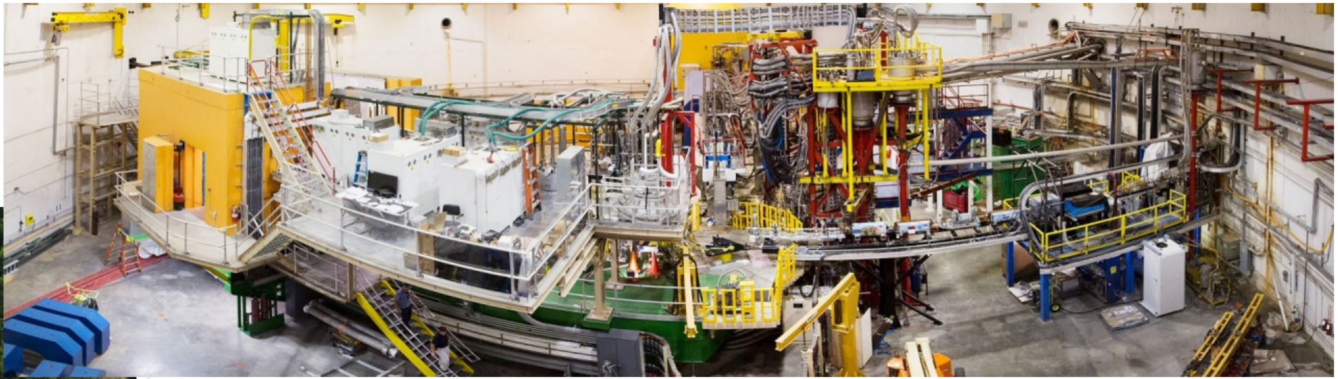
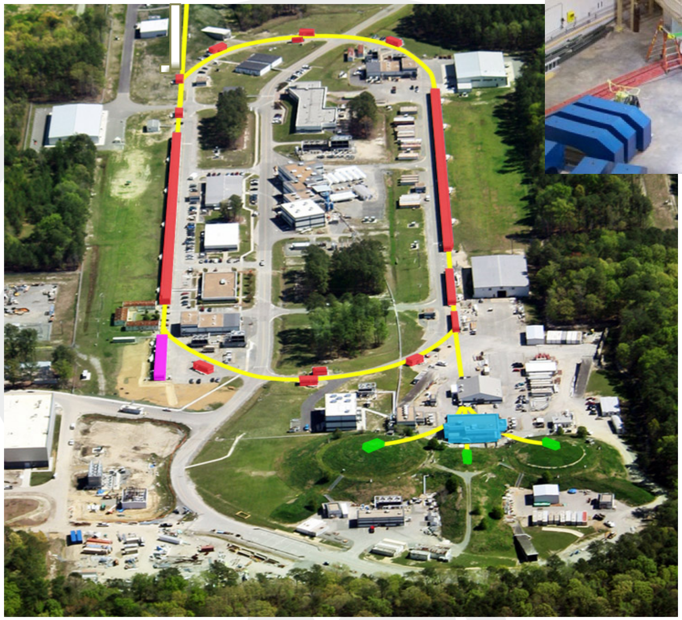
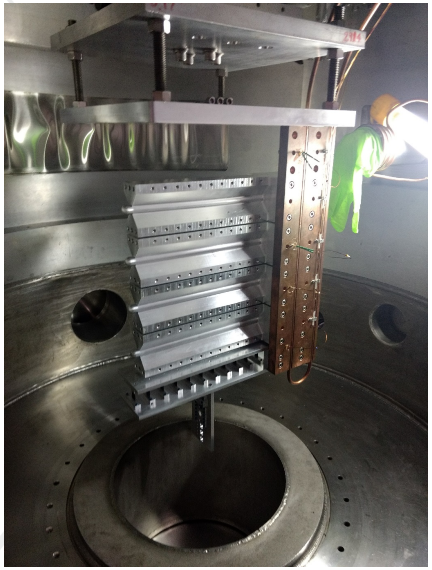
Overview of d/u and the SoLID Contribution

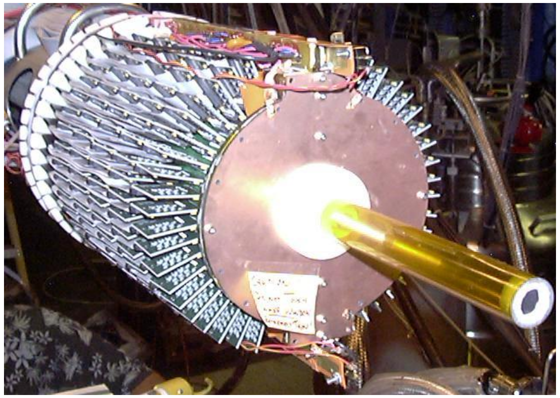
Cynthia Keppel
Thomas Jefferson National Accelerator Facility
June 2022

INT Workshop on Parity-Violation and other Electroweak Physics at JLab 12 GeV and Beyond









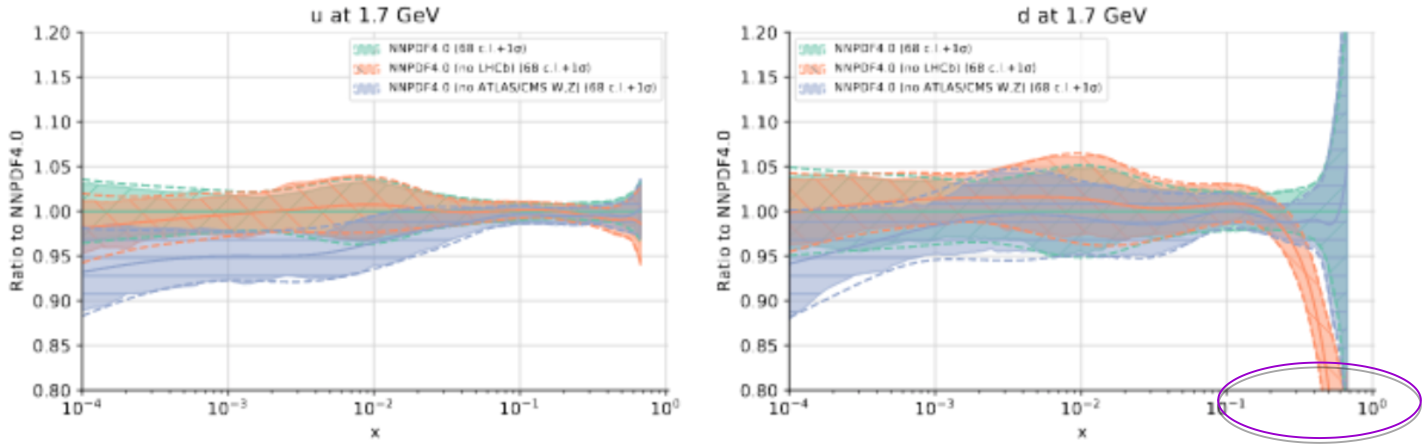
Jefferson Lab

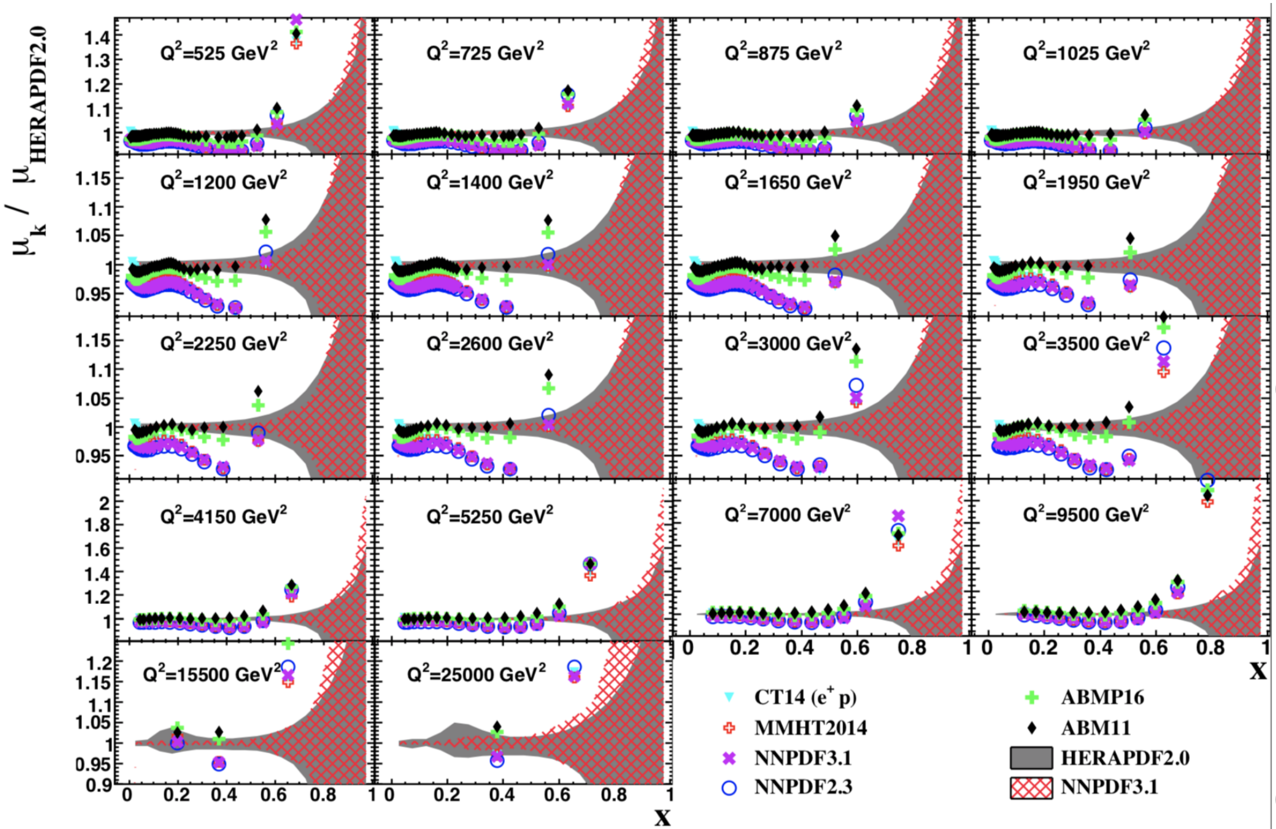
U.S. DEPARTMENT OF ENERGY | Office of Science

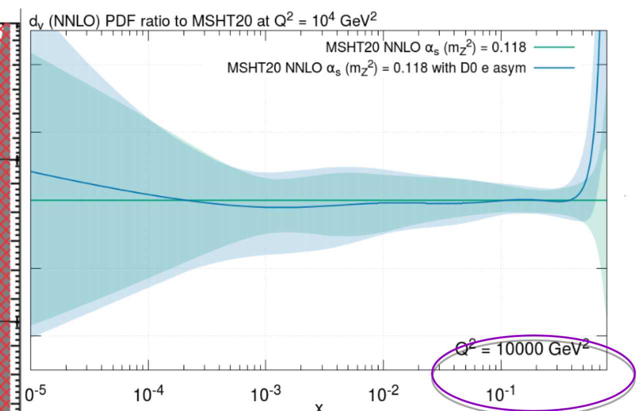
JSA

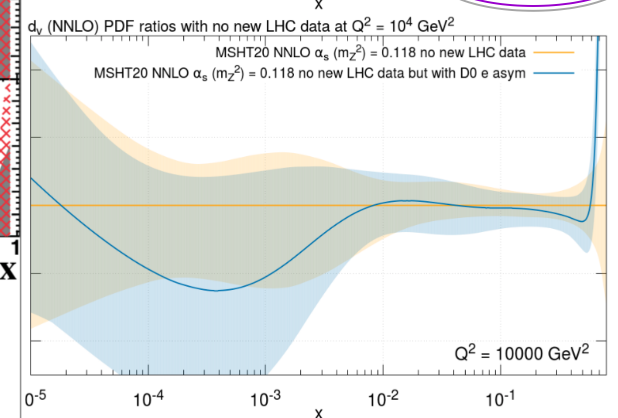
Current status: large uncertainties on PDFs at large x

Sampling of PDF results shown at PDF4LHC meeting

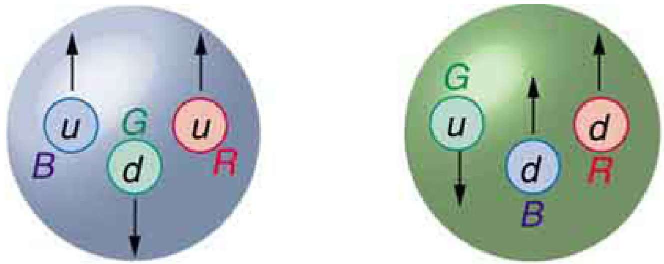








Why is the x > ~0.3 valence regime interesting?

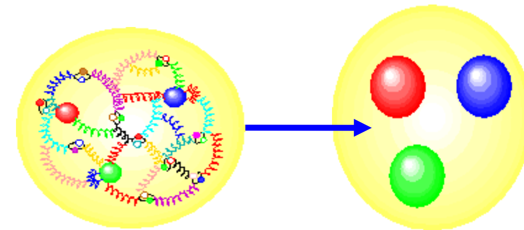


	Proton	Neutron
Spin	$\frac{1}{2}+\frac{1}{2}-\frac{1}{2}=\frac{1}{2}$	$-\frac{1}{2}+\frac{1}{2}+\frac{1}{2}=\frac{1}{2}$
Charge	$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$	$+\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$

- Partonic structure in the valence region ***defines*** a hadron
  - Baryon number, charge, flavor content, total spin, …
- Keen discriminator of hadron structure models: QCD and others can make absolute predictions for structure functions
- "Valence regime" at large x, low Q^2 evolves to low x, high Q^2
  - Intersection of nuclear and particle physics
- A generation of experiments at JLab focused on high x

Multiple predictions for d/u at 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:

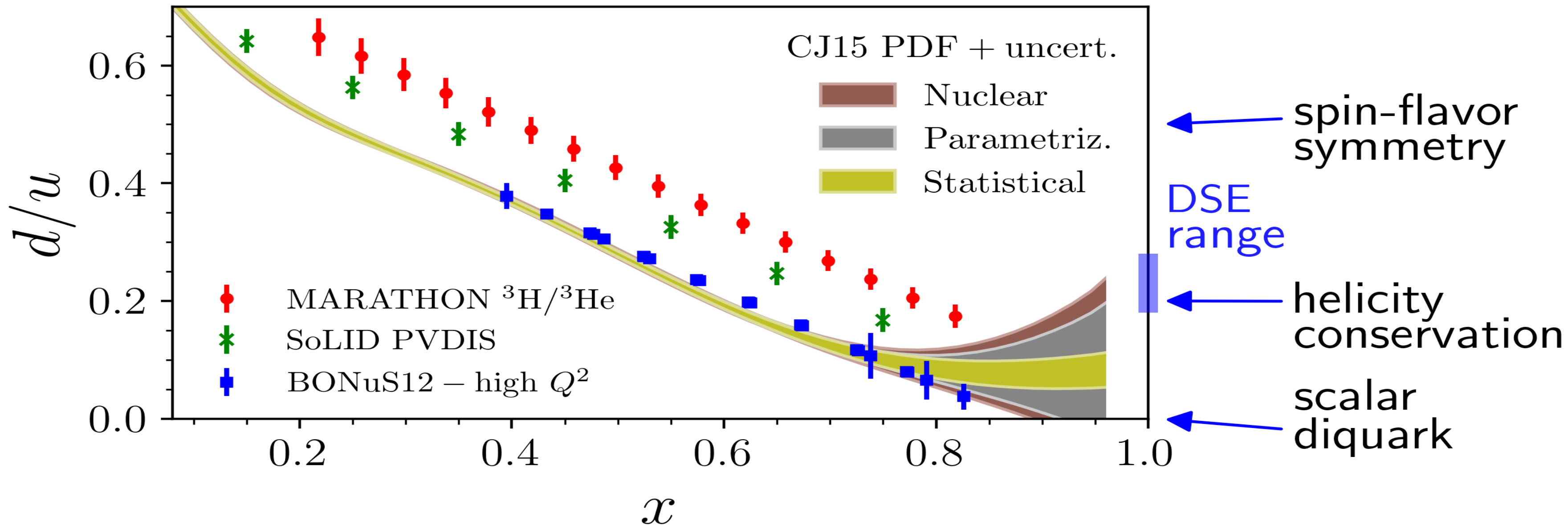
- N. Isgur, PR**D 59** (1999)
- S Brodsky et al NP **B441** (1995)
- W. Melnitchouk and A. Thomas PL **B377** (1996)
- R.J. Holt and C. D. Roberts, Rev. Mod. Phys. 82 (2010)
- I. Cloet et al, Few Body Syst. **46** (2009) 1.
- C. Roberts, R.Holt, S. Schmidt, Phys. Lett. B 727 (2013) 249

A measurement (or several) are needed…

Multiple experimental efforts at JLab12 to determine *d/u* at high-*x*

- **MARATHON** - 3H / 3He mirror nuclei
- **SoLID PVDIS**
- **BONuS12** – proton spectator tagging

Also:
TDIS
Hall C F2p, F2d
(CJ, JAM)



A. Accardi

Multiple experimental efforts at JLab12 to determine *d/u* at high-*x*

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Also:
TDIS
Hall C F2p, F2d
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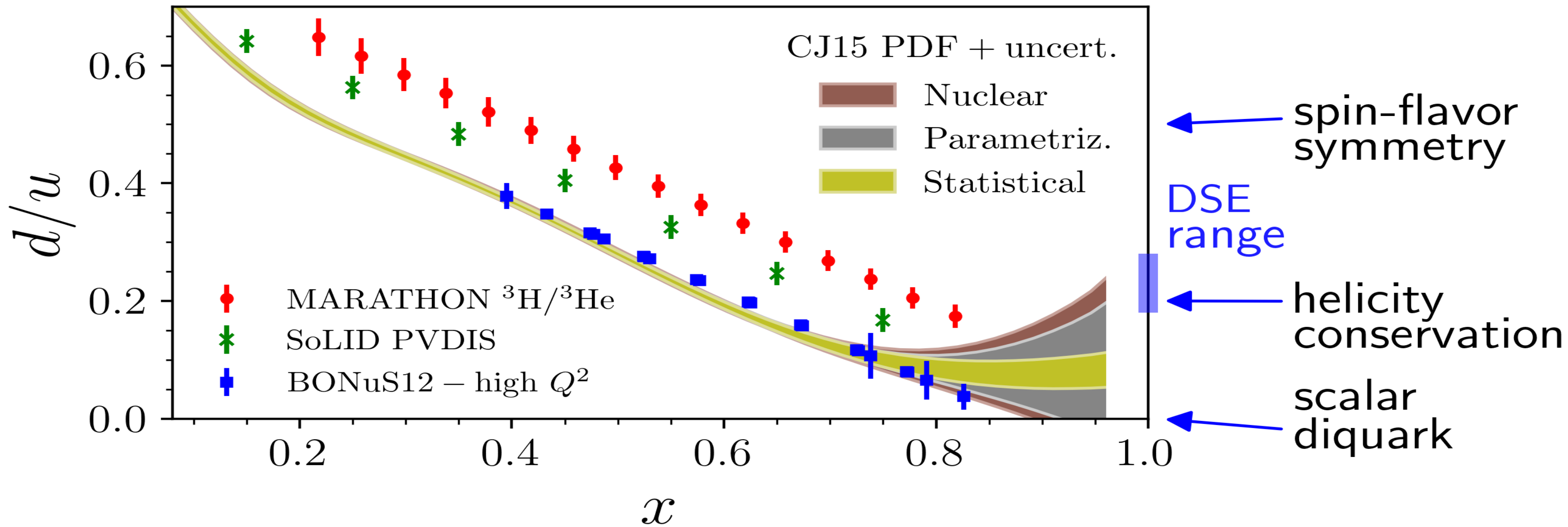
What is the unique role for SoLID here?



