Bound and Free Nucleons: Experimental Studies

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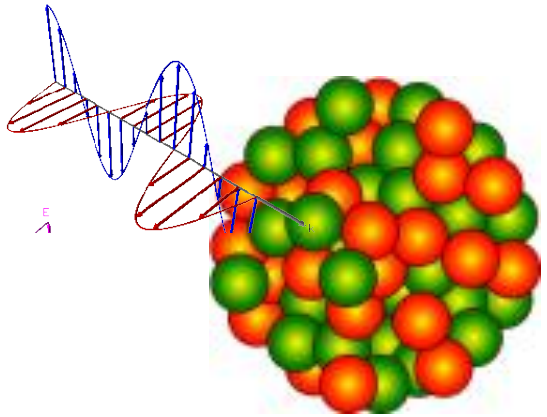
Medium modification

- $M_{quarks} \sim 2\% M_{proton}$
- $M_{nucleons} \sim 99\% M_{208Pb}$
- Is the proton modified in the nuclear medium?
- Compare free and bound proton formfactors and structure functions
- Proton electric and magnetic formfactors, $G_E(Q^2)$ and $G_M(Q^2)$:
  - give information about the relative distributions of the **quark longitudinal momenta** and **transverse positions**
  - Nonrelativistically, $G_E(Q^2)$ is the Fourier transform of the charge distribution.
- Proton structure function, $F_2(x_B)$
  - Quark momentum distribution



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

Q^2 = 4-momentum transfer squared
ν = energy transfer

Measuring form factors

General $\mathrm{H}(\vec{e},e'\vec{p})$ cross section, including *e* and *N* polarization:

$$\frac{d\sigma}{d\Omega} \propto G_E^2(Q^2) + A(Q^2,\theta_e)G_M^2(Q^2) + CP_eP_N^{\perp}G_EG_M + DP_eP_N^{\parallel}G_M^2$$

$G_E^2 << G_M^2$: makes Rosenbluth separation very difficult (especially at hi Q^2)

Use polarization to measure the larger interference term G_EG_M

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

Need:

- Polarized electrons
- Measure proton (or neutron) polarization

Nucleon Scattering and polarisation

How do we measure the polarisation of a nucleon ??
Measure it, rescatter it, then remeasure it to determine the angle θ,ϕ it rescatters through.

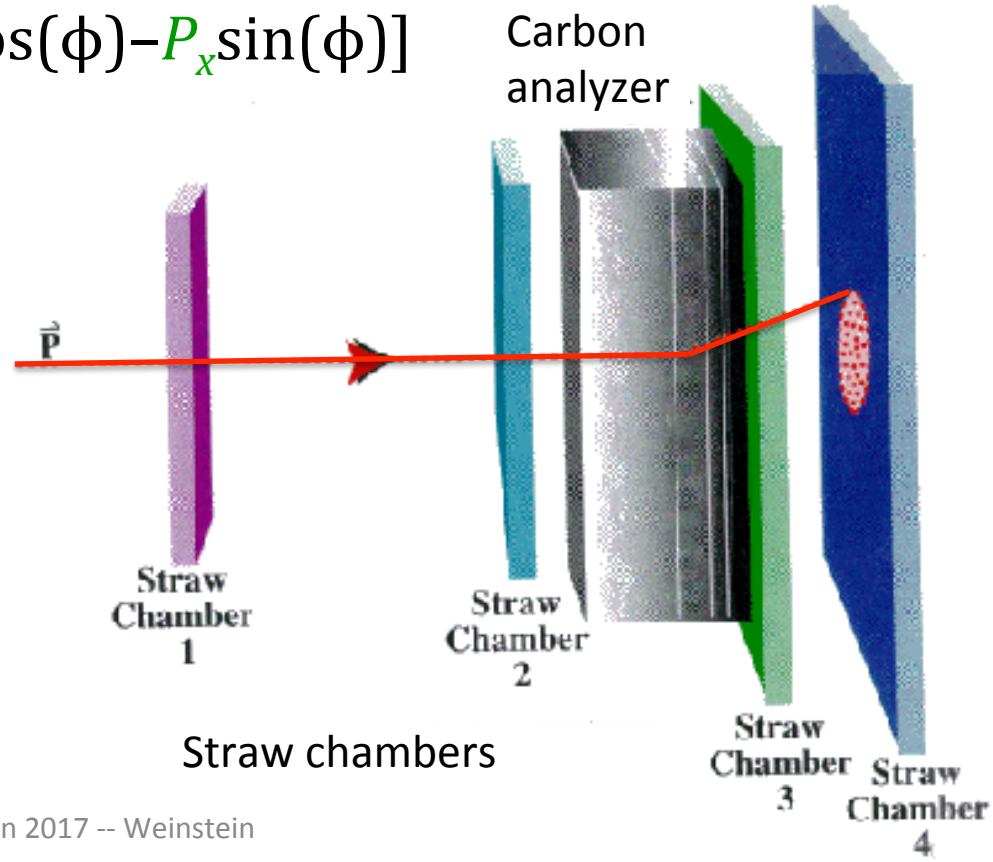
Polar angle distribution for unpolarised nucleons

