Collinear Nucleon Structure at Large X

HEP-2023

Jan 9-13, 2023, at UTFSM, Valparaiso (Chile)

Sebastian Kuhn

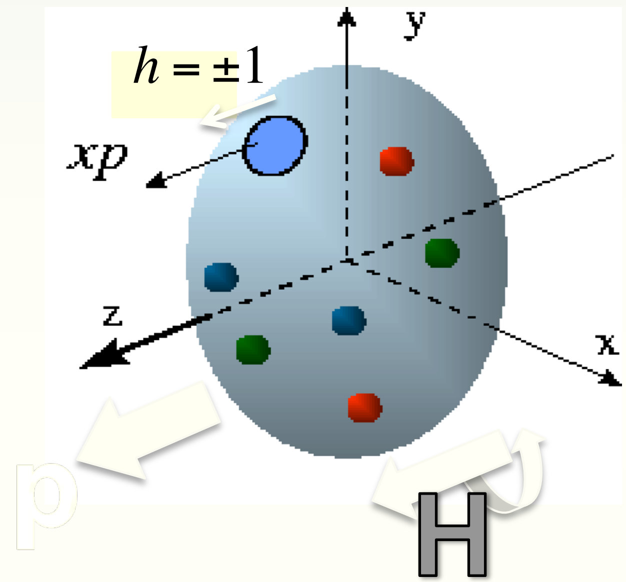
Old Dominion University, Norfolk (VA), USA

Overview

- Longitudinal valence structure of the nucleon
  - Why do we care?
  - Where are we right now? What do we need?
- Unpolarized structure function of the neutron
  - The overall landscape
  - BONuS12 experiment at Jefferson Lab
- Spin structure at high x
  - Existing world data
  - Recent results (Exp. and Theory)
  - Upcoming experiments
- The polarized EMC effect
- Future Facilities – what more can we do?
  - JLab at 20+ GeV?
  - EIC
- Conclusions

Collinear Structure functions

- Understand origin of mass and spin of hadrons
- Important as limiting cases and constraints for TMDs, GPDs etc.
- Most stringent tests of pQCD, Lattice QCD and phenomenological models
  - NN…LO + DGLAP *)
  - Sophisticated and mature PDF extractions
  - Well-established higher twist and target mass effects
  - Quark-hadron duality
- Important input for collider physics
- Input for investigations of modifications of quark distributions in nuclei



$$q(x;Q^2), \langle h\cdot H\rangle q(x;Q^2)$$

"1-D" Parton Distributions (PDFs)
(integrated over all transverse variables)

*) E.g.,
$$g_1^{p}(x,Q^2)=\frac{1}{2}\sum_q e_q^2\Delta q_v(x,Q^2)\otimes\left(1+\frac{\alpha_s(Q^2)}{2\pi}\Delta C_q^{(1)}+\left(\frac{\alpha_s(Q^2)}{2\pi}\right)^2\Delta C_{ns}^{(2)}\right)$$
$$+e_q^2(\Delta q_s+\Delta\overline{q_s})(x,Q^2)\otimes\left(1+\frac{\alpha_s(Q^2)}{2\pi}\Delta C_q^{(1)}+\left(\frac{\alpha_s(Q^2)}{2\pi}\right)^2\Delta C_s^{(2)}\right)$$
$$+\frac{2}{9}\left(\frac{\alpha_s(Q^2)}{2\pi}\Delta C_g^{(1)}+\left(\frac{\alpha_s(Q^2)}{2\pi}\right)^2\Delta C_g^{(2)}\right)\otimes\Delta g(x,Q^2)$$

MIRJALILI and TEHRANI
PHYSICAL REVIEW D **105,** 074023 (2022)

Valence Region: Structure Functions for $x \to 1$

- Dominated by up and down valence quarks –> quantum numbers of the nucleon
- Important for higher power x^n moments -> Mellin Moments, LQCD
- Related to high-Q^2, moderate x through DGLAP

- MANY predictions based on models, pQCD and Lattice QCD *):

SU(6)-symmetric proton wave function in the "naïve" quark model:

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

In this model: d/u = 1/2, Δu/u = 2/3, Δd/d = -1/3 for all x

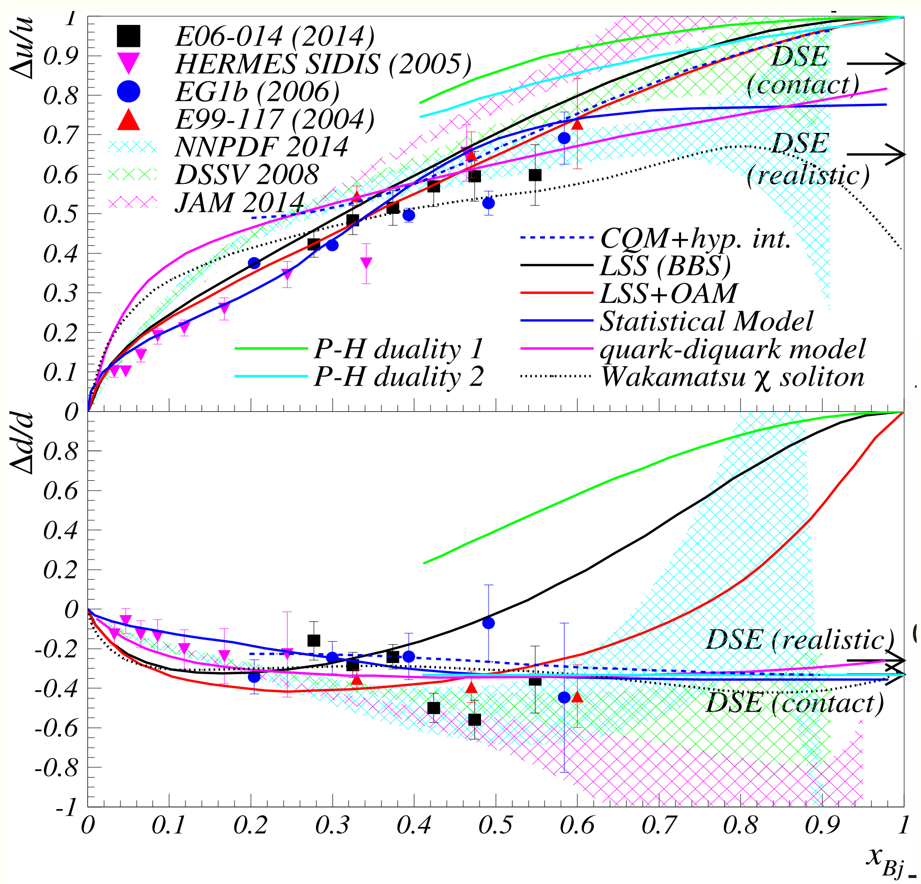
Hyperfine structure effect in QM: S=1 suppressed => d/u = 0, Δu/u = 1, Δd/d = -1/3 for $x \to 1$

pQCD: helicity conservation (q$\uparrow\uparrow$p) => d/u -> 2/(9+1) = 1/5, Δu/u -> 1, Δd/d -> 1 for $x \to 1$

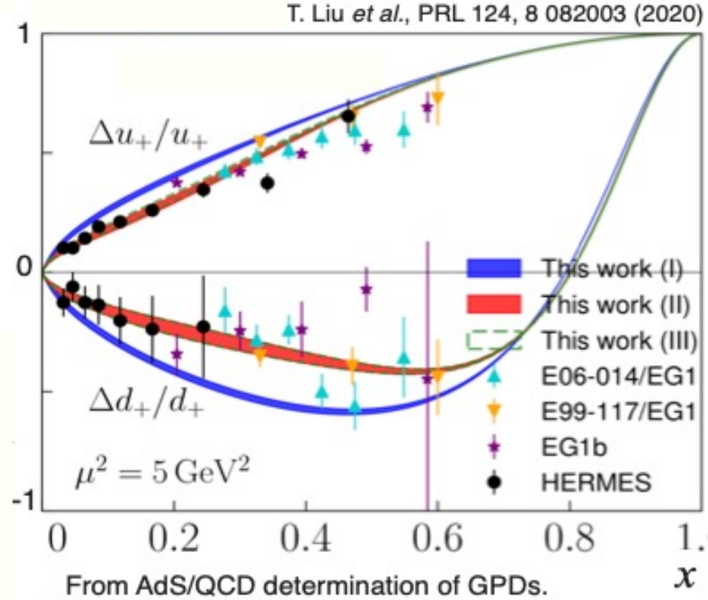
Other approaches: Dyson-Schwinger Equation, statistical models, pQCD + orbital angular momentum, AdS (Light-front holographic QCD)

*) Moments, quasi-PDFs, pseudo-PDFs

Recent theoretical predictions



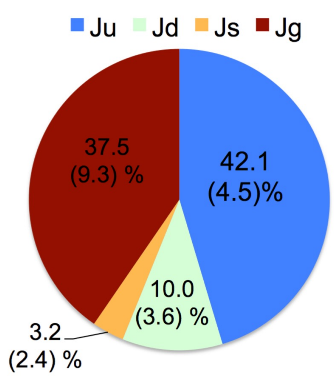
T. Liu *et al.*, PRL 124, 8 082003 (2020)

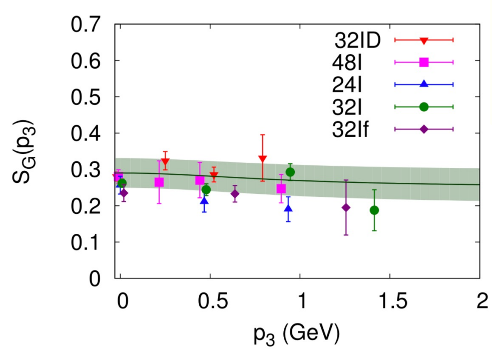


From AdS/QCD determination of GPDs.
No free parameters.
Predicts *Δd/d* changes sign near x=0.8.
Reproduces QCD counting rules used for BBS/LSS.

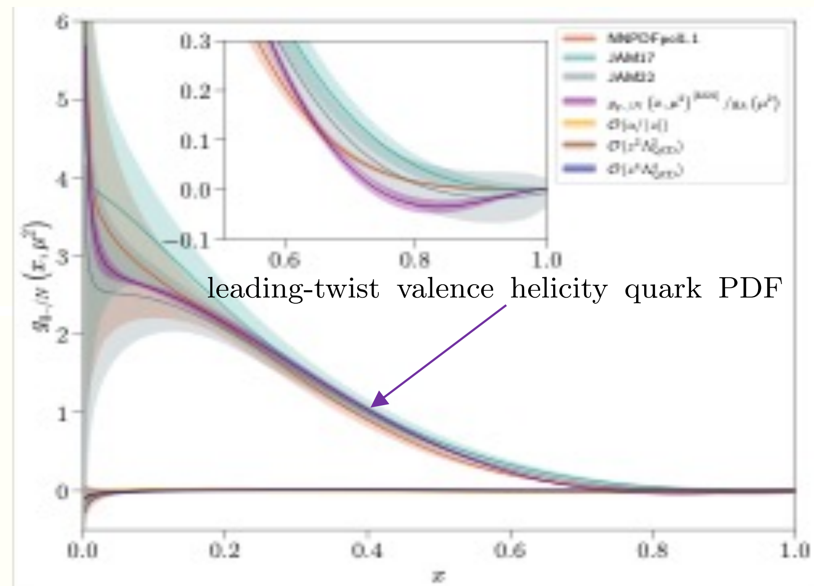
R.G. Edwards et al. JLAB-THY-22-3751 arXiv:2211.04434v1
Non-singlet quark helicity PDFs of the nucleon from pseudo-distributions

Ji, Yuan and Zhao: arXiv2009.01291 [hep-ph]





LATTICE QCD

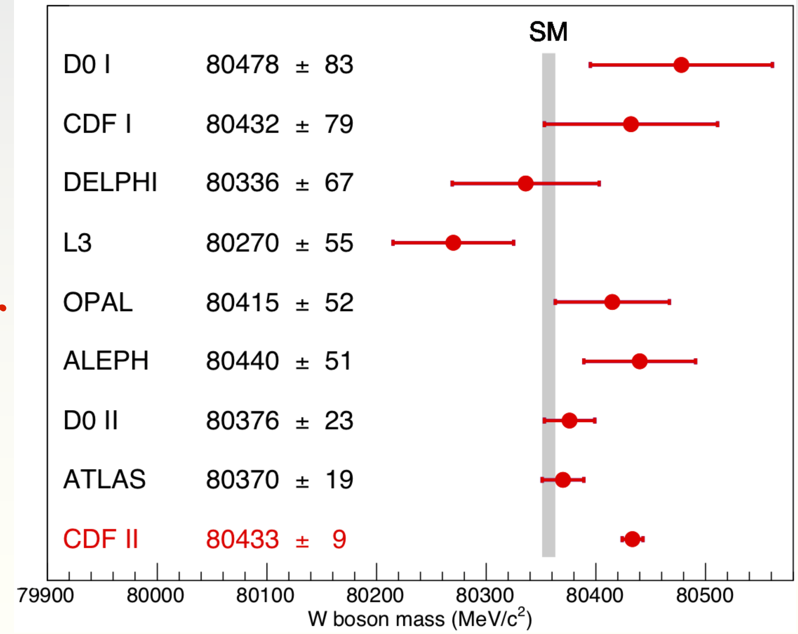


High-x PDFs: Input for Collider experiments

Ex.: High-Precision Measurement of the W Boson Mass with the CDF II Detector

Ashutosh Kotwal, Duke University

Jefferson Lab Users Meeting June 14, 2022



CDF Collaboration *et al.*, *Science* **376**, 170–176 (2022)

Parton Distribution Functions

- Affect W boson kinematic line-shapes through acceptance cuts
- We use NNPDF3.1 as the default NNLO PDFs
- Use ensemble of 25 'uncertainty' PDFs => 3.9 MeV
- Central values from NNLO PDF sets CT18, MMHT2014 and NNPDF3.1 agree within 2.1 MeV of their midpoint
- As an additional check, central values from NLO PDF sets ABMP16, CJ15, MMHT2014 and NNPDF3.1 agree within 3 MeV of their midpoint

"For example, the cj15 set includes all Tevatron data on the W -charge asymmetry, as well as the lepton- charge asymmetry from W boson decays and quasi-free neutron scattering data from the Jefferson Lab BONuS experiment [95, 96] "

Science AAAS

Supplementary Materials for

High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration

Corresponding author: A. V. Kotwal, ashutosh.kotwal@duke.edu

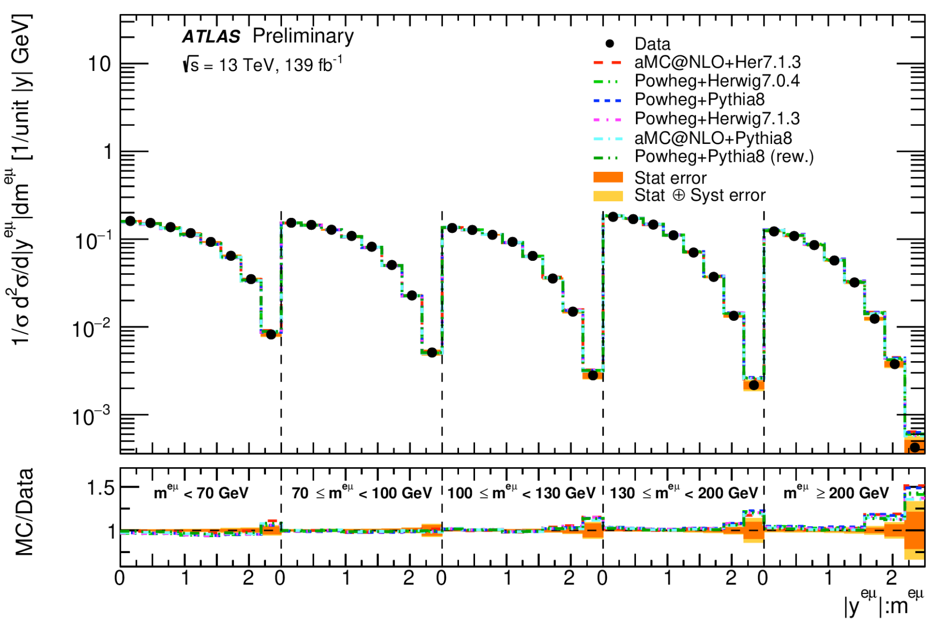
Science **376**, 170 (2022)
DOI: 10.1126/science.abk1781

95. N. Baillie, S. Tkachenko, J. Zhang, P. Bosted, S. Bültmann, M. E. Christy, H. Fenker, K. A. Griffioen, C. E. Keppel, S. E. Kuhn, W. Melnitchouk, V. Tvaskis, K. P. Adhikari, D. … Measurement of the neutron F_2 structure function via spectator tagging with CLAS. *Phys. Rev. Lett.* **108**, 142001 (2012). doi:10.1103/PhysRevLett.108.142001 Medline

96. S. Tkachenko, N. Baillie, S. E. Kuhn, … D. Watts, X. Wei, L. B. Weinstein, M. H. Wood, L. Zana, I. Zonta, Measurement of the structure function of the nearly free neutron using spectator tagging in inelastic $^2H(e,e'p_s)X$ scattering with CLAS. *Phys. Rev. C* **89**, 045206 (2014).

