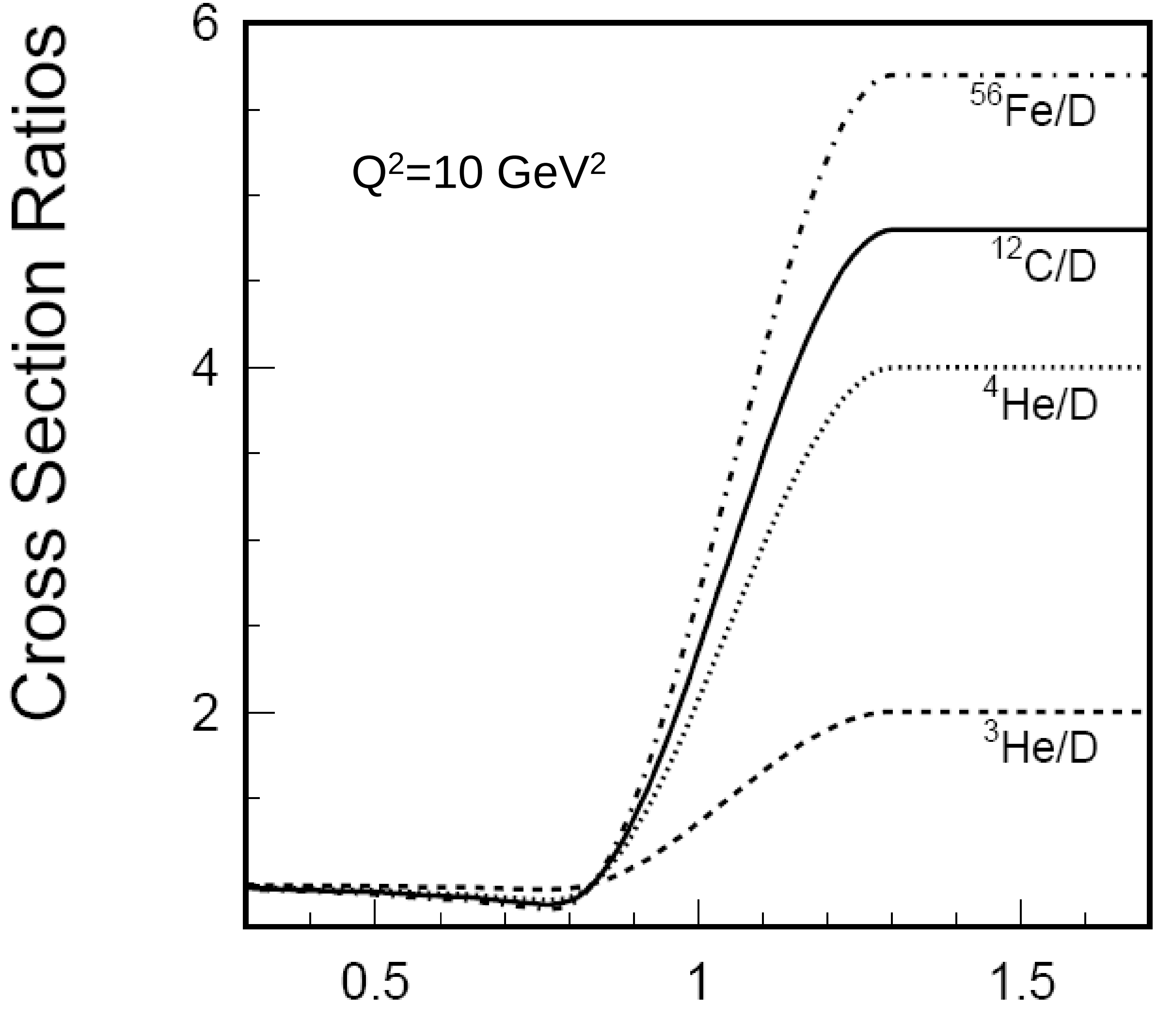
$$P_d(x_B) = 2\pi \cdot \int_{P\min}^{\infty} p^2 \cdot n_d(p) \cdot dp$$

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

$$P_A(x_B) = 2\pi \cdot \int_{P\min}^{\infty} p^2 \cdot n_A(p) \cdot dp$$

$$\frac{\sigma_A}{\sigma_d} = \frac{1 - P_A(x_B)}{1 - P_d(x_B)}$$

Higinbotham, Gomez, Piasetzky arXiv:1003.4497 [hep-ph]