x and y (transverse) components of nucleon polarisation

$$n(\theta,\phi) = n_o(\theta)\{1 + A(\theta)[P_y \cos(\phi) - P_x \sin(\phi)]$$

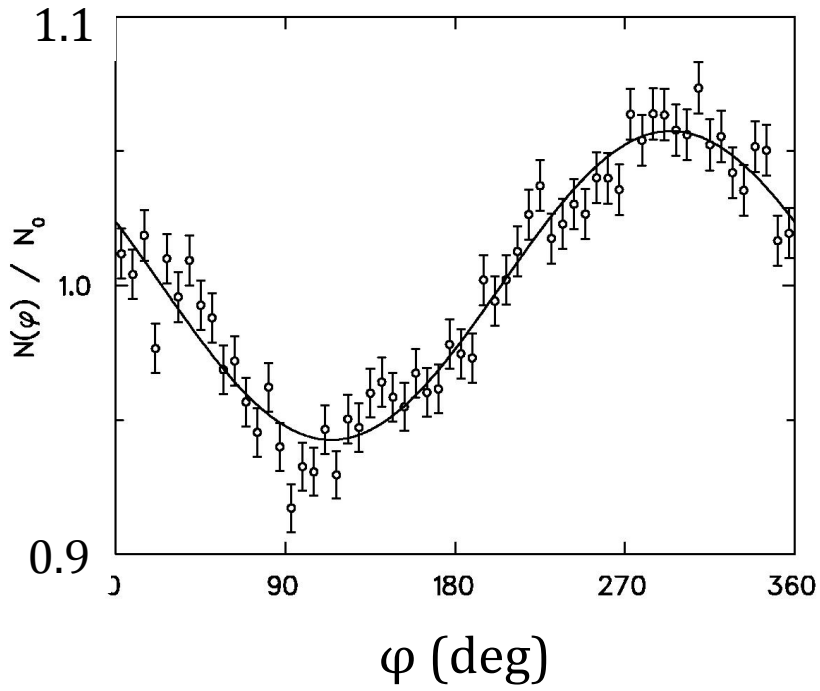
Nucleon angular distribution

Analysing power of scatterer

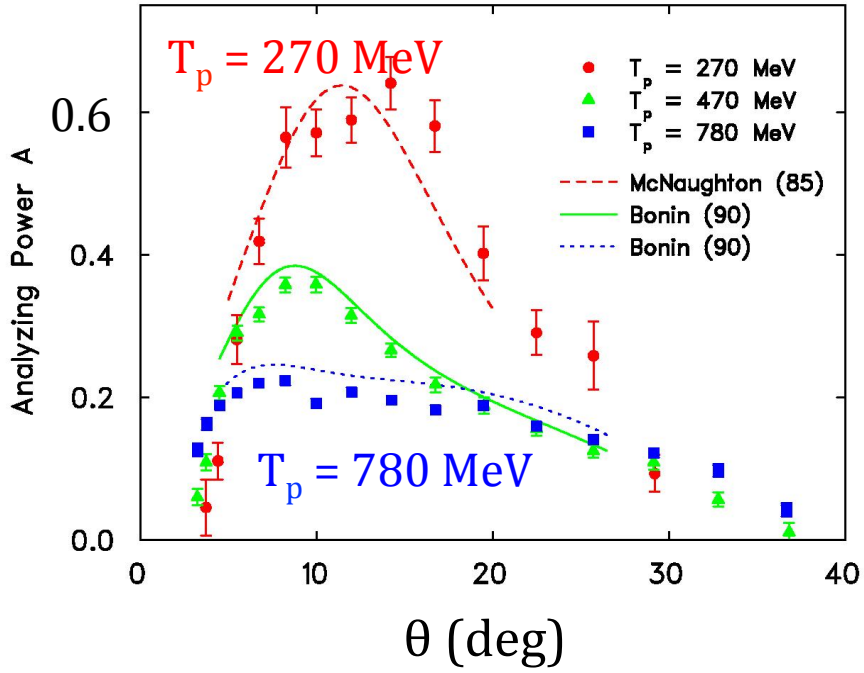


Straw chambers

Measuring proton polarization

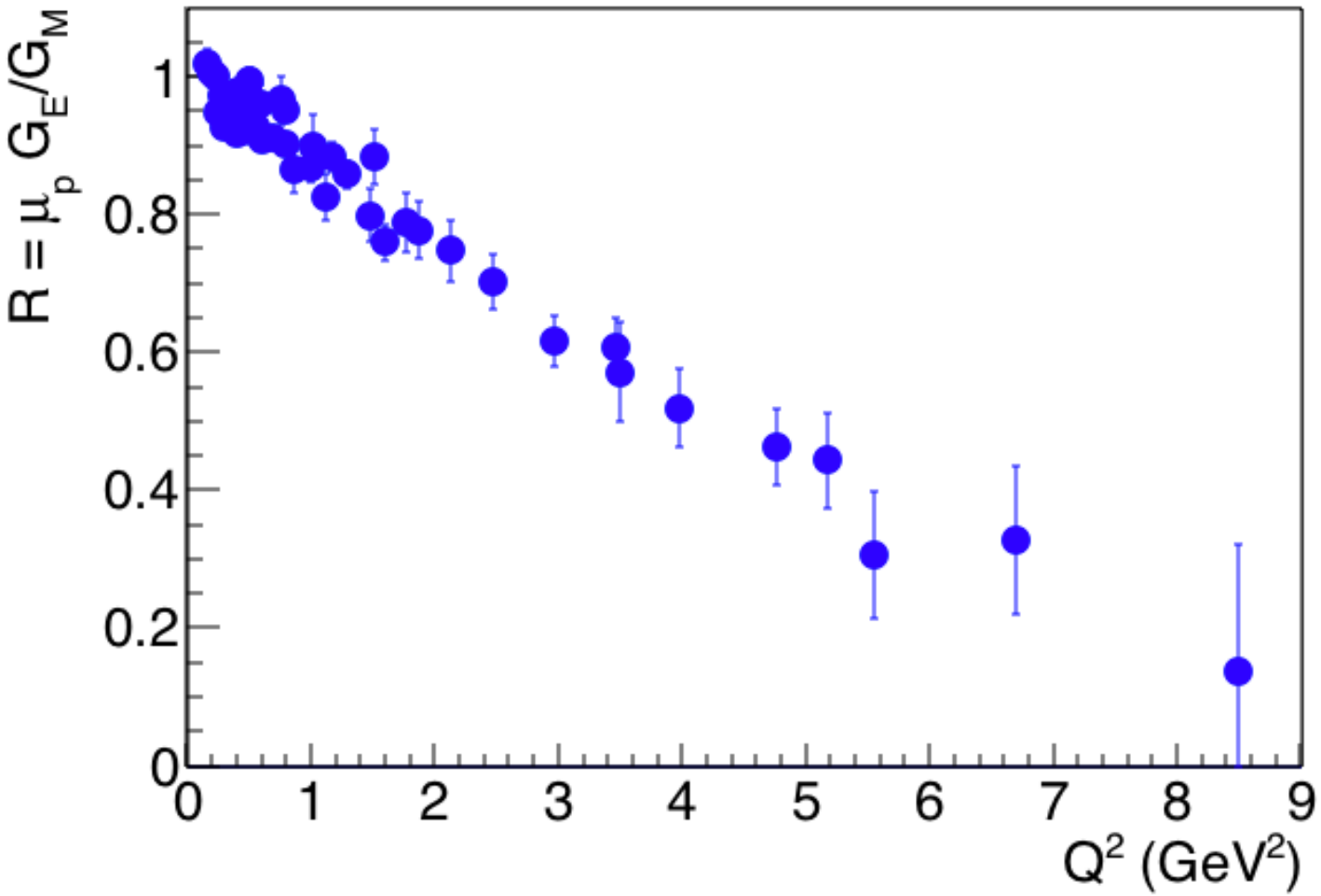


Angular distribution of protons scattered from a carbon analyzer



Analyzing power of the Hall A Focal Plane Polarimeter

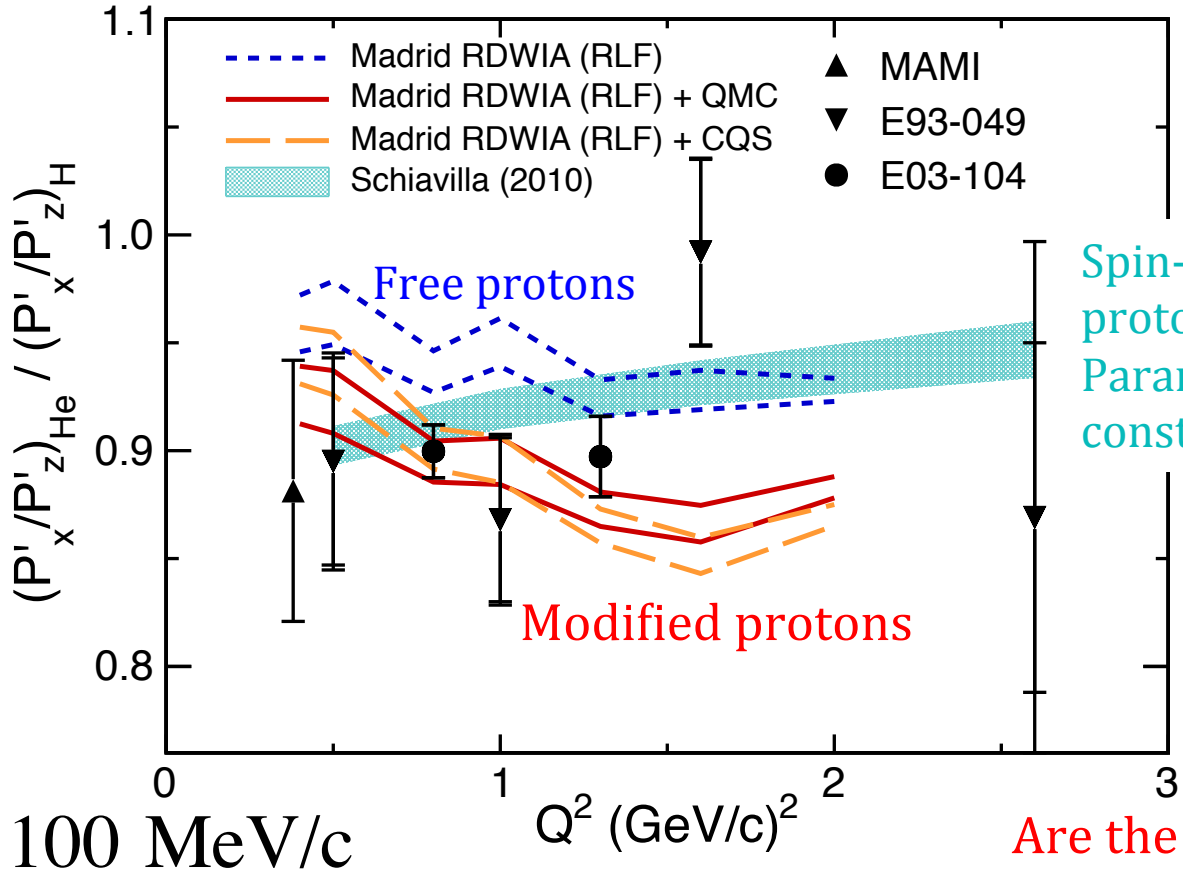
The free proton form factor ratio



Proton formfactors in the nucleus

Measure the double ratio of P_t/P_l for ^{4}He($\vec{e}$, e' $\vec{p}$) and H($\vec{e}$,e' $\vec{p}$)

$$R = \frac{P_t / P_l(A)}{P_t / P_l(\mathrm{H})} \approx \frac{G_E / G_M(A)}{G_E / G_M(\mathrm{H})}$$



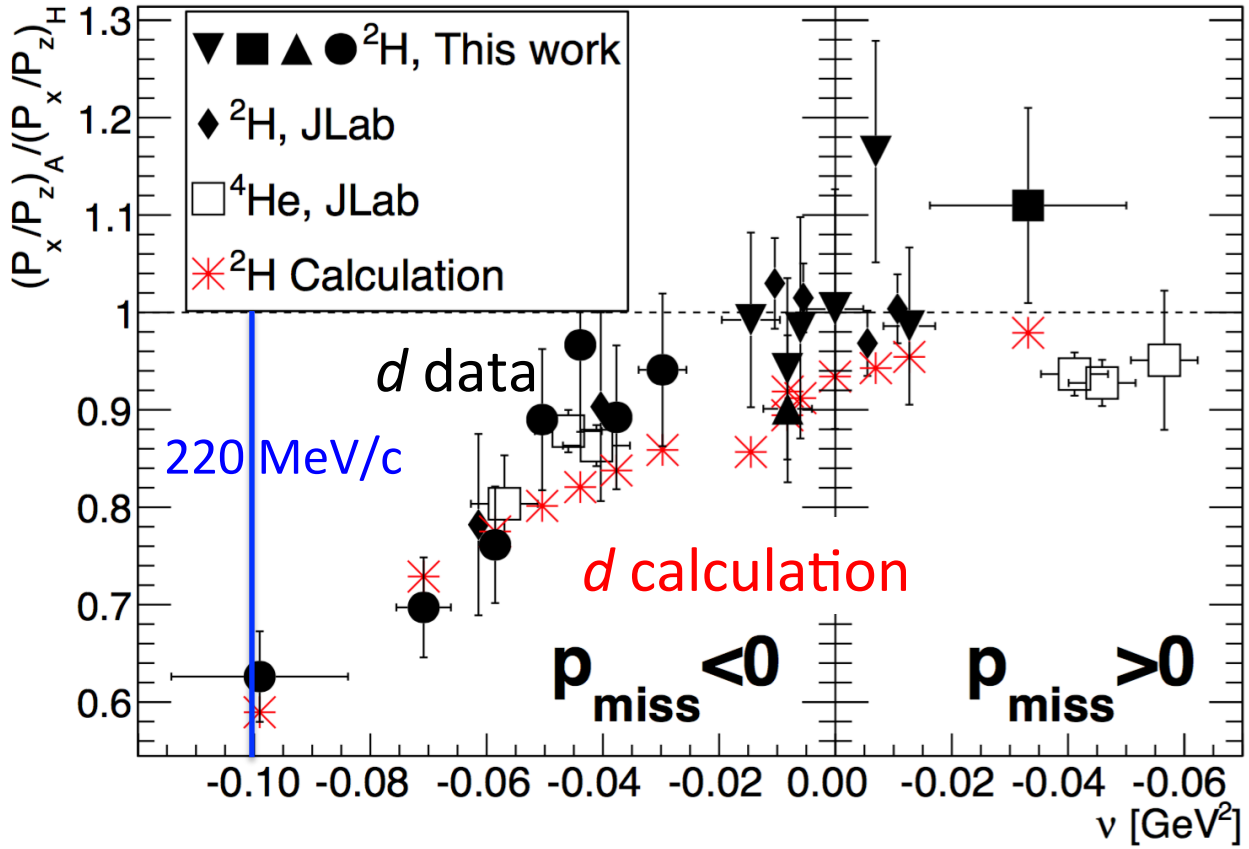
Spin-dependent proton rescattering. Parameters not well constrained

$p_{miss} \approx 100$ MeV/c

Are the FF modified??? Probably.

Proton formfactors in the nucleus

$$R = \frac{P_t / P_l(A)}{P_t / P_l(\mathrm{H})} \approx \frac{G_E / G_M(A)}{G_E / G_M(\mathrm{H})}$$



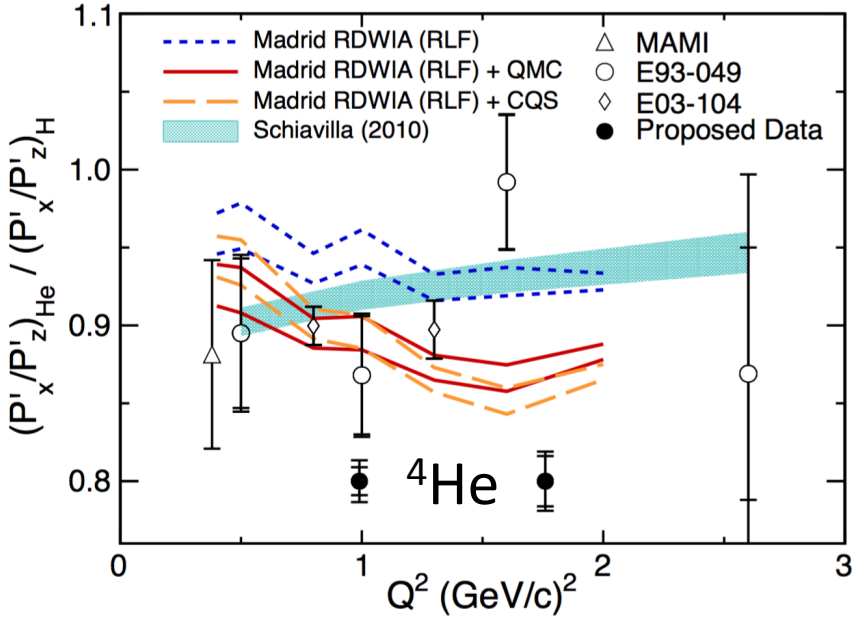
$Q^2 \approx 0.2,\ 0.4\ \mathrm{GeV}^2$

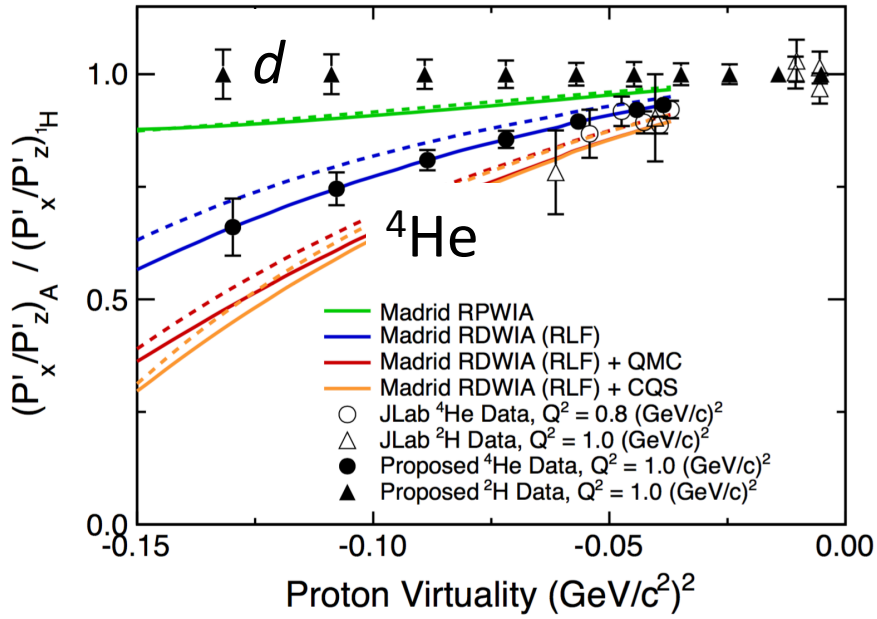
What about higher proton momentum? Effect unclear.

arXiv:1602.06104

Proton formfactors in the nucleus: Future

$$R = \frac{P_t / P_l(A)}{P_t / P_l(\mathrm{H})} \approx \frac{G_E / G_M(A)}{G_E / G_M(\mathrm{H})}$$

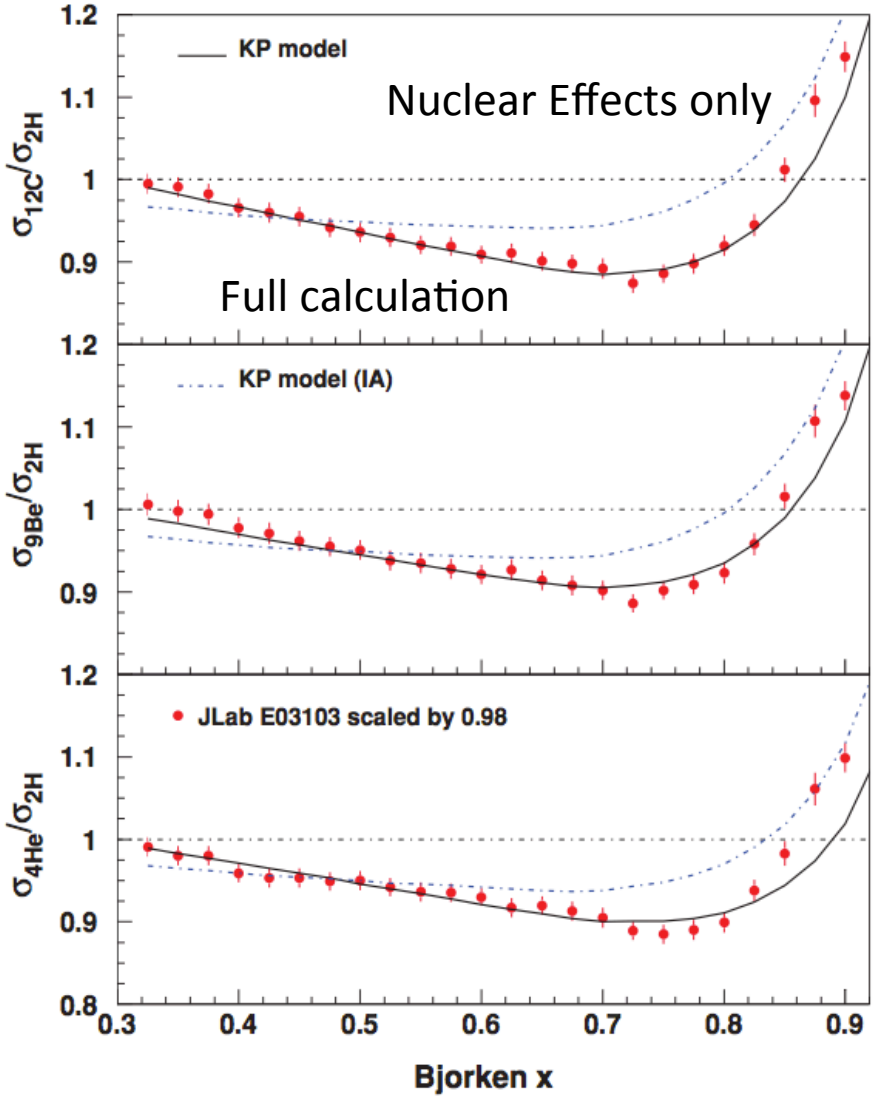




JLab expt 12-11-002: measure *R* for *d* and ^{4}He to higher virtuality and better precision