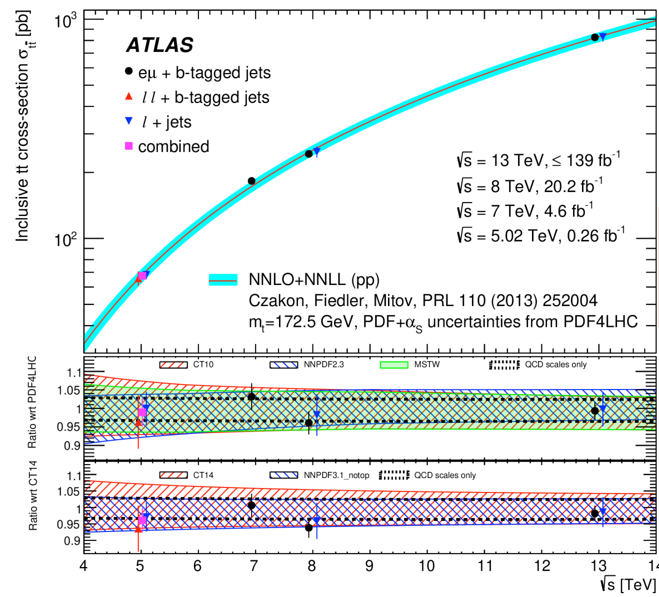
Cross sections

ATLAS-CONF-2022-061



- **Differential and double differential distributions**
- Full Run-2, eμ final state
- Inclusive production cross section
  - σtt =836±1(stat)±12(syst)±16(lumi)±2(beam)pb

arXiv:2207.01354 TOPQ-2018-40



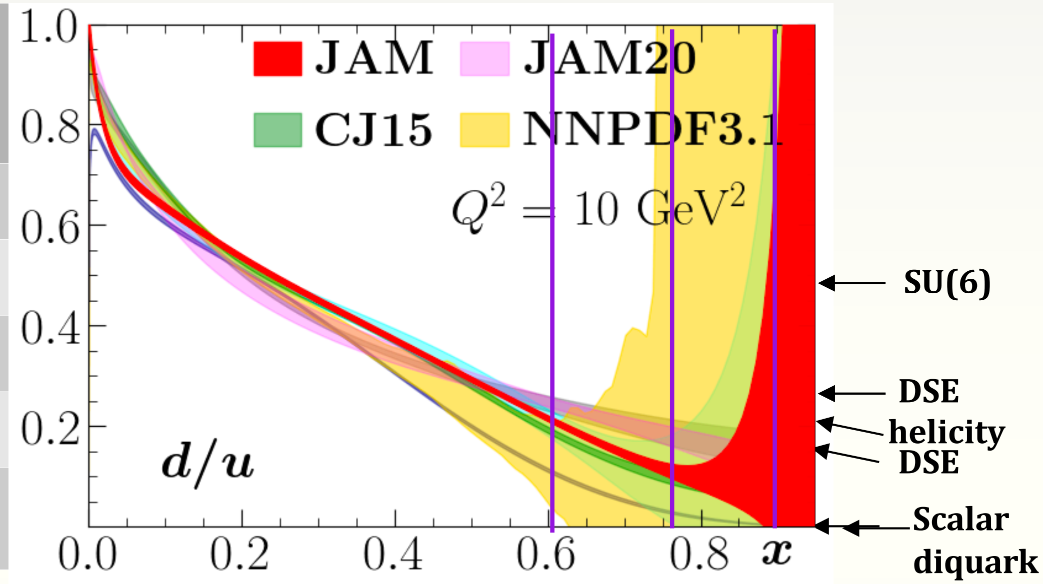
- **5.02 TeV**
- dilepton and single-lepton
- *σtt*=67.5±0.9(stat.)±2.3(syst.) ±1.1(lumi.)±0.2(beam) pb
- Relative uncertainty~3.9%
- In agreement with theoretical QCD calculations at NNLO
- Constrains proton parton distribution functions at large Bjorken-*x*

- **Run-1, 7 TeV *l*+jets**
- Multidimensional event classifier based on support vector machines
- *σtt*=168.5±0.7 (stat.)+6.2–5.9 (syst.)+3.4–3.2 (lumi.) pb

TOPQ-2017-08
arXiv:2212.00571

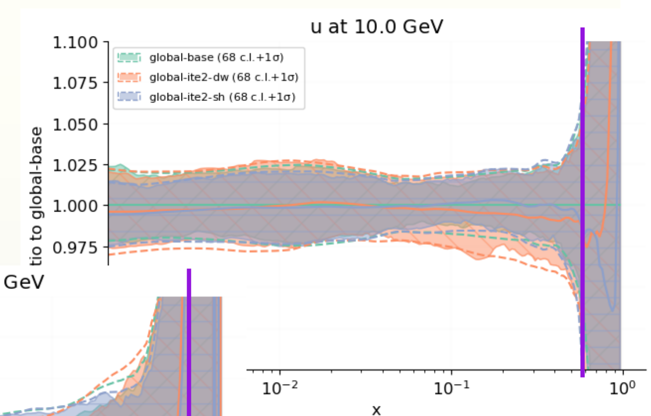
Unpolarized PDFs– high *x*

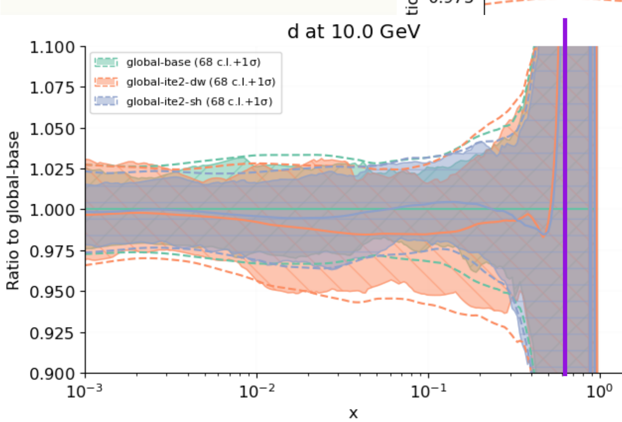
Nucleon Model	F_2^n/F_2^p $x \to 1$	d/u $x \to 1$
SU(6) Symmetry	2/3	0.5
Scalar diquark dominance	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
PQCD (helicity conservation)	3/7	0.2