A. Accardi

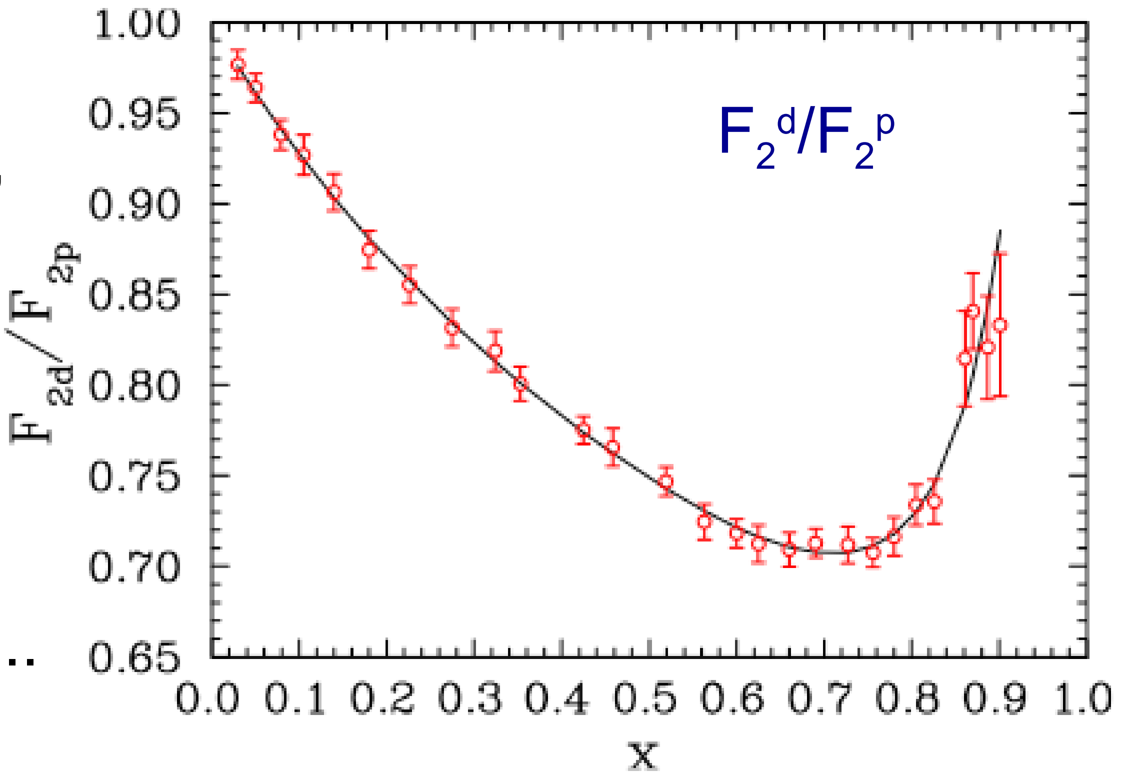
Neutron structure is typically derived from deuterium target data by subtracting proton data

…..but…..

The deuteron is a nucleus!

n, p e- scattering different…and…

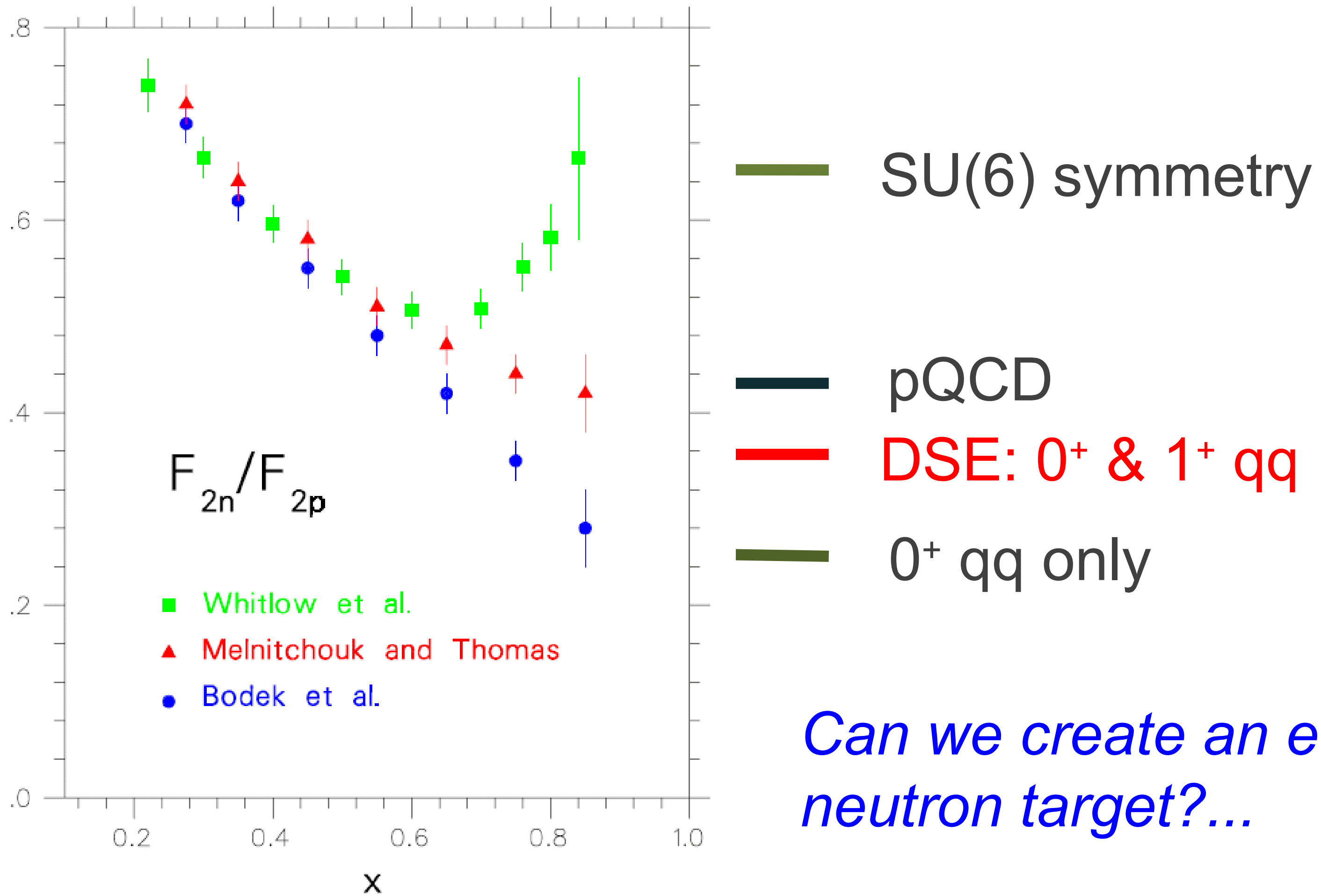
Large uncertainty in unfolding nuclear effects (Fermi motion, off-shell effects, deuteron wave function, coherent scattering, final state interactions, nucleon structure modification ("EMC"-effect),……….



SLAC data

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

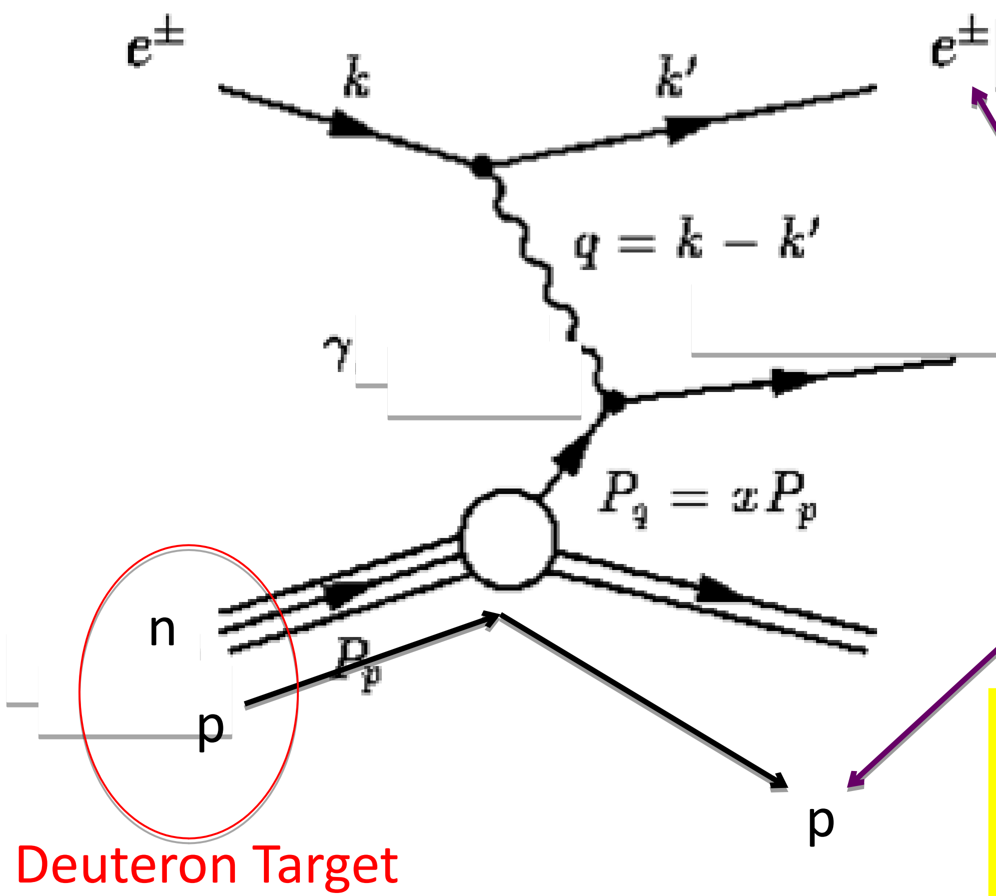
- Conflicting fundamental theory pictures
- F_2^n data inconclusive due to uncertainties in deuterium nuclear corrections
- *Translates directly to large uncertainties on d(x), g(x) parton distribution functions*

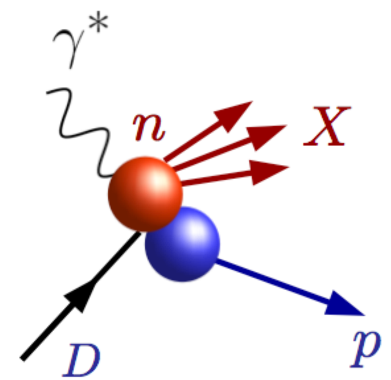


Can we create an effective neutron target?...

TDIS to access nucleon valence structure

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





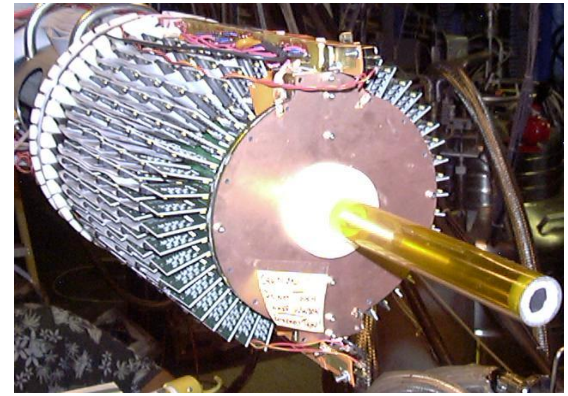
Measure DIS electron in coincidence with proton tag

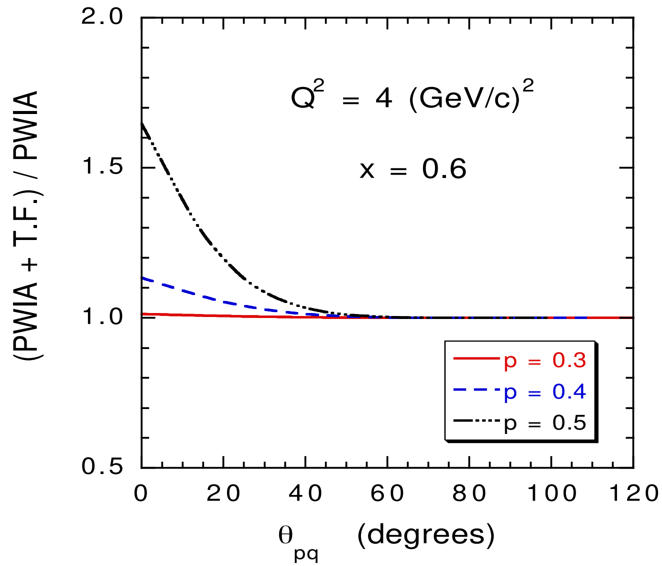
- “Hard” scattering inelastic event (high Q, W)
- Proton remains intact
- Low momentum proton = nucleons barely off shell

✓ Neutron target!

