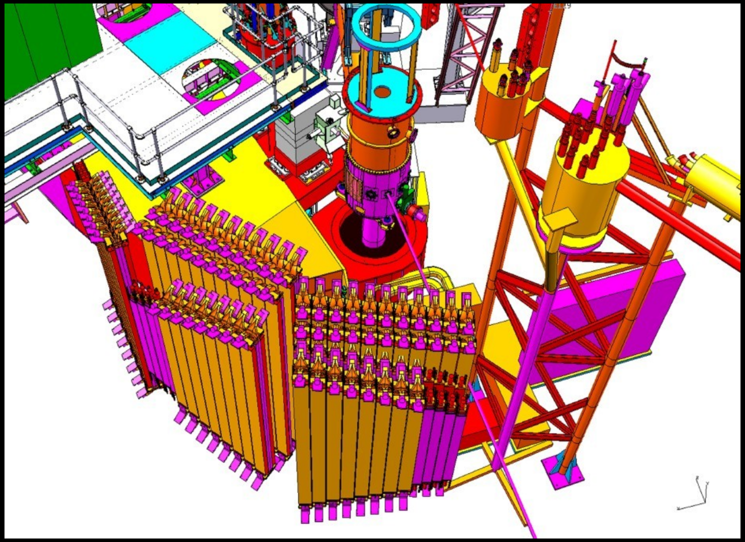
Jefferson Lab
EXPLORING THE NATURE OF MATTER

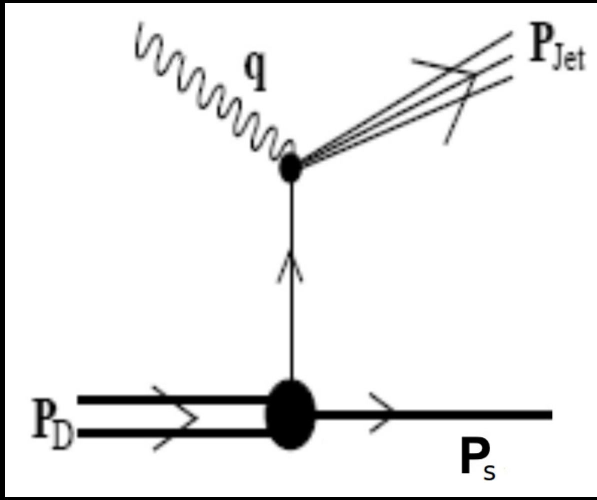
TEL AVIV UNIVERSITY | OLD DOMINION UNIVERSITY | MIT

In Medium Nucleon Structure Function, SRC, and the EMC Effect



Proposal PR12-11-107

Spokepersons:
O. Hen (TAU), L. B. Weinstein (ODU),
S. A. Wood (JLab), S. Gilad (MIT)

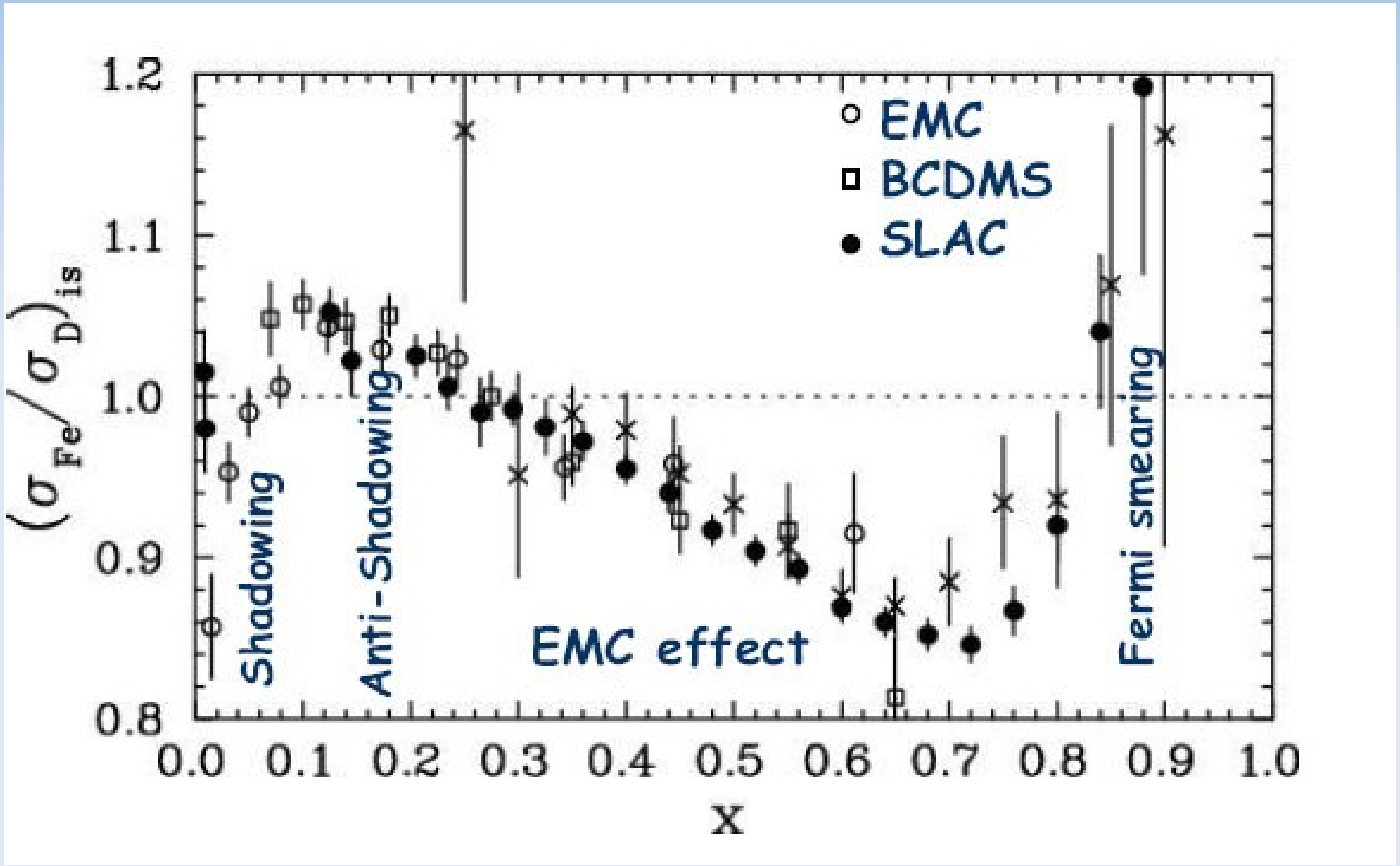


Collaboration:
Experimental groups from : ANL, CNU, FIU, HU, JLab, KSU, MIT, NRCN, ODU, TAU, U. of Glasgow, U. of Ljubljana, UTFSM, UVa
Theoretical support: Accardi, Ciofi Degli Atti, Cosyn, Frankfurt, Kaptari, Melnitchouk, Mezzetti, Miller, Ryckebusch, Sargsian, Strikman

PAC 38 Aug. 2011

The European Muon Collaboration (EMC) effect

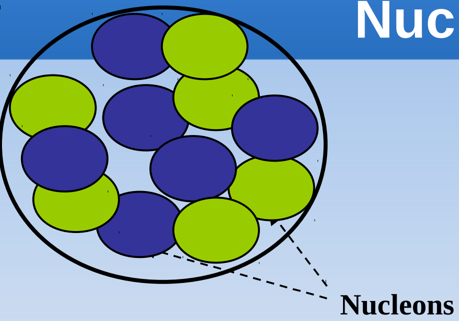
DIS cross section per nucleon in nuclei ≠ DIS off a free nucleon



Can **not** be explained only by simple Fermi motion and binding effects

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)

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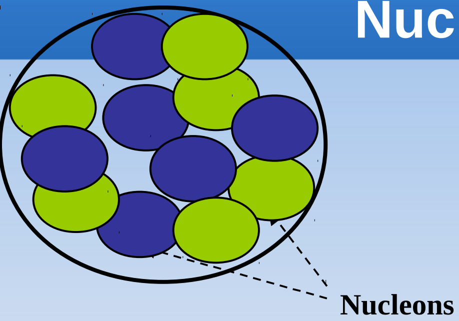

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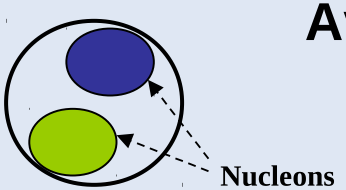
Deuteron: binding energy ~2 MeV

Average nucleons separation ~2 fm



Naive expectation :

DIS off a deuteron = DIS off a free proton neutron pair

DIS scale: several tens of GeV

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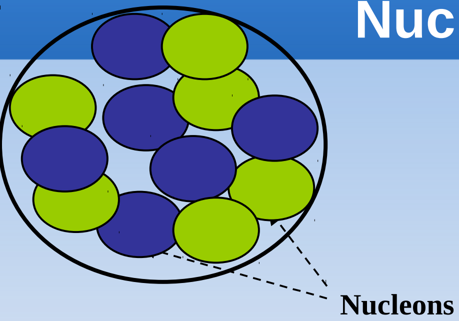

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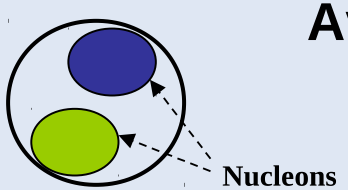

Naive expectation :

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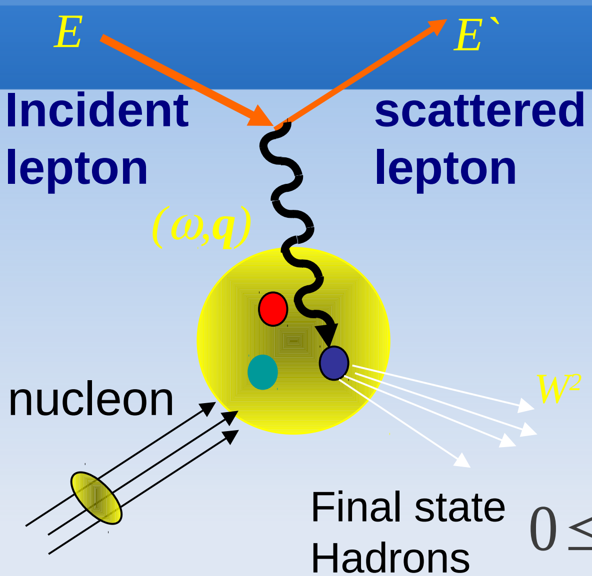
Question 1:

$$\sigma_d^{DIS} \overset{?}{=} \sigma_p^{DIS} + \sigma_n^{DIS}$$

Is there an 'EMC effect' in Deuterium ?

Deep Inelastic Scattering (DIS)

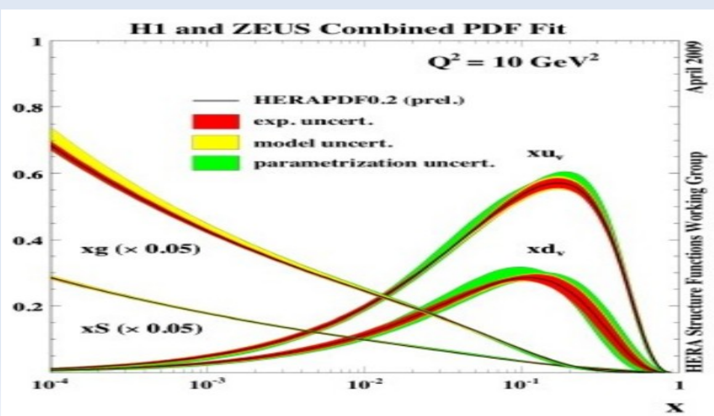
Inclusive electron scattering A(e,e')

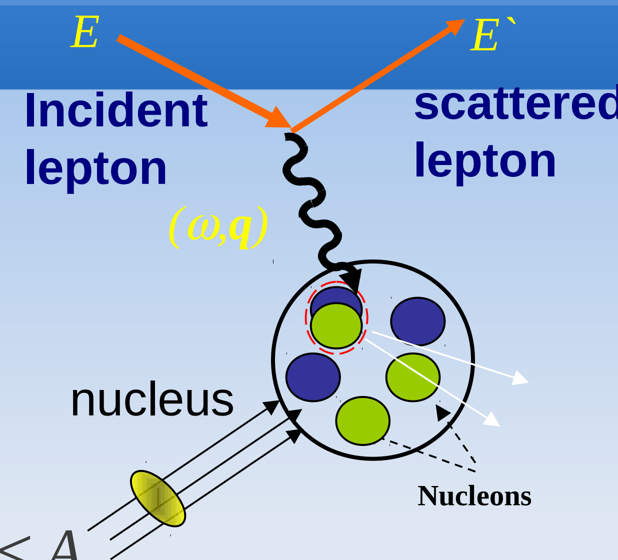


$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$
$$\omega = E' - E$$
$$x_B = \frac{Q^2}{2m\omega}$$

$$0 \le x_B \le 1$$

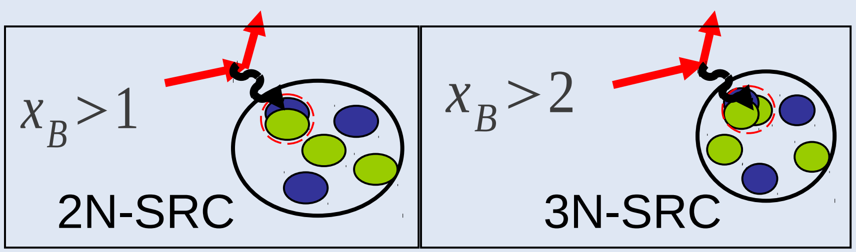
x_B gives the fraction of nucleon momentum carried by the struck parton





$$0 \le x_B \le A$$

x_B counts the minimum number of nucleons involved

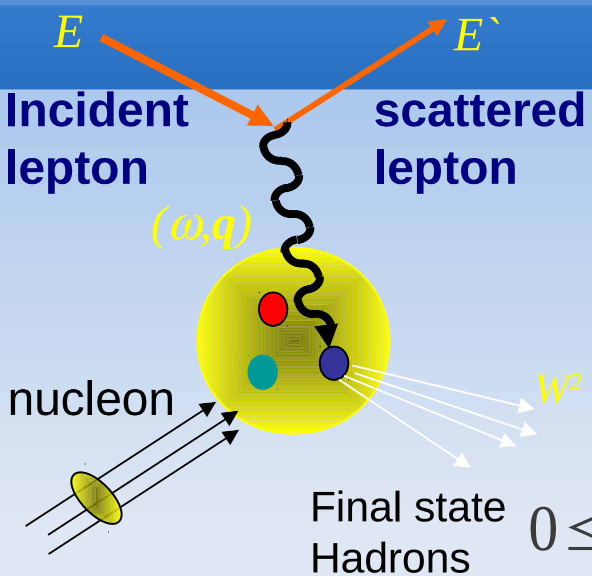


x_B>1 determines minimum p_{miss}

→ sensitive to the high momentum tail of the nuclear wave function

→ scaling

Deep Inelastic Scattering (DIS)



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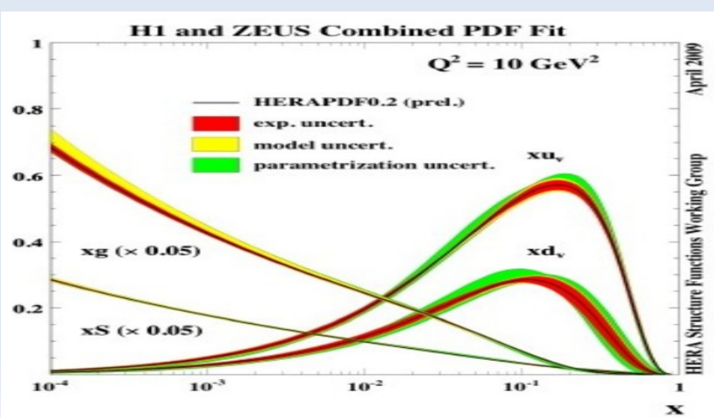

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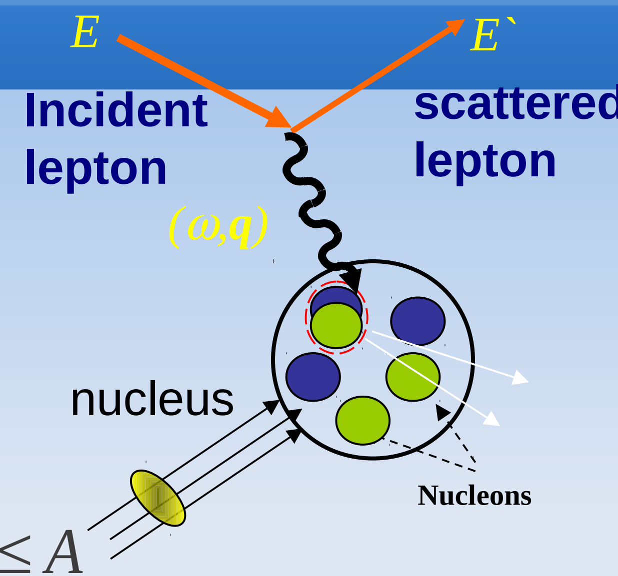

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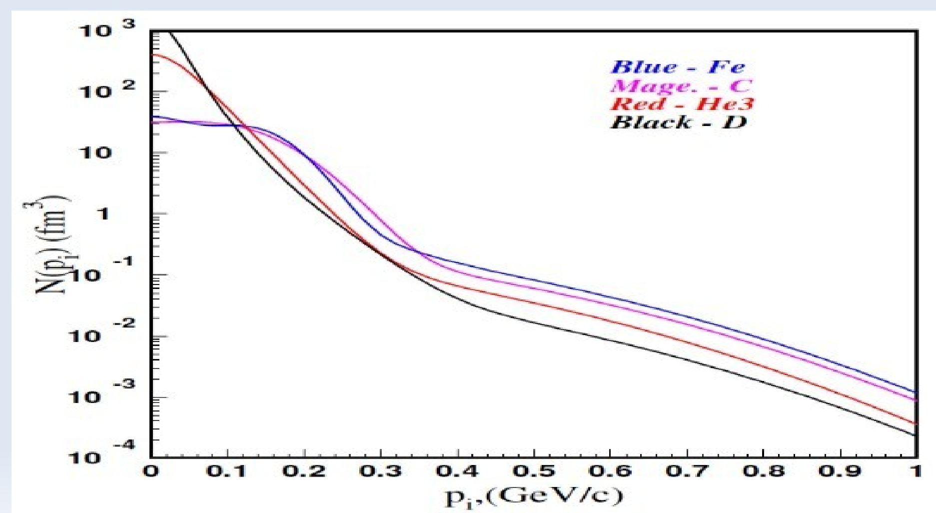
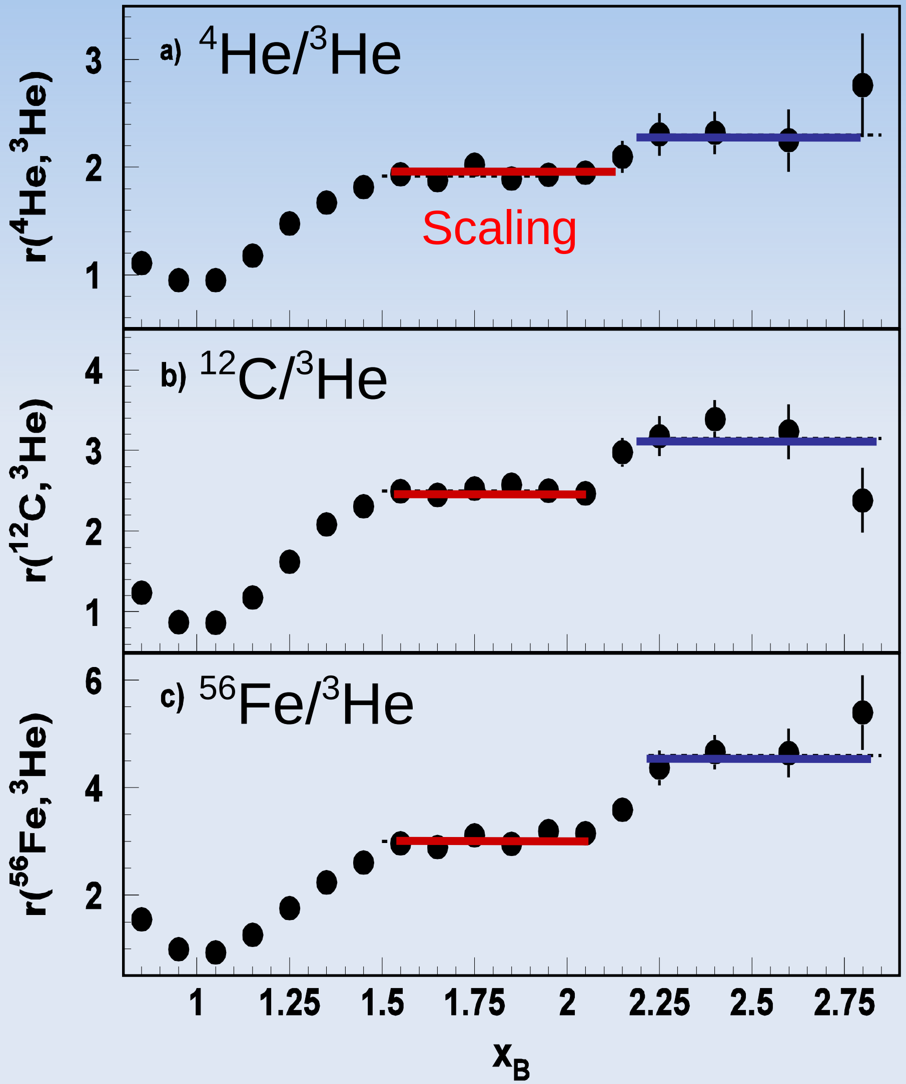


JLab CLAS A(e,e') Result



Plateau shows same high-p distributions

Scale factors give relative probabilities for SRC

20% probability for 2N-SRC in ^{12}C

1-2% probability for 3N-SRC

K. Sh. Egiyan et al. PRC 68, 014313 (2003)
K. Sh. Egiyan et al. PRL. 96, 082501 (2006)

<u>More A/d data:</u>
SLAC D. Day et al. PRL 59,427(1987)
JLab. Hall C E02-019

More on 2N-SRC from inclusive and exclusive data

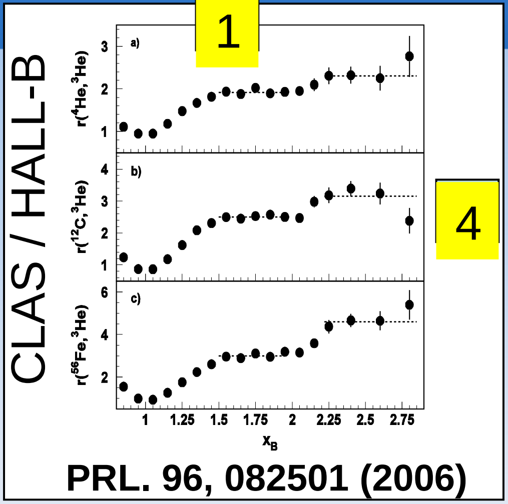
1 The probability for a nucleon to have p ≥ 300 MeV/c in medium nuclei is 20-25%

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

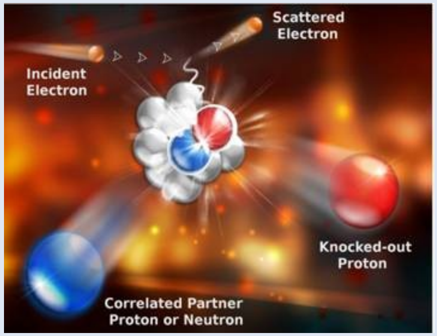
1 2 ~80% of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.

