Neutron Spin Asymmetry A_1n in the High-x Region

Jian-ping Chen, JLab, For A_1n (E12-06-110) Collaboration

JLab User Meeting, June 23-25, 2026

- Introduction: Why Spin? Why High-x?
- Status before 12 GeV A1n experiment
- **JLab12 Hall C measurement of A_1n/ A_1He3 in high-x (valence quark) region**
- Future precision study of valance and sea quark spin
- Summary

Acknowledgment: Thanks to X. Zheng(spokesperson), M. Chen (student), M. Rehfuss(student), M. Nycz(postdoc), R. Trotta(postdoc),… and A_1n collaborators for the work in this talk and slides

Introduction

Why Spin? Why High x?

Precision Study of QCD

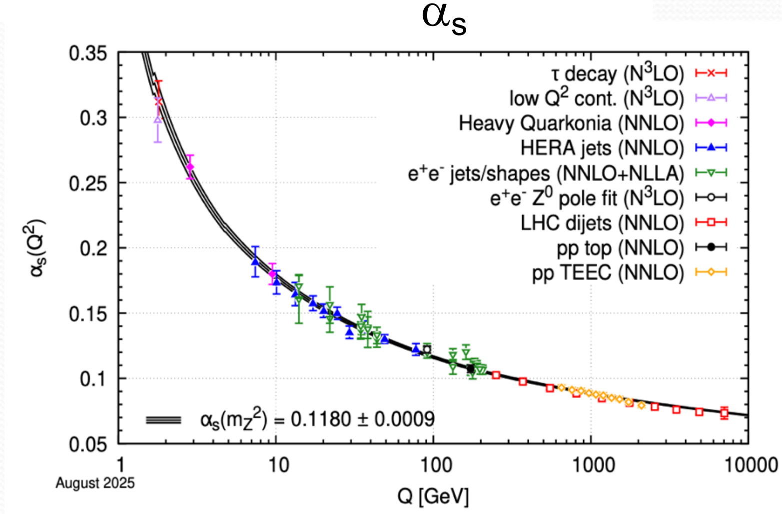
- QCD has been well-established as The theory for Strong Interaction for decades, yet is poorly-understood in Strong Region where the real world lives (~ nucleon size (fm), energy (GeV)).

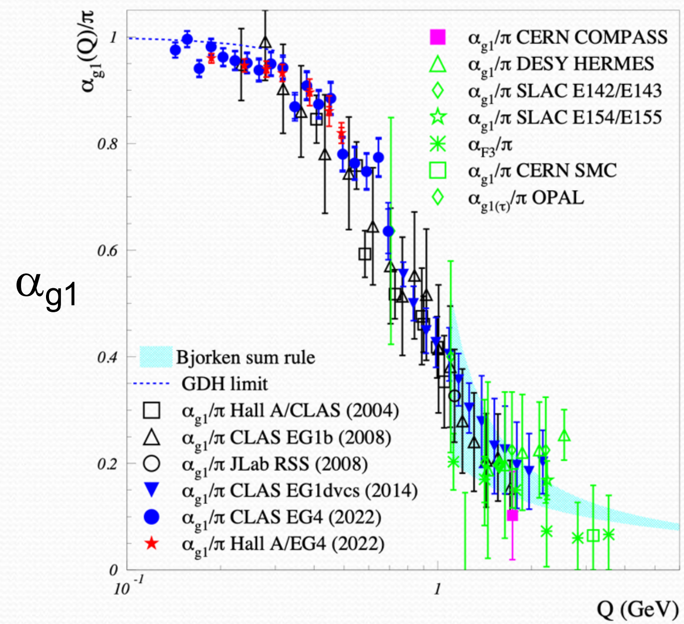
  - Tested in perturbative region over many order of magnitudes

  - Only to few %, contrast to EW theory tested to up to 10^{-12} !

- Precision study is essential for understand Strong QCD/nucleon structure and for search for NEW Physics beyond Standard Model

- Theoretical developments in Strong QCD:
  - Lattice QCD
  - Schwinger-Dyson, Continuum Schwinger Method
  - adS/CFT, Holographic QCD
  - …



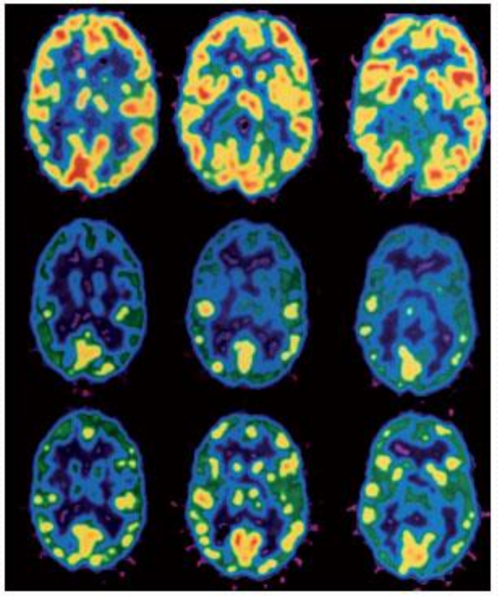


A. Deur, V. Burkert, J. P. Chen and W. Korsch Particles, 5-171 (2022)

Why Spin: Nature Spin Milestones

- Nature: (www.nature.com/milestones/milespin)
  - 1896: Zeeman effect (milestone 1)
  - 1922: Stern-Gerlach experiment (2)
  - 1925: Spinning electron (3)
  - 1928: Dirac equation (4)
  - Quantum magnetism (5)
  - 1946: Nuclear magnetic resonance (NMR) (8)
  - 1950-51: NMR for chemical analysis (10)
  - 1973: Magnetic resonance imaging (MRI) (15)
  - 1975-76:NMR for protein structure determination (16)
  - 1990: Functional MRI (19)
  - 1997: Semiconductor spintronics (23)
  - 1935: Proton anomalous magnetic moment
  - 1980s: Proton spin puzzle
  - Transverse spin puzzle and more…
  - Breakthroughs in nucleon spin study?

Pauli and Bohr watch a spinning top



Nucleon Spin Structure Study

- 1980s: EMC (CERN) + early SLAC

  quark contribution to proton spin is very small

  $\Delta\Sigma = (12 +- 9 +- 14)\%$! ‘spin crisis’ or “spin puzzle”

- 1990s: SLAC, SMC (CERN), HERMES (DESY)

  $\Delta\Sigma = 20\text{–}30\%$, the rest: gluon and quark orbital angular momentum

  $(½)\Delta\Sigma + L_q + \Delta G + L_G = 1/2$ Jaffe-Manohar sum rule

  $(½)\Delta\Sigma + \mathcal{L}_q + J_G = 1/2$ Ji sum rule

  Bjorken Sum Rule verified to <10% level

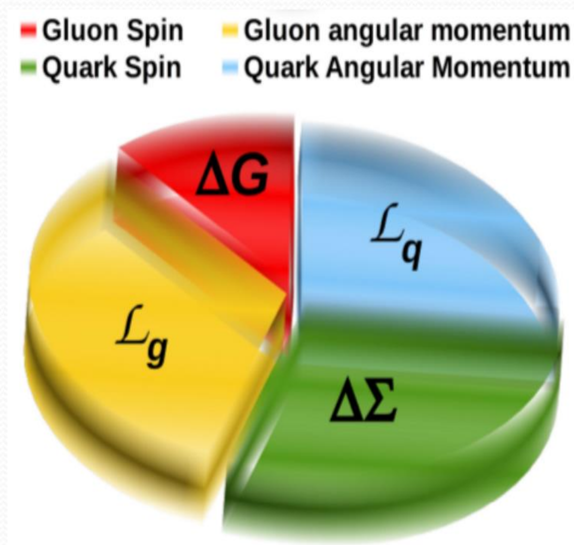
- 2000s- COMPASS (CERN), HERMES, RHIC-Spin, JLab

  $\Delta\Sigma \sim 20\text{–}30\%$; ΔG not small (RHIC-Spin, future EIC)

  Orbital angular momentum significant → 3-d structure

  High-x (valence quark): Clean Region

  Sea quark important



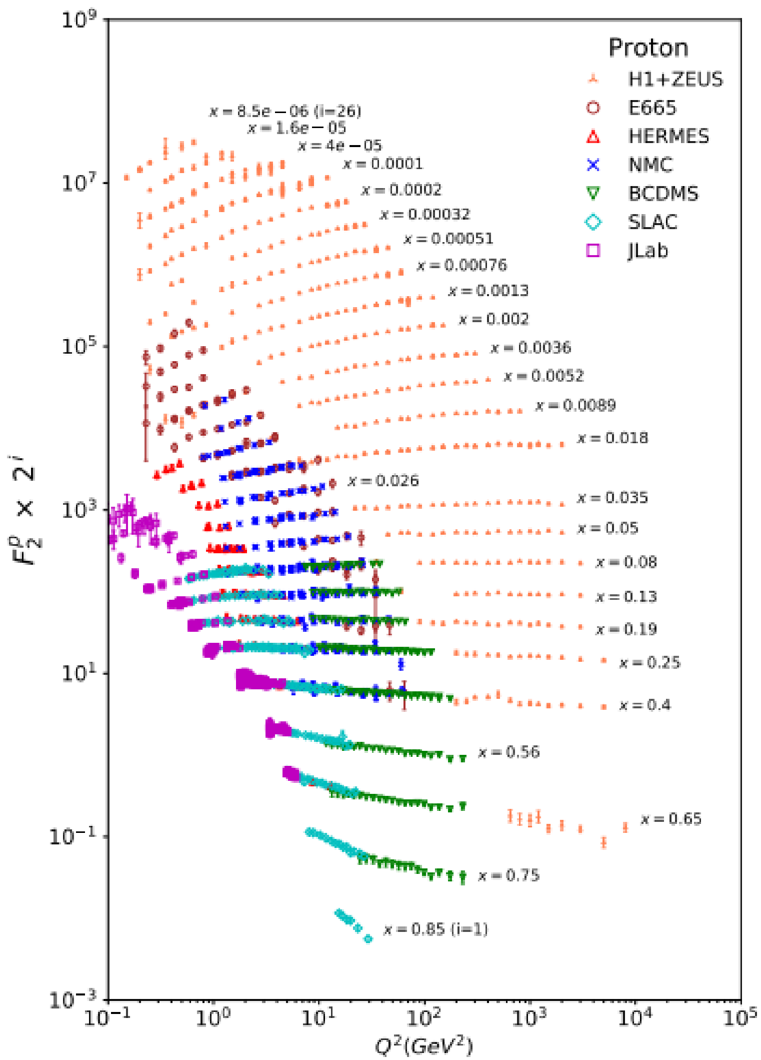
Reviews: Sebastian, Chen, Leader, arXiv:0812.3535, PPNP 63 (2009) 1;

