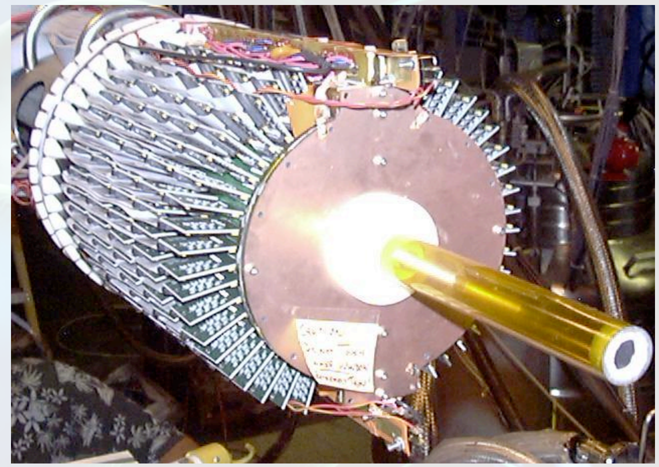
Neutron Structure at Large x



Thia Keppel
DIS 2013

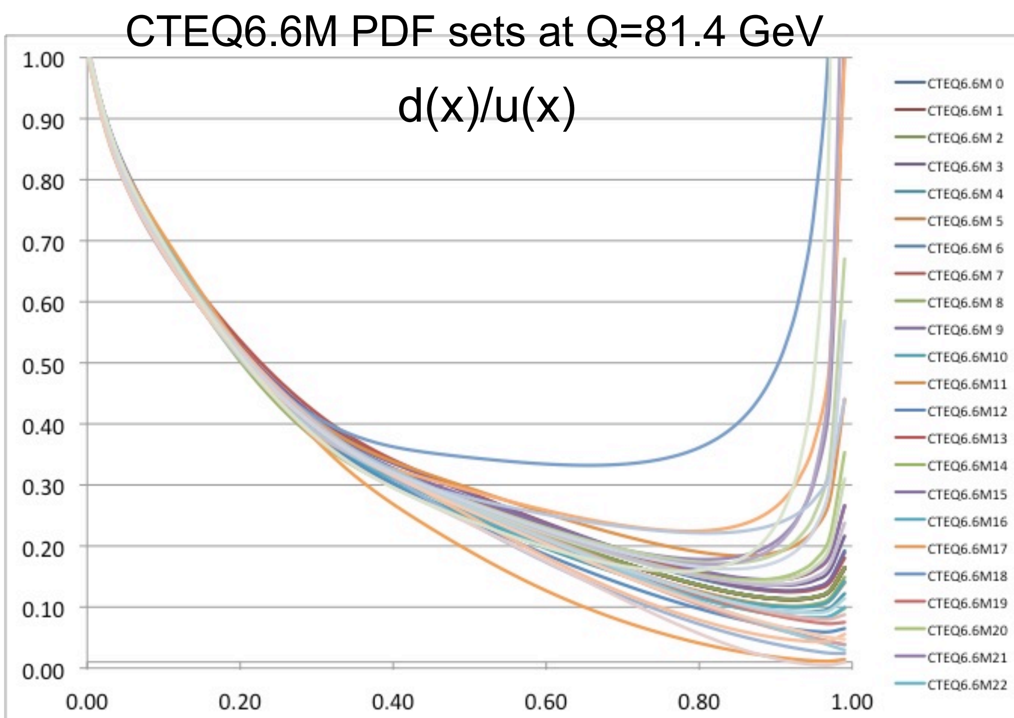
Neutron provides access to d(x) - essentially unknown at large x

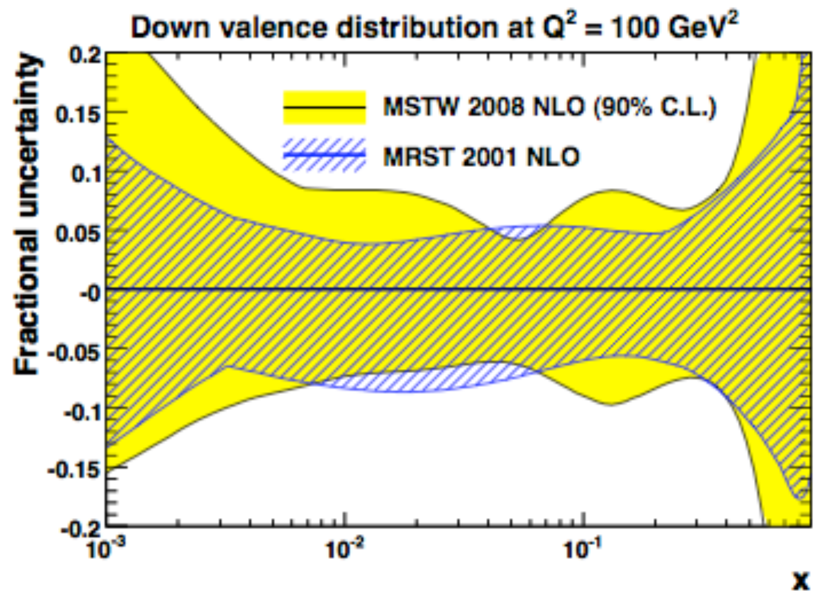
Lack of high Q, W structure function data

- no free neutron target (nuclear corrections)

Conflicting fundamental theory pictures

Lack of data period

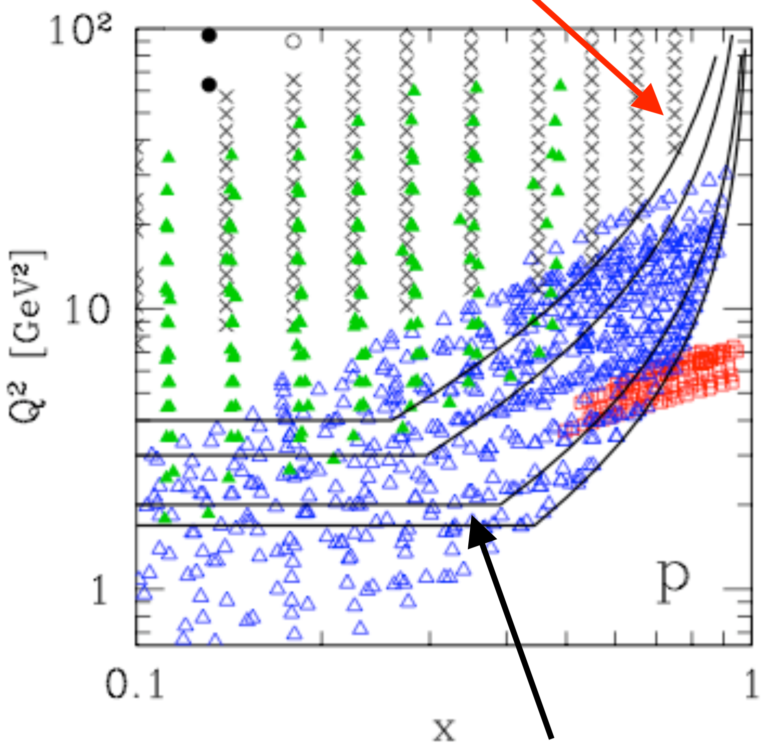




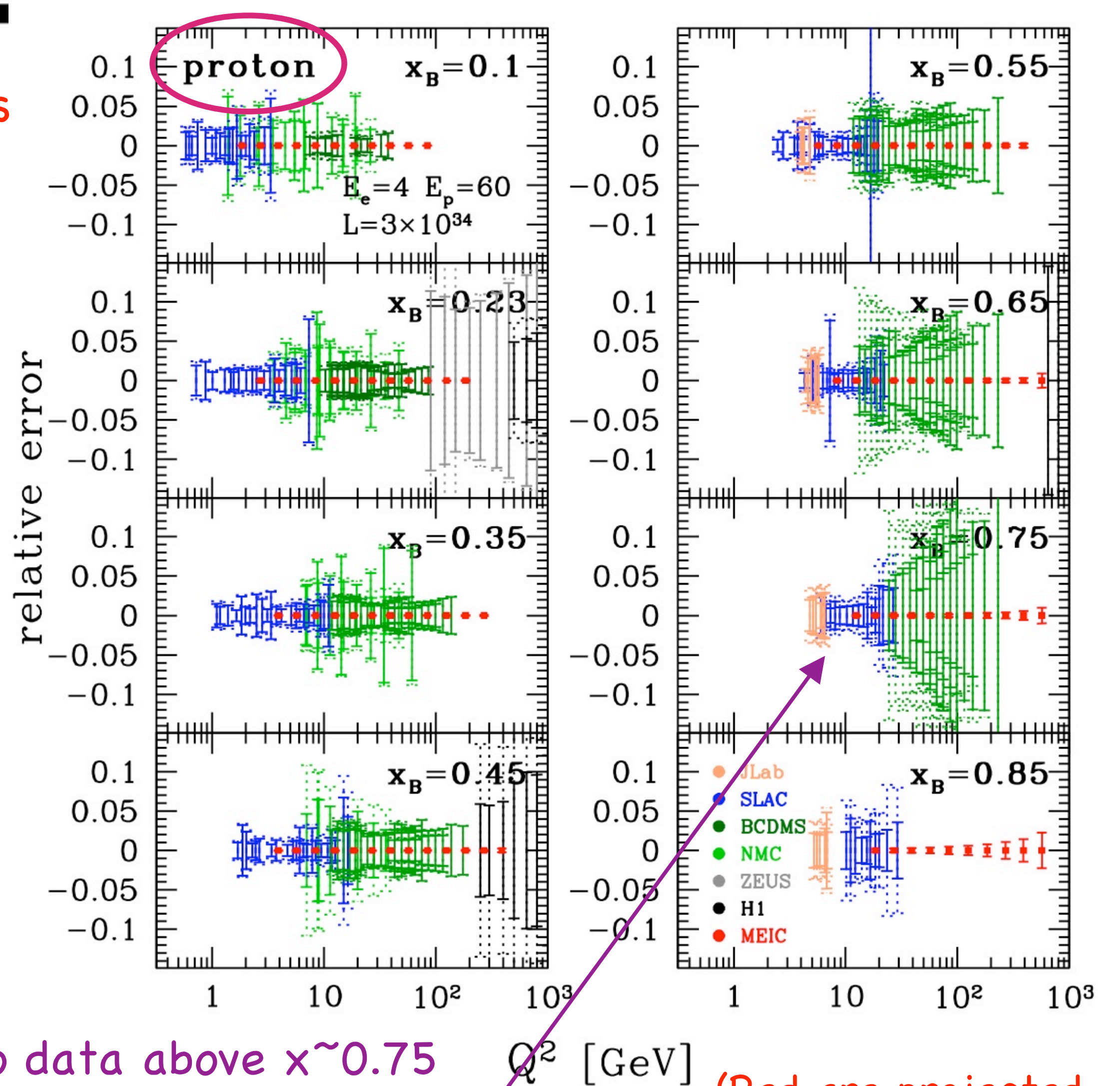
There is some help coming….

Typical W, Q cuts are VERY restrictive….