3 2N-SRC dominated by np pairs

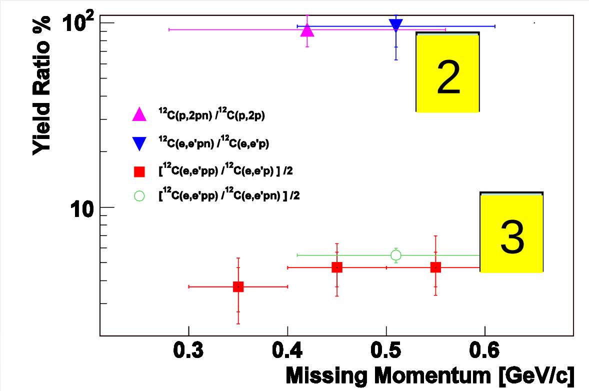
4 Three nucleon SRC are present in nuclei



PRL. 96, 082501 (2006)

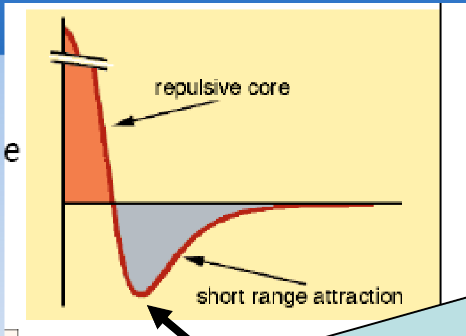


EVA / BNL
JLab / HALL-A

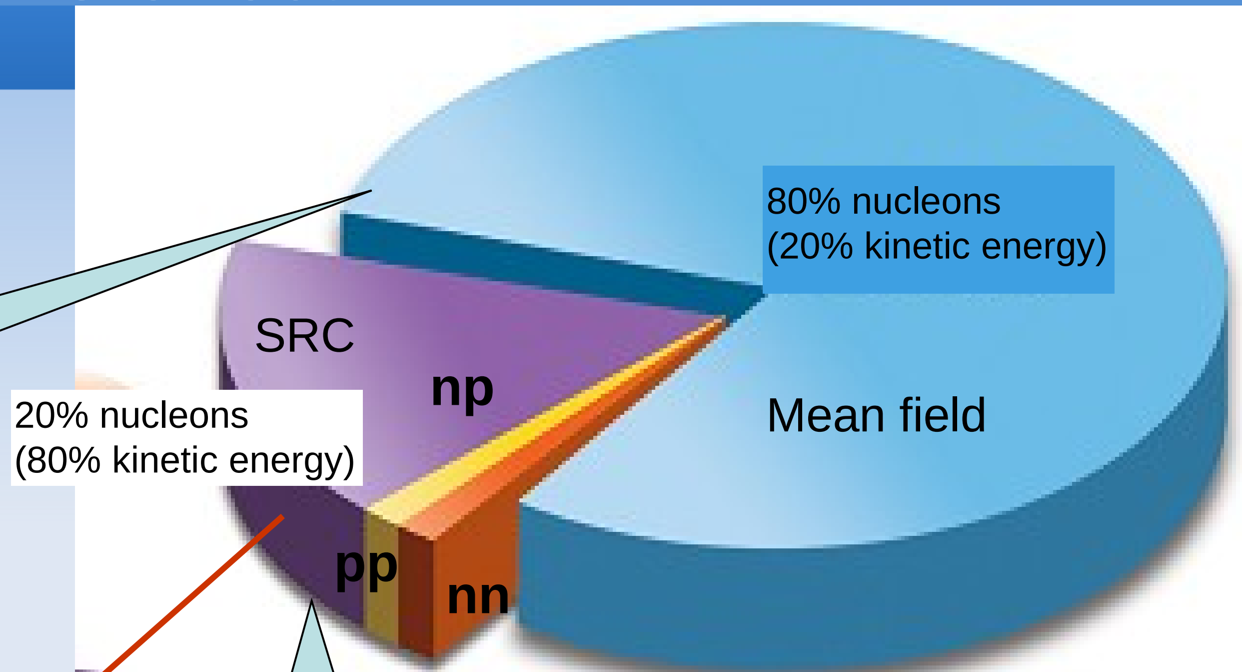


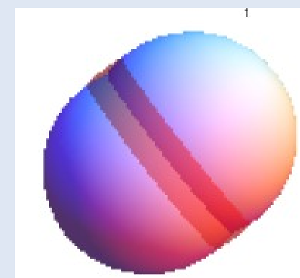
PRL 162504(2006); Science 320, 1476 (2008)

Where is the EMC effect ?



Largest attractive force

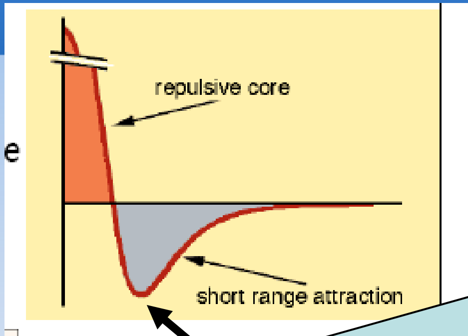




OR

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

Where is the EMC effect ?



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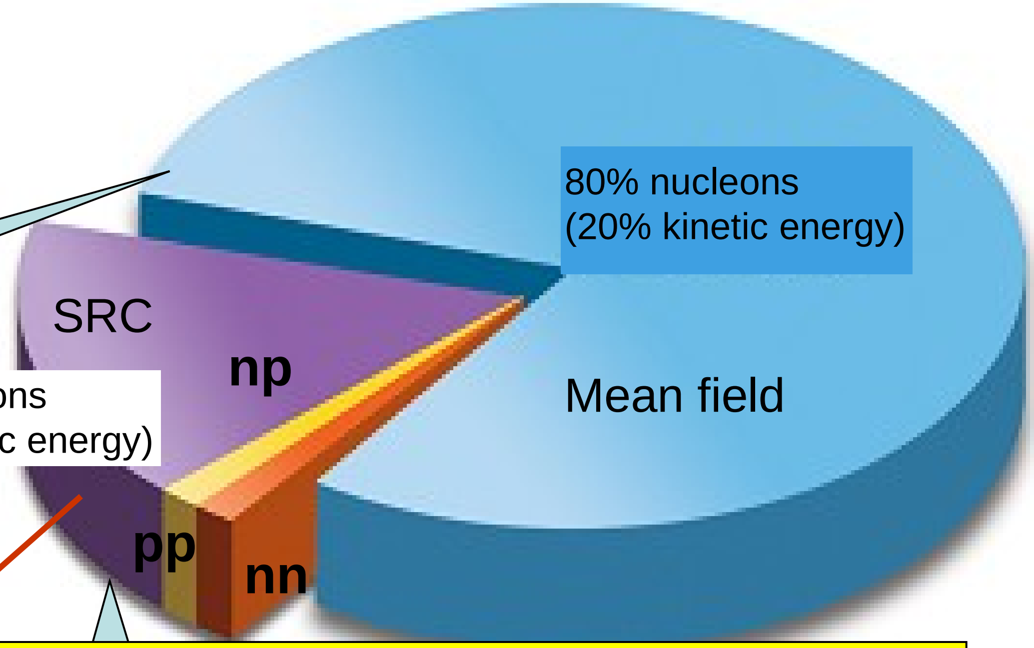
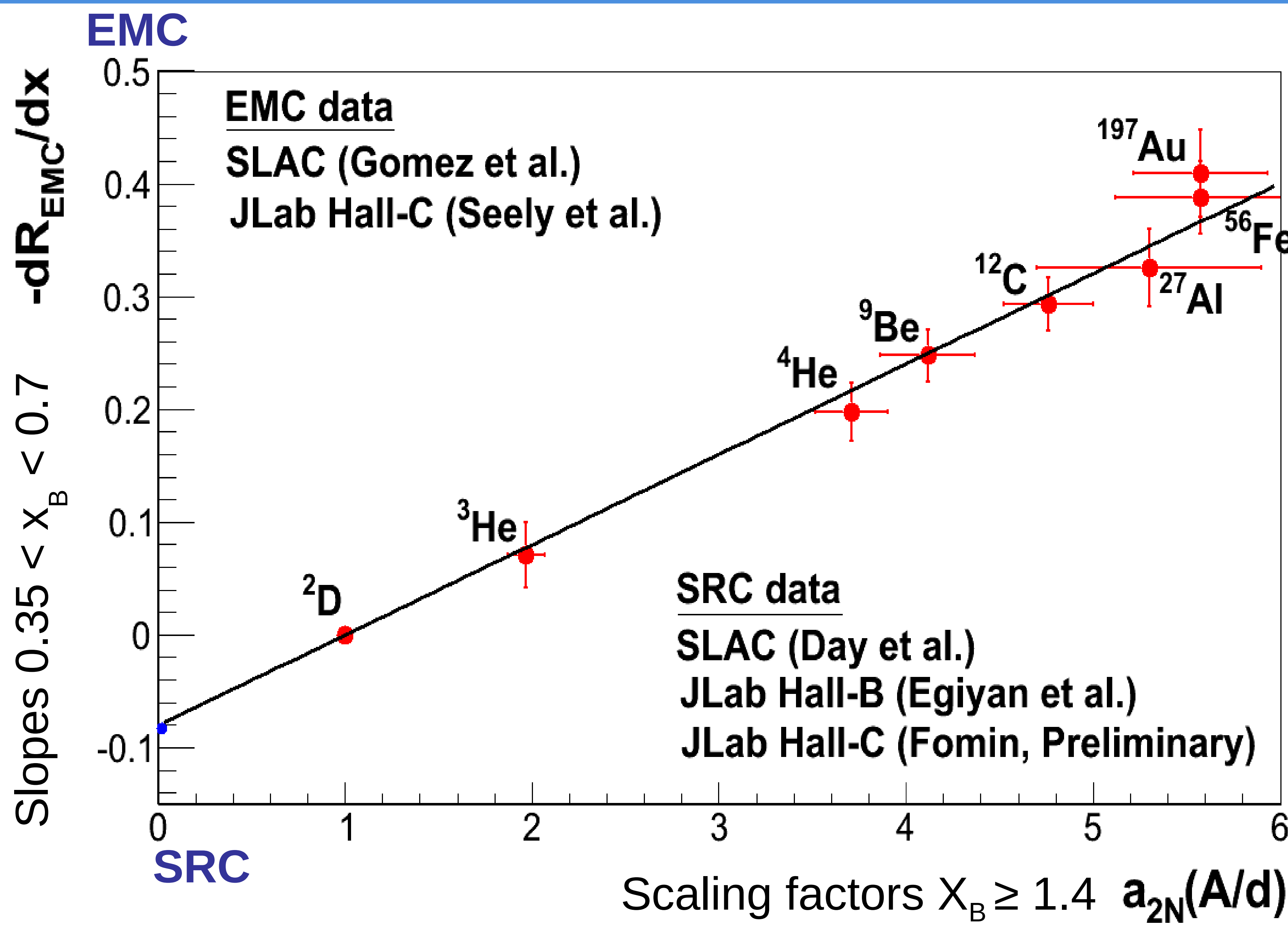
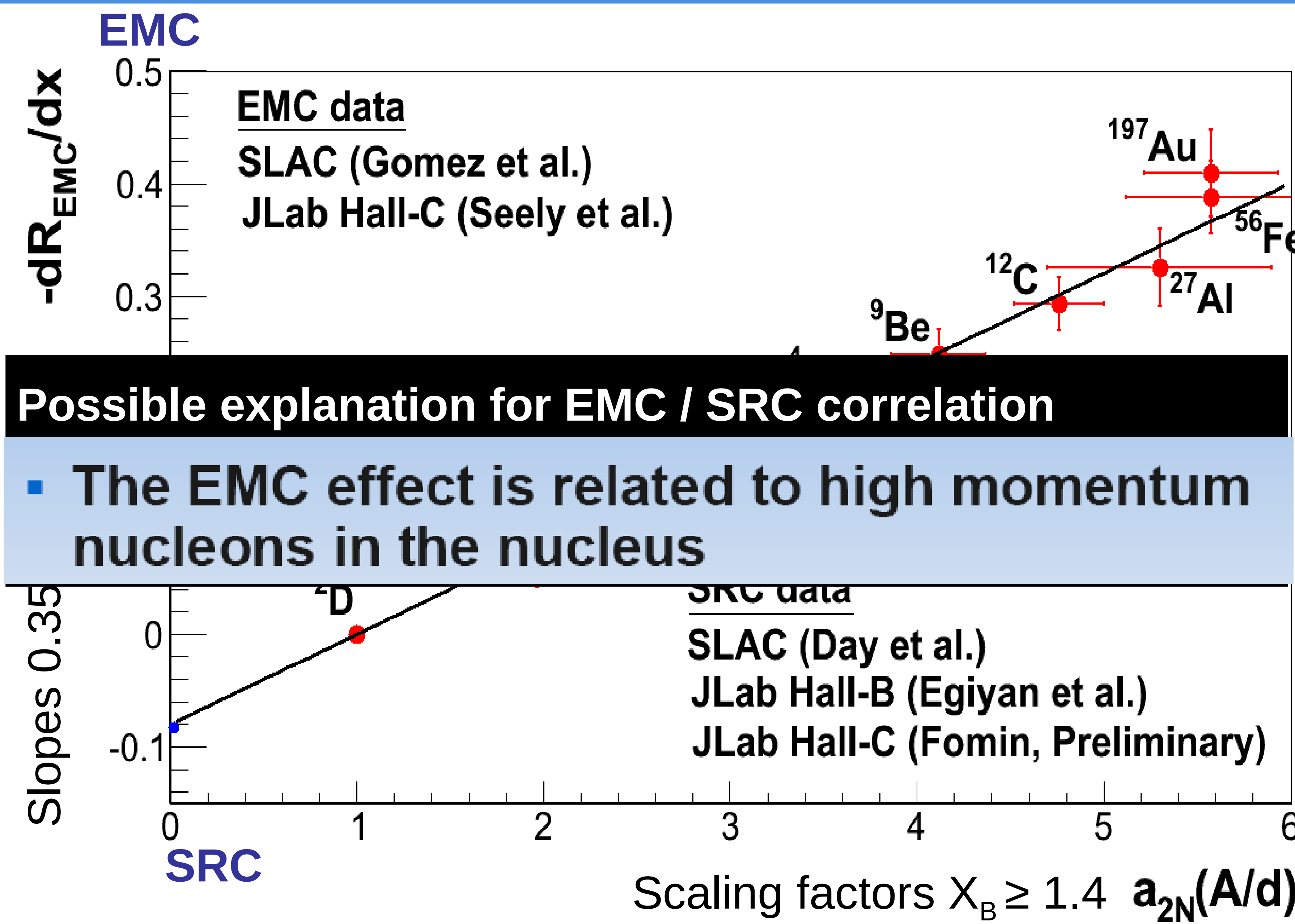


Question 2:

Is the EMC effect predominantly associated with high momentum nucleons?



L. B. Weinstein et al. PRL. 106, 052301 (2011)



Possible explanation for EMC / SRC correlation

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

L. B. Weinstein et al. PRL. 106, 052301 (2011)

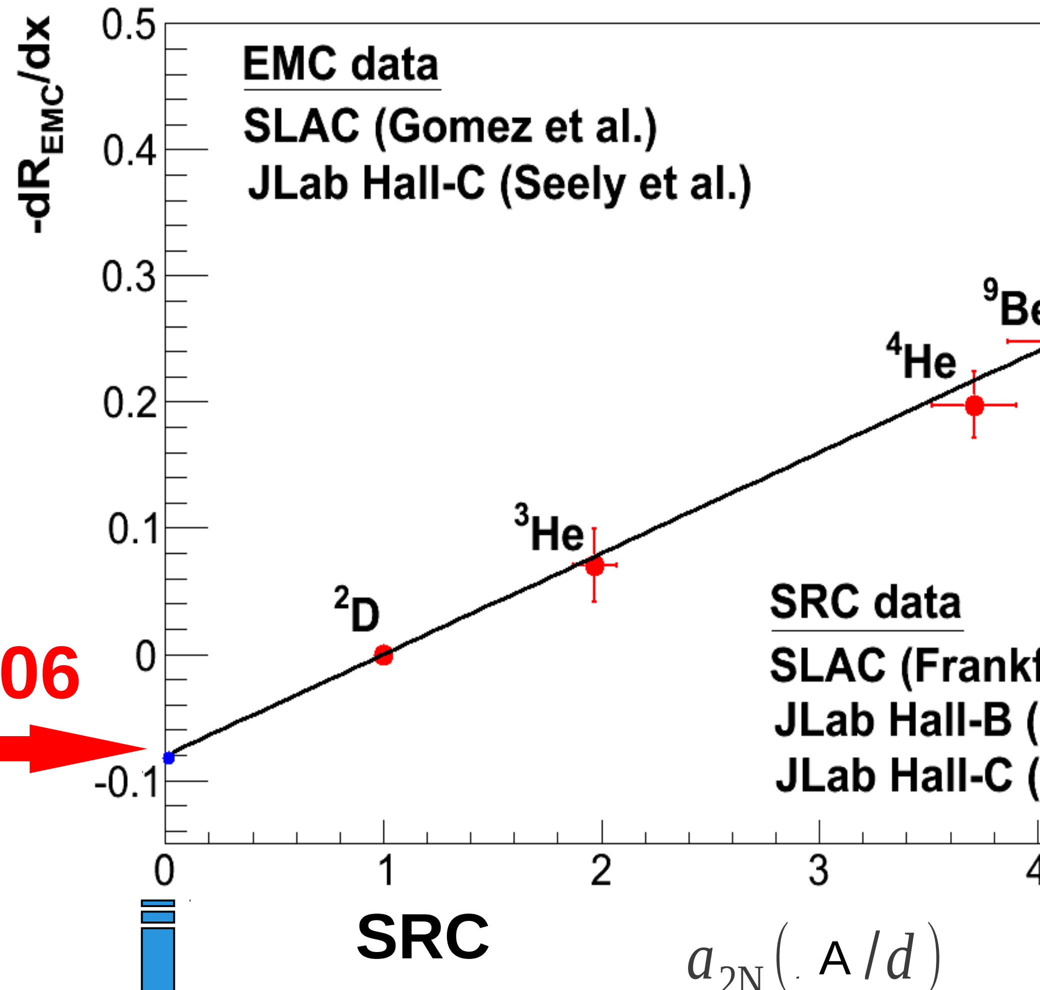
Question 1:

Is there an 'EMC effect' in Deuterium ?

$$\sigma_d^{DIS} \neq \sigma_p^{DIS} + \sigma_n^{DIS}$$

0.079±0.06

$$\frac{\sigma_d}{\sigma_p + \sigma_n}(x=0.6) = \textbf{0.975}$$



SRC=0 free nucleons

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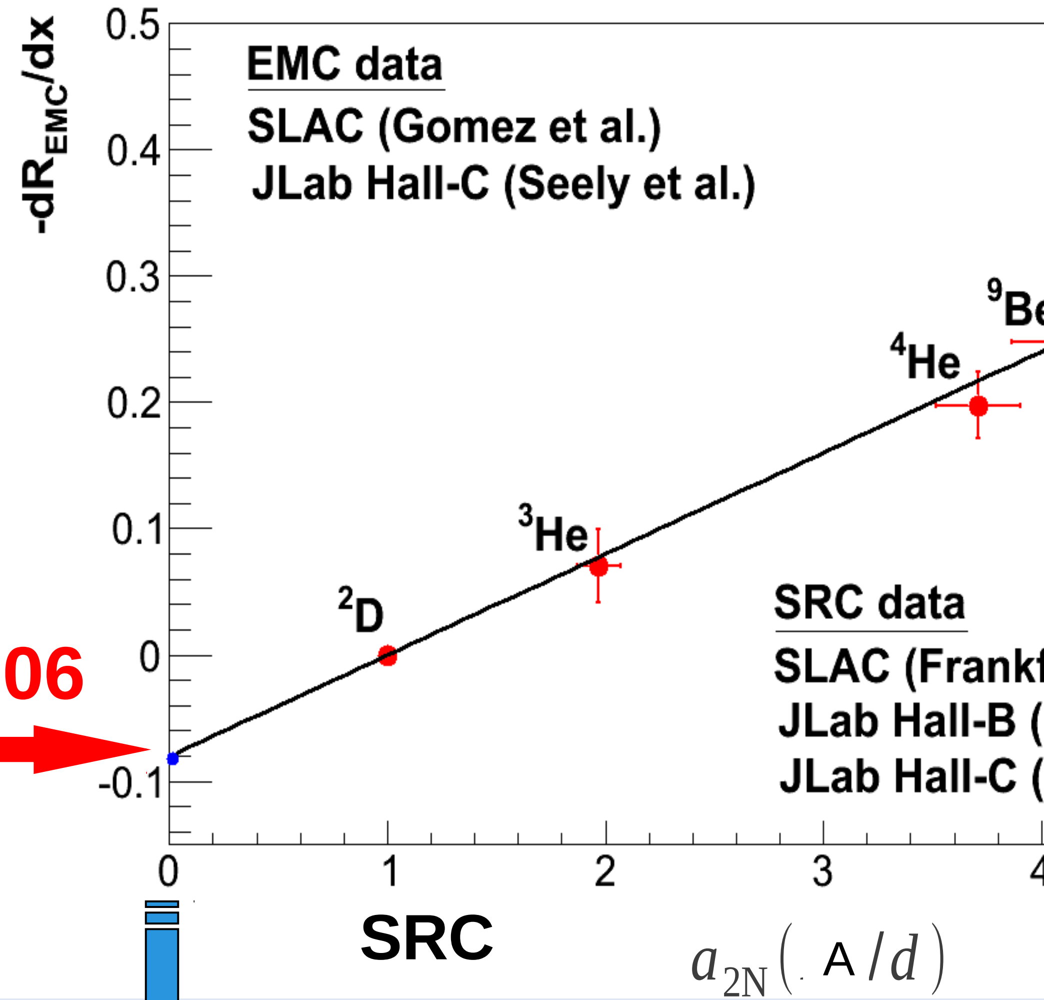

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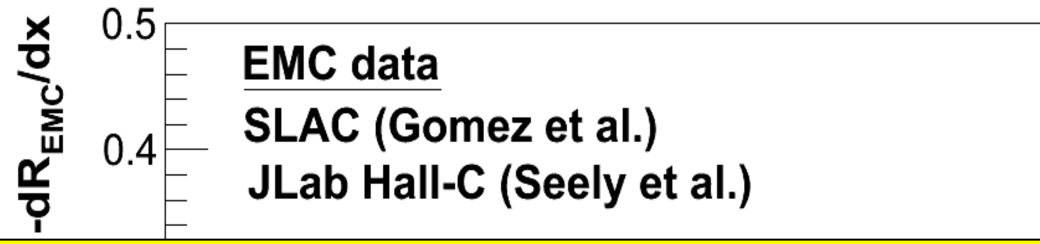
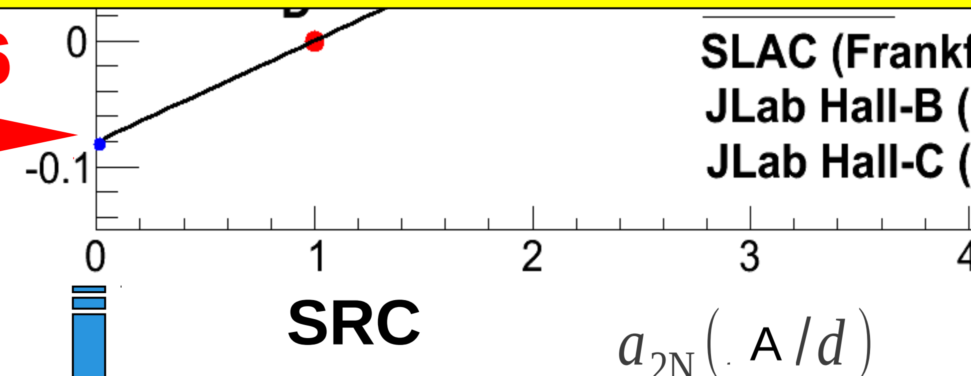


Question 3:

Is there a large ‘EMC effect’ in tagged DIS off Deuterium ?

➔ **Is the In-Medium structure function momentum dependent?**



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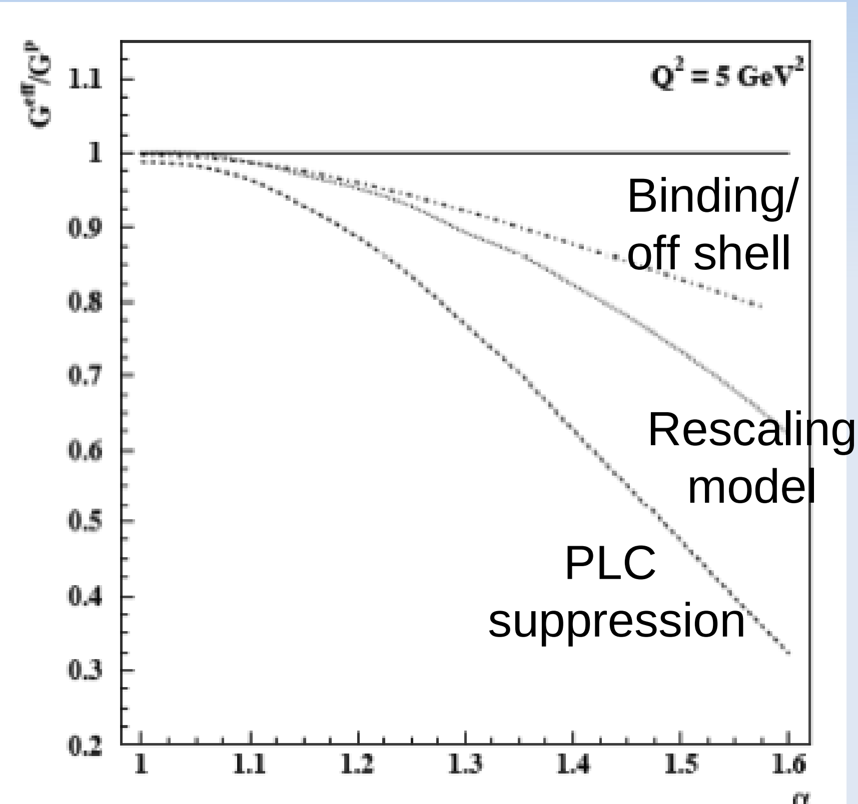
SRC=0 free nucleons

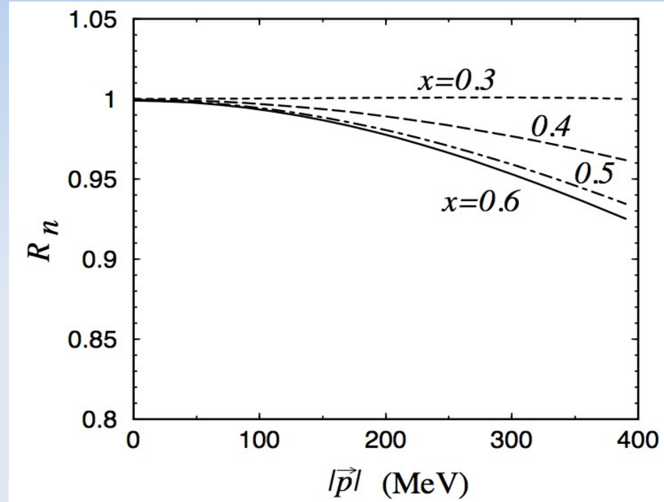
Question 4:

How does the nucleon structure function F_2 depend on the nucleon virtuality ?