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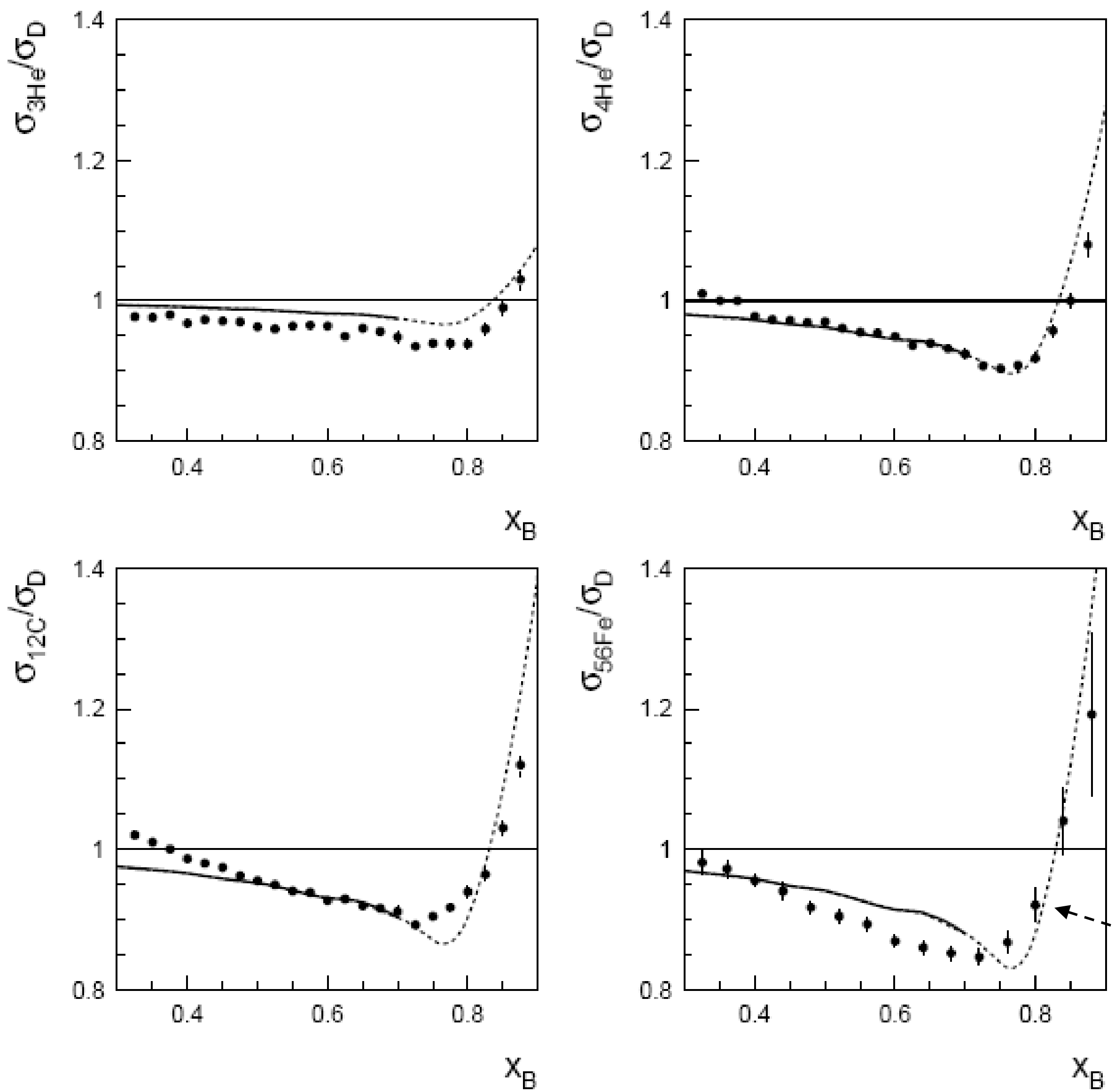


Data:

$^3He, ^4He, ^{12}C$

J. Seely et al.

PRL 103, 202301 (2009).

^{56}Fe

J. Gomez et al.

PR D49, 4348 (1994).

interpolation

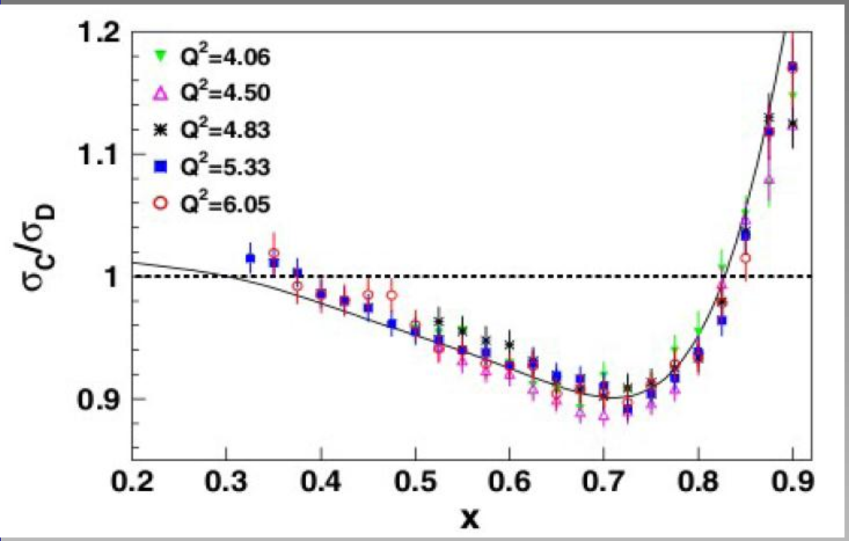
Higinbotham, Gomez, Piasetzky arXiv:1003.4497 [hep-ph]

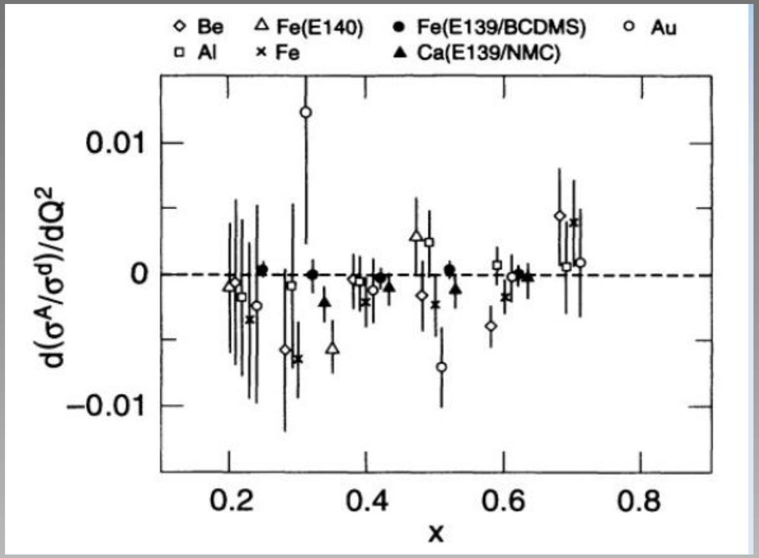
Very weak Q^2 dependence

EMC

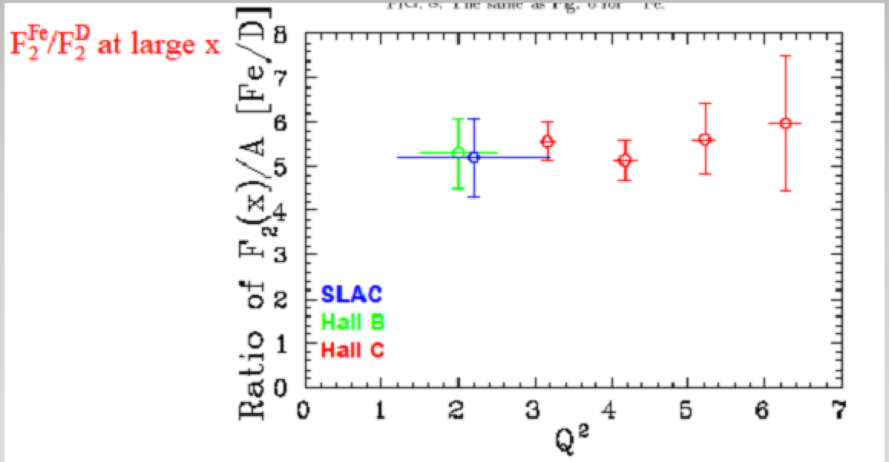
JLab J. Seely et al.

