Deep Inelastic Scattering in the Valence Regime

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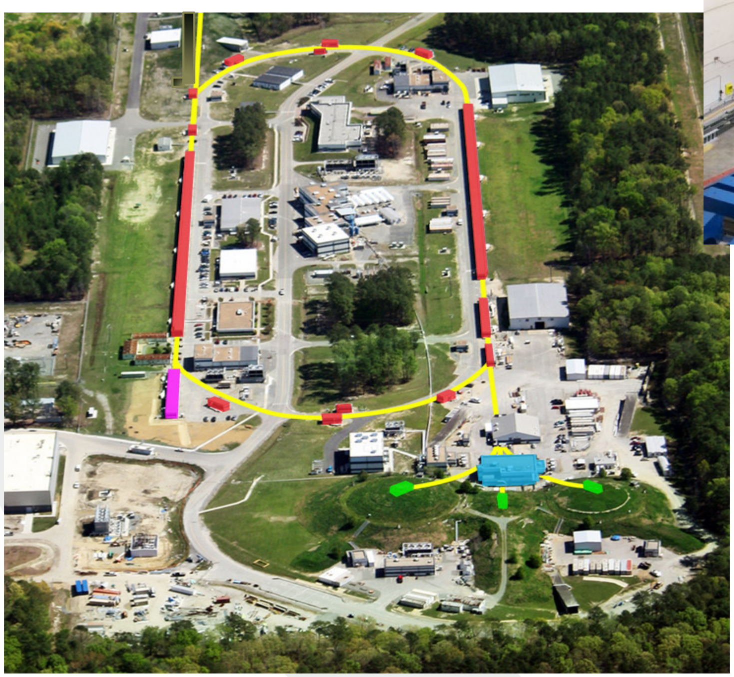
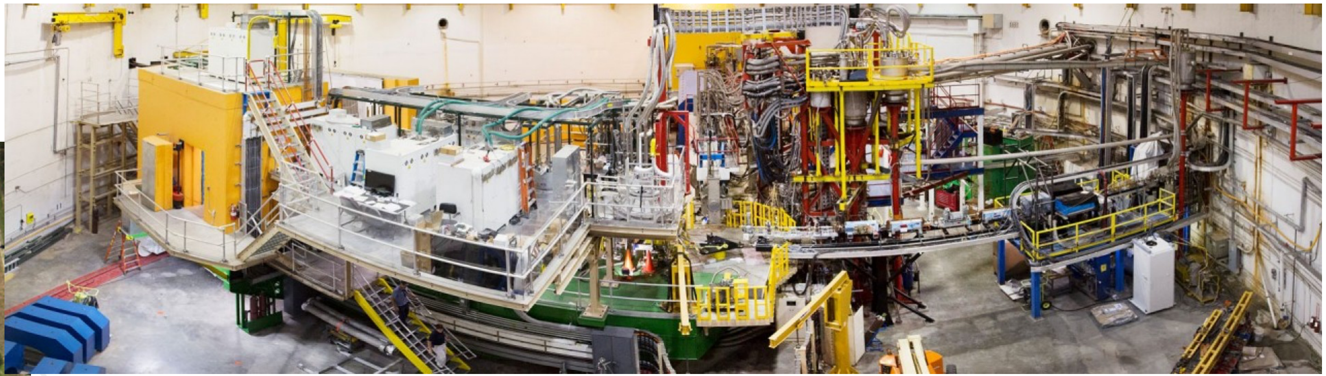
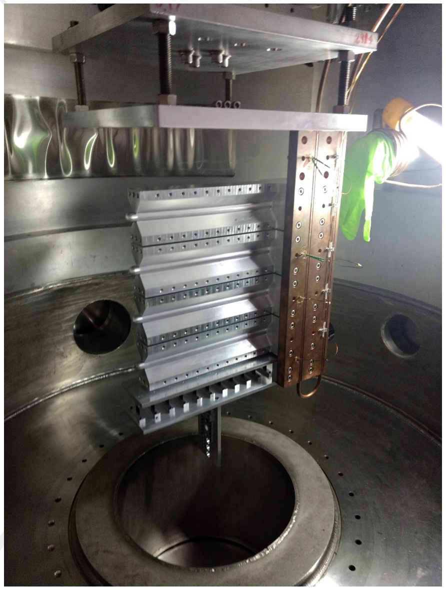
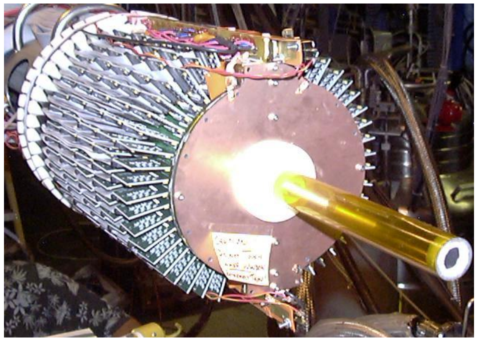
Thomas Jefferson National Accelerator Facility

Initial Stages 2019
New York City









Jefferson Lab

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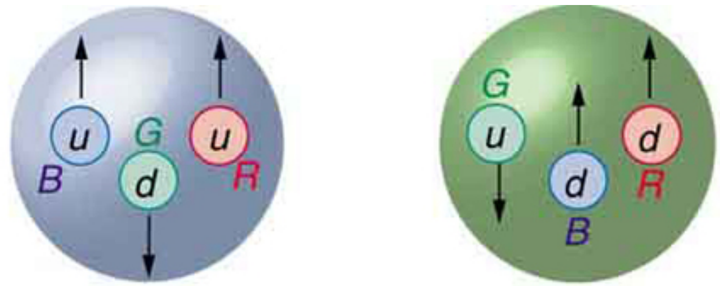
JSA

Why is the valence regime interesting?



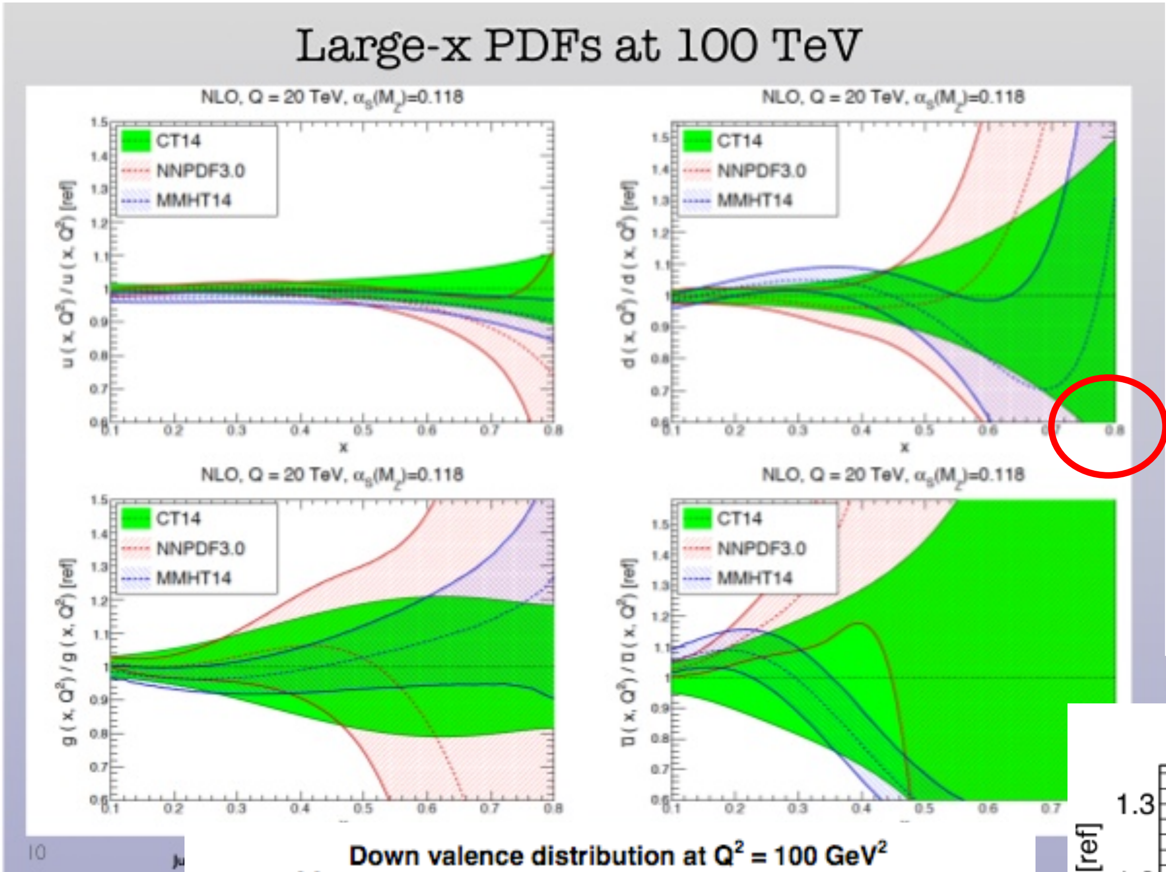
Proton / Neutron

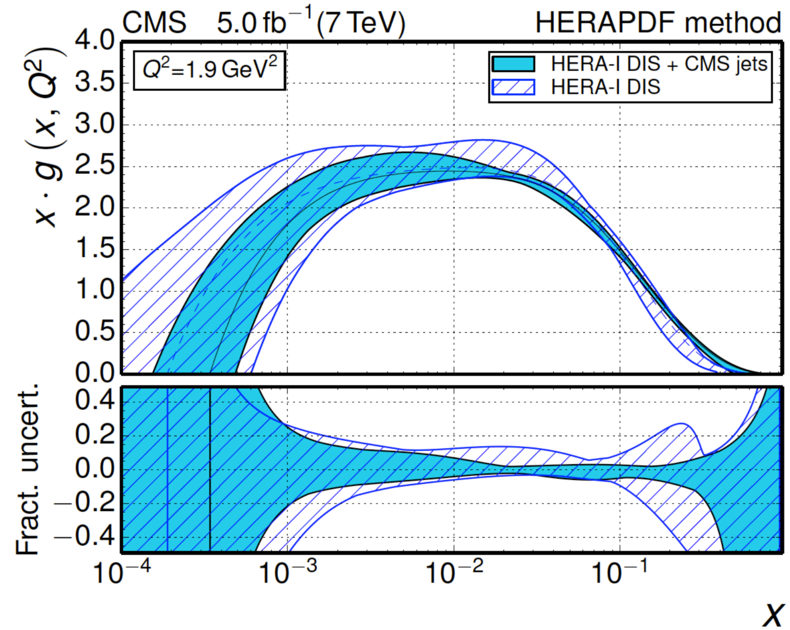
Spin: $\frac{1}{2}+\frac{1}{2}-\frac{1}{2}=\frac{1}{2}$ $\qquad -\frac{1}{2}+\frac{1}{2}+\frac{1}{2}=\frac{1}{2}$

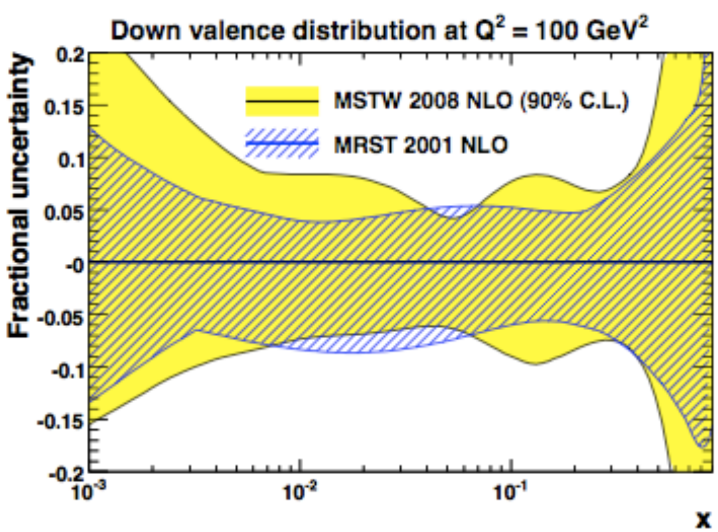
Charge: $+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$ $\qquad +\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$

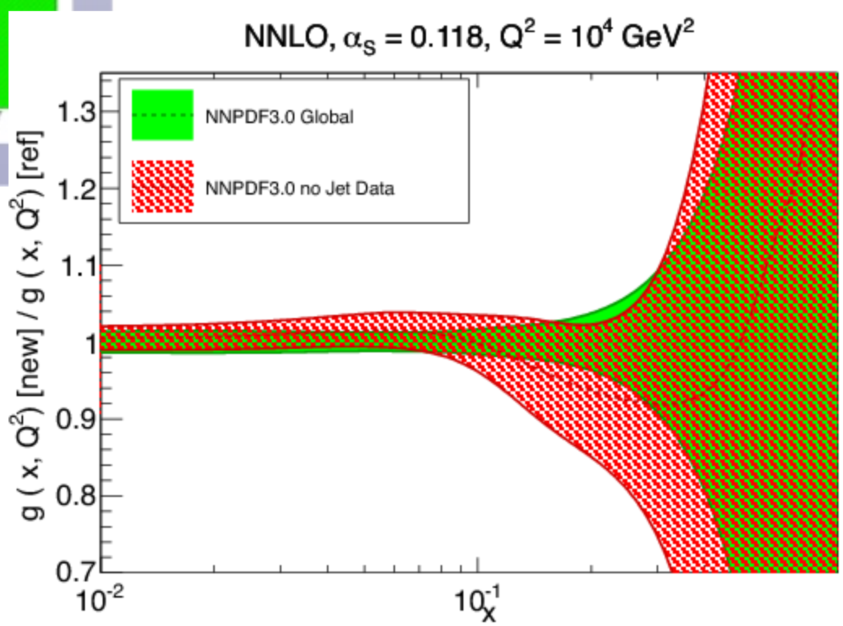
- Partonic structure in the valence region ***defines*** a hadron
  - Baryon number, charge, flavor content, total spin, …
- Keen discriminator of nucleon structure models
- “Valence regime” at large x, low Q^2 evolves to low x, high Q^2
  - Intersection of nuclear and particle physics
- New generation of experiments at JLab focused on high x

Present status: large uncertainties on pdfs at large x

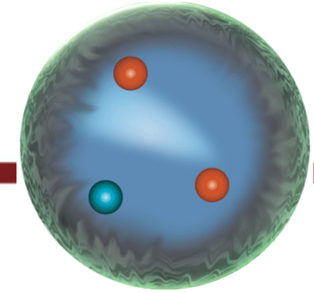








Nucleon Structure Example: F_2^n/F_2^p (neutron/proton) ratio at Large x



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

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

  - SU(6) spin/flavor symmetry in u,d
    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

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

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

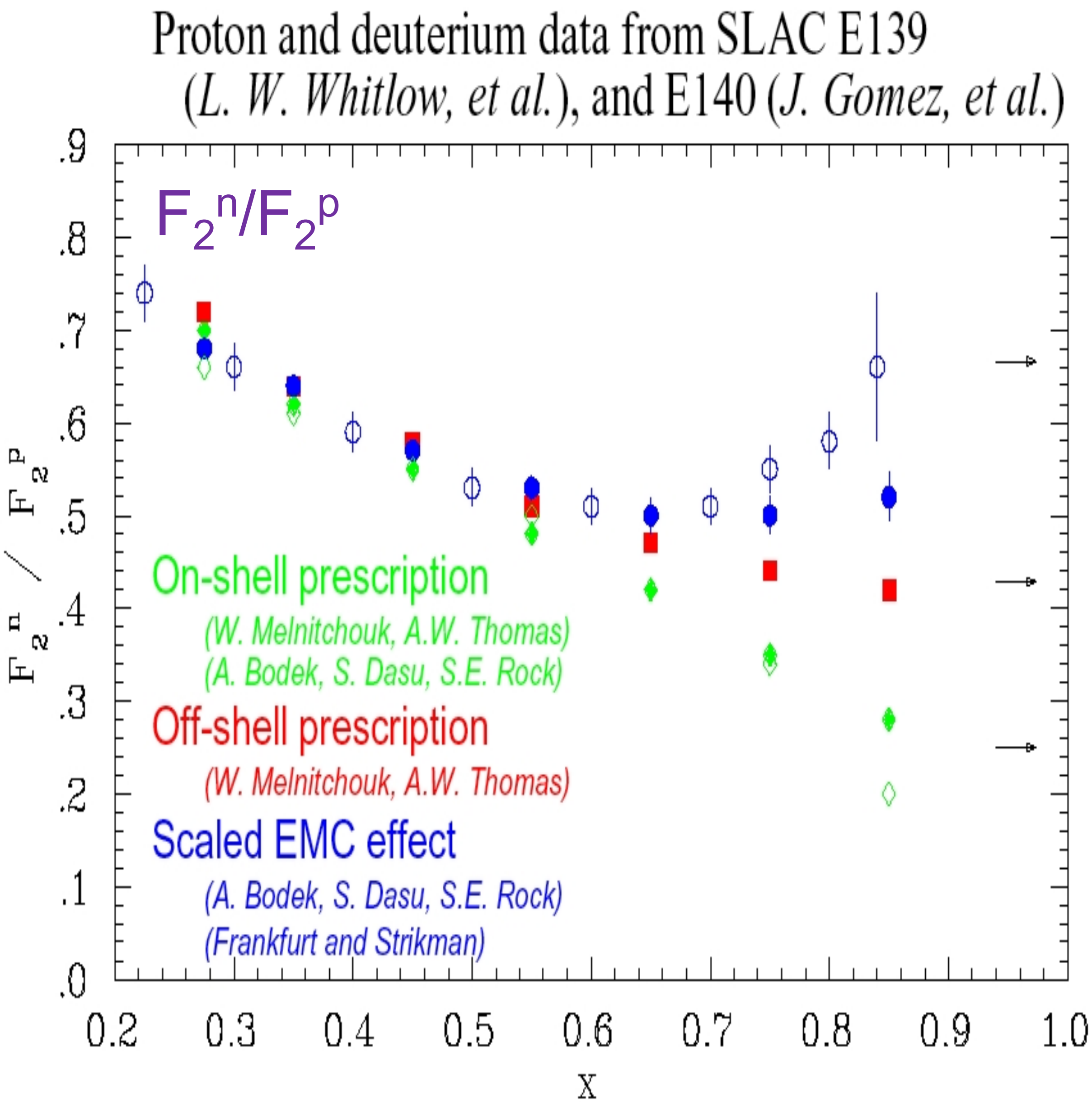
A Longstanding Problem!

