Nucleon Spin Structure from Inclusive Lepton Scattering

Xiaochao Zheng
（郑晓超 , Tsinghua U. B. Eng '96, M.S. '99 ）
University of Virginia

- One Century of Spin
- Highlights of Jefferson Lab 1D Spin Experiments
  - Spin moments (sum rules and polarizabilities) at very low Q^2
  - Preliminary A_1^p and A_1^d from CLAS12 RGC
  - Preliminary $A_1(^3He)$ and A_1^n from Hall C E12-06-110
- Summary

Acknowledgment: Thanks to J.-P. Chen, S. Kuhn, and collaborators, and the JAM collaboration for providing the material

Jefferson Lab

1901 SHANDONG UNIVERSITY
山东大学

One Century of Spin

1922 Stern-Gerlach experiment

1925 Pauli's paper on the "two value-ness" of electrons

Kronig's idea on spin, as commented by Pauli: "it is indeed very clever but of course has nothing to do with reality"

Goudsmit & Uhlenbeck:

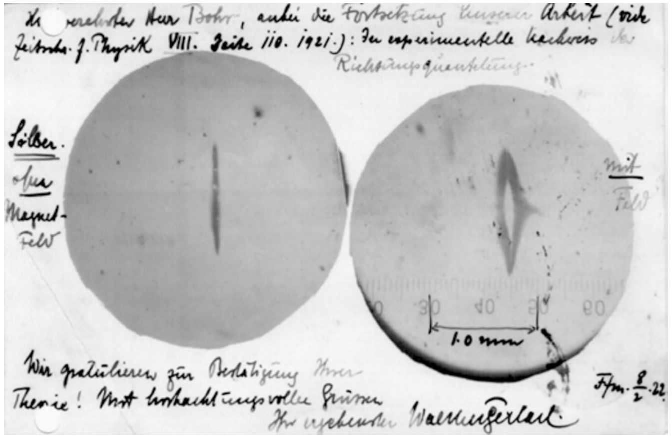
(Goudsmit:) "And I wrote a note in May that the Pauli principle became easier to understand when introducing different quantum …: mL and ms; ms being always the same, plus or minus 1/2. (In those days it was slightly different, one used 1 and 0, but that does not really matter.) And if you used these for the Pauli principle, then it became much simpler ...., as one does today of course.

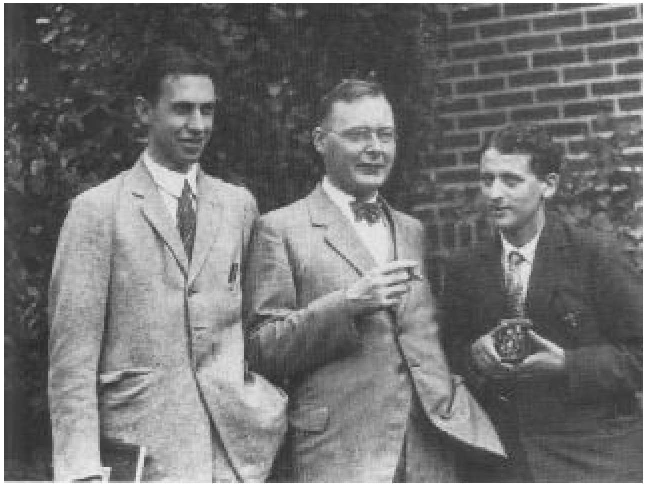
When the day came I had to tell Uhlenbeck about the Pauli principle -- of course using my own quantum numbers -- then he said to me: "But don't you see what this implies? It means that there is a fourth degree of freedom for the electron. It means that the electron has a spin, that it rotates". then I asked him: "What is a degree of freedom?

… After Lorentz pointed out the self energy problem, Uhlenbeck got frightened, went to Ehrenfest and said: "Don't send it off, because it probably is wrong; it is impossible, one cannot have an electron that rotates at such high speed and has the right moment". And Ehrenfest replied: "It is too late, I have sent it off already". … … "Well, that is a nice idea, though it may be wrong. But you don't yet have a reputation, so you have nothing to lose".

And that was it: the spin; thus is was discovered, in that manner.

Uhlenbeck would later refer to the "luck and privilege to be students of Ehrenfest"



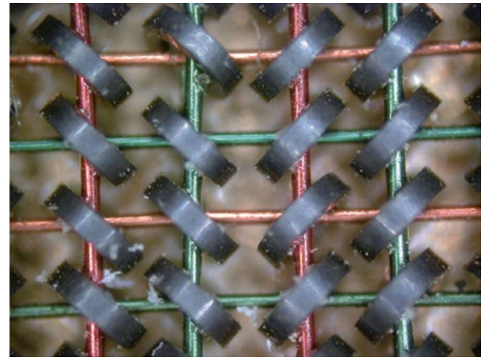


https://lorentz.leidenuniv.nl/history/spin/goudsmit.html

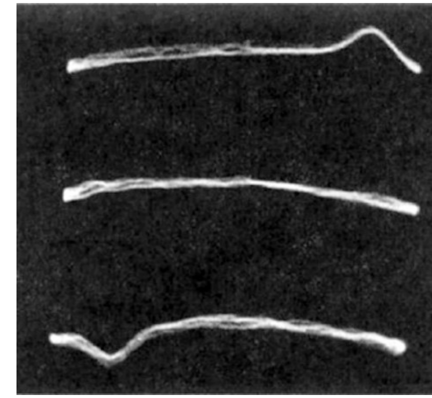
One Century of Spin

The Dirac equation

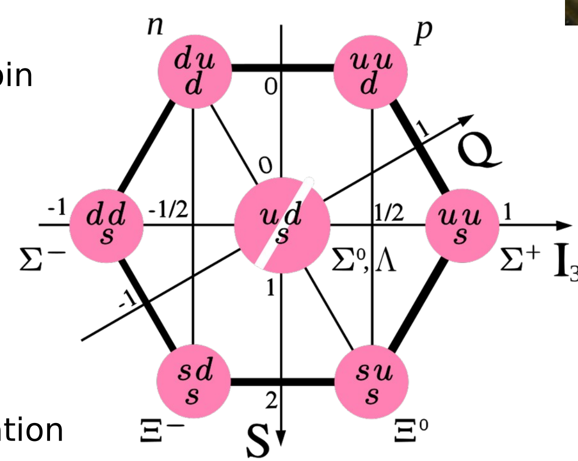
An illustration of RAM (as used for APOLLO)



The first NMR signal of water

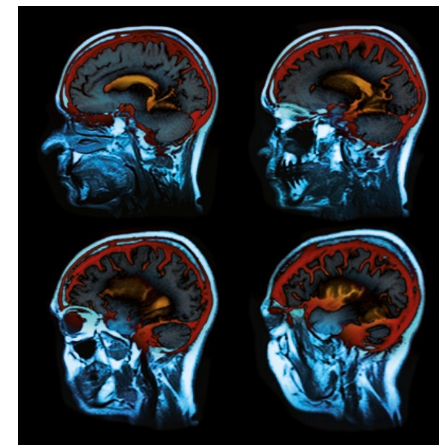


Isotopic spin

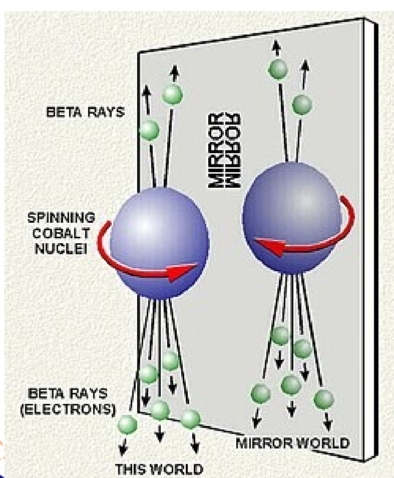


Revolution in data storage

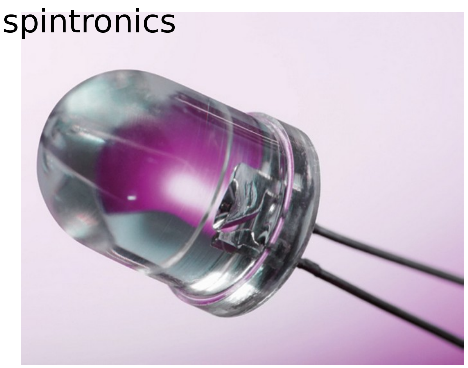
MRI



Parity violation

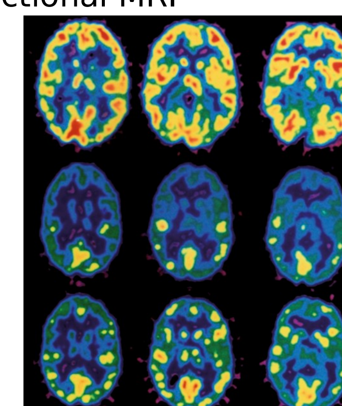


The rise of semiconductor spintronics



Quantum Computing!

functional MRI

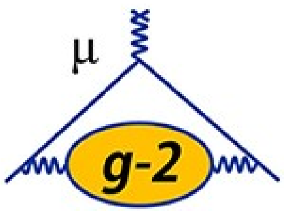


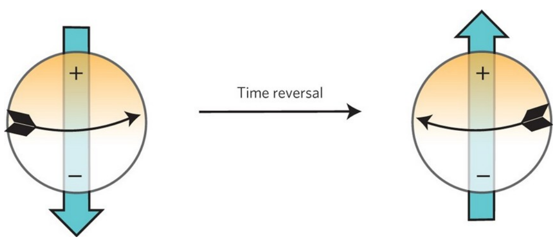
Ref: Nature Physics Milestones in Spin

One Century of Spin – at SPIN2025

山东大学
SHANDONG UNIVERSITY 1901

Beyond the Standard Model





MOLLER

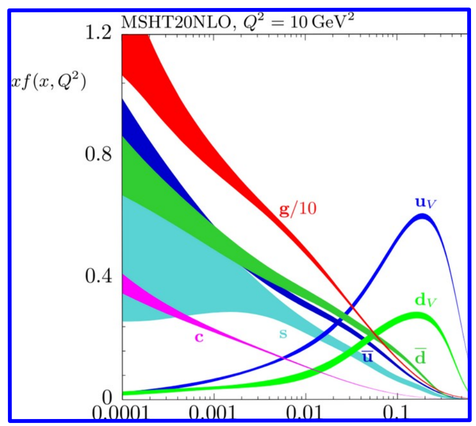
SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

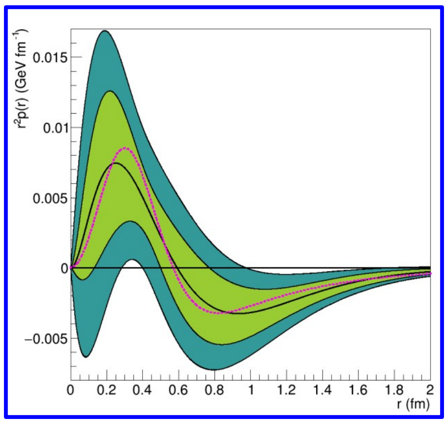
apologies if this list is short!

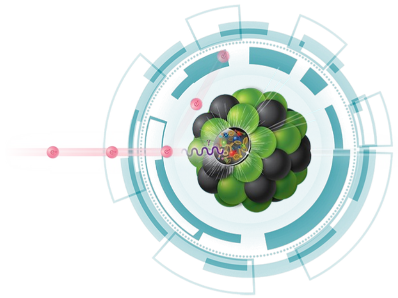
Properties of the Nucleon

PRoton Radius

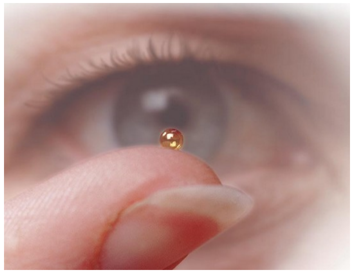
TMD

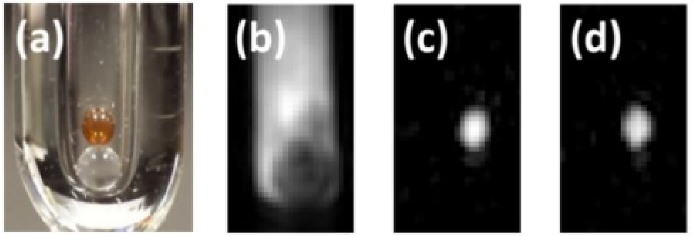






Spin Polarized Fusion

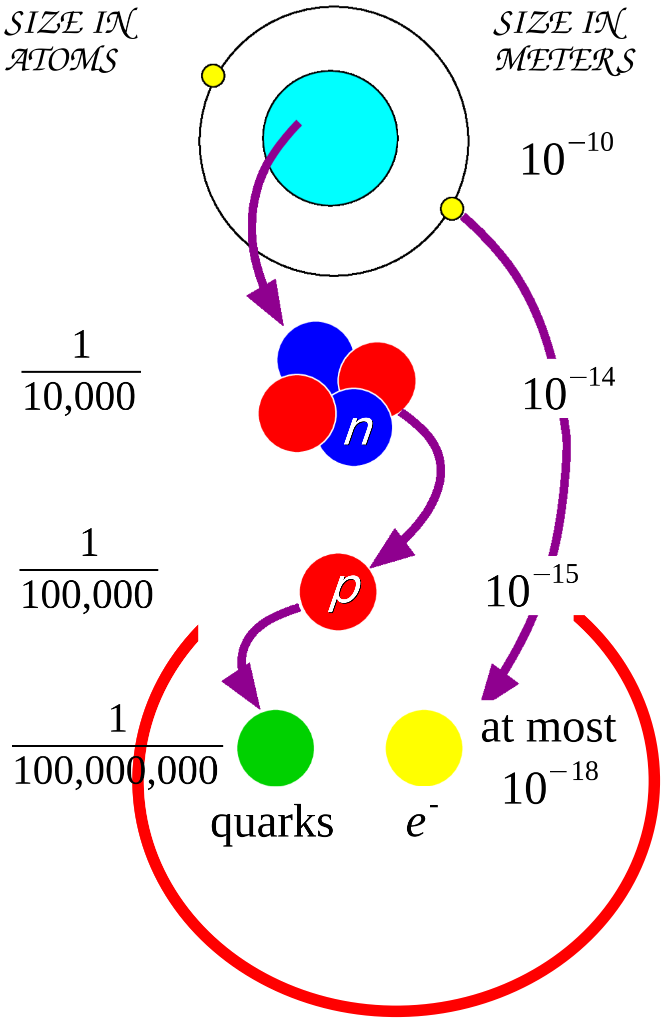




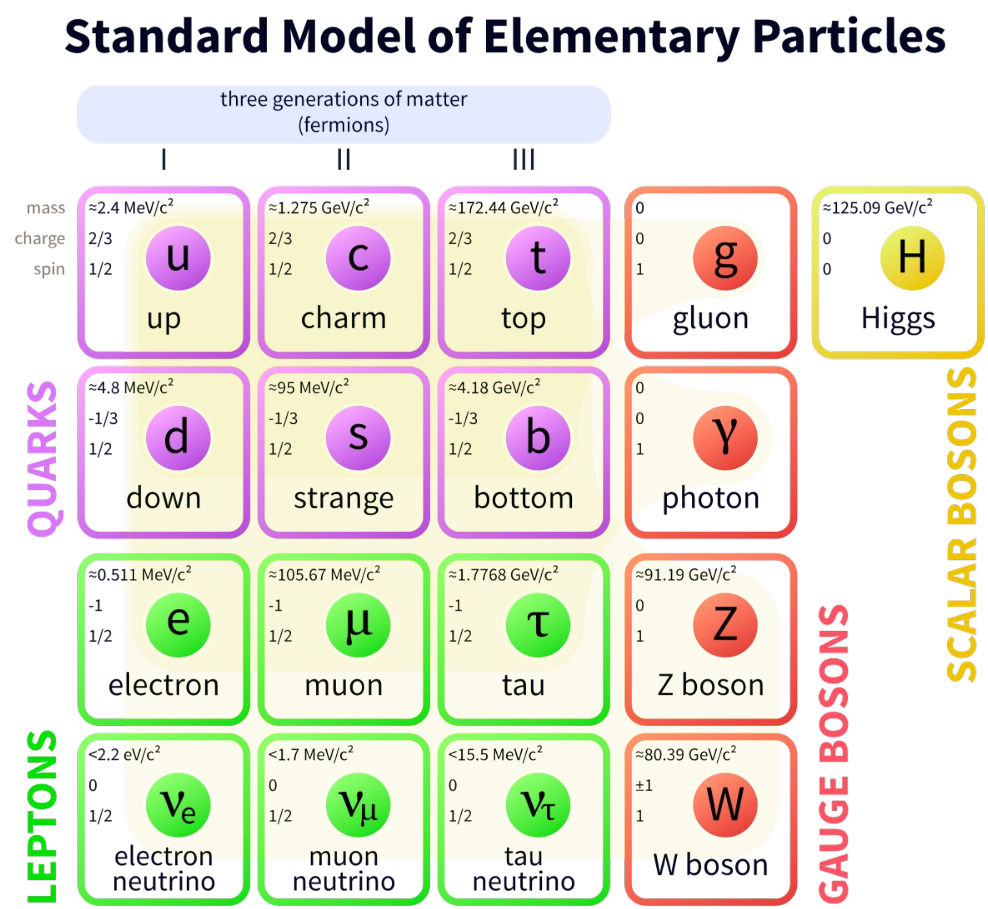
Jefferson Lab

26th International Spin Symposium (Spin2025), Sept.22-26, 2025, Qingdao, China

The Standard Model



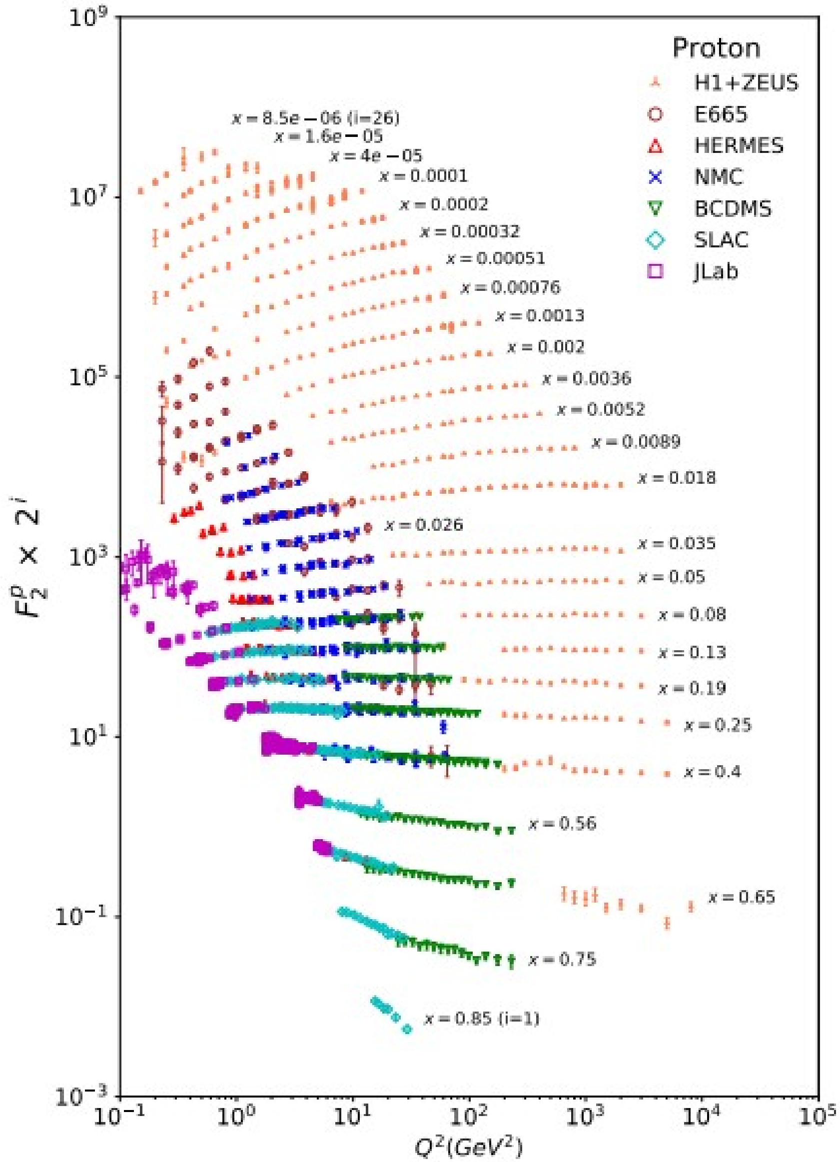
1) the elementary fermions – quarks and leptons
2) the symmetry + gauge invariance → interactions
3) mass of most elementary particles

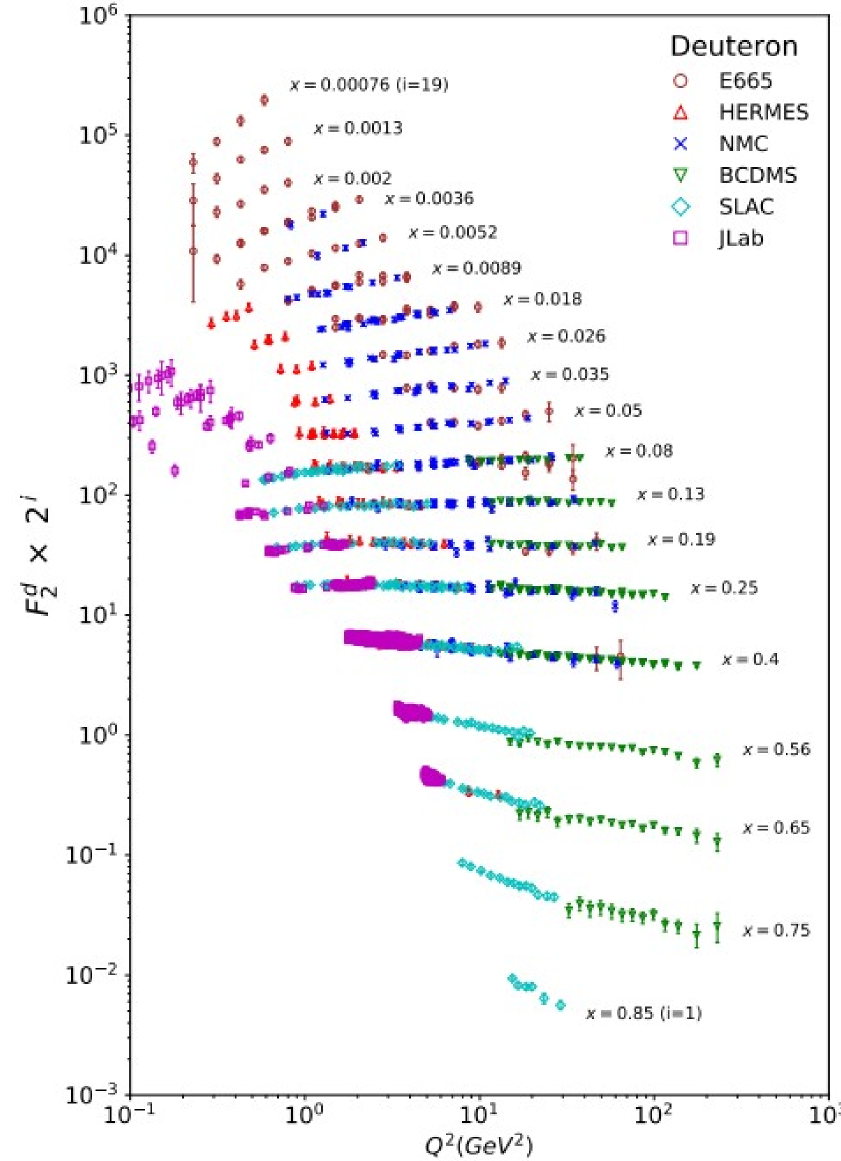


$$D^{\mu} = \partial^{\mu} - i\,g_1 \frac{Y}{2} B^{\mu} - i\,g_2 \frac{\tau_i}{2} W_i^{\mu} - i\,g_3 \frac{\lambda_{\alpha}}{2} G_{\alpha}^{\mu}$$