$Q^2 > 4\ \text{GeV}^2$, $W^2 > 12.25\ \text{GeV}^2$ cuts



Reduced CJ cuts, $W^2 > 3.5\ \text{GeV}^2$



Typical cuts essentially include no data above x~0.75

What large x data that is used has large uncertainty

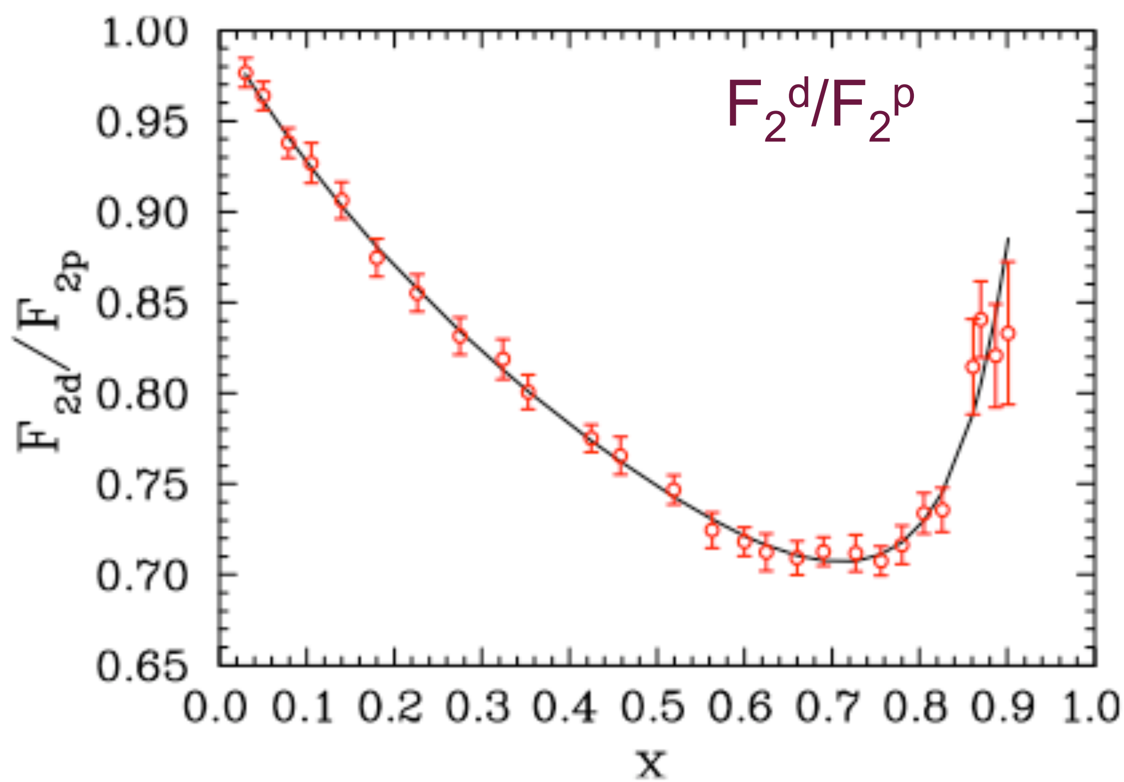
(Red are projected mEIC data points.)

The deuteron is a nucleus….

Neutron structure *(and hence d(x)* is typically derived from deuterium target data by subtracting proton

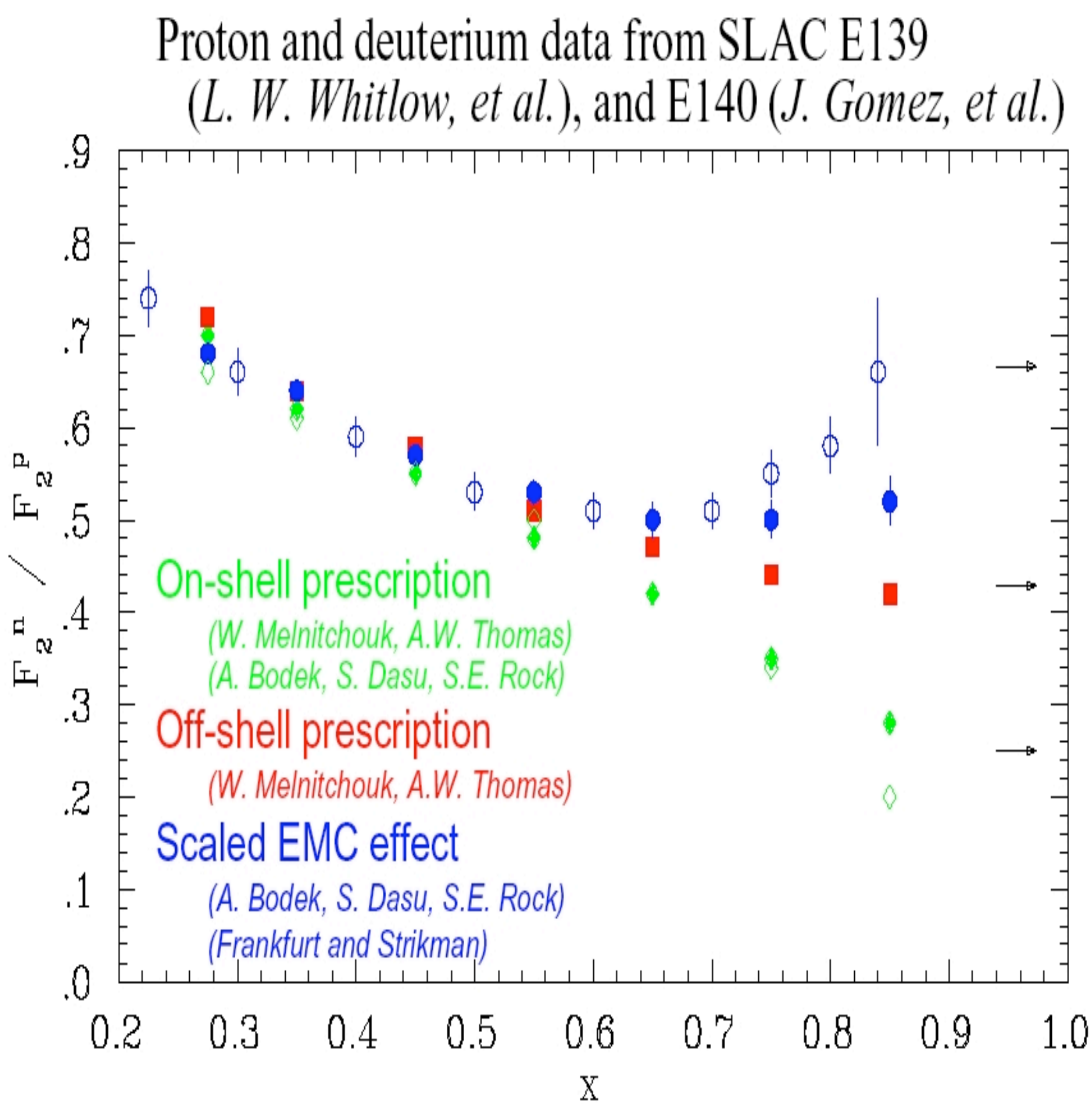
…..but…..

Large uncertainty in unfolding nuclear effects (Fermi motion, off-shell effects, deuteron wave function,coherent scattering, final state interactions, nucleon structure modification ("EMC"-effect)……………..



SLAC data

This is a major obstacle….



SAME data set

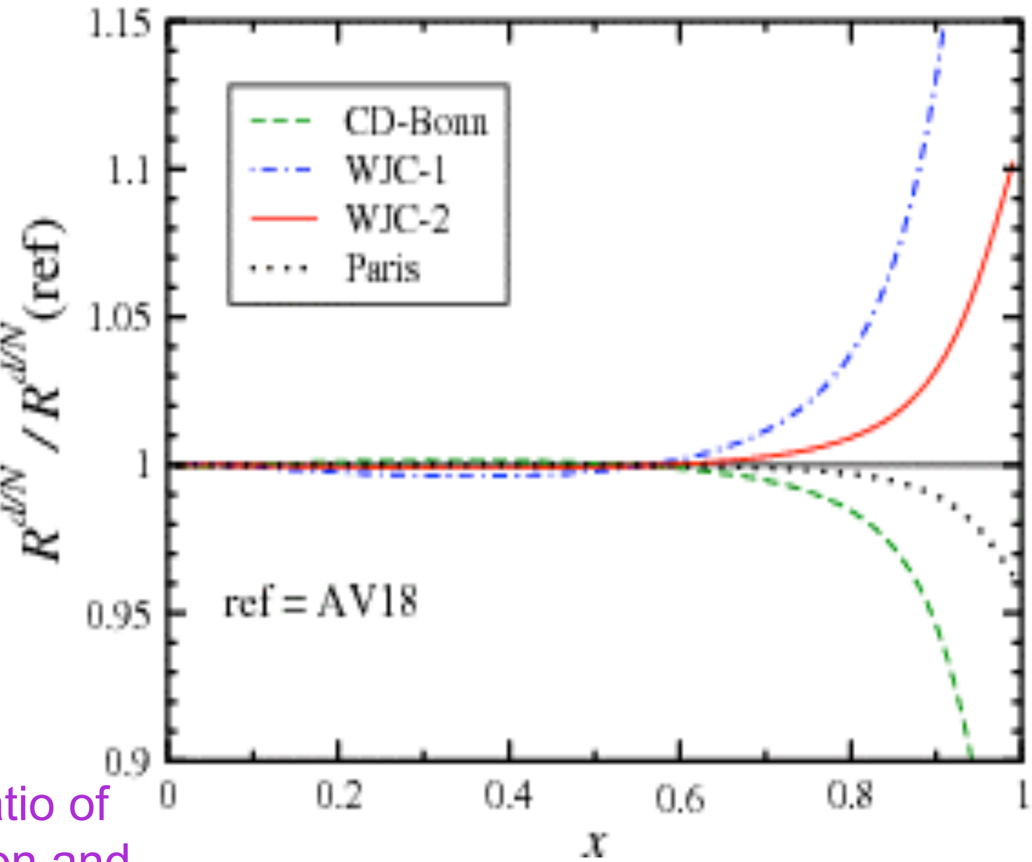
DIFFERENT nuclear effect analyses

$0.2 < F_2^n/F_2^p < 0.8$

?!?!

Large x - Large Nuclear Effects

Deuteron wave function model dependence



R – ratio of deuteron and nucleon F_2 structure functions

- Even simple "Fermi Smearing" leads to significant dependence on D wave function
- Different models for off-shell and "EMC" effects lead to large additional variations
- Translates directly to large x valence pdf uncertainties

Accardi *et al*, Phys. Rev. D84:014008 (2011) *Uncertainties in Determining Parton Distributions at Large x* *"CJ" Fit*

F_2^n/F_2^p is fundamental to understanding the nucleon structure

Proton Wavefunction (Spin and Flavor Symmetric)

$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle$$

$$-\frac{1}{3}|d\uparrow(uu)_{S=1}\rangle - \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
pQCD	3/7	1/5

Predictions for d/u at large x_{Bj}

Proton Wavefunction (Spin and Flavor Symmetric)

$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle$$
$$-\frac{1}{3}|d\uparrow(uu)_{S=1}\rangle - \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
pQCD	3/7	1/5

u, d same shape u = 2d

SU(6) spin-flavor symmetry:

The mass difference between N and Δ implies symmetry breaking

Predictions for d/u at large x_{Bj}

Proton Wavefunction (Spin and Flavor Symmetric)

$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle - \frac{1}{3}|d\uparrow(uu)_{S=1}\rangle - \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
pQCD	3/7	1/5

SU(6) symmetry broken - scalar valence diquark, u dominance

S=0 diquark dominance

- d/u=(0)/(1/2)=0
- Hyperfine-perturbed quark model (Isgur *at al.*) with one-gluon-exchange; MIT bag model with gluon exchange (Close & Thomas); Phenomenological quark-diquark (Close) and Regge (Carlitz)

Predictions for d/u at large x_{Bj}

Proton Wavefunction (Spin and Flavor Symmetric)

$$\left|p\uparrow\right\rangle = \frac{1}{\sqrt{2}}\left|u\uparrow(ud)_{S=0}\right\rangle + \frac{1}{\sqrt{18}}\left|u\uparrow(ud)_{S=1}\right\rangle - \frac{1}{3}\left|u\downarrow(ud)_{S=1}\right\rangle - \frac{1}{3}\left|d\uparrow(uu)_{S=1}\right\rangle - \frac{\sqrt{2}}{3}\left|d\downarrow(uu)_{S=1}\right\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
pQCD	3/7	1/5

S_z = 0, di-quark dominance, spin projection is zero

- d/u=(1/9)/(1/2+1/18)=1/5
- pQCD with helicity conservation (Farrar and Jackson); quark counting rules (Brodsky *et al.)*

[There are even more predictions…]

Predictions for d/u at large x_{Bj} - large range in theory

	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Scalar Diquark	1/4	0
H-P Quark Model	1/4	0
pQCD	3/7	1/5
Counting Rules	3/7	1/5
Many more!		