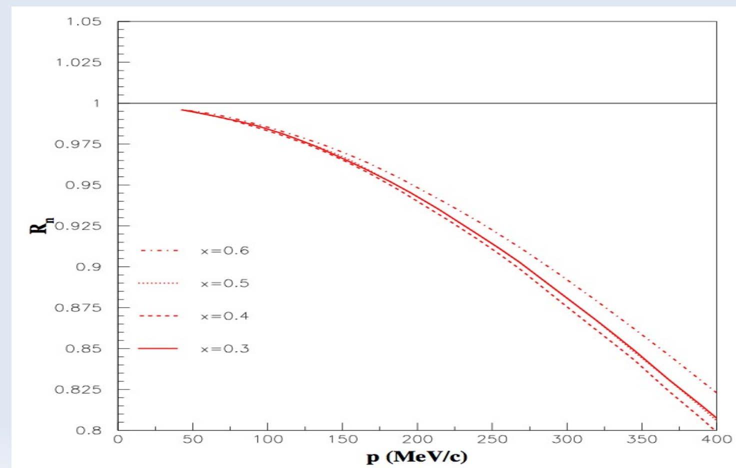


Z. Phys. A359 (1997) 99

$$\alpha_s = (E_s - p_s^z)/m_s$$



Phys. Lett. B 335, 11 (1994)



Phys. Lett. B 356, 157 (1995)

Note: Other models predict no dependence on virtuality

Theory Report

PR12-11-107: ***In Medium Nucleon Structure Functions, SRC and the EMC effect***

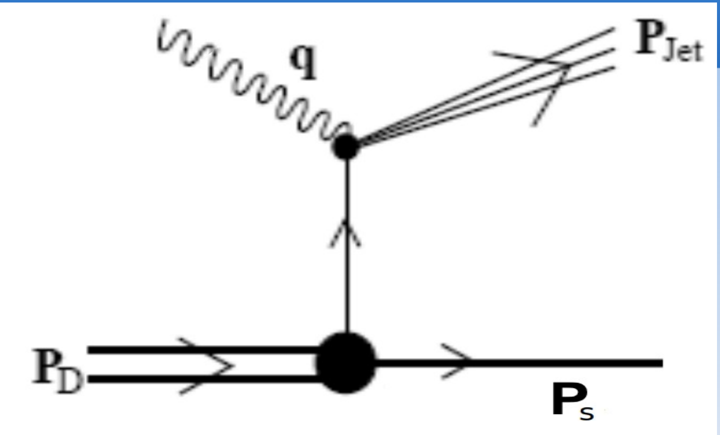
A.V. Radyushkin, M.R. Pennington

This is a well motivated experiment that has to be done, and one JLab is well placed to perform.

We Agree :)

Now: can we do it ?

Measurement technique



Goal: Measure DIS off high p nucleon

1. Spectator Tagging:

$d(e,e'N_s)$, DIS in coincidence with a fast, backwards, recoil nucleon.

➔ **Selects DIS off high momentum (high virtuality) nucleons**

$$v = p^2 - M_p^2 \qquad x' = \frac{Q^2}{2p_\mu q^\mu}$$

$$W'^2 = (q^\mu + p_d^\mu - p_s^\mu)^2$$

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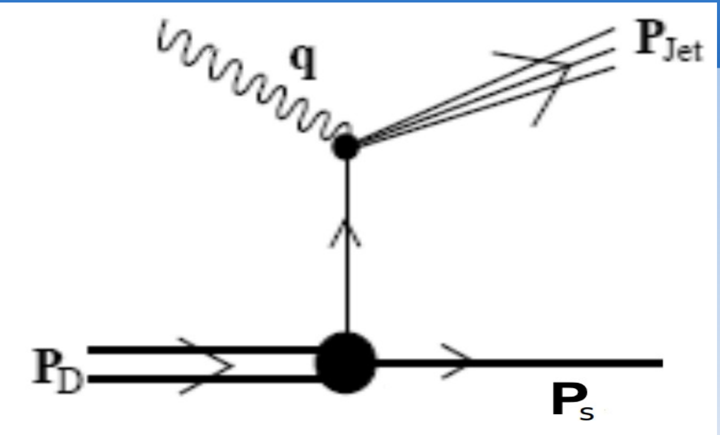

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2. cross sections ratio

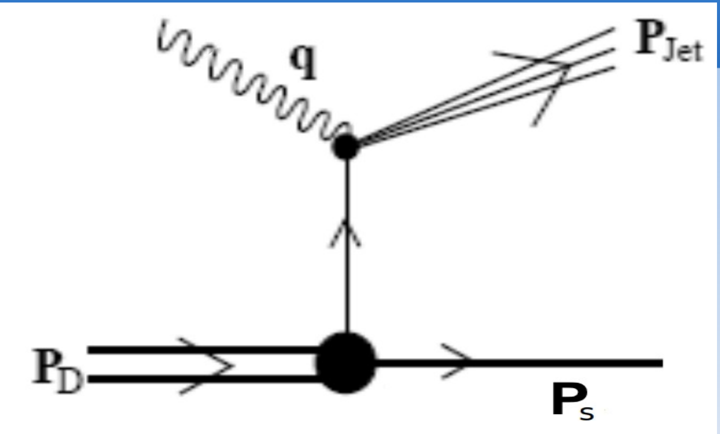
➔ **Minimize experimental uncertainties**

$$\frac{\sigma_{DIS}(x'_{high}, Q_1^2, \vec{p}_s)}{\sigma_{DIS}(x'_{low}, Q_2^2, \vec{p}_s)}$$

$x'_{high} \geq 0.45$ $\qquad 0.25 \geq x'_{low} \geq 0.35$

(No 'EMC effect ' is expected)

Measurement technique



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2. cross sections ratio

➔ **Minimize experimental and theoretical uncertainties**

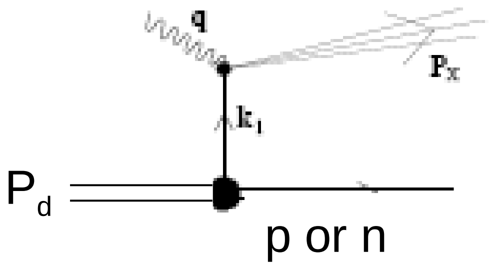
$$\frac{\sigma_{DIS}(x'_{high}, Q_1^2, \vec{p}_s)}{\sigma_{DIS}(x'_{low}, Q_2^2, \vec{p}_s)} \cdot \frac{\sigma_{DIS}^{free}(x_{low}, Q_2^2)}{\sigma_{DIS}^{free}(x_{high}, Q_1^2)} \cdot R_{FSI} = \frac{F_2^{bound}(x'_{high}, Q_1^2, \vec{p}_s)}{F_2^{free}(x_{high}, Q_1^2)}$$

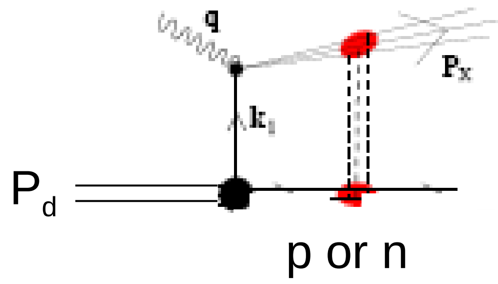
$x'_{high} \geq 0.45$

$0.25 \geq x'_{low} \geq 0.35$
(No 'EMC effect ' is expected)

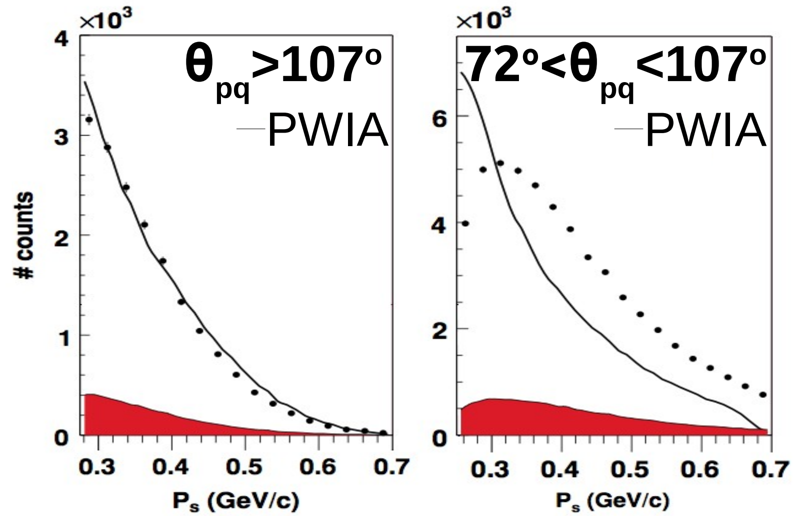
R_{FSI} is the FSI correction factor

Obstacles (FSI)





$d(e,e'p_s)$



DEEPS, PRC 73, 035212 (2006)

What do we know about FSI:

Decrease with Q^2

Increase with W'

Not sensitive to x'

Small for θ_{pq}>107°

How are we going to minimize (correct for) FSI:

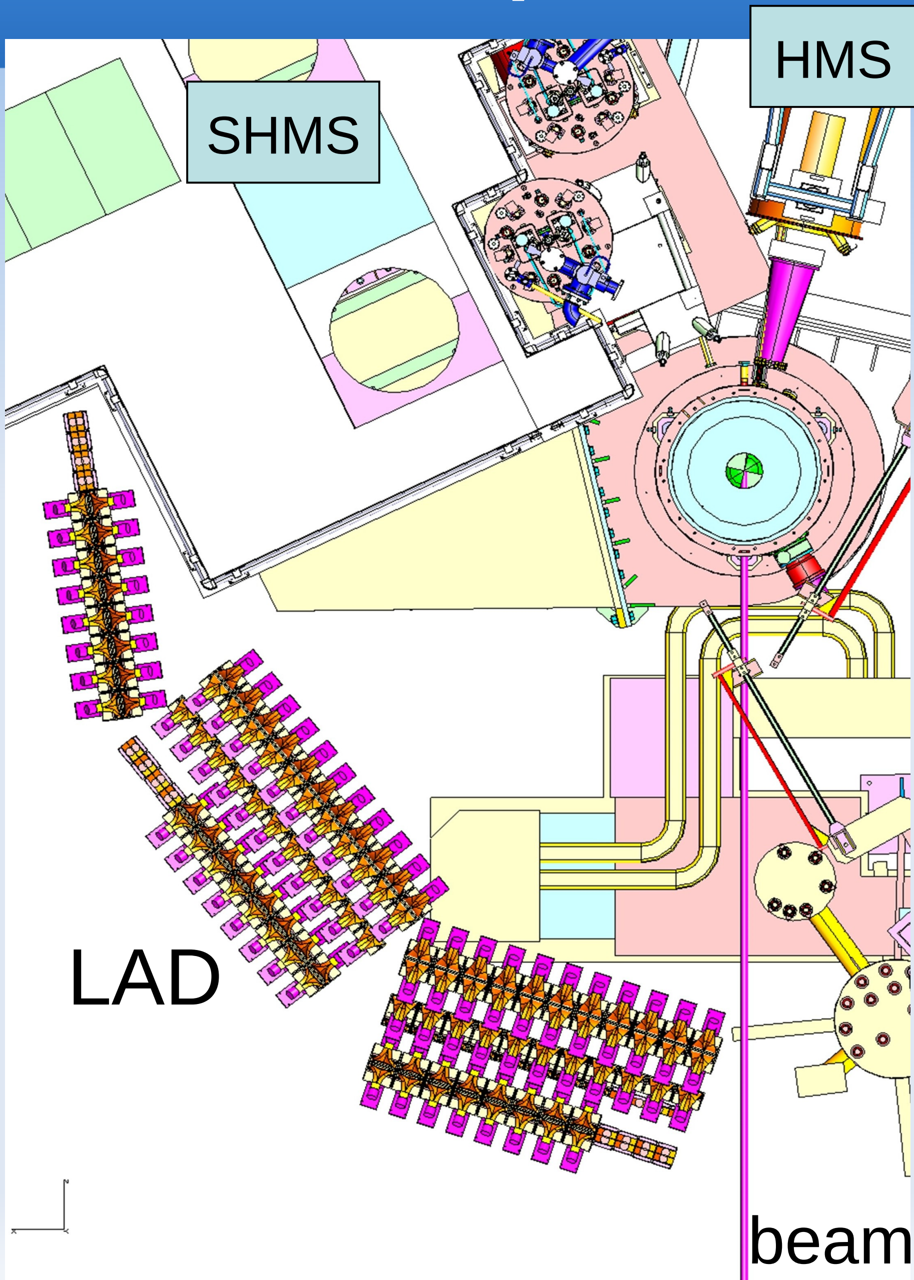
* Collect data at very large recoil angles (small FSI) and at ~90° (large FSI)

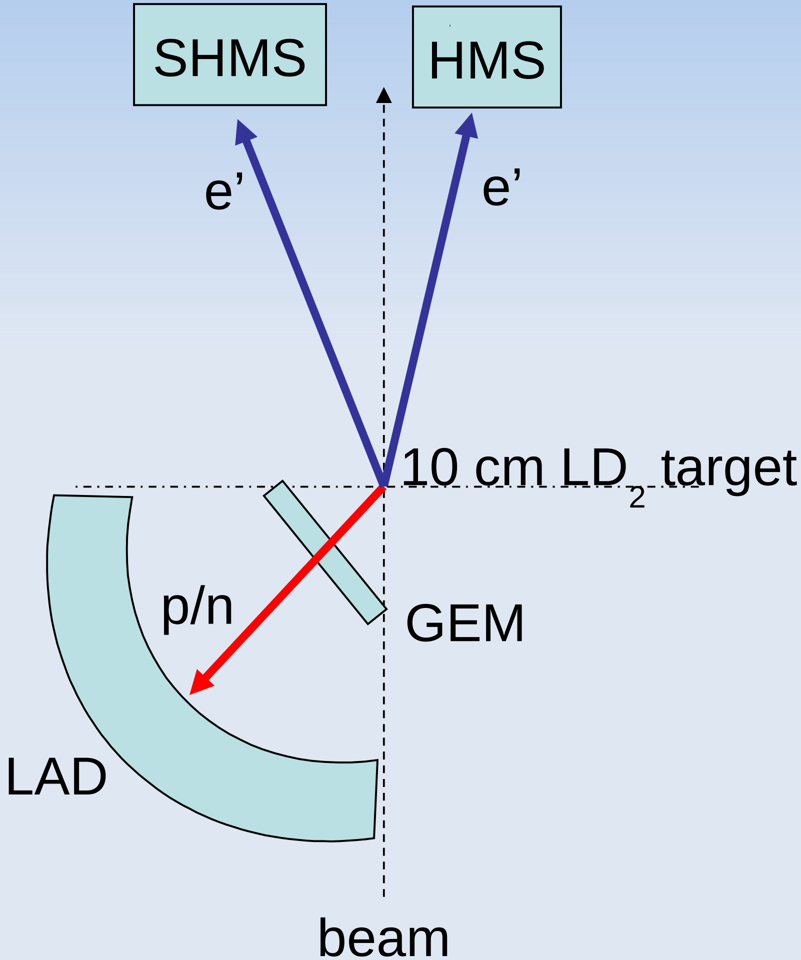
* look at ratios of two different x'

* Use the low x' large phase space to check / adjust the FSI calculations (Study the dependence of FSI on Q^2, W' and θ_{pq})

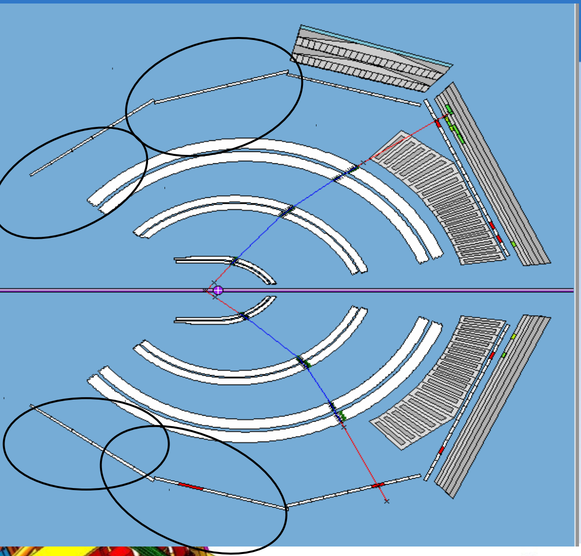
* Get a large involvement of theoretical colleges at all stages of proposal, measurement, analysis

Experimental setup - Hall-C

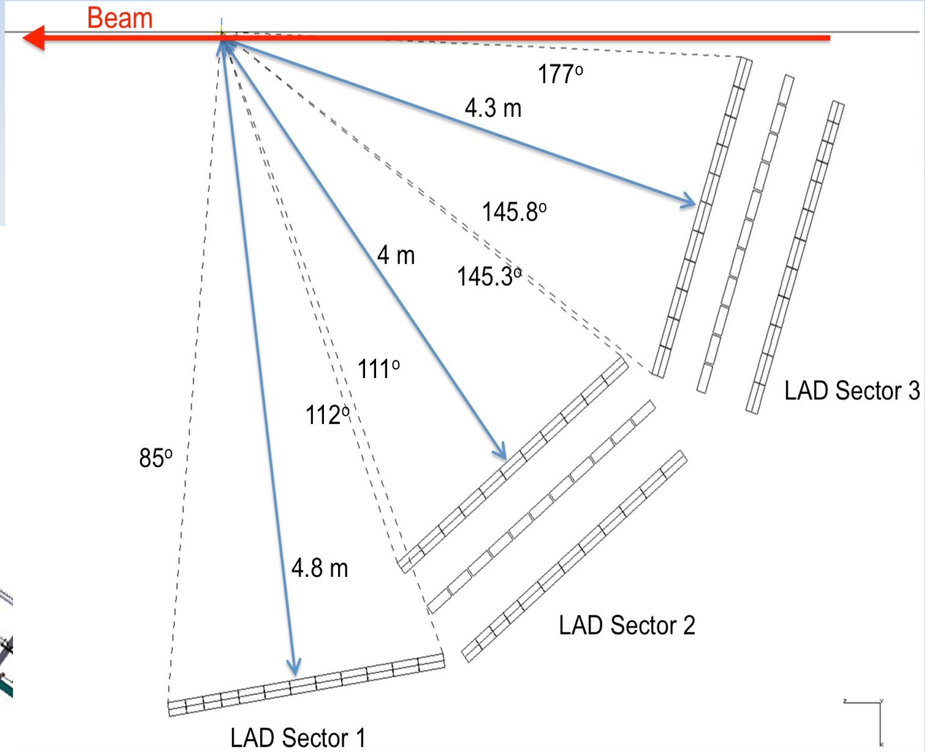


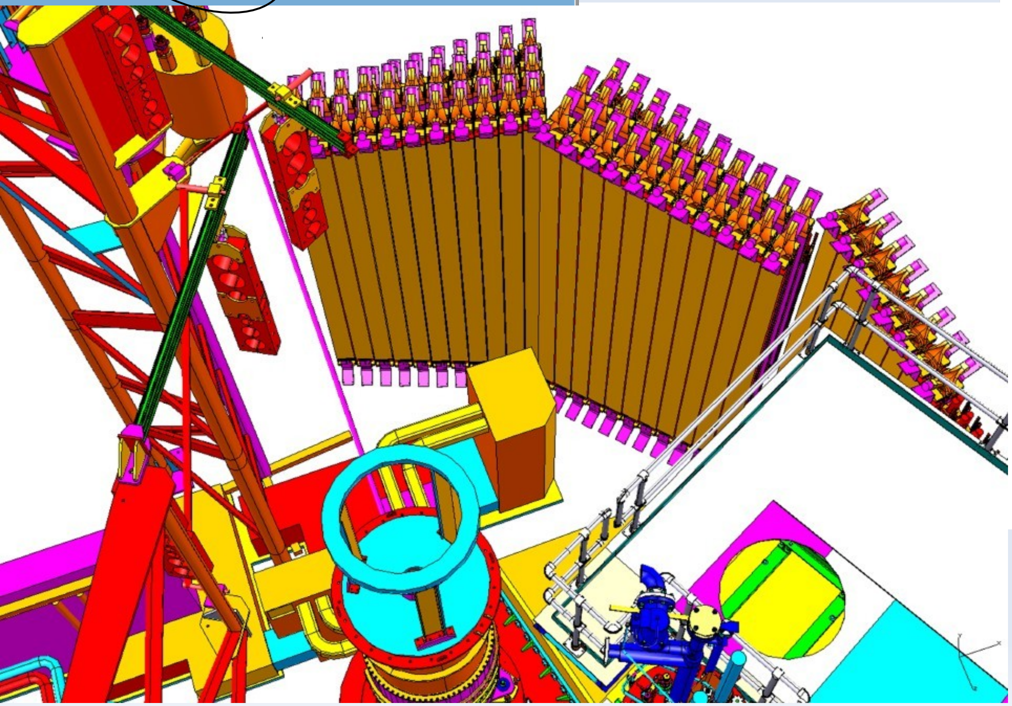


Large Acceptance Detector (LAD)



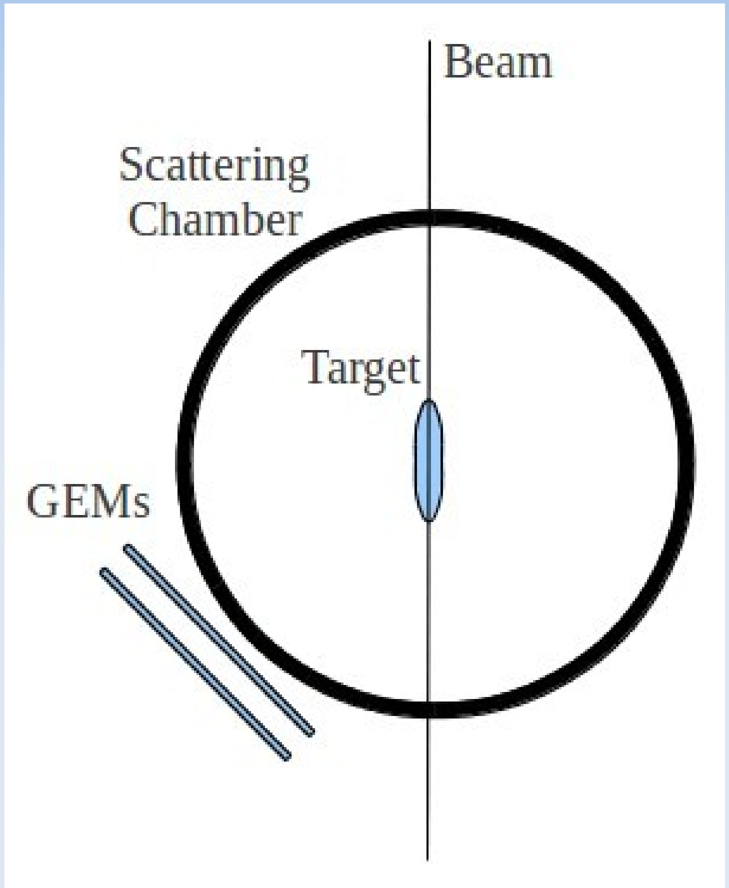
Use retired CLAS-6 TOF counters.
132, 5-cm thick counters in 12 panels.
1.5 sr, ~20% neutron detection efficiency

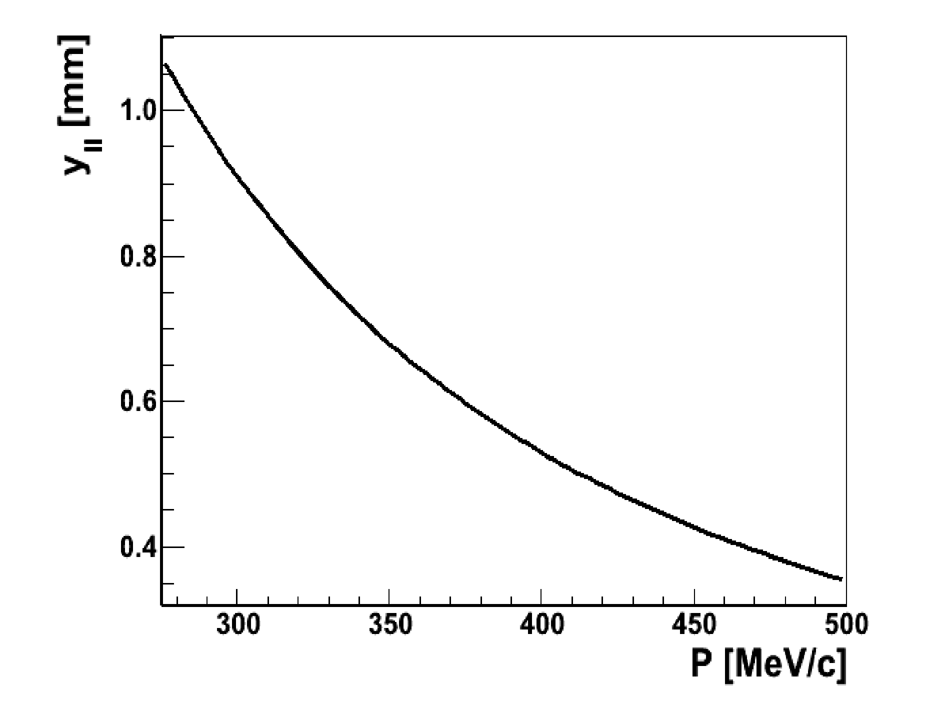




GEM based Vertex cut

Dominated by Multiple Scattering



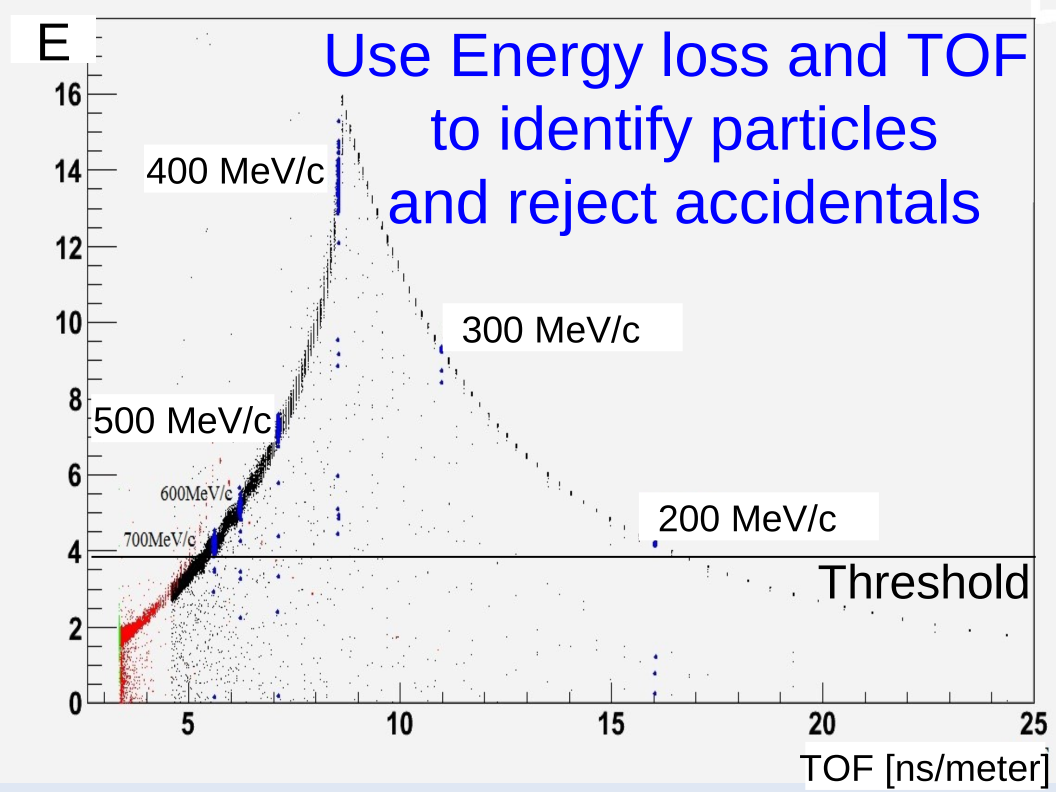


UVA group has experience and is interested in developing the GEMs for this experiment