SLAC J. Gomez et al.





SRC



J. Arrington talk, Minami 2010.

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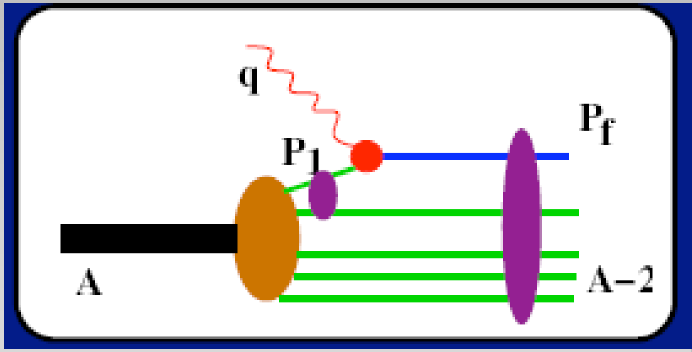
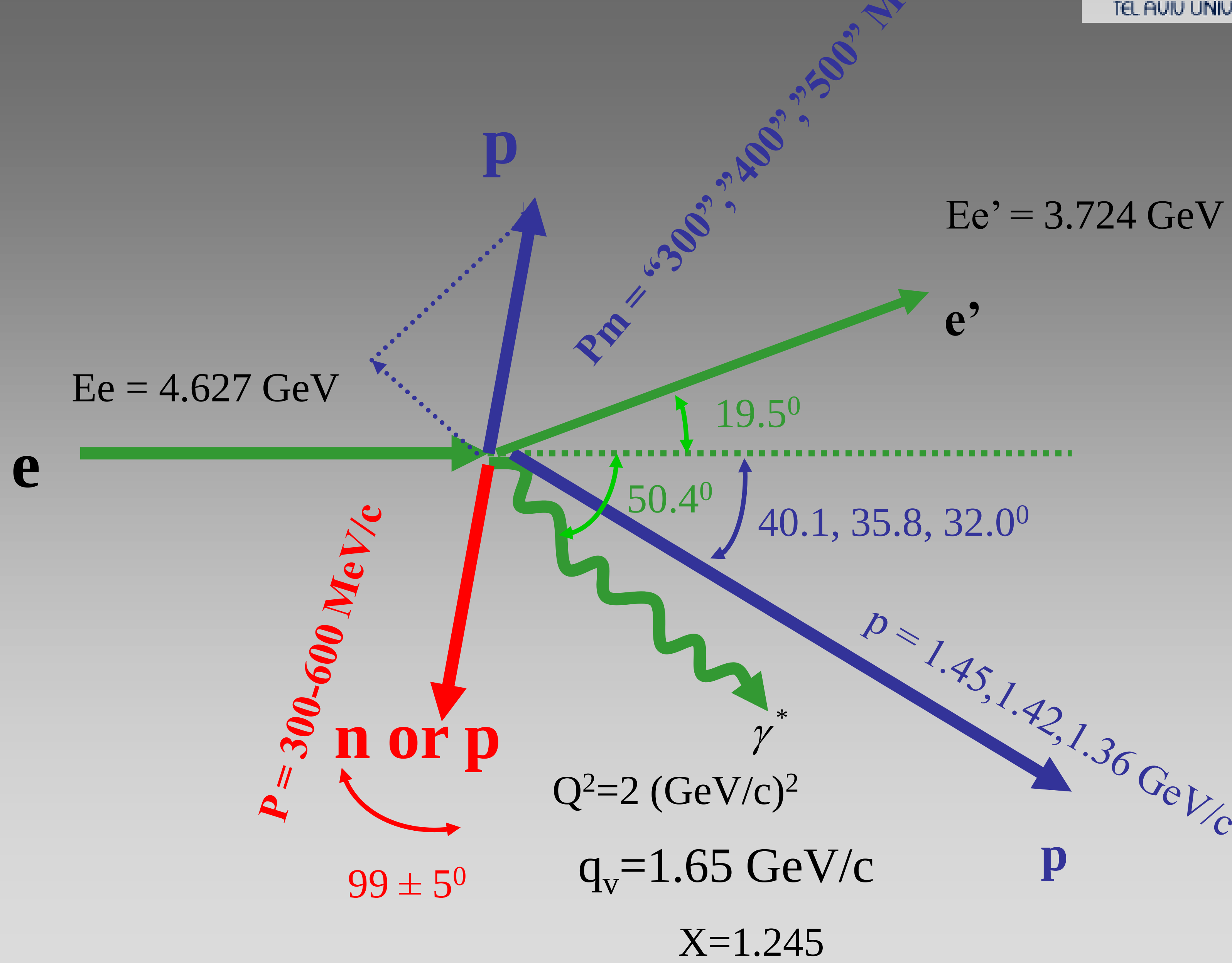
★ Conserve the CM momentum of the pair.