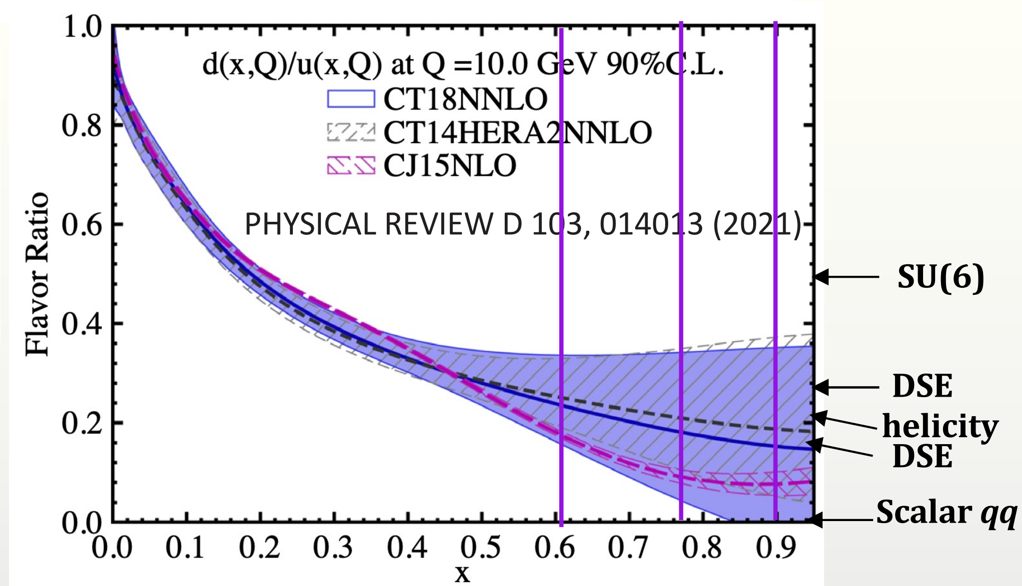


NNPDF3.1

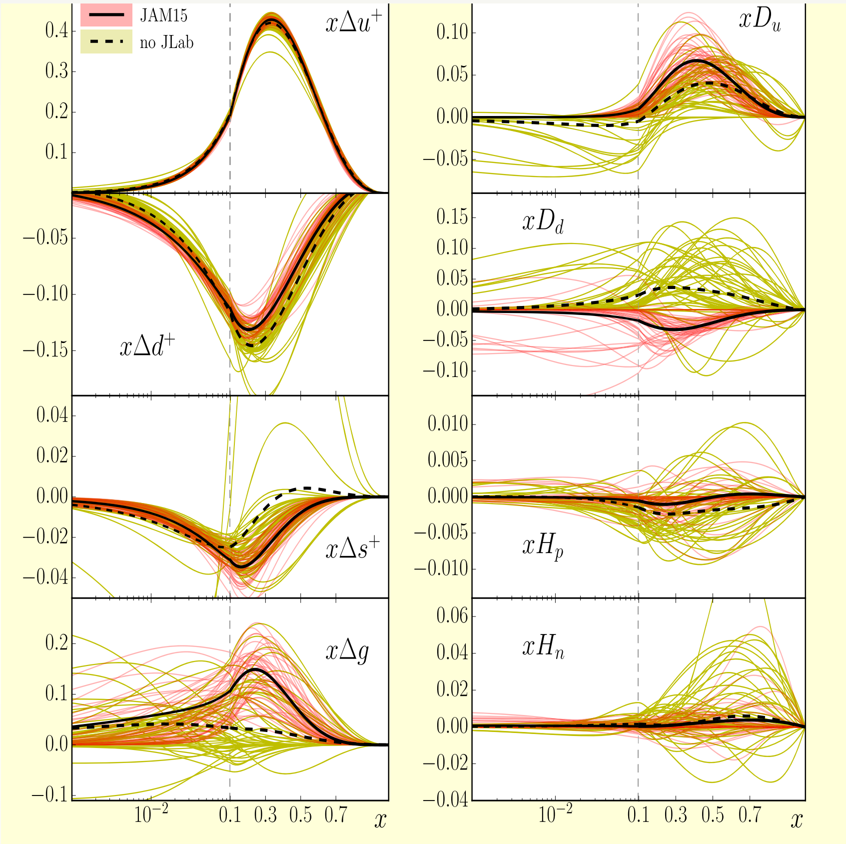
arXiv:2011.00009

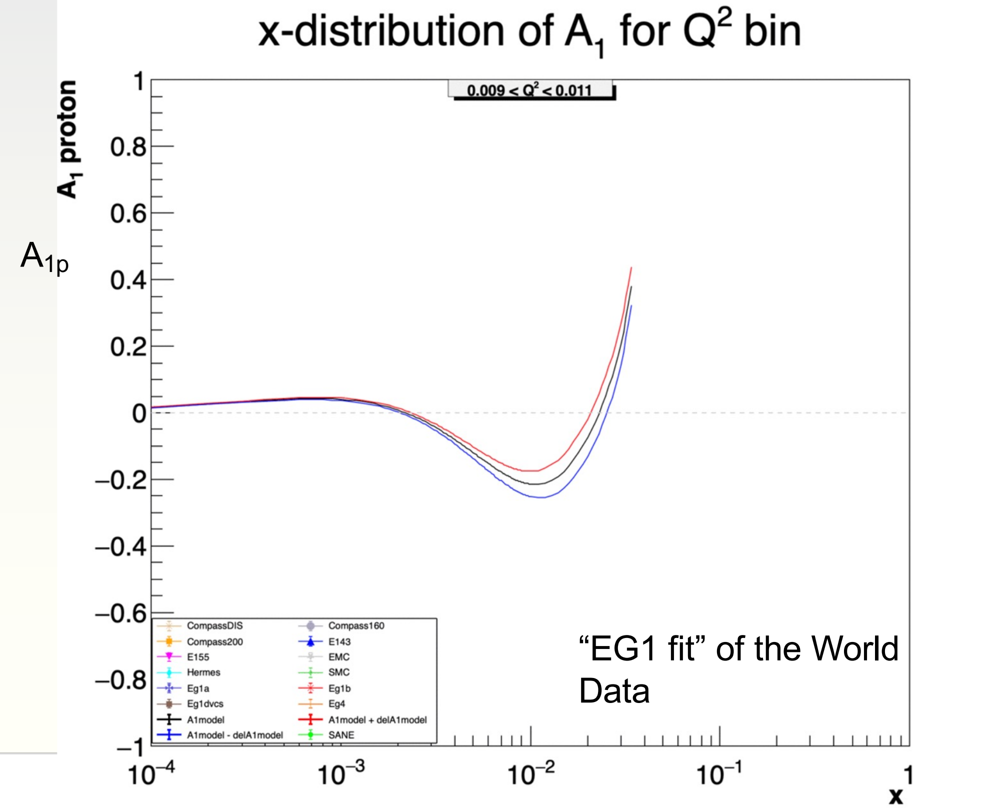


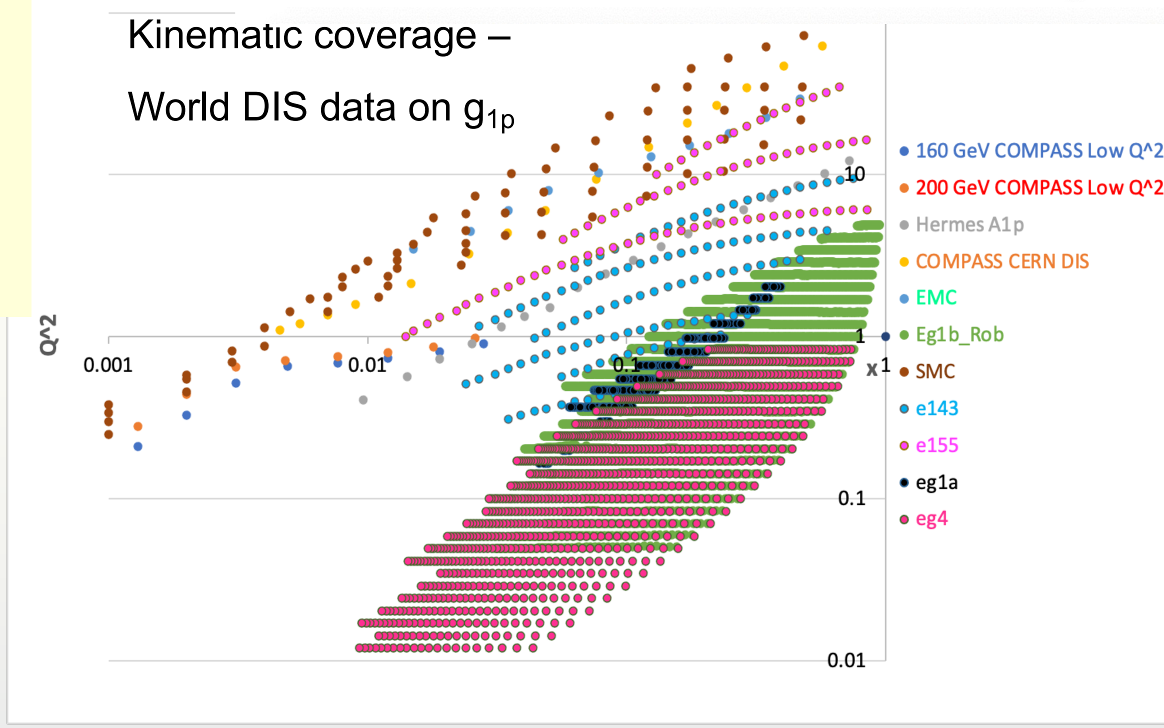




Spin Structure Functions in the last 40 years



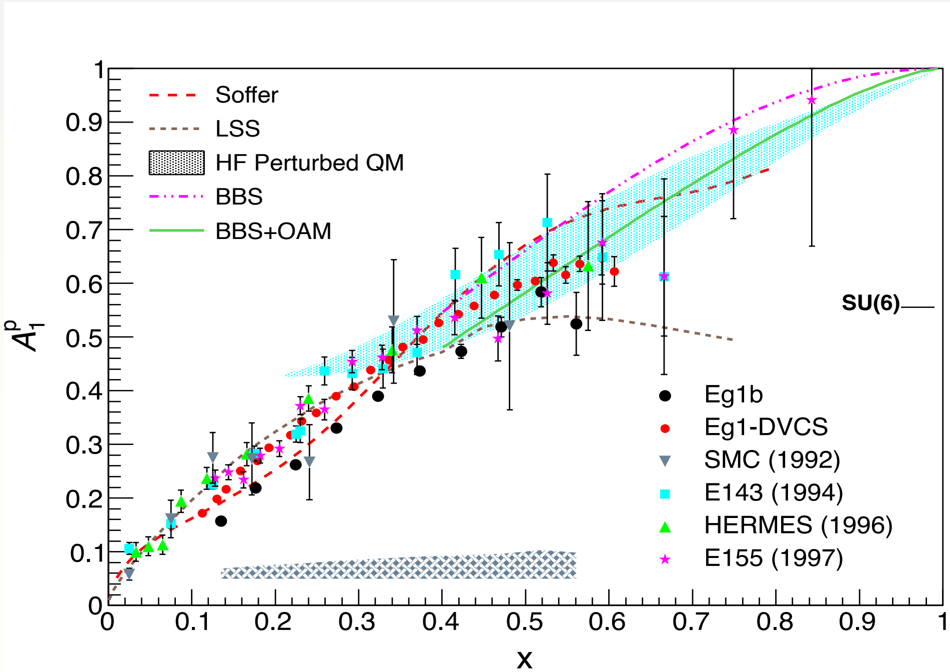


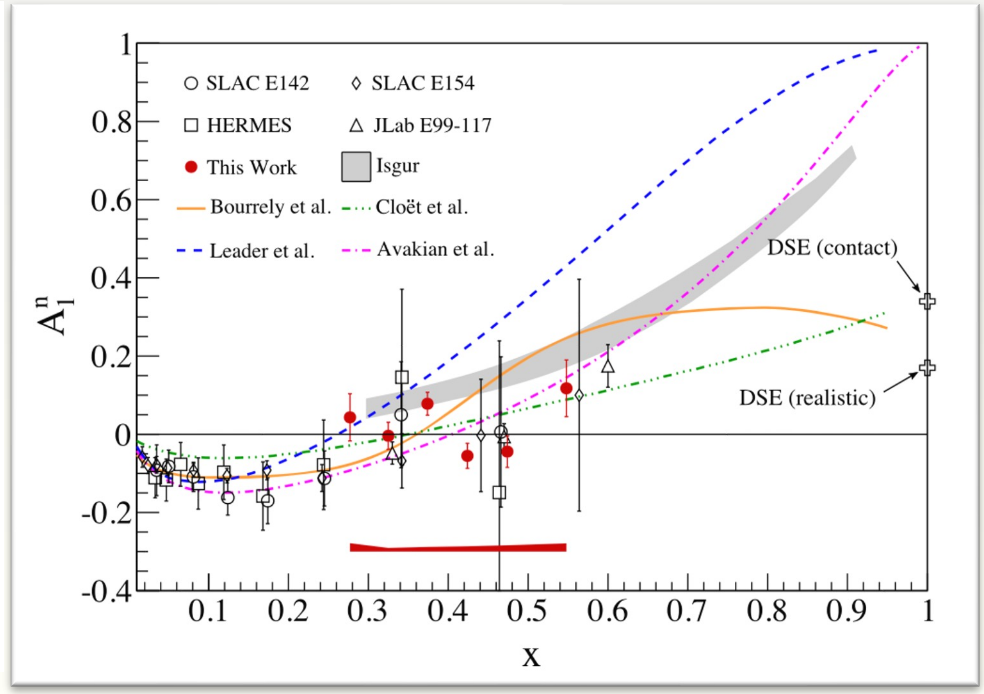


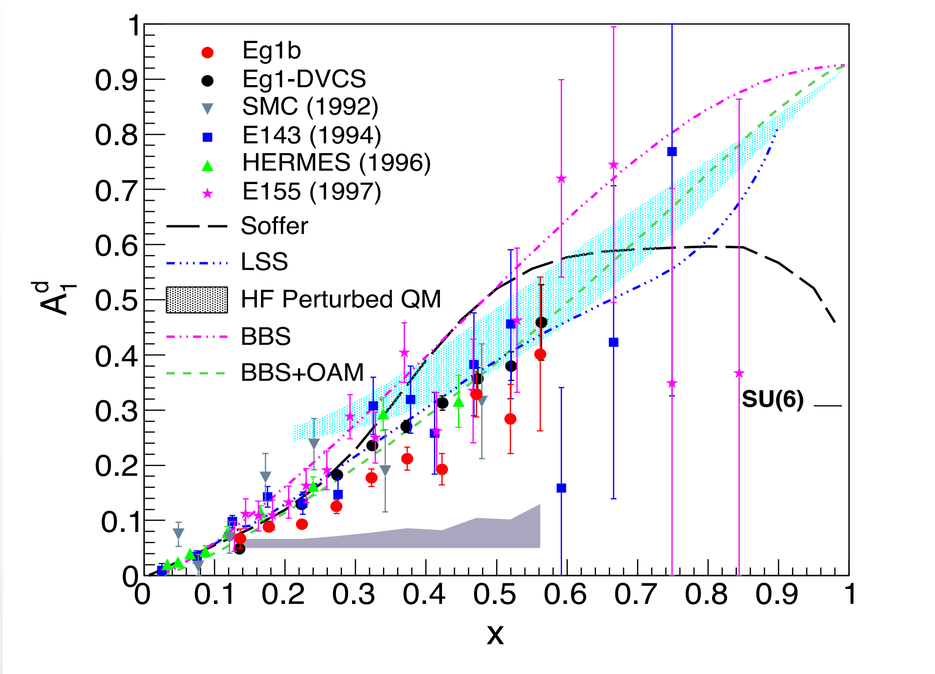
Nobuo Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier, and A. Accardi:"Iterative Monte Carlo analysis of spin-dependent parton distributions", Phys. Rev. D **93**, 074005 (5 April 2016).

A. Deur, Y. Prok, V. Burkert, D. Crabb, F.-X. Girod, K. A. Griffioen, N. Guler, S. E. Kuhn, and N. Kvaltine: "High precision determination of the Q^2 evolution of the Bjorken sum", Phys. Rev. C **90**, 012009 (July 2014).

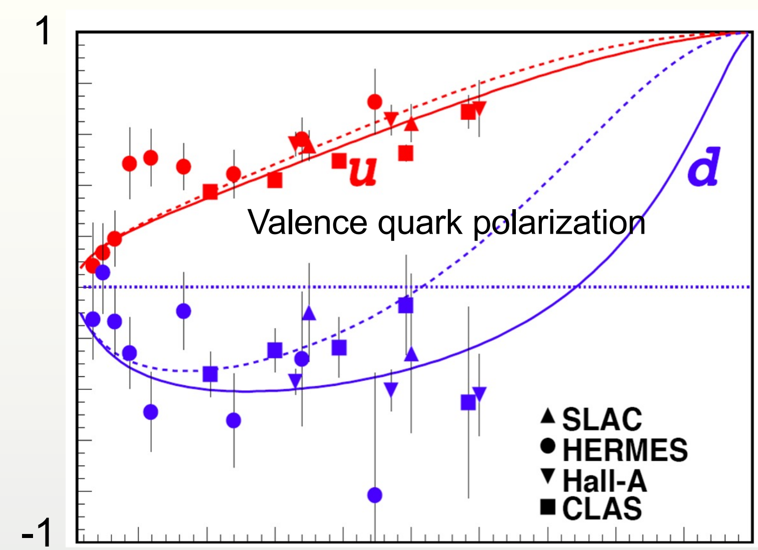
Existing Spin Structure Functions at high *x*





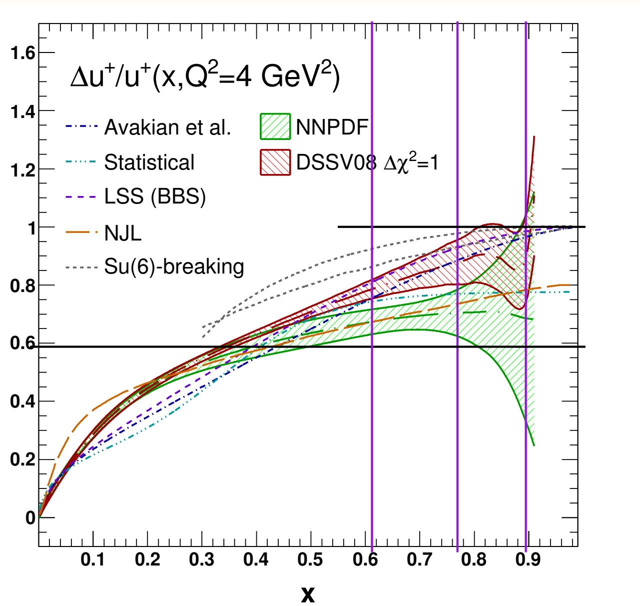


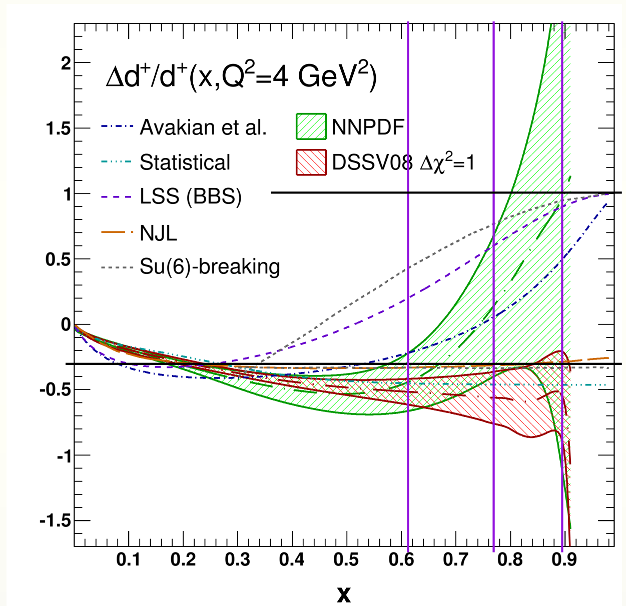
Parno et al., Phy Let B DOI: 10.1016/j.physletb.2015.03.067
X. Zheng et al., PRL 92, 012004 (2004); PRC 70, 065207 (2004)

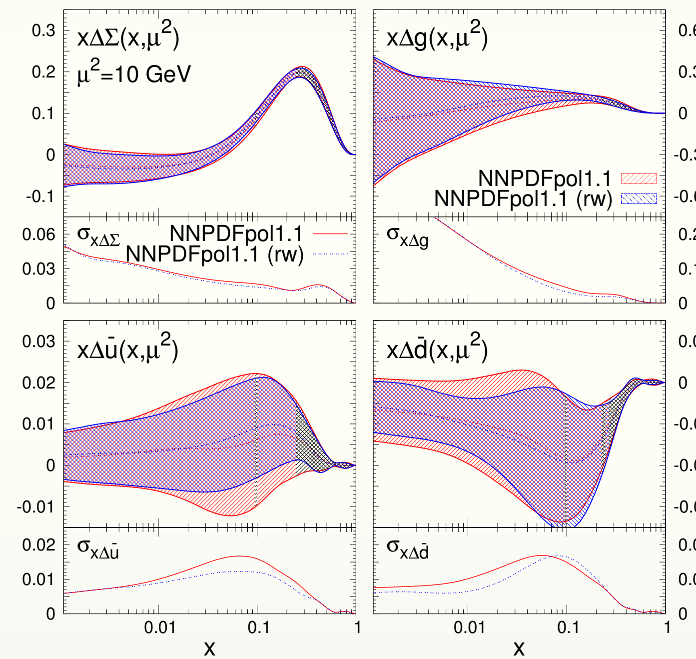


Present Status on polarized PDFs

- NNDPFpol1.1+RHIC W data analysis





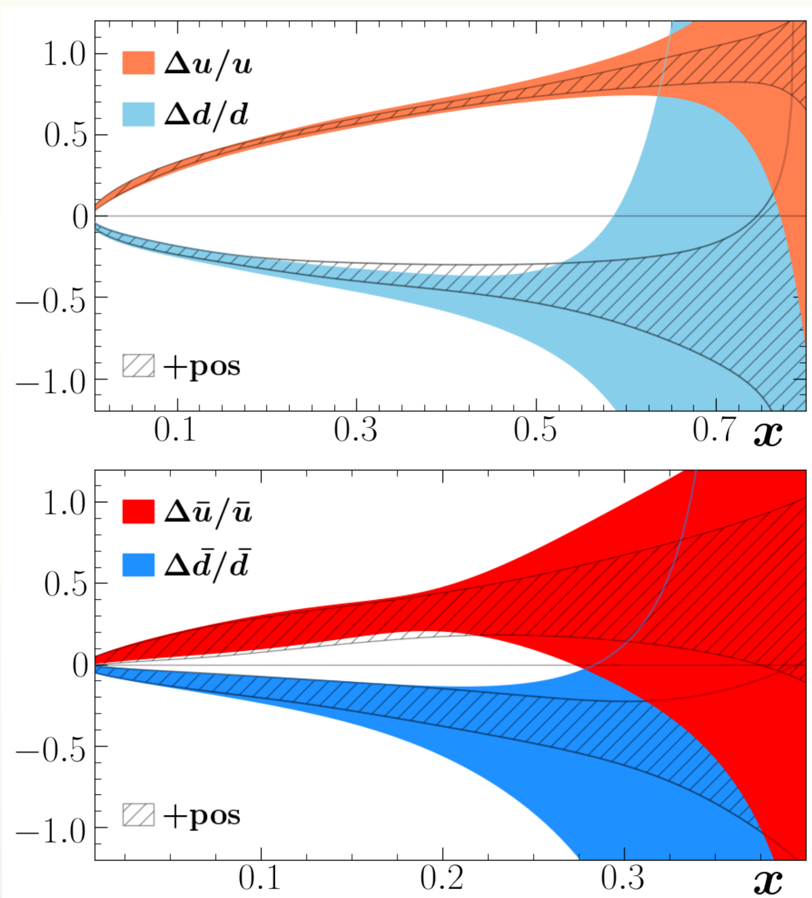


arXiv:1410.7290v2 [hep-ph] 23 Jan 2015

arXiv:1702.05077v1 [hep-ph] 16 Feb 2017

Present Status on polarized PDFs

- Newest JAM analysis including RHIC and COMPASS data



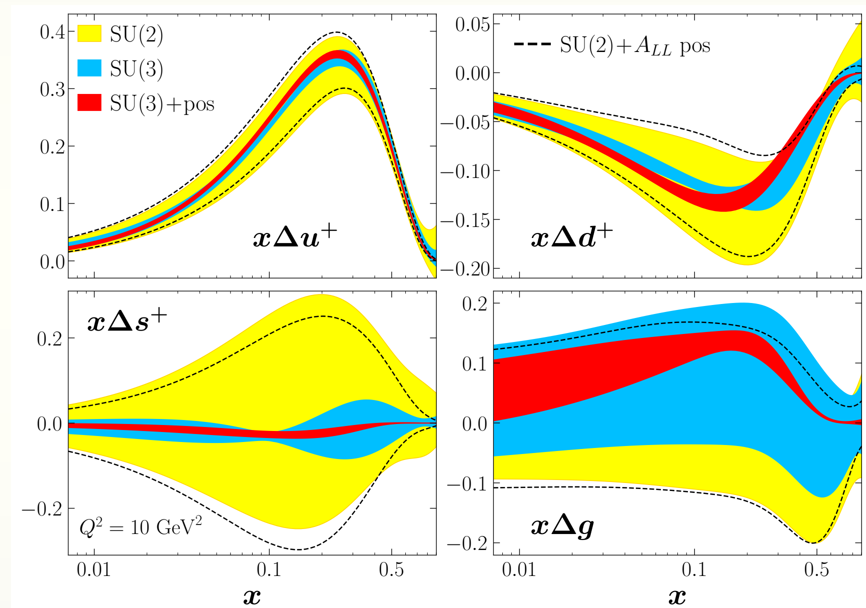
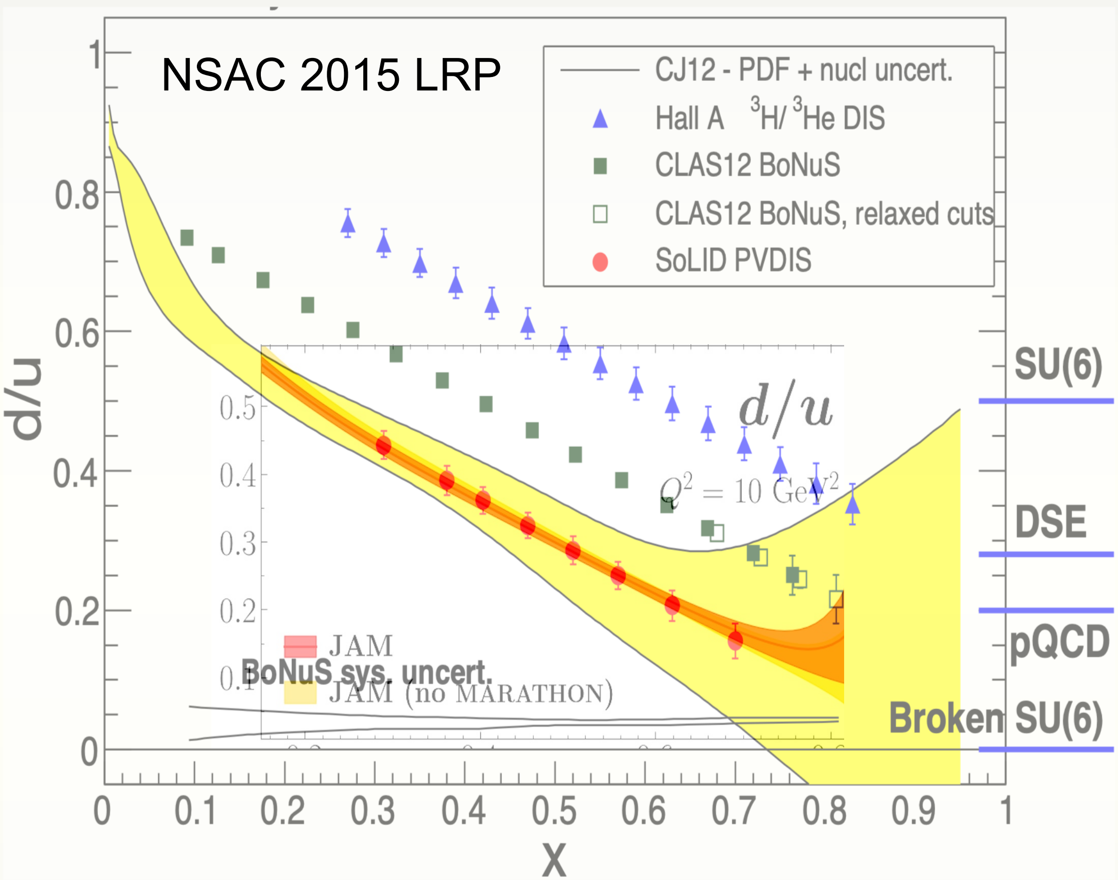