The EMC Effect and nucleon structure

- Nuclear Effects:
  - Fermi motion
  - Binding energy
- Full Calculation
  - Nucleon modification
  - Nuclear pions
  - shadowing



Nucleon modification:

Phenomenological change to bound nucleon structure functions, proportional to virtuality (p^2)

Kulagin and Petty, PRC 82, 054614 (2010)

The EMC Effect and nucleon structure

- Nuclear Effect
  - Fermi mo
  - Binding e
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  - Nucleon r
  - Nuclear p
  - shadowin

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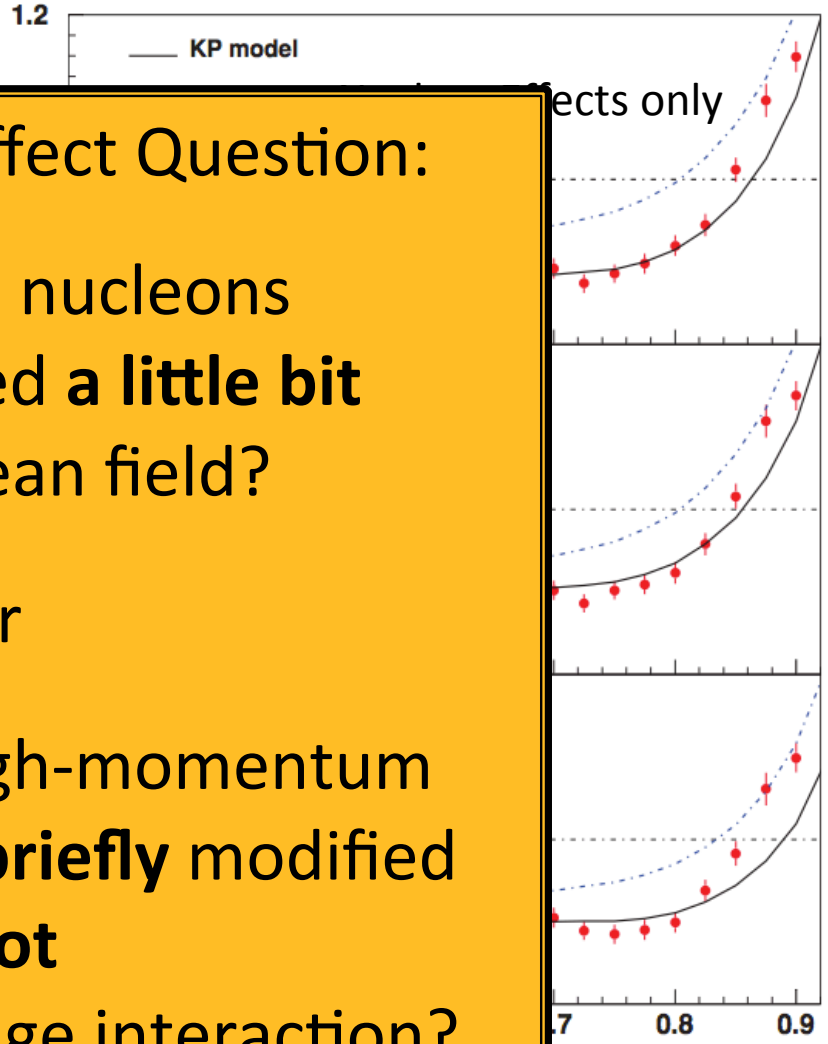


The Big EMC Effect Question:

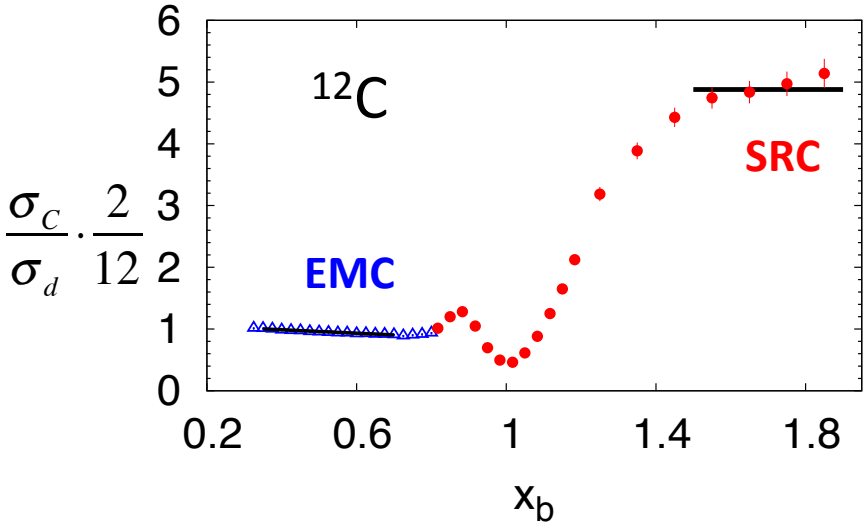
Are **all** the nucleons
each modified **a little bit**
by the mean field?

or

Are the **few** high-momentum
nucleons each **briefly** modified
a lot
by the short range interaction?

Kulagin and Petty, PRC 82, 054614 (2010)

Correlations Between EMC and SRC

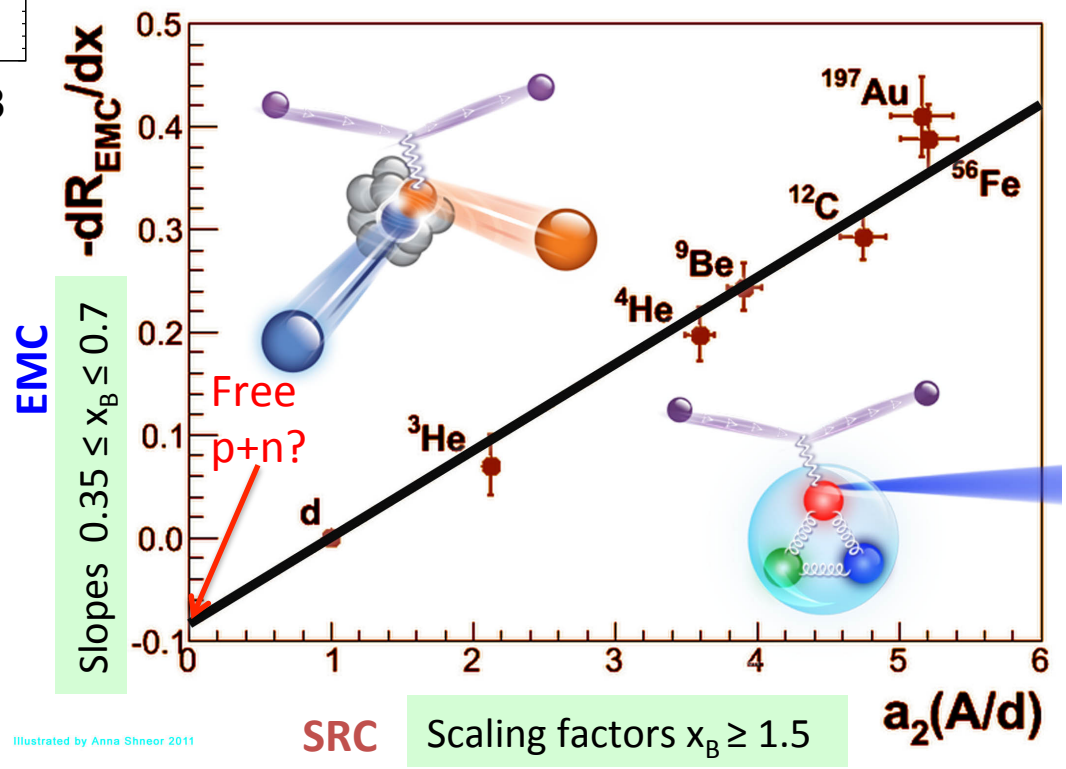


SRC

- High nucleon momenta

JLab data

J. Seely *et al.*, PRL **103** (2009) 202301
N. Fomin et al., Phys. Rev. Lett. **108** (2012) 092502



SRC Scaling factors $x_B \ge 1.5$

Weinstein *et al.*, PRL **106**, 052301 (2011)
O. Hen *et al.*, PRC **85**, 047301 (2012)

EMC

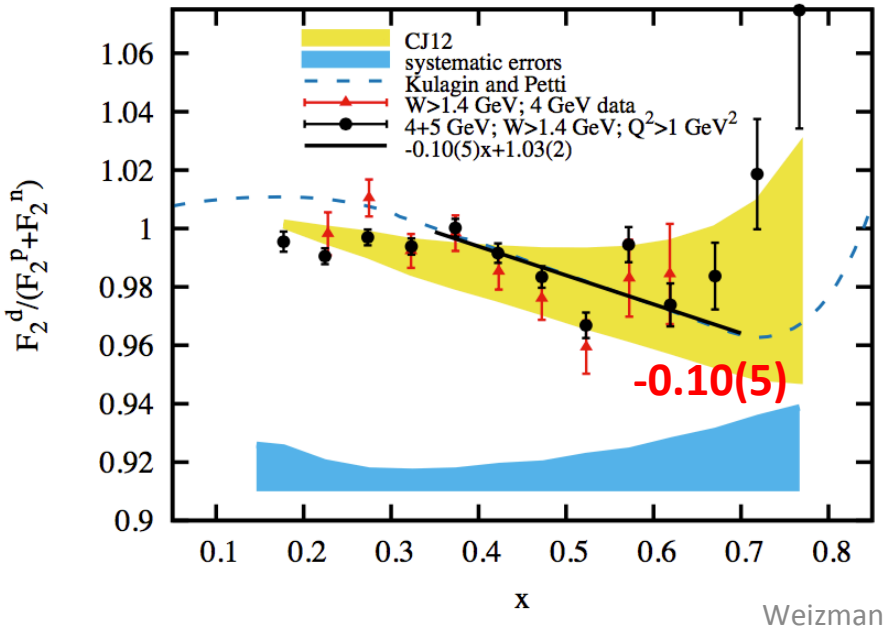
- Is EMC related to high-momentum nucleons?
- Are high-momentum nucleons modified?

Explore Connection between EMC and SRC

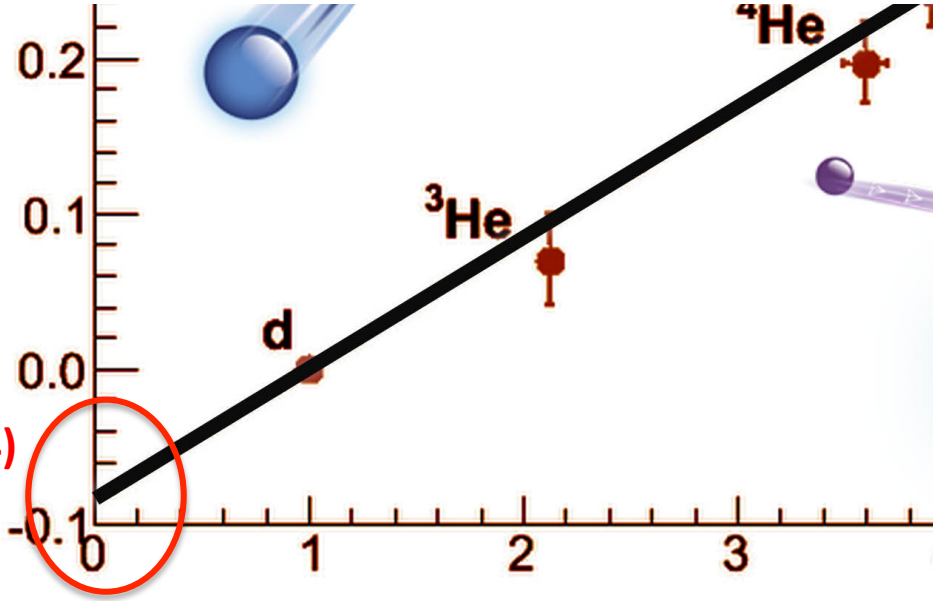
Do high-momentum nucleons have a large EMC effect?

Deuteron

- Is there an "EMC" effect in the deuteron?
- Is the "EMC" effect larger at high-momentum?