$$0.25 < F_2^n/F_2^p < 0.75 \quad ?!$$

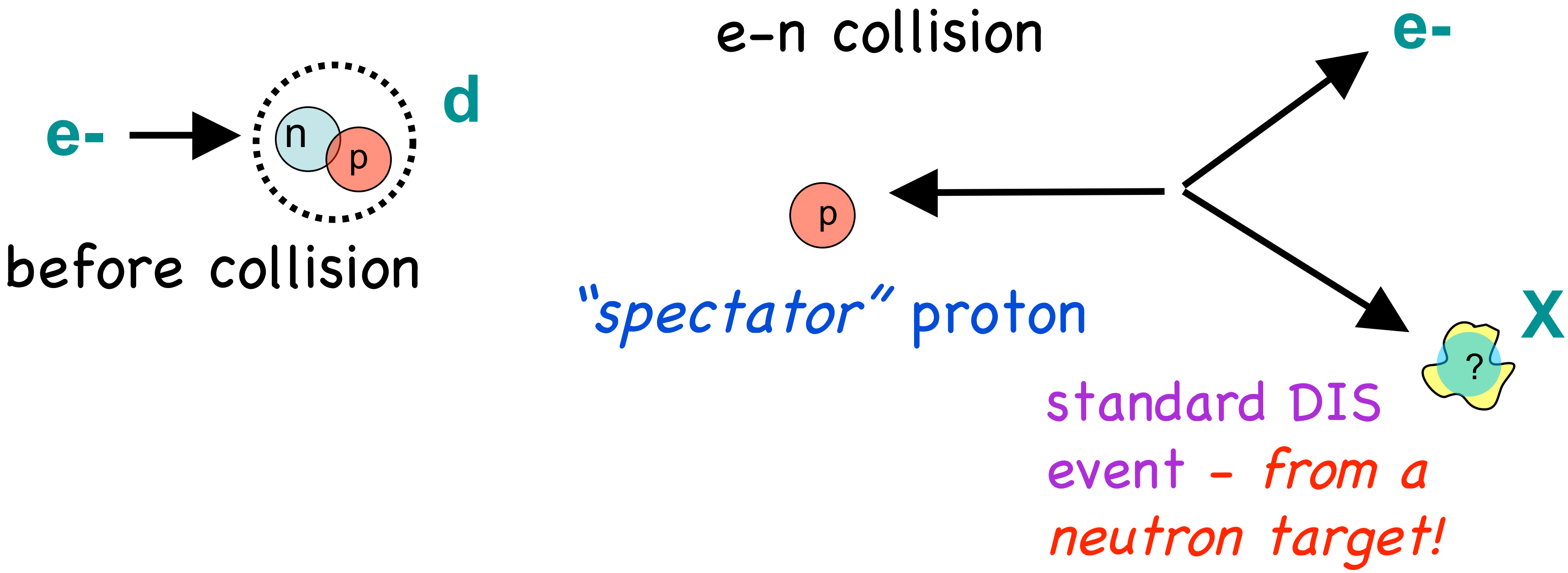
Review Articles :

Isgur, Phys. Rev. D59, 34013 (1999)

Brodsky et al., Nucl. Phys. B441, 197 (1995)

Melnitchouk and Thomas, Phys. Lett. B377, 11 (1996)

The Spectator Tagging Approach: An Effective Free Neutron Target from Deuterium….



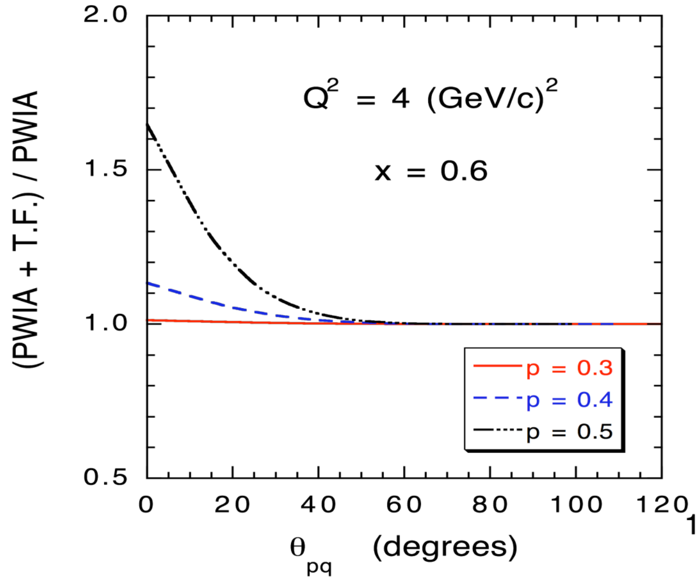
L.L. Frankfurt and M.I. Strikman, Phys. Rep. 76, 217 (1981)

C. Ciofi degli Atti and S. Simula, Phys. Lett. B319, 23 (1993); Few-Body Systems 18, 55 (1995)

S. Simula, Phys. Lett. B387, 245 (1996); Few-Body Systems Suppl. 9, 466 (1995)

W. Melnitchouk, M. Sargsian and M.I. Strikman, Z. Phys. A359, 99 (1997)

Choice of Spectator Momentum (low!) and Angle (large!)

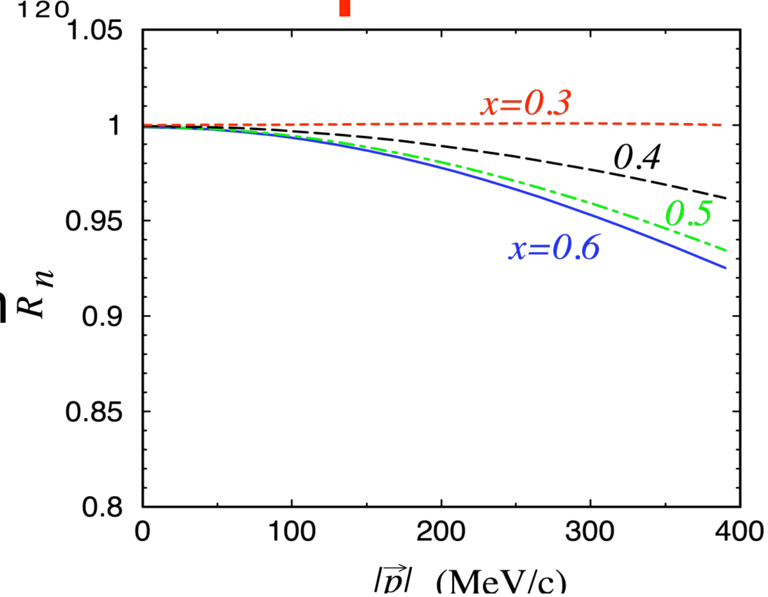


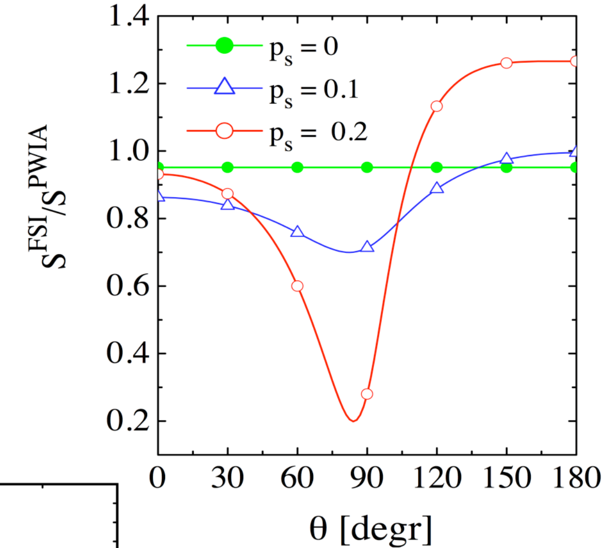
Target fragmentation

negligible for large angle

Bound / free neutron structure

O **(1%) for low momentum -** ***drives the experiment***

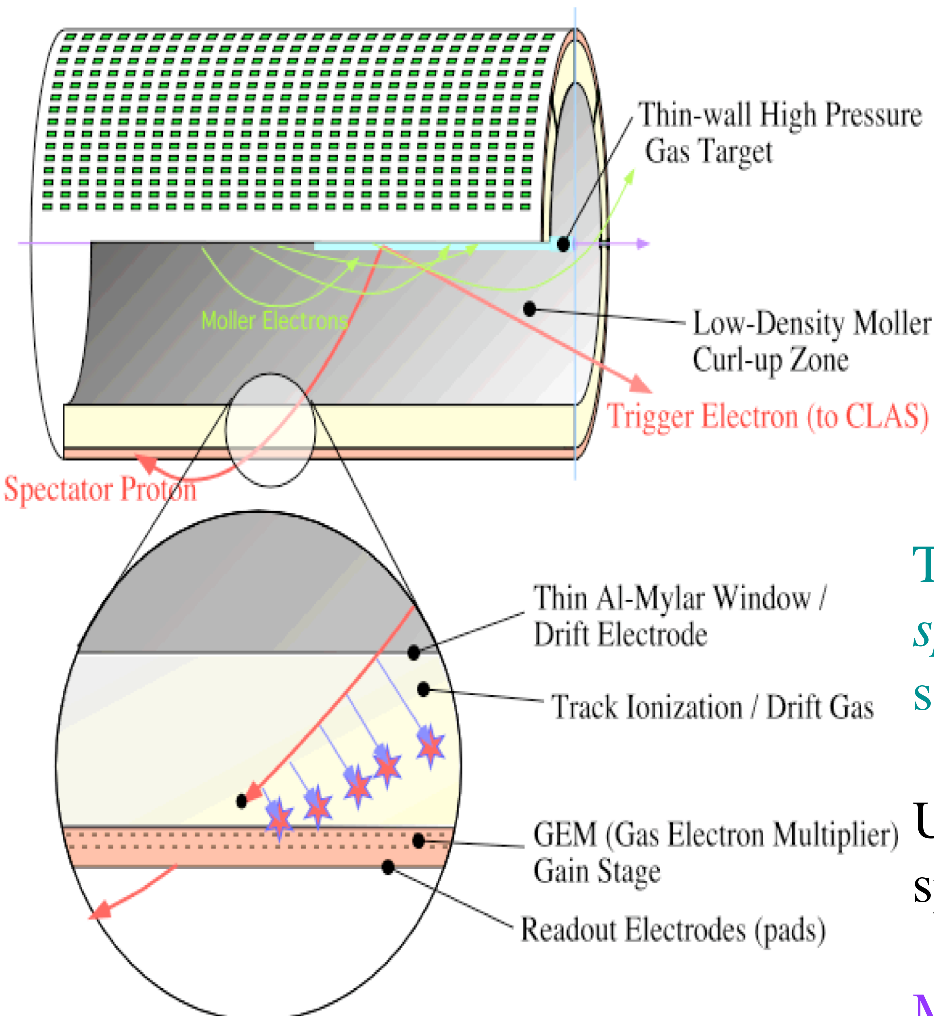


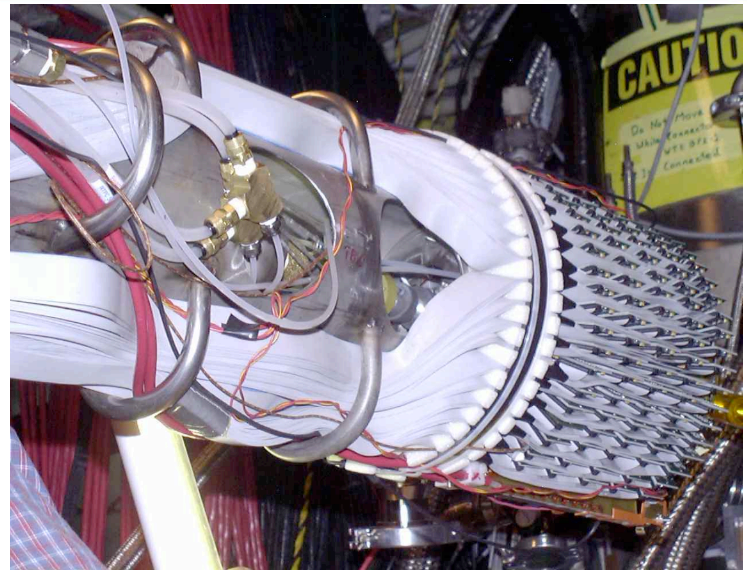


Final state interactions

O **(5%) for low momentum**

BONUS Experiment at JLab





Tag low momentum, backward angle *spectator* proton in deuterium = electron scattering from a free *Neutron* target

Use GEM-based radial TPC in JLab CLAS spectrometer

Measure neutron structure function F_2 to study quark structure of the nucleon at large x

BONUS in CLAS (Hall B at Jefferson Lab)

