Inclusive DIS, SIDIS, and Accessing Nuclear Pions with TDIS

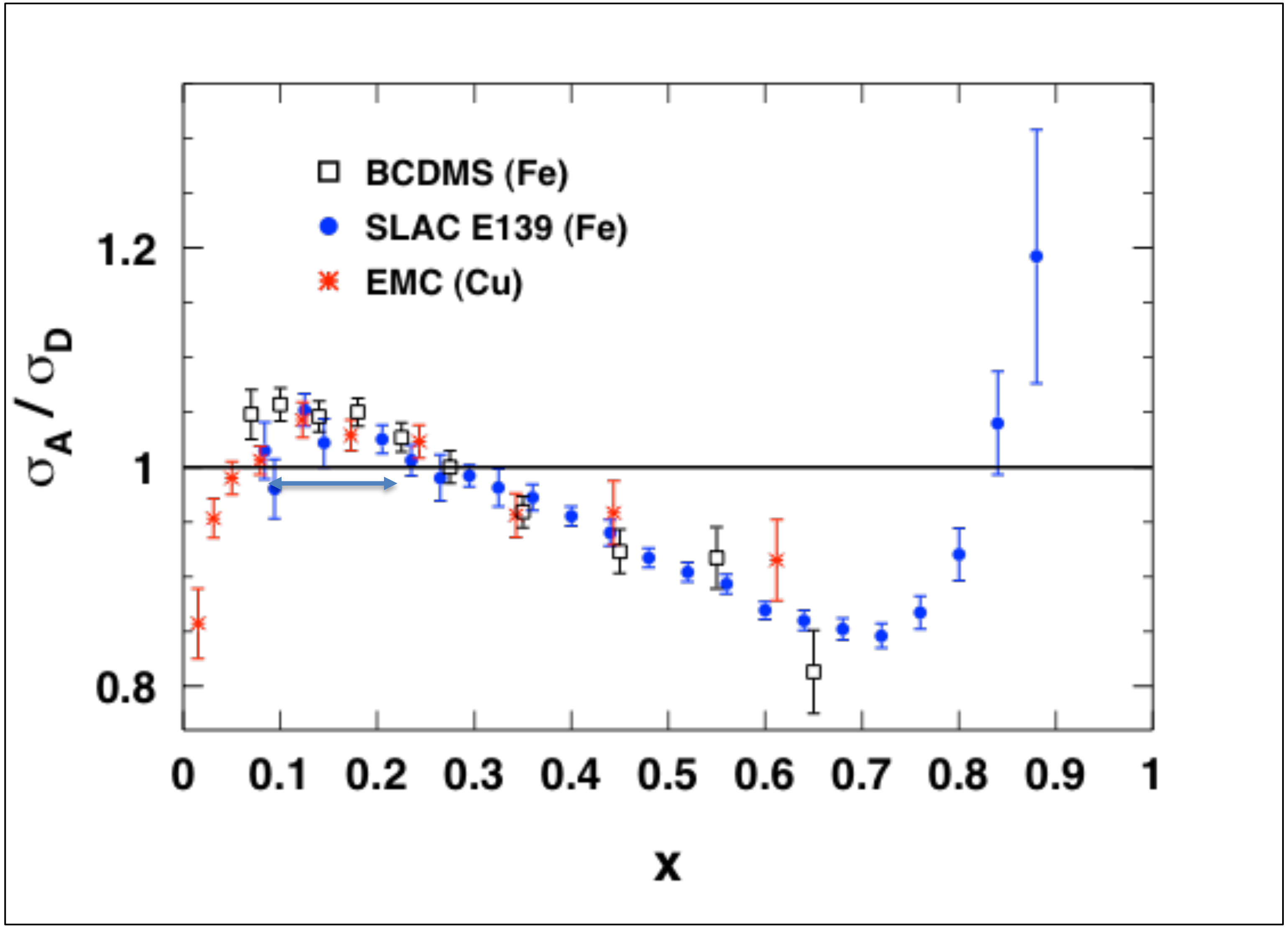
Dave Gaskell (JLab) and Dipangkar Dutta (MSU)

Science at Mid-x: Anti-Shadowing and the Role of the Sea

July 22-23, 2022

Anti-Shadowing in Inclusive DIS

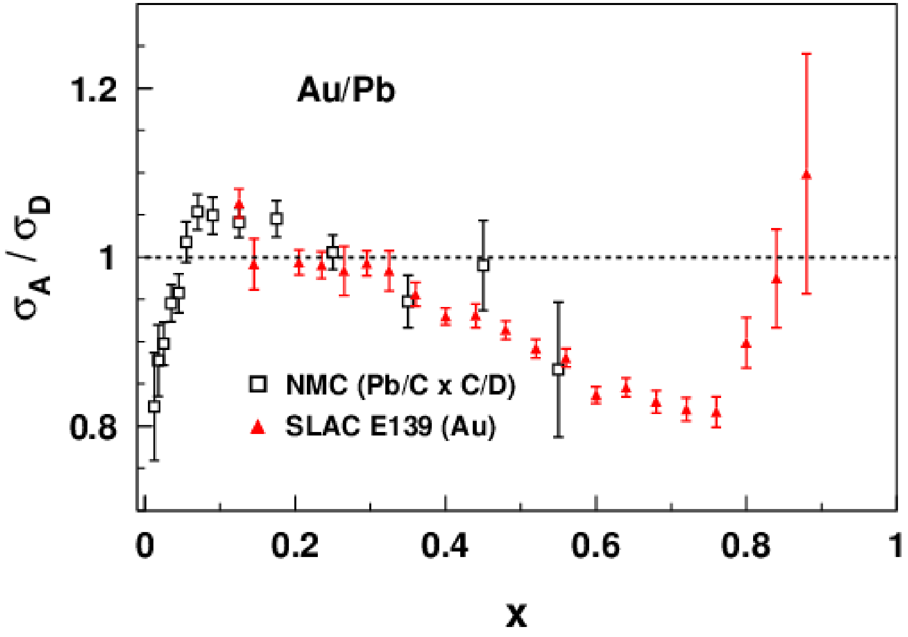
Anti-shadowing data/measurements from unseparated cross sections
→ Can we improve precision/reach for σ_A/σ_D?
→ Is it the same for σ_T and σ_L?

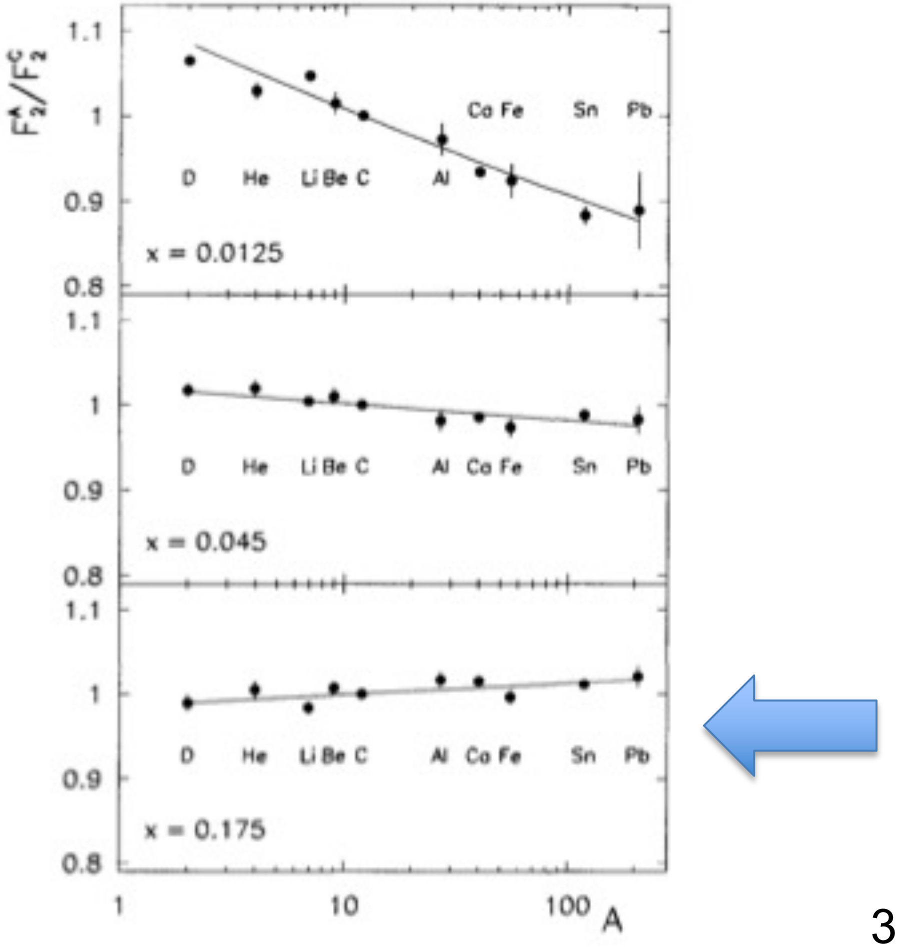


Inclusive Ratios

Anti-shadowing small effect (~few %) → normalization uncertainties crucial
→ At JLab, normalization uncertainties for A/D ratios typically ~1.5%
→ Could be improved with extra effort (improved solid target thickness measurements, etc.), but difficult to overcome uncertainty in cryotarget thickness

NMC measurements achieved ultimate precision to-date
→ A/D: Normalization uncertainty = 0.4%
→ C/D: Normalization uncertainty = 0.2%

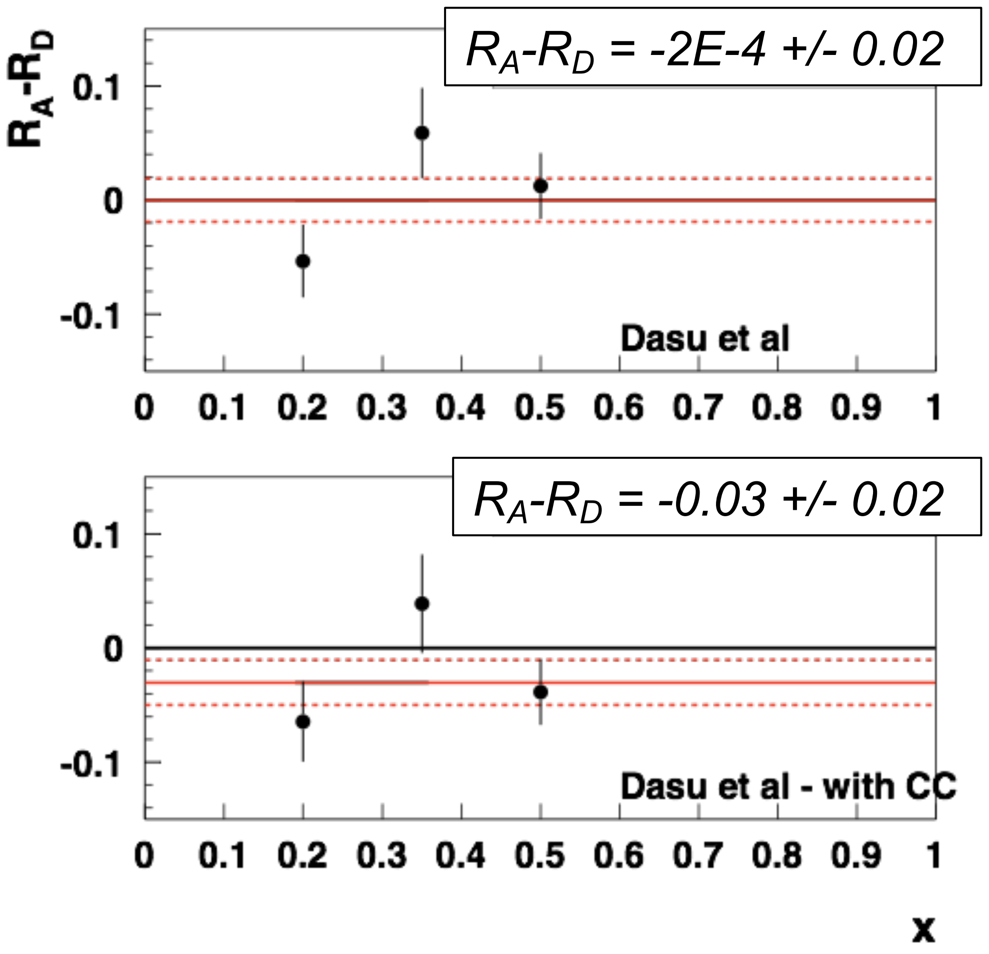




Nuclear Dependence of R?

