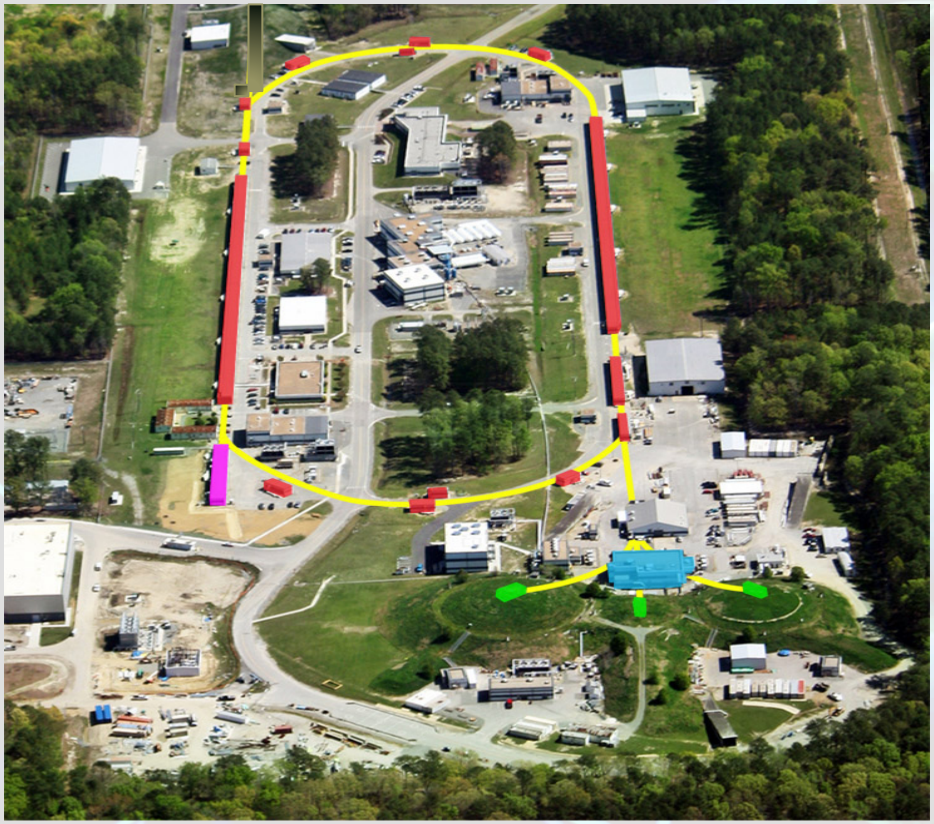
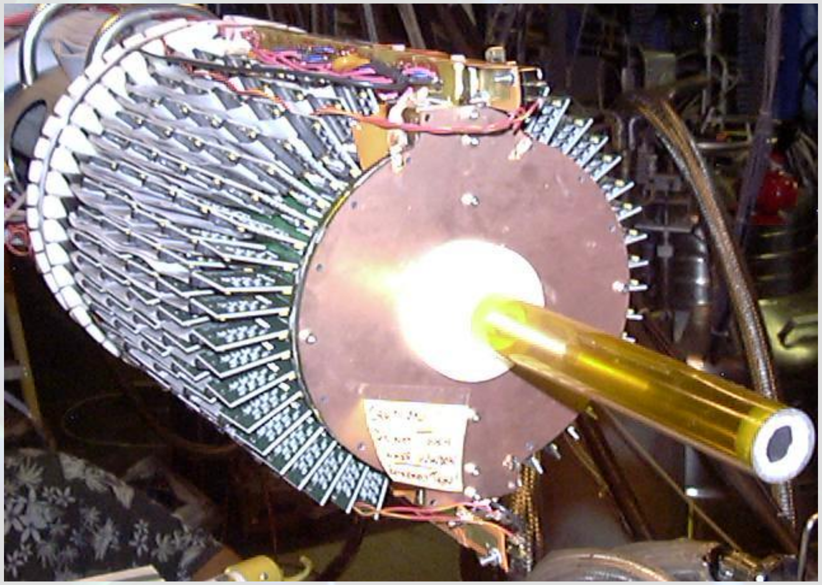
The Partonic Structure of Nucleons in the Valence Regime



Thia Keppel



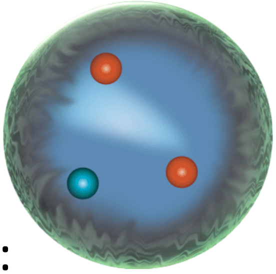
6th International Workshop on High Energy Physics in the LHC Era
Valparaiso, Chile 2016

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Why is the valence regime interesting?

- Valence region defines a hadron –
  baryon number, charge, flavor content, total spin, …
- Keen discriminator of nucleon structure models
- High x valence regime at low Q^2 evolves to low x, high Q^2 -> impact on HEP
- New generation of experiments at JLab focused on high x
- SeaQuest Drell-Yan experiment E906 at FNAL focused on high x sea
- Proposed Electron Ion Collider can also explore high x

Nucleon Structure Example: F_2^n/F_2^p (neutron/proton) ratio at Large x



- SU(6)-symmetric wave function of the proton in the quark model:

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

  - u and d quarks same shape, SU(6) spin/flavor symmetry
  - In this model: d/u = 1/2, $F_2^n/F_2^p = 2/3$ for x -> 1
  - But, N and Δ would be degenerate in mass….

- SU(6) symmetry is broken: N-Δ Mass Splitting
  - Mechanism produces mass splitting between S=1 and S=0 diquark spectator.
  - symmetric states are raised, antisymmetric states are lowered (~300 MeV).
  - S=1 suppressed => d/u = 0, $F_2^n/F_2^p = 1/4$, for x -> 1

- pQCD: helicity conservation (q↑↑p) => d/u =2/(9+1) = 1/5, $F_2^n/F_2^p = 3/7$ for x -> 1

- Dyson-Schwinger Eq.: Contains finite size S=0 and S=1 diquarks
  - d/u = 0.28, $F_2^n/F_2^p = 0.49$ for x -> 1

There are more!

Multiple predictions for Large x

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

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

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
pQCD	3/7	1/5

Review Articles:

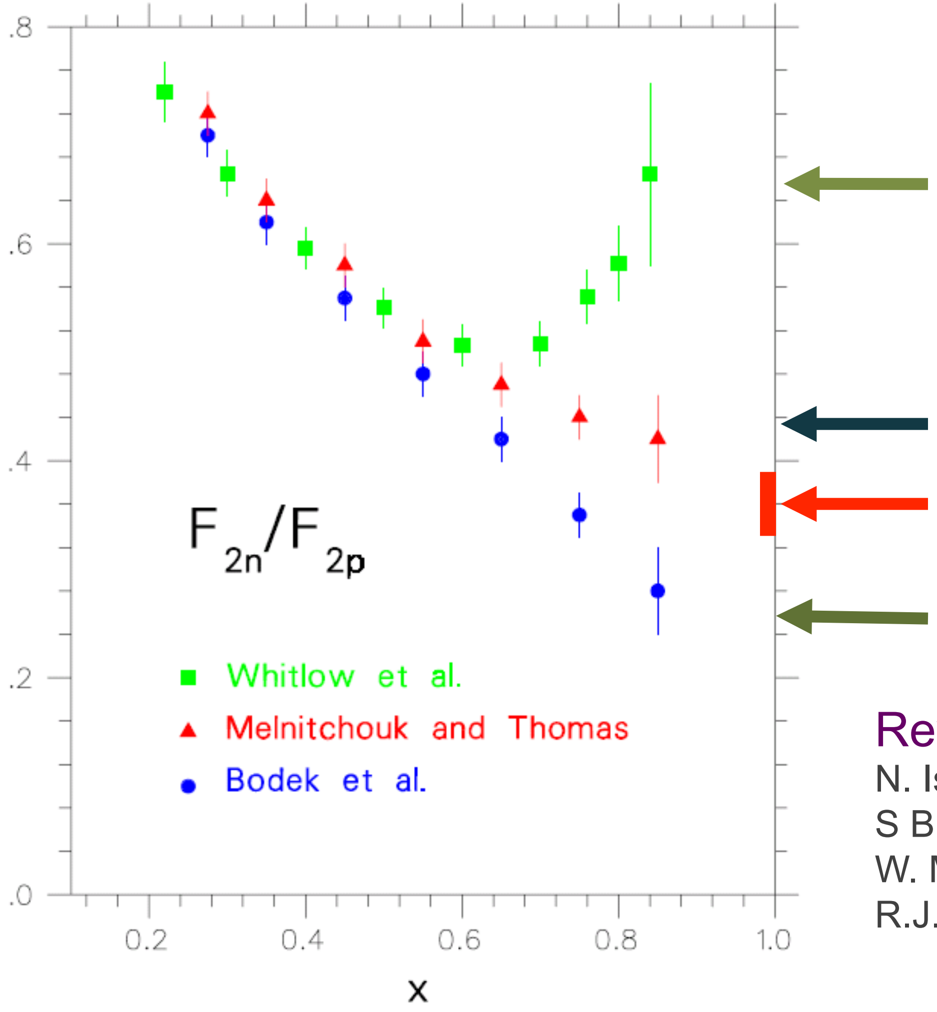
- N. Isgur, PR**D 59** (1999)
- S Brodsky et al NP **B441** (1995)
- W. Melnitchouk and A. Thomas PL **B377** (1996)
- R.J. Holt and C. D. Roberts, Rev. Mod. Phys. 82 (2010)

F_2^n/F_2^p (and, hence, d/u) is essentially unknown at large x:

- Conflicting fundamental theory pictures

- F_2^n data inconclusive due to uncertainties in deuterium nuclear corrections

- Translates directly to large uncertainties on d(x), g(x) parton distribution functions



SU(6) symmetry

pQCD

DSE: 0^+ & 1^+ qq

0^+ qq only

Review Articles:

N. Isgur, PRD **59** (1999)
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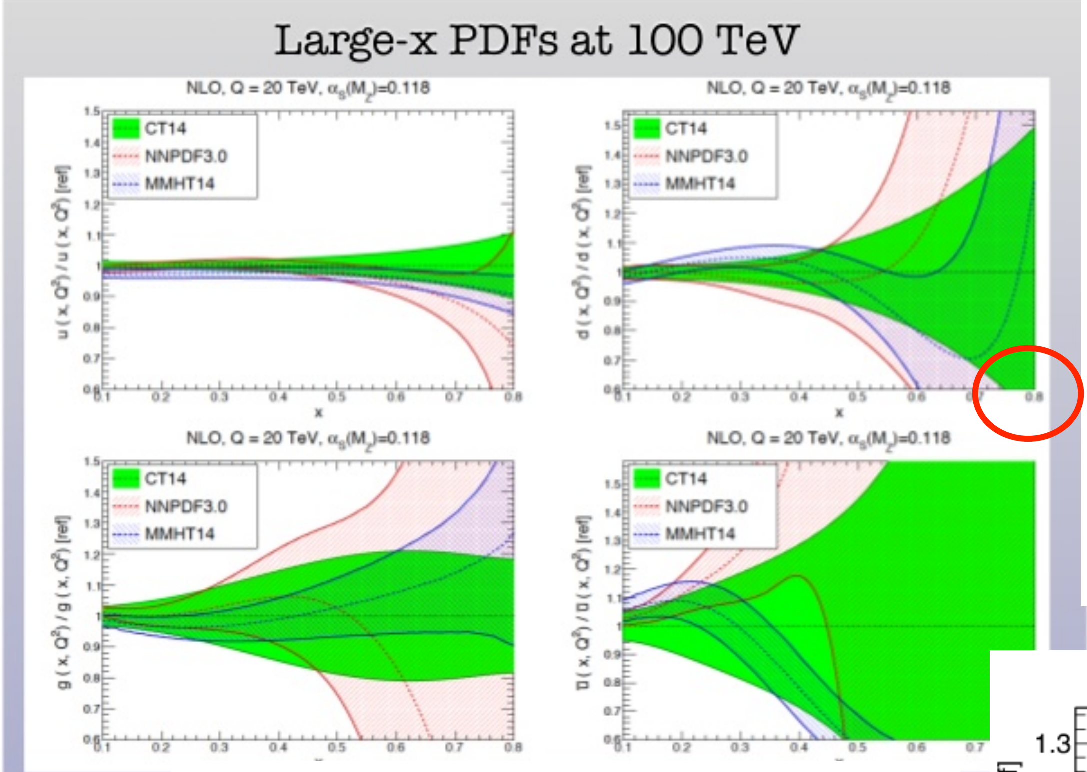
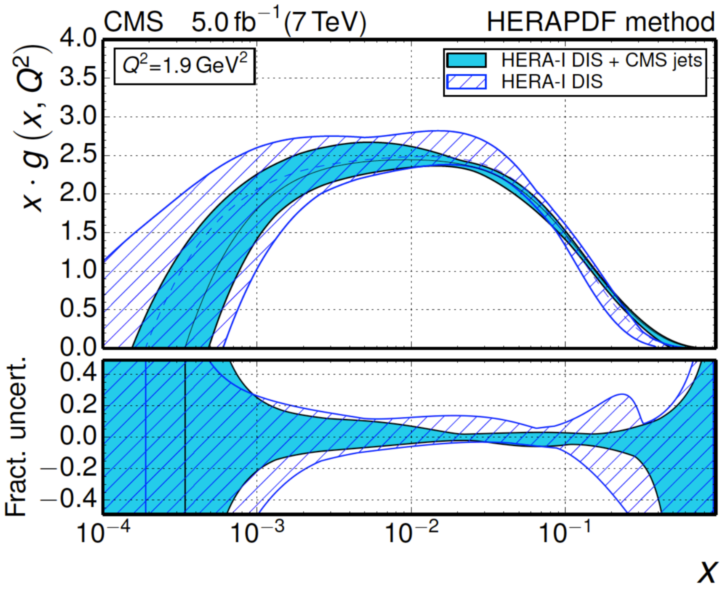
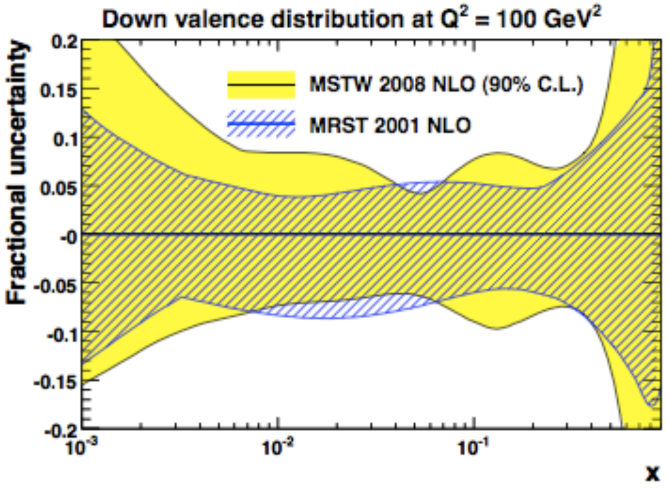
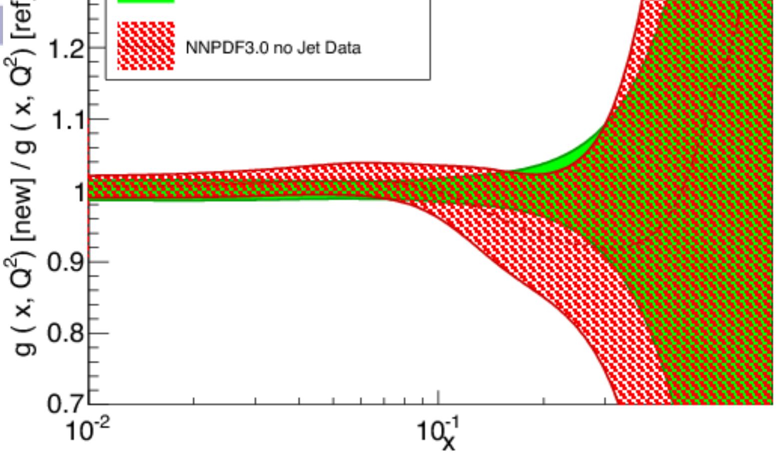
Present status: Large uncertainties on pdfs at large x