Numerous 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)
- I. Cloet et al, Few Body Syst. **46** (2009) 1.

A measurement is needed…

....but.... deuteron nuclear effects are an obstacle!



No free neutrons, so use the deuteron

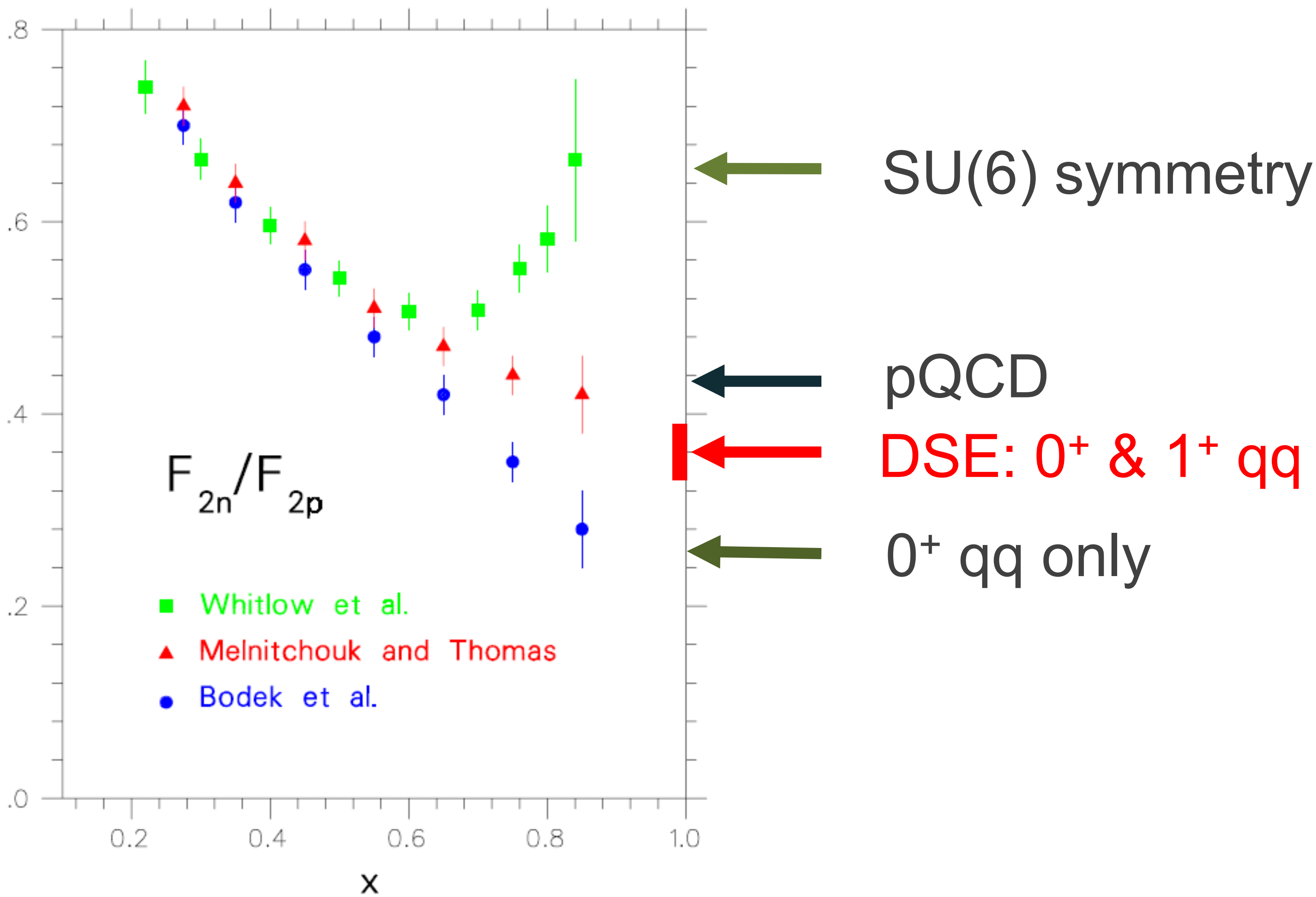
<u>SAME</u> data set

Different nuclear effect analyses

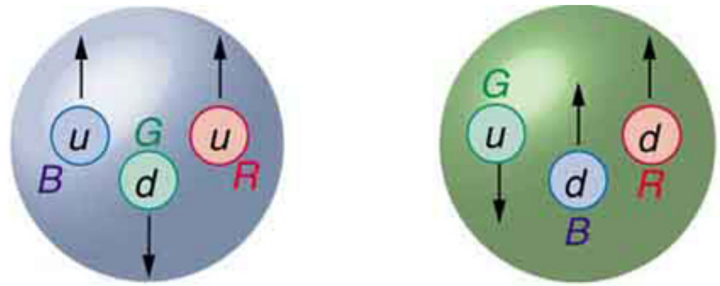
$0.2 < F_2^n/F_2^p < 0.8$?!?!

F_2^n/F_2^p (and, hence, d/u) 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*



Why is the valence regime interesting?



	Proton	Neutron
Spin	$\frac{1}{2}+\frac{1}{2}-\frac{1}{2}=\frac{1}{2}$	$-\frac{1}{2}+\frac{1}{2}+\frac{1}{2}=\frac{1}{2}$
Charge	$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$	$+\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$

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- “Valence regime” at large x, low Q^2 evolves to low x, high Q^2
  - Intersection of nuclear and particle physics
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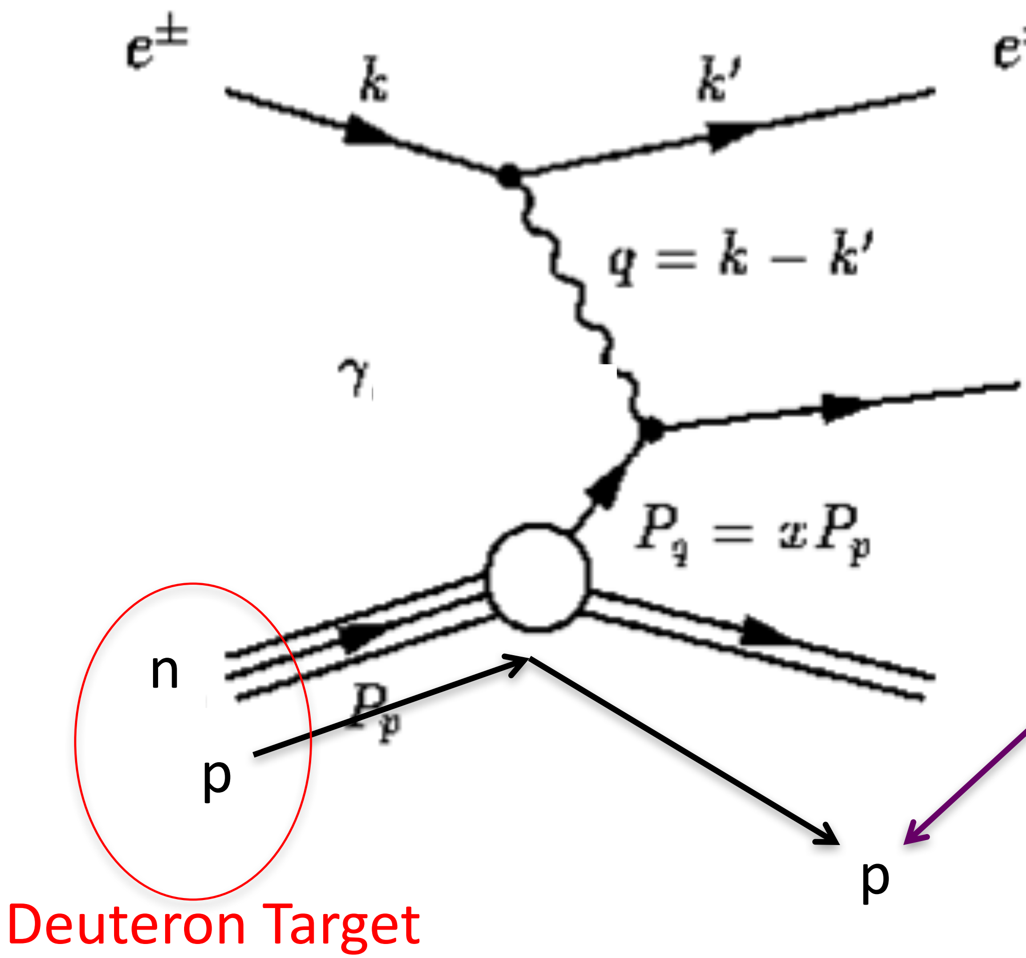
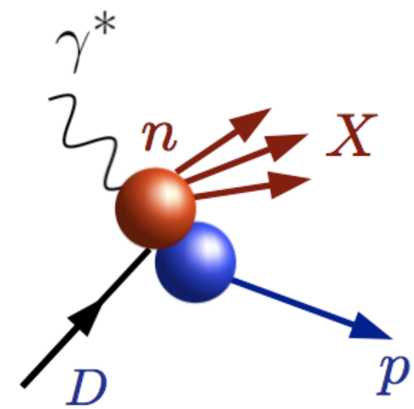
- New generation of experiments at JLab focused on high x

TDIS to access nucleon valence structure

"BONuS" Experiment at Jefferson Lab – use fixed target Tagged DIS to create an effective ***free neutron*** target





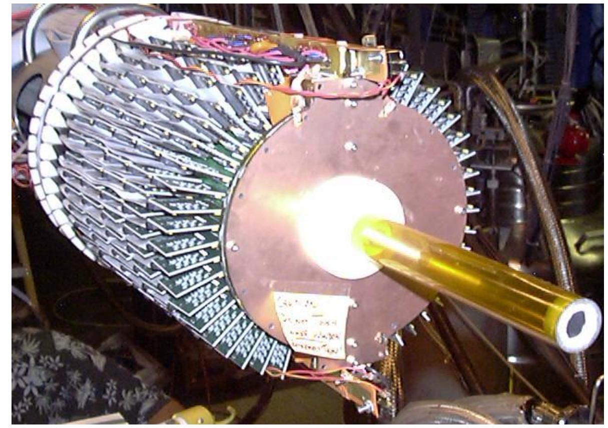
Measure DIS electron in coincidence with proton tag

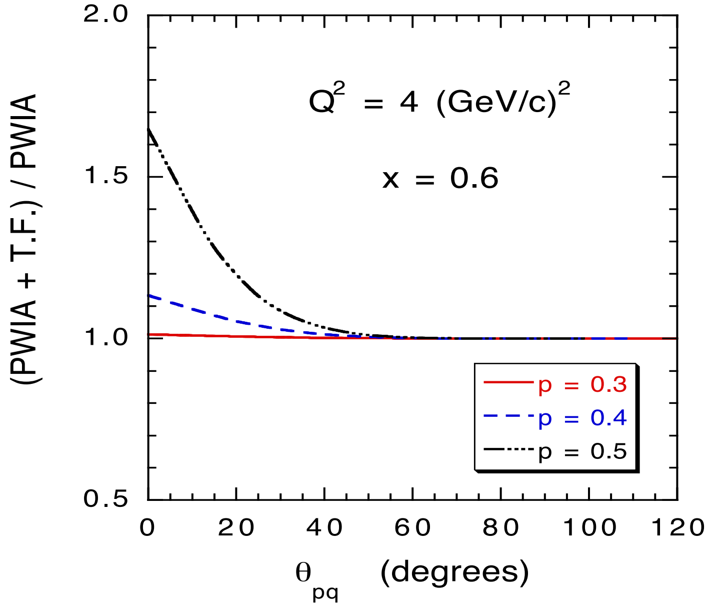
- "Hard" scattering inelastic event (high Q, W)
- Proton remains intact
- Low momentum proton = nucleons barely off shell

✓ Neutron target!

The BONuS approach:

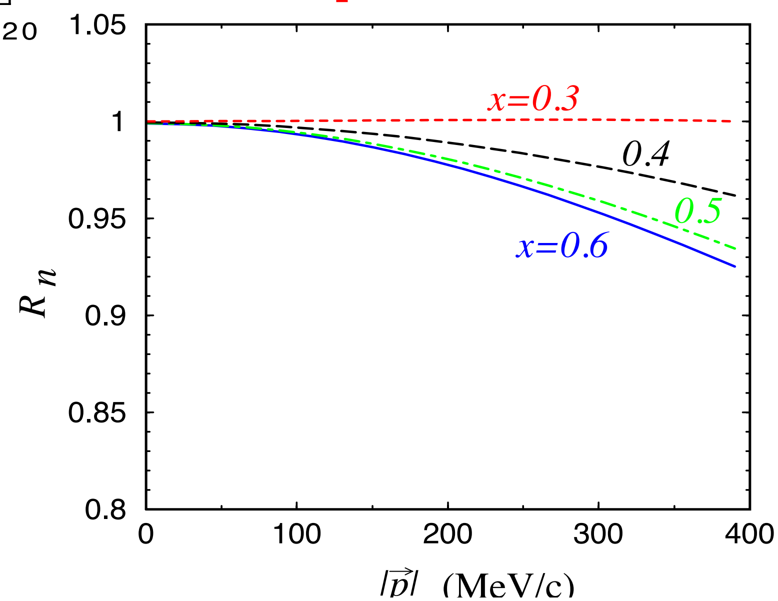
use low mass radial TPC detector / target in magnetic field to TAG "spectator" proton at (very) low momenta (~65 MeV/c) and large angles (> 90° in lab) ***….difficult but doable***

