Towards a Better Picture of Parton Distribution Functions at Large x - Results from JLab12

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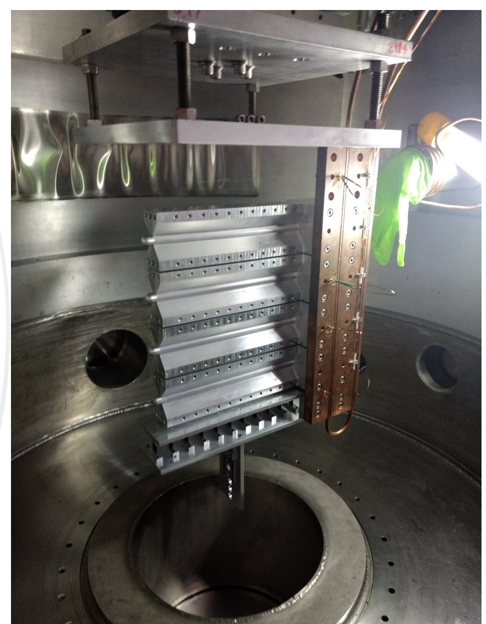
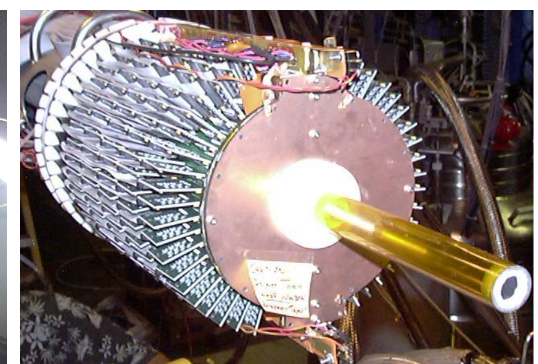
Jefferson Lab Users Organization Annual Meeting 2020





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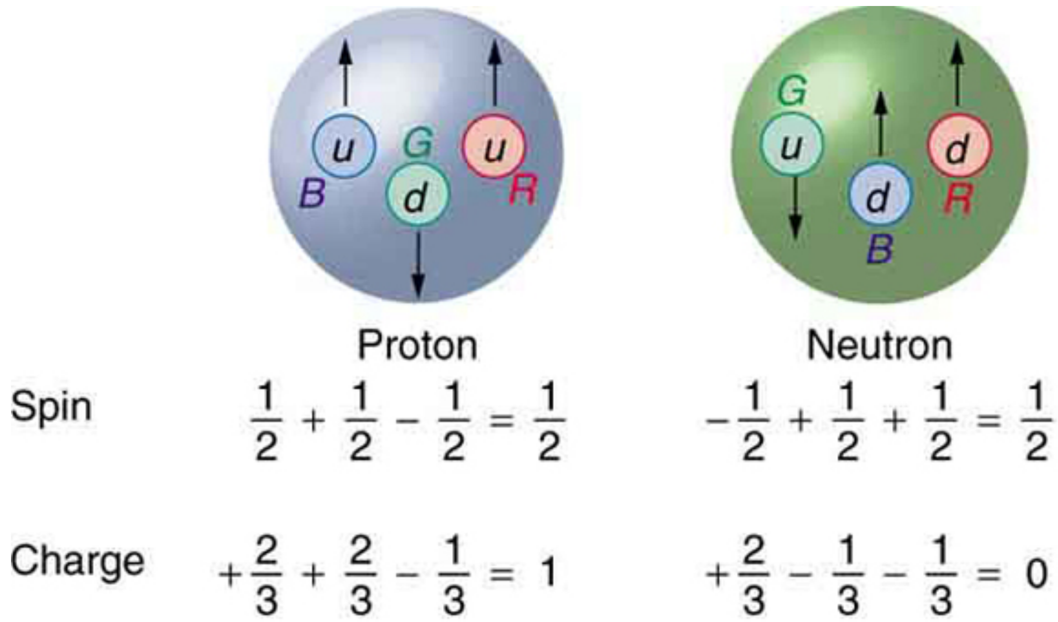
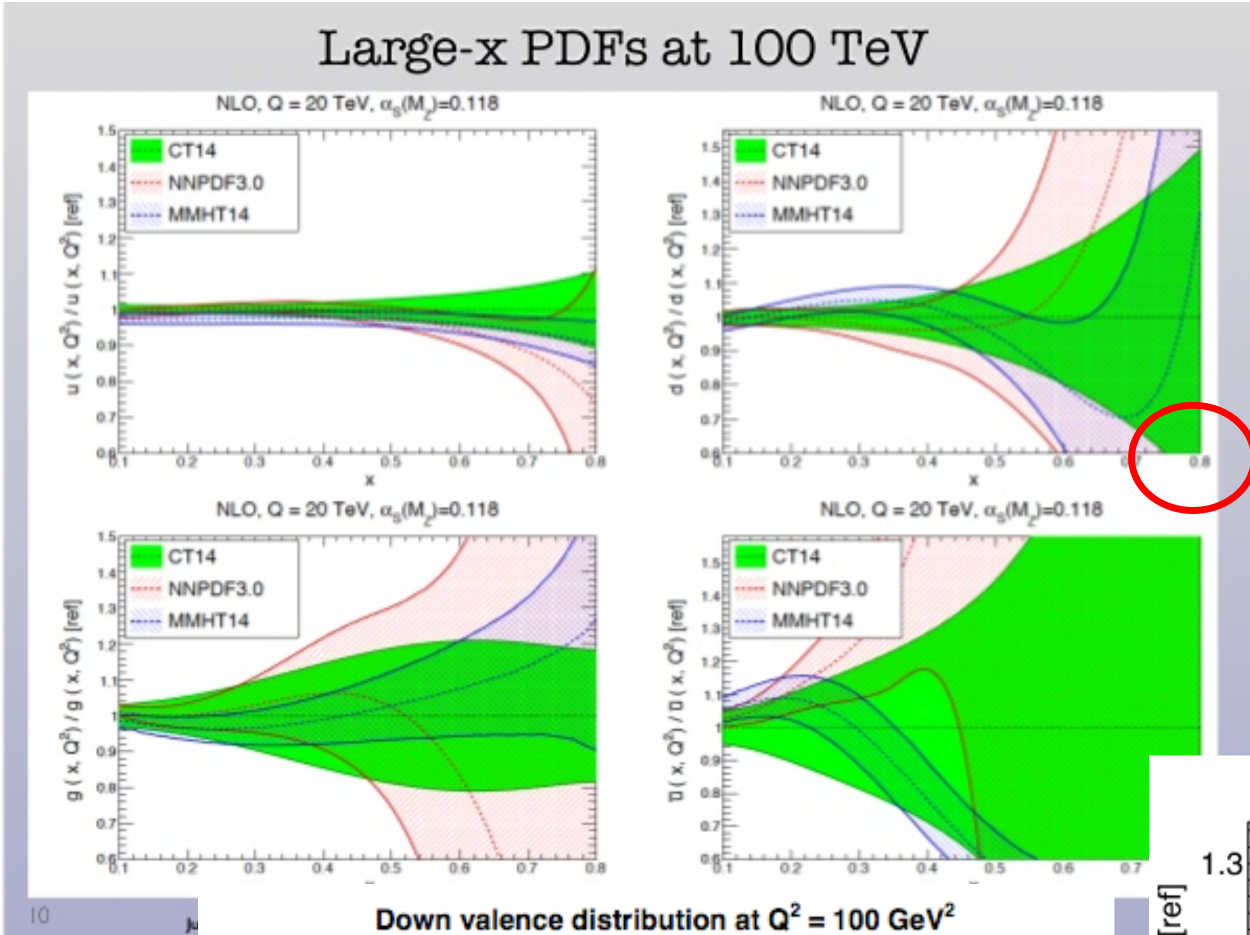
JSA

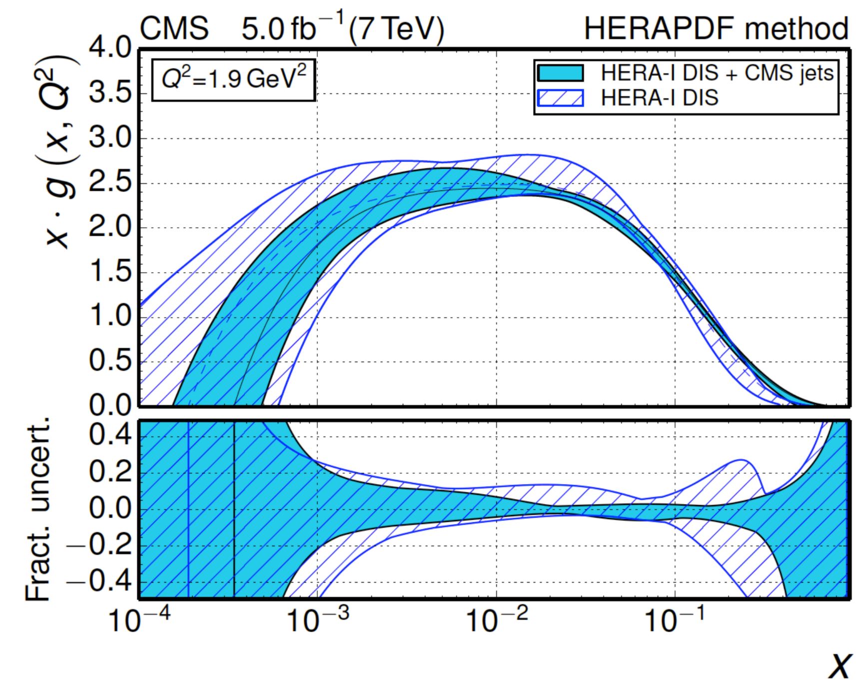
Why is the valence regime interesting?

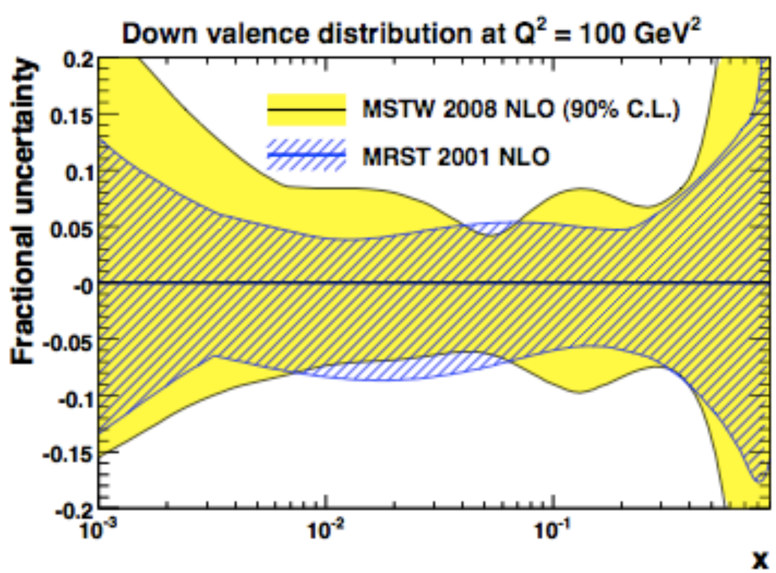


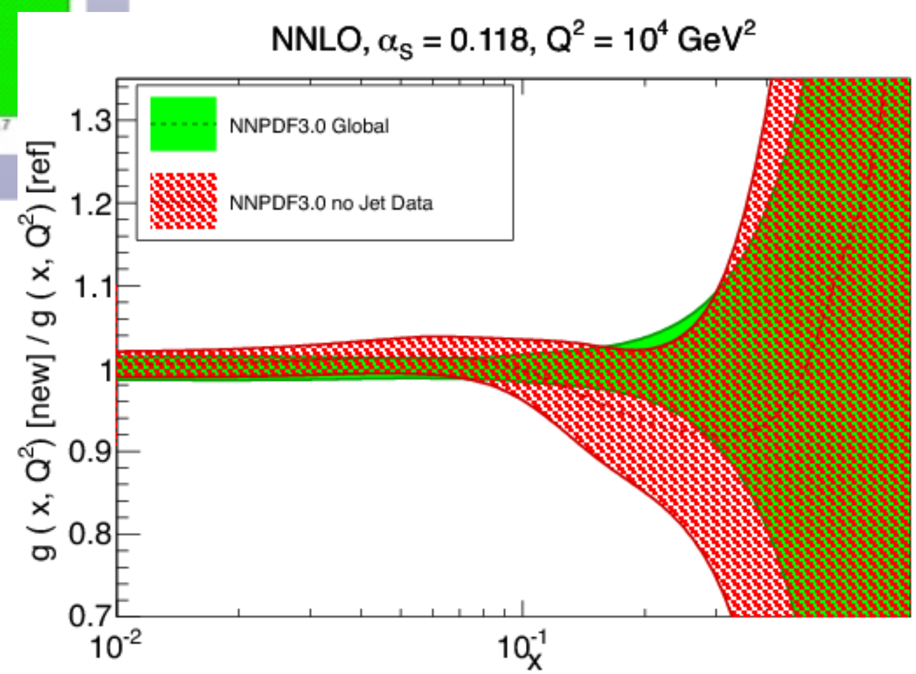
- Partonic structure in the valence region ***defines*** a hadron
  - Baryon number, charge, flavor content, total spin, …
- Keen discriminator of nucleon structure models
- “Valence regime” at large x, low Q^2 evolves to low x, high Q^2
  - Intersection of nuclear and particle physics
- New generation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

