Measurement of the Neutron Spin Asymmetry in the Deep Valence Quark Region

Xiaochao Zheng

University of Virginia

September 25, 2023

- Motivation
- Jefferson Lab 12 GeV A_1^n (E12-06-110) in Hall C
  - → Preliminary $A_1(^3He)$ from E12-06-110
- Summary

For the JLab E12-06-110 Collaboration

Jefferson Lab

Motivation for Understanding the Nucleon Spin

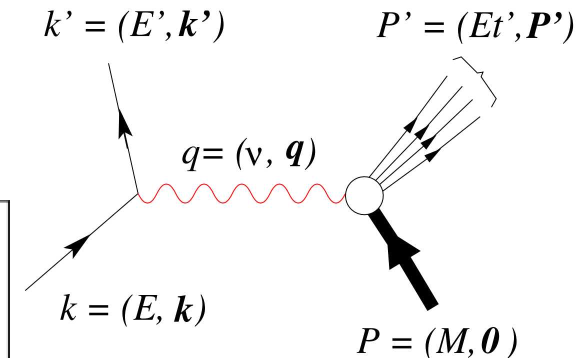
The scale of quarks and gluons is the limit to how far we've ever probed nature.

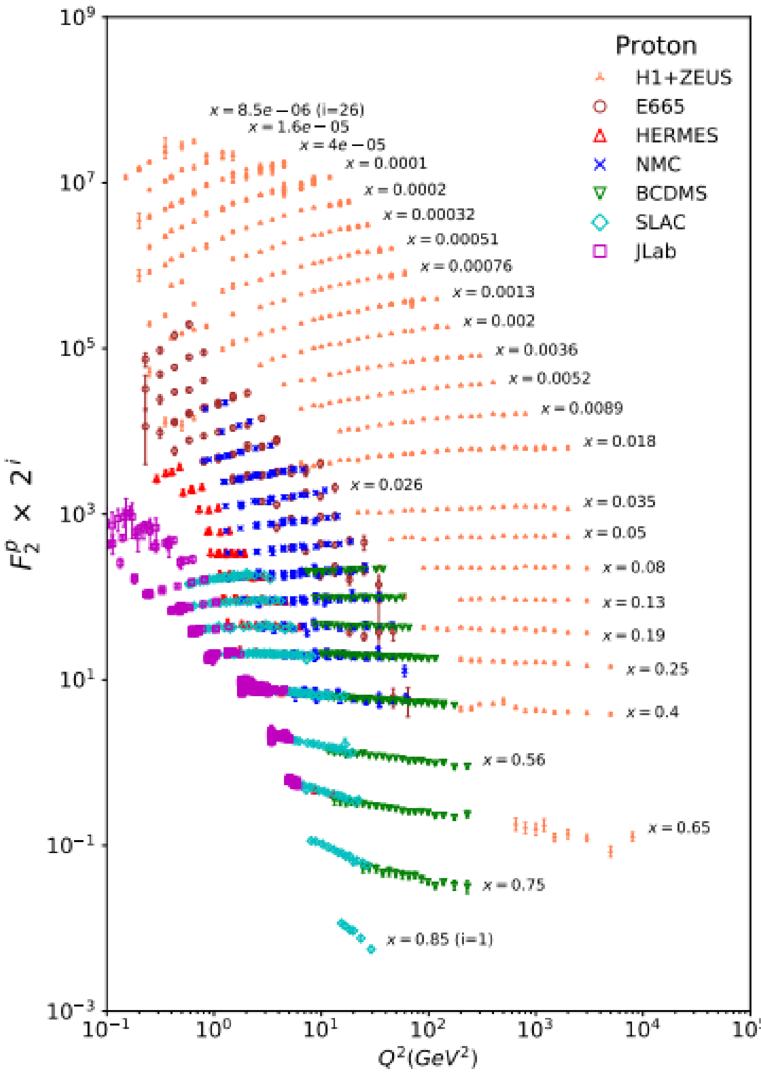
- How do quarks and gluons give rise to the properties (mass, spin) of the proton and the neutron?
- Can we explain the proton spin structure from QCD?

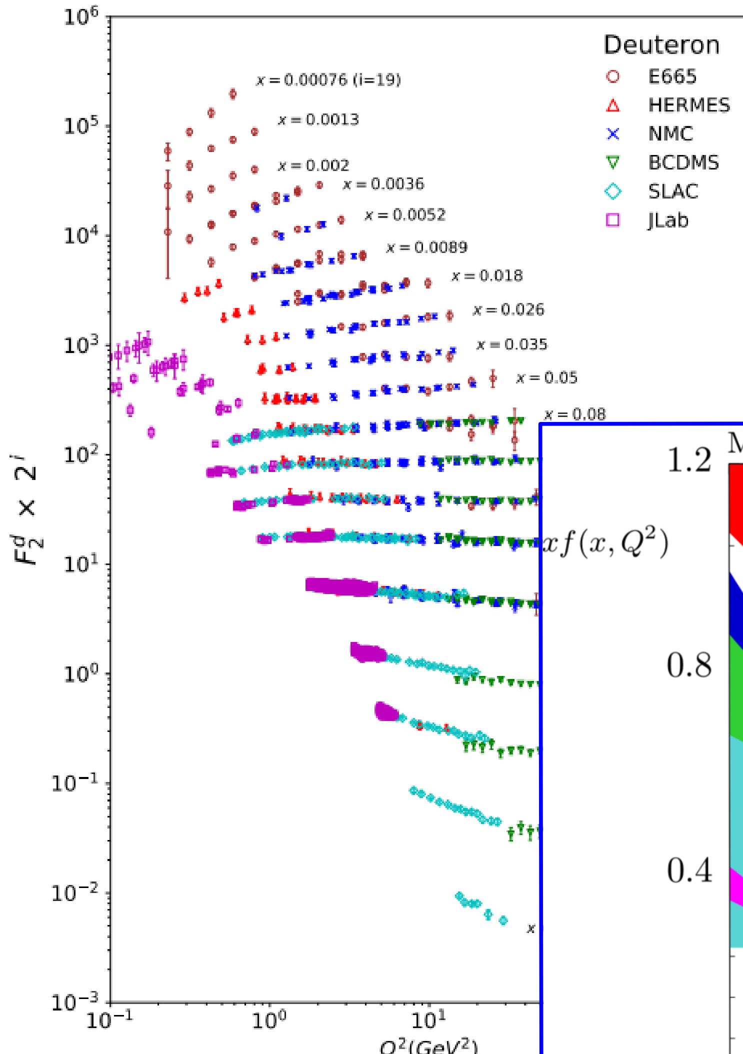
Magdalena Kowalska/CERN/ISOLDE team

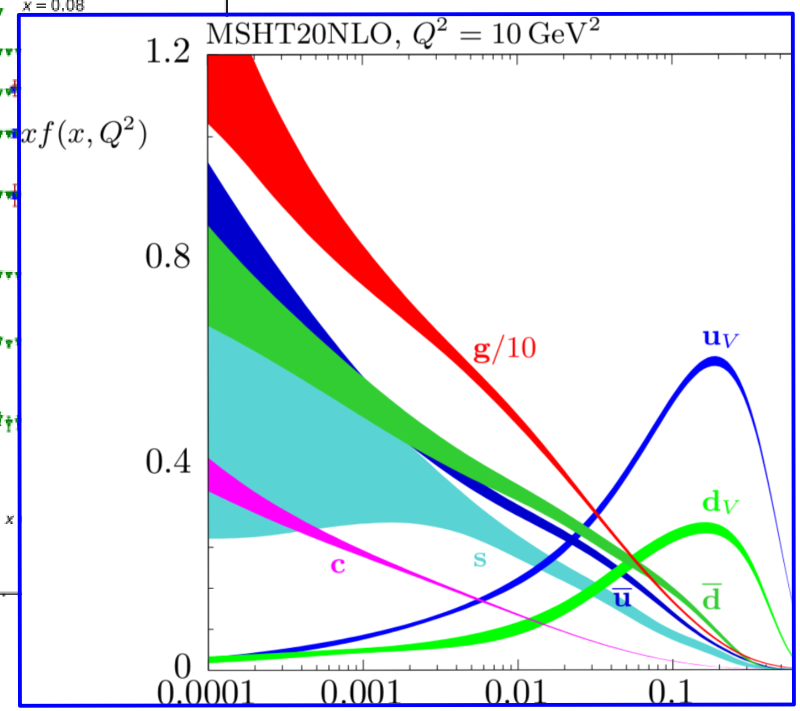
Inclusive Lepton Scattering Formalism (Unpolarized)

$$\frac{d^2\sigma_0}{d\Omega dE'} \propto \sigma_{Mott}\left[\alpha F_2(x,Q^2)+\beta F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$





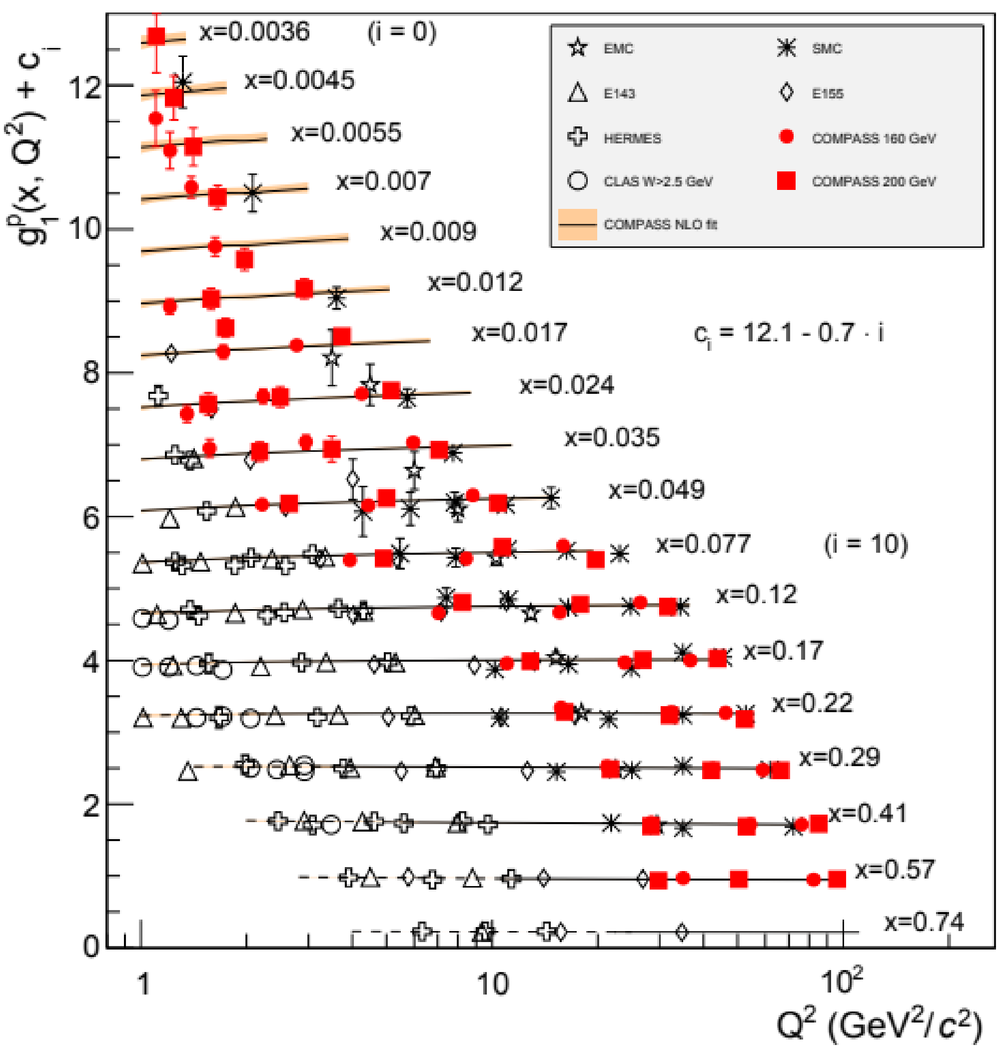


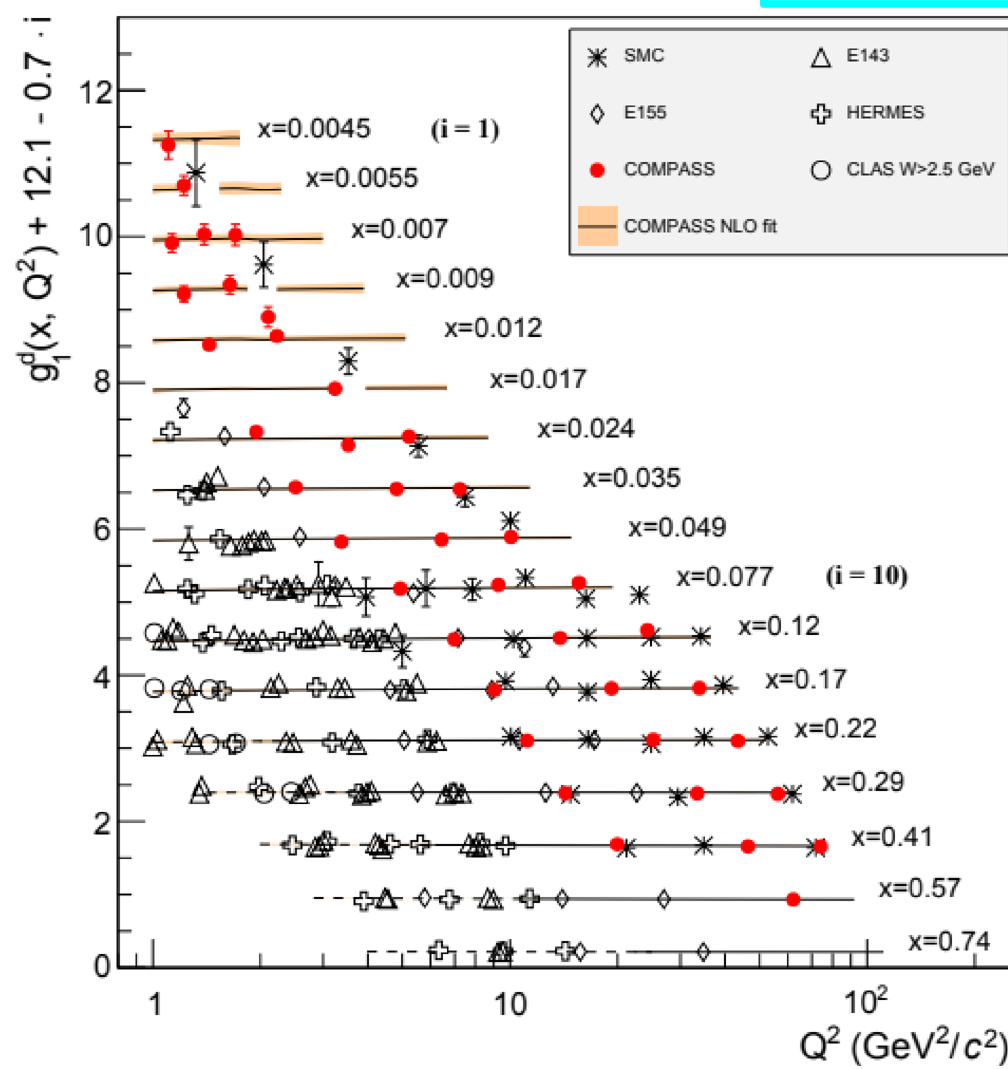


Inclusive Lepton Scattering Formalism (Polarized)

$$\frac{d^2\sigma^{\uparrow\downarrow}}{d\Omega\, dE'} - \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega\, dE'} \propto \sigma_{point\text{-}like}\left[\alpha' g_1(x, Q^2) + \beta' g_2(x, Q^2)\right]$$

now in PDG2022





https://academic.oup.com/ptep/article/2020/8/083C01/5891211

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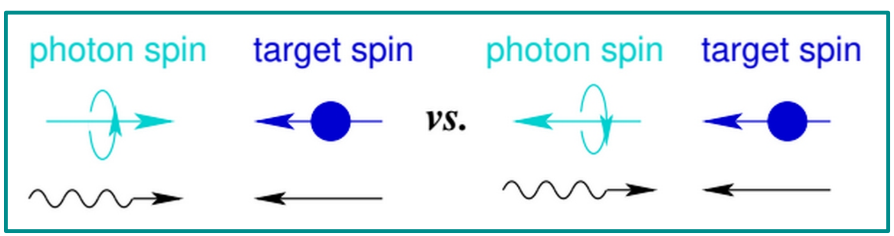
Spin at high x as part of the Nucleon Structure and QCD Study