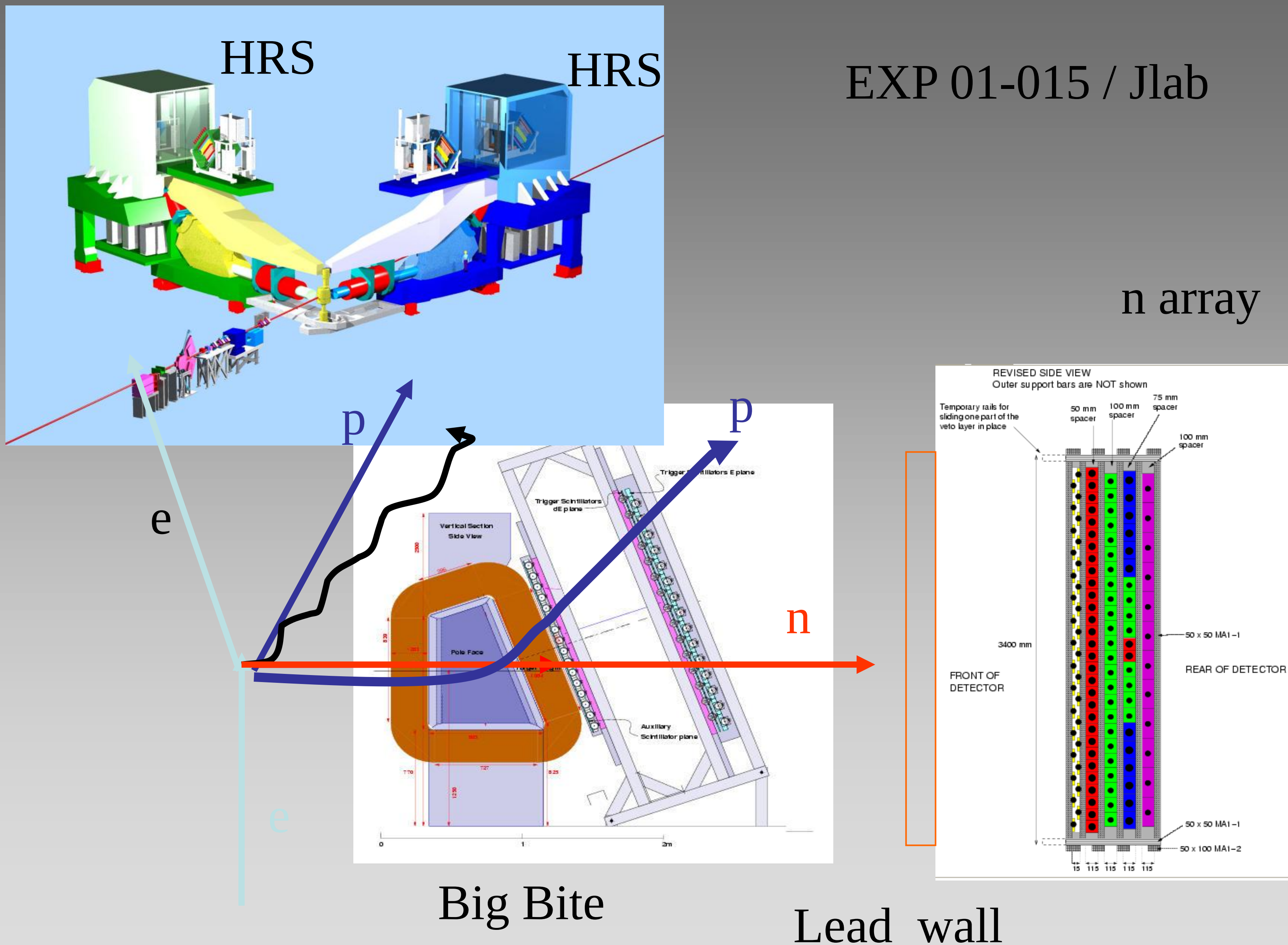


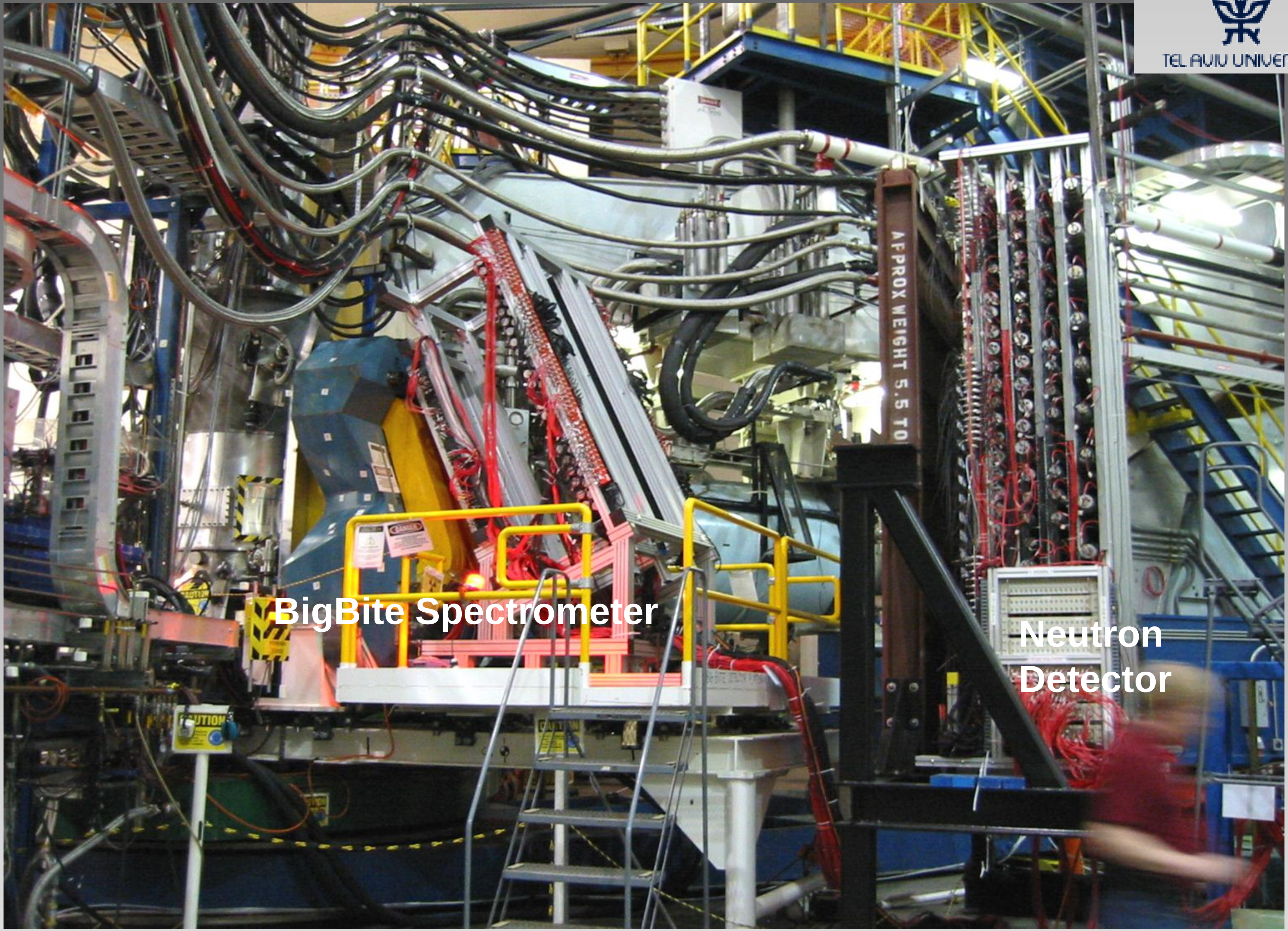
The kinematics selected for the measurement