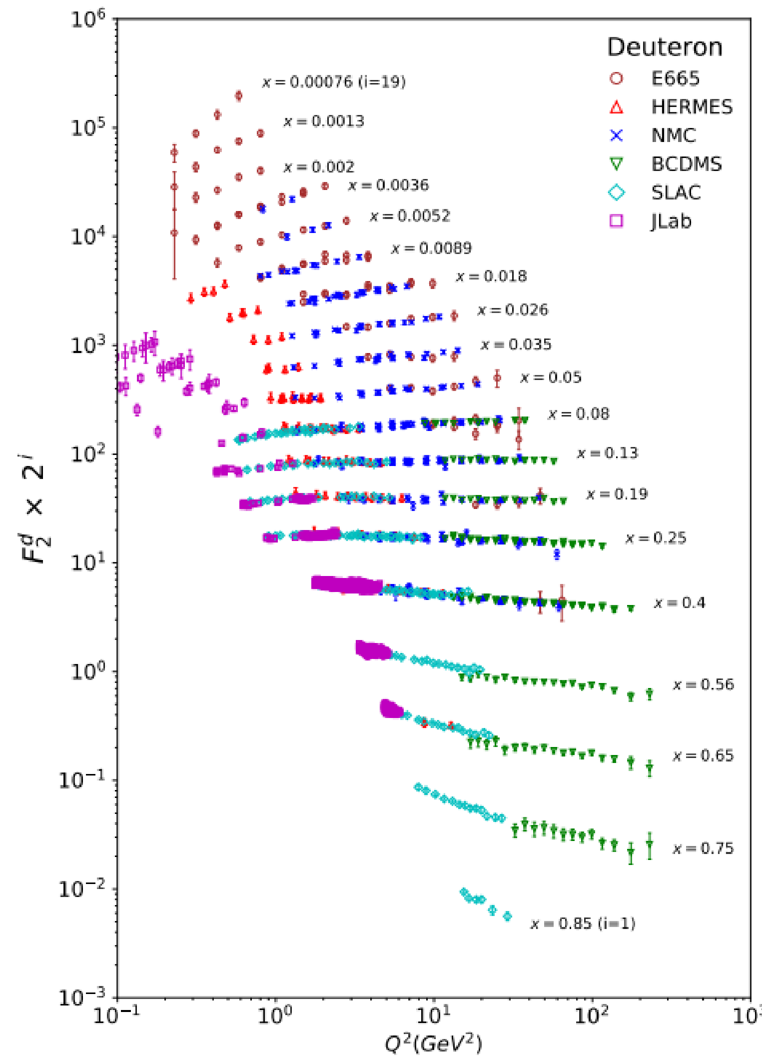
J. P. Chen, arXiv:1001.3898, IJMPE 19 (2010) 1893

Spin Chapter in Encyclopedia: B. Badelek and J. P. Chen, to be published (2026)

Structure of the Nucleon (Unpolarized)

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





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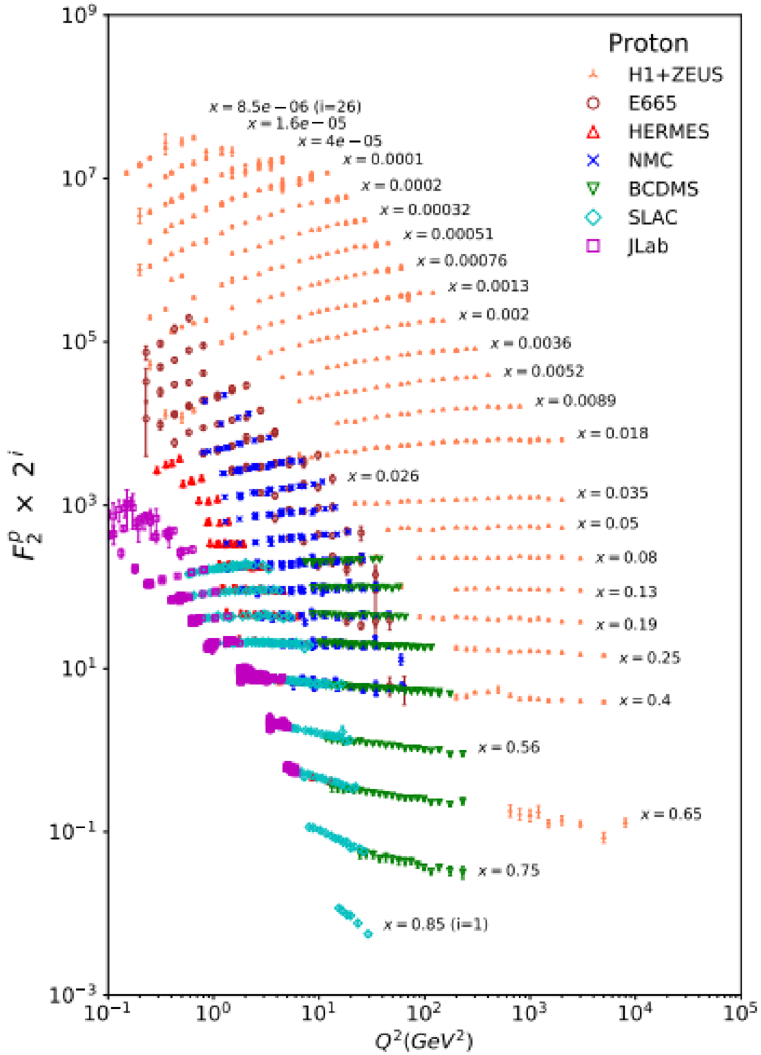
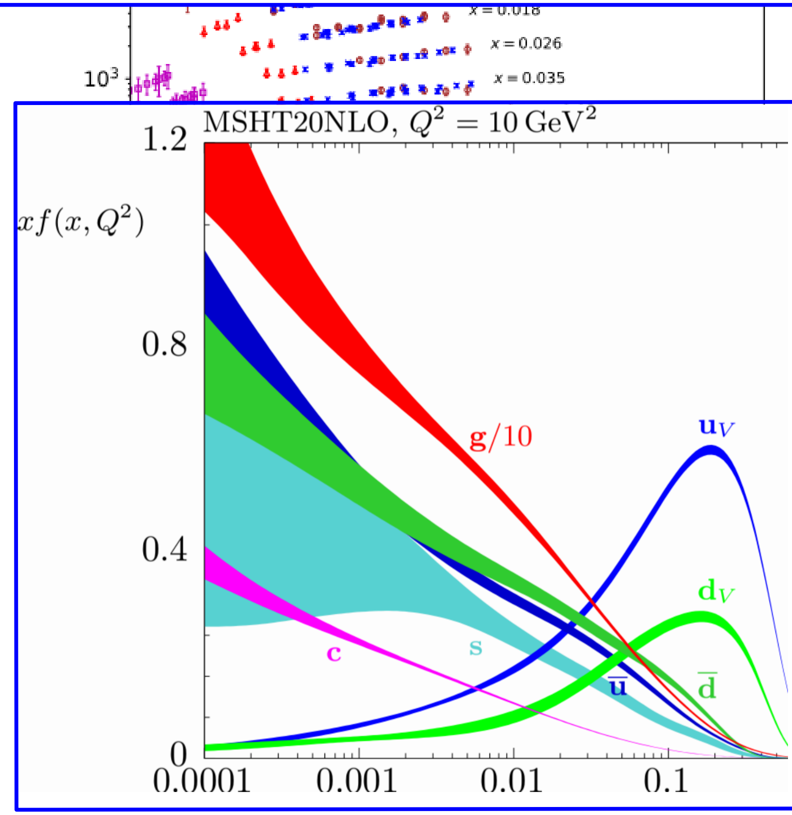


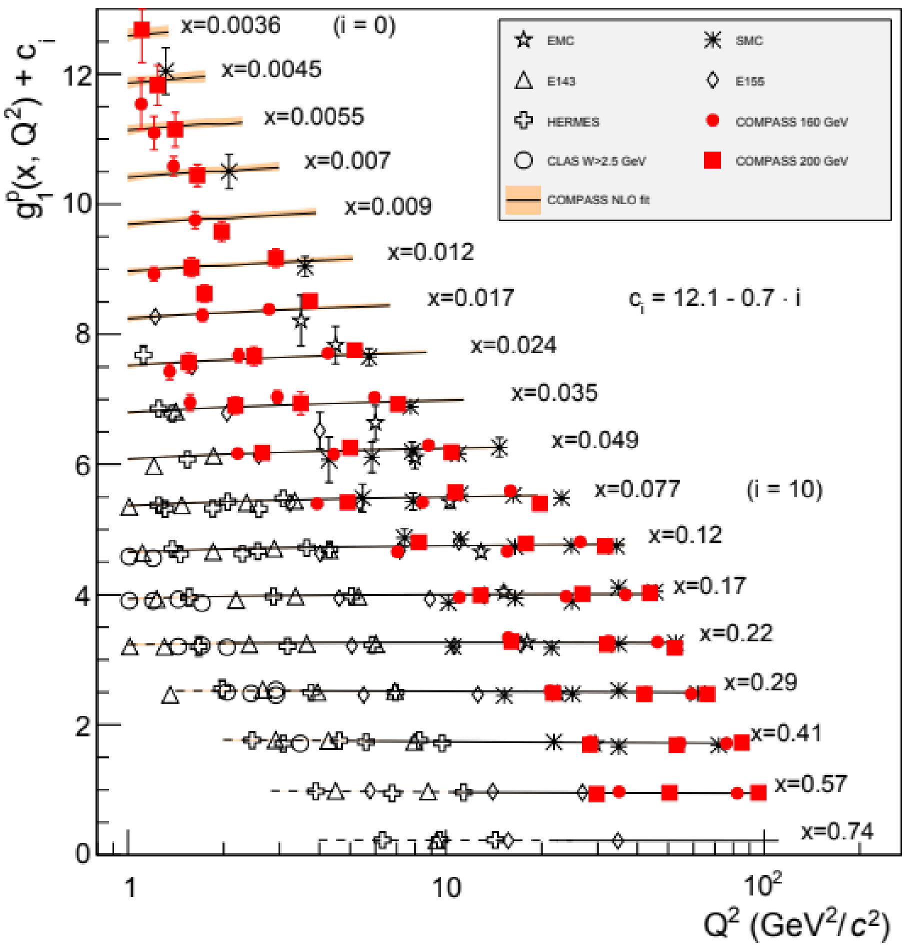
Bjorken scaling: experimental evidence of point-like, spin-1/2 quarks inside the nucleon