Present status: large uncertainties on PDFs at large x

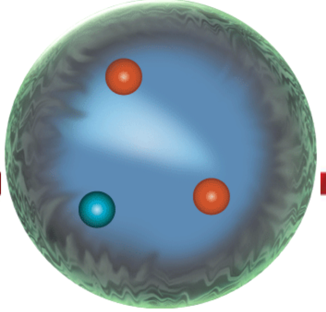








Nucleon Structure Example: F_2^n/F_2^p (neutron/proton) ratio at Large x



- 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

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

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

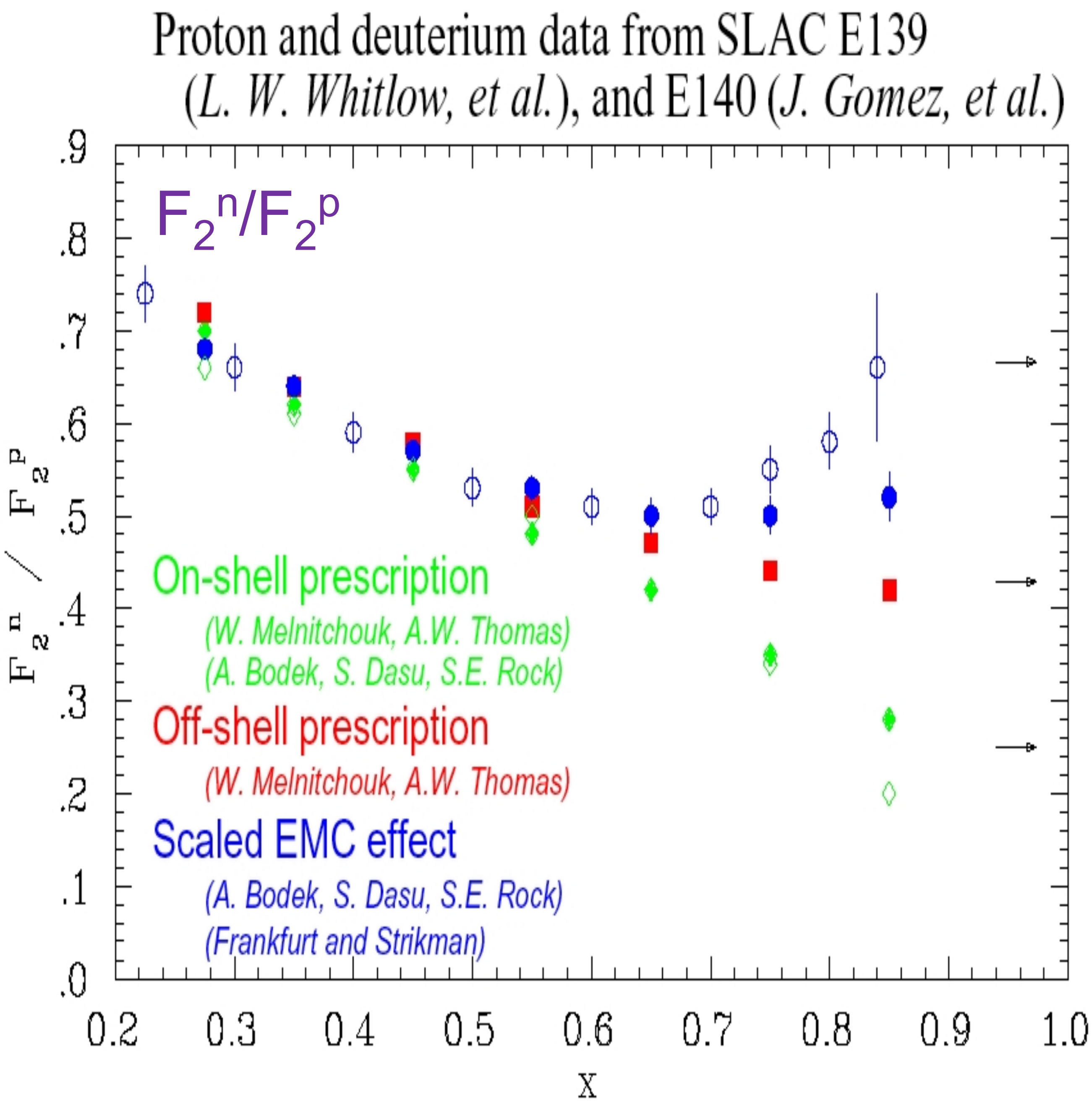
A Longstanding Problem!

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

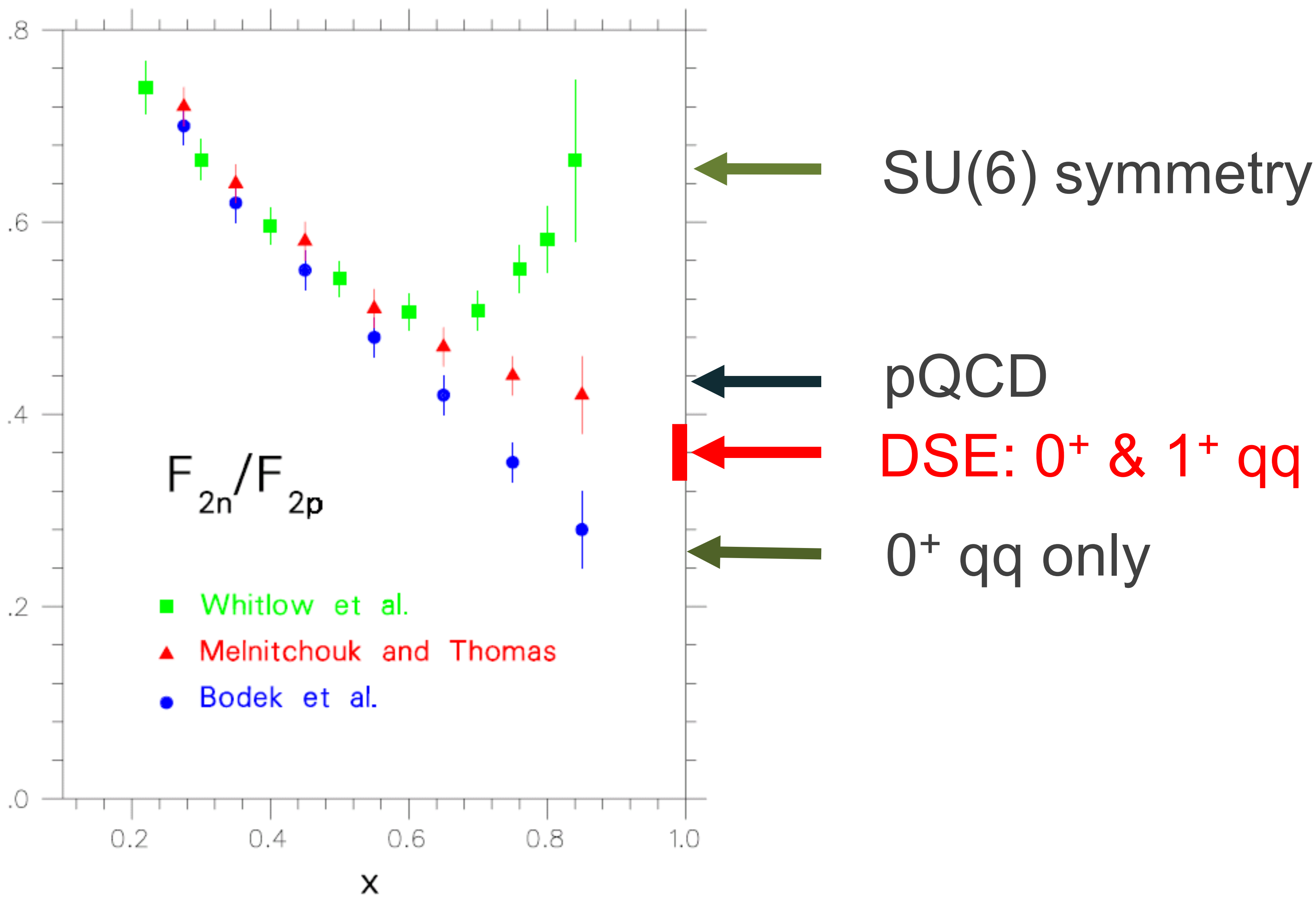
SAME data set

Different nuclear effect analyses

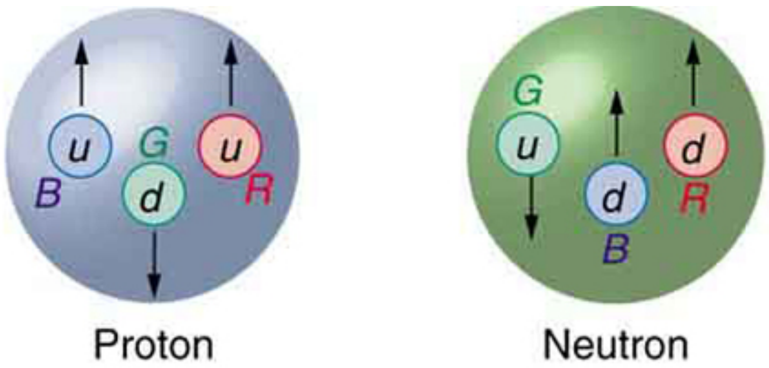
$0.2 < F_2^n/F_2^p < 0.8$?!?!

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

- Partonic structure in the valence region ***defines*** a hadron
  - Baryon number, charge, flavor content, total spin, …
- "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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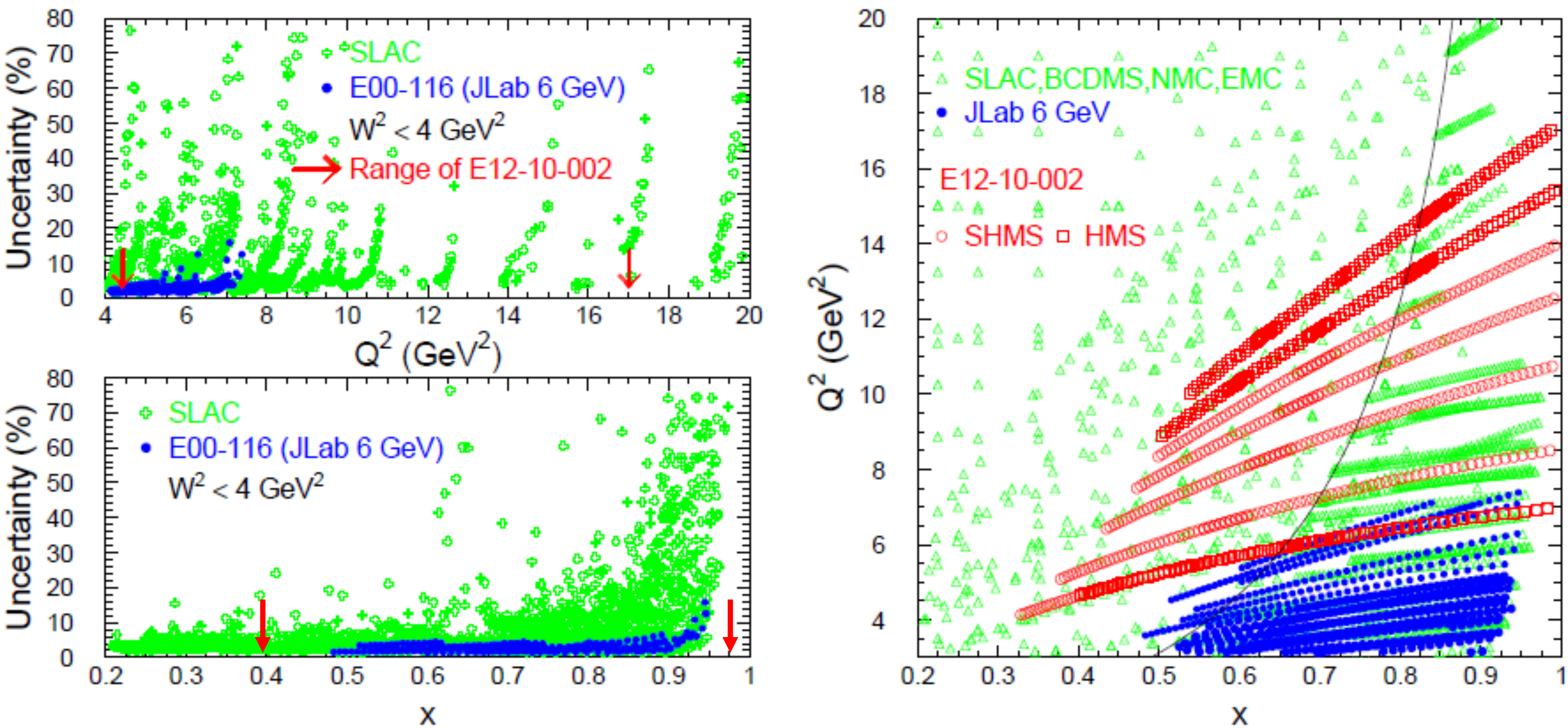
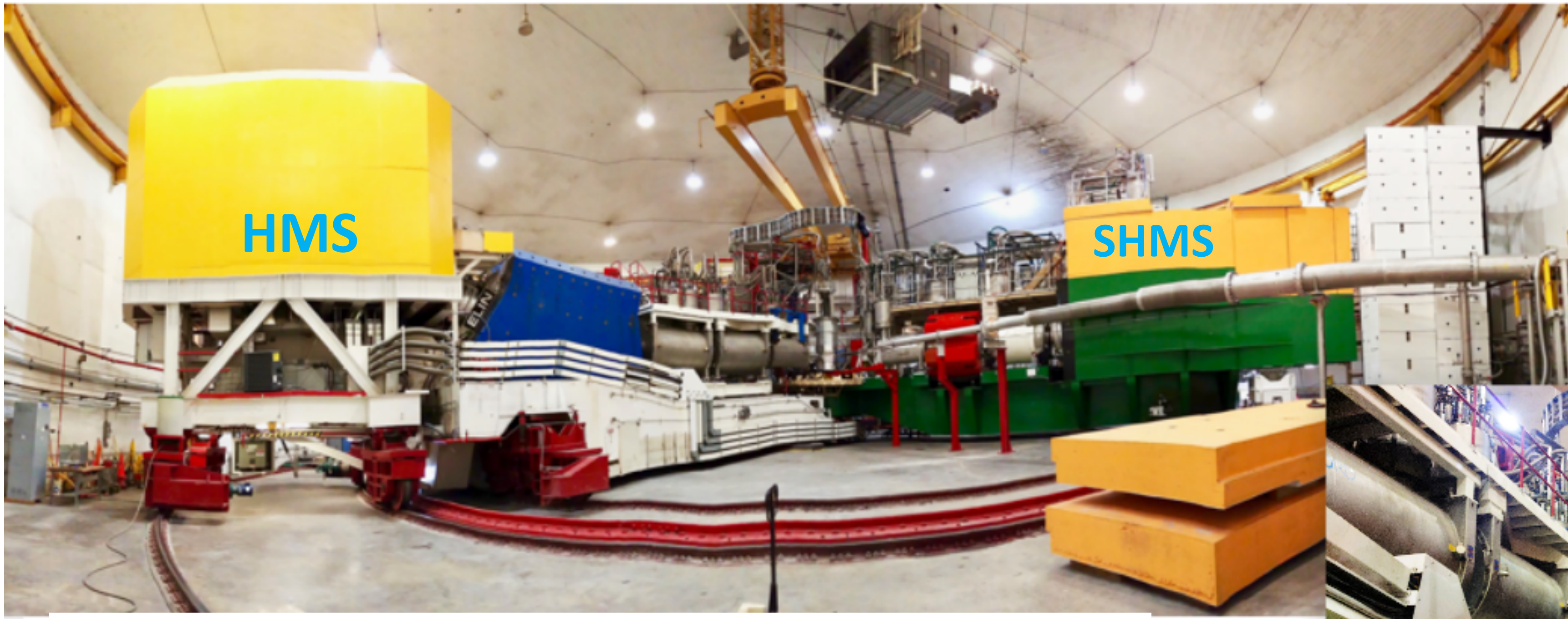
F_2^p & F_2^d Structure Functions in Hall C