Large-x PDFs at 100 TeV

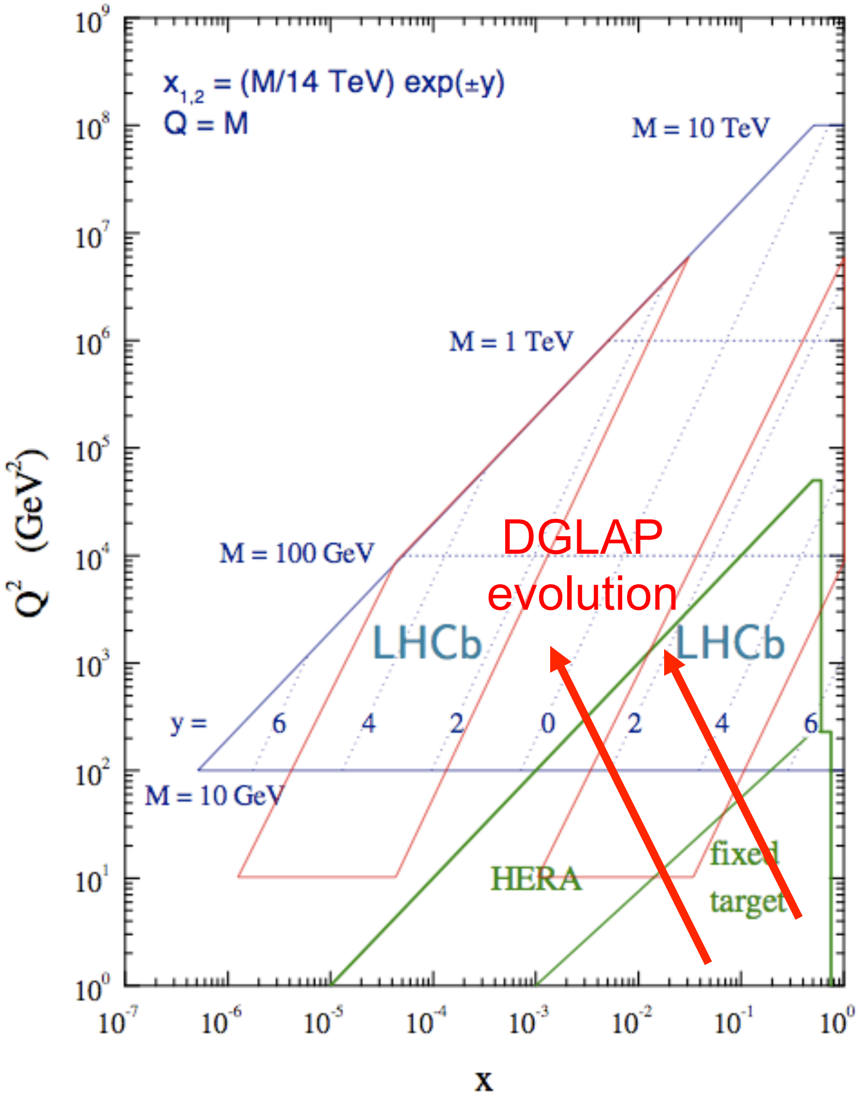




NNLO, $\alpha_S = 0.118$, $Q^2 = 10^4$ GeV^2



pdf Evolution



- DGLAP evolution allows high Q pdfs to be generated from those at lower Q
- Evolution at a value x_0 only requires knowledge of the pdfs at values of $x \geq x_0$
- As a result, high-x, low-Q feeds lower-x, higher-Q
- *Wide kinematic range over which pdfs must be known*

Example of kinematic coverage – heavy particle production in a collider

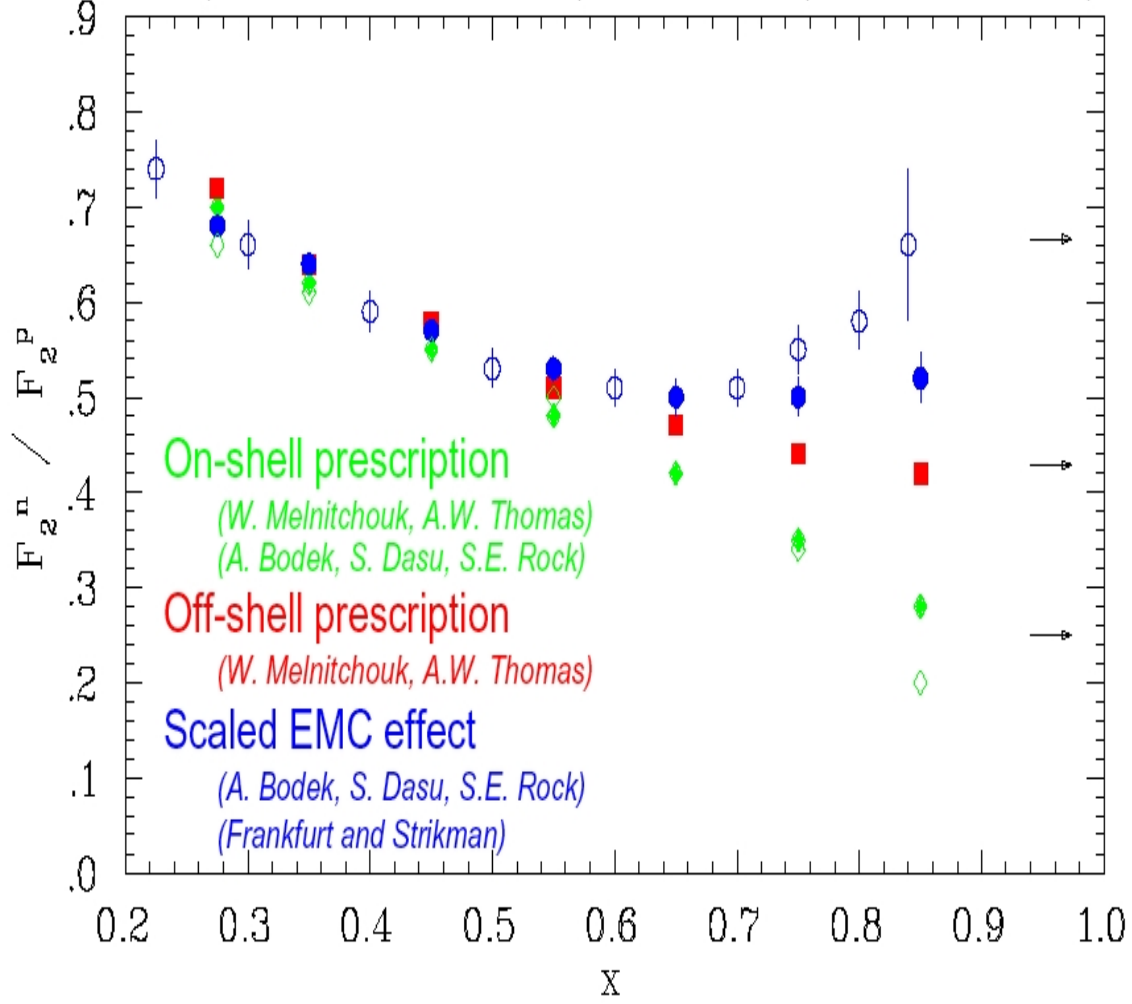
- Mass M, center-of-mass energy $\sqrt{s}$, rapidity Y
- $x_a = \frac{M}{\sqrt{s}}\, e^{Y} \qquad x_b = \frac{M}{\sqrt{s}}\, e^{-Y} \qquad x_a\, x_b = \frac{M^2}{s}$
- $\frac{M^2}{s} \leq x_i \leq 1$
- Factorization scale ("Q") $\sim M$
- Large Y with large M means one x is small, the other large.
- For a $q\overline{q} \to M + X$ subprocess at the LHC one would have a $\overline{q}$ at small x with a valence q at large x

Understanding small x means understanding large x

Why is the valence regime interesting?

- Valence region defines a hadron –
  baryon number, charge, flavor content, total spin, …
- Keen discriminator of nucleon structure models
- High x valence regime at low Q^2 evolves to low x, high Q^2 -> impact on HEP
- *New generation of experiments at JLab focused on high x*
- SeaQuest Drell-Yan experiment E906 at FNAL focused on high x sea
- Proposed Electron Ion Collider can also explore high x

Deuteron nuclear effects are a major obstacle….


Proton and deuterium data from SLAC E139 (*L. W. Whitlow, et al.*), and E140 (*J. Gomez, et al.*)

SAME data set

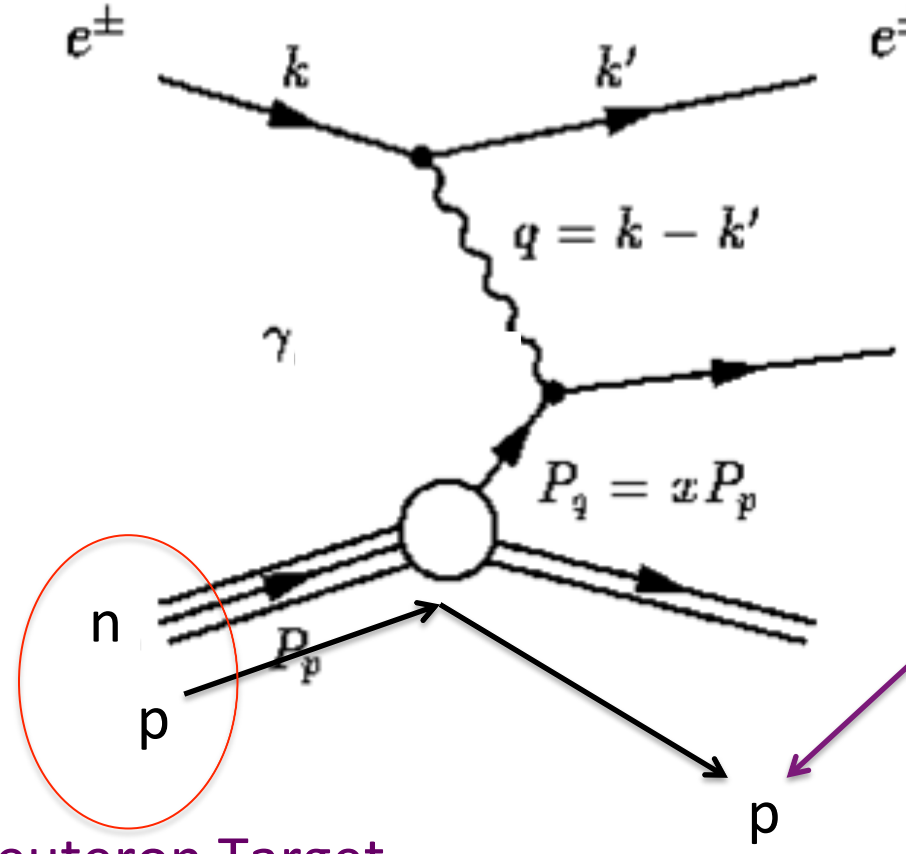
DIFFERENT nuclear effect analyses

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

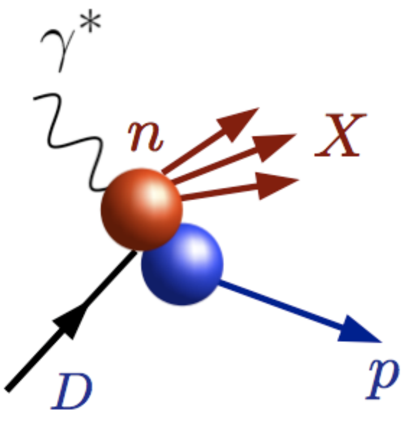
?!?!

BONUS at JLab – first experiment to use target tagging at JLab to create an effective *free* neutron target

e-n scattering



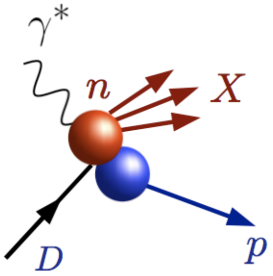
Deuteron Target



Measure DIS electron in coincidence with proton tag

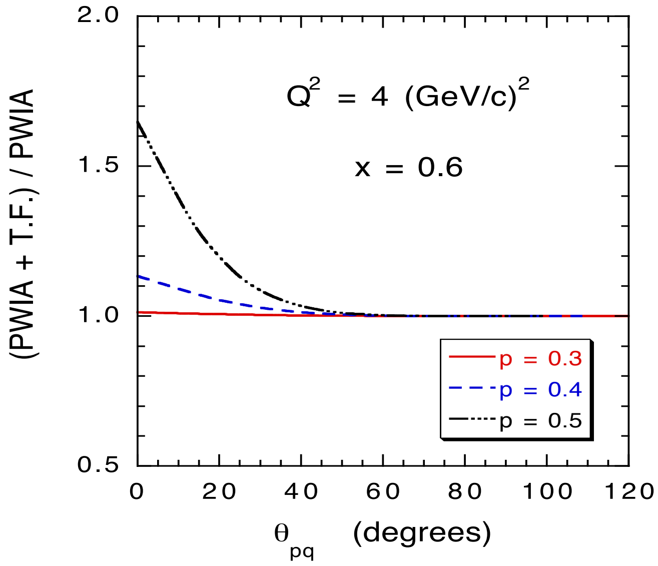
The lower the spectator proton momentum, the closer to a free neutron…

The BONUS approach: tag spectator proton at (very) low momentum *and* large angle in electron-deuteron scattering