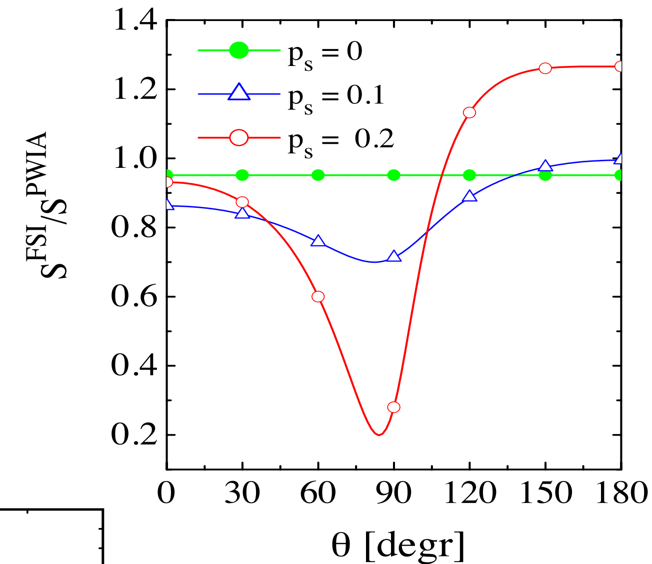




Bound / free neutron structure

***O* (1%)**





Target fragmentation

negligible

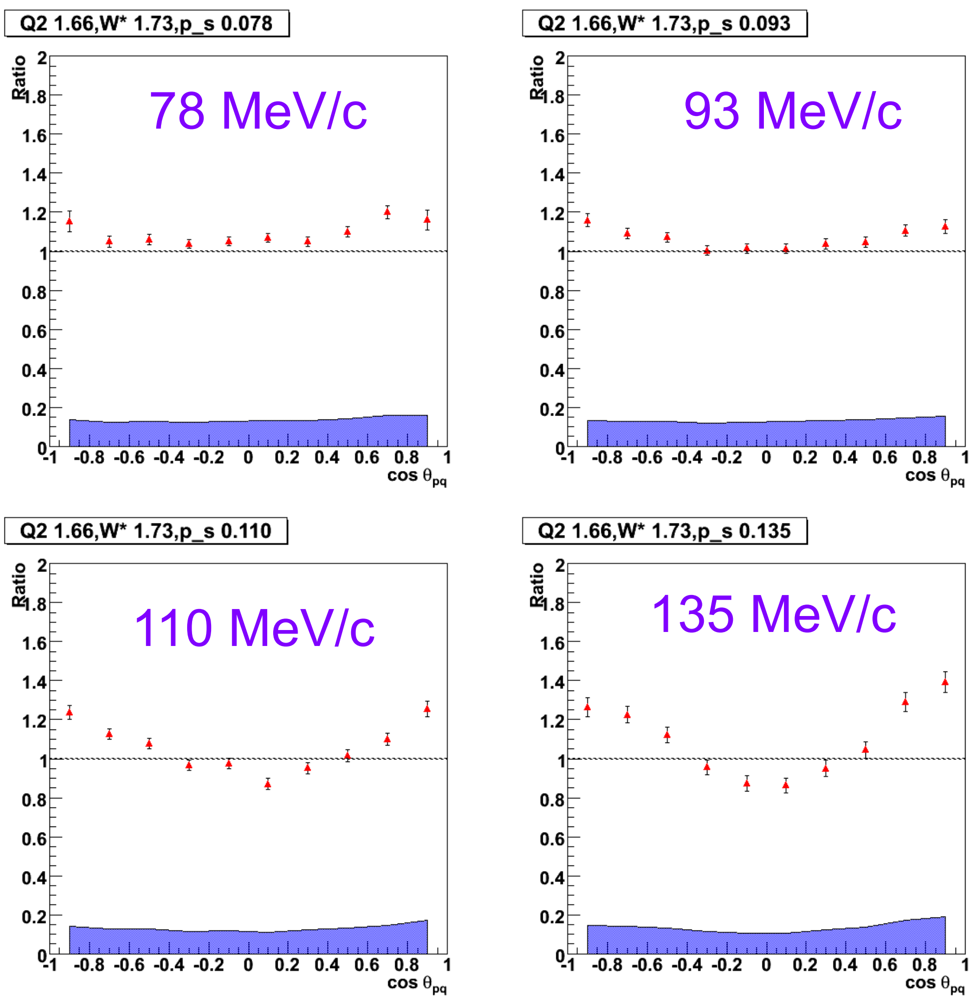
Final state interactions

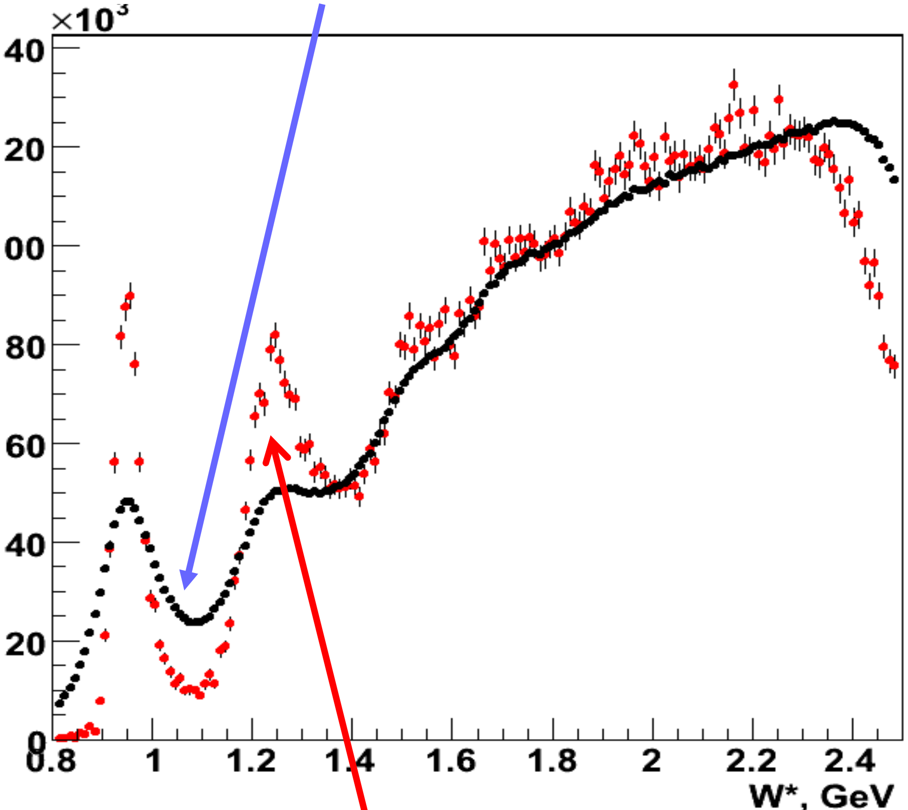
***O* (5%)**

The technique works!

angle - momentum dependence

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





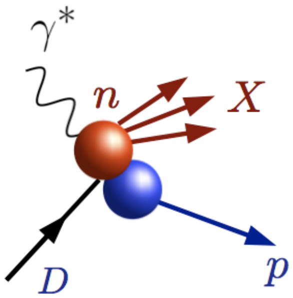
$$W^{*2} = (p_n + q)^2 = p_n^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2$$

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

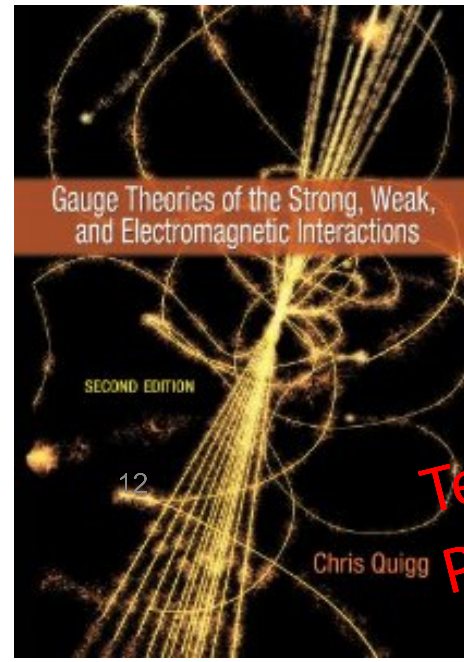
$\cos\theta_{pq}$

$\cos\theta_{pq}$

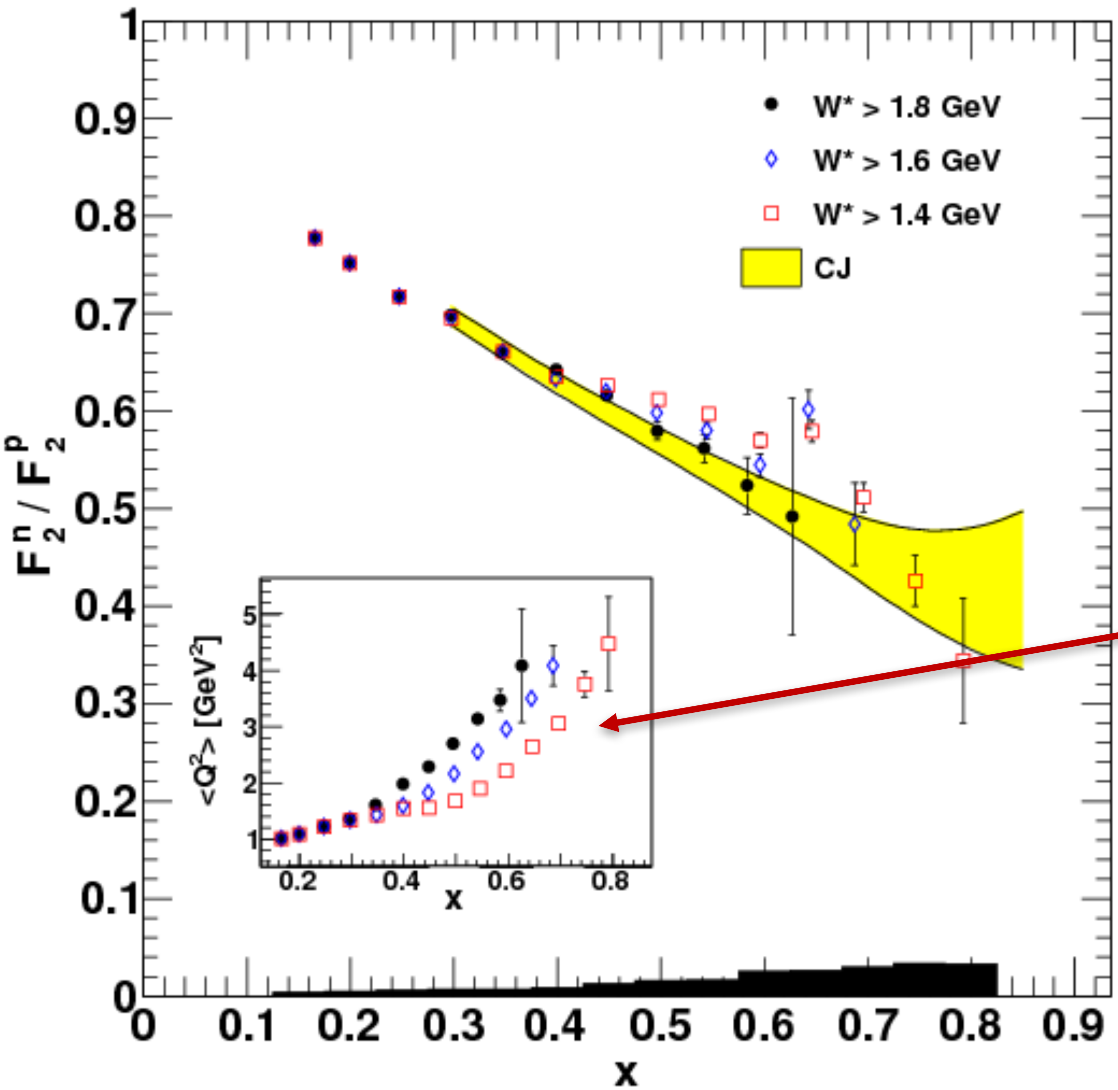
BONUS effective neutron target via TDIS *achieved!*



Phys.Rev. C92 (2015) no.1, 015211
Phys.Rev. C91 (2015) no.5, 055206
Phys. Rev. C89 (2014) 045206 – editor's suggestion
Phys. Rev. Lett. 108 (2012) 199902
Nucl. Instrum. Meth. A592 (2008) 273-286



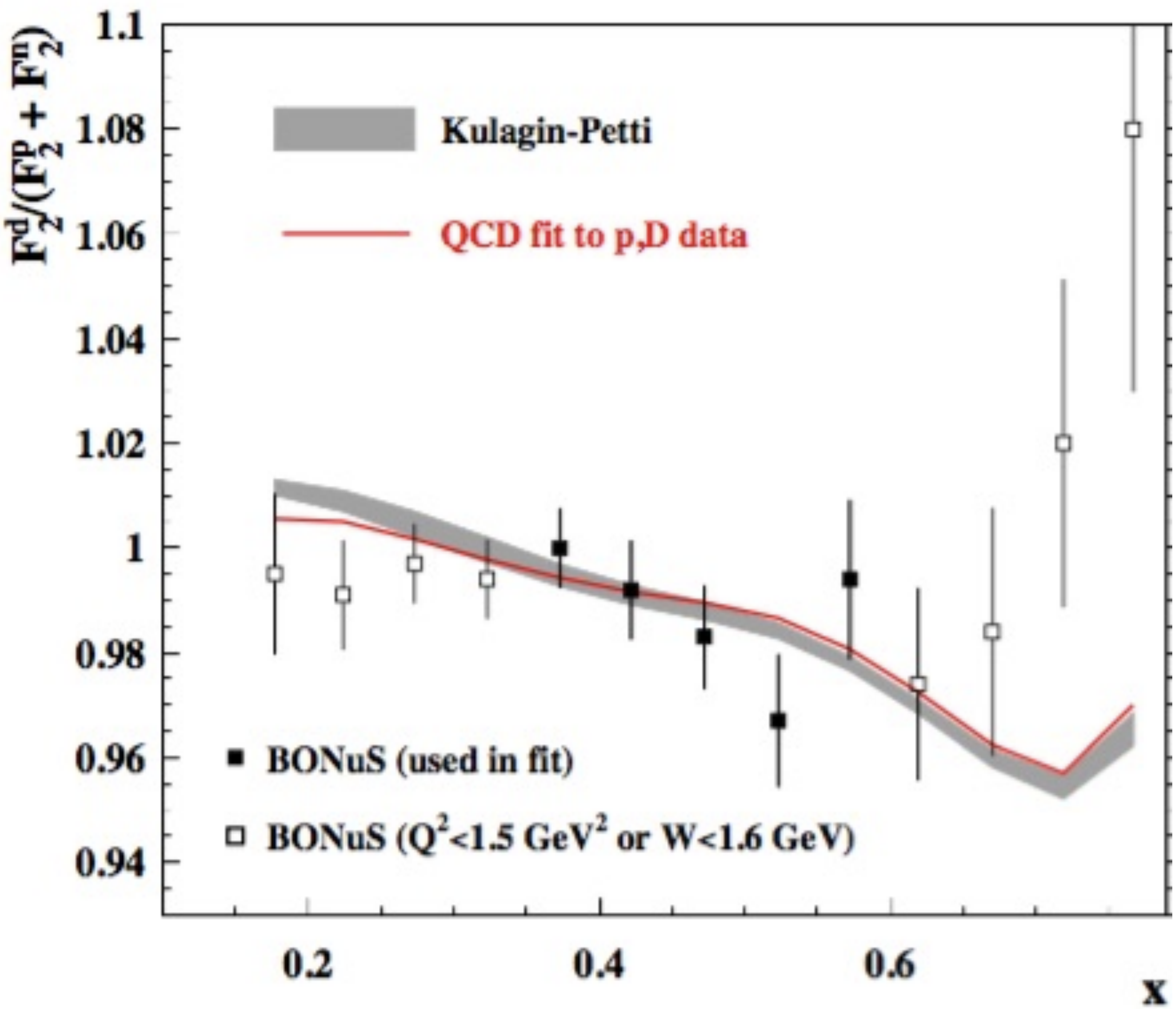
Textbook Physics!



- Not quite high enough x, Q^2
- Nonetheless still powerful as input for global PDF fits…

EMC effect in deuterium – correction for (nuclear) PDFs

$F_2^D/(F_2^n + F_2^p)$ with F_2^n from BONUS

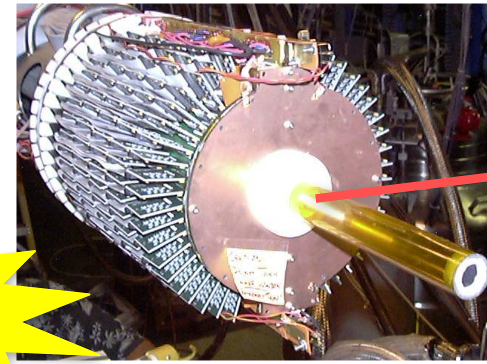


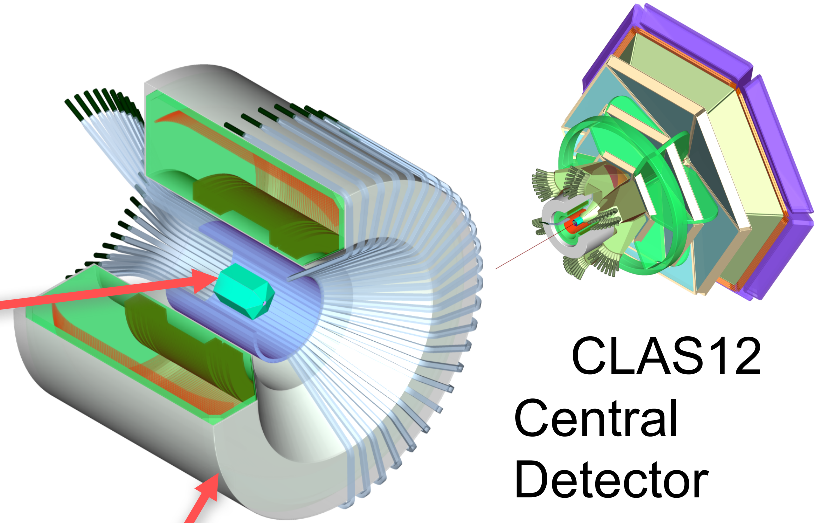
S.I. Alekhin, S.A. Kulagin, R. Petti Phys. Rev. D 96, 054005 (2017)

"The recent direct measurement of the deuteron nuclear correction by the BONuS experiment substantially reduces this uncertainty by constraining the normalization of the overall nuclear corrections."

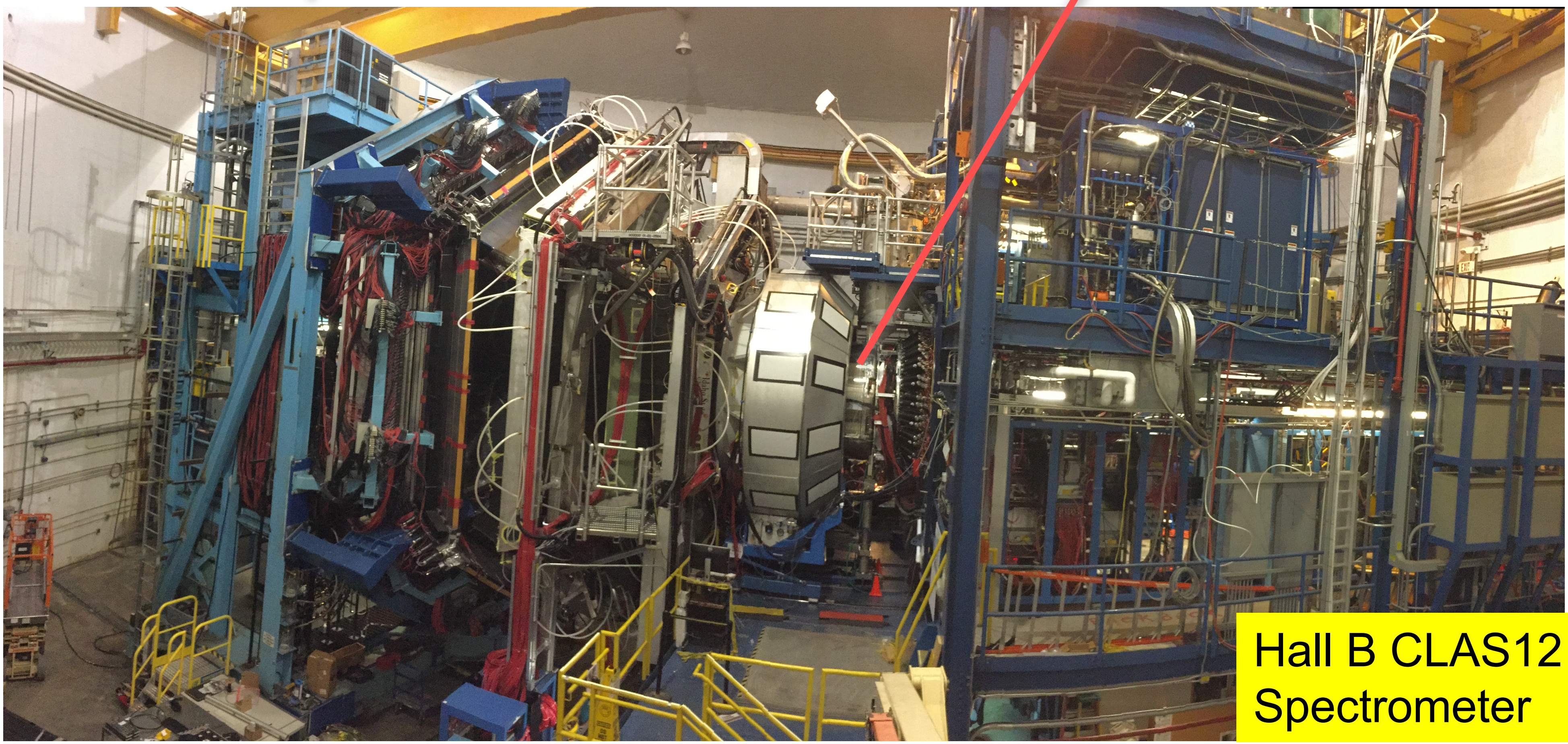
E12-06-113 “BONUS12”: Larger x and higher Q^2