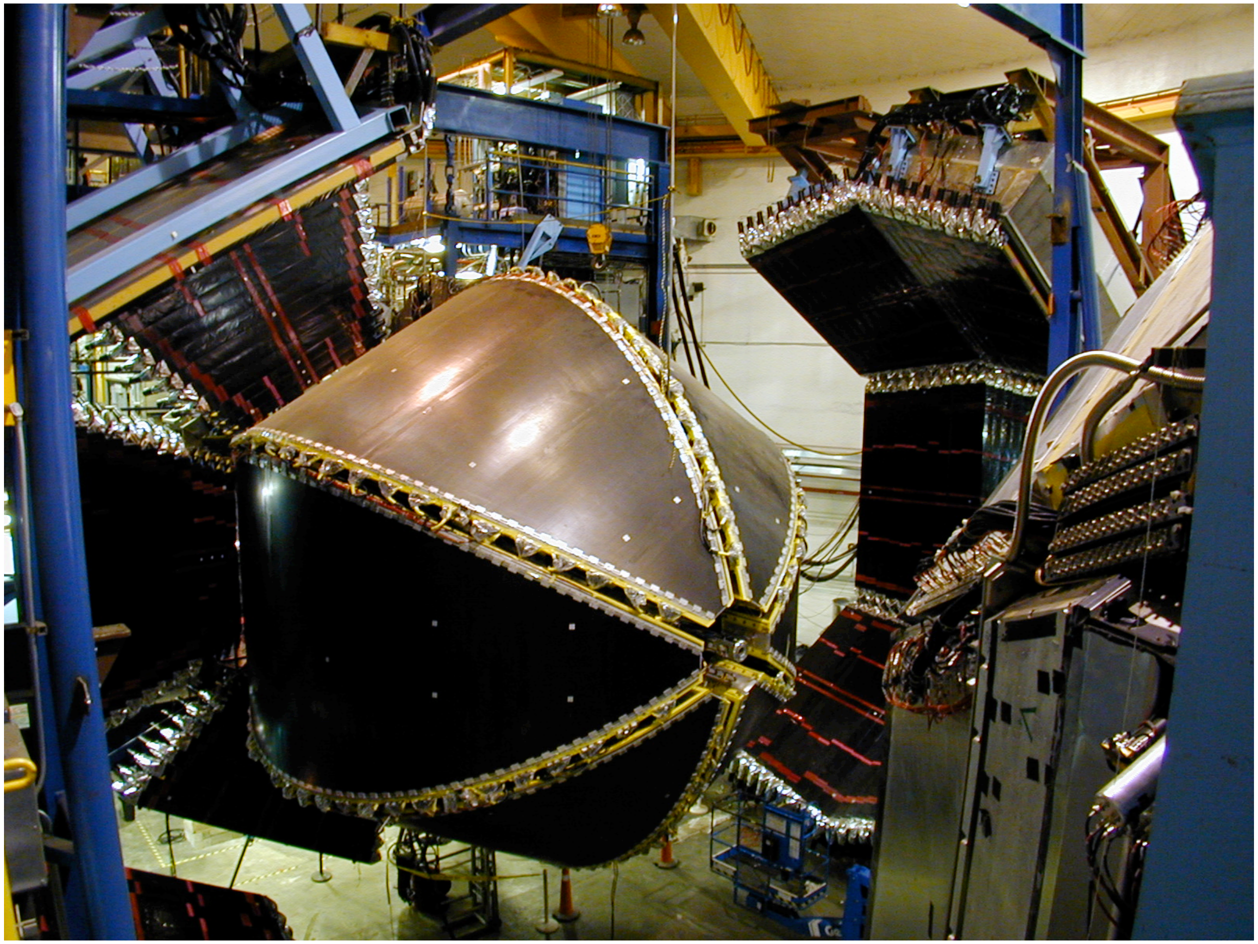
rTPC inside Solenoid inside CEBAF Large Acceptance Spectrometer (CLAS)

Track scattered e^- in CLAS

Locate e^- interaction point in target.

Electron tracked in CLAS provides trigger to BONUS radial TPC

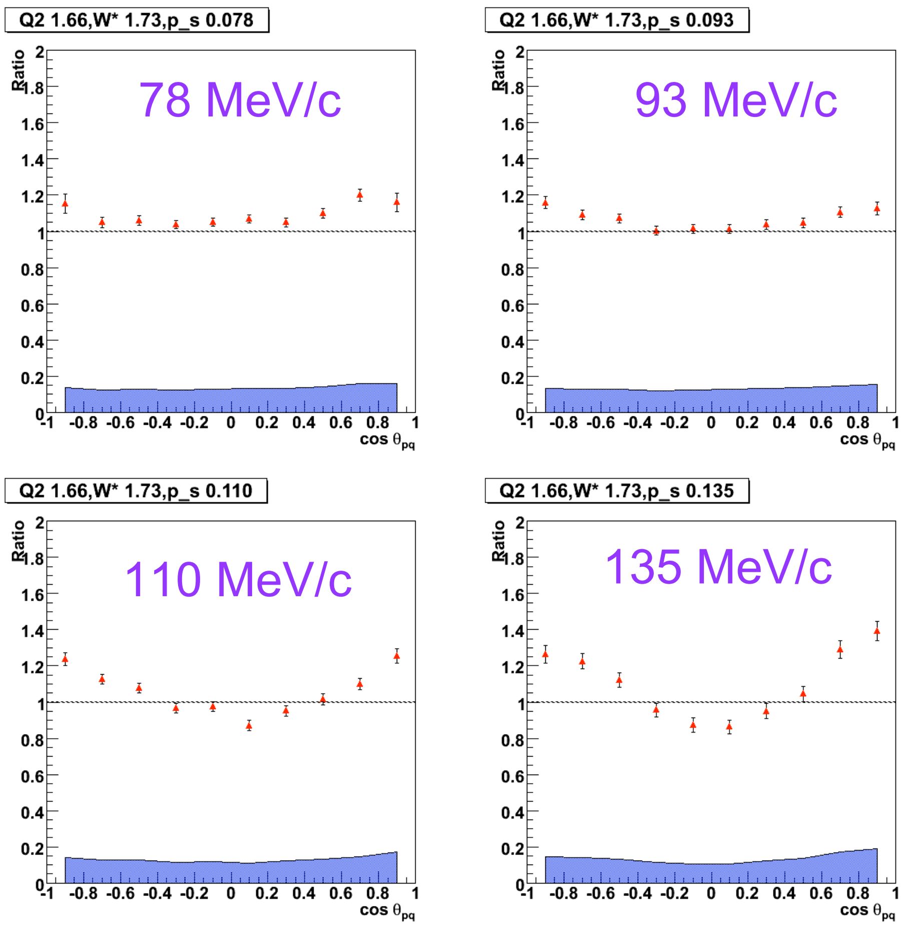
Link $p_{spectator}$ with electron vertex.



CLAS is made of Drift Chambers, Time of Flight Scintillators, Cerenkov counters and Electromagnetic Calorimeters for tracking, momentum determination, and Particle ID

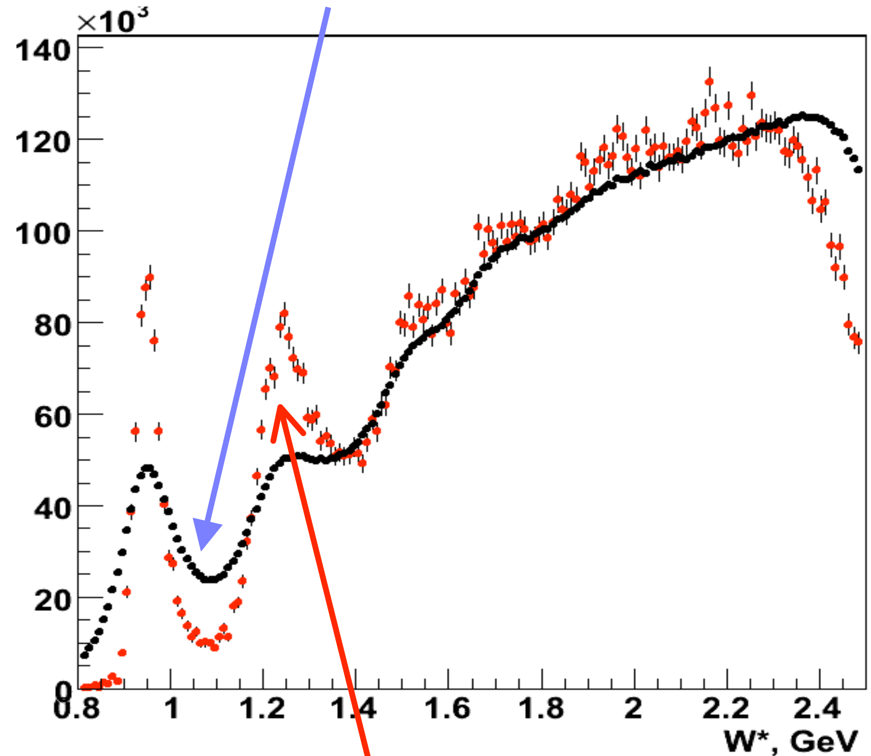
Results - I: *The technique works!*

angle - momentum dependence



$\cos\theta_{pq}$

$$W^2 = M^2 + 2M\nu - Q^2$$



$$W^{*2} = (p_n + q)^2 = p_n^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2$$

$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$

Results - II

N.K. Baillie, et al, PRL 108, 199902 (2012)

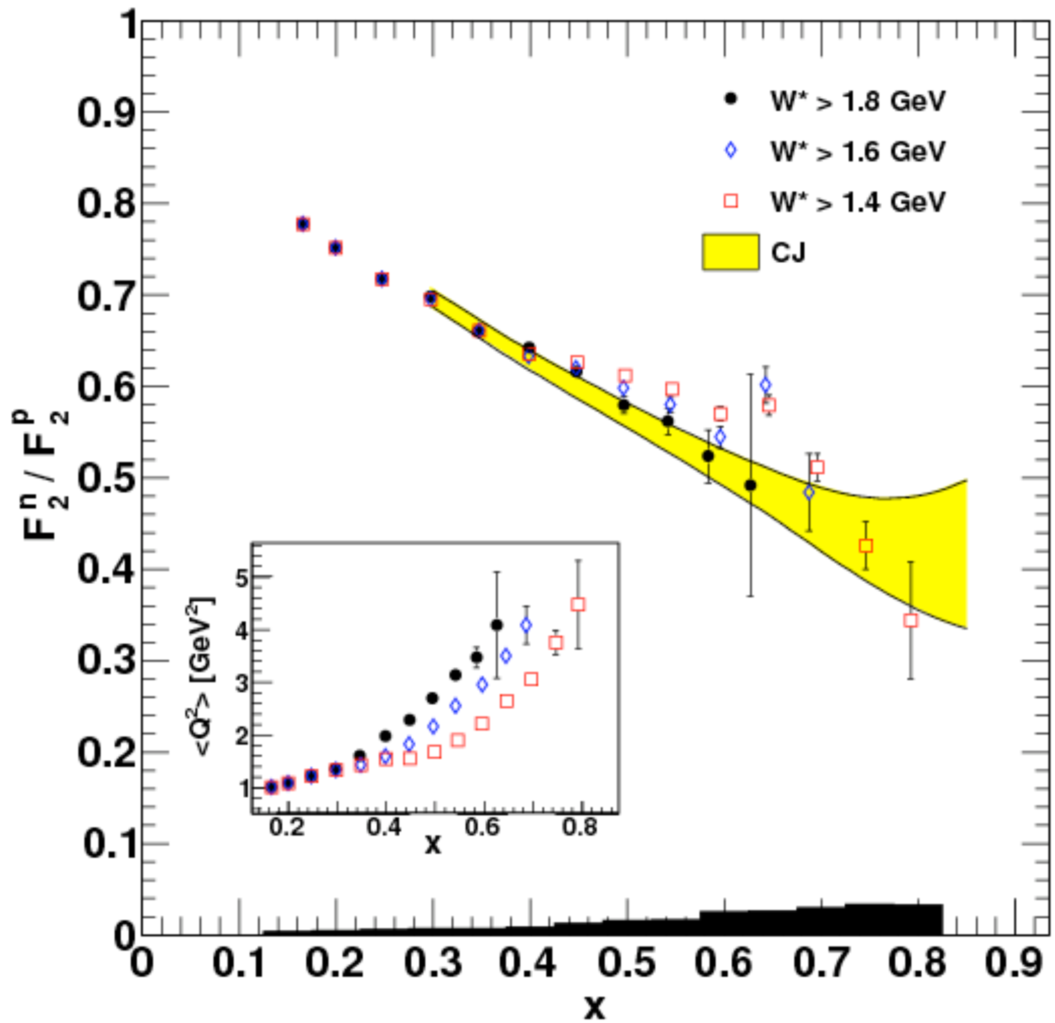
$P_{spectator} < 100$ MeV/c,

$\theta_{spectator} < 90$

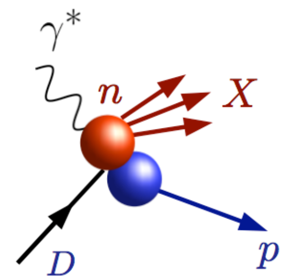
Textbook physics :) Plot is in Gauge Theories of the Strong, Weak, and Electromagnetic Interactions (Chris Quigg)