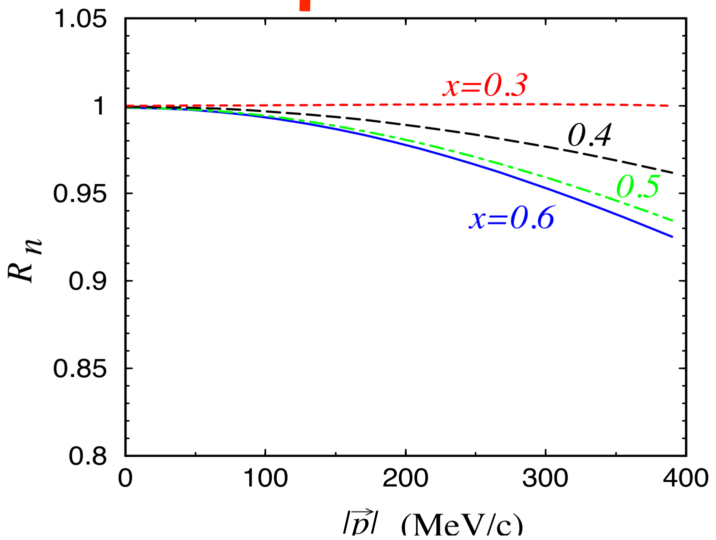
Bound / free neutron structure

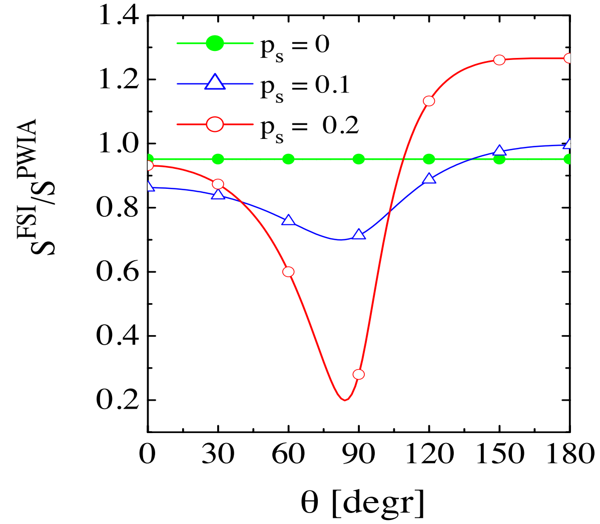
O **(1%)**



Target fragmentation

negligible



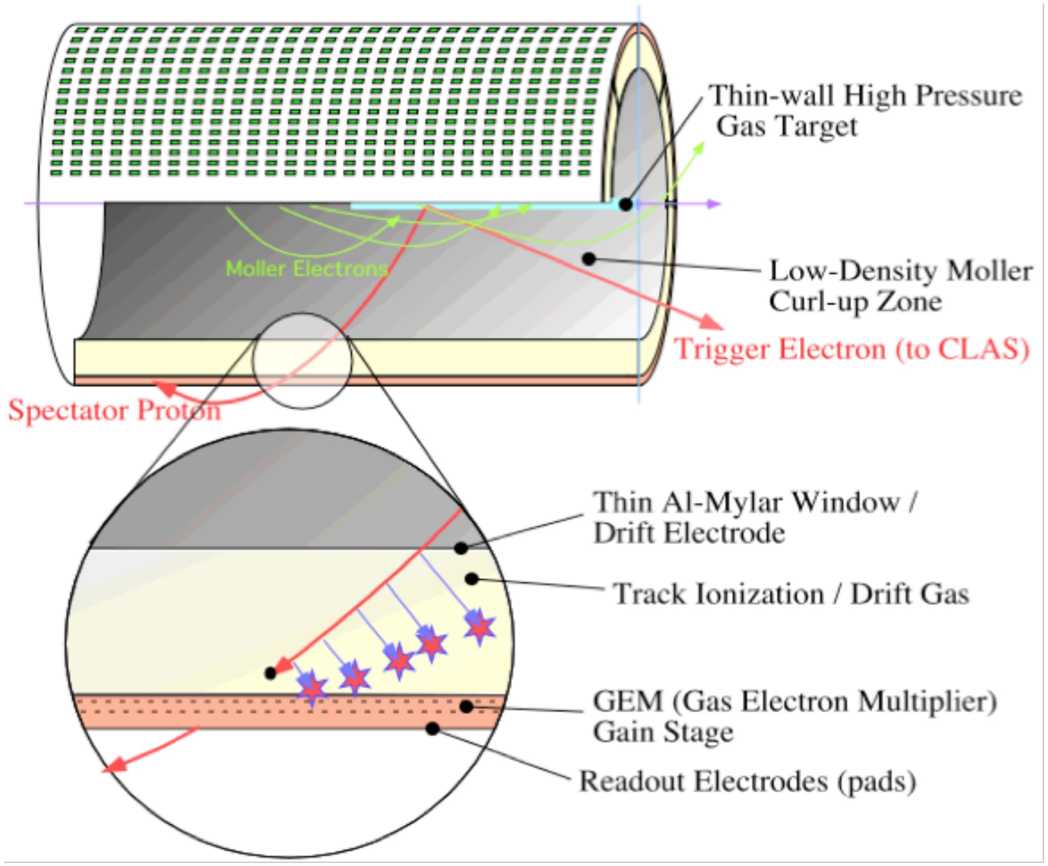


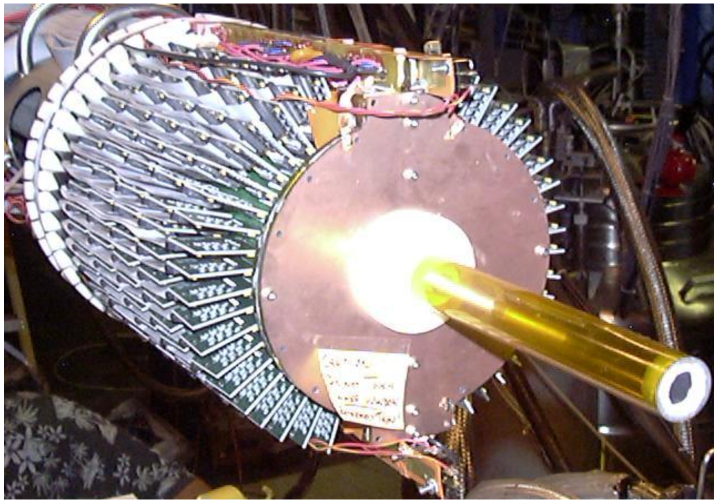
Final state interactions

O **(5%)**

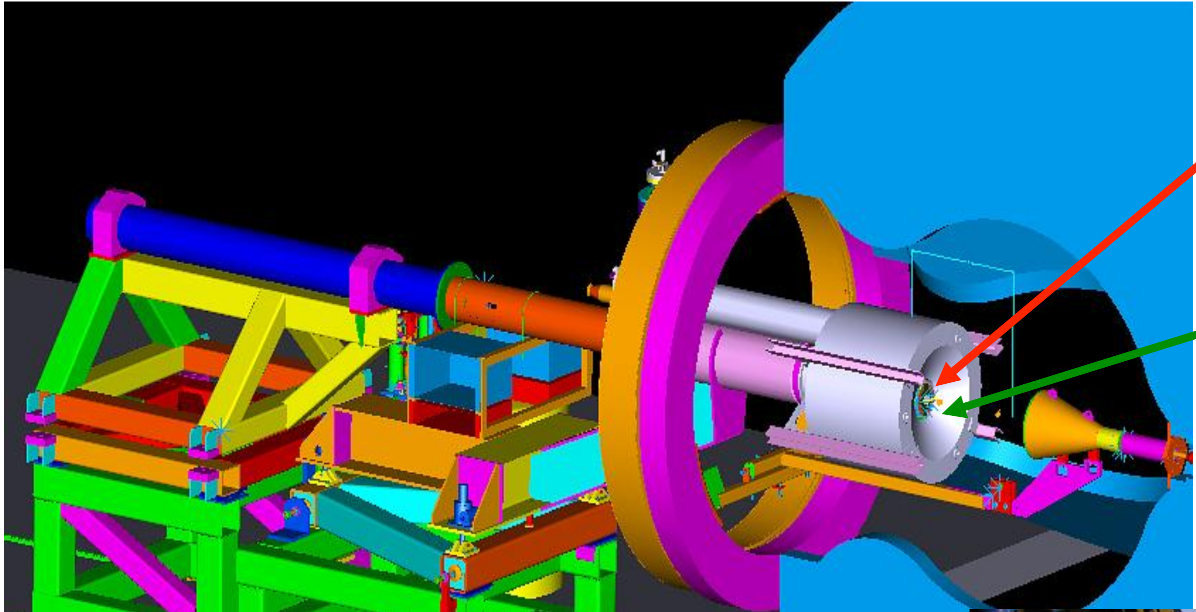
Spectator Proton Tagging

- *Low momentum* spectator must escape target
    - Thin deuterium gas target
    - Low density detector media
    - Minimal insensitive material
- Large acceptance
    - Backward angles important
    - Symmetric about the target
- Detector sensitive to spectators, insensitive to background
    - Use solenoidal field to contain Moller electrons
- GEM-based radial TPC



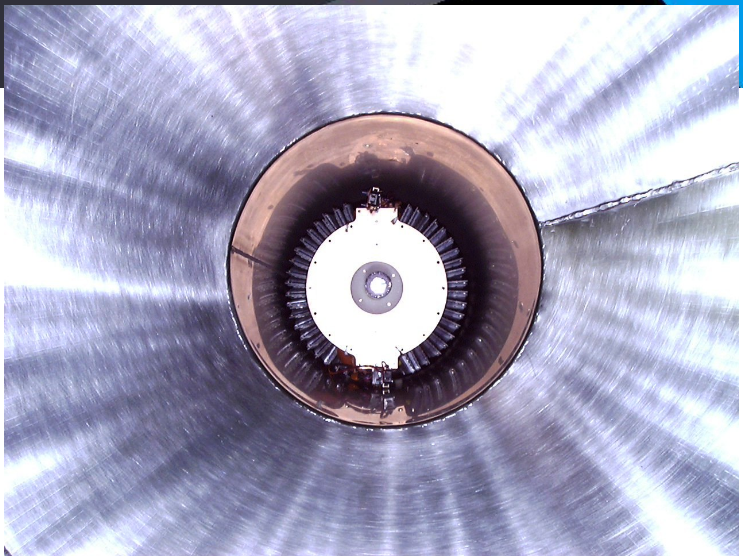


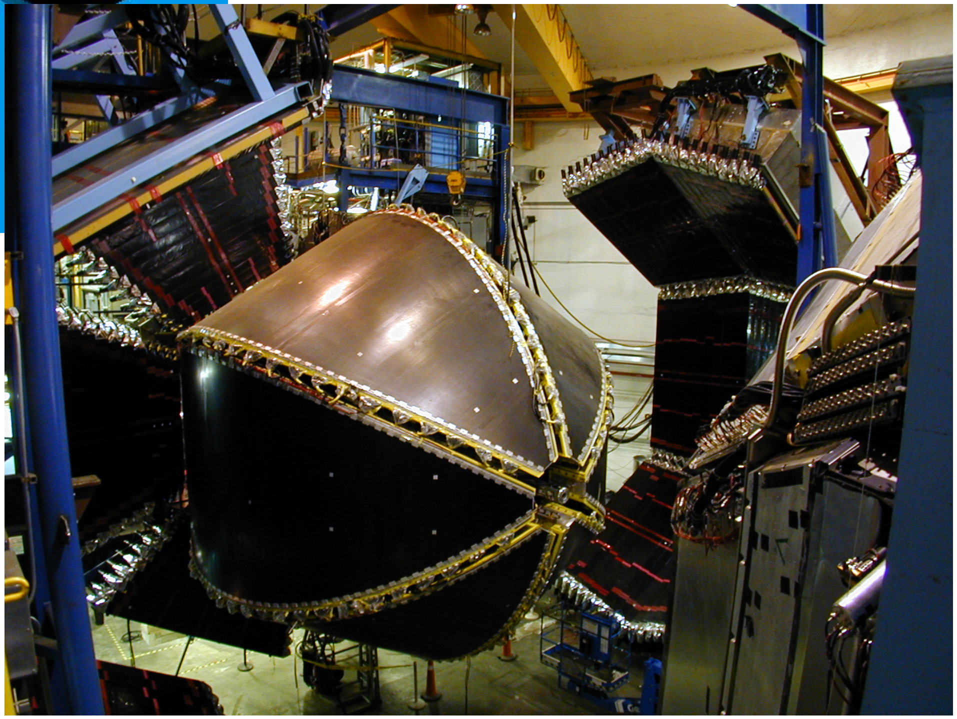
GEM-based radial Time Projection Chamber



BoNuS rTPC
(low momentum p
detector)

Solenoid Magnet
(track curvature in
TPC)

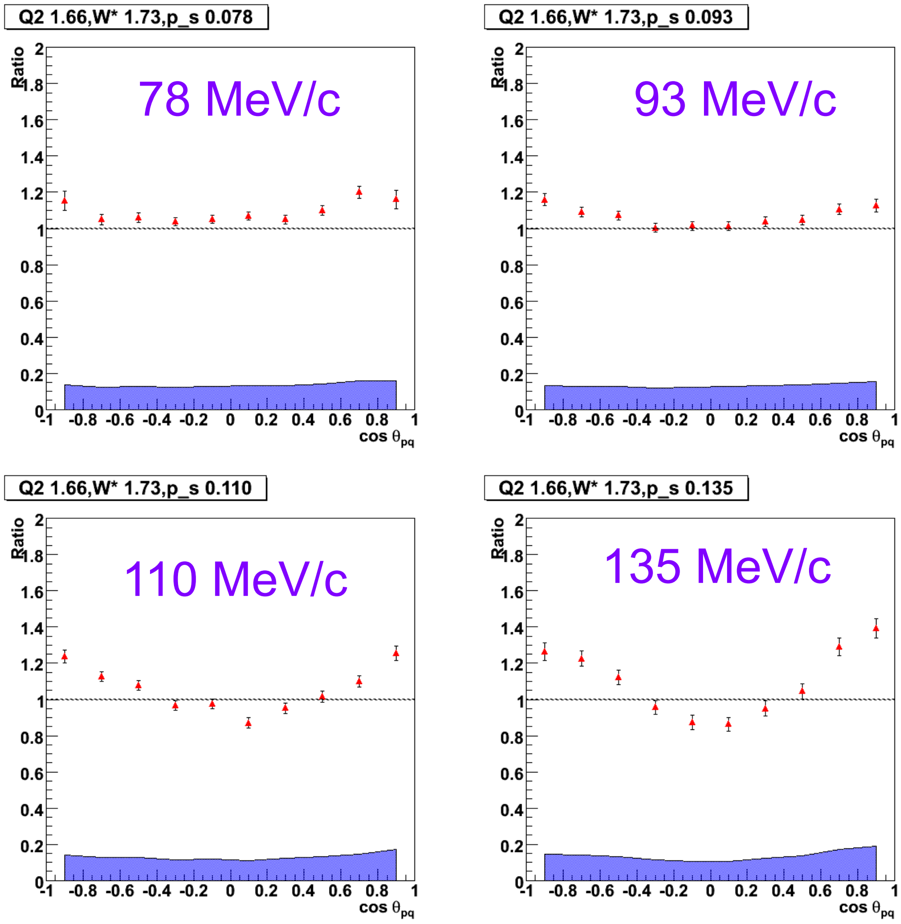


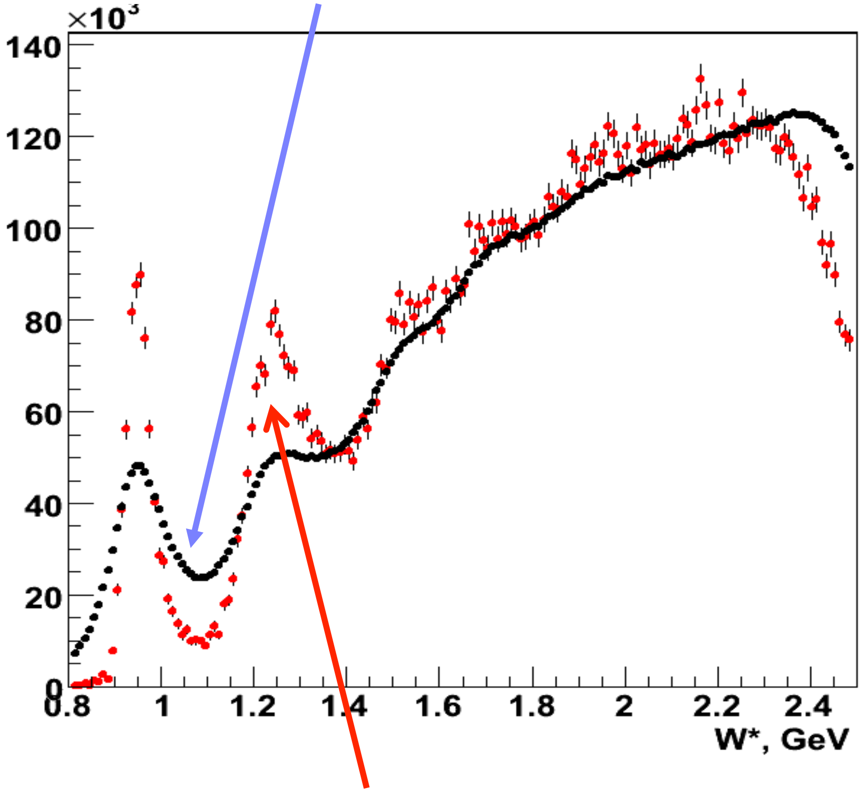


The technique works!