Experimental setup

EXP 01-015 / Jlab





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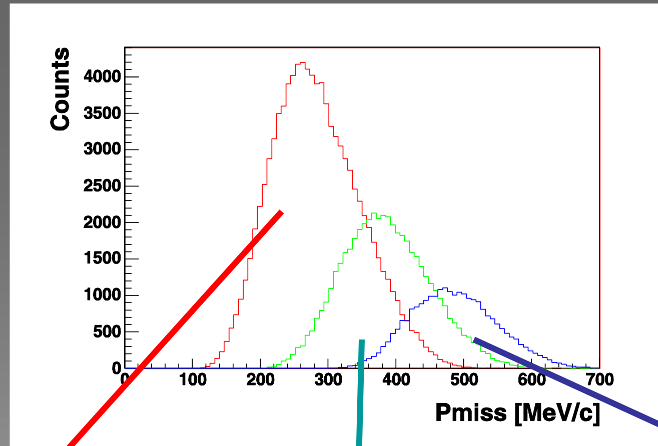
EXP 01-015 **Jlab / Hall A** Dec. 2004 – Apr. 2005

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

$x_B>1$

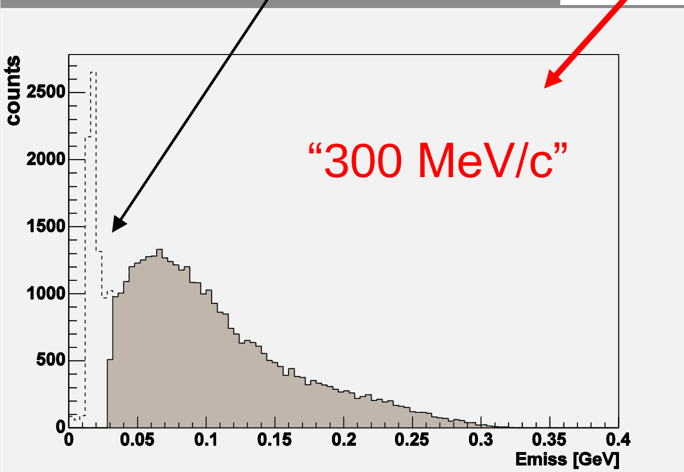


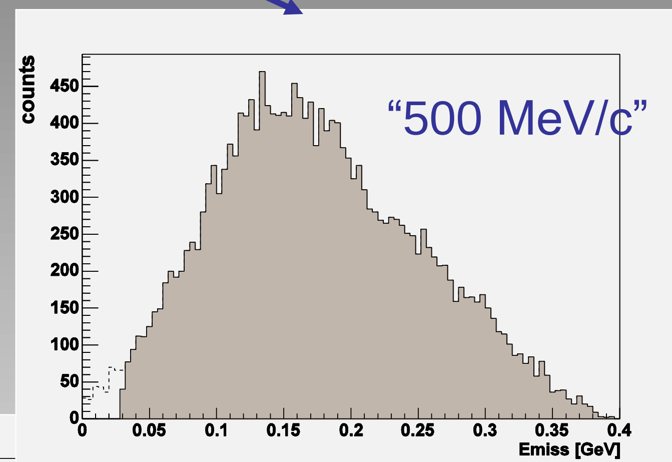
"300 MeV/c"

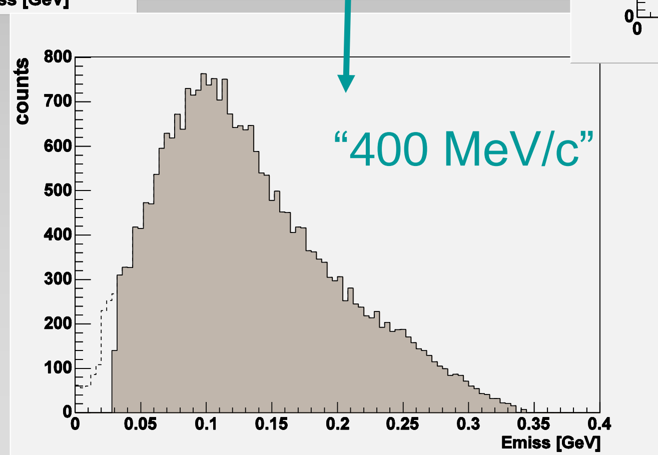
"400 MeV/c"

"500 MeV/c"