[BoNuS: Griffioen et al, PRC **92,** 015211 (2015)]



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

$$\frac{\sigma_d}{\sigma_p + \sigma_n}(x_B = 0.6) \approx 0.976$$

~2.4% modification, ~5% high momentum:

$$\frac{\sigma_p^*}{\sigma_p} \approx \frac{\sigma_n^*}{\sigma_n} \approx \frac{2.4\%}{5\%} \approx 0.5$$

Testing the BIG Question:

Measure the in-medium structure function F_2 in DIS as a function of nucleon momentum

$$\frac{d^3\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{1}{\nu}F_2(x_B,Q^2) + \frac{2}{M}F_1(x_B,Q^2)\cdot\tan^2\left(\frac{\theta_e}{2}\right)\right]$$

(F_1 and F_2 are related by R, the measured ratio of longitudinal and transverse cross sections. Thus measuring the cross section yields F_2.)

① **No** nucleons modified

② **All** nucleons modified

➔ F_2 independent of momentum

➔ small modification

③ **SRC** nucleons modified

➔ F_2 varies with momentum

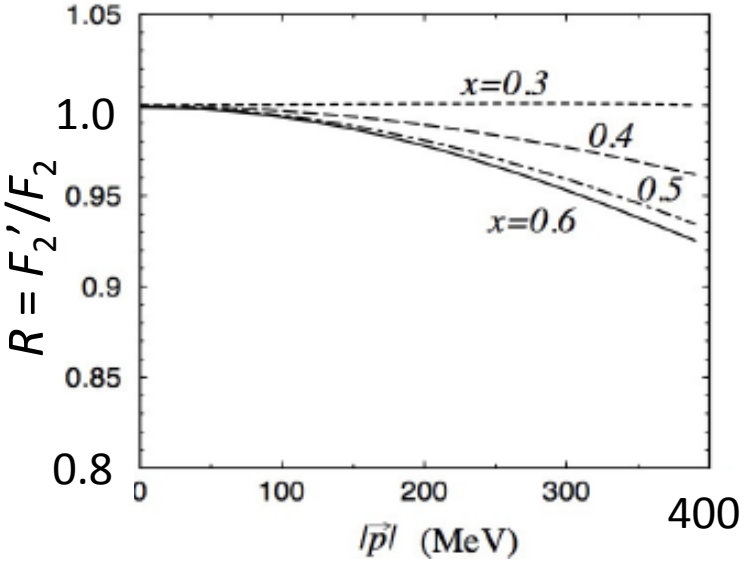
➔ big modification

F_2 Momentum Dependence

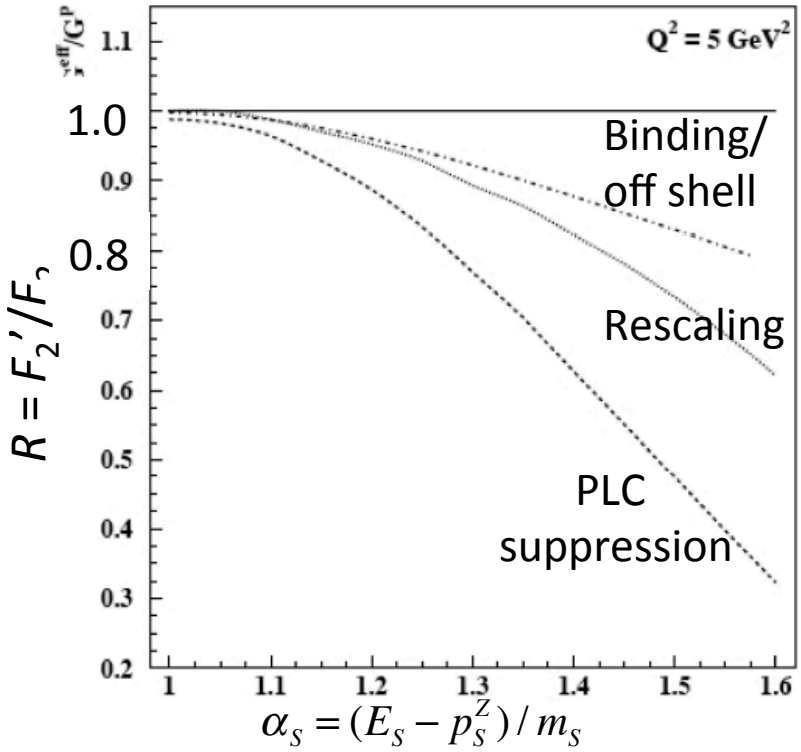
Dependence on:

- Models
- Nucleon momentum and x_B
- Nucleon momentum, not x_B

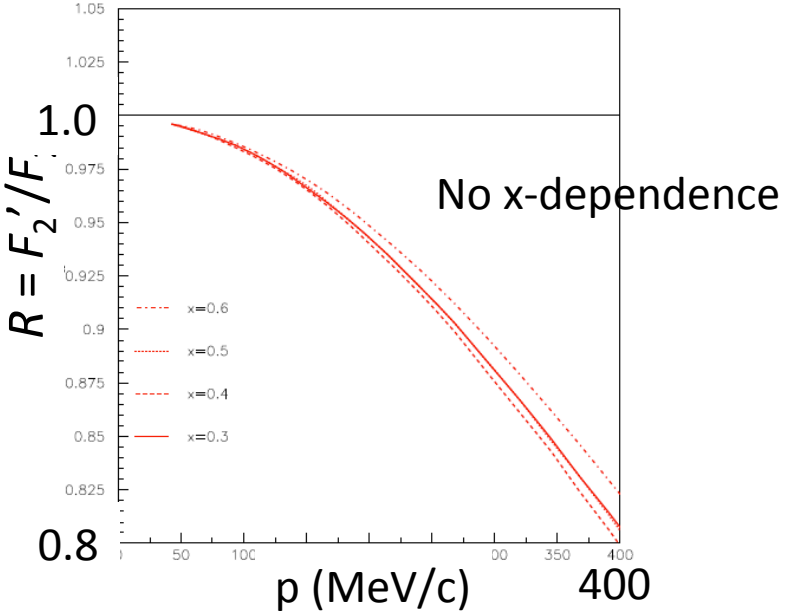
Melnitchouk, Schreiber, Thomas, Phys. Lett. B **335**, 11 (1994)



Melnitchouk, Sargsian, Strikman,
Z. Phys. A **359**, 99 (1997)



Gross, Liuti, Phys. Lett. B **356**, 157 (1995)



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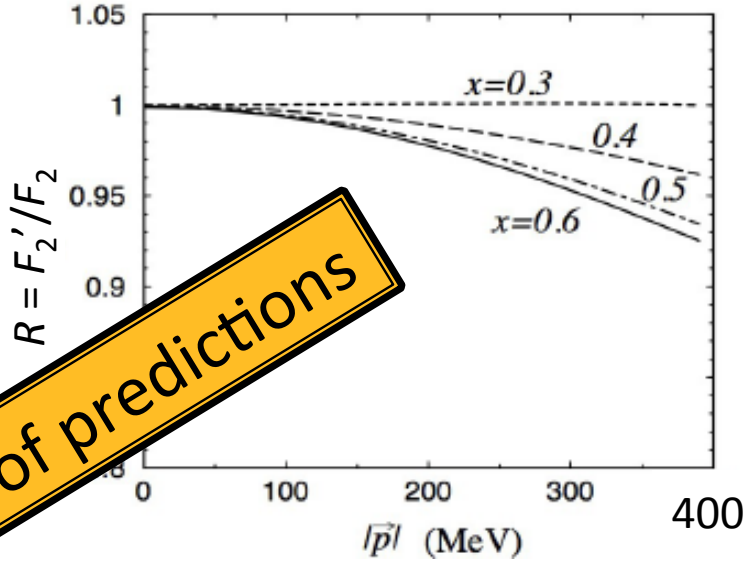

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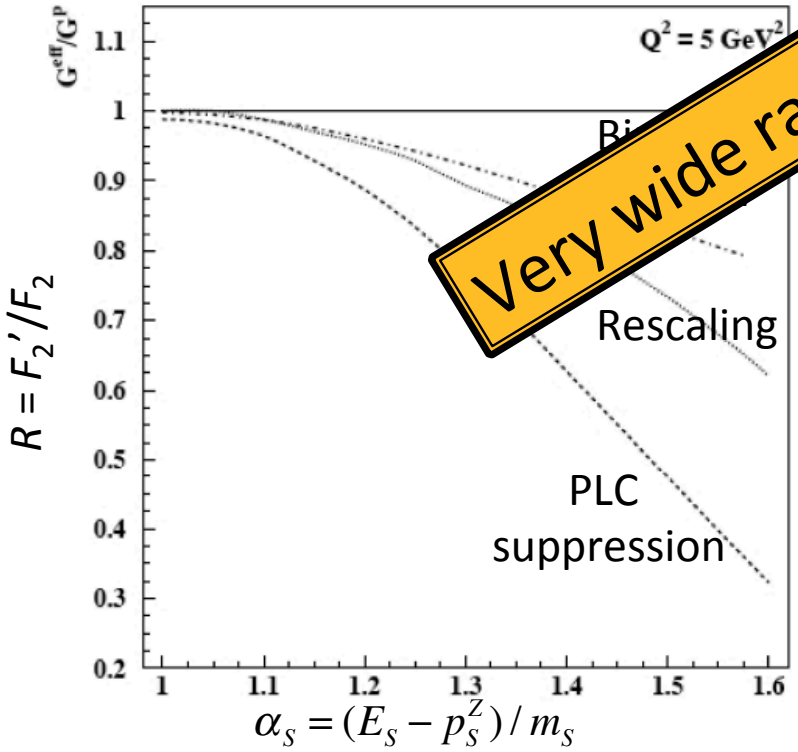
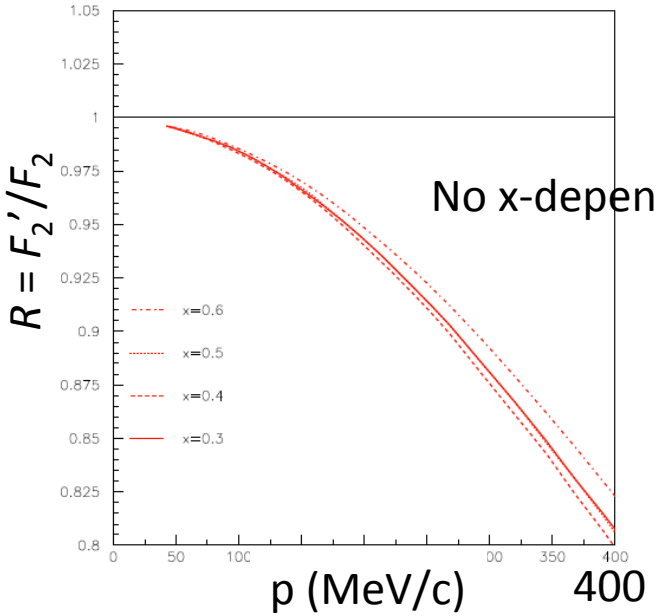


Very wide range of predictions

Gross, Liuti, Phys. Lett. B **356**, 157 (1995)

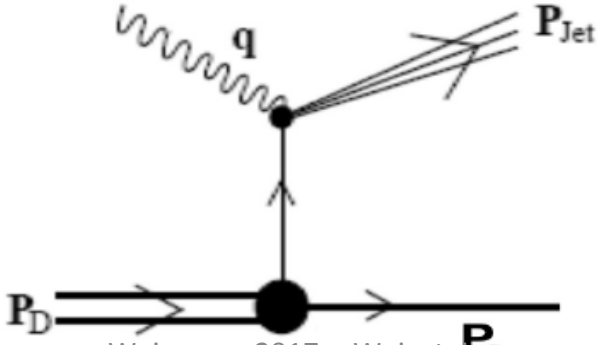


Measurement: Spectator Tagging

d(e,e'p_s) – CLAS6 (recoil p)
E12-11-107 – Hall C + LAD (recoil p)
This experiment – CLAS12 + BAND (recoil n)

Experimental method

- (e,e') Deep Inelastic Scattering from deuterium
- Tag high-momentum nucleons with 300-700 MeV/c backward-recoiling ("spectator") partner nucleon using d(e,e'N_S)



Experimental Method

d(e,e'N_S) cross section factorizes into the cross section (F_2) and the distorted momentum distribution.

Fix the recoil kinematics and measure x-section ratios at 2 different x':

$$\frac{d^4\sigma}{dx_1' dQ_1^2 d\vec{p}_S} \Big/ \frac{d^4\sigma}{dx_2' dQ_2^2 d\vec{p}_S} = (K_1/K_2)\left[F_2^*(x_1', \alpha_S, p_T, Q_1^2) / F_2^*(x_2', \alpha_S, p_T, Q_1^2) \right]$$

For x_1' ≈ 0.5 – 0.6 and x_2' ≈ 0.3 we shall measure:

$$F_2^*(x_1', \alpha_S, p_T, Q_1^2) / F_2^*(x_2', \alpha_S, p_T, Q_2^2) = \left(\frac{d^4\sigma}{dx_1' dQ_1^2 d\vec{p}_S} / K_1 \right) \Big/ \left(\frac{d^4\sigma}{dx_2' dQ_2^2 d\vec{p}_S} / K_2 \right)$$

$$x' = \frac{Q^2}{2 p_\mu q^\mu} = \frac{Q^2}{2[(M_d - E_S)\omega + \vec{p}_S \cdot \vec{q}]}$$

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

x' is x-Bjorken for the moving struck nucleon

$\vec{p}_s$ maps to (α_s, p_T)

Experimental Method (cont.)