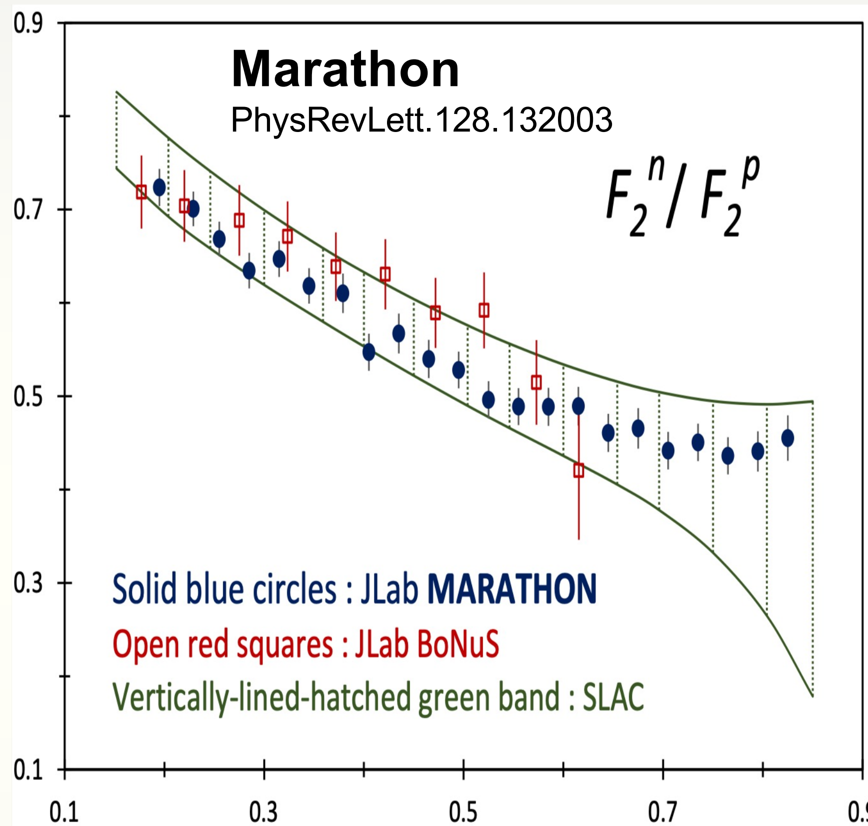
FIG. 6. Expectations values for spin-dependent Δu^+, Δd^+, Δs^+, and Δg PDFs at $Q^2 = 10$ GeV^2 fitted under various theory assumptions according to the SU(2) (yellow 1σ bands), SU(3) (blue 1σ bands) and SU(3)+positivity (red 1σ bands) scenarios, as well as with the SU(2) scenario but filtered to ensure A_{LL} positivity at large x (dashed lines).

arXiv:2202.03372v1 [hep-ph] 7 Feb 2022

arXiv:2201.02075v1 [hep-ph] 6 Jan 2022

JLab@12 GeV d/u



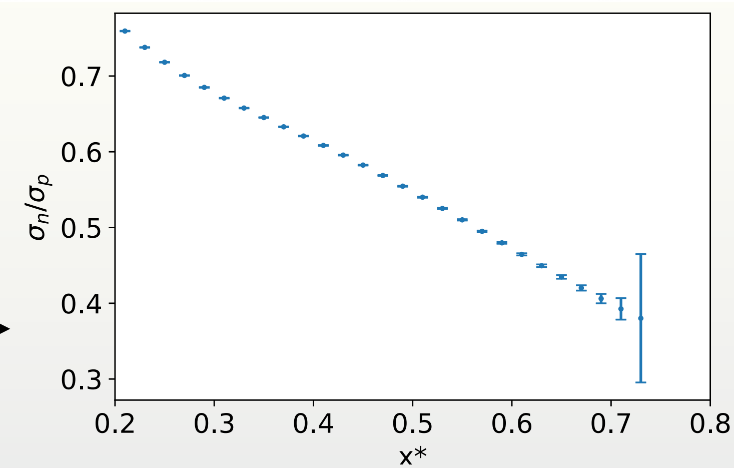


BONuS12:

Dark Symbols: W* > 2 GeV (x* up to 0.8, bin centered x* = 0.76)

Open Symbols: “Relaxed cut” W* > 1.8 GeV (x* up to 0.83)

…also: Additional data from ALERT and TDIS →

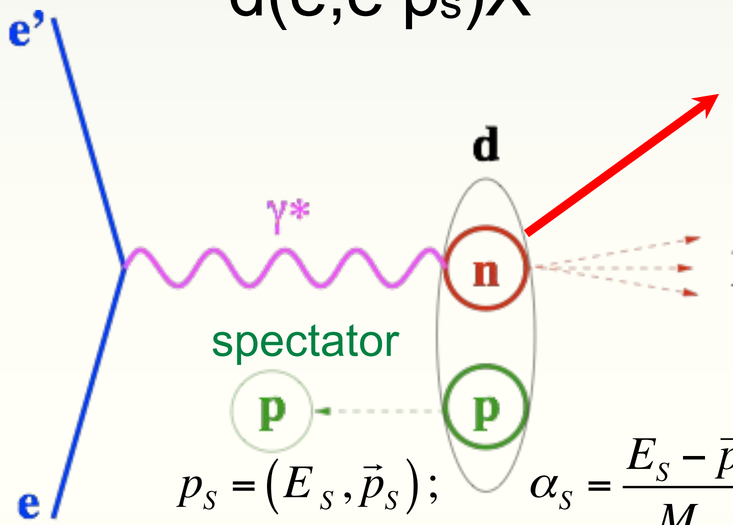


Courtesy Arun Tadepalli

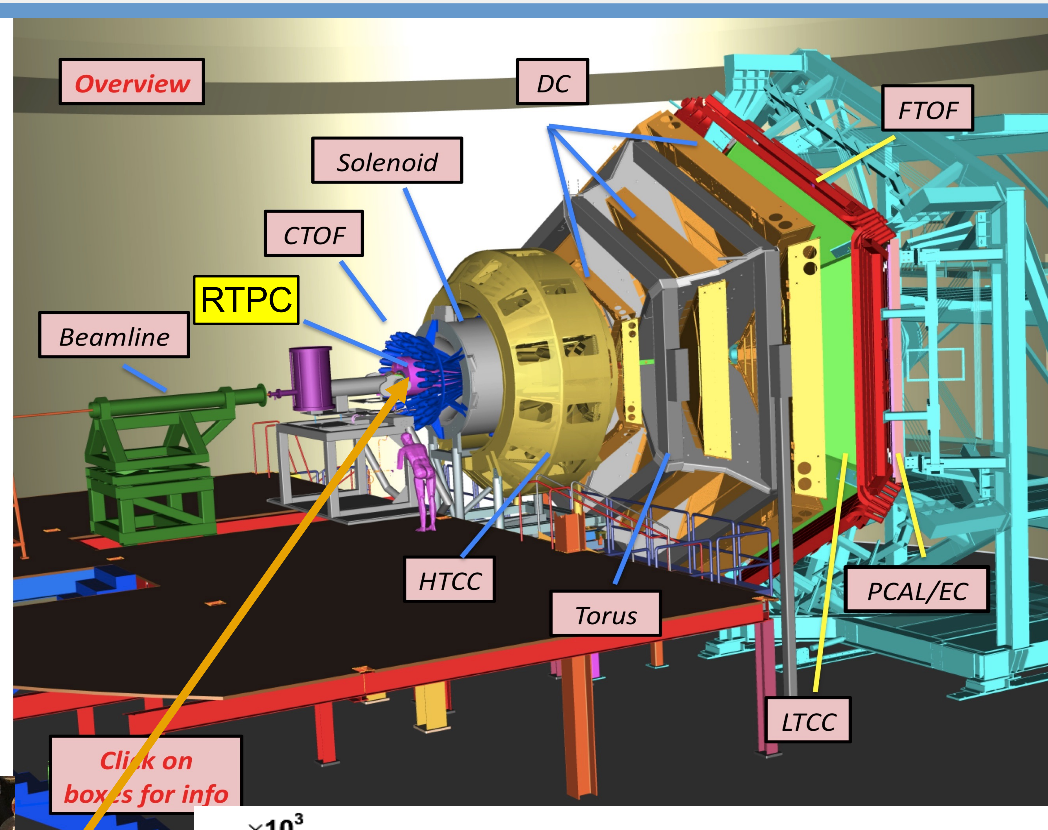
BONuS12 with CLAS12 (Run Group F in 2020)

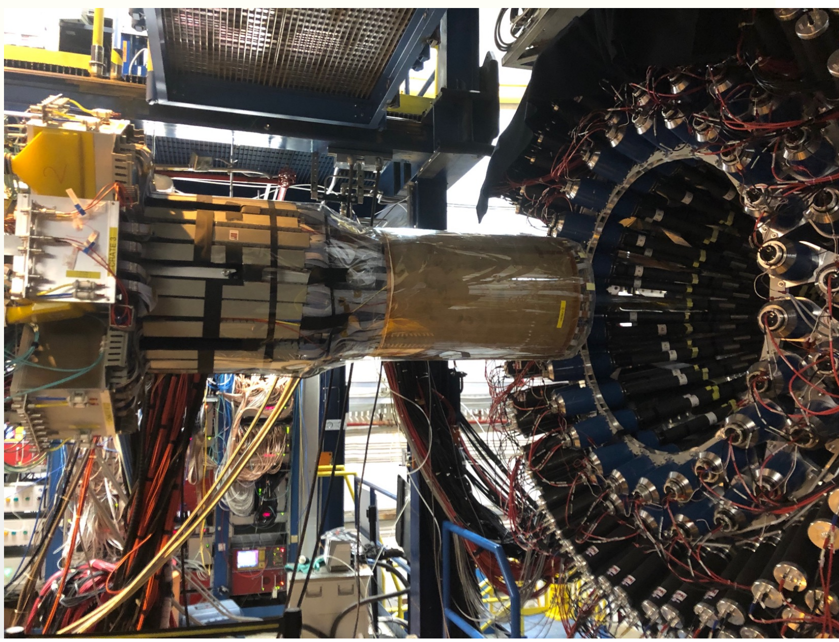
F_{2n}/F_{2p} through spectator tagging

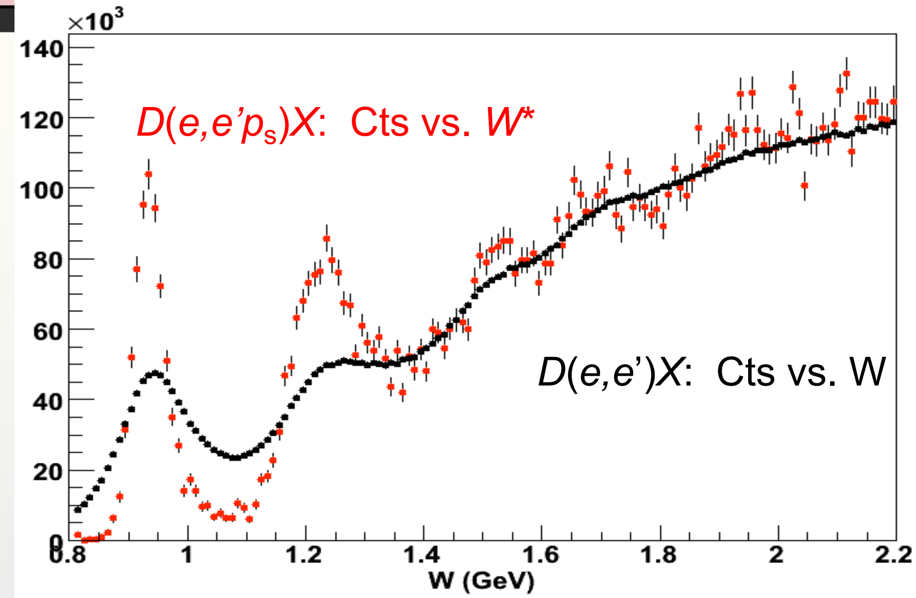
$d(e,e'p_s)X$



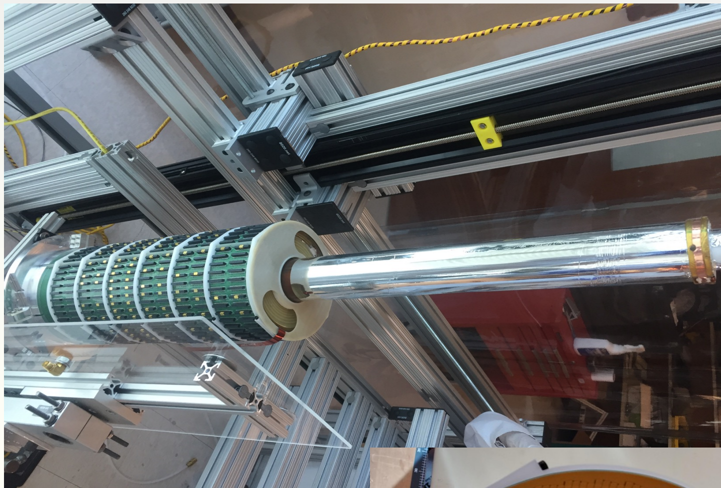
$$p_S = (E_S, \vec{p}_S); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D / 2}$$



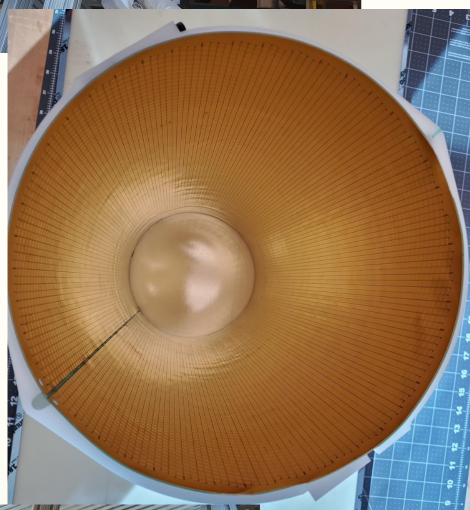




BONuS12 Radial Time Projection Chamber

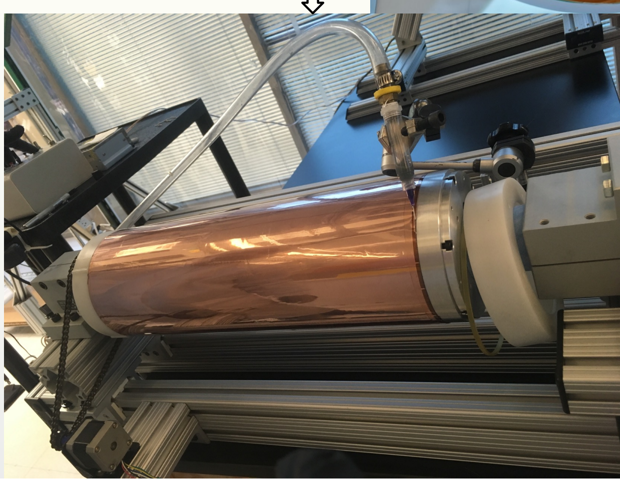


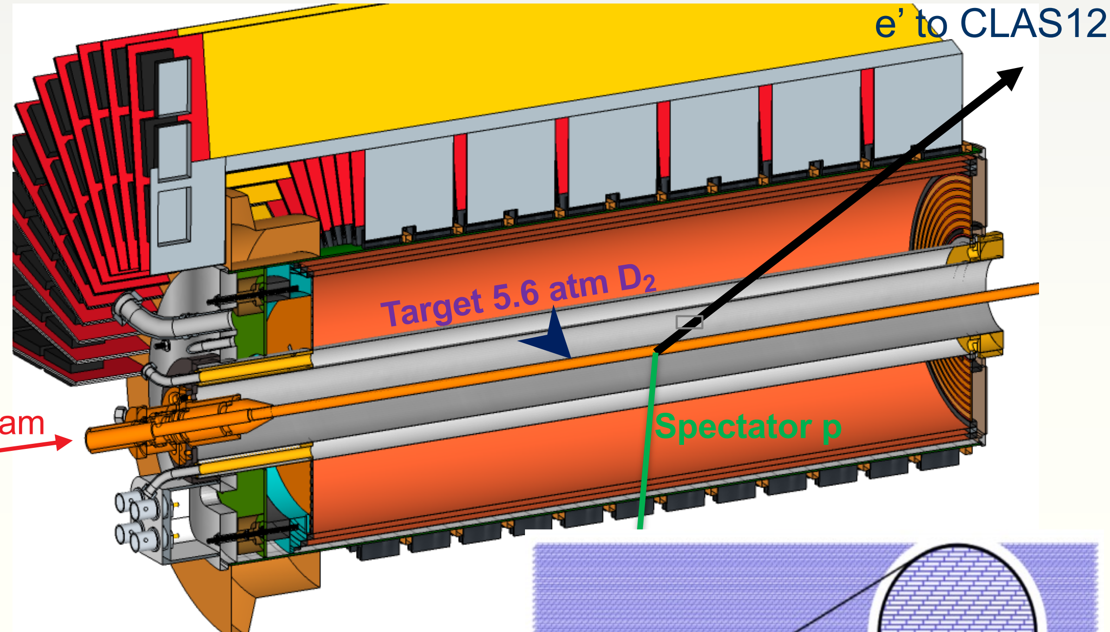
Installation of Cathode + ground foil assembly