Assuming a 0.5-1 cm vertex reconstruction resolution

Improves (e,e'p_s) S/BG by a factor of 2-4

Proton Detection



- Singles measured at 90º in Hall-A
- Overestimates background at larger angles
- Detailed signal to BG simulations

Momentum resolution (300-500MeV/c):

$$\frac{\Delta p}{p} = \frac{\Delta TOF}{TOF} = \frac{0.250\text{ns}}{(50-33)\text{ns}} = 0.5-0.8\%$$

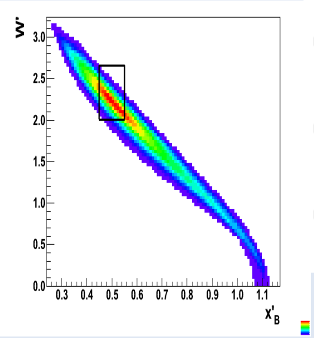
S/BG

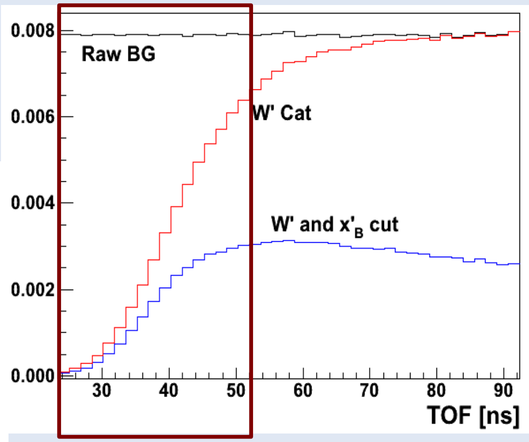
α_s	1.2	1.3	1.4	1.5
$x'_B>0.45$	1:1	1:2	1:2	1:2
$0.25<x'_B<0.35$	3:1	1:1	1:1	1:1

Neutron Detection

- 5 LAD layers
- Veto charged particles using GEM and first layer
- 5 MeVee threshold reduces n and γ background
- Done in Hall-A and B with scintillator detectors
- Detailed, bin by bin, background simulation, based on Hall-C singles neutron measurements and simulations
  - 1:200 S/BG ratio at high x'
    - Cut on x' and W'
    - Remove worst bins
    - Cut on θ_{pq} >110^{o}

  ➔ 1:20 S/BG ratio at high x'



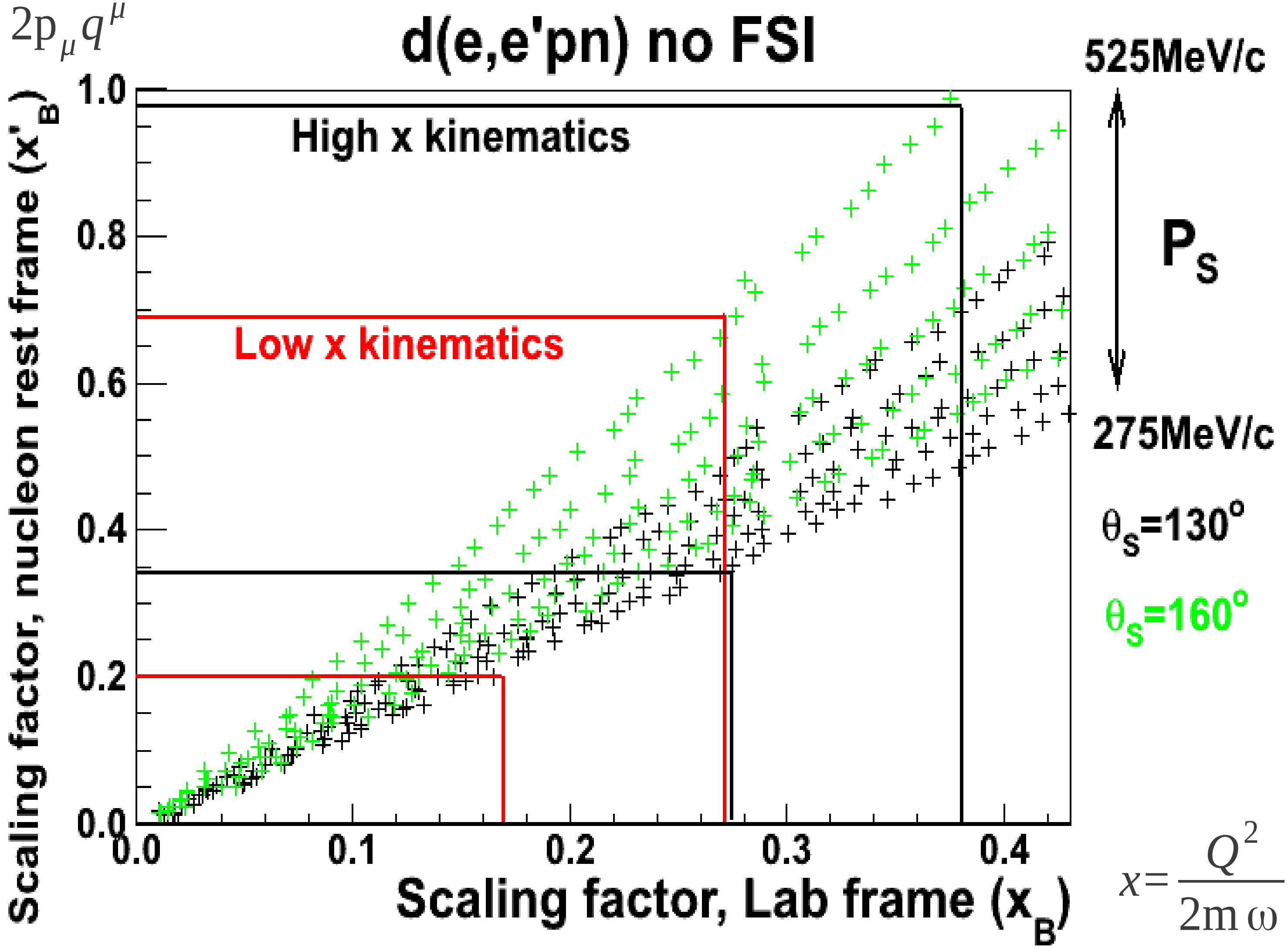


- Subtract random background with mixed events

Kinematics: x_B Vs. x'_B

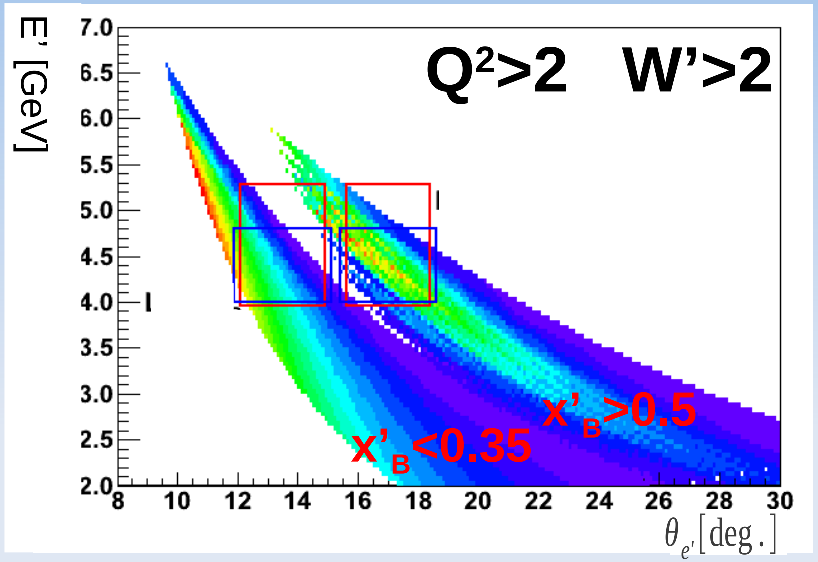
Moving to the Struck Nucleon Rest Frame

$$x' = \frac{Q^2}{2p_\mu q^\mu}$$

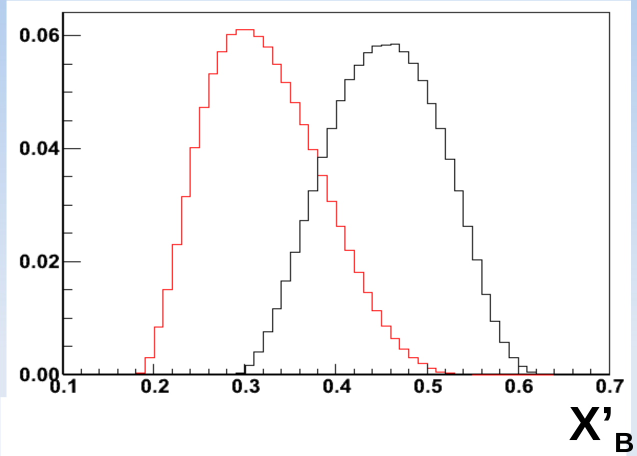


$$x = \frac{Q^2}{2m\,\omega}$$

Kinematics



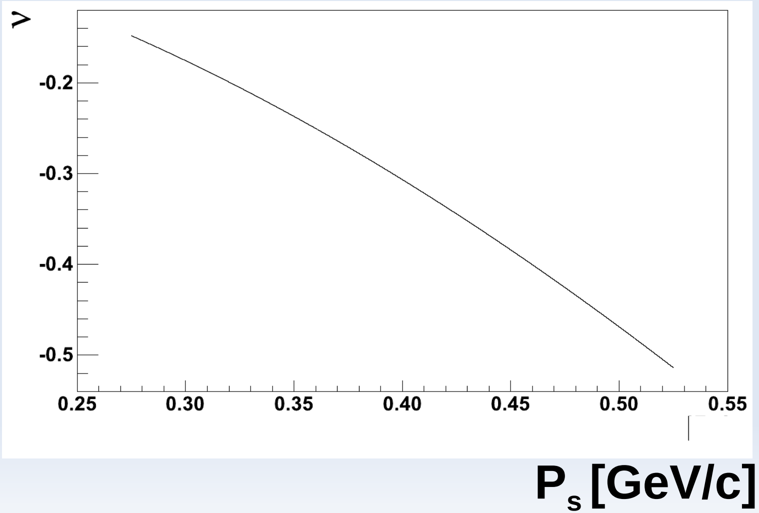
Scattered Electron

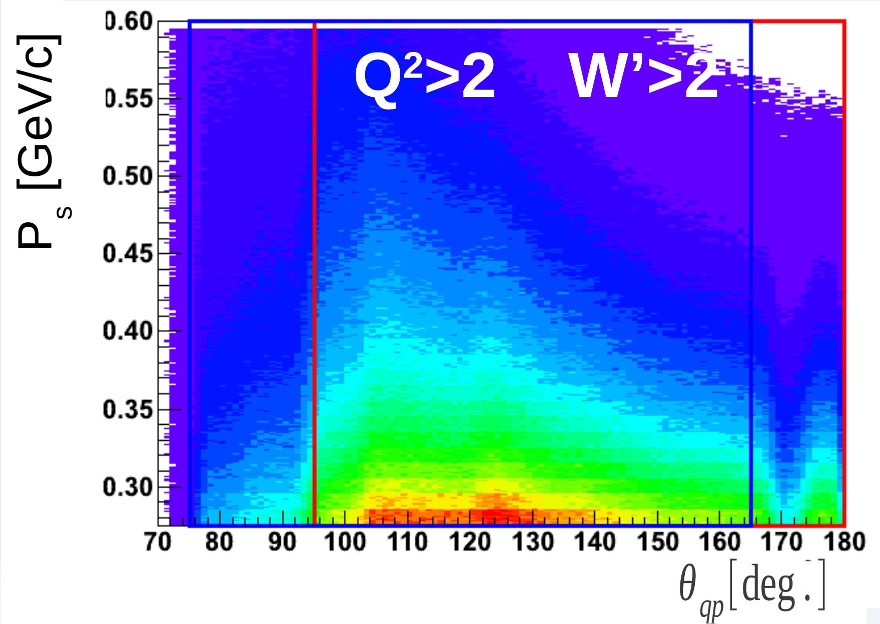


$$x' = \frac{Q^2}{2p_\mu q^\mu}$$

virtuality

Recoil Nucleon





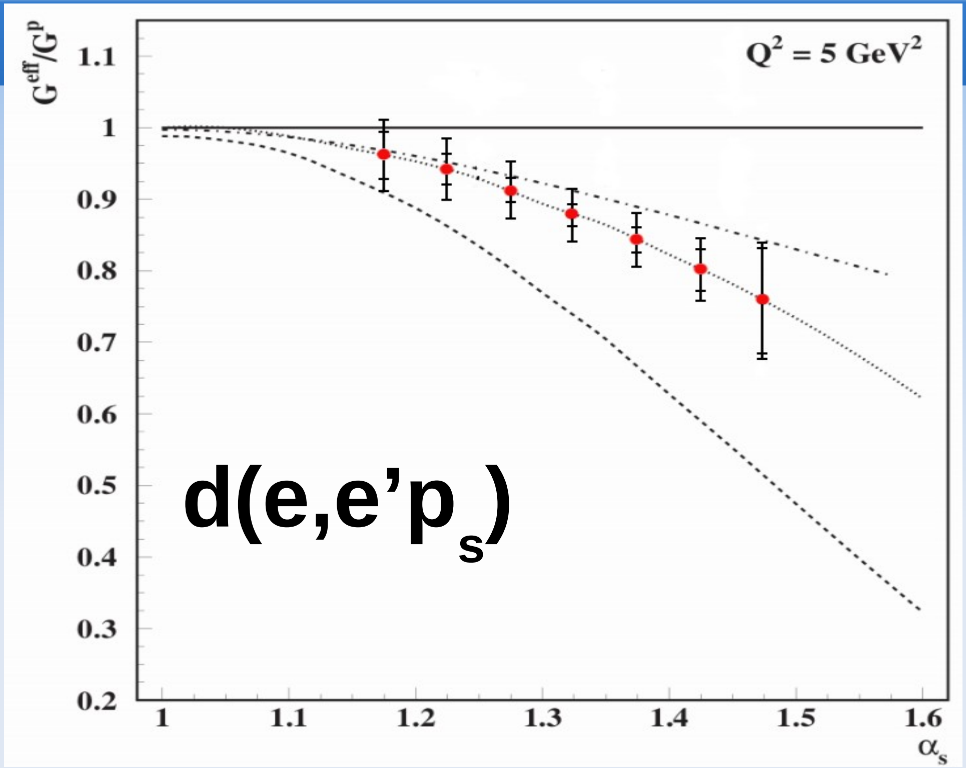
Beam Time Request

- Setup and Calibration: **6 days**
- Production:
  - – **SHMS**: low x'_B **HMS**: high x'_B **300 hours**
  - – **SHMS**: high x'_B **HMS**: low x'_B **300 hours**
  - – **SHMS**: high x'_B **HMS**: high x'_B **210 hours**

  Total Production Time: 34 days

  [Determined by the $(e,e'p_s)$ statistics]
- **Total Beam Time: 40 Days**
- PAC approval will justify the effort of intact removal of LAD counters

Expected Results

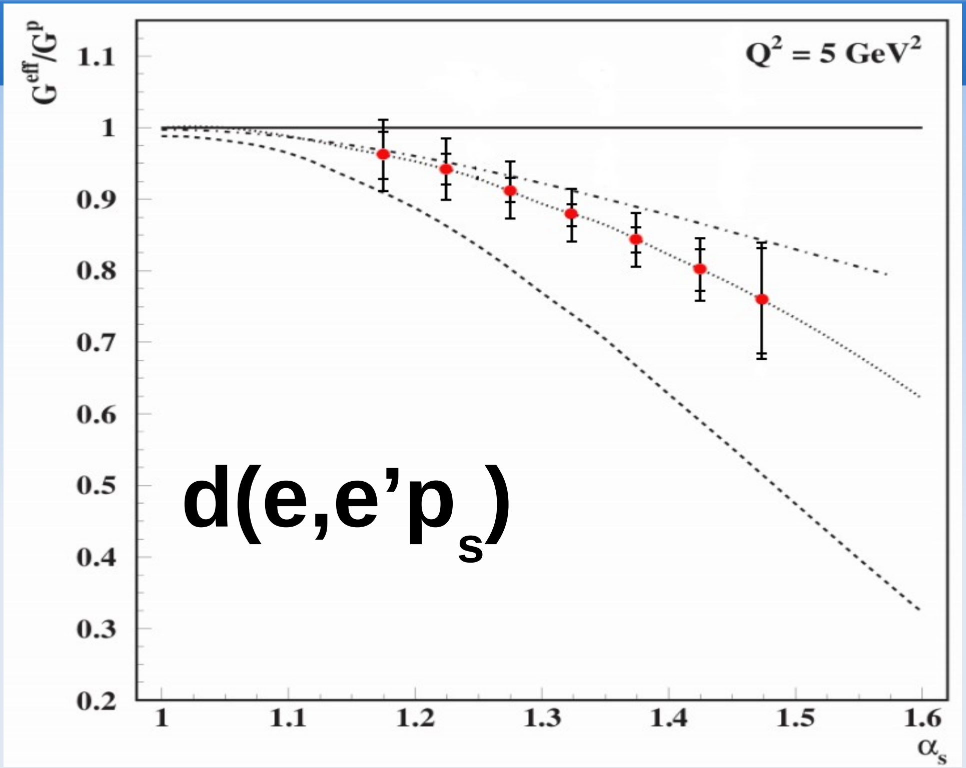


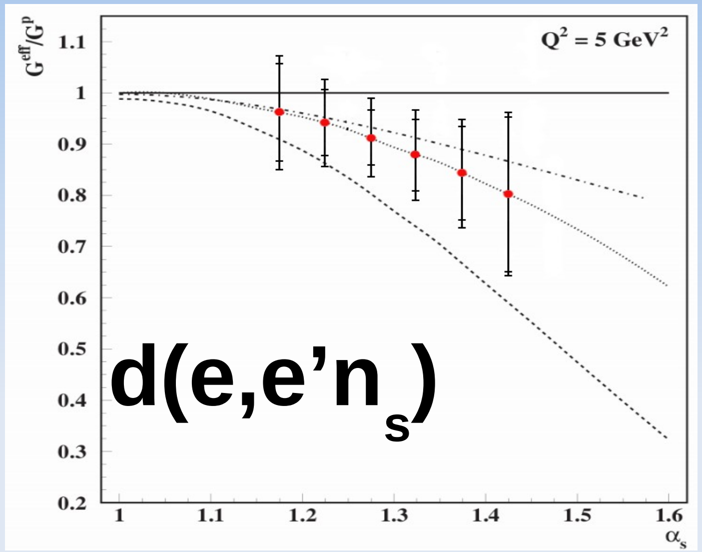
$\alpha_s = (E_s - p_s^z) / m_s$

Systematic Uncertainties (**4-7% total**):

- SHMS and HMS efficiency and acceptance (1-2%)
- LAD efficiency (3% protons, 5% neurons)
- Al walls subtraction (1%)
- FSI ratio (4%)
- Free nucleon structure function ratio (1% protons, 4% neutrons)

Expected Results





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- FSI ratio (4%)
- Free nucleon structure function ratio (1% protons, 4% neutrons)

summery

A direct measurement of the nucleon structure function in the nuclear medium as a function of its virtuality / momentum

Is it modified?

Can it explain the EMC effect?

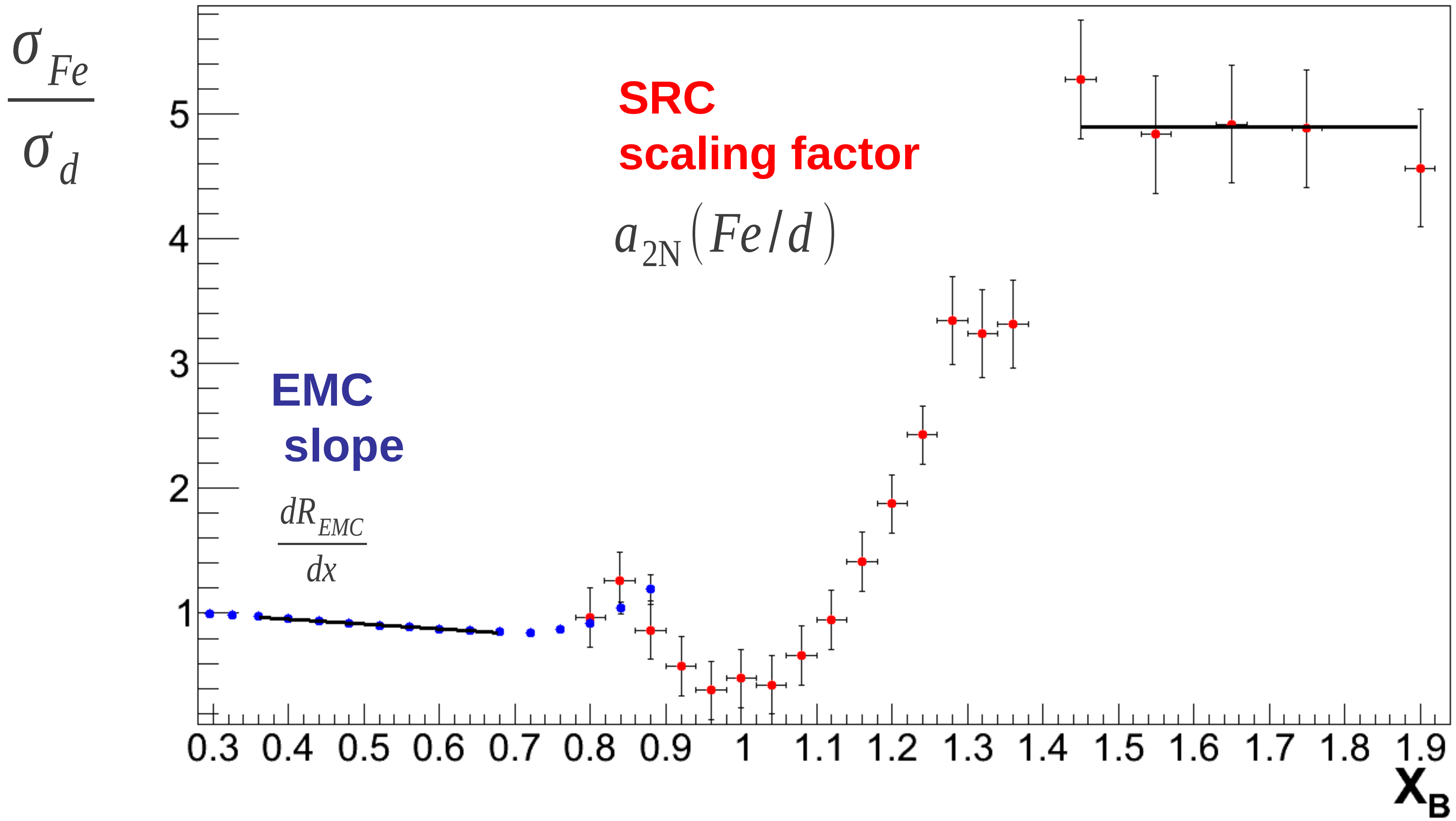
How is it related to short range correlated nucleons?

This is not a EMC measurement. A further EMC measurement is proposed in LOI 11-104

Thank You!