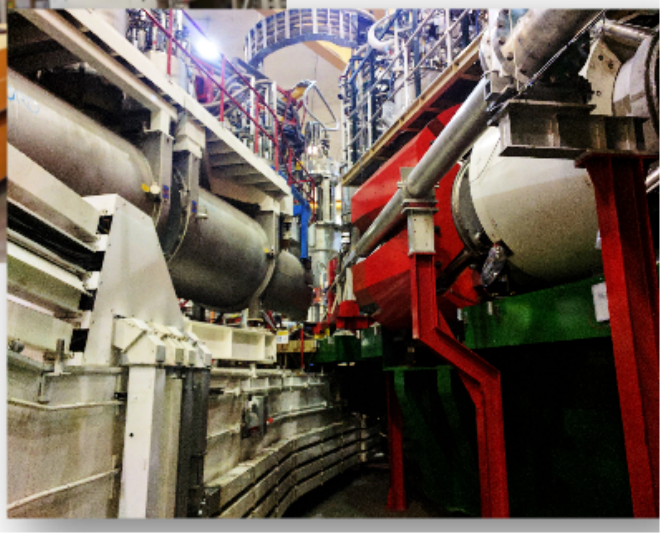
JLab12 Hall C commissioning experiment aims to reduce uncertainties in F_2^p and F_2^d structure functions at large x and high Q



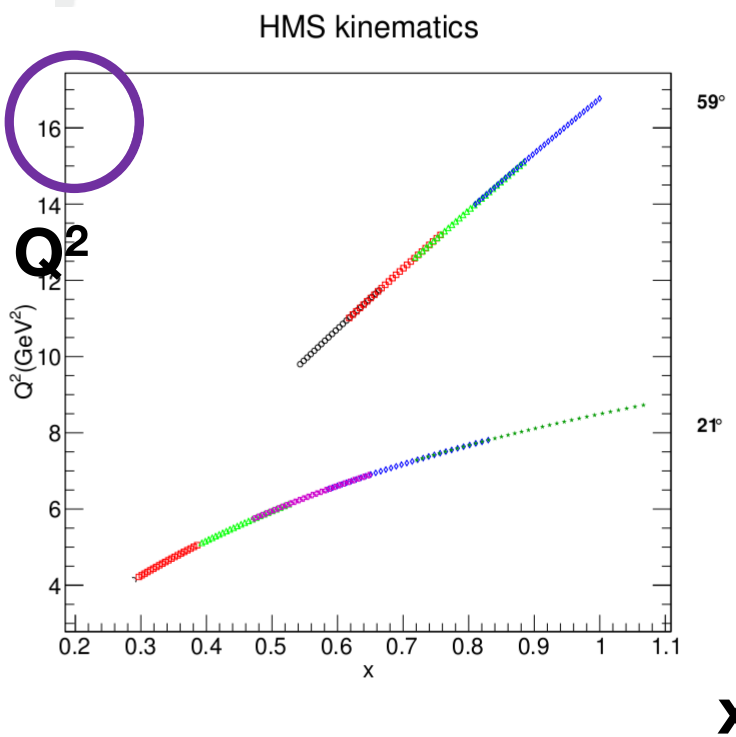
Goal @ 12 GeV: <2% total precision cross sections, (as achieved by E00-116 @ 6 GeV)

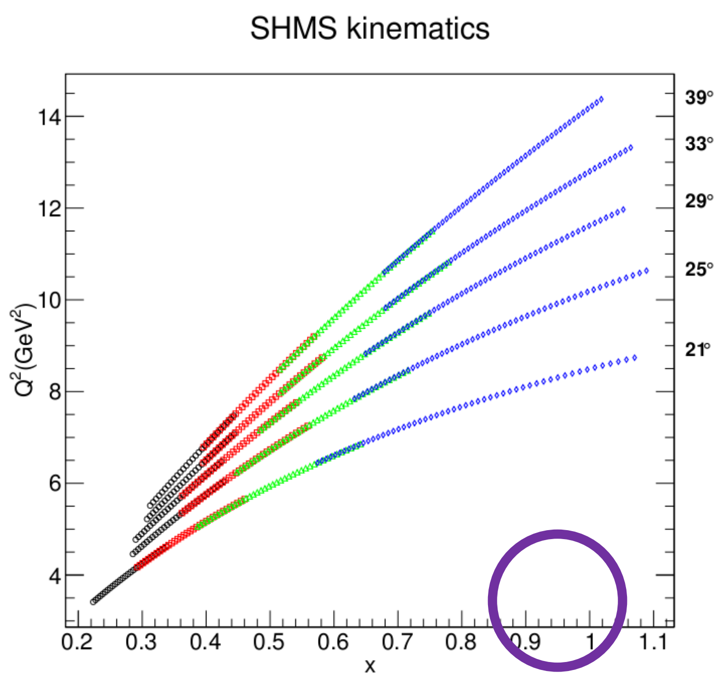
E12-10-002: High Precision Measurement of the F_2 Structure Function on p,D





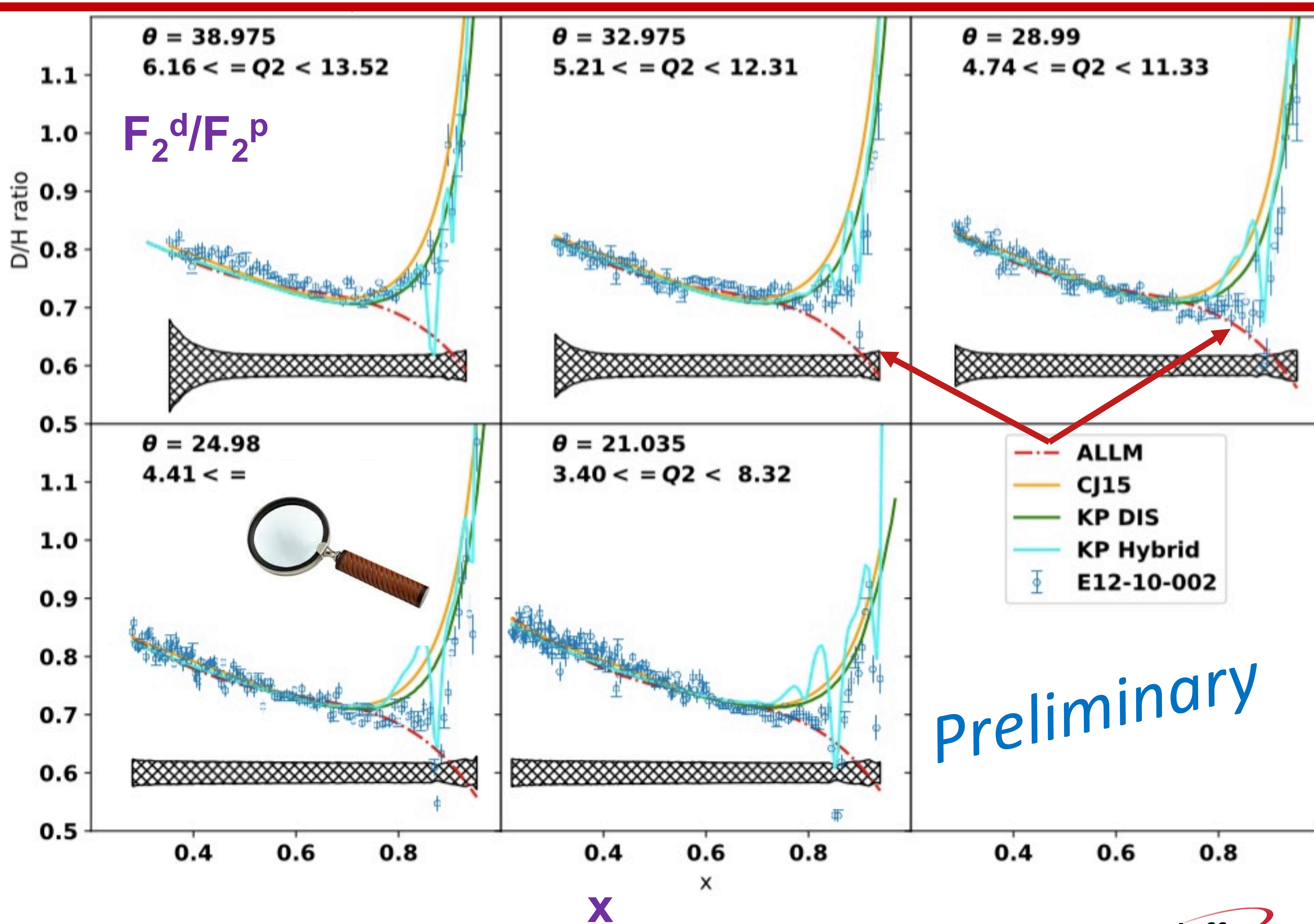
- 10.6 GeV beam
- Targets: LH2, LD2, Al





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

Preliminary Results: Structure Function Ratios (d/p)



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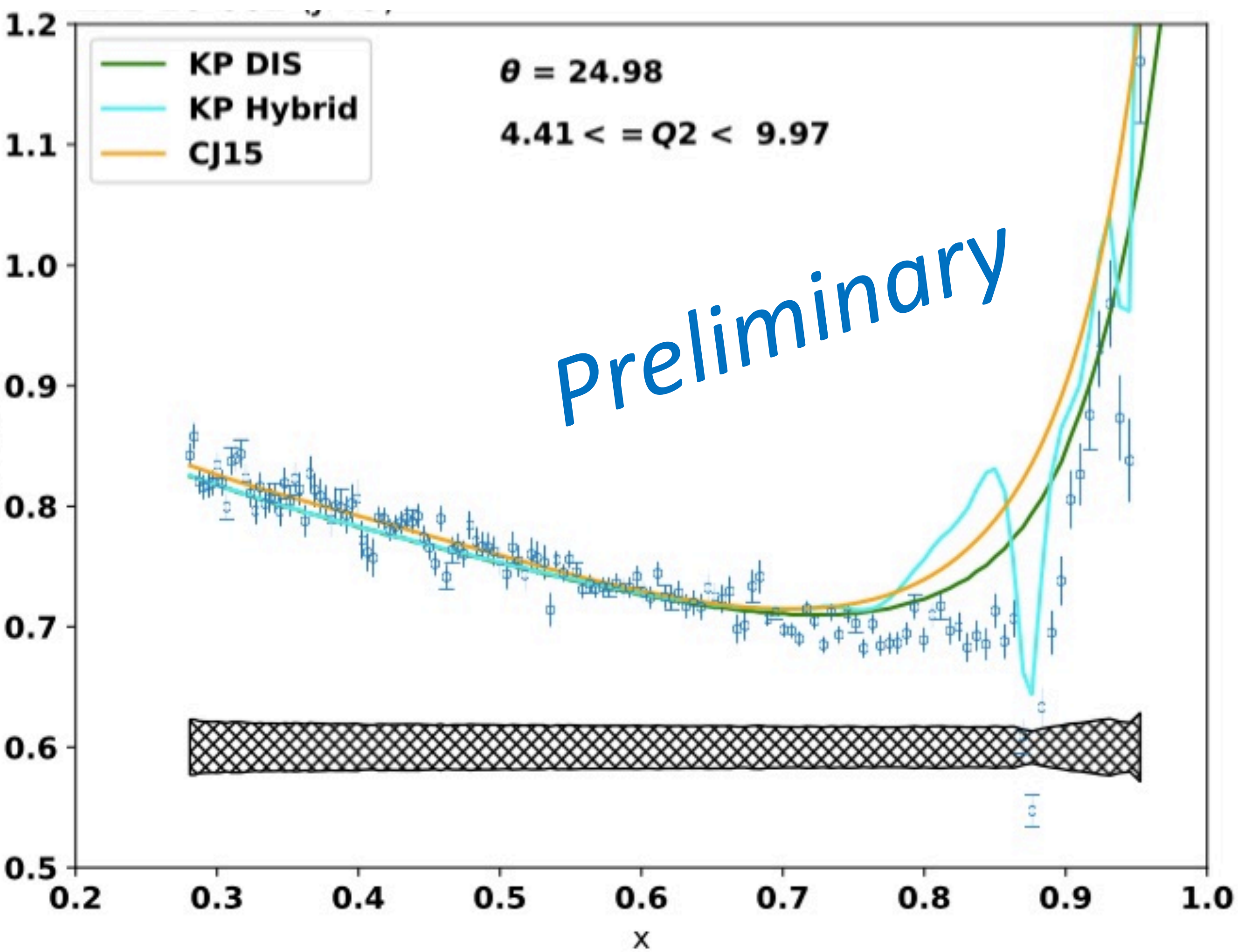
Preliminary Results: Structure Function Ratios (d/p)

F_2^d/F_2^p



x

Still working on:

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

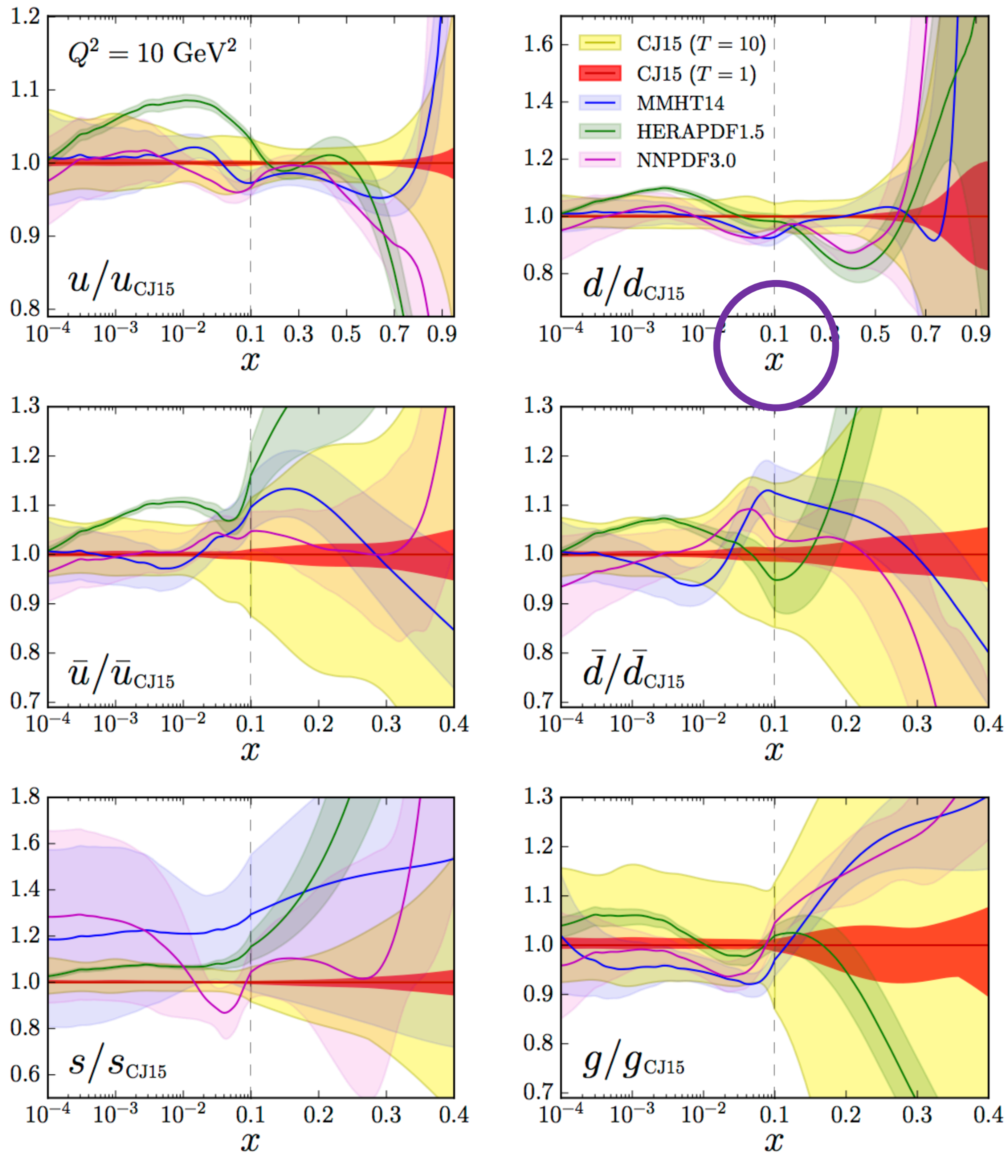
New models, global fits:

- AKP (and Christy) including resonance regime
- Need global framework with deuteron corrections

CTEQ-Jefferson Lab "CJ" PDF Fits

- CTEQ-based PDF fit **optimized for larger x, lower Q²**
  - 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



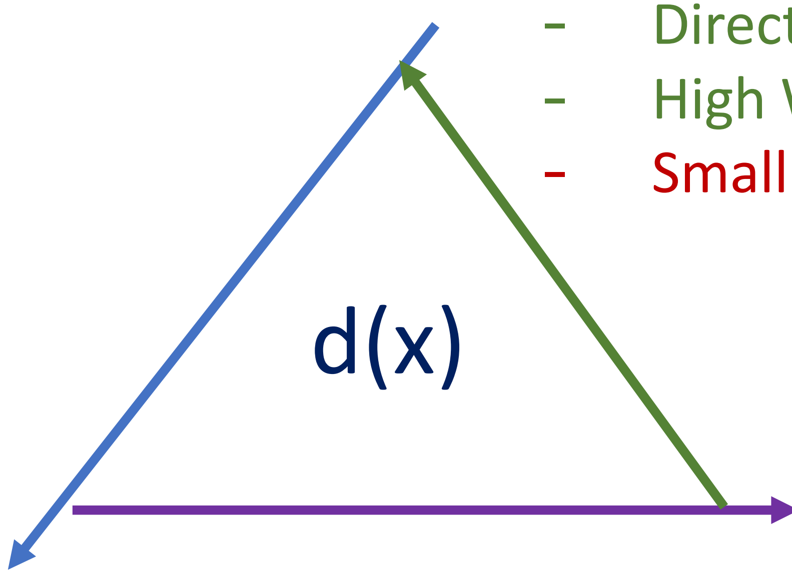
http://lhapdf.hepforge.org/lhapdf5/pdfsets

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



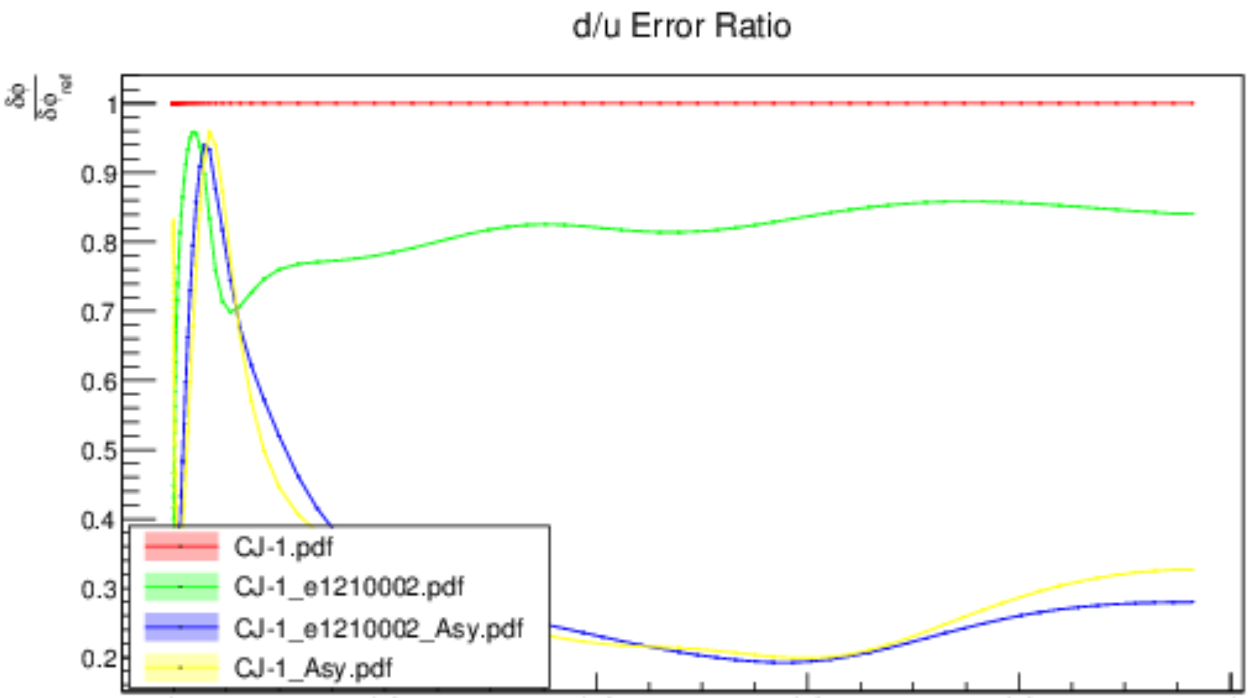
"BONuS" tagged neutron target

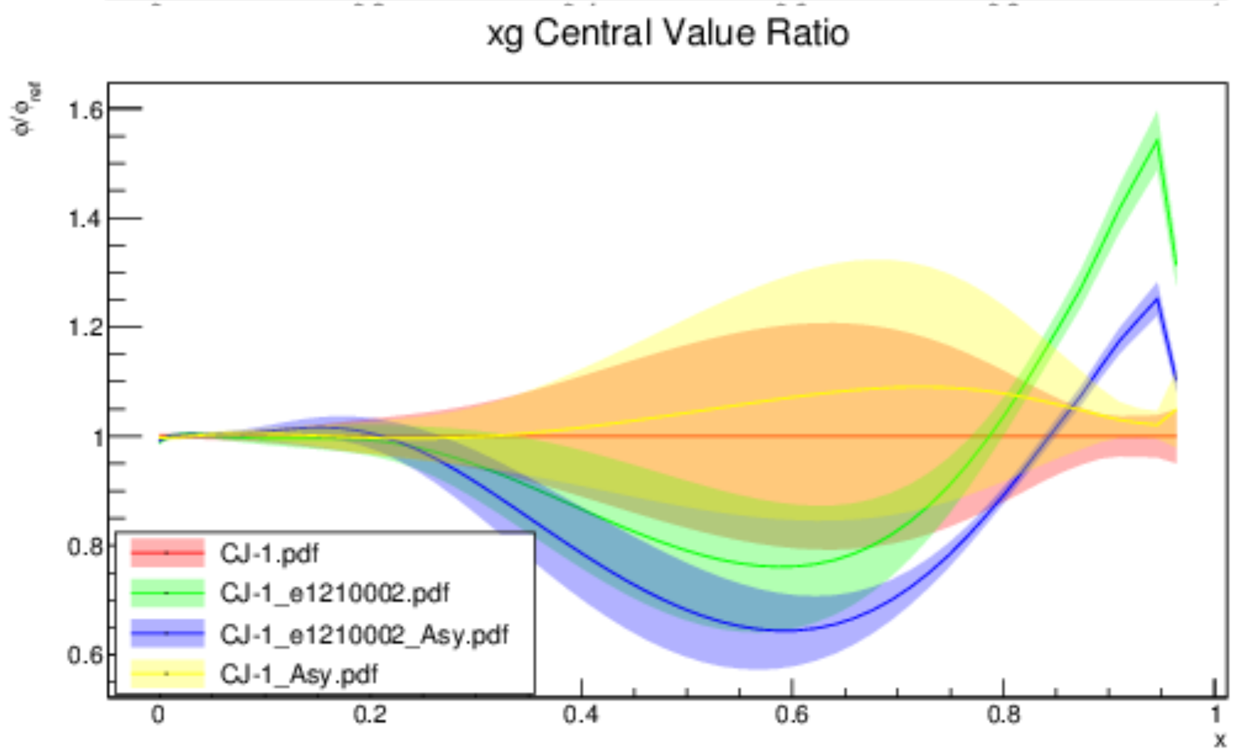
- Nearly model-independent *neutron* data
- Current data obtained in 6 GeV JLab era at low W, Q

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

Also adding BNL data (Sanghwa Park, A. Accardi, CK,..)

Current Data Constraints on d(x) at Large x:
The whole is greater than the sum of the parts.

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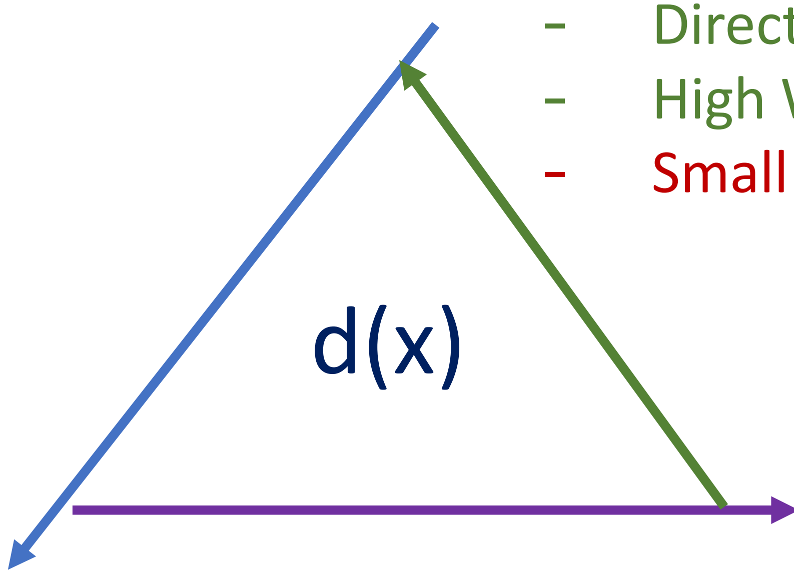

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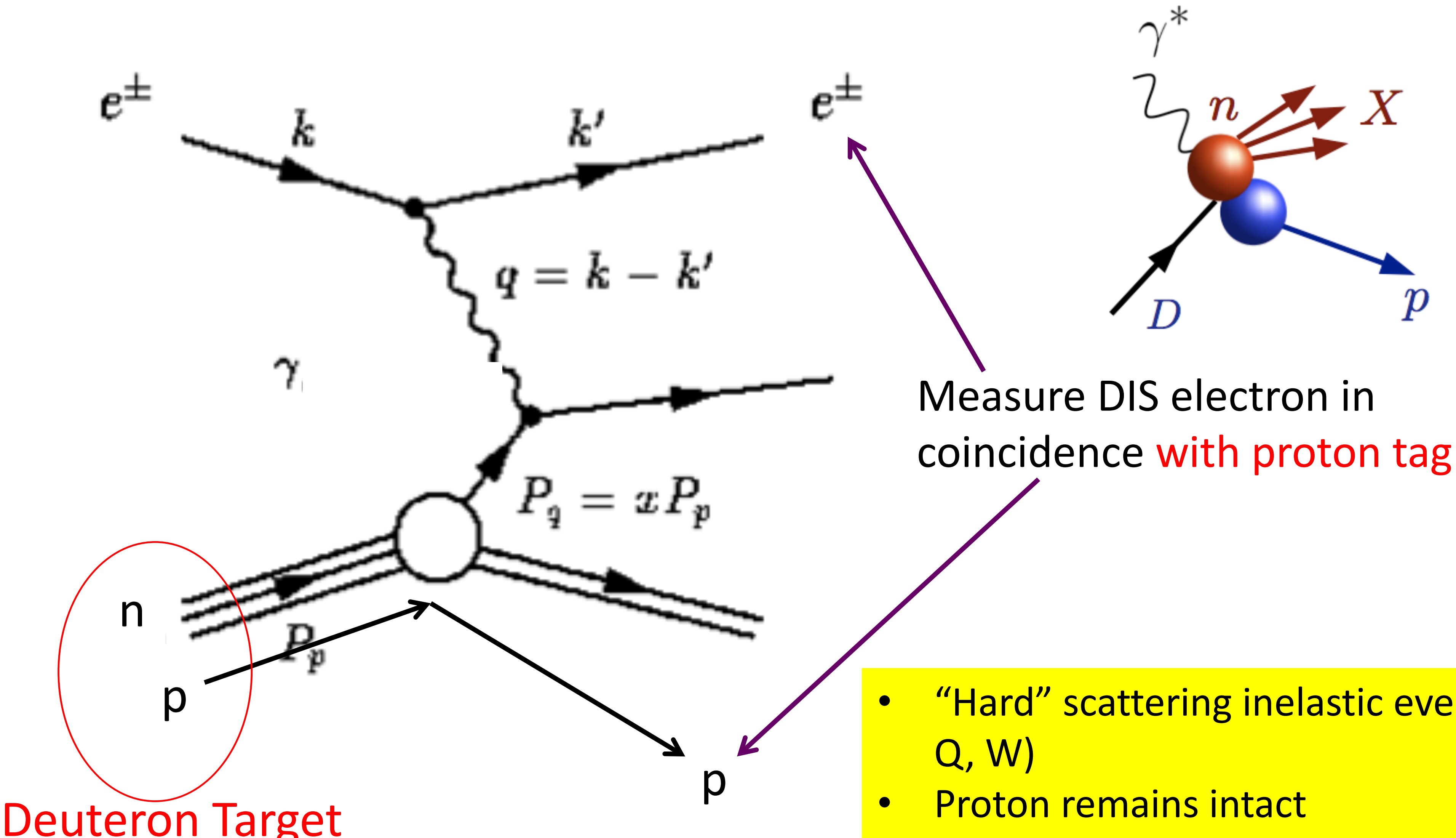
TDIS to access nucleon valence structure

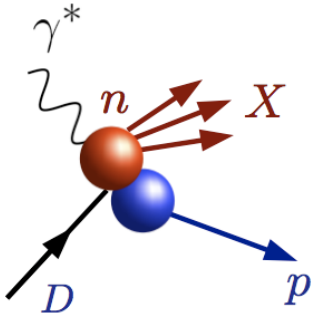
"BONuS" Experiment at Jefferson Lab – use fixed target Tagged DIS to create an effective *free neutron* target