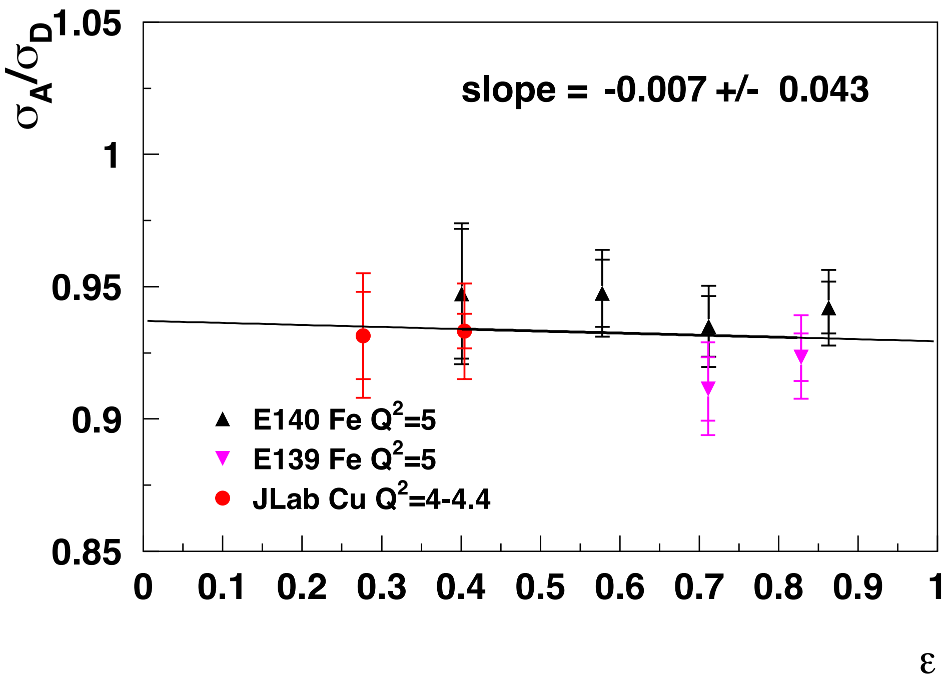
Few direct measurements of R_A-R_D at any x, much less in anti-shadowing region

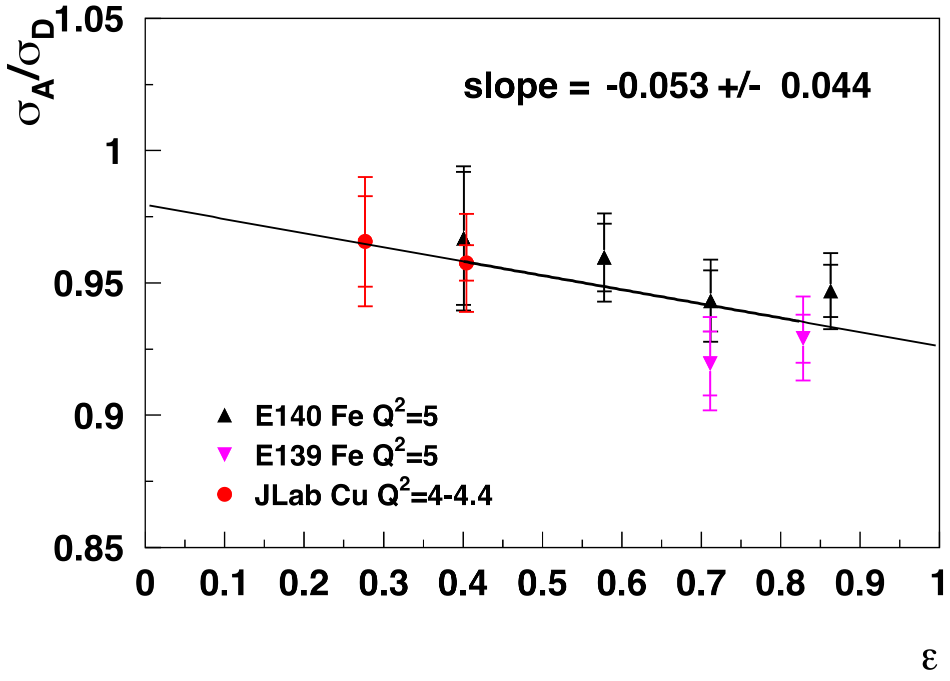
E140 made measurements from Fe and Au at x=0.2, 0.35 0.5
→ Original results consistent with no nuclear dependence
→ When re-analyzed to include Coulomb Corrections, some hint of non-zero R_A-R_D



Nuclear Dependence of R at large x

x=0.5 Q^2=5 GeV^2

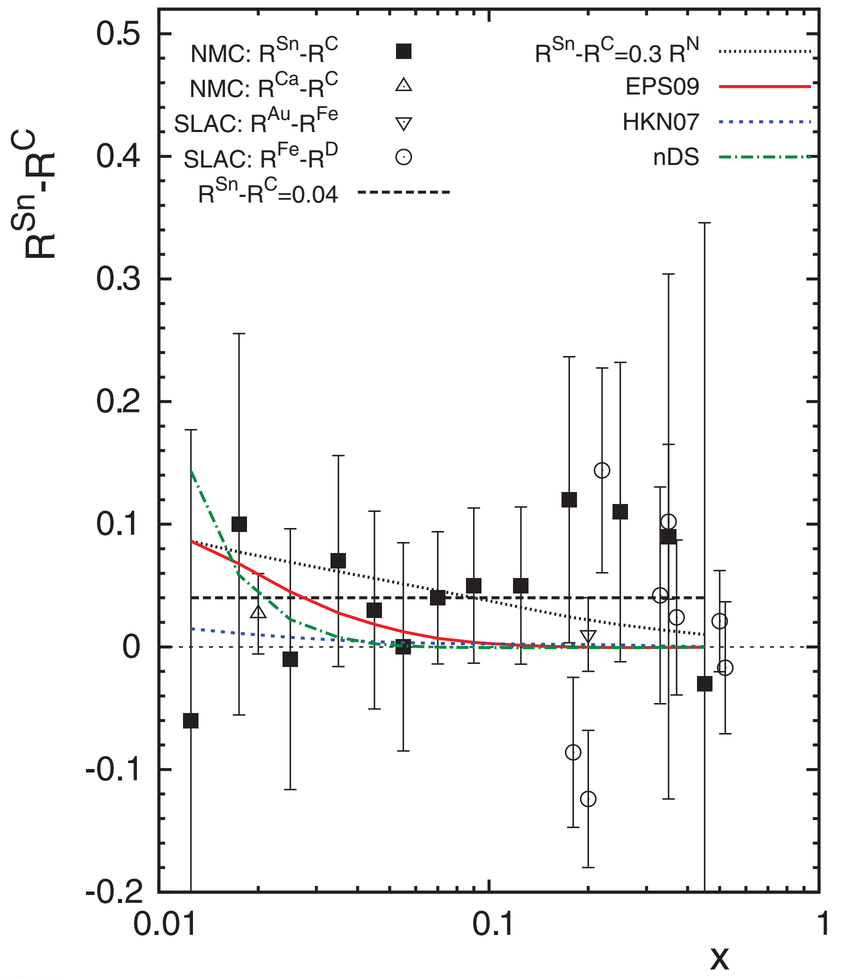




Combined analysis of E140, E139, and JLab Hall C data suggests non-zero R_A-R_D at x=0.5

Other Hints of non-zero R_A-R_D

NMC results for R_{Sn}-R_C systematically larger than zero

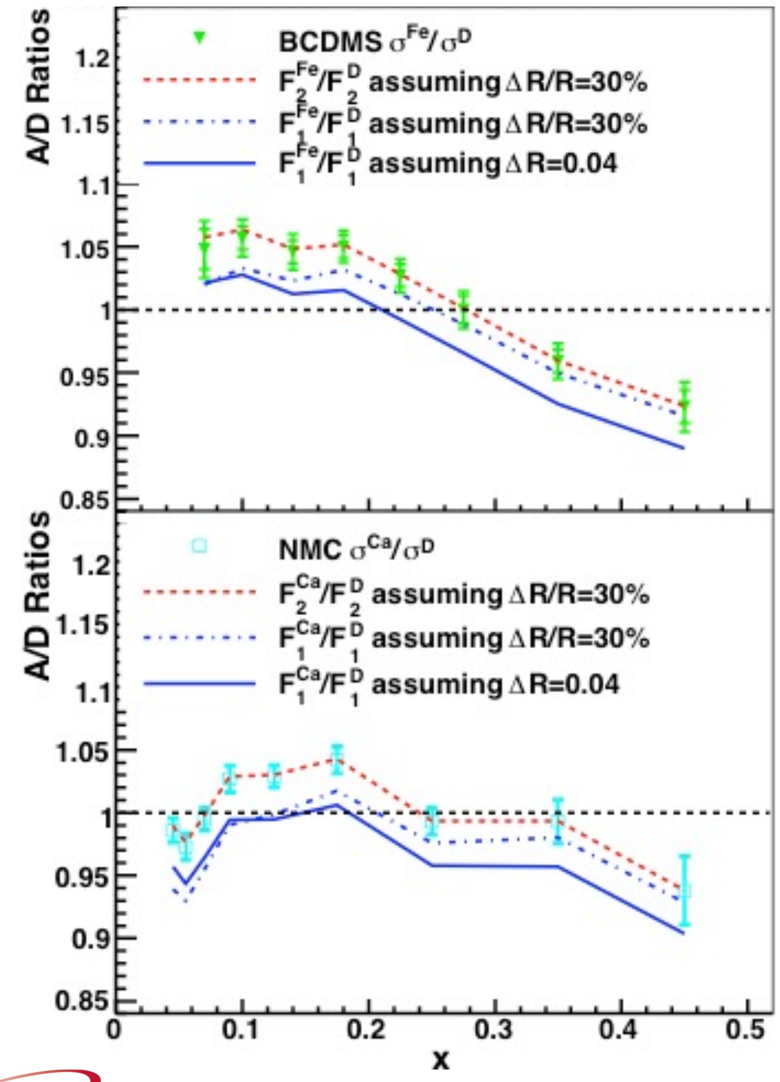


$R_{Sn} - R_C$ = 0.040 +/- 0.026 (stat) +/- 0.020 (sys)

→Averaged over x=0.0125 – 0.45
→$\langle Q^2 \rangle$ = 10 GeV^2

What are the consequences for A/D ratios for F_1 and F_2 if this is true?

Consequences of R_A-R_D >0

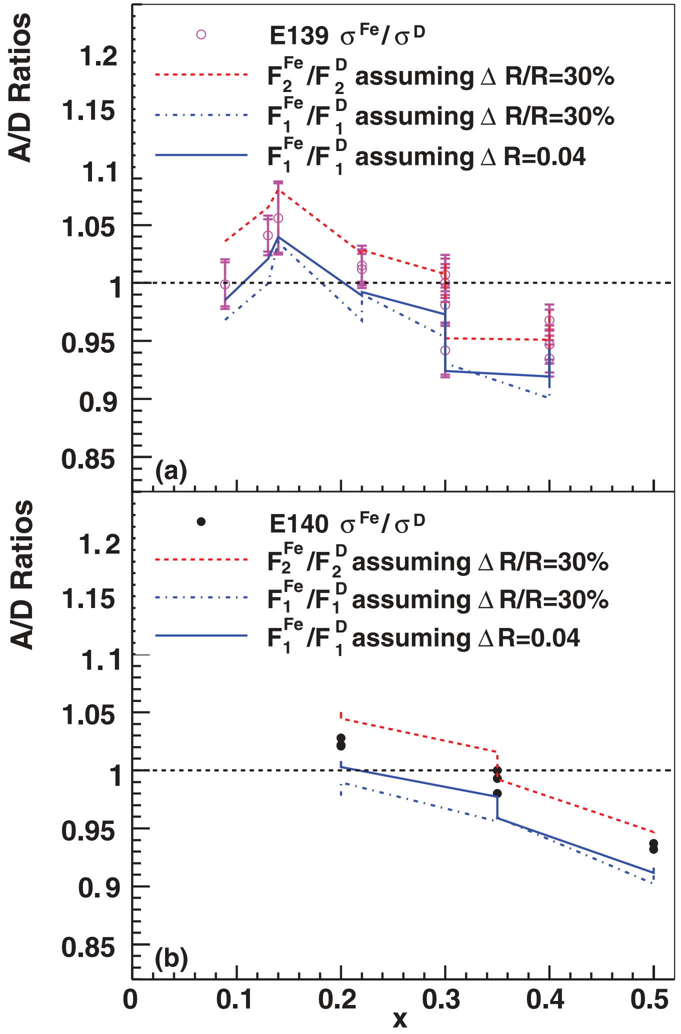


$$\frac{\sigma_A}{\sigma_D} = \frac{F_1^A(x)}{F_1^D(x)}\left[1 + \frac{\epsilon(R_A - R_D)}{1 + \epsilon R_D}\right]$$

F_1 ratio purely transverse

Anti-shadowing disappears for F_1 ratio, remains for F_2

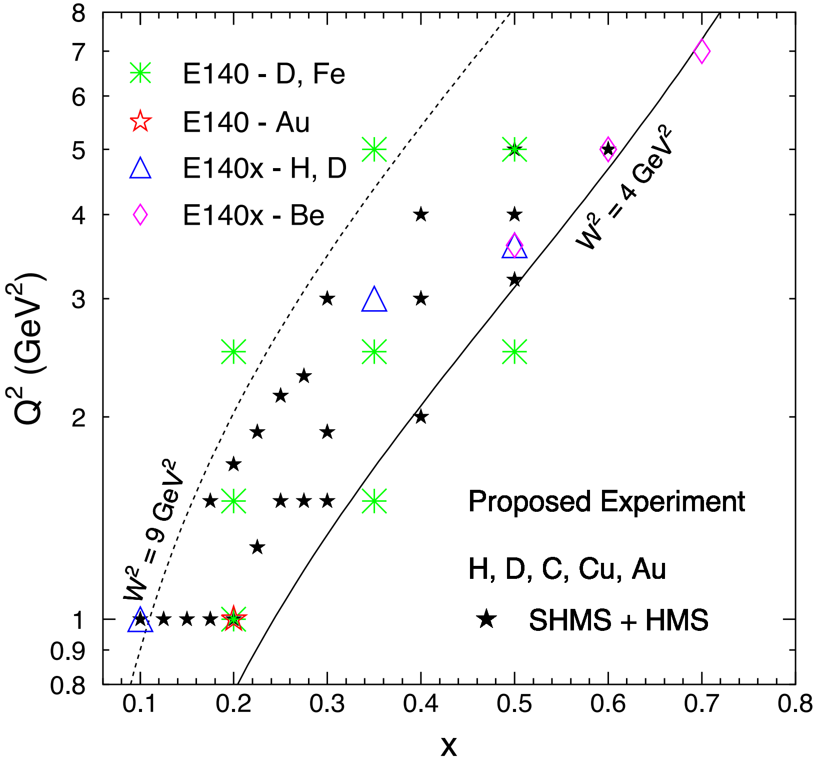
Anti-shadowing from longitudinal photons?