The BONuS approach:

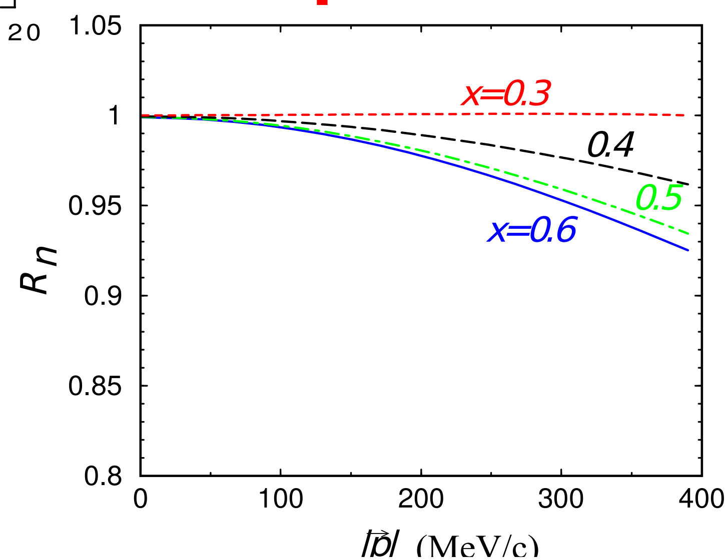
use low mass radial TPC detector / target in magnetic field to TAG "spectator" proton at (very) low momenta (~65 MeV/c) and large angles (> 90° in lab) ***….difficult but doable***

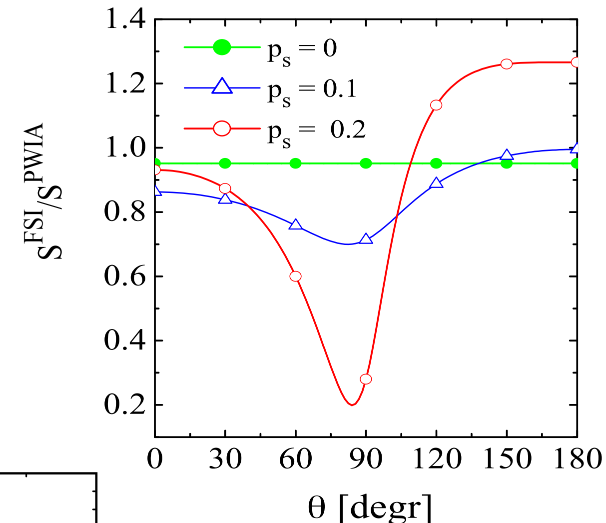




Bound / free neutron structure

O **(1%)**





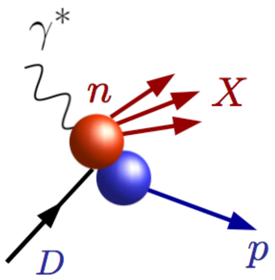
Target fragmentation

negligible

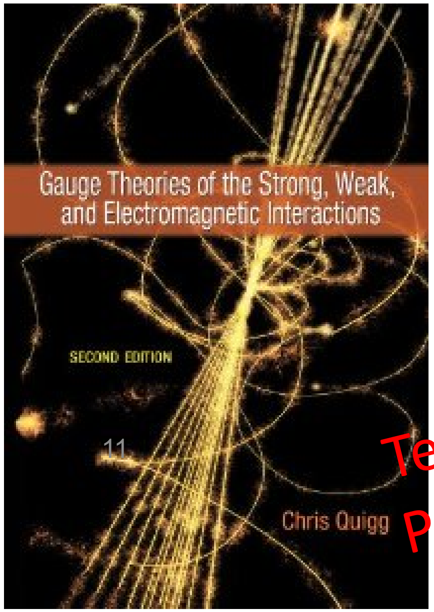
Final state interactions

O **(5%)**

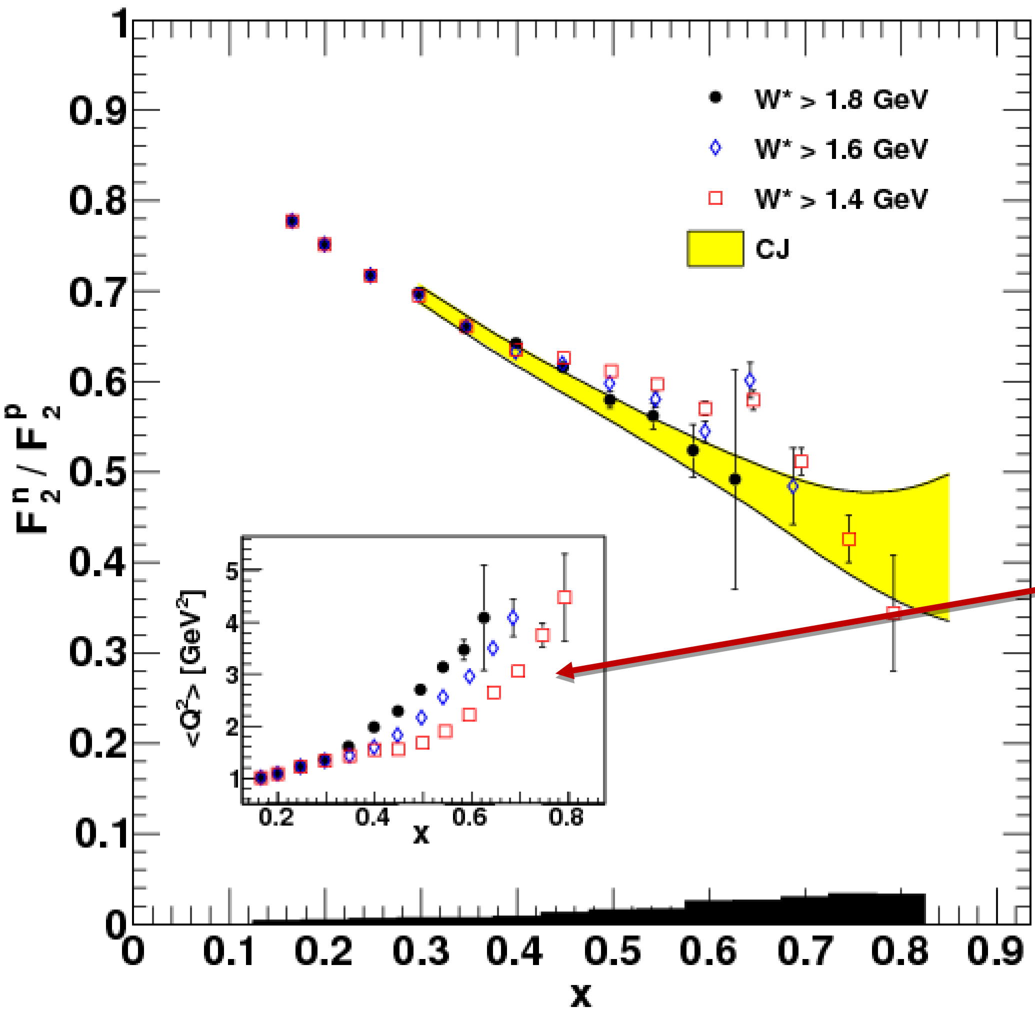
BONUS effective neutron target via TDIS *achieved!*



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



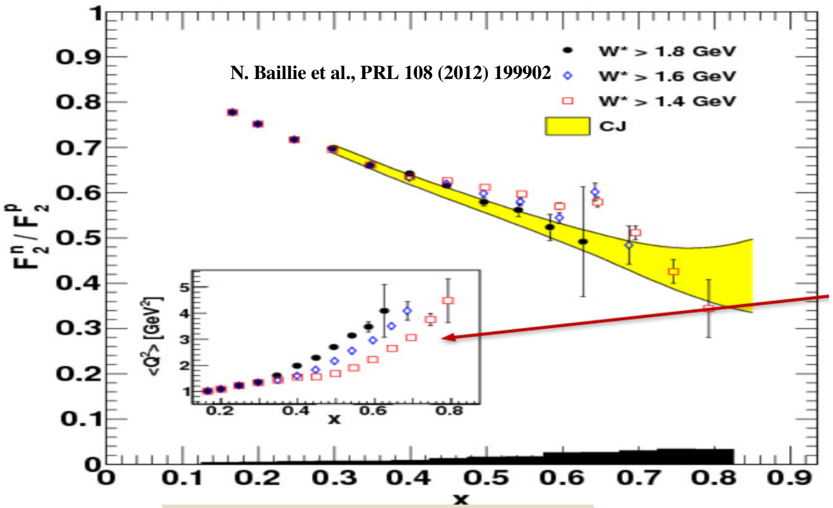
Textbook Physics!



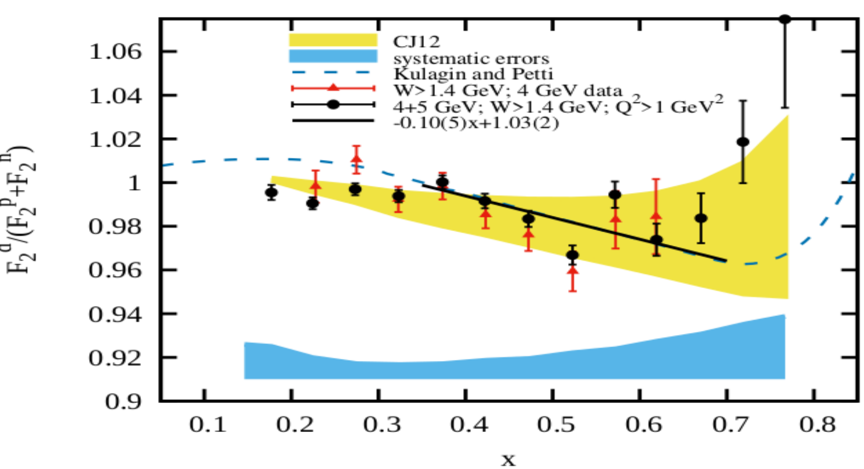
- Not quite high enough x, Q^2 in 6 GeV era
- Nonetheless still powerful as input for global PDF fits…

Results from E_b = 6 GeV BONuS Experiment

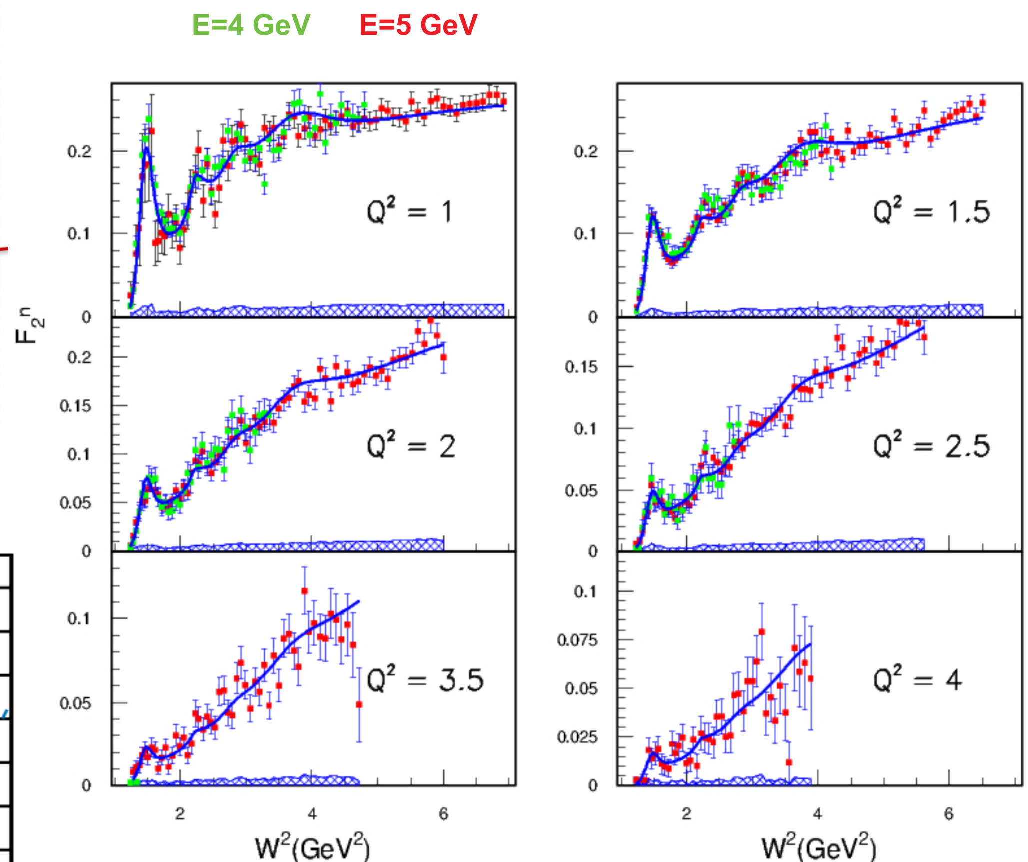
F_2^n / F_2^p



Deuteron EMC effect



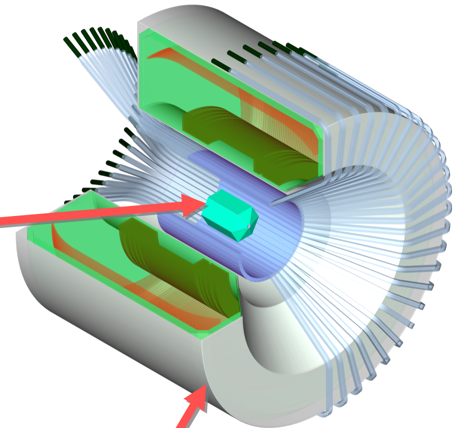
Neutron resonance states and duality

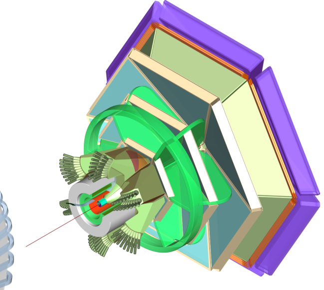


Also studies of the onset of FSI ongoing

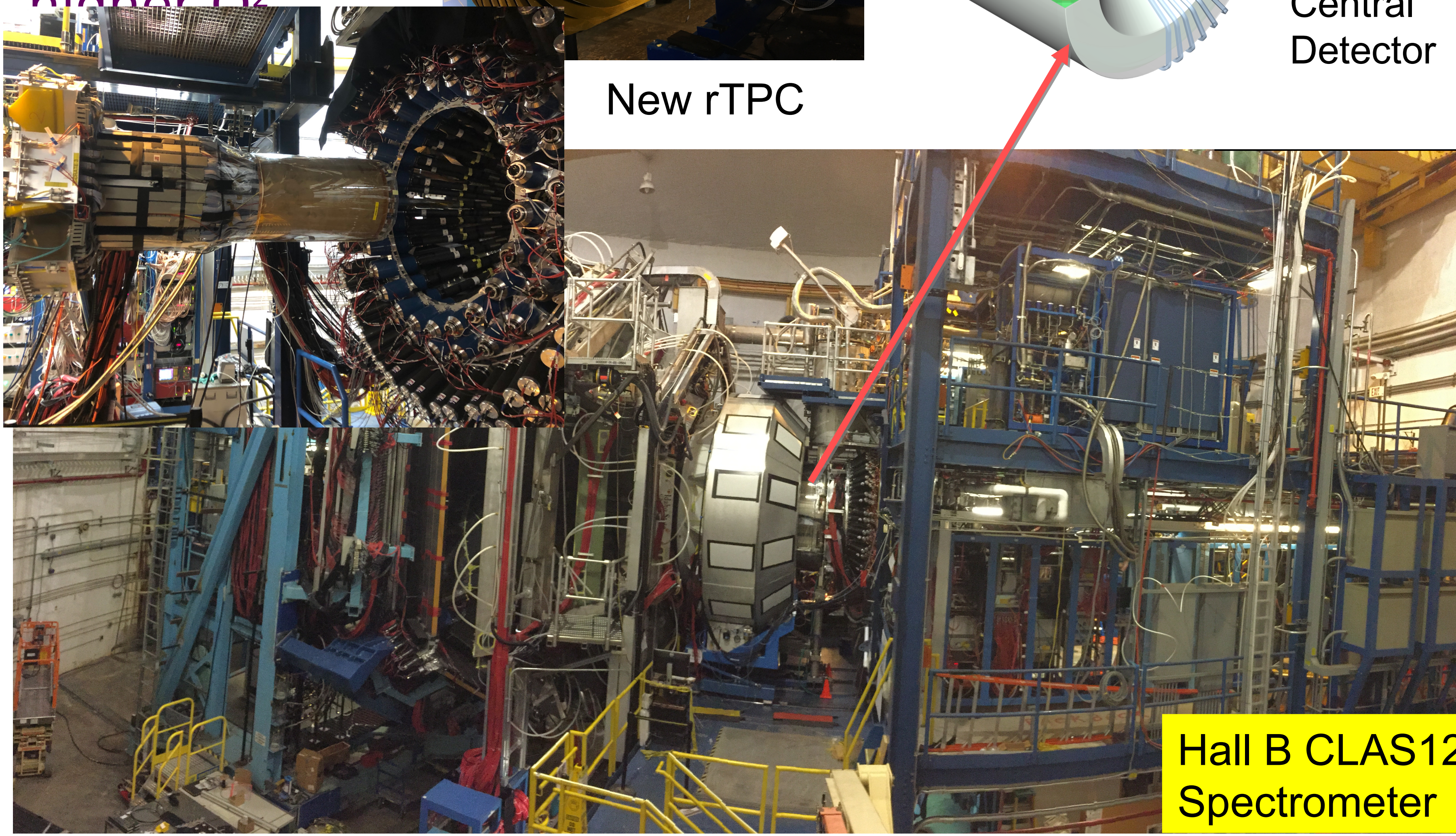
2020 E12-06-113 “BONUS12”: Larger x and higher Q^2

New rTPC





CLAS12 Central Detector

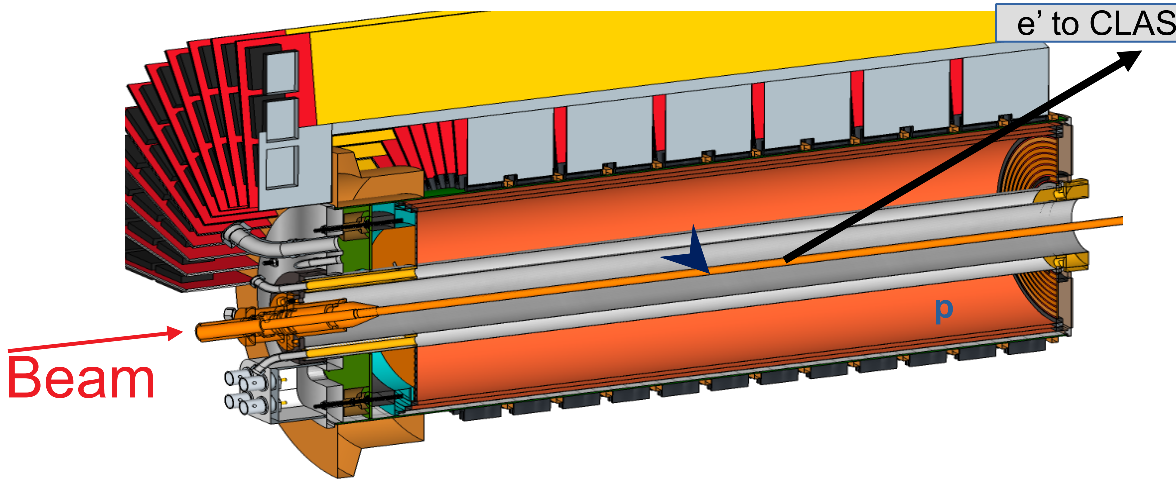


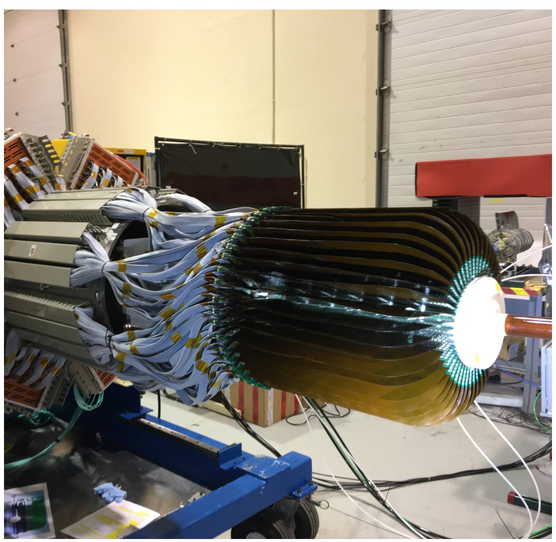
Hall B CLAS12 Spectrometer

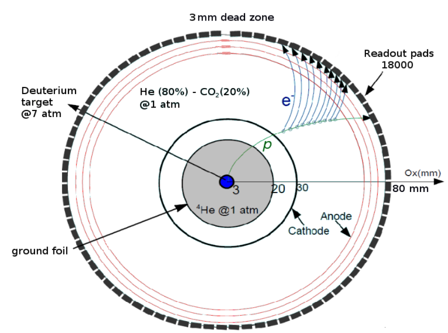
New Radial Time Projection Chamber (RTPC)