<u>EMC-SRC correlation</u>

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

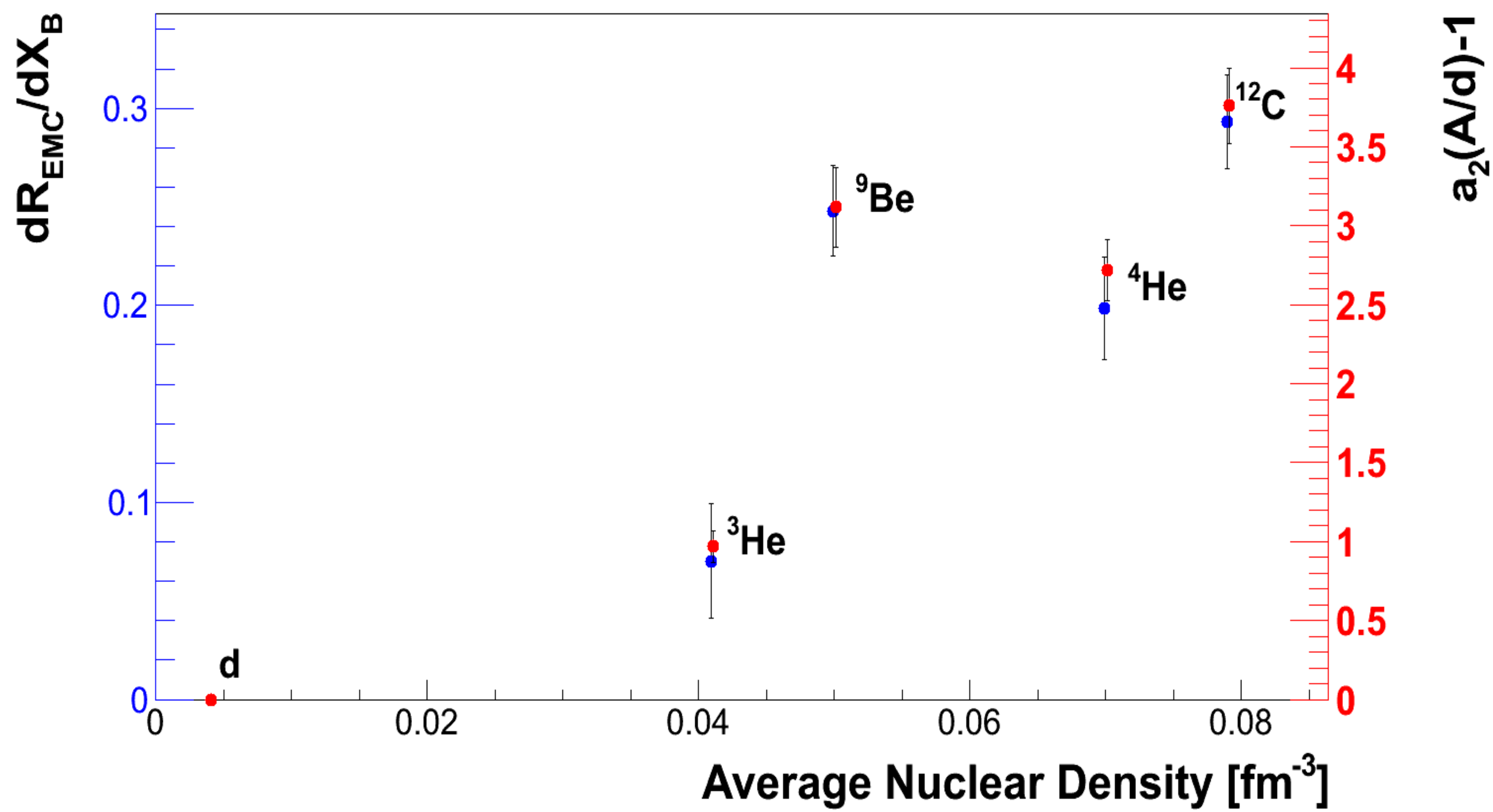


SLAC data:

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

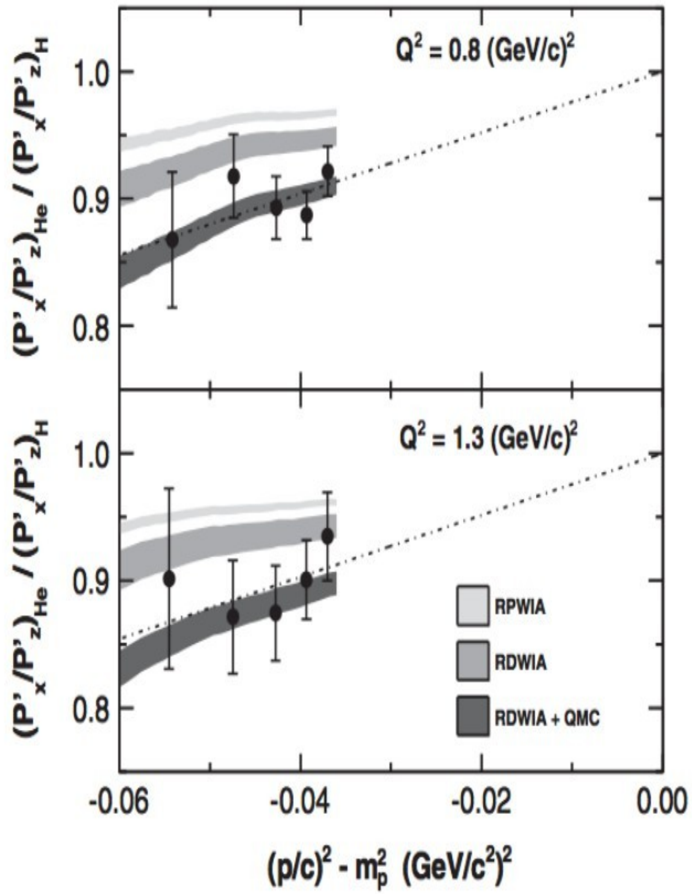
Gomez et al., Phys. Rev. D49, 4348 (1983). **Q^2=2, 5, 10, 15 GeV/c^2 (averaged)**

Comparing the EMC and SRC strengths



Virtuality dependent medium modification of the form factor ratio

Medium modification of form factor ratios



The double ratio of proton polarization in the x' and z' directions for $^4He(\vec{e},e'\vec{p})^3H$ relative to $H(\vec{e},e'\vec{p})$ plotted versus nucleon virtuality showing deviation from the free nucleon for $Q^2 = 0.8$ and 1.3 GeV^2

M. Paolone, et al., Phys. Rev. Lett. 105, 072001 (2010)

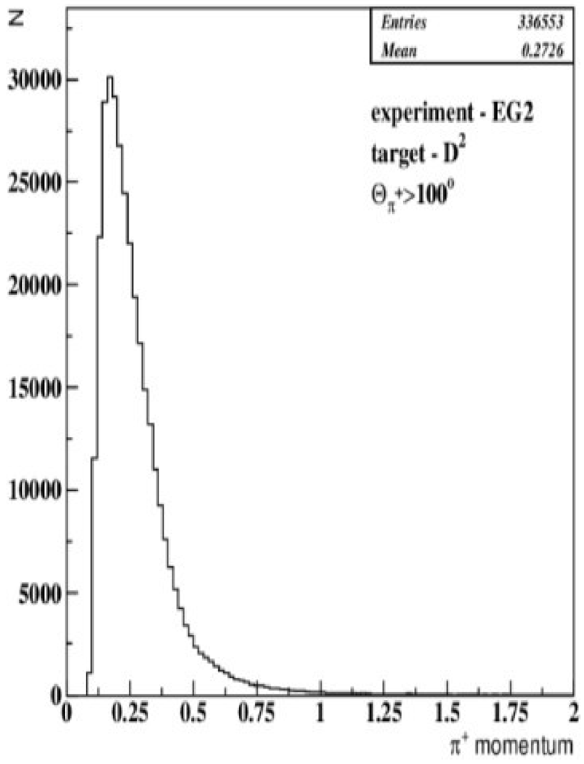
- Medium modification of the proton's form factor ratio (G_e/G_m) observed in polarization transfer measurements
- The observed modification grows as a function of nucleon virtuality
- PR11-107 will cover a much larger virtuality range of ~ 0.2-0.5 $(GeV/c^2)^2$

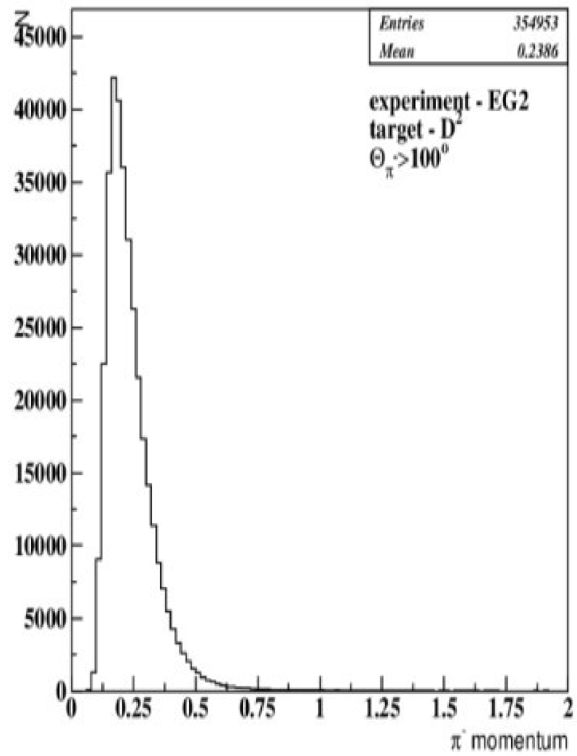
Pion Background

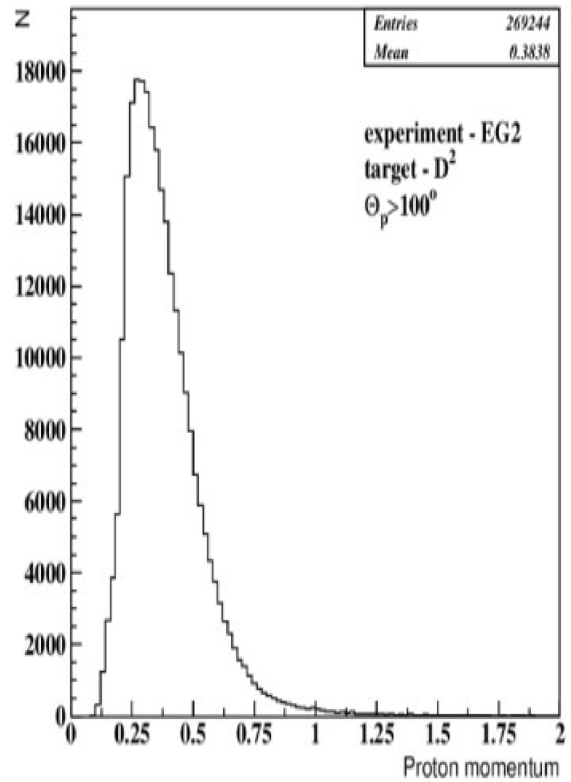
(response to TAC report)

Pion Background

CLAS EG2 data



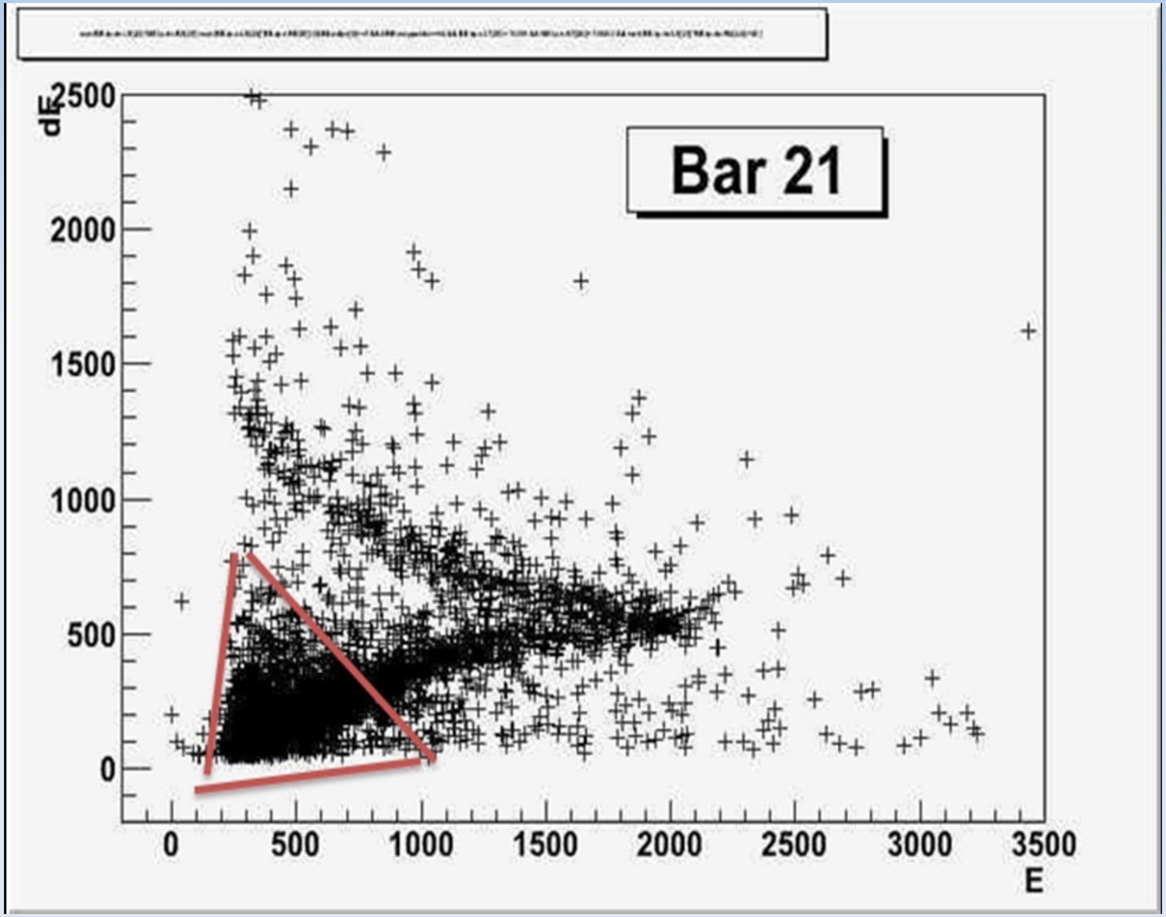




Pi:Proton = 3:1

Pion Background

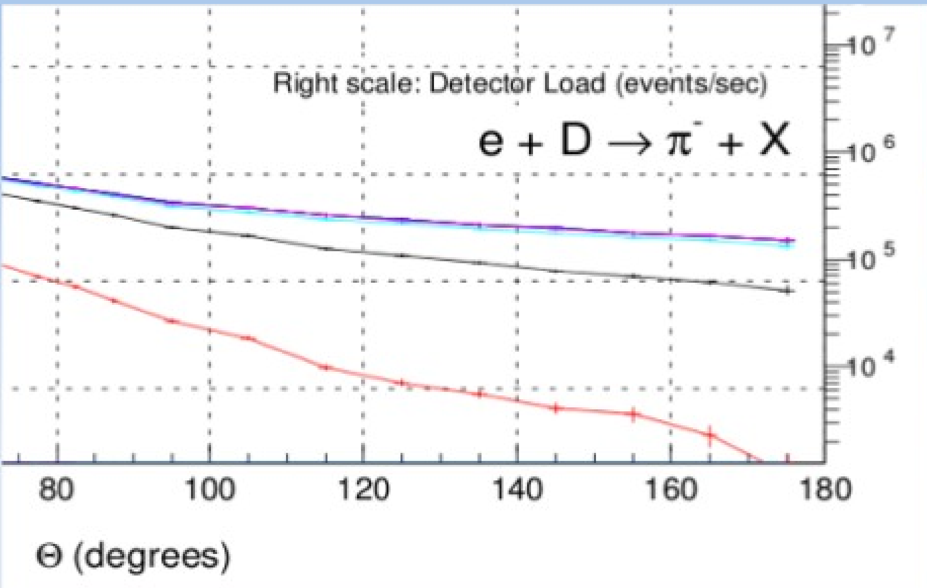
Hall-A E07-006 (SRC) data, BigBite at 92° no magnetic field

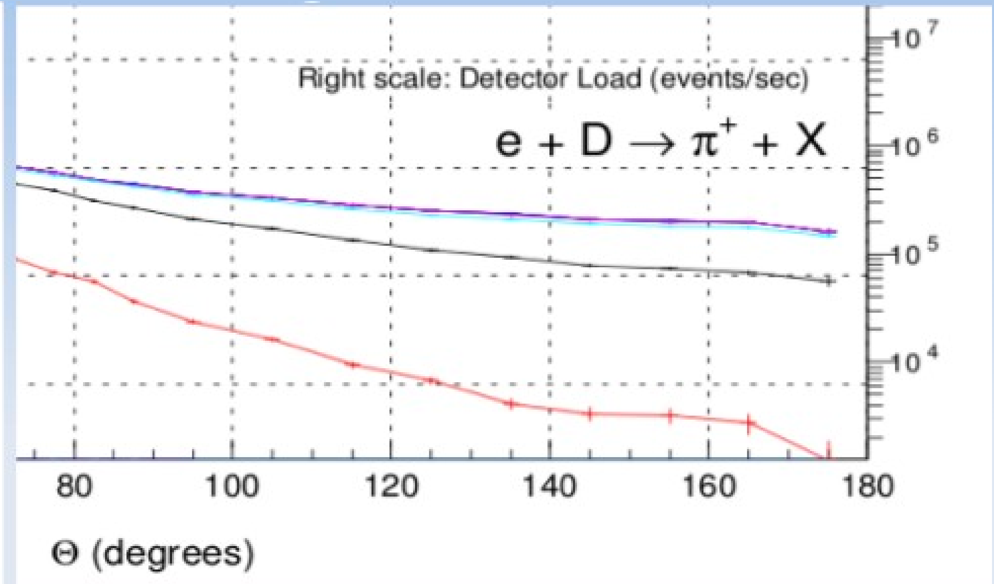


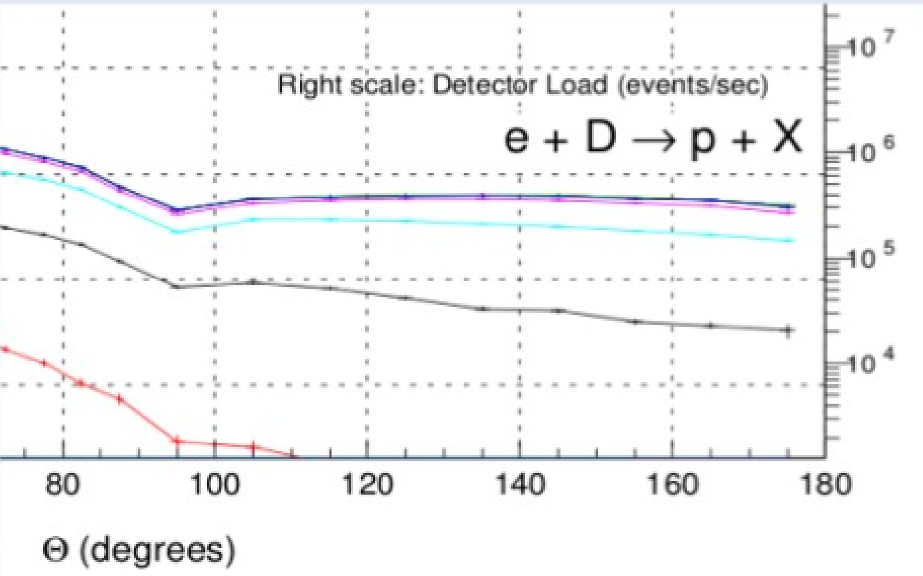
Pi:Proton = 3:1

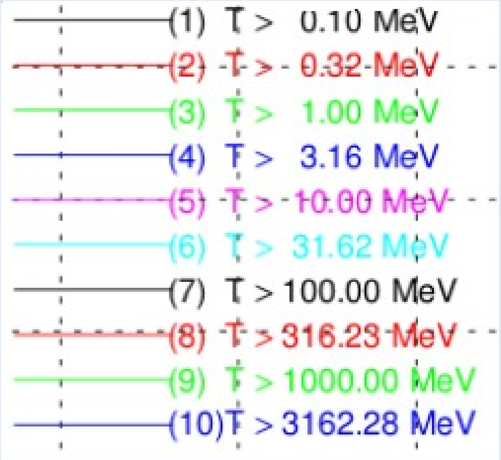
Pion Background

Simulations by Pavel Degtiarenko









Pi:Proton = 5:1

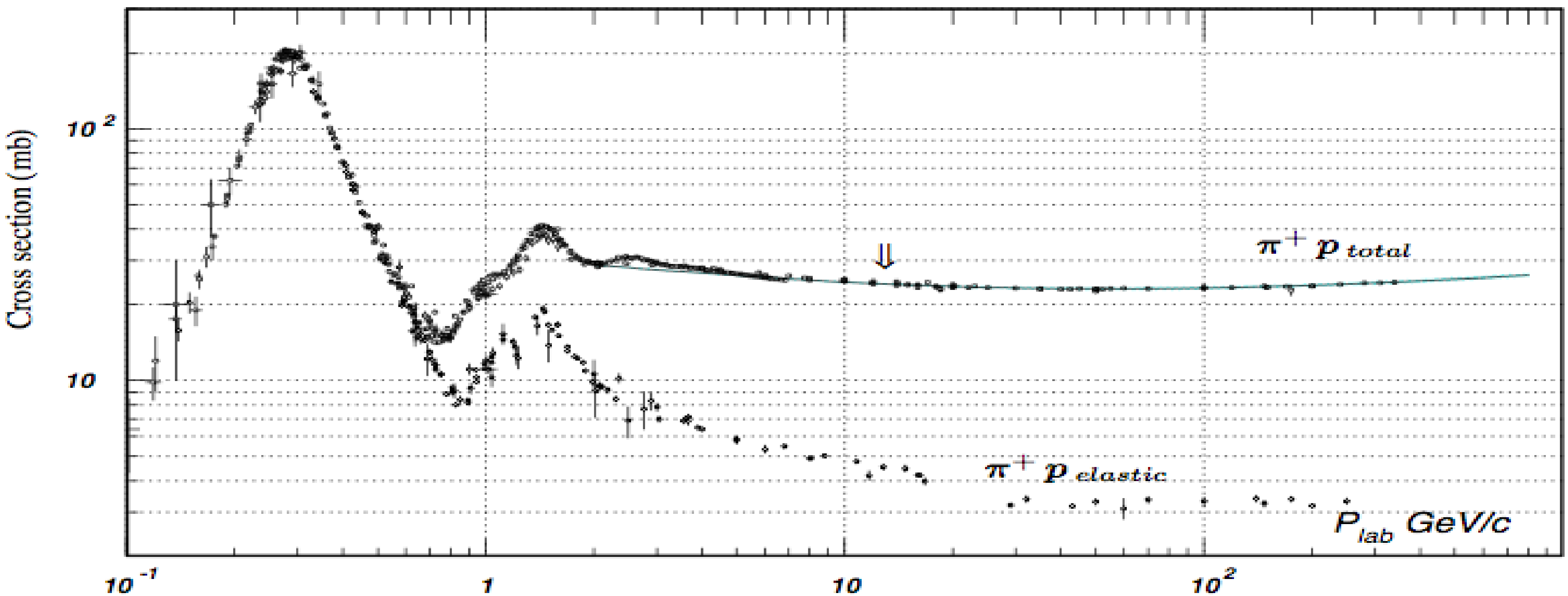
Pion Background

Backwards pion to proton ratio is ~1:5

Pions are a problem only in they nuclear interact within the LAD scintillator counters

The (pi,p) cross section drops for low energy pion

Backwards pions are not an issue



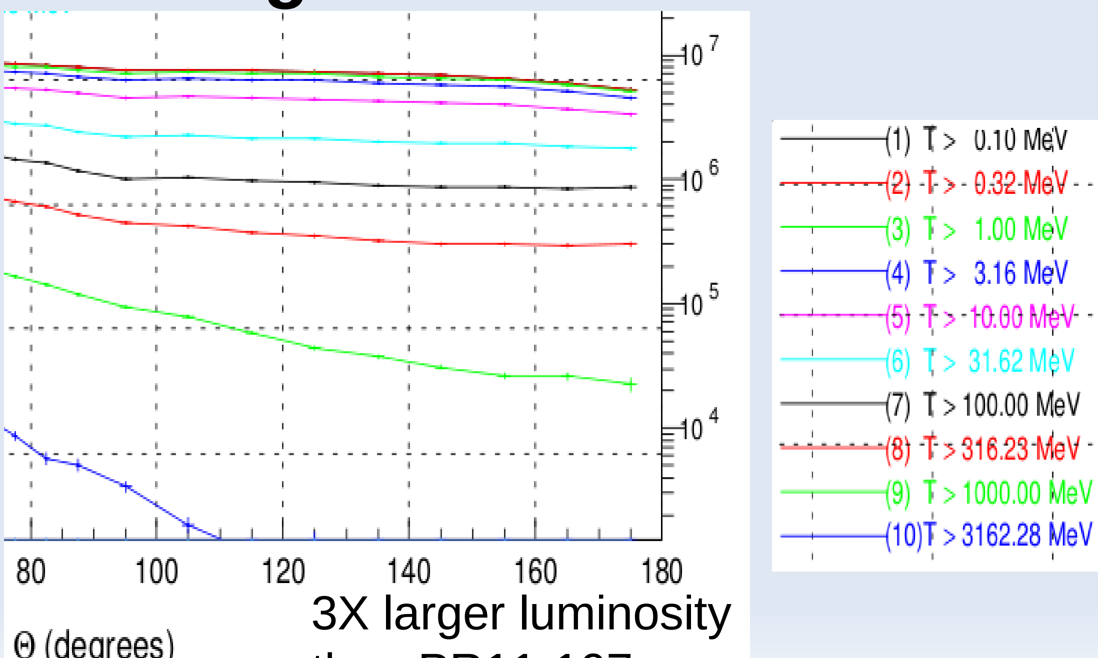
Neutron singles Rates

(response to TAC report)