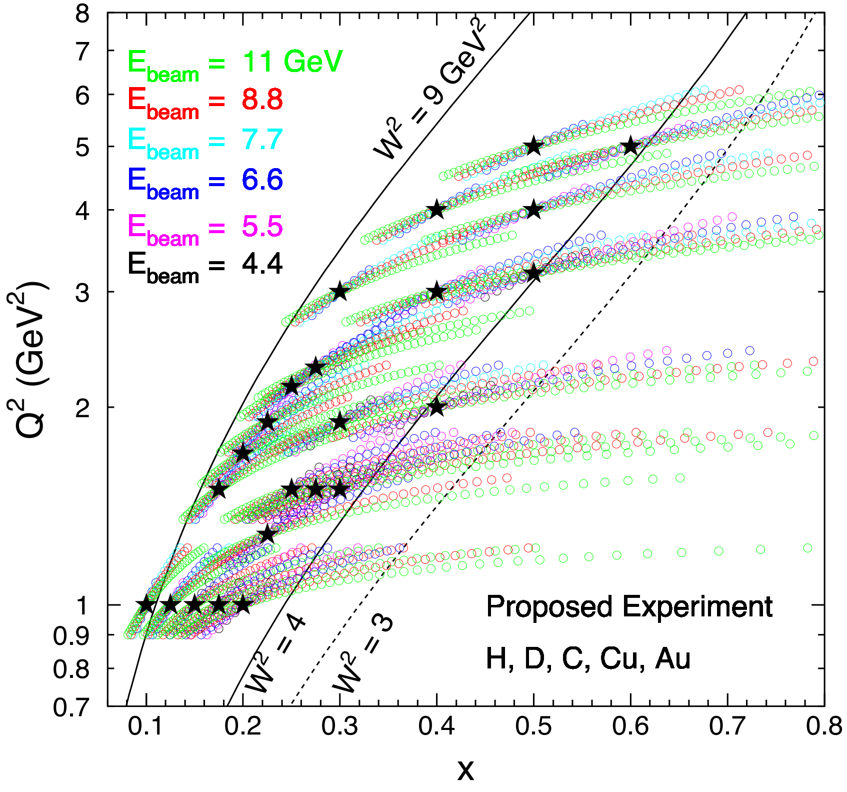


V. Guzey et al, PRC 86 045201 (2012)

E12-14-002 – Hall C @ 11 GeV

Precision Measurements and Studies of a Possible Nuclear Dependence of R
Spokespersons: S. Malace, E. Christy, DG, C. Keppel, H. Szumila-Vance

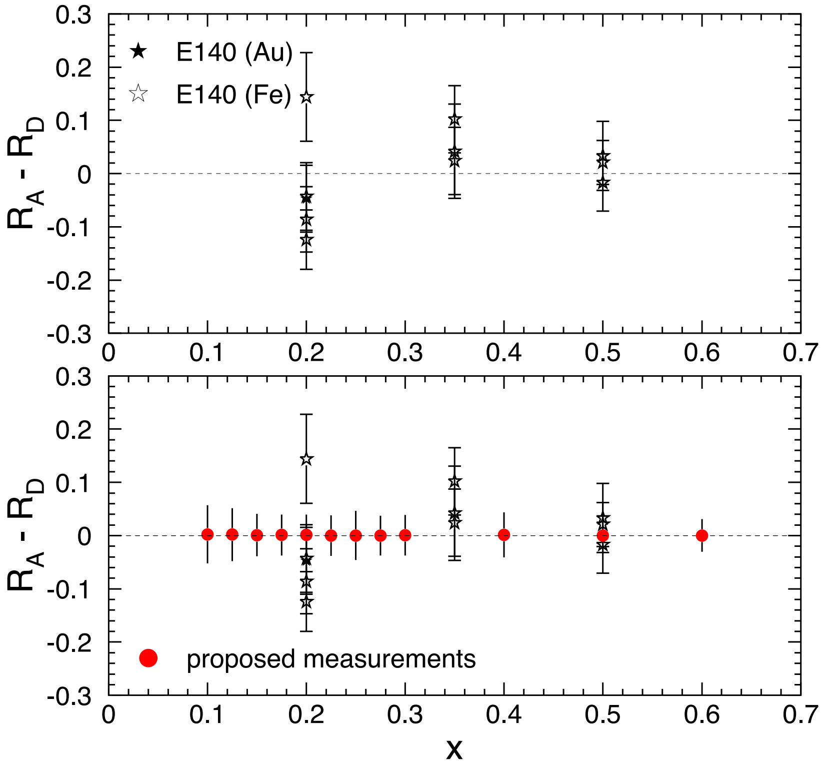


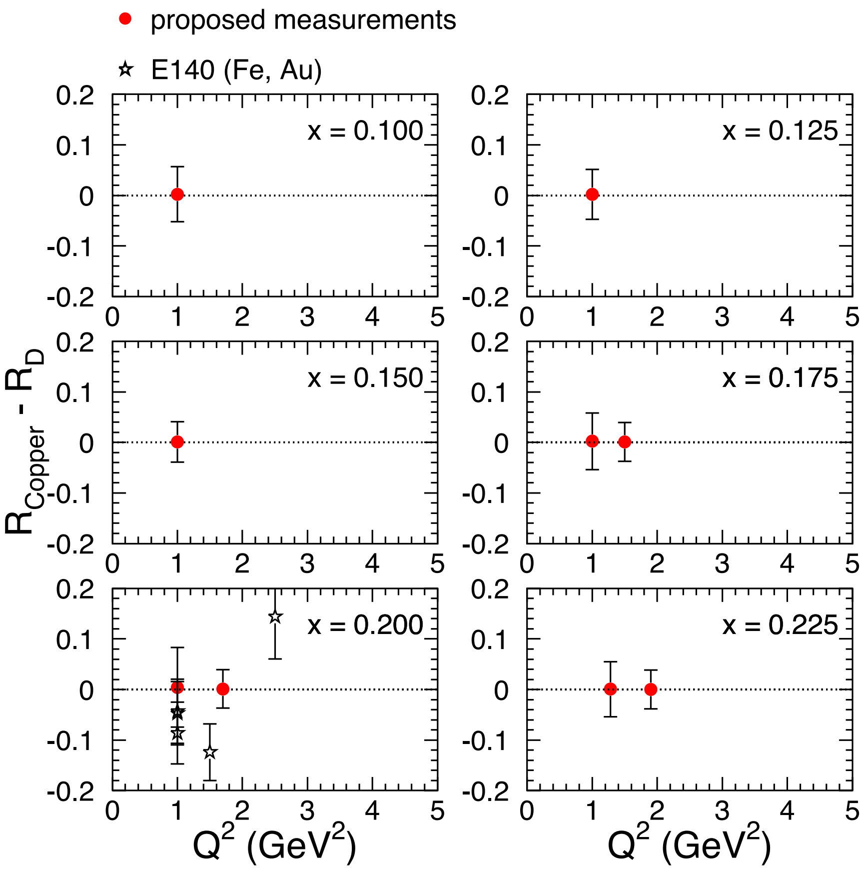


Measure R_A-R_D for C, Cu, Au for x=0.1-0.6
→ Significant overlap with E140, but more x/Q^2 settings

Jefferson Lab

E12-14-002 – Hall C @ 11 GeV

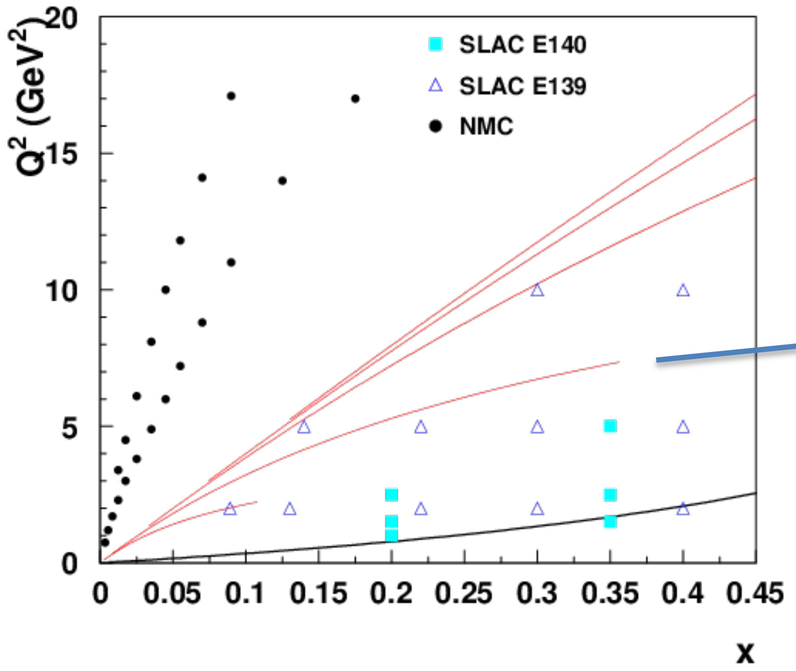


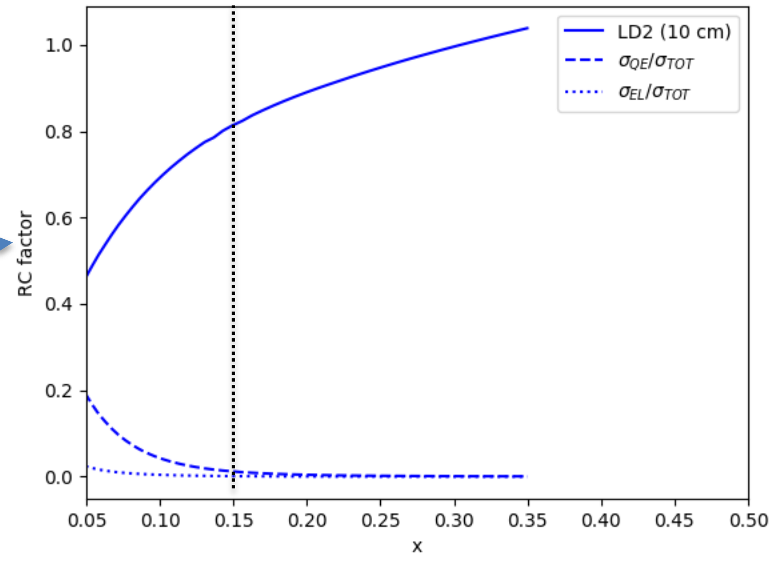


Limitations:

1. Modest Q^2 range at low x
2. Few targets (C, Cu, Au)
3. C and Au at only a subset of settings

R_A-R_D at JLab24





x=0.15: At 22 GeV, radiative corrections grow quickly for angles larger than 10 degrees

→ 22 GeV, 10 degrees → Q^2=4.36 GeV2, ε=0.57

→ 17 GeV, 23.9 degrees, ε=0.17

→ $\Delta\varepsilon$ = 0.4 → not ideal

→ Q^2=3 GeV^2 can be measured with $\Delta\varepsilon$~0.6

Other possible improvements: greater variety of targets, different N/Z, etc.