- Minimize experimental and theoretical uncertainties by measuring cross-section ratios

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

FSI correction factor

x' = x from a moving nucleon

$$x'_{high}\geq 0.5$$

$$0.25\geq x'_{low}\geq 0.35$$ No EMC Effect expected

$$x'_B=\frac{Q^2}{2p_\mu q^\mu}\overset{\text{(For d)}}{=}\frac{Q^2}{2[(M_d-E_S)\omega+\vec{p}_S\cdot\vec{q}]}$$

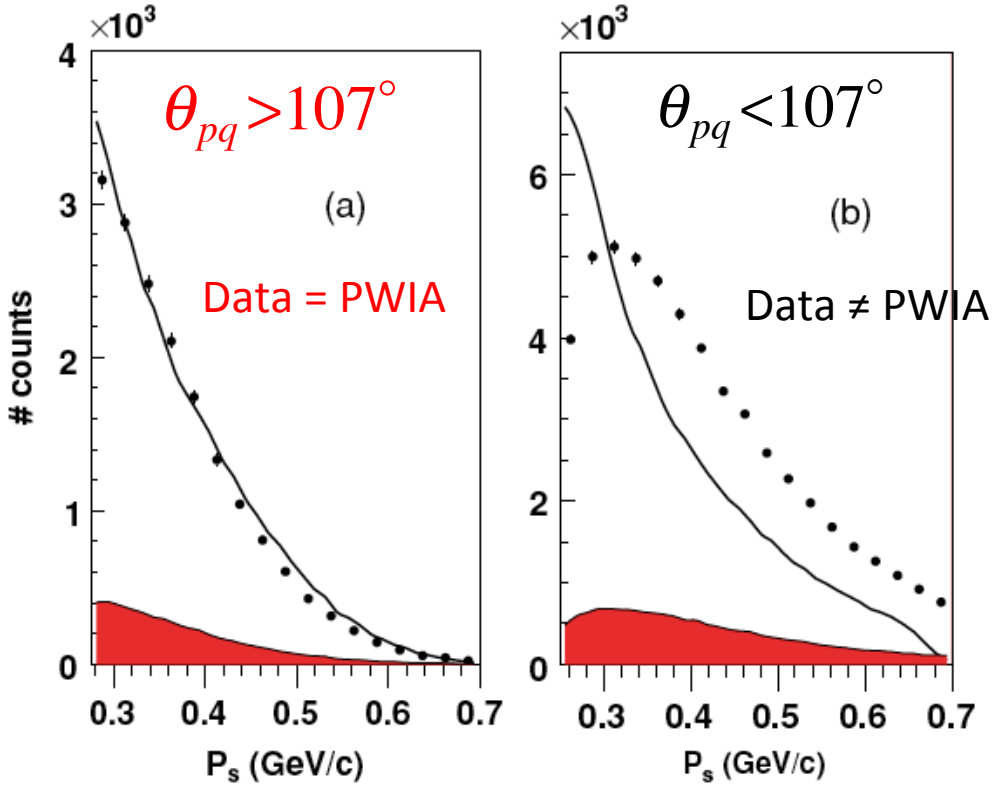
$$x_B=\frac{Q^2}{2m_N\omega}$$

Minimizing Final State Interactions (FSI)

D(e,e'p_s)

FSI:

- Decrease with Q^2
- Increase with W' (invariant mass)
- Not sensitive to x'_B
- Small for $\theta_{pq} > 107°$



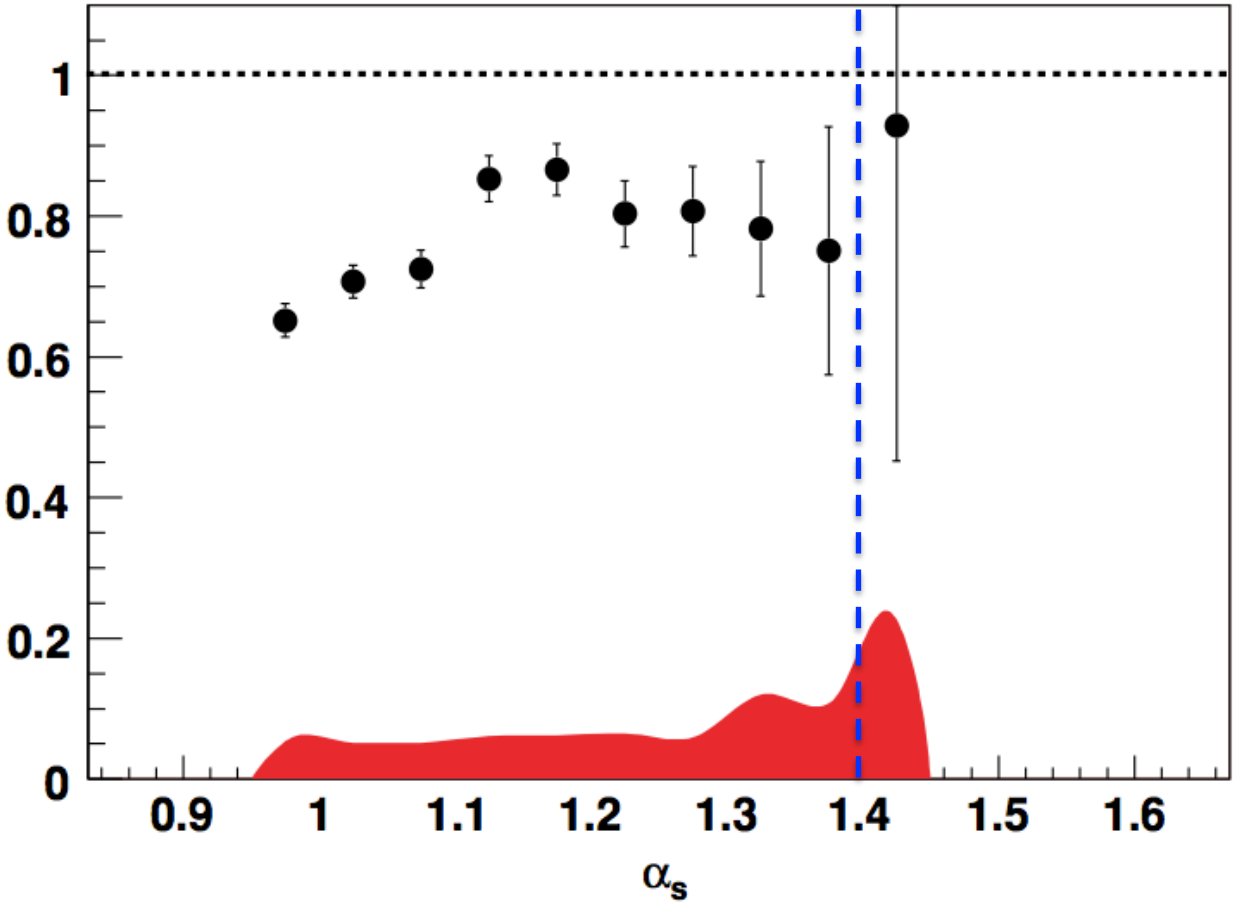
A. V. Klimenko *et al.*, PRC **73**, 035212 (2006)

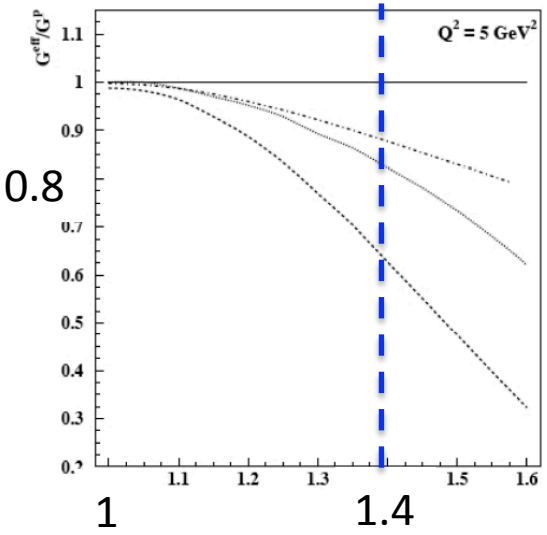
We shall:

- Take ratios at large recoil angles
- Involve theoretical colleagues
- Take more data at $\theta_{pq} \sim 90°$ (to characterize FSI)
- Take data at two x'
- Use low x' data to study FSI dependence on Q^2, W'^2, θ_{pq}

CLAS6 Results: d(e,e'p_s)

$$\frac{\left|\frac{F_2(x'=0.55,Q^2=2.8)}{F_2(x'=0.25,Q^2=1.8)}\right|_{\text{data}}}{\left|\frac{F_2(x'=0.55,Q^2=2.8)}{F_2(x'=0.25,Q^2=1.8)}\right|_{\text{free}}}$$





Inconclusive!

Klimenko et al, PRC **73**, 035212 (2006)