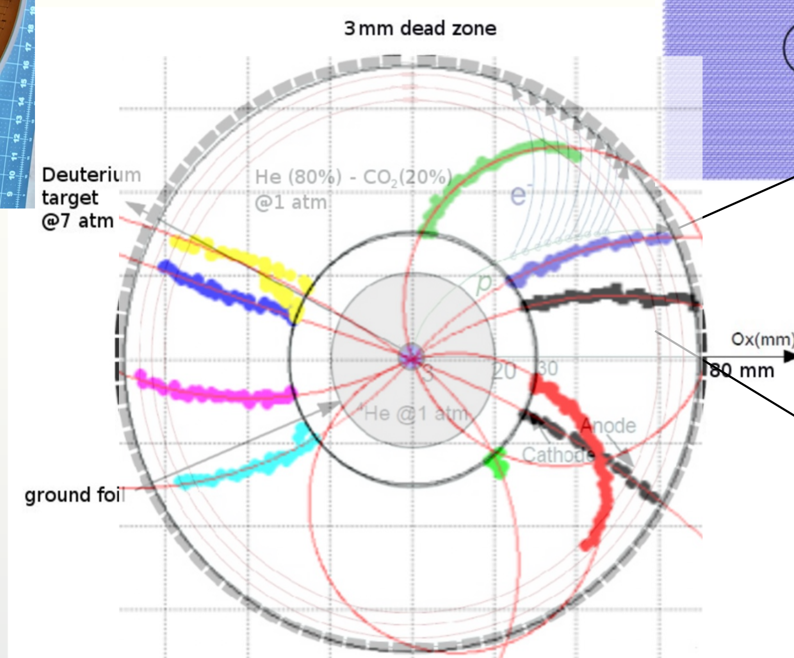


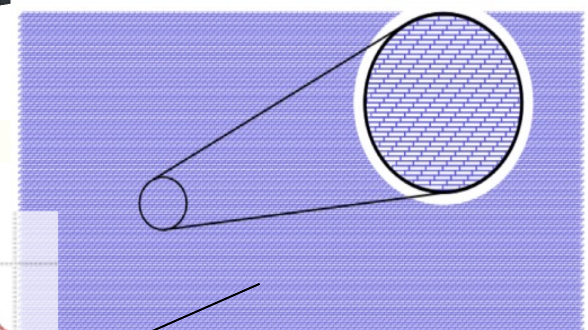
Wrapped Padboard inner surface

GEM foil wrapping and gluing



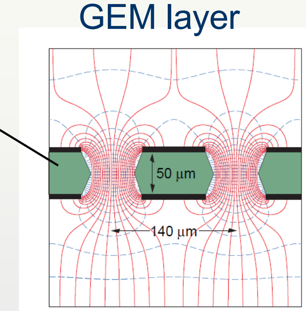




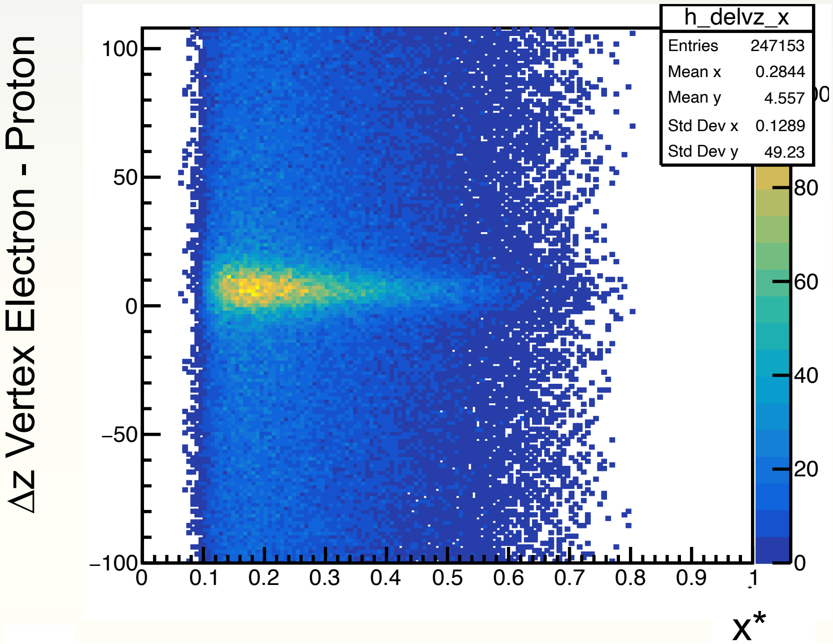


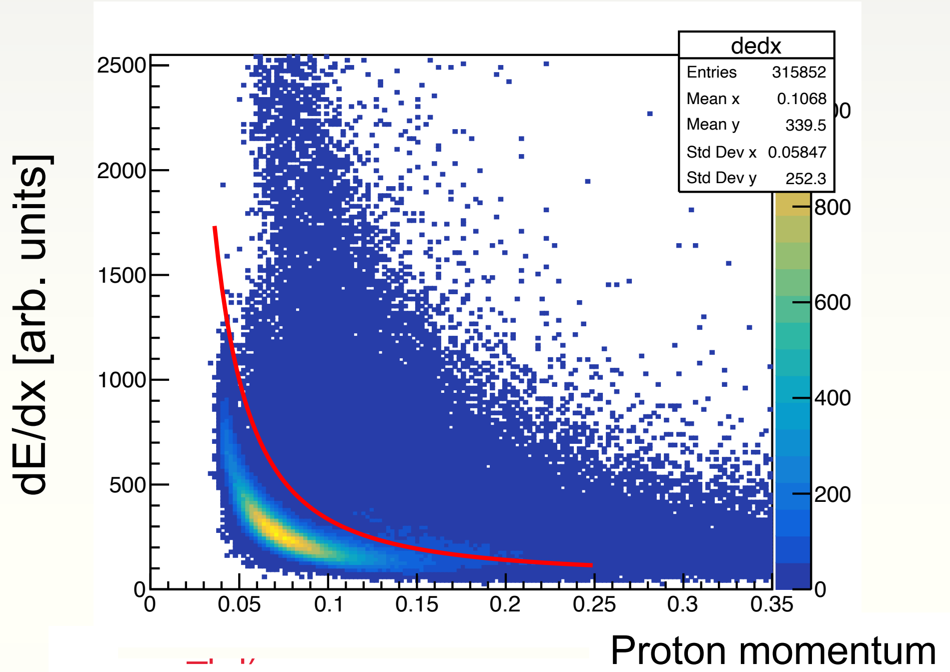
Readout Pads

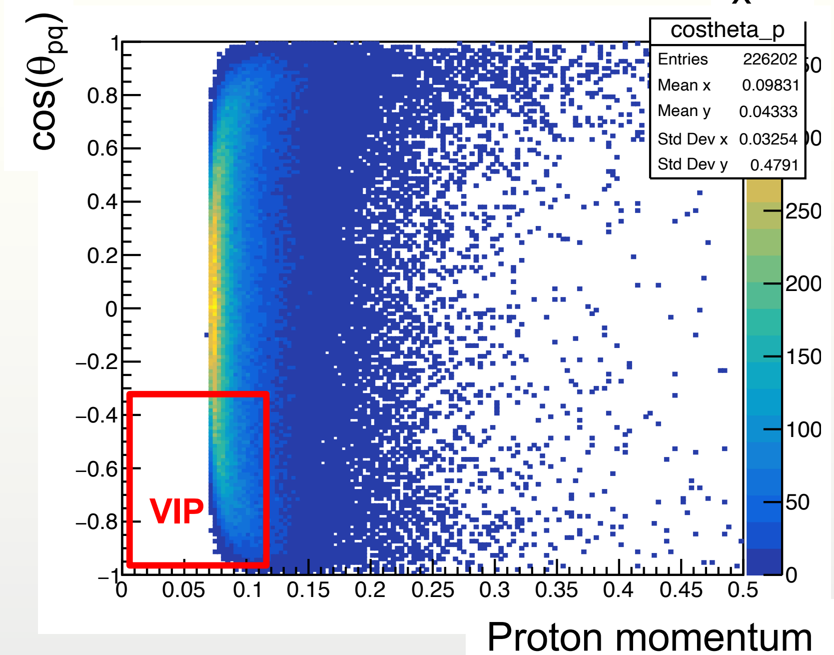
GEM layer

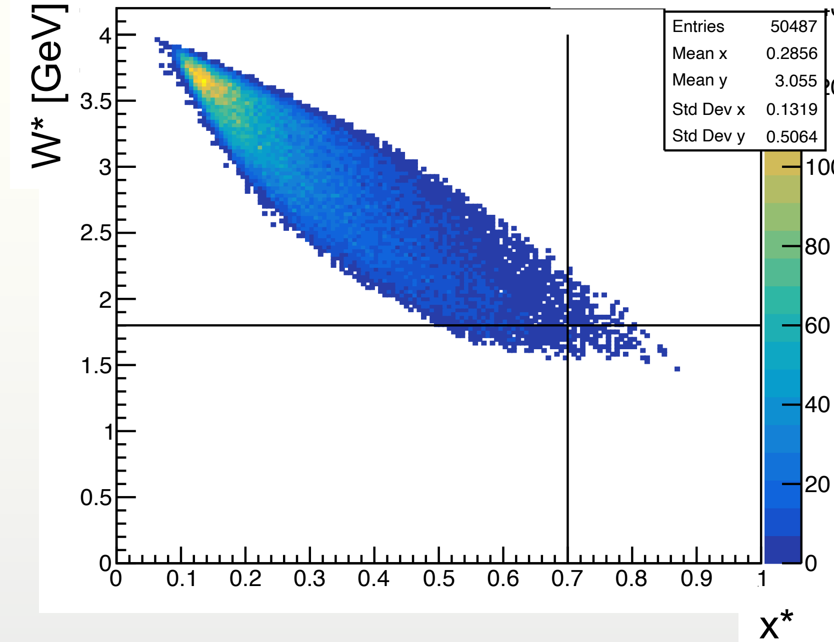


Preliminary BONuS12 Results

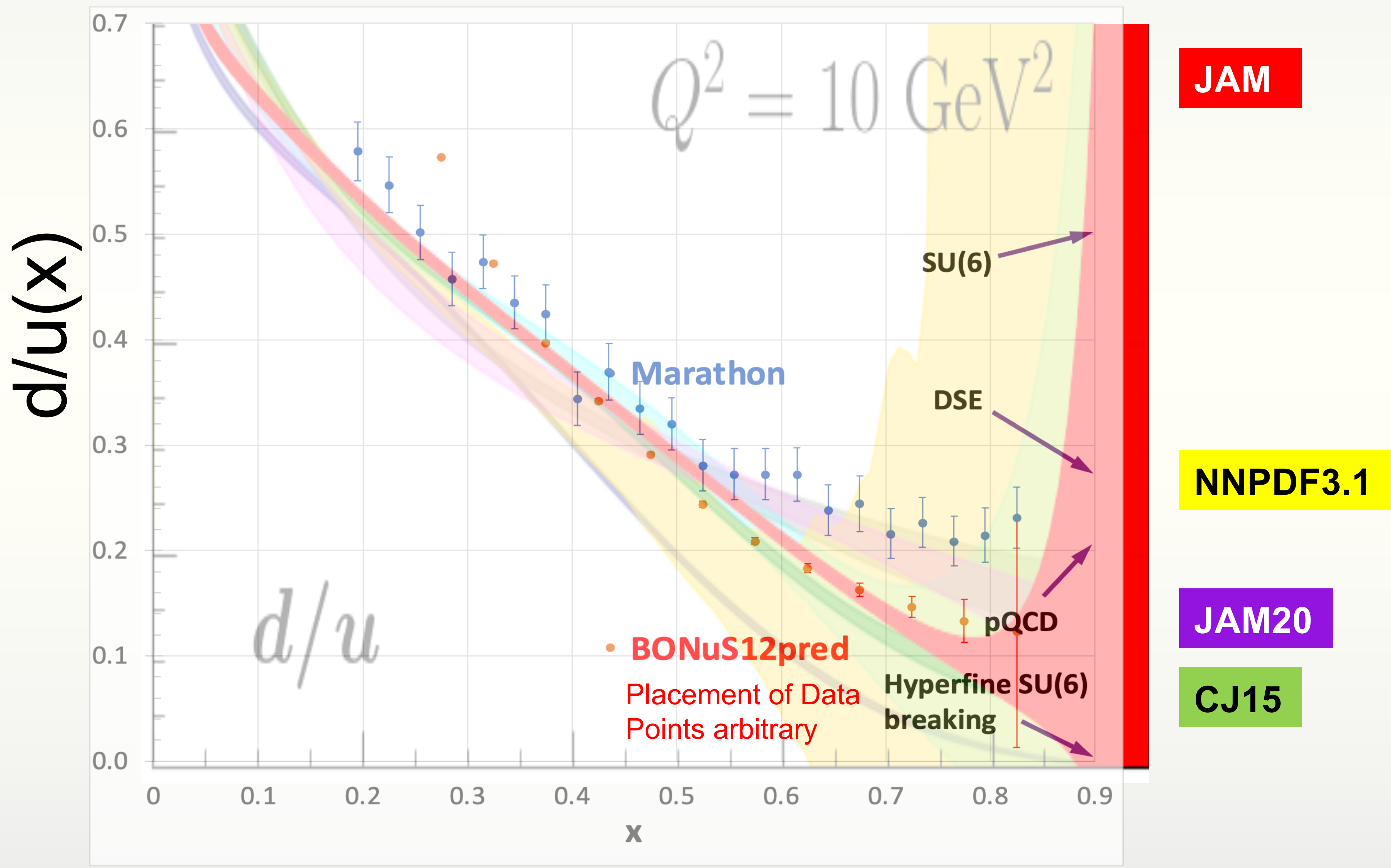








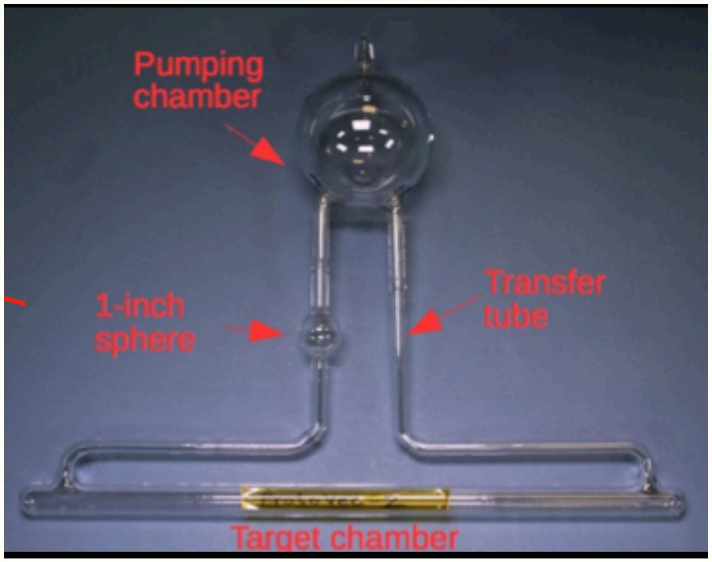
BONuS12 Expected Uncertainties

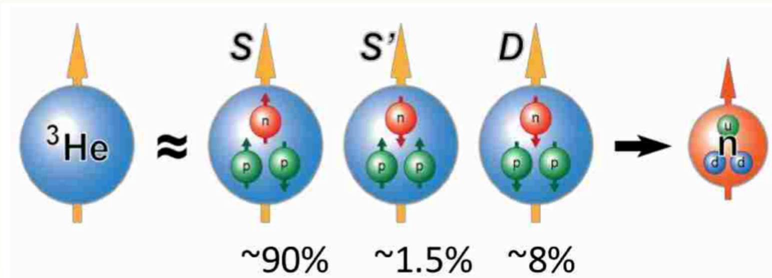


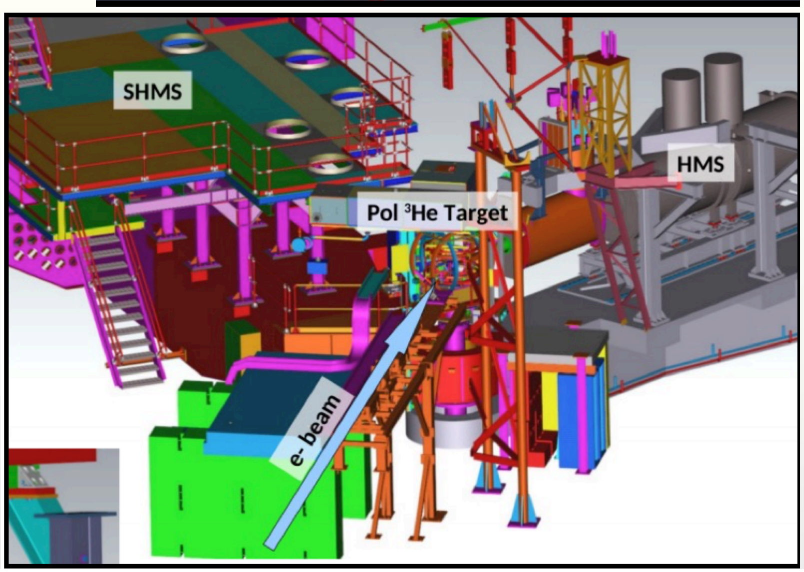
A_{1n} in Jefferson Lab's Hall C

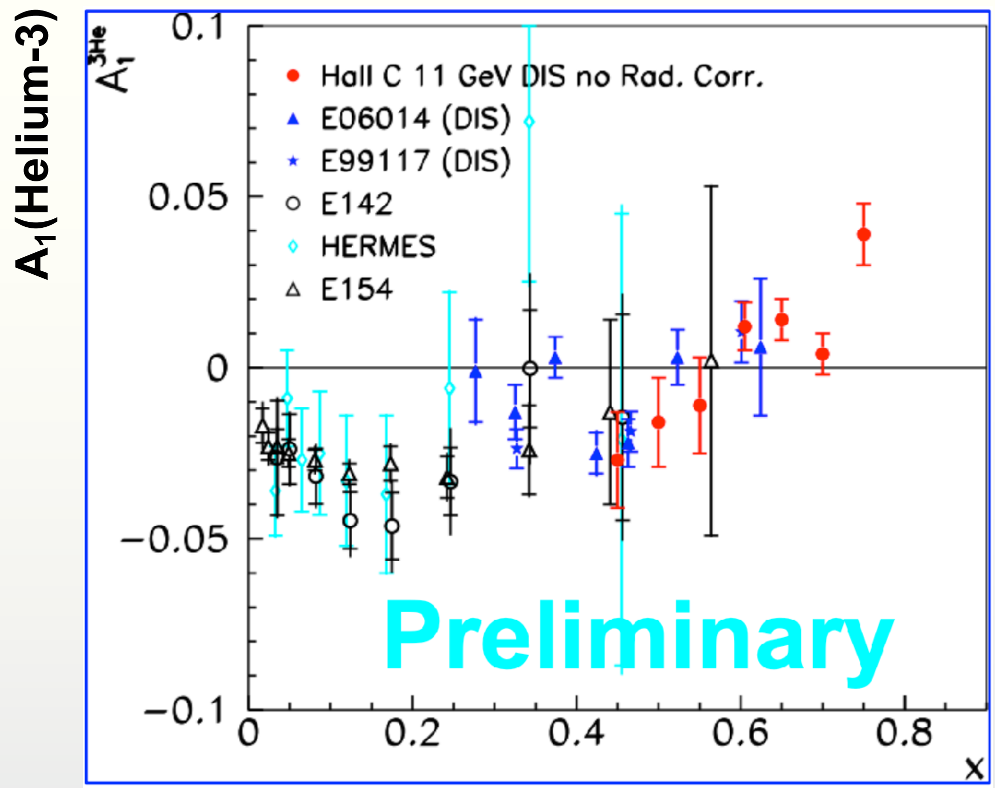
E12-06-110 in Hall C: 1/12/2020 – 3/13/2020; 10.4 GeV polarized electrons on polarized ^{3}He