SIDIS at 24 GeV

SIDIS at higher energy discussed extensively at previous workshop
→ "The Next Generation of 3D Imaging": https://indico.jlab.org/event/539/

Experimental perspectives:

CLAS12: https://indico.jlab.org/event/539/contributions/10159/

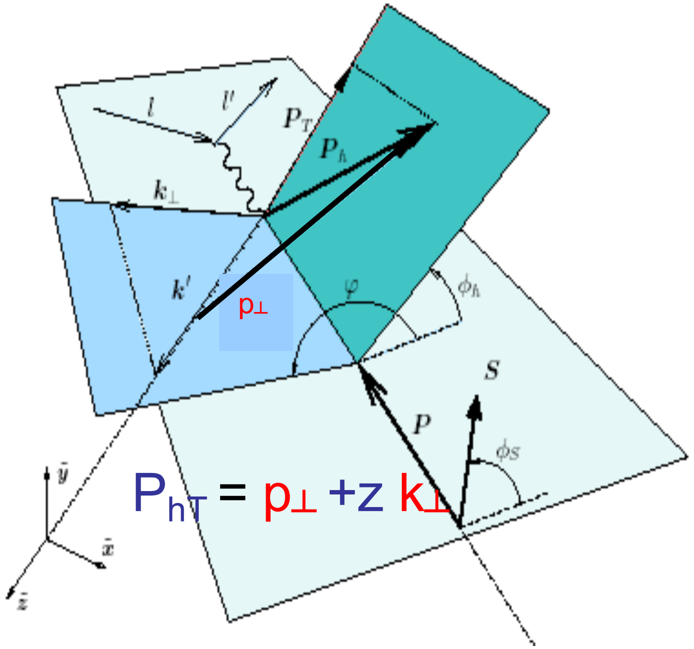
SOLID: https://indico.jlab.org/event/539/contributions/10161/

Hall C: https://indico.jlab.org/event/539/contributions/10163/

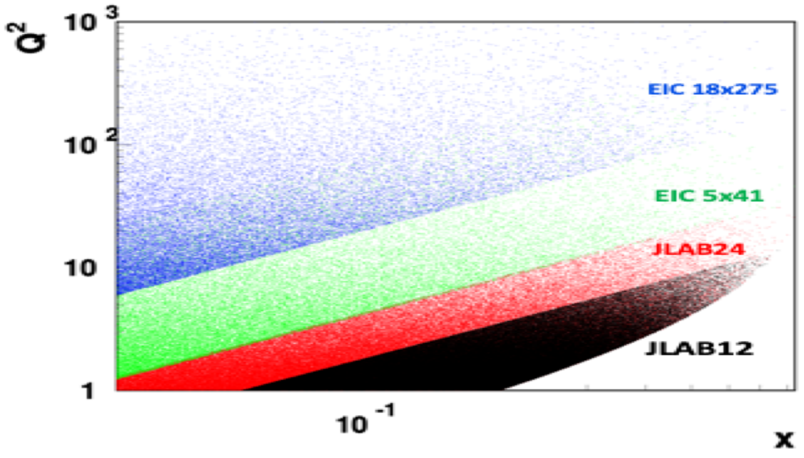
Common theme: expanded phase space coverage (larger Q^2) from mid to large x

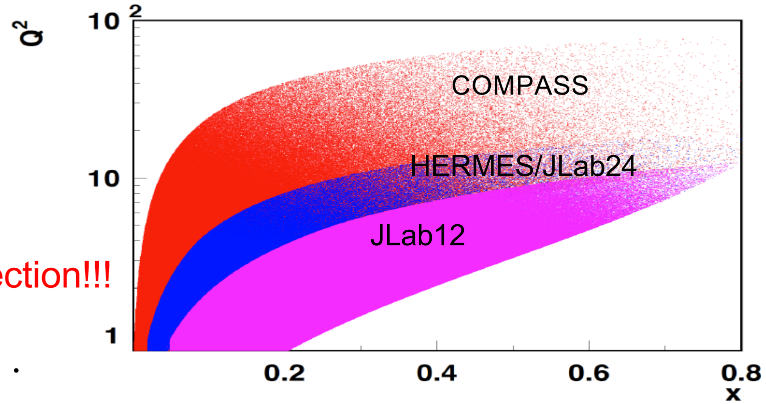
CLAS12 at higher energy: Harut Avakakian

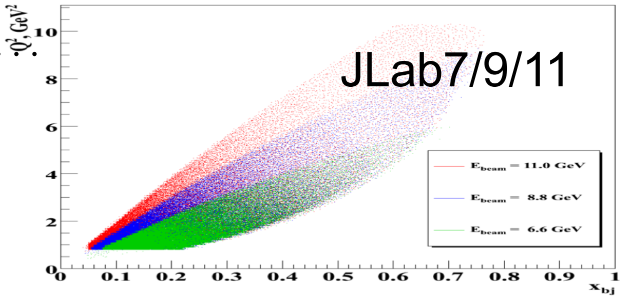
SIDIS kinematical coverage and observables



EIC







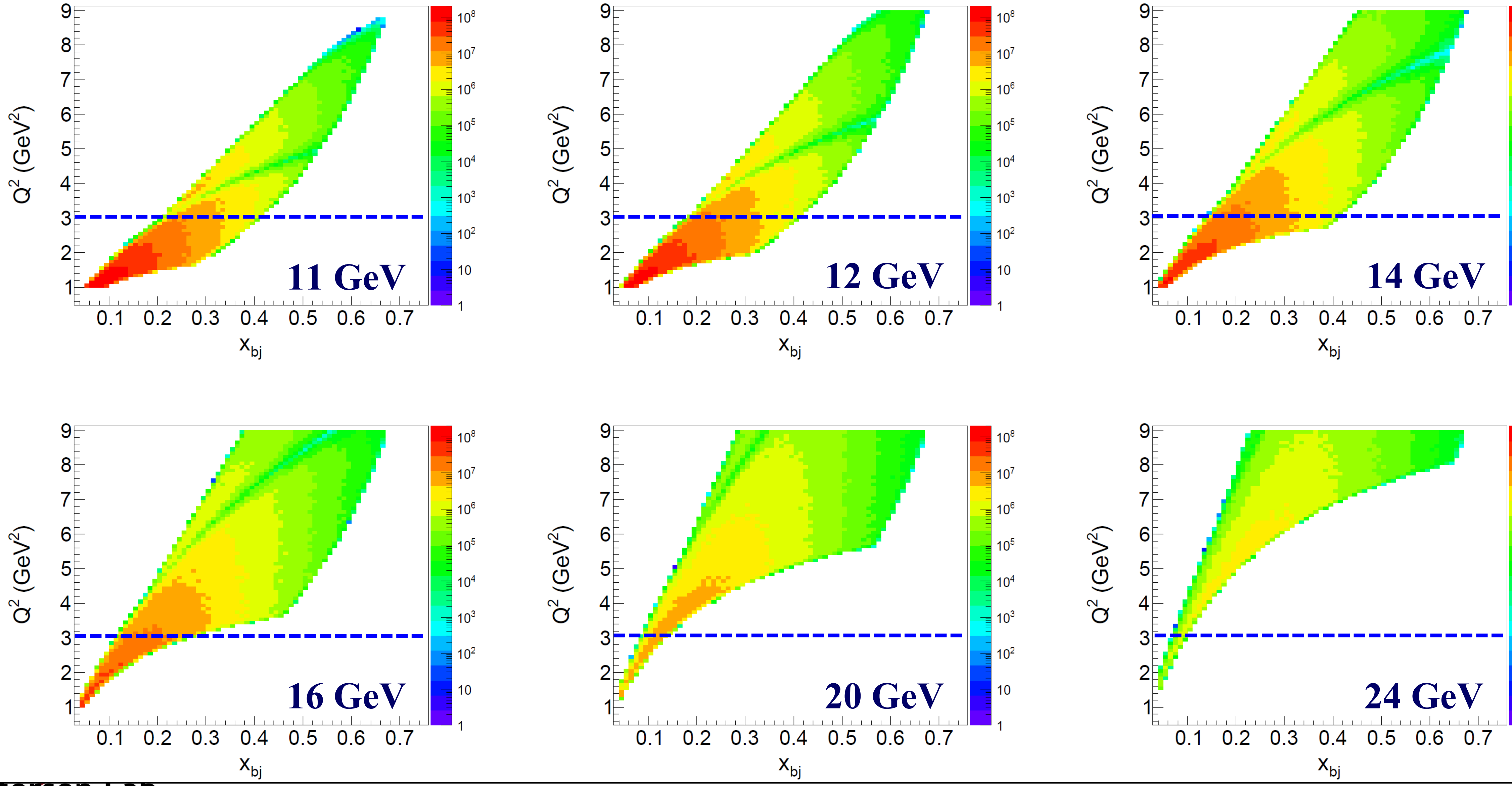
SIDIS experiments measure azimuthal dependence of the cross section!!!

$$\sigma \propto F_{UU} + P_b\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi + P_t\epsilon F_{UL}^{\sin 2\phi}\sin 2\phi + \ldots$$

$$+\epsilon F_{UU,L} + |S_\perp|[F_{UT}^{\sin\phi-\phi_S}\sin(\phi-\phi_S) + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S] + \ldots$$

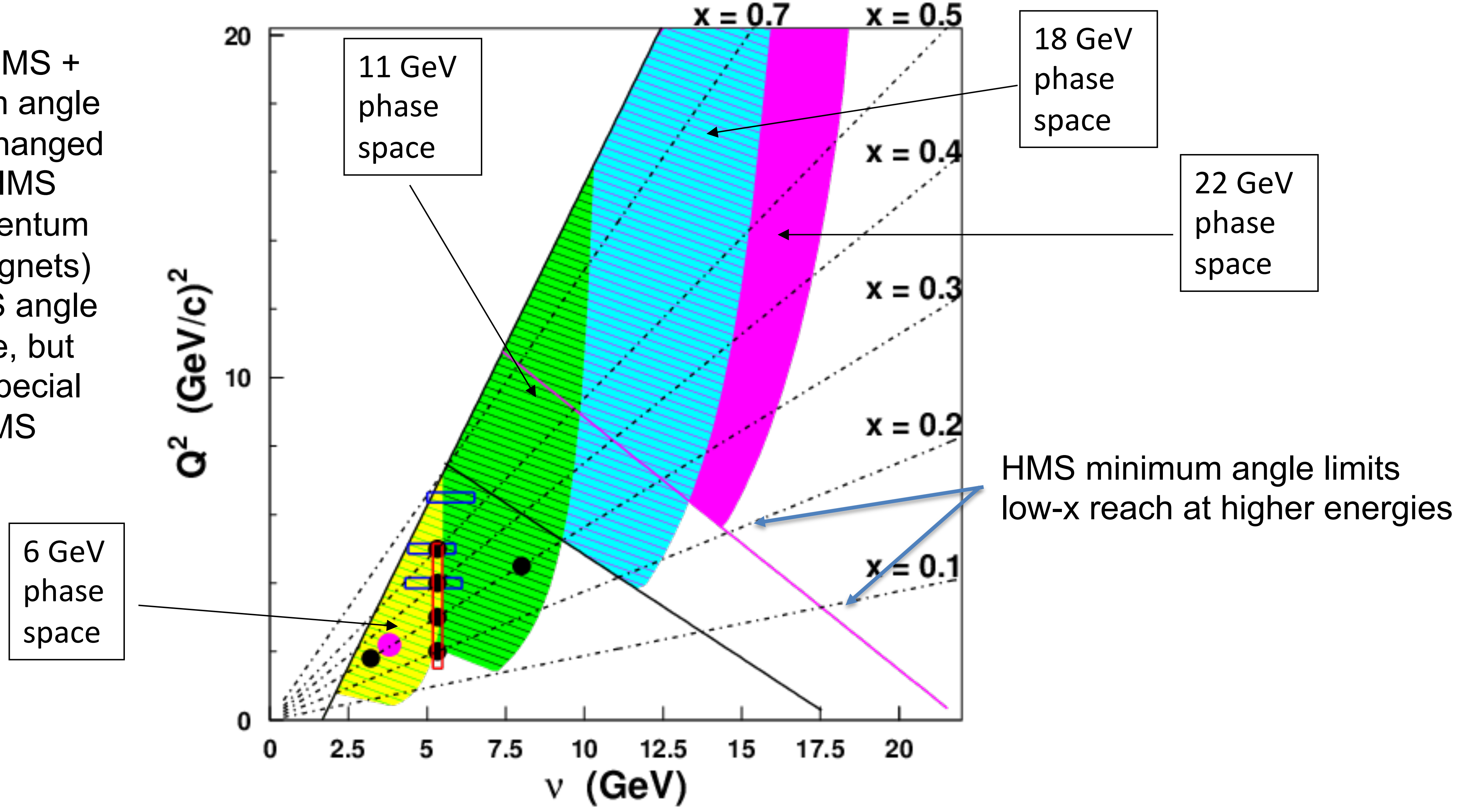
- Studies of azimuthal modulations give access to underlying 3D partonic distributions
- QCD predicts only the Q^2-dependence of 3D PDFs

Phase - space examples obtained with the ^{3}He target at various beam energies: Q^2 vs. x_{bj}

