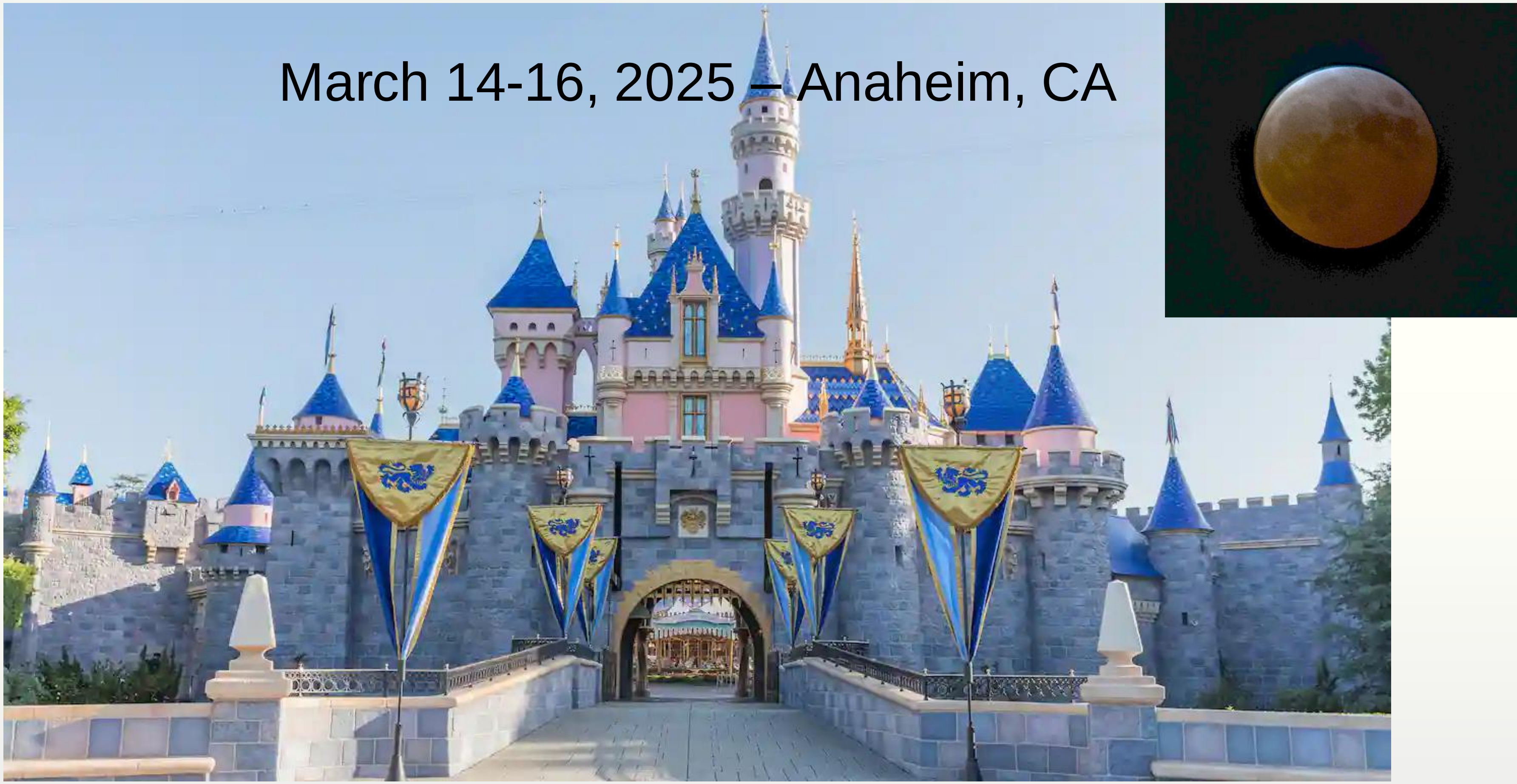
Nucleon structure in the extreme valence region

11th workshop of the APS Topical Group on Hadronic Physics

March 14-16, 2025 – Anaheim, CA



Sebastian Kuhn

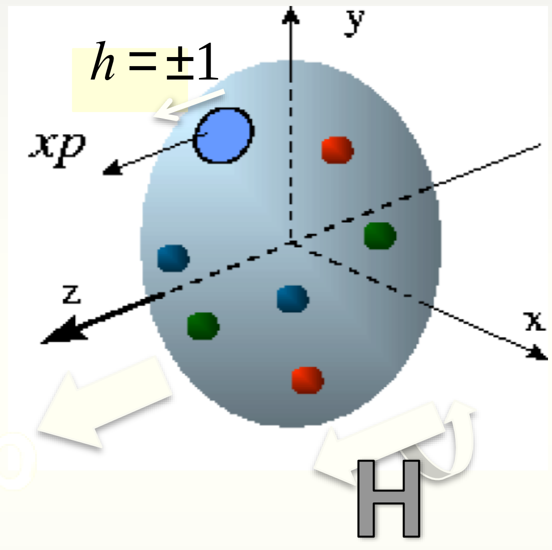
Old Dominion University, Norfolk (VA), USA

Overview

- Collinear valence structure of the nucleon
  - Test of our understanding of bound-state QCD
- Unpolarized structure function of the neutron
  - Present landscape
  - BONuS12 experiment at Jefferson Lab
- Spin structure at high x
  - Present landscape
  - Recent and planned experiments
- Future Facilities – what more can we do?
  - JLab at 20+ GeV?
  - EIC
- Conclusions

Collinear Structure functions

- Important for understand origin of mass and spin of hadrons
- Important as limiting cases and constraints for TMDs, GPDs etc.
- Large *x*: Stringent tests of pQCD, Lattice QCD, DS approach, and phenomenological models
  - NN…LO + DGLAP *)
  - Input for novel and mature PDF extractions
  - Test of higher twist and target mass effects, resummation
  - Quark-hadron duality
- Important input for collider physics
- Input for investigations of modifications of quark distributions in nuclei



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

"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 => relevant for LHC Physics

- MANY predictions based on models, pQCD, DS equation 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)

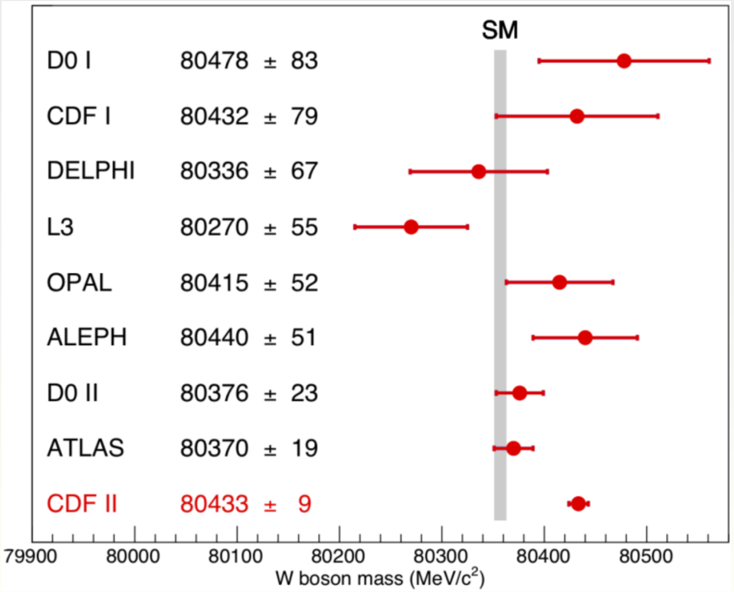
*) Moments, quasi-PDFs, pseudo-PDFs

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

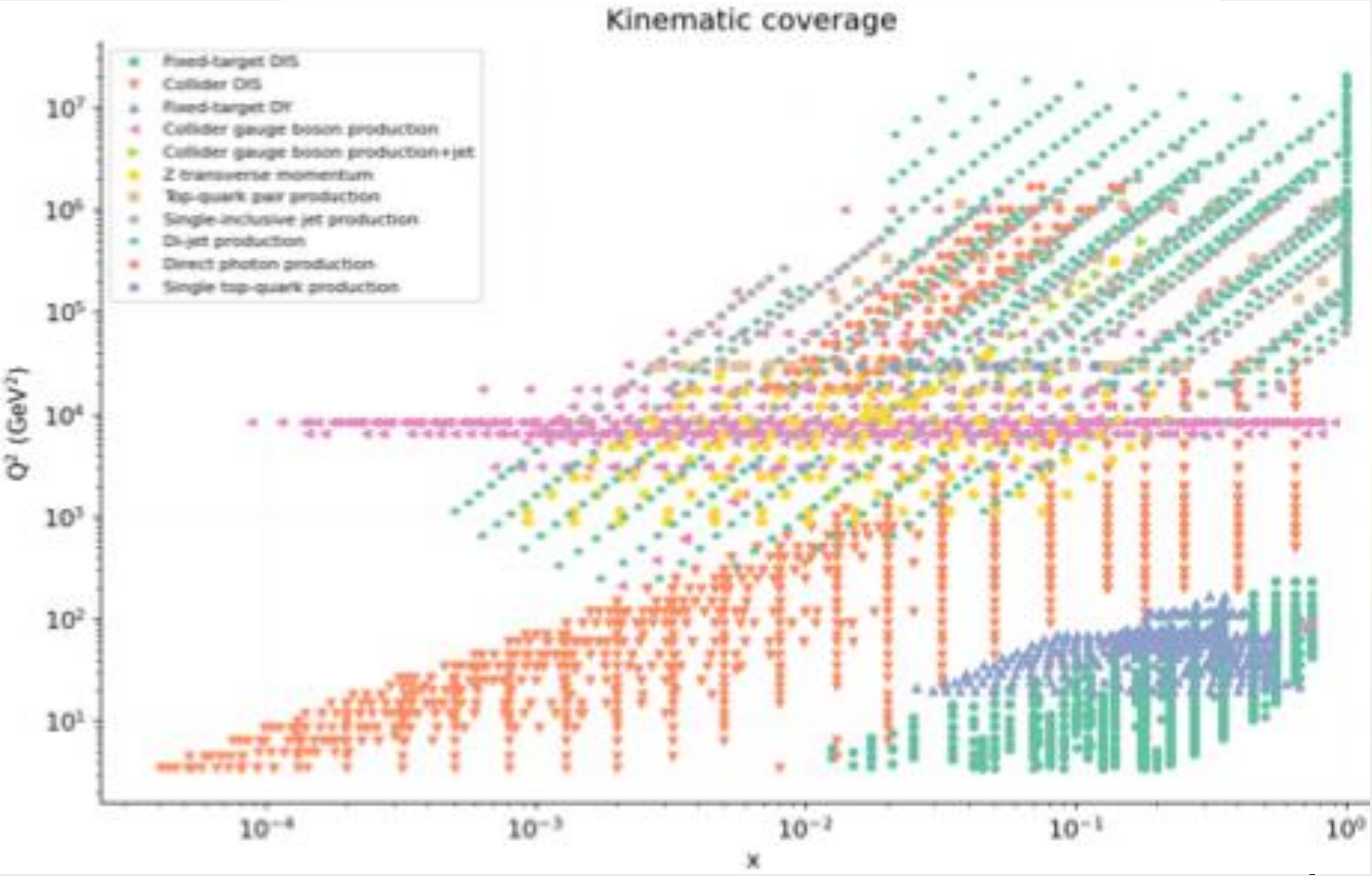
Corresponding author: A. V. Kotwal, ashutosh.kotwal@duke.edu

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

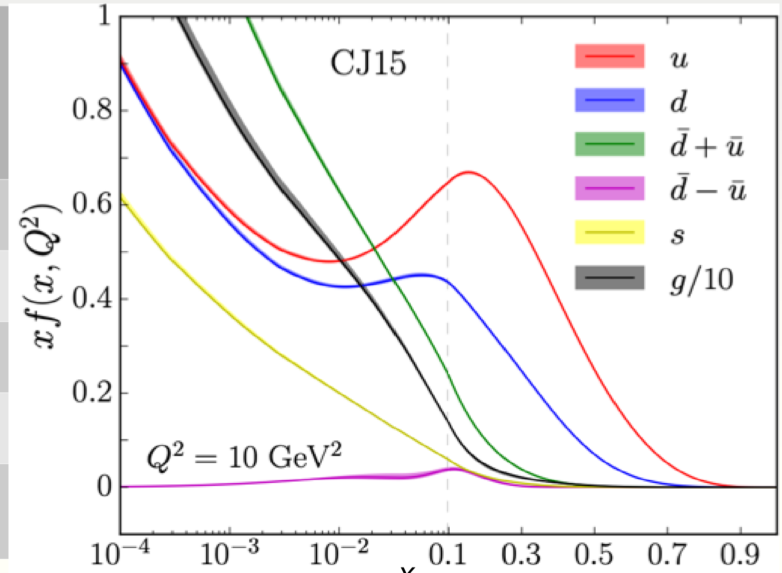
96. S. Tkachenko, N. Baillie, S. E. Kuhn, …
D. Watts, X. Wei, L. B. Weinstein, M. H. Wood, L. Zana, I. Zonta, Measurement of the structure function of the nearly free neutron using spectator tagging in inelastic ^{2}H(e,$e'p_s$)X scattering with CLAS. *Phys. Rev. C* **89**, 045206 (2014).