Neutron Singles Rates

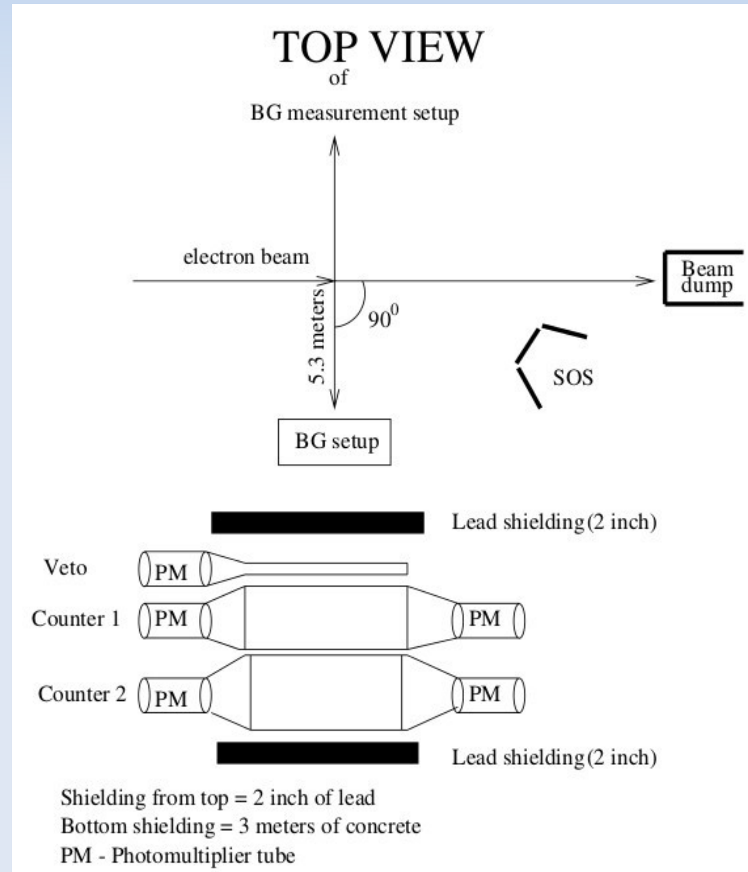
Hall-C singles neutron measurements are consistent with the simulations (~10^6 Hz/sr for our luminosity)

Simulations by Pavel Degtiarenko



3X larger luminosity than PR11-107

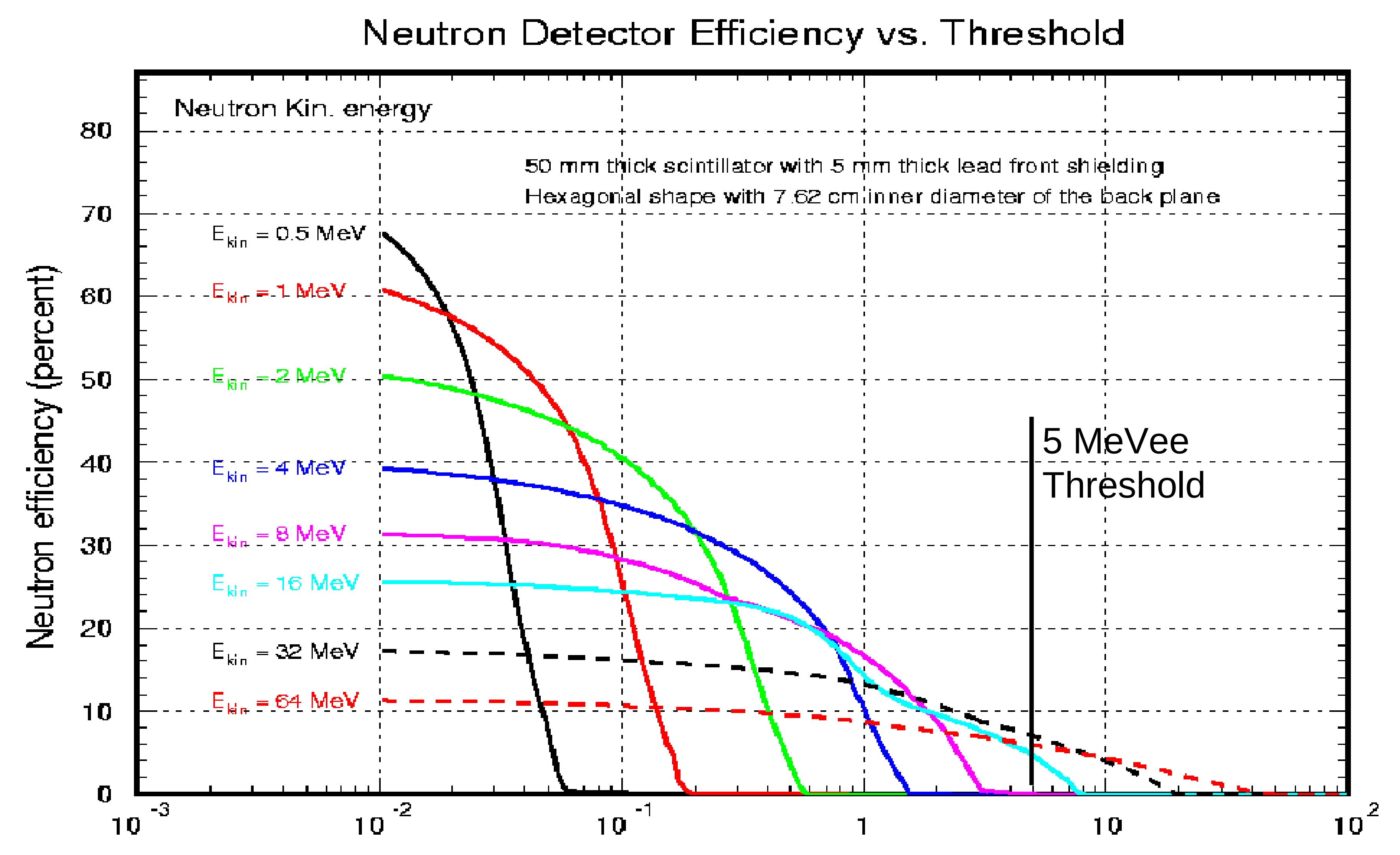
Singles Measurements at Hall-C



E01-015 proposal, December (2000)

Neutron Detection Efficiency

Neutron Detection Efficiency



SHMS, HMS, and LAD calibration plan

(response to TAC report)

SHMS, HMS and LAD calibration plan

Final calibration run plan is dependent on the final LAD design and flexibility. From our experience with the exclusive SRC experiments (E01-015 and E07-006) we expect these measurements to include:

- Standard spectrometers calibrations.
- Neutron detection efficiency measurement using kinematically complete d(e,e'pn) measurements with the electron and proton detected by the spectrometers and the neutron by LAD.
- H(e,e’p) measurements with the electron being detected by the spectrometers and well defined (energy and angle) protons by LAD.

  (Will be used for TOF, energy loss, threshold, and coincidence times measurements)
- Al Dummy target to get the target cell window contribution.

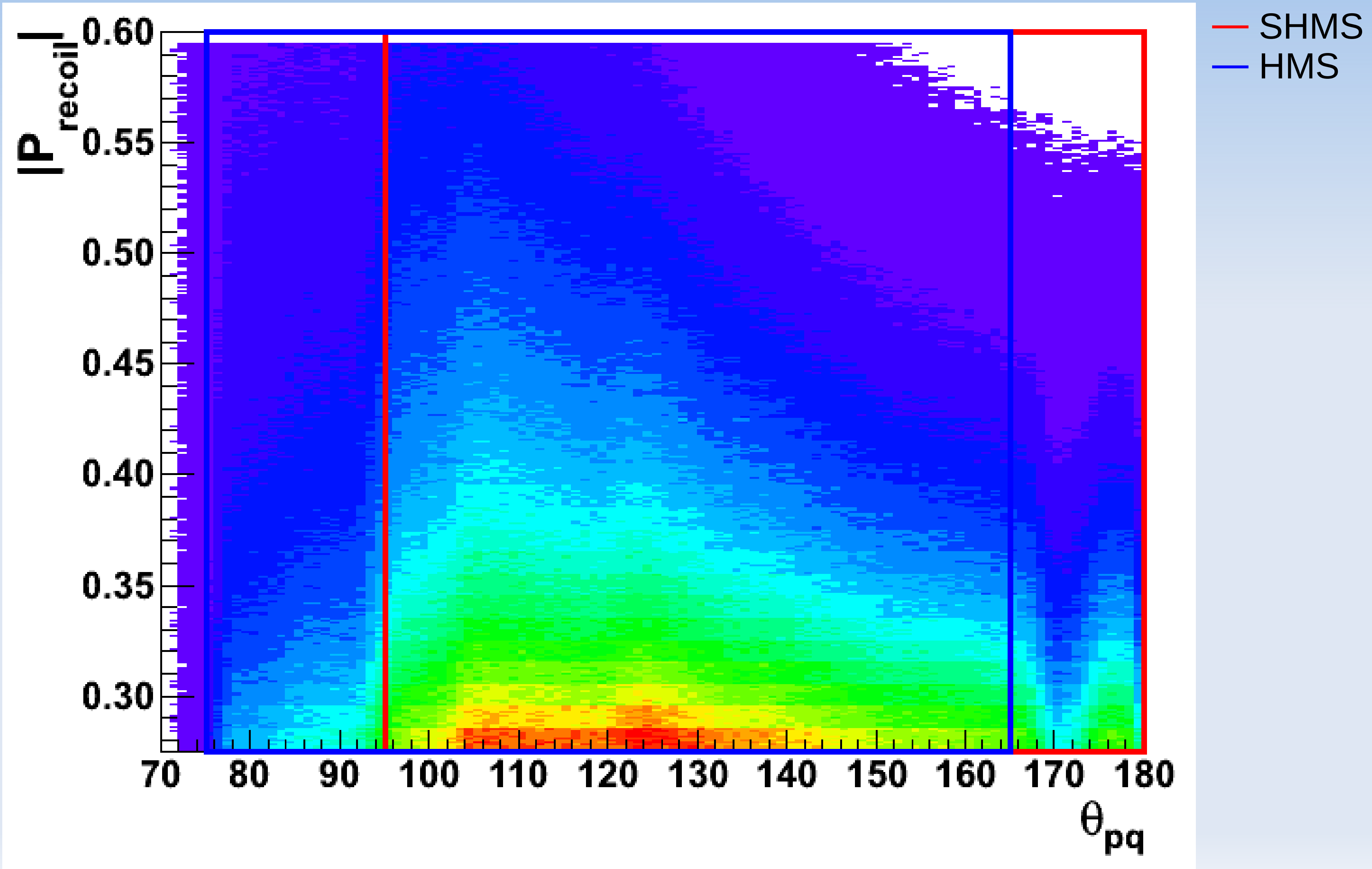
Kinematics

Electron Kinematics

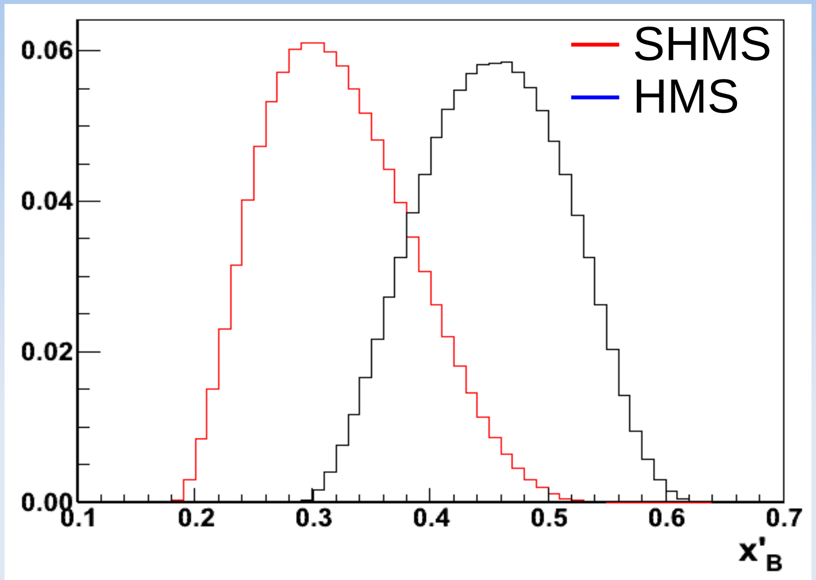
Low x' range (central values):	**High x' range (central values):**
$E_{\text{in}} = 10.9$ GeV	$E_{\text{in}} = 10.9$ GeV
$E' = 4.4$ GeV	$E' = 4.4$ GeV
$\theta_e = 13.5^o$	$\theta_e = -17^0$
$Q^2 = 2.65\ \text{GeV}^2$	$Q^2 = 4.19\ \text{GeV}^2$
$\lvert \vec{q} \rvert = 6.7\ \text{GeV}/c$	$\lvert \vec{q} \rvert = 6.8\ \text{GeV}/c$
$\theta_q = -8.8^0$	$\theta_q = 10.8^0$
$x = 0.217$	$x = 0.34$

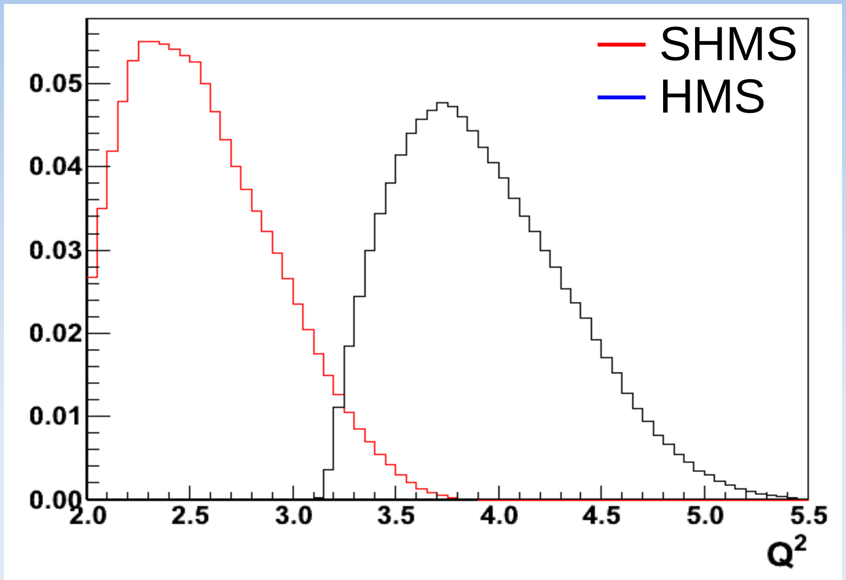
12 GeV needed for kinematical range and higher cross section

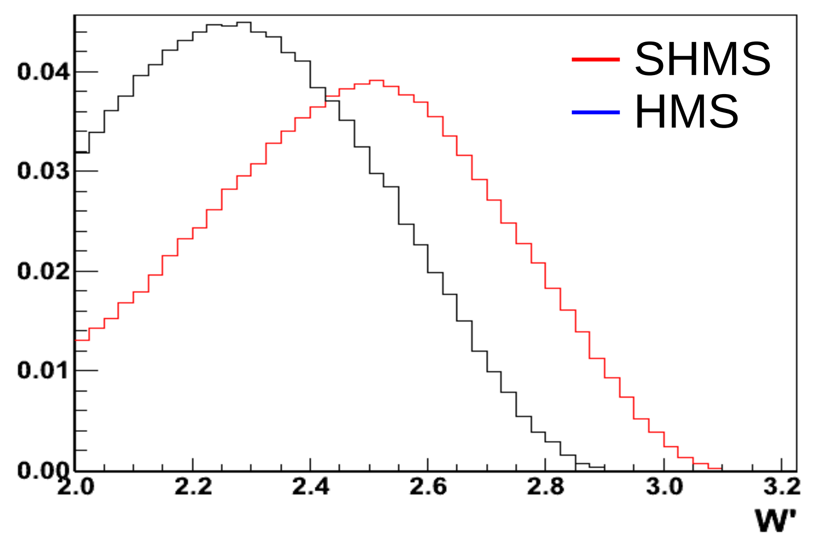
LAD Phase Space Coverage

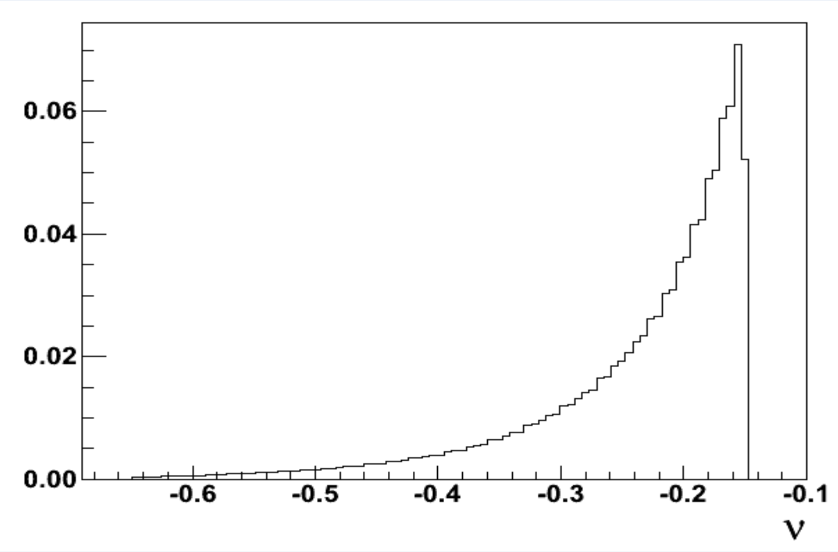


Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)

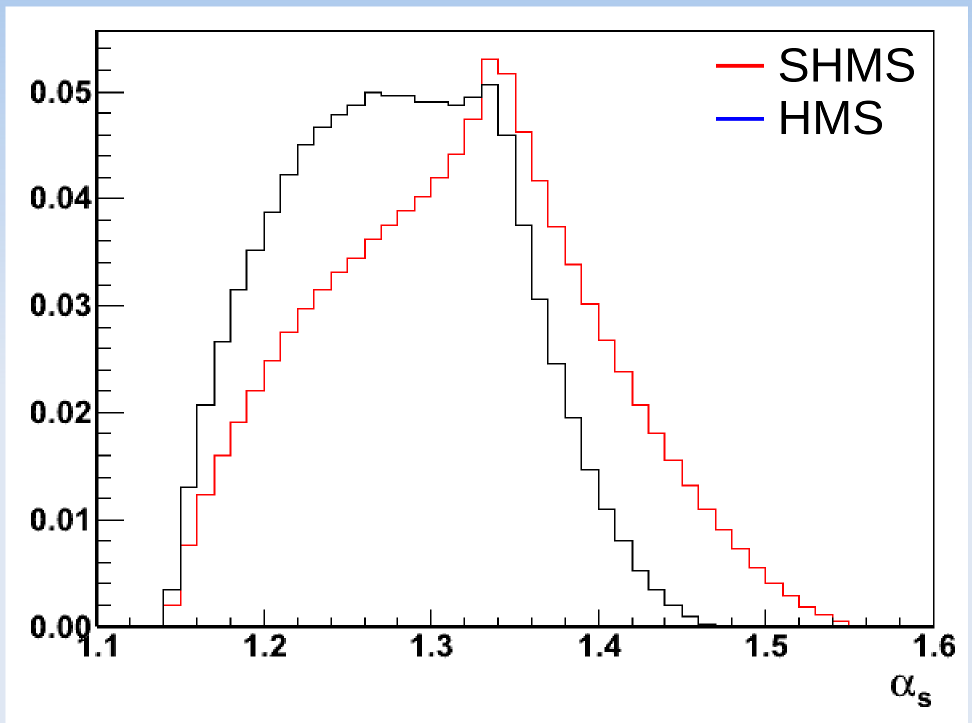


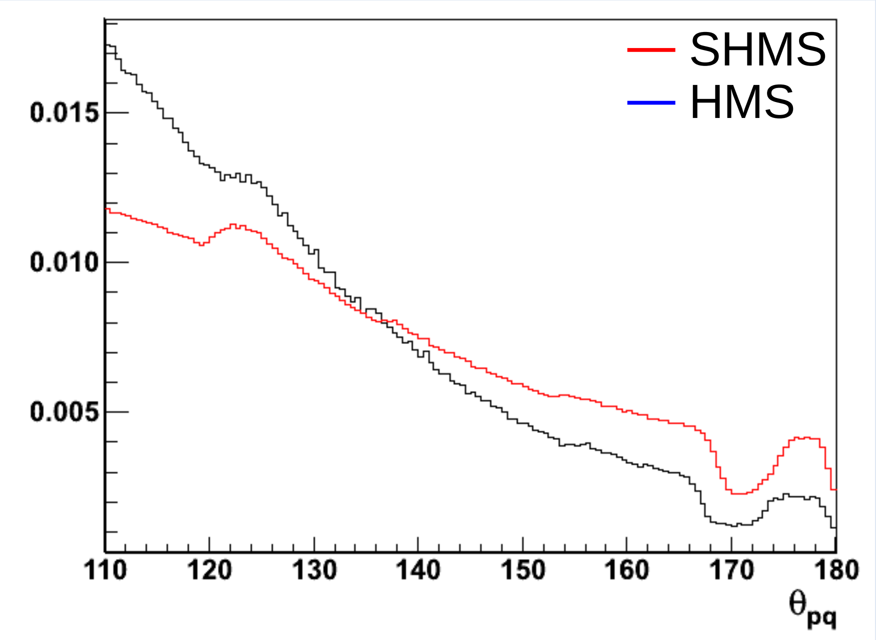




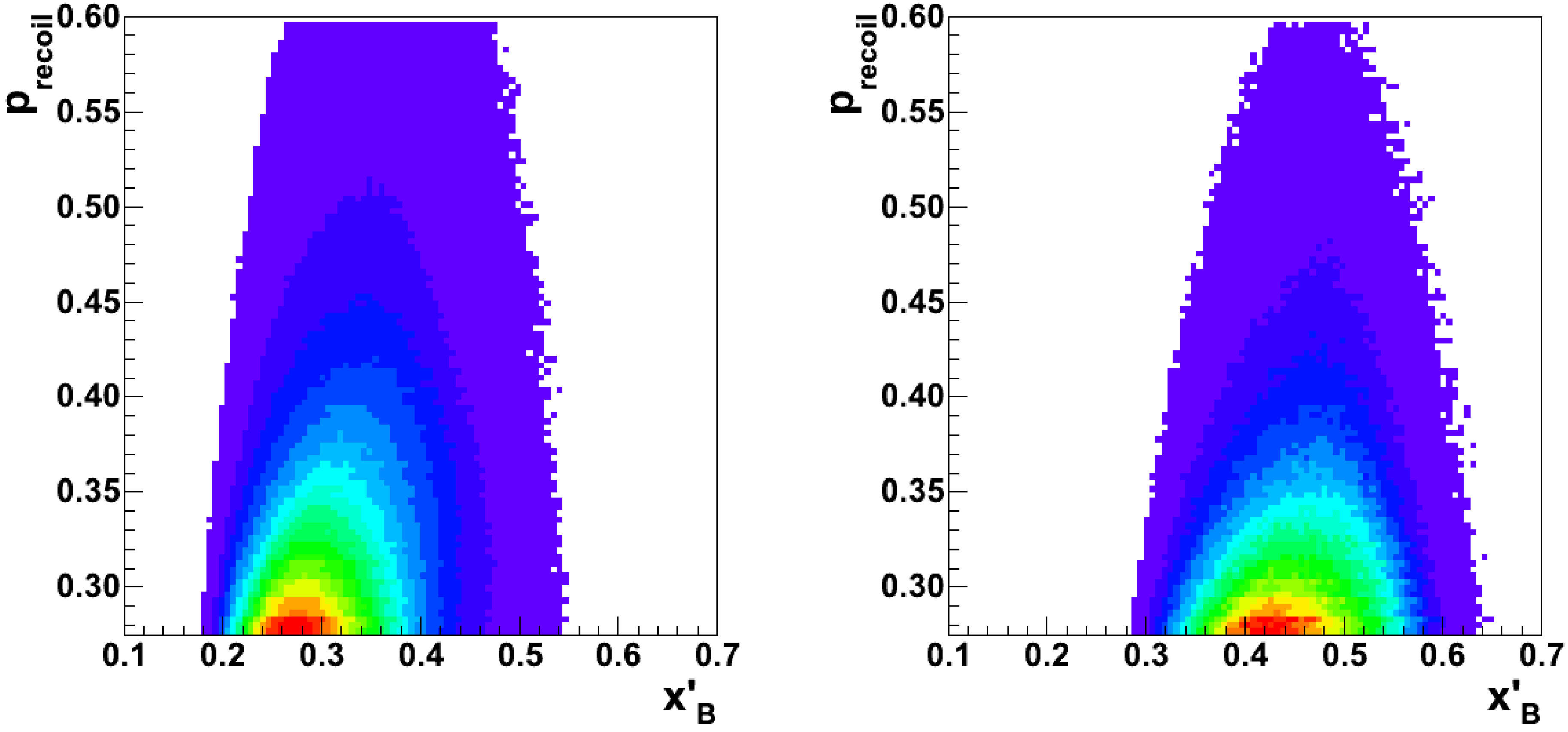


Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)