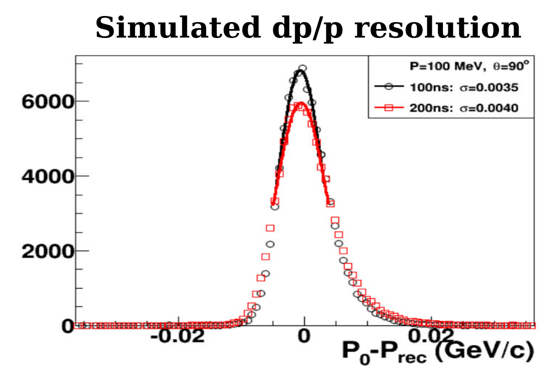
- → Active length: 40 cm
- → Radial drift distance: 4 cm
- → Drift gas He/CO_2 (80/20)
- → 3 GEM amplification layers
- → 16 HV sectors per GEM
  (Segmented in ✈)
- → Pad readout: 2.8 mm x 4 mm

=> 17,280 channels







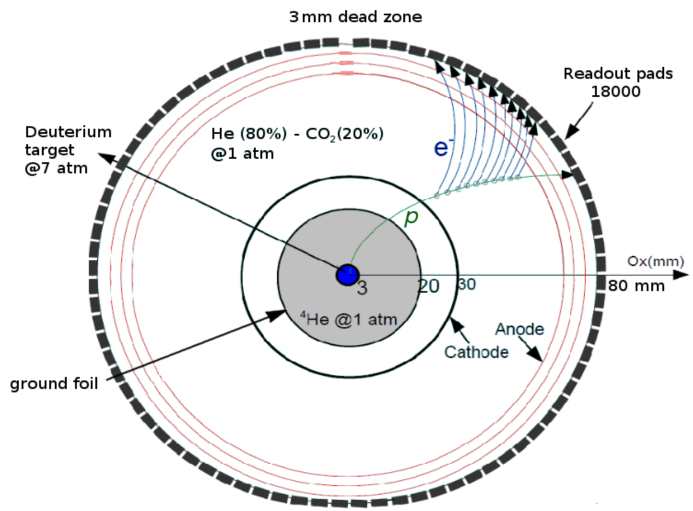


CLAS12 RG-F (BONuS12) Data Summary

Finished data taking in September 2020

→ Data taking split by start of pandemic

Beam Energy	Target	Spring 2020	Summer 2020
2.1 GeV	H2	81M	185M
	D2	37M	45M
	4He	19M	44M
	Empty	1M	22M
	Total	138M	296M
10.5 GeV	H2	151M	266M
	D2	2275M	2355M
	4He	77M	51M
	Empty	21M	45M
	Total	2524M	2717M



- Charge sum over track hits + track length

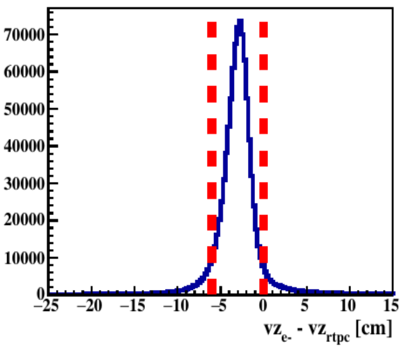
→ dE/dx

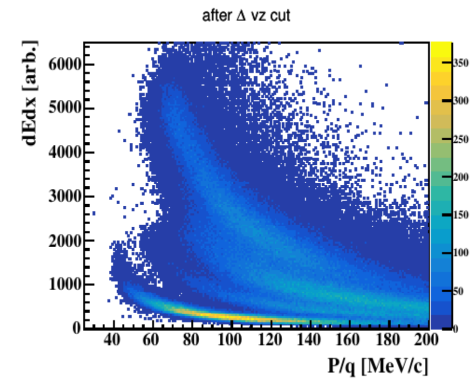
- Good separation of bands for p, d, triton, ^{4}He

- Improvements to pad-pad gain variations in future

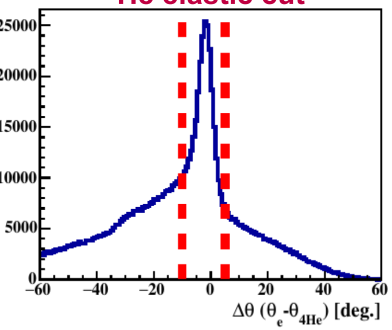
^{4}He

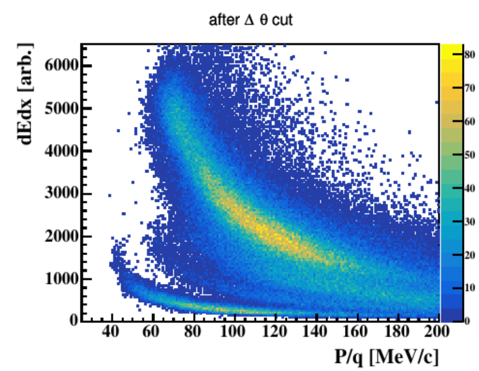
Common Vertex Cut





^{4}He elastic cut

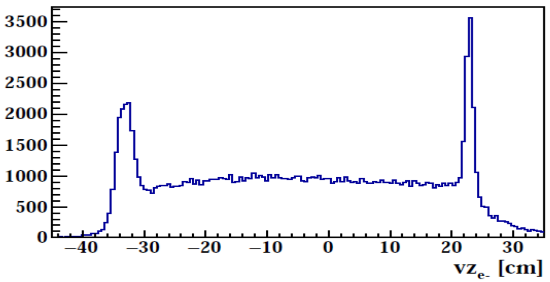


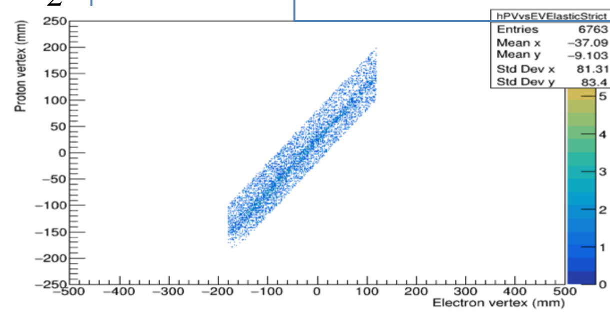


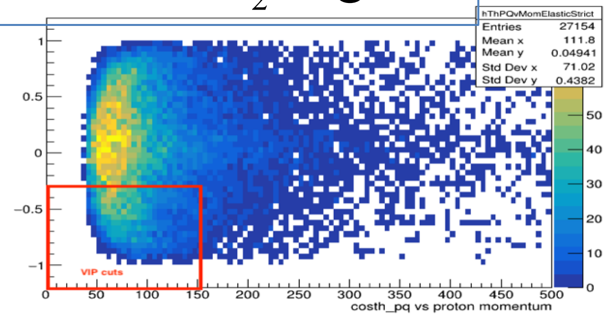
Preliminary Analysis – 5 Pass Data (subset)

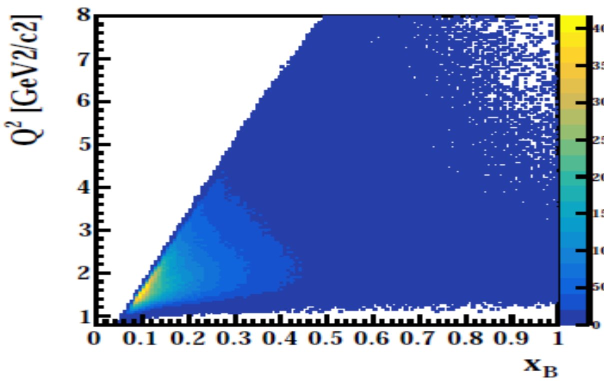
e^- @10.4 GeV beam on D_2

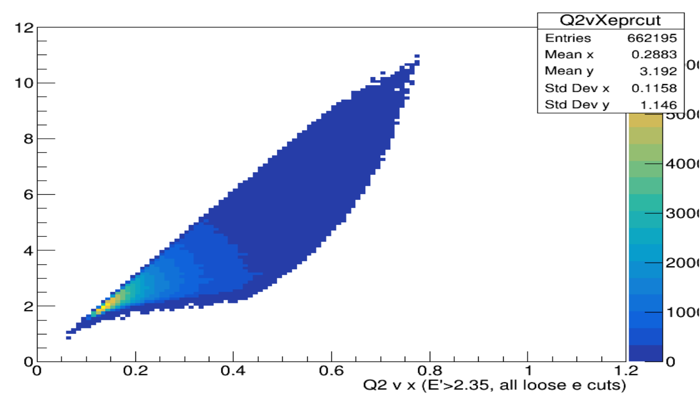
Proton Selection on D_2 target

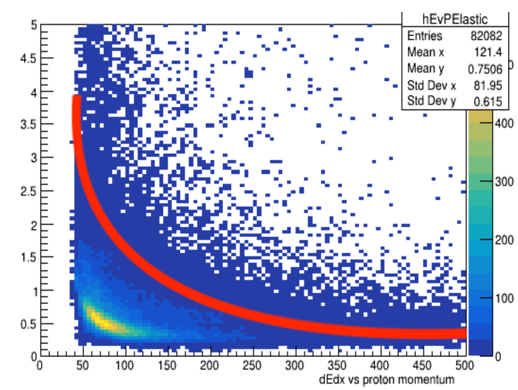








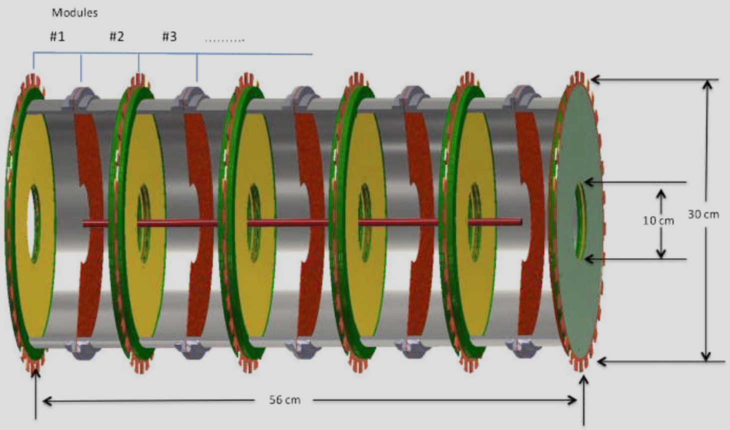




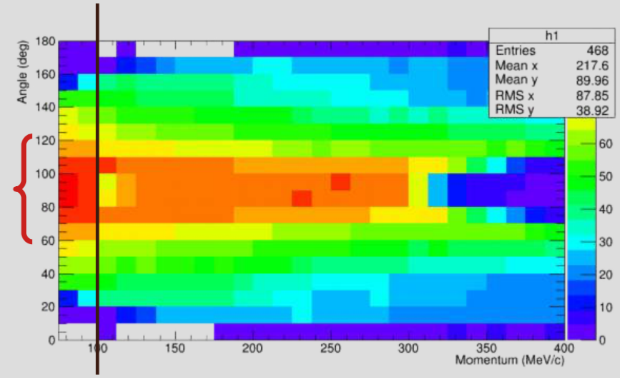
→ Expect first results on F2n / F2p by end of 2022

Also Hall A "TDIS" Experiment RunGroup Approved for F_2^n

The TDIS experiment



mTPC current design. Courtesy N.Liyanage



Efficiency > 50% for transverse recoil protons with p < 300 MeV/c

Latest TDIS configuration from conditional release document used for our studies and satisfactory as is

Running over Hydrogen or Deuterium at 4 atm with a beam intensity of 50 μA will be capable of providing instantaneous luminosity of:

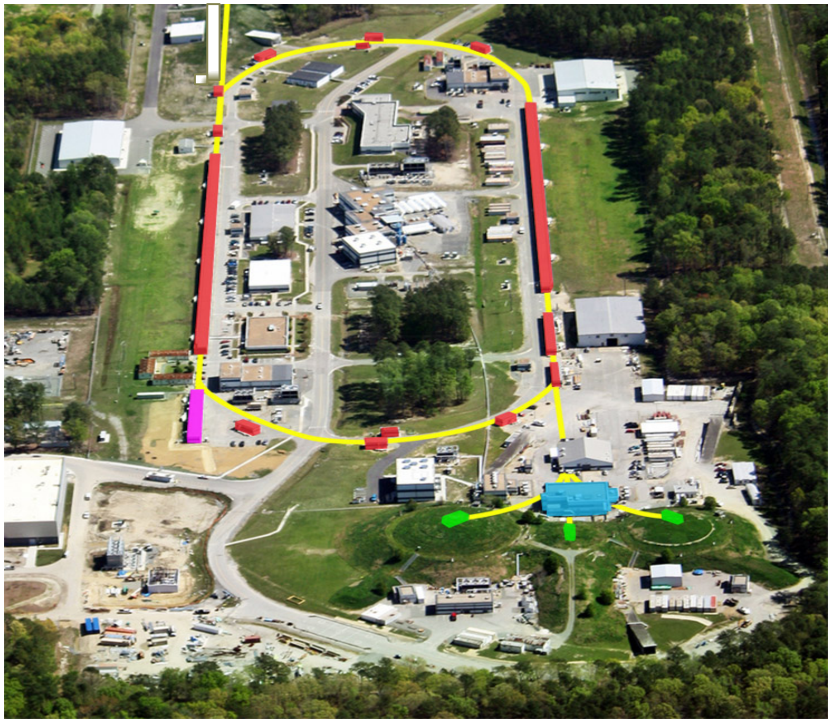
2.9×10^{36} cm^{-2} s^{-1}

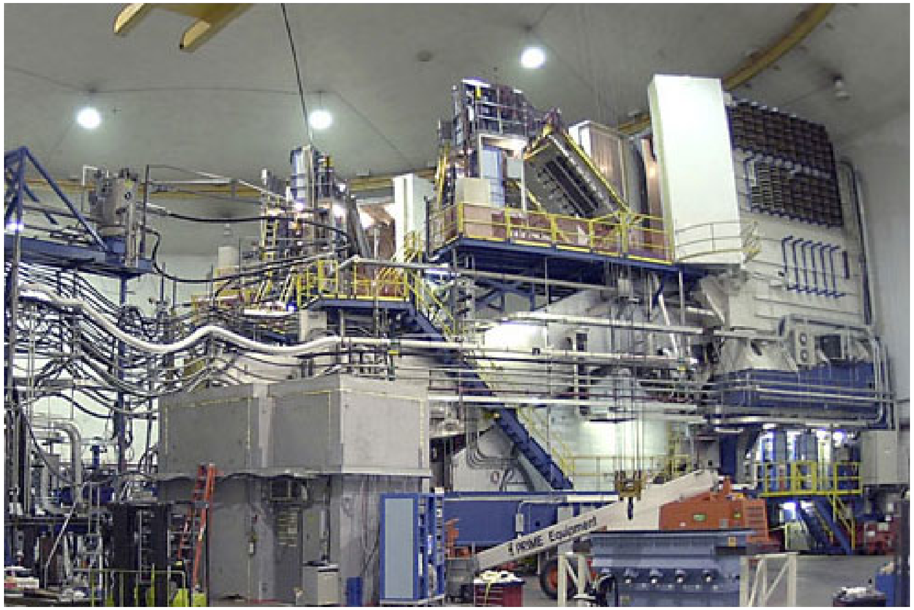
10

Same technique for measuring F_2^n as BONuS, but:

- different detector, different systematics
- independent physics normalization
- higher luminosity = higher statistics at the largest x, Q^2

<u>*Or…*</u> a nuclear physicists approach to the d/u question….