Unpolarized PDFs



Unpolarized PDFs – high *x*

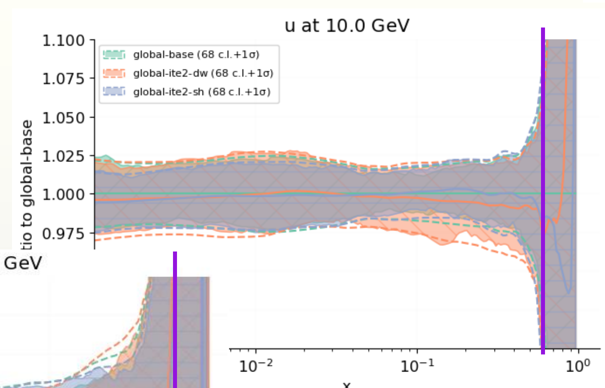
Nucleon Model	F_2^n/F_2^p $x \to 1$	d/u $x \to 1$
SU(6) Symmetry	2/3	0.5
Scalar diquark dominance	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
PQCD (helicity conservation)	3/7	0.2

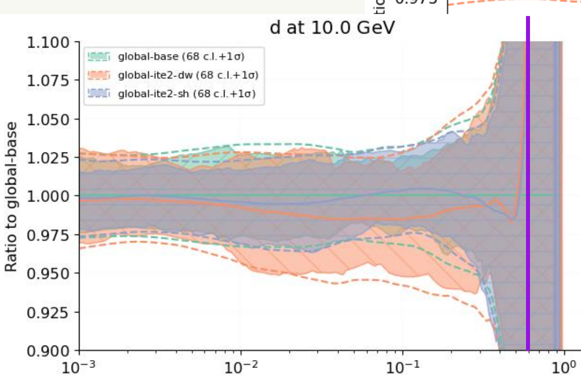


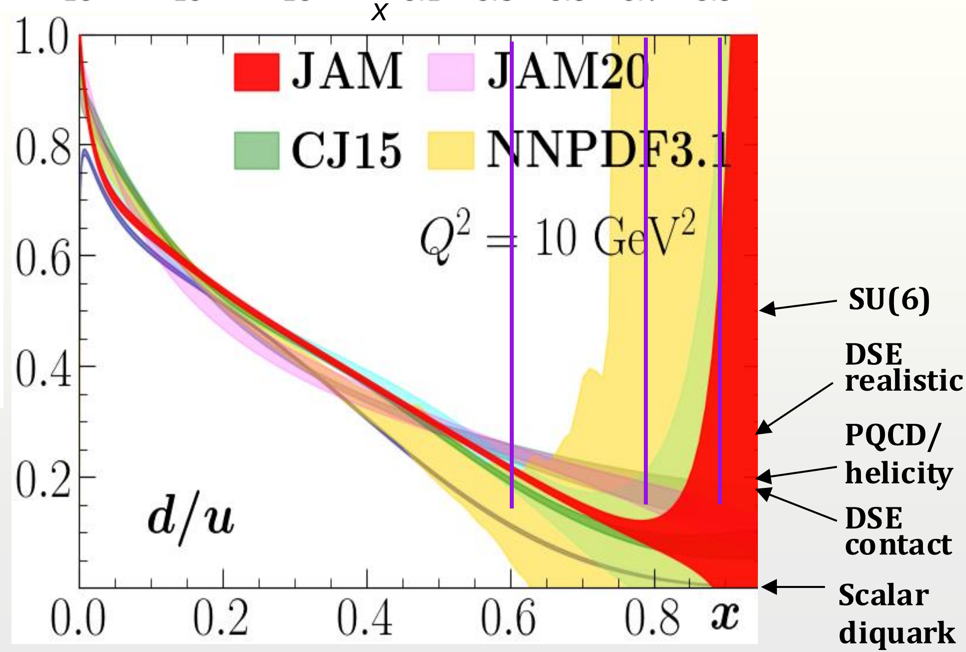
A. Accardi, et al., PRD 93 (2016)

NNPDF3.1

arXiv:2011.00009

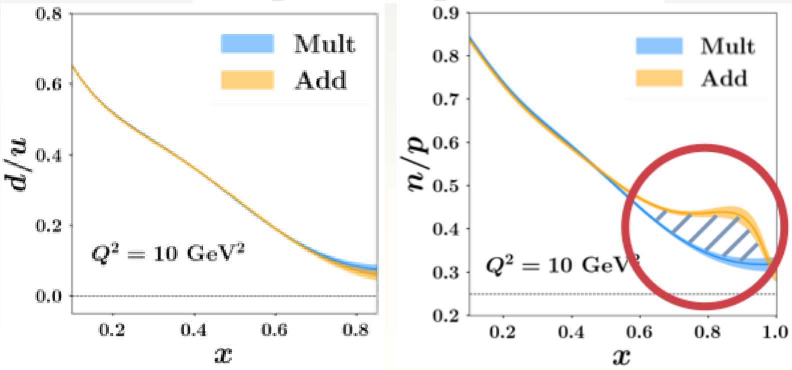


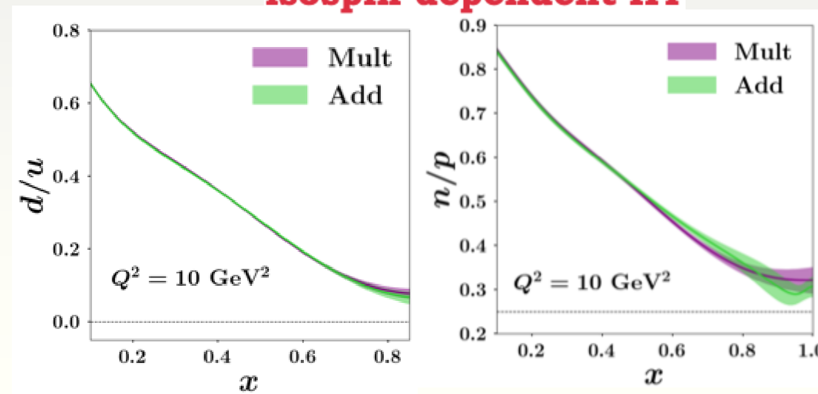




Issues affecting extraction of d/u

- Higher twist/target mass correction



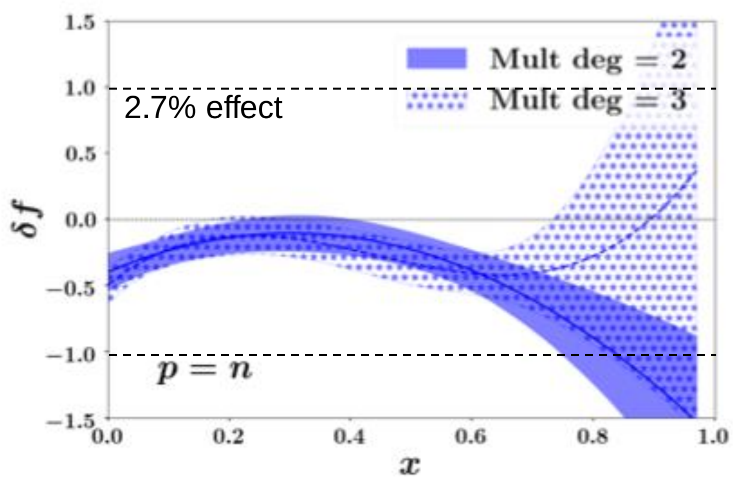


M. Cerruti, A. Accardi et al.

- Nuclear binding correction

○ Polynomial model $\delta f(x) = \sum_n a_{off}^{(n)} x^n$

Alekhin, Kulagin, Petti, PRD 96 (2017)
Alekhin, Kulagin, Petti, PRD 105 (2022)
Alekhin, Kulagin, Petti, PRD 107 (2023)



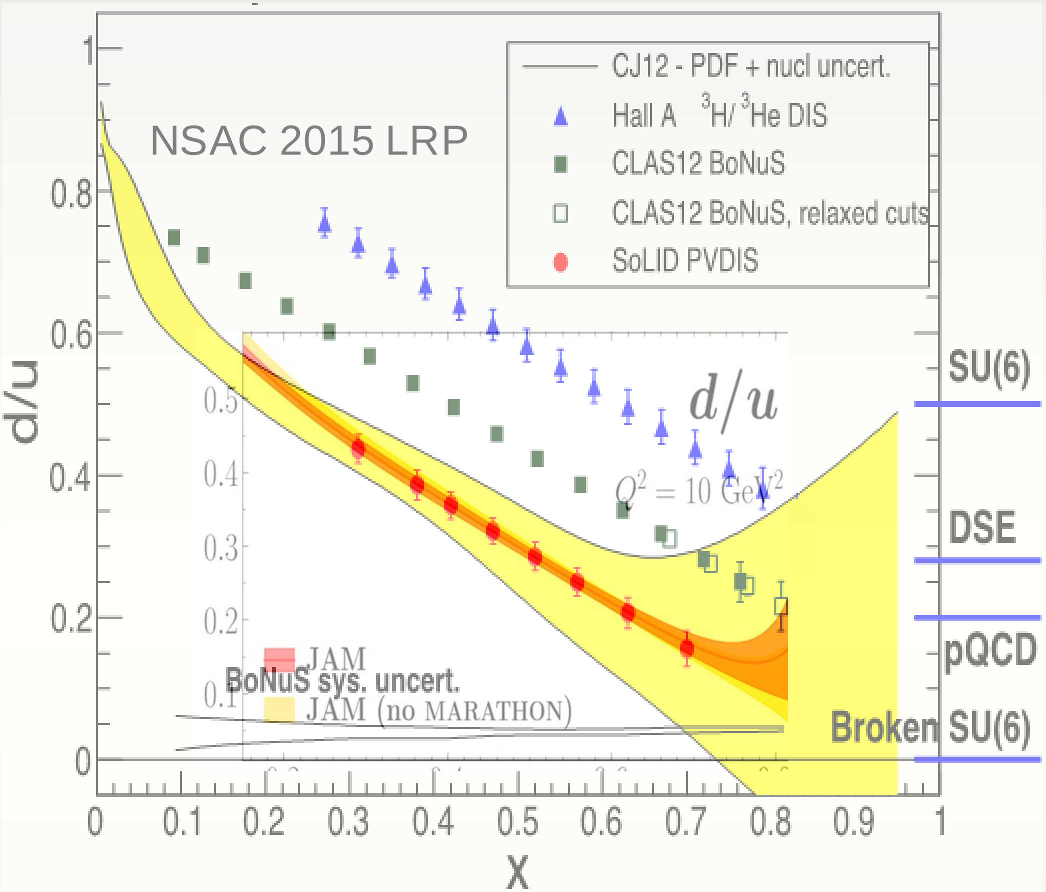
$$q_N(x, Q^2, p^2) = q_N^{\text{free}}(x, Q^2)\left[1 + \frac{p^2 - M^2}{M^2}\delta f(x)\right]$$

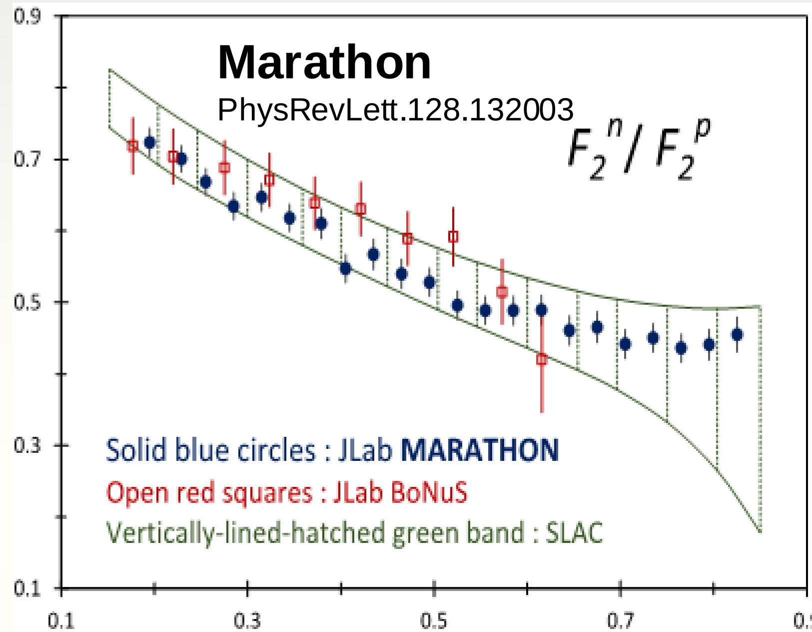
$\Rightarrow$ Constrain power of CJ dataset only up to x = 0.6