High Impact



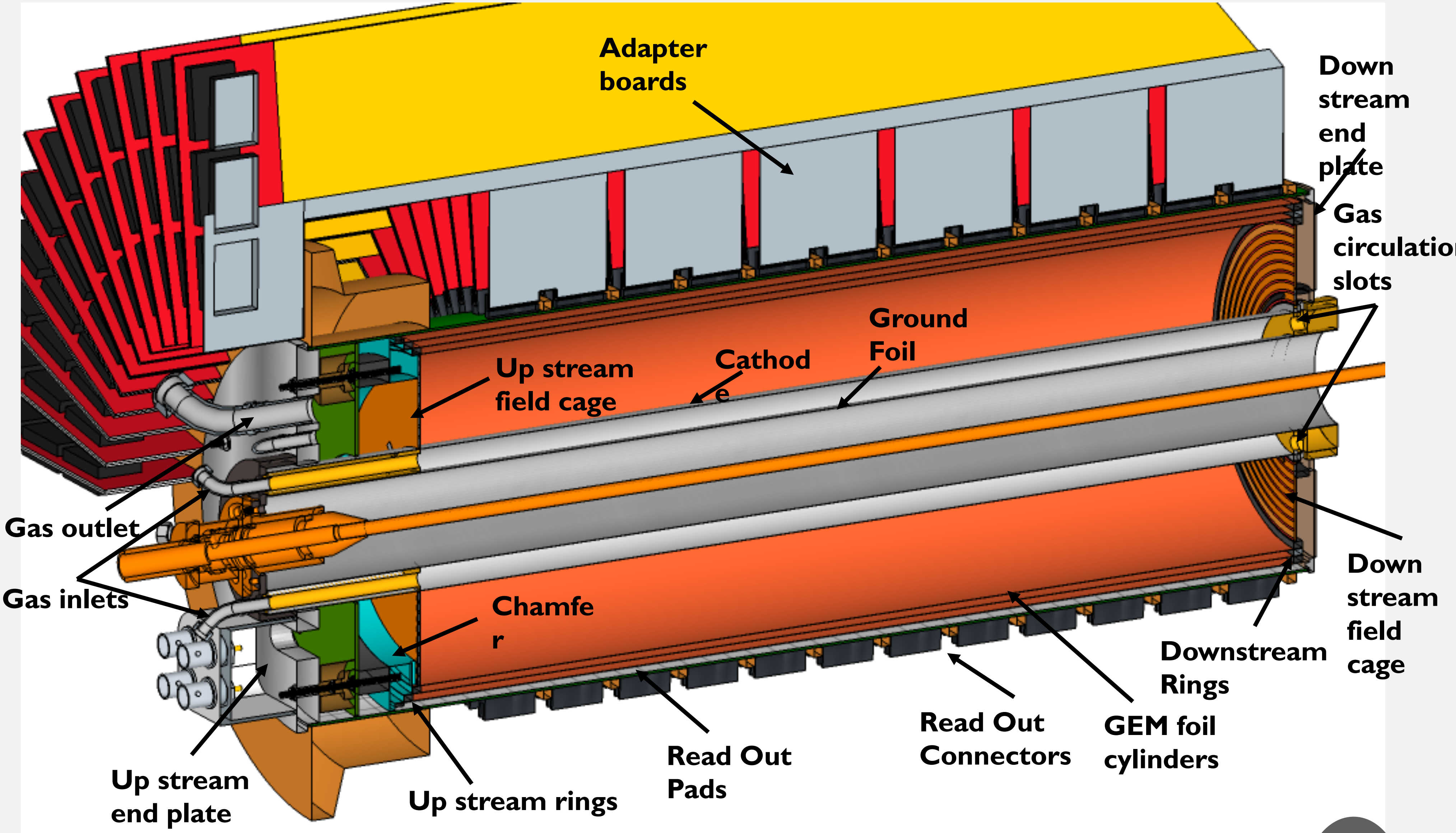


CLAS12 Central Detector



Hall B CLAS12 Spectrometer

BONUS12 RTPC



RTPC UNDER CONSTRUCTION

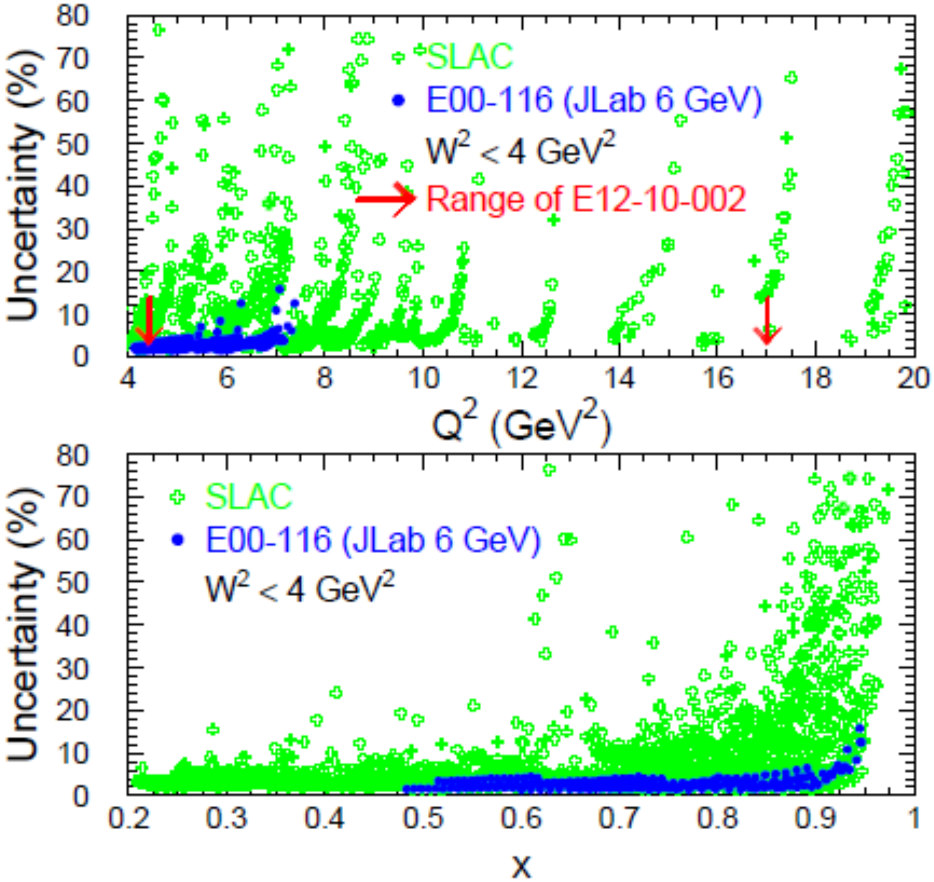
Preparing for Fall 2020 run!

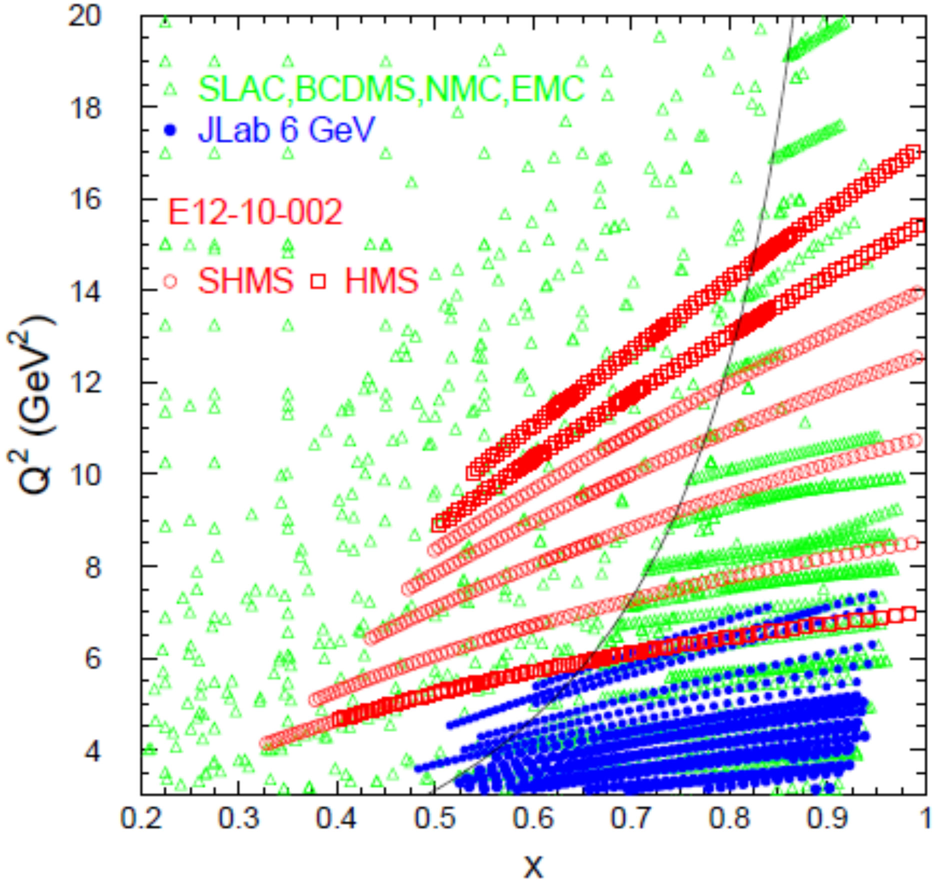
Self aligning puller assembly

Removal of glued capton cylinder using puller mechanism

F_2^p & F_2^d Structure Functions in Hall C

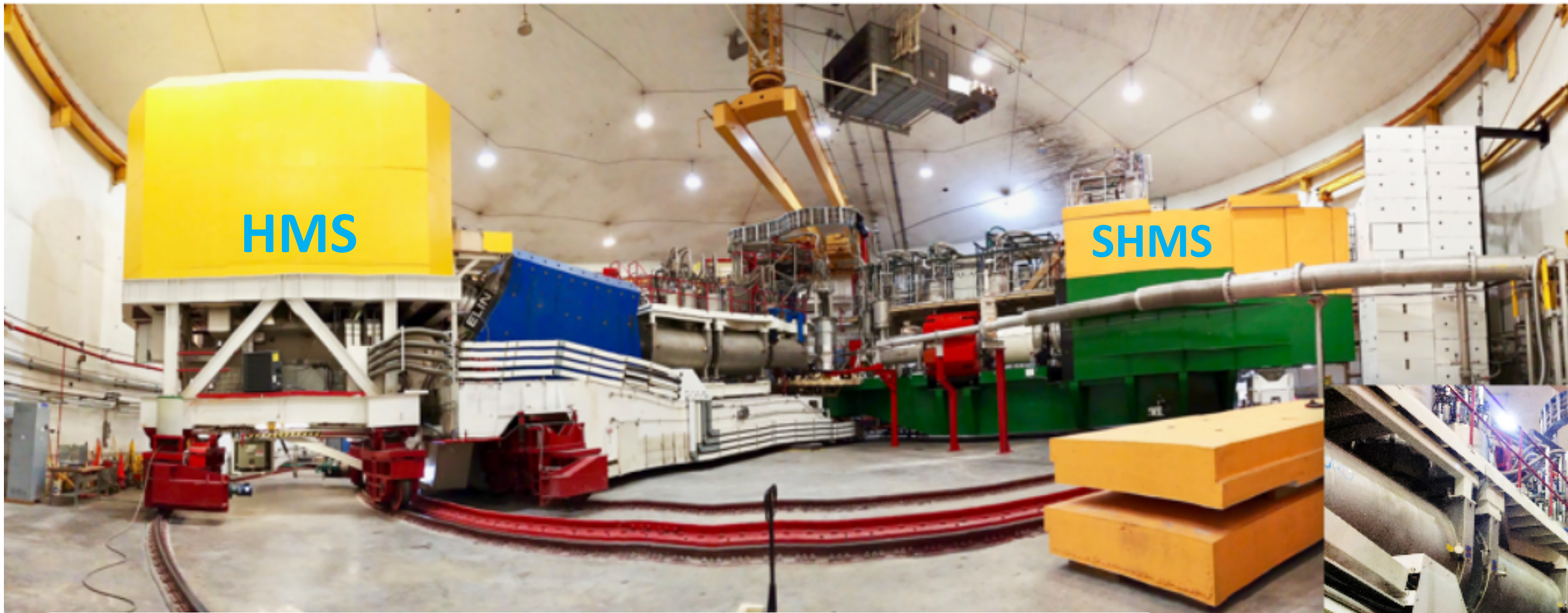
JLab12 Hall C commissioning experiment aims to reduce uncertainties in F_2^p and F_2^d structure functions at large x and high Q



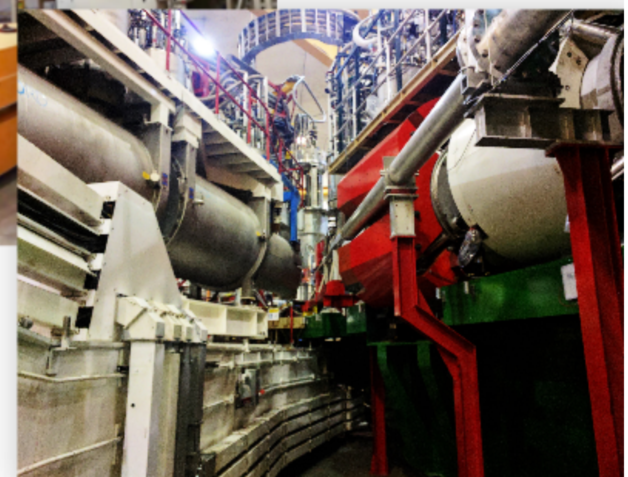


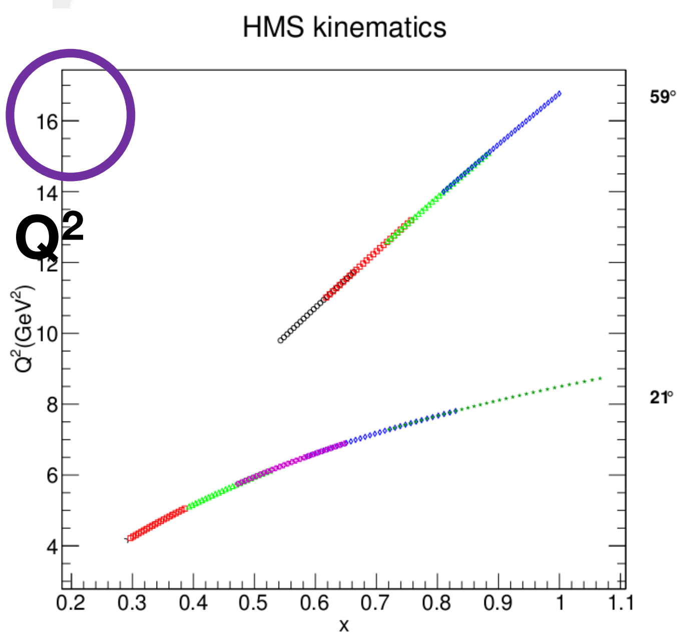
Goal @ 12 GeV: <2% total precision cross sections, (as achieved by E00-116 @ 6 GeV)

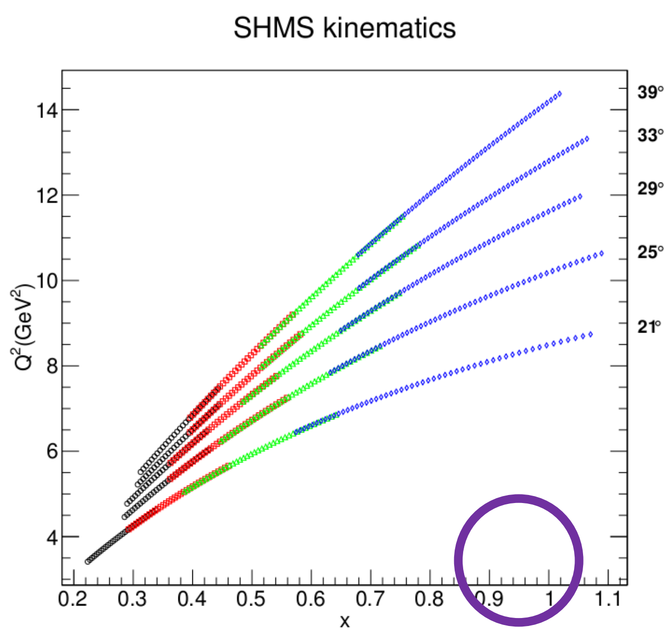
E12-10-002: High Precision Measurement of the F_2 Structure Function on p,D