d(e,e'p$_s$) at higher energy at JLab

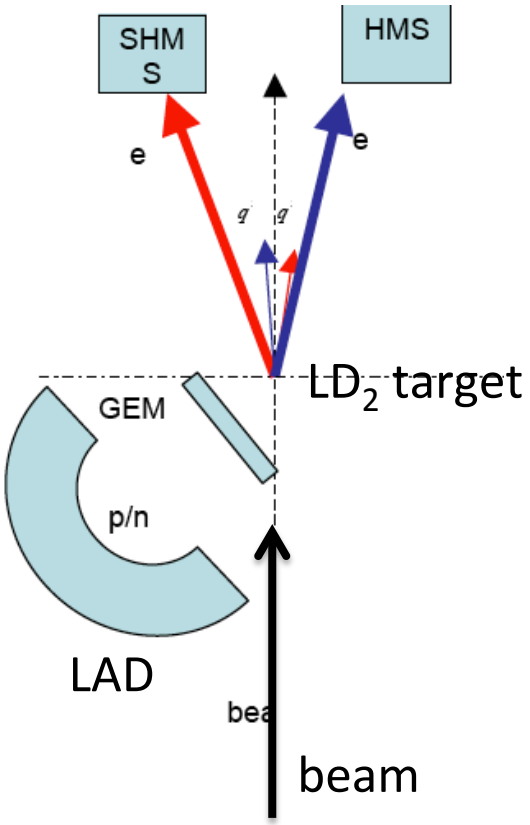
Hall C HMS and SHMS detect *e*-

LAD detects recoiling proton

LAD: ~1.5 sr of CLAS6 scintillators

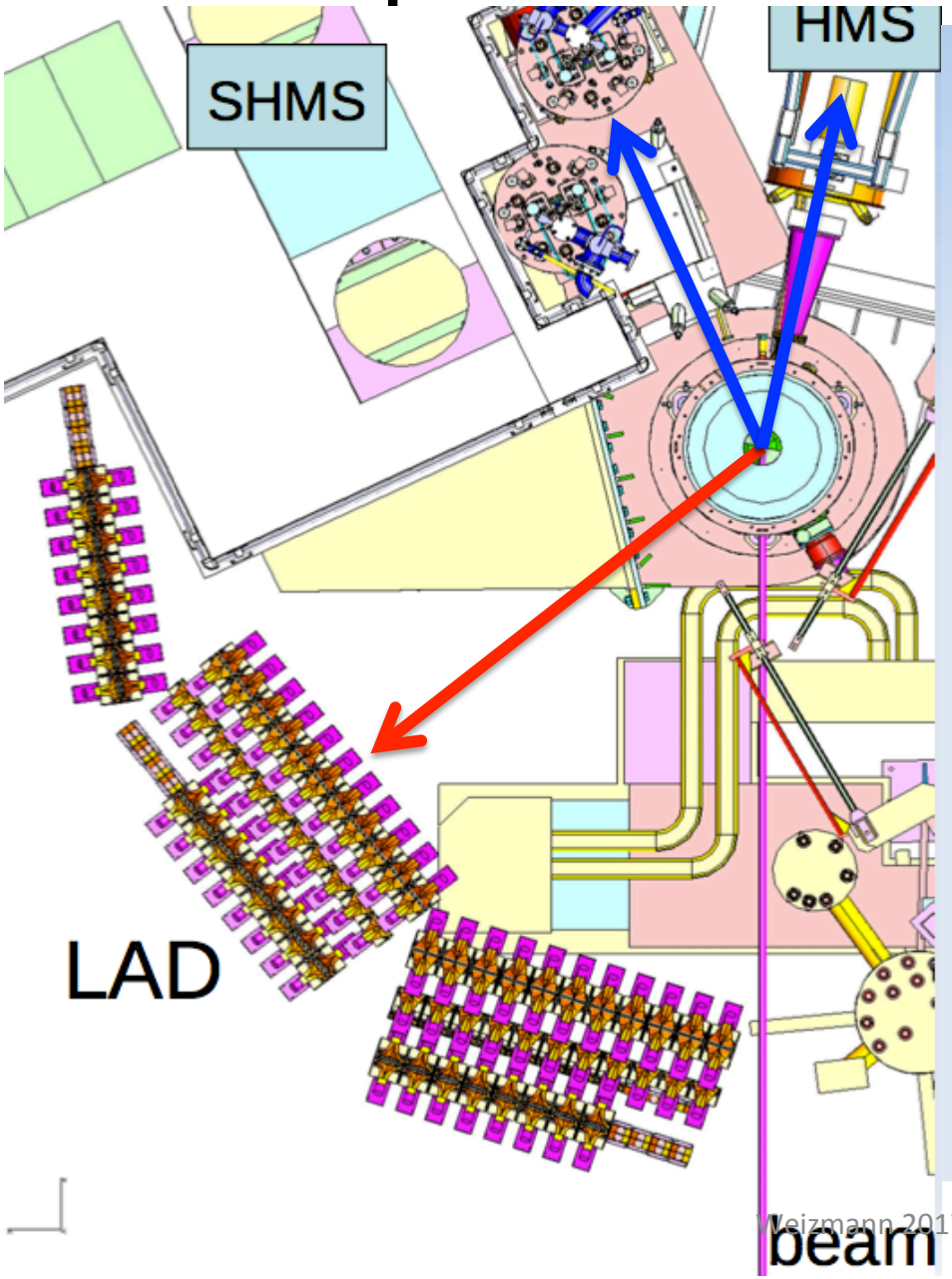
Central values of kinematics

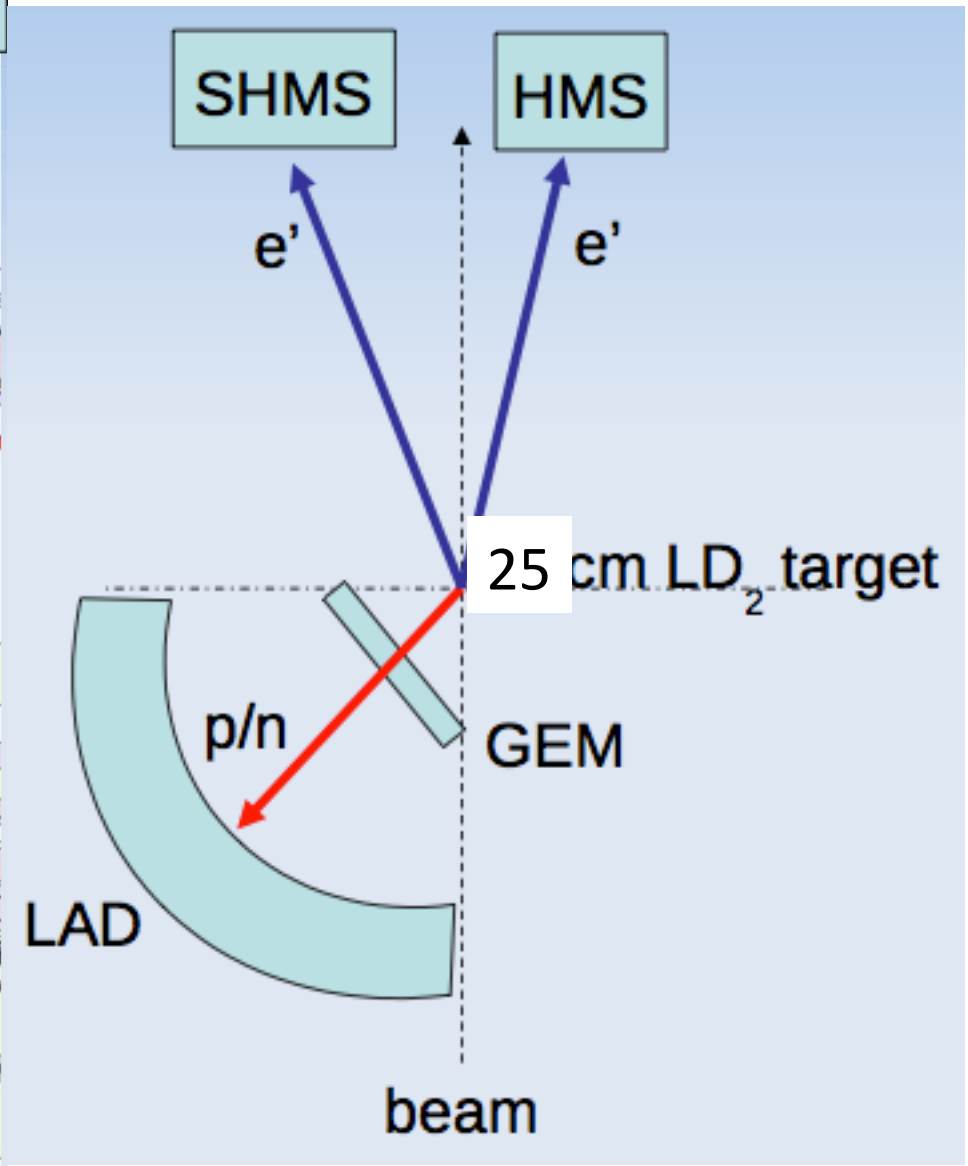
Low *x*'	High *x*'
$E_{in} = 10.9$ GeV	$E_{in} = 10.9$ GeV
$E' = 4.4$ GeV	$E' = 4.4$ GeV
$\theta_e = 13.5^o$	$\theta_e = -17^0$
$Q^2 = 2.65$ GeV^2	$Q^2 = 4.19$ GeV^2
$\lvert\vec{q}\rvert = 6.7$ GeV/c	$\lvert\vec{q}\rvert = 6.8$ GeV/c
$\theta_q = -8.8^0$	$\theta_q = 10.8^0$
$x = 0.217$	$x = 0.34$



Collect both LAD-HMS and LAD-SHMS coincidences

Experimental Set Up – Hall C

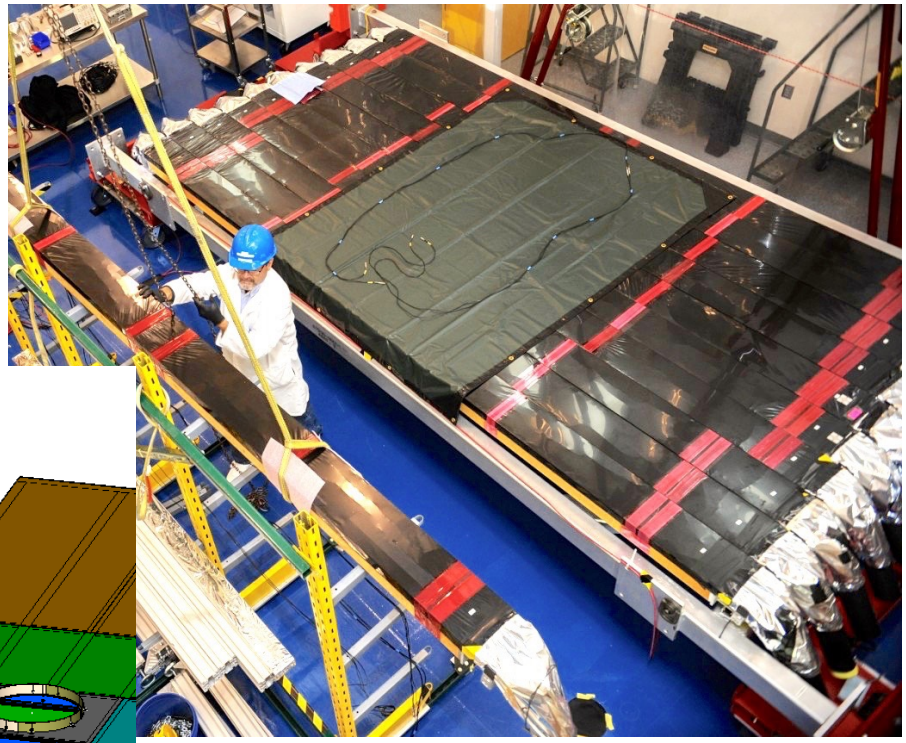


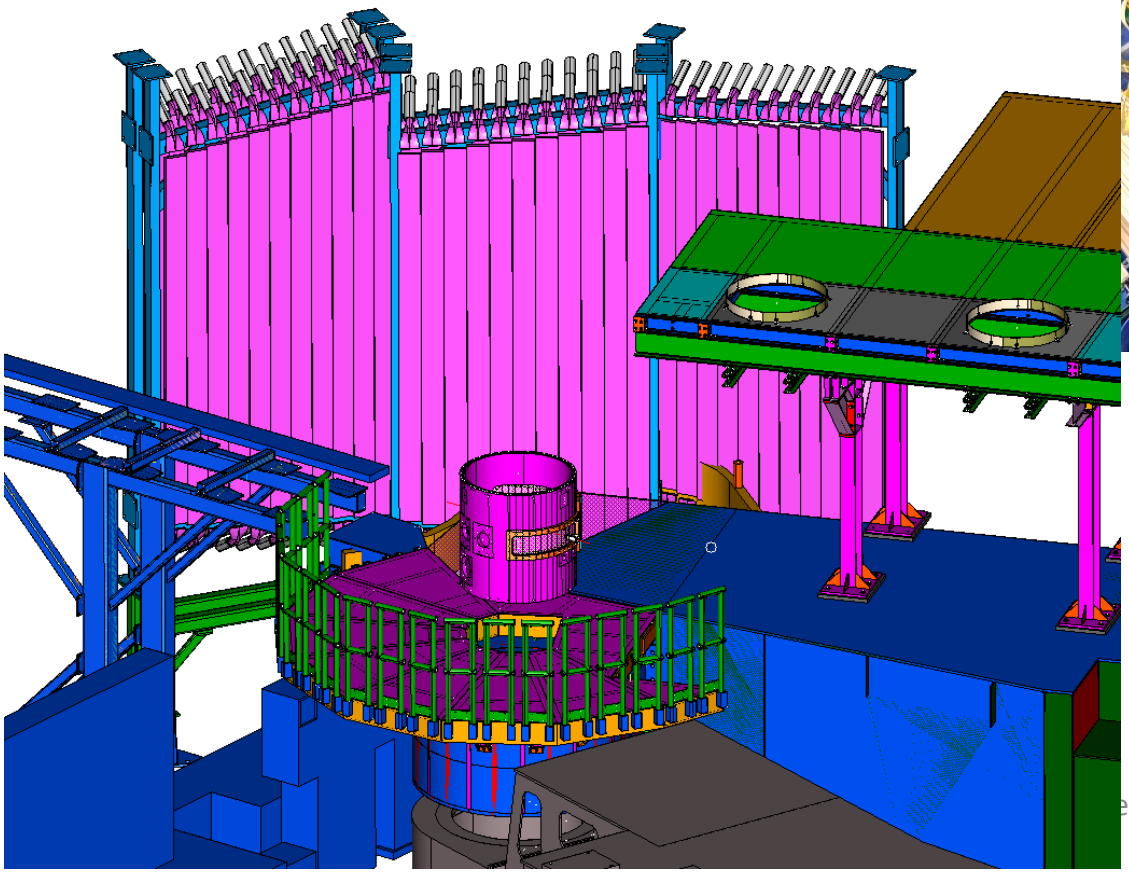


Large Acceptance Detector (LAD)

Refurbished retired CLAS6 TOF counters:

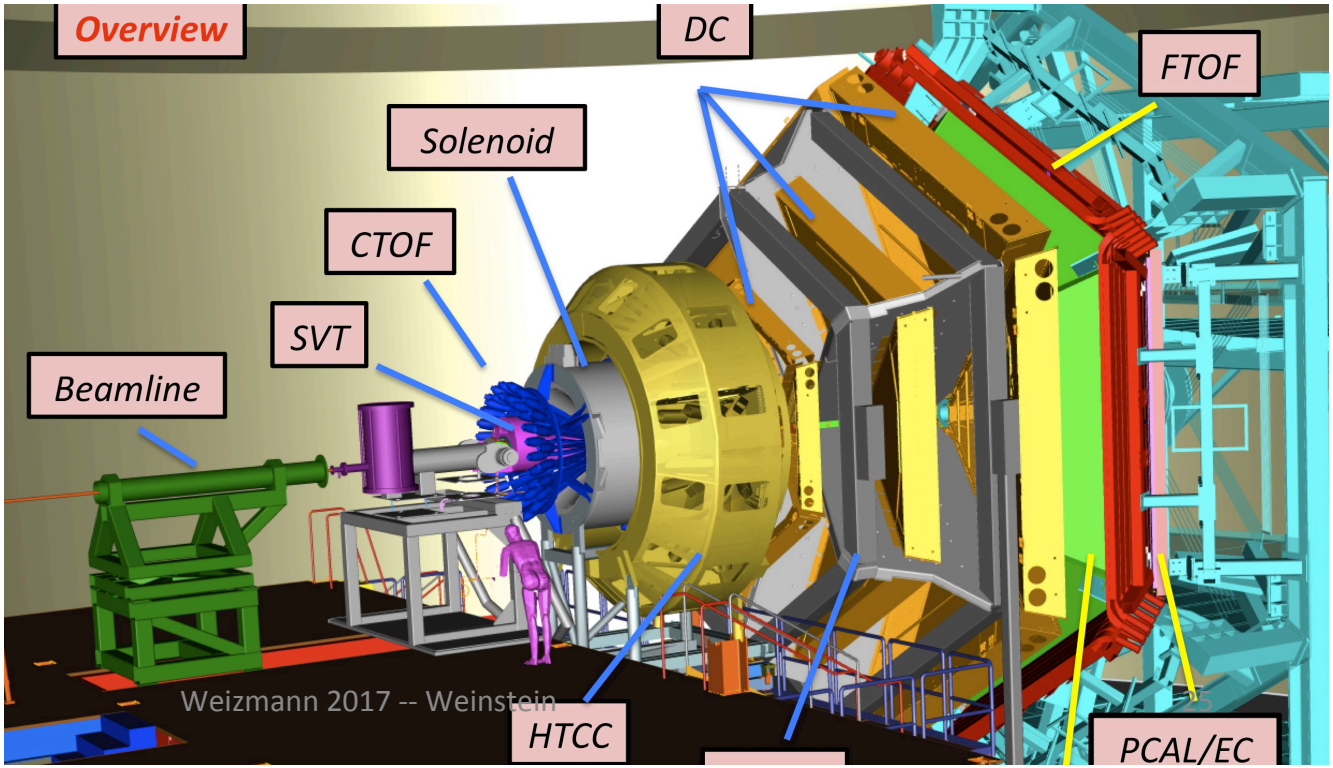
- 5 panels, 55 counters
- ~4-m×22-cm×5-cm per counter
- ~5 m from target