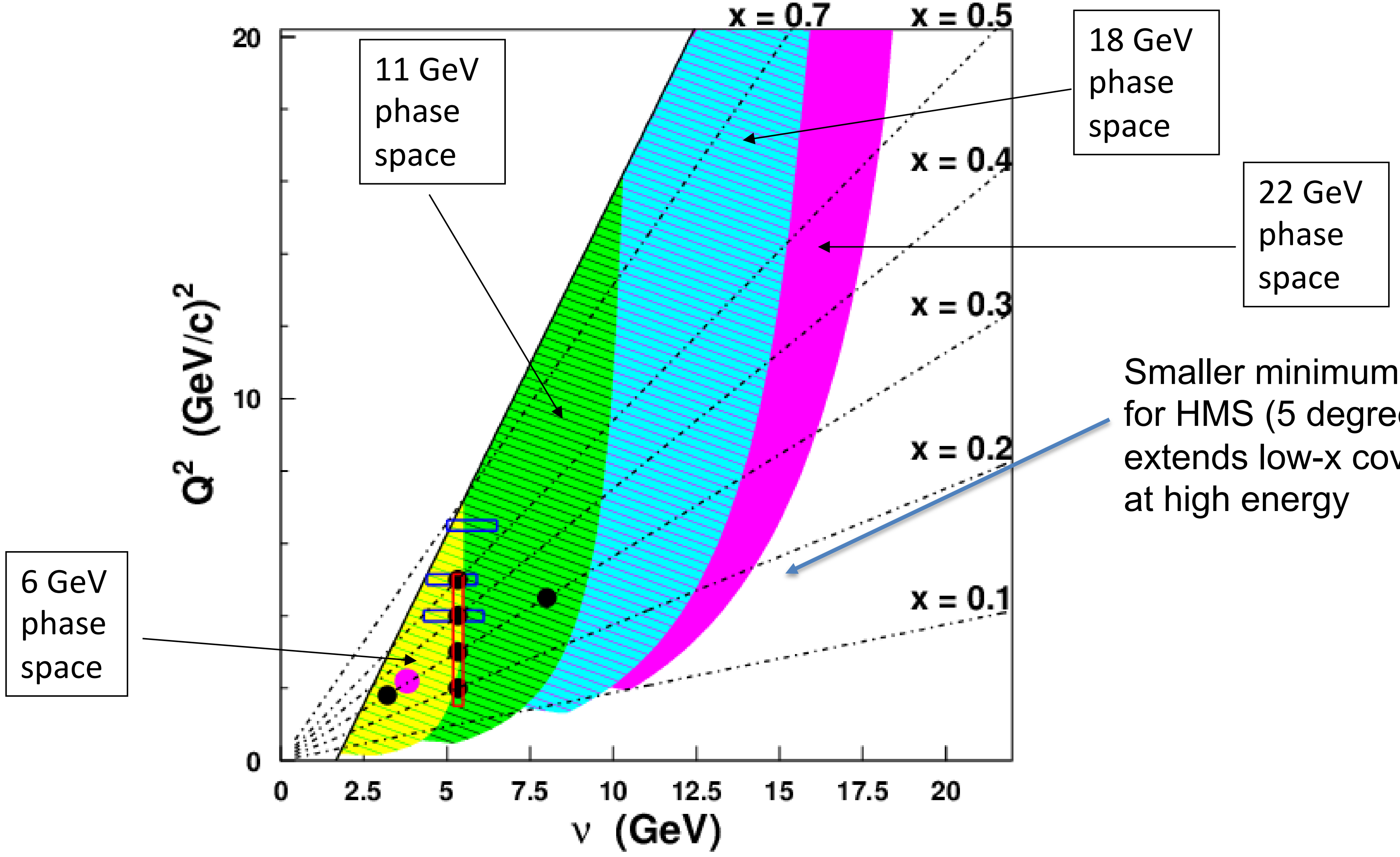


22 GeV Hall C SIDIS Phase Space – HMS+SHMS

Assumptions: HMS + SHMS minimum angle constraints unchanged
→ Increase in HMS maximum momentum (higher field magnets)
→ Smaller HMS angle may be possible, but would require special bender like SHMS



Hall C SIDIS Phase Space – Smaller HMS angle



Smaller minimum angle for HMS (5 degrees) extends low-x coverage at high energy

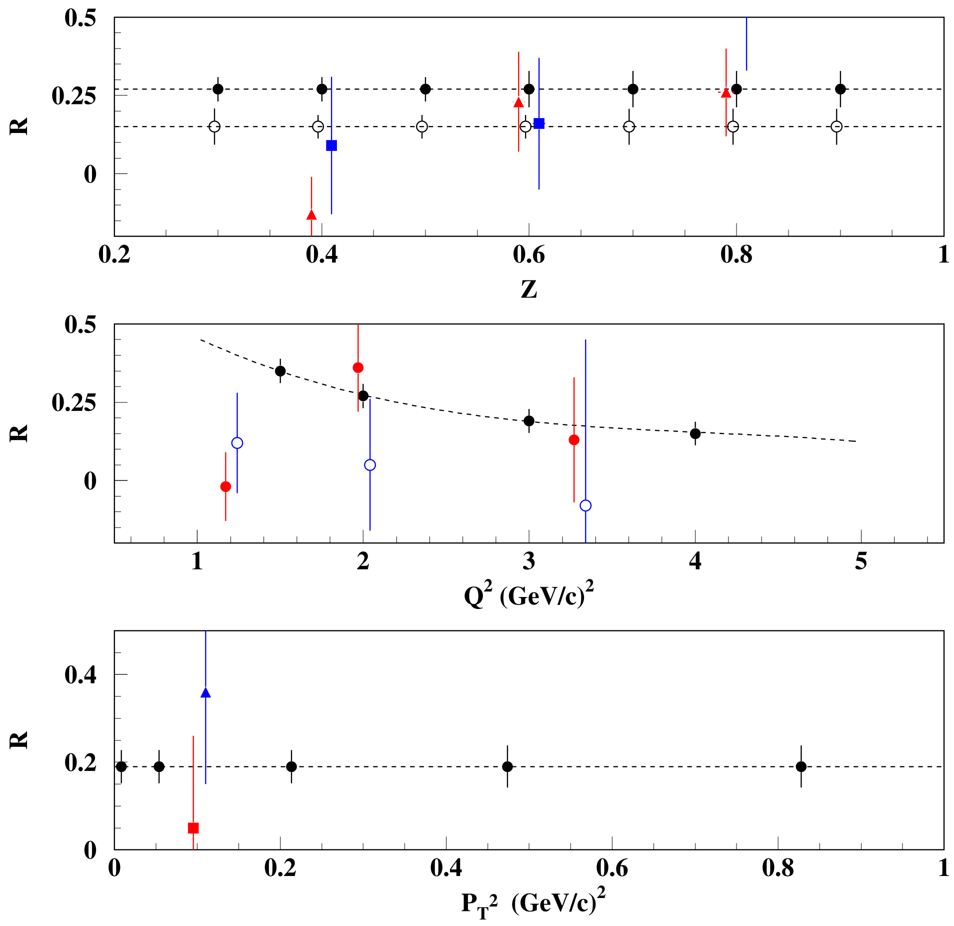
R in SIDIS

E12-06-104: Measurement of the Ratio $R=\sigma_L/\sigma_T$ in Semi-Inclusive Deep-Inelastic Scattering
Spokespersons: R. Ent, P. Bosted, E. Kinney, H. Mkrtchyan

Is R in SIDIS same as DIS?

Same behavior at mid and large x?

What about nuclear dependence?



$x=0.2$, $Q^2=2$ GeV^2

$x=0.4$, $Q^2=4$ GeV^2

$x=0.15$-0.4

$x=0.3$, $Q^2=3$ GeV^2

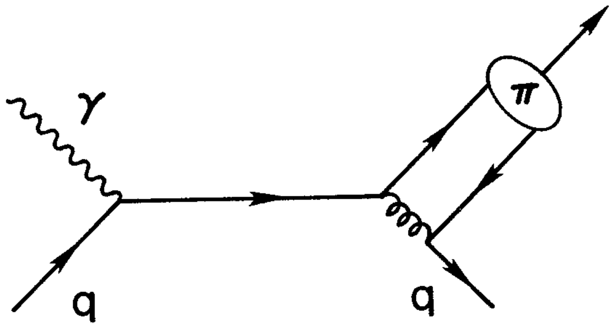
Nuclear Pions from SIDIS

Sensitivity to nuclear pions using SIDIS in anti-shadowing region?

E. Berger, ANL-HEP-CP-87-45, NPAS Workshop on Electronuclear Physics with Internal Targets

Pion contribution to SIDIS cross section at large z

$$\frac{d\sigma(x,Q^2,z)}{dxdydz} \propto \frac{1}{2}\left[1+(1-y)^2\right](1-z)^2 + \frac{4}{9}(1-y)F_\pi(Q^2)$$



Only contributes to "H_2" → from long. photons. ***L-T separation needed***

At x=0.15, Q^2=3 GeV^2 JLab higher energy would allow access up to z=0.8 with W'>2 GeV

Measure with light nucleus like ^{4}He where hadron attenuation effects are small

Would require higher beam energy ***and*** smaller angle capability for HMS (~6 degrees)

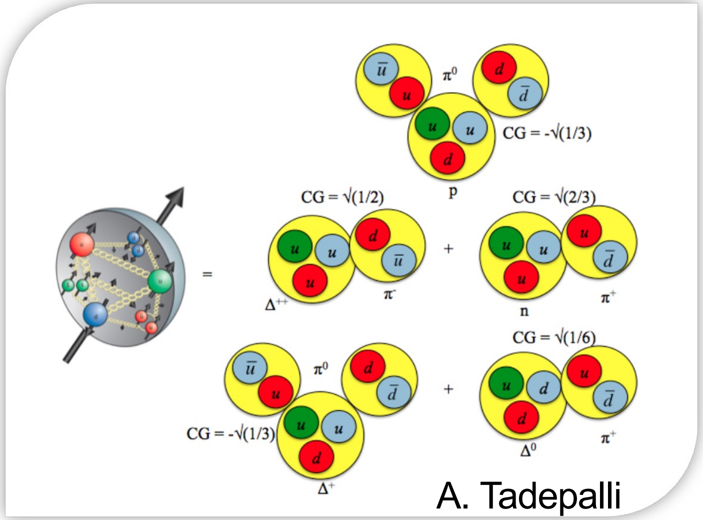
The TDIS program at Lab

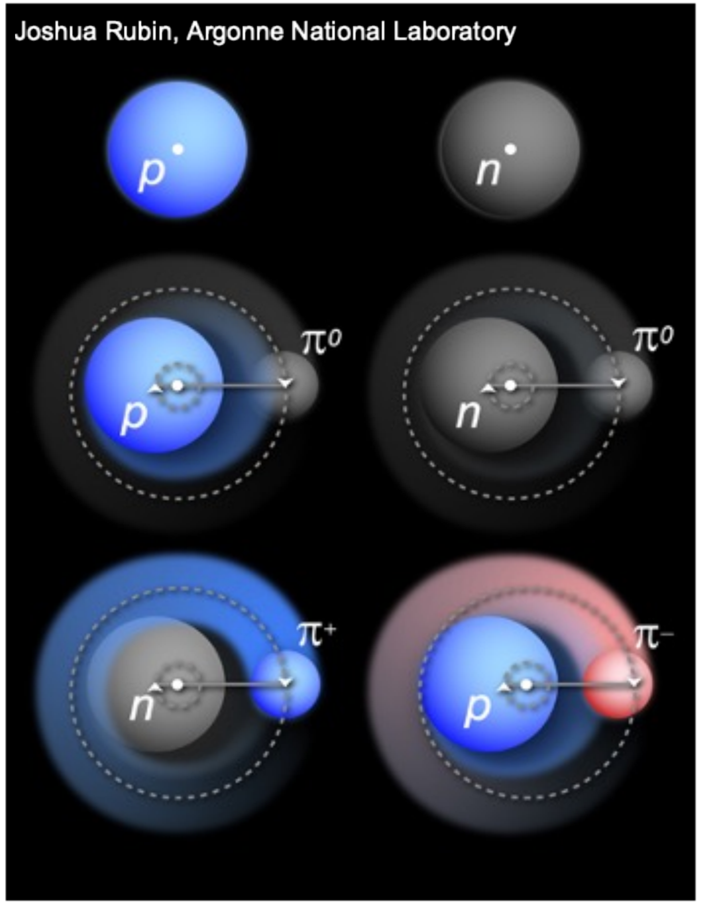
Accessing the mesonic content of nucleons using the Sullivan process

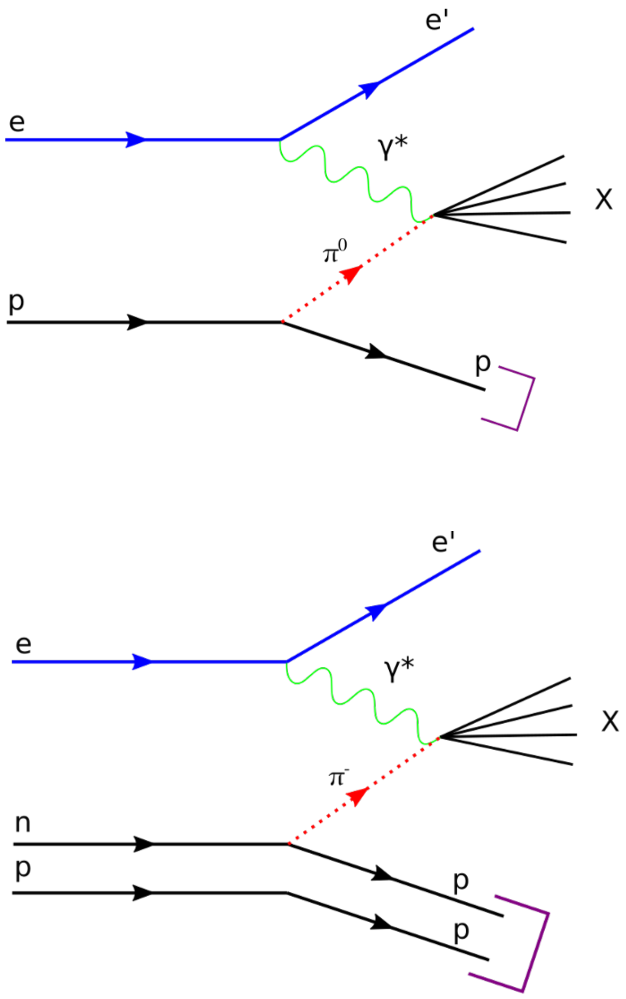
Meson cloud model

$$|p> \;\rightarrow\; \sqrt{1-a-b}|p_0> + \sqrt{a}(-\sqrt{\frac{1}{3}}|p_0\pi^0> + \sqrt{\frac{2}{3}}|n_0\pi^+>)$$
$$+\sqrt{b}(\sqrt{\frac{1}{2}}|\Delta_0^+\pi^-> - \sqrt{\frac{1}{3}}|\Delta_0^+\pi^0> + \sqrt{\frac{1}{6}}|\Delta_0^0\pi^+>)$$

proton as a linear combination of a “bare” proton plus pion-nucleon and pion-delta states