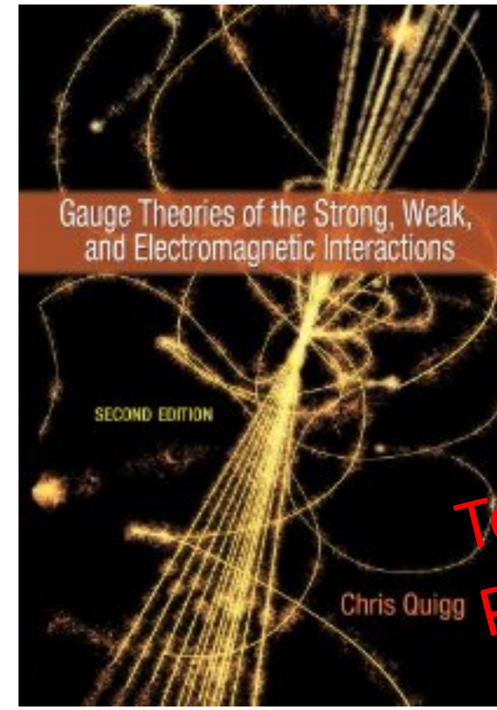
Measure DIS electron in coincidence with proton tag

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

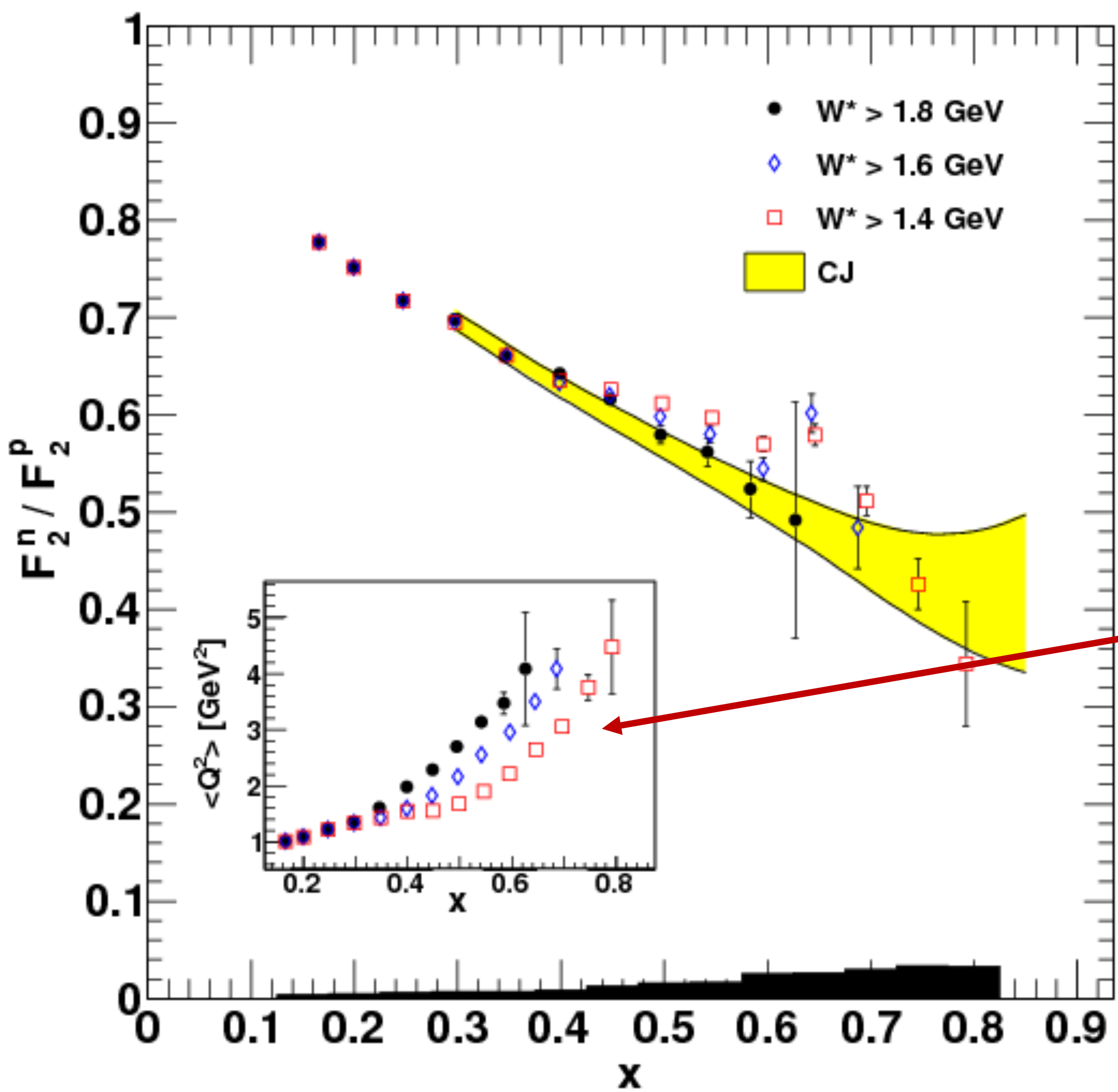
BONUS effective neutron target via TDIS *achieved!*



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



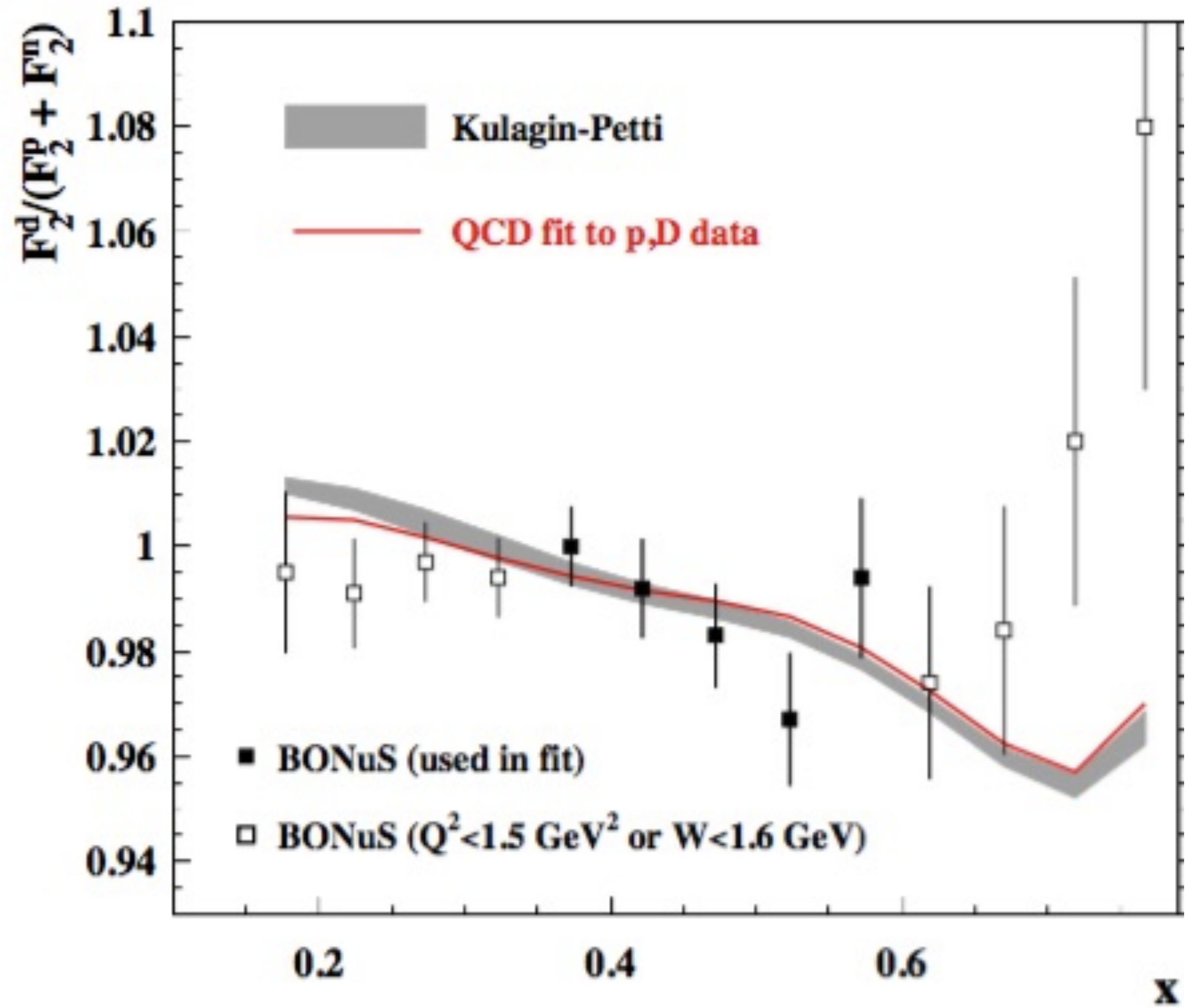
Textbook Physics!



- 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

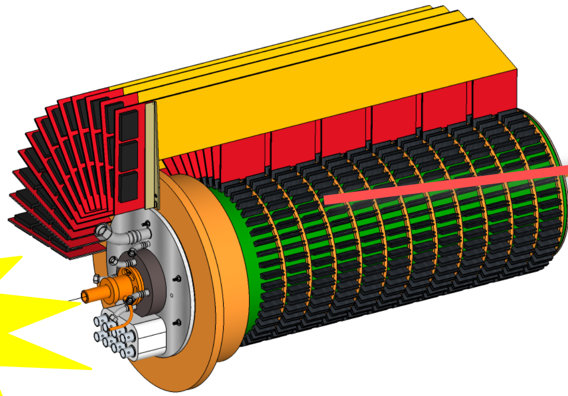


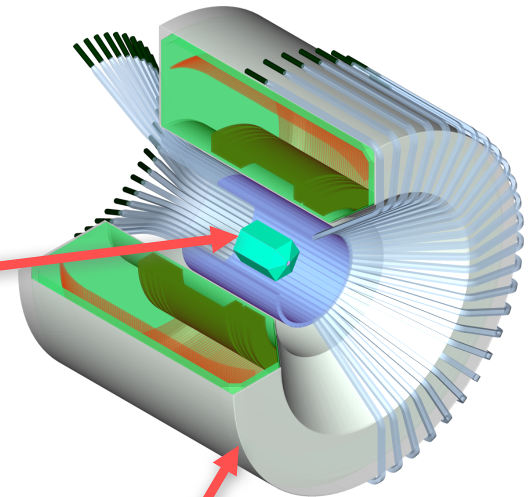
S.I. Alekhin, S.A. Kulagin, R. Petti Phys. Rev. D 96, 054005 (2017)

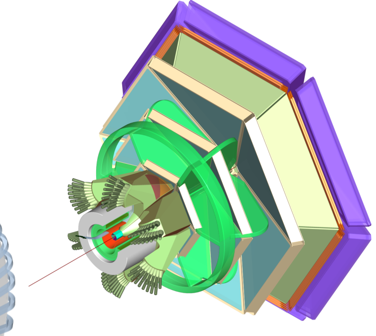
"The recent direct measurement of the deuteron nuclear correction by the BONuS experiment substantially reduces this uncertainty by constraining the normalization of the overall nuclear corrections."