Scaling violation: best evidence that QCD works
Data agree with QCD (NLO) calculations very well



Spin Structure of the Nucleon

proton



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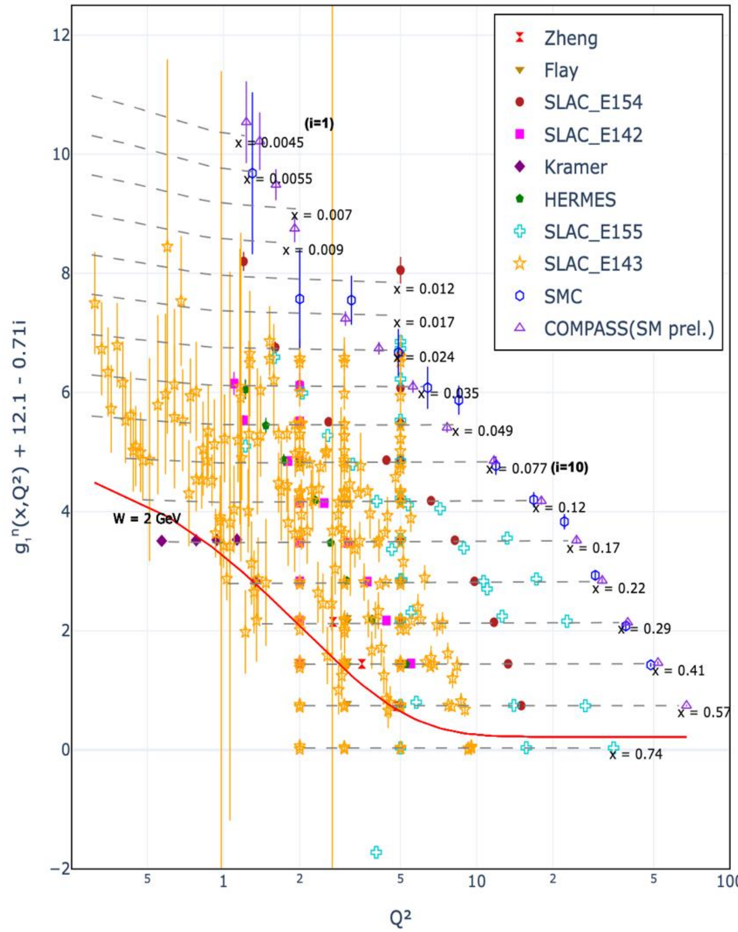
neutron

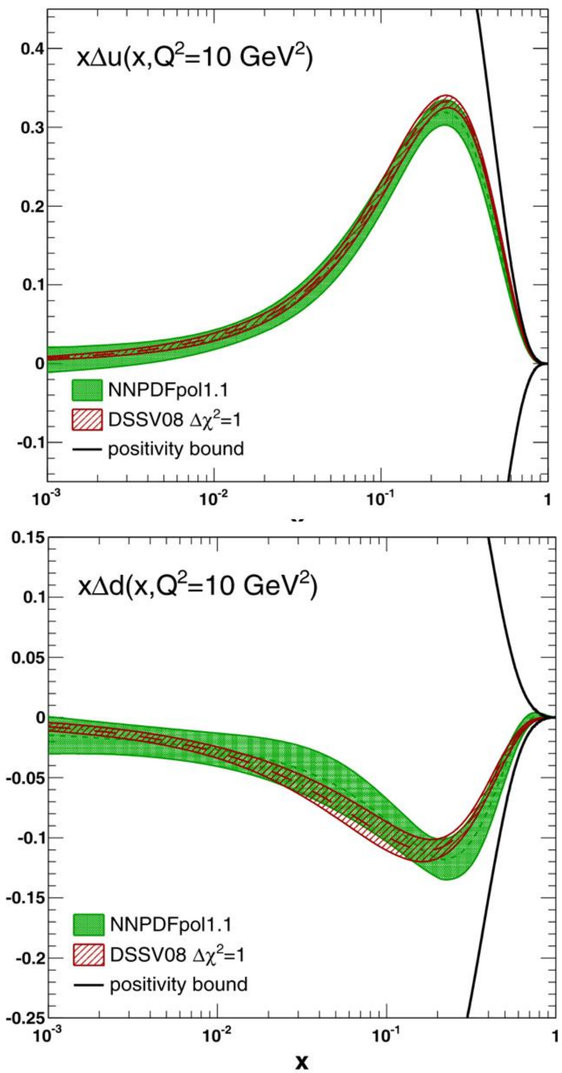


website built by Scarlett Morse (UVA):
https://qnz3gx.github.io/sim.github.io/

Polarized PDFs of the Nucleon

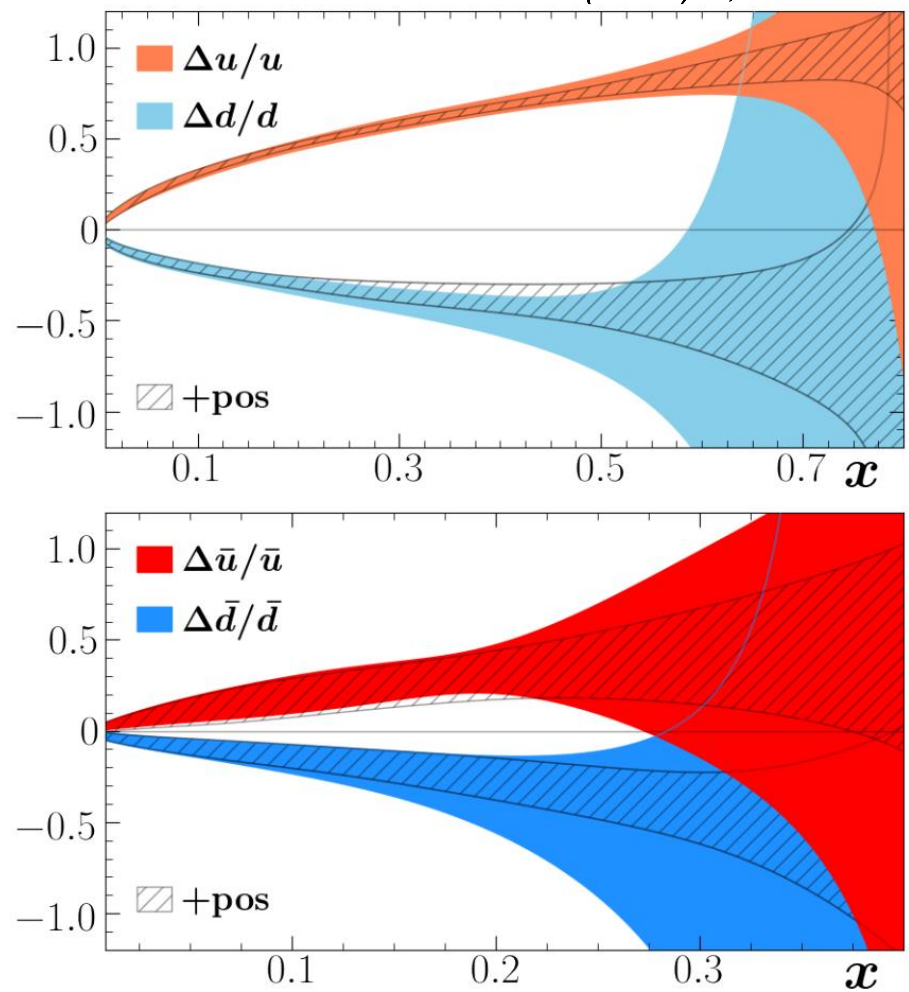
NNPDF pol 1.1

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



JAM Analysis

C. Cocuzza et al., PRD 106 (2022) 3, L031502

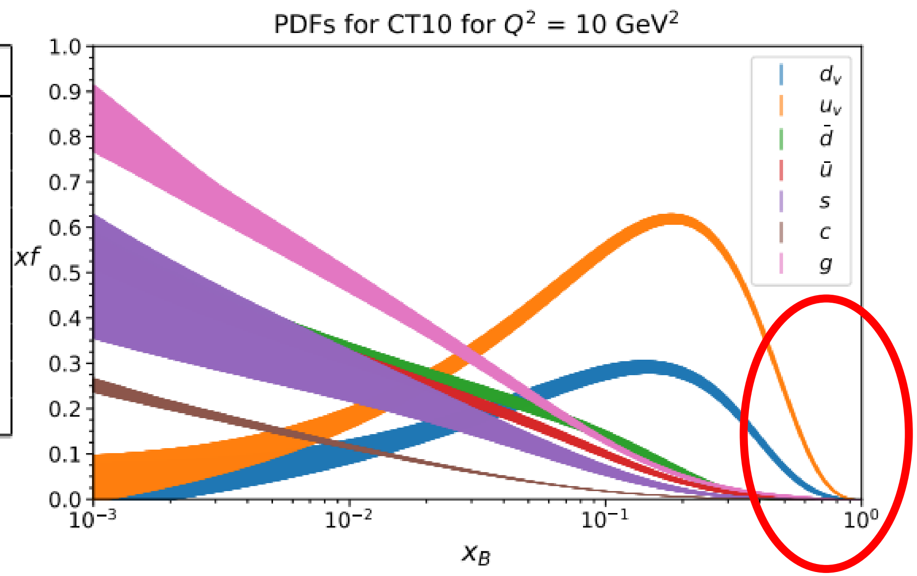


light quark polarization at Q^2=10 GeV^2.

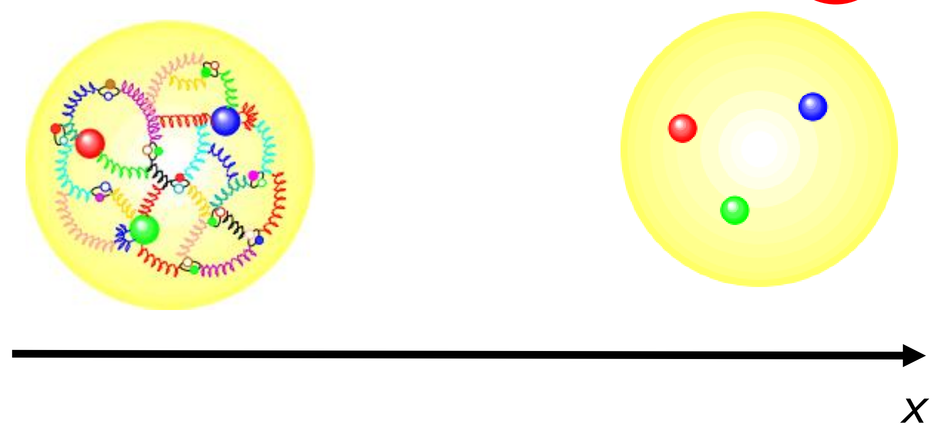
Why high x?