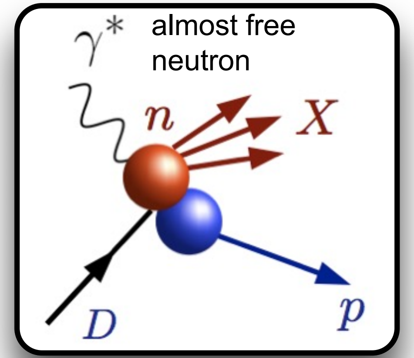




The TDIS program at Lab

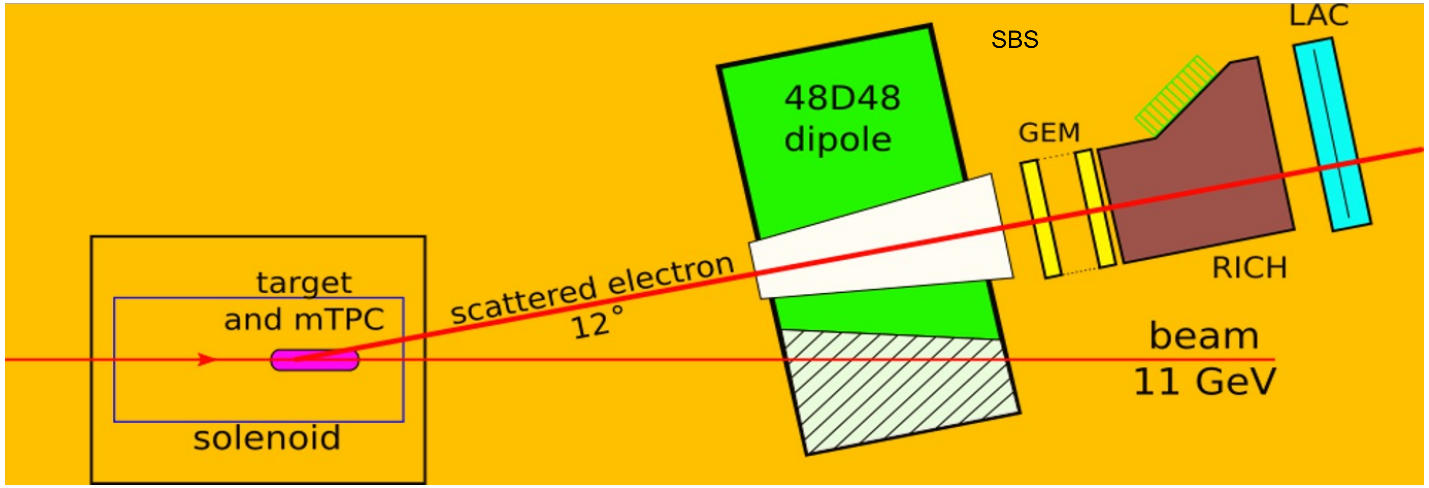
Uses the spectator tagging technique pioneered at JLab

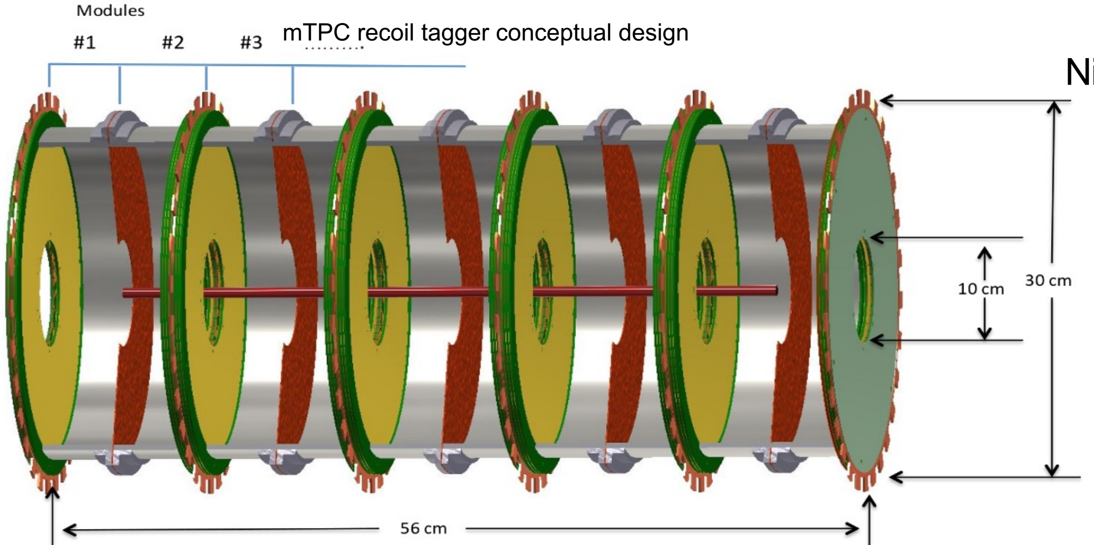
Spectator tagging:
a well established technique (BoNuS expt.)



Deuteron

Spectator proton
(backward going slow proton)



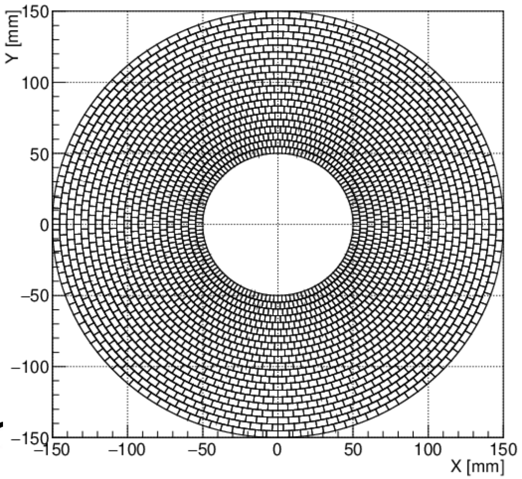


Nilanga Liyanage

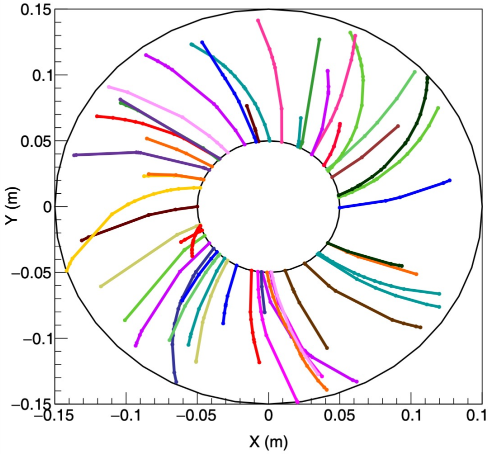
DIS event – reconstruct x, Q^2, W^2, also M_X of recoiling hadronic system

$$R^T = \frac{d^4\sigma(ep \to e'Xp')}{dxdQ^2dzdt} \Big/ \frac{d^2\sigma(ep \to e'X)}{dxdQ^2}\Delta z\Delta t \sim \frac{F_2^T(x,Q^2,z,t)}{F_2^p(x,Q^2)}\Delta z\Delta t.$$

Readout pads of mTPC



simulated mTPC tracks

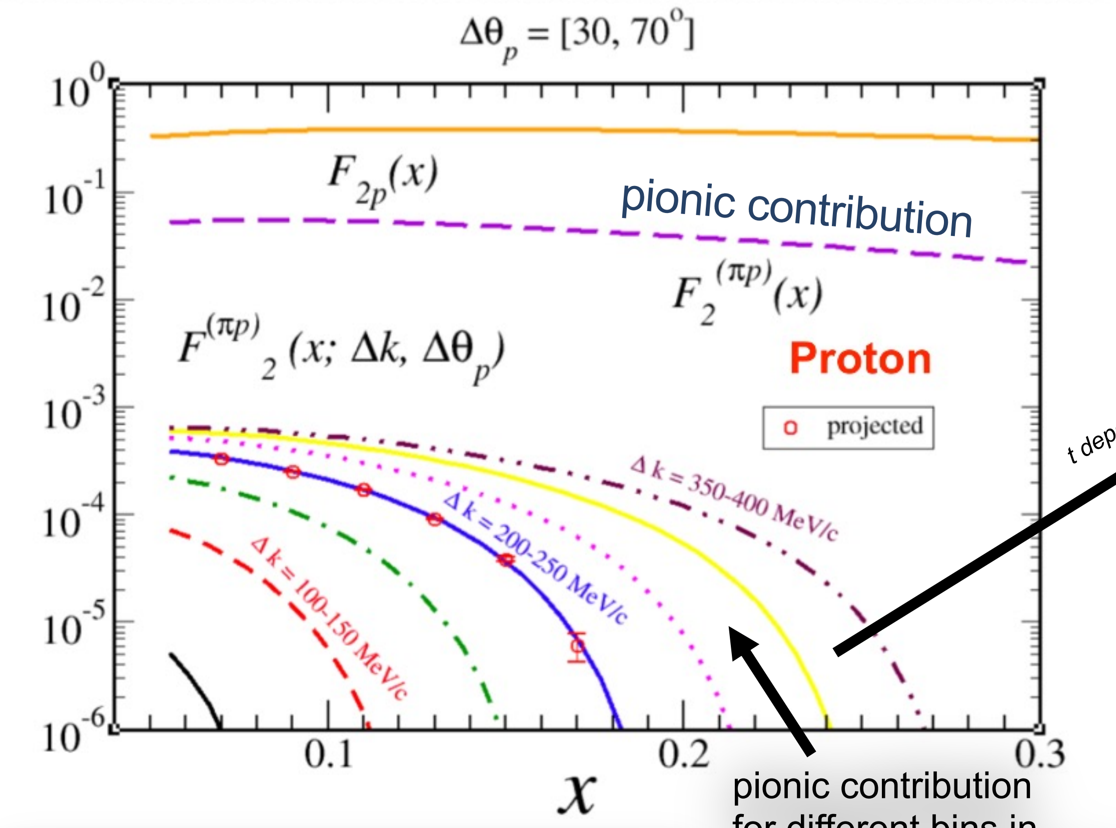


Jefferson

The TDIS program at Lab

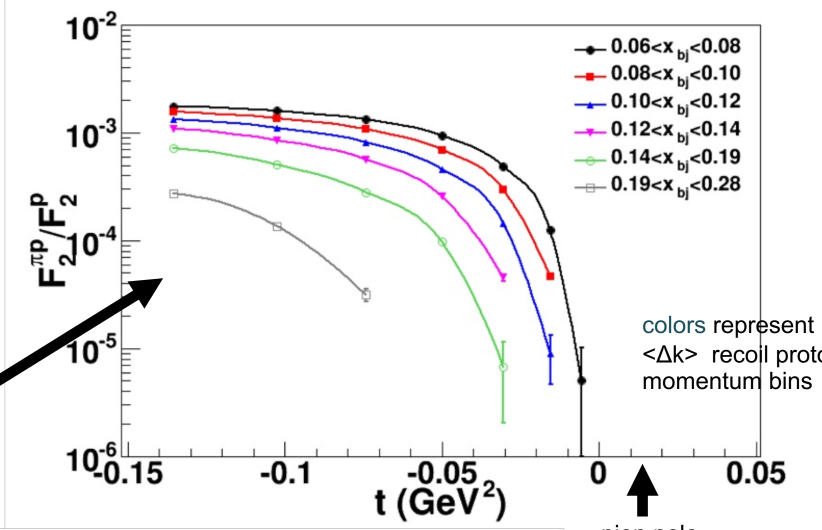
Extract the pion structure function (projected results)

T. J. Hobbs, Few-body Systems, 56, 363 (2015)



pionic contribution for different bins in recoil proton momentum

t dependence

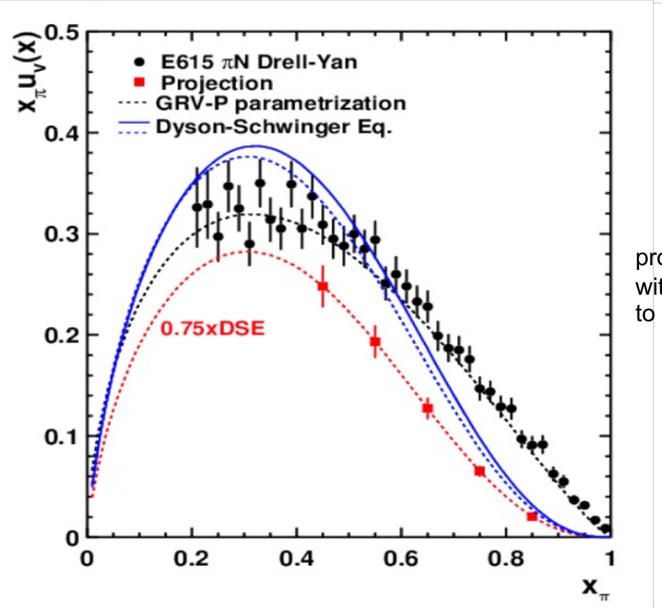


colors represent <Δk> recoil proton momentum bins

pion pole

$$F_2^{(\pi N)}(x, z, k_\perp) = f_{\pi N}(z, k_\perp)\, F_{2\pi}\left(\frac{x}{z}\right)$$