Success of QCD in the perturbative regime

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

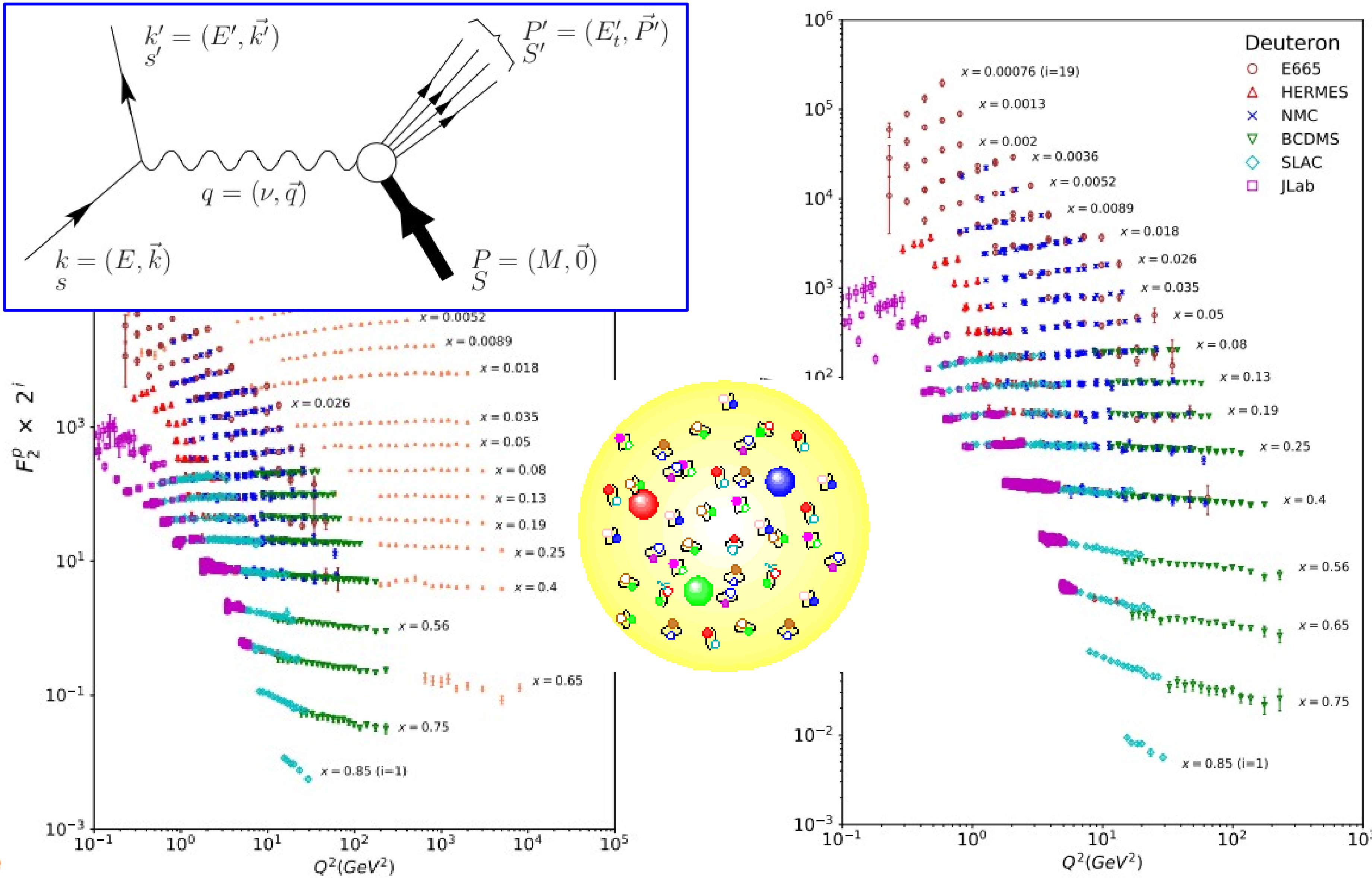




https://academic.oup.com/ptep/article/2020/8/083C01/5891211

Success of QCD in the perturbative regime

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

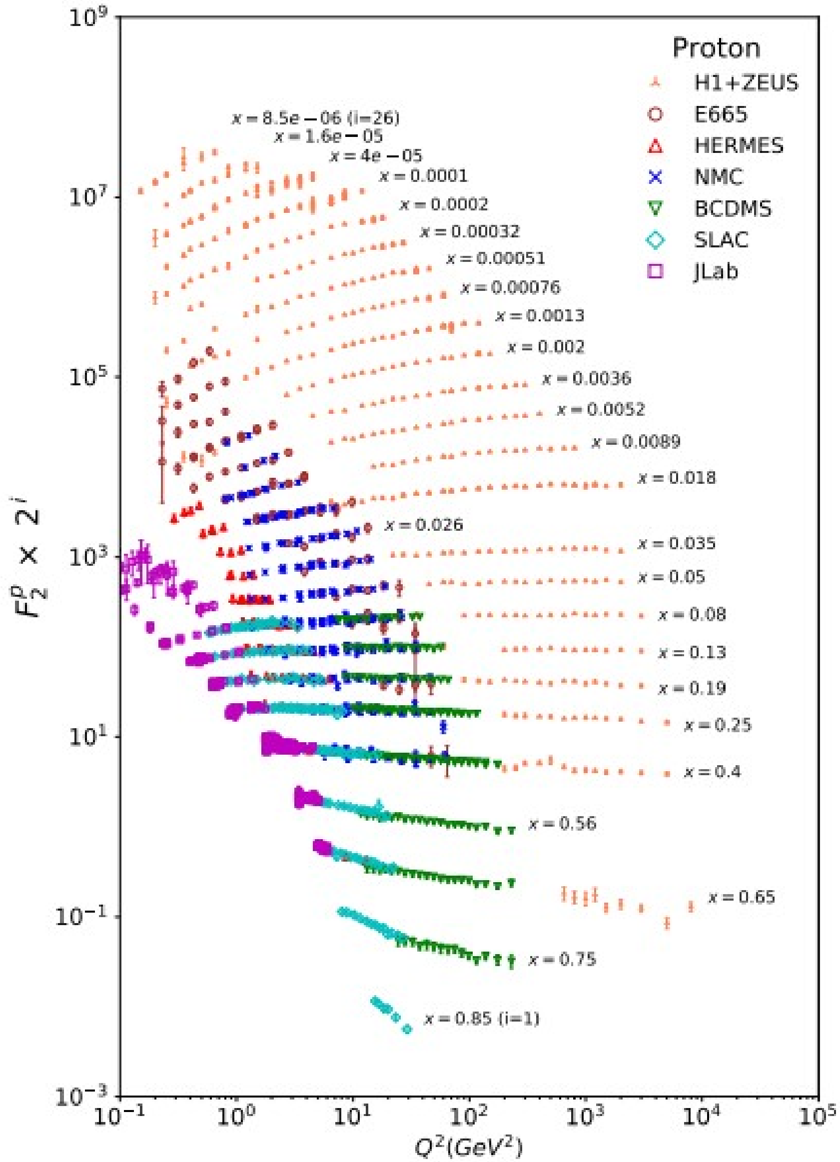


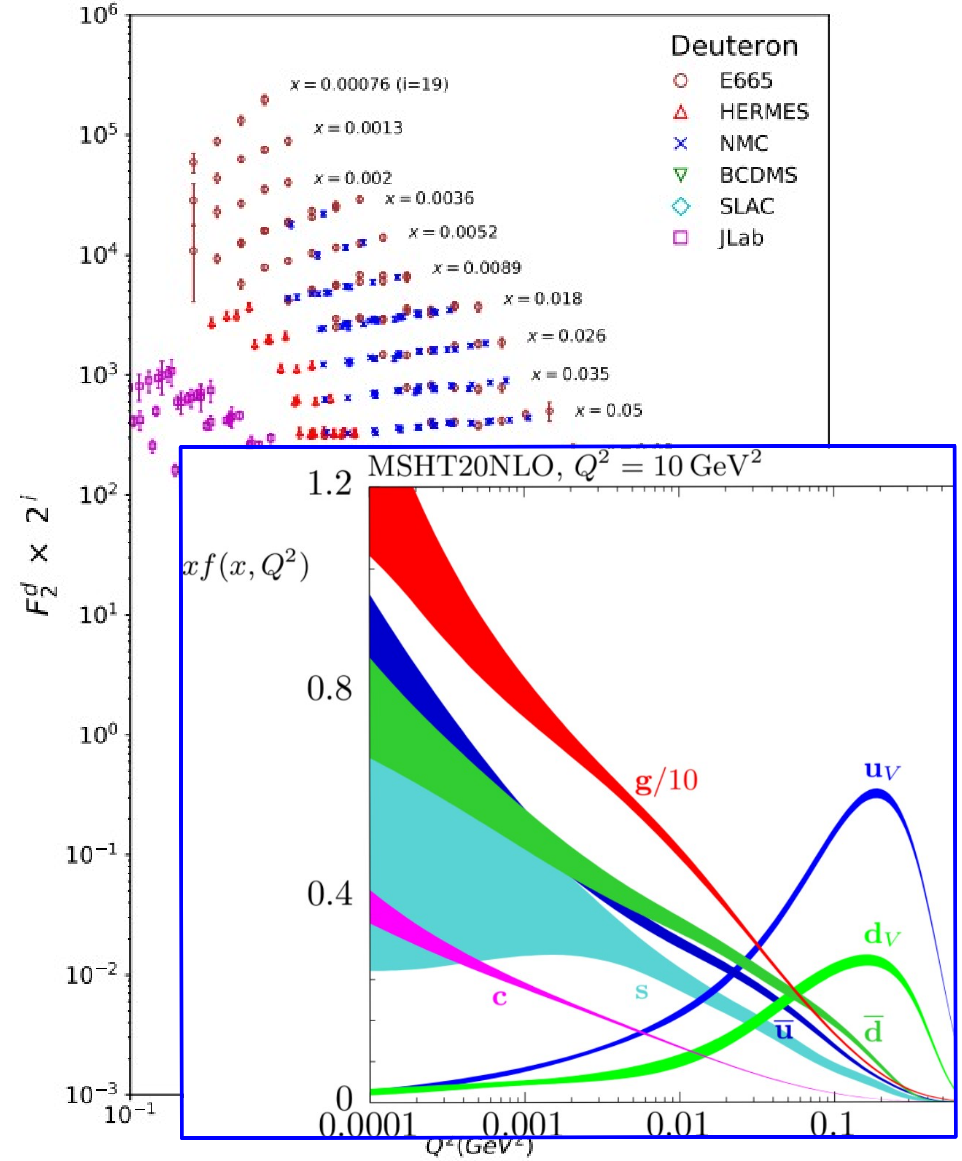
https://academic.oup.com/ptep/article/2020/8/083C01/5891211

Success of QCD in the perturbative regime

The defining features with the nucleon structure and strong interaction were made between 1933 and 1973, ending with

$$\alpha_s(Q^2) \approx \frac{4\pi}{(11 - 2n_f/3)\ln(Q^2/\Lambda^2)}$$





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

What Now? What about Non-perturbative QCD?

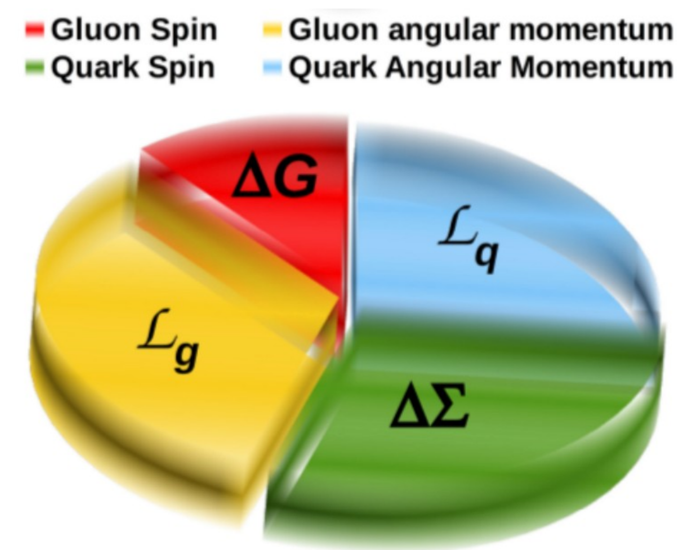
but first, a look at the proton spin

What Now? What about Non-perturbative QCD?

but first, a look at the proton spin

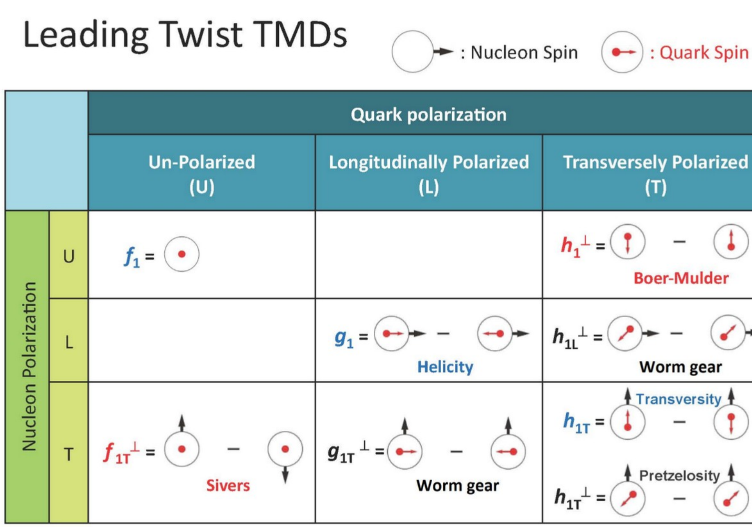
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + l_q + l_g$$ – "Jaffe-Manohar sum rule"

or $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$ – "Ji sum rule"



Experiments that help solving the proton spin puzzle:

- Double-polarized inclusive lepton scattering
- Semi-inclusive DIS, Transverse Momentum Distributions
- Exclusive processes (DVCS, T-DVCS, DDVCS, DVMP...)
- Drell Yan processes
- pp collisions: jet and pion production
- RHIC: W/Z productions
- … …global fits (e.g. JAM), lattice QCD calculation

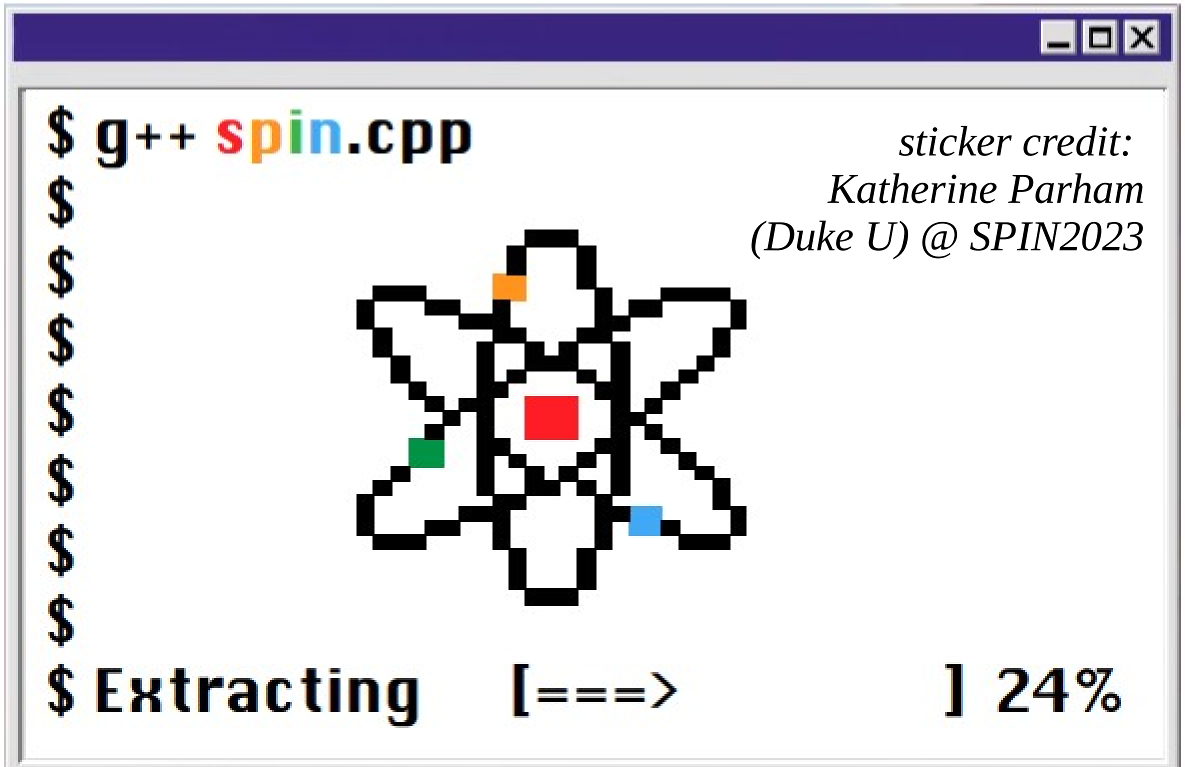


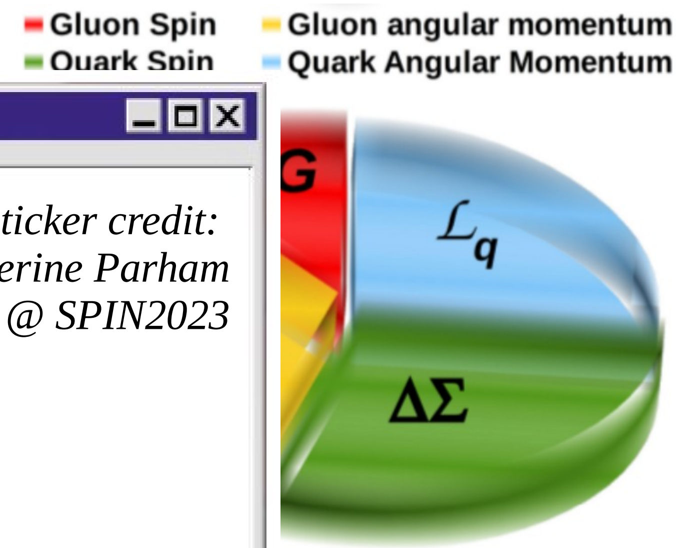
What Now? What about Non-perturbative QCD?

but first, a look at the proton spin

$$\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\Delta G+L+L$$ "Jaffe-Manohar sum rule"

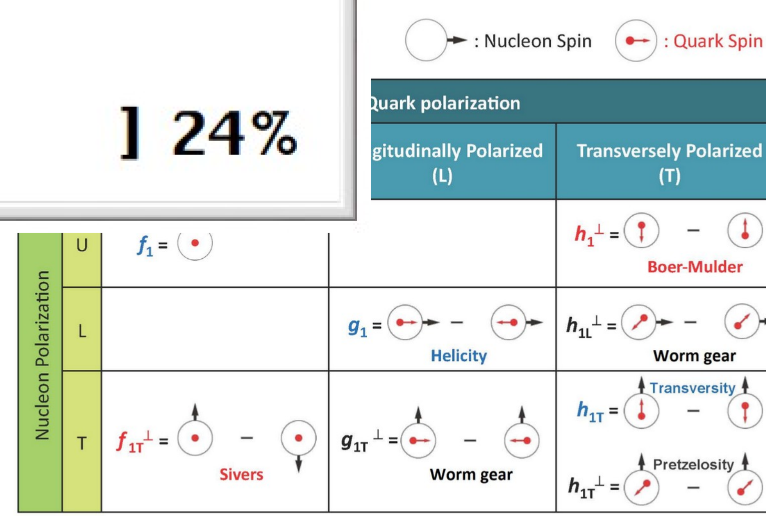
or $$\frac{1}{2}=\frac{1}{2}\Delta\Sigma$$





Experiments that

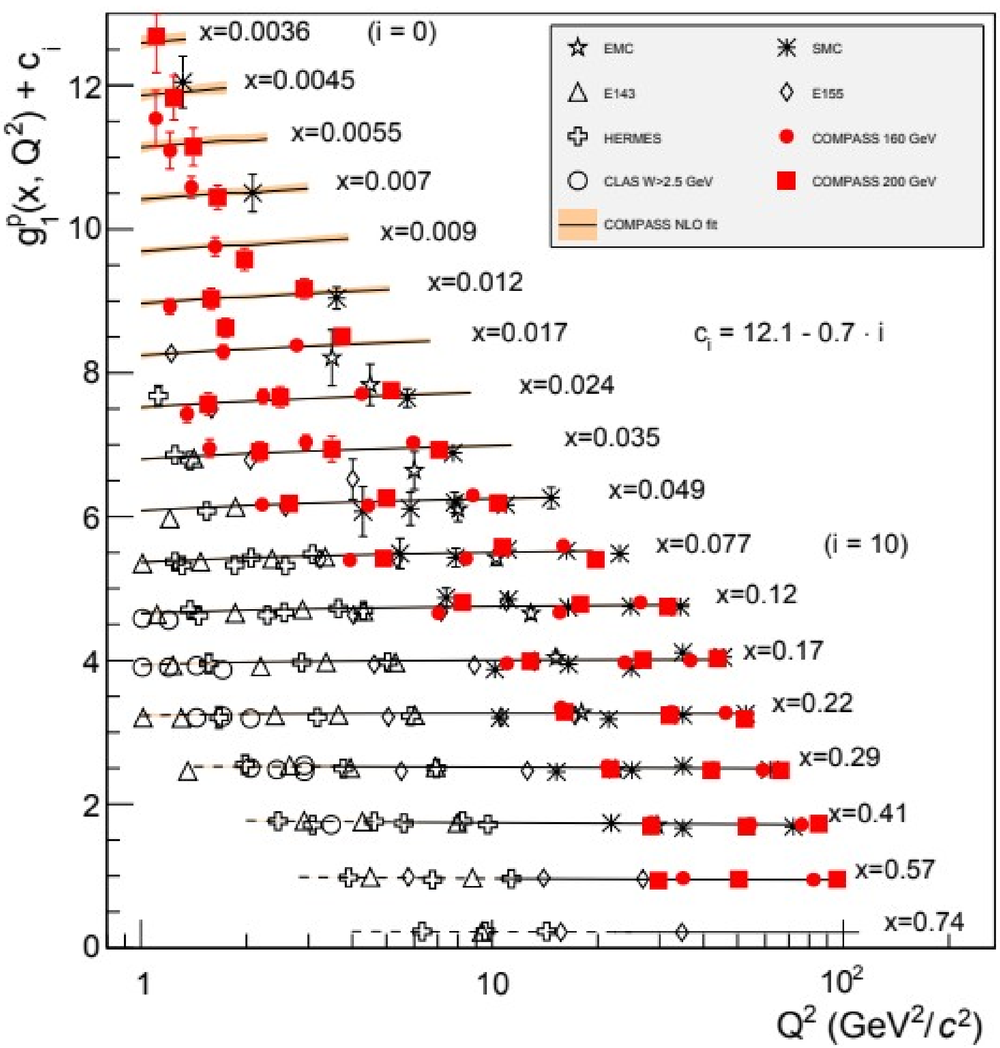
- Double-polarized
- Semi-inclusive DI
- Exclusive process
- Drell Yan process
- pp collisions: jet a
- RHIC: W/Z productions
- … …global fits (e.g. JAM), lattice QCD calculation