CLAS12 + Backward Angle Neutron Detector (BAND)

CLAS12



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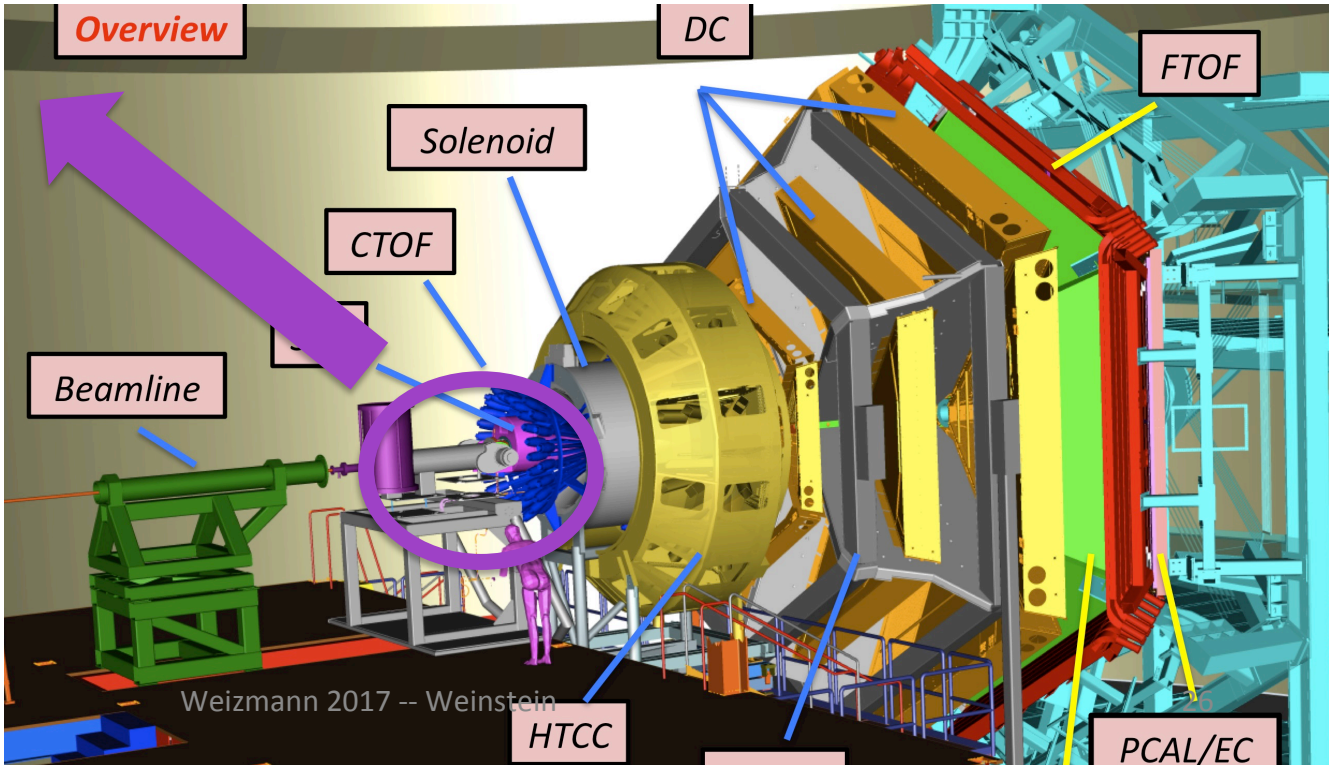
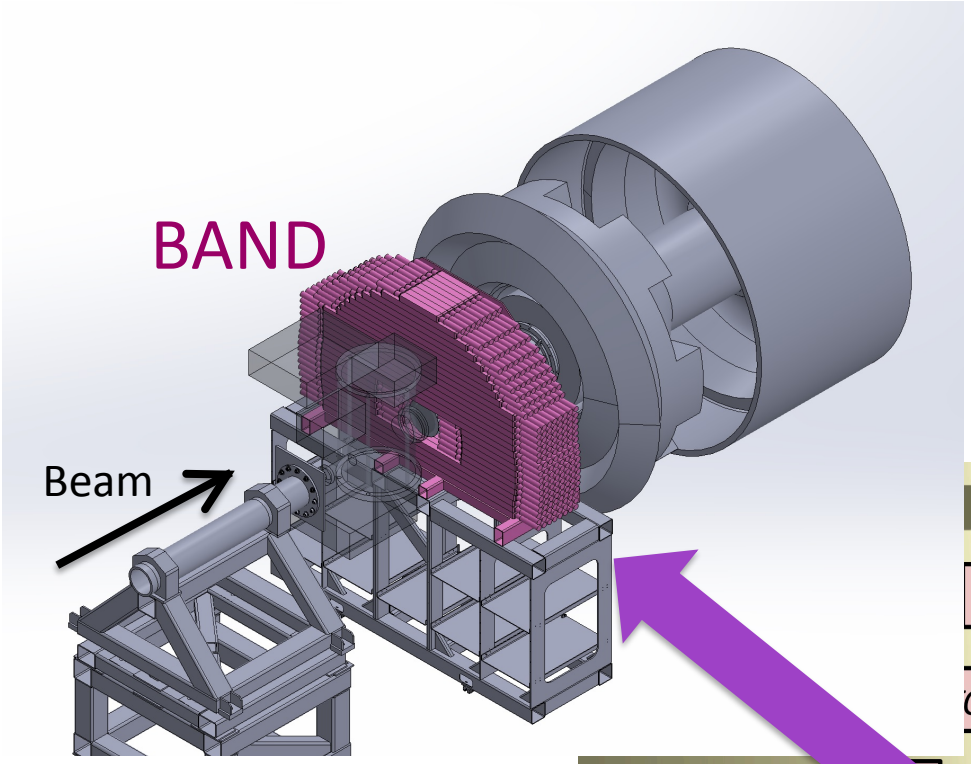
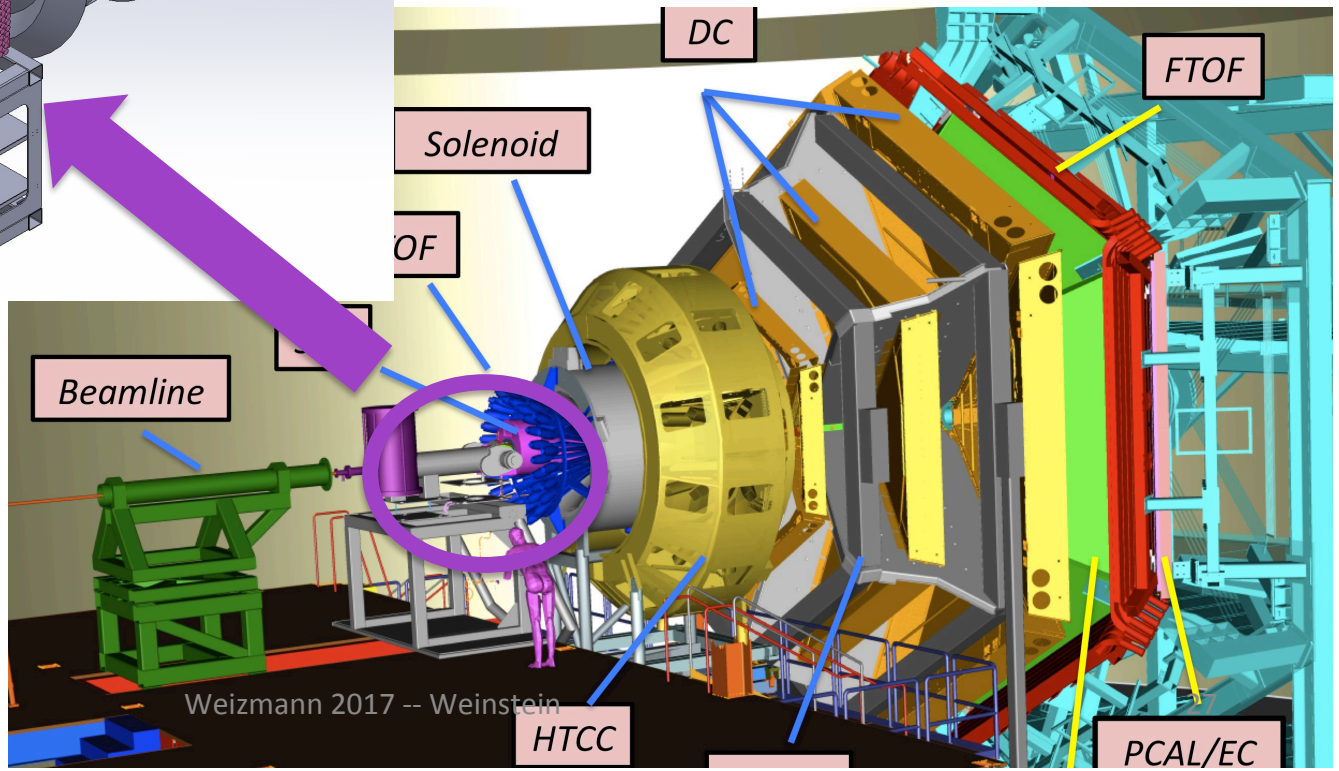
CLAS12



CLAS12 + Backward Angle Neutron Detector (BAND)