William Henry 2022 Jefferson Lab Users Organization Annual Meeting







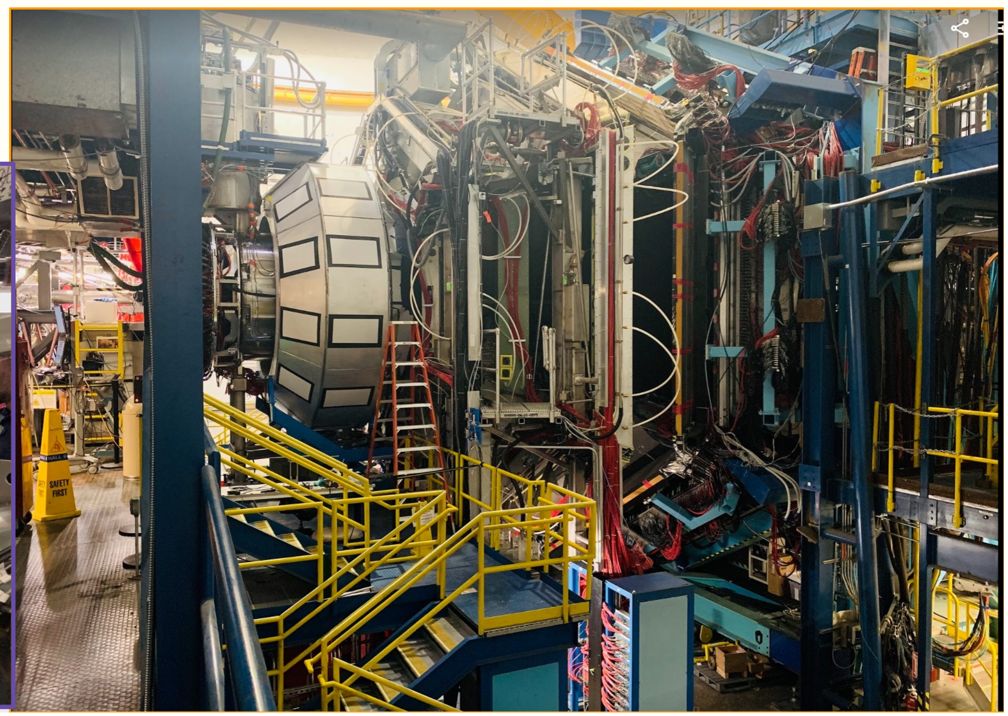


RG-C with CLAS12

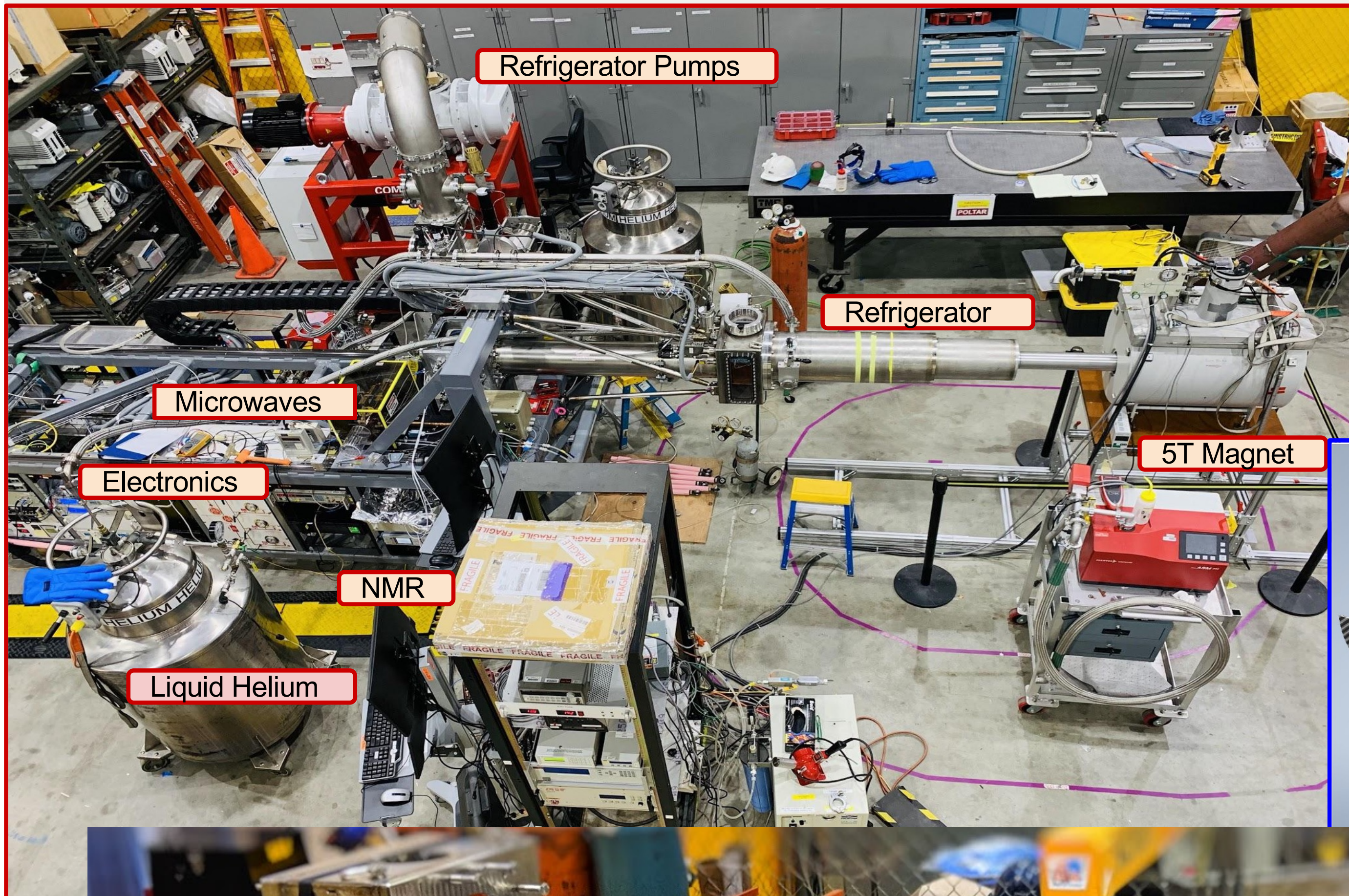
- ❑ Measure DIS inclusive spin structure functions (A_1, g_1) of the proton and deuteron.
  - ❑ Include tagging with π, K SIDIS to extract flavor-separated Δq
- ❑ Measure spin- and transverse momentum-dependent (TMD) PDFs (SIDIS).
- ❑ Deeply Virtual Compton Scattering (DVCS) to access Generalized Parton Distributions (GPDs) - Measure target single and beam/target double spin asymmetries in proton and neutron DVCS.

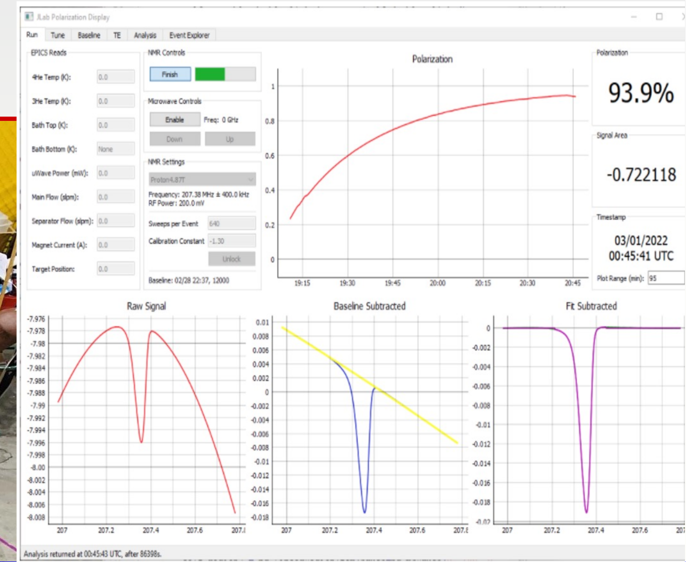
- Scheduled from June 2022 through March 2023 (240 Calendar Days)
- 10.6 GeV, 10 nA polarized electrons on 3 g/cm^2 polarized NH_3 / ND_3 ($\mathcal{L} = 10^{35}$)
- Dynamic Nuclear Polarization at 1 K, 5 T with 140 GHz μwave on irradiated ammonia

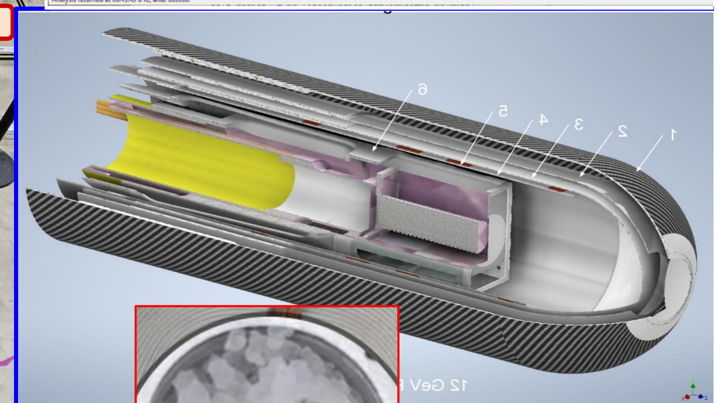
Polarized target "APOLLO"



Longitudinally Polarized Target for CLAS12







Jefferson Lab

OLD DOMINION UNIVERSITY®

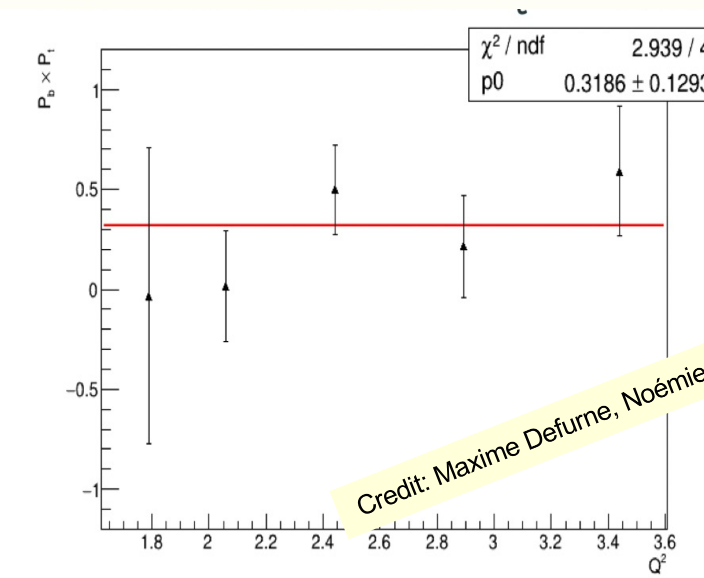
UNIVERSITY of VIRGINIA

CHRISTOPHER NEWPORT UNIVERSITY

First (VERY preliminary) data

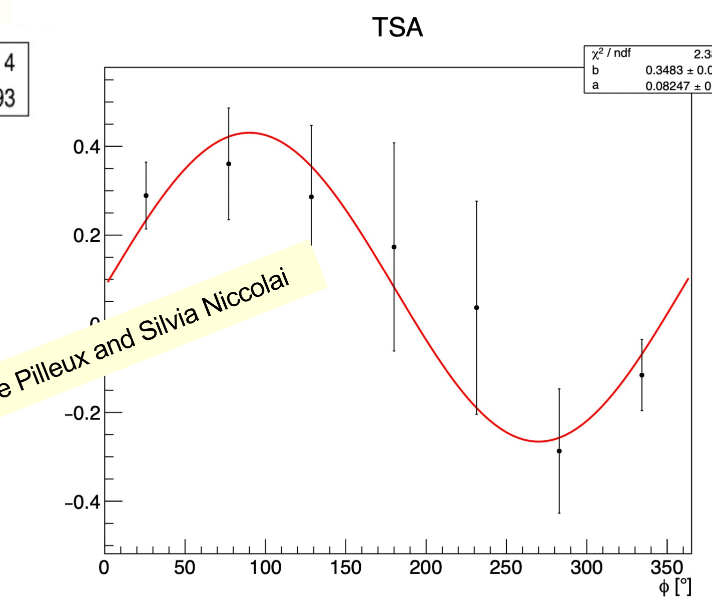
Based on a few % of data set collected so far; near-online analysis