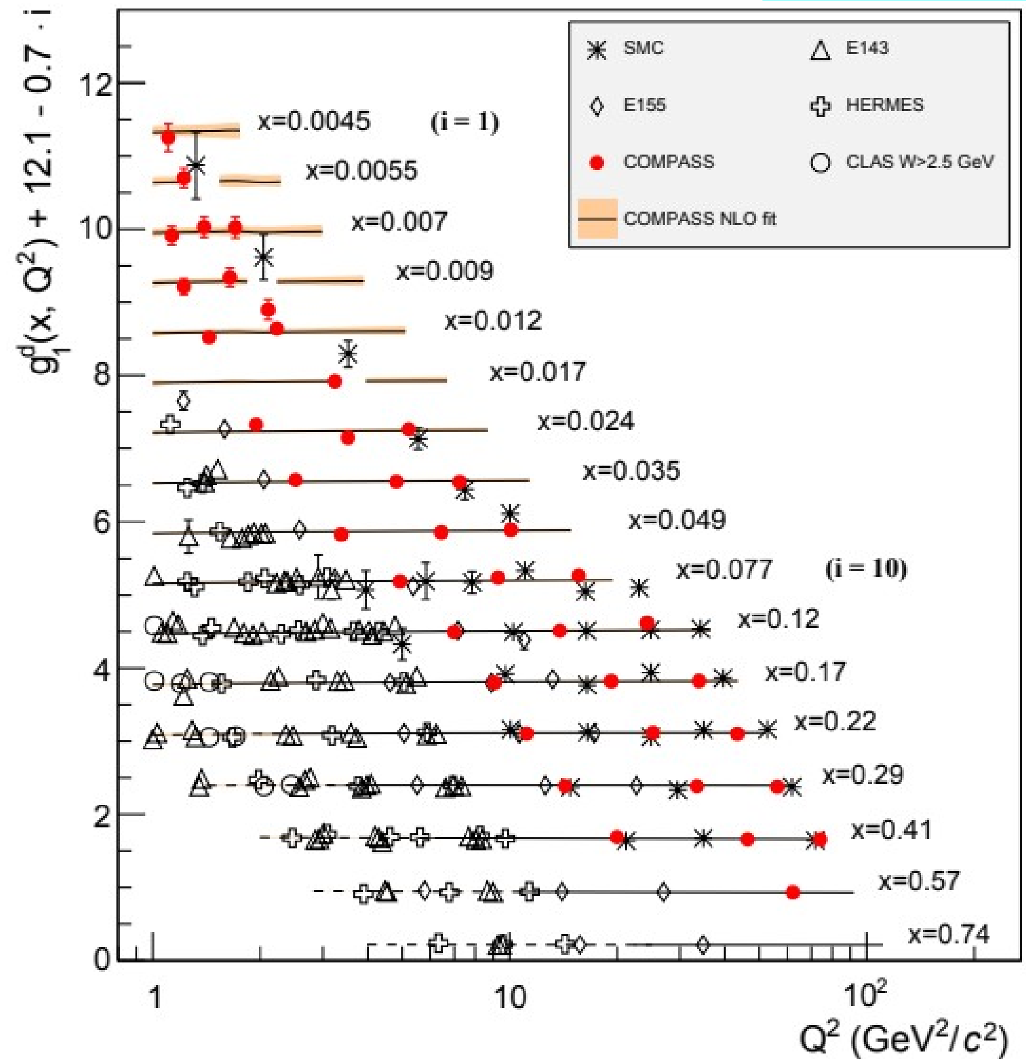


World Data on Polarized Structure Functions

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

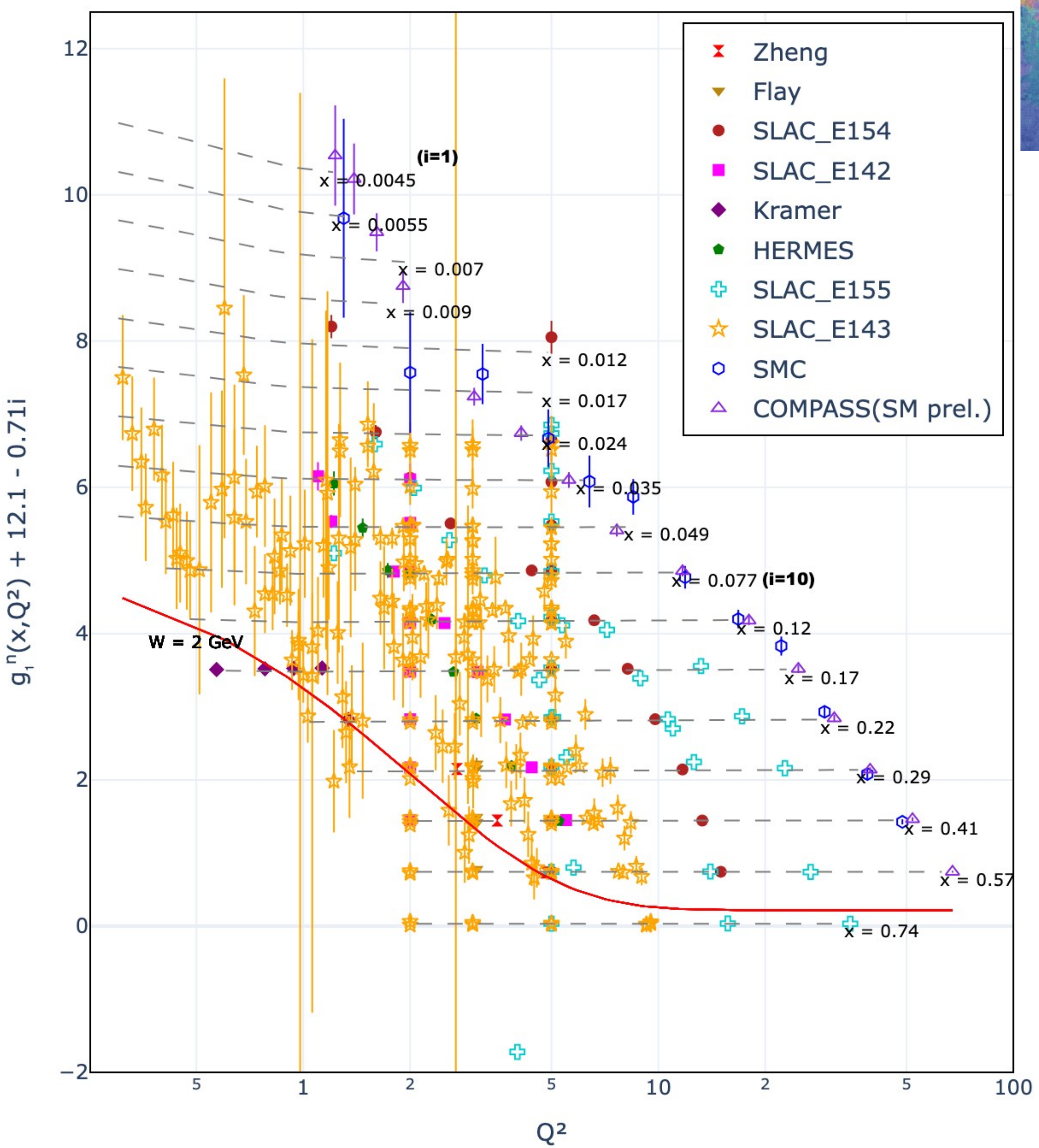
now in PDG2022

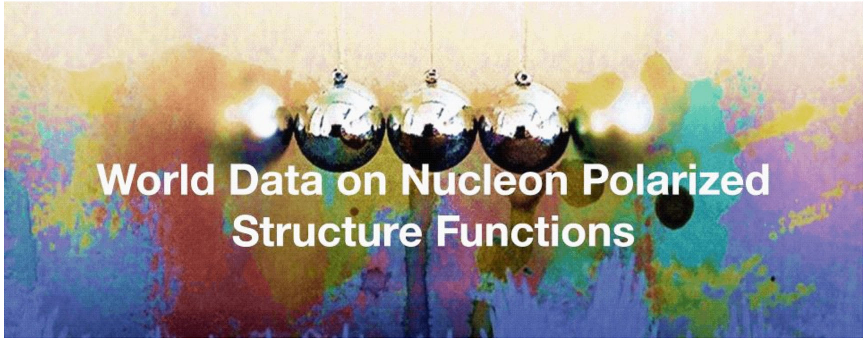




https://academic.oup.com/ptep/article/2020/8/083C01/5891211

The Neutron



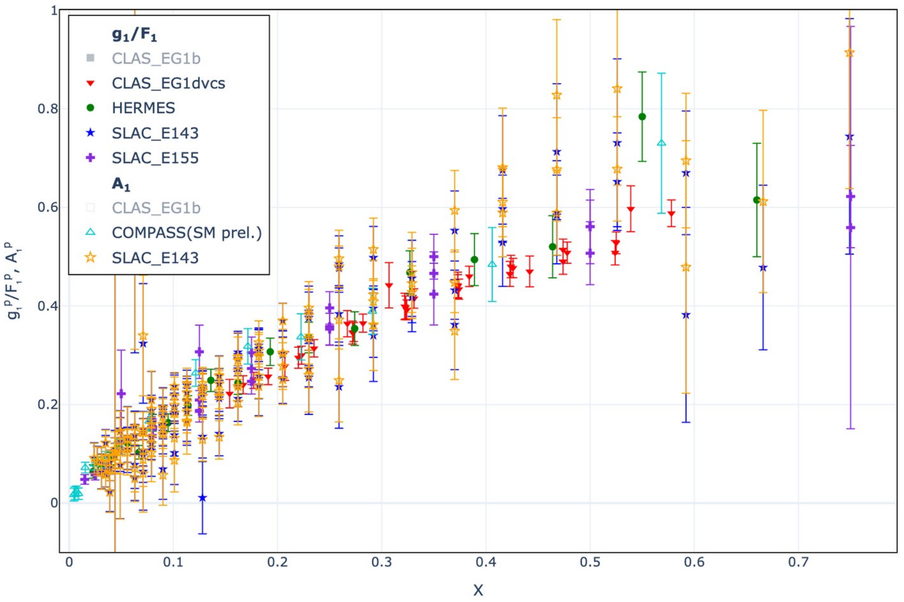


website built by Scarlett Morse (UVA):
https://qnz3gx.github.io/sim.github.io/

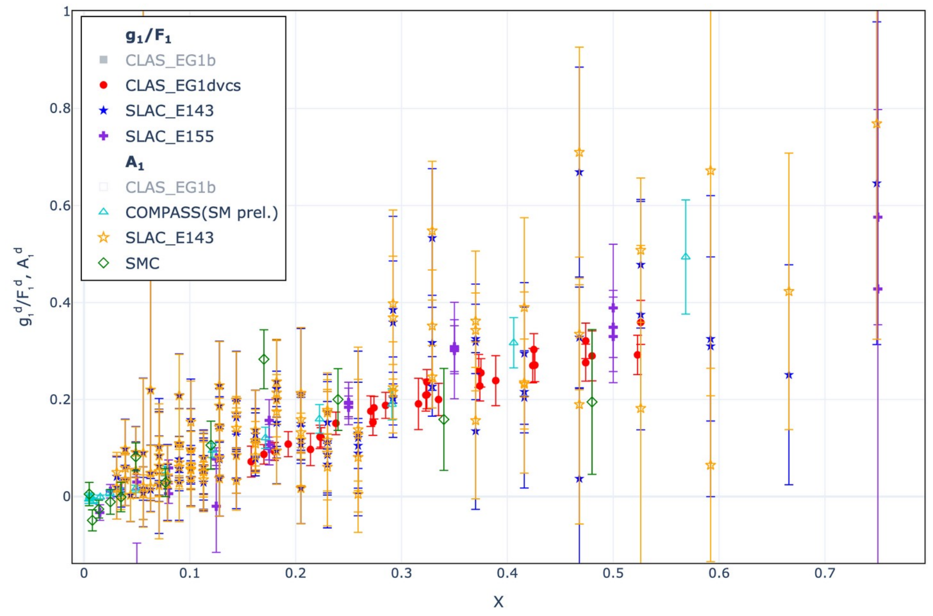
World Data on Spin Asymmetries

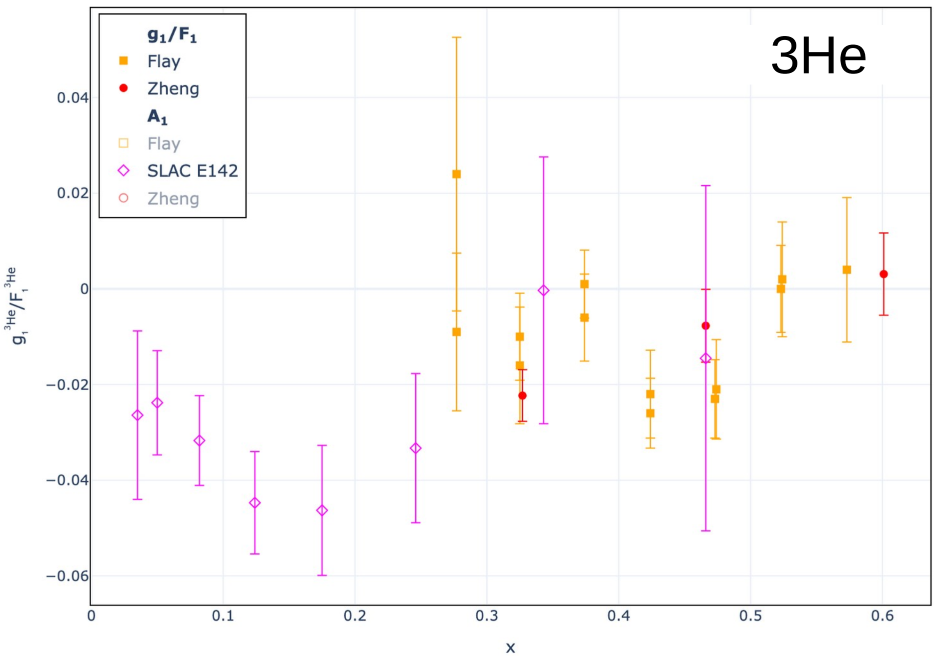
$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1}$$

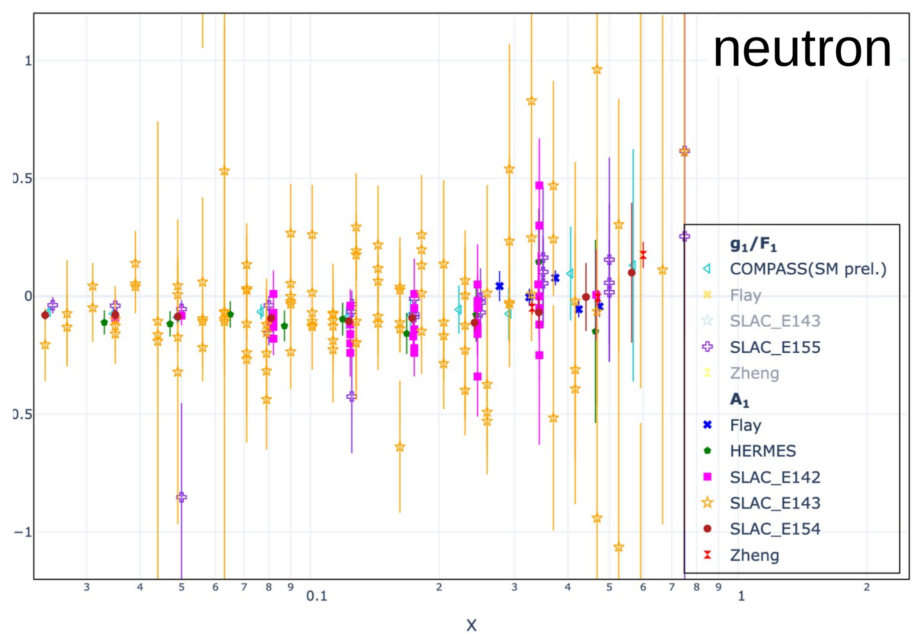
proton



deuteron





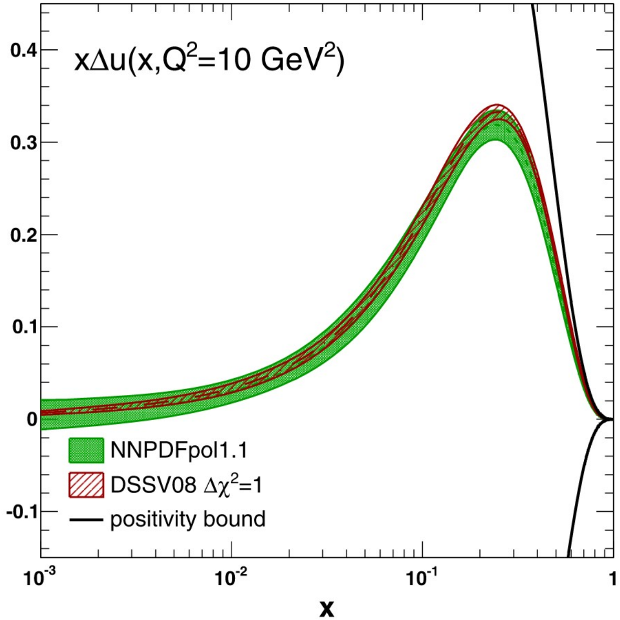


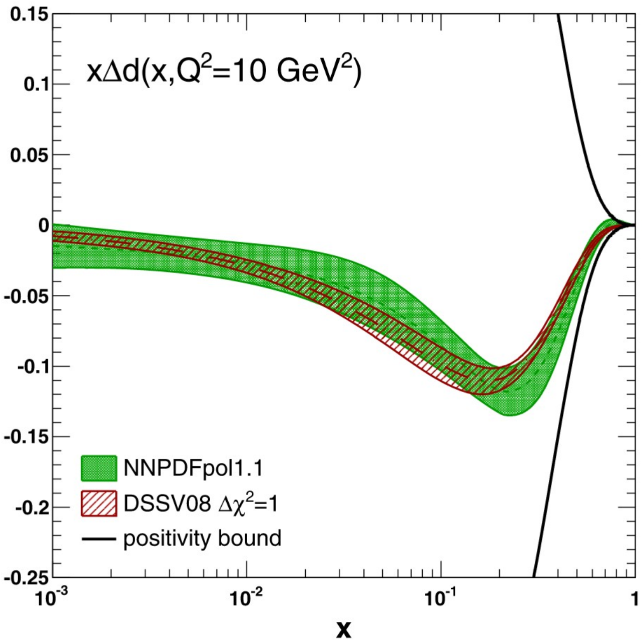
website built by Scarlett Morse (UVA): https://qnz3gx.github.io/sim.github.io/

Present Status on Polarized PDFs

NNPDF pol 1.1

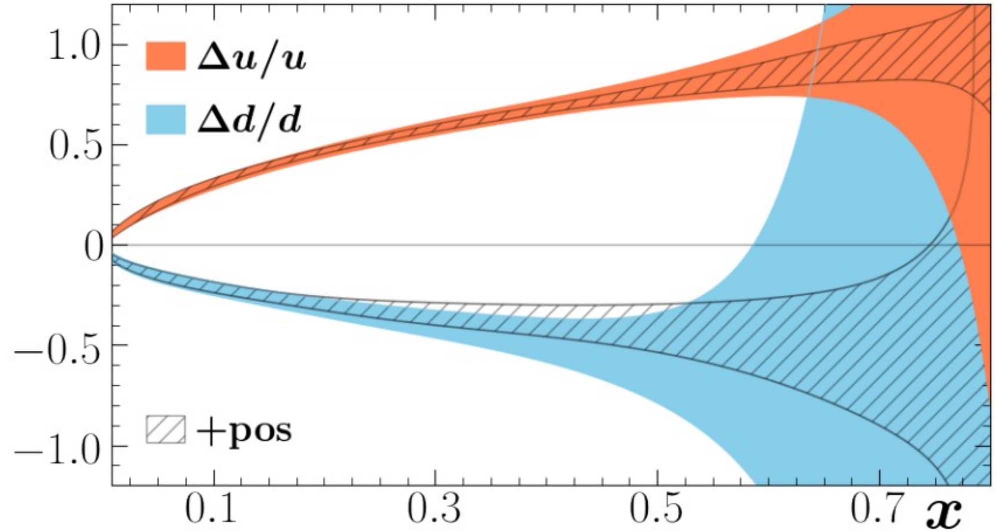
https://doi.org/10.1016/j.nuclphysb.2014.08.008

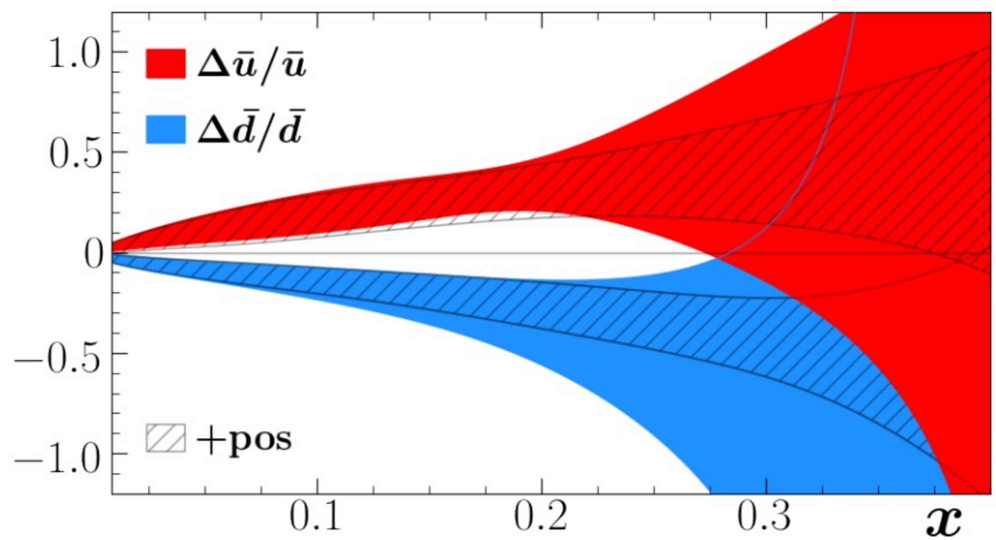




JAM Analysis

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

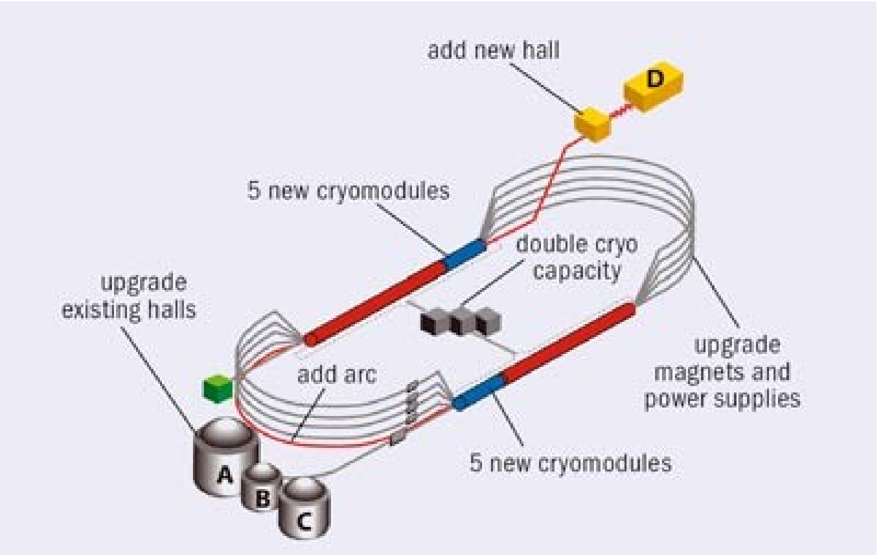


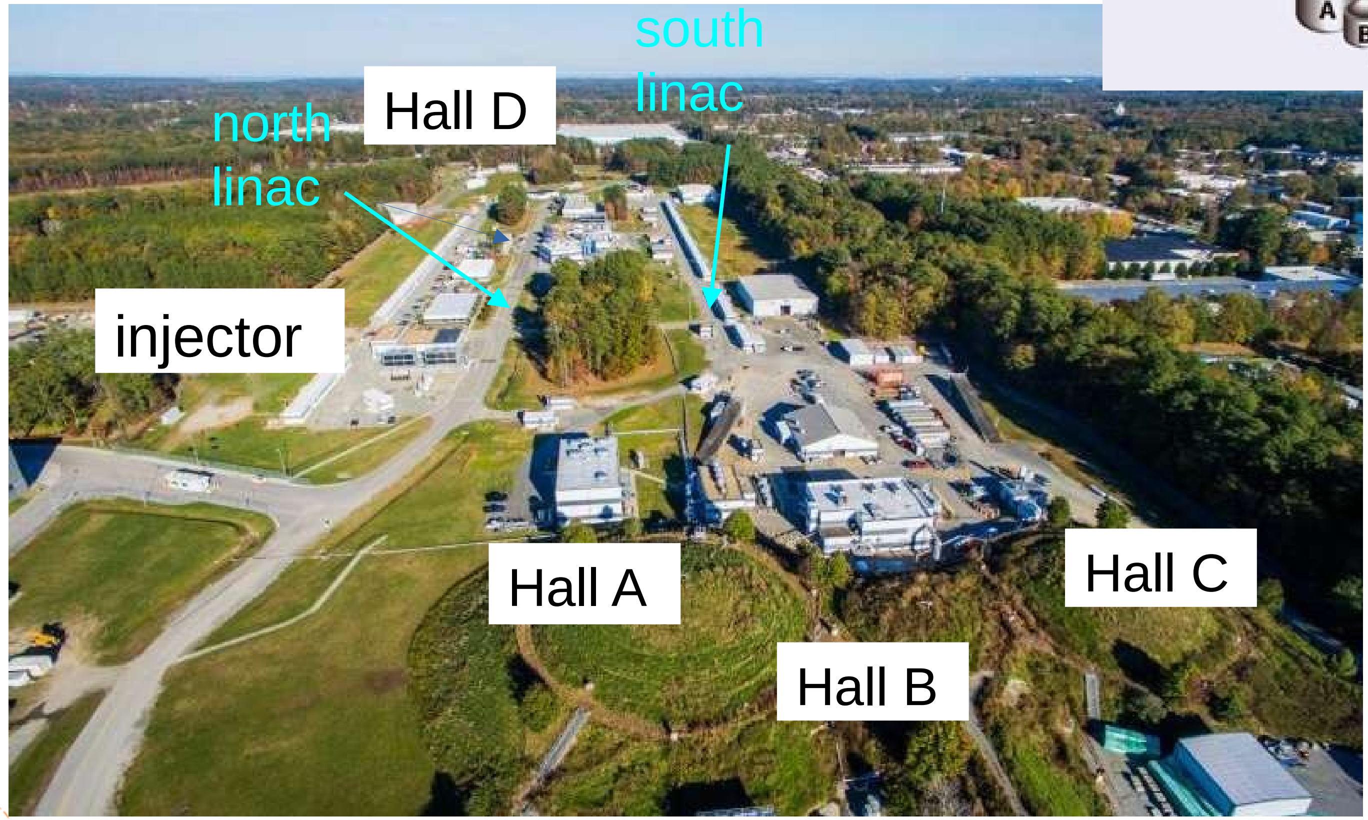


light quark polarization at Q^2=10 GeV^2.