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

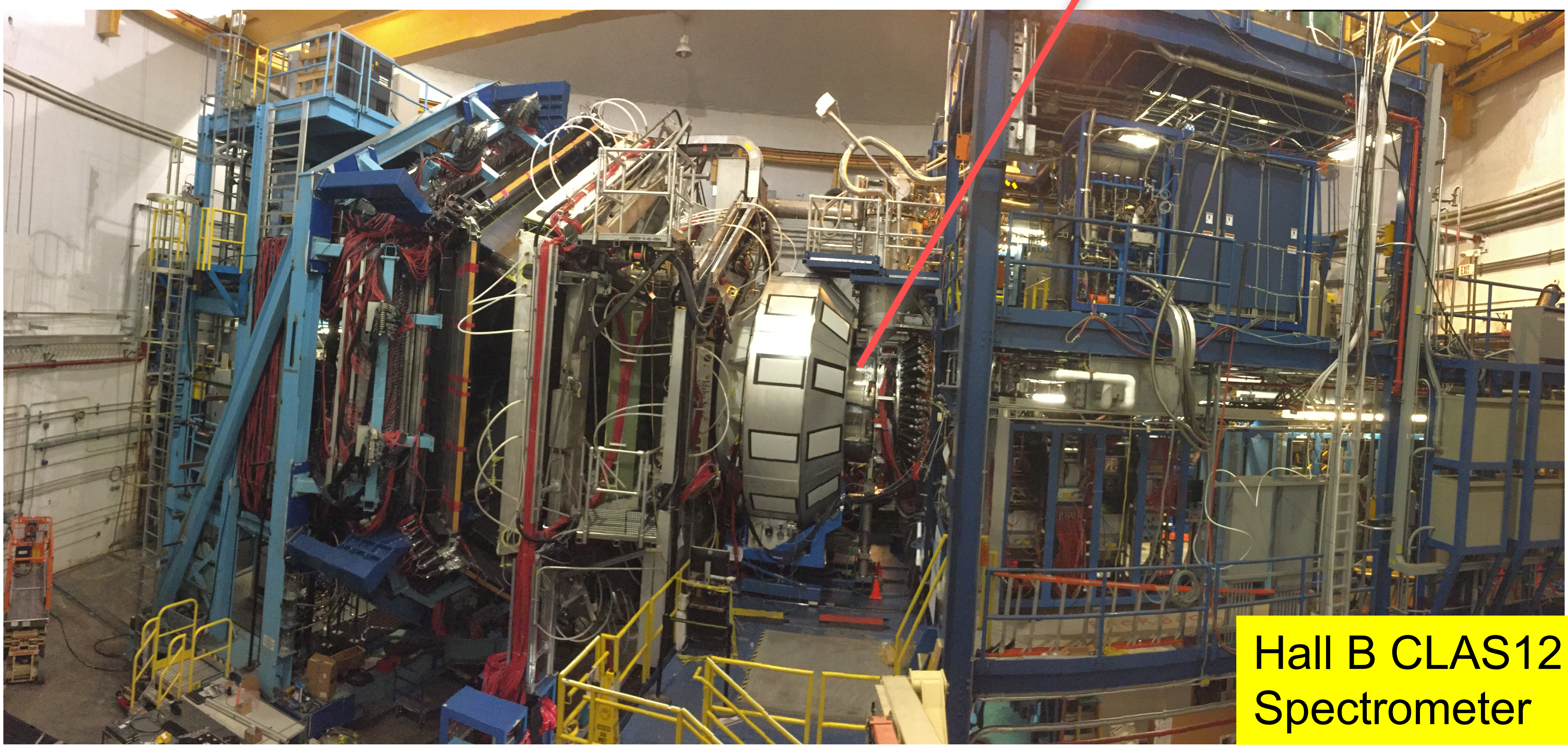
High Impact







CLAS12 Central Detector

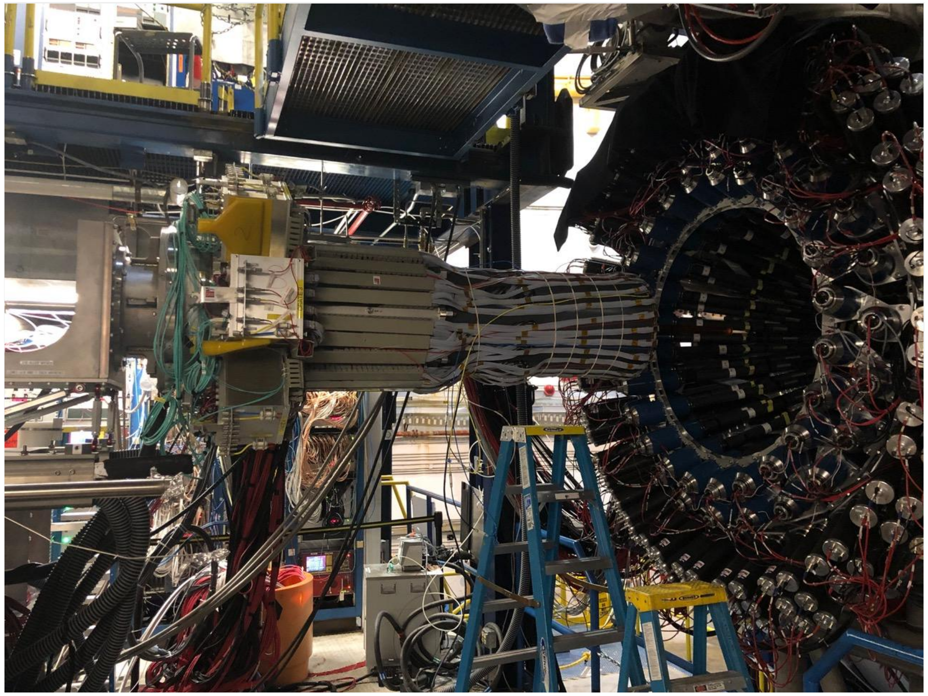


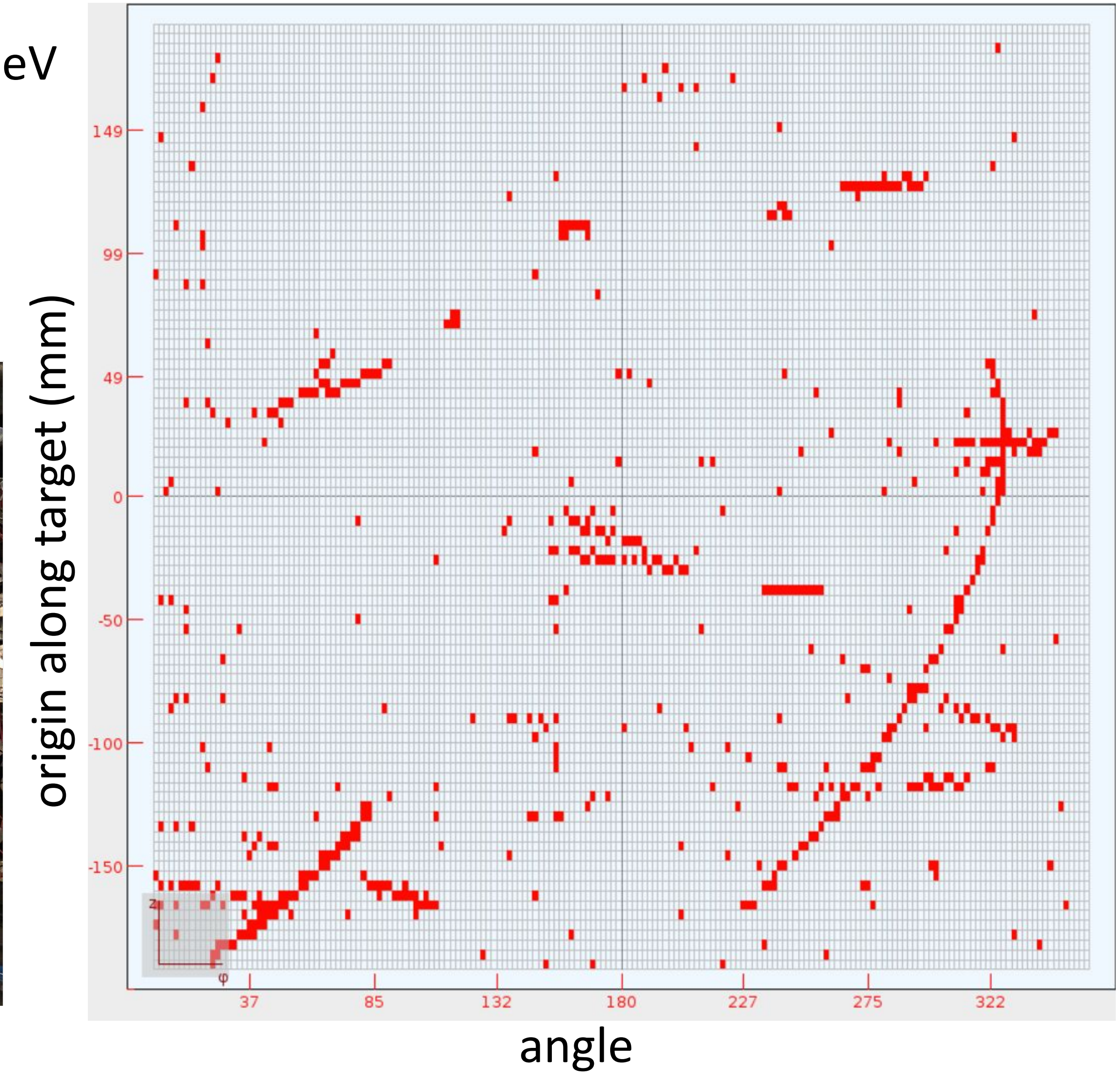
Hall B CLAS12 Spectrometer

BoNUS12

- RTPC1 installed for BONuS in Hall B, operated for ~a month
- Replaced mid-March with RTPC3 – ready to run!

300 nA on D_2 at 10.4 GeV





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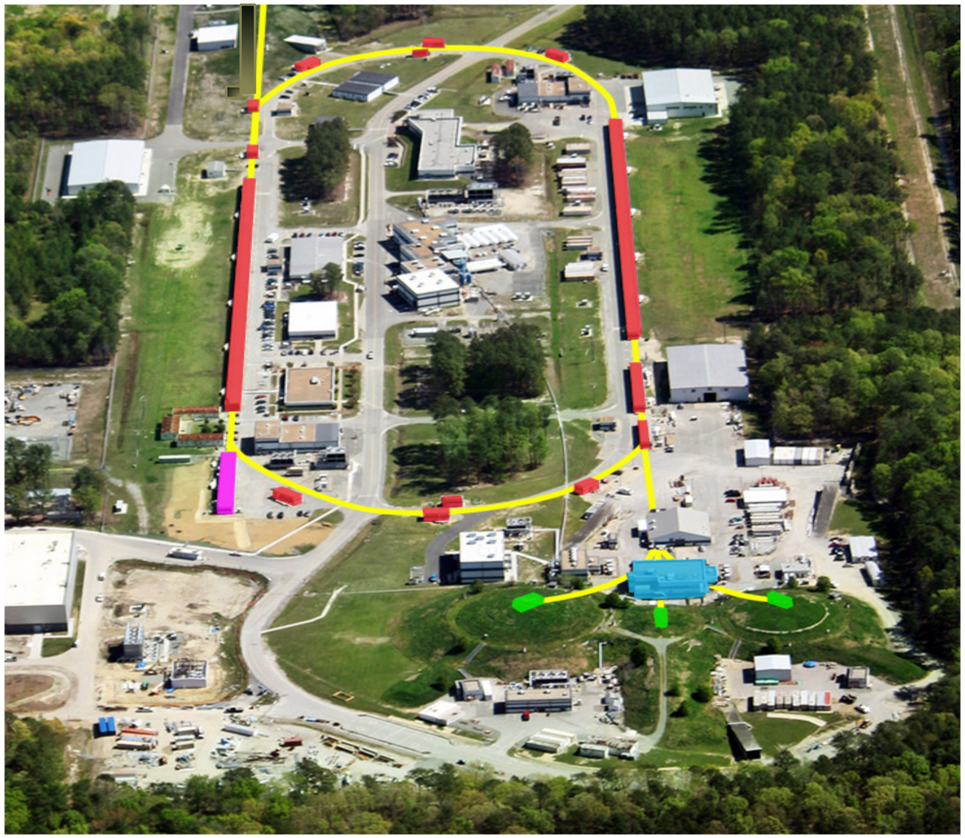
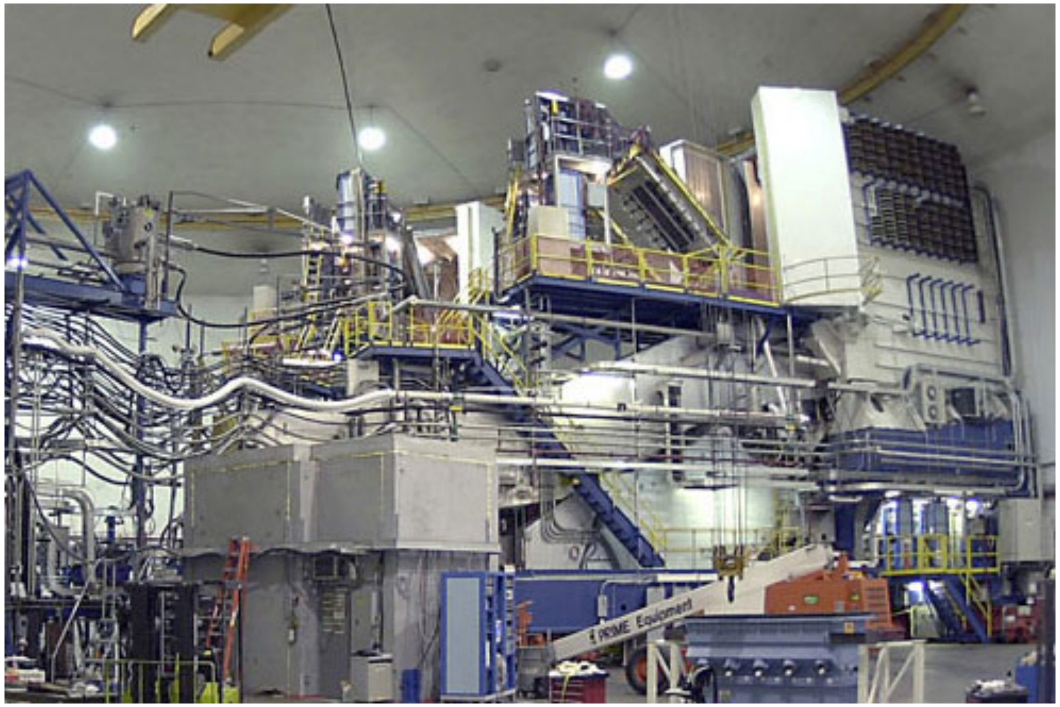
Or, a nuclear physicists approach to the problem….



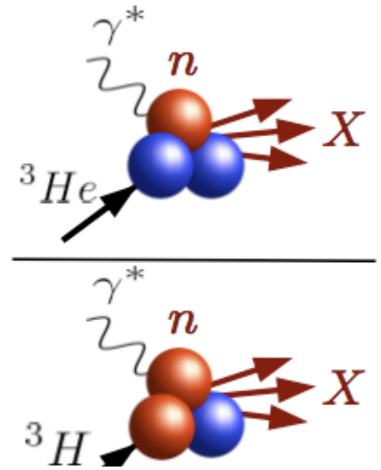


JLab Hall A HRS Spectrometer

- 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

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



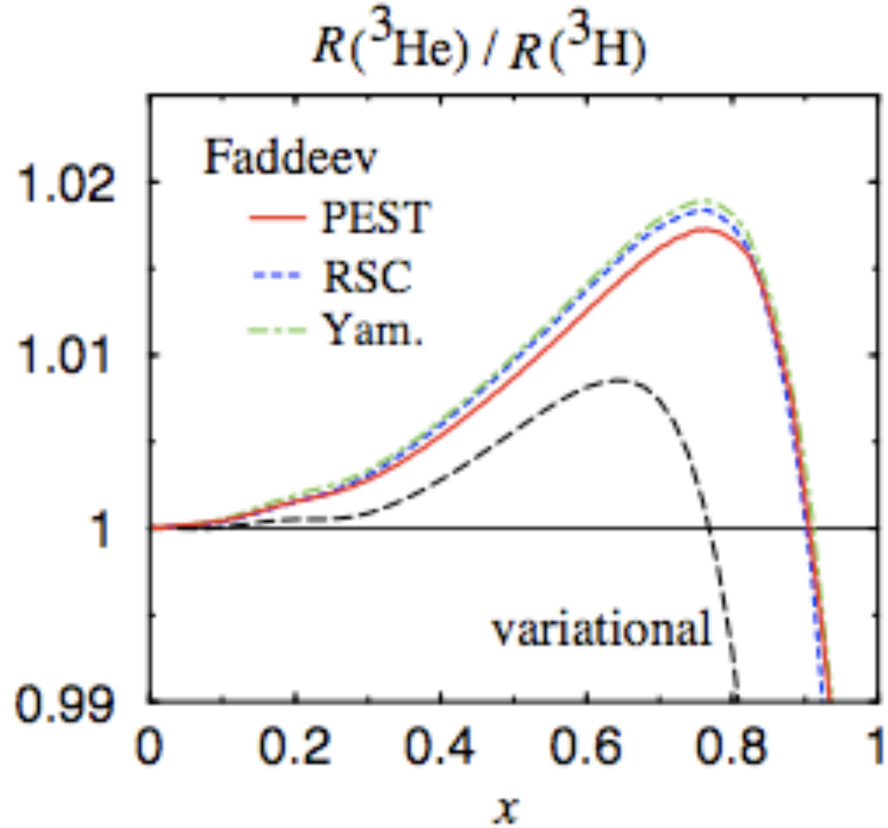
I. Afnan et al, PRC 68 (2003)