ND_3 target polarization from quasi-elastic scattering

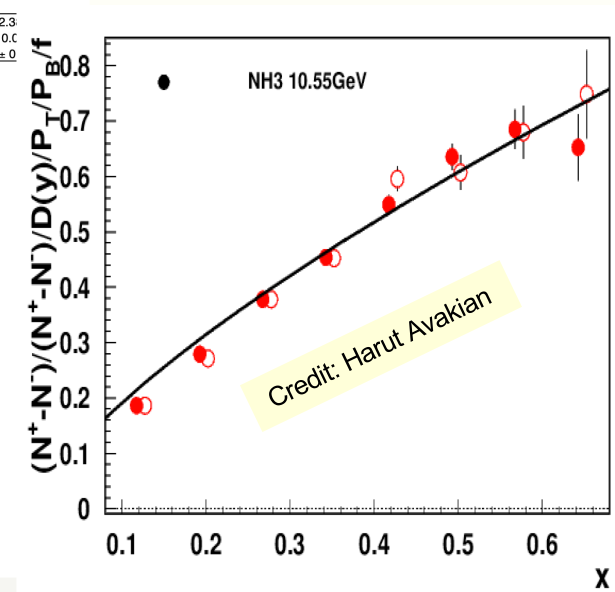


Proton DVCS from FTon period

$< Q^2 > = 2.231, < x_B > = 0.1801, < -t > = 0.4061$



$A_{||}$ in DIS on proton

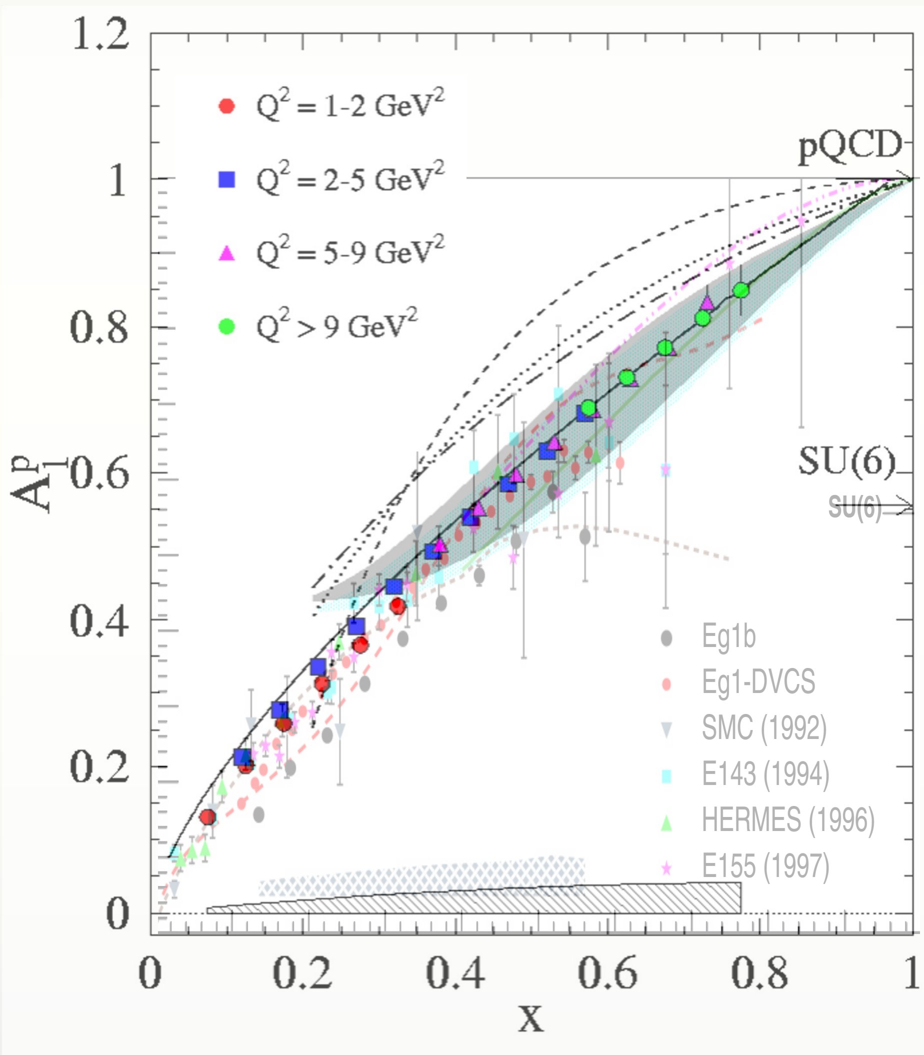


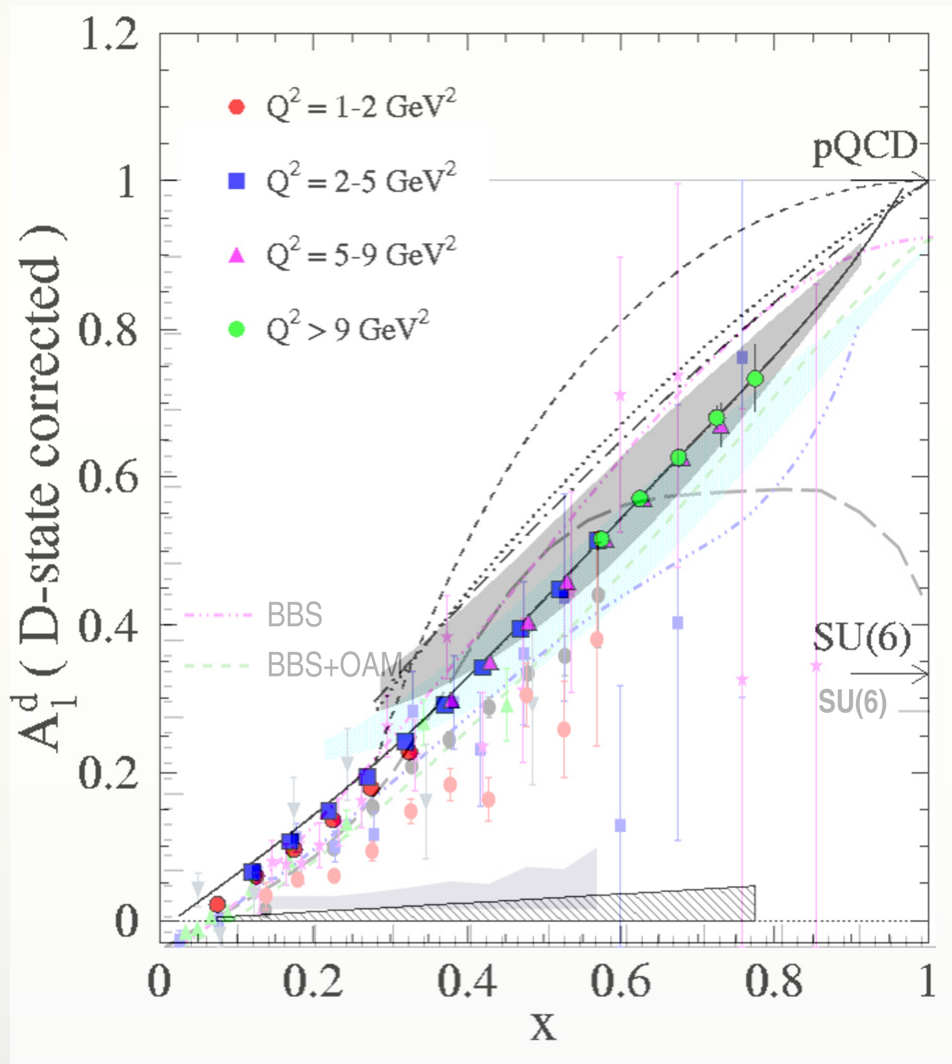
Predicted Data from CLAS12 - DIS

Proton

$W > 2;\ Q^2 > 1$

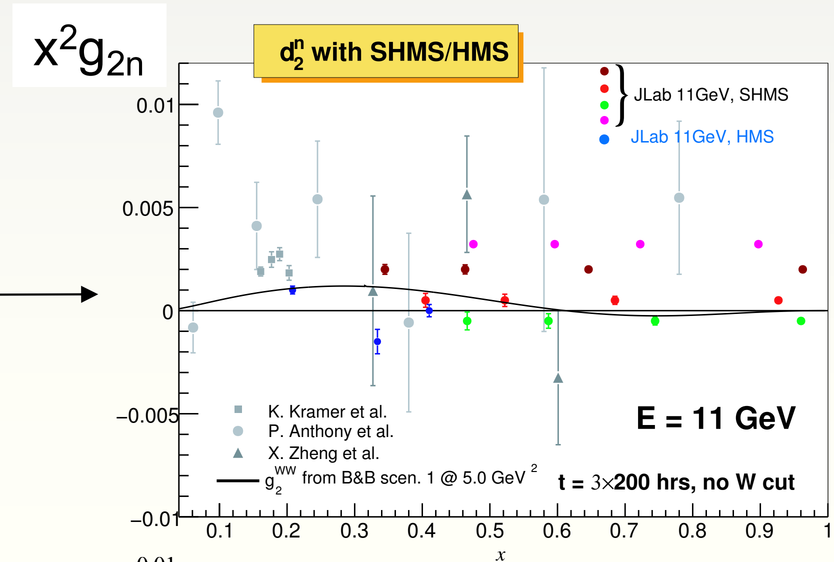
Deuteron



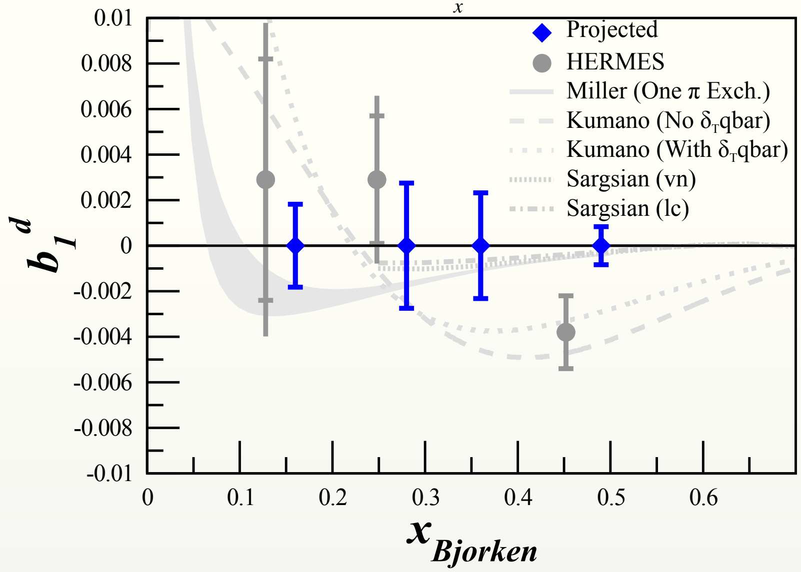


Other SF experiments

- g_2 on proton and neutron
  (E12-06-121)



- Tensor structure function b_1
  (E12-11-110)



- Unpolarized structure function F_{2N}, R; PVDIS, …

EMC effect

- Fundamental question: How does nuclear binding modify the high-x structure function of the nucleon?
- Relevant for the extraction of neutron structure functions from experimental data on d, ^{3}He, ^{3}H
- Many models: mean field, Short range correlations (SRC), Light-Front Holography (LFHQCD), …

C. Cocuzza et al., PHYSICAL REVIEW LETTERS **127**, 242001 (2021)

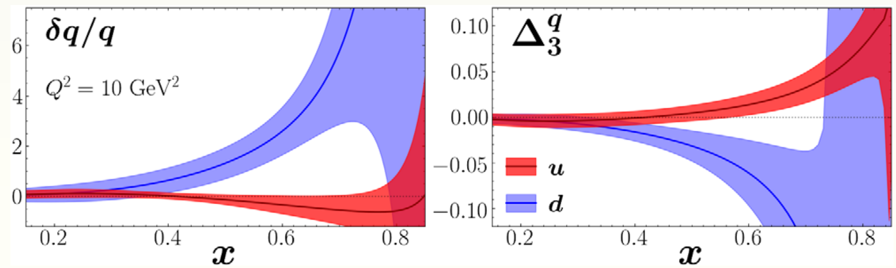
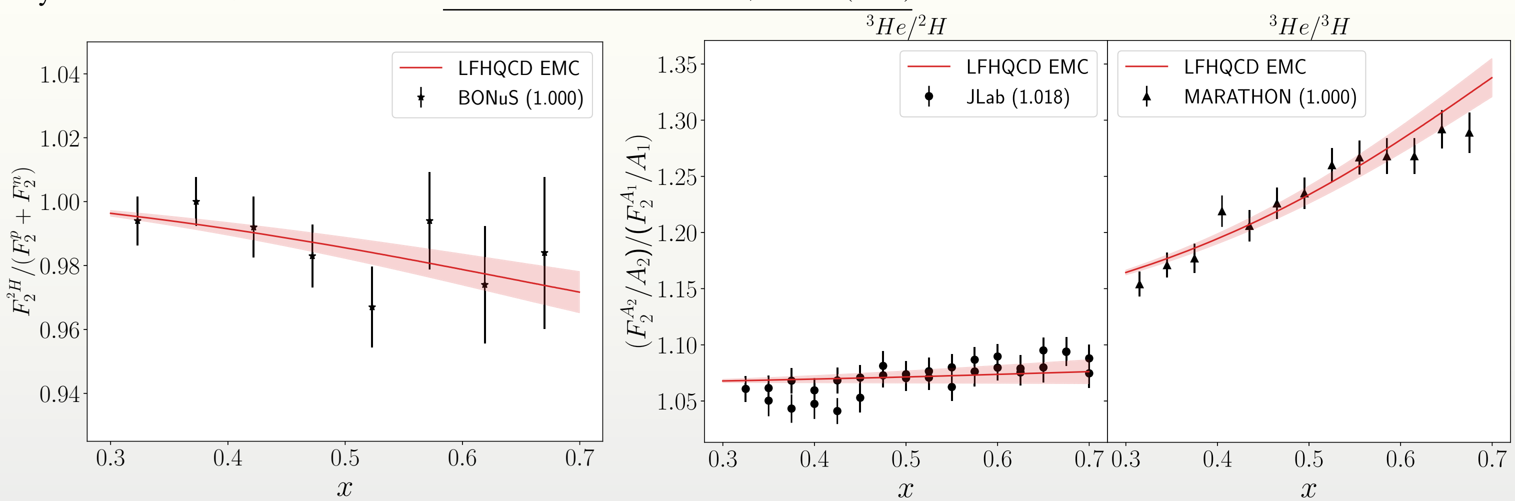
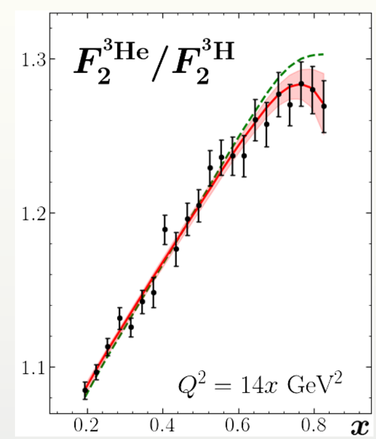


FIG. 3. Ratio of off-shell to on-shell PDFs $\delta q/q$ (left) and the difference between proton valence quarks in ^{3}He and ^{3}H normalized to the sum, Δ_3^q (right), for valence u (red bands) and d (blue bands) quarks, at $Q^2 = 10$ GeV^2.

Dmitriy N. Kim and Gerald A. Miller PHYSICAL REVIEW C **106**, 055202 (2022)

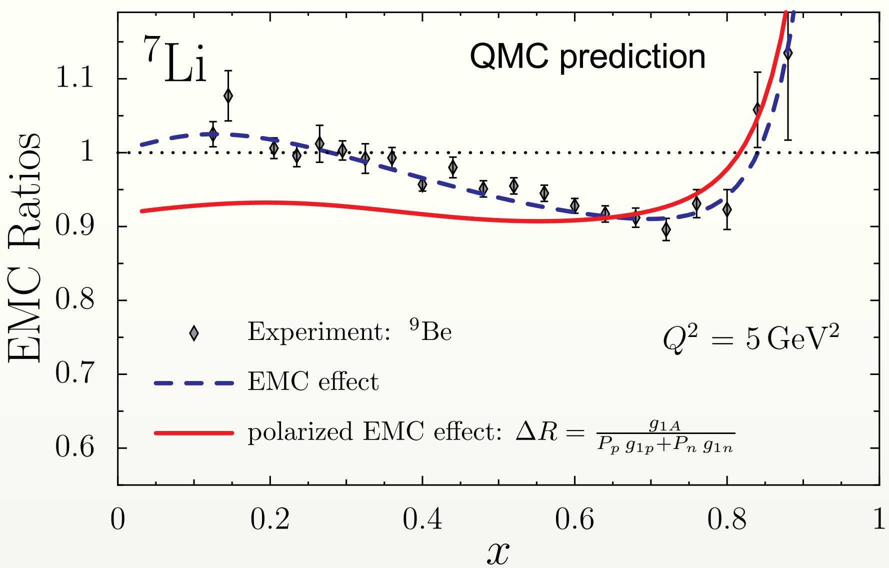




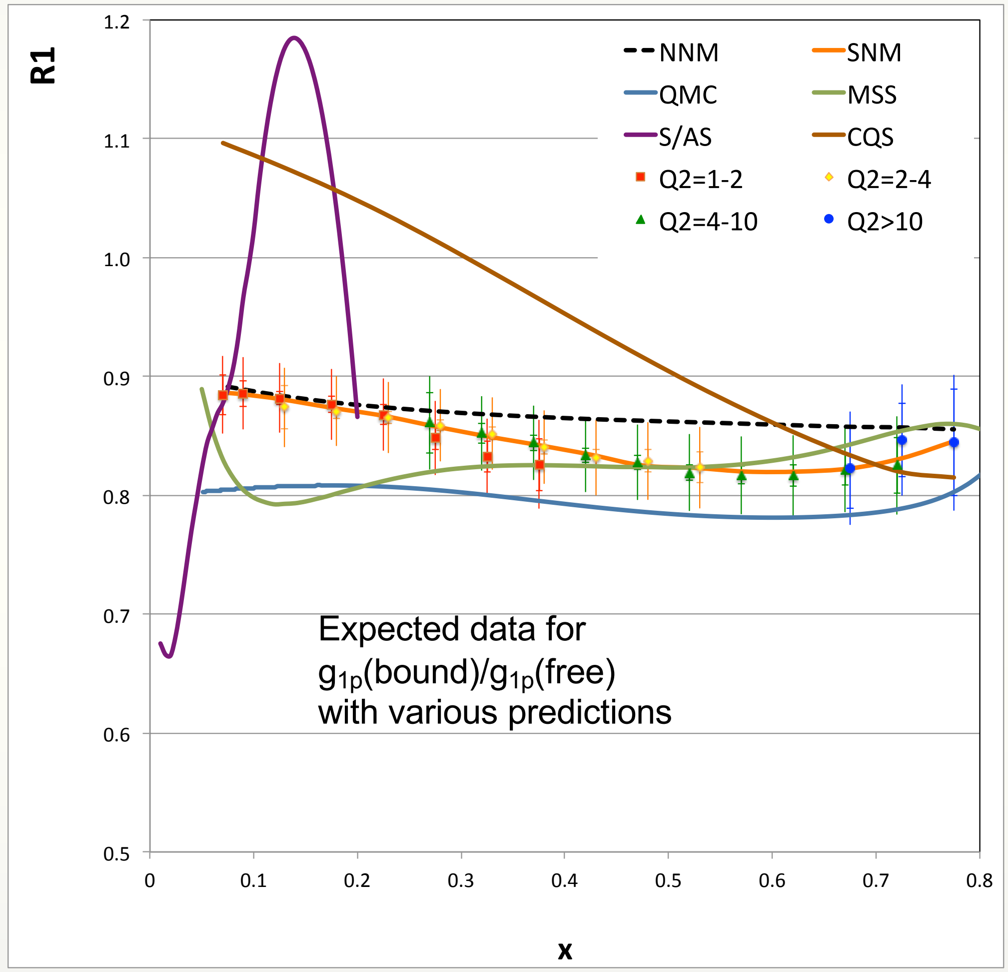
Polarized EMC effect

(Approved Experiment RG-G with CLAS12 at Jefferson Lab)

- A large number of experiments is studying modifications of bound nucleon structure function F_2 on a wide range of nuclei – data average over ALL nucleons!
- Unique test of EMC models: Measure modification of **polarized** structure function g_{1p} on a single valence nucleon!

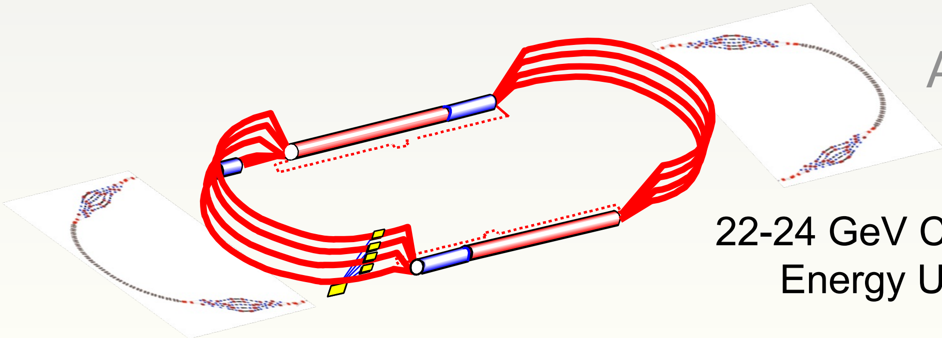


$\Delta\sigma$ Ratio $\propto$ $[N^+-N^-](^7Li) / [N^+-N^-](p)$



NNM = Shell model prediction (p 87% pol.) SNM = Standard Nuclear Model (convolution w/out change in medium; equiv. to SRC model) QMC = Mean Field (Quark-Meson Coupling) MSS (rescaling/modified sea scheme) S/AS = Shadowing/Antishadowing (Guzey/Strikman) CQS = Chiral Quark Soliton (Smith/Miller)

Future: JLab at 20+ GeV?