Recent Highlights from Jefferson Lab Inclusive Polarized Electron Scattering Experiments

Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab

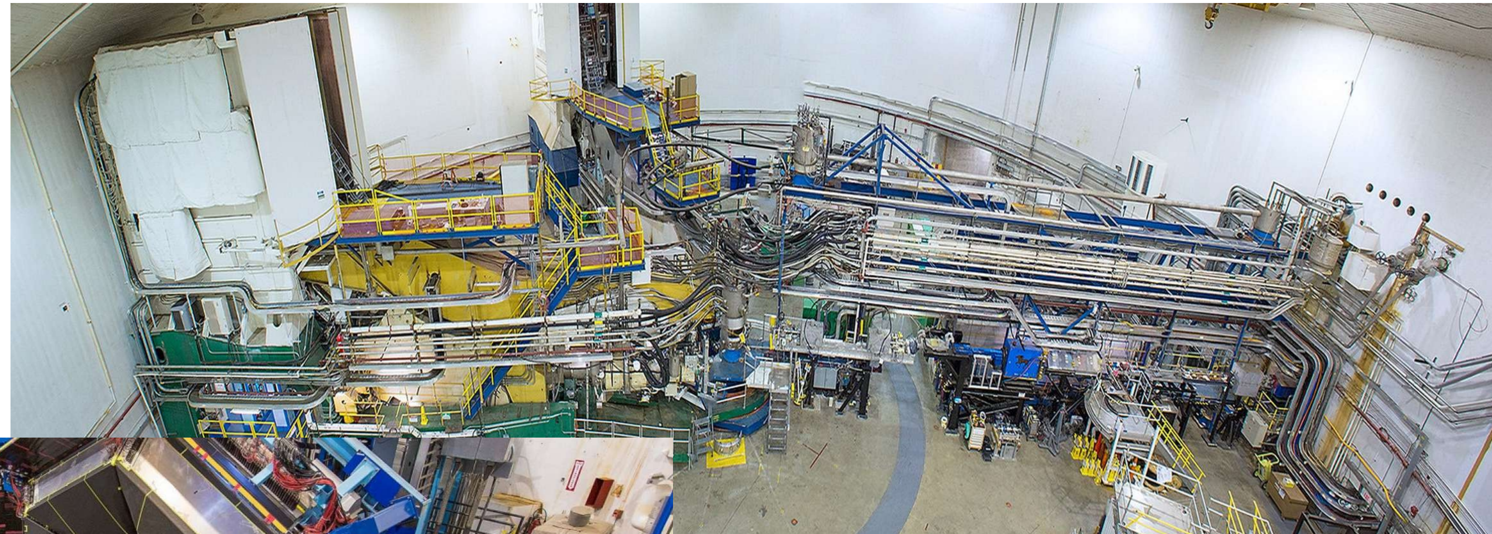




$$\lambda = \frac{hc}{12\,GeV} = 0.1\,fm$$

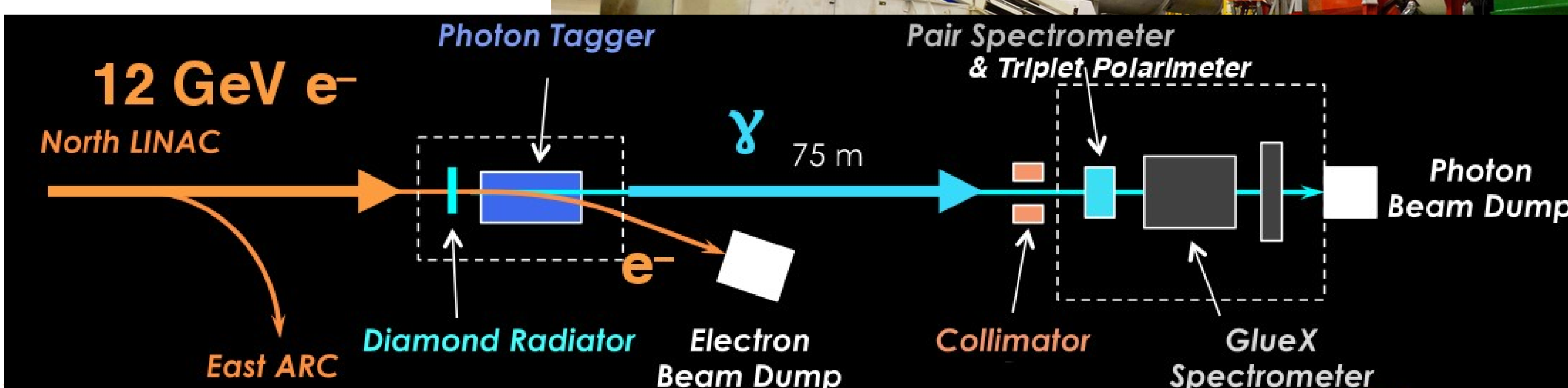
https://cebaf.jlab.org/

Hall A
(HRS, SBS)



Hall B
(CLAS12)

Hall C (HMS,
SHMS, NPS)



Hall D
(GlueX)

Very Low Q^2

(Some) Moments and Sum Rules

- Bjorken Sum Rule: (current algebra, isospin symmetry)

$$\int (g_1^p - g_1^n)\,dx = \frac{1}{6} g_A \left(1 + \frac{\alpha_S(Q^2)}{\pi} + \ldots\right) + \text{non-perturbative corrections}$$

axial charge

- GDH Sum Rule (real photon):

(gauge and Lorentz invariance, unitarity)

anomalous magnetic moment

$$\int_{\nu_{th}}^{\infty} (\sigma^{1/2} - \sigma^{3/2}) \frac{d\nu}{\nu} = -\frac{2\alpha\pi^2\kappa^2}{M^2}$$

- GDH Sum Rule (virtual photon):

$$I_{TT}(Q^2) = \frac{M^2}{8\pi^2\alpha} \int_{\nu_{th}}^{\infty} \frac{K}{\nu} \frac{\sigma_{TT}}{\nu} d\nu = \frac{2M^2}{Q^2} \int_0^{x_{th}} A_1 F_1\, dx \xrightarrow[Q^2 \to 0]{} -\frac{2\alpha\pi^2\kappa^2}{M^2}$$

$$\frac{16\alpha\pi^2}{Q^2} \int_0^1 g_1\, dx = 2\alpha\pi^2 S_1$$

spin dependent DDVCS amplitude:

low-to-intermediate Q2: chiral PT, OPE

Higher Moments – Spin Polarizabilities

- Generalized forward spin polarizability:

$$\gamma_0 = \frac{16\alpha M^2}{\pi Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]dx = \frac{16\alpha M^2}{\pi Q^6}\int_0^{x_0} x^2\left[A_1 F_1\right]dx$$

- Longitudinal-Transverse polarizability:

$$\delta_{LT} = \frac{16\alpha M^2}{\pi Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]dx$$

These polarizabilities quantify the nucleon spin's precession under the effect of the (virtual) photon

- Twist-3 term d2:

$$d_2(Q^2) = \int_0^1 x^2\left[2g_1(x,Q^2) + 3g_2(x,Q^2)\right]dx = 3\int_0^1 x^2\left[g_2(x,Q^2) - g_2^{WW}(x,Q^2)\right]dx$$

Calculations exist or possible from lattice QCD, Dyson-Schwinger Equations, or Chiral PT

Higher Moments – Spin Polarizabilities

- Generalized forward spin polarizability:

$$\gamma_0 = \frac{16\alpha M^2}{\pi Q^6} \int_0^{x_0} x^2 \left[g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right]$$

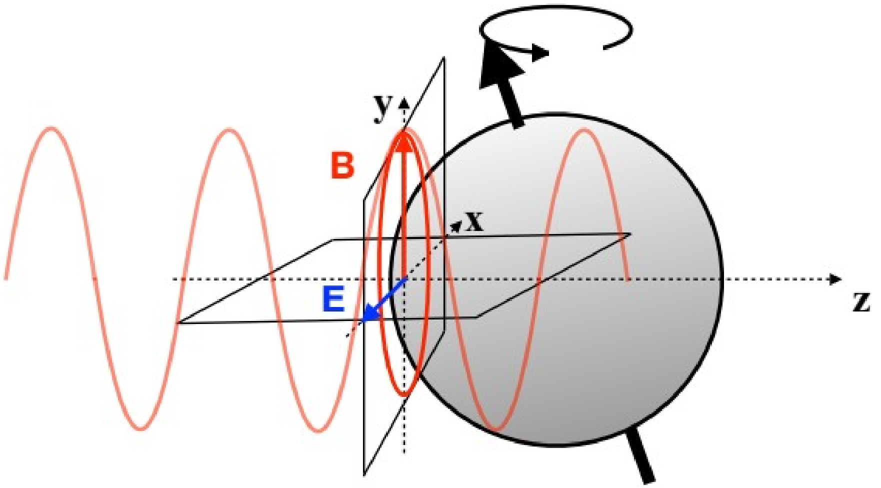


Figure credit: A. Deur

- Longitudinal-Transverse polarizability:

$$\delta_{LT} = \frac{16\alpha M^2}{\pi Q^6} \int_0^{x_0} x^2 \left[g_1 + g_2 \right] dx$$

These polarizabilities quantify the nucleon spin's precession under the effect of the (virtual) photon

- Twist-3 term d_2:

$$d_2(Q^2) = \int_0^1 x^2 \left[2g_1(x,Q^2) + 3g_2(x,Q^2) \right] dx = 3\int_0^1 x^2 \left[g_2(x,Q^2) - g_2^{WW}(x,Q^2) \right] dx$$

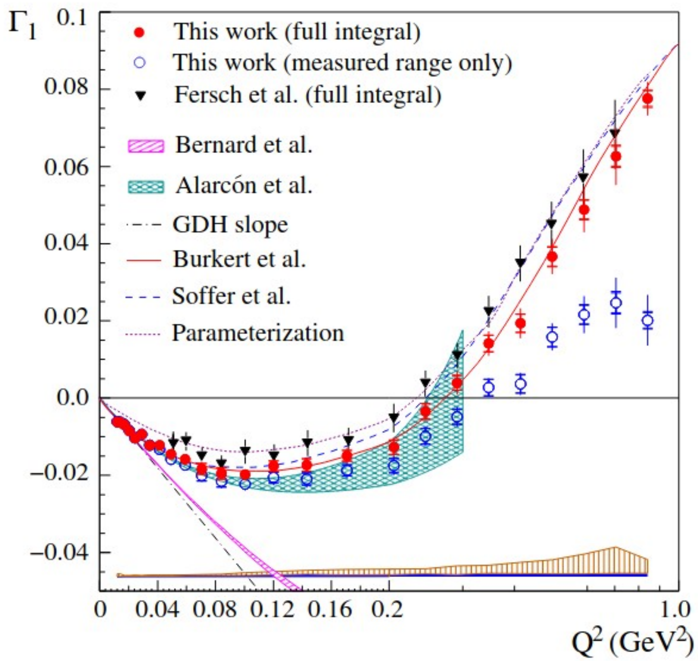
Calculations exist or possible from lattice QCD, Dyson-Schwinger Equations, or Chiral PT

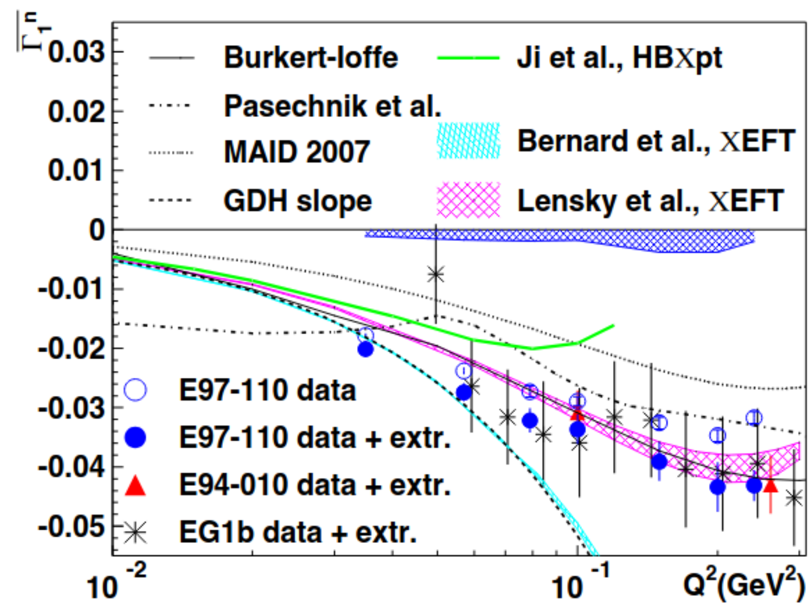
JLab low-Q^2 data on proton and neutron

proton **neutron**

Γ_1

EG4:
Nat. Phys., 17, 736 (2021)

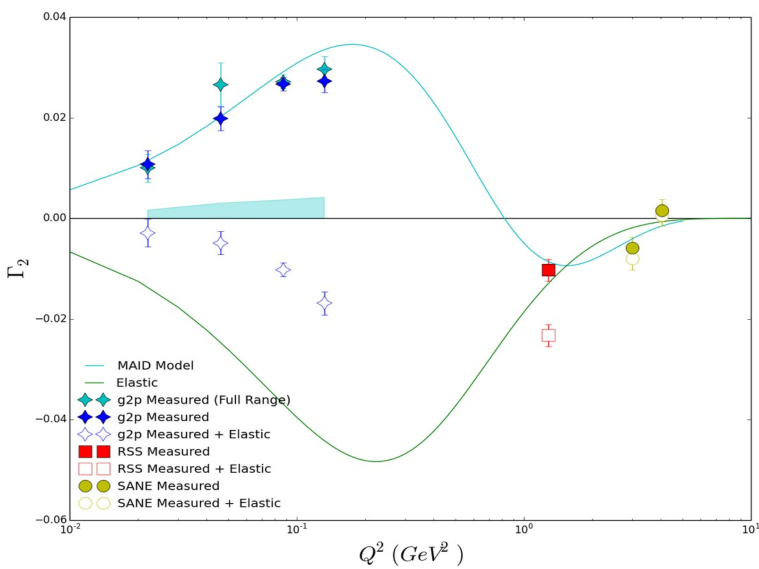


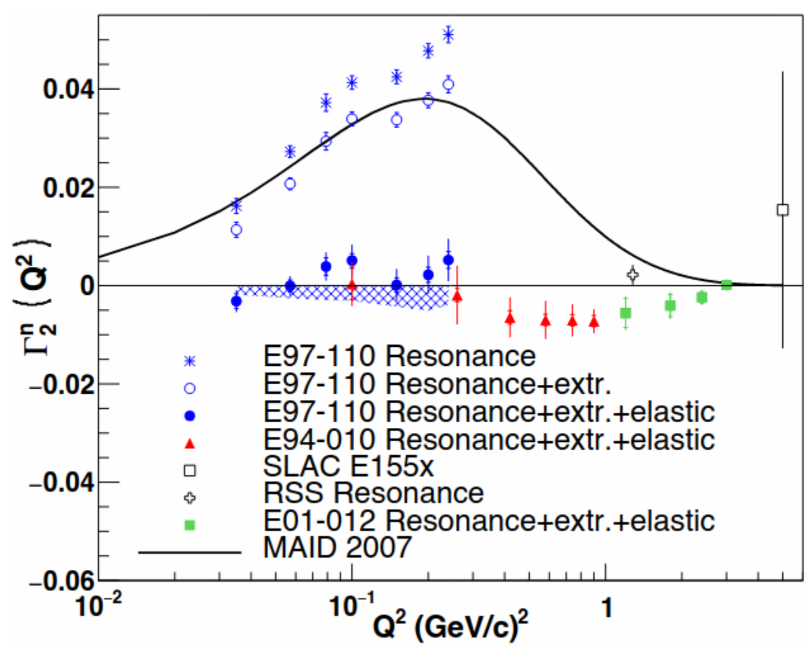


SAGDH:
PLB 805, 135428 (2020)

Γ_2

g2p exp:
Preliminary results



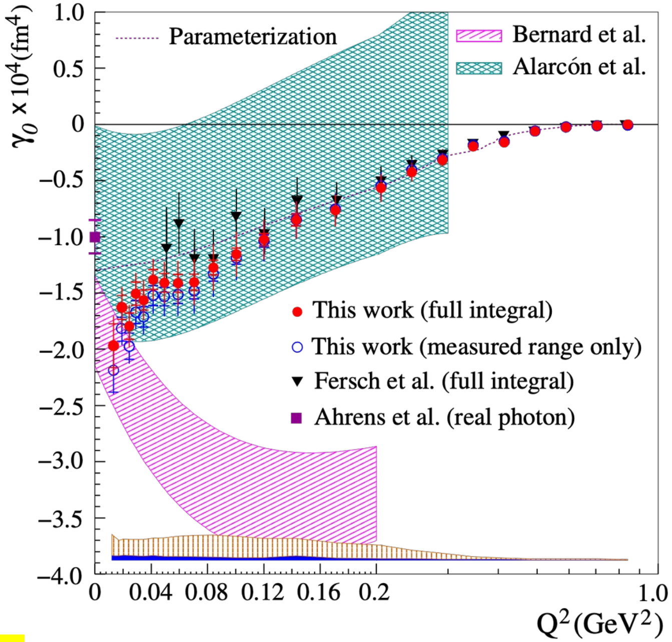


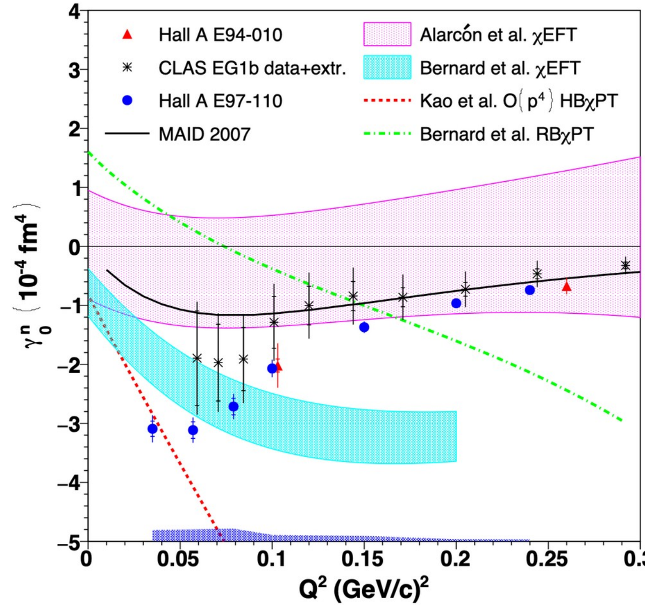
Spin Polarizabilities

proton | **neutron**

γ_0

EG4:
Nat. Phys., 17, 736-741 (2021)

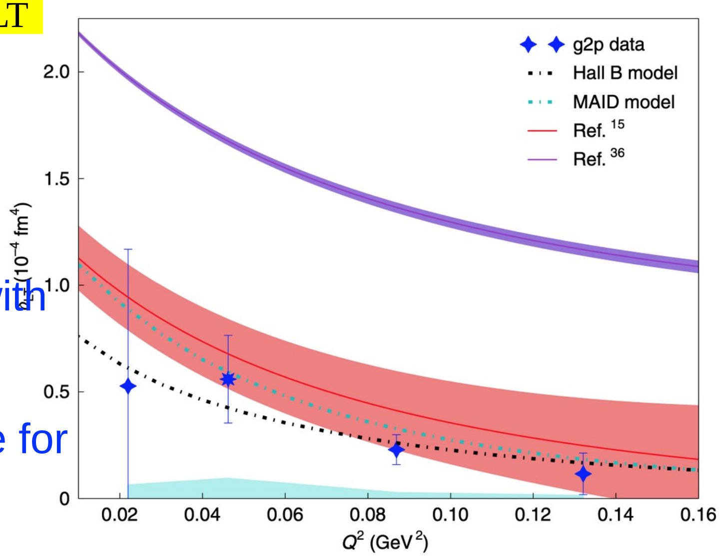


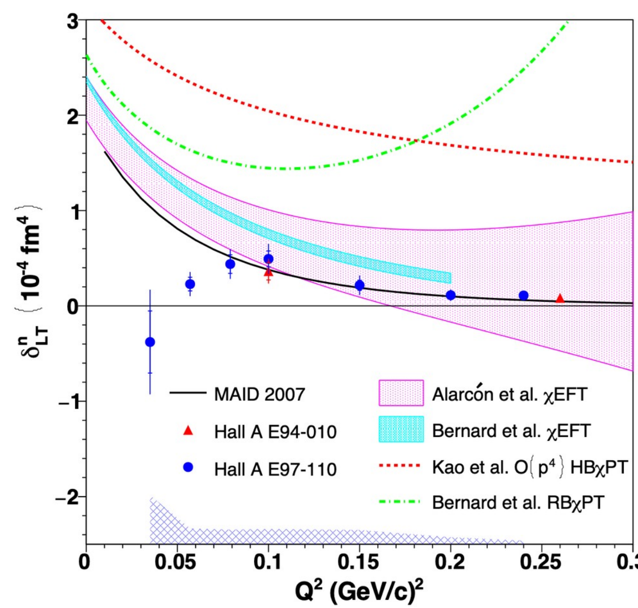


SAGDH:
Nat. Phys., 17, 687 (2021)

δ_{LT}

g2p:
Nat. Phys.
18, 1441
(2022**)**



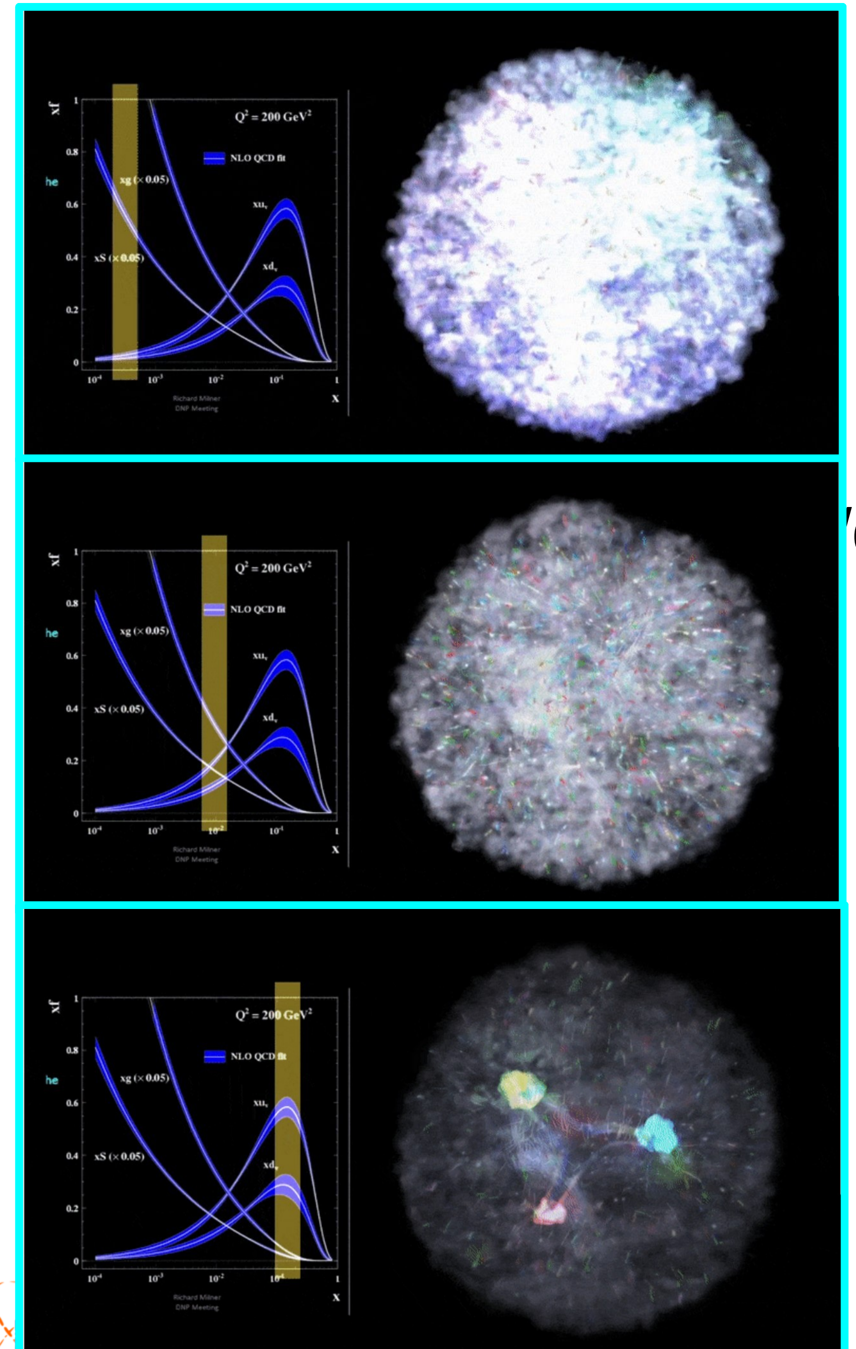


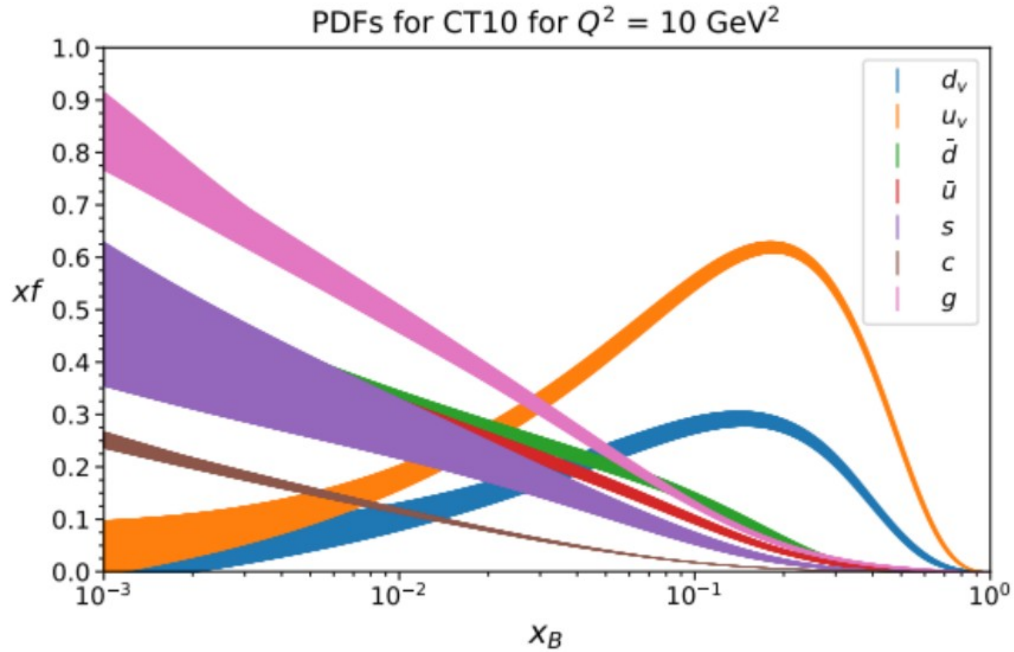
"delta_LT puzzle"!