- 10.6 GeV beam
- Targets: LH2, LD2, Al





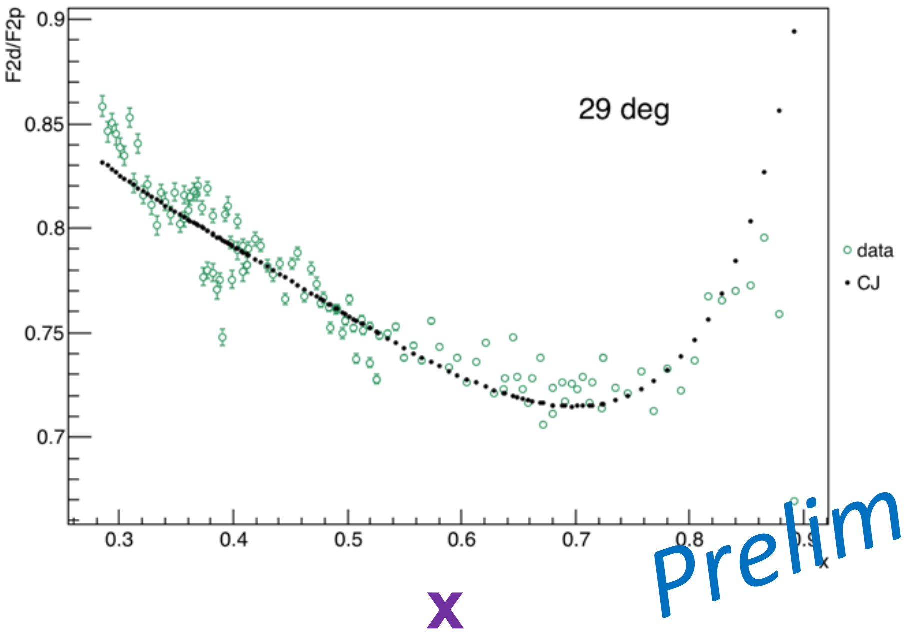


x

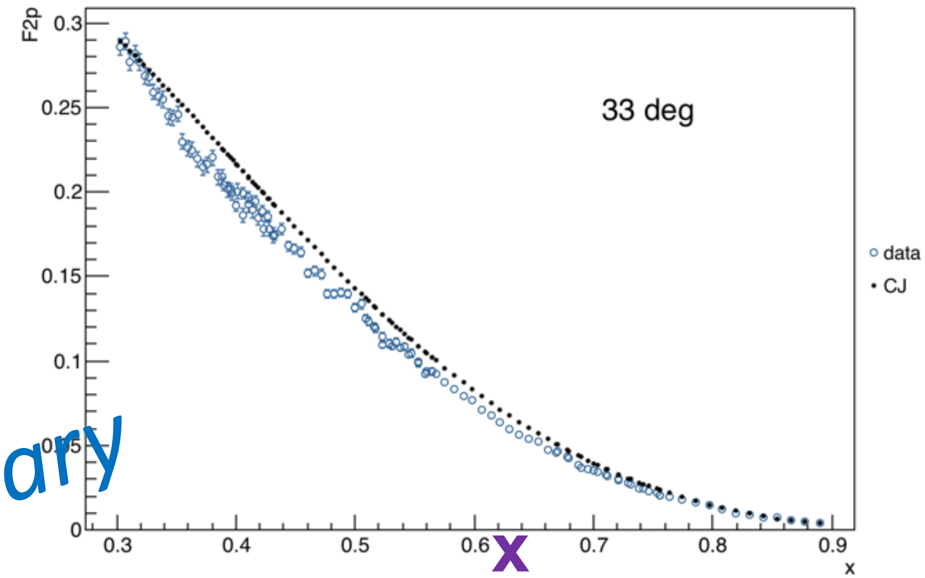
- Fix energy and angle
- Scan in momentum
- Effective scan in x
- Stringent check on spectrometer acceptance

Preliminary Results: Structure Functions (and CJ fit)

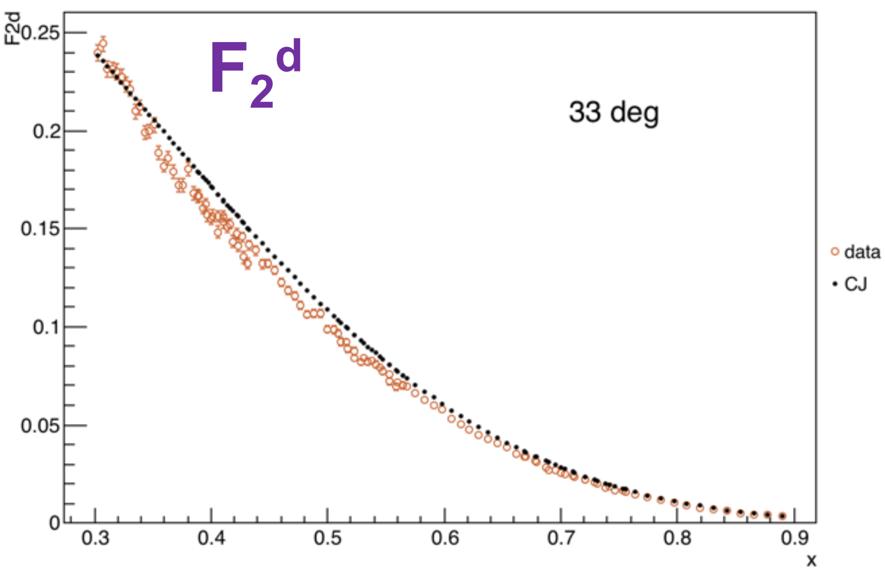
F_2^d/F_2^p



F_2^p



F_2^d



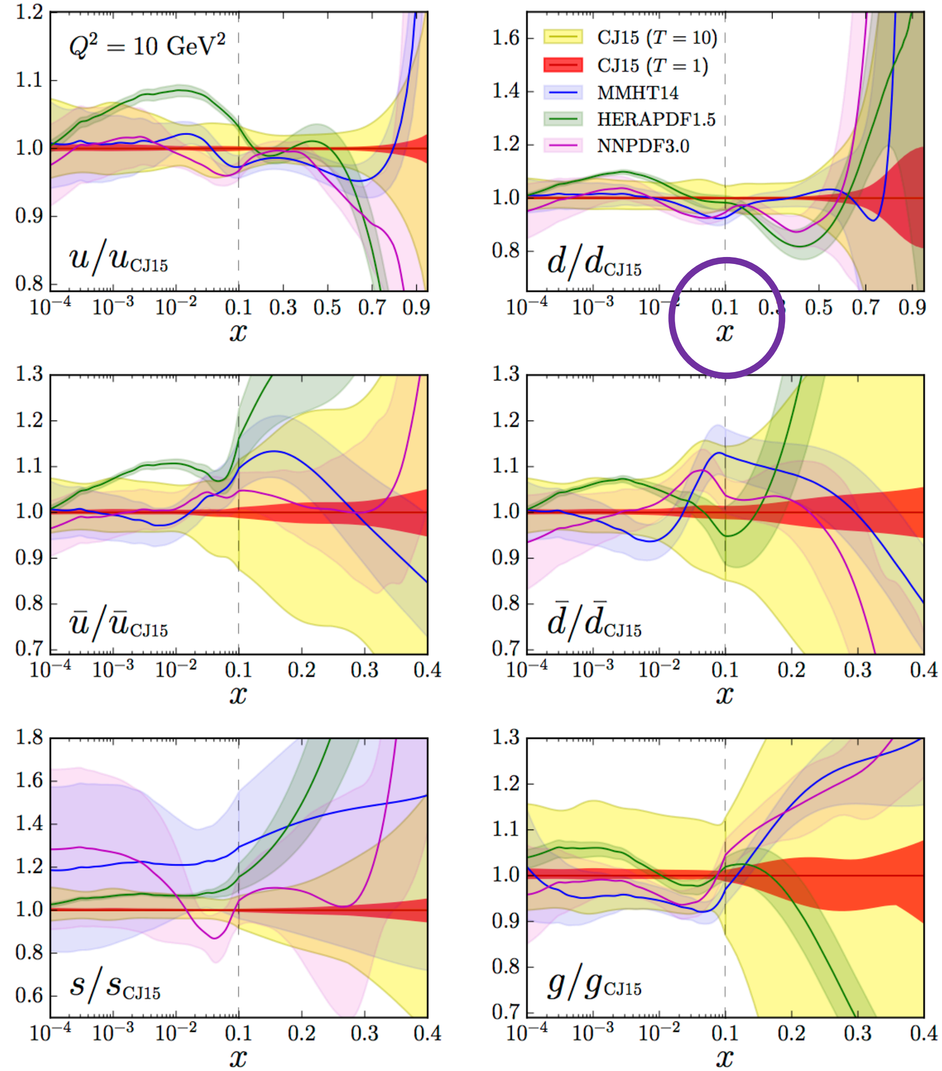
Still working on:

- Some background subtractions
- Systematic uncertainties
- Looking towards F_2d/F_2p paper submission this Fall

CTEQ-Jefferson Lab “CJ” PDF Fits

- CTEQ-based PDF fit **optimized for larger x, lower Q^2**
  - Necessary for experiments at Jefferson Lab, neutrino experiments, spin structure,…
  - Valence regime increasingly important for lattice comparisons
- Uses data previously subject to kinematic cuts (SLAC and JLab largely)
- Incorporates higher twist, target mass corrections
- Allow d/u to go to a constant
- *Need accurate deuteron nuclear corrections for DIS data*

http://www.jlab.org/CJ



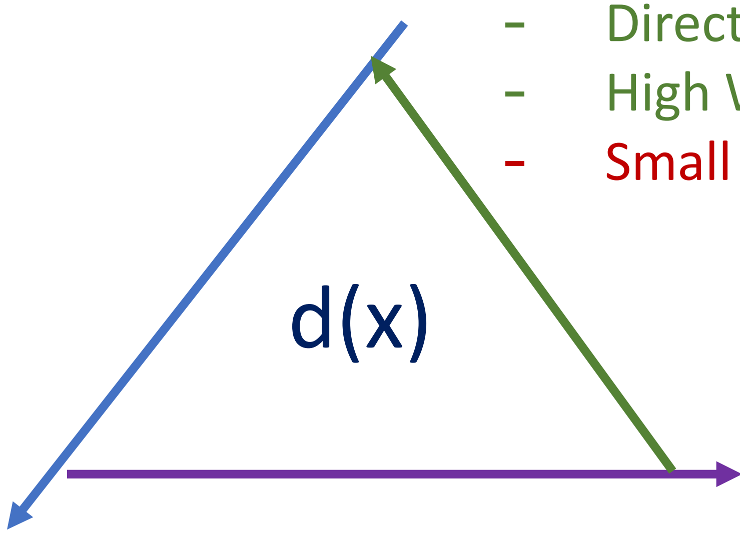
http://lhapdf.hepforge.org/lhapdf5/pdfsets

Current Data Constraints on d(x) at Large x:

The whole is greater than the sum of the parts.

D0, CDF W asymmetries

- Direct sensitivity to d(x)
- High W, Q
- Small data set



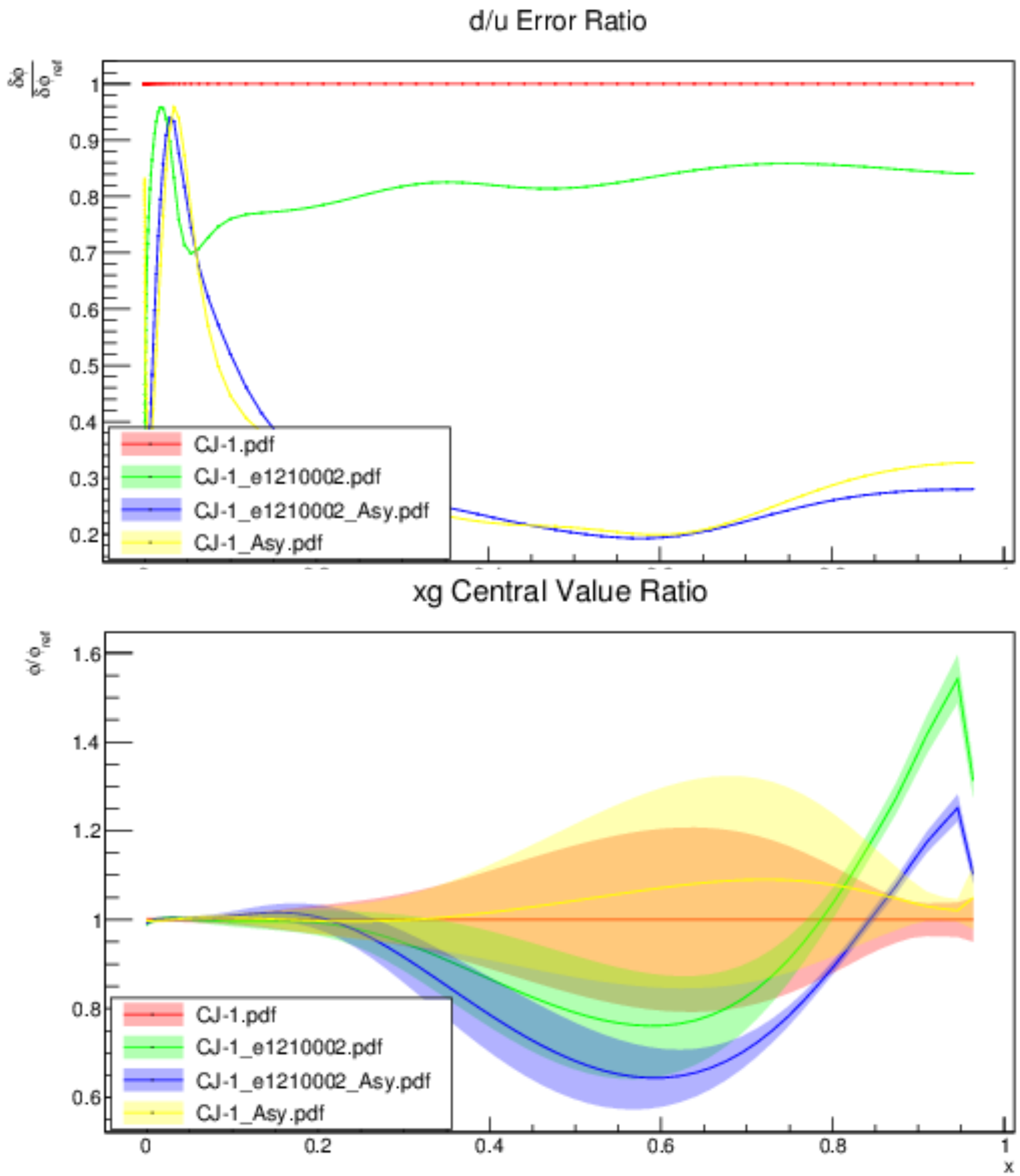
"BONuS" tagged neutron target

- Nearly model-independent *neutron* data
- Data obtained in 6 GeV JLab era at low W, Q

Deep inelastic deuterium

- Large body of data from multiple experiments
- Range in x and Q^2
- Requires deuteron nuclear corrections

Preliminary Results: PDF uncertainties

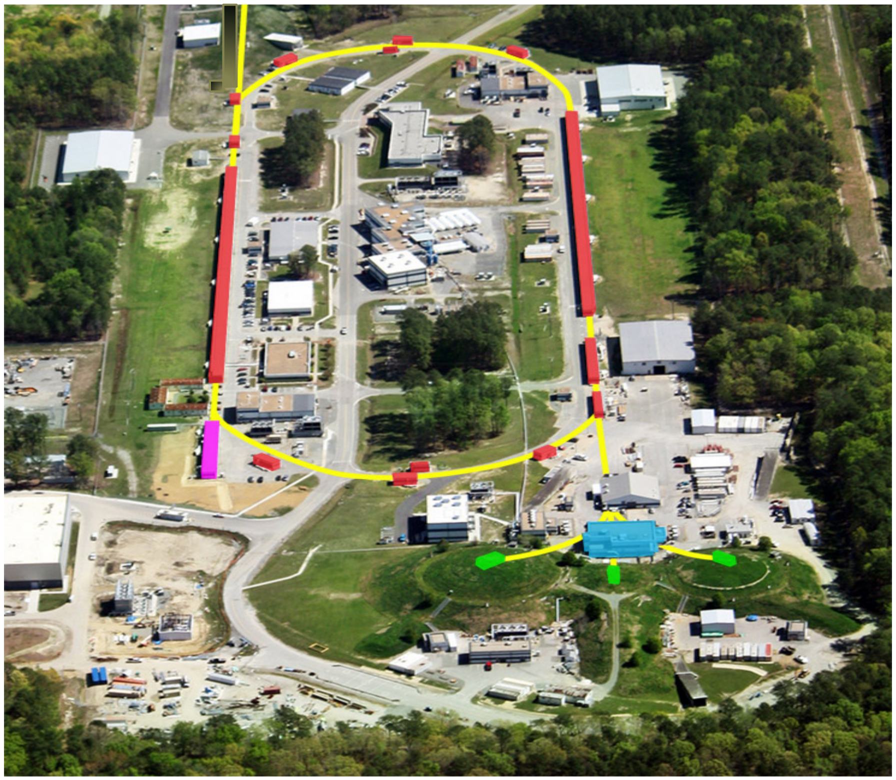


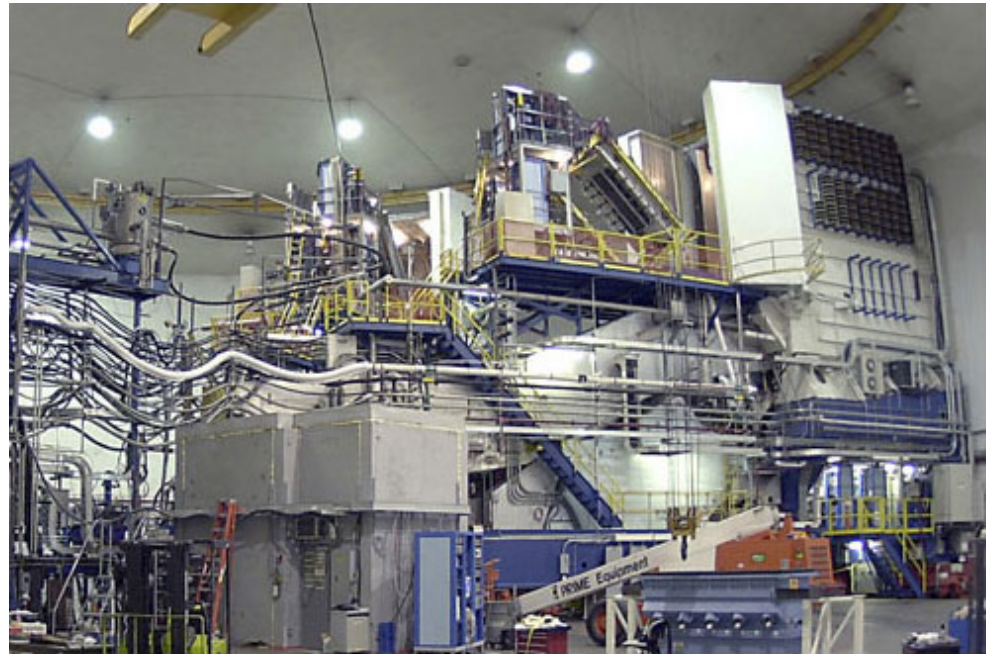
Initial studies adding new data to CJ pdf fit… error reduction, but d(x) still largely determined by FNAL W asymetry data

Will add BNL data

Jefferson Lab

Or, a nuclear physicists approach to the problem….