BONuS12: $p_S < 0.1$ GeV/c =>

Multiplier < 0.027

JLab@12 GeV d/u- the full program





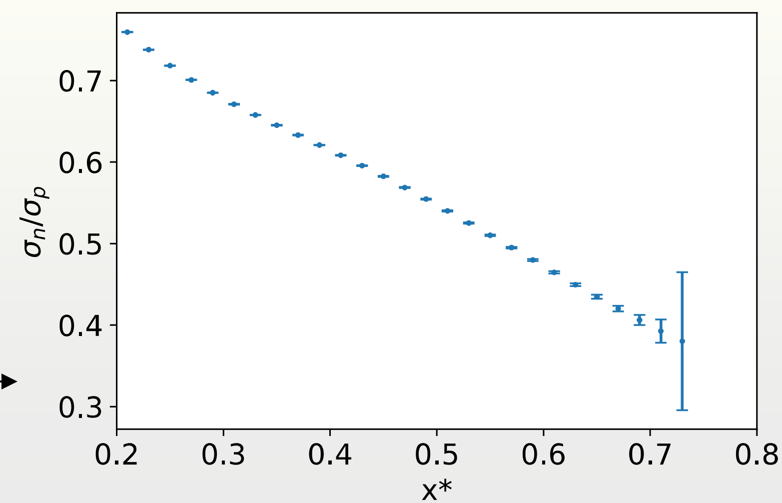
BONuS12:

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 →

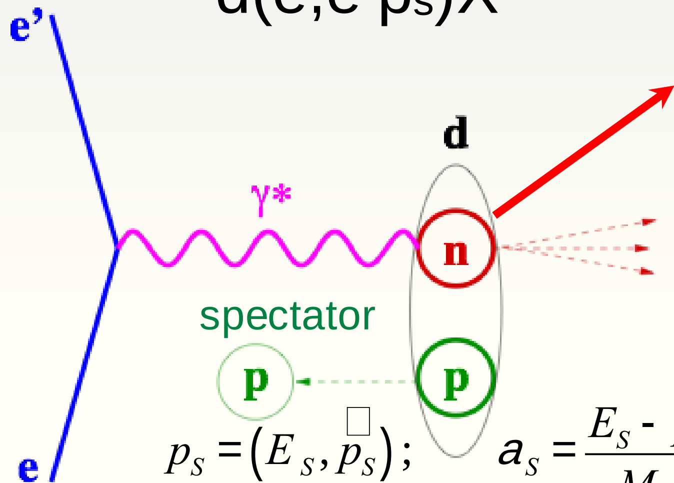
Courtesy Arun Tadepalli



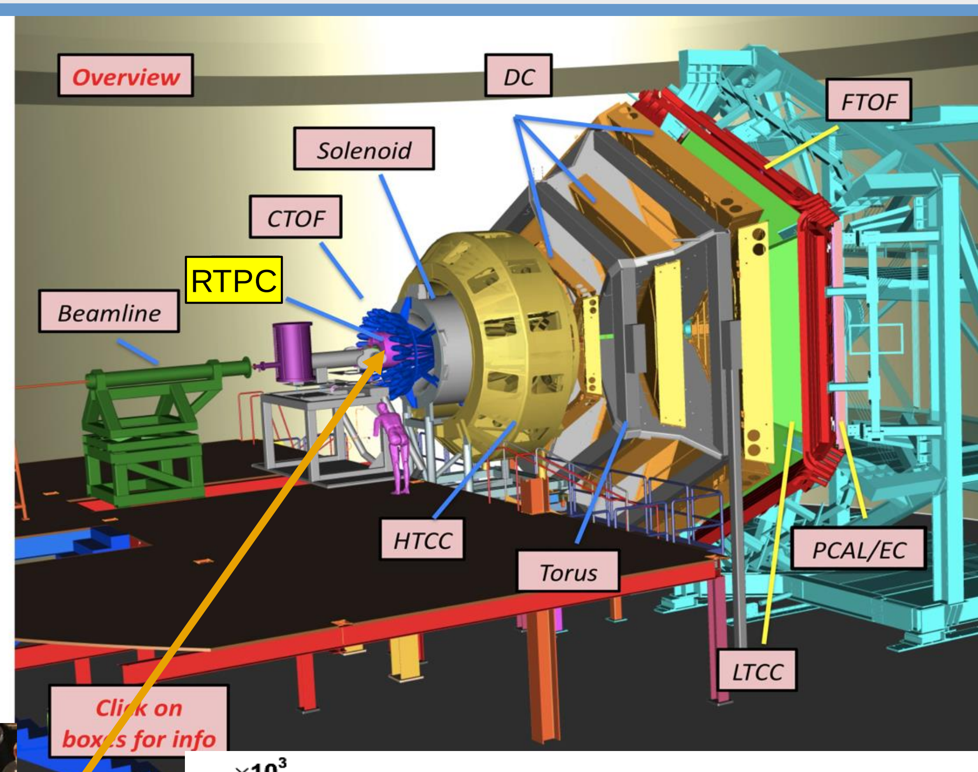
BONuS12 with CLAS12 (Run Group F in 2020)

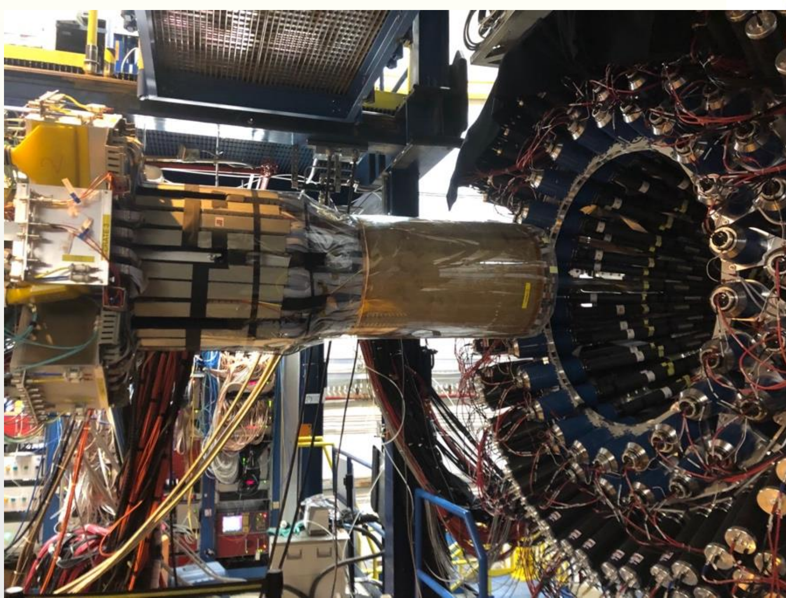
F_{2n}/F_{2p} through spectator tagging

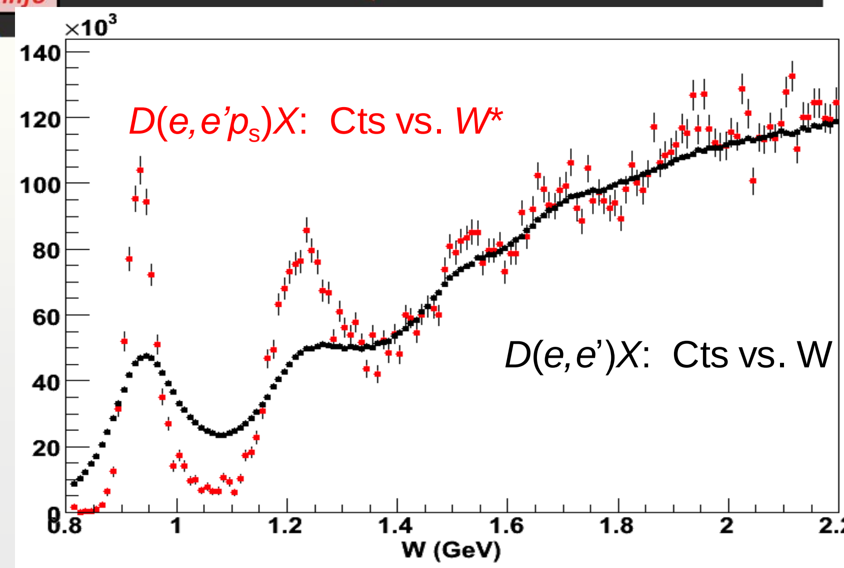
$d(e,e'p_s)X$



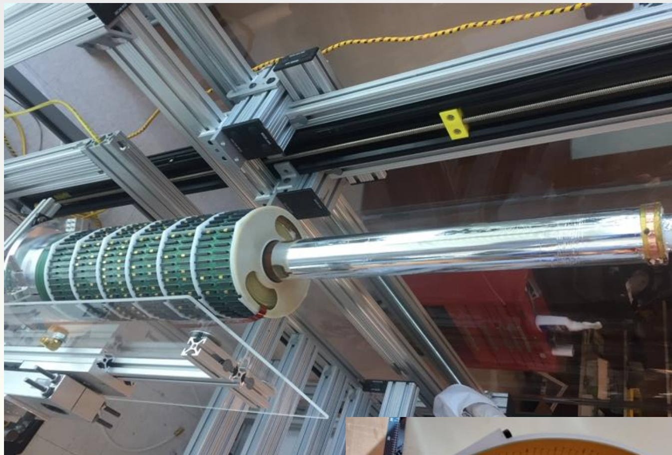
$$p_S = (E_S, \vec{p}_S); \quad a_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$



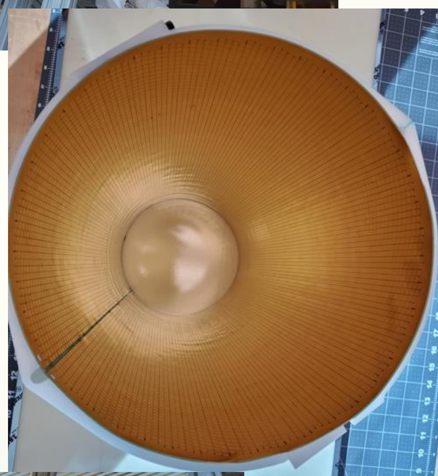




BONuS12 Radial Time Projection Chamber

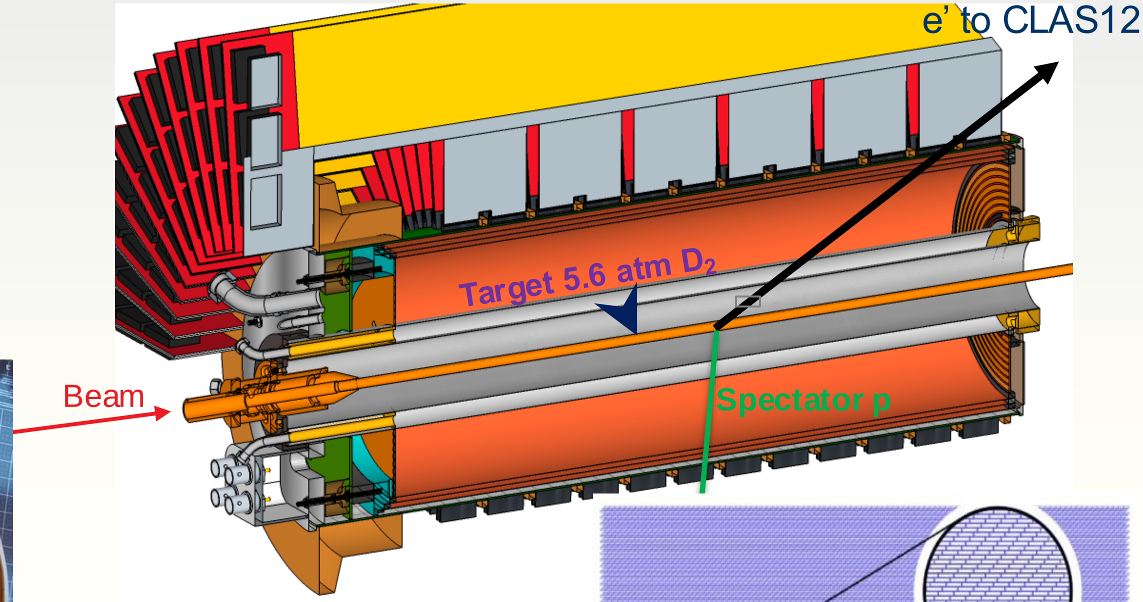


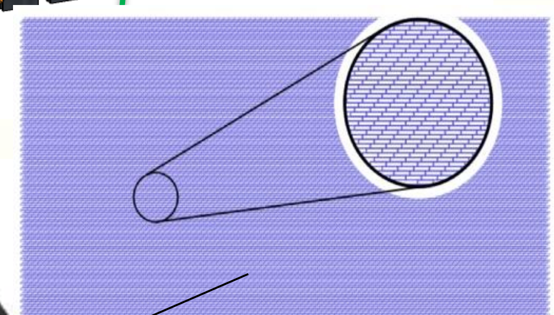
Installation of Cathode + ground foil assembly