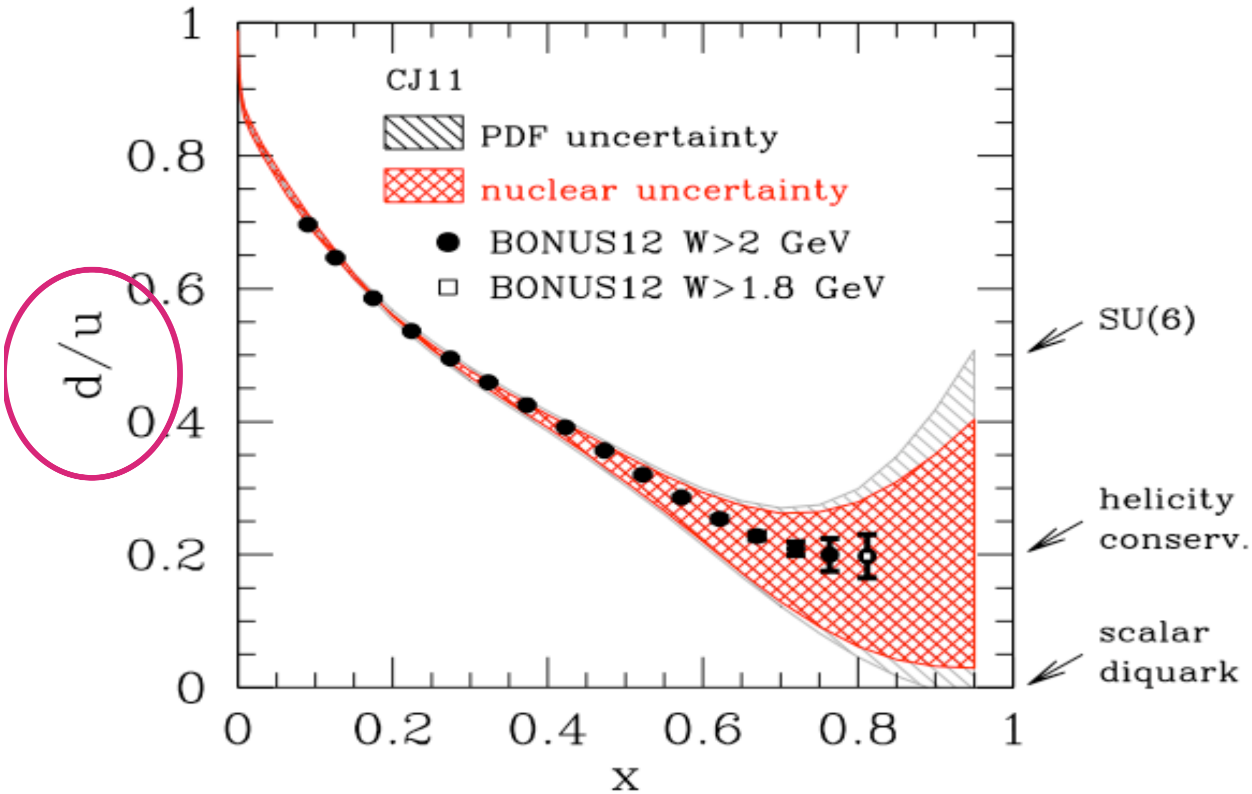
For CJ fit - see Accardi talks at this meeting

Still not quite large enough x……



12 GeV JLab running approved



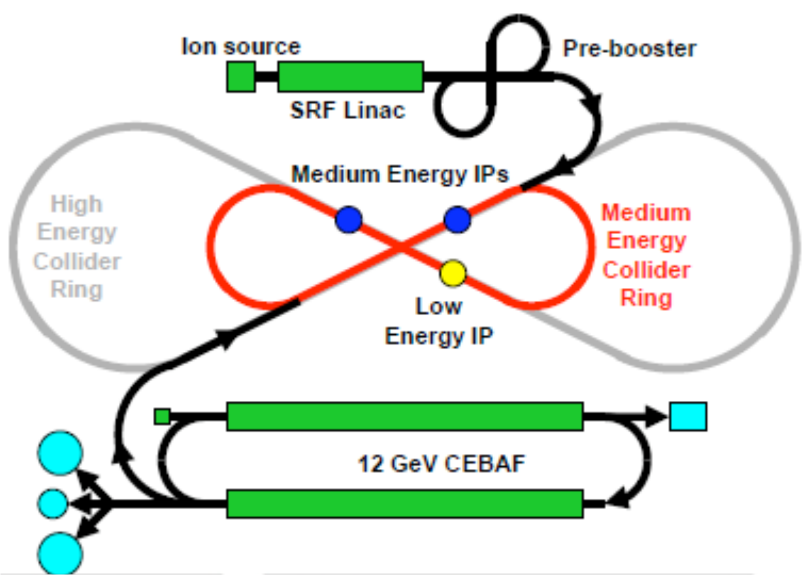


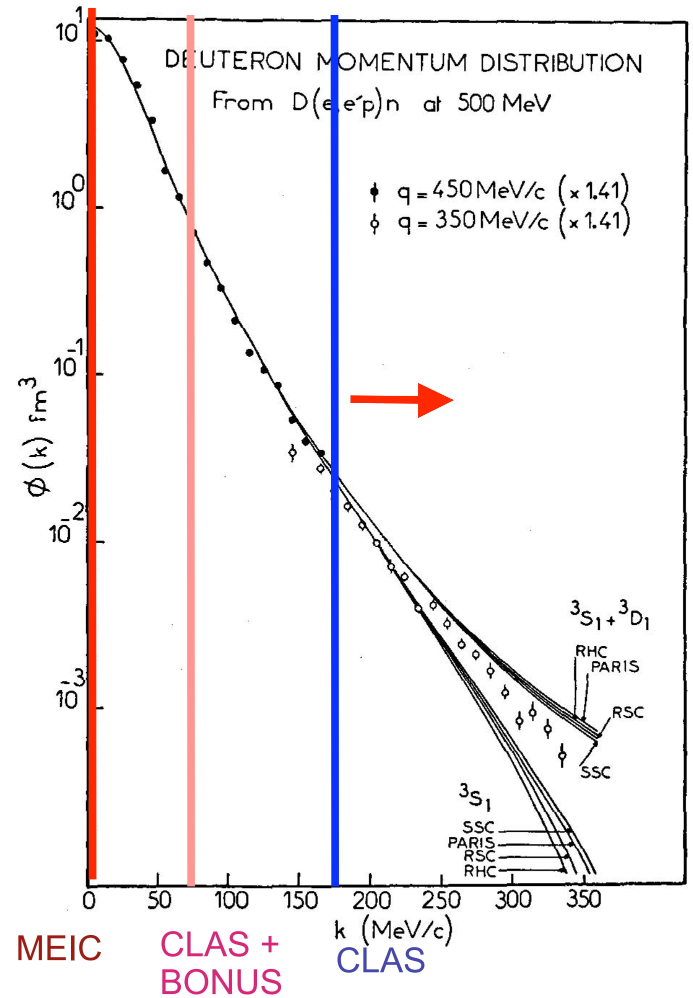
Projected BONUS12 uncertainties statistical + systematic

CJ 2011 pdfs - with nuclear uncertainty

Spectator tagging at (m)EIC

- A collider allows straightforward tagging of spectators
- 4 x 10.6 Tm arc dipoles bend 30 GeV/nucleon beam 106.0 mr
- Detectors ~1mm from beam achieve proton detection with < 100μ resolution

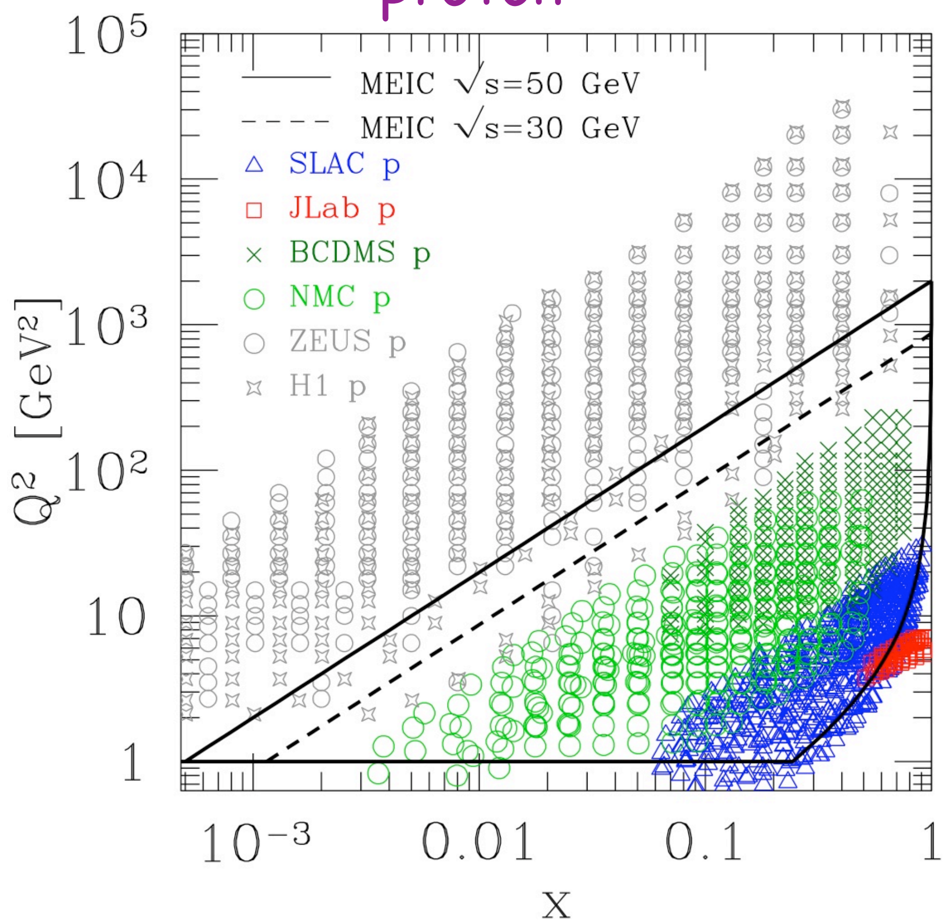




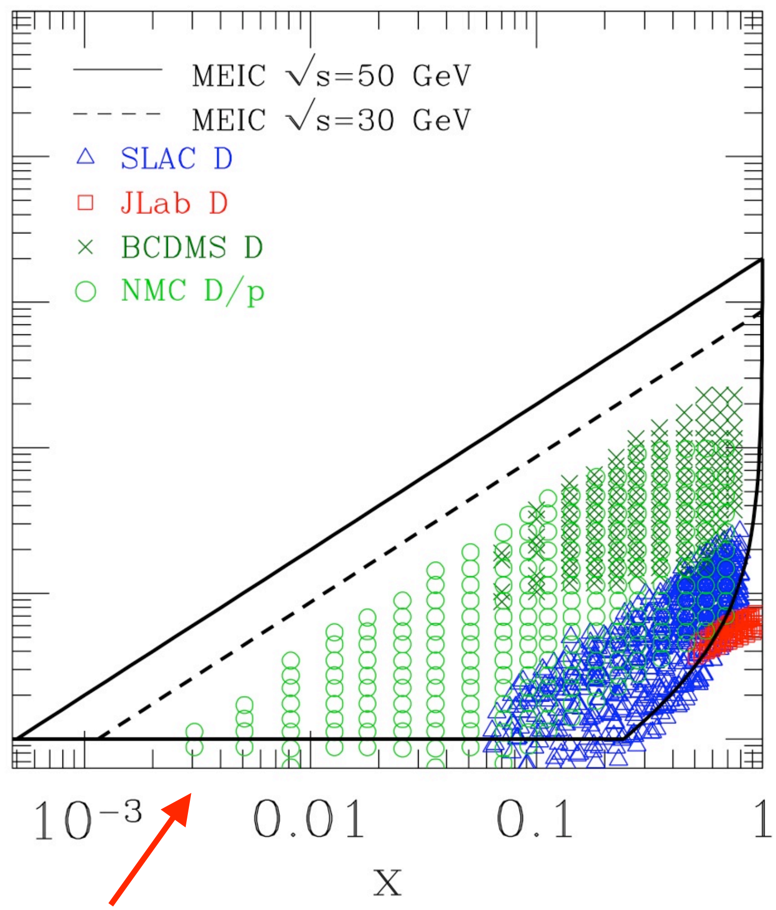
Proton tagging concept looks doable!