Good agreement with χEFT calculations (apart from normalization value for Bernard *et al.*

Very High *x* (Deep Valence Quark Region)

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





x

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

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

Prediction on Polarized SF and PDF at high x

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

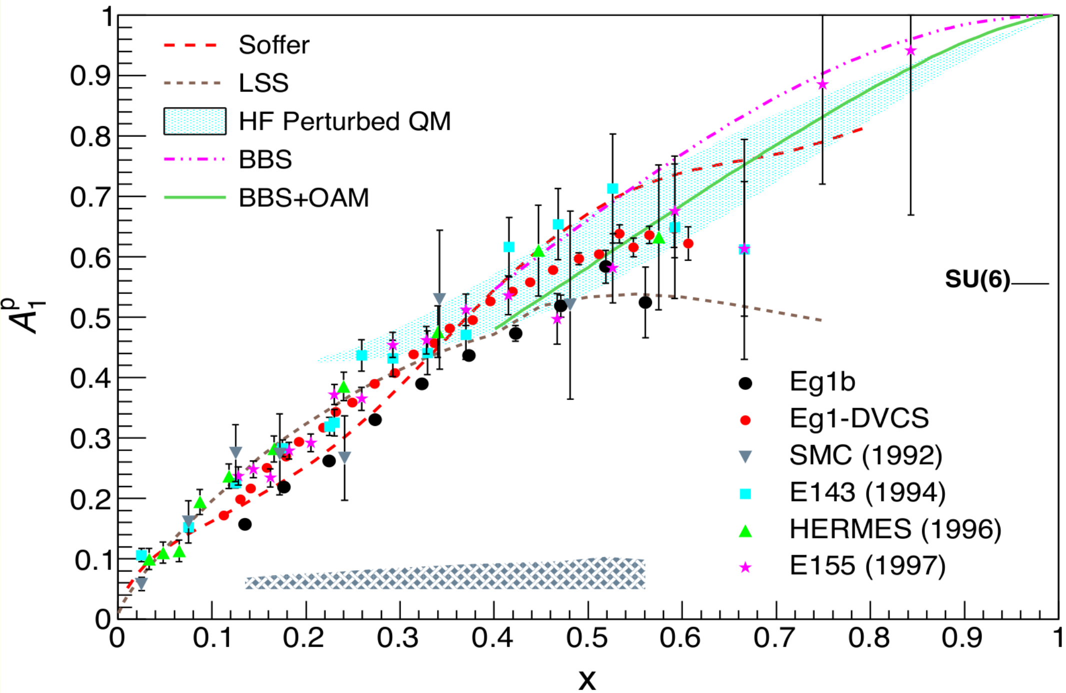
	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-1	0.49	0.28	−0.11	0.65	−0.26	0.17	0.59
DSE-2	0.41	0.18	−0.07	0.88	−0.33	0.34	0.88
$0^+_{[ud]}$	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	−0.06	0.80	−0.25	0.35	0.77
SU(6)	$\frac{2}{3}$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

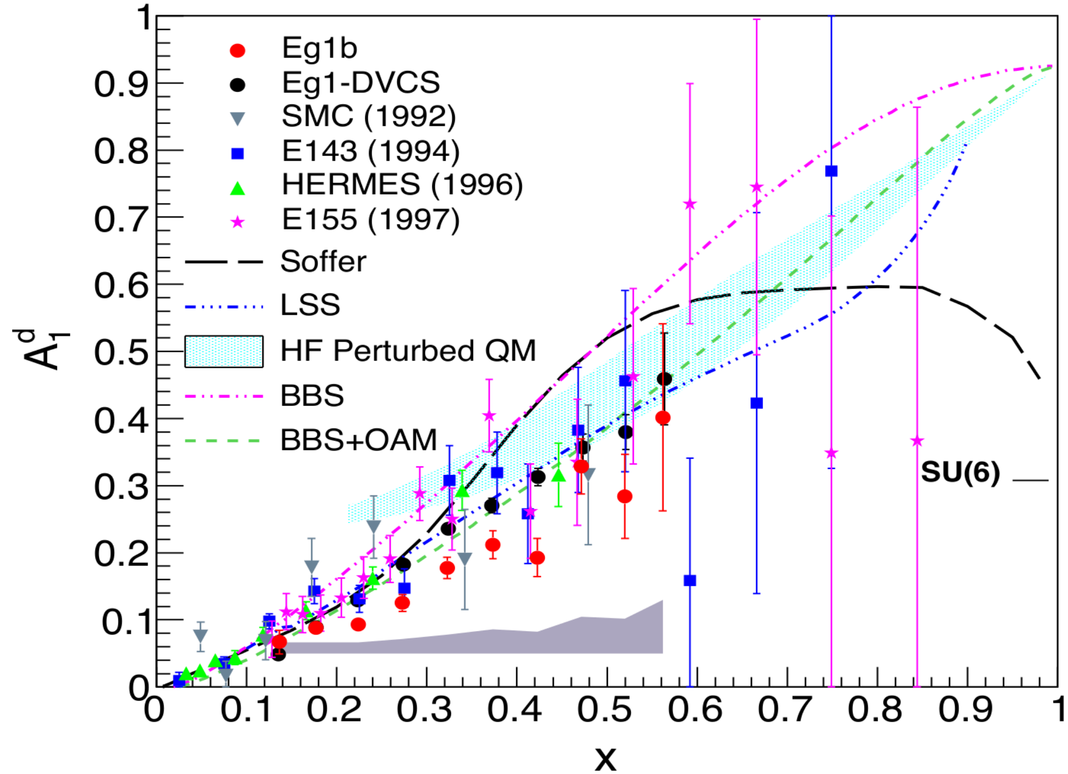
Table 1: Selected predictions for the $x = 1$ value of the indicated quanti-

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

see talk by C. Roberts

World DIS Data on A1p,d,n





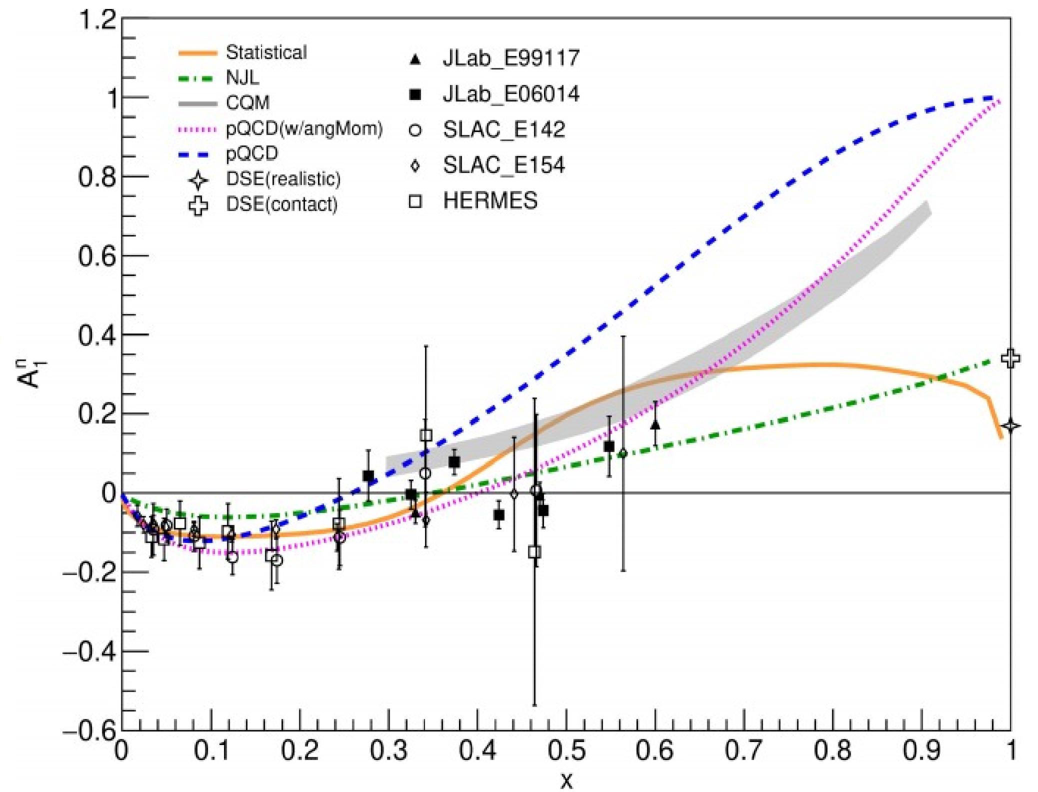


Figure credit: D. Flay

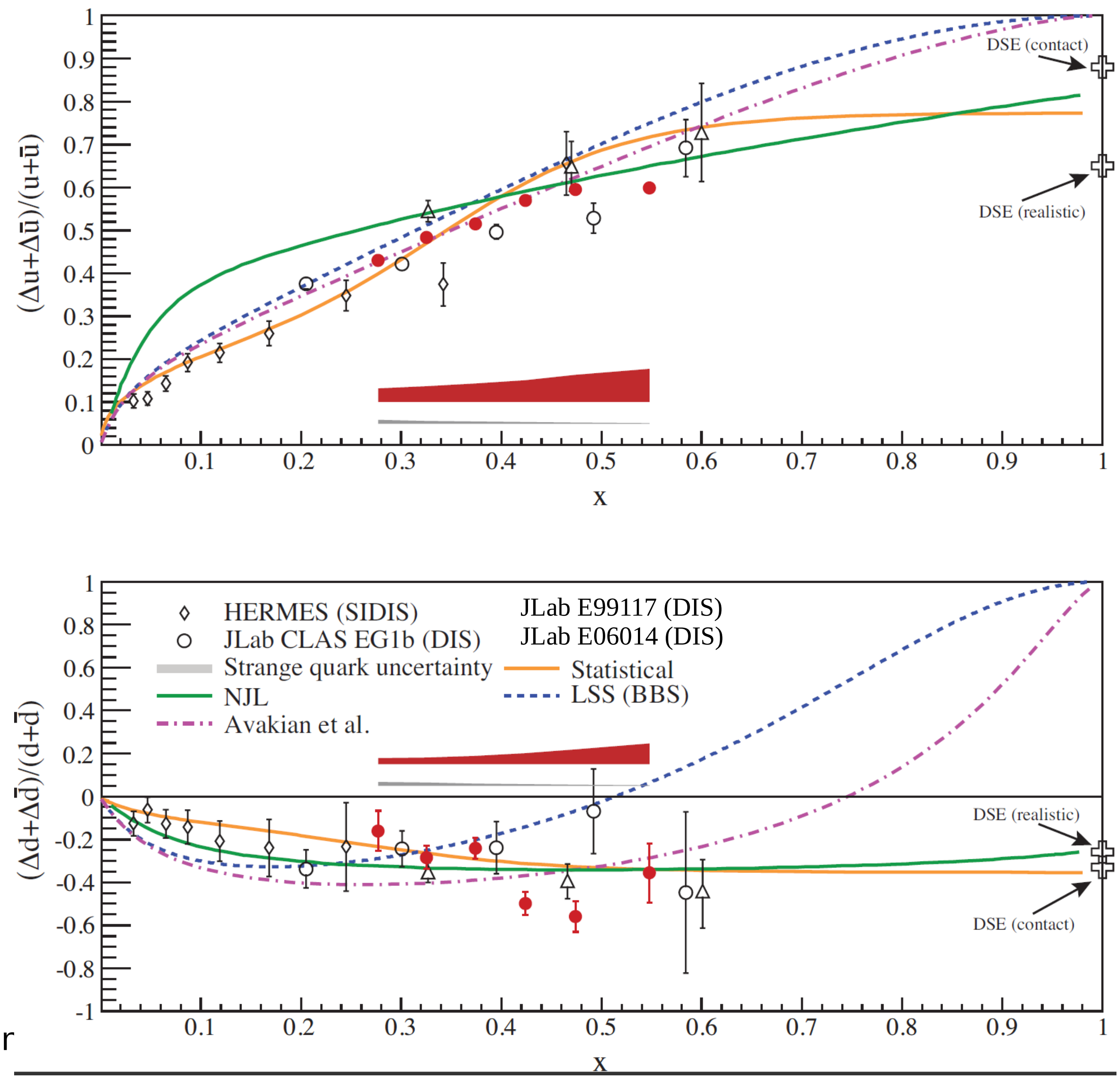
D. Parno et al. Phys.Rev.Lett. 113 (2014) 2, 022002, 1404.4003

Existing World Data on Spin at High X

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

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

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



Figures from

D. Parno et al.

PRL 113 (2014) 2, 022002, 1404.4003

HLFQCD Prediction on Polarized PDFs

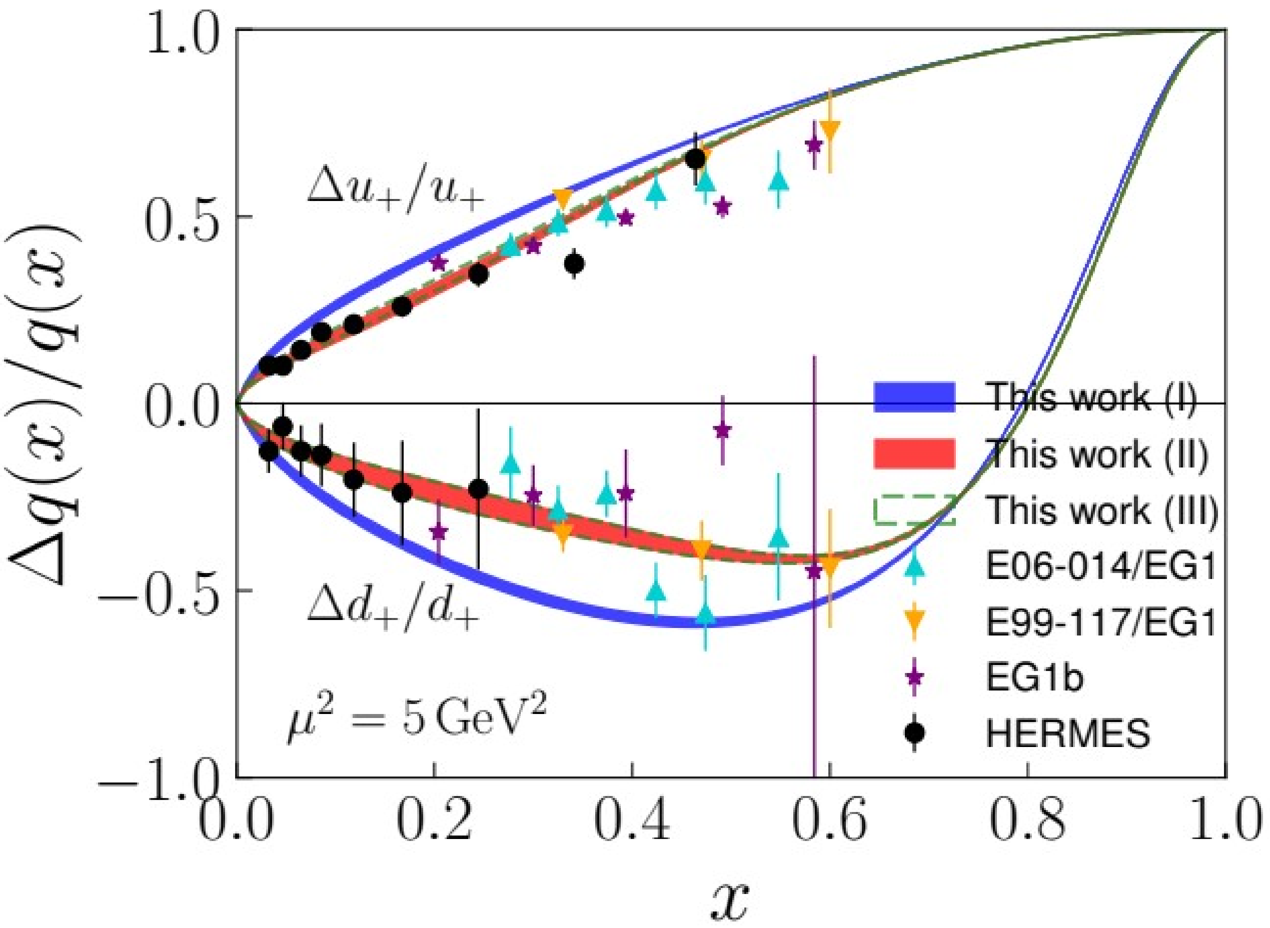
Based on the gauge-gravity correspondence, light-front holography, and the generalized Veneziano model. We find that the spin-dependent quark distributions are uniquely determined in terms of the unpolarized distributions by chirality separation without the introduction of additional free parameters.

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.

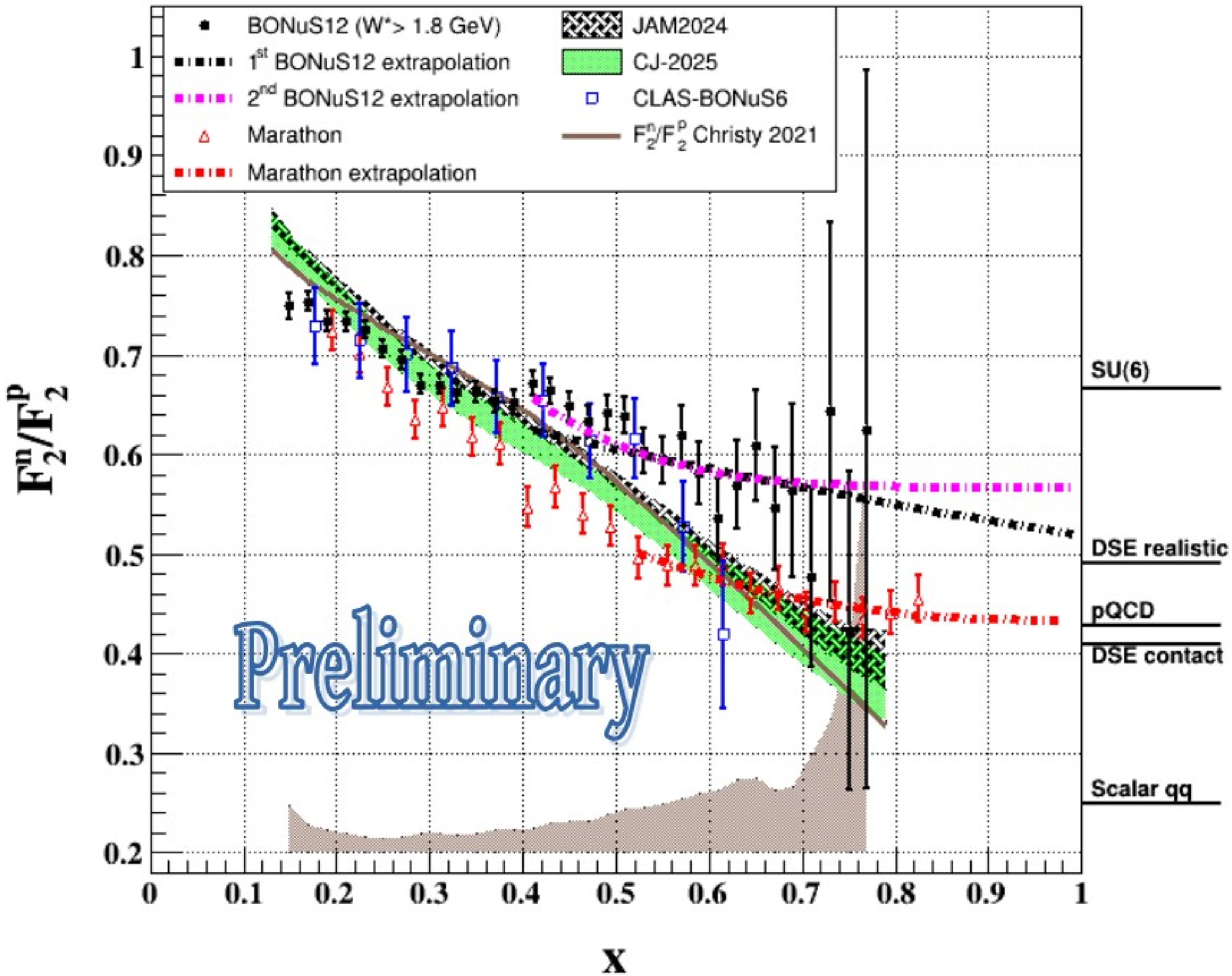
T. Liu et al.,

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

arXiv:1909.13818



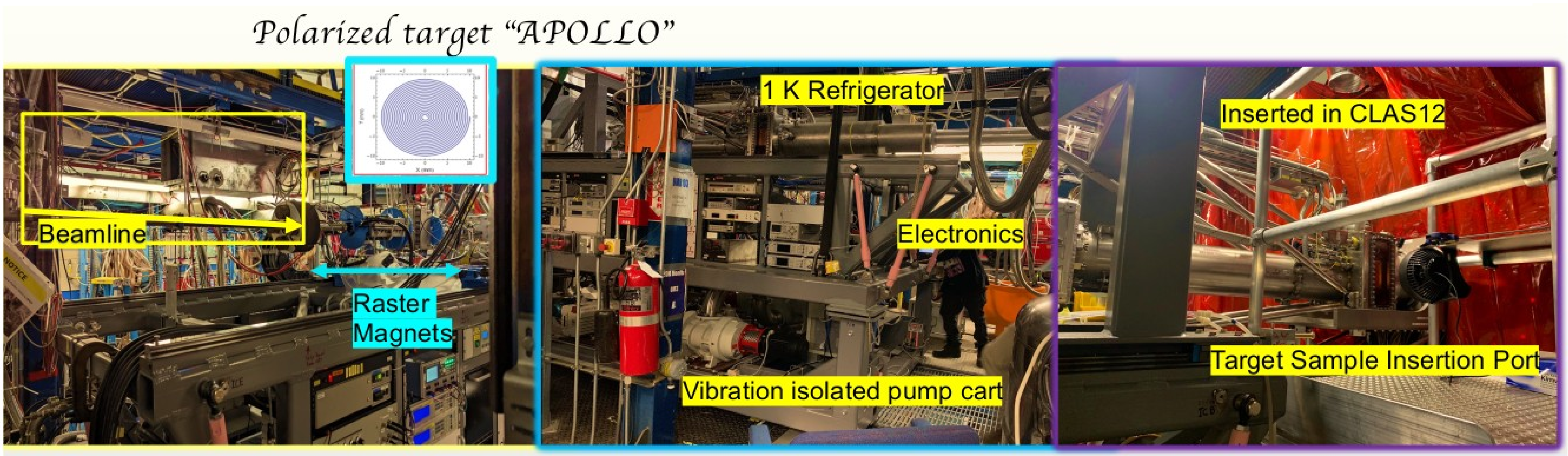
BONuS12 Preliminary Results (2/2)