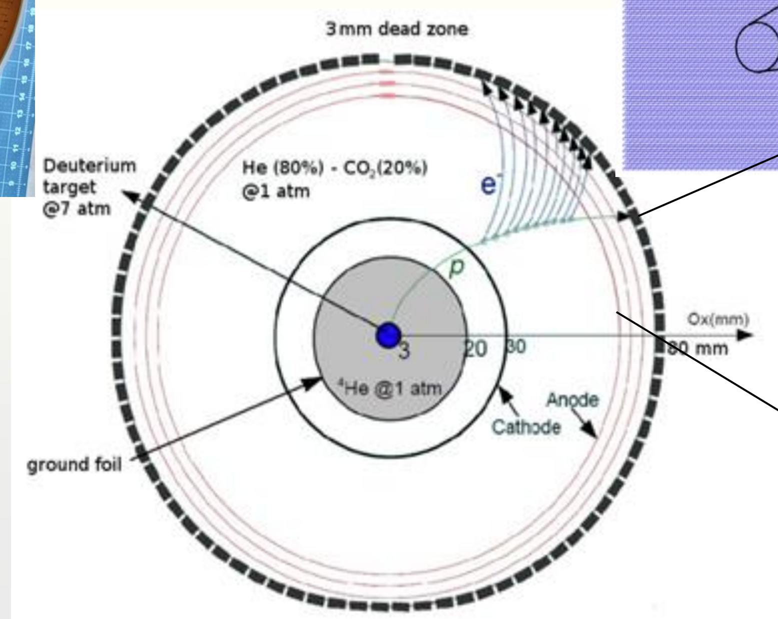
Wrapped Padboard inner surface

GEM foil wrapping and gluing

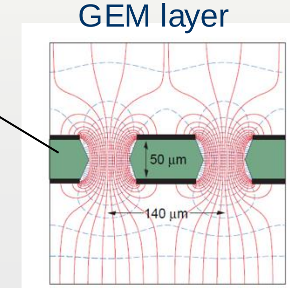




Readout Pads



GEM layer



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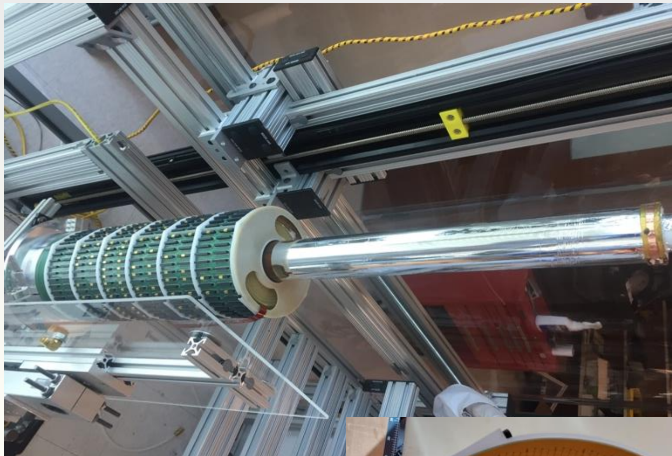
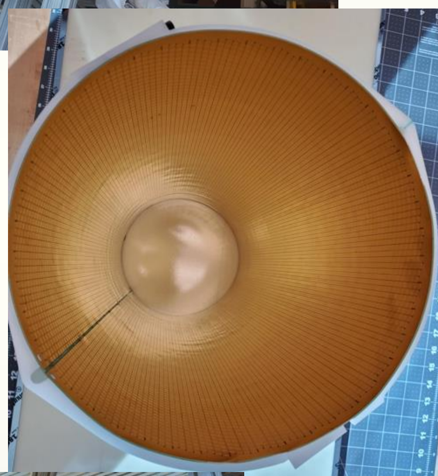
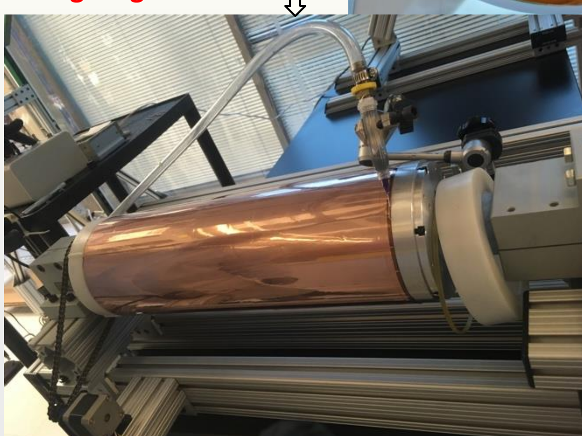


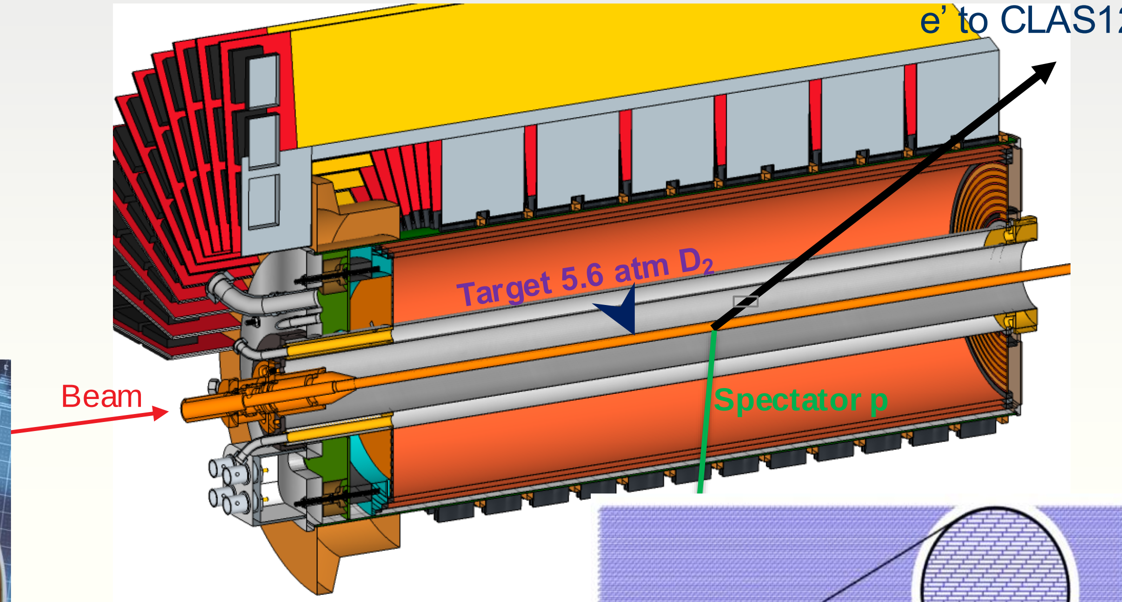
Installation of Cathode + ground foil assembly