Tagged SF pion "flux" Pion SF



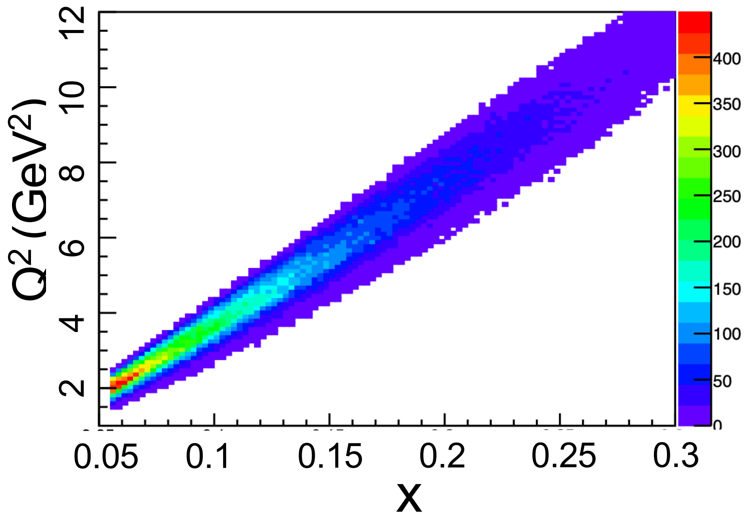
projected pion structure function with "pion flux" normalized to D-Y data at x_π = 0.45

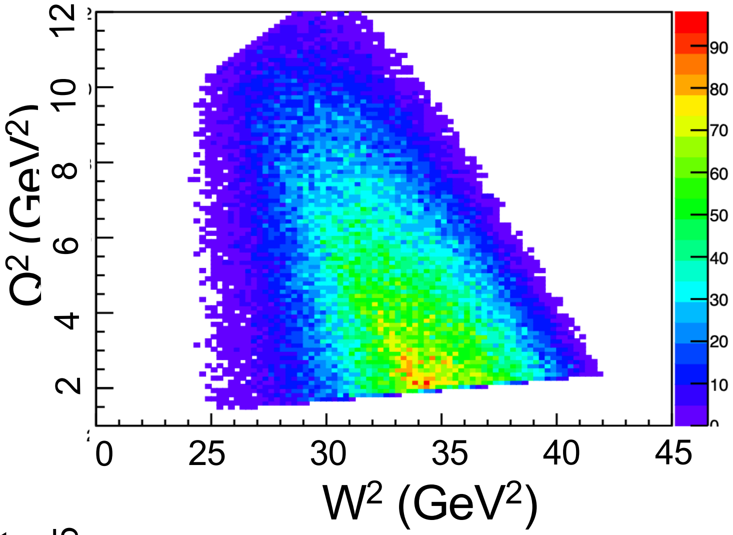
TDIS @ 20 GeV JLab

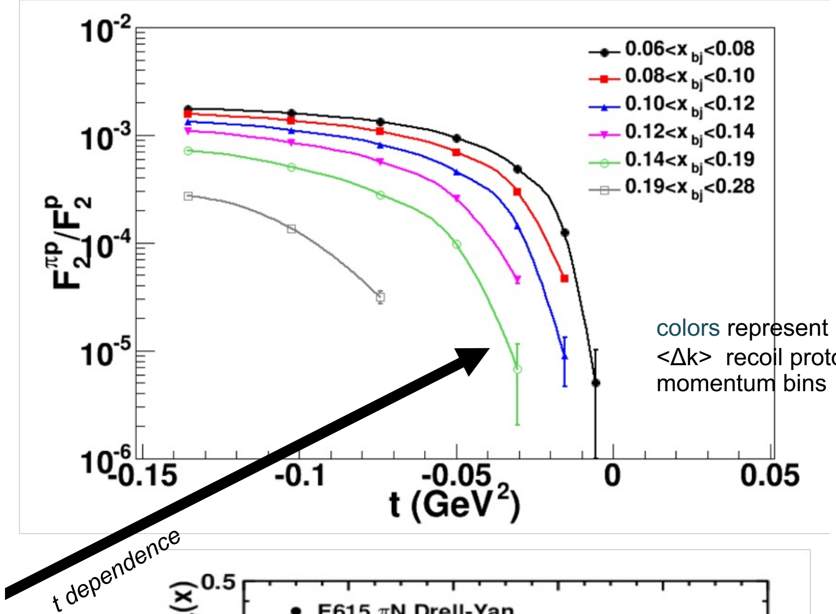
Extended kinematic coverage, better constraints on *t* dependence

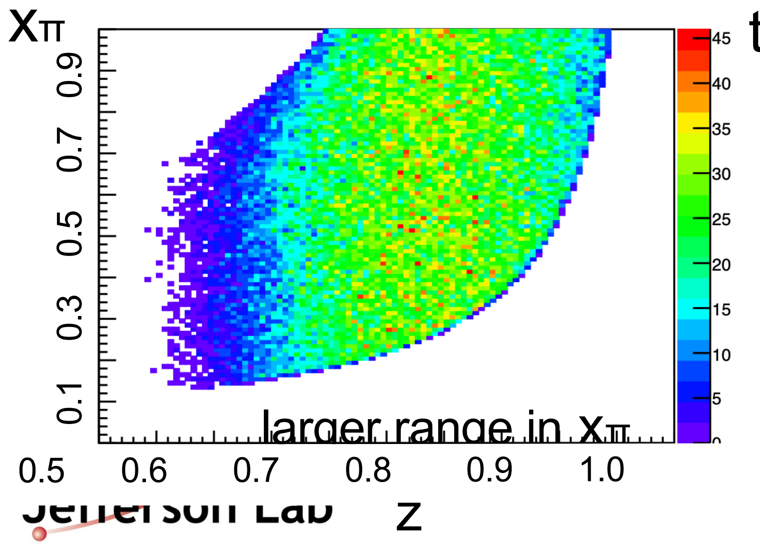
coverage of low x
0.05 < x <0.2

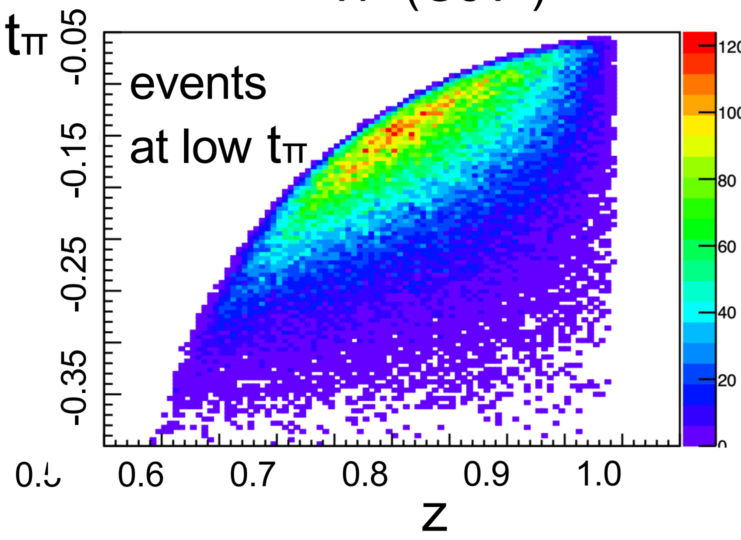
<Q^2> and <W^2> significantly
larger than TDIS @11 GeV

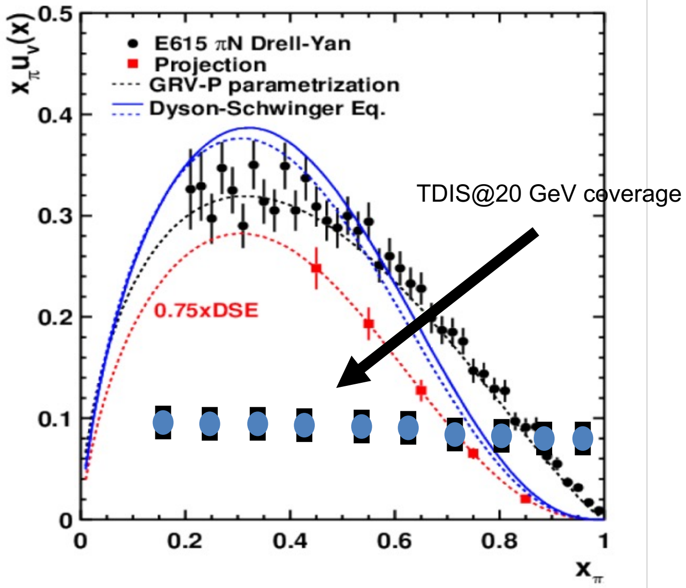




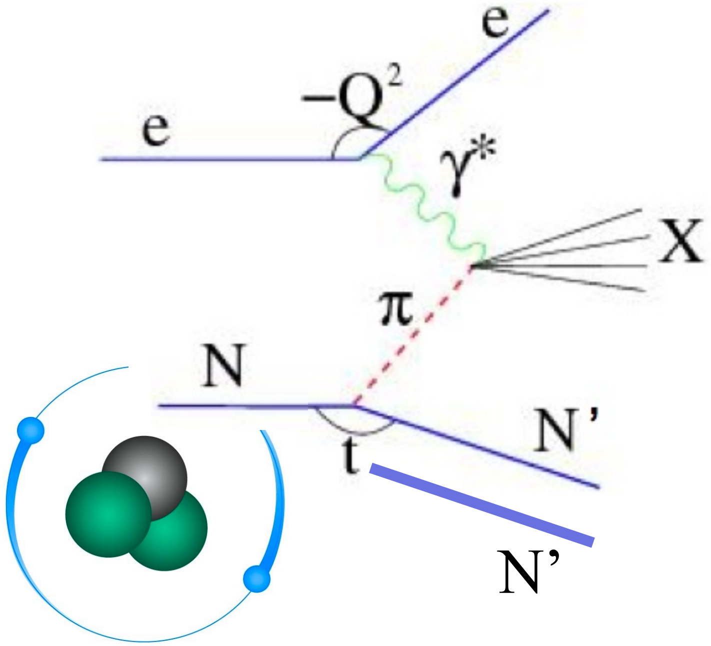






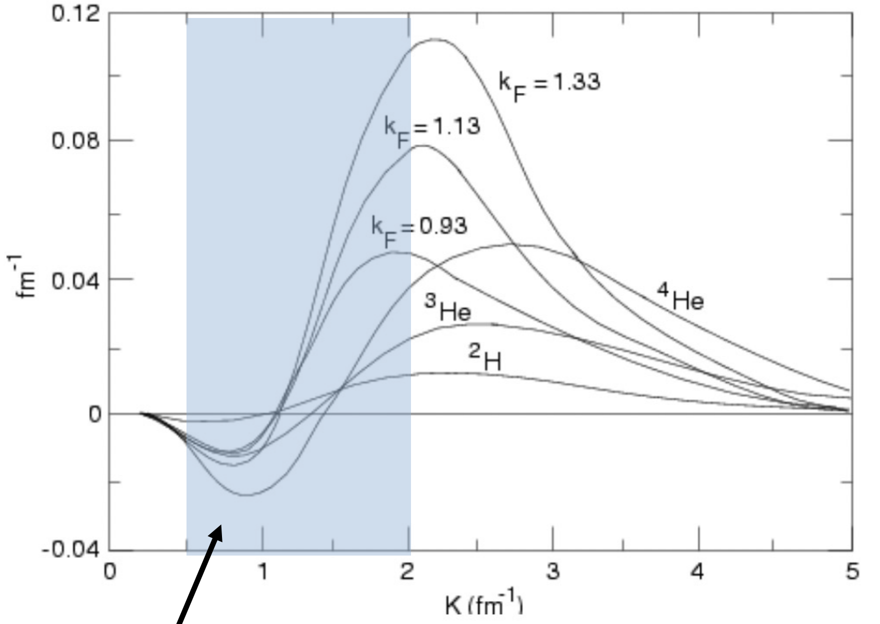


TDIS and Nuclear Pions

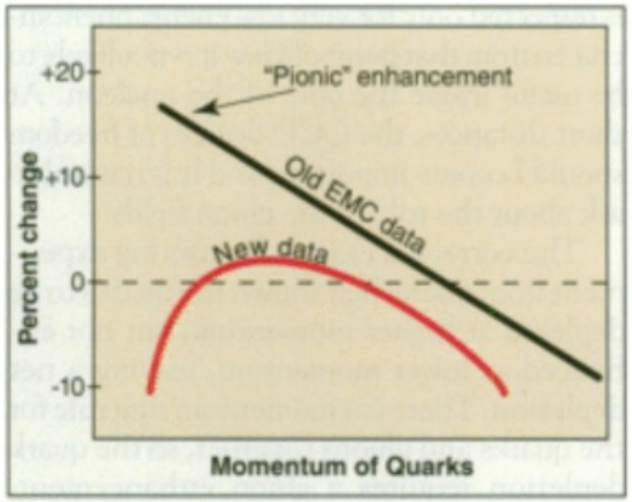


Use TDIS setup to measure the pionic content of ^{3}He and ^{4}He

Friman, Pandharipande, and Wiringa, PRL **51** 763 (1983)



Pion excess $k^2\langle\delta n_\pi(k)\rangle/2\pi A$
as a function of virtual pion momentum



Bertsch, Frankfurt & Strikman, Science 259, 773 (1993)

TDIS Recoil proton momentum: P_p = 0.1 - 0.4 GeV/c & $P_p = -P_\pi$ look for excess pions relative to ^{2}H