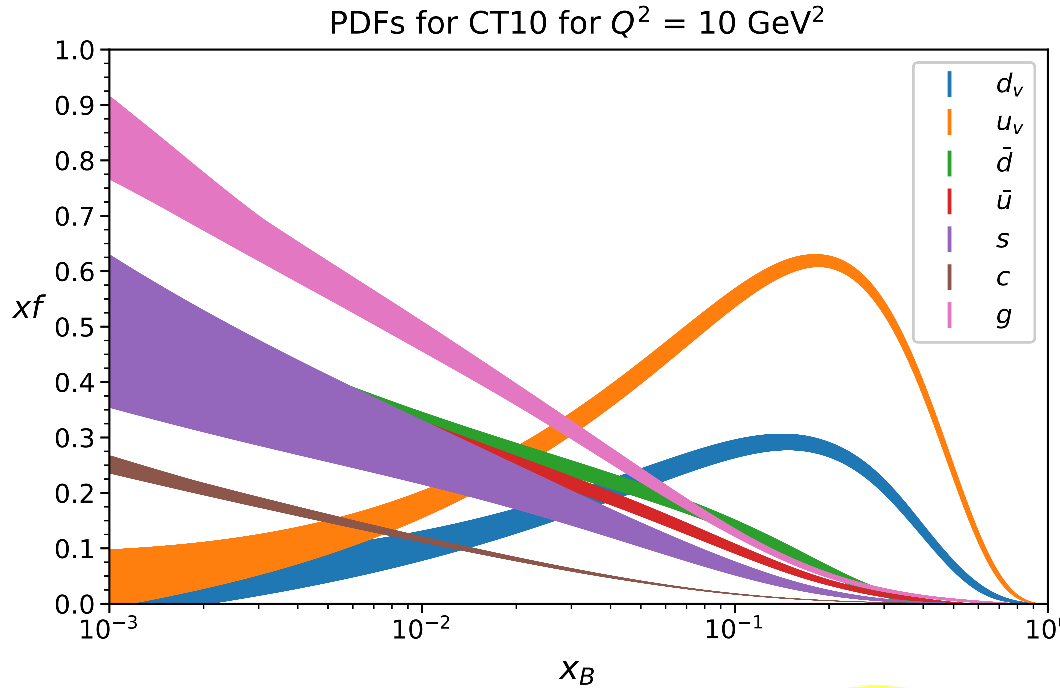
- In the deep valence quark region, we can make predictions for structure functions from a variety of models and theories.

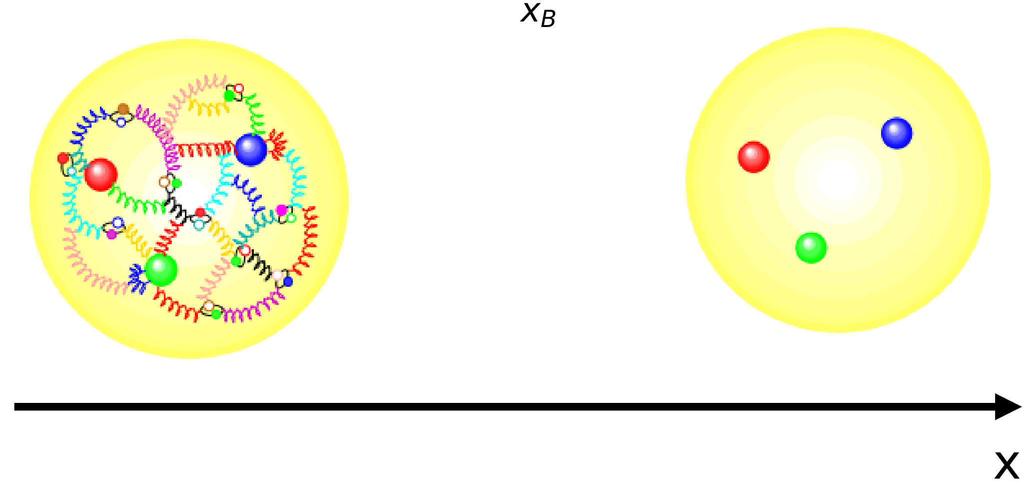
  - F_2^p/F_2^n and d/u
  - A_1^p, A_1^n , or $\Delta u/u$ and $\Delta d/d$

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$



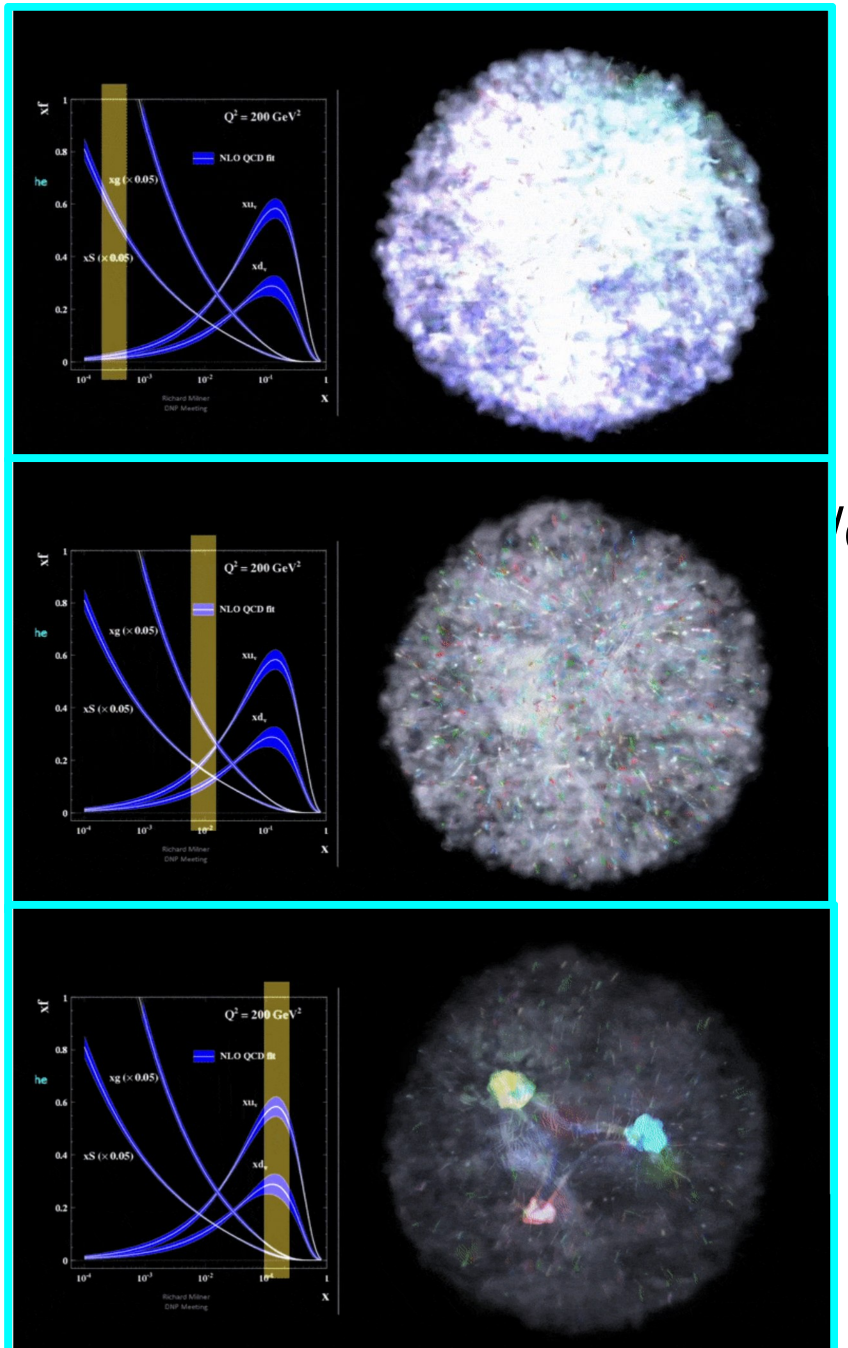
$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1}$$ at large Q^2

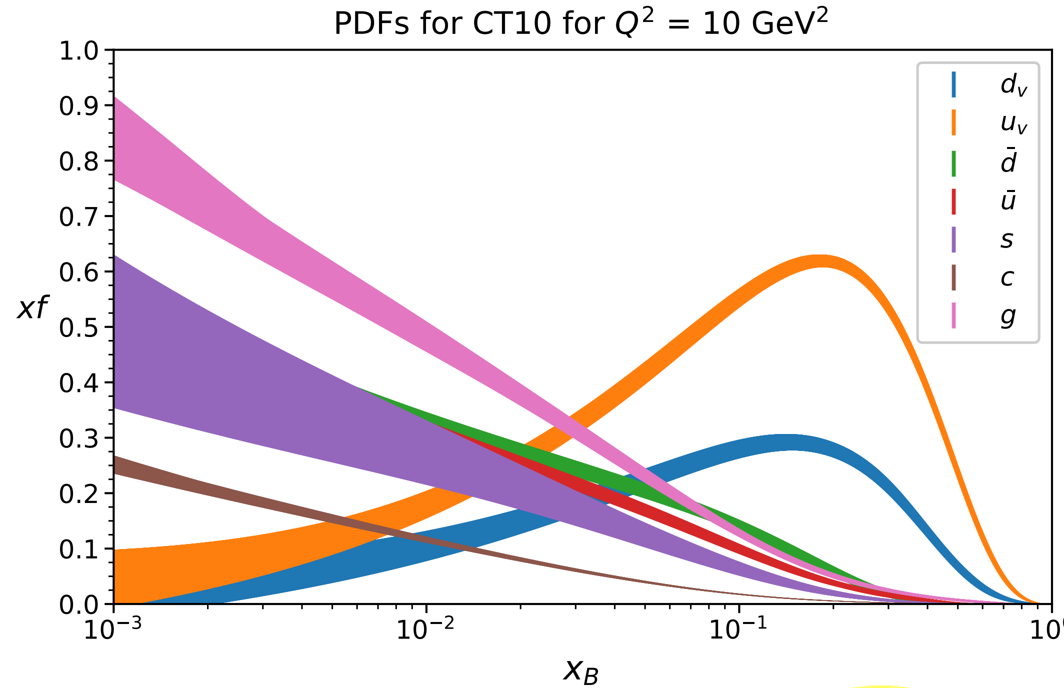


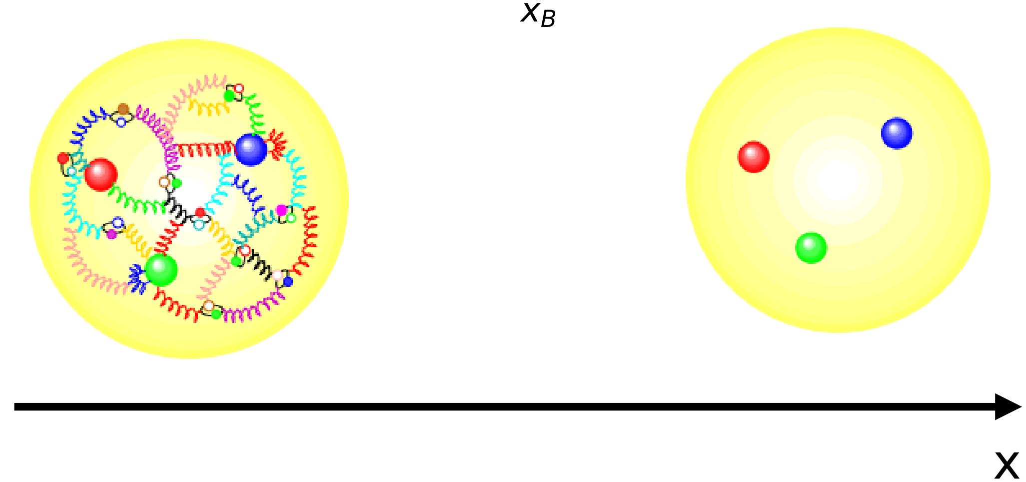


Jefferson Lab

Spin at high x as part of the Nucleon Structure and QCD Study







https://www.youtube.com/watch?v=Dt8FZ4ksWiY

https://arts.mit.edu/visualizing-the-proton/

Prediction on Polarized SF and PDF at high x

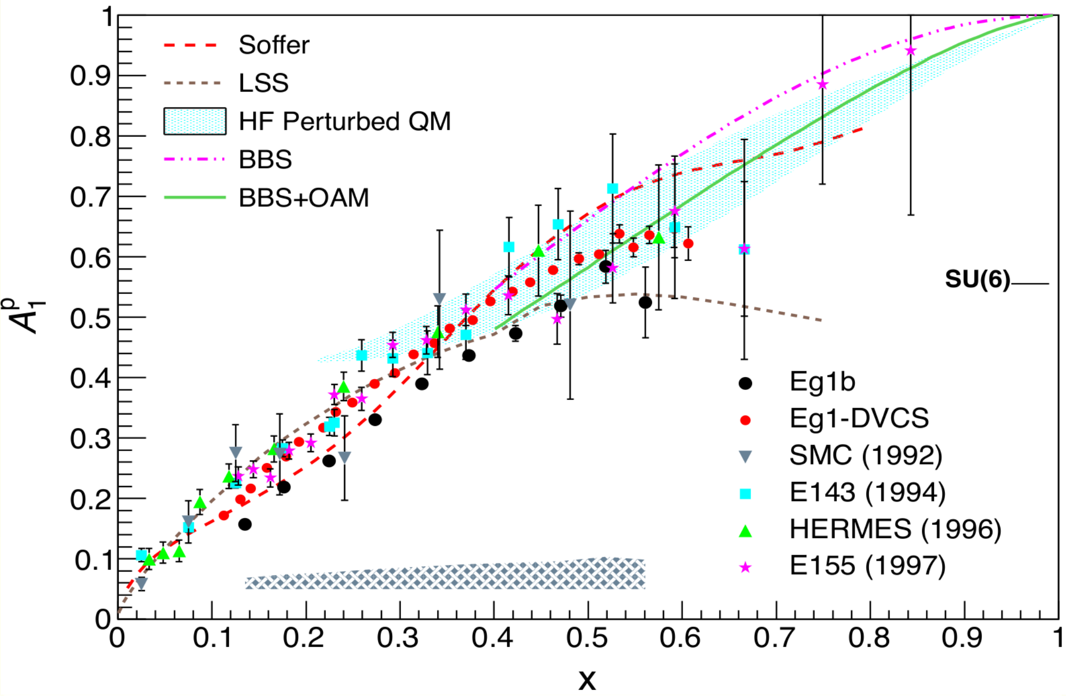
$$|p^{\uparrow}\rangle = \frac{1}{\sqrt{2}}|u^{\uparrow}(ud)_{00}\rangle + \frac{1}{\sqrt{18}}|u^{\uparrow}(ud)_{10}\rangle - \frac{1}{3}|u^{\downarrow}(ud)_{11}\rangle - \frac{1}{3}|d^{\uparrow}(uu)_{10}\rangle - \frac{\sqrt{2}}{3}|d^{\downarrow}(uu)_{11}\rangle$$