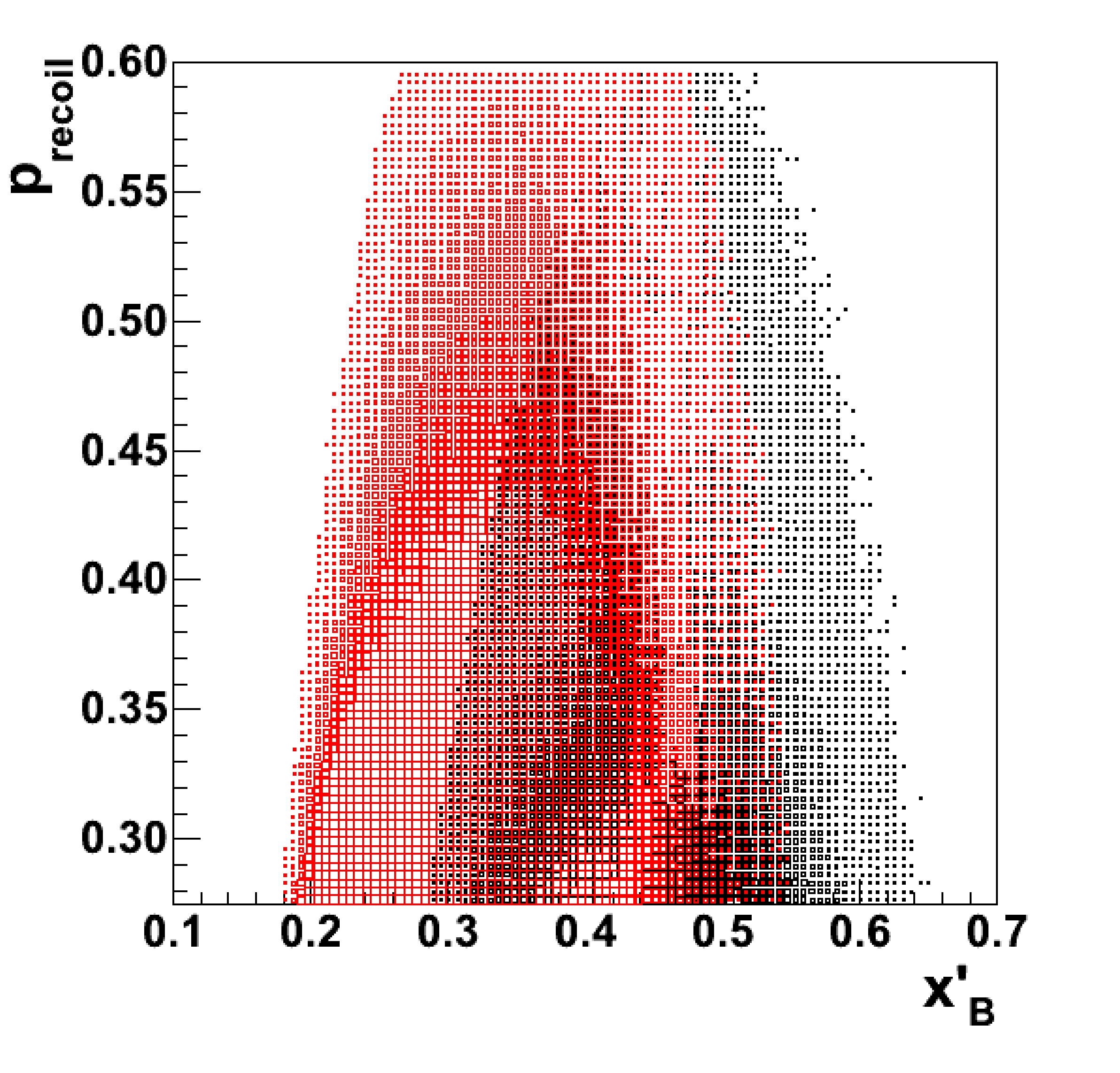




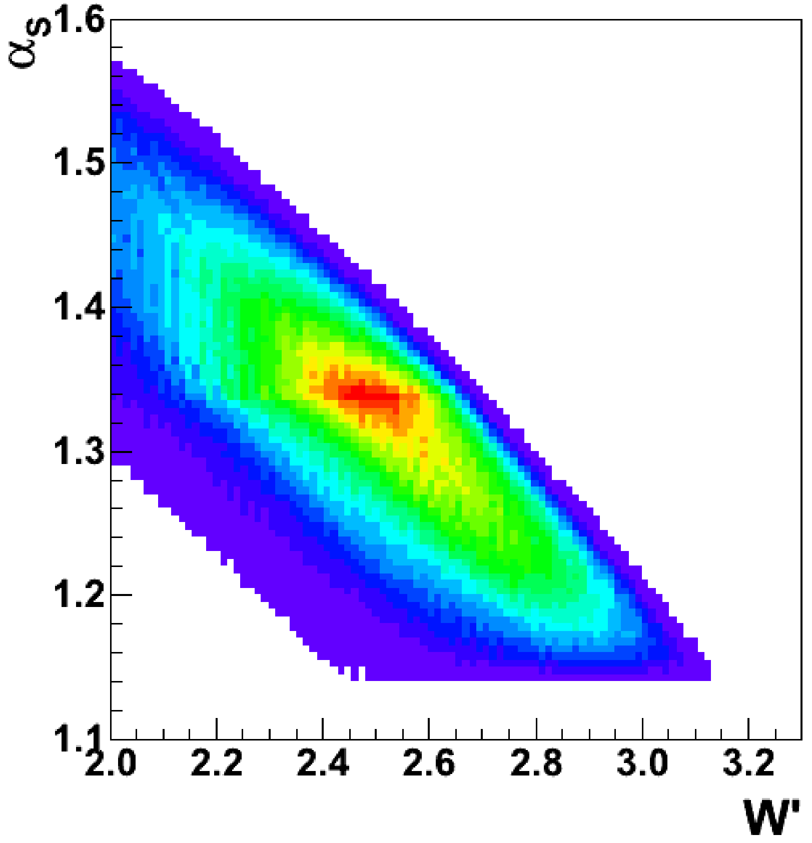
Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)

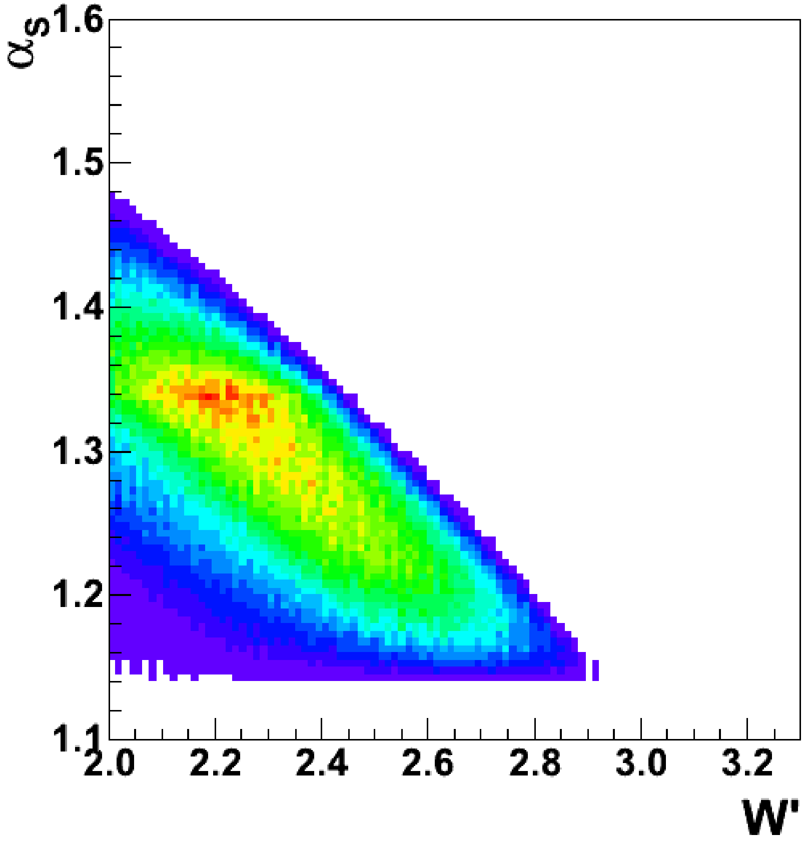


Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)

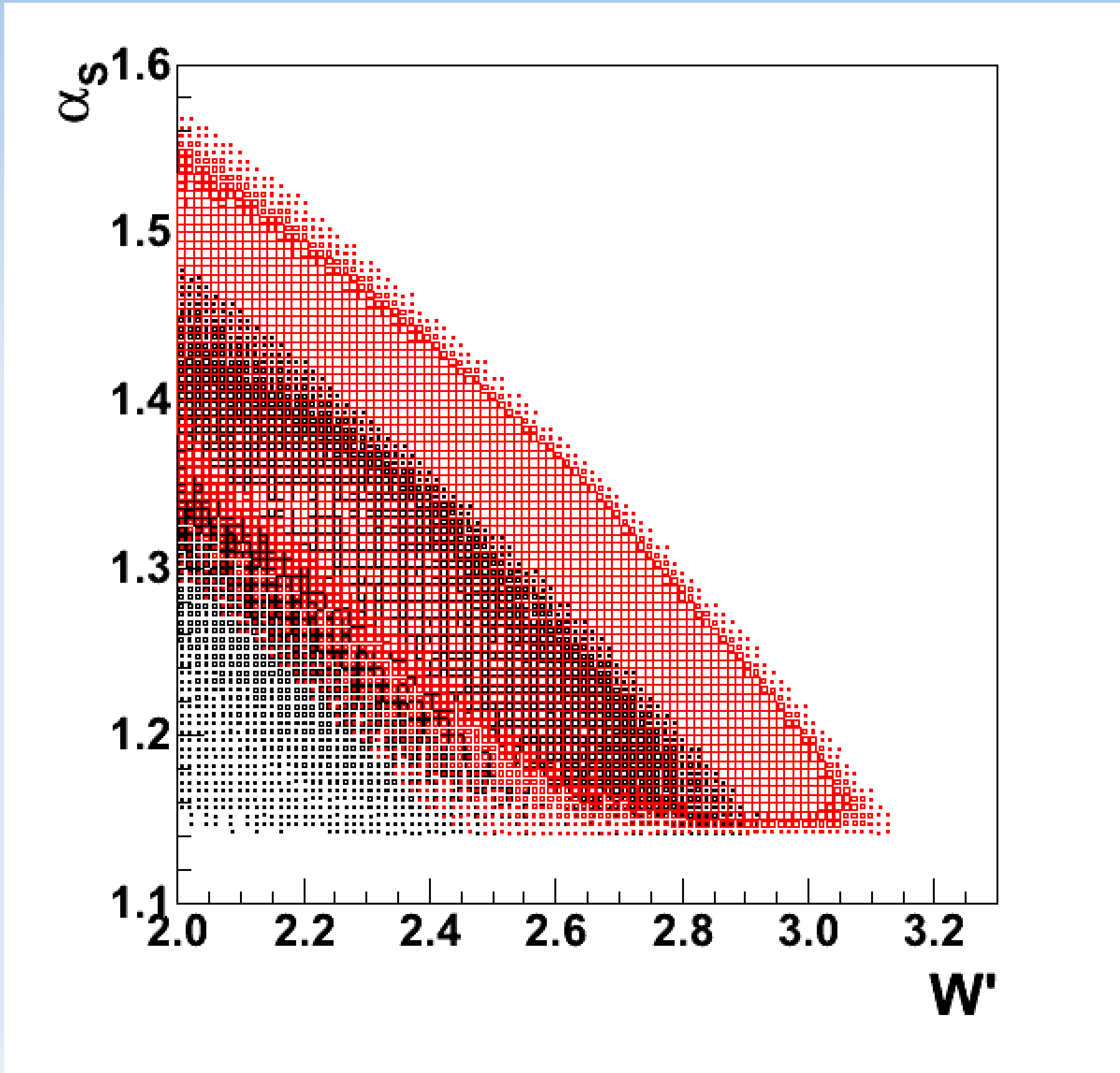


Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)

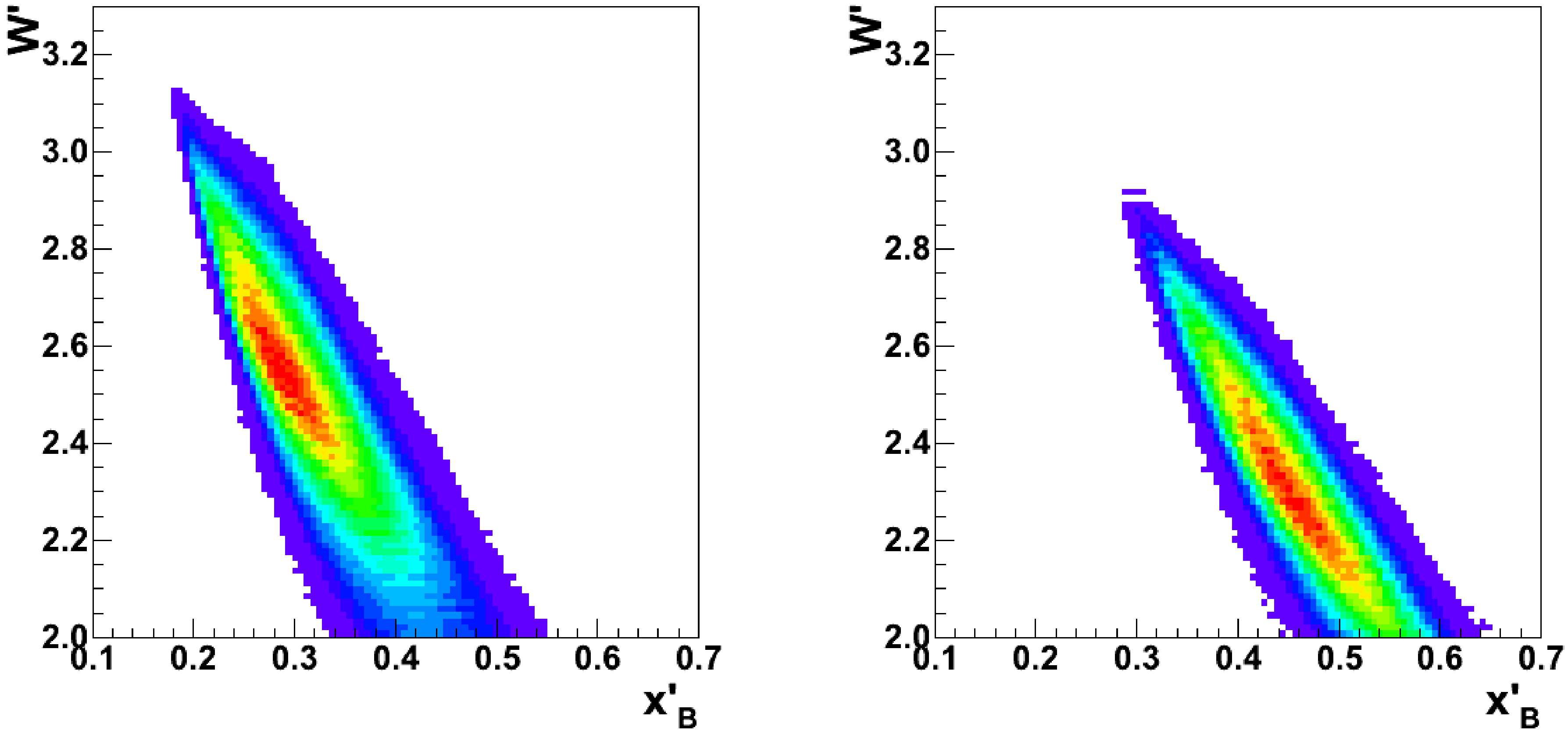




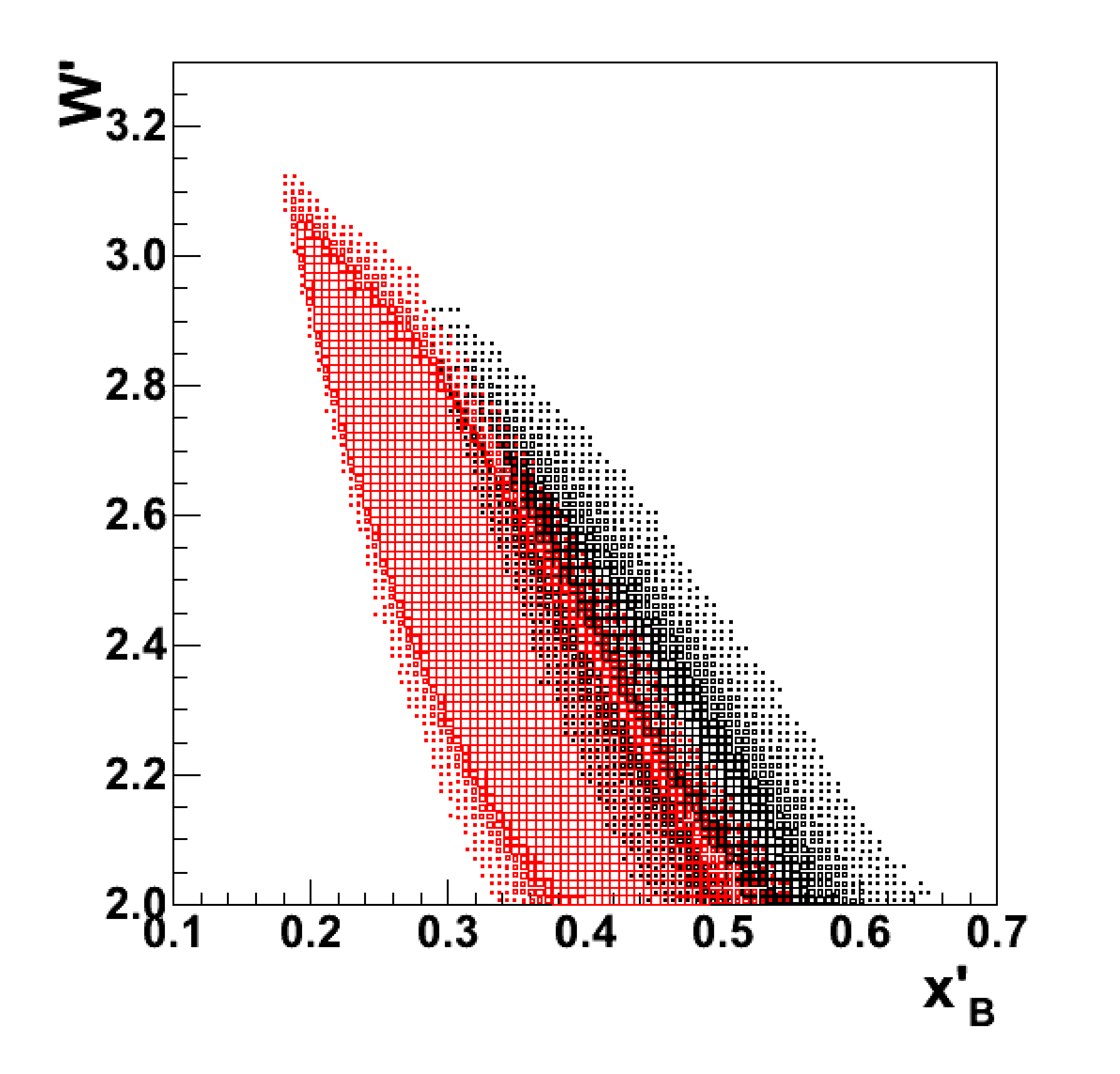
Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)



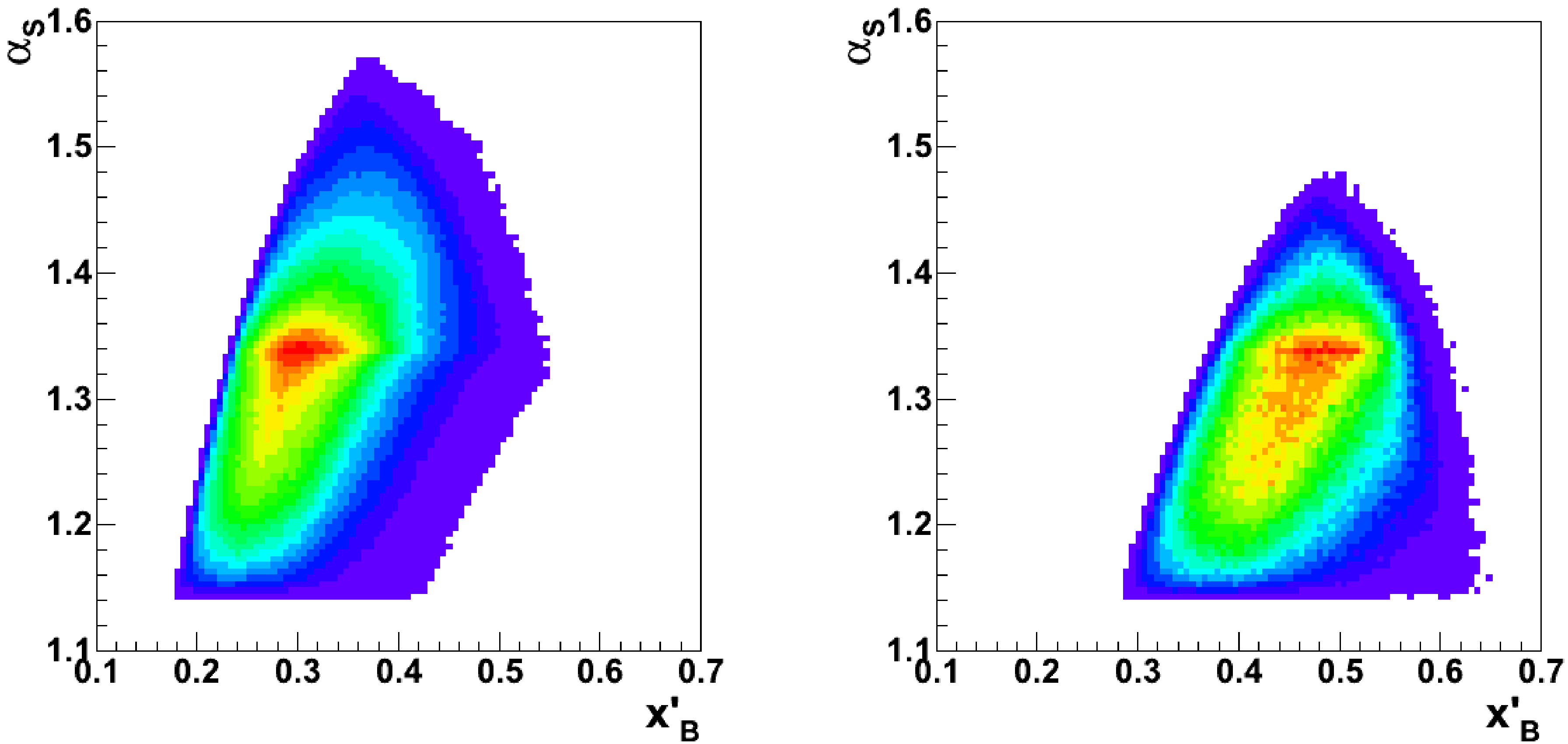
Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)



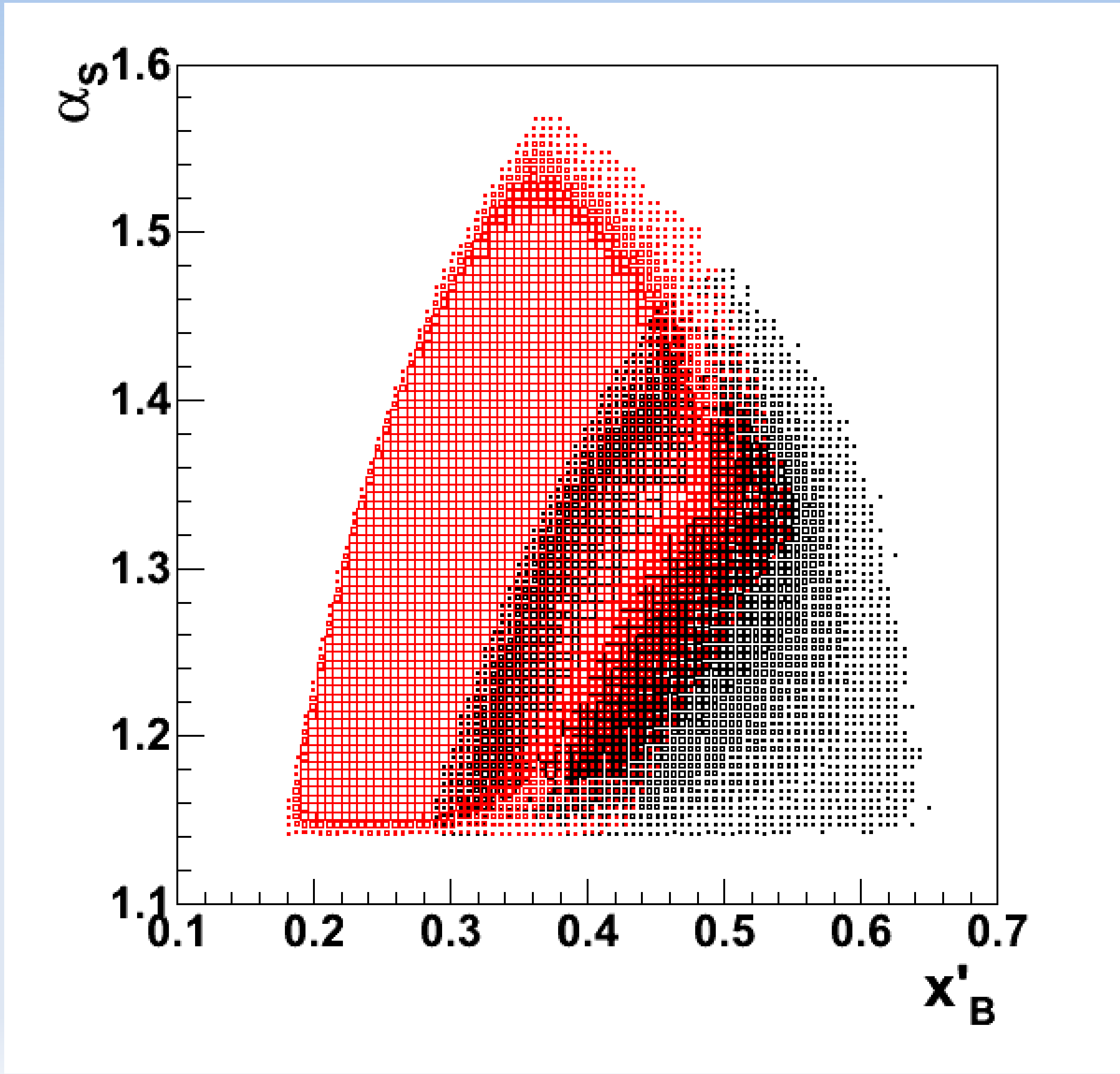
Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)