angle - momentum dependence

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





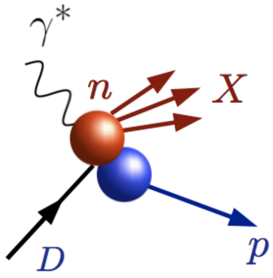
$$W^{*2} = (p_n + q)^2 = p_n^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2$$

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

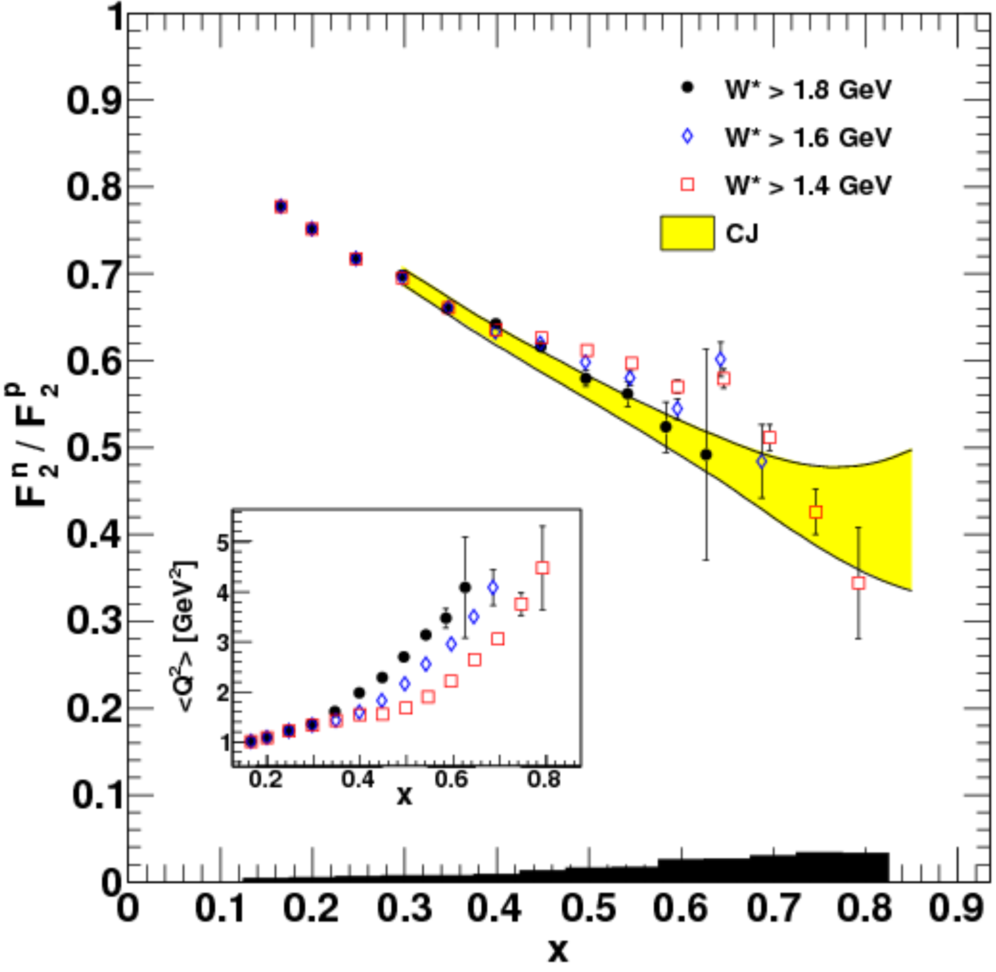
$\cos\theta_{pq}$

$\cos\theta_{pq}$

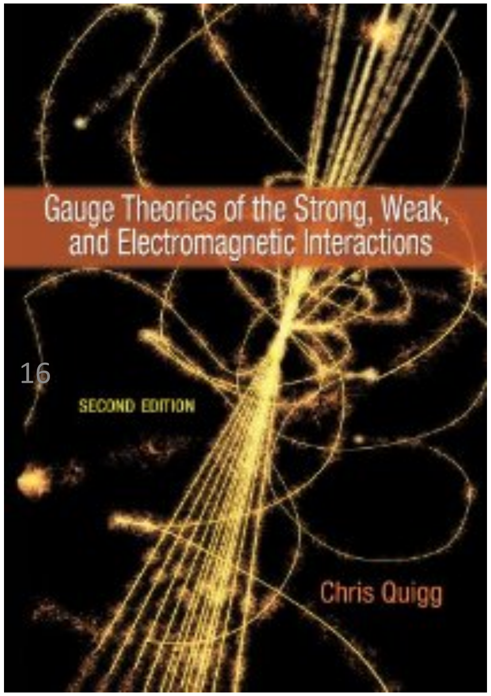
Neutron target via low momentum proton tagging *achieved*



Phys. Rev. Lett. 108 (2012) 199902
Phys. Rev. C89 (2014) 045206 – editor's suggestion
Nucl. Instrum. Meth. A592 (2008) 273-286
Phys. Rev. C92 (2015) 1, 015211
Phys. Rev. C91 (2015) 5, 055206



+ Textbook Physics!



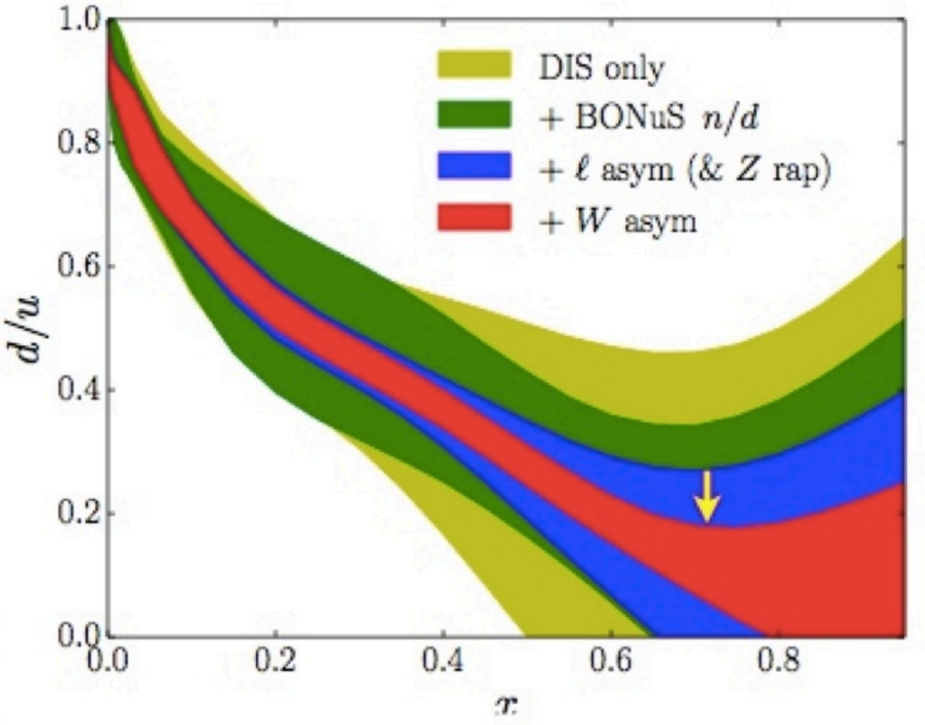
- Likely not quite high enough x, W, Q^2 - BONUS at 12 GeV coming!
- Now input for (CTEQ-JLab) global PDF fits

CTEQ-Jefferson Lab "CJ" Global Fitting Effort

High *x* region requires use of data at lower *W, Q*^{2}, which in turn requires for instance…

- Careful treatment of sub-leading 1/*Q*^{2} corrections
  - target mass corrections
  - dynamical higher twists
- Correcting for nuclear effects in deuteron
  - binding + Fermi motion (well known)
  - nucleon off-shell (less well known)
- Flexible d quark parameterization

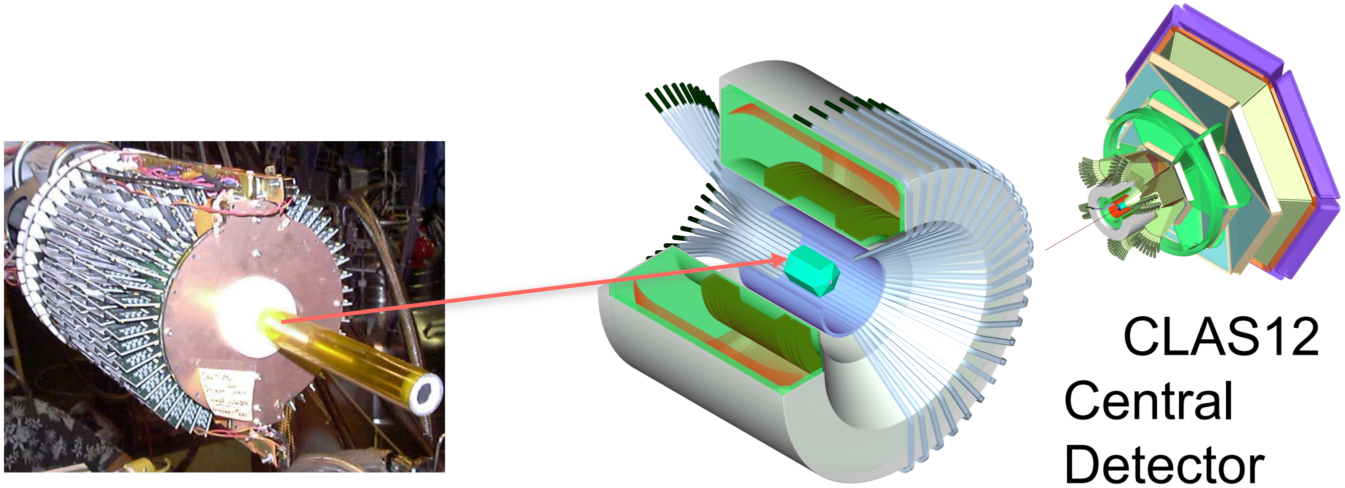
d/u



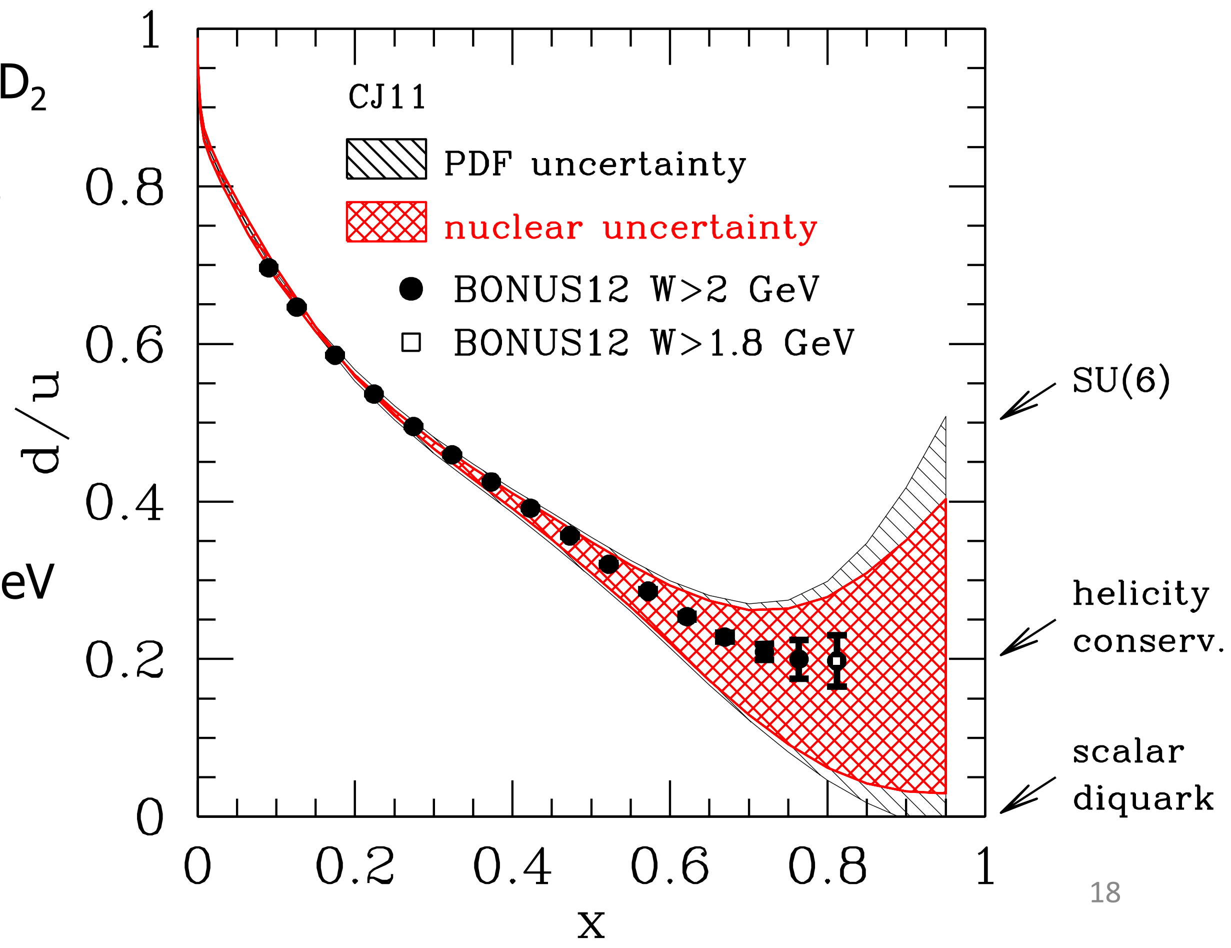
CJ15 release this month!