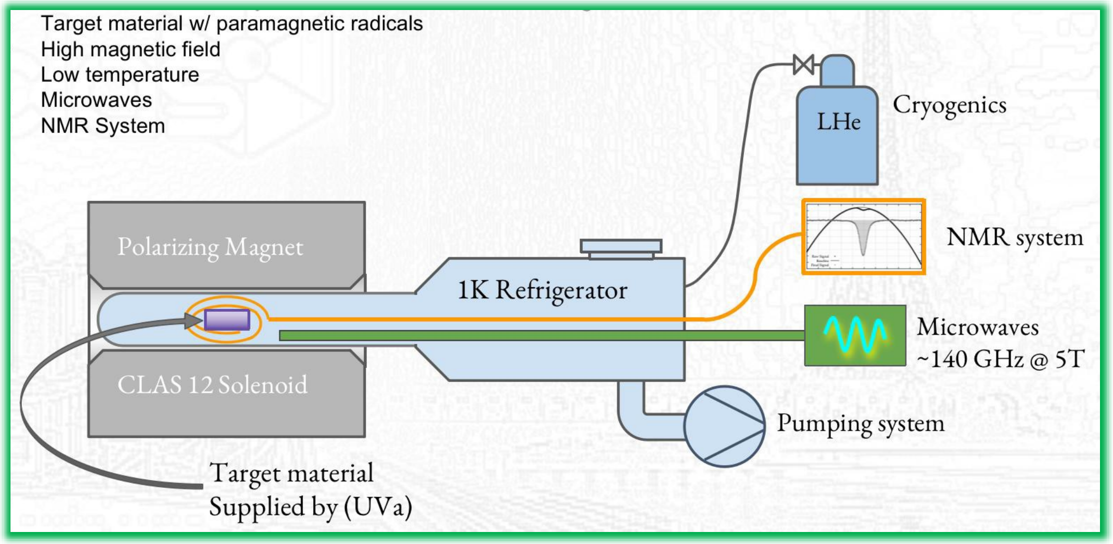
BONuS12 talk at JLUO2025

JLab 12 GeV Run Group C (RG-C) Experiments

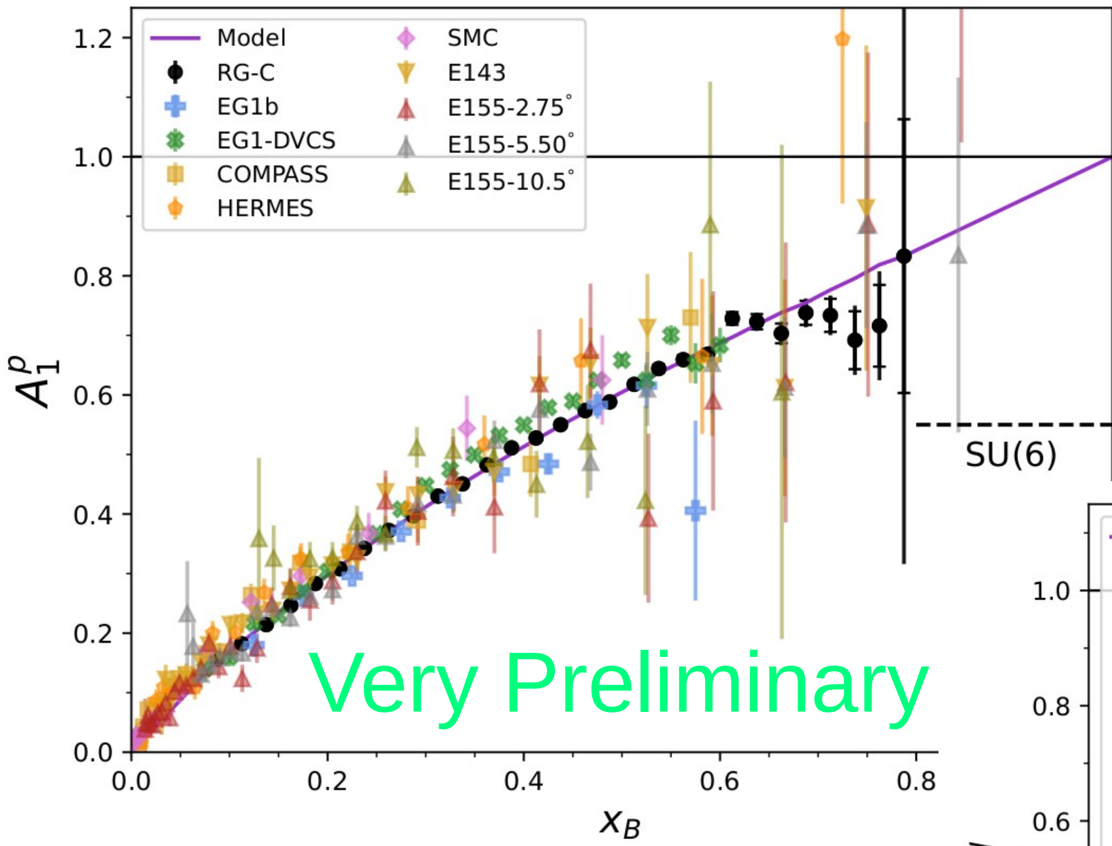
- Measured DIS inclusive spin structure functions (A1 and g1) of the proton and deuteron
  - → Include tagging with pion, kaon SIDIS to extract flavor-separated
- Measured spin- and transverse momentum-dependent (TMD) PDFs, back-to-back hadrons, forward dihadrons … (SIDIS)
- DVCS to access generalized parton distributions (GPDs), measured target spin and beam/target double spin asymmetries in proton and neutron DVCS.
- Ran from June 2022 through March 2023, 10.6 GeV, 4nA polarized electrons on 5-cm long polarized NH3 and ND3 target cells (60% of approved beam time)
- Dynamic nuclear polarization at 1K, 5 T with 140 GHz microwave on irradiated ammonia, longitudinal only (Ammonia POLarized LOngitudinally)

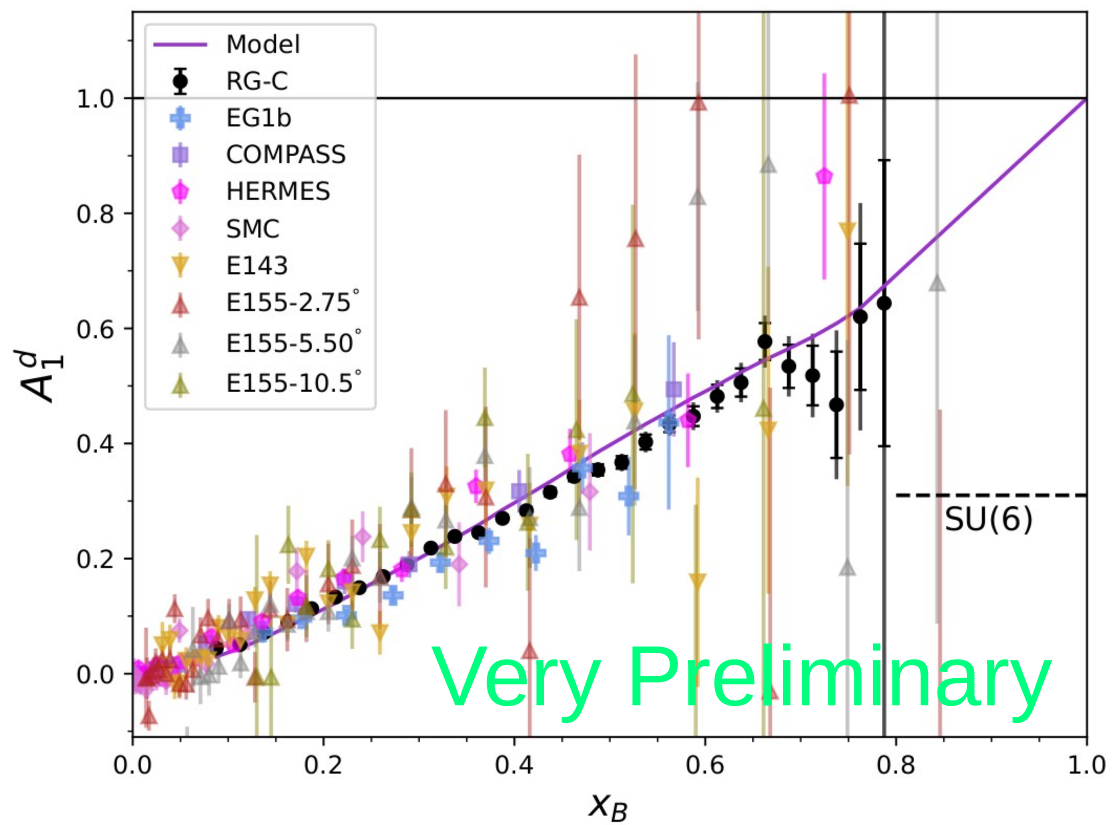


The Polarized NH3/ND3 Target for CLAS12 "APOLLO"



Preliminary Results from RG-C DIS A1p and A1d





Note: still need to apply radiative corrections, fine-tune fiducial cuts and dilution factor.

RG-C phase 2 forthcoming

Neutron results forthcoming

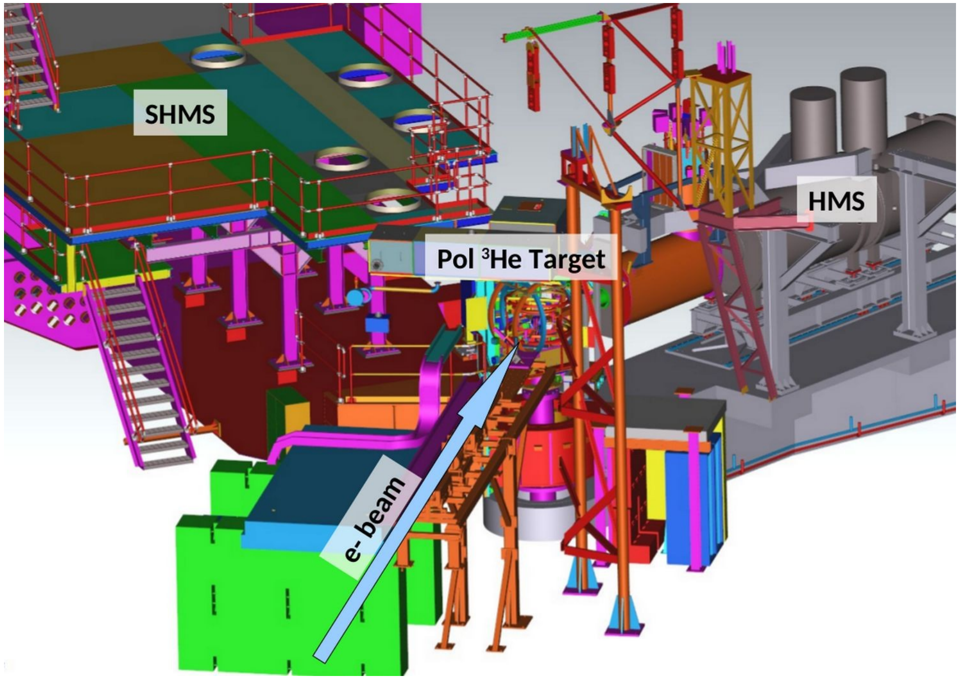
Figure credit: D. Upton, S. Kuhn (ODU)

JLab 12 GeV A1n Experiment 12-06-110 (Hall C)

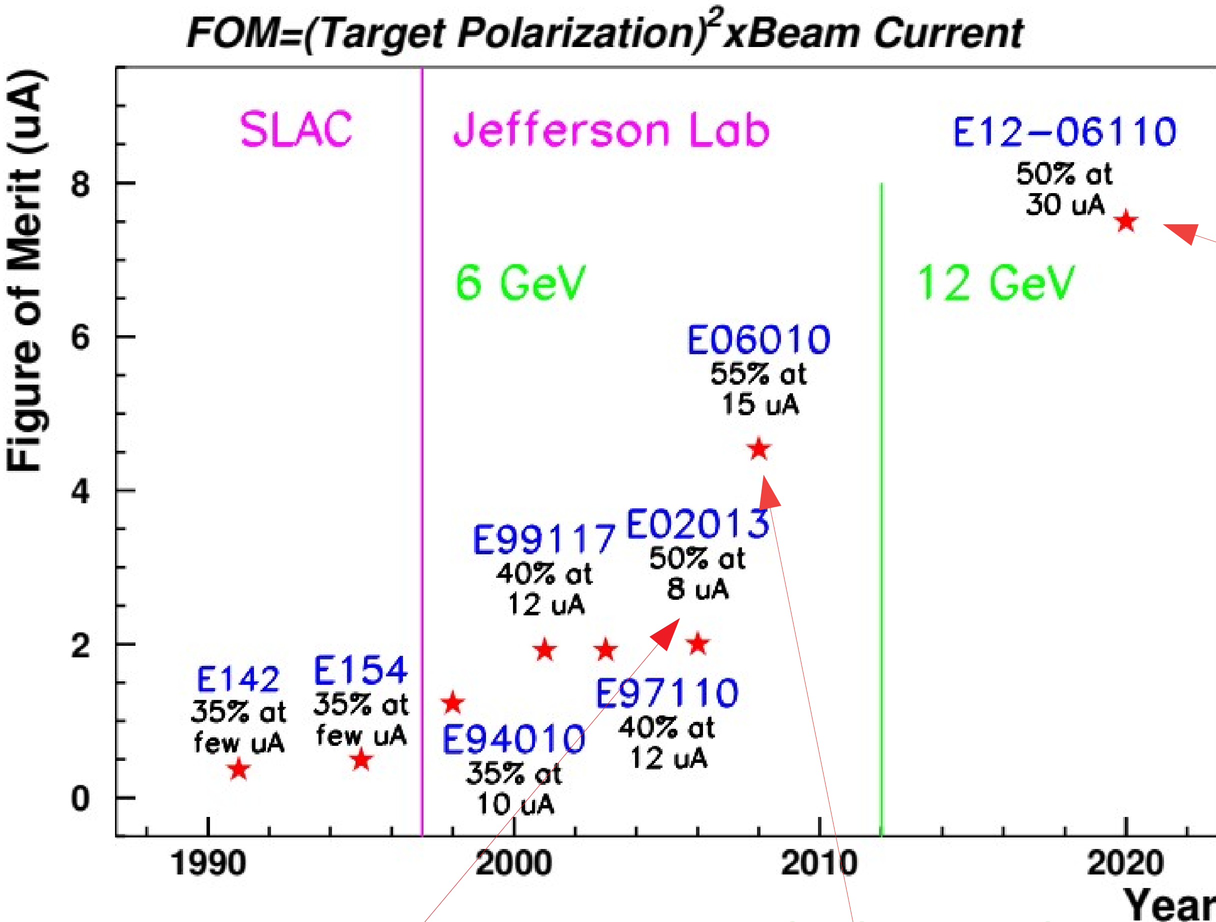
- Measured both Apar and Aperp on 3He
- 10.4 GeV beam, 85% longitudinal polarization, 30 uA
  - First in Hall C's 12 GeV era to utilize polarized beam
- HMS and SHMS detecting electrons in the inclusive mode
- Polarized 3He target (40cm)
  - first time use in Hall C
  - 50-55% in-beam polarization → factor 2 increase in 3He target FOM vs. 6 GeV era
- Ran from Dec. 2019 to March 2020

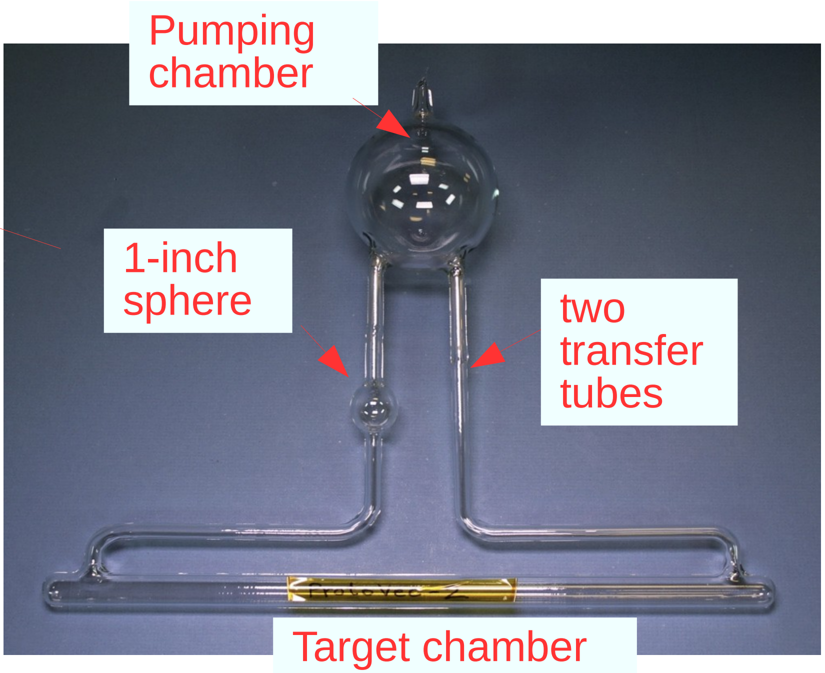
Kine	Spec	E_b GeV	E_p GeV	θ ($\circ$)	beam time (hours)
$\Delta(1232)$	SHMS	2.17	-1.79736	8.5	4.0
Elastic	SHMS	2.17	-2.12860	8.5	8.0

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



Polarized ^{3}He Targets Performance Evolution



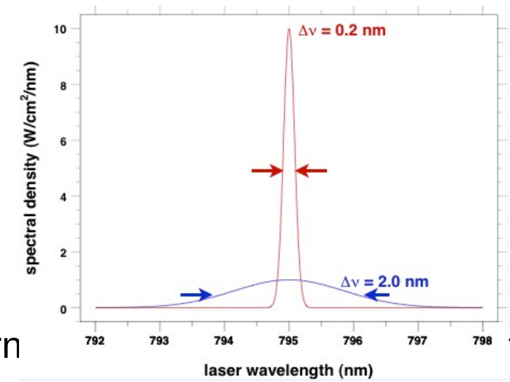


12 GeV era Target Cell:

Convection Cell (replacing 6 GeV diffusion cells.)

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

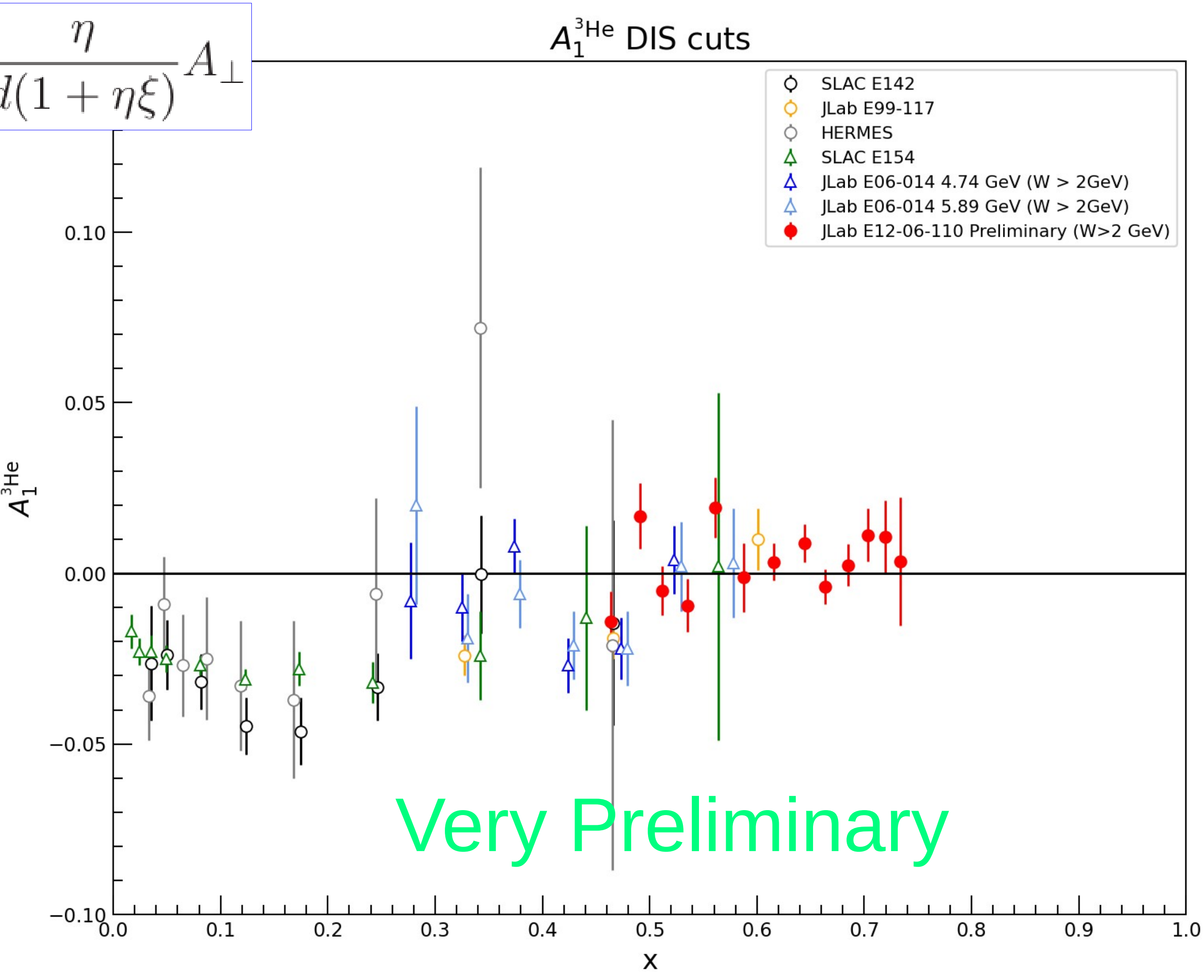
Transversity (E06-010):
Started to use narrow band laser.



GEn-II: even better FOM: 60-cm long cell!