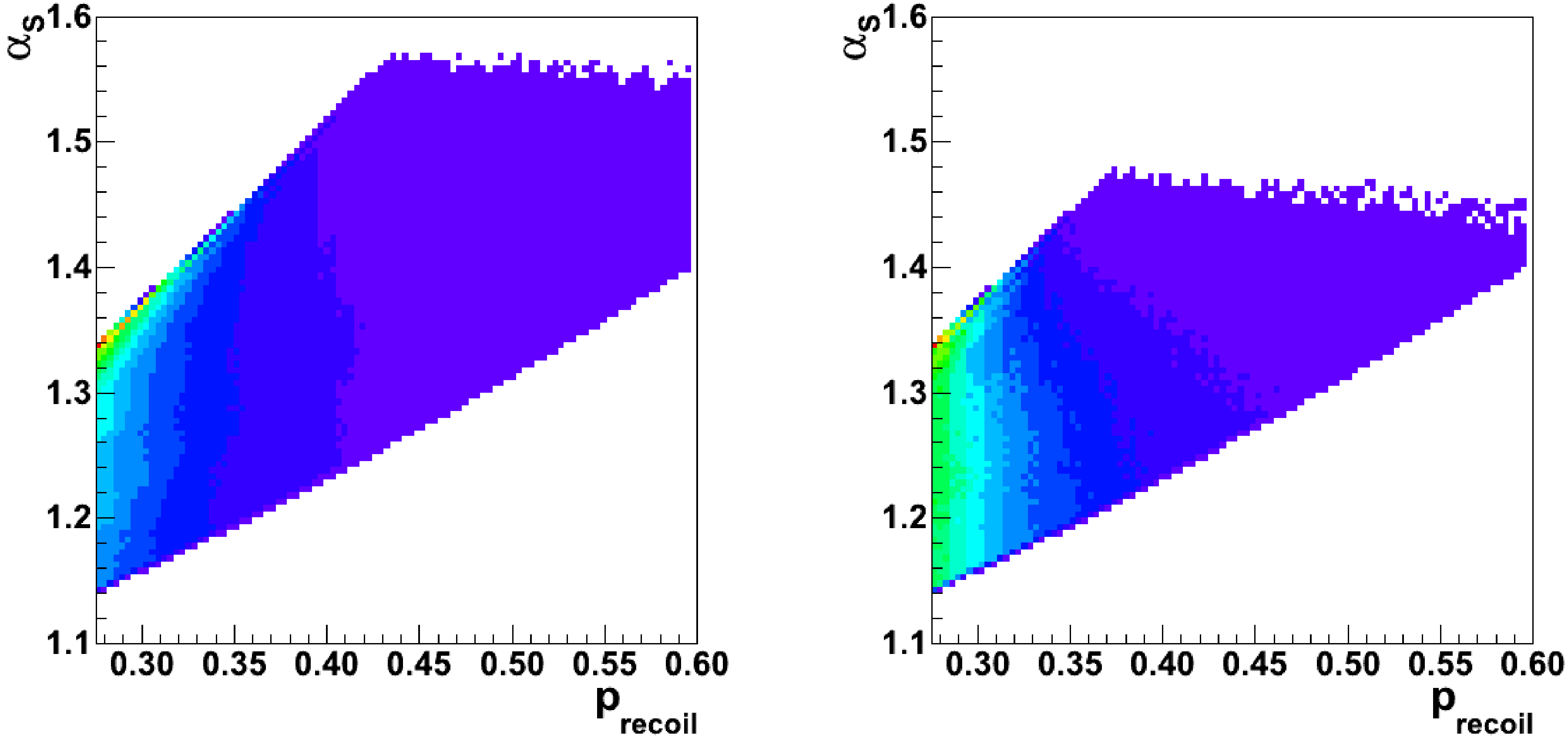
Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)



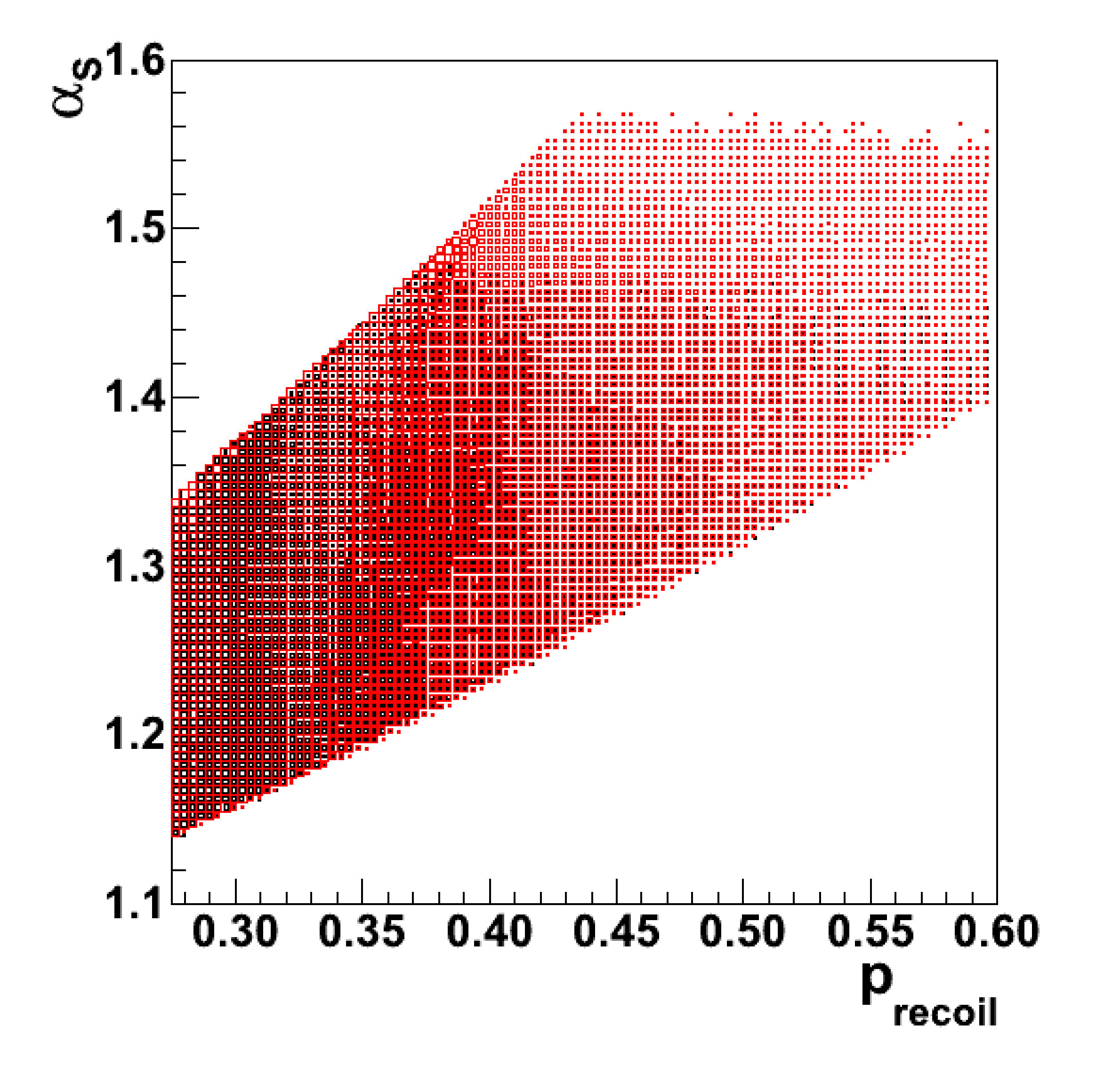
Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)



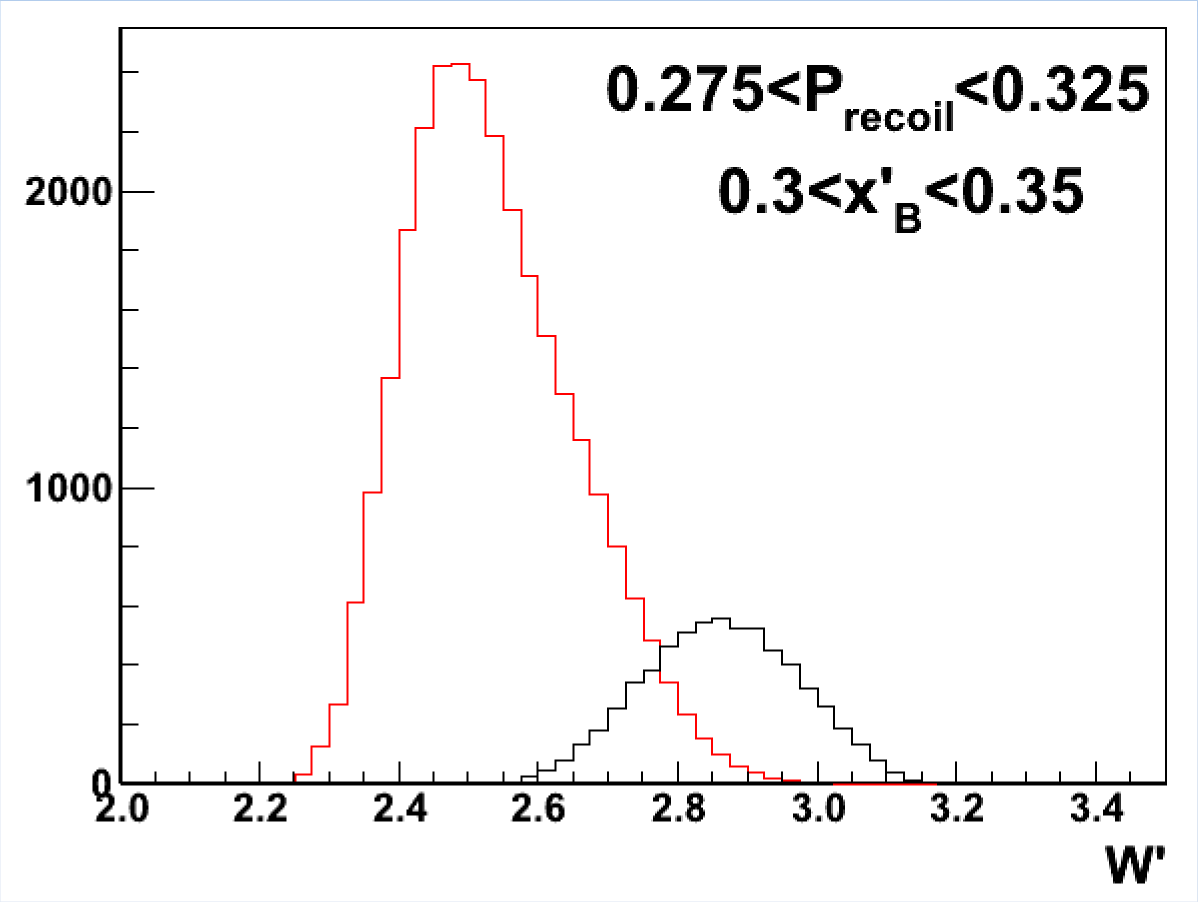
Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)



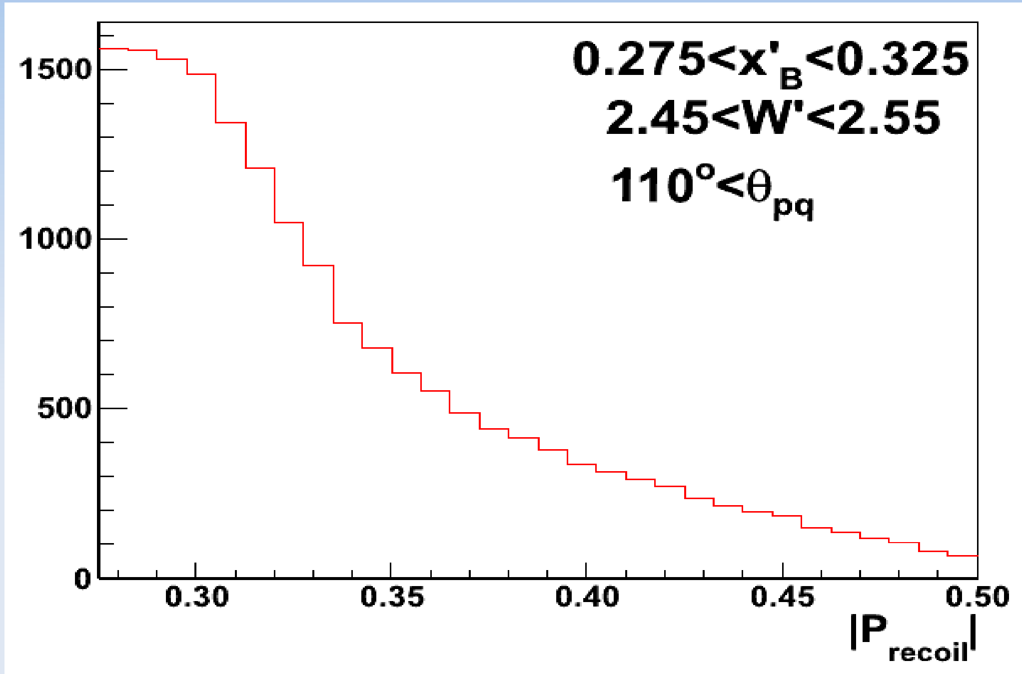
Phase Space Coverage (W'>2, Q^2>2, θ_{pq}>110°)

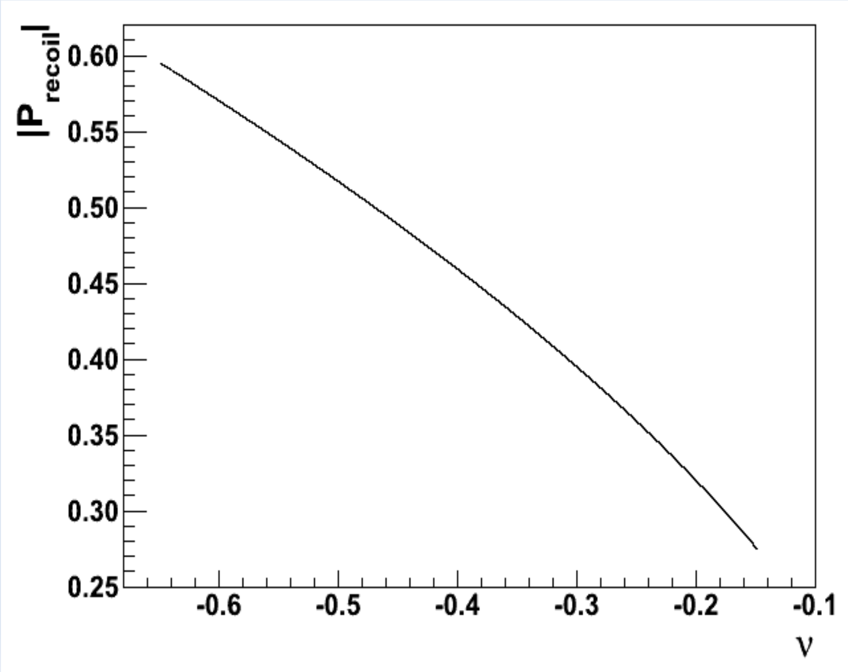


Analysis Example
I – W' Dependence

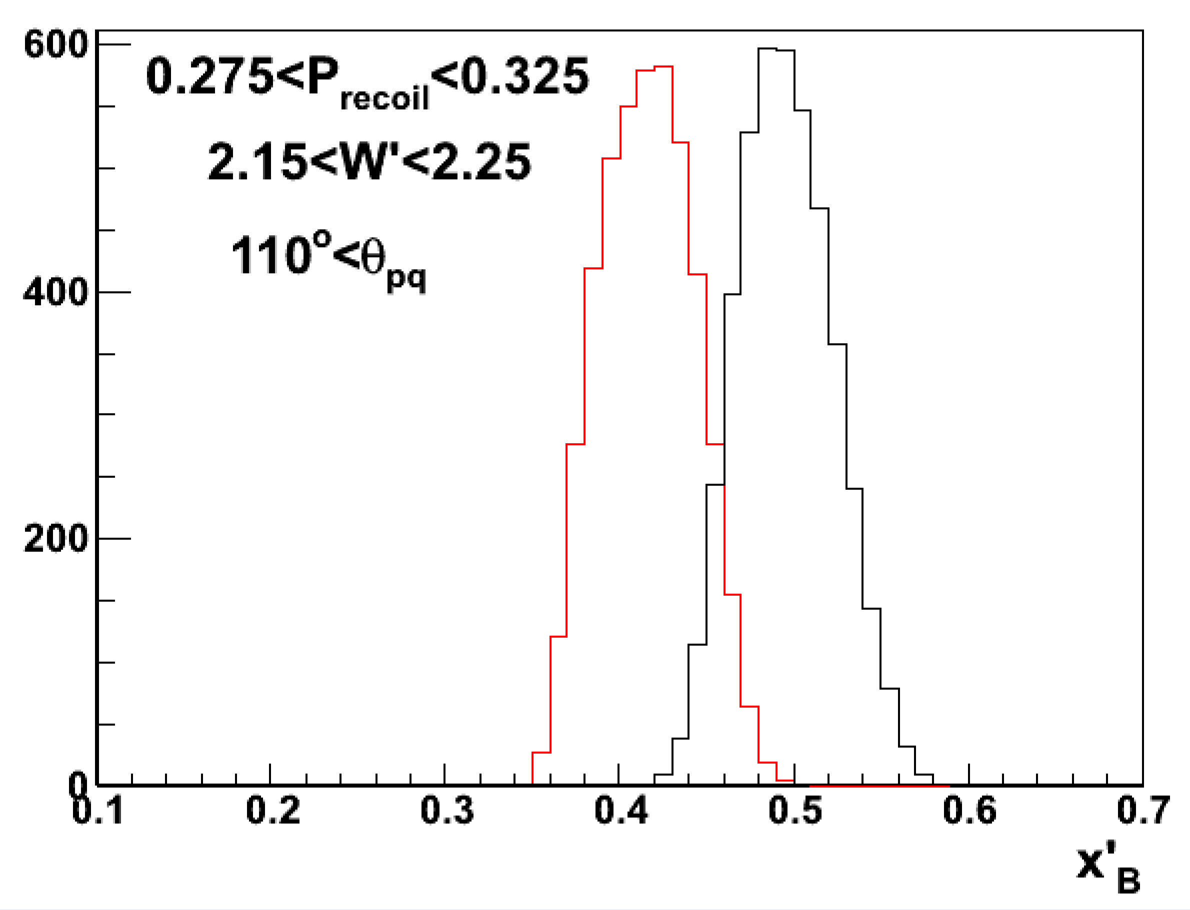


Analysis Example
II – P_{recoil} Dependence



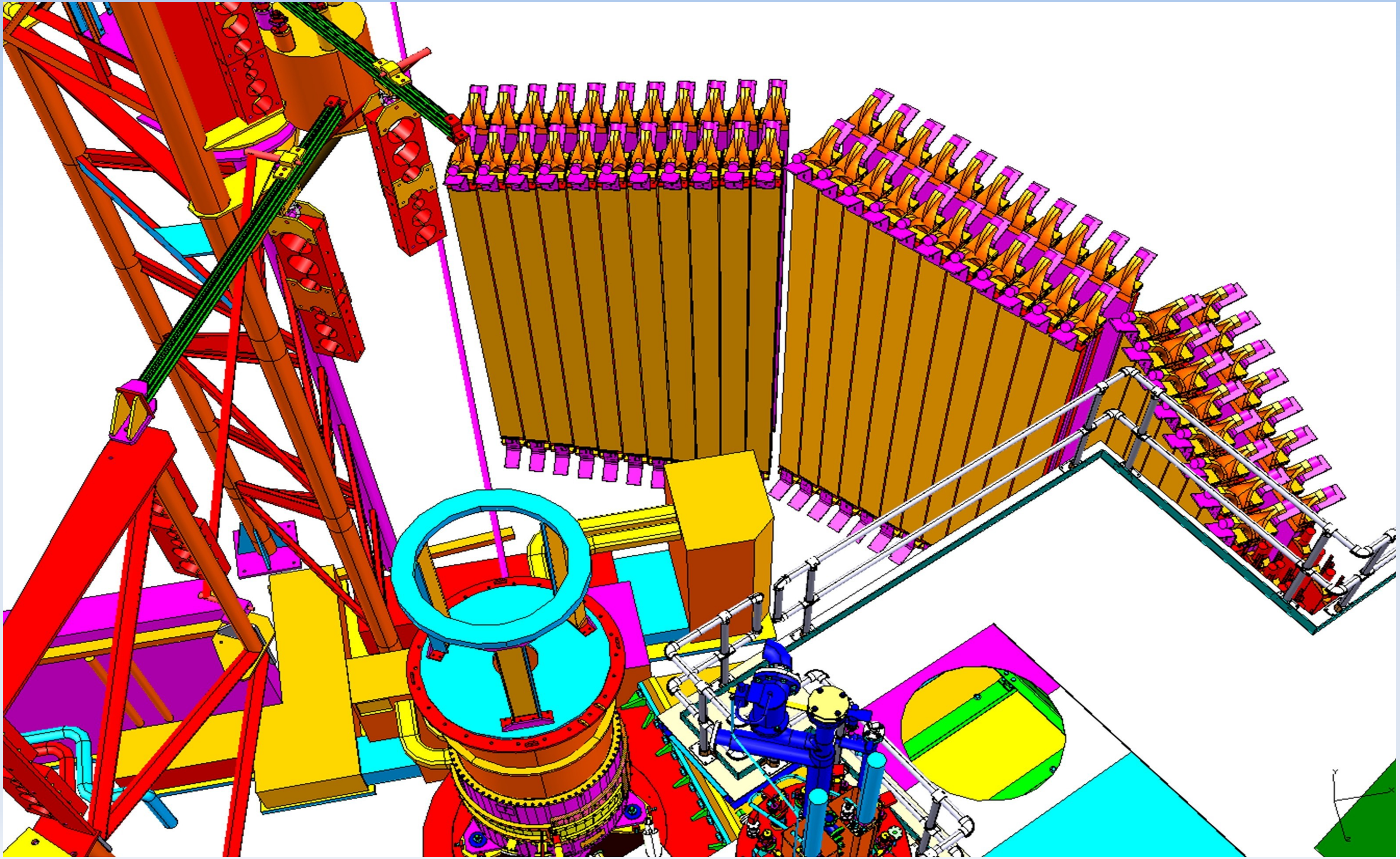


Analysis Example
III – x'_B Dependence

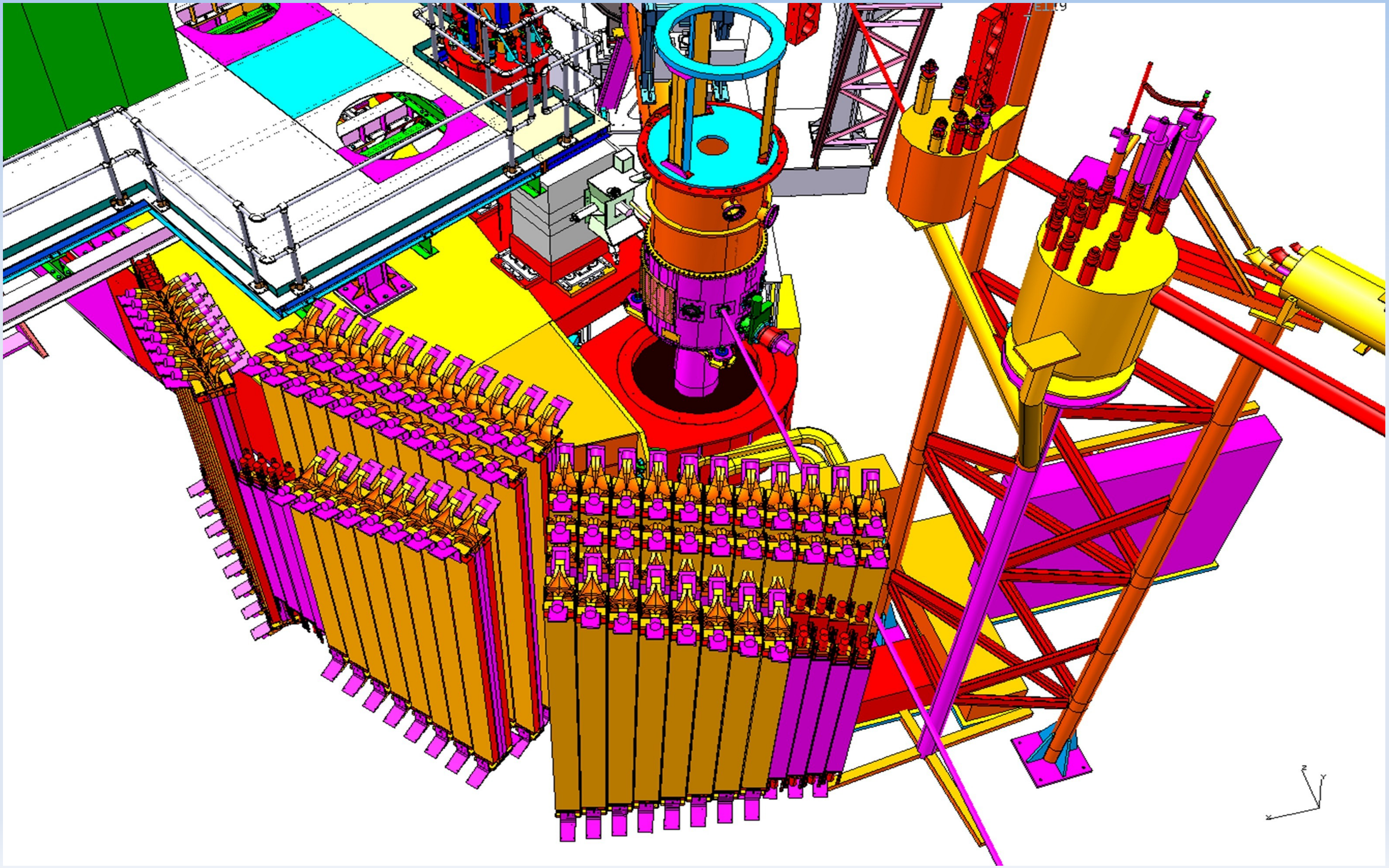


LAD Drawings

LAD Drawings



LAD Drawings



LAD Drawings