Still need data above x ~ 0.65

E12-06-113 BONUS at 12 GeV

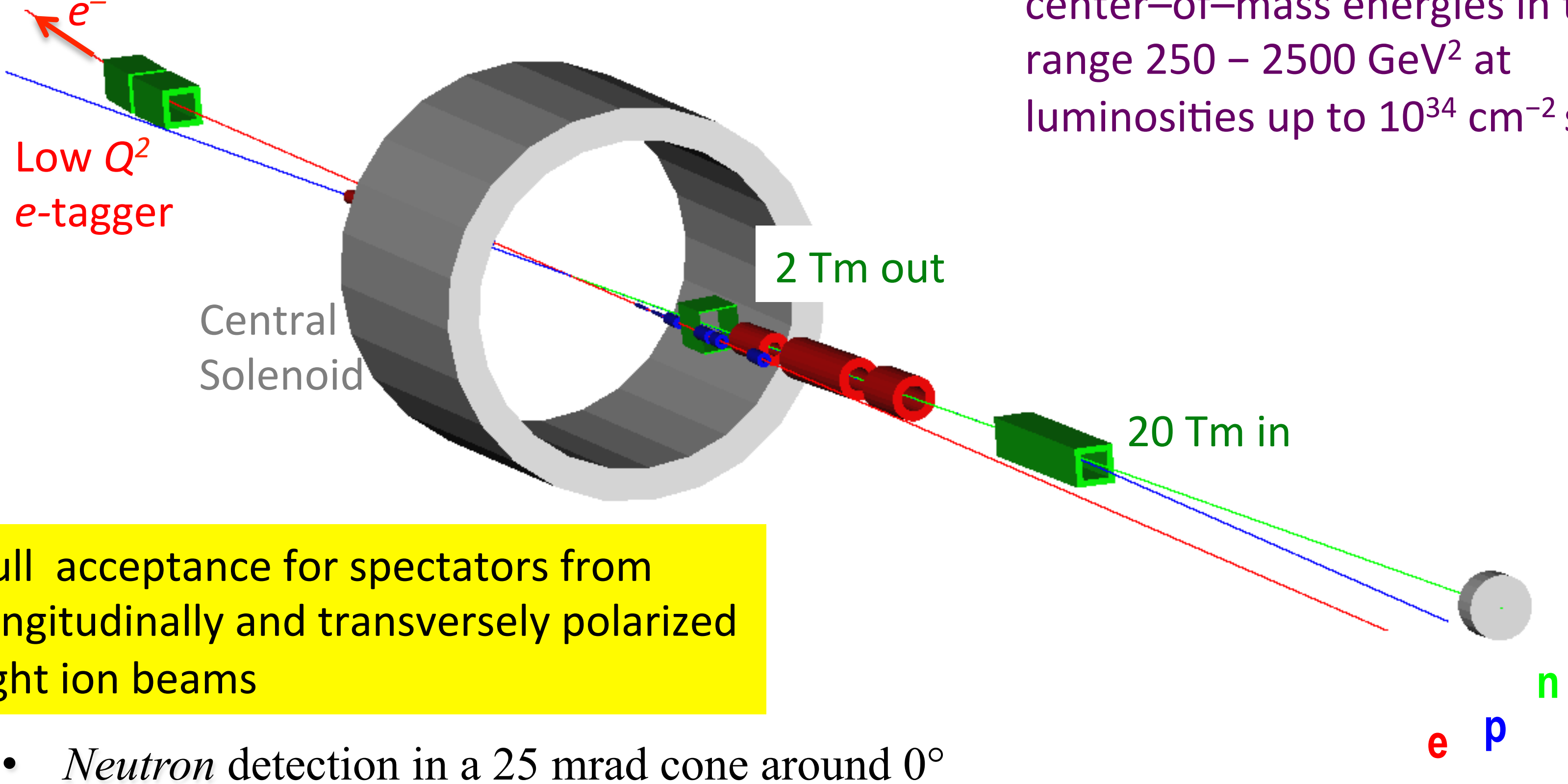


- Data taking of 35 days on D_2 and 5 days on H_2 with $\mathrm{L} = 2 \cdot 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$
- DIS region with
  - $Q^2 > 1\ \mathrm{GeV}^2/c^2$
  - $W^* > 2$ GeV
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110°$
- Relaxed cut of $W^* > 1.8$ GeV gives max. $x^* = 0.83$
- Anticipated 2018 run



Spectator Tagging at the EIC

The technique is uniquely suited to colliders: there is no target material absorbing low-momentum nucleons



The EIC designs provide electron–nucleon squared center–of–mass energies in the range 250 – 2500 GeV^2 at luminosities up to $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

- Full acceptance for spectators from longitudinally and transversely polarized light ion beams

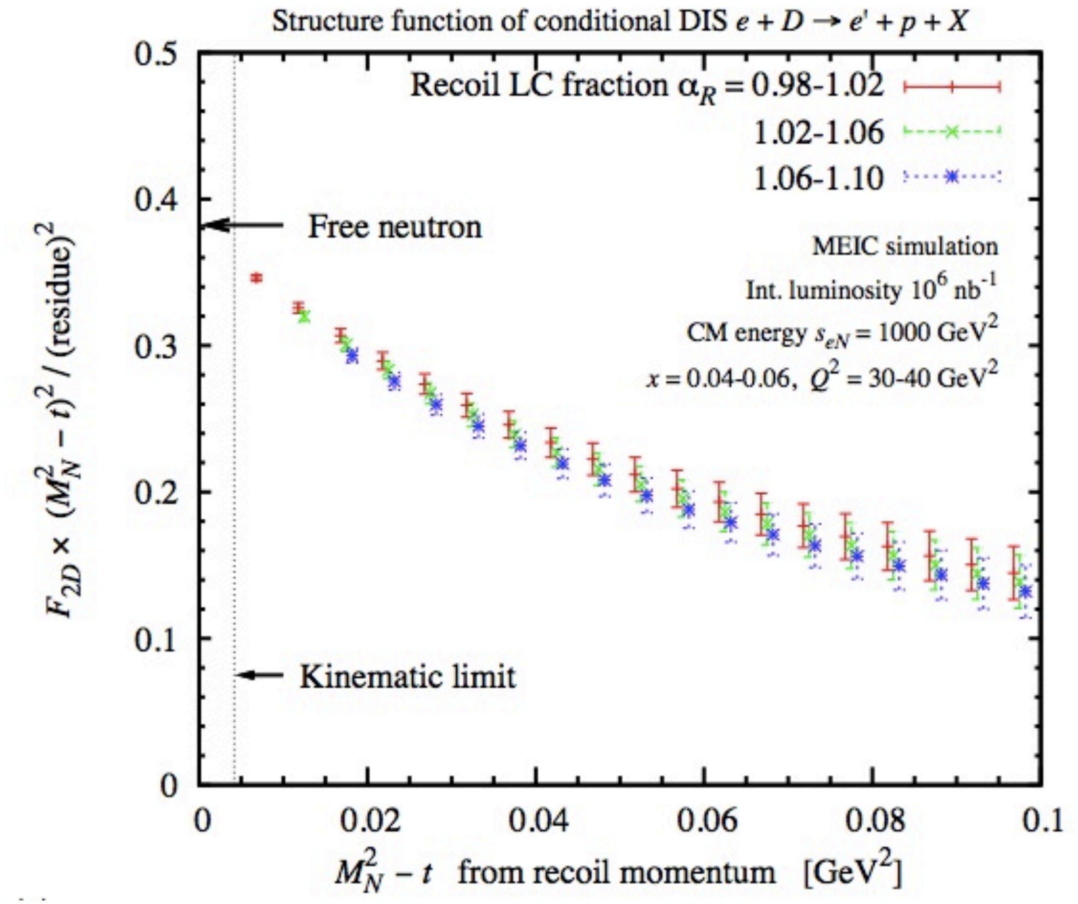
- *Neutron* detection in a 25 mrad cone around 0°
- Secondary high dispersive ion focus ~40 m downstream of IP

Projected Data Example: Neutron Structure at the EIC

e + D → e′ + p + X *a la BONUS*

$\alpha_R \equiv 2(E_R + p^z_R)/(E_D + p^z_D)$

residue = free neutron

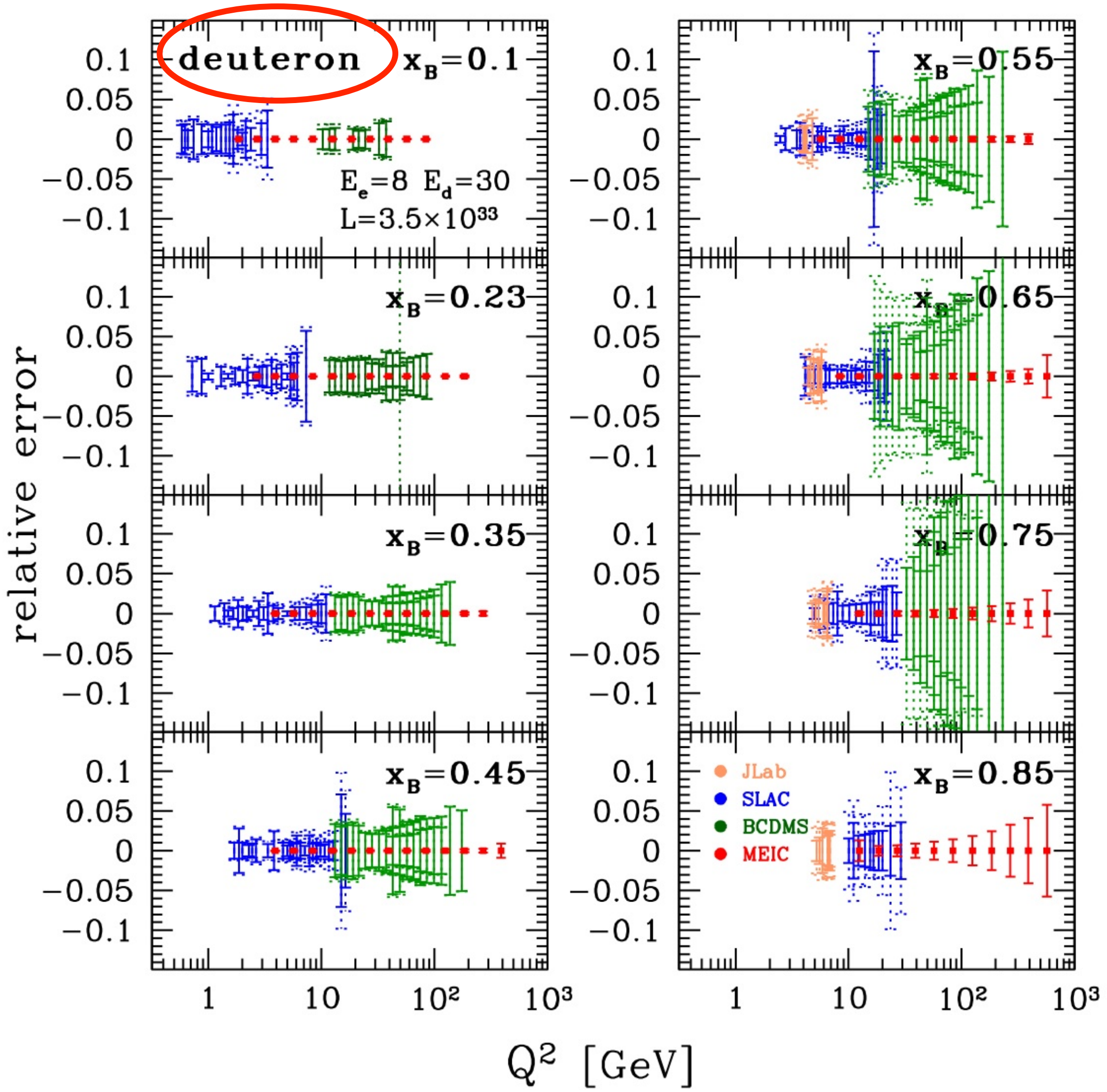


Tagged measurements require coverage for [protons] with low momenta relative to beam momentum (pT < 200 MeV, pT/ p(beam) ~ 0.8 – 1.2), and good momentum resolution (ΔpT ~ 20 MeV).

Tagging also requires that the intrinsic momentum spread in the ion beam be small to allow for accurate reconstruction.

EIC being designed for tagging

More Projected EIC 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

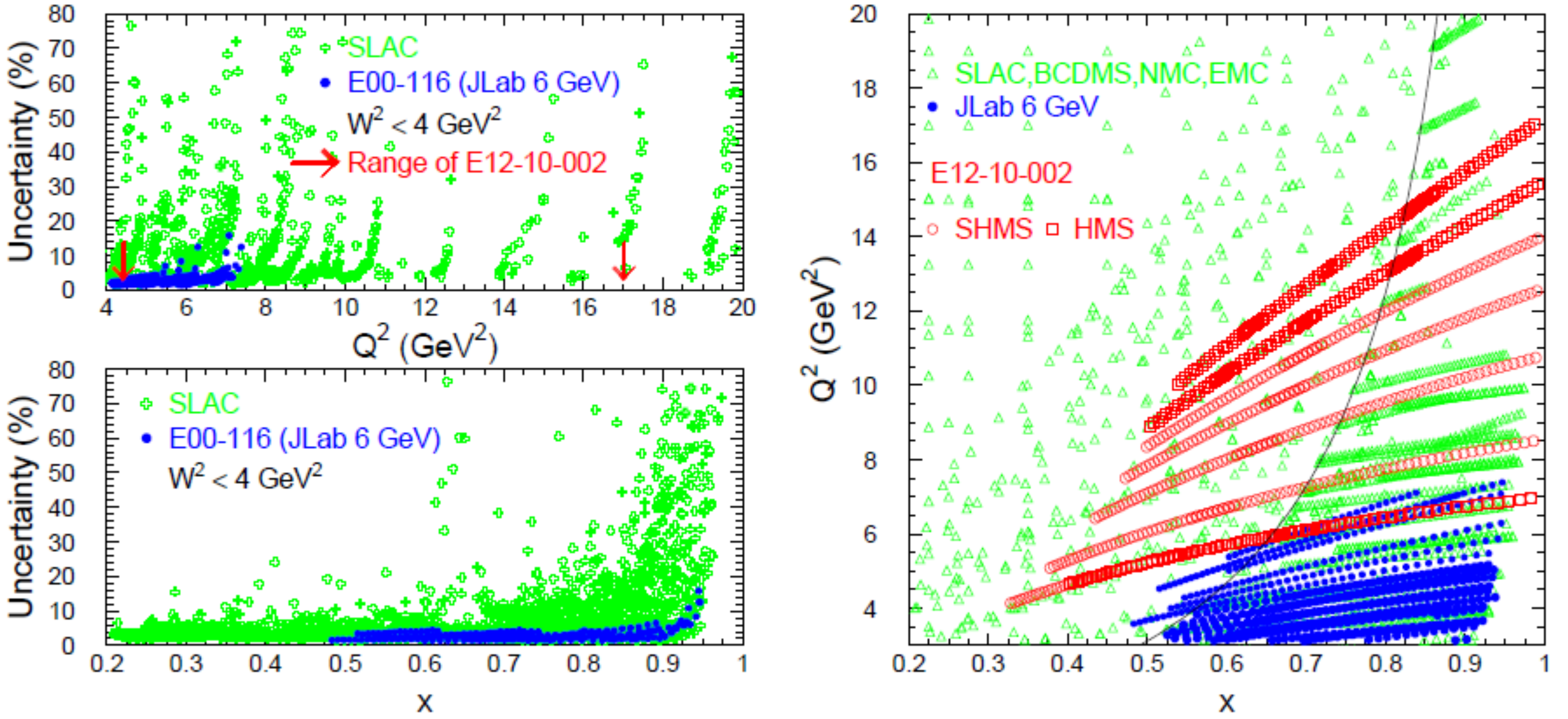
Proton even better (smaller neutron cross section)

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 in the nearer term

JLab12 Hall C commissioning experiment (Fall 2016 start) aims to reduce uncertainties in F_2^p and F_2^d structure functions at large x and high Q



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

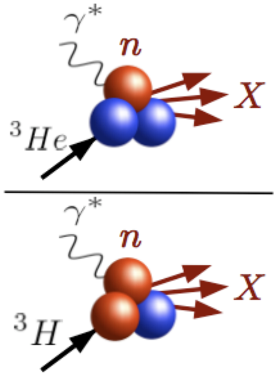
Nuclear Physicists' Approach to F_2^n

- Problem:
  - The deuteron experiments present extraction complications.
- Nuclear physicists' solution: Add another nucleon!
- $^3H/^3He$ ratio: minimizes nuclear physics uncertainties

I. Afnan et al, PRC 68 (2003)

Another approach to F_2^n: 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

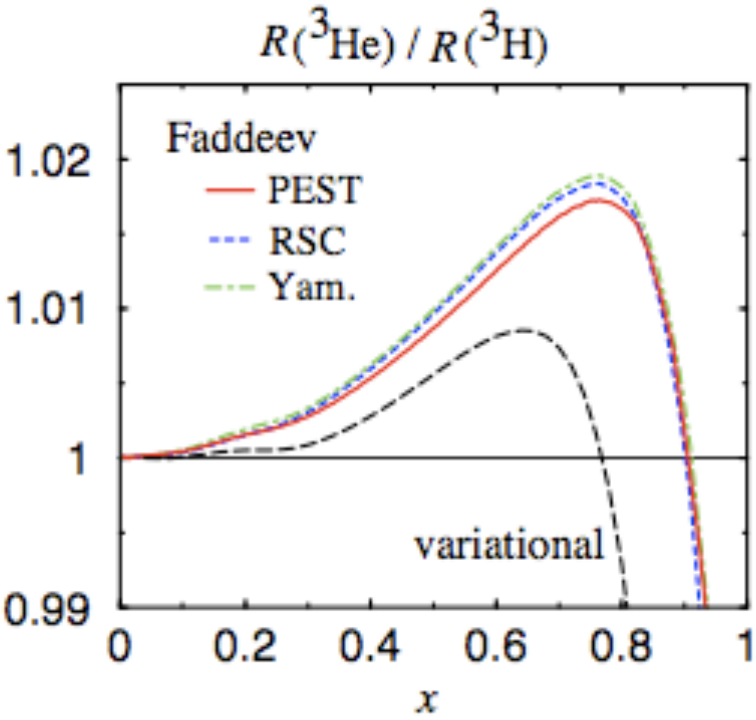
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