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

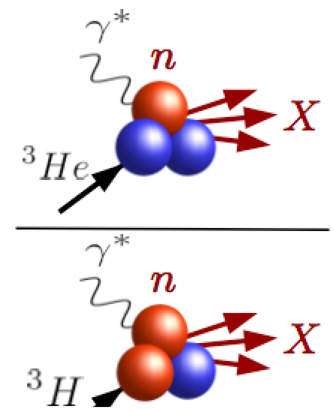
$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n}\,, \qquad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}$$

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

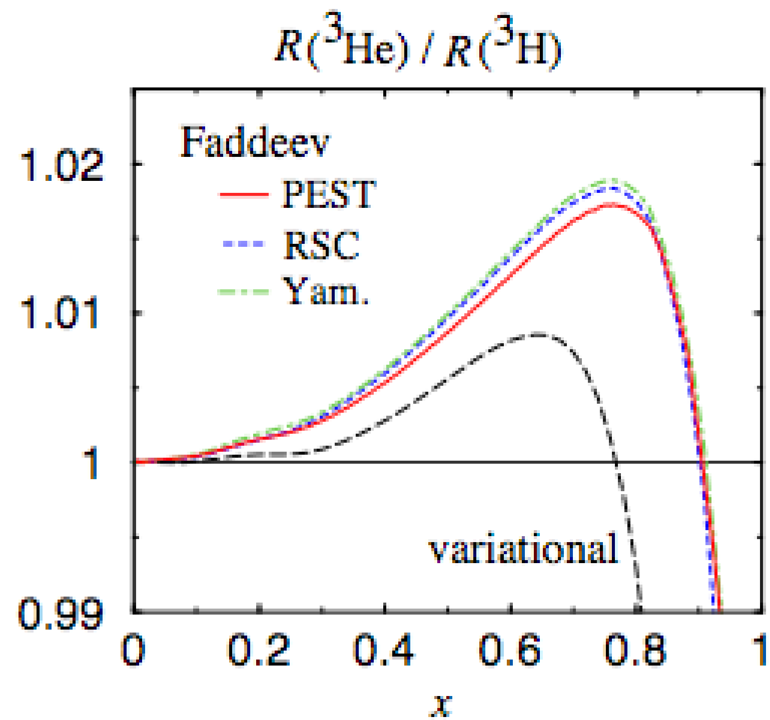
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

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



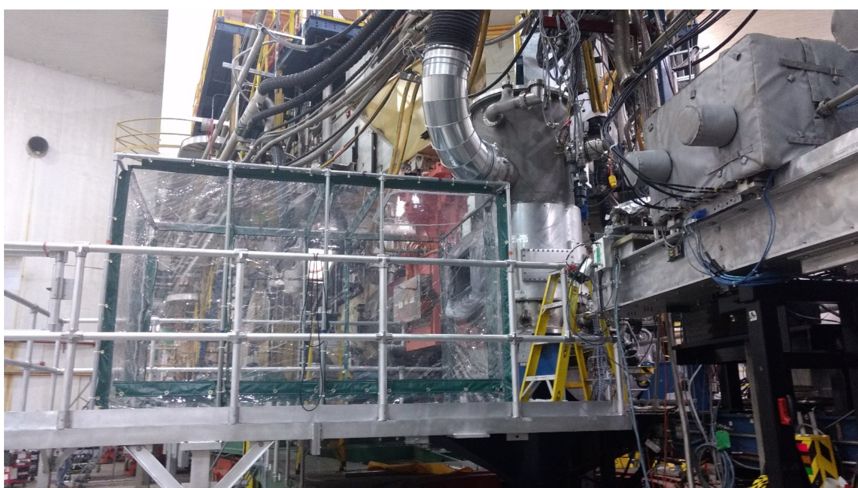
I. Afnan et al, PRC 68 (2003)

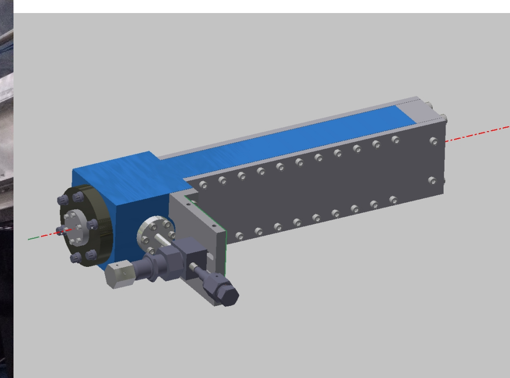


Hall A Tritium Target first in over 3 decades!!

Lab	Year	Quantity (kCi)	Thickness (g/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**

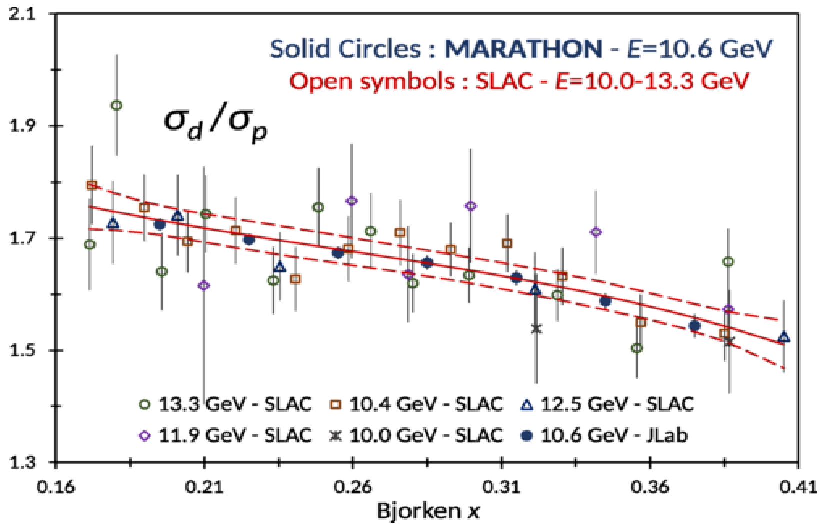
JLab Luminosity ~ 2.0×10^{36} tritons/cm²/s

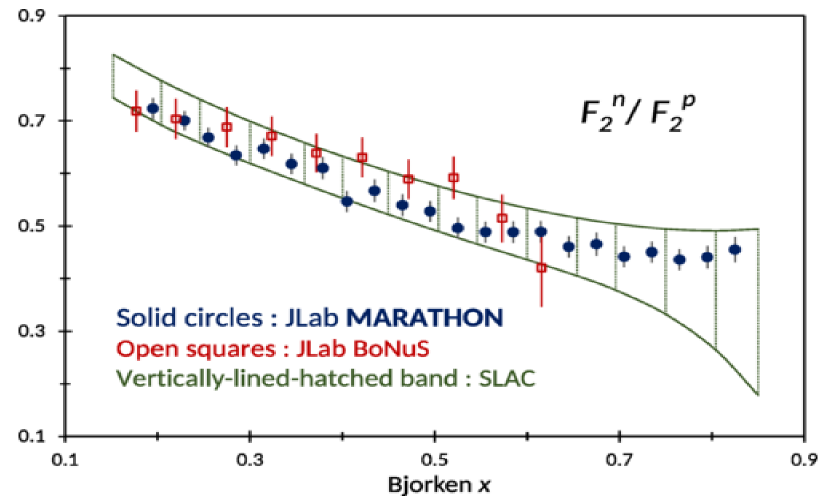


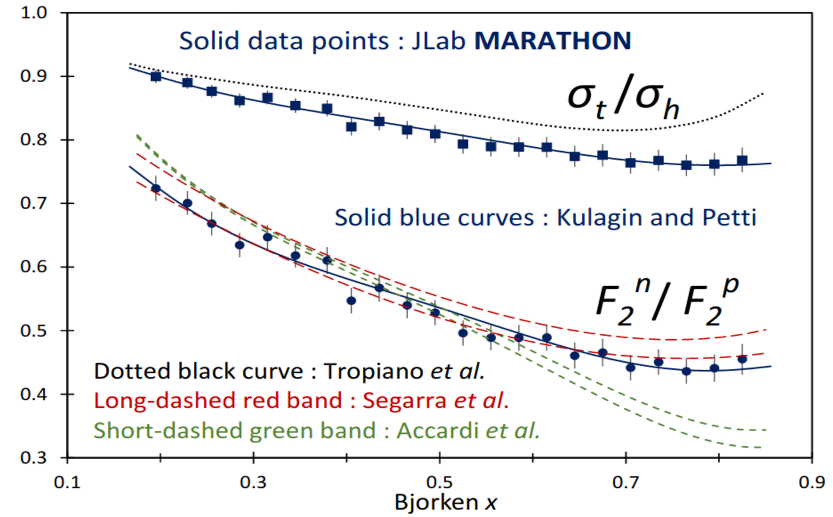


MARATHON Results (D. Abrams et. al. PRL 129, 132003 (2022))

See H. Liu talk next up!







→ **MARATHON F2n / F2p data consistent with BONuS at 6 GeV, with smaller uncertainties and extending to much larger x**

→ **Consistent with Kulagin-Petti Model, but in tension with CJ pdf at largest x**

But…. Tropiano et al. considered isospin dependent off-shell modifications

A. J. Tropiano, J. J. Ethier, W. Melnitchouk, and N. Sato Phys. Rev. C 99, 035201 (2019)

→ Consider 2 different isoscalar off-shell cor

- CTEQ-JLab (CJ)

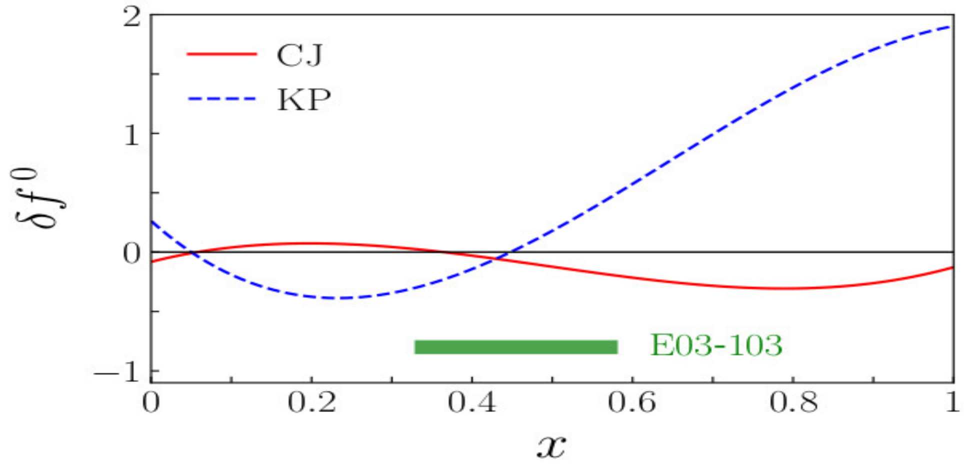
- Kulagin-Petti (KG)

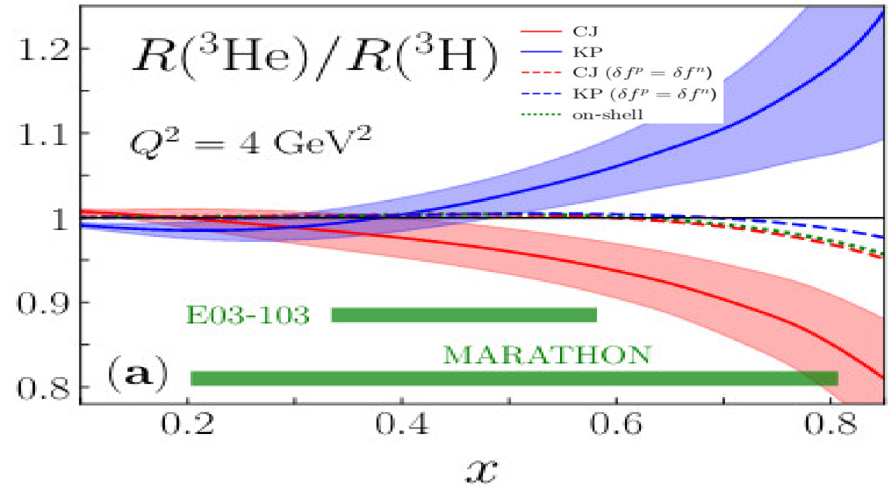
→ Fit ^{3}He/D ratios from JLab Hall C E03-103 t proton off-shell function. *Then the neutron is*

$$\delta f^n = \frac{1}{F_2^n}\left[(F_2^p + F_2^n)\delta f^0 - F_2^p\,\delta f^p\right]$$
$$= \delta f^0 - \frac{F_2^p}{F_2^n}(\delta f^p - \delta f^0).$$

- *Resulting super ratios have significar differences @ x>0.6*

$$R_{3H} = \frac{F_2^{3H}}{2F_2^n + F_2^p} \quad R_{3He} = \frac{F_2^{3He}}{F_2^n + 2F_2^p}$$

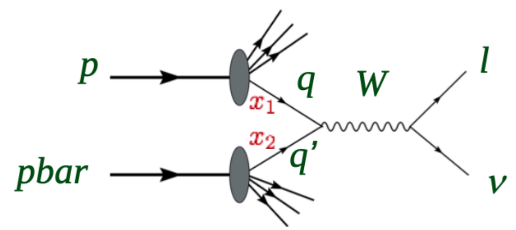




*Such and effect can **not** be unambiguously disentangled from F_2^n with A=3 inclusive data.* (see also C. Cocuzza et al., *Phys.Rev.Lett.* 127 (2021

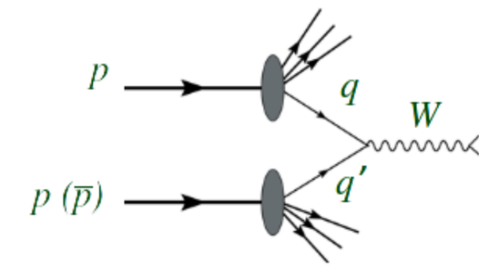
d(x) at Large x: Constraints

The whole is greater than the sum of the parts.



D0, CDF (RHIC, LHCb) asymmetries

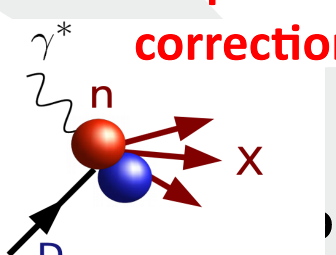
- Direct sensitivity to d(x)
- High W, Q
- **Small data set**



d(x)
+ nuclear
dynamics

Deep inelastic deuterium

- Large body of data from multiple experiments
- Extensive range in x and Q^2
- **Requires deuteron nuclear corrections – and precision**



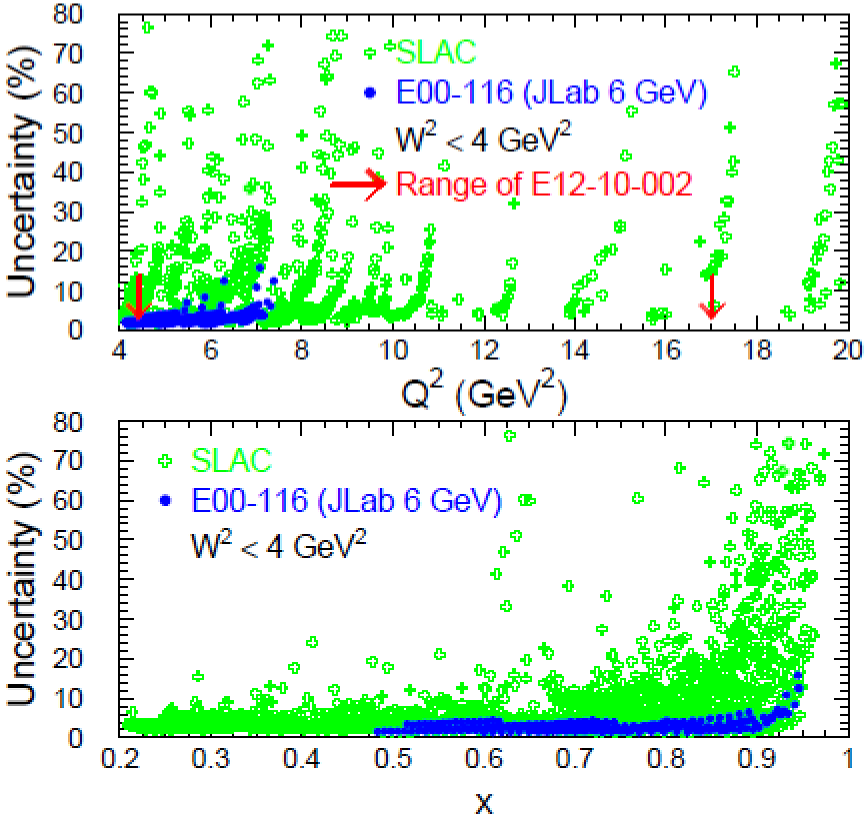
Nuclear target approaches

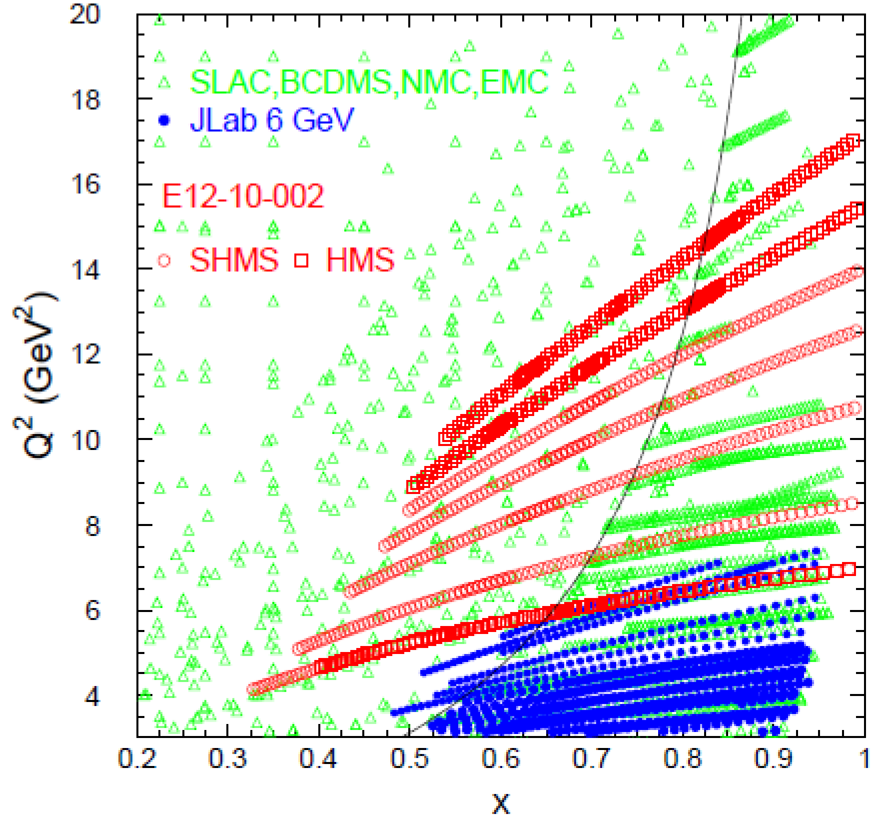
- **Nearly** model-independent *neutron* data from BONuS **obtained in 6 GeV JLab era at low W, Q**
- MARATHON 12 GeV extends range, **nuclear correction questions**
- Two experiments to verify TDIS technique at 12 GeV