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

Model	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
CSM	0.45(5)	0.23(6)	-0.14(3)	0.63(8)	-0.38(7)	0.15(5)	0.58(8)
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	0.2	-0.06	0.8	-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
HLFQCD	0.28	0.035	0.035	1	1	1	1



- a clean region where QCD (and models) can make predictions for (the ratio of) structure functions
- ratios of pol/unpol pdfs at x→ 1 provide unambiguous, scale invariant, non-perturbative features of QCD



Spin at high x

Model	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
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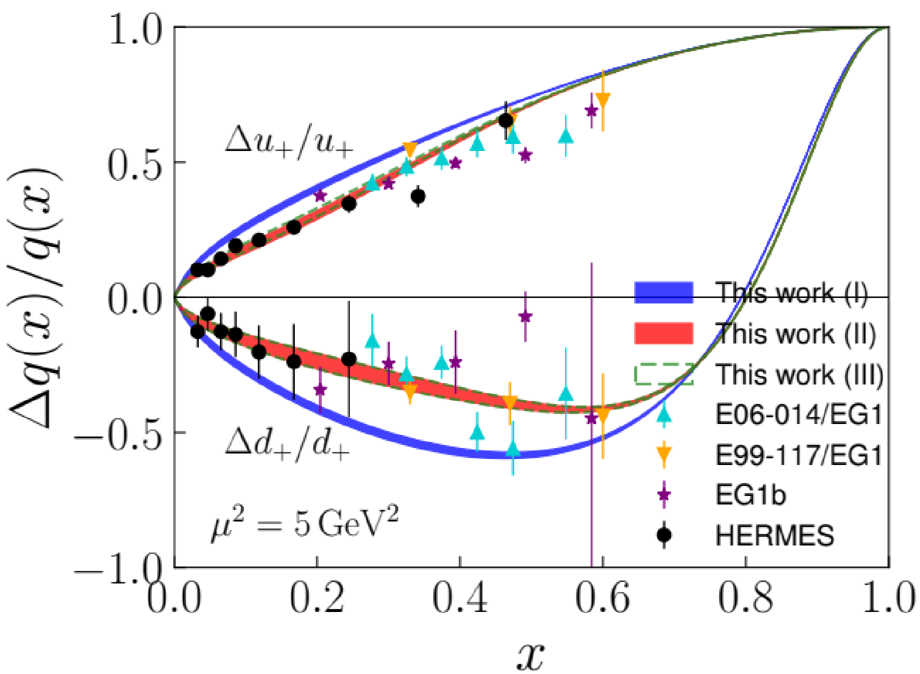
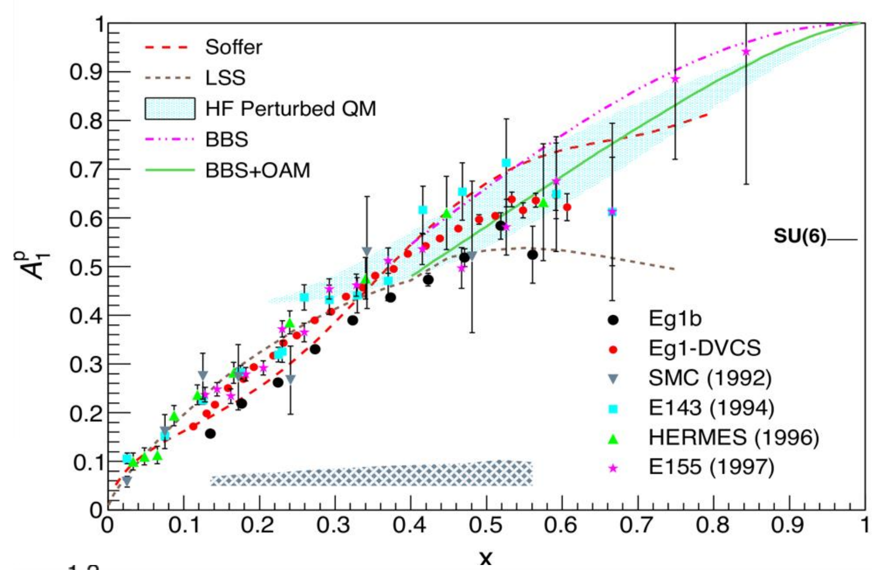
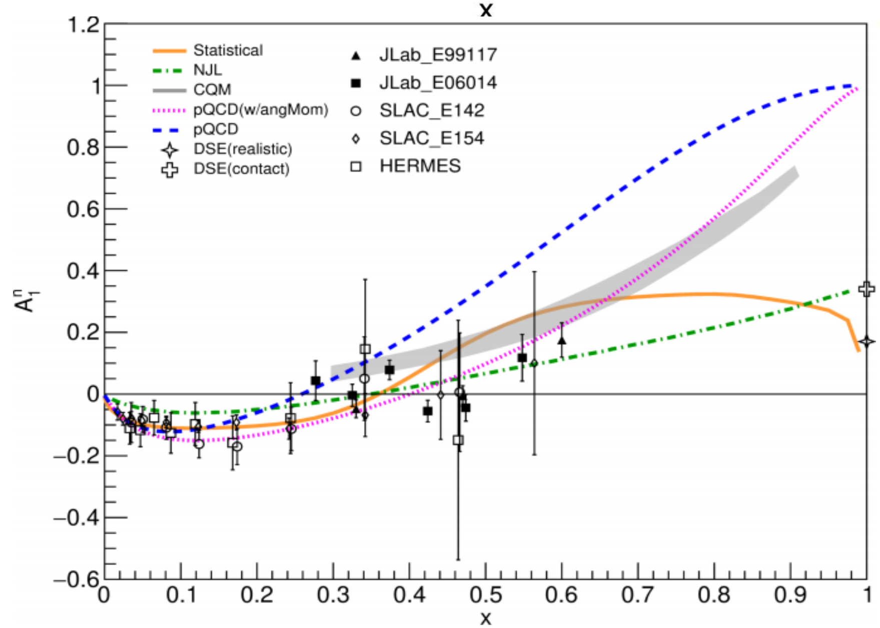


T. Liu et al., Phys. Rev. Lett. 124, 082003 (2020)arXiv:1909.13818





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

JLab 12 GeV A_1n Experiment

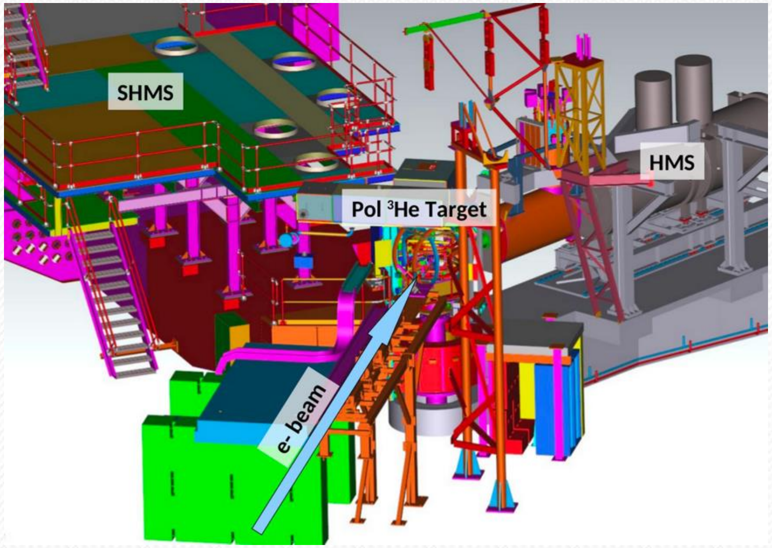
E12-06-110 in Hall C

A_1n@High-x: E12-06-110 in Hall C

Spokespersons: X. Zheng, G. Cates, J. P. Chen, Z. E. Meziani
Ph.D Students: M. Chen, M. Rehfuss

- 30 uA, 85% polarized 10.4 GeV electron beam
- 40 cm L/T polarized ^{3}He with in-beam polarization reach up to 60% (average ~ 55%)
  luminosity ($2x10^{36}$ $cm^{-2}s^{-1}$) and FOM are
  a factor of 2 improved over the world record
- HMS and SHMS detecting electrons in the inclusive mode

Data taking from Dec. 2019 to March 2020



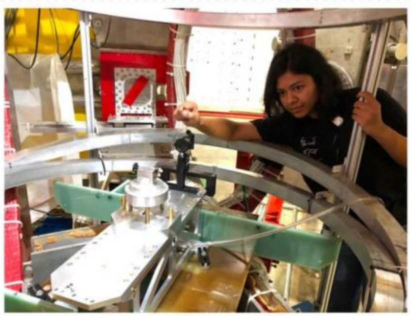
Kine	Spec	E_b GeV	E_p GeV	θ ($\circ$)	beam time (hours)
Δ(1232)	SHMS	2.17	-1.79736	8.5	4.0
Elastic	SHMS	2.17	-2.12860	8.5	8.0

Kine	Spec	E_b GeV	E_p GeV	θ ($\circ$)	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

Hall C 12 GeV A_1n/d_2n Collaboration

PhD (all graduated) **People** Spokespeople

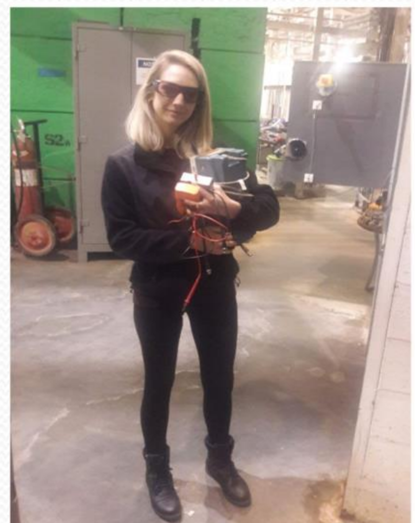
D. Androic, W. Armstrong, T. Averett, X. Bai, J. Bane, S. Barcus, J. Benesch, H. Bhatt, D. Bhetuwal, D. Biswas, A. Camsonne, G. Cates, J-P. Chen, J. Chen, M. Chen, C. Cotton, M-M. Dalton, A. Deur, B. Dhital, B. Duran, S.C. Dusa, I. Fernando, E. Fuchey, B. Gamage, H. Gao, D. Gaskell, T.N. Gautam, N. Gauthier, 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, I. Li, 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, R. Trotta, A. Usman, H. Voskanyan, S. Wood, B. Yale, C. Yero, A. Yoon, J. Zhang, Z. Zhao, X. Zheng, *J. Zhou*