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

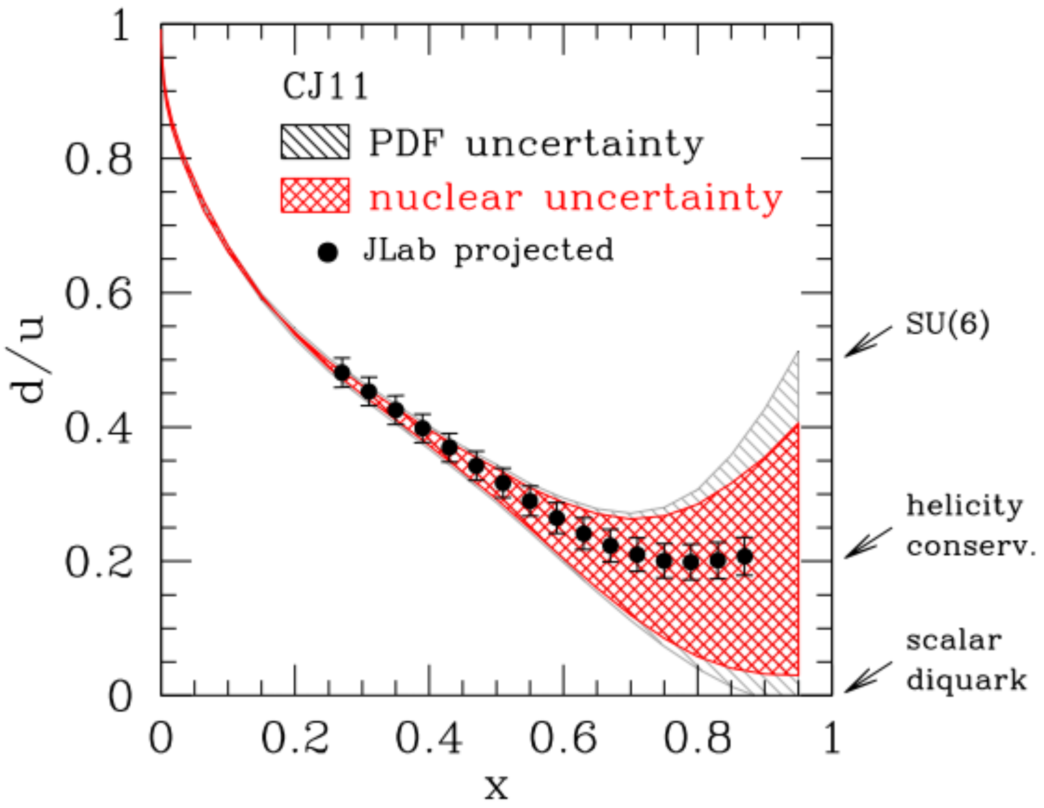
- Relies only on *difference* in nuclear effects in ^{3}H, ^{3}He

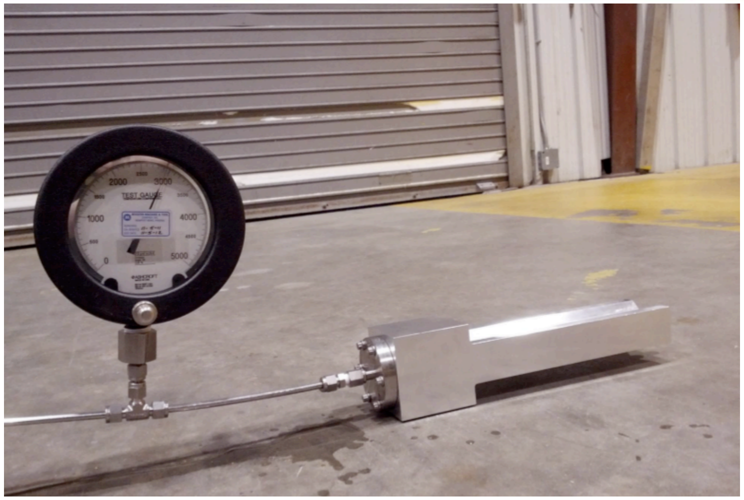
- Calculated to within 1%

- Most systematic and theoretical uncertainties cancel



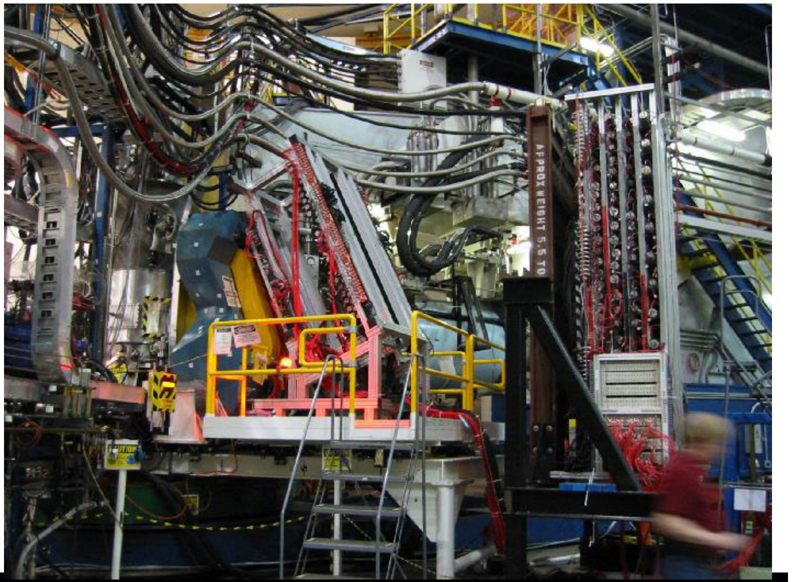
DIS from A=3 nuclei – *Projected results from Fall 2016 run*





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)

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

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

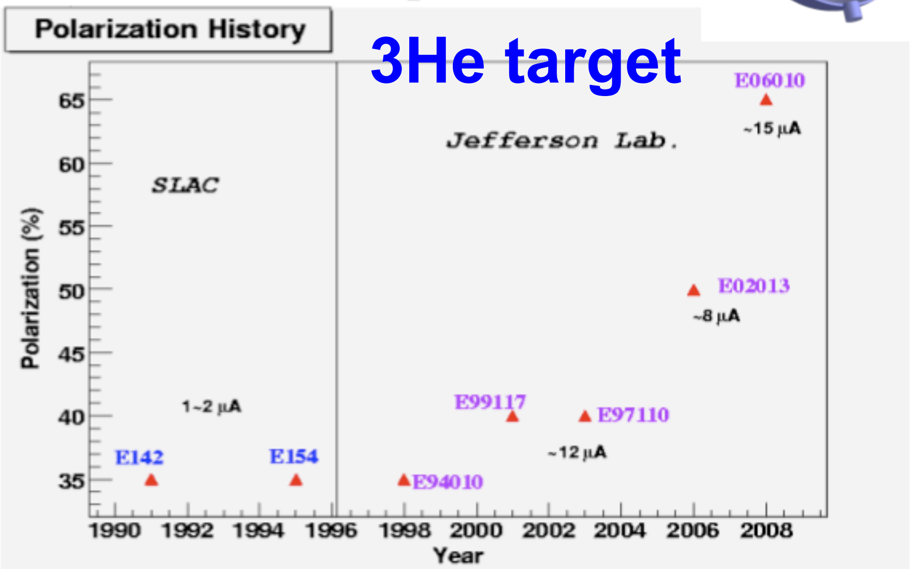
Nucleon Model	F_2^n/F_2^p	d/u	Δu/u	Δd/d	A_1^n	A_1^p
SU(6)	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark	1/4	0	1	-1/3	1	1
pQCD	3/7	1/5	1	1	1	1

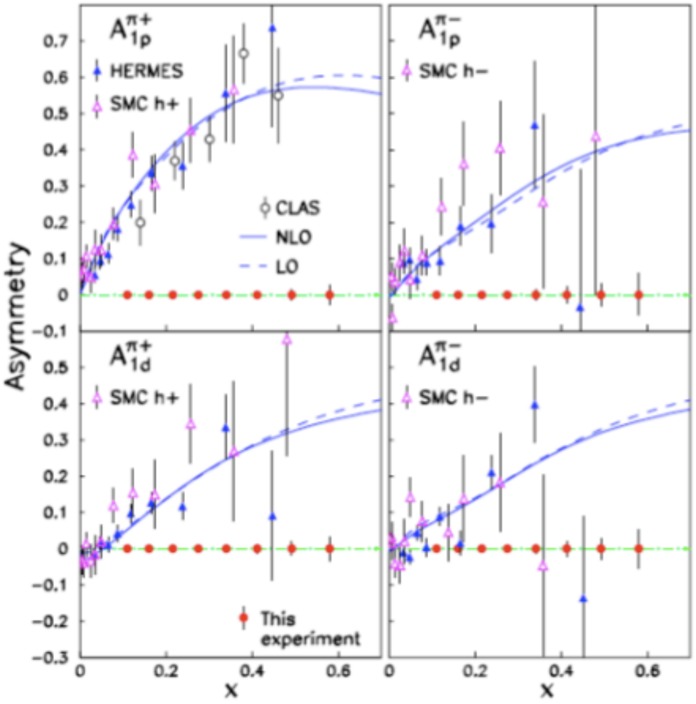
Polarized structure function data can provide d/u theory guidance

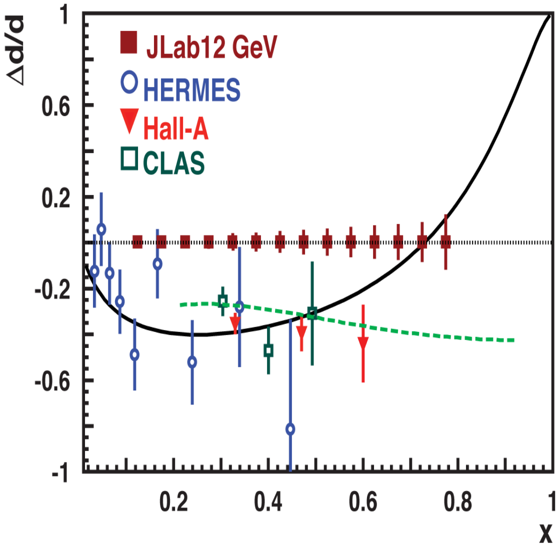
Measuring High-x Structure Functions - polarized

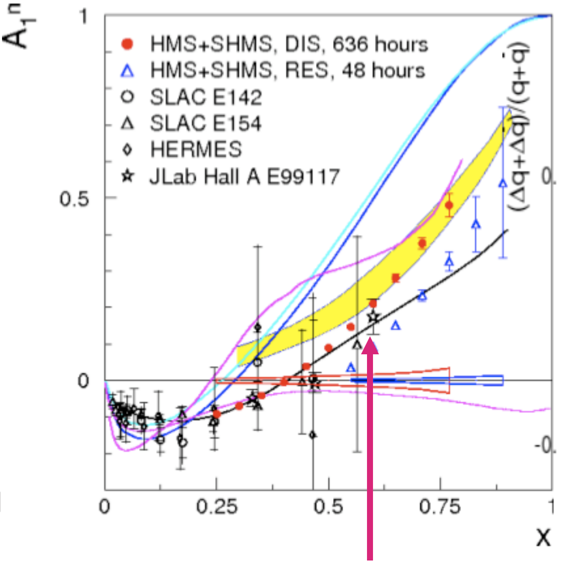
REQUIRES:

- High beam, target polarization
- High electron current
- Large solid angle spectrometers
- PDF efforts – “JAM” collaboration
- Broad JLab12 program!