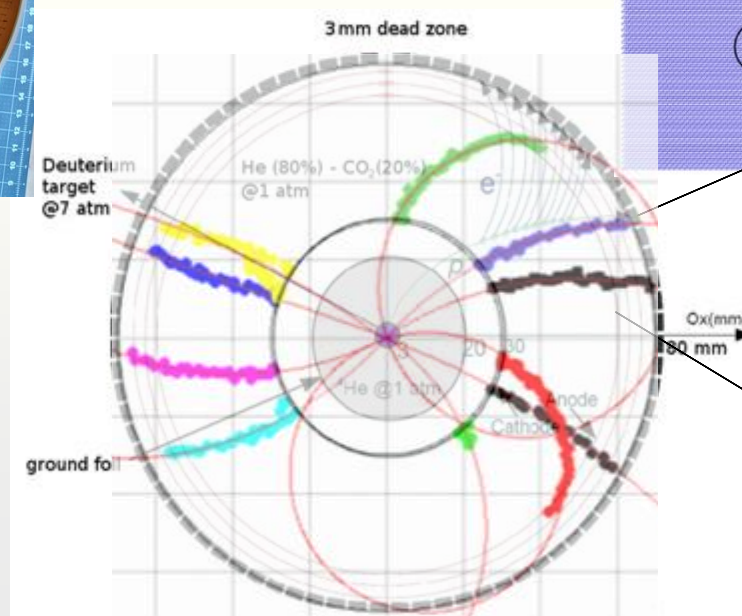


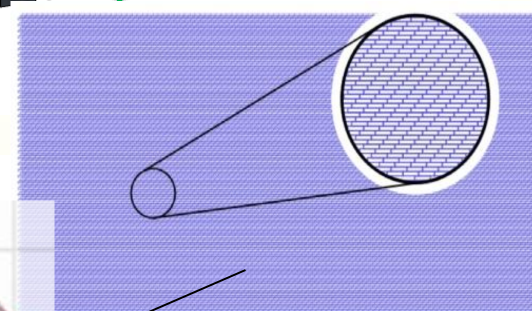
Wrapped Padboard inner surface

GEM foil wrapping and gluing



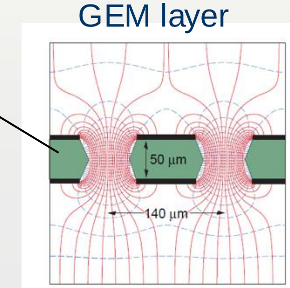




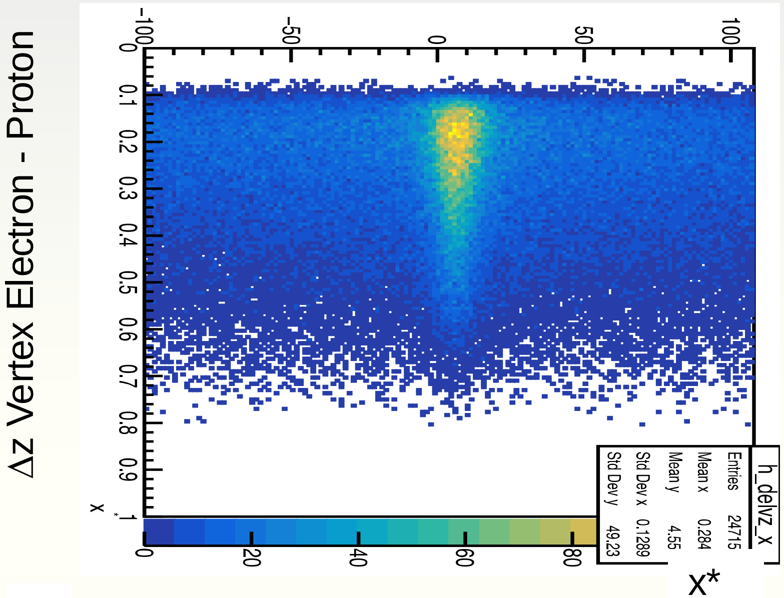


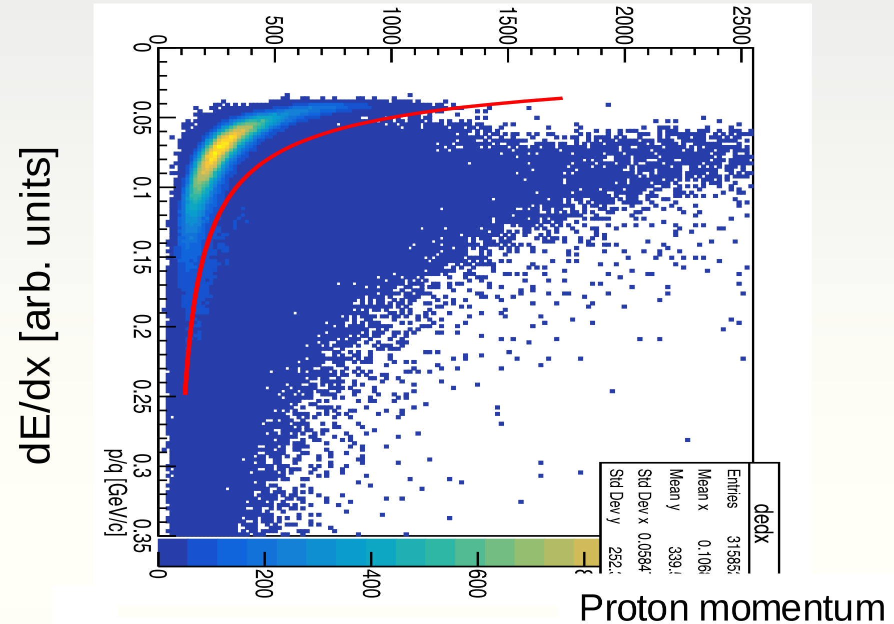
Readout Pads

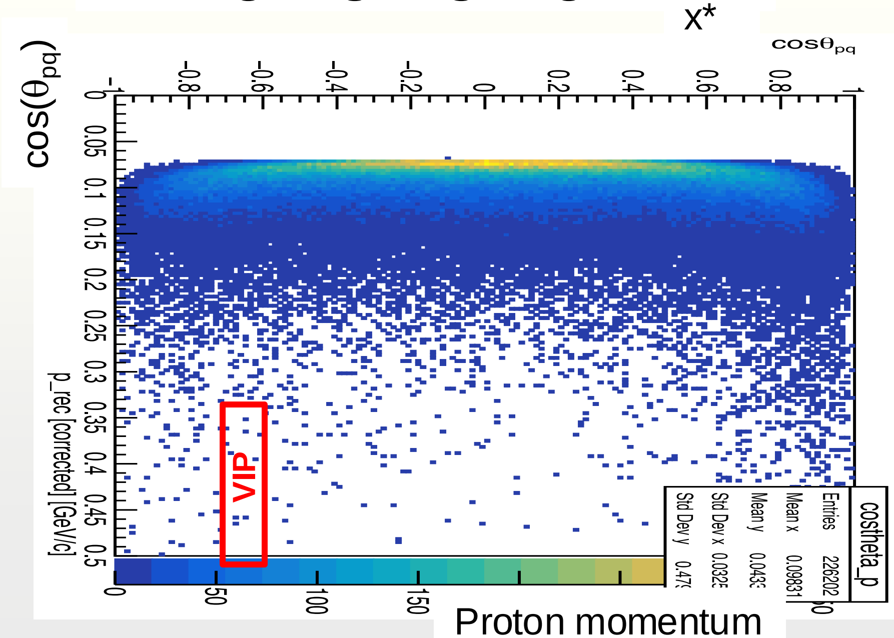
GEM layer

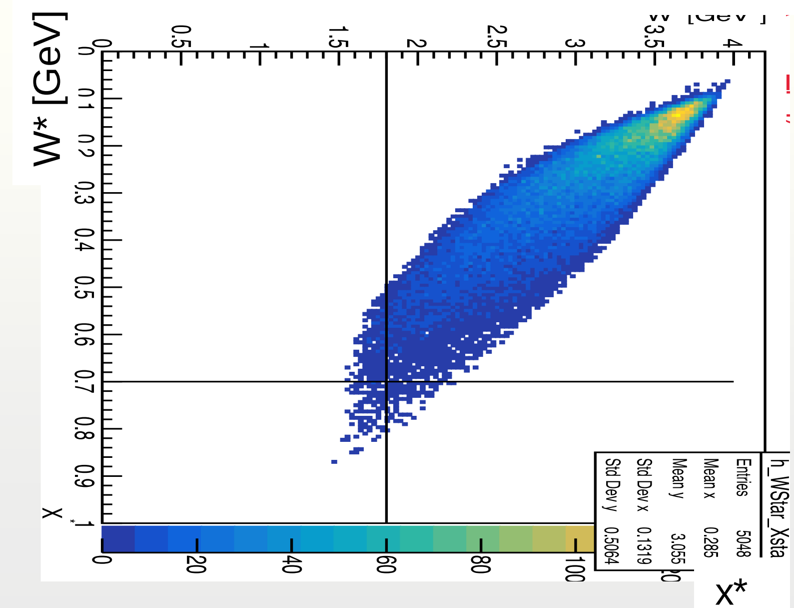


BONuS12 Kinematics





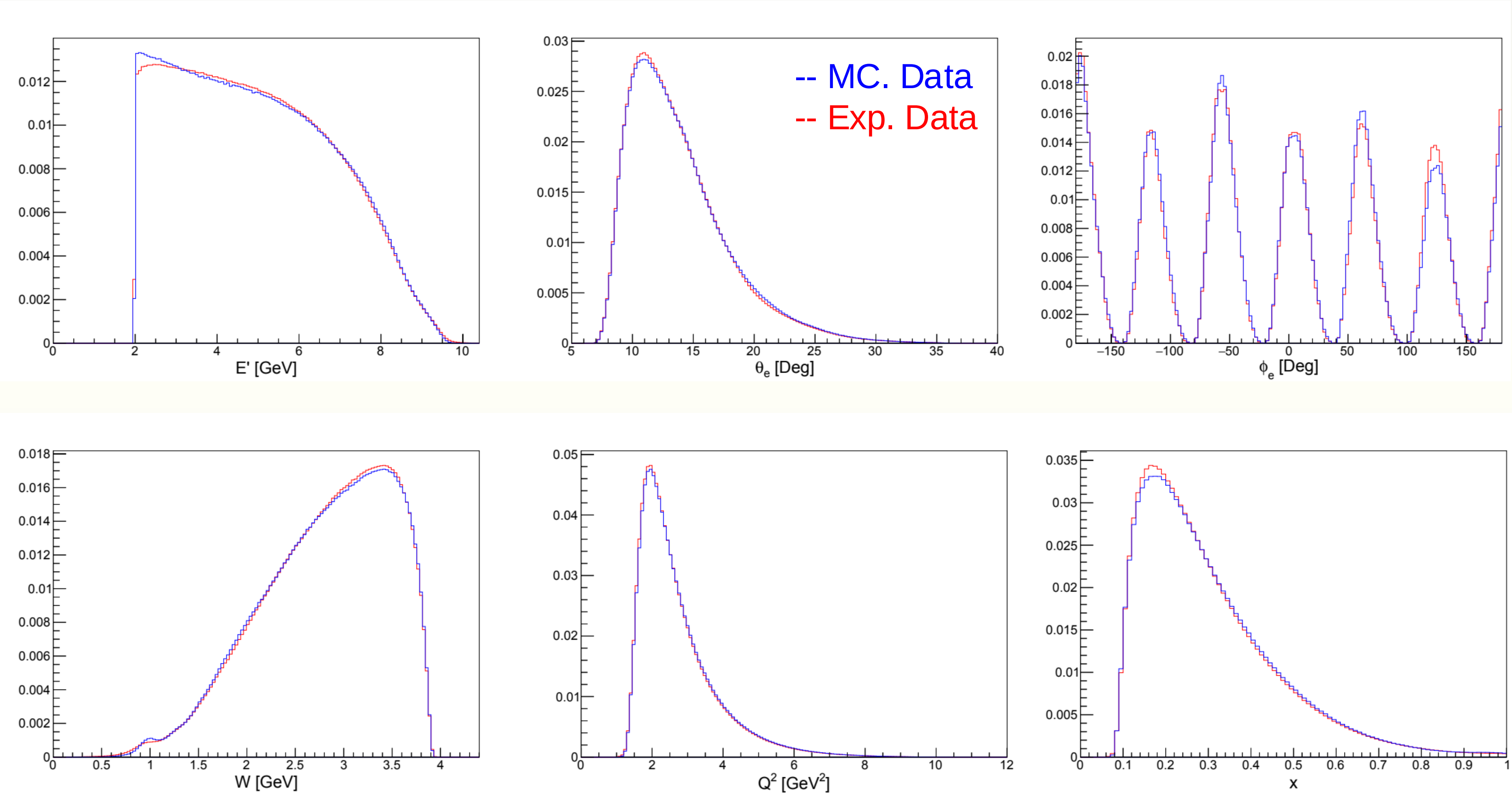




Data vs. MC : D(e,e')X

- Improved RTPC implementation in GEMC.
- **Generator**: An extension version from previous Bonus experiment
- that accommodates the higher beam energy.