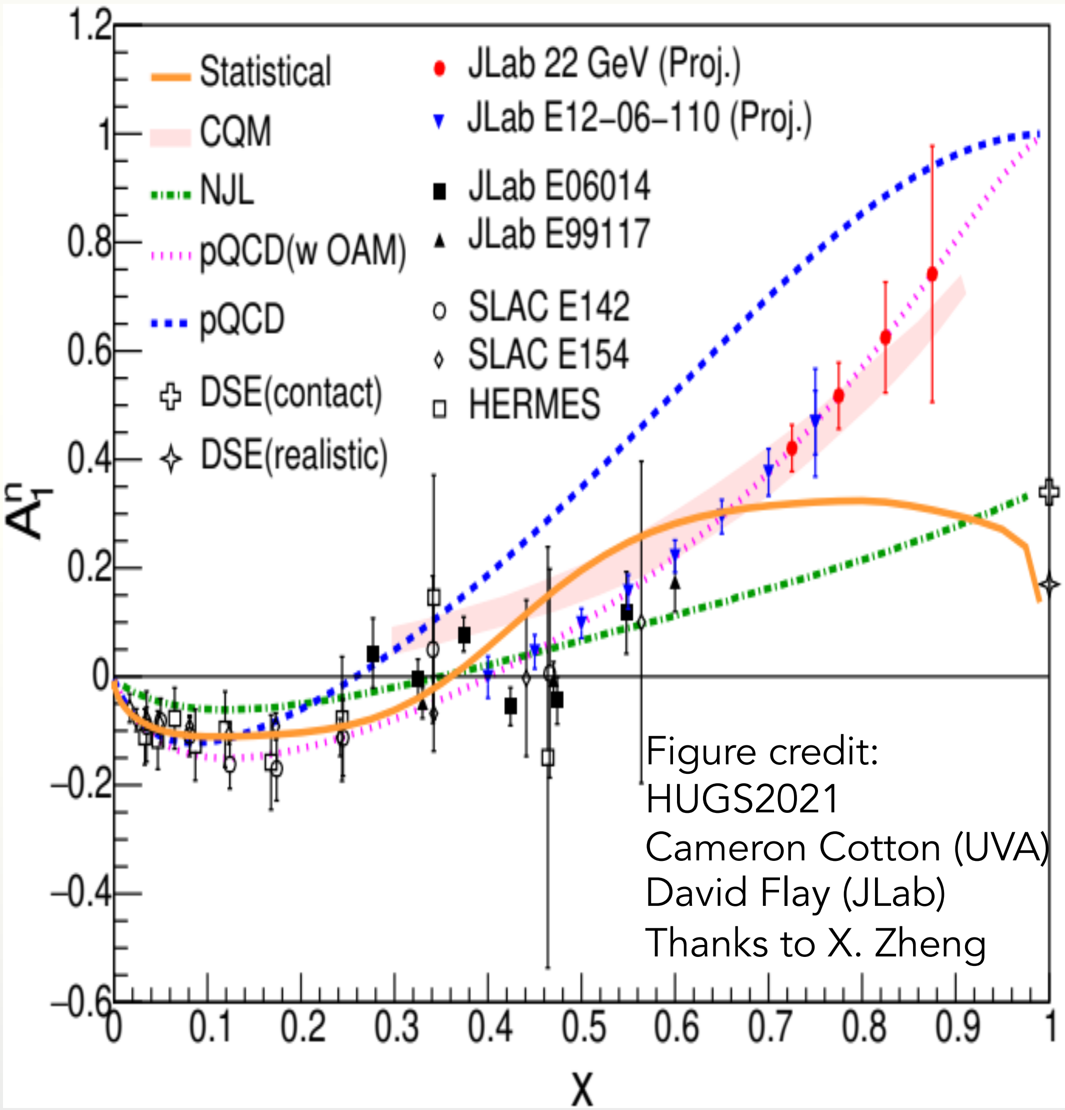
22-24 GeV CEBAF FFA
Energy Upgrade

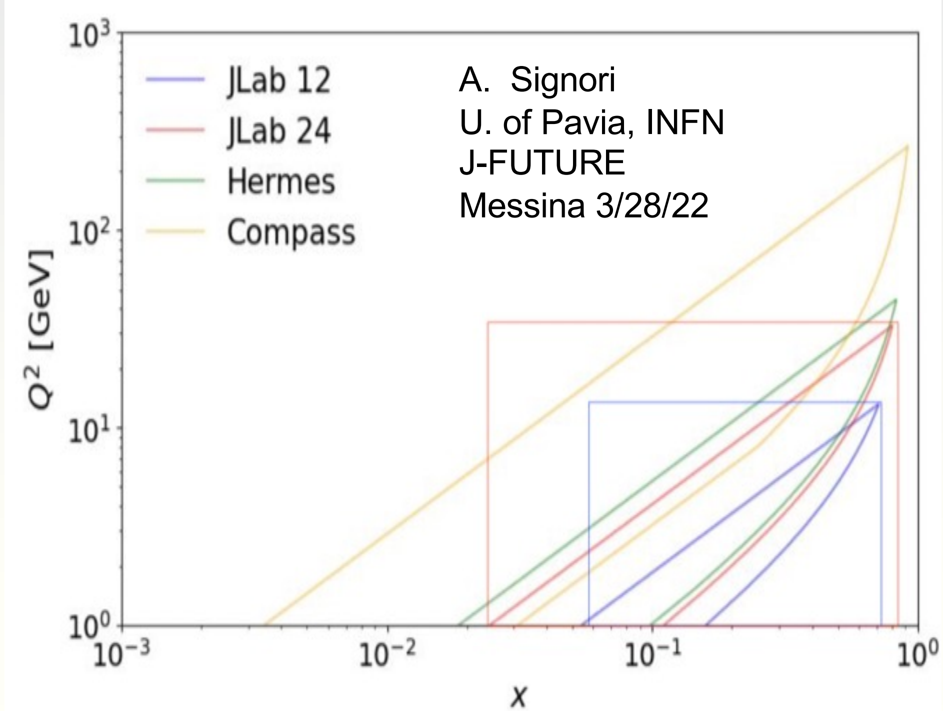
Alex Bogacz
J-FUTURE Workshop
Jefferson Lab / Messina University

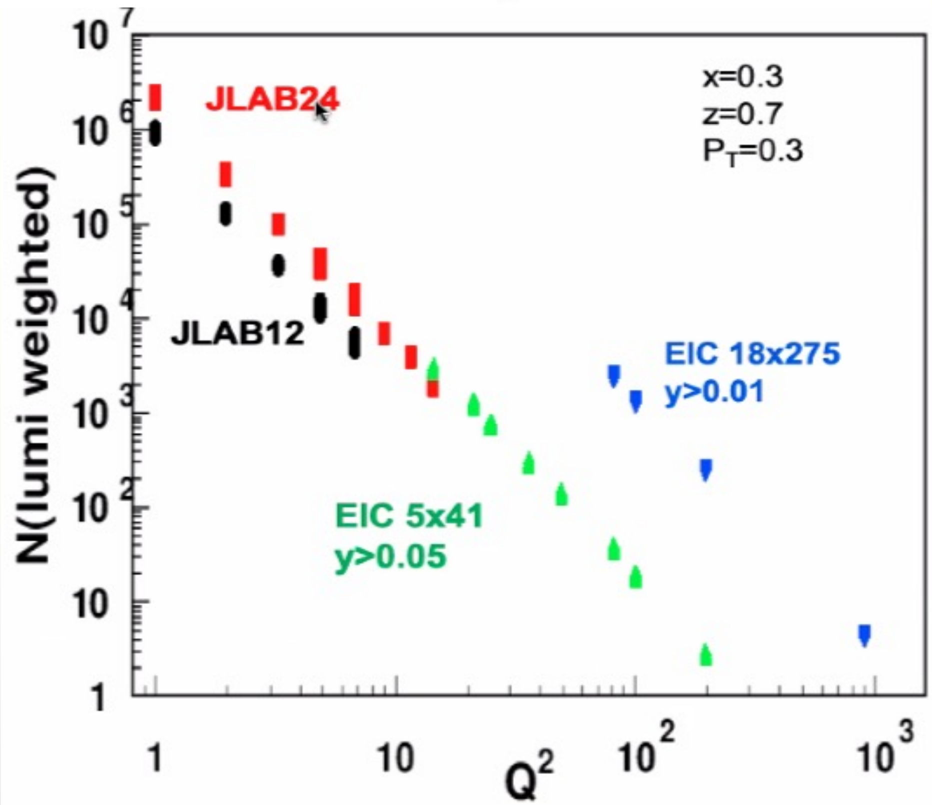
- Halve distance to $x = 1$, higher Q^2: Definite determination of asymptotic limit… *)
- …AND to $x = 0$ => Study "valence" sea quarks (pion cloud)
- Increase Q^2 range for all x -> DGLAP => Study "valence" gluon helicity
- Even for same x, Q^2: higher energy -> higher rates -> better statistics
- *(Super)Rosenbluth* – expand range in ε for fixed x, Q^2 => R, g_2, A_2
- Extend flavor tagging with SIDIS to higher x, Q^2:
- Issues: Still need to deal with nuclear uncertainties.

*) Higher Q^2: Suppress higher twist, study logarithmic resummation

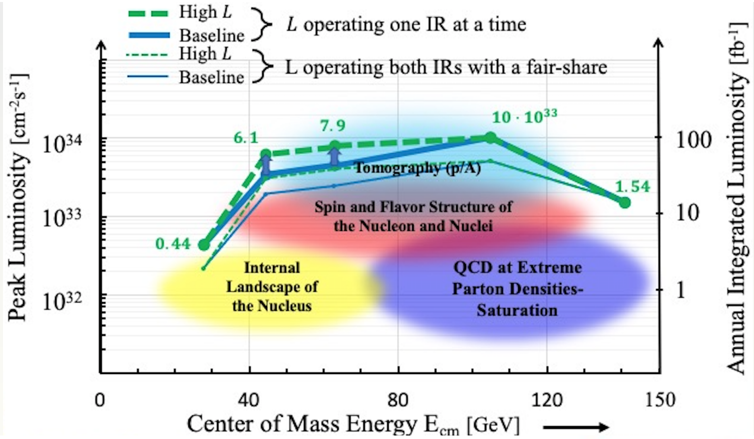
From 12 to 24 GeV

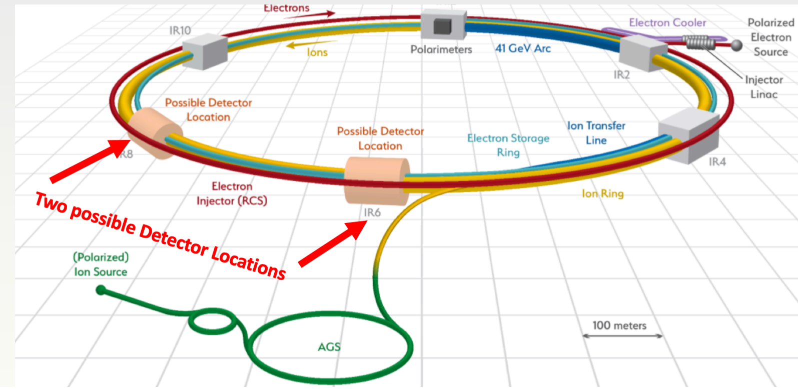


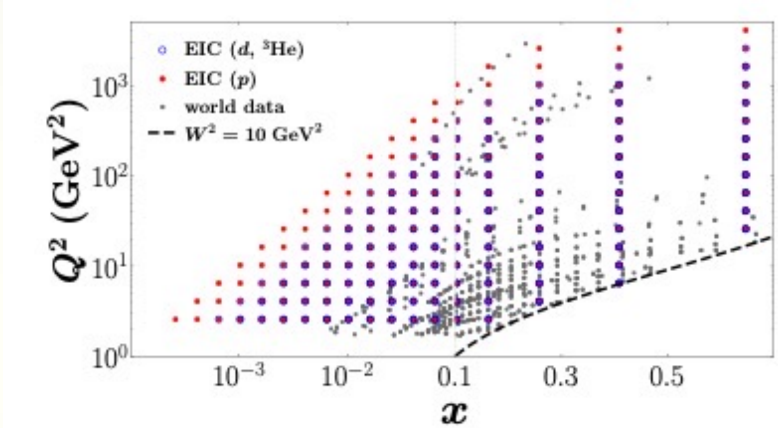


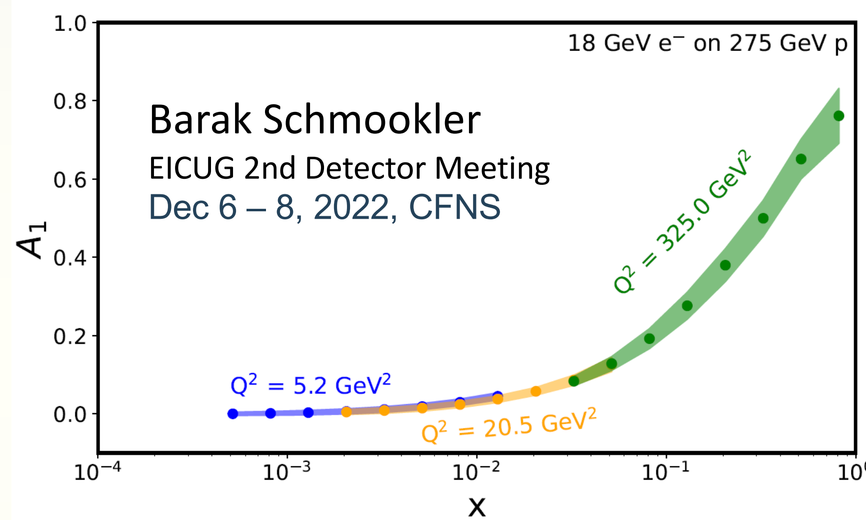


EIC



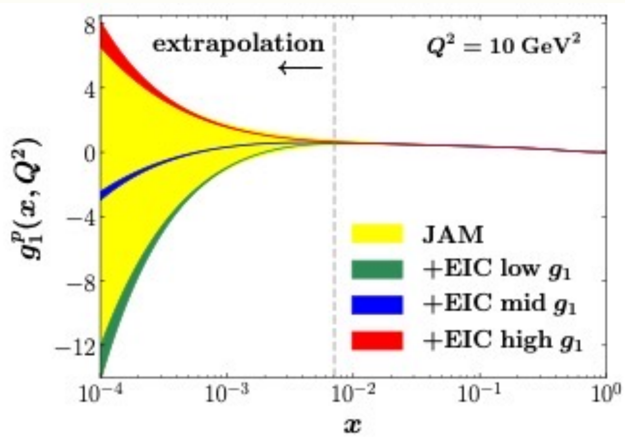




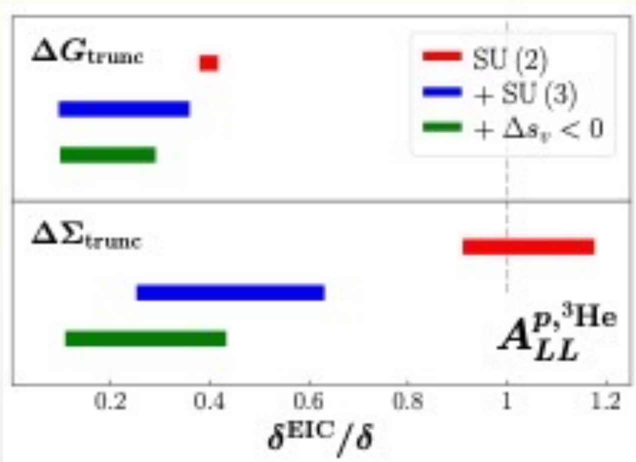


Y. Zhou et al., Phys. Rev. D **104**(2021)034028 arXiv:2105.04434v1

Expected reduction of present SSF uncertainties from EIC



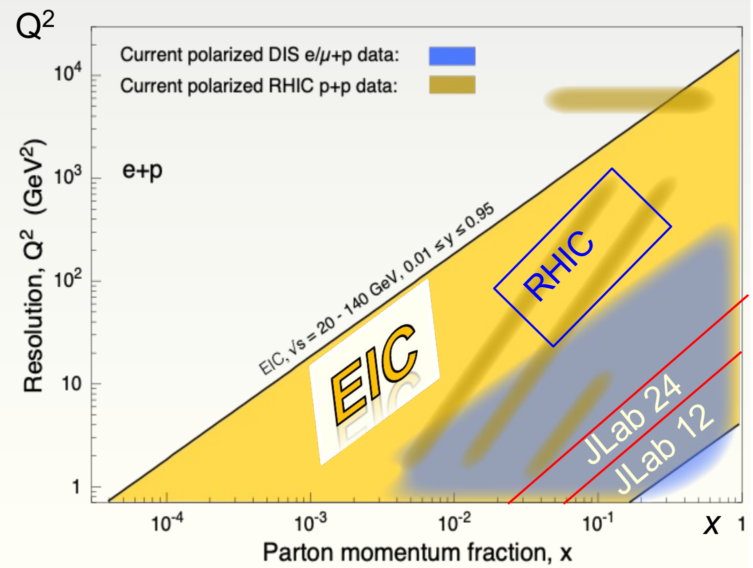
Inclusive p A_{LL}, enforce SU(3)



Gluon and quark singlet moments from EIC

- Missing piece to solve the proton spin puzzle: Low-x extrapolation, gluon contribution
- Include weak IA for flavor separation
- Extend spectator tagging to **all** nucleon momenta in the nuclear rest frame => Extrapolate to the free nucleon pole

SUMMARY: COMPLETING THE COLLINEAR PICTURE



Enormous Progress on understanding Collinear PDFs fueled by large new data sets and sophisticated phenomenology. Still, some questions remain:

- **d/u, Δu/u and Δd/d at highest *x* ?** } JLab @ 12 -> 24 GeV
- **Nuclear effects on nucleon structure** }
- **Understanding the sea – Δs, $\bar{u}$ - $\bar{d}$, Δ$\bar{u}$ - Δ$\bar{d}$** JLab, FNAL, RHIC, AMBER, LHC
- **Axial and Tensor charges of the nucleon** COMPASS, JLab
- **Gluon helicity distribution at large *x* AND at small *x*?**
  What is the integral ΔG?
  Total contribution of parton helicity to proton spin? JLab + DGLAP, RHIC, COMPASS
- **What happens at really small x << 0.01?**

EIC

Conclusions

- Structure functions in the valence region remain of high theoretical interest and provide crucial input to precision collider experiments
- Jefferson Lab at 12 GeV is starting to have significant impact on our understanding of this region
- Jefferson Lab at 24 GeV can expand the coverage in x from 0.75 to 0.9 and more than double the range in Q^2, thereby minimizing the extrapolation to $x \to 1$.
- Jefferson Lab and EIC together cover the entire kinematic region necessary to complete the “spin puzzle”.
- Essential ingredient: Extract neutron (polarized) structure functions from measurements on nuclei (d, ^3He) => we must understand the EMC effect in detail.