F_2 Structure Function Phase Space

proton

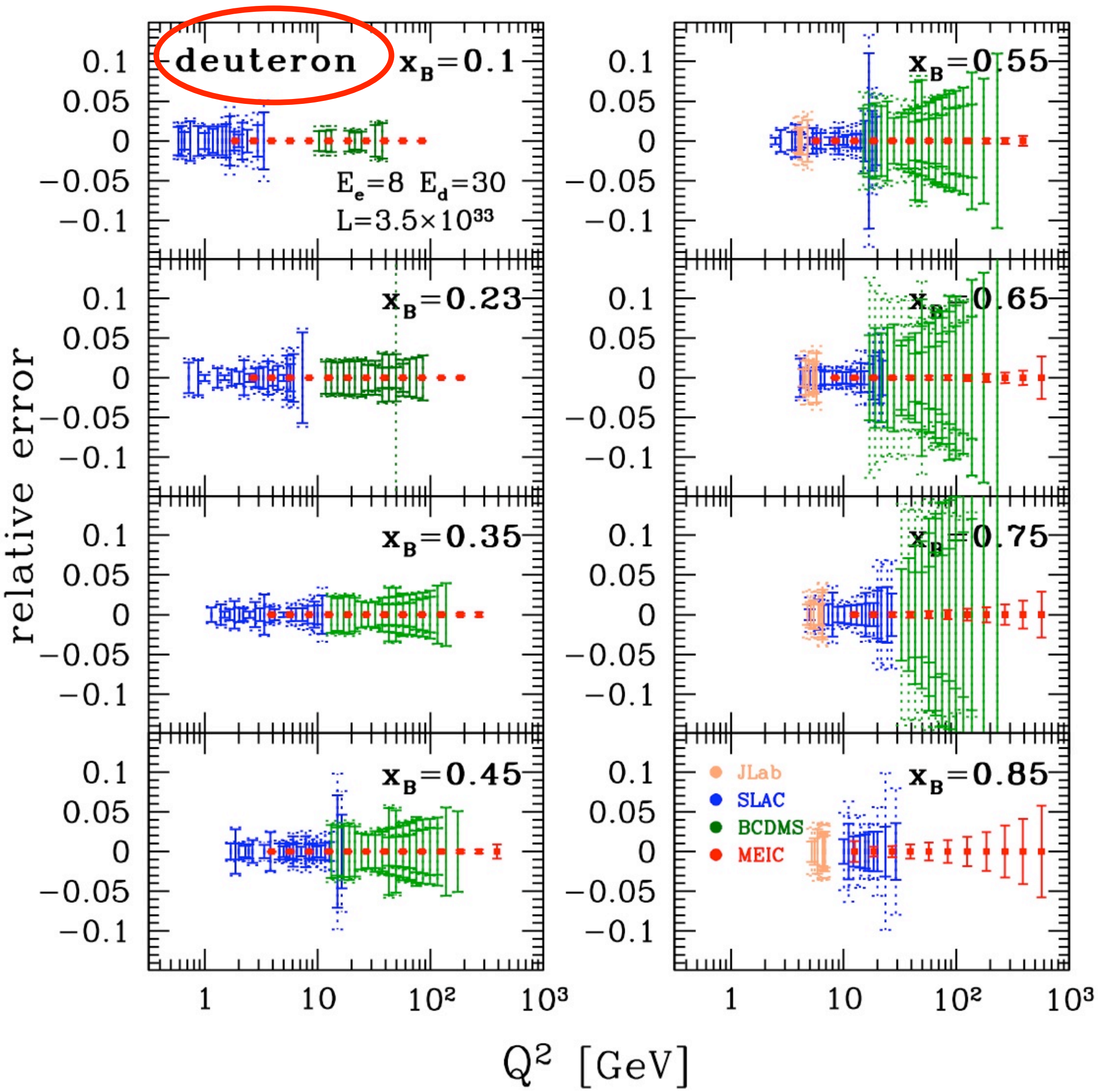


deuteron - *much less information available*



MEIC will probe lower x in the shadowing region, and higher Q^2 at large x.

Projected mEIC Results - F_2^d Structure Function Relative Uncertainty



Solid lines are statistical errors, dotted lines are stat+syst in quadrature

Huge improvement in Q^2 coverage and uncertainty

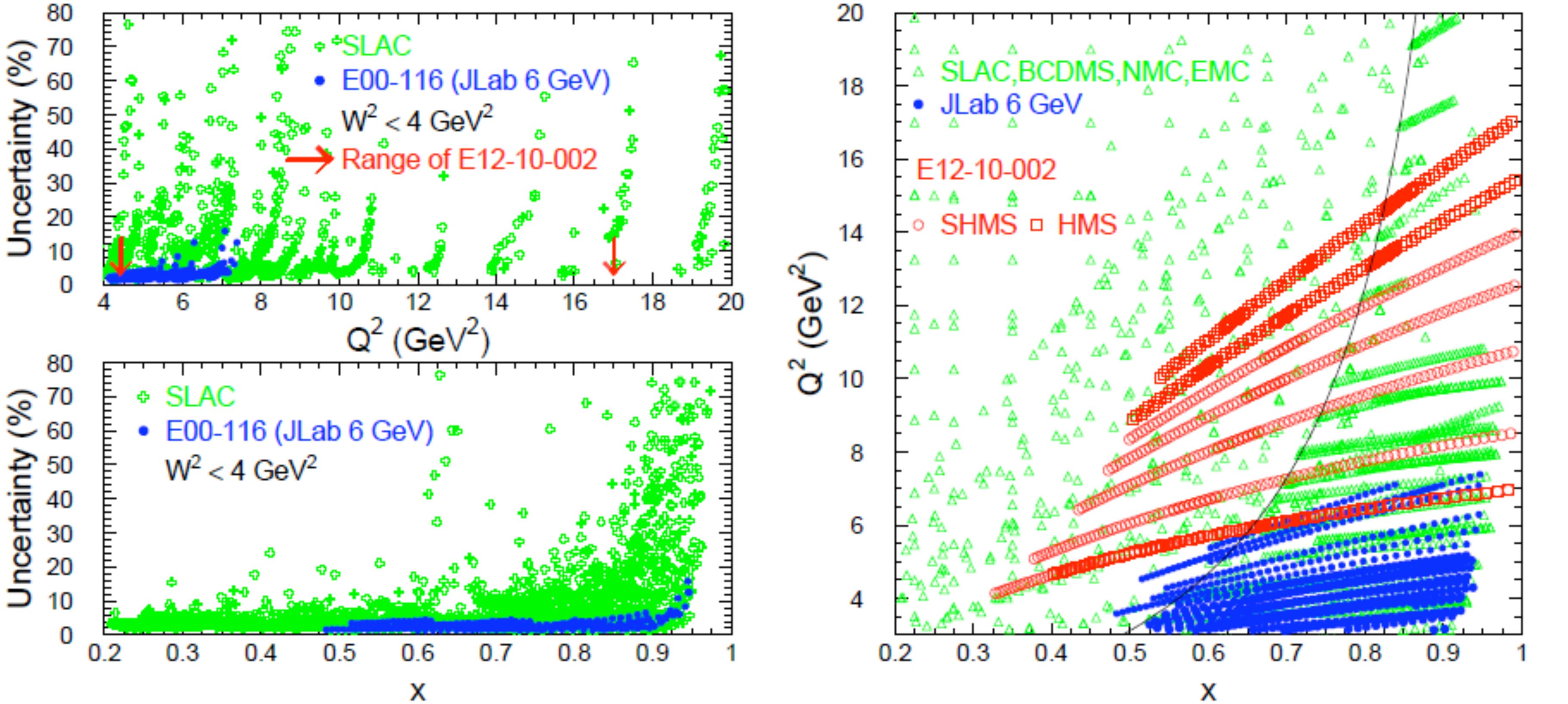
Proton even better (smaller neutron cross section)

Could greatly aid global pdf fitting efforts

EIC will have excellent kinematics to measure n/p at large x!

F_2^p & F_2^d Structure Functions at High-x

One of envisioned JLab12 Hall C commissioning experiments aims to reduce uncertainties in F_2^p and F_2^d structure functions accessible within 12-GeV phase space



Goal @ 12 GeV: similar precision as E00-116 (@ 6 GeV)

Back to something nearer term…

Hall A Projected Experiment Schedule as of 8/2012 (on wiki!)

	February - May	August – December	February - June	August - December	February - June	September - December
2014	GMp / DVCS – I (APEX)	GMp / DVCS - I				
2015			$^3H/^3He$ (A_1^n)	PREX (APEX)		
2016					A_1^n (SBS) (DVCS-II) (APEX)	SBS (A_1^n) (DVCS-II) (APEX)

SBS

MOLLER,
SOLID...?....

DIS from A=3 nuclei

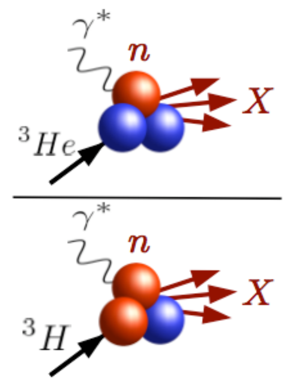
$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n}\,, \qquad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}$$

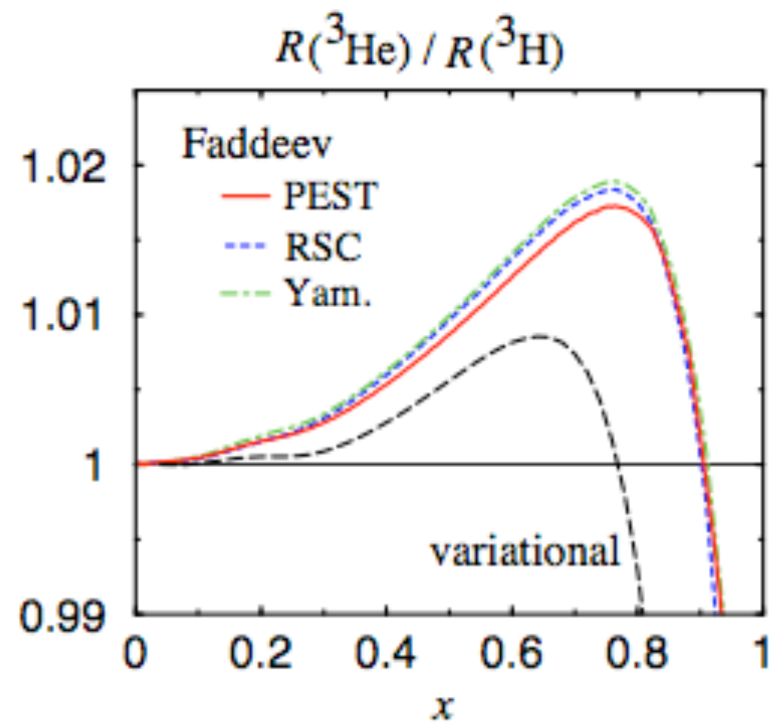
- Mirror symmetry of A=3 nuclei
  - Extract F_2^n/F_2^p from ratio of measured ^{3}He/^{3}H structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