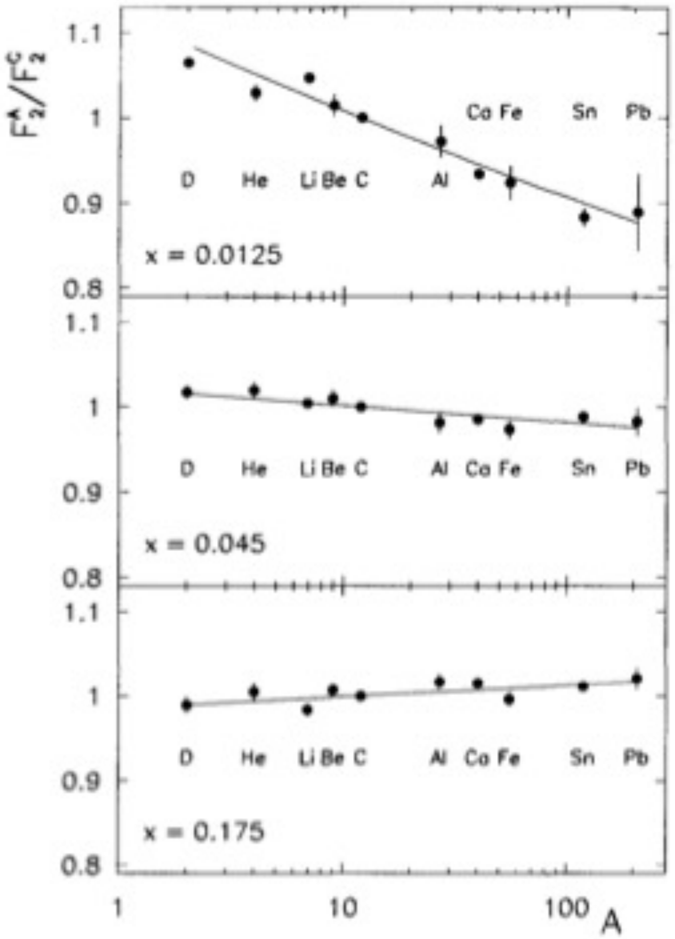
Also extract pion structure function from ^{2}H, ^{3}He and ^{4}He allowing a pionic EMC effect measurement.
@ 20 GeV will allow high W^2 coverage of $0.05 < x < 0.3$

Summary

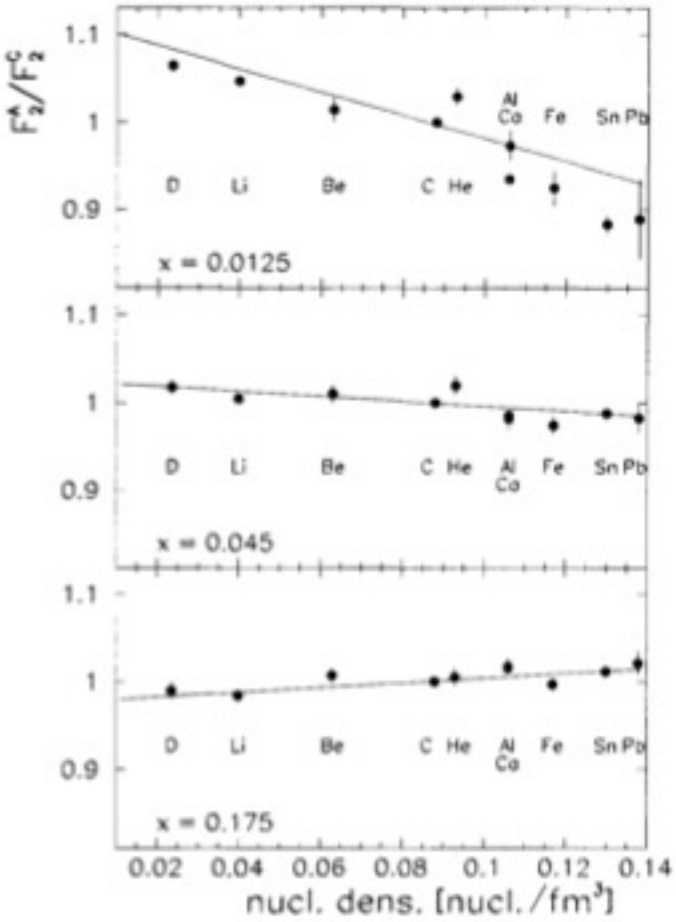
- Measurement of $R=\sigma_L/\sigma_T$ in anti-shadowing region important to clarify whether anti-shadowing is present on both σ_L and σ_T
  - Approved Hall C E12-14-002 will measure R_A-R_D for C, Cu, and Au
  - Larger Q^2 range, lower x accessible w/higher energy
- SIDIS
  - Larger Q^2 range at low and high x, large W' at large z
  - Hall C cannot access anti-shadowing region above E=13-14 GeV
  - L-T separations → access to nuclear pions?
- TDIS
  - Nuclear pions using tagged DIS

EXTRA

A-Dependence from NMC

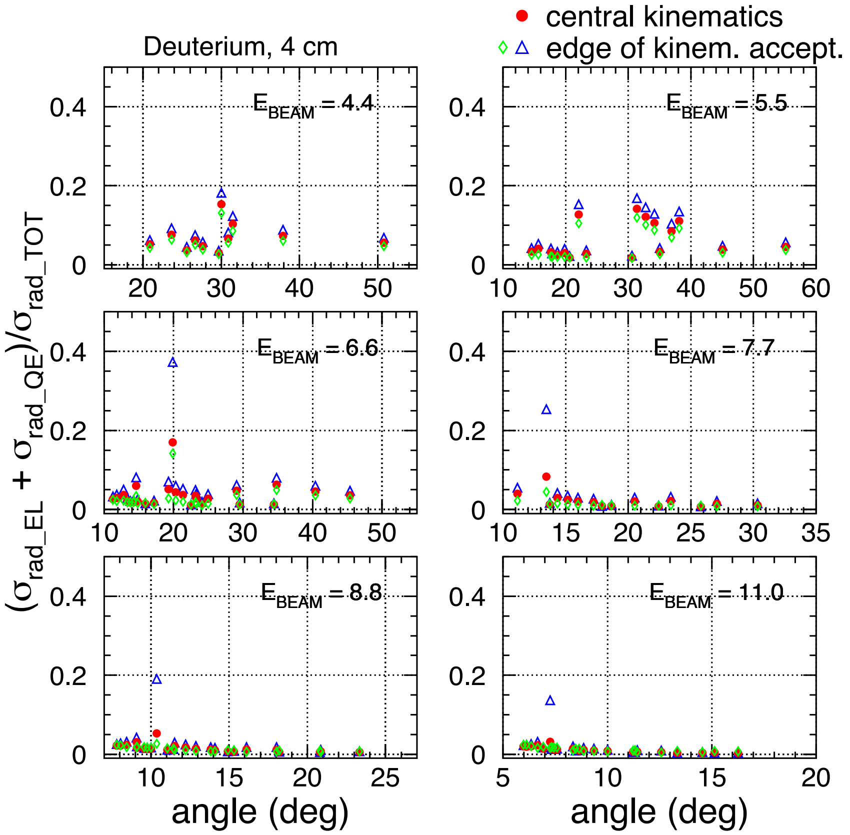


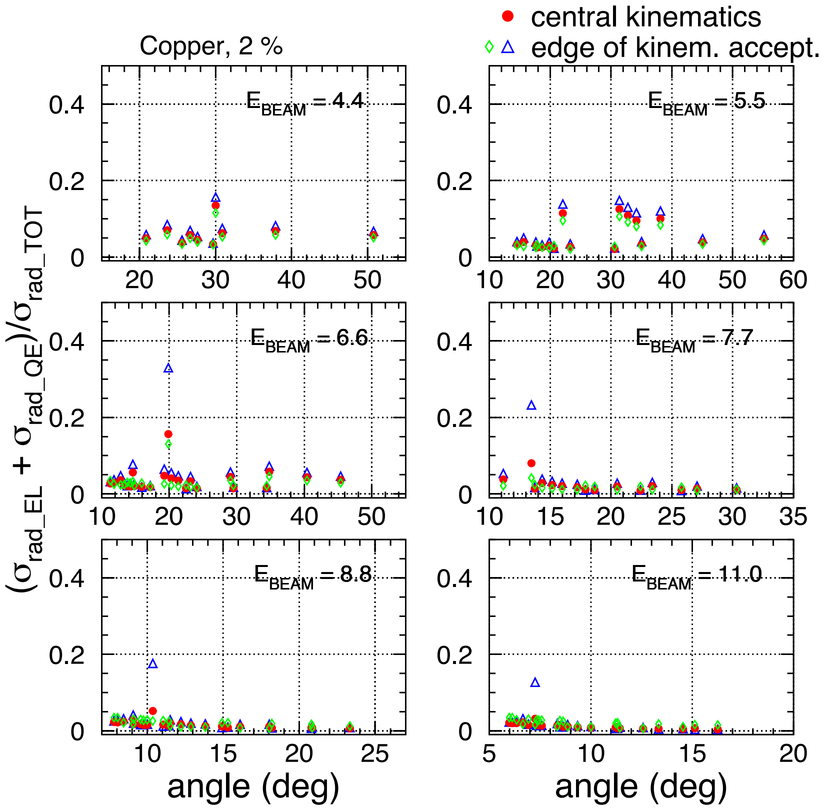
Normalization uncertainties = 0.2-0.4%



NMC: *Arneodo et al, Nucl. Phys. B 481, 3 (1996)*

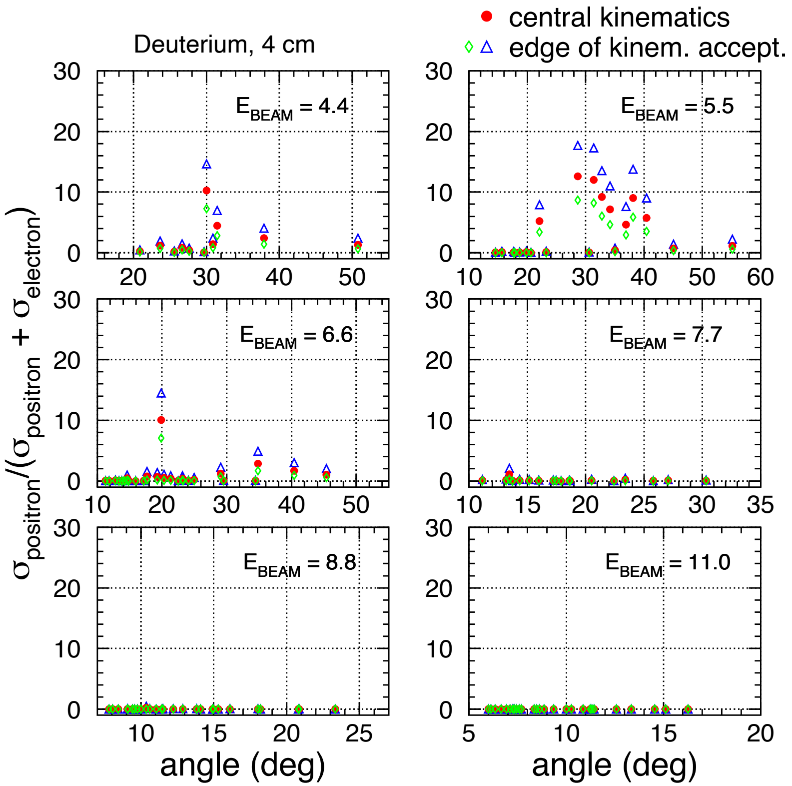
E12-14-002: Radiative Corrections

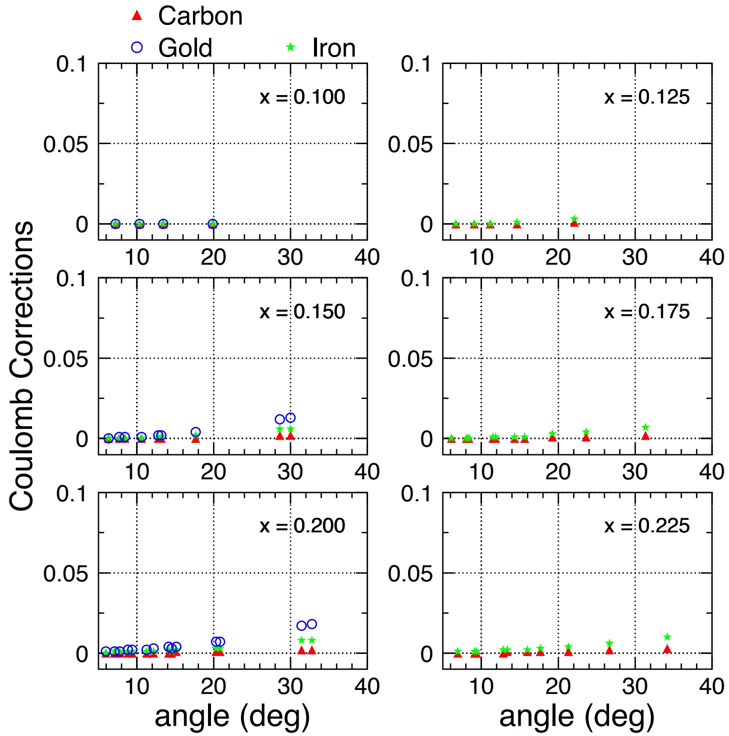




Radiated QE and elastic fraction of total radiated cross secxtion for E12-14-002

E12-14-002: CSBG and Coulomb Corrections





Charge symmetric backgrounds and Coulomb corrections for E12-14-002

Jefferson Lab