M. Chen

Institutions

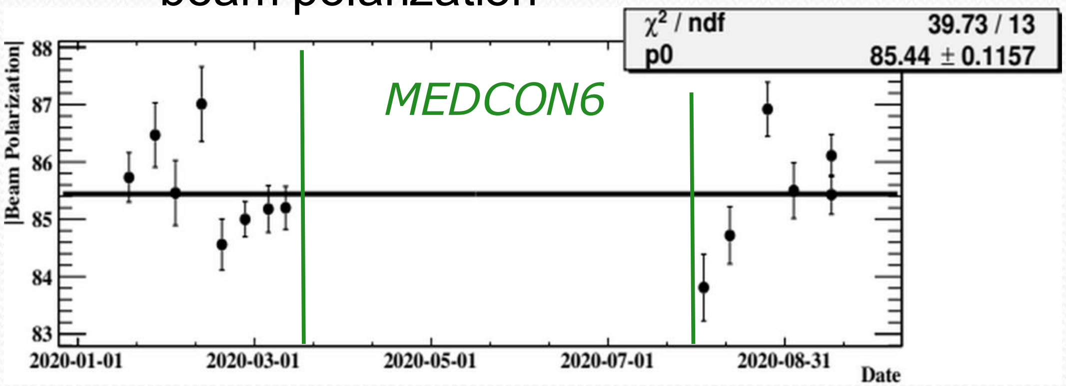
A.I. Alikhanian National Science Laboratory; Argonne National Laboratory; Artem Alikhanian National Laboratory (AANL).; Christopher Newport University; Duke University; Florida International University; Hampton University ; James Madison University ; Jefferson Lab; Kent State University; Mississippi 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

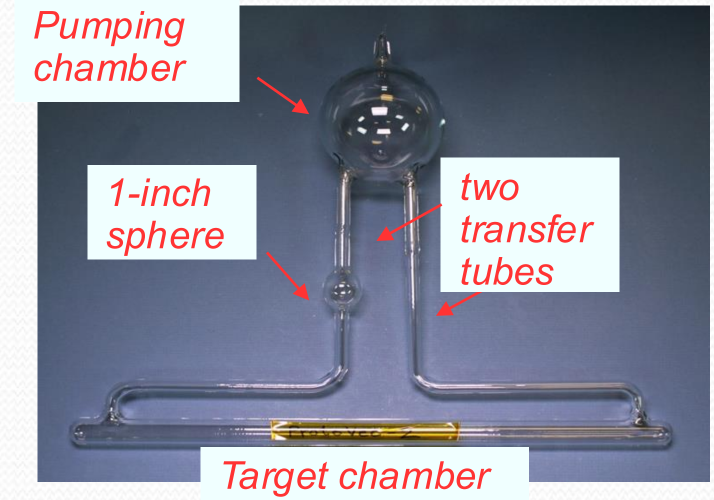


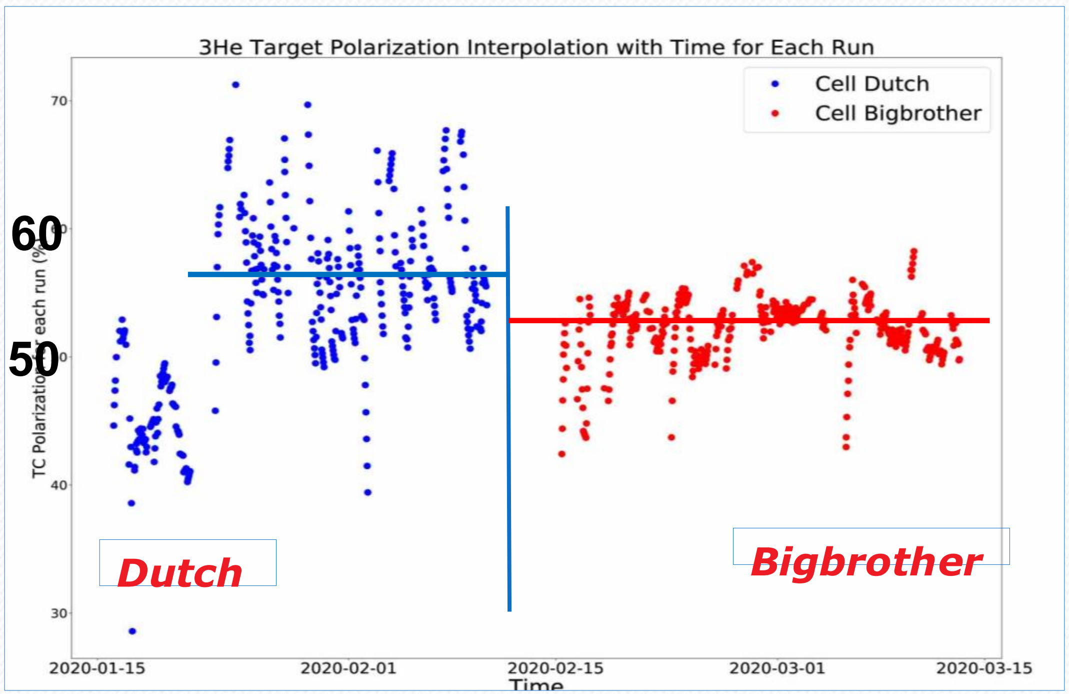
M. Rehfuss

Polarizations During A_1n

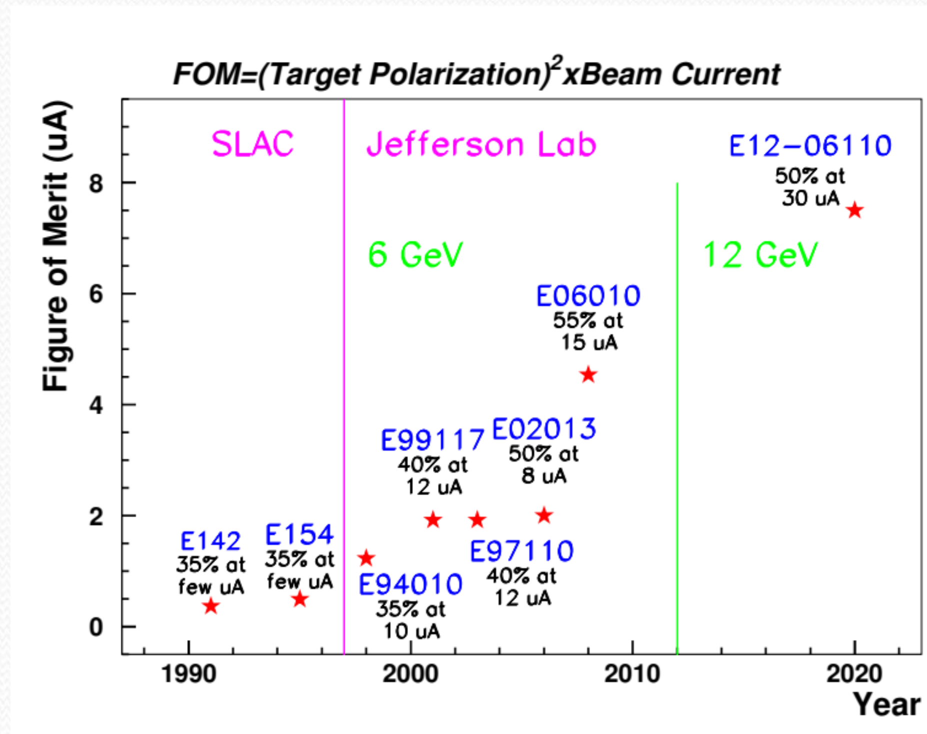
beam polarization





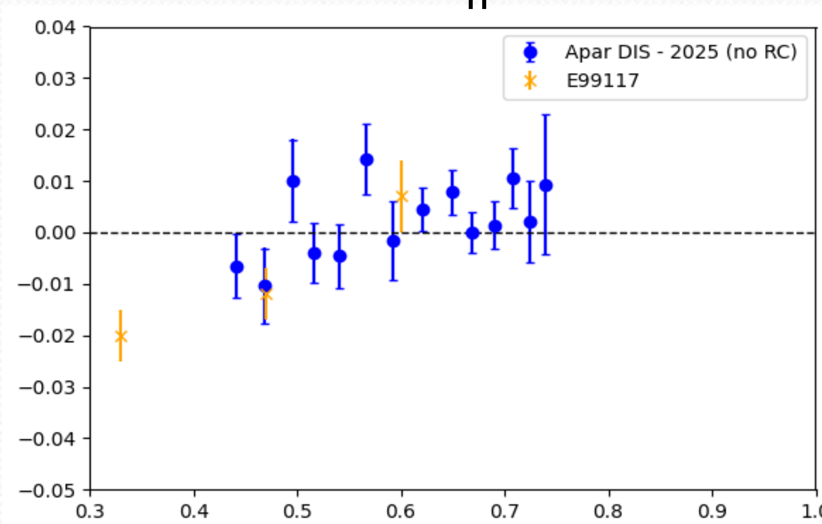


target polarization

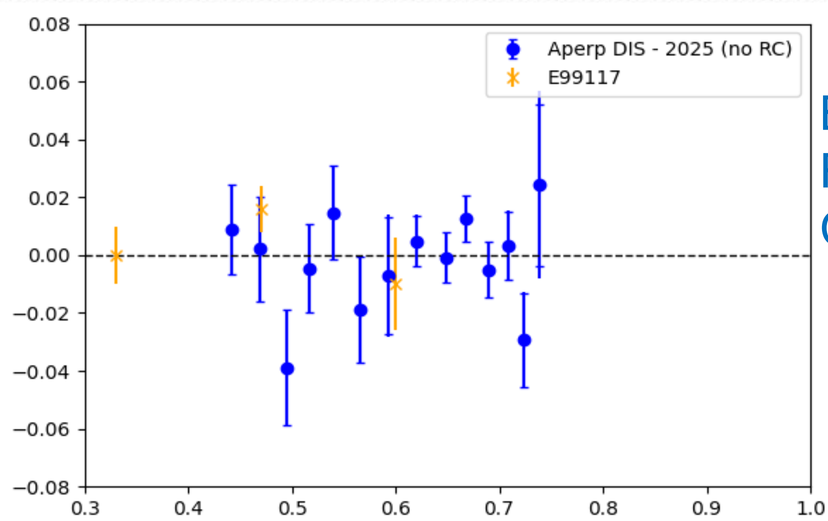


Preliminary Results on ^{3}He Asymmetries (DIS)