- 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

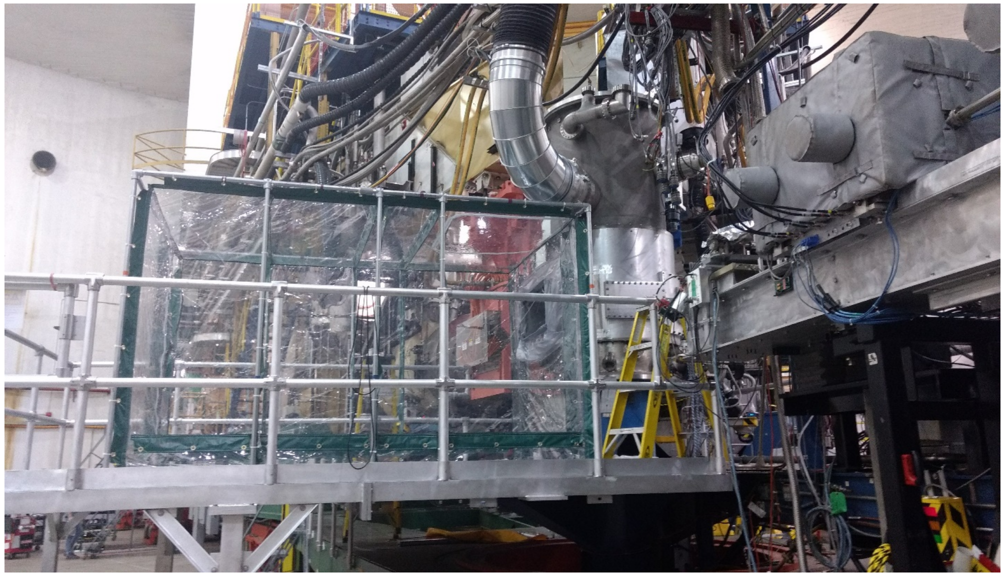
- Relies only on *difference* in nuclear effects in ^{3}H, ^{3}He
- Calculated to within 1%
- Most systematic and theoretical uncertainties cancel



Hall A Tritium Target: 2018-2019 run, the first ^3H in decades

Lab	Year	Quantity (kCi)	Thickness (g/cm²)	Current (μA)	Current *x* thickness (μA-g/cm²)
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**

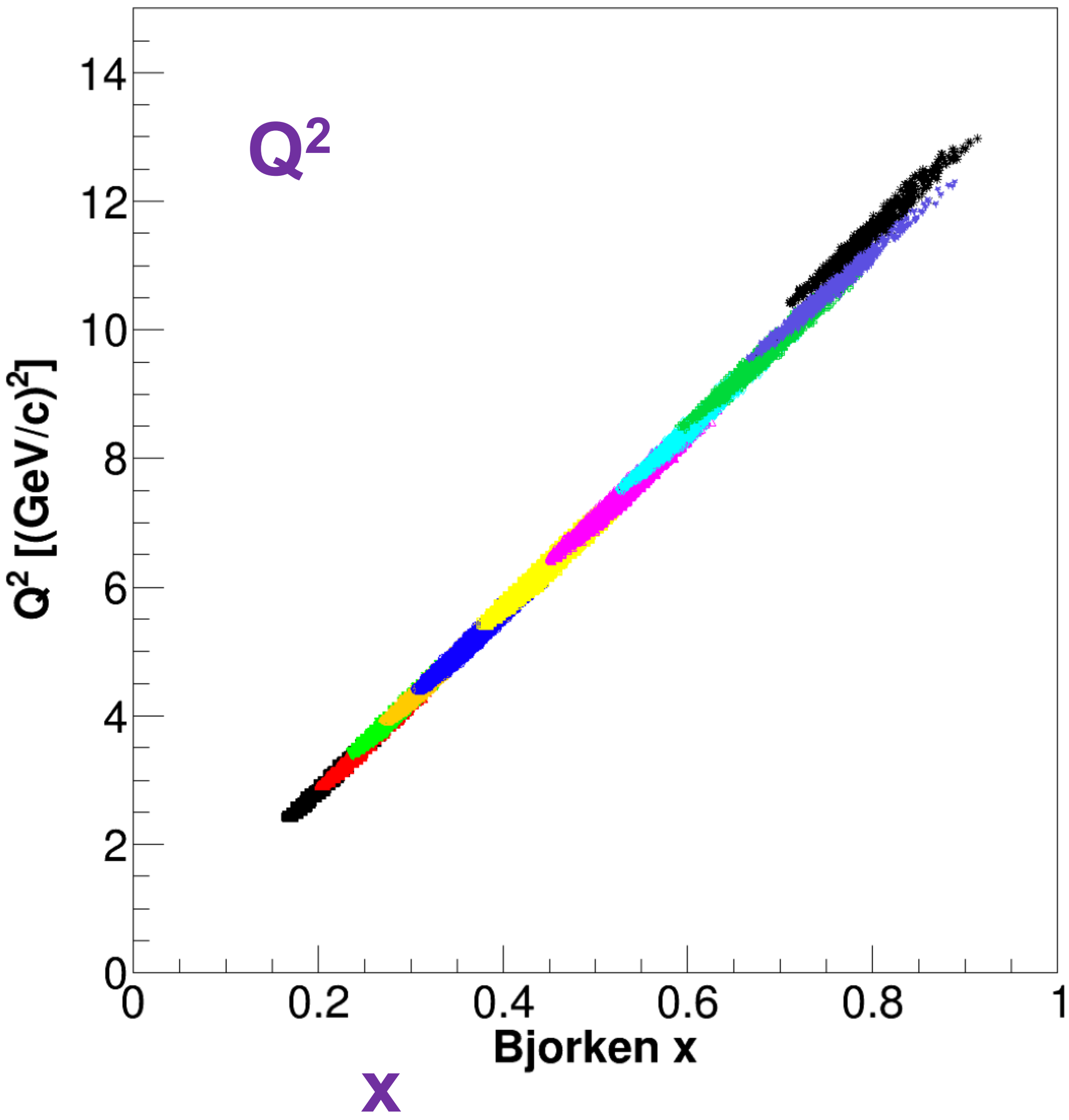
JLab Luminosity ~ 2.0×10^{36} tritons/cm²/s

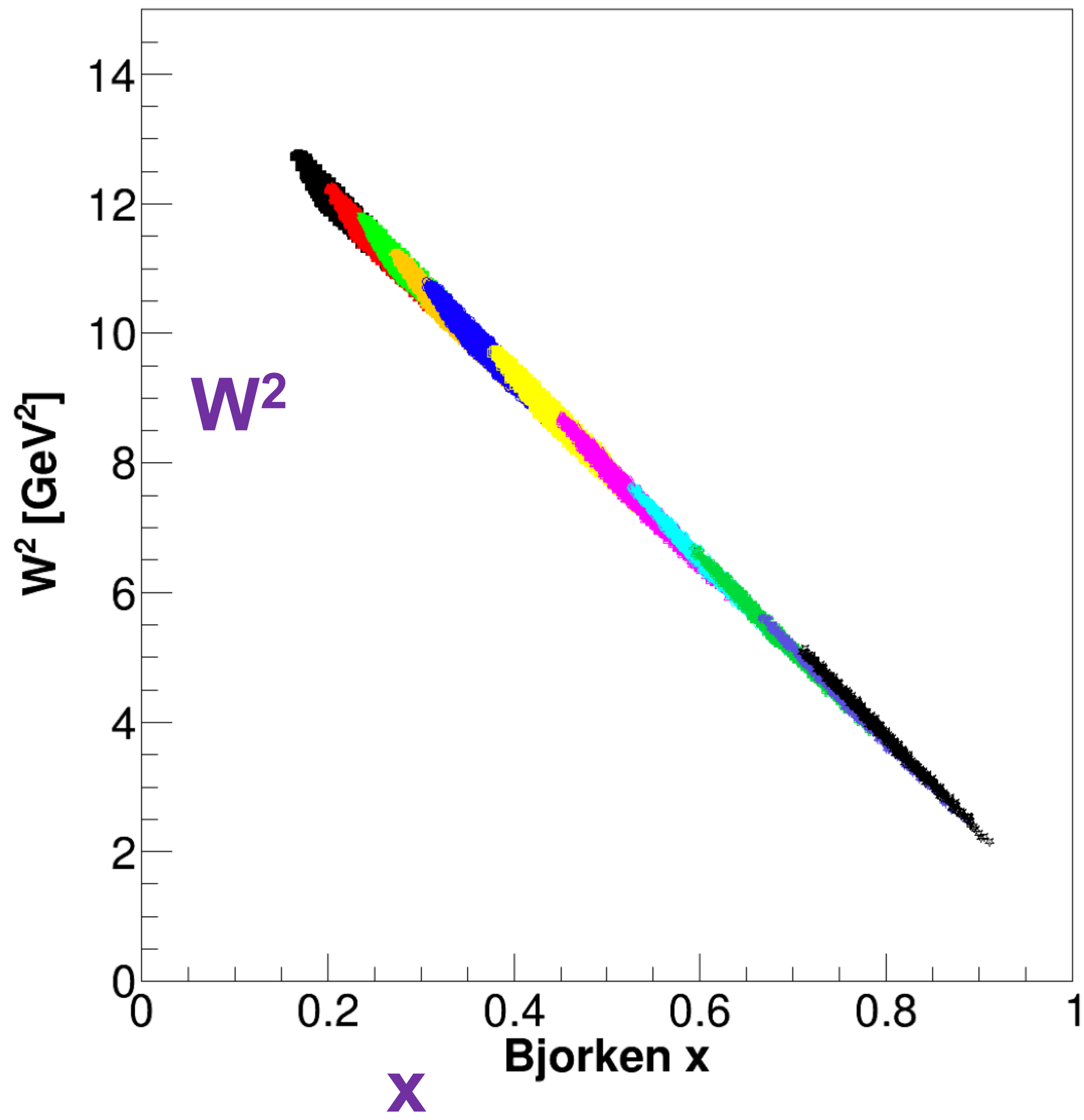


Heat Exchanger

Tritium (T2)
He-3
D2
H2
Empty
Solid Targets

Kinematic Coverage of MARATHON





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

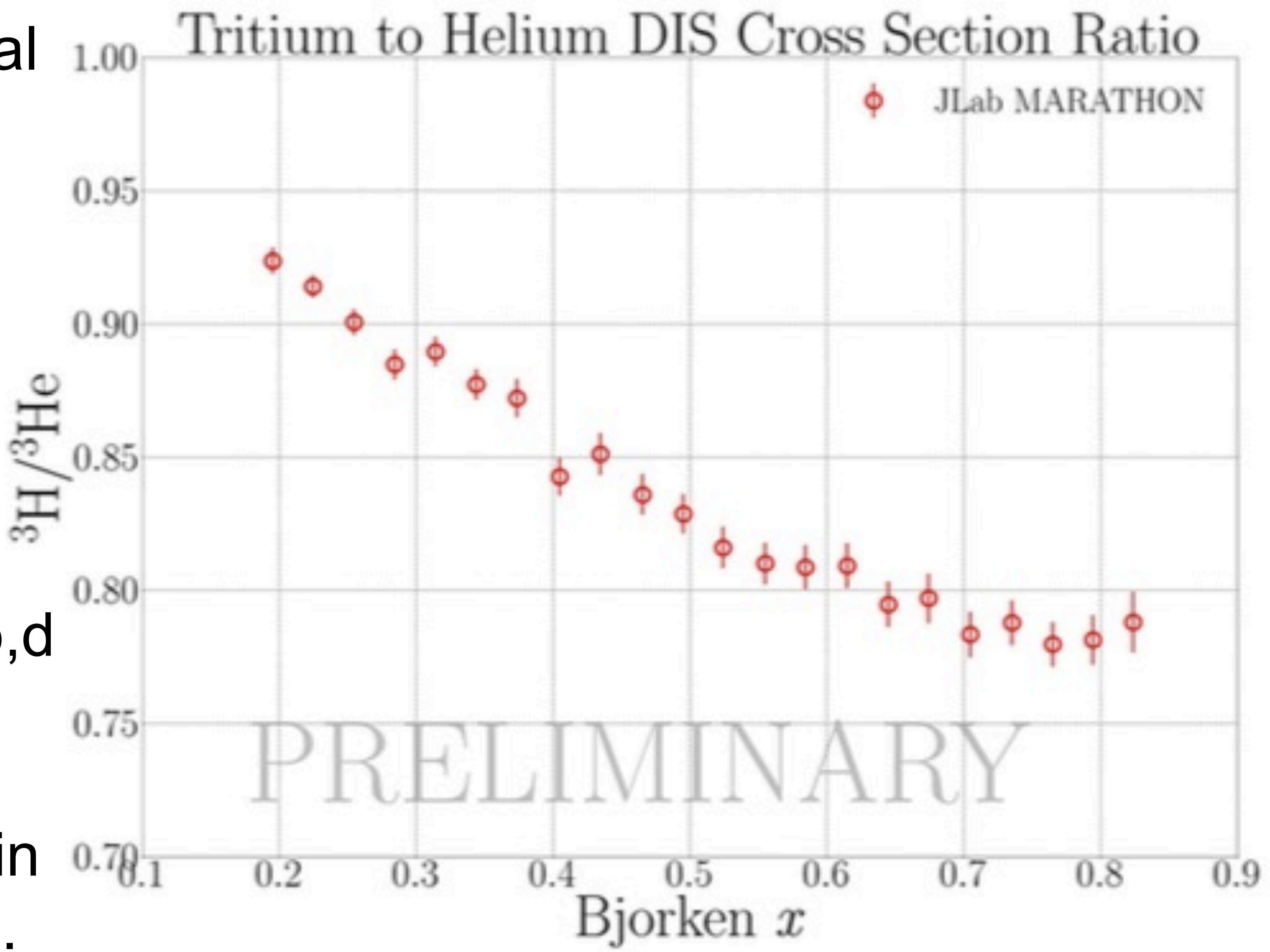
JLab MARATHON preliminary results

This is the actual (preliminary) data!