U.S. DEPARTMENT OF ENERGY | Office of Science
JSA

F_2^p & F_2^d Structure Functions from JLab Hall C

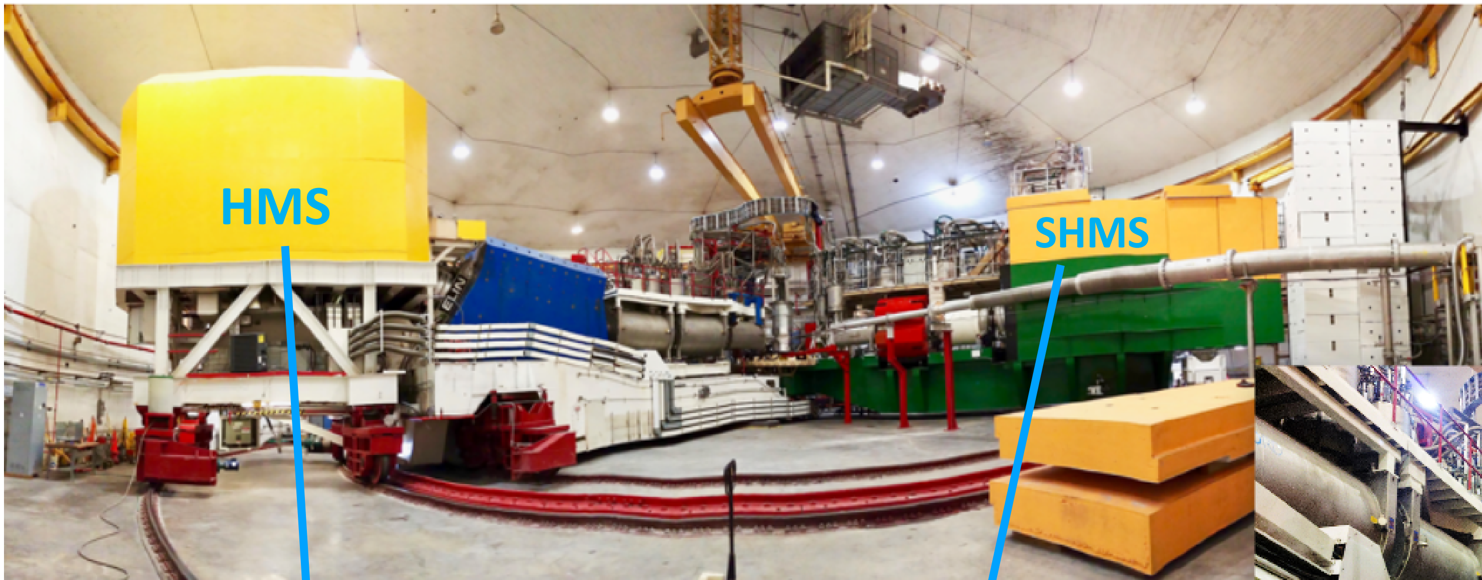
JLab12 Hall C commissioning experiment aimed to reduce uncertainties in F_2^p and F_2^d structure functions at large x and high Q^2



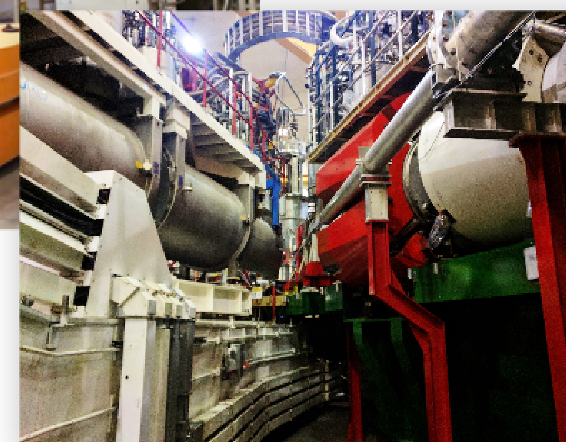


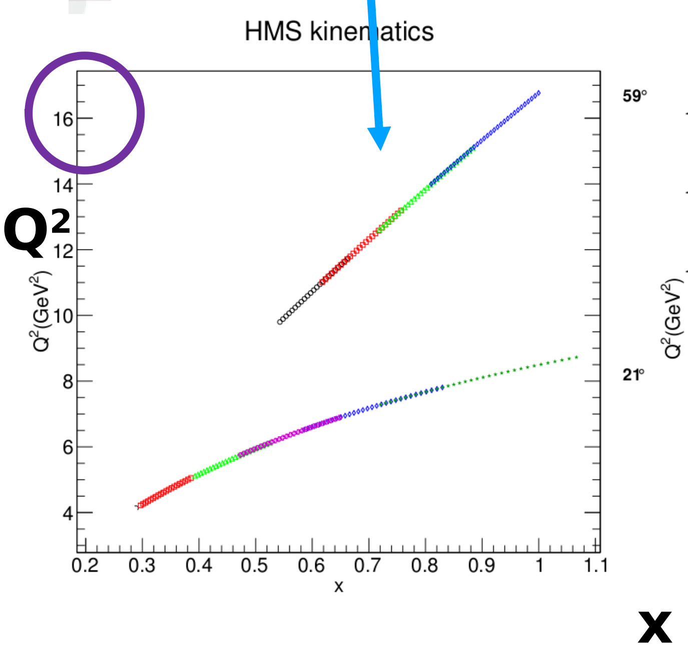
Goal @ 12 GeV: ~2% total precision cross sections, (as achieved previously @ 6 GeV)

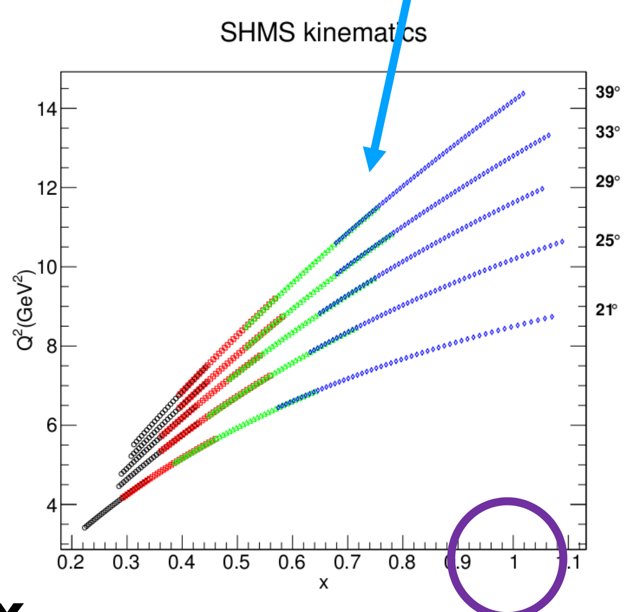
Hall C E12-10-002: High Precision Measurement of the F_2 Structure Function on p,D



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

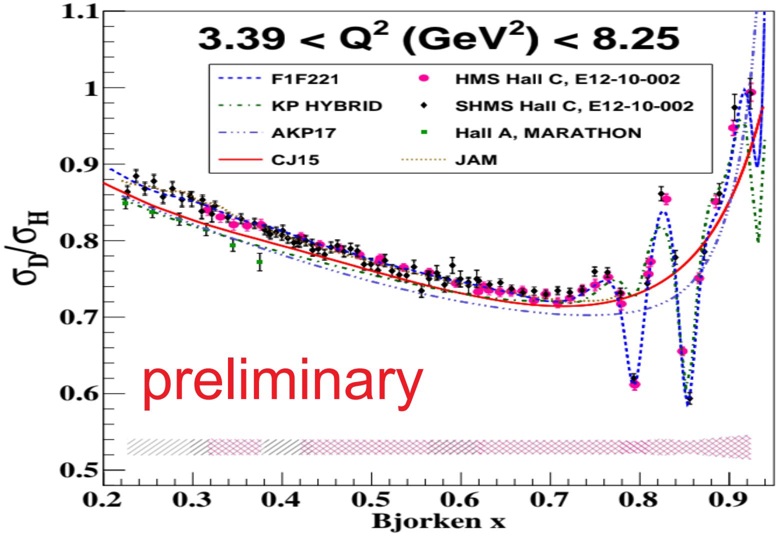


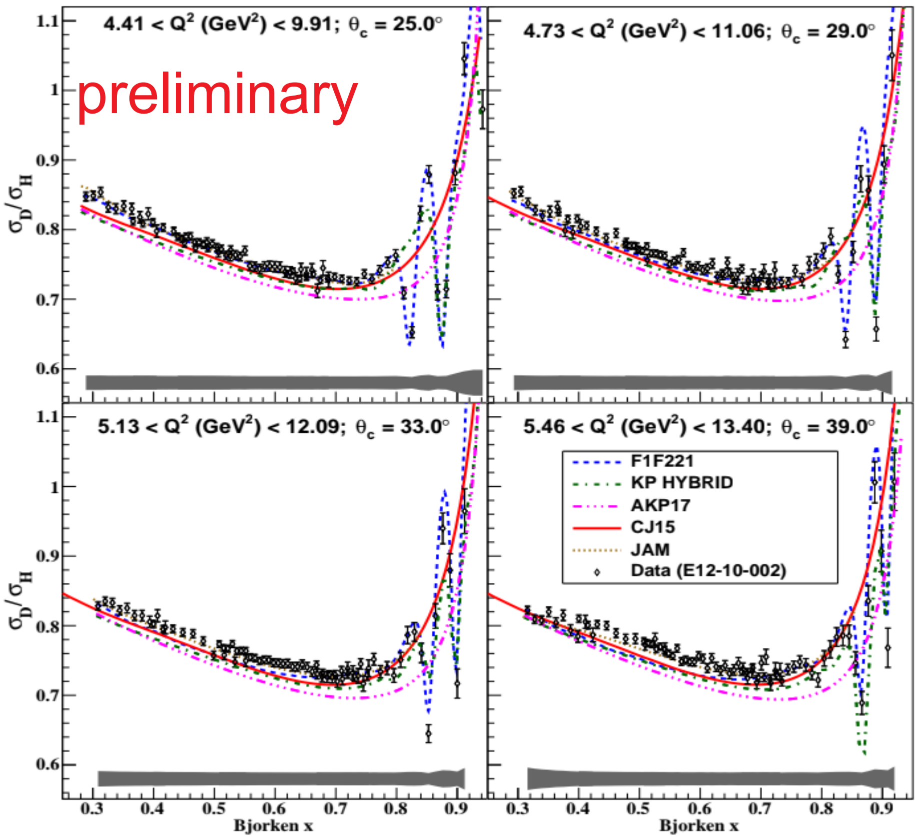




- Fix energy and angle
- Scan in momentum
- Effective scan in x
- Stringent check on spectrometer acceptance

First results from JLab Hall C E12-10-002



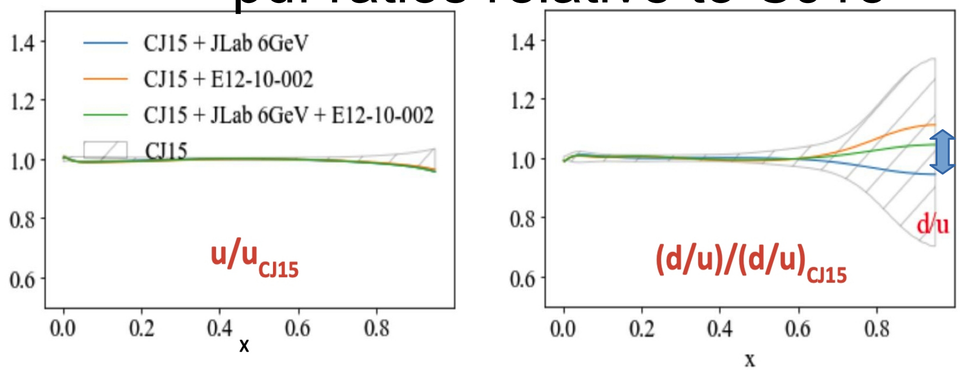


- Significant improvement in precision
- First publication in preparation

Preliminary CJ pdf Impact Studies

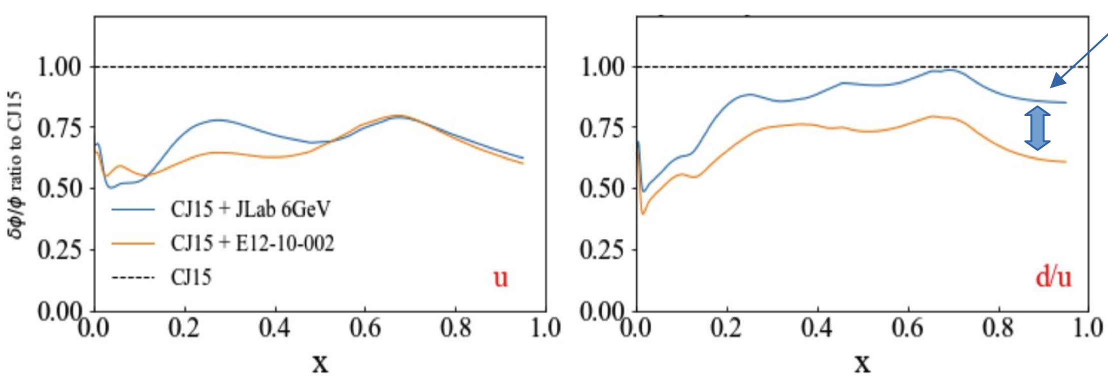
Studies courtesy of A. Accardi and Shujie Li

pdf ratios relative to CJ15



Including E12-10-002 changes d/u central value by **15-20%**

pdf uncertainty ratios relative to CJ15



Including E12-10-002 reduces uncertainty **~30%**

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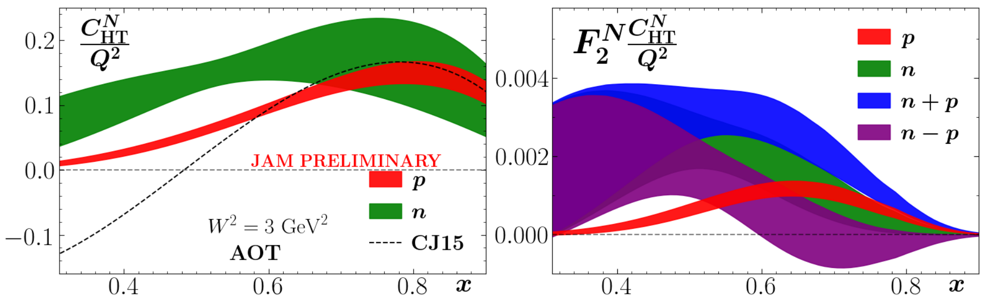
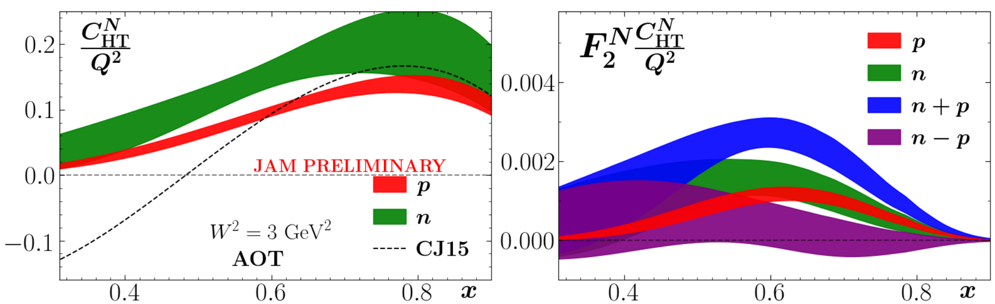
Preliminary JAM pdf Impact Studies

Studies courtesy of C. Cocuzza, W. Melnitchouk, N. Gonzalez

Without E12-10-002

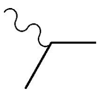


With E12-10-002

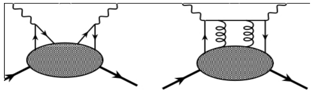


$$F_2(x,Q^2) = F_2^{\mathrm{LT}}(x,Q^2)\left(1+\frac{C_{\mathrm{HT}}(x)}{Q^2}\right)$$