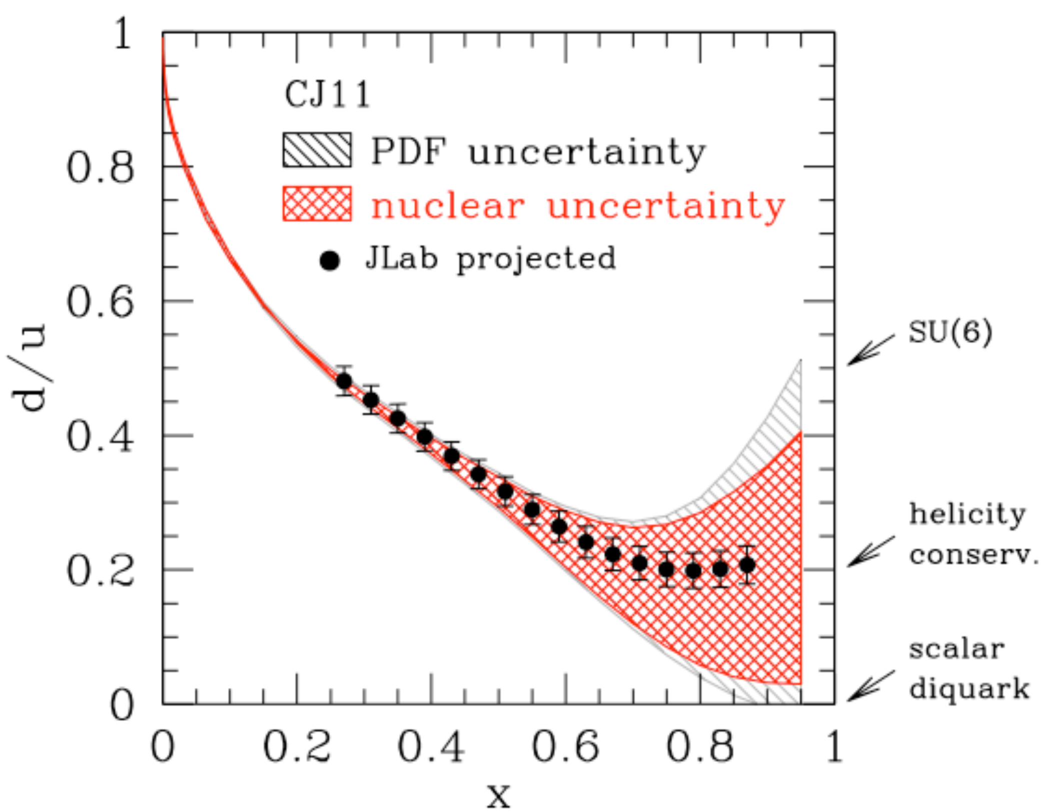
$\mathcal{R}$ = SUPER ratio of "EMC ratios" for ^{3}He and ^{3}H

- Relies only on *difference* in nuclear effects in ^{3}H, ^{3}He
- Calculated to within 1%
- Most systematic and theoretical uncertainties cancel

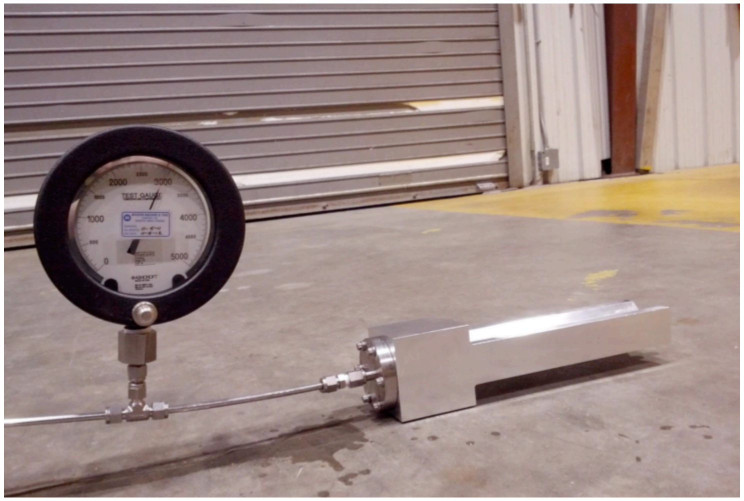




DIS from A=3 nuclei - Projected Results

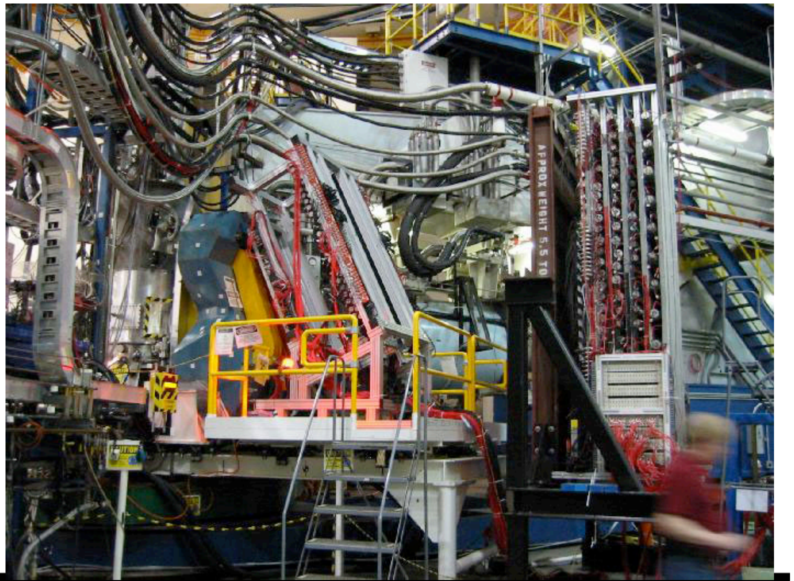


CJ pdfs - see Accardi talk



Test cell factor ~10 safety test, burst pressure above 3500 psi

Hall A BigBite Spectrometer



Polarized predictions for d/u at large x

Proton Wavefunction (Spin and Flavor Symmetric)

$$
\left|p\uparrow\right\rangle = \frac{1}{\sqrt{2}}\left|u\uparrow(ud)_{S=0}\right\rangle + \frac{1}{\sqrt{18}}\left|u\uparrow(ud)_{S=1}\right\rangle - \frac{1}{3}\left|u\downarrow(ud)_{S=1}\right\rangle
$$

$$
-\frac{1}{3}\left|d\uparrow(uu)_{S=1}\right\rangle - \frac{\sqrt{2}}{3}\left|d\downarrow(uu)_{S=1}\right\rangle
$$

Nucleon Model	F_2^n/F_2^p	d/u	$\Delta u/u$	$\Delta d/d$	A_1^n	A_1^p
SU(6)	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark	1/4	0	1	-1/3	1	1
pQCD	3/7	1/5	1	1	1	1

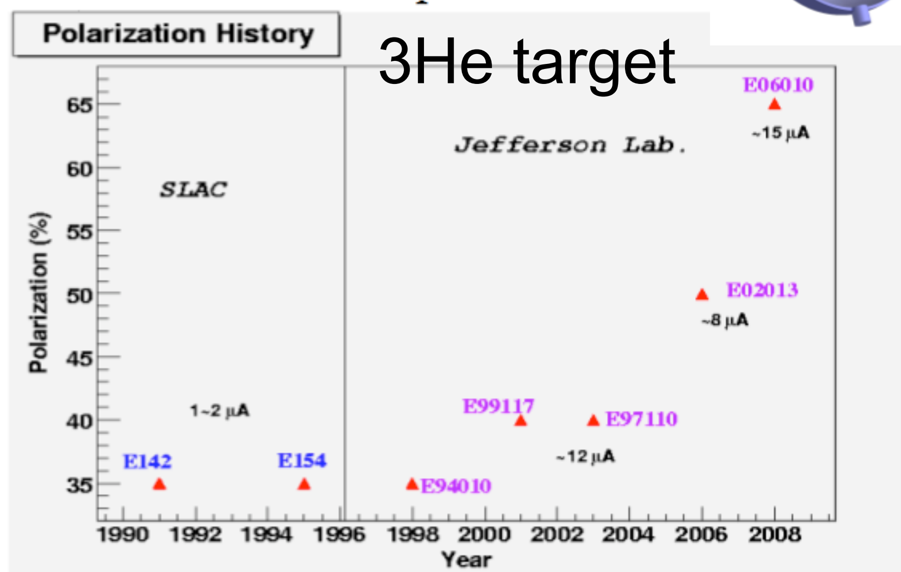
Polarized structure function data can provide d/u theory guidance

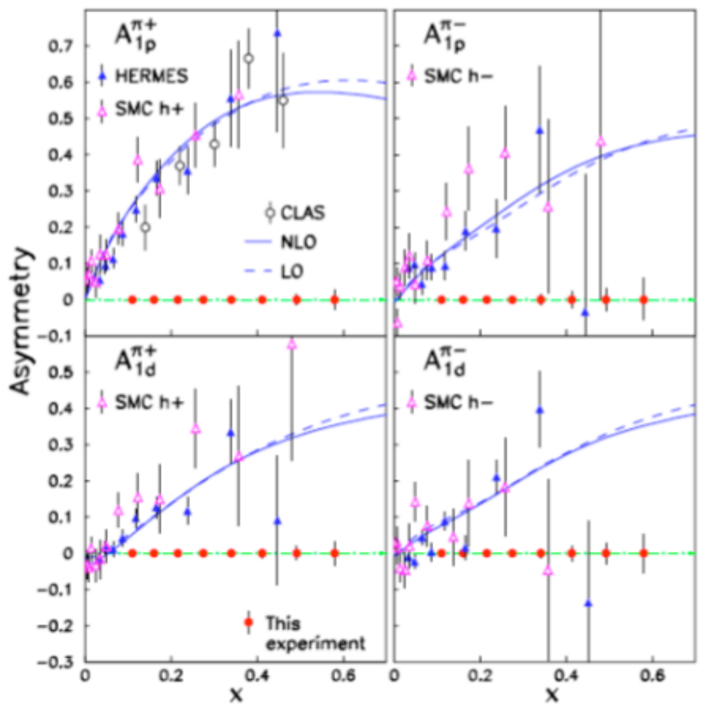
Measuring High-x Structure Functions - polarized

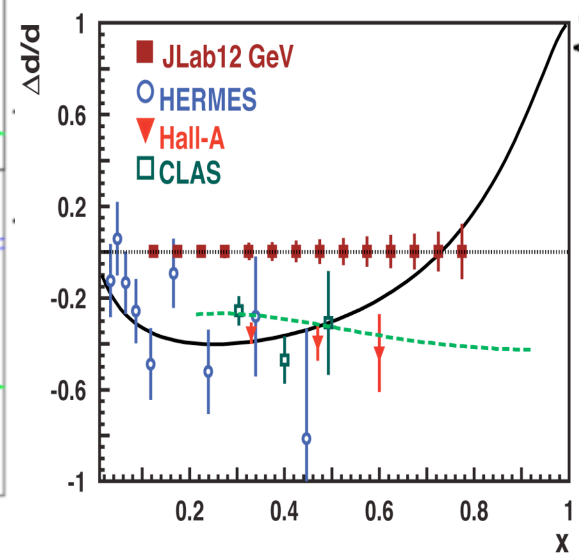
REQUIRES:

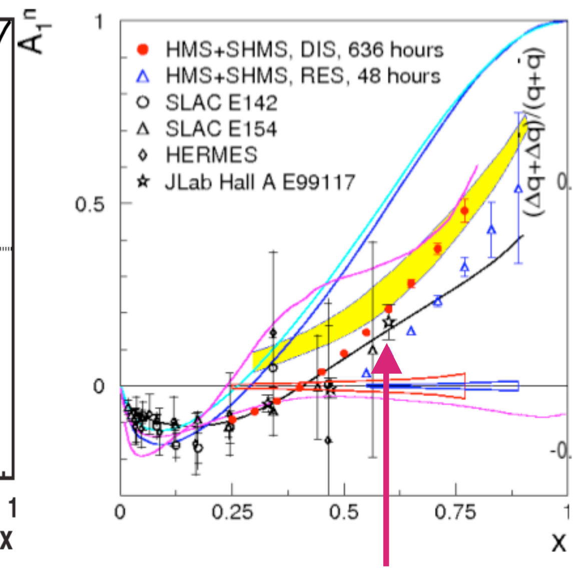
- High beam, target polarization
- High electron current
- Large solid angle spectrometers
- PDF efforts - JAM (see Accardi talk!)
- Broad JLab12 program!