JLab Hall A HRS Spectrometer

- Problem:
  - The deuteron experiments present free nucleon extraction complications.
- *Solution:* Add another nucleon!
- $^3H/^3He$ ratio: minimizes nuclear physics uncertainties

Deep Inelastic Scattering 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

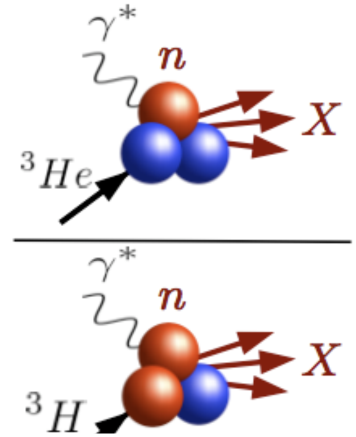
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

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

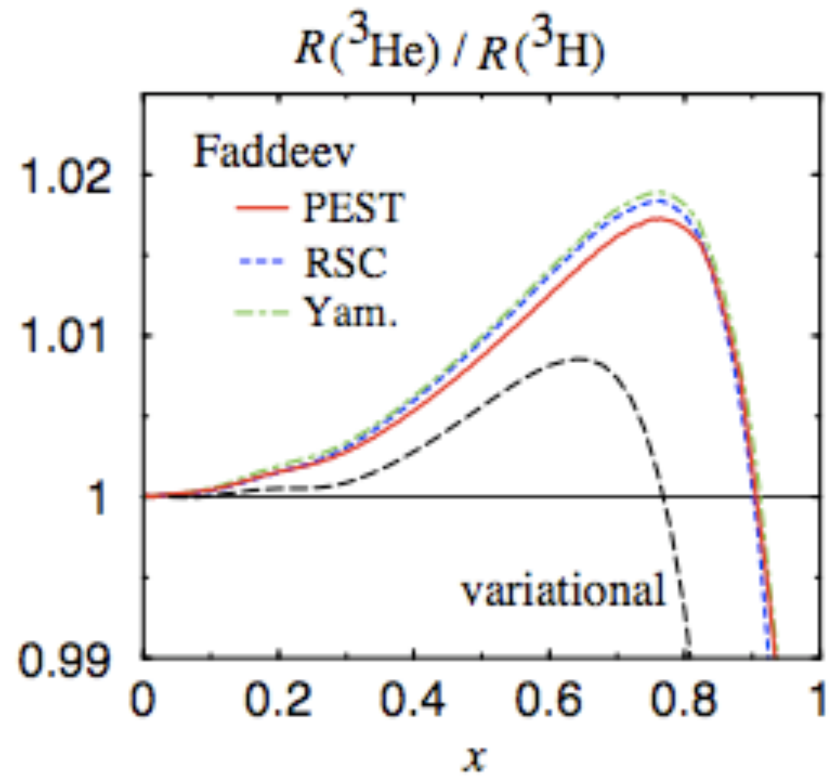
- Relies only on *difference* in nuclear effects in ^{3}H, ^{3}He

- Calculated to within 1%

- Most systematic and theoretical uncertainties cancel



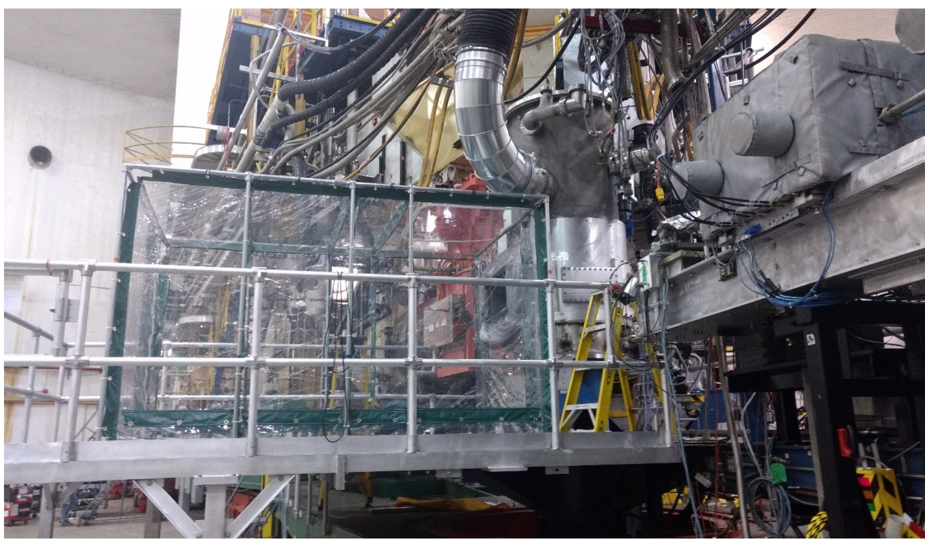
I. Afnan et al, PRC 68 (2003)

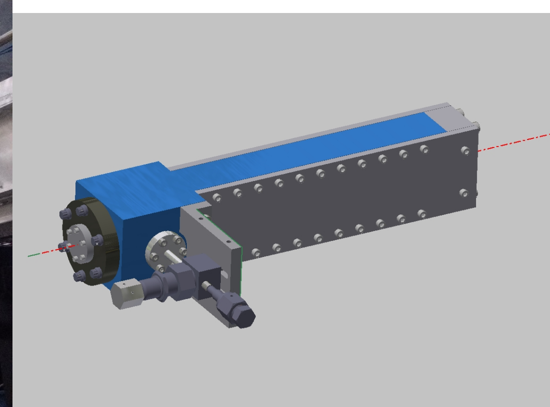


Hall A Tritium Target first in over 3 decades!!

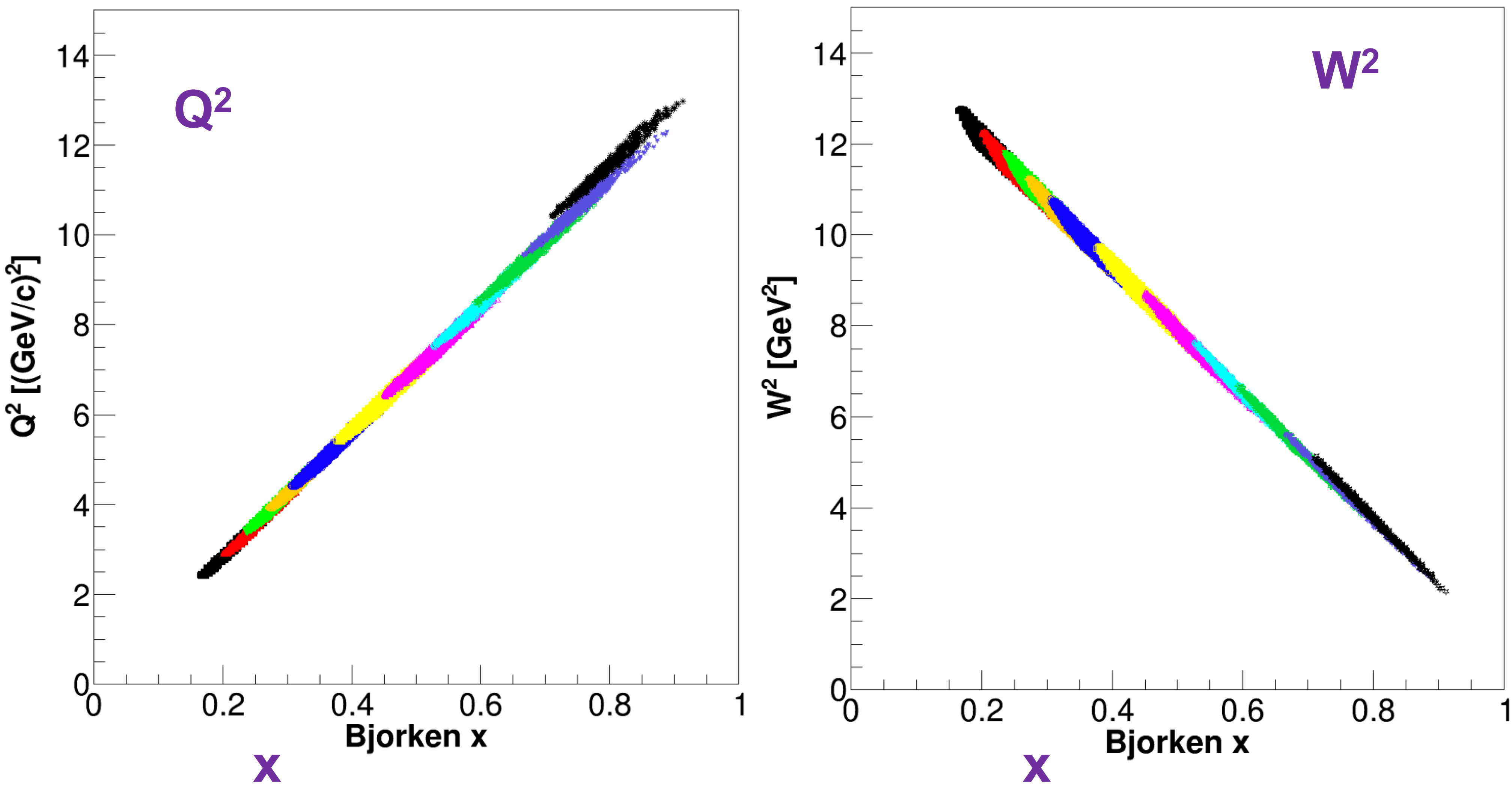
Lab	Year	Quantity (kCi)	Thickness (g/cm^2)	Current (μA)	Current *x* thickness (μA-g/cm^2)
Stanford	1963	25	0.8	0.5	0.4
MIT-Bates	1982	180	0.3	20	6.0
Saskatoon	1985	3	0.02	30	0.6
JLab	**2017**	**1**	**0.08**	**20**	**1.6**

JLab Luminosity ~ 2.0×10^{36} tritons/cm^2/s





Kinematic Coverage of MARATHON



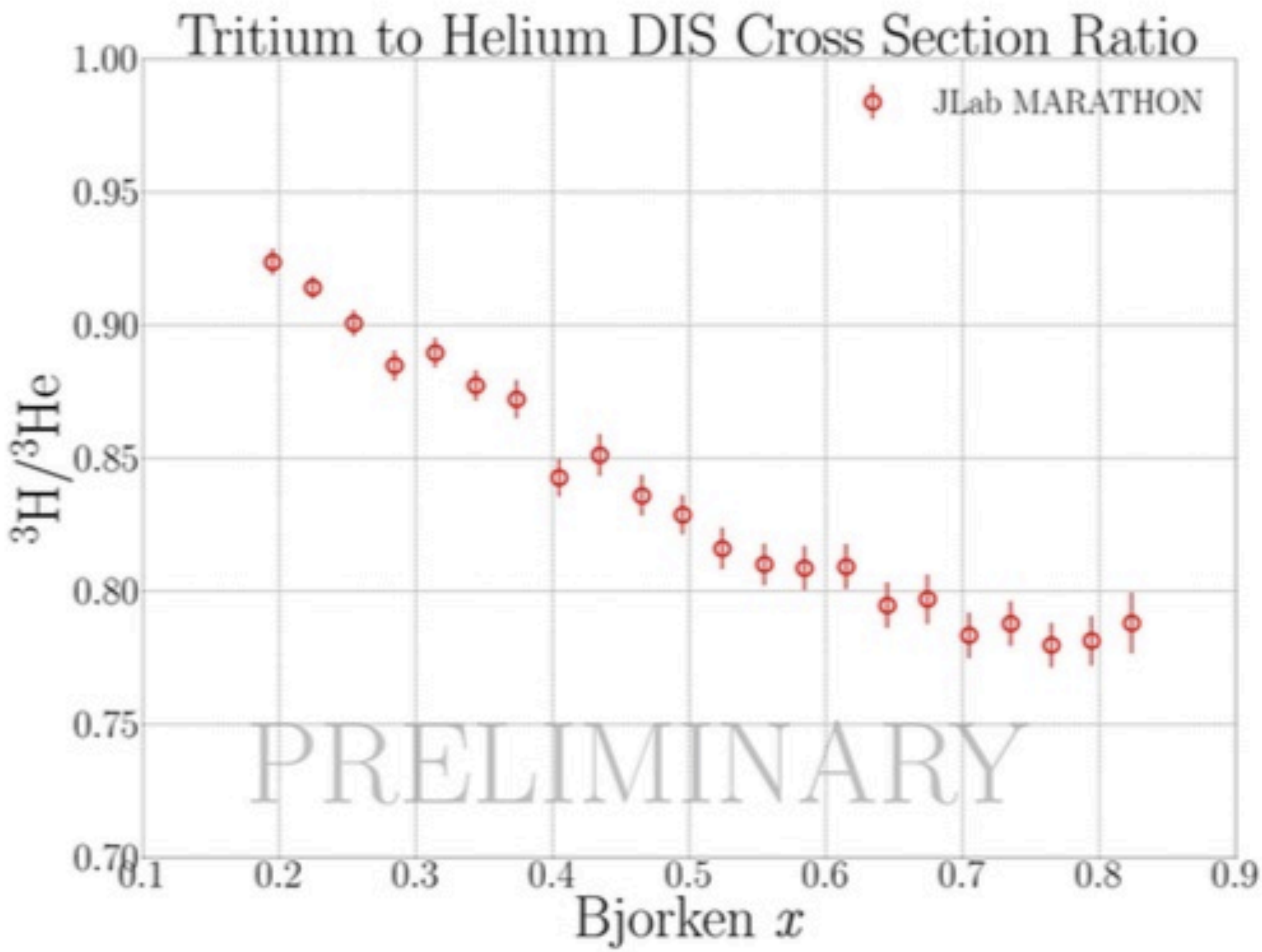
* DIS with 10.6 GeV electron beam on ^{3}H, ^{3}He and ^{2}H targets. The electron scattering angle ranged between 17 and 36 deg.

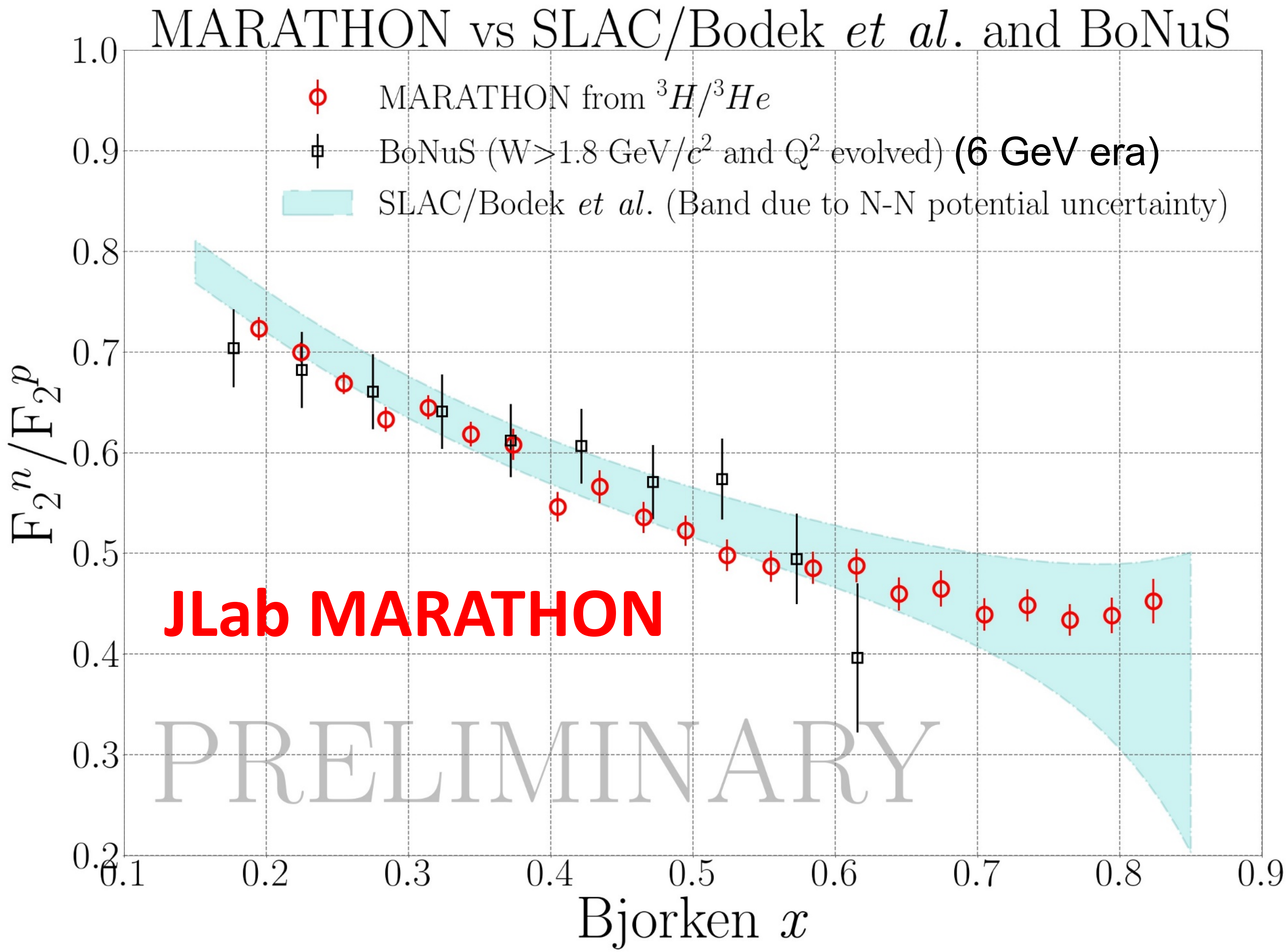
JLab MARATHON preliminary results

This is the actual (preliminary) data!