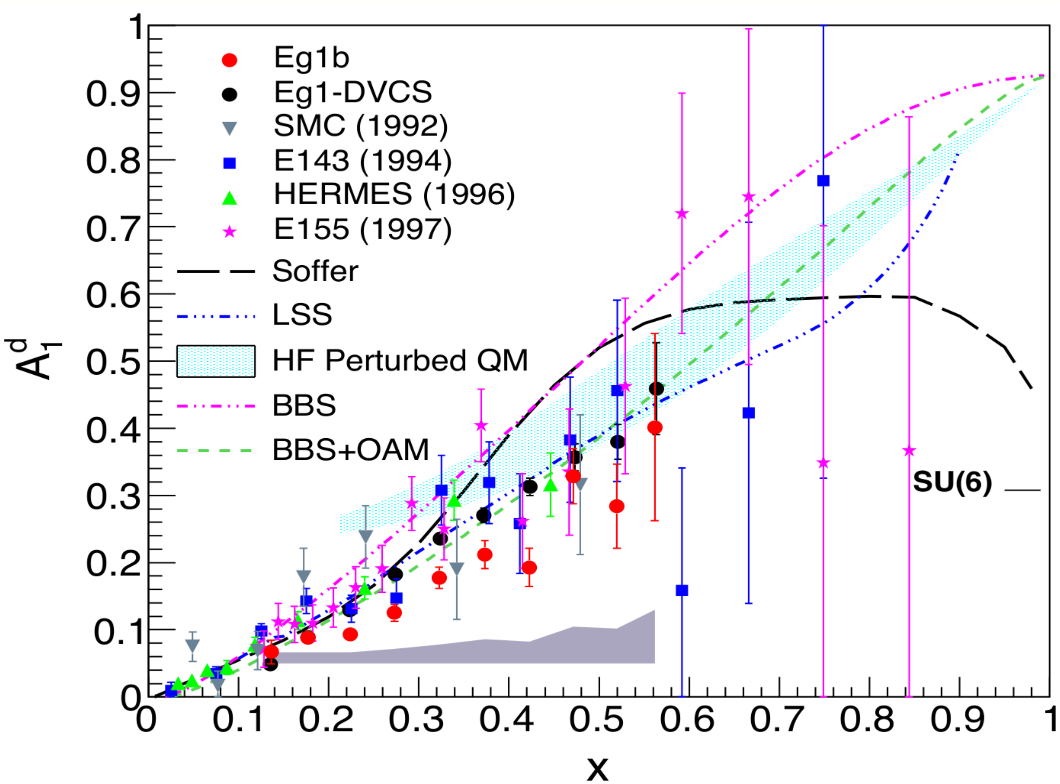
	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-1	0.49	0.28	−0.11	0.65	−0.26	0.17	0.59
DSE-2	0.41	0.18	−0.07	0.88	−0.33	0.34	0.88
$0^+_{[ud]}$	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	−0.06	0.80	−0.25	0.35	0.77
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
CQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{3}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1

Table 1: Selected predictions for the $x = 1$ value of the indicated quanti-

C. Roberts, R.Holt, S. Schmidt, Phys. Lett. B 727 (2013) 249. arxiv: 1308.1236

Existing World Data on Spin Structure at High X





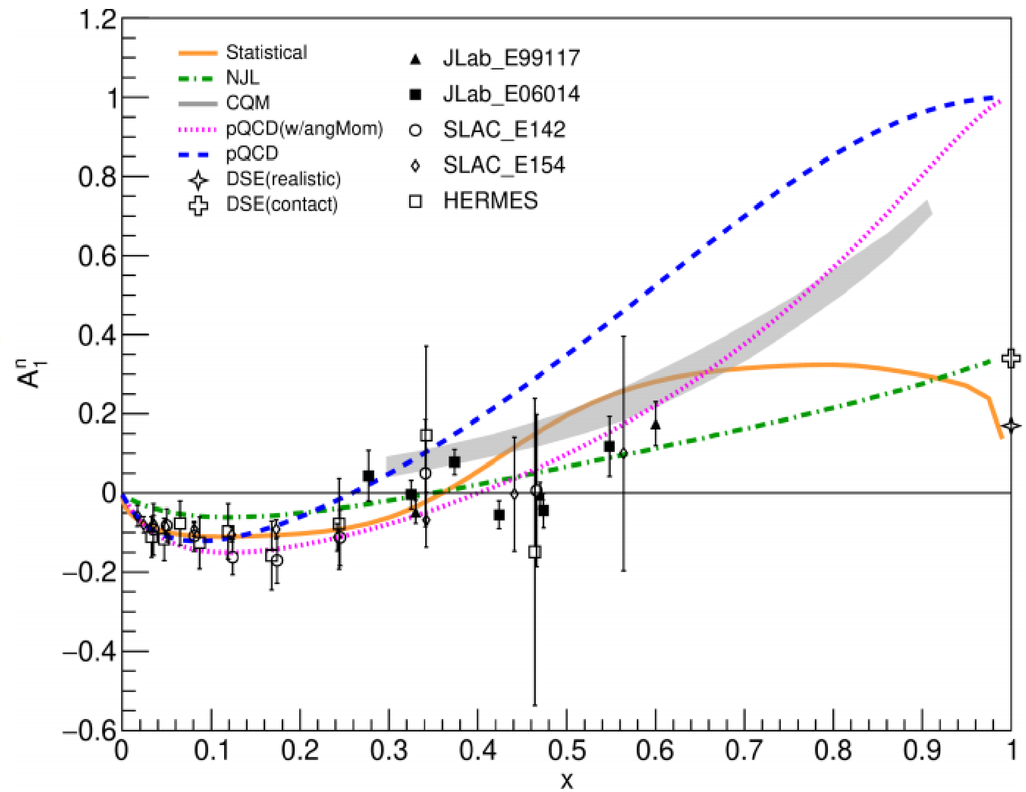


Figure credit: D. Flay

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

Existing World Data on Spin at High X

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

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

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

D. Parno et al.

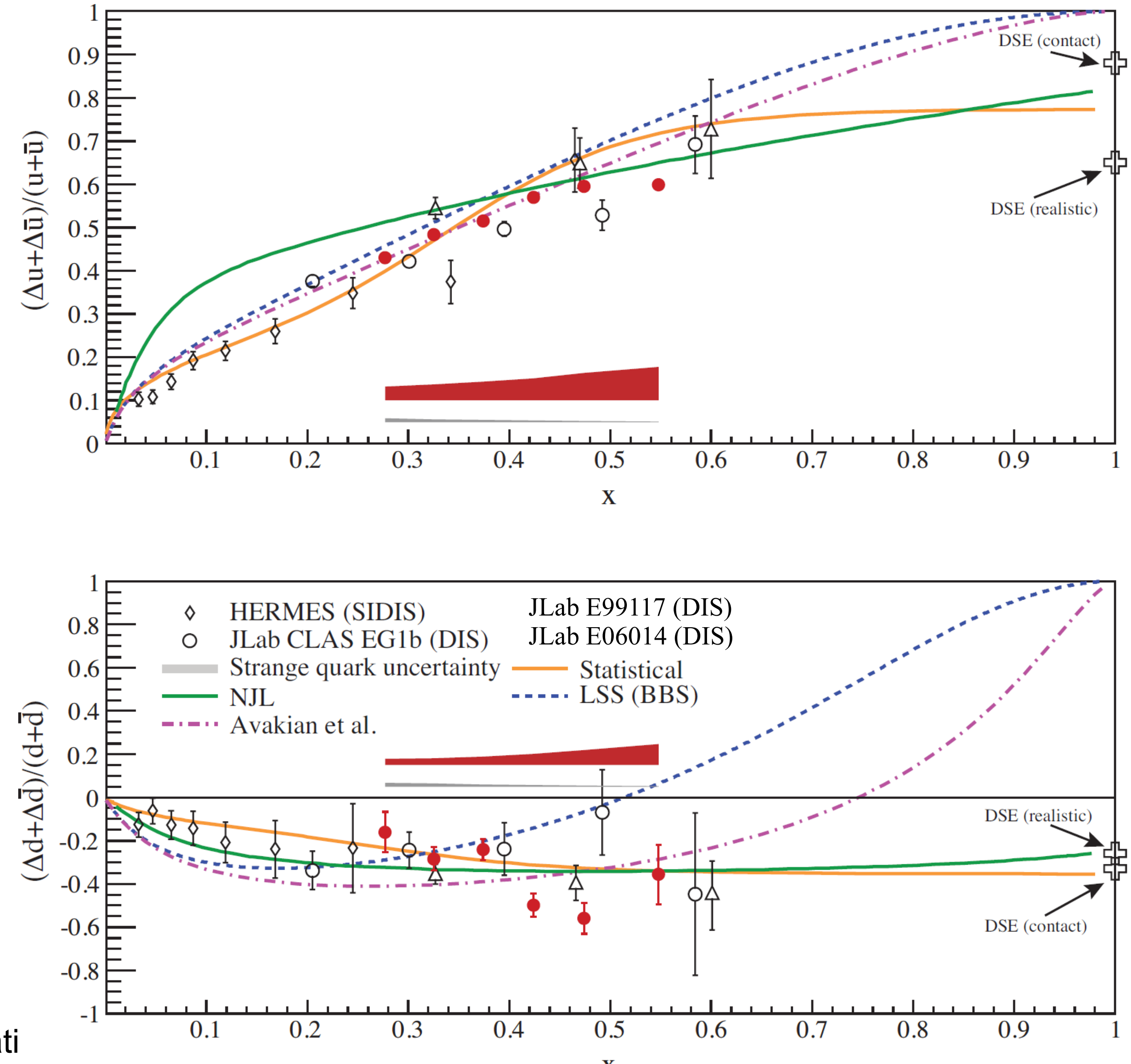
PRL 113 (2014) 2, 022002, 1404.4003

X. Zheng et al.

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

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

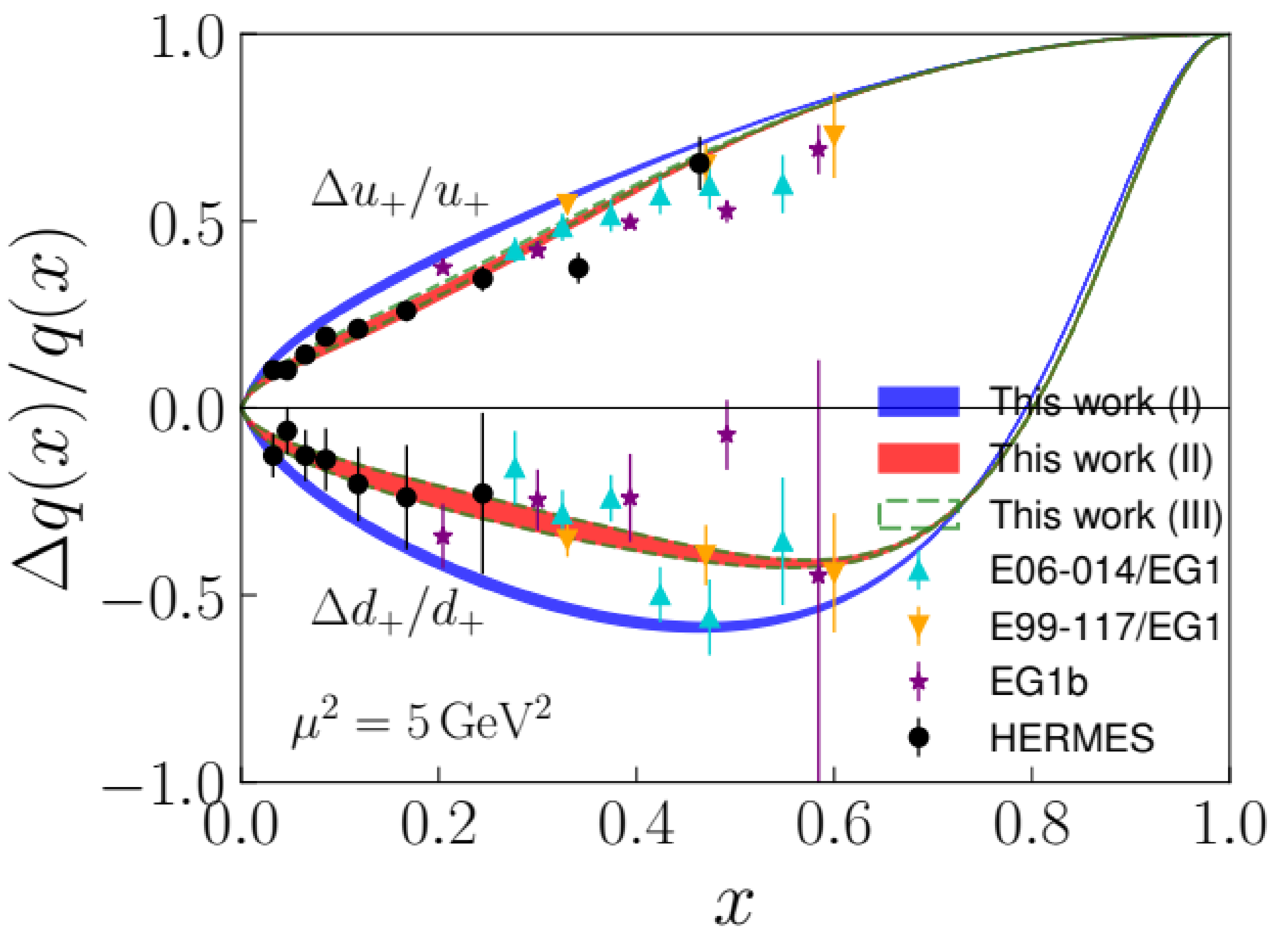
→ also see talks by Chris Cocuzza (Tuesday 2pm) and Nobuo Sato (Thursday 9:30am)



LFHQCD Prediction on Polarized PDFs

Based on the gauge-gravity correspondence, light-front holography, and the generalized Veneziano model. We find that the spin-dependent quark distributions are uniquely determined in terms of the unpolarized distributions by chirality separation without the introduction of additional free parameters.

In particular, we predict the sign reversal of the polarized down-quark distribution in the proton at x = 0.8 ± 0.03, a key property of nucleon substructure which will be tested very soon in upcoming experiments.