3He target



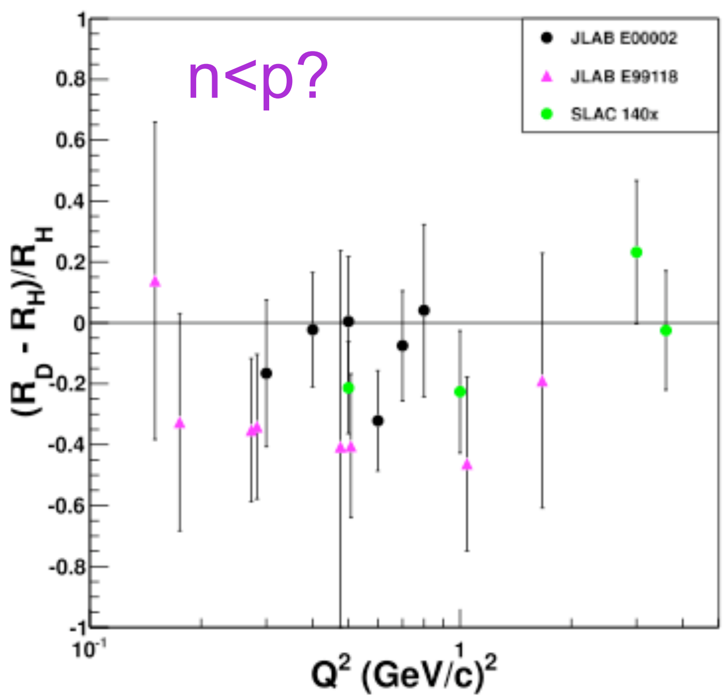






Need Longitudinal/Transverse separations to measure F_2 to highest precision - *could be some A-dependence*

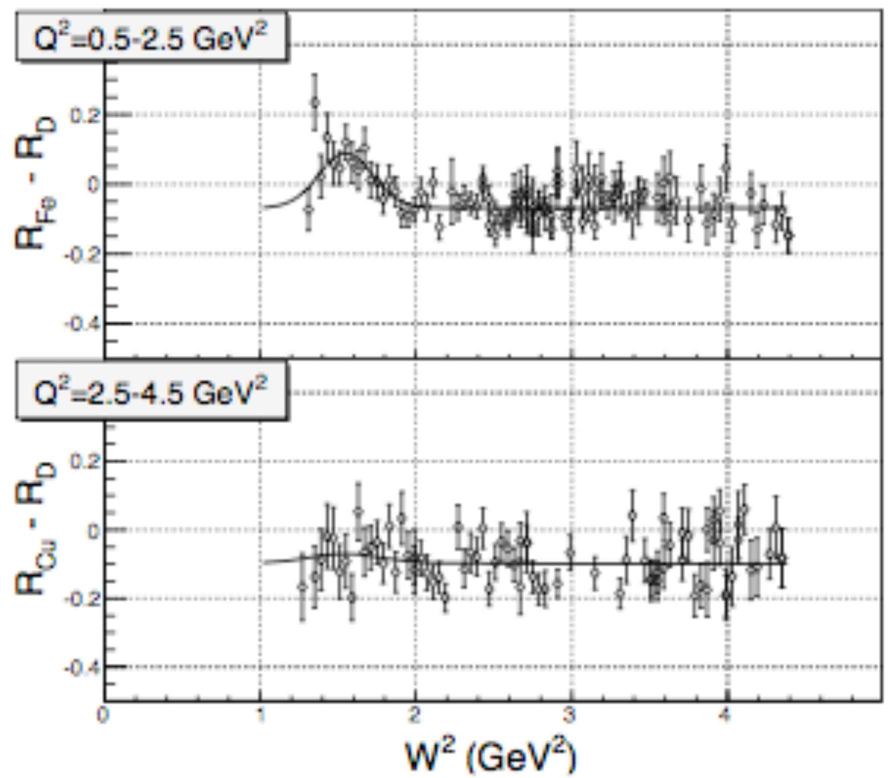
Nuclear dependence in F_L



JLab E00-002 (V. Tvaskis, et al, publication in drai

Previously measured only where R (F_L) ~ 0

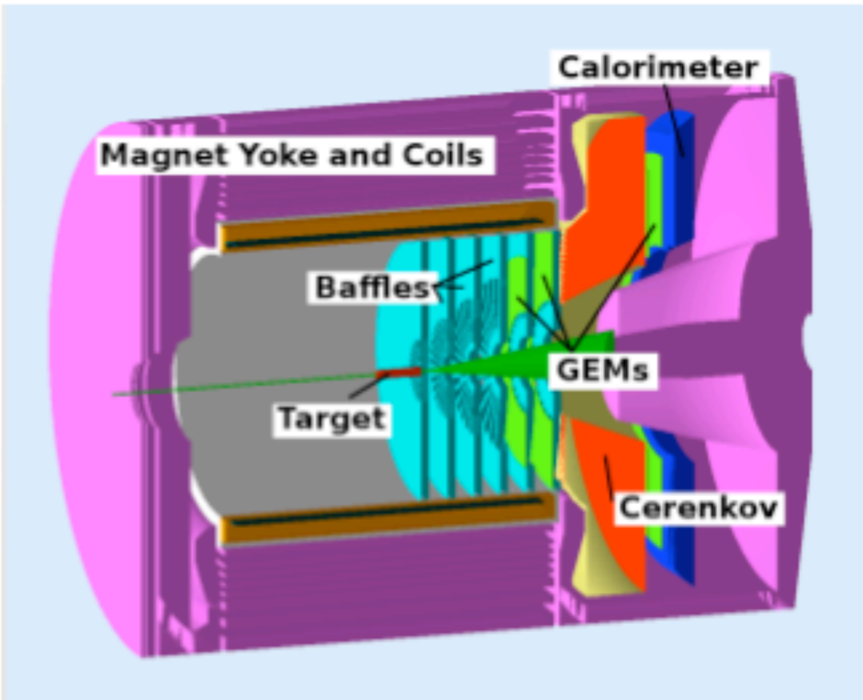
Preliminary results from JLab E06-109 (D), E04-001 (A) Dissertation of V. Mamyan (UVA)



Doesn't look like a big effect, but remember R is small (~0.2), so this is about a 30% effect!

PVDIS Measurements - SoLID Proposed Setup

Solenoidal **L**arge **I**ntensity **D**evice - 12 GeV Hall A at JLab
Parity-violating DIS program on deuterium and hydrogen



SoLID provides large acceptance

- $2 < p < 8$ GeV
- $2 < Q^2 < 10$ GeV^2
- $0.2 < x_{\mathrm{bj}} < 1$
- Acceptance $\sim 40\%$
- Lumin $\sim 5 \times 10^{38}$ Hz/cm^2

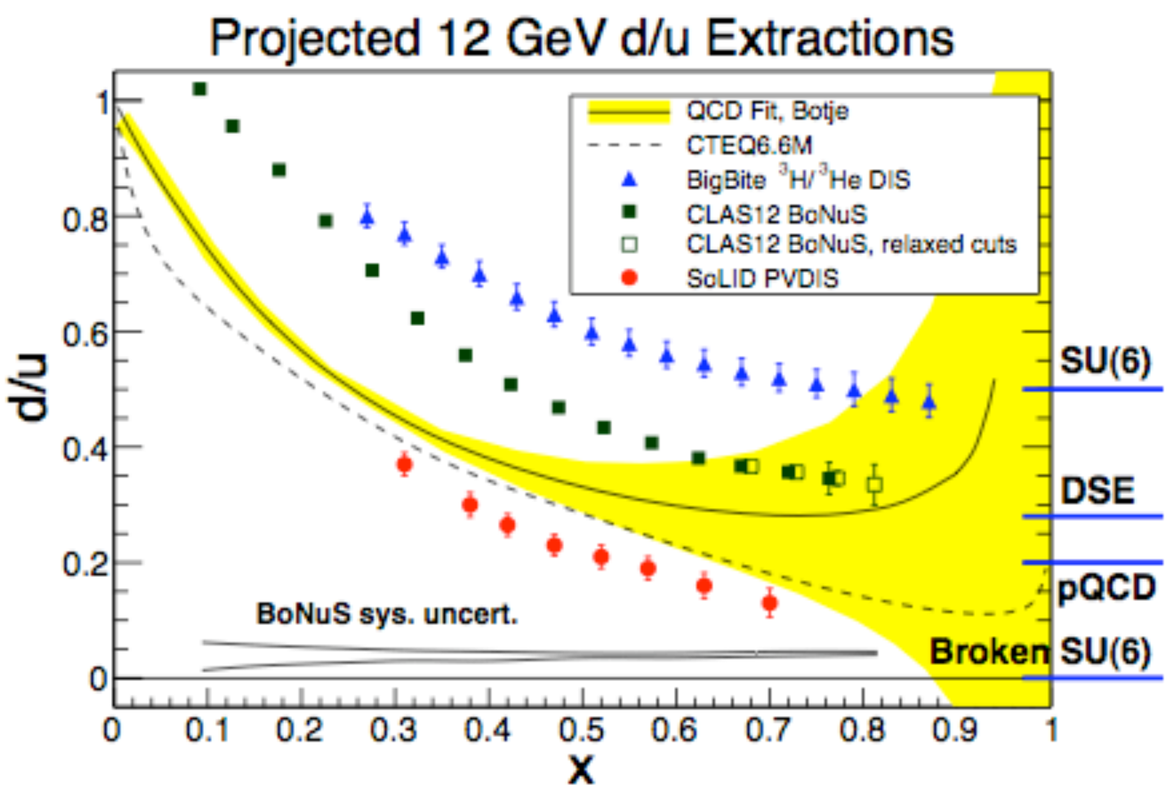
$$A_{\mathrm{PV}} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

$$a_1(x) = 2\frac{\sum C_{1q} e_q (q+\bar{q})}{\sum e_q^2 (q+\bar{q})}, \quad a_3(x) = 2\frac{\sum C_{2q} e_q (q-\bar{q})}{\sum e_q^2 (q+\bar{q})}$$

Clean Measurement of d/u with PVDIS

For high x on proton target:

$$a_1^p(x) = \left[\frac{12C_{1u}u(x) - 6C_{1d}d(x)}{4u(x) + d(x)}\right] \approx \left[\frac{1 - 0.91d(x)/u(x)}{1 + 0.25d(x)/u(x)}\right]$$

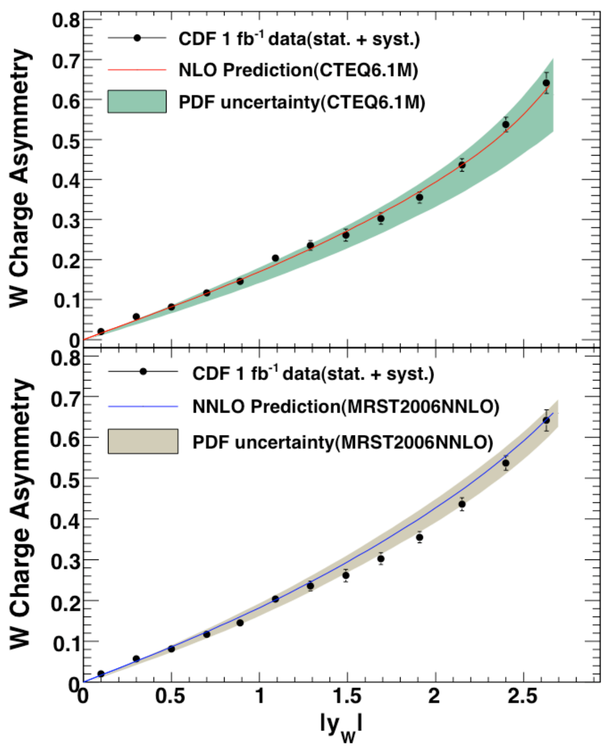


DSE - Wilson *et al.*, Phys Rev C**89**, 025205 (2012)

- Three JLab 12 GeV experiments:
  - CLAS12 BoNuS - spectator tagging
  - BigBite - DIS $^3\mathrm{H}/^3\mathrm{He}$ Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of d/u is made directly from *ep* DIS: *no nuclear corrections*

Other Approaches

- ν+*p* and ν-*bar*+*p* :
  - WA21 already has data
    (but need to reconstruct cross-sections from published "quark distributions"... very difficult)
- HERMES tagged structure functions (?)
- Duality (a lot of data now available)
- Collider experiments:
  - DY at large x_F
  - W-asymmetries at large rapidity
  - Lepton asymmetries



Summary

- There is a light at the end of the d(x)/u(x) large x tunnel - a lot of experiments en route!
- Jefferson Lab at 12 GeV dedicated experiments
- Will require some patience, first new experiment JLab Hall A ~2015
- *d(x) will help with g(x)*
    - F_L too!