Still working on systematic uncertainties

Use ratio of nuclear effects in ^{3}H, ^{3}He to get....




MARATHON vs SLAC/Bodek et al. and BoNuS
MARATHON from $^3H/^3He$
BoNuS (W>1.8 GeV/c^2 and Q^2 evolved) (6 GeV era)
SLAC/Bodek et al. (Band due to N-N potential uncertainty)
JLab MARATHON
PRELIMINARY
F_2^n/F_2^p
Bjorken x
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Polarized predictions for d/u structure at large x

Proton Wavefunction (Spin and Flavor Symmetric)

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

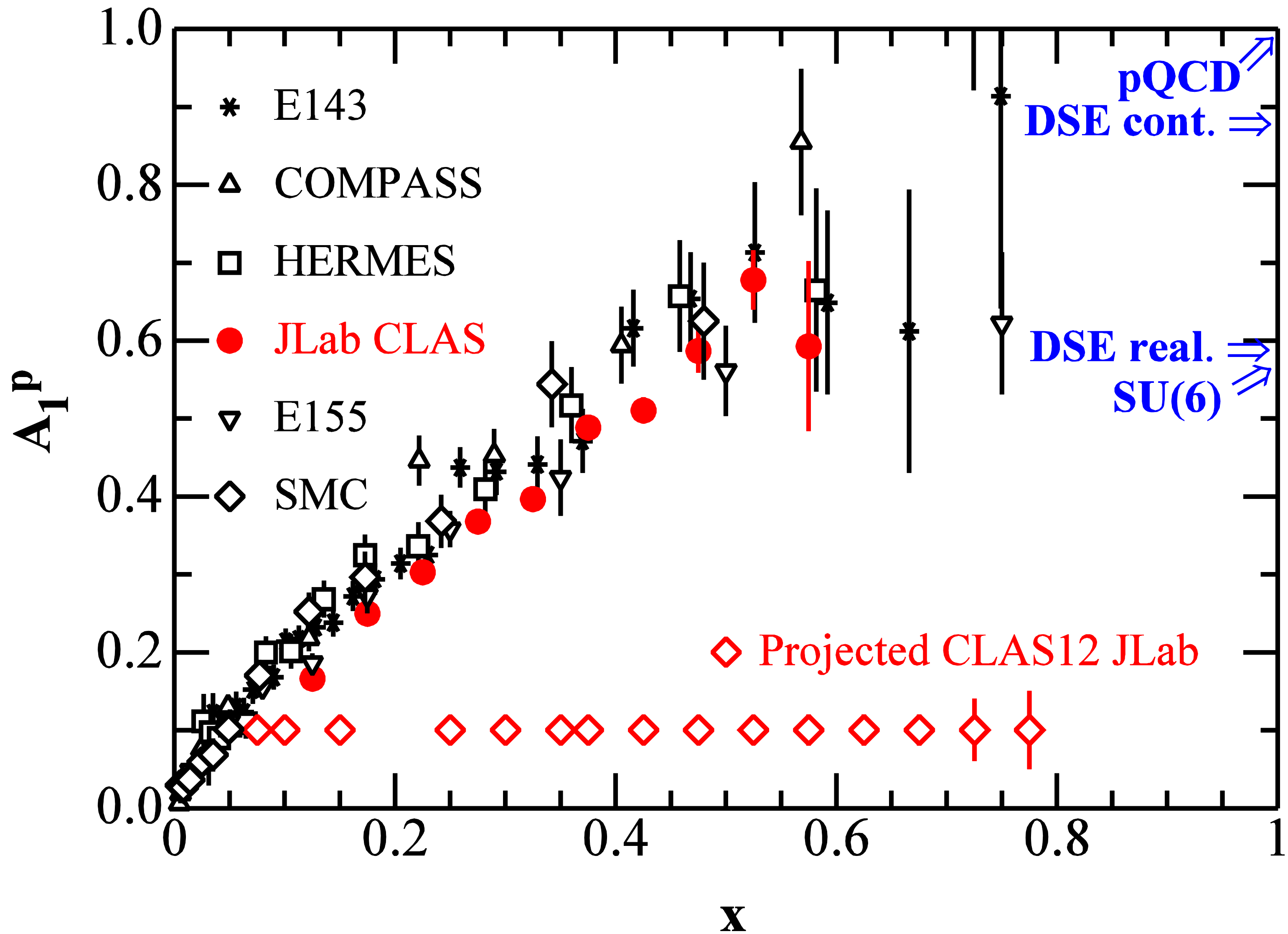
Model	F_2^n/F_2^p	d/u	$\Delta u/u$	$\Delta d/d$	A_1^n	A_1^p
SU(6) = SU3 flavor + SU2 spin	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark + Hyperfine	1/4	0	1	-1/3	1	1
pQCD + HHC	3/7	1/5	1	1	1	1
DSE-1 (realistic)	0.49	0.28	0.65	-0.26	0.17	0.59
DSE-2 (contact)	0.41	0.18	0.88	-0.33	0.34	0.88

Lepton scattering spin structure experiments (mostly inclusive):

JLab's focus is high precision large x and low to intermediate Q^2 values

Experiment	Ref.	Target	Analysis	W (GeV)	x_{Bj}	Q^2 (GeV^2)
E80 (SLAC)	[101]	p	A_1	2.1 to 2.6	0.2 to 0.33	1.4 to 2.7
E130 (SLAC)	[102]	p	A_1	2.1 to 4.0	0.1 to 0.5	1.0 to 4.1
EMC (CERN)	[103]	p	A_1	5.9 to 15.2	1.5×10^{-2} to 0.47	3.5 to 29.5
SMC (CERN)	[250]	p, d	A_1	7.7 to 16.1	10^{-4} to 0.482	0.02 to 57
E142 (SLAC)	[244]	^{3}He	A_1, A_2	2.7 to 5.5	3.6×10^{-2} to 0.47	1.1 to 5.5
E143 (SLAC)	[245]	p, d	A_1, A_2	1.1 to 6.4	3.1×10^{-2} to 0.75	0.45 to 9.5
E154 (SLAC)	[246, 247]	^{3}He	A_1, A_2	3.5 to 8.4	1.7×10^{-2} to 0.57	1.2 to 15.0
E155/x (SLAC)	[248, 249]	p, d	A_1, A_2	3.5 to 9.0	1.5×10^{-2} to 0.75	1.2 to 34.7
HERMES (DESY)	[253, 254]	p, ^{3}He	A_1	2.1 to 6.2	2.1×10^{-2} to 0.85	0.8 to 20
E94010 (JLab)	[256]	^{3}He	g_1, g_2	1.0 to 2.4	1.9×10^{-2} to 1.0	0.019 to 1.2
EG1a (JLab)	[257]	p, d	A_1	1.0 to 2.1	5.9×10^{-2} to 1.0	0.15 to 1.8
RSS (JLab)	[258, 259]	p, d	A_1, A_2	1.0 to 1.9	0.3 to 1.0	0.8 to 1.4
COMPASS (CERN) DIS	[251]	p, d	A_1	7.0 to 15.5	4.6×10^{-3} to 0.6	1.1 to 62.1
COMPASS (CERN) low-Q^2	[280]	p, d	A_1	5.2 to 19.1	4×10^{-5} to 4×10^{-2}	0.001 to 1.
EG1b (JLab)	[260, 261, 262, 263]	p, d	A_1	1.0 to 3.1	2.5×10^{-2} to 1.0	0.05 to 4.2
E99-117 (JLab)	[264]	^{3}He	A_1, A_2	2.0 to 2.5	0.33 to 0.60	2.7 to 4.8
E99-107 (JLab)	[265]	^{3}He	g_1, g_2	2.0 to 2.5	0.16 to 0.20	0.57 to 1.34
E01-012 (JLab)	[266, 267]	^{3}He	g_1, g_2	1.0 to 1.8	0.33 to 1.0	1.2 to 3.3
E97-110 (JLab)	[268]	^{3}He	g_1, g_2	1.0 to 2.6	2.8×10^{-3} to 1.0	0.006 to 0.3
EG4 (JLab)	[269]	p, n	g_1	1.0 to 2.4	7.0×10^{-3} to 1.0	0.003 to 0.84
SANE (JLab)	[271]	p	A_1, A_2	1.4 to 2.8	0.3 to 0.85	2.5 to 6.5
EG1dvcs (JLab)	[270]	p	A_1	1.0 to 3.1	6.9×10^{-2} to 0.63	0.61 to 5.8
E06-014 (JLab)	[272, 273]	^{3}He	g_1, g_2	1.0 to 2.9	0.25 to 1.0	1.9 to 6.9
E06-010/011 (JLab)	[278]	^{3}He	single spin asy.	2.4 to 2.9	0.16 to 0.35	1.4 to 2.7
E07-013 (JLab)	[72]	^{3}He	single spin asy.	1.7 to 2.9	0.16 to 0.65	1.1 to 4.0
E08-027 (JLab)	[309]	p	g_1, g_2	1. to 2.1	3.0×10^{-3} to 1.0	0.02 to 0.4

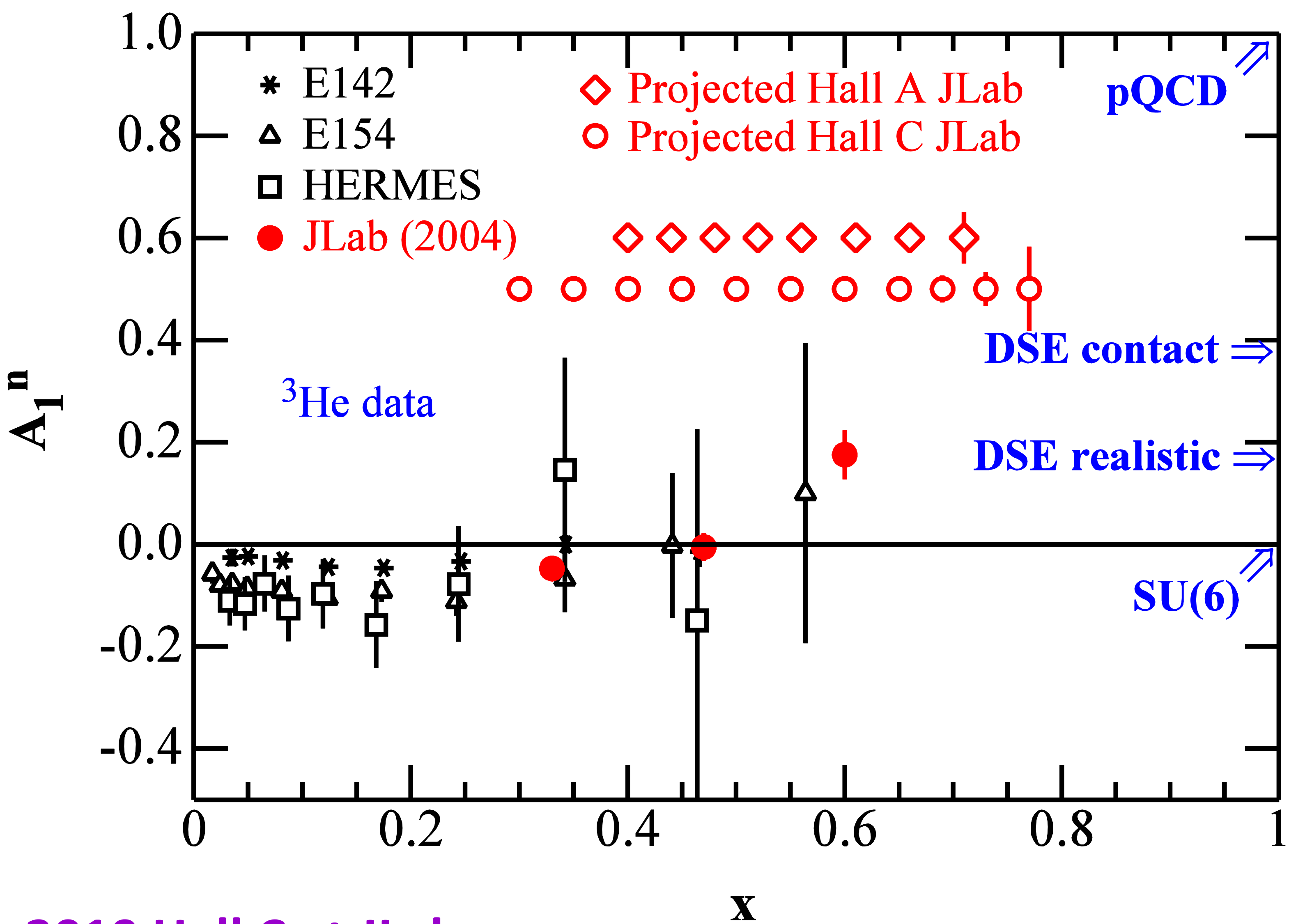
Measurements and Projections for A_1^p



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

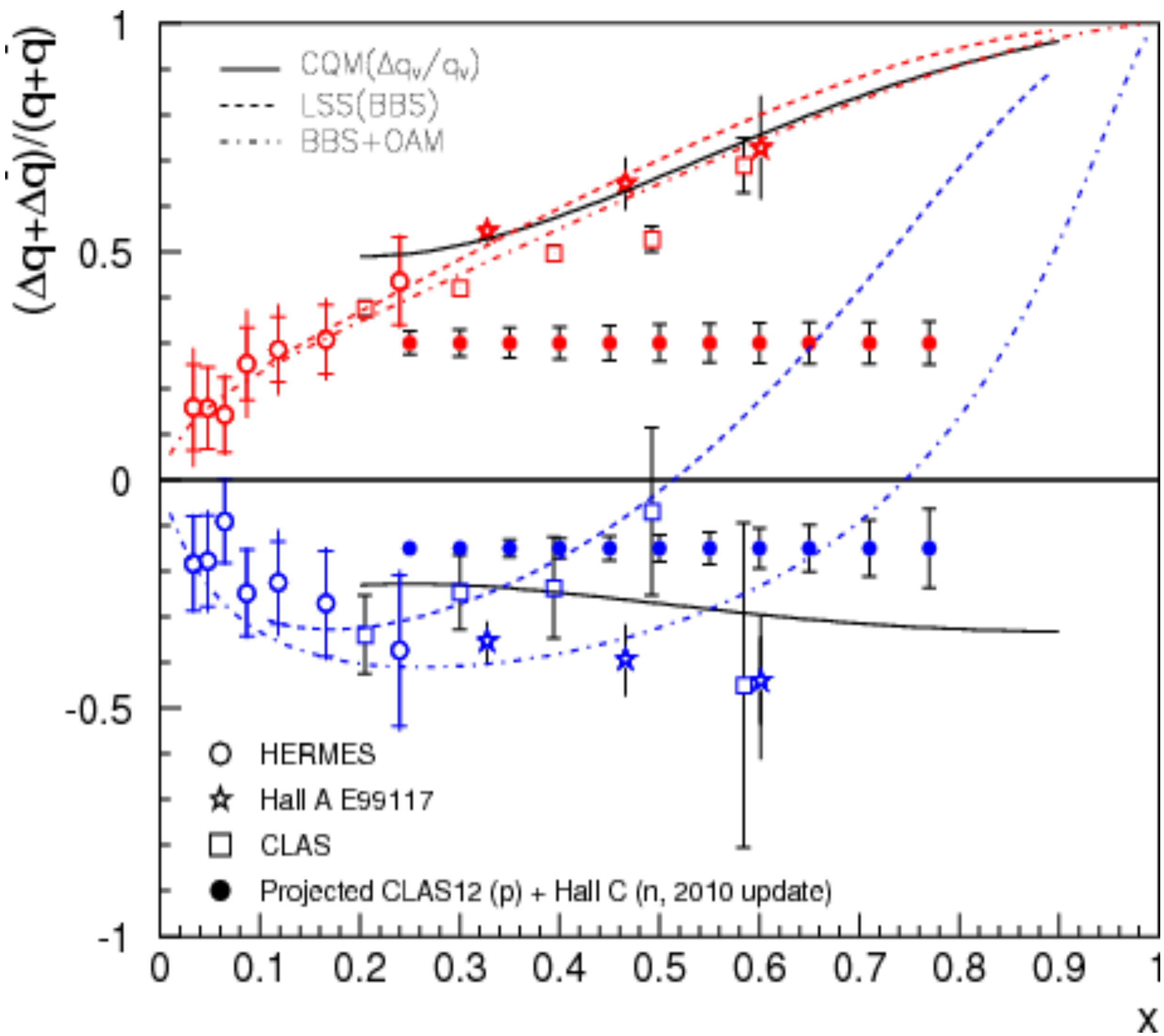


2019 Hall C at JLab

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.

Measurements and Projections for A_1^n



Combined results from Hall C (neutron) and Hall B (proton): polarized pdfs

2019 Hall C at JLab

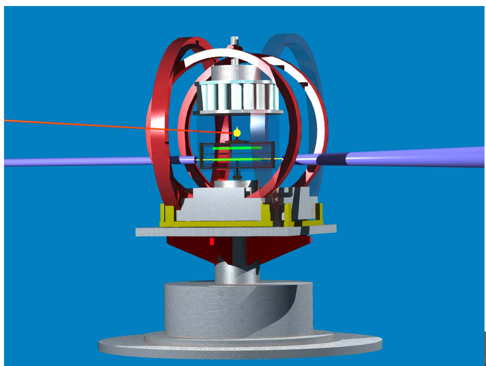
JLab E12-06-110, X. Zheng, J.-P. Chen, Z.-E. Meziani, G. Cates et al.
JLab E12-06-122, B. Wojtsekhowski, G. Cates, N. Liyanage, Z.-E. Meziani, G. Rosner, X. Zheng, et al.