T. Liu et al.,

Phys. Rev. Lett. 124, 082003 (2020)

arXiv:1909.13818

Hall C 12 GeV A1n/d2n Collaboration

PhD (two graduated)

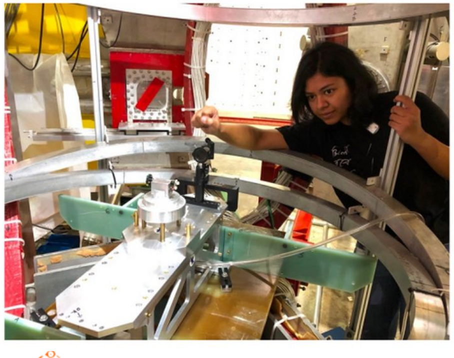
People

Spokespeople

D. Androic, W. Armstrong, T. Averett, X. Bai, J. Bane, S. Barcus, J. Benesch, H. Bhatt, D. Bhetuwal, D. Biswas, A. Camsonne, G. Cates, J-P. Chen, J. Chen, M. Chen, C. Cotton, M-M. Dalton, A. Deur, B. Dhital, B. Duran, S.C. Dusa, I. Fernando, E. Fuchey, B. Gamage, H. Gao, D. Gaskell, T.N. Gautam, N. Gauthier, C.A. Gayoso, O. Hansen, F. Hauenstein, W. Henry, G. Huber, C. Jantzi, S. Jia, K. Jin, M. Jones, S. Joosten, A. Karki, B. Karki, S. Katugampola, S. Kay, C. Keppel, E. King, P. King, W. Korsch, V. Kumar, R. Li, S. Li, W. Li, D. Mack, S. Malace, P. Markowitz, J. Matter, M. McCaughan, Z-E. Meziani, R. Michaels, A. Mkrtchyan, H. Mkrtchyan, C. Morean, V. Nelyubin, G. Niculescu, M. Niculescu, M. Nycz, C. Peng, S. Premathilake, A. Puckett, A. Rathnayake, M. Rehfuss, P. Reimer, G. Riley, Y. Roblin, J. Roche, M. Roy, M. Satnik, B. Sawatzky, S. Seeds, S. Sirca, G. Smith, N. Sparveris, H. Szumila-Vance, A. Tadepalli, V. Tadevosyan, Y. Tian, A. Usman, H. Voskanyan, S. Wood, B. Yale, C. Yero, A. Yoon, J. Zhang, Z. Zhao, X. Zheng, J. Zhou

Institutions

A.I. Alikhanian National Science Laboratory; Argonne National Laboratory; Artem Alikhanian National Laboratory (AANL).; Christopher Newport University; Duke University; Florida International University; Hampton University ; James Madison University ; Jefferson Lab; Kent State University; Mississippi State University; Ohio University; Old Dominion University; Rutgers University; Syracuse University; Temple University; The College of William and Mary; Univ. of Ljubljana; University of Connecticut; University of Kentucky; University of Kentucky; University of New Hampshire; University of Regina; University of Tennessee; University of Virginia; University of Virginia; University of Zagreb



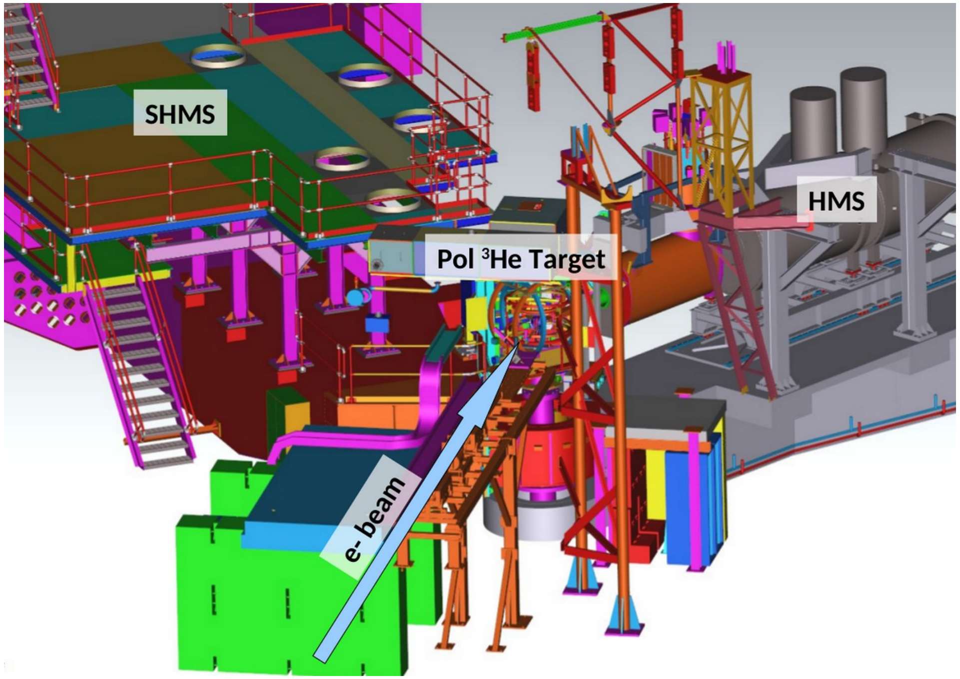
Jefferson Lab

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

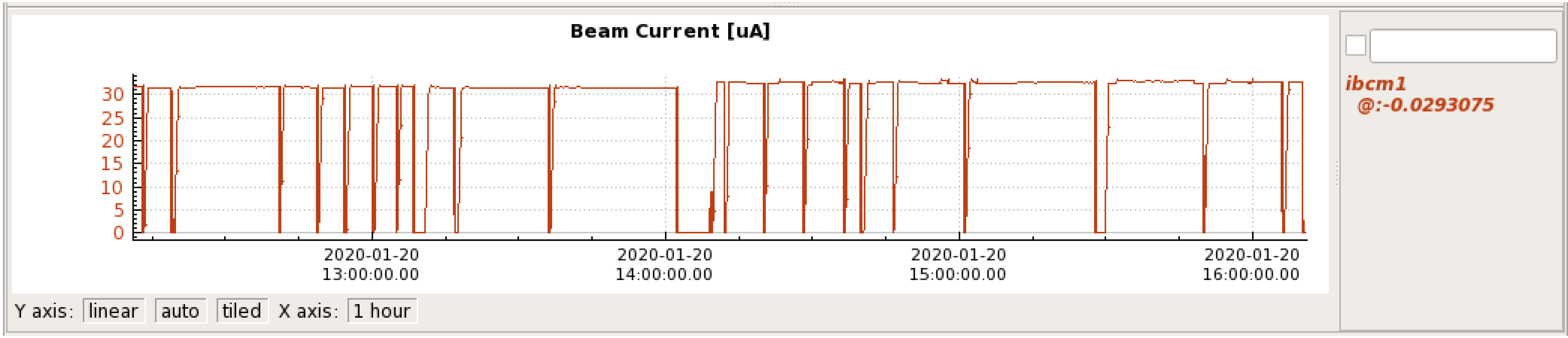
- 10.4 GeV beam, 85% longitudinal polarization, 30 uA
  - First in Hall C's 12 GeV era to utilize polarized beam
- HMS and SHMS detecting electrons in the inclusive mode
- Polarized 3He target (40cm)
  - first time use in Hall C
  - 50-55% in-beam polarization → factor 2 increase in 3He target FOM vs. 6 GeV era

Kine	Spec	E_b GeV	E_p GeV	θ (○)	beam time (hours)
$\Delta(1232)$	SHMS	2.17	-1.79736	8.5	4.0
Elastic	SHMS	2.17	-2.12860	8.5	8.0

Kine	Spec	E_b GeV	E_p GeV	θ (○)	e^- production (hours)	e^+ prod. (hours)	Tot. Time (hours)
DIS							
3	HMS	10.38	2.90	30.0	88.0	0.0	88.0
4	HMS	10.38	3.50	30.0	511.0	0.0	511.0
B	SHMS	10.38	3.40	30.0	511.0	4.0	515.0
C	SHMS	10.38	2.60	30.0	88.0	4.0	92.0



Beam Quality During A1n



- Beam charge asymmetry controlled by parity DAQ (PREX-II/CREX) – below 50ppm per one-hour run
- Beam polarization measured by Moller polarimetry

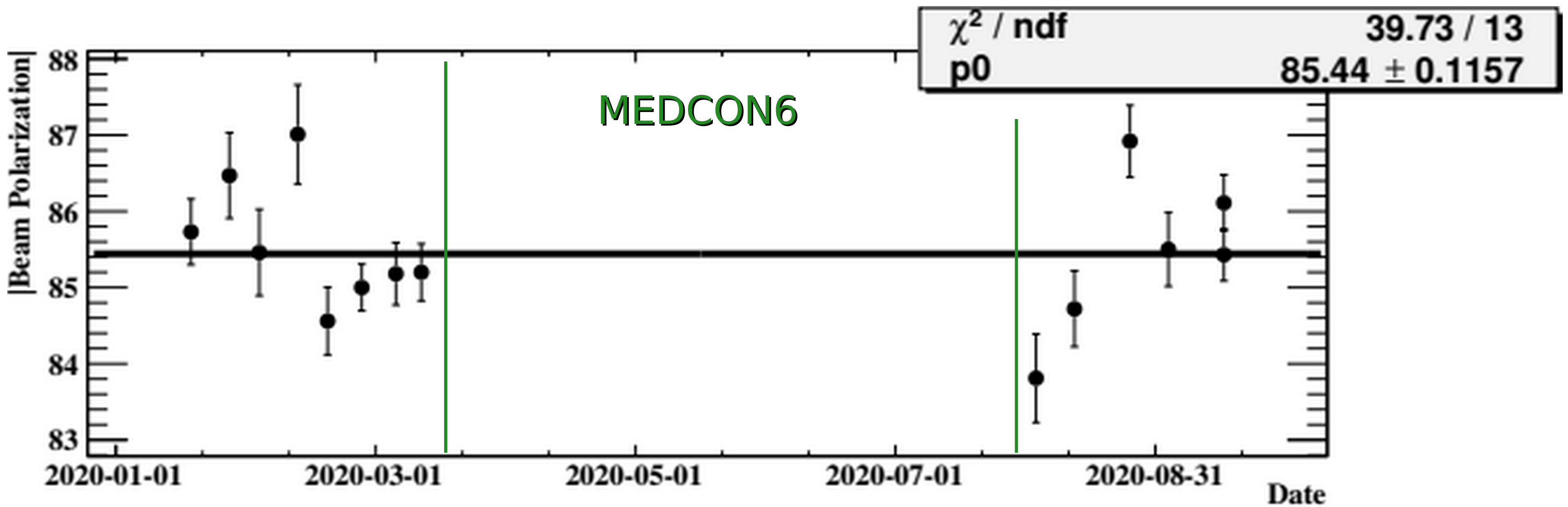
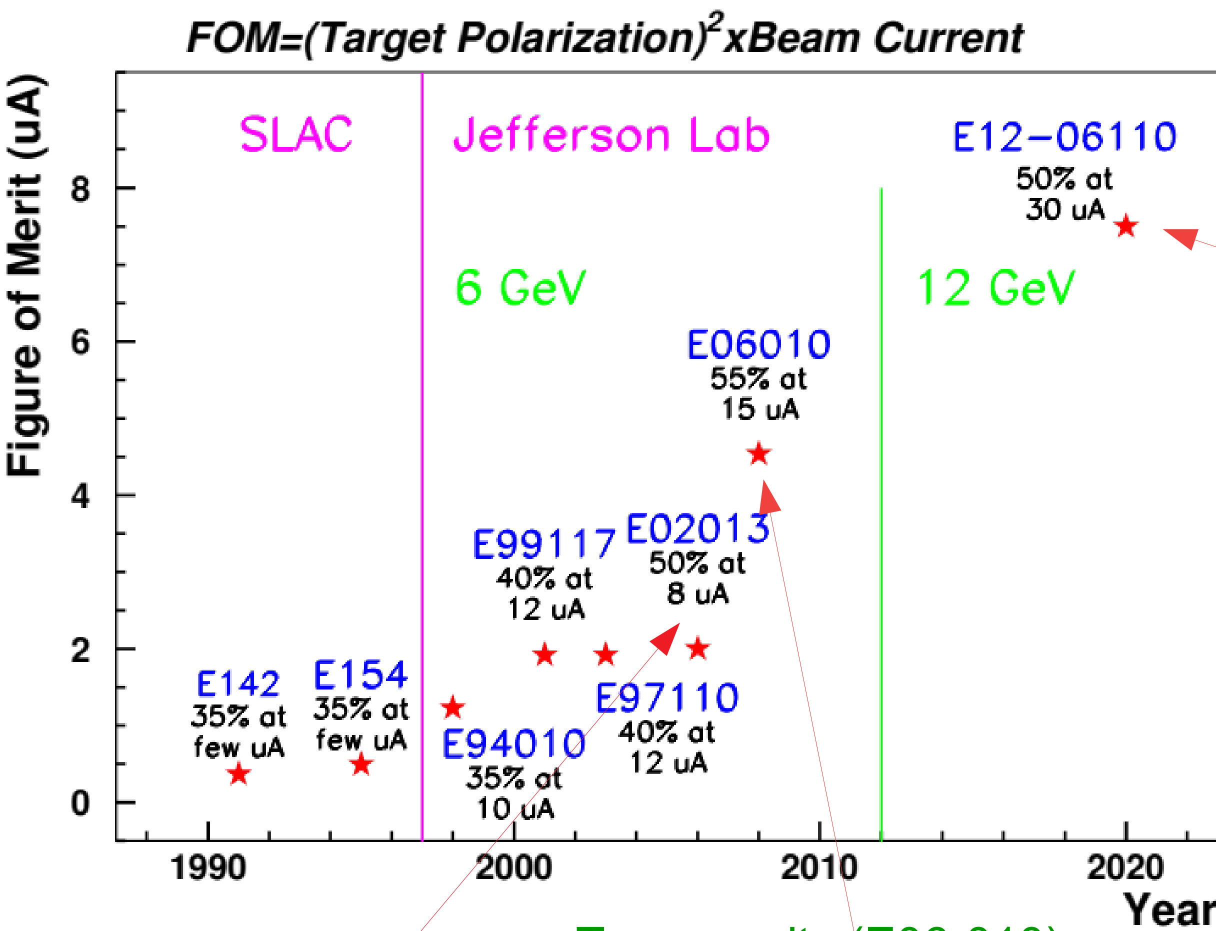
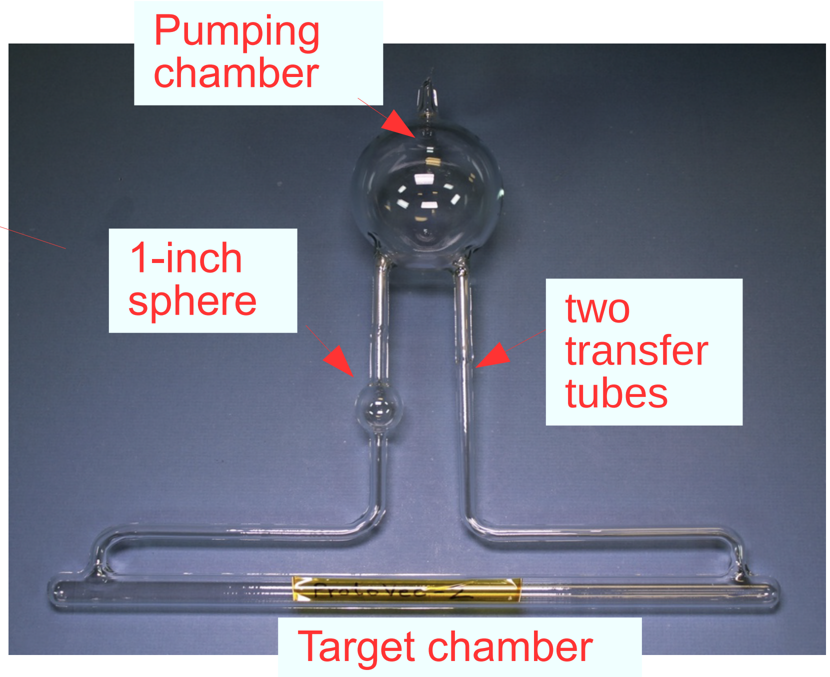


Figure credit: W. Henry

Polarized ^{3}He Targets Performance Evolution



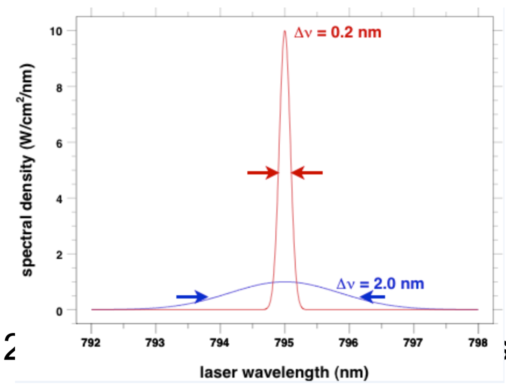


G_E^n (E02-013):

Started to use Rb/K hybrid alkali cell.

Transversity (E06-010):

Started to use narrow band laser.



12 GeV era Target Cell:

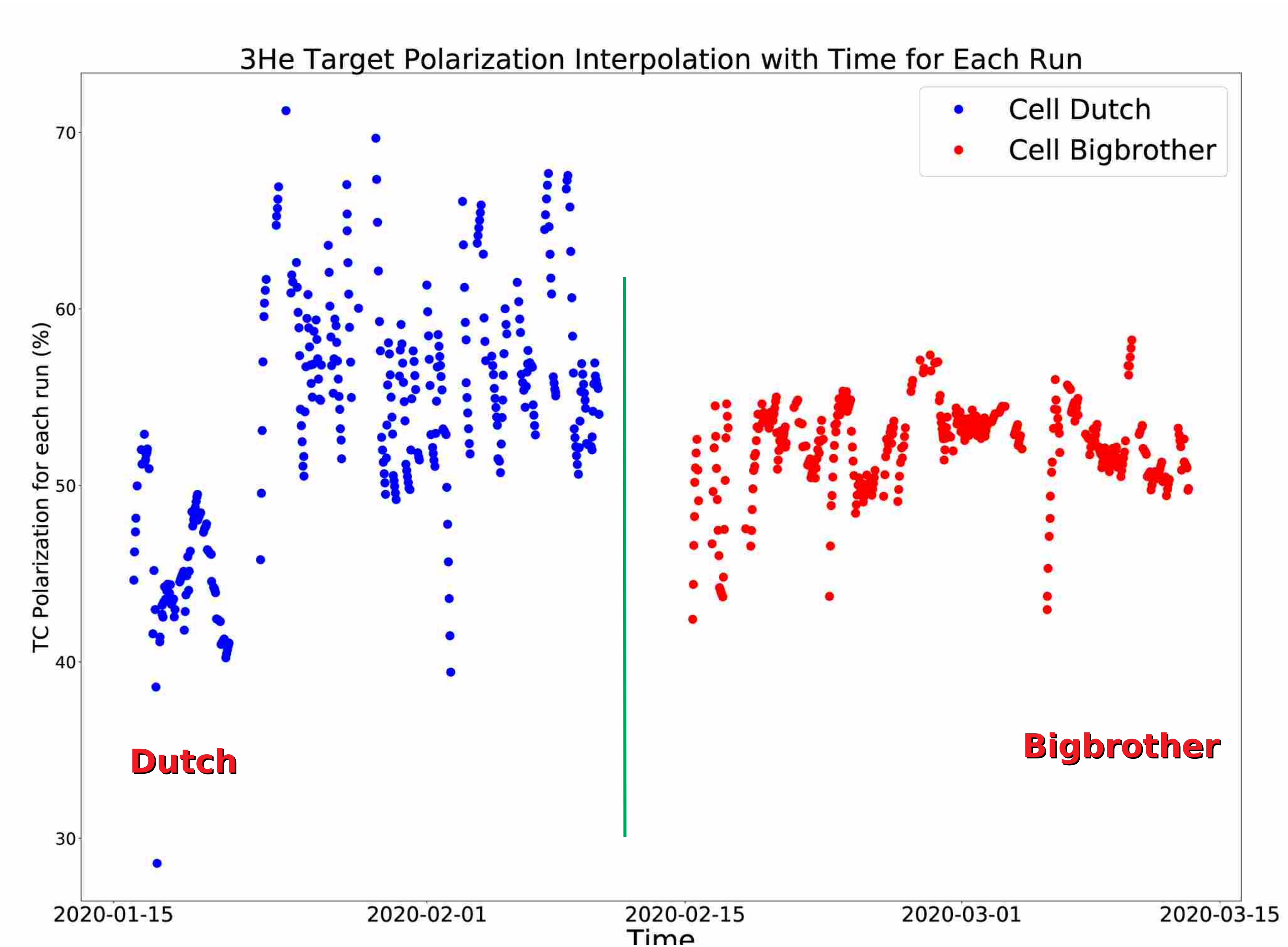
Convection Cell (replacing 6 GeV diffusion cells.)

GEn-II (running now):

→ see talks by
Chris Jantzi (Tuesday 5pm) and
Arun Tadepalli (Wednesday 10am)

Production Cell Performance

(for targets used in A_1^n experiment)

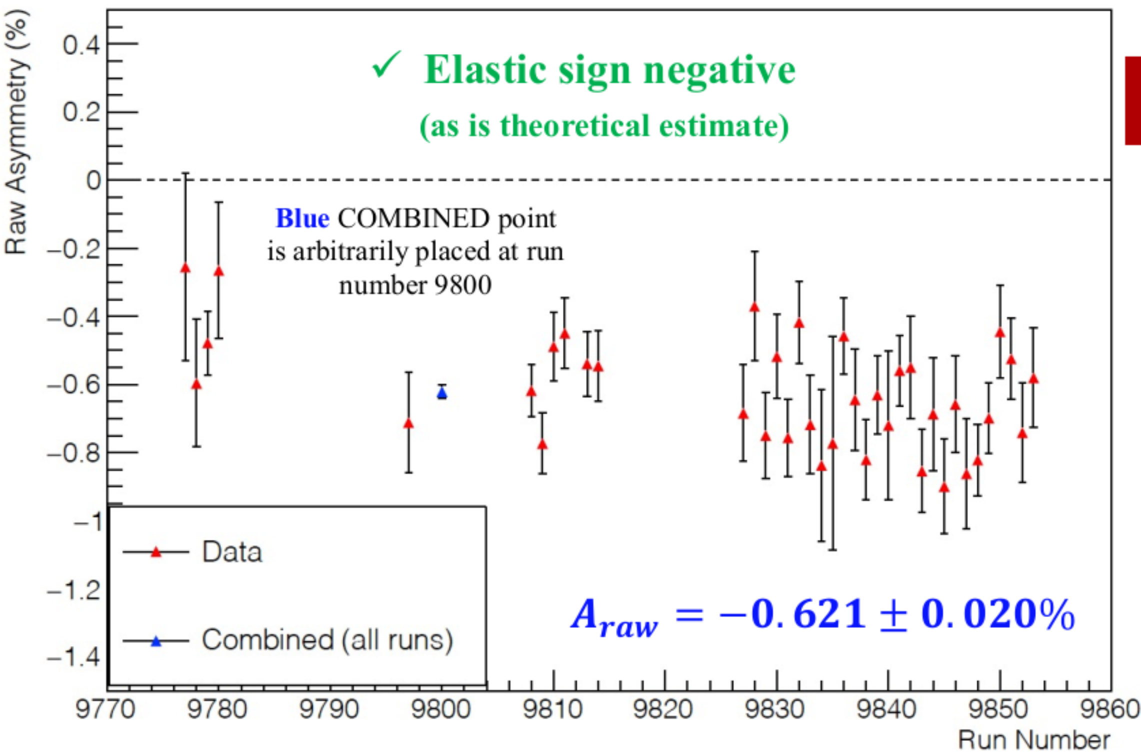


A_{para}: ^{3}He Elastic Asymmetries

By definition: N^{+} should describe the # of incident e^{-} whose spin is **anti-∥** to the ^{3}He target spin

$$A_{\parallel} = \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\uparrow\Uparrow}}$$

SHMS Elastic Runs



e^{-} beam spin direction:

Period	IHWP = IN	IHWP = OUT	^{3}He spin direction
1-pass (Dec. 2019) (elastic + delta)	UPSTREAM ($\vec{e}^{-}$ anti-∥ $\overrightarrow{^{3}He}$) ($\vec{e}^{-}$ anti-∥ beam direction)	DOWNSTREAM ($\vec{e}^{-}$ ∥ $\overrightarrow{^{3}He}$) ($\vec{e}^{-}$ ∥ beam direction)	180°: DOWNSTREAM 90°: BEAM LEFT
	pass change		
5-pass (DIS) (thru SHMS 10354, HMS 3162)	DOWNSTREAM ($\vec{e}^{-}$ ∥ $\overrightarrow{^{3}He}$) ($\vec{e}^{-}$ ∥ beam direction)	UPSTREAM ($\vec{e}^{-}$ anti-∥ $\overrightarrow{^{3}He}$) ($\vec{e}^{-}$ anti-∥ beam direction)	180°:DOWNSTREAM 90°: BEAM LEFT
	Wien-flip		
5-pass (DIS) (SHMS 10355+, HMS 3163+)	UPSTREAM ($\vec{e}^{-}$ anti-∥ $\overrightarrow{^{3}He}$) ($\vec{e}^{-}$ anti-∥ beam direction)	DOWNSTREAM ($\vec{e}^{-}$ ∥ $\overrightarrow{^{3}He}$) ($\vec{e}^{-}$ ∥ beam direction)	180°: DOWNSTREAM 90°: BEAM LEFT

$$A_{raw} = \frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$

SHMS Elastic Runs:
^{3}He @ 180°
E_p= -2.1286 GeV, 8.5°

- **^{3}He target spin direction fixed**
- Incident e^{-} spin direction (relative to its momentum) changes with IHWP state, Wien-flip, and pass change → imperative to keep N^{+}, N^{-} consistent!

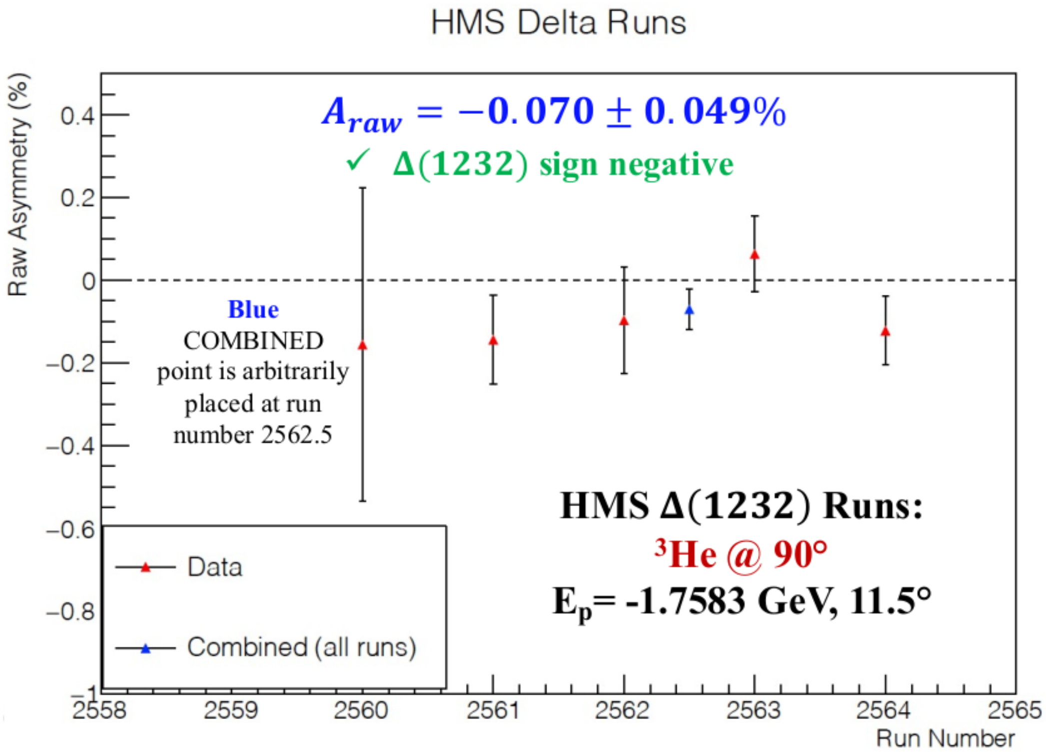
- Credit to Melanie Cardona (Temple U.)

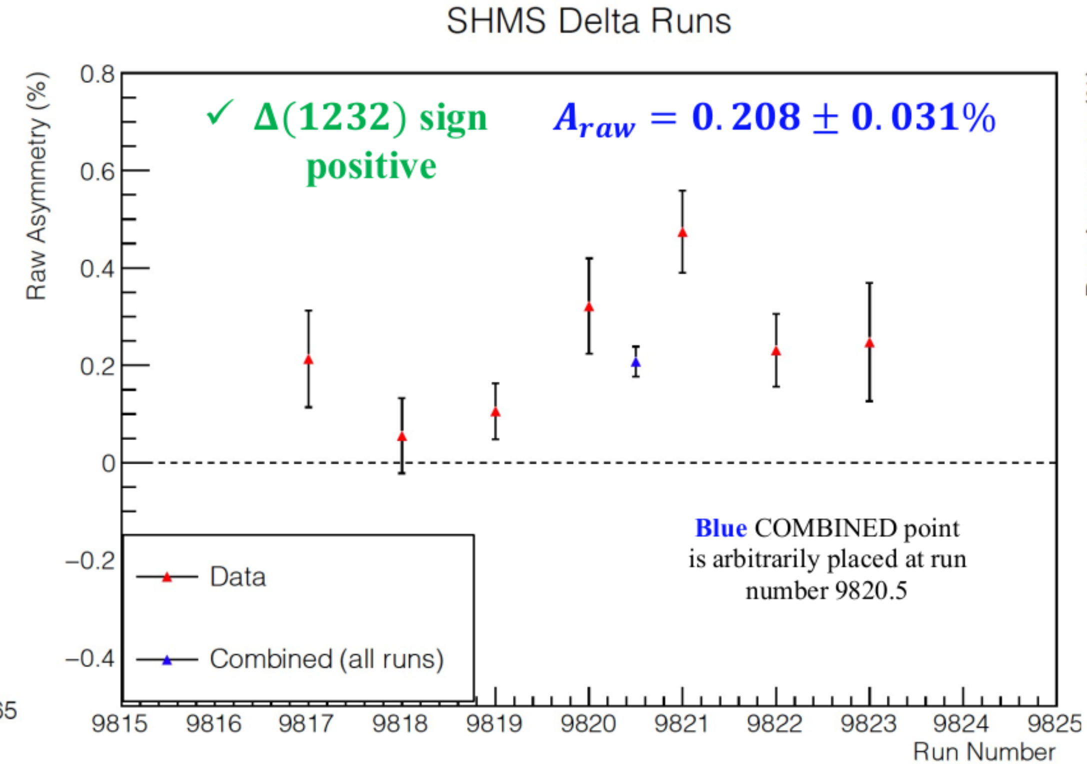
A_{perp}: ^{3}He Δ(1232) Asymmetries

By definition: N^+ should describe the # of incident e^- whose spin is **anti-∥** to the **beam direction**, and the scattered e^- being detected on the **same side of the beam** as that to which the **^{3}He spins are pointing**:

$$A_\perp = \frac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{\sigma^{\downarrow\Rightarrow} + \sigma^{\uparrow\Rightarrow}}$$

(beam left → SHMS!)





$$A_{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

SHMS Δ(1232) Runs:
^{3}He @ 90°
E_p= -1.7583 GeV, 8.5°

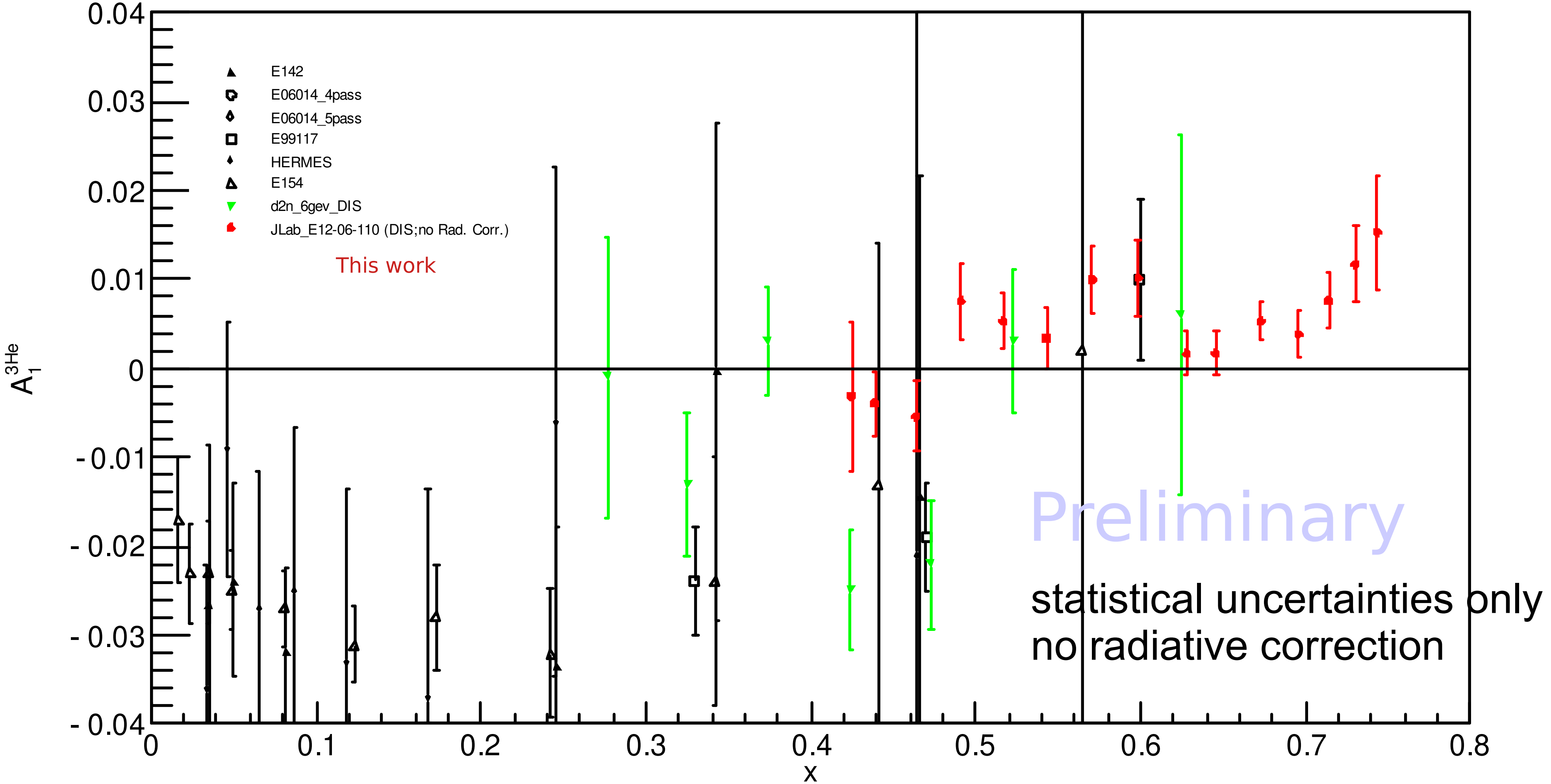
- Credit to Melanie Cardona (Temple U.)

Jefferson Lab

Asymmetry A_1^{3He}

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

with DIS W>2 GeV cut

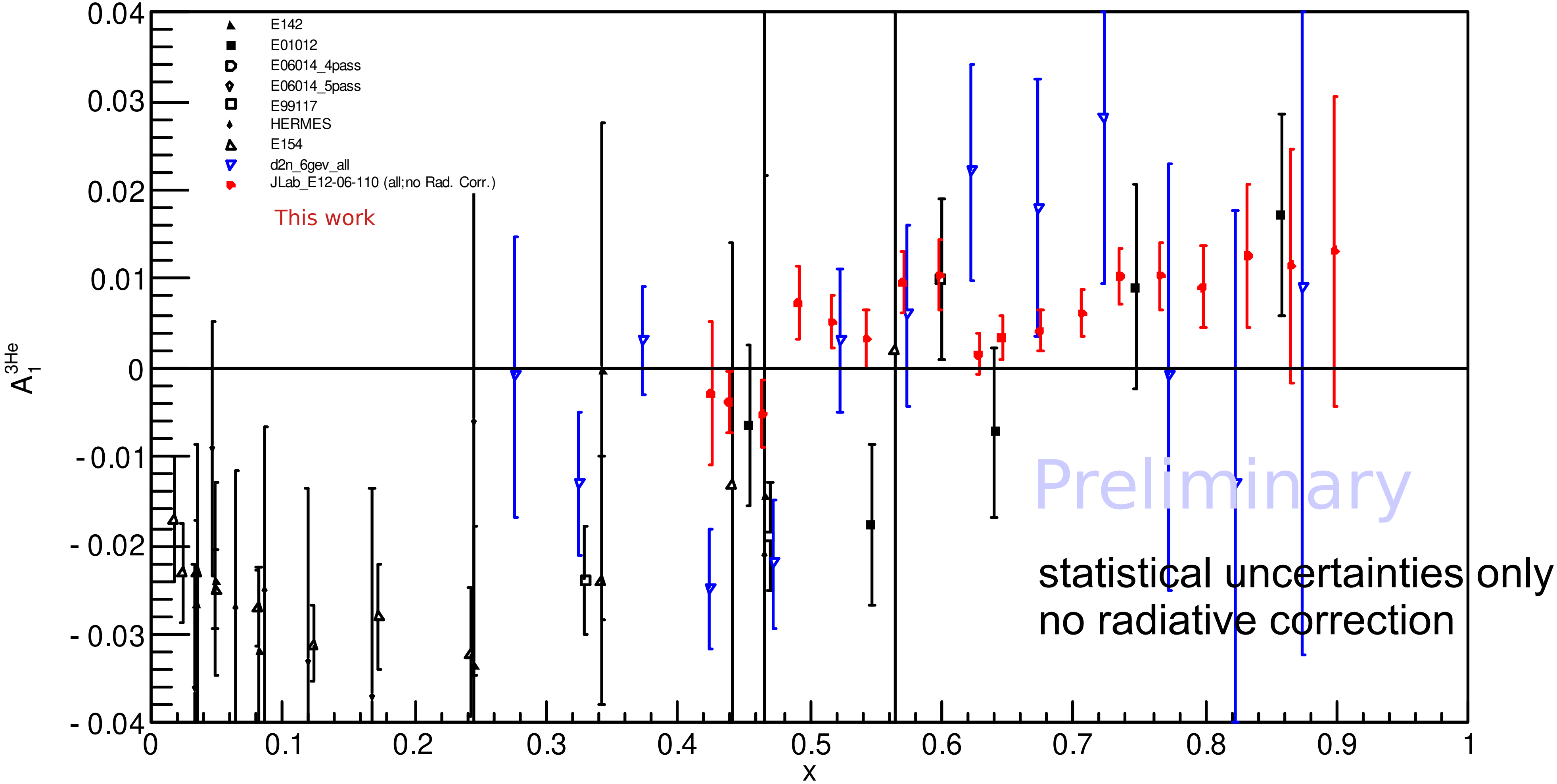


- Credit to Mingyu Chen (UVA)

Asymmetry A_1^{3He}

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

no DIS W>2 GeV cut



- Credit to Mingyu Chen (UVA)

Next (3) Steps

Radiative Corrections:

Plan:

→ use RadCor and Polrad, with existing parameterization as input

→ check with existing data (unpol and pol 3He)

Extracting A1n from A1(3He)

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

Extracting delta q/q from A1n

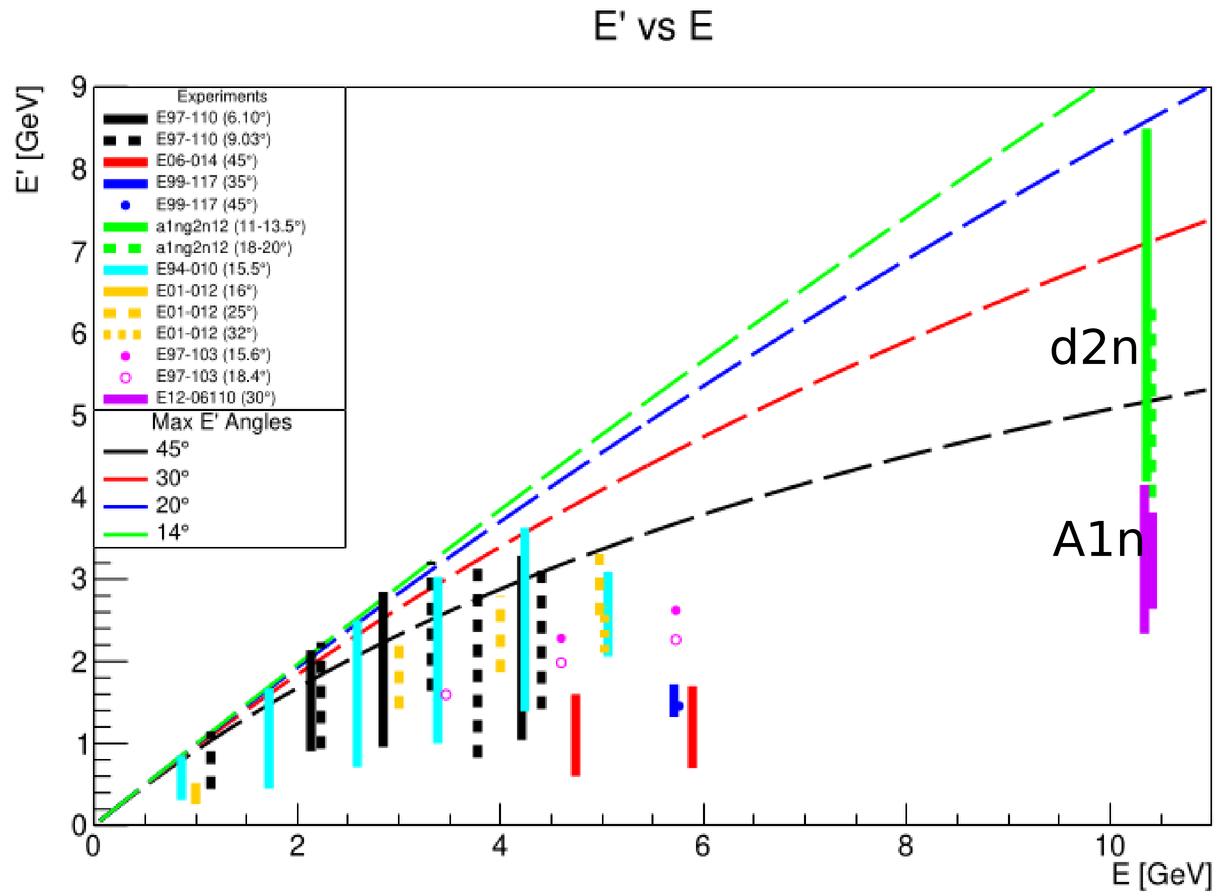


Figure credit: Carter Hedinger (UVA)

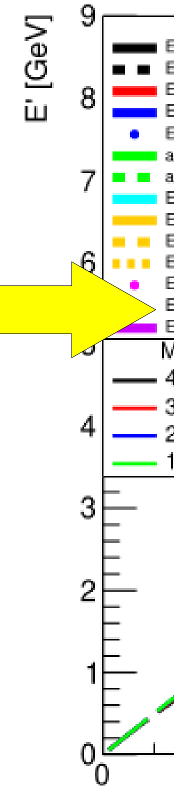
Next (

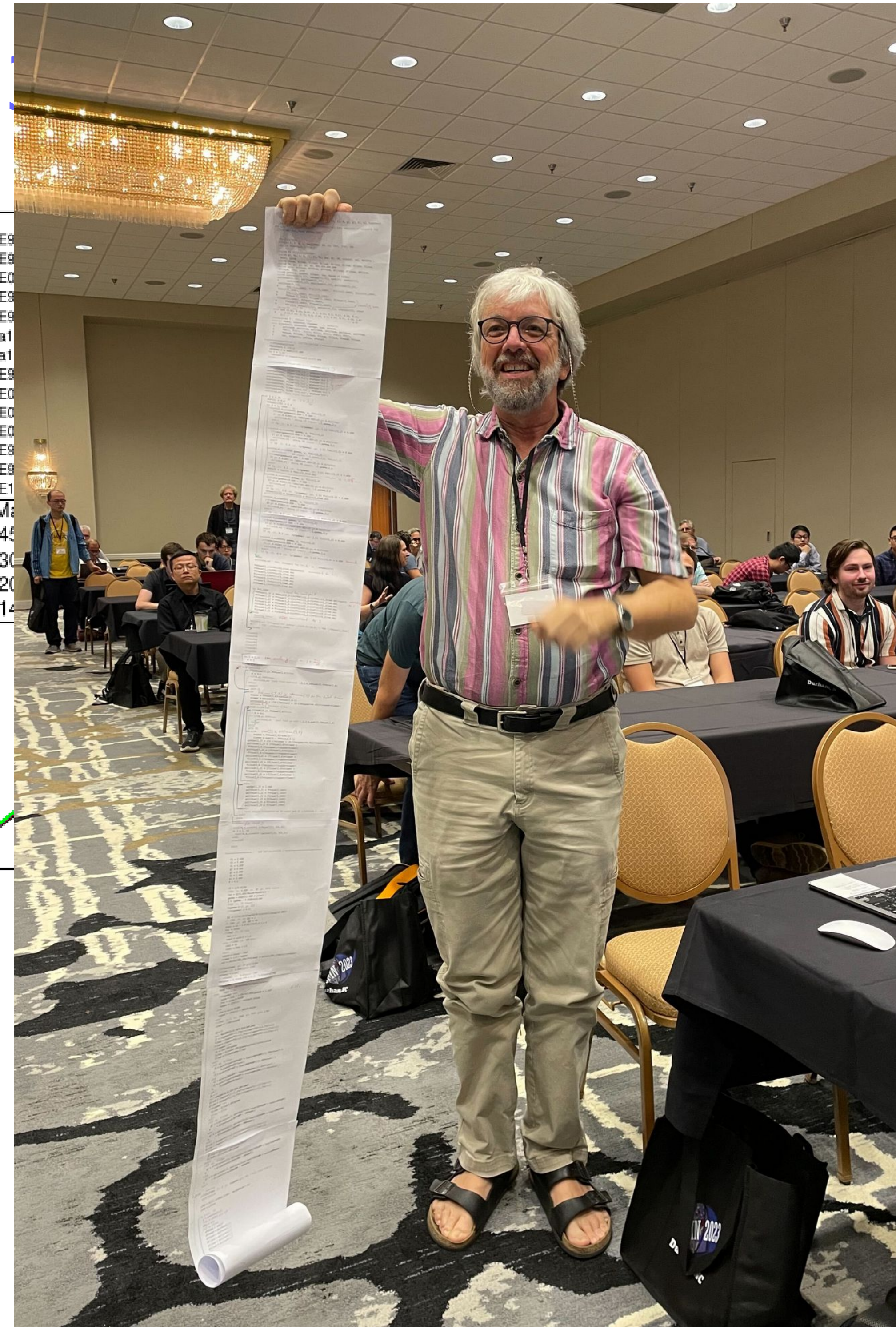
Radiative Corrections:

Plan:

→ use RadCor and Polrad, with existing parameterization as input

→ check with existing data (unpol and pol 3He)





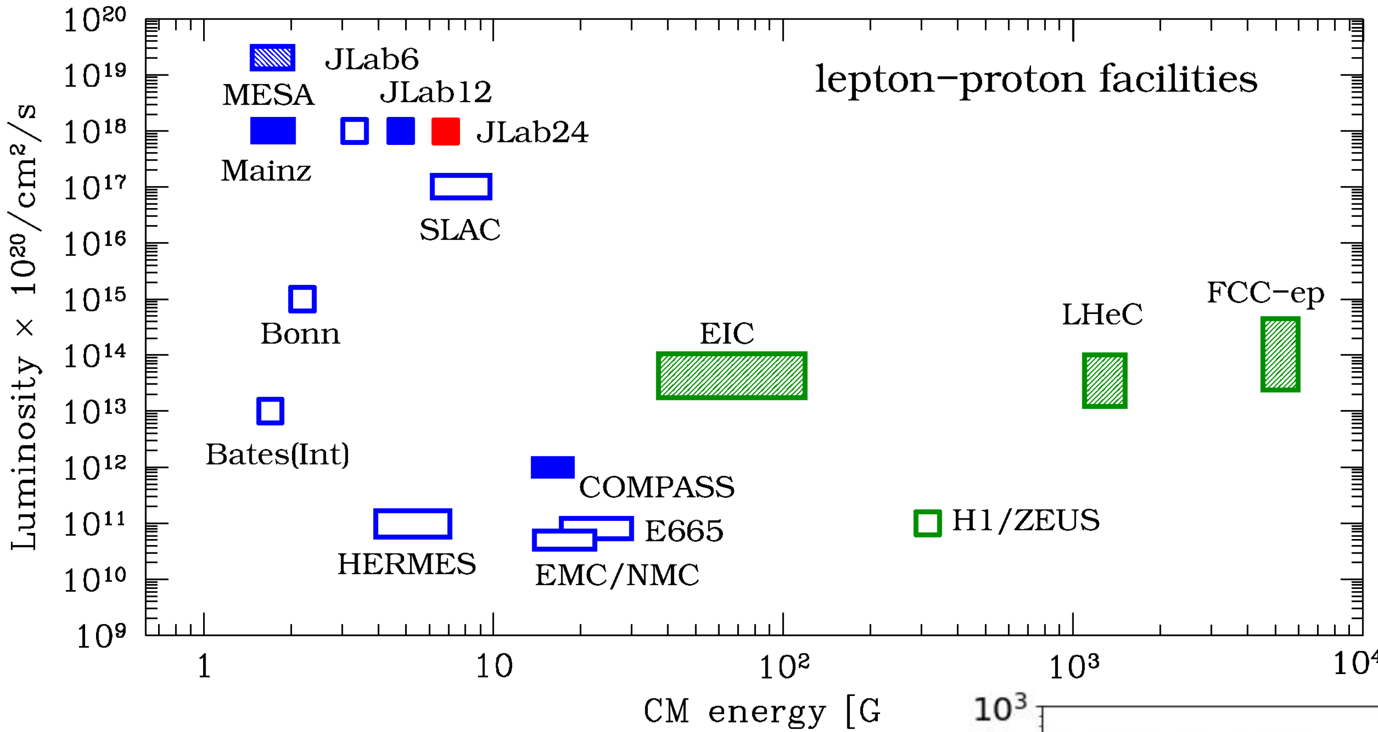
Extracting A1n from A1(3He)

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

Extracting delta q/q from A1n

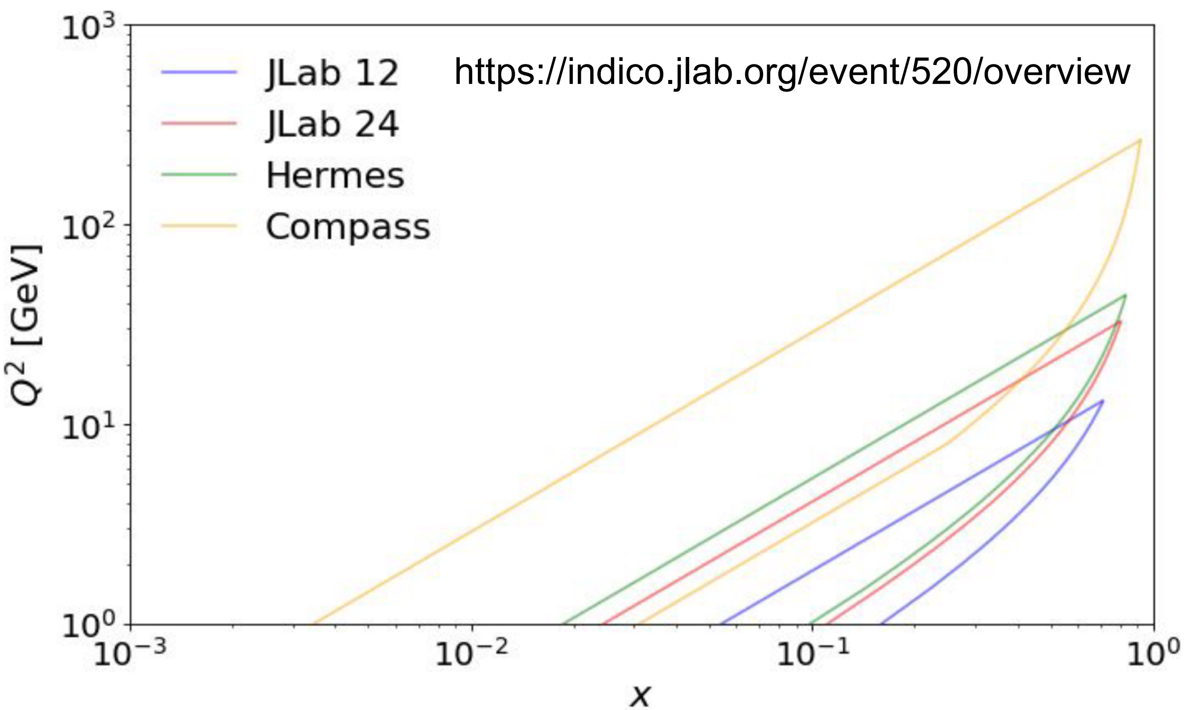
Not-so-near Future – JLab 24 GeV Upgrade?

e-Print: 2112.00060



From A. Signori's J-Future talk

https://indico.jlab.org/event/520/overview



– See Cameron Cotton's talk later today

Jefferson Lab

Summary and Outlook

- Measurement of the neutron A_1 completed at JLab in 2020
  - 10.4 GeV 85% beam; 40cm long 50-55% polarized ^{3}He target, 30 uA beam
  - DIS up to x=0.75
  - A1(3He) preliminary results shown
  - Remaining to do: radiative corrections; 3He → n extraction; quark polarization extraction

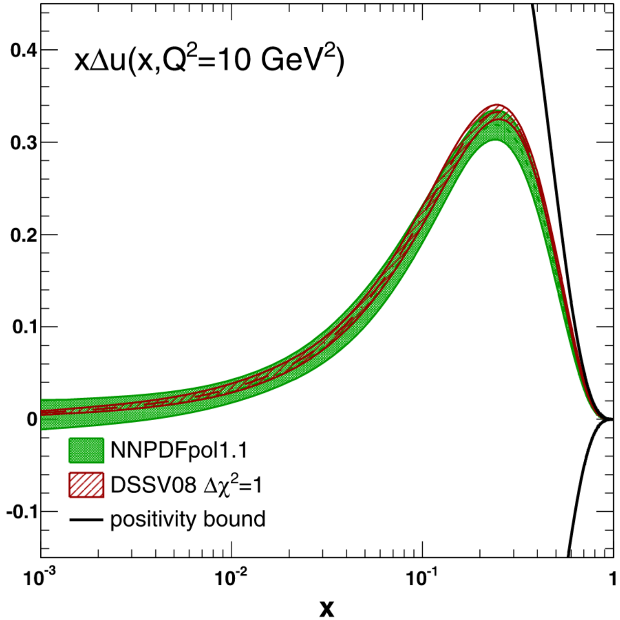
This work is supported by DOE, Office of Science, Nuclear Physics, Medium Energy Physics

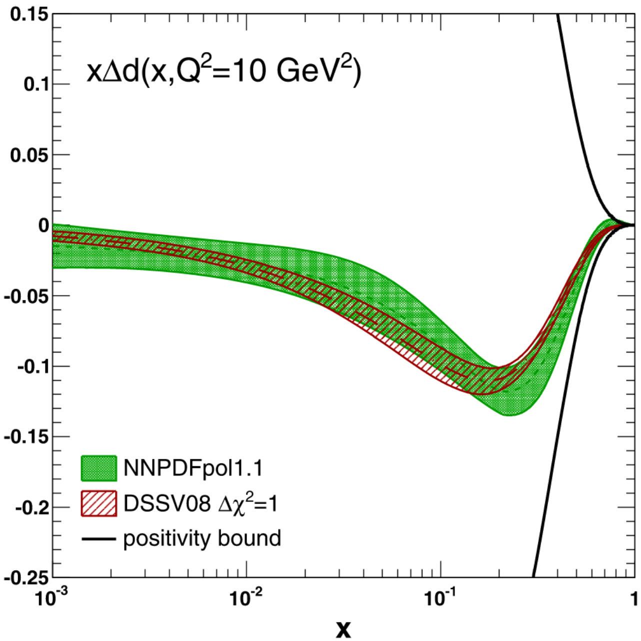
Backup Slides

Present Status on Polarized PDFs

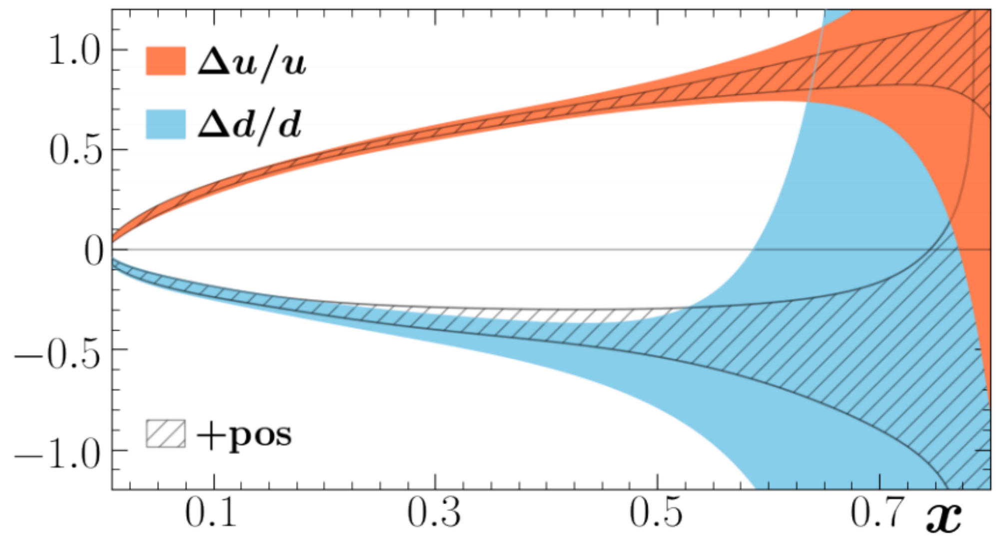
NNPDF pol 1.1

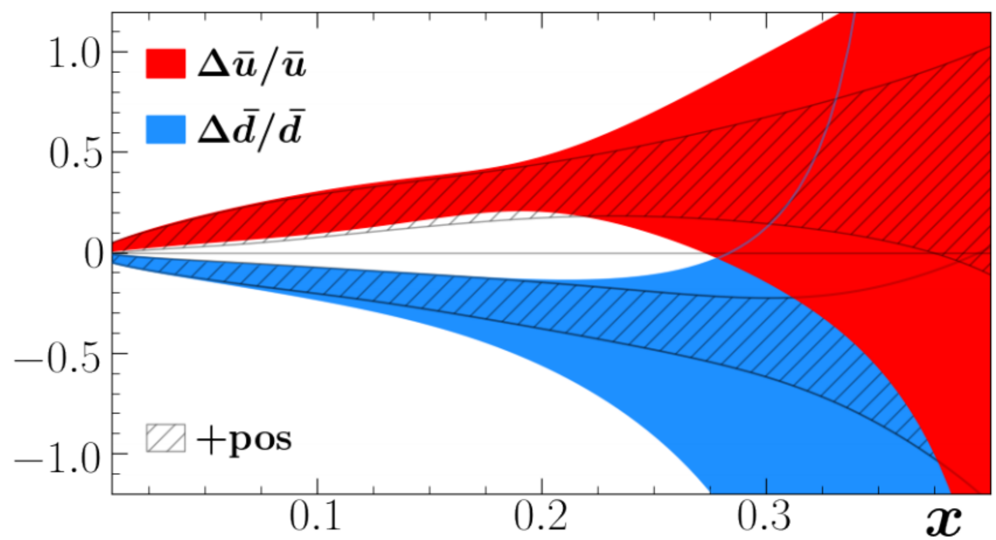
https://doi.org/10.1016/j.nuclphysb.2014.08.008





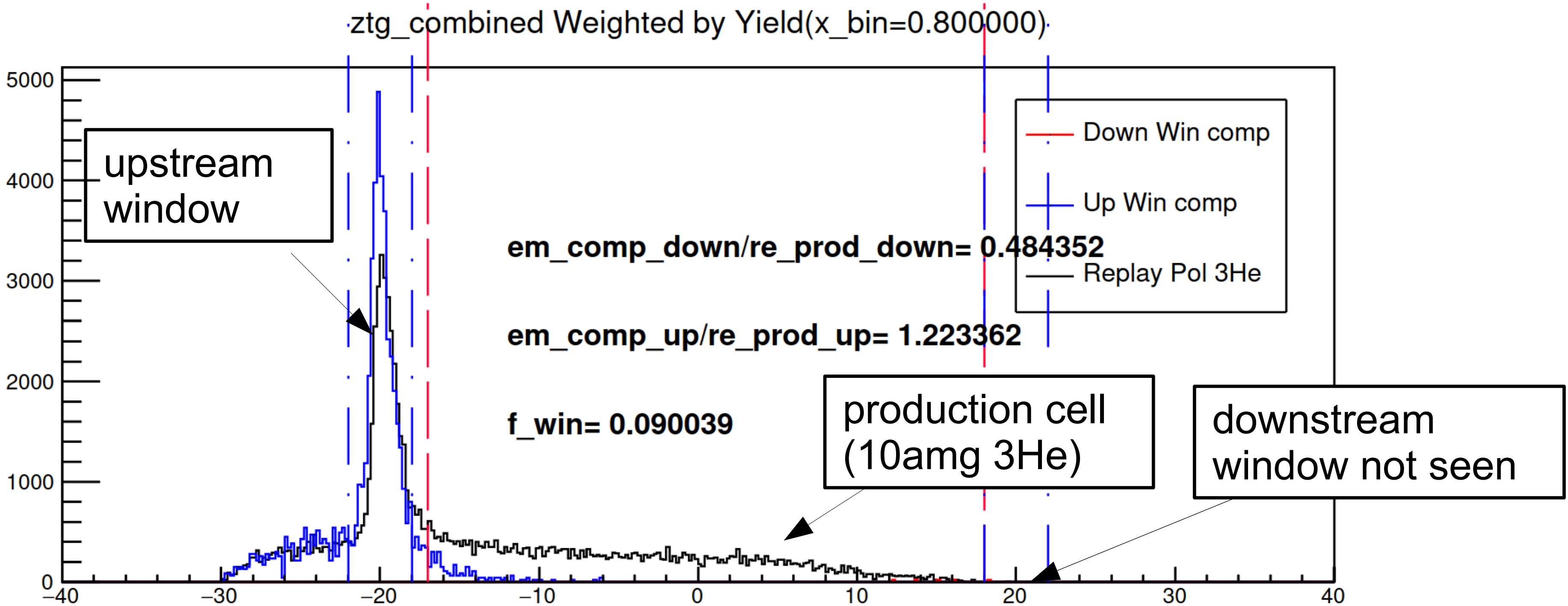
JAM Analysis (arxiv: 2202.03372)

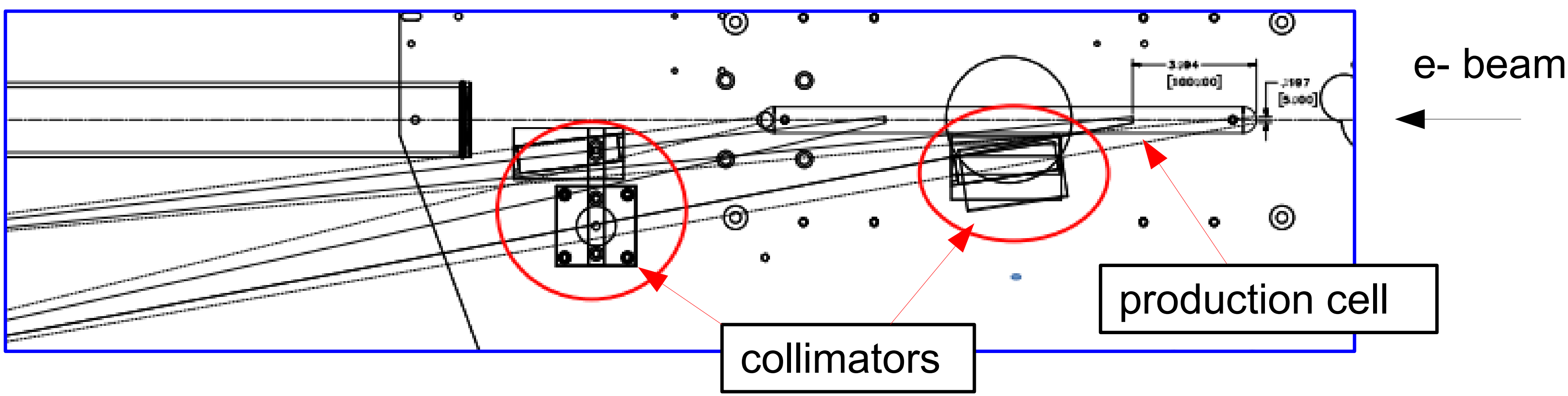




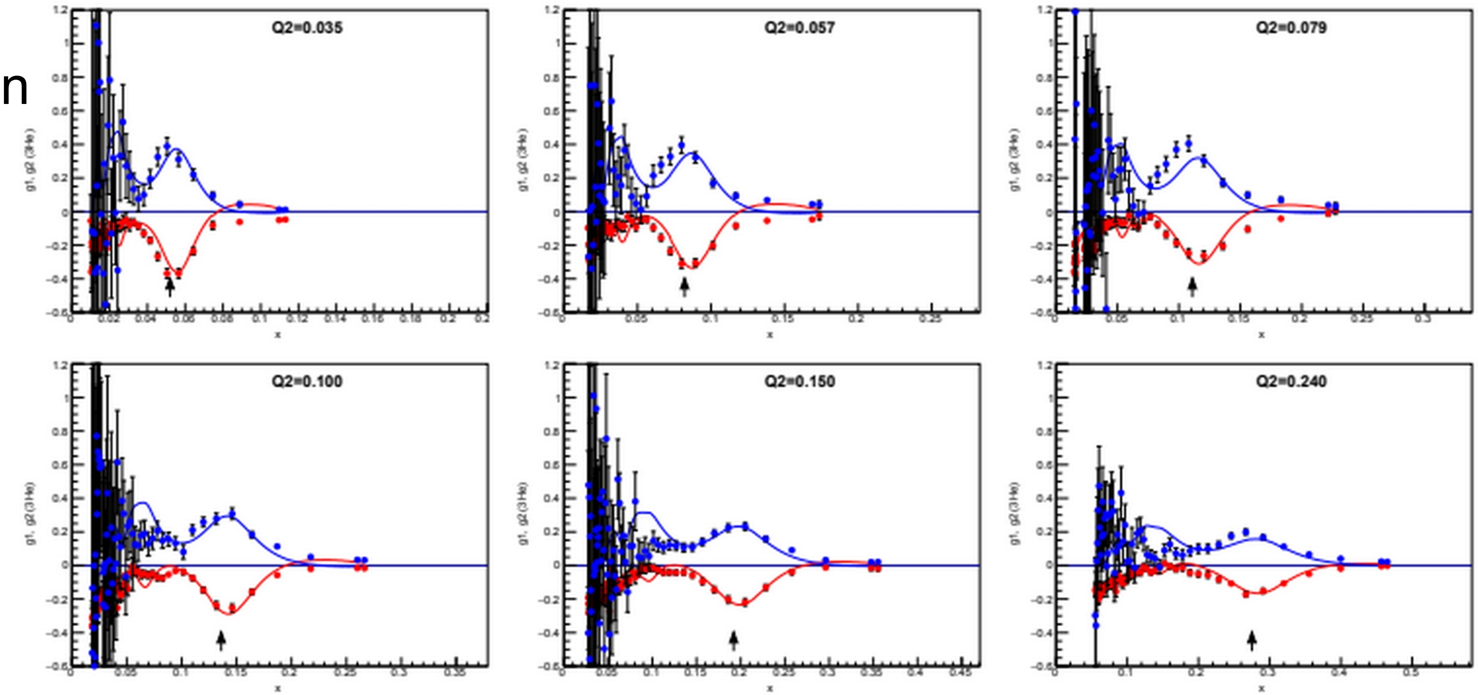
light quark polarization at Q^2=10 GeV^2.

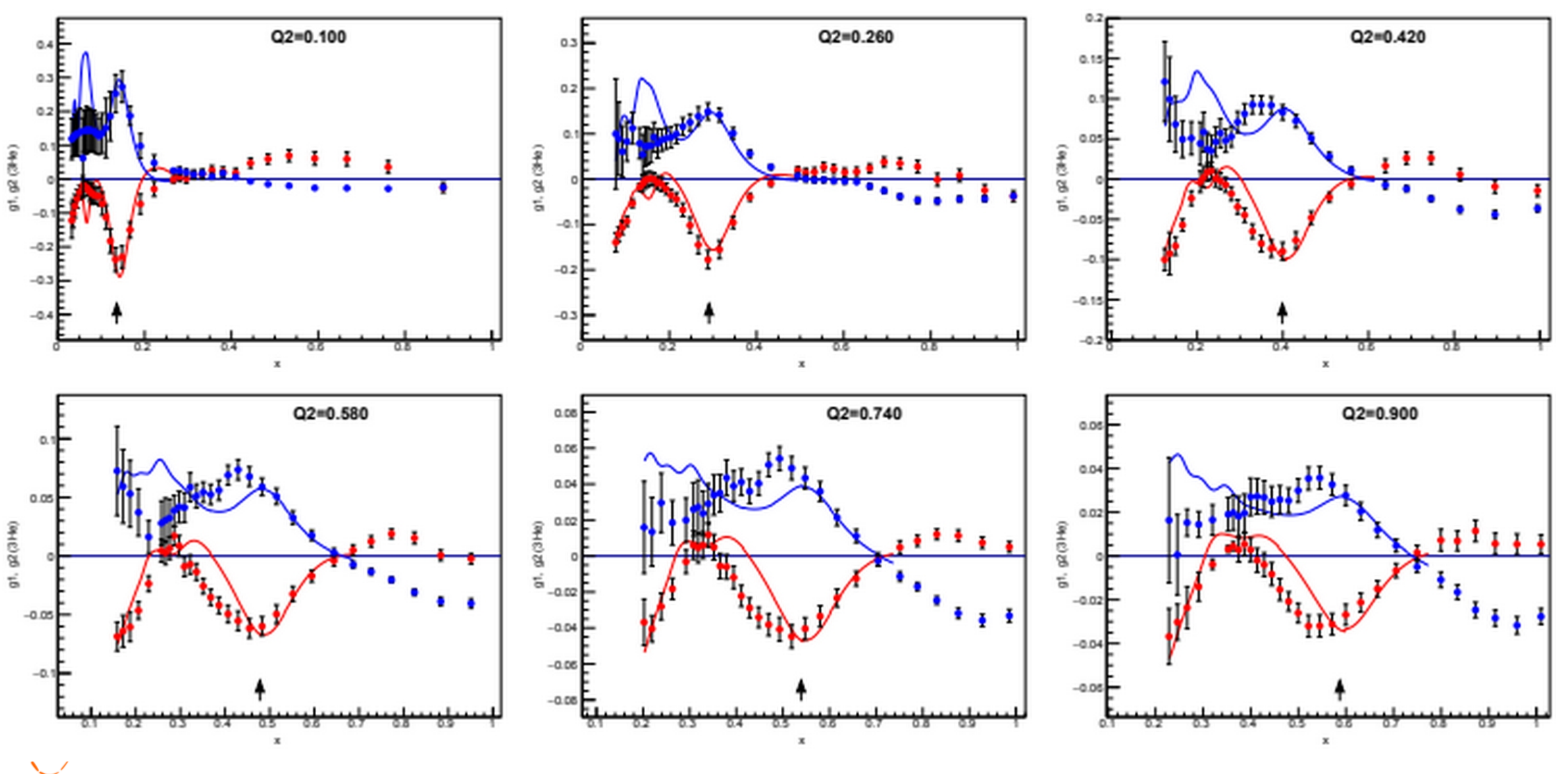
Background from Unpolarized Glass Windows





CLAS Parameterization of g1, g2 in the resonance region

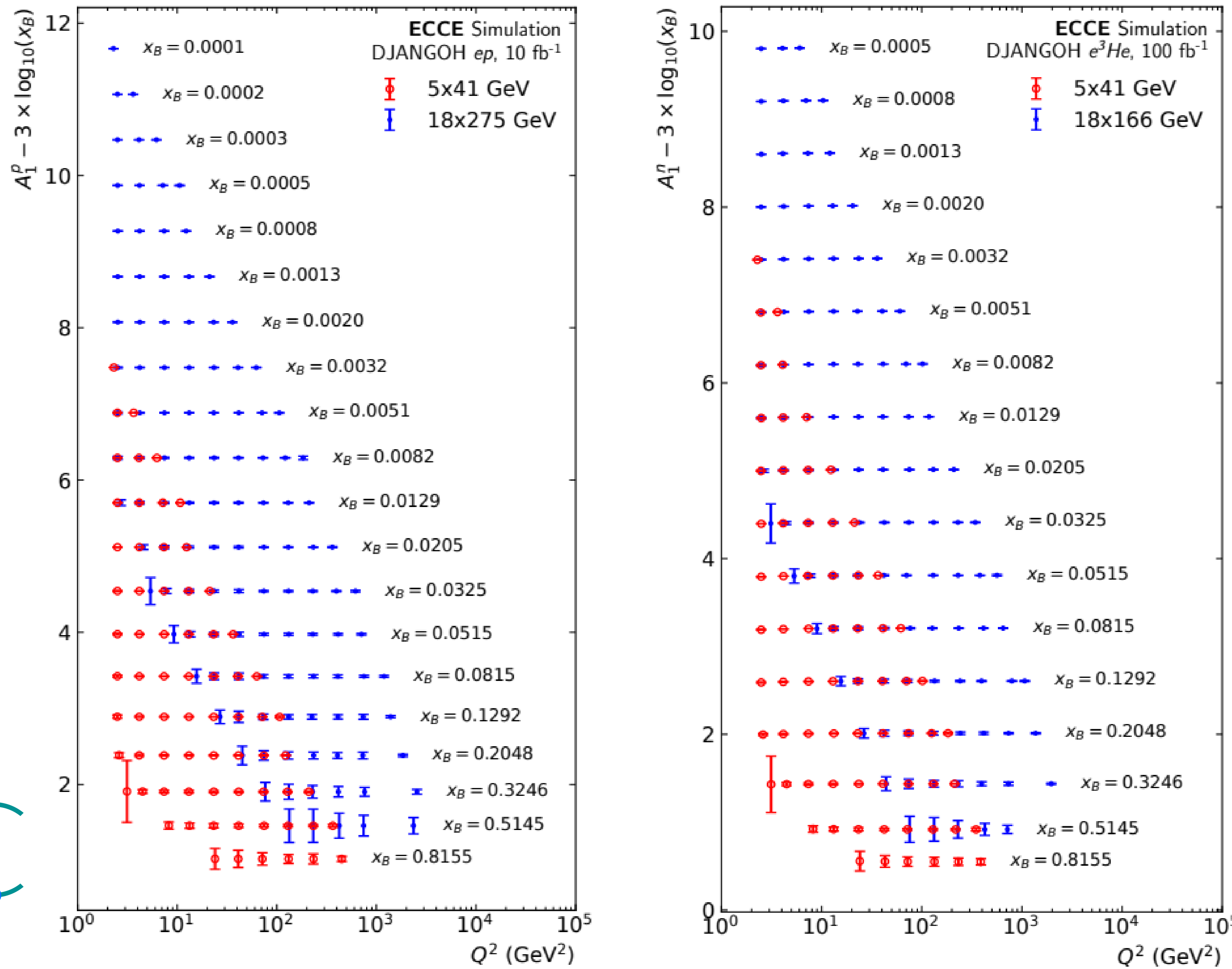




High X Spin Structure Function at the Electron Ion Collider

Figure credit:
Tyler Kutz,
Dien Nguyen,
Jackson Pybus

and ECCE



Jefferson Lab