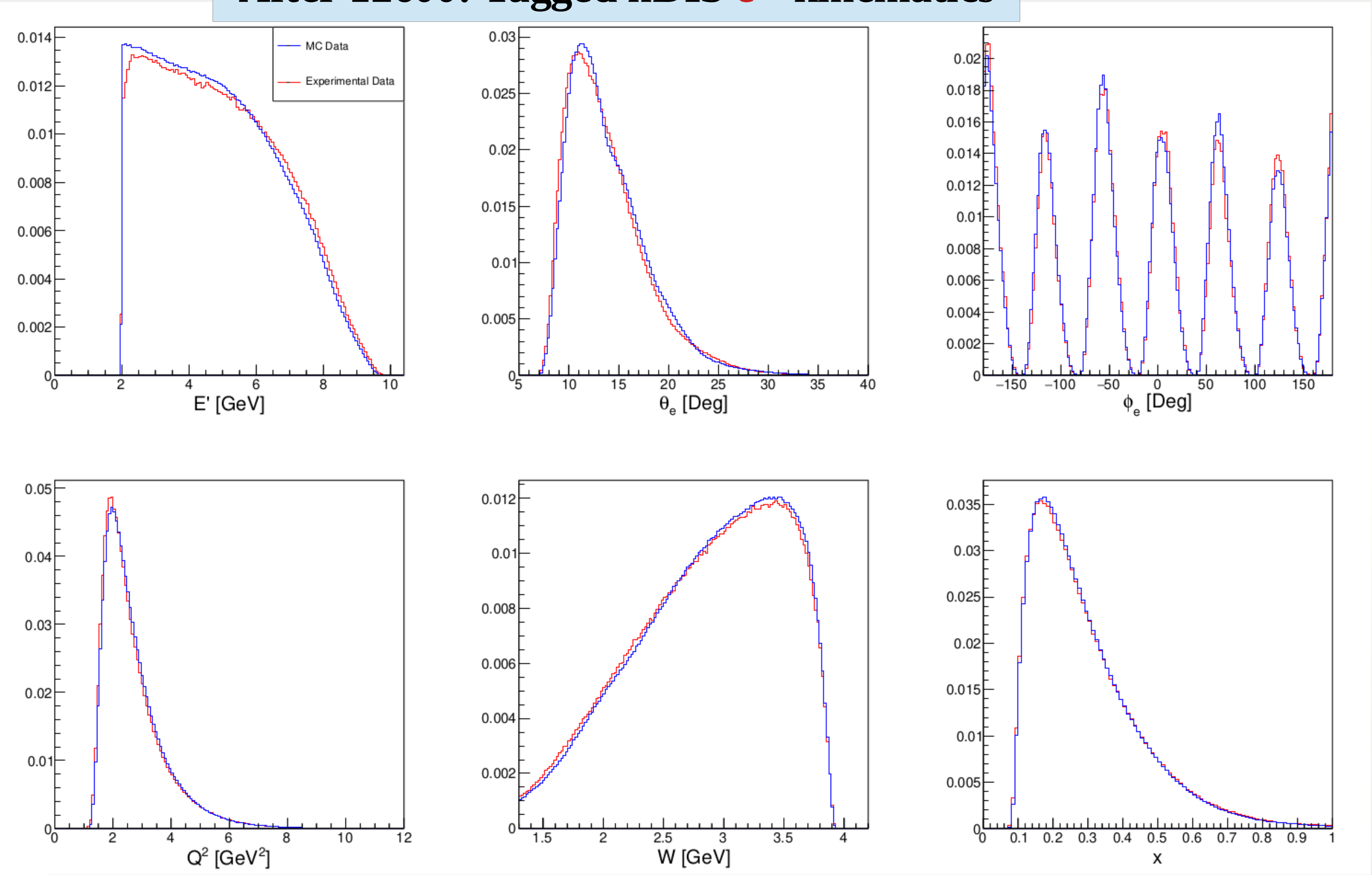
Inclusive e⁻ kinematics



ODU

Data vs. MC: D(e,e'p_s)X

After 12600: Tagged nDIS e^- kinematics

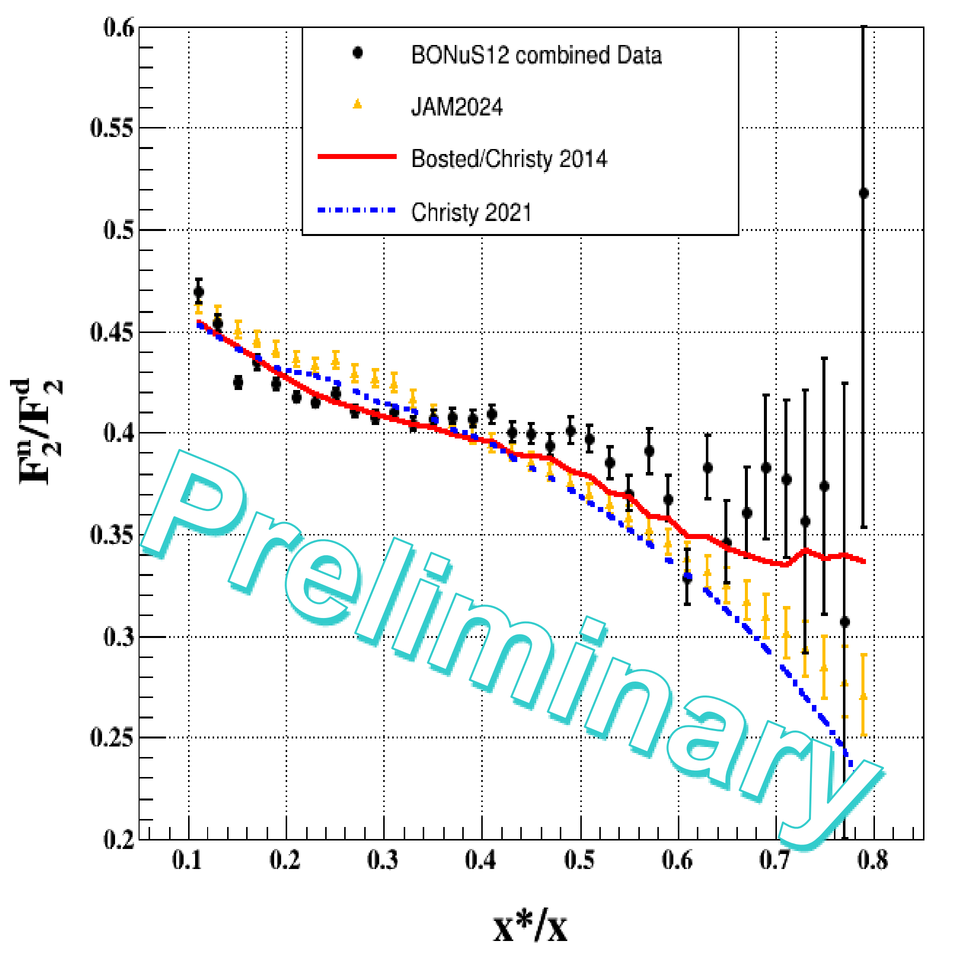


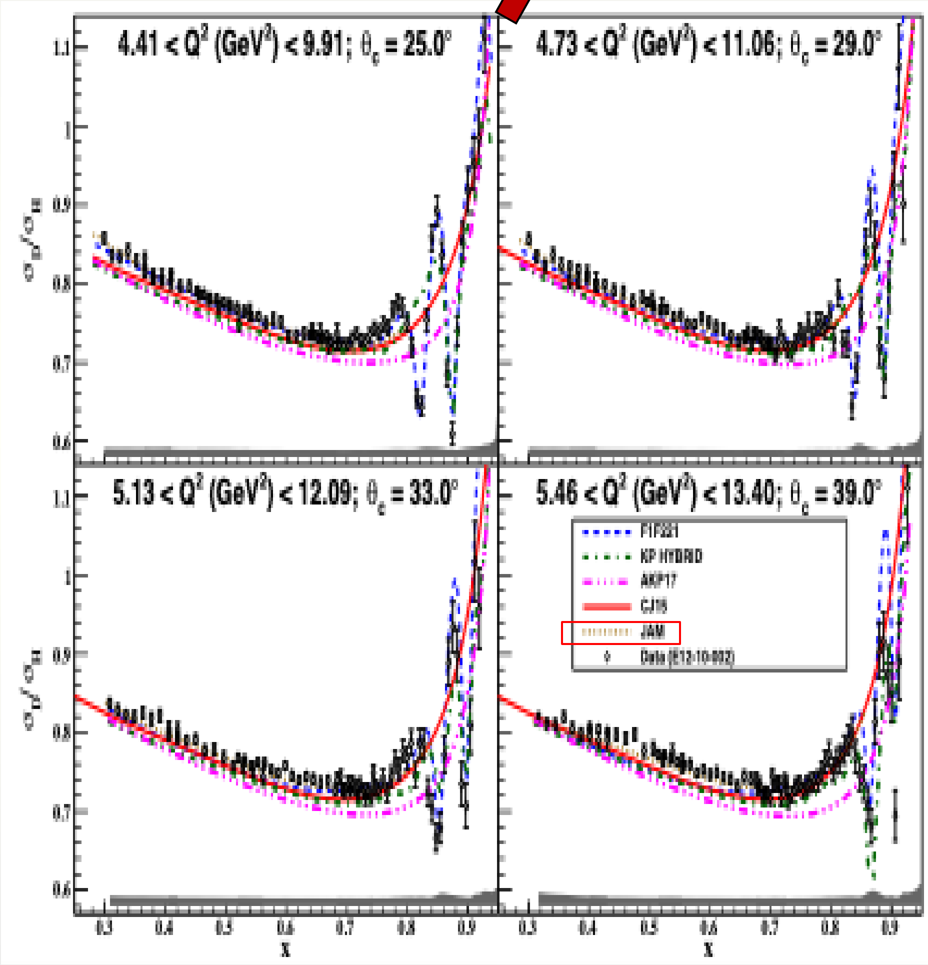
ODU

BONuS12 Near-Final Results

$$\left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} = \text{Constant} \cdot \left(\frac{F_{2n}}{F_{2d}}\right)^{\text{Gen}} * \frac{\left(Y_{\text{tag}}^{\text{Data}} / Y_{\text{inc}}^{\text{Data}}\right)}{\left(Y_{\text{tag}}^{\text{MC}} / Y_{\text{inc}}^{\text{MC}}\right)}$$

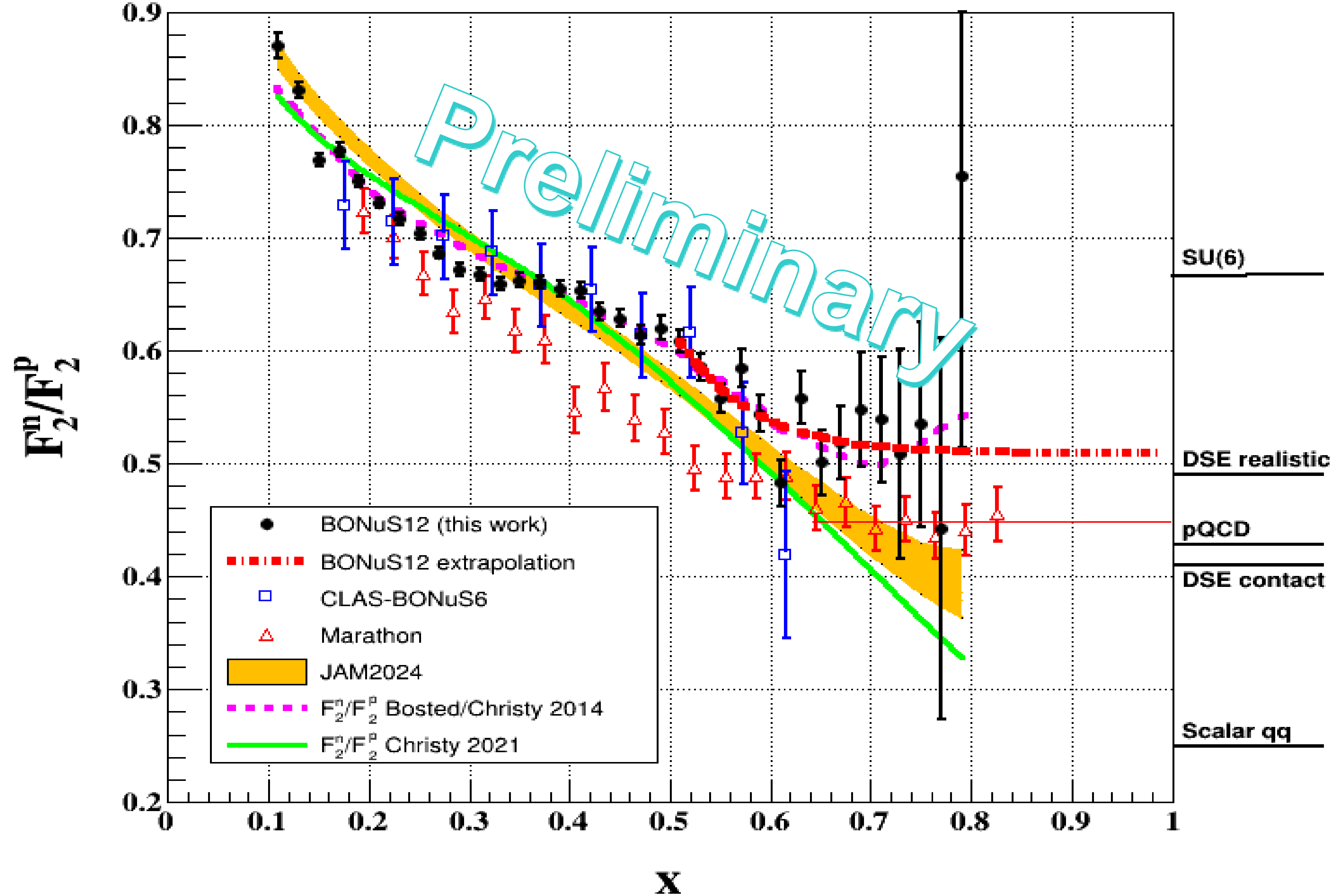
$$\left(\frac{F_2^n}{F_2^p}\right)^{\text{true}} = \left(\frac{F_{2n}}{F_{2d}}\right)^{\text{true}} * \left(\frac{F_{2d}}{F_{2p}}\right)^{\text{fit}}$$



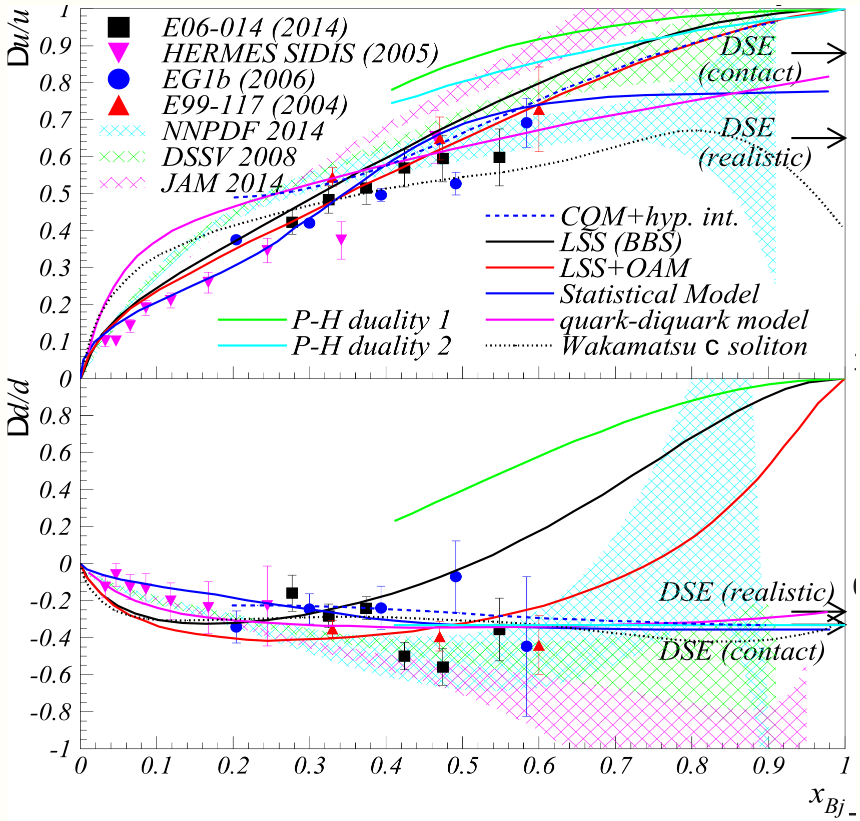


D. Biswas et al., arXive hep-ex 2409.15236

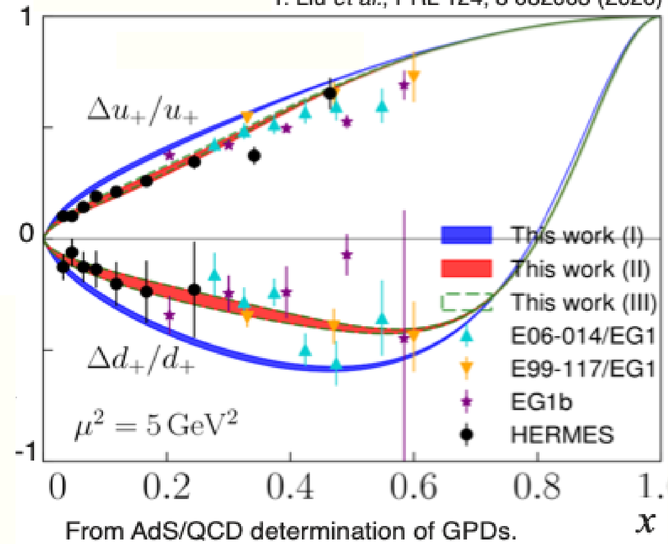
BONuS12 Near-Final Results



SSFs: Recent theoretical predictions



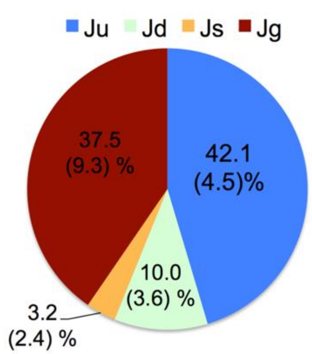
T. Liu *et al.*, PRL 124, 8 082003 (2020)

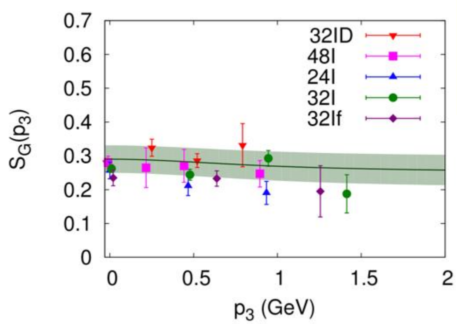


From AdS/QCD determination of GPDs.
No free parameters.
Predicts *Δd/d* changes sign near x=0.8.
Reproduces QCD counting rules used for BBS/LSS.

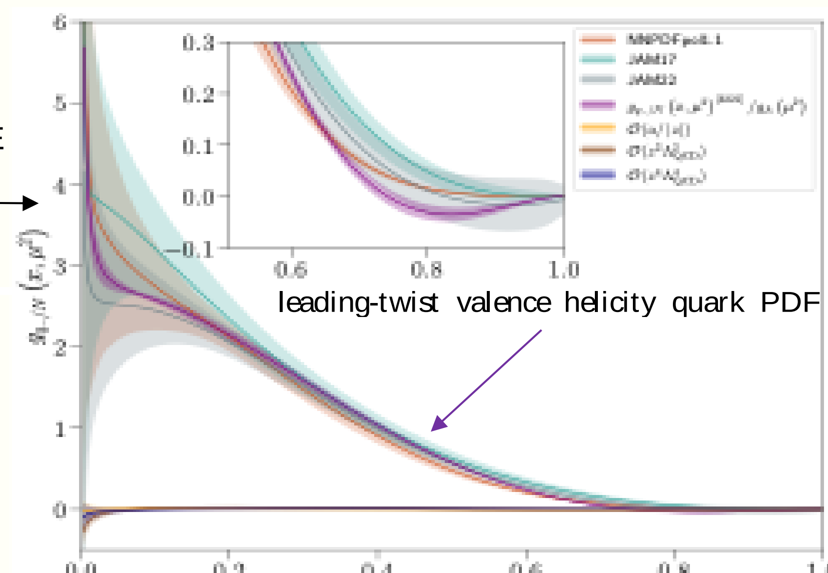
R.G. Edwards et al. JLAB-THY-22-3751 arXiv:2211.04434v1
Non-singlet quark helicity PDFs of the nucleon from pseudo-distributions

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

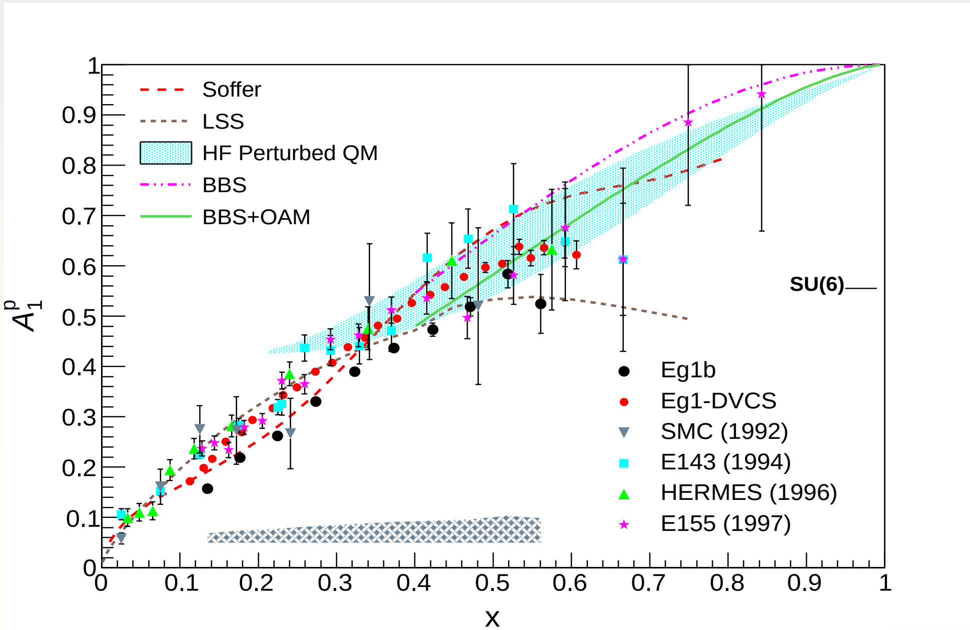


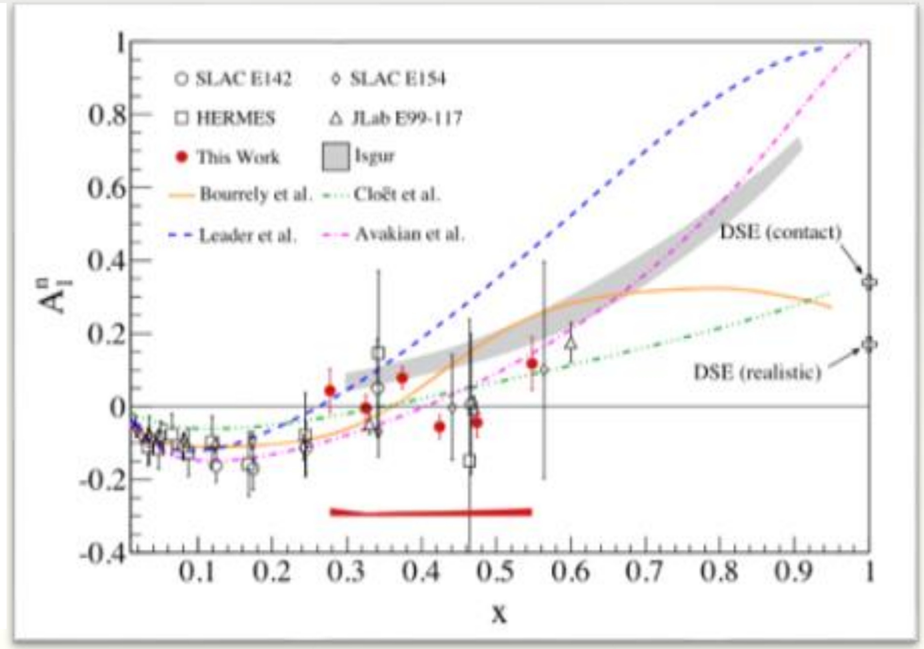


LATTICE QCD

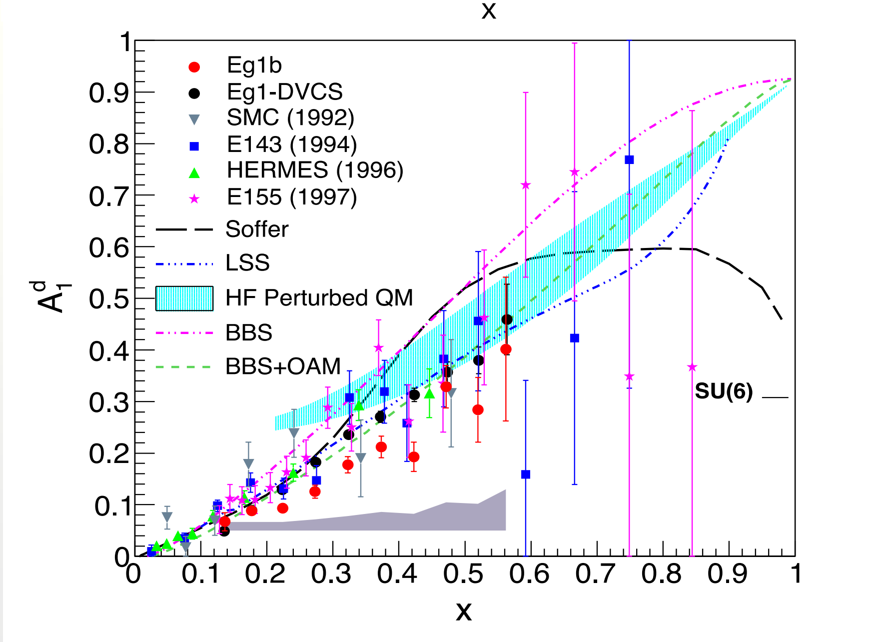


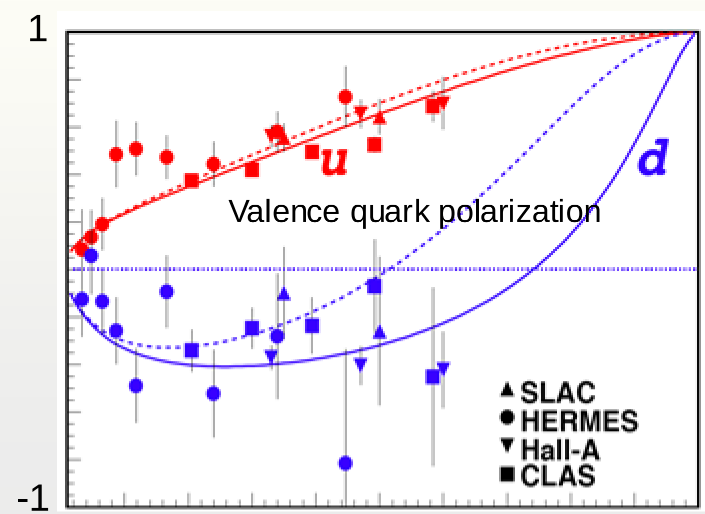
Existing Spin Structure Functions at high *x*





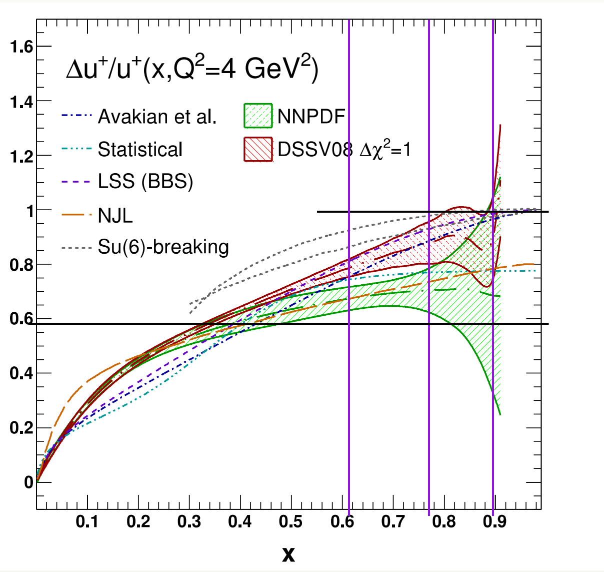
Parno et al., Phy Let B DOI: 10.1016/j.physletb.2015.03.067
X. Zheng et al., PRL 92, 012004 (2004); PRC 70, 065207 (2004)

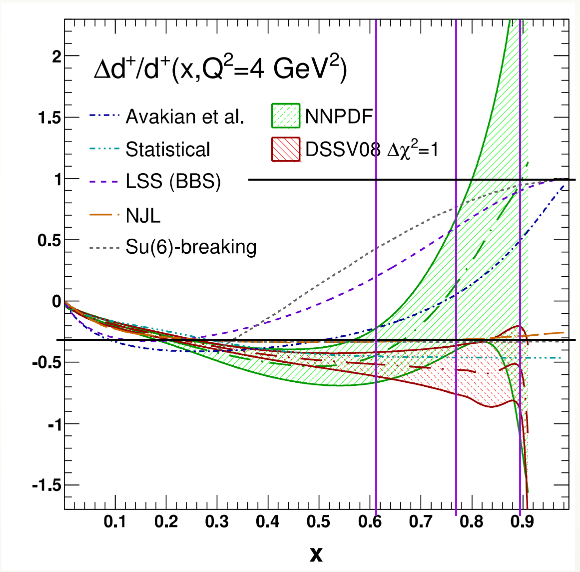




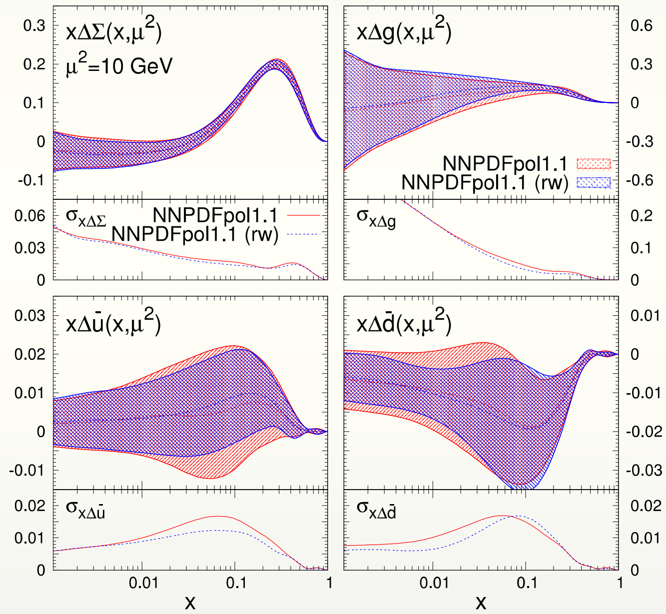
Present Status on polarized PDFs

- NNDPFpol1.1+RHIC W data analysis





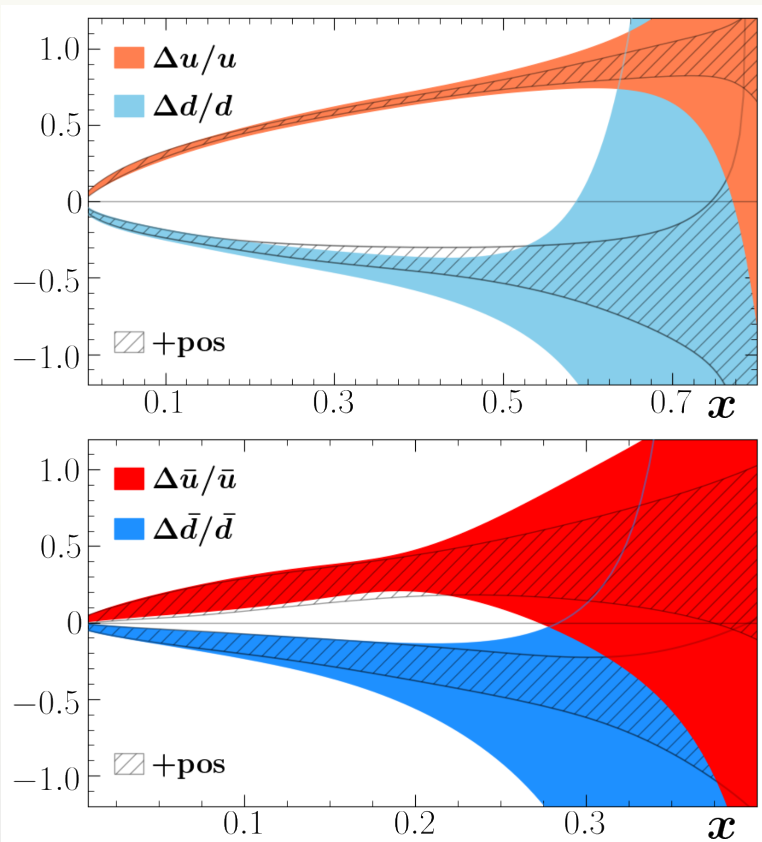
arXiv:1410.7290v2 [hep-ph] 23 Jan 2015



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

Present Status on polarized PDFs

- Newest JAM analysis including RHIC and COMPASS data



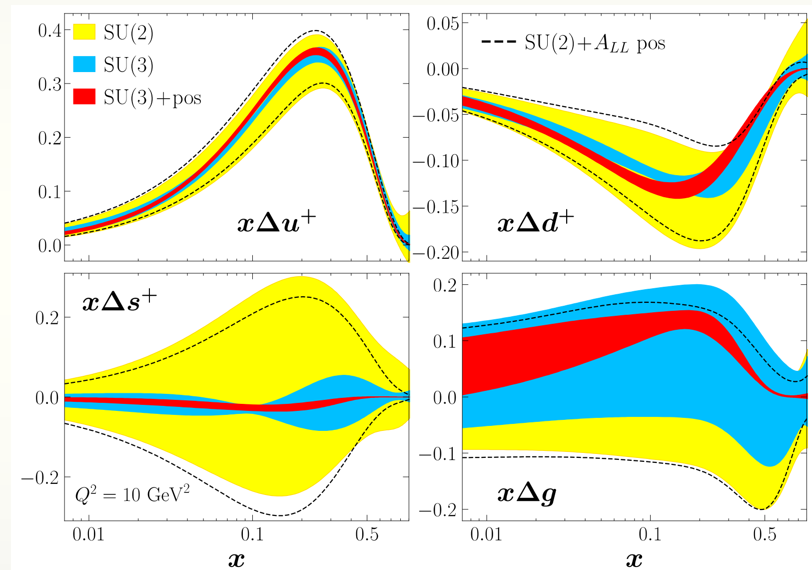


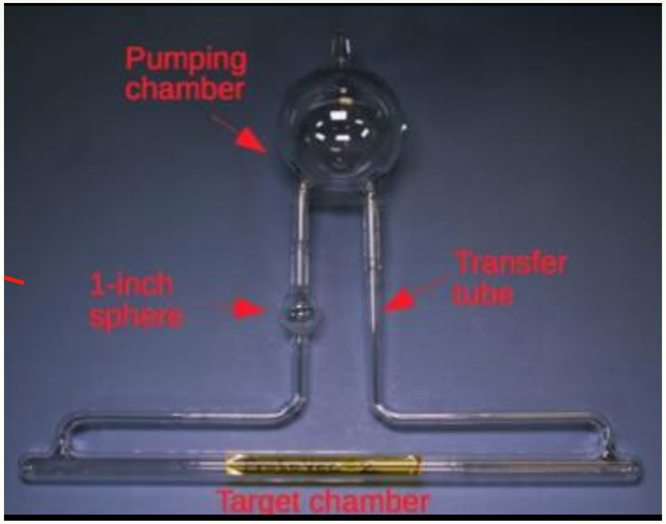
FIG. 6. Expectations values for spin-dependent Δu^+, Δd^+, Δs^+, and Δg PDFs at $Q^2 = 10$ GeV^2 fitted under various theory assumptions according to the SU(2) (yellow 1σ bands), SU(3) (blue 1σ bands) and SU(3)+positivity (red 1σ bands) scenarios, as well as with the SU(2) scenario but filtered to ensure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

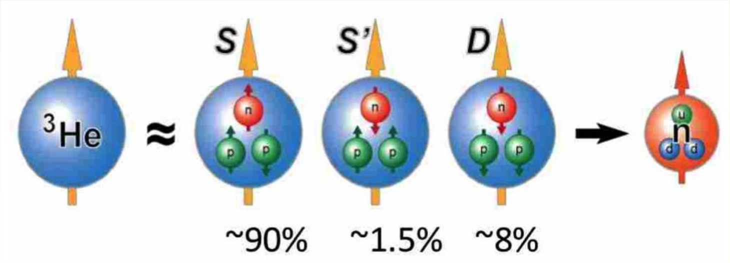
arXiv:2202.03372v1 [hep-ph] 7 Feb 2022 arXiv:2201.02075v1 [hep-ph] 6 Jan 2022

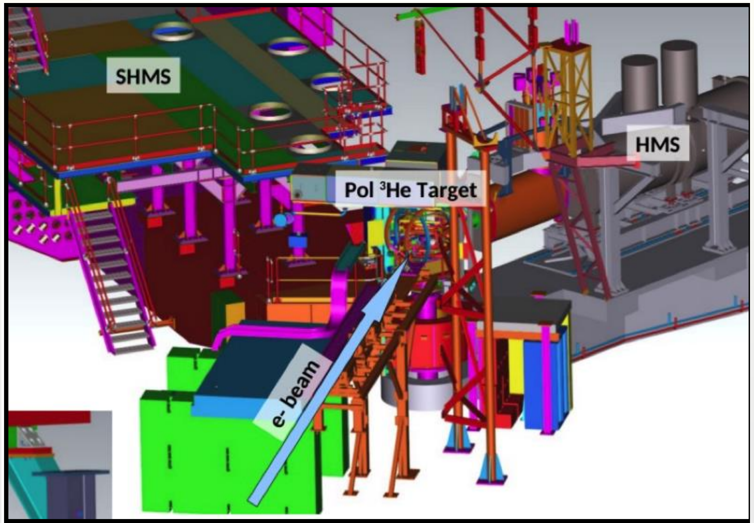
A_{1n} in Jefferson Lab's Hall C

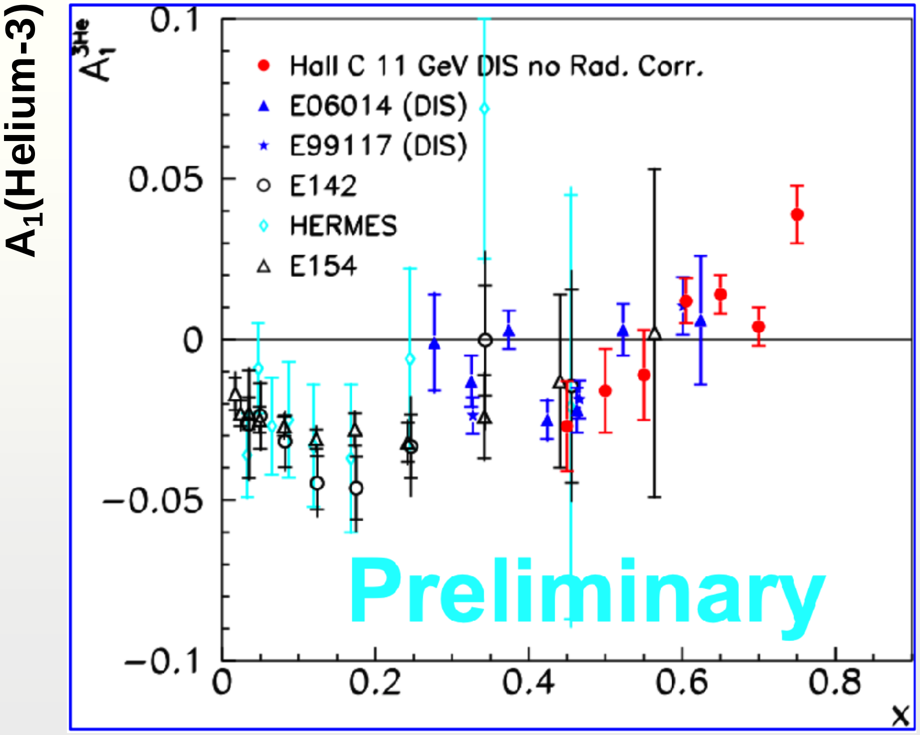
E12-06-110 in Hall C: 1/12/2020 – 3/13/2020; 10.4 GeV polarized electrons on polarized ^3He

William Henry 2022 Jefferson Lab Users Organization Annual Meeting







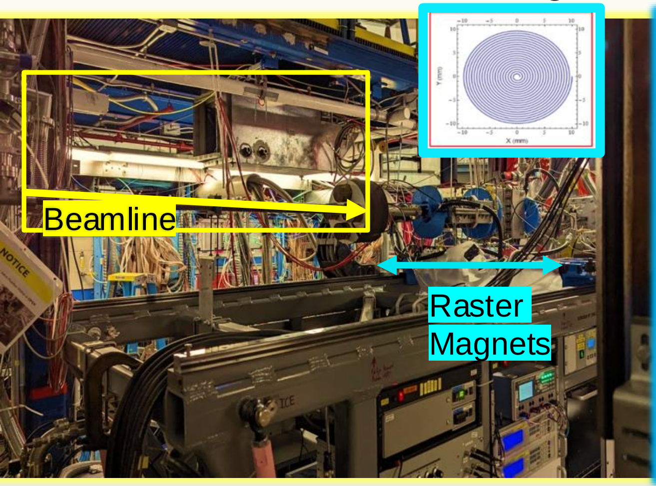