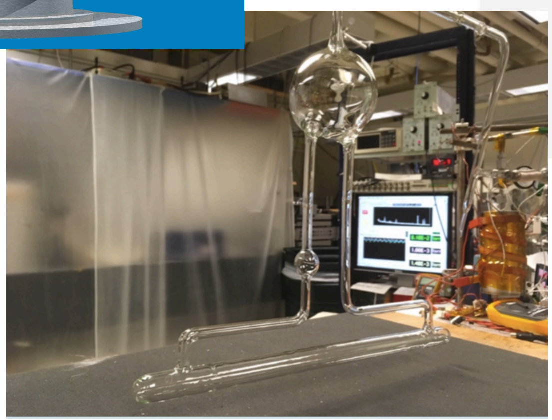
Measuring polarized structure functions: A_1^n

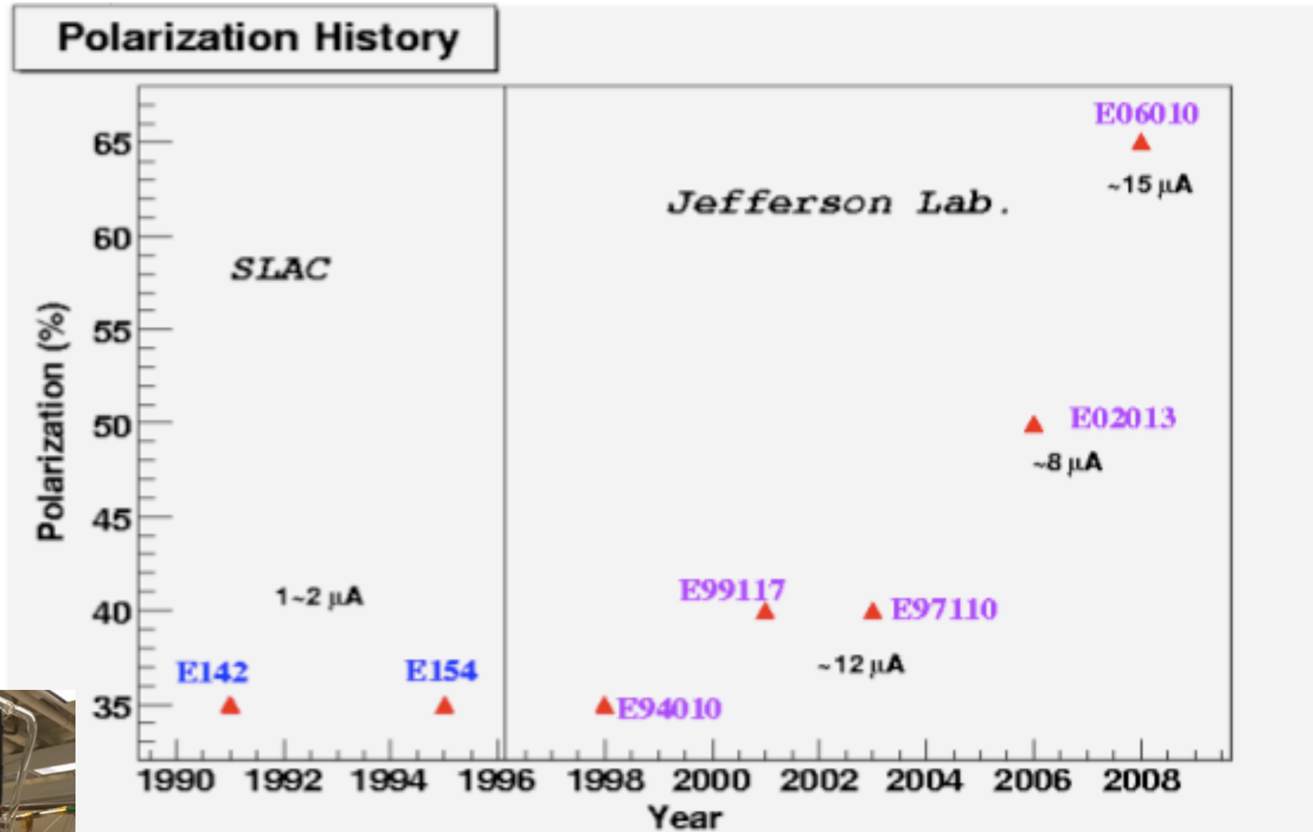
REQUIRES:

- High beam polarization
- High target polarization
- High electron current
- Part of a broad JLab12 program!

^{3}He target





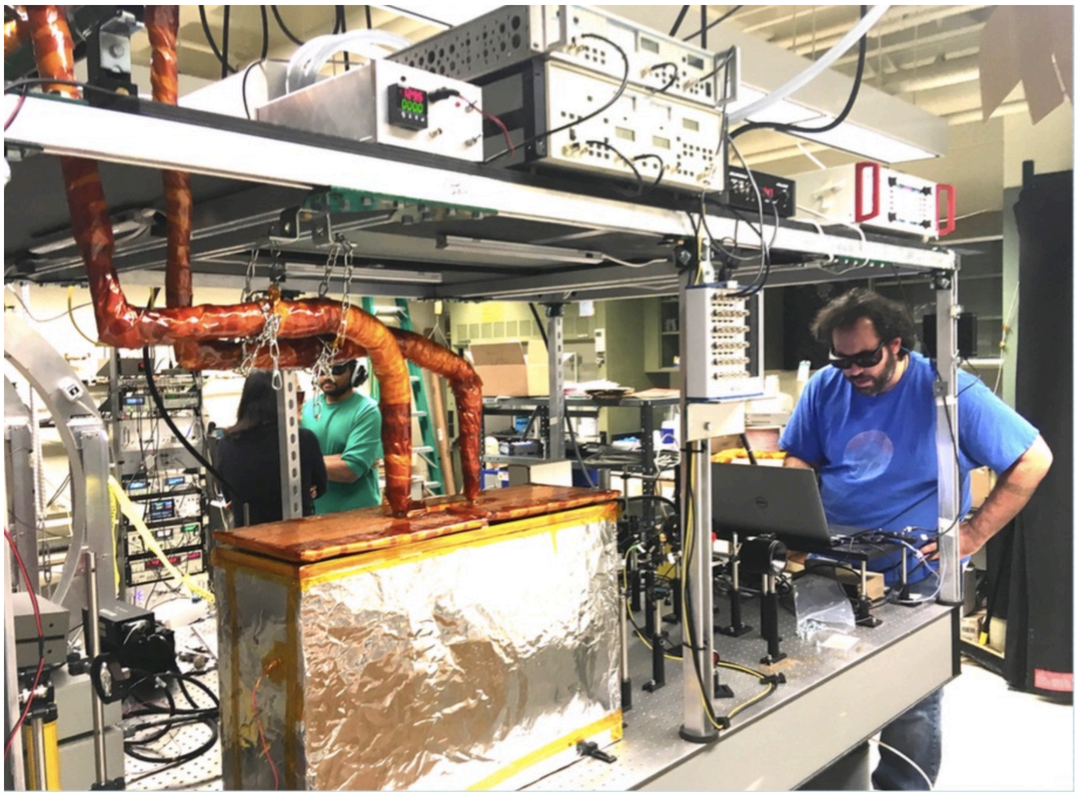


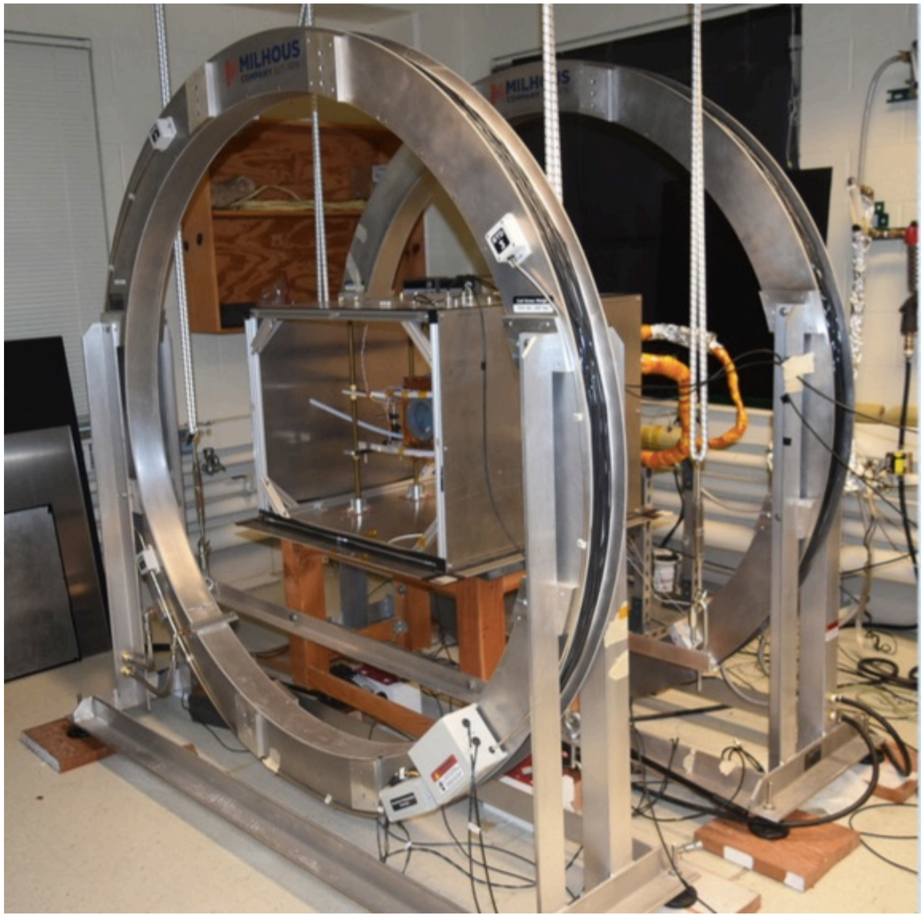
Measuring polarized structure functions: A_1^n

Current status:

- Design complete, components on hand/ordered
- Target cell filling and characterization ongoing
- Hall C installation to start July 2019

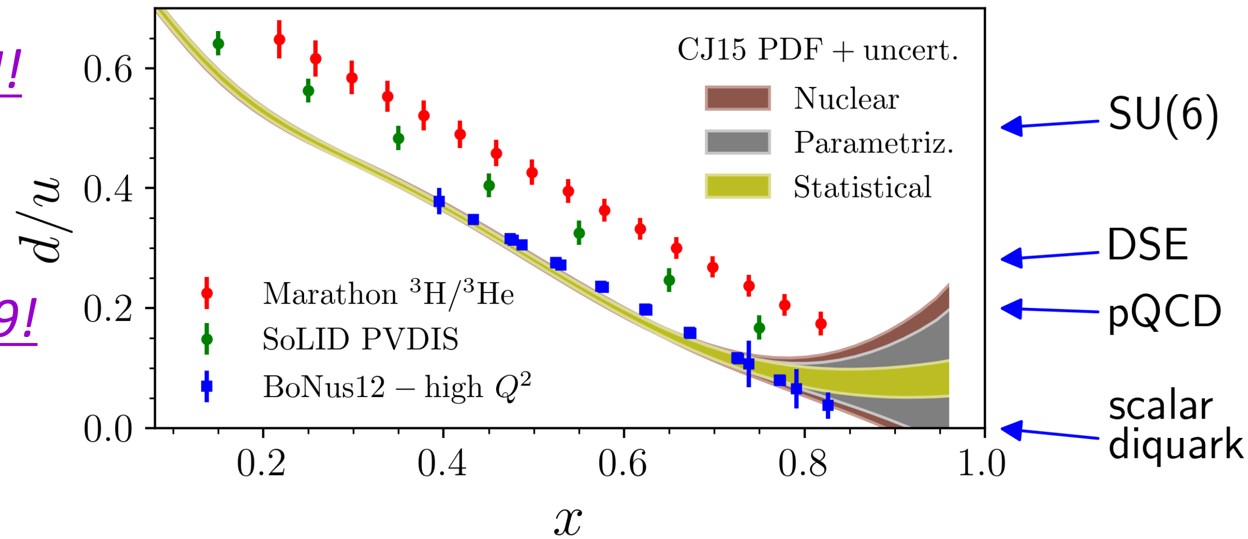
Photos courtesy of
G. Cates, UVA





Probing the Valence Regime: Summary

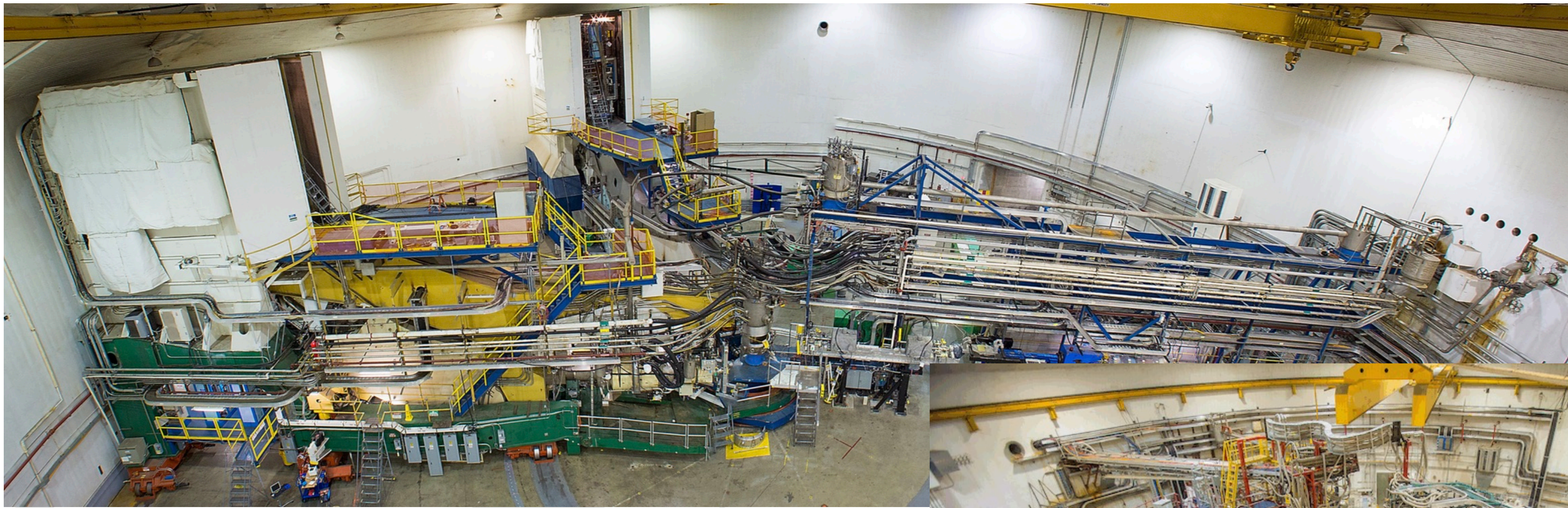
- New generation of experiments at JLab at 12 GeV will access the regime where valence quarks dominate
- First experiments *HAVE RUN!*
  - Hall C F2p,d
  - Hall A ^{3}H/^{3}He
- More experiments *FALL 2019!*
  - Hall C A1n
  - Hall B BONuS
- More to follow (PVDIS, A1p, g2n….)
- Dedicated theory efforts also underway (CJ, JAM,..)
- Also SeaQuest Drell-Yan experiment E906 at FNAL focused on high x sea
- Also also W-asymmetry data from RHIC



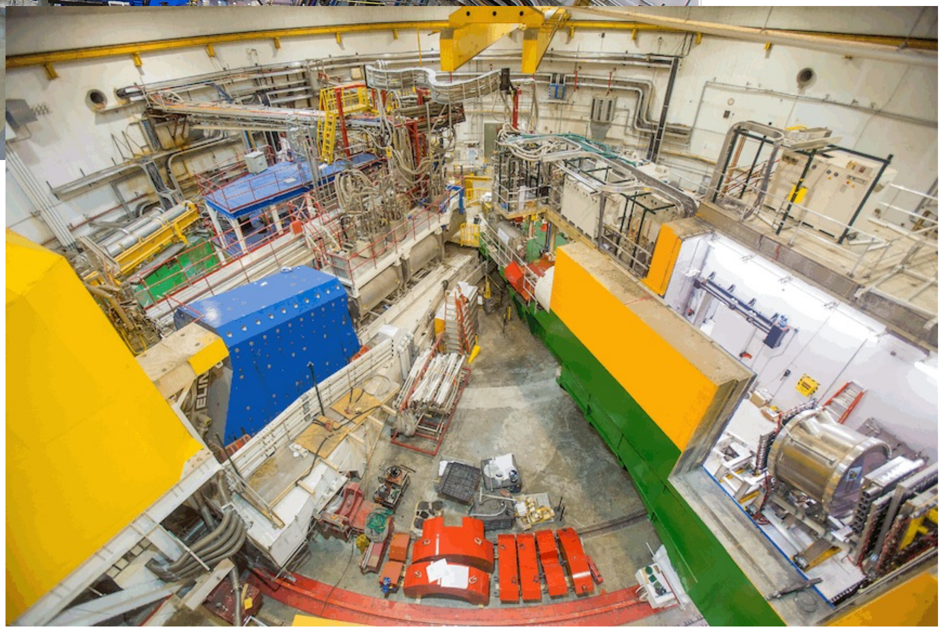
Expect large improvements in our understanding of the valence regime in the next 1-2 years!

- Mesonic Structure (pi,k PDFs)
- Semi-Inclusive DIS
  - Generalized PDFs
  - Transvers Momentum Dependent Parton Distributions
- JLab12 **broad** program… dark matter searches (4 and counting), glueballs/exotic searches (Hall D), parity violation to study neutron skin, standard model tests, short range correlations, superfast quarks (x>1), EMC effect, proton radius,……***more!***…
- Proposed Electron Ion Collider

Thank You!



Jefferson Lab
Hall A



Jefferson Lab
Hall C