$^{12}C(e,e'p)^{11}B$







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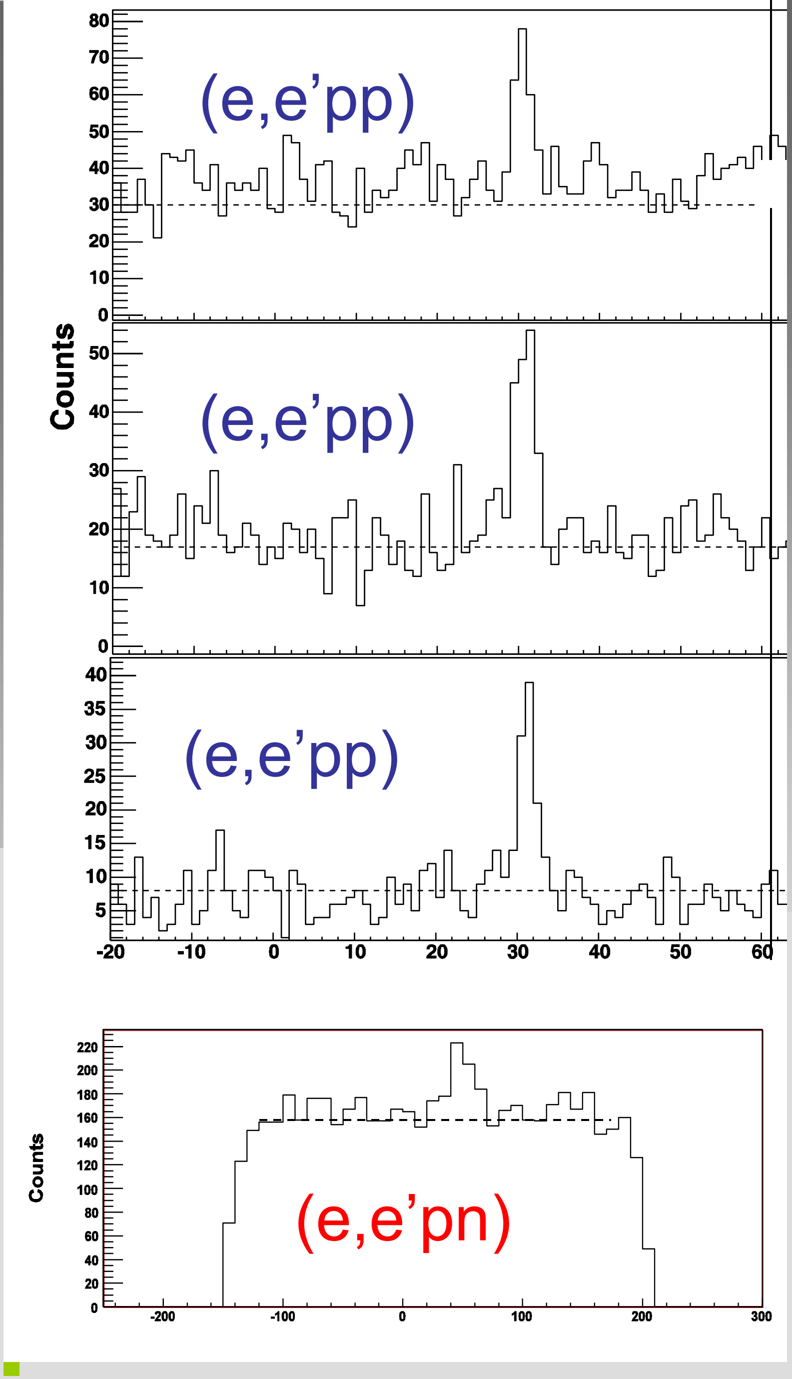


TOF [ns]

P_{mis}=“300” MeV/c

(Signal : BG= 1.5:1)

P_{mis}=“400” MeV/c

(Signal : BG= 2.3:1)

P_{mis}=“500” MeV/c

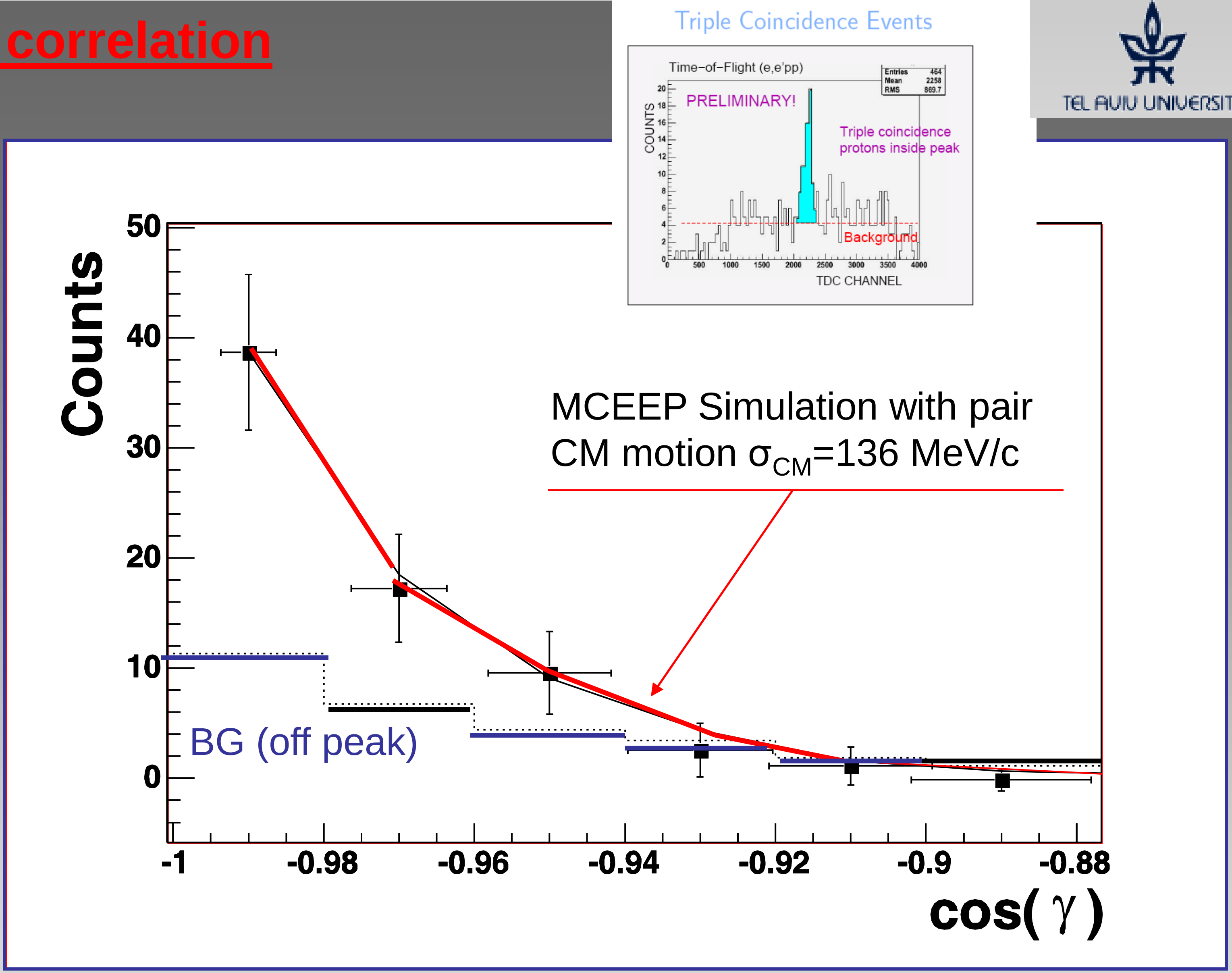
(Signal : BG= 4:1)