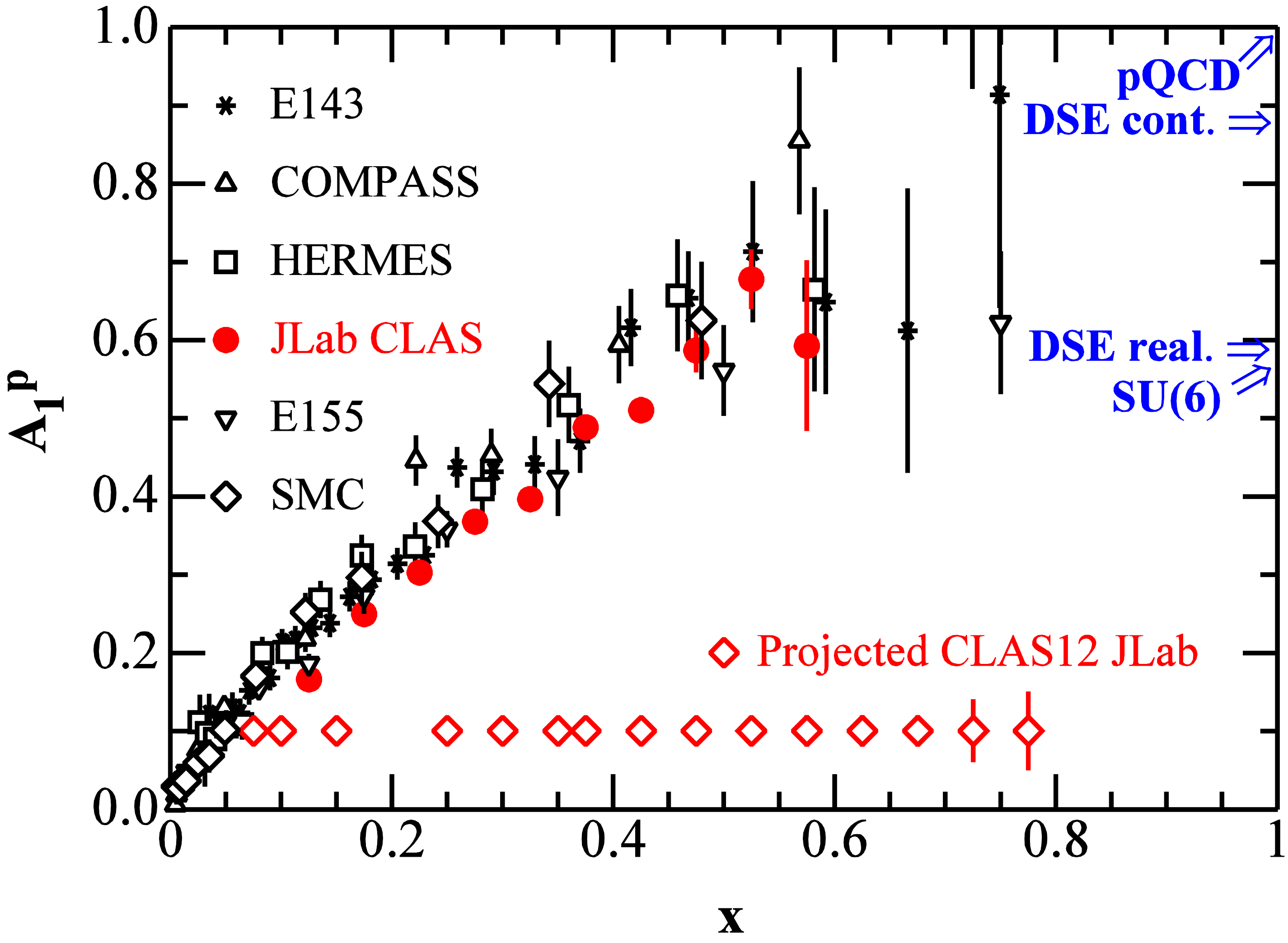








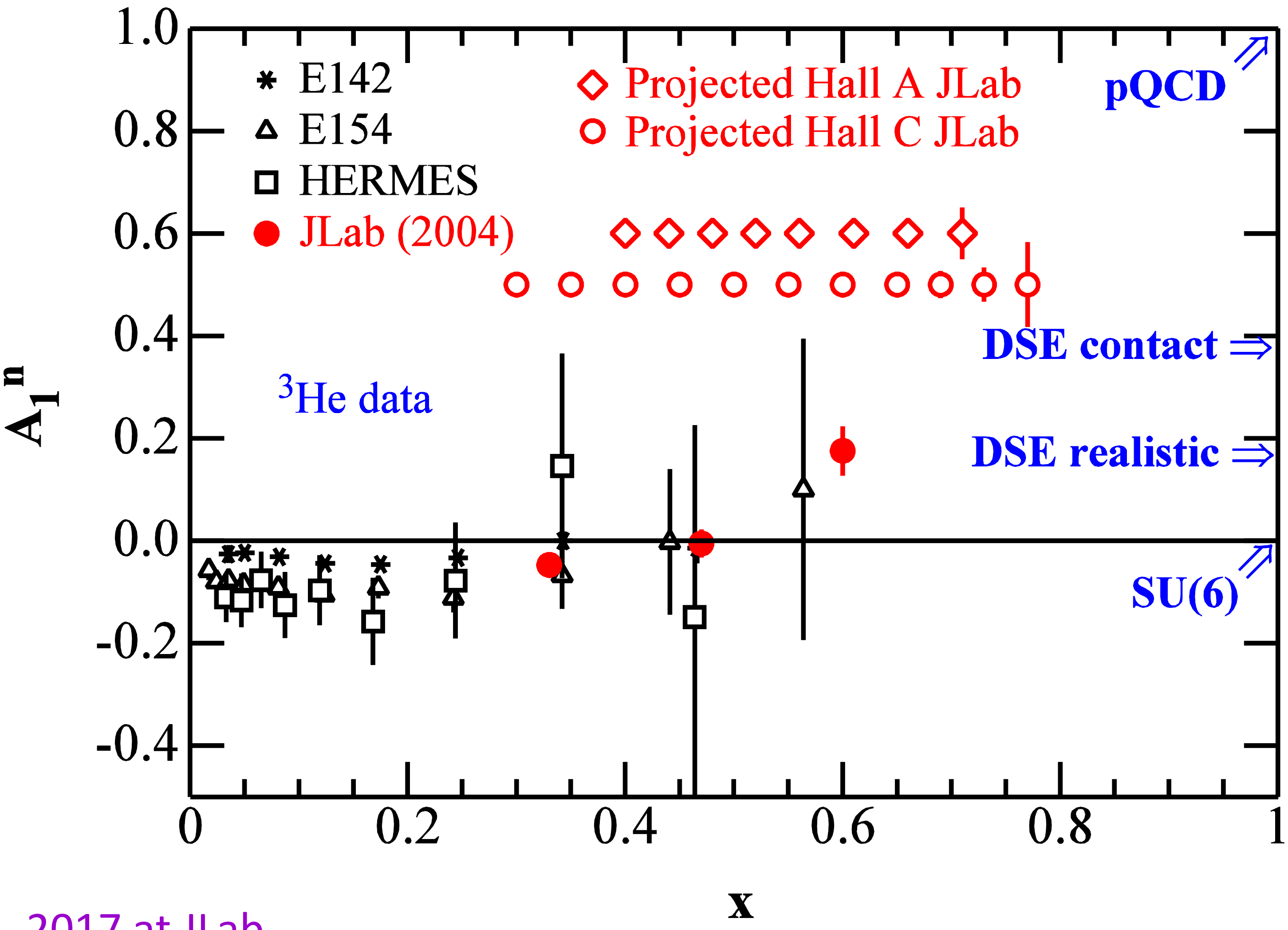
Measurements and Projections for A_1^p



JLab E12-06-109, S. Kuhn, D. Crabb, A. Deur, V. Dharmawardane, T. Forest, K. Griffioen, M. Holtrop, Y. Prok, et al.

C. D. Roberts, R. Holt, S. Schmidt, Phys. Lett. B **727** (2013) pp. 249–254

Measurements and Projections for A_1^n



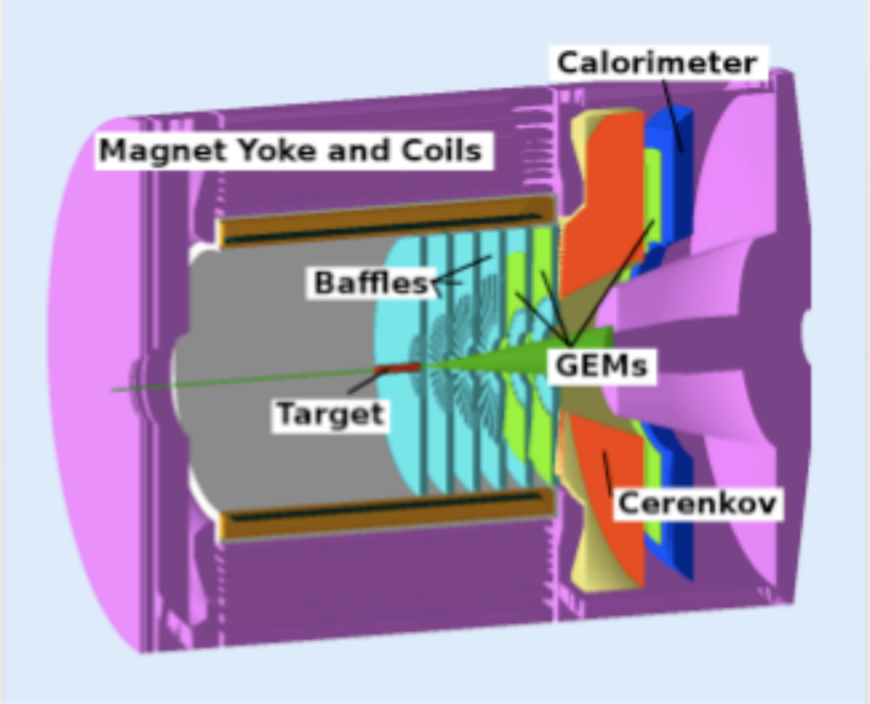
2017 at JLab

JLab E12-06-110, X. Zheng, J.-P. Chen, Z.-E. Meziani, G. Cates et al.

JLab E12-06-122, B. Wojtsekhowski, G. Cates, N. Liyanage, Z.-E. Meziani, G. Rosner, X. Zheng, et al.

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

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

CD0 ~2019

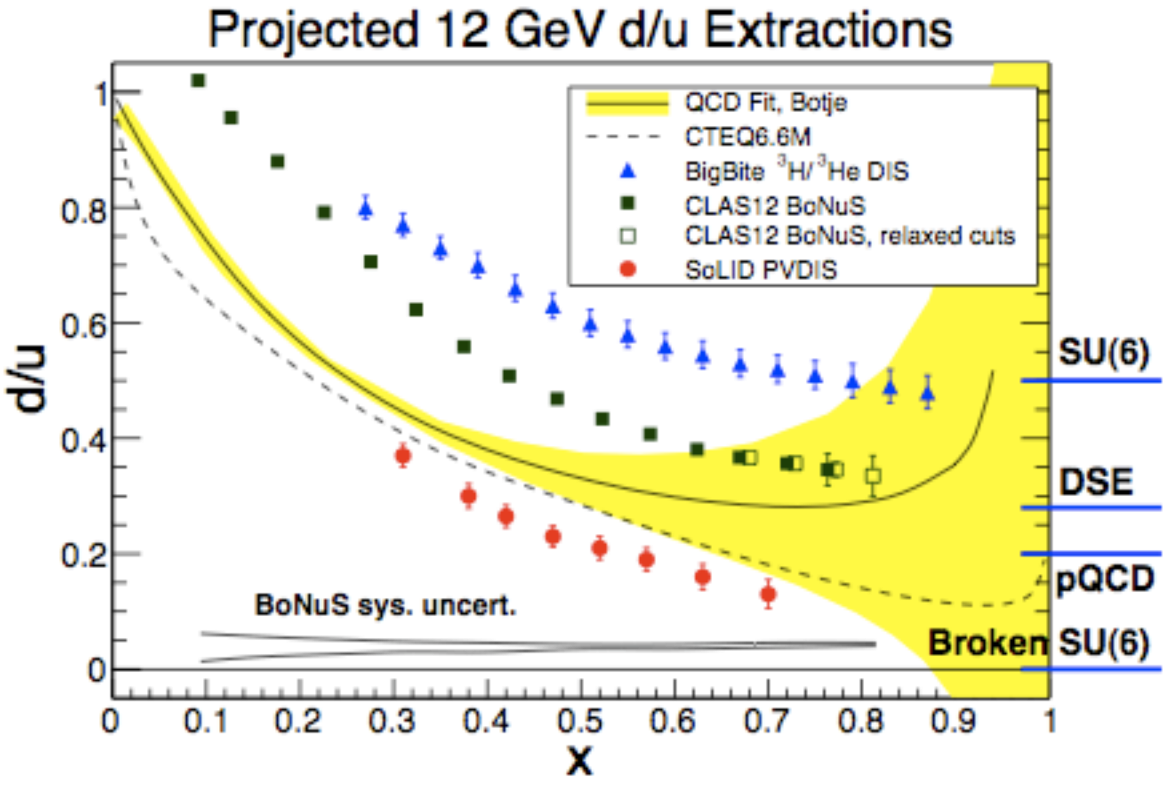
$$A_{\mathrm{PV}} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2} a_3(x)\right]$$

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

Clean Measurement of d/u with PVDIS

For high x on proton target:

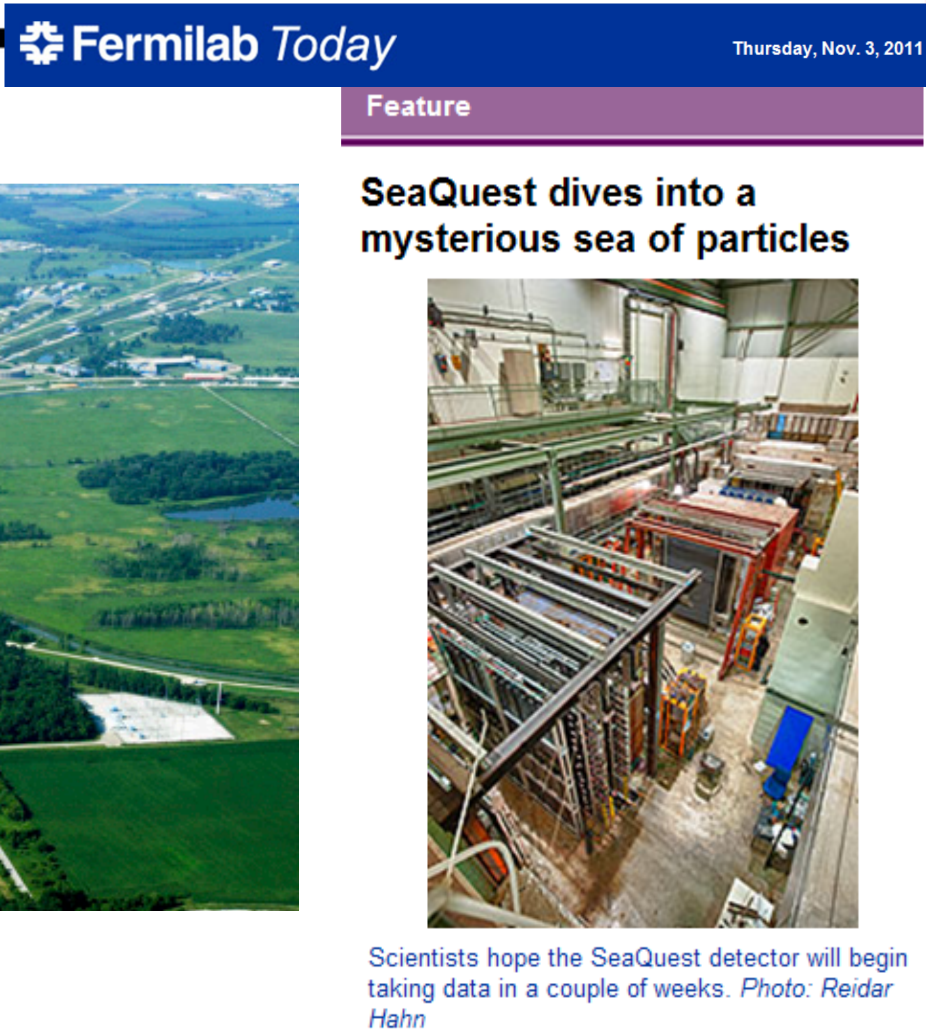
$$a_1^p(x) = \left[\frac{12C_{1u}u(x) - 6C_{1d}d(x)}{4u(x) + d(x)}\right] \approx \left[\frac{1 - 0.91d(x)/u(x)}{1 + 0.25d(x)/u(x)}\right]$$



- 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*

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

SeaQuest at FNAL - 120 GeV protons



Fermilab *Today*

Thursday, Nov. 3, 2011

Feature

SeaQuest dives into a mysterious sea of particles

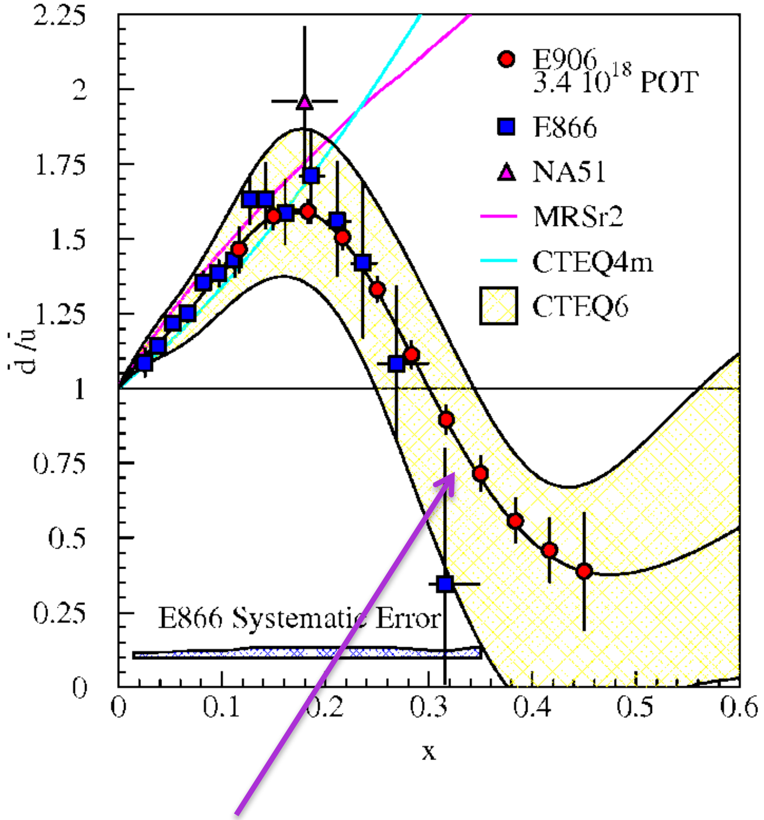
Scientists hope the SeaQuest detector will begin taking data in a couple of weeks. *Photo: Reidar Hahn*

FNAL E906

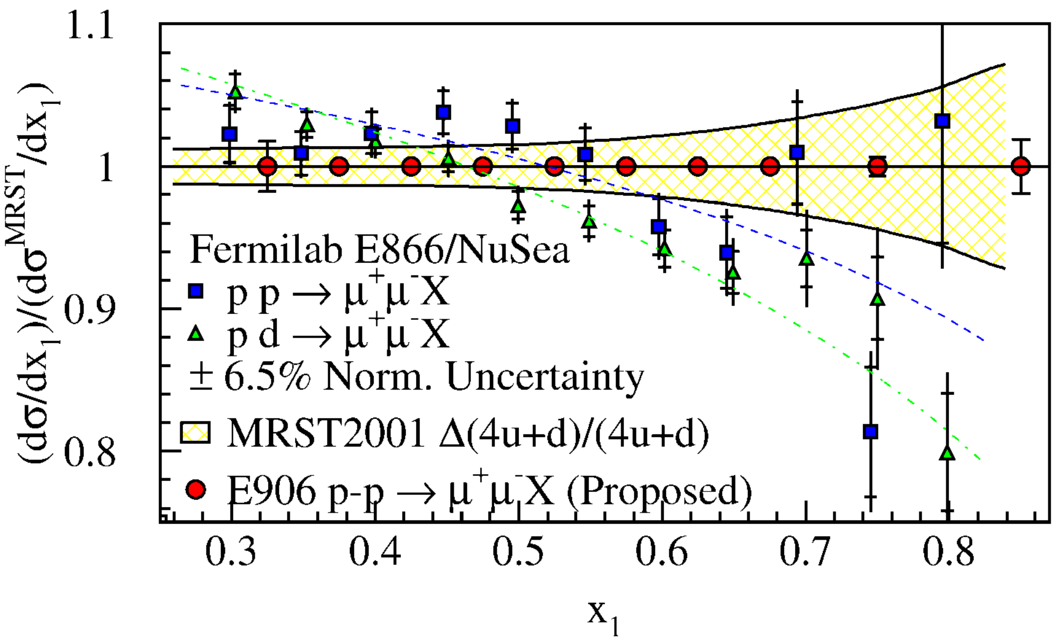
Longer term: Polarized FNAL, J-PARC at 50 GeV

Drell-Yan measurement of anti-quark distributions

currently running



No model predicts dbar/ubar <1.