Very Preliminary Results on A1(3He) (DIS)

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

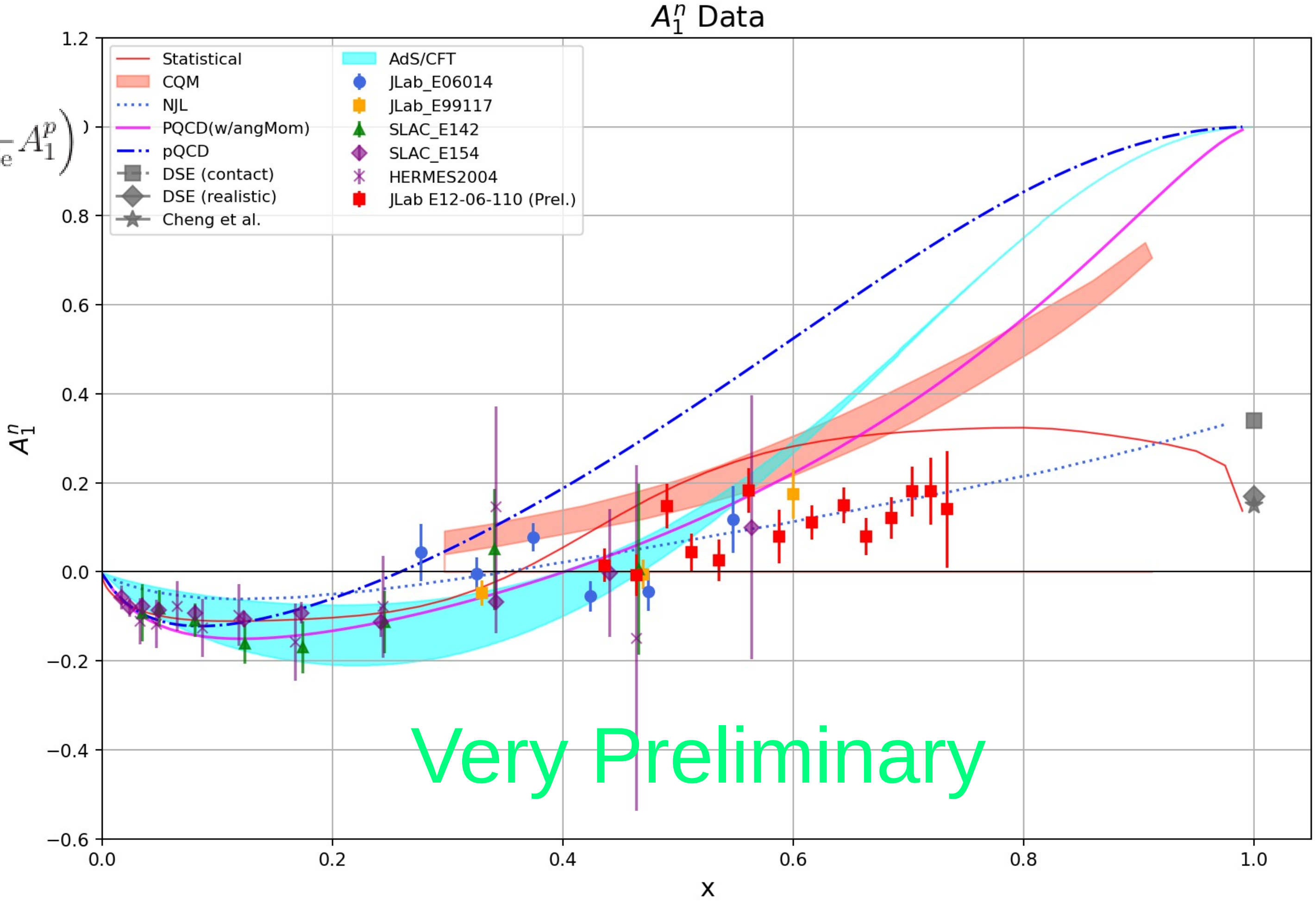


Work done by: M. Chen, M. Nycz, R. Trotta, XZ (and the E12-06-110 collaboration)

Very Preliminary Results on A1n (DIS)

A1n extracted using effective polarizations, the 6 GeV fit for the proton A1p, F1F221 (p, n, plus our own 3He fit)

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



From https://arxiv.org/pdf/1308.3723, the difference between effective polarization and full nuclear smearing is significant above x=0.6. We will study full nuclear smearing next.

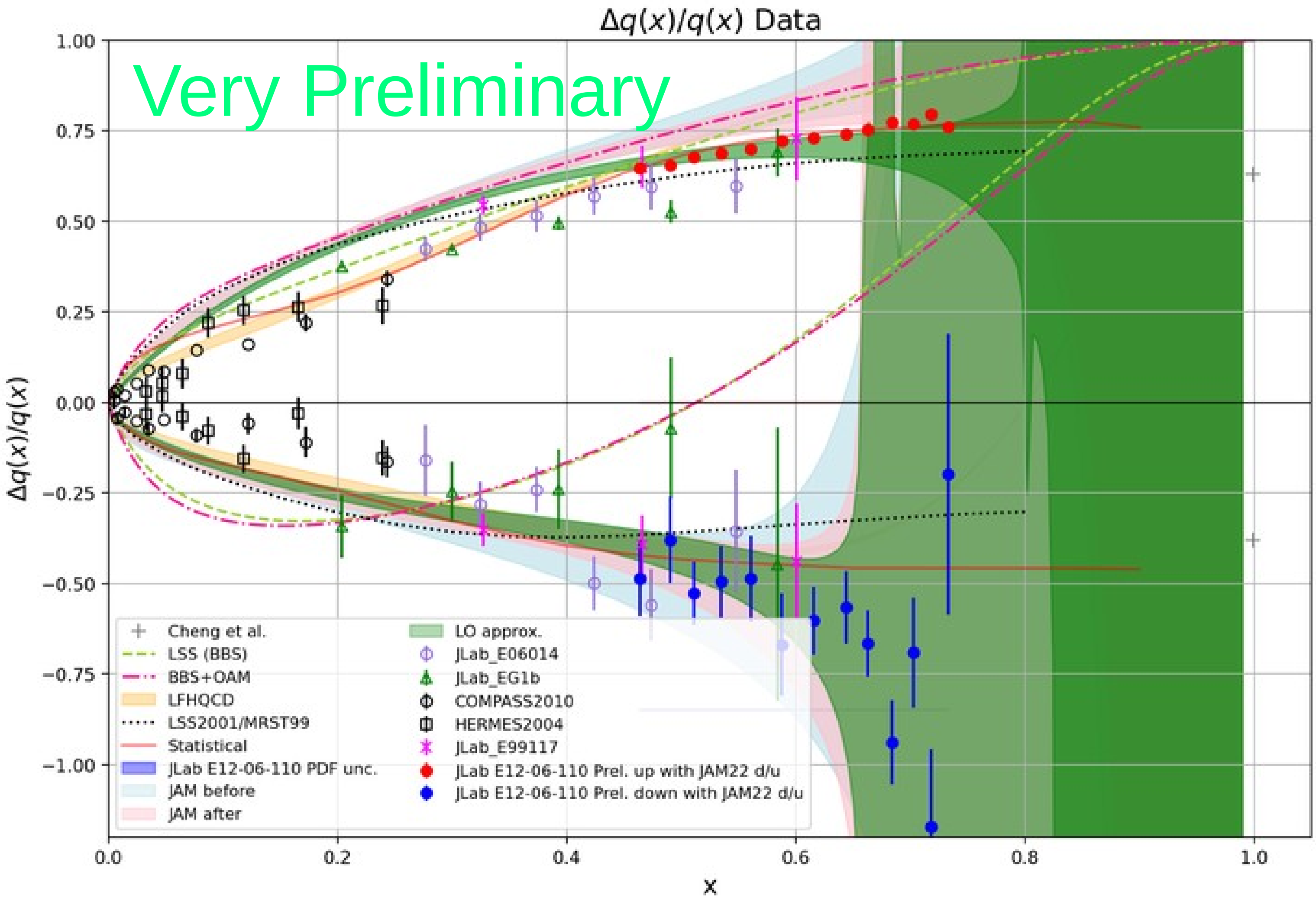
Very Preliminary Results on Quark Polarizations

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

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

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

(JAM22 here)



Pink: Full global analysis

Green: LO approx. (naive parton model)

Note: divergent issue. Fits with the positivity constraint ongoing

Figure credit:

C. Cocuzza, N. Sato

(JAM collaboration)

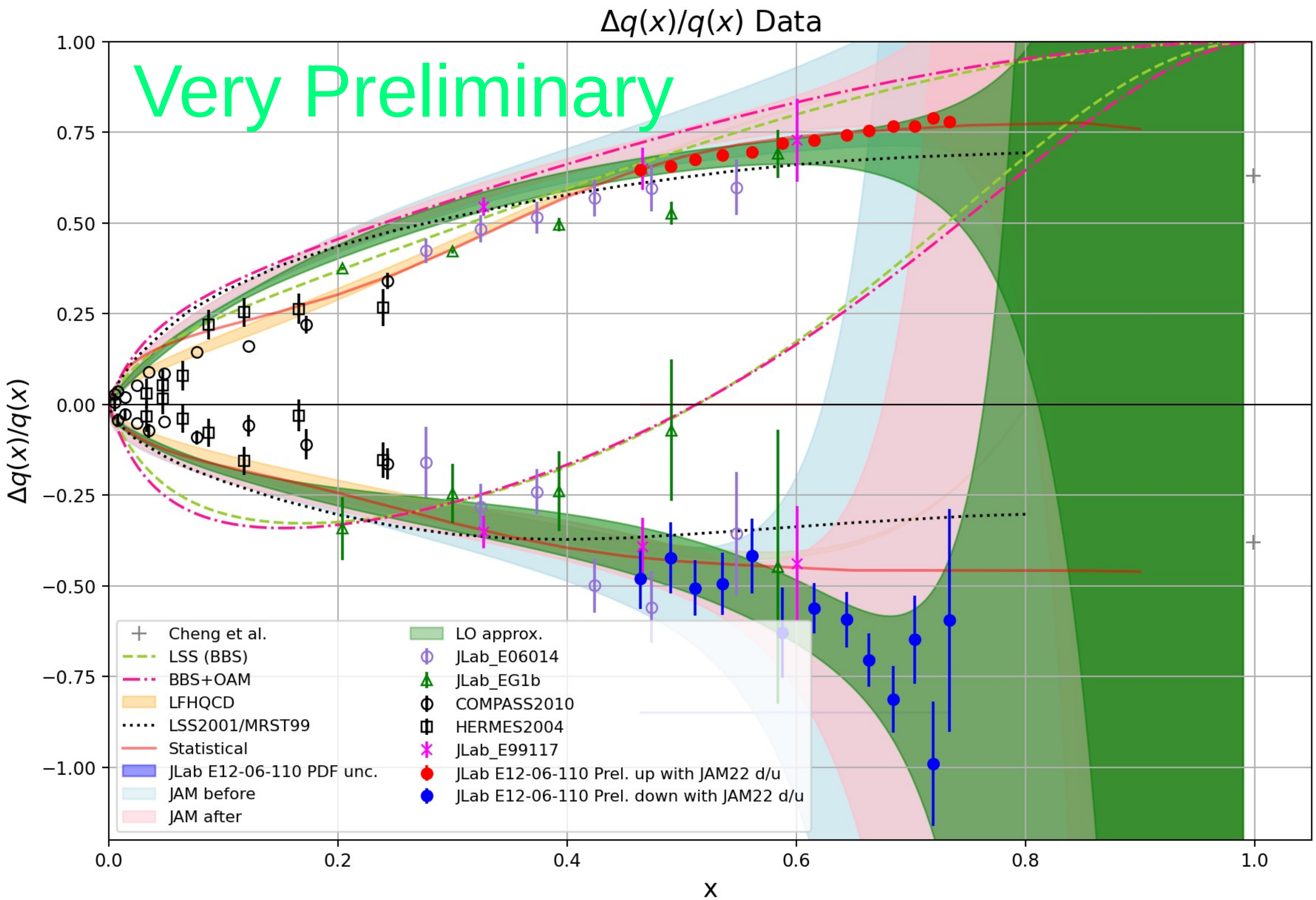
Very Preliminary Results on Quark Polarizations

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

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

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

(JAM22 here)



Pink: Full global analysis

Green: LO approx. (naive parton model)

Note: divergent issue. Fits with the positivity constraint ongoing

Figure credit:

C. Cocuzza, N. Sato

(JAM collaboration)

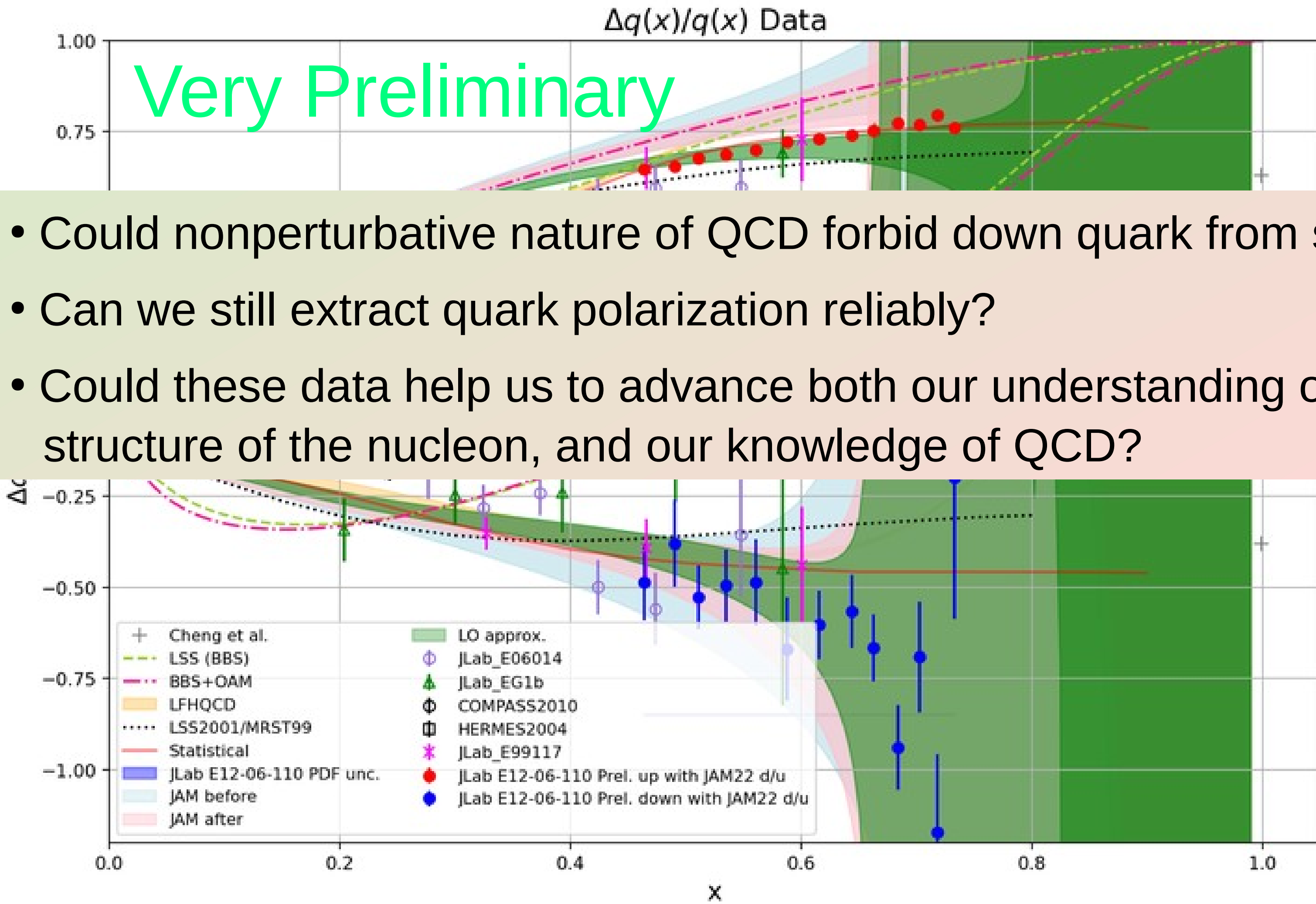
Now with positivity constraint

Very Preliminary Results on Quark Polarizations

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

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

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



- Could nonperturbative nature of QCD forbid down quark from spinning "up"?
- Can we still extract quark polarization reliably?
- Could these data help us to advance both our understanding of the spin structure of the nucleon, and our knowledge of QCD?

...sis

...aive

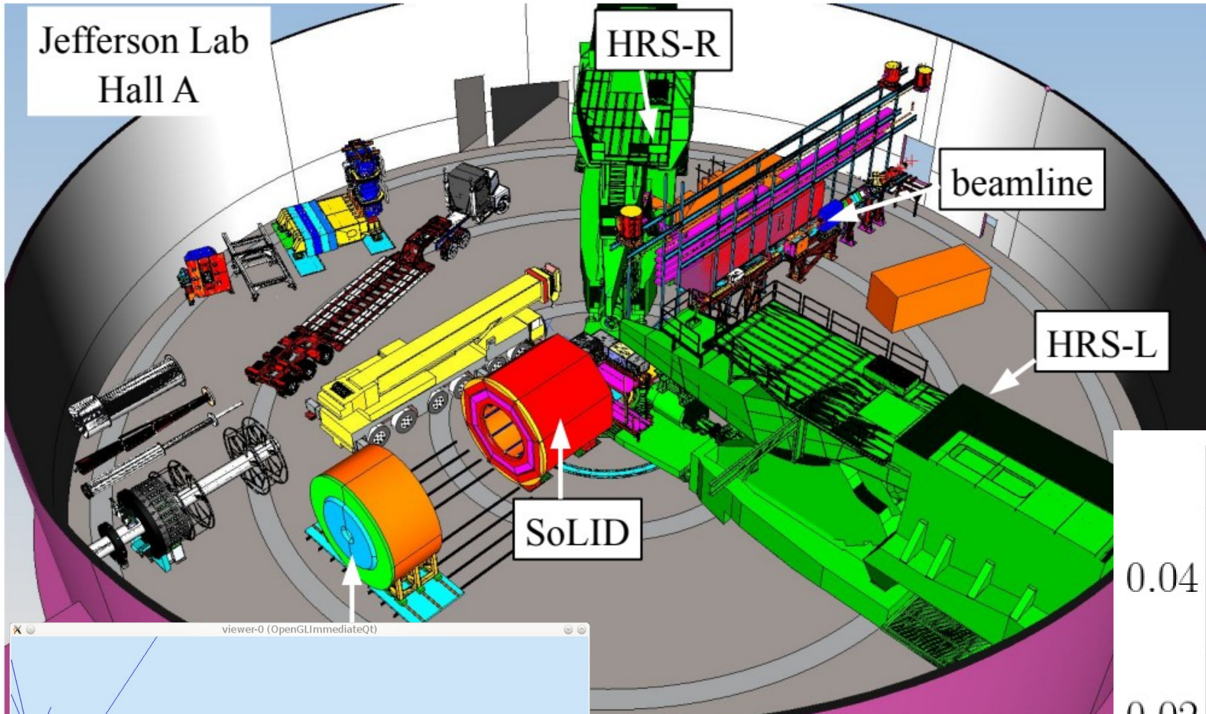
...Fits with the positivity constraint ongoing

Figure credit:

C. Cocuzza, N. Sato

(JAM collaboration)

SoLID @ 11 GeV



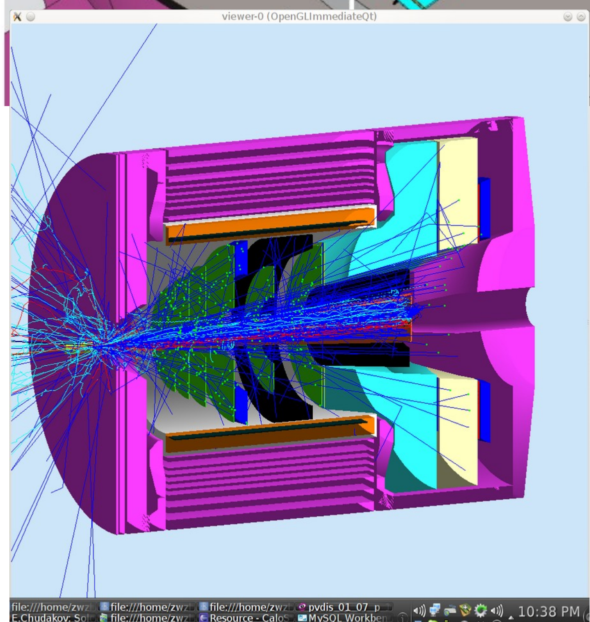
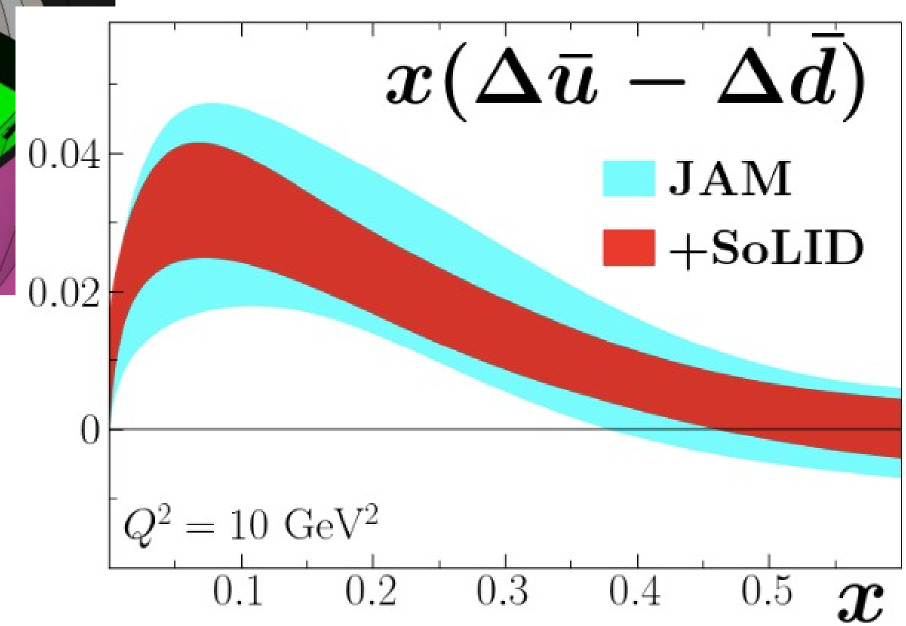


Figure credit:
C. Cocuzza
(JAM collaboration)



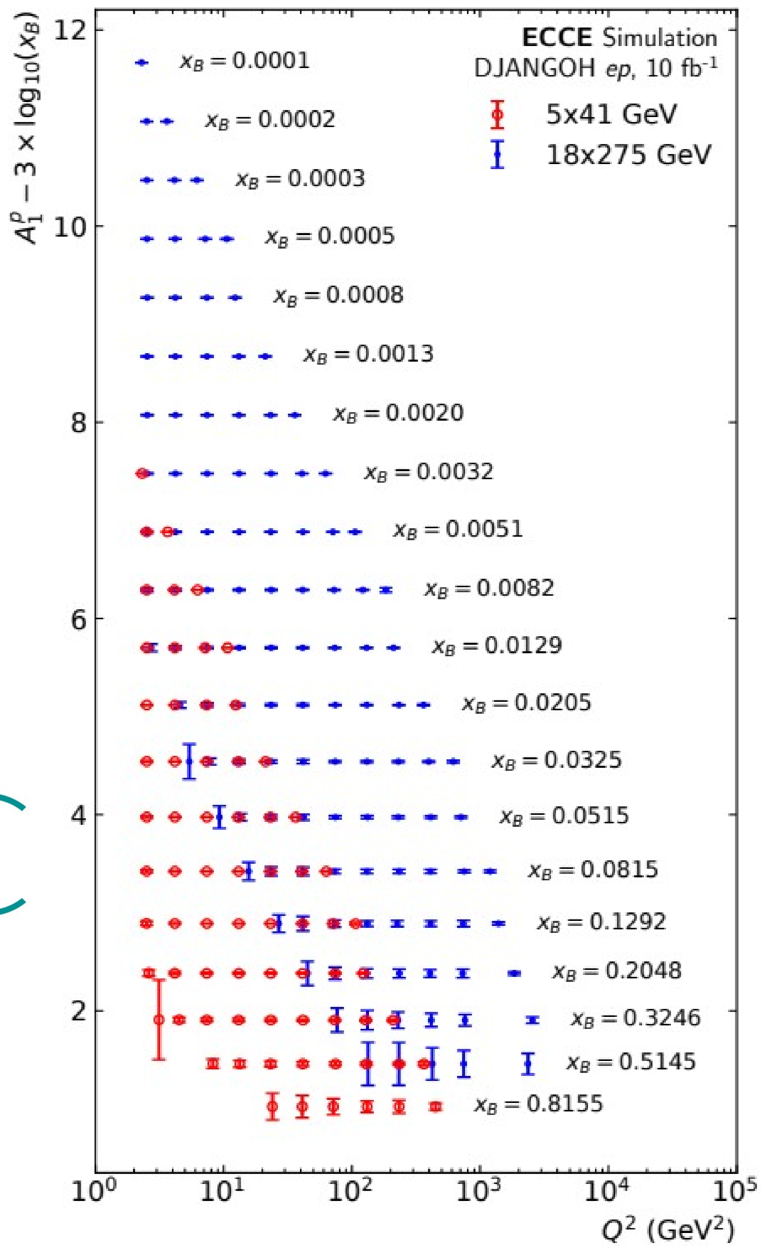
see talk by H. Gao

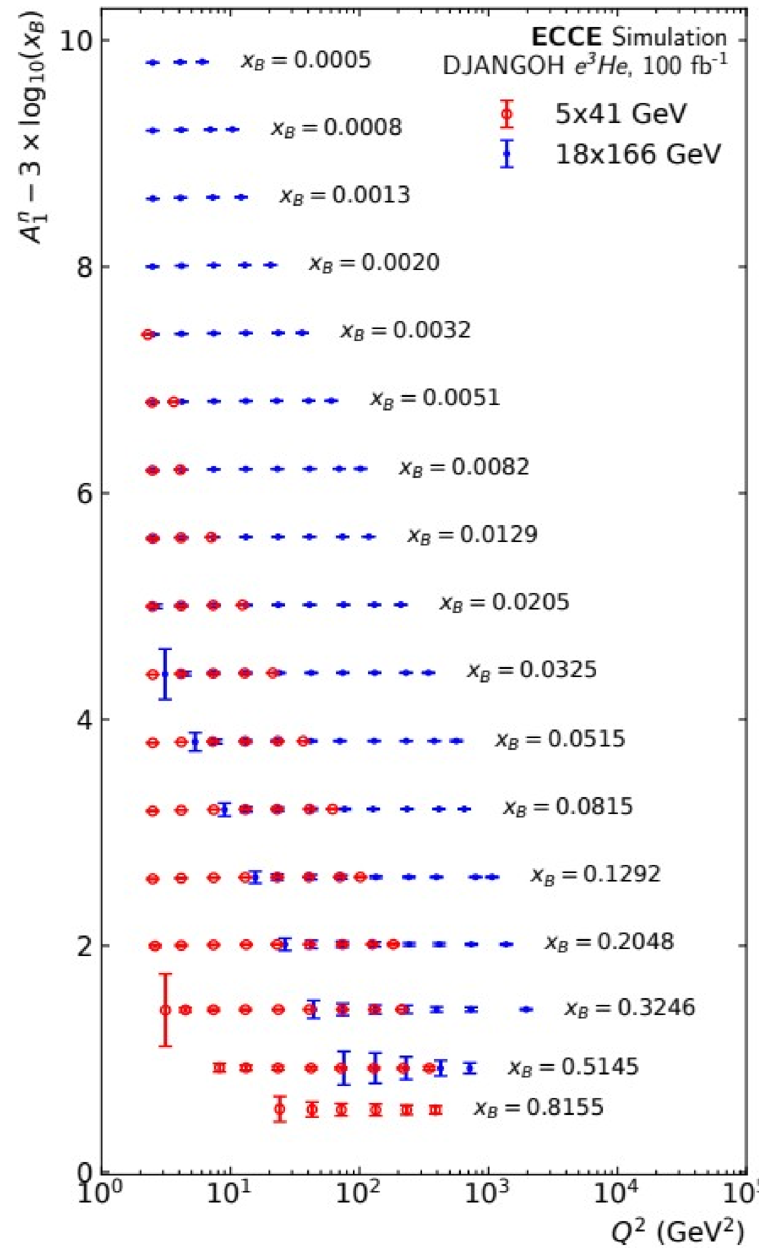
- SoLID (SIDIS on 3He) helps test if the polarized sea is **flavor asymmetric**, just like the unpolarized sea