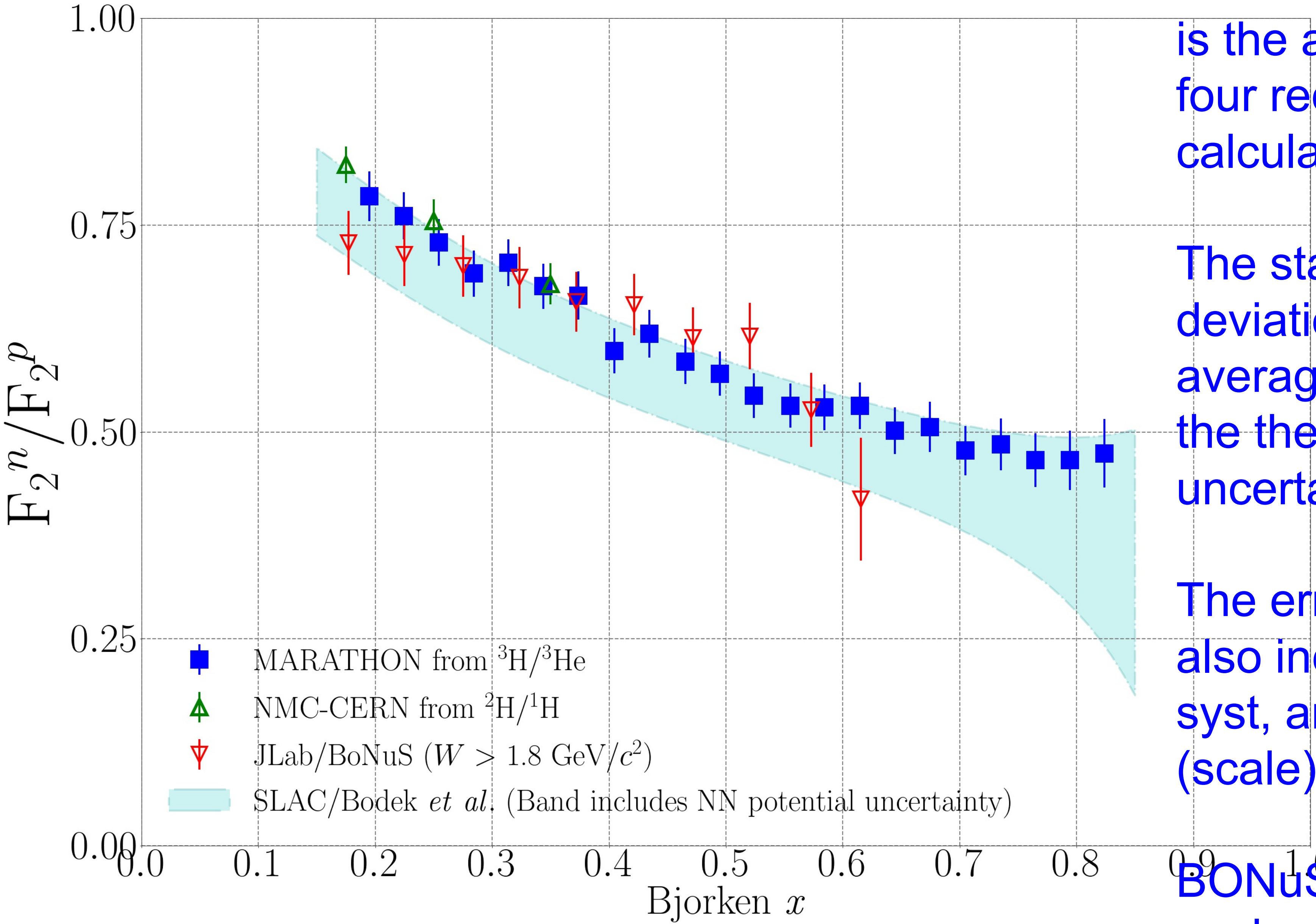
Still finalizing systematic uncertainties

Also measure p,d

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



Hall A MARATHON – preliminary (*publication preparation underway*)



The super ratio used is the average of four recent theory calculations.

The standard deviation of the average is used as the theory model uncertainty.

The error bars shown also include random syst, and overall (scale) uncertainties.

BONuS6 data evolved to MARATHON Q^2

Polarized predictions for d/u structure at large x

Proton Wavefunction (Spin and Flavor Symmetric)

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

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

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):

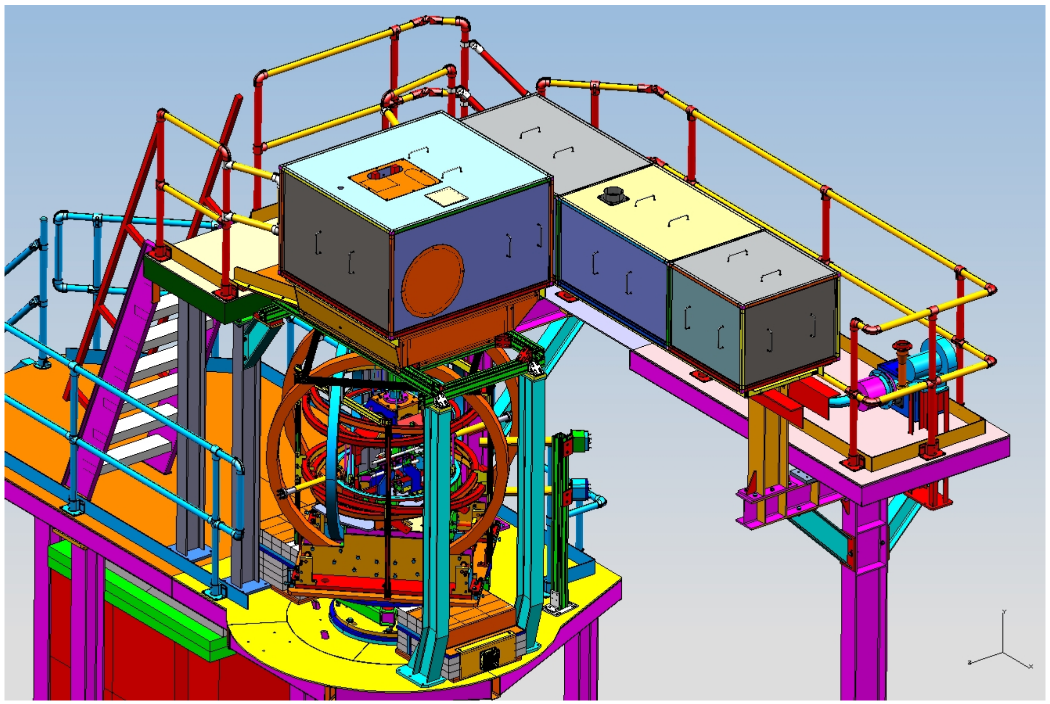
JLab's focus is high precision large x and low to intermediate Q^2 values

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

A_1^n in Hall C 2020 (completed, d_2^n to run next) ³He target

REQUIRES:

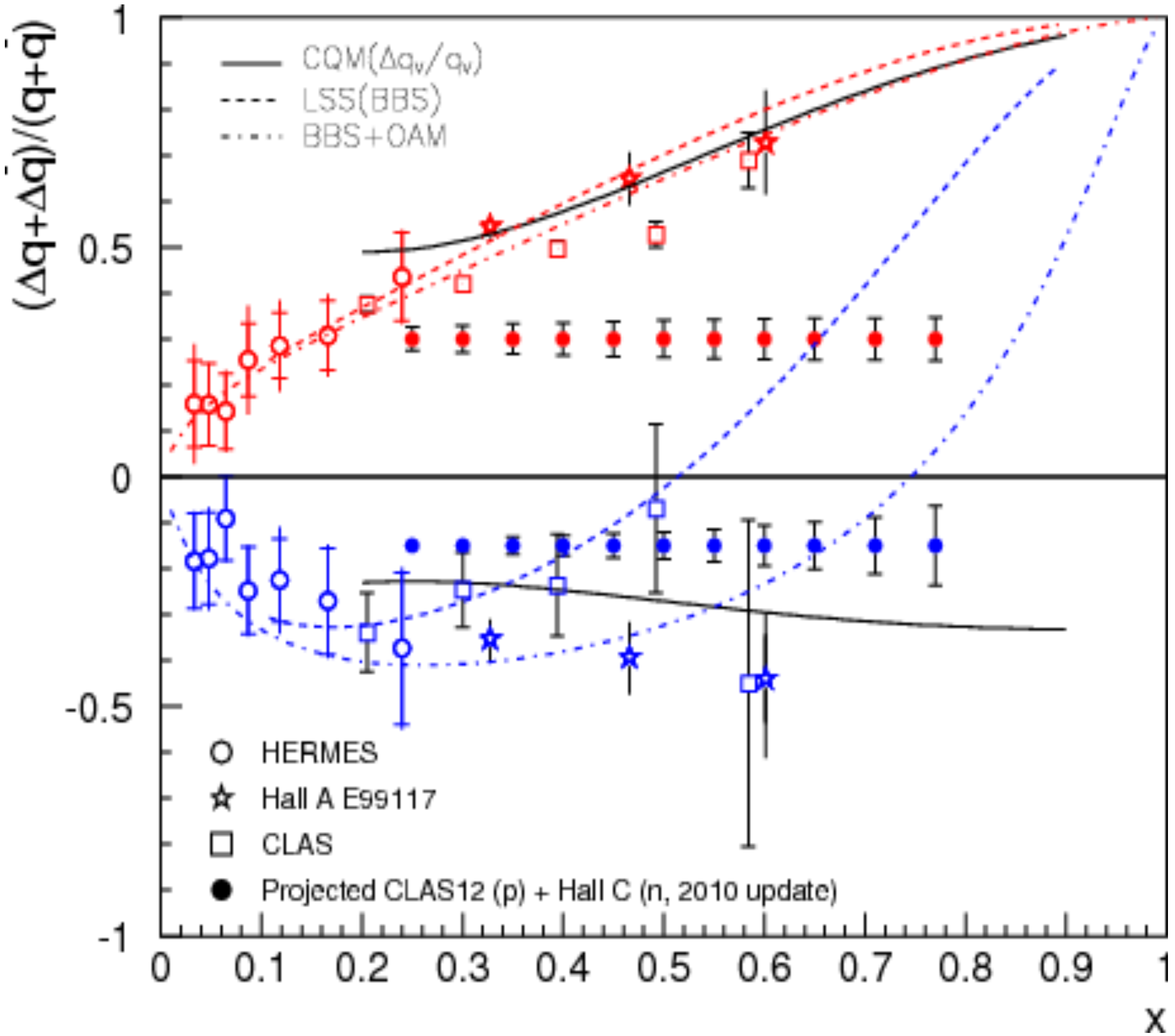
- High beam and target polarization
- High electron current



Polarized ³He for A1n/d2n:

- 30 uA on 40 cm, ~10 atm ³He gas
- L ~ 2.2 x10^{36} $cm^{-2}s^{-1}$ - *double previous highest luminosity*
- In-beam polarization ~ 55%
- Polarimetry precision ~ 3%

Component of a Broad JLab Spin Structure Program

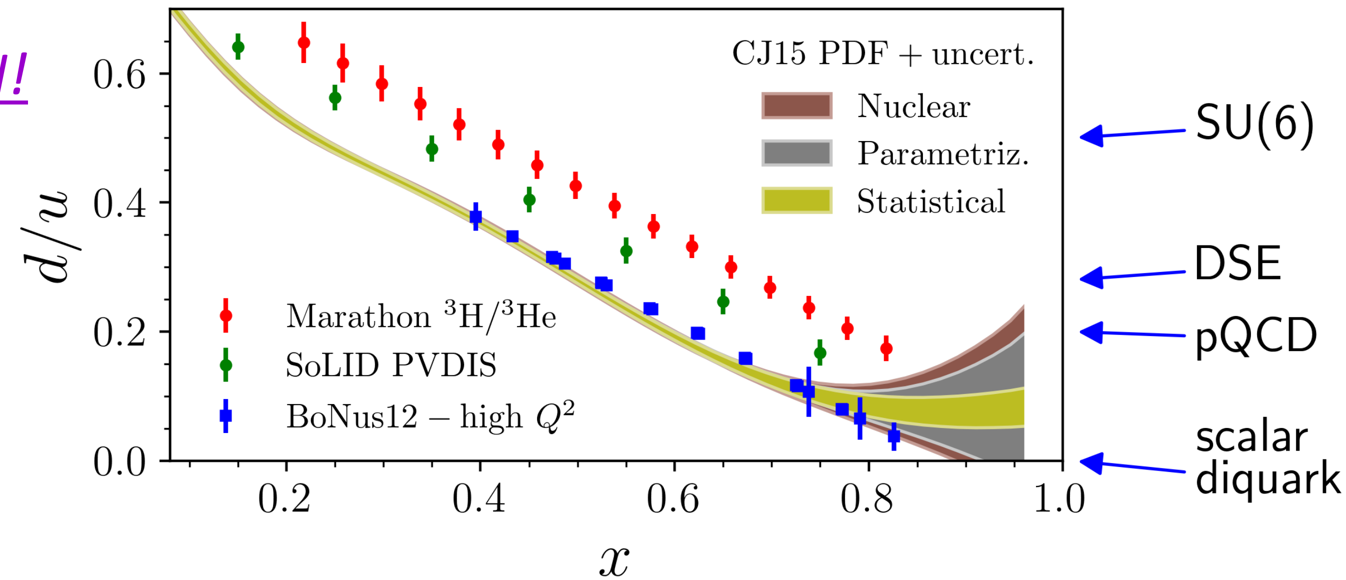


Combined results from Hall C (neutron) and Hall B (proton): polarized pdfs

Input for JAM and other global polarized pdf fitting efforts

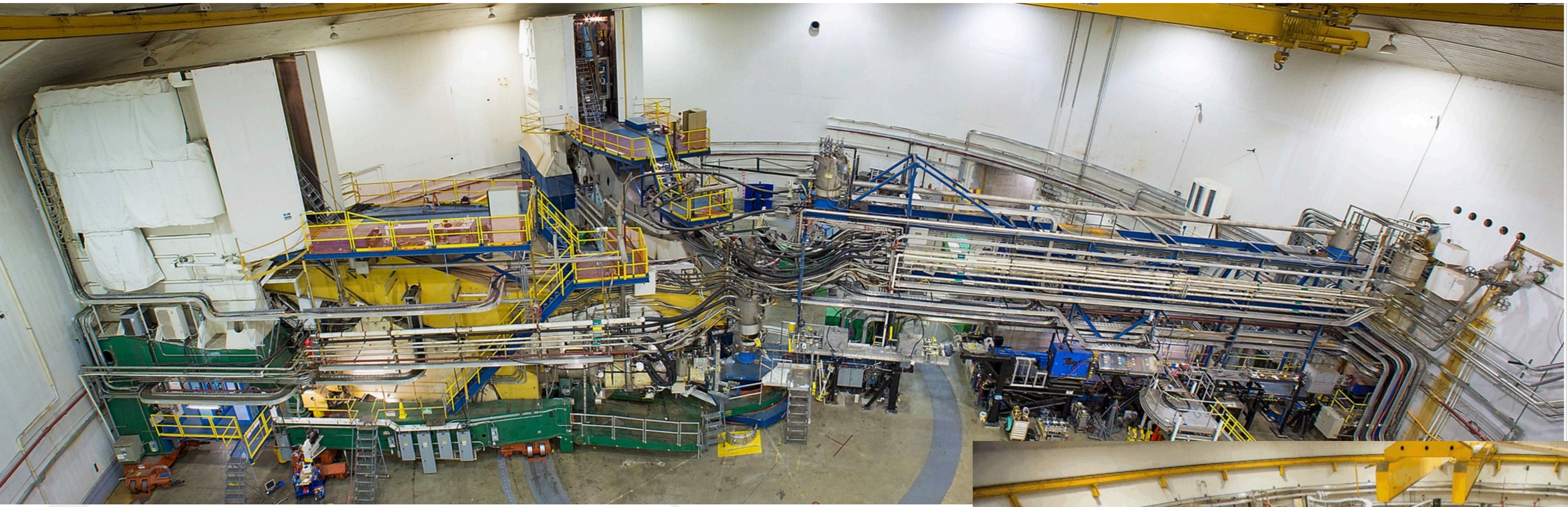
Probing the Nucleon Valence Regime: Summary

- 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 $^3H/^3He$
- More experiments *2020!*
  - 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 very near future!

Thank You!



Jefferson Lab Hall A

Jefferson Lab
Hall C