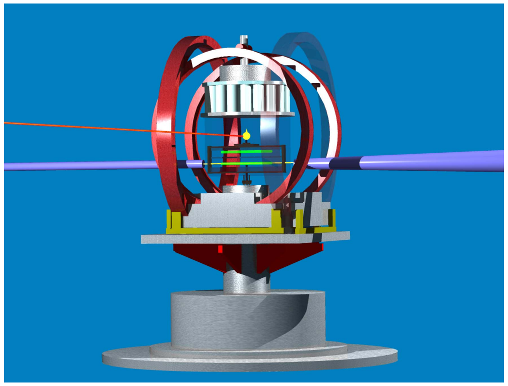


Reach high-x through *beam proton*—large x_{beam}.

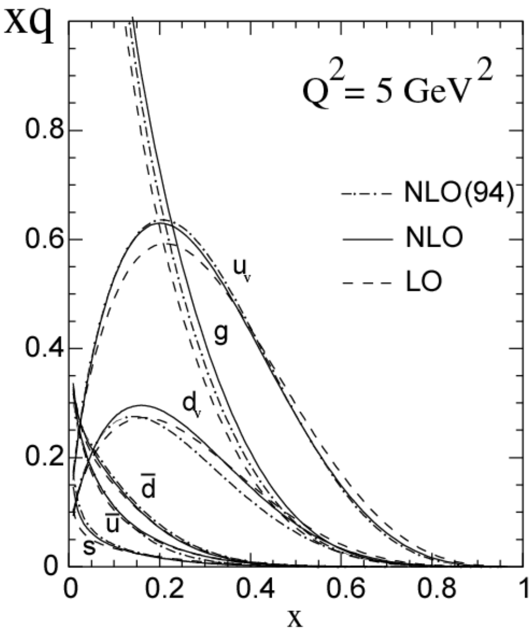
Proton-Proton: no nuclear corrections

Probing the Valence Regime: Summary

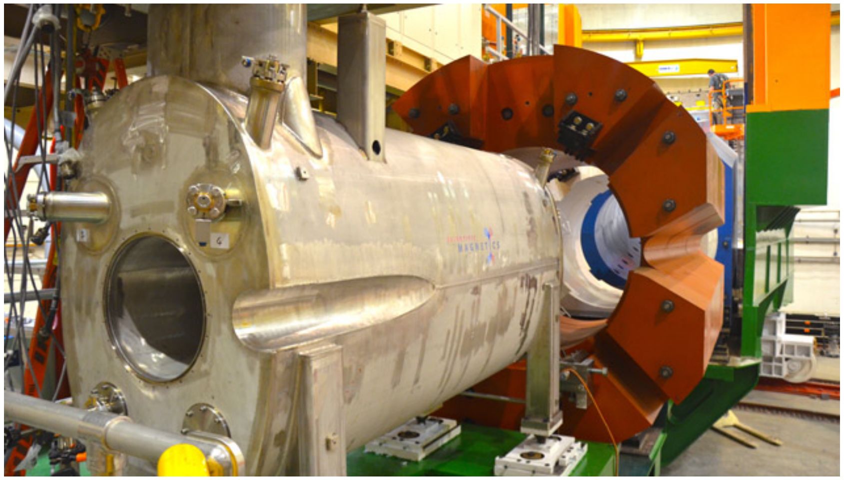
- JLab at 12 GeV will access the regime where valence quarks dominate



- First experiments *THIS FALL!*
  - Hall C F2p,n
  - Hall A 3H/3He
  - Ongoing program

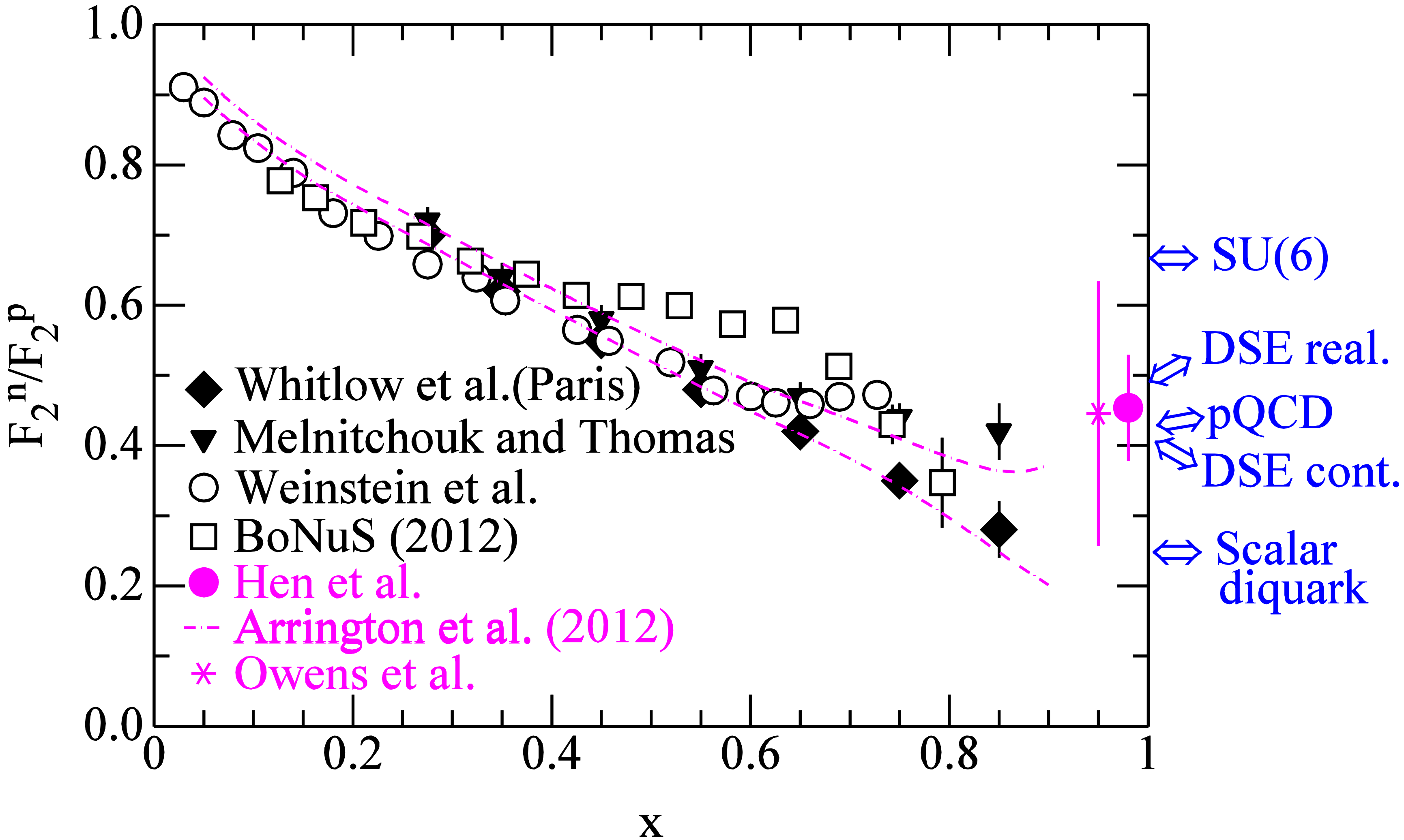


- Also new data from SeaQuest at FNAL
- EIC on the horizon
- Dedicated theory efforts also underway
  - "CJ", (CTEQ-Jefferson Lab) and "JAM" collaborations
- *Expect large improvements in our understanding of the valence regime over the next 1-5 years!*



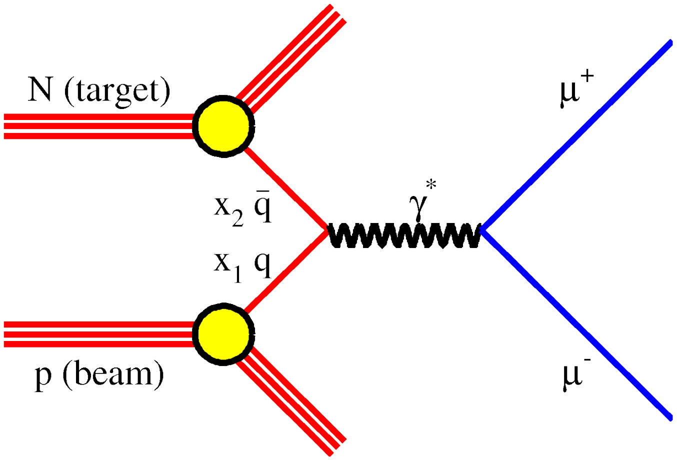
Thank You!

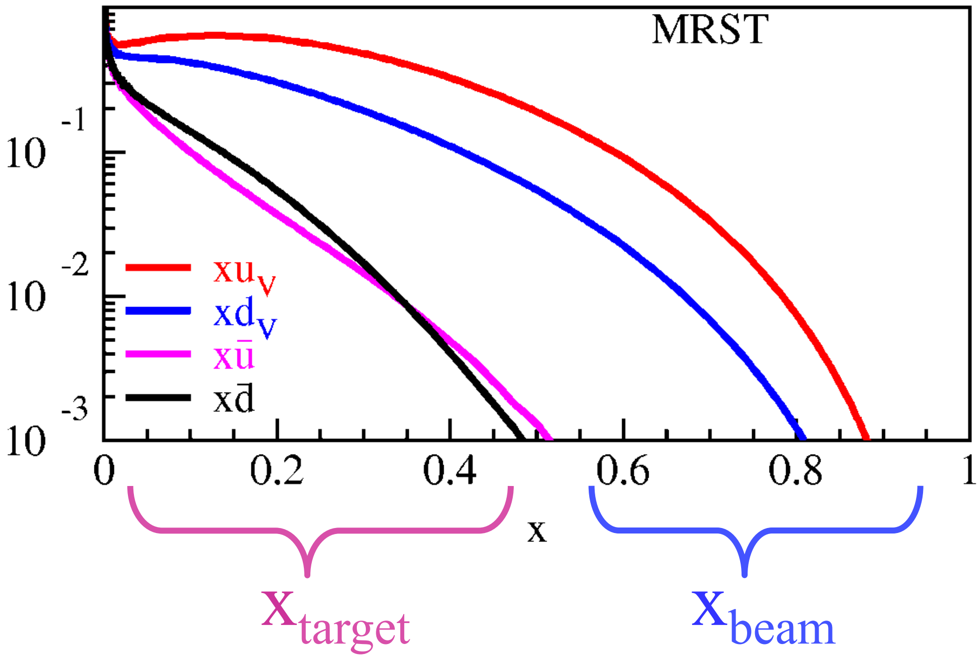
Present status: Neutron to proton structure function ratio



R. Holt, C. D. Roberts, RMP **82** (2010) 2991

Drell-Yan Interactions



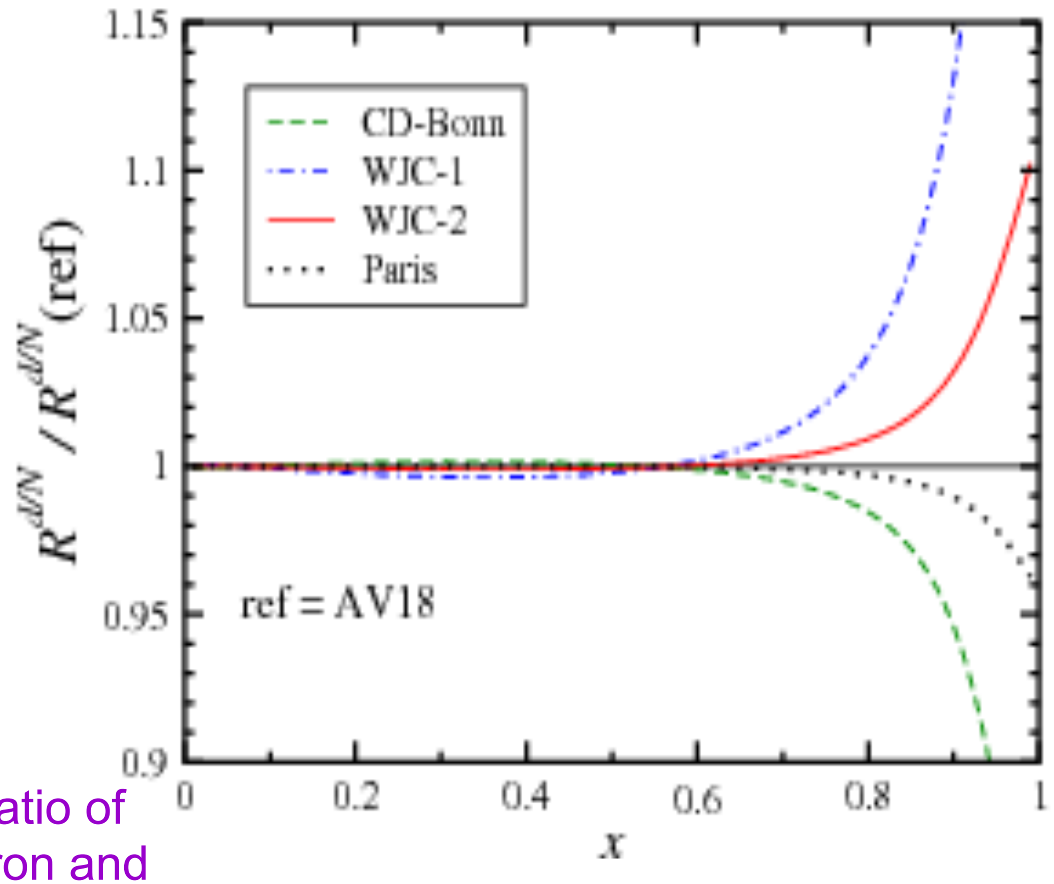


$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b\gg x_t} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

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” (CTEQ/JLab)*