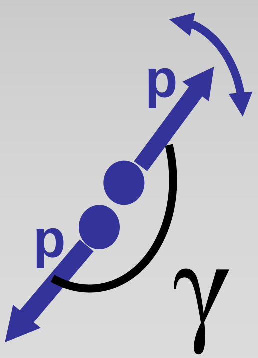
P_{mis}=“500” MeV/c

(Signal : BG= 1:7)

Directional correlation

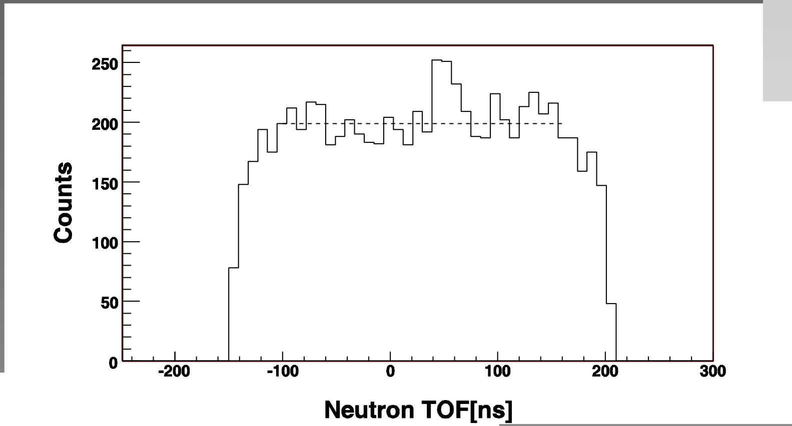
$^{12}C(e,e'pp)$

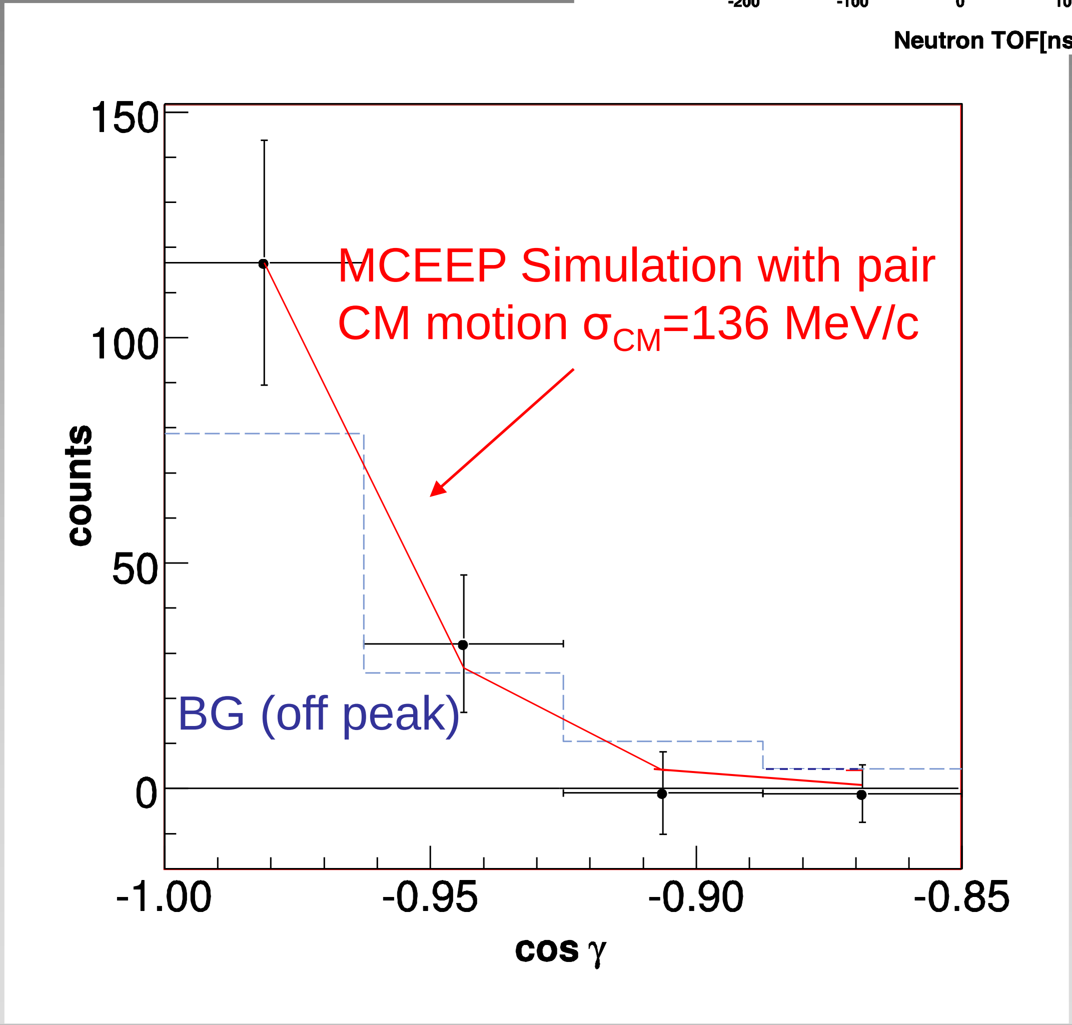


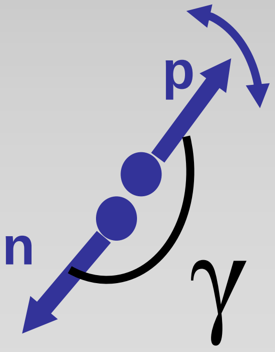


Directional correlation

$^{12}C(e,e'pn)$

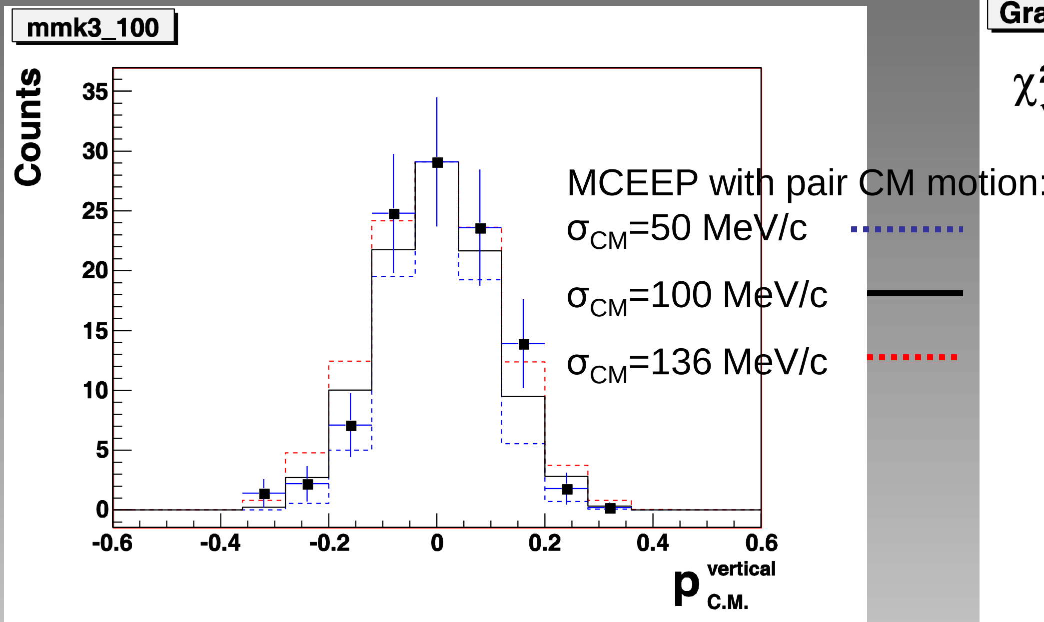


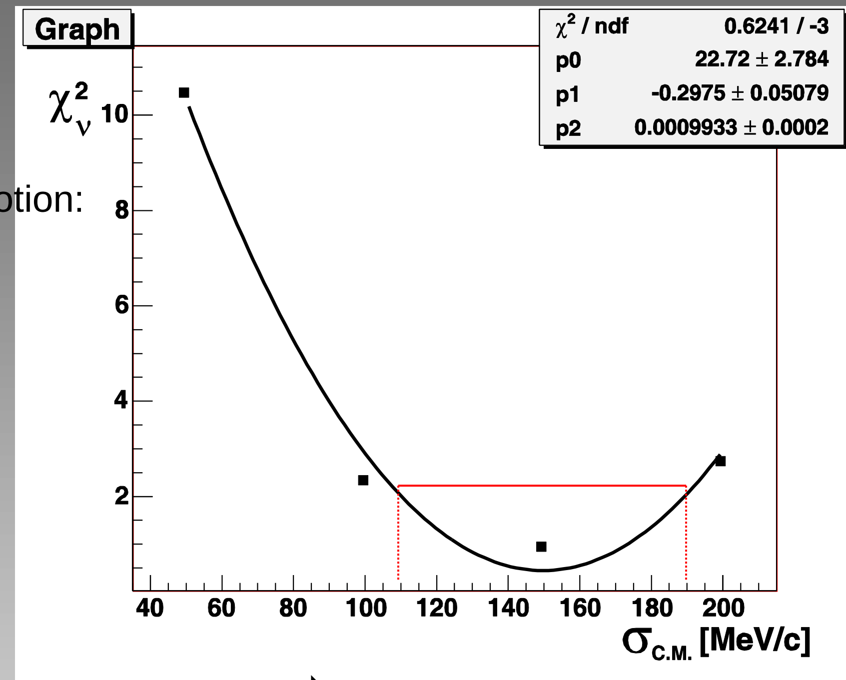




CM motion of the pair:

$P_{c.m}^{vertical}$, "500 MeV/c " setup





2 components of $\vec{p}_{c.m}$ and 3 kinematical setups

This experiment : σ_{CM}=0.136 ± 0.020 GeV/c

(p,2pn) experiment at BNL : σ_{CM}=0.143±0.017 GeV/c

Theoretical prediction (Ciofi and Simula) : σ_{CM}=0.139 GeV/c

The **free** neutron structure function

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

For

$0.35 \le X_B \le 0.7$

$$\frac{\sigma_d}{\sigma_p + \sigma_n} = 1 - a(x_B - b)$$

Fermi smearing using relativistic deuteron momentum density

□ SLAC Data, J. Arrington et al. JPG 36(2009)205005.

- - - - World parameterization of Fd, Fp

With medium correction

■ Extracted from this work

—— Corrected for the EMC effect as calculated in a PLC model