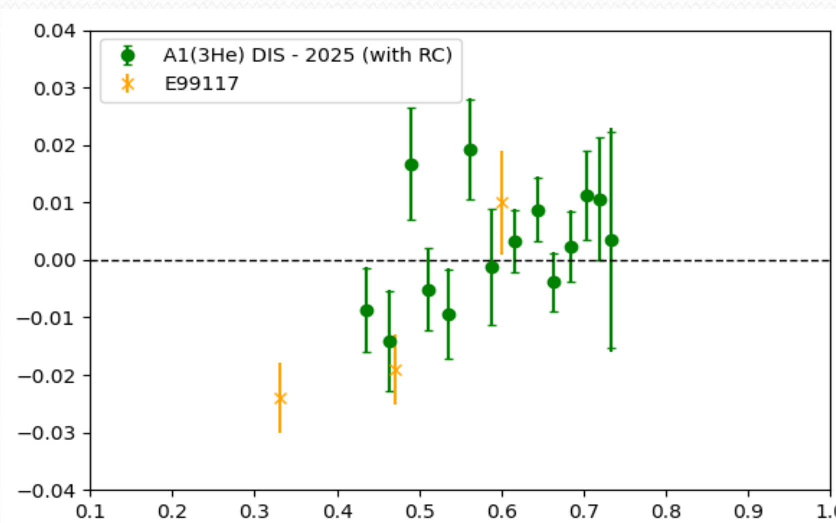
$A_{||}$

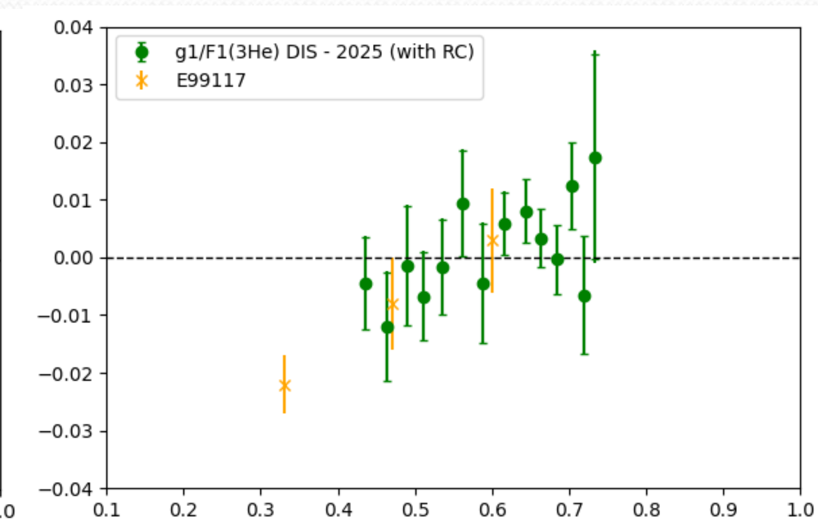


$A_{\perp}$



Before Radiative Corrections





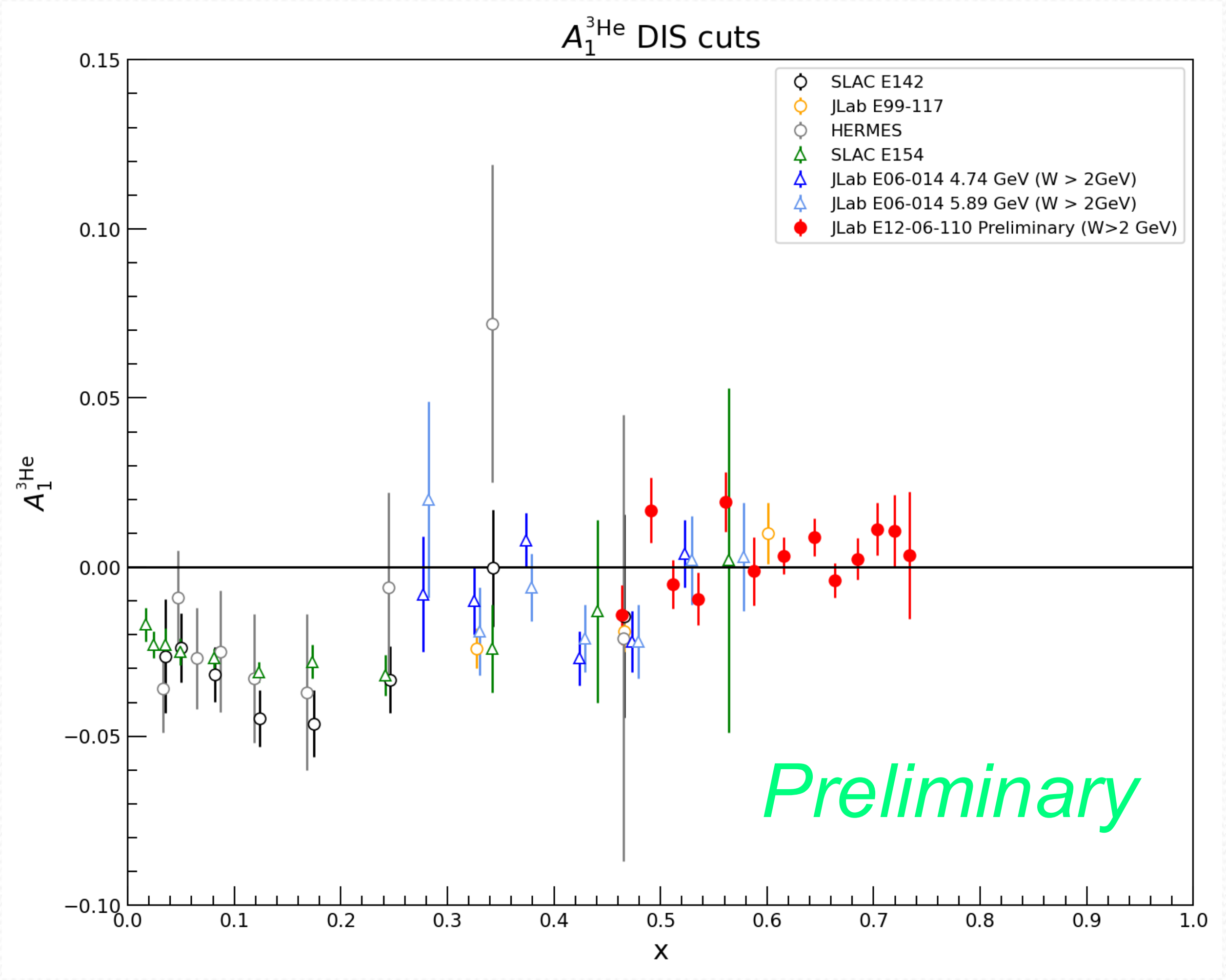
After Radiative Corrections

A_1

g_1/F_1

Preliminary Results on $A_1(^3He)$ (DIS)

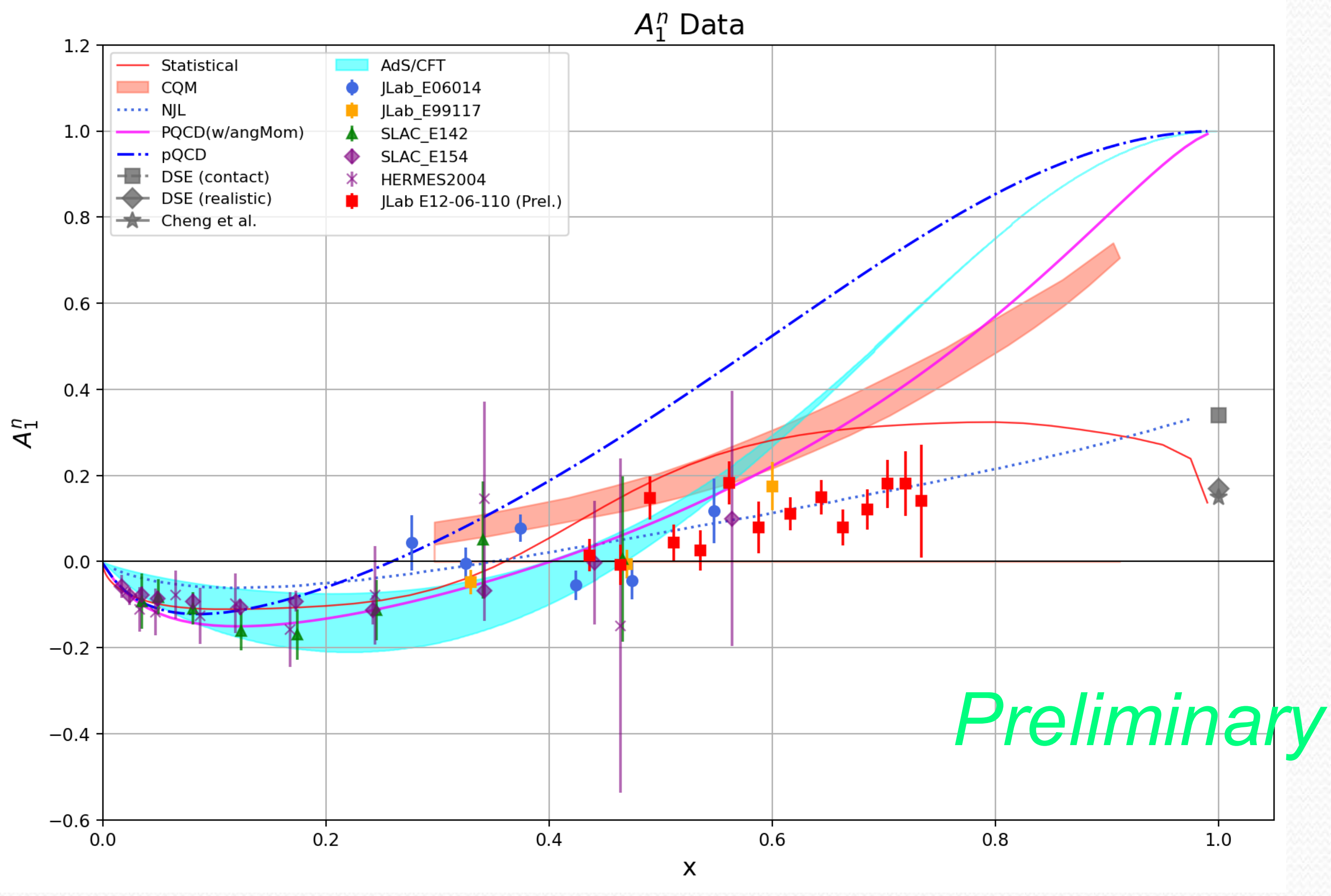
$$A_1 = \frac{1}{D(1+\eta\xi)}A_\parallel - \frac{\eta}{d(1+\eta\xi)}A_\perp$$



Preliminary Results on A_1n (DIS)