Leading-twist
pQCD evolution



Higher-twist
eg. Quark-quark correlations



- Inclusion of E12-10-002 significantly reduces uncertainty for neutron H-T

=> reduction in d-quark uncertainty

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Also! Polarized predictions for d/u structure at large x

Proton Wavefunction (Spin and Flavor Symmetric)

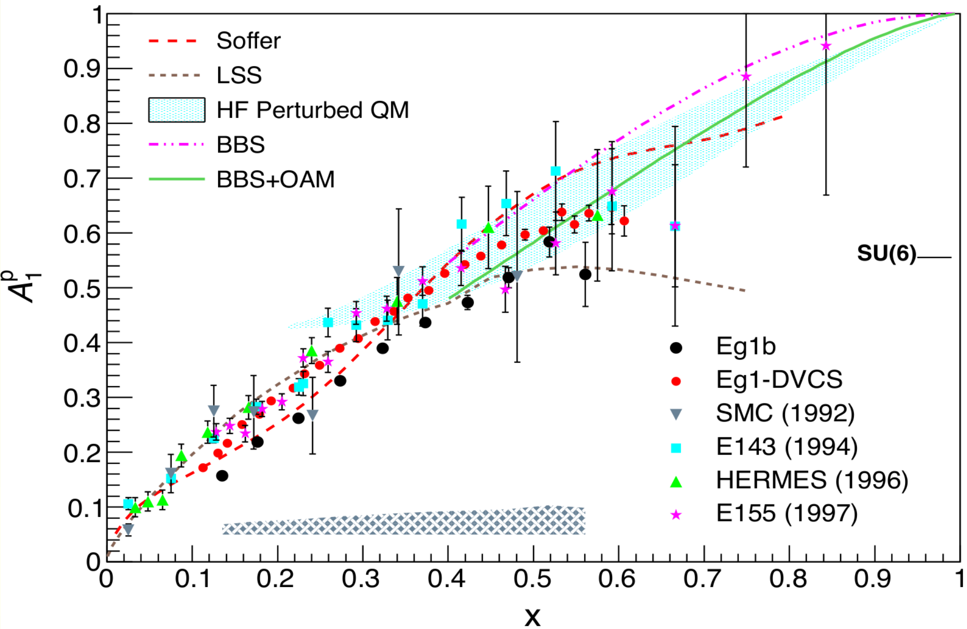
$$\left| p\uparrow \right\rangle = \frac{1}{\sqrt{2}}\left| u\uparrow (ud)_{S=0} \right\rangle + \frac{1}{\sqrt{18}}\left| u\uparrow (ud)_{S=1} \right\rangle - \frac{1}{3}\left| u\downarrow (ud)_{S=1} \right\rangle$$

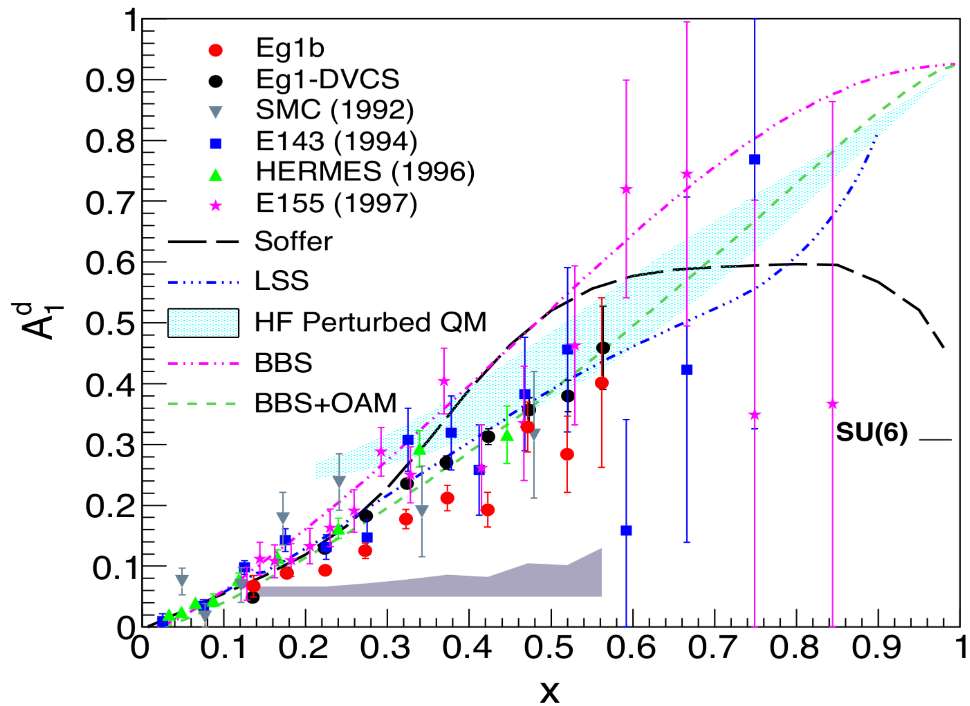
$$- \frac{1}{3}\left| d\uparrow (uu)_{S=1} \right\rangle - \frac{\sqrt{2}}{3}\left| d\downarrow (uu)_{S=1} \right\rangle$$

Model	F_2^n/F_2^p	d/u	Δ u/u	Δ 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

Existing World Data on Spin Structure at High X

(thanks Xiaochao!)





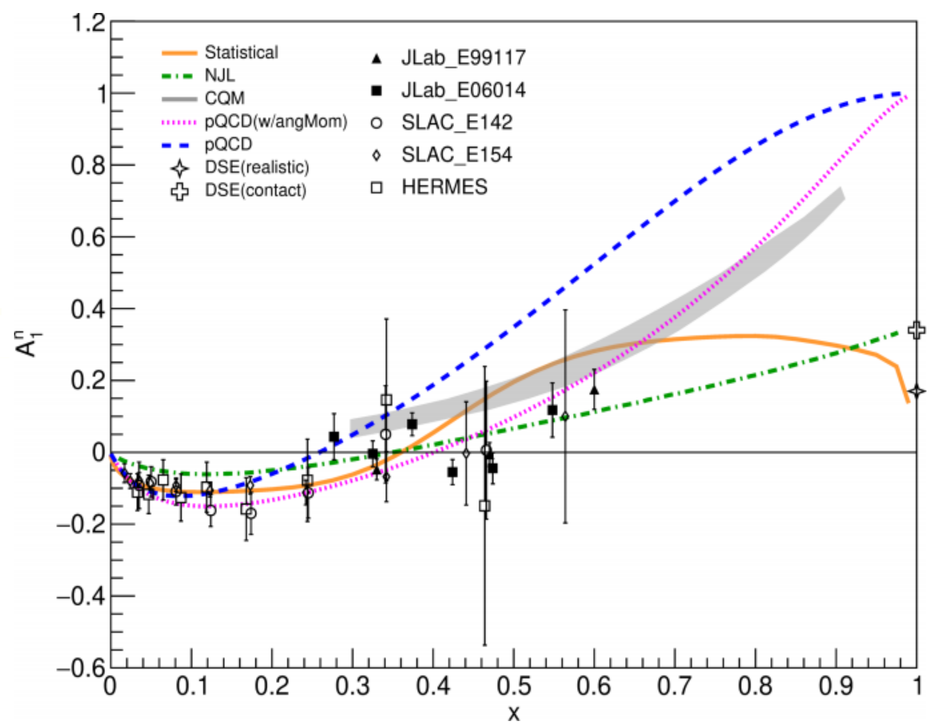


Figure credit: D. Flay

D. Parno et al. Phys.Rev.Lett. 113 (2014) 2, 022002, 1404.4003

Existing World Data on Spin at High X

$$\frac{\Delta u+\Delta\bar{u}}{u+\bar{u}}=\frac{4}{15}\frac{g_1^p}{F_1^p}(4+R^{du})-\frac{1}{15}\frac{g_1^n}{F_1^n}(1+4R^{du})$$

$$\frac{\Delta d+\Delta\bar{d}}{d+\bar{d}}=\frac{-1}{15}\frac{g_1^p}{F_1^p}\left(1+\frac{4}{R^{du}}\right)+\frac{4}{15}\frac{g_1^n}{F_1^n}\left(4+\frac{1}{R^{du}}\right)$$

$$R^{du}=\frac{d+\bar{d}}{u+\bar{u}}$$

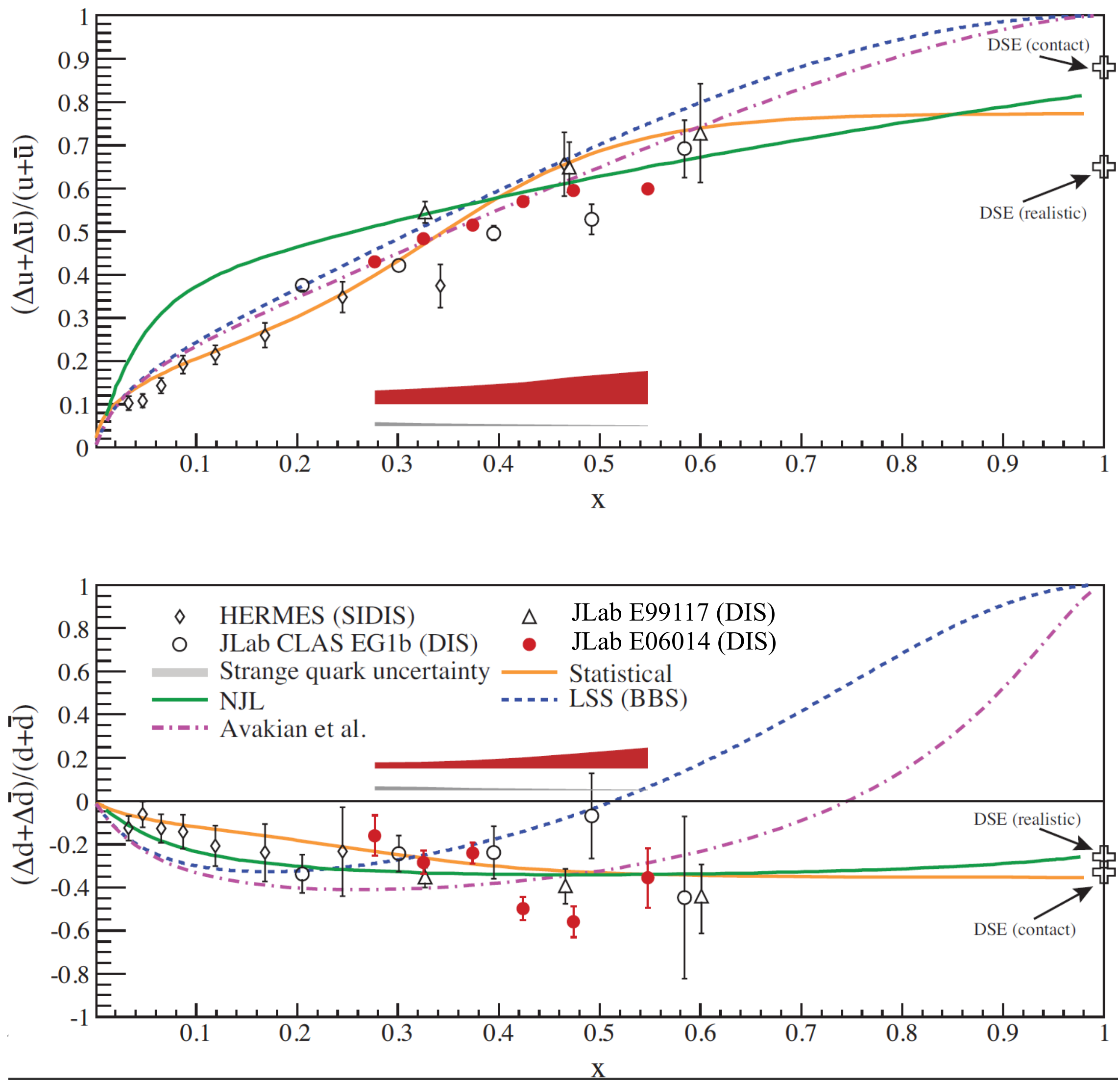
D. Parno et al.

PRL 113 (2014) 2, 022002, 1404.4003

X. Zheng et al.

PRL 92 (2004) 012004, arXiv: nucl-ex/0308011;

PRC 70 (2004) 065207, arXiv: nucl-ex/0405006.



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JLab 12 GeV A_1^n E12-06-110 (Hall C)

- First experiment in Hall C's 12 GeV era to utilize polarized beam
- 10.4 GeV beam, 85% polarization
- HMS and SHMS detecting electrons in the inclusive mode
  - both at 30 deg to reach high x
- First time polarized 3He target is installed in Hall C
  - achieved 30 uA beam incident on 40-cm long target, with 50-55% in-beam polarization
  - factor 2 increase in 3He target FOM vs. 6 GeV era

- Ran in Hall C from Nov 2019 to March 2020 (run group continued in July-Sept.2020)
- Spokespeople: J.P. Chen, G.D. Cates, Z.-E. Meziani, X. Zheng
- Grad students:
  - Mingyu Chen, Melanie Cardona
- Postdocs:
  - A. Tadepalli, W. Henry
  - M. Nycz, J. Zhang

One part of a broad 12 GeV spin structure program! Taking data in Hall B as we talk…!...

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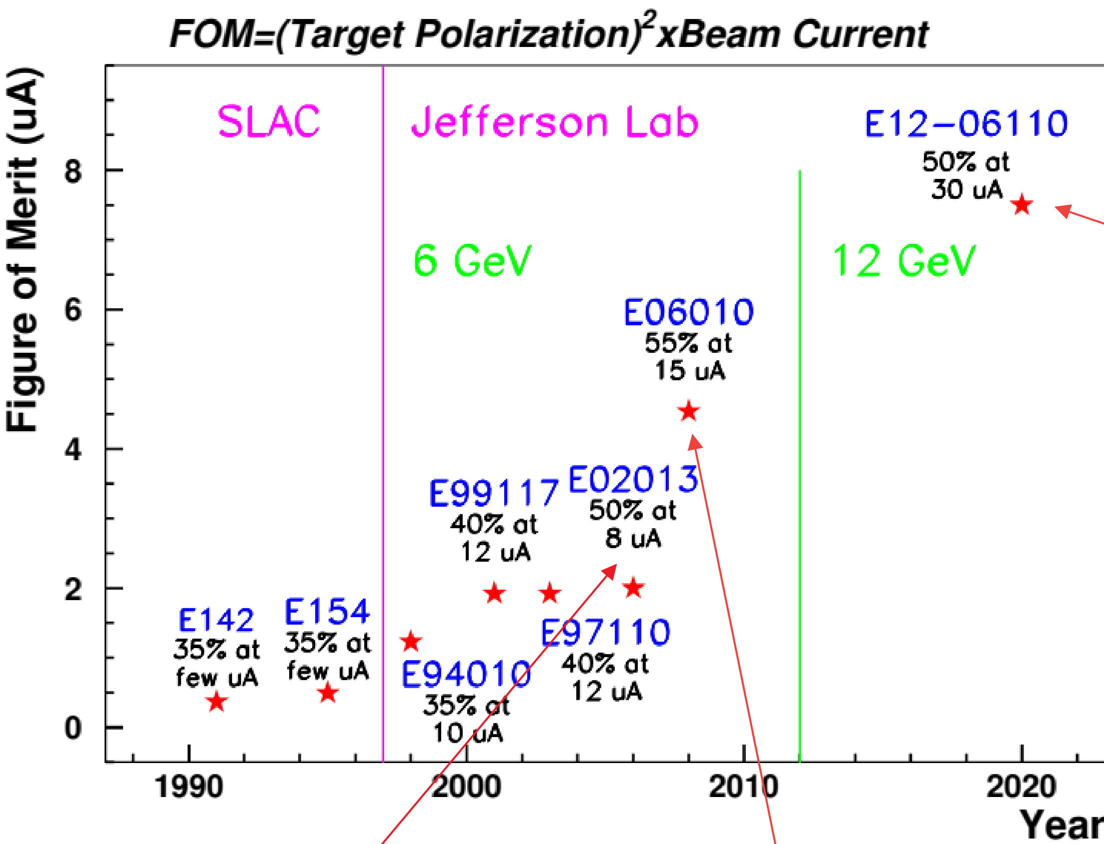
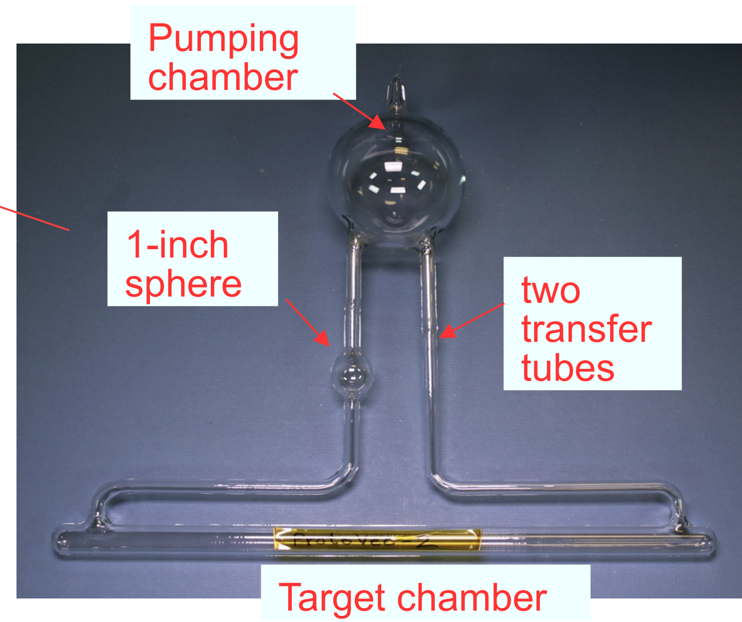
Polarized ^{3}He Target Performance Evolution





G_E^n (E02-013):
Started to use Rb/K hybrid alkali cell.