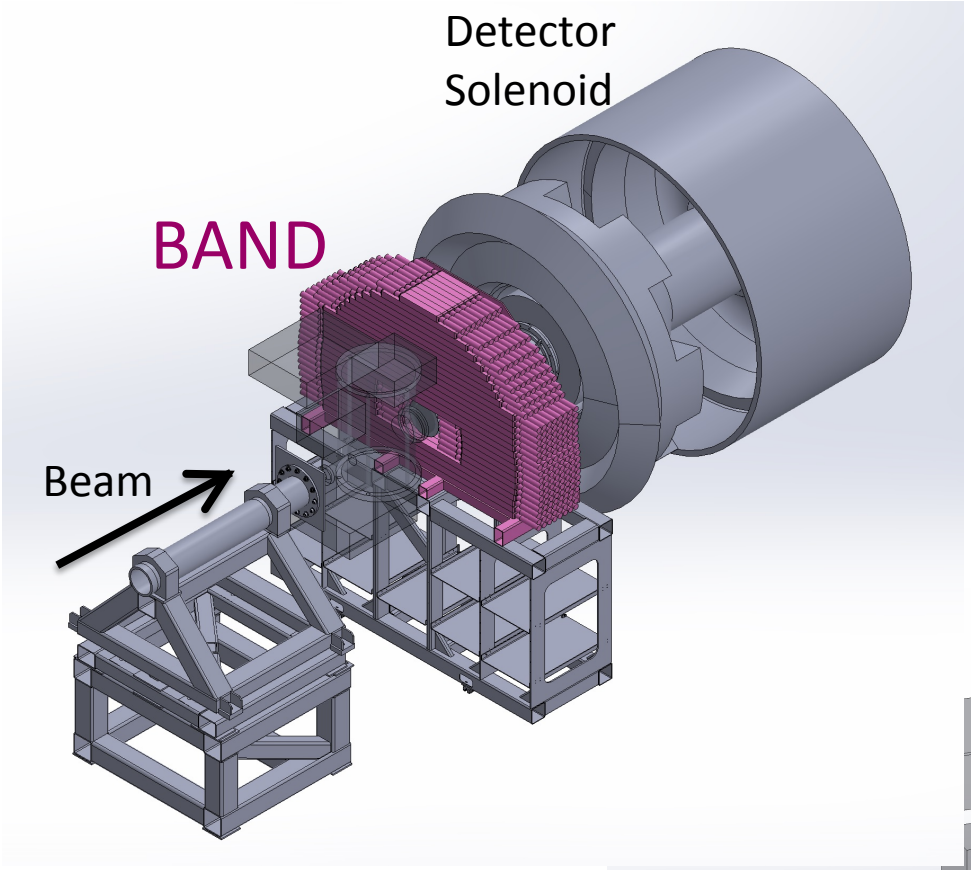


CLAS12



BAND engineering by
Inaki Vega,
UTFSM, Valparaiso, Chile

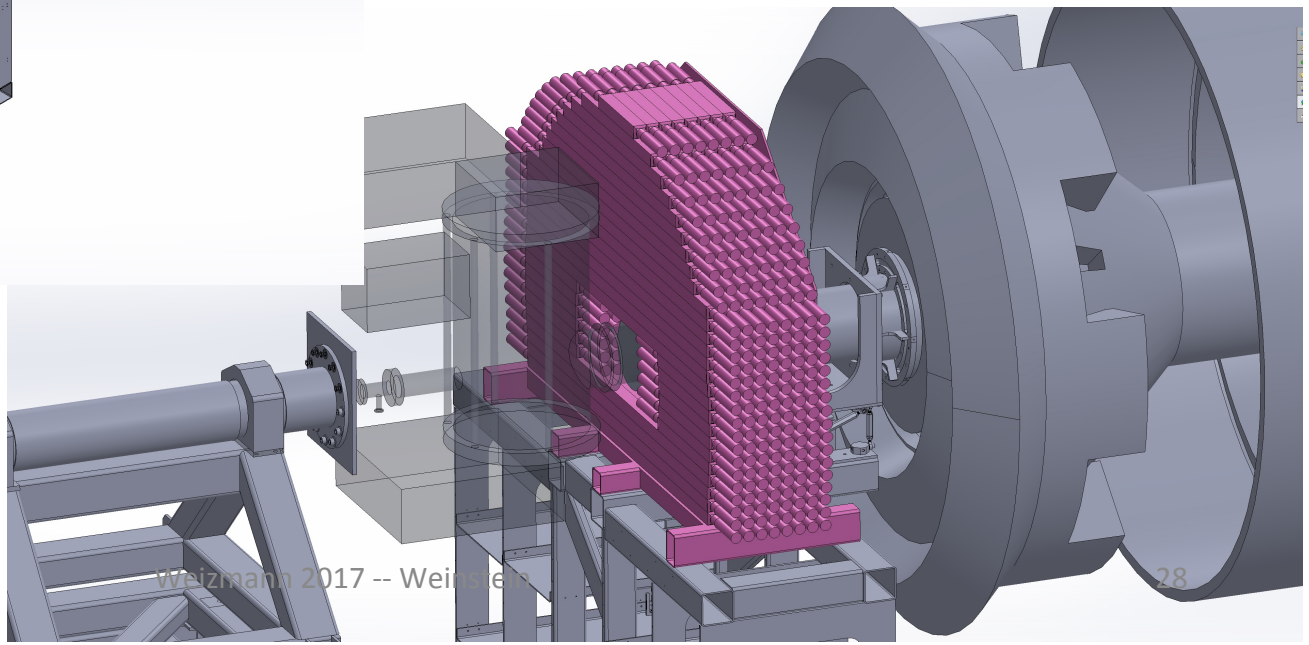
CLAS12 + Backward Angle Neutron Detector (BAND)



BAND:

- $160^o < \theta_n < 170^o$
- 2.5 m from target
- Five 7-cm layers of scintillant
  - 35 cm thick
- 20 rows, 250 PMTs

Mounted upstream of CLAS12

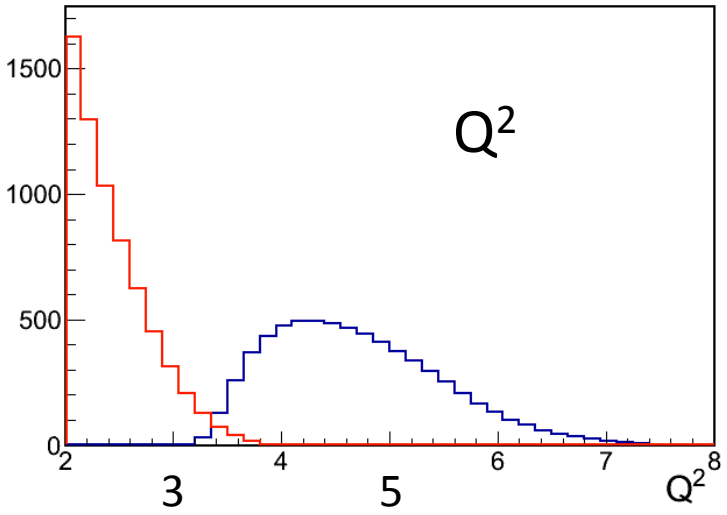


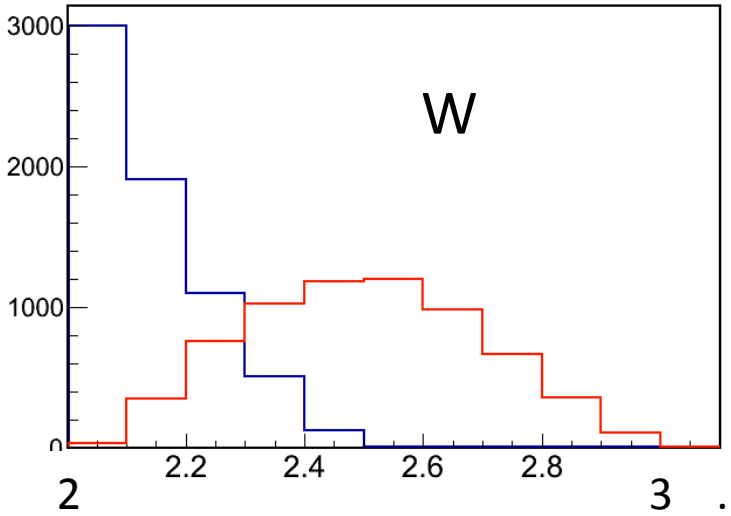
Engineering by Inaki Vega, UTFSM, Valparaiso, Chile

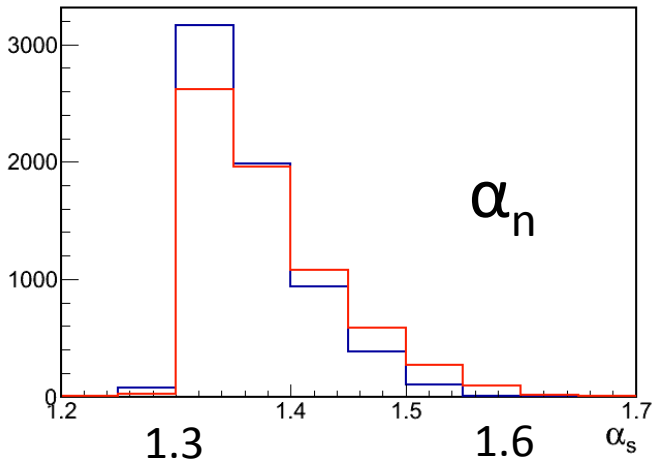
Deuteron (e,e'n_s) Kinematics

E_0 = 11 GeV
Q^2 > 2 GeV^2
W' > 2 GeV

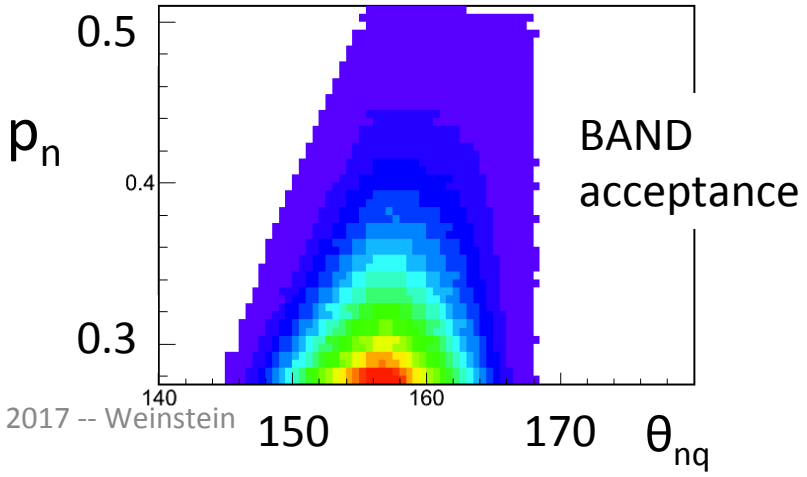
Measure cross section ratio
- for 0.5 < x' to 0.25 < x' < 0.35
- as a function of p_n or α_n





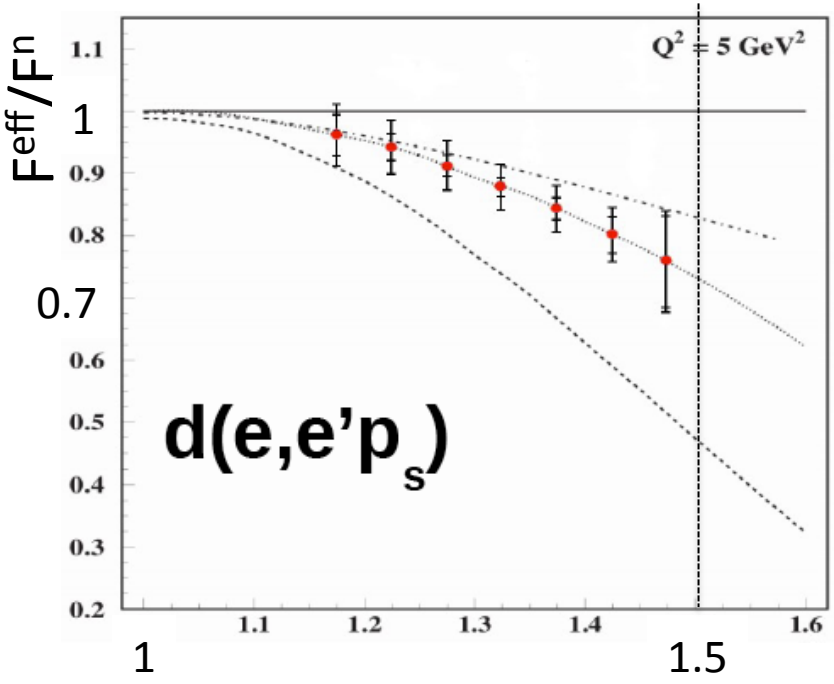


α_n

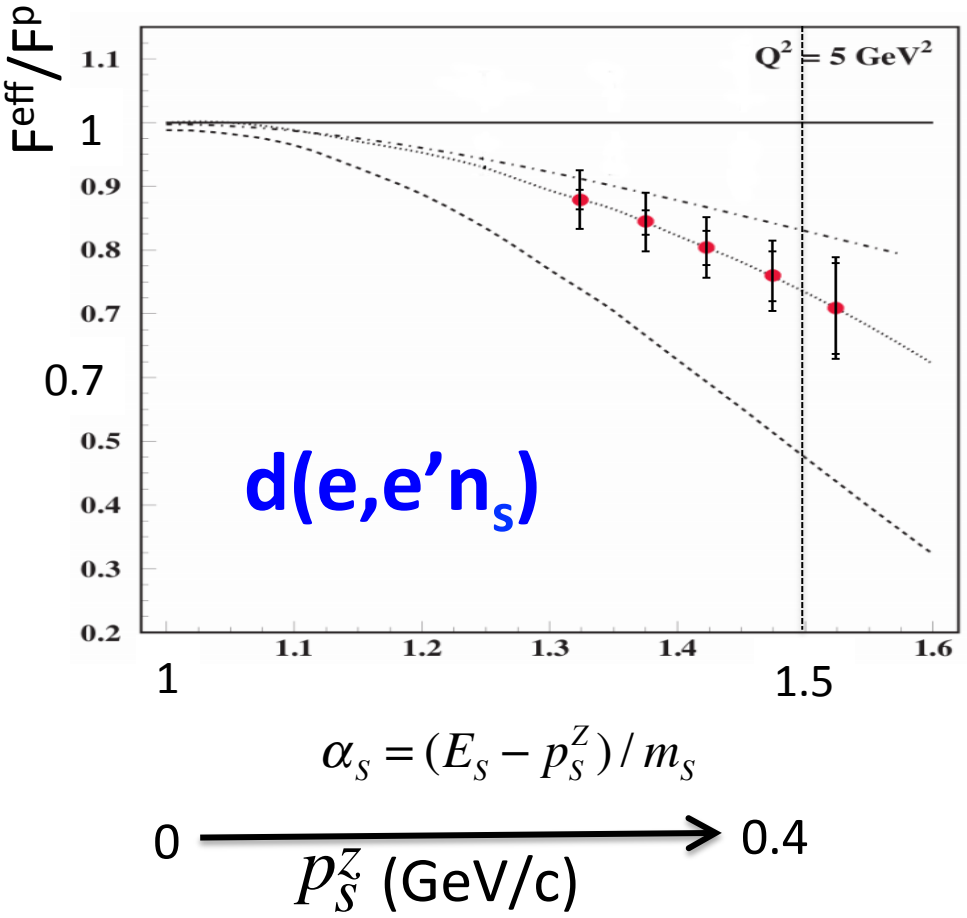


Expected Results

Hall C + LAD



CLAS12 + BAND



(results for 75 days beam time at $L = 10^{35}$)

Summary: Measuring Nucleon Medium Modification

Physics:

- EMC effect strongly implies that bound nucleons are modified
- SRC and EMC are linearly correlated
- Both phenomena are likely related to high-momentum nucleons

Elastic formfactors: $A(\vec{e},e'\vec{p})$ Some evidence for modification

Structure functions: Measure d(e,e'n_s) and d(e,e'p_s) at JLab

- Directly measure the proton and neutron structure functions in the nuclear medium as a function of momentum (virtuality)

- Which nucleons are modified in the nucleus?
- Can this explain the EMC effect?
- How is this related to short range correlations?