High X Spin Structure Function at the Electron Ion Collider

Figure credit:
Tyler Kutz,
Dien Nguyen,
Jackson Pybus

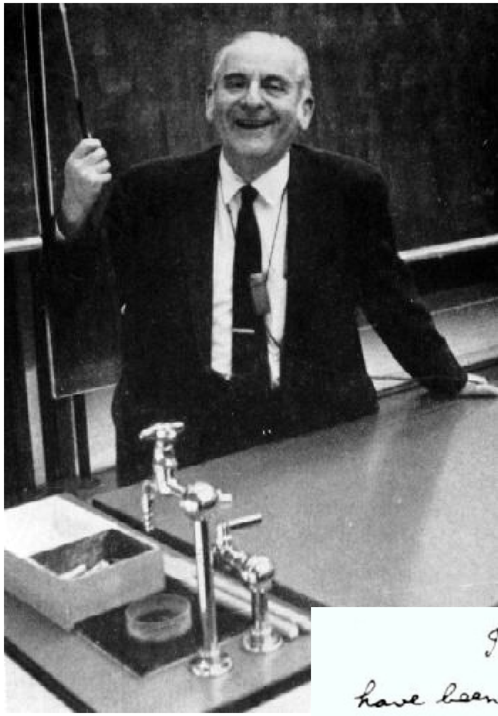
and ECCE





see EPIC talk
by W. Lin

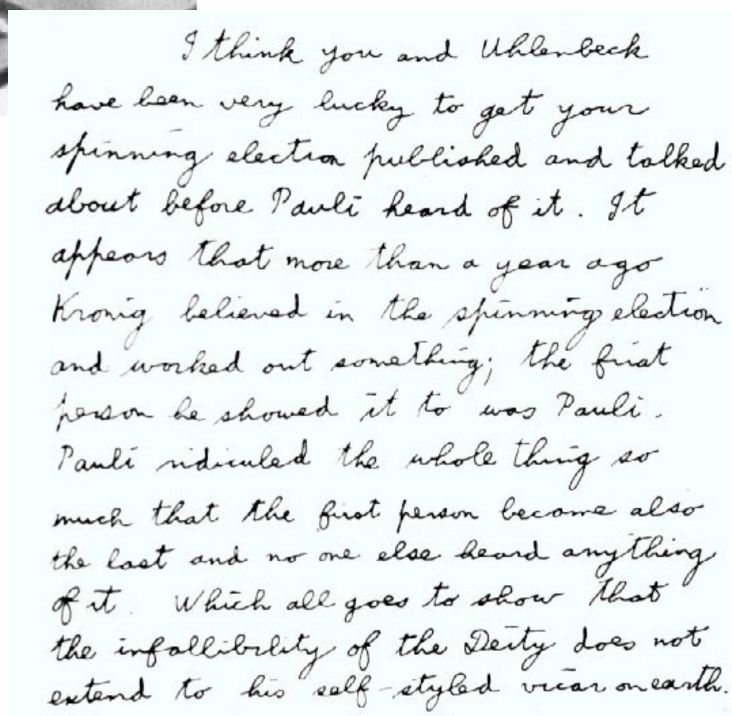
One Century of Spin



I think I still have Heisenberg's letter. In it he writes a formula .... I did not understand a bit of it. And then he says somewhere: "What have you done with the factor 2?" Which factor?

That is the way the history looks and it is a somewhat curious history. Who, precisely, should get credit for it? Such things are not possible without also giving credit to all other people who have contributed. But one aspect stands out which is of particular importance for young people. First: you need not be a genius to make an important contribution to physics because, I do admit, the electron spin is an important contribution. That I know now, then we did not know, but now I do. They all told me so.

Then I want to say one more thing: even if you make a minor contribution, (even) if it is not important, then this gives an enormous satisfaction. Therefore I do believe that one should not always aspire to tackle what is most important, but try to have fun working in physics and obtain results.



I think you and Uhlenbeck have been very lucky to get your spinning electron published and talked about before Pauli heard of it. It appears that more than a year ago Kronig believed in the spinning electron and worked out something; the first person he showed it to was Pauli. Pauli ridiculed the whole thing so much that the first person became also the last and no one else heard anything of it. Which all goes to show that the infallibility of the Deity does not extend to his self-styled vicar on earth.

Part of a letter by L.H. Thomas to Goudsmit (25 March 1926).
Reproduced from a transparency shown by Goudsmit during his 1971 lecture. The original is presumably in the Goudsmit archive kept by the AIP Center for History of Physics.

https://lorentz.leidenuniv.nl/history/spin/goudsmit.html

Backup Slides

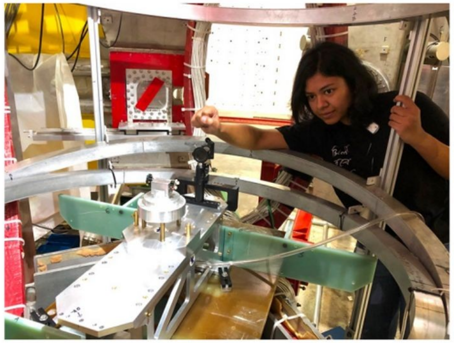
Hall C 12 GeV A1n/d2n Collaboration

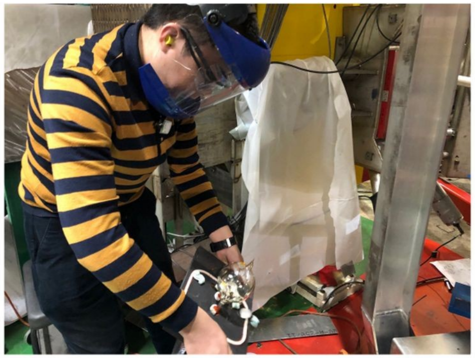
PhD (two graduated)

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





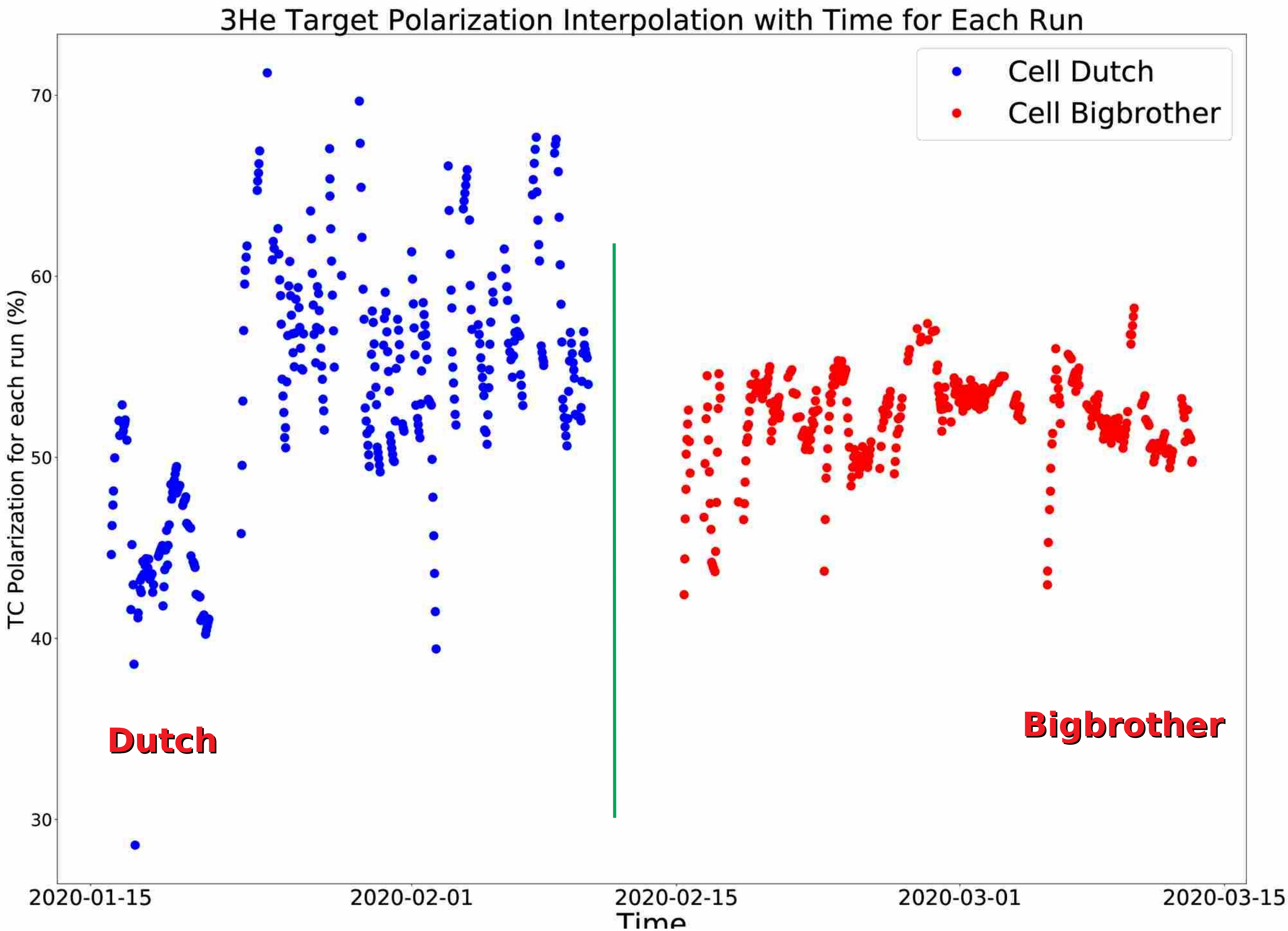
Institutions

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

Production Cell Performance

(for targets used in A_1^n experiment)



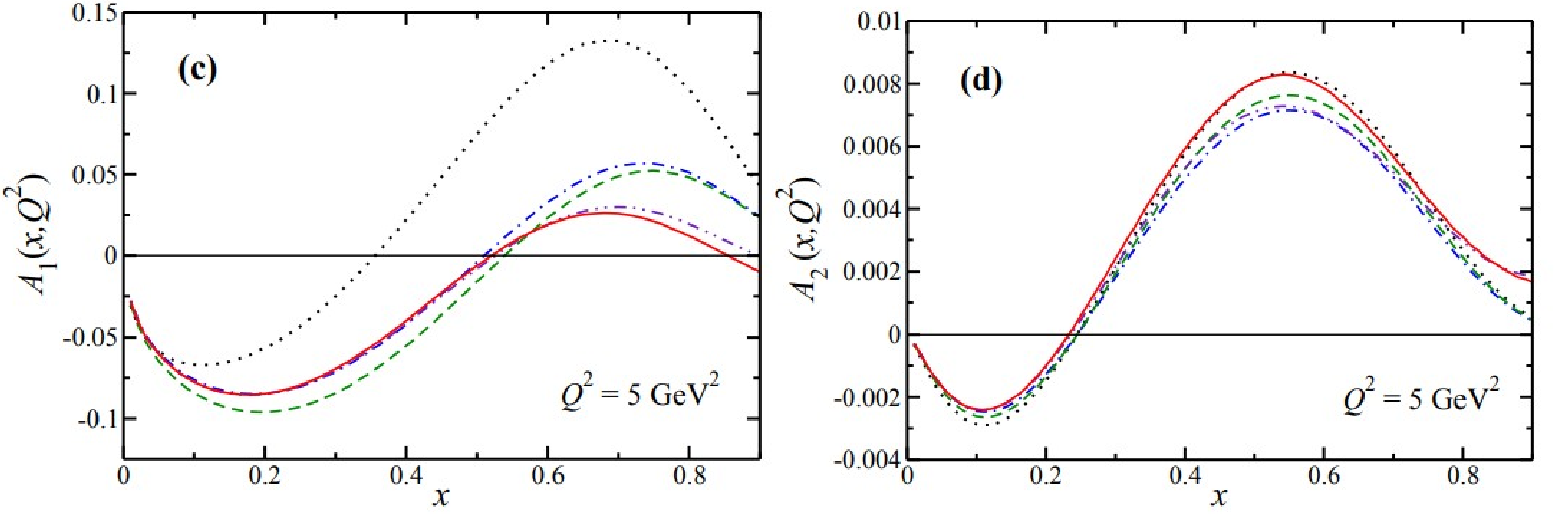
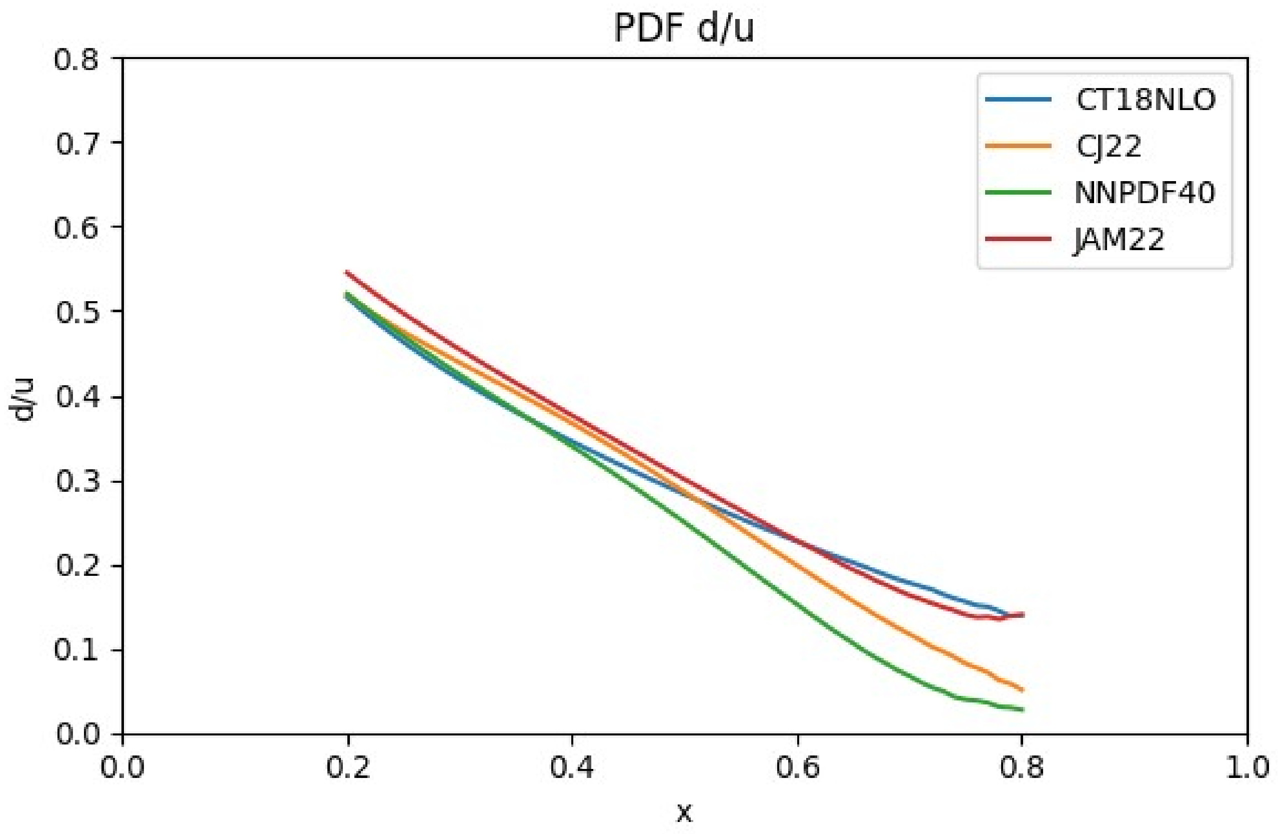
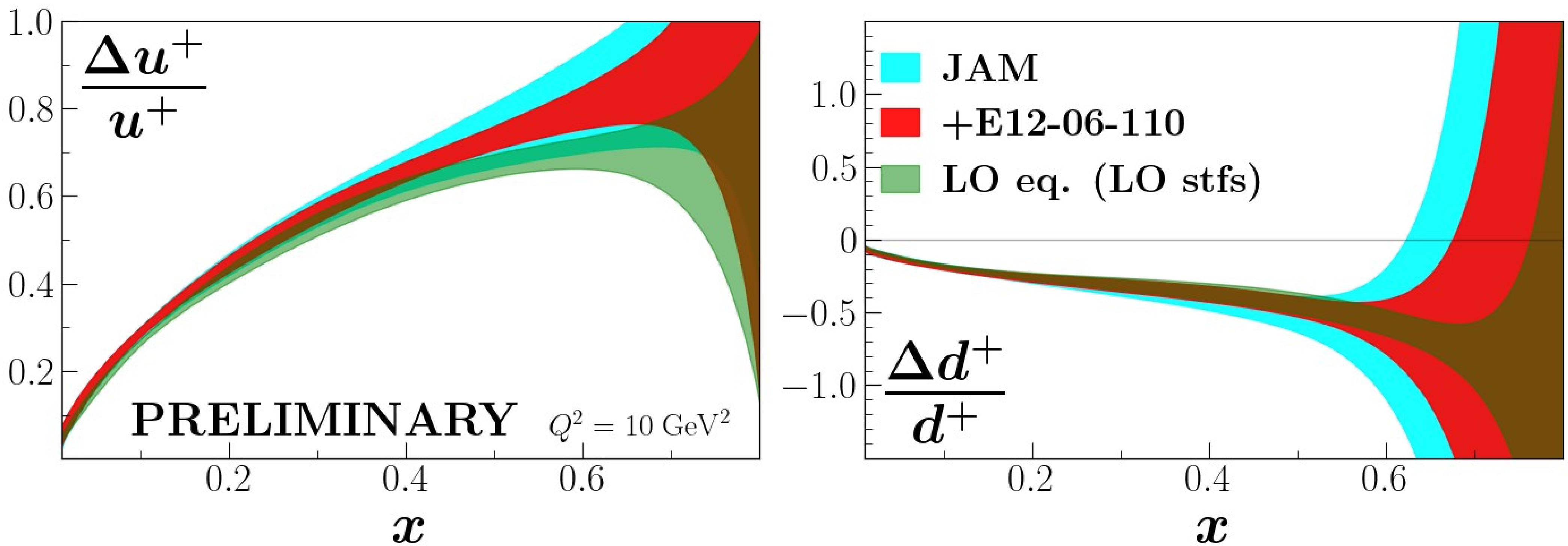


FIG. 6: As in Fig. 2, but for the polarization asymmetries A_1 and A_2 of the neutron and ^{3}He at $Q^2 = 1$ GeV^2 [**(a)** and **(b)**] and $Q^2 = 5$ GeV^2 [**(c)** and **(d)**], constructed from ratios of the spin-dependent structure functions in Fig. 2 and the unpolarized F_1 structure function from the Bosted-Christy parametrization [55]. Note that the ^{3}He asymmetries are scaled by a factor $(1 + 2F_1^p/F_1^n)$.

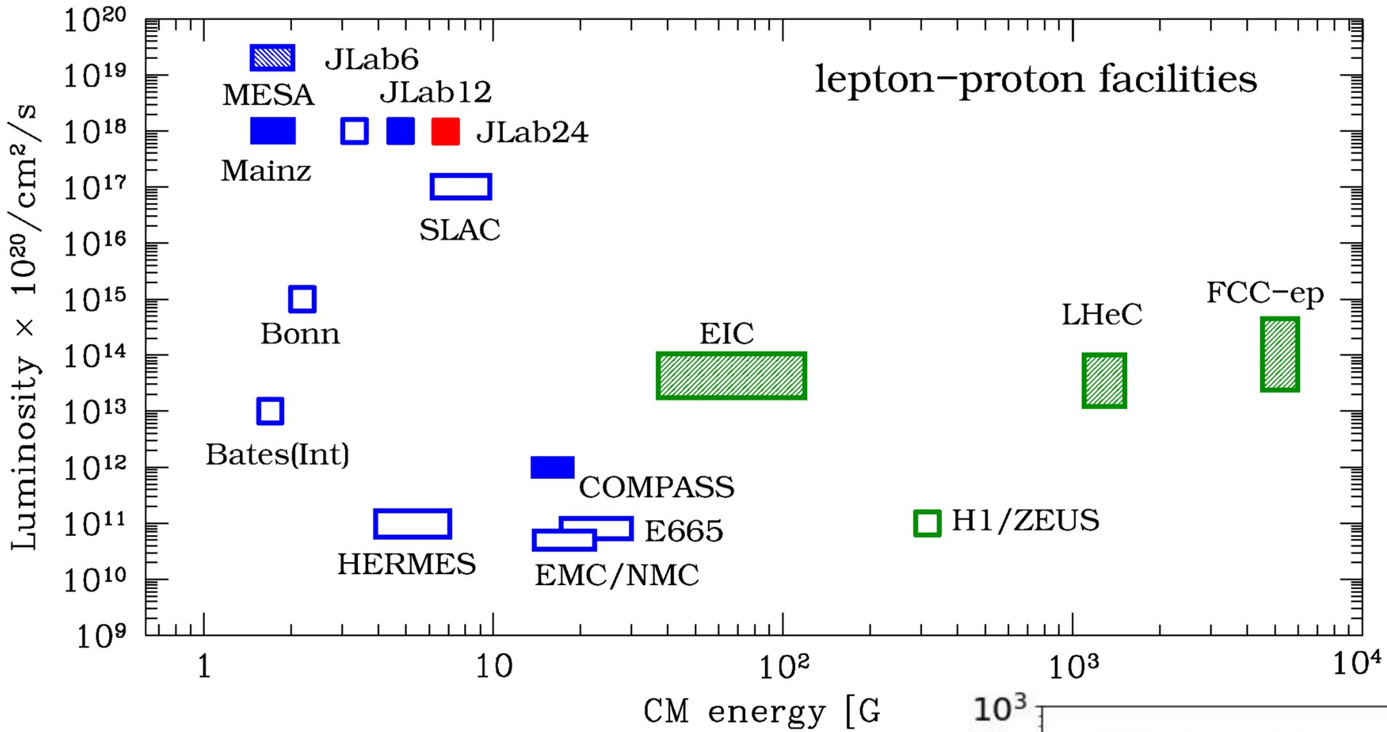

PDF d/u
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
d/u
0.0
0.2
0.4
0.6
0.8
1.0
x
CT18NLO
CJ22
NNPDF40
JAM22



$\frac{\Delta u^+}{u^+}$
PRELIMINARY
$Q^2 = 10$ GeV^2
JAM
+E12-06-110
LO eq. (LO stfs)
$\frac{\Delta d^+}{d^+}$
x

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