Transversity (E06-010):
Started to use narrow band laser.

12 GeV era Target Cell:

Convection Cell (replacing 6 GeV diffusion cells.)

GEn-II:
Expect another factor 2 increase in FOM (larger pumping chamber)

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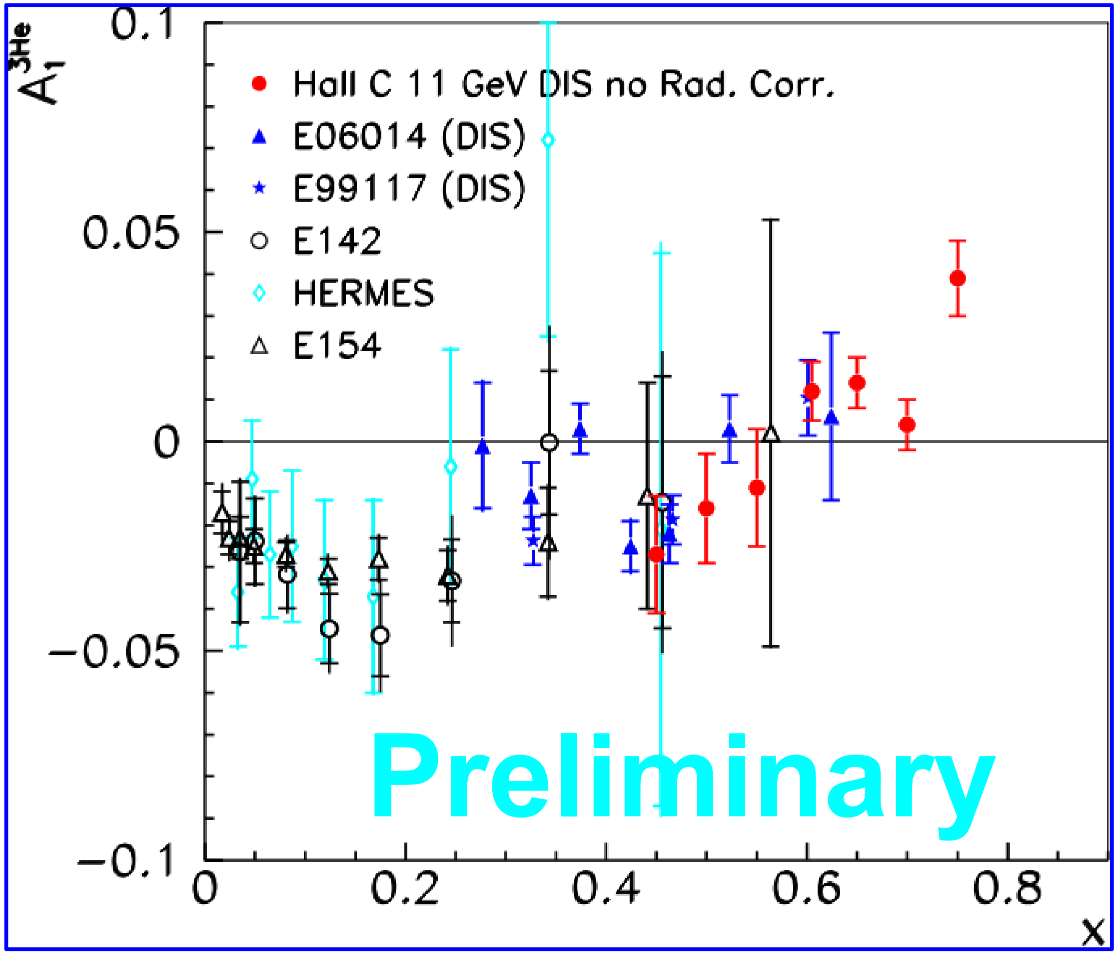
$$A_1 = \frac{1}{D(1+\eta\xi)} A_{\parallel} - \frac{\eta}{d(1+\eta\xi)} A_{\perp}$$

Preliminary $A_1(^3He)$ Results



These are **without** radiative corrections

statistical uncertainties only

Next to do:
- Radiative corrections
- finalizing all systematic uncertainties
- nuclear corrections

$$A_1^n = \frac{F_2^{3He}\left[A_1^{3He} - 2\frac{F_2^p}{F_2^{3He}} P_p A_1^p \left(1 - \frac{0.014}{2P_p}\right)\right]}{P_n F_2^n \left(1 + \frac{0.056}{P_n}\right)}$$

Near and Far-Future Projection including JLab 24 GeV

- 30 days of 22 GeV
- Projection using Hall C's
  - HMS @ 30 deg, 4.6 GeV
  - SHMS @ 20 deg, 7.8 GeV
- Polarized 3He target
  - 40cm, 50%, 30uA
- "F1F221 fit" for ^{3}He → neutron "nuclear correction"
- projections (12 and 24 GeV) plotted on pQCD

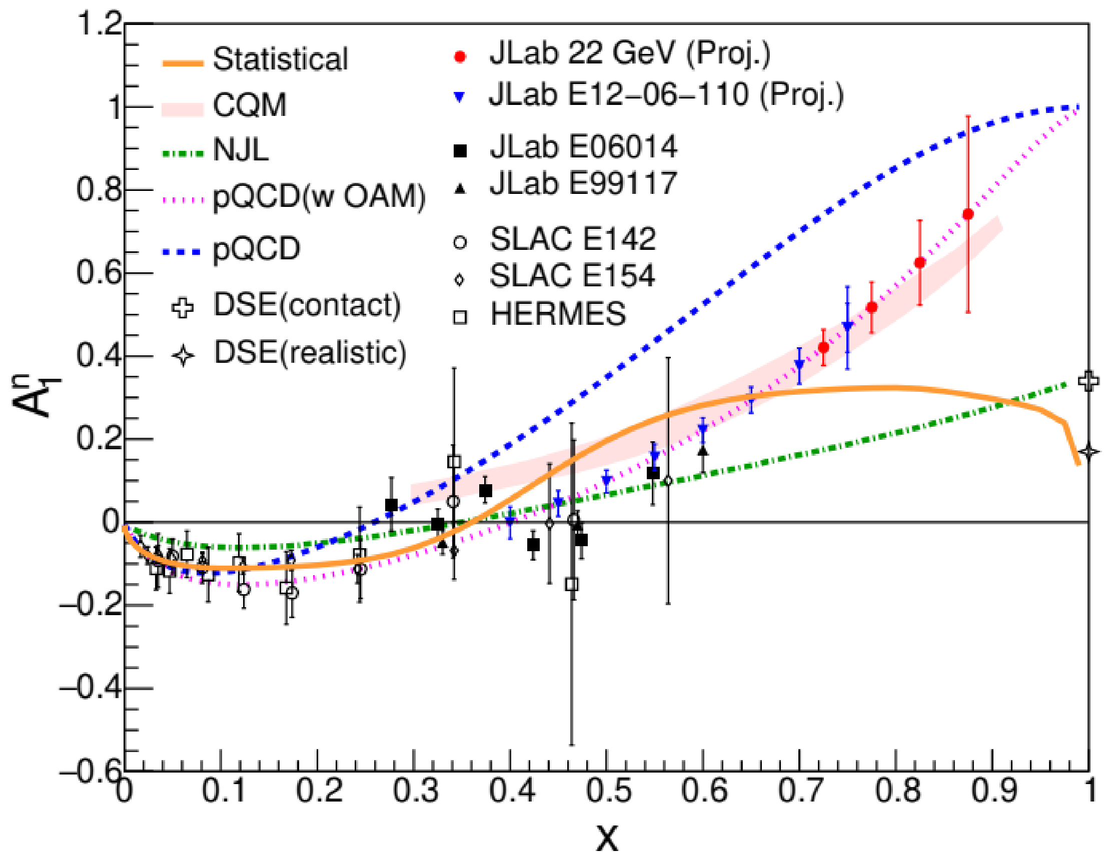


Figure credit:
Cameron Cotton (UVA/HUGS2021)
David Flay (JLab)

Similar x, Q extended range expected for unpolarized DIS, tagged and untagged

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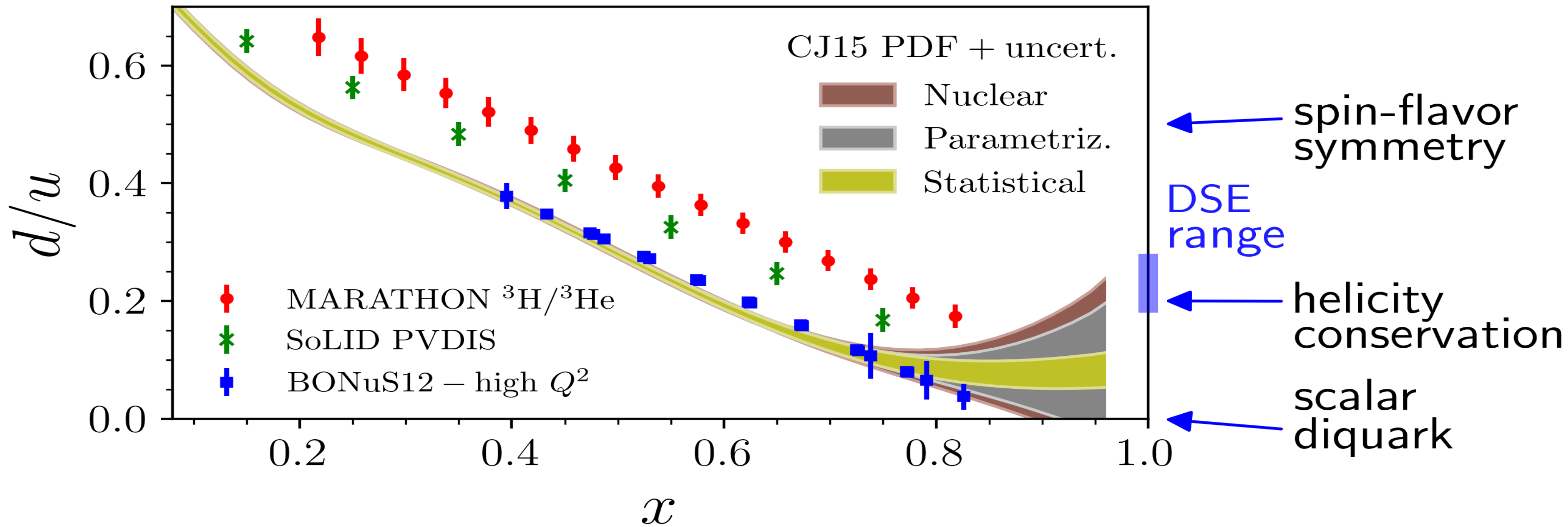
Multiple experimental efforts at JLab12 to determine *d/u* at high-*x*

- **MARATHON** - 3H / 3He mirror nuclei
- **SoLID PVDIS**
- **BONuS12** – proton spectator tagging

Also:
TDIS
Hall C F2p, F2d
(CJ, JAM)

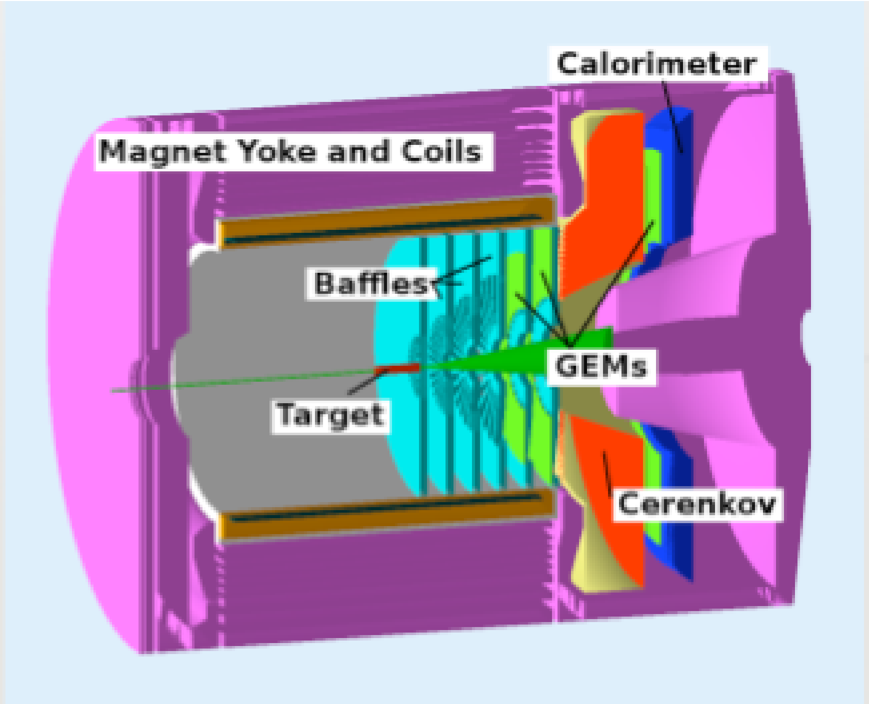
What is the unique role for SoLID here?



A. Accardi

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

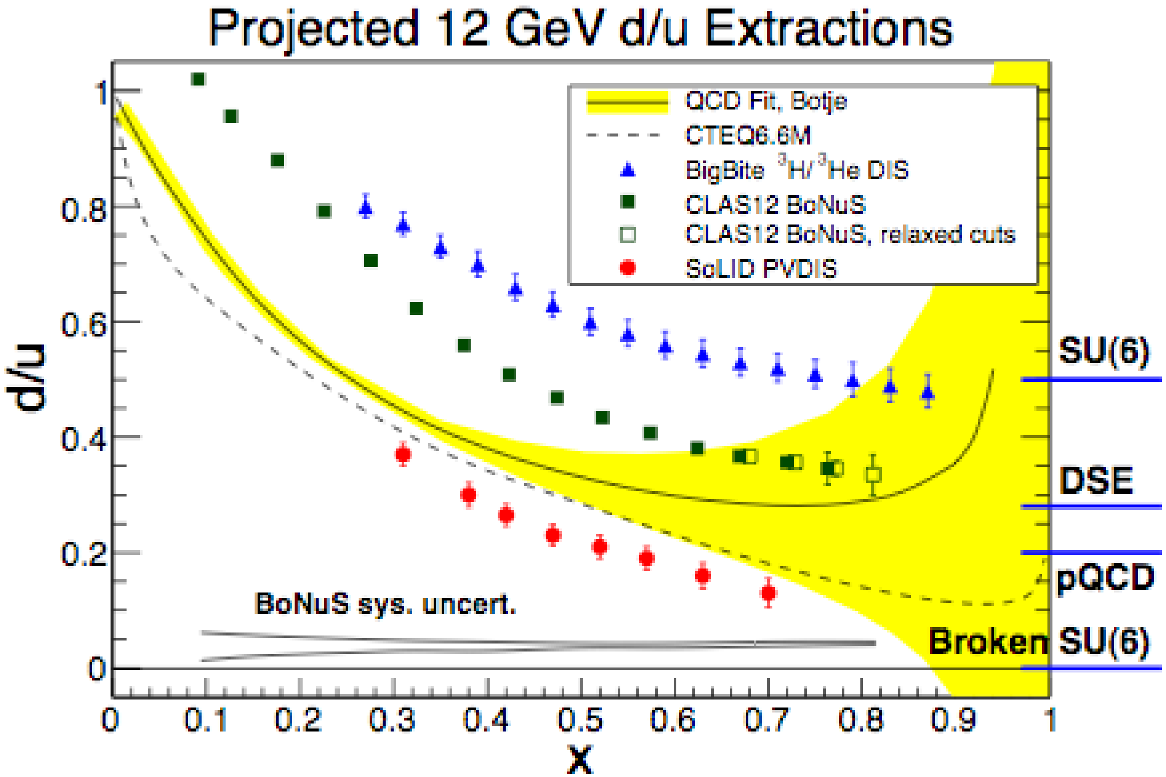
$$A_{\mathrm{PV}} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

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

Clean Measurement of d/u with PVDIS

For high x on proton target:

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



- The SoLID extraction of d/u is made directly from ep DIS: *no nuclear corrections*

Probing the Valence Regime: the role of SoLID

- SOLID PVDIS is ***the only*** d/u measurement that is ***nuclear effect free***
- BONuS still requires a deuteron target
  - SoLID will check BONuS technique
  - SoLID will thereby help to determine correct deuteron corrections
  - This can facilitate using the large global deuterium data set!
- The MARATHON results have been interpreted using different approaches to the nuclear effects in the A=3 nuclei. See, for example:

  Phys.Rev.Lett. 127 (2021) 24, 242001 and *Phys.Rev.Lett.* 128 (2022) 13, 132003
- A nuclear effect free measurement can provide information if there are (or are not) isoscalar off-shell effects
- SOLID will enable us to learn about nuclear effects in light nuclei by providing a testing ground for models of the MARATHON and BONUS data

  SoLID will provide a benchmark for precisely leveraging the beautiful MARATHON, BONuS, TDIS, F2d data to higher x

Thank You!