A_1n extracted using effective polarizations, a fit for the proton A_1p, F1F2-21 (p, n, plus our own ^3He fit)

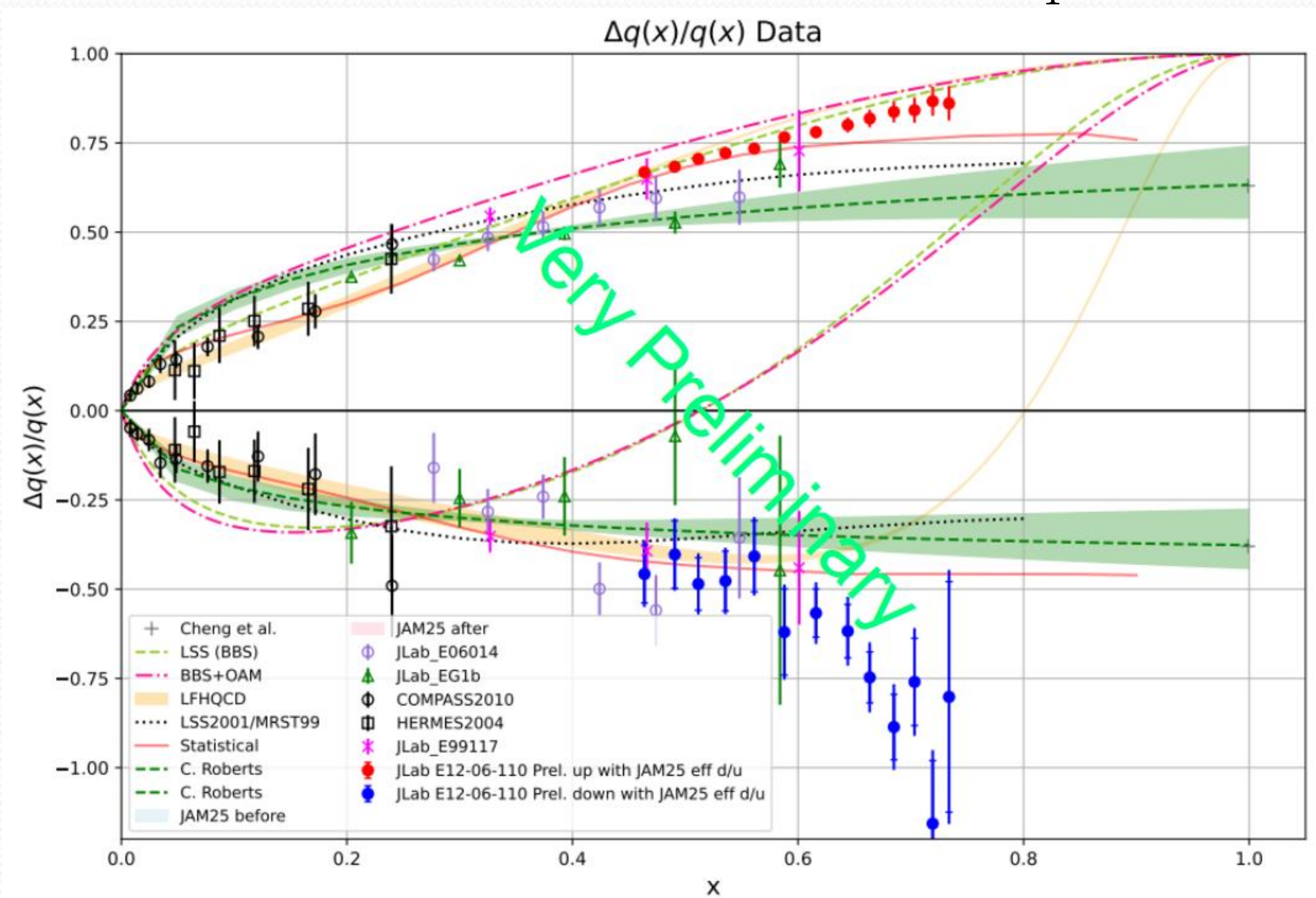
$$A_1^n = \frac{1}{P_n}\frac{F_2^{^3He}}{F_2^n}\left(A_1^{^3He} - 2P_p\frac{F_2^p}{F_2^{^3He}}A_1^p\right)$$



Preliminary Results on Quark Polarizations

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

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



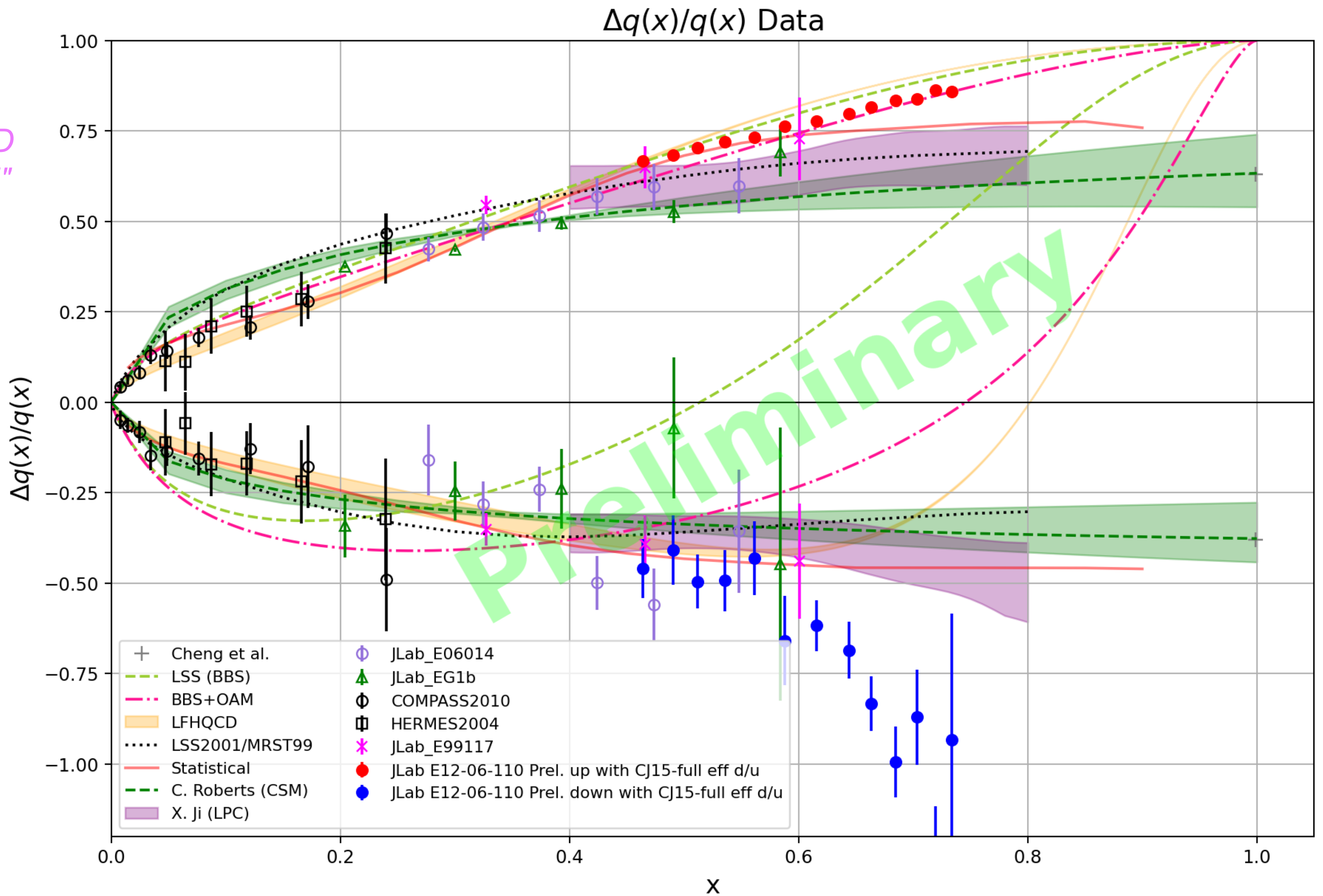
$$R^{du} = \frac{d + \bar{d}}{u + \bar{u}}$$

At high x, we need to consider significant TMC and dynamic HT

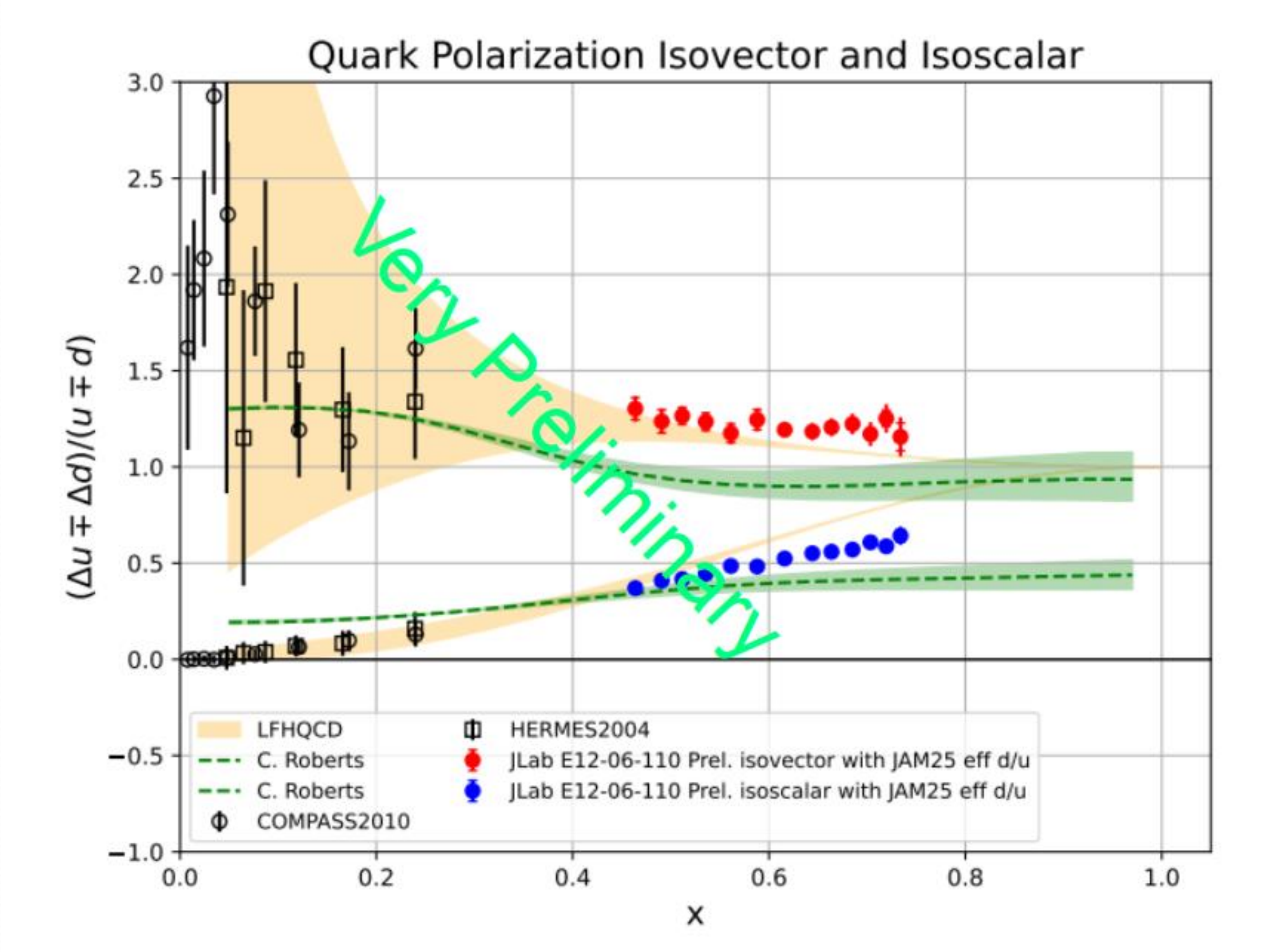
Comparison with predictions:

- *X. Ji et al: LQCD*
  "LPC, to be published"
  LPC: = Lattice Parton Collaboration (based in China)
- *C. Roberts et al.: CSM*
- *T. Liu et al.: LFHQCD.*

…



Isospin (Flavor) Combinations



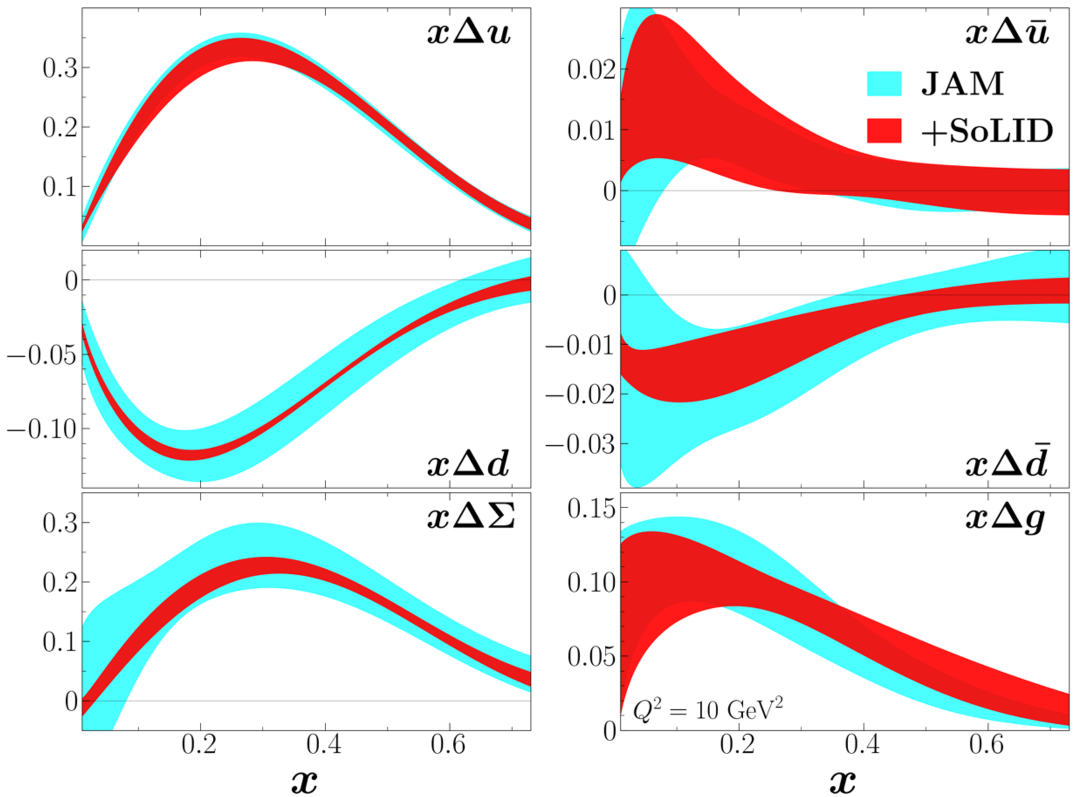
Future: Precision Spin Program with SoLID

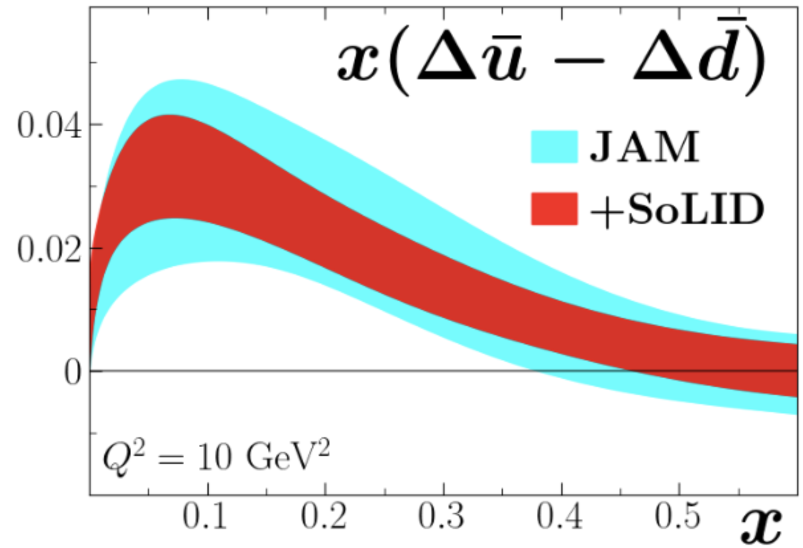
Flavor separation – valence and sea quark spin

SoLID Run-group Proposal: SIDIS with Polarized ^{3}He

JAM QCD global analysis: **from Christopher Cocuzza**

Constrains light valence and sea quark polarized PDFs



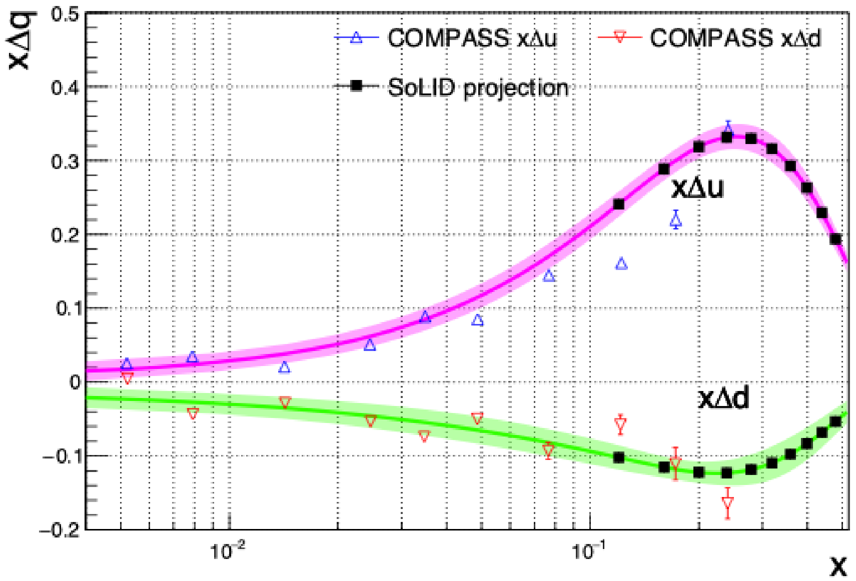


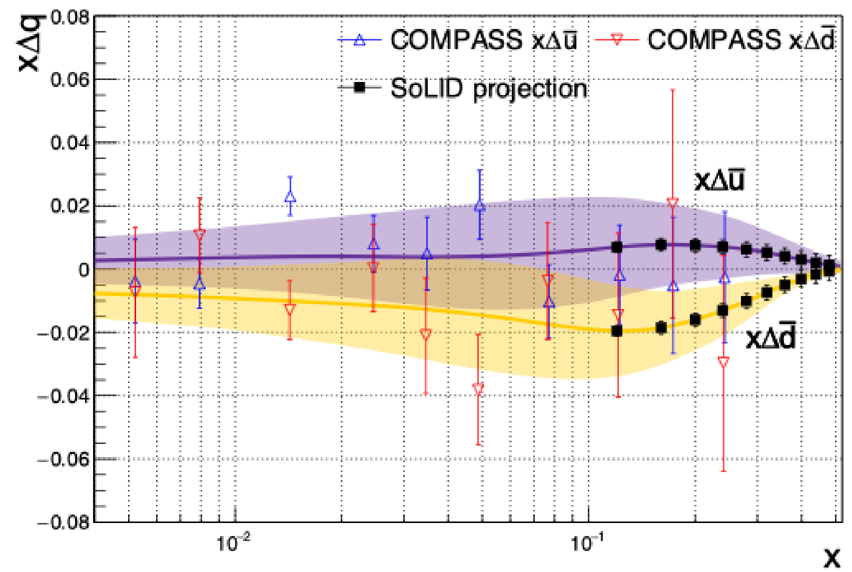
- SoLID's polarized ^{3}He SIDIS data will tighten uncertainties on both valence and sea helicity PDFs, with main impact on d and d_bar quarks

- SoLID helps test if the polarized sea is **flavor asymmetric**

SoLID @ JLab22 SIDIS Polarized u, d and Sea PDFs

- LO extraction (assuming x-z factorization)
  Using LO Fragmentation Function DSSFFLO
- Order-of-magnitude improvements in statistic precision for light sea PDFs





Bands are current uncertainties from NNPDF

Summary and Outlook

- Experiment E12-06-110 measurement of the neutron A_1
  - 10.4 GeV 85% beam; 40cm long ~55% polarized ^3He target, 30 uA beam
  - DIS up to x=0.75
- Progress:
  - 3He asymmetries done
  - Neutron asymmetries extracted using effective pol method done
  - Quark polarizations – simple extraction done
  - First paper drafted
  - Inclusive pion cross section and asymmetry extraction started
- Physics:
  - At high x, A_1n does not approach 1 as pQCD calculations predicted
  - The trend increases less rapid than global fits to earlier data
  - d quark polarization stays negative: non-perturbative nature?
- Future:
  - Precision study of valance and sea quark spin planned with SoLID

JLab is making great contributions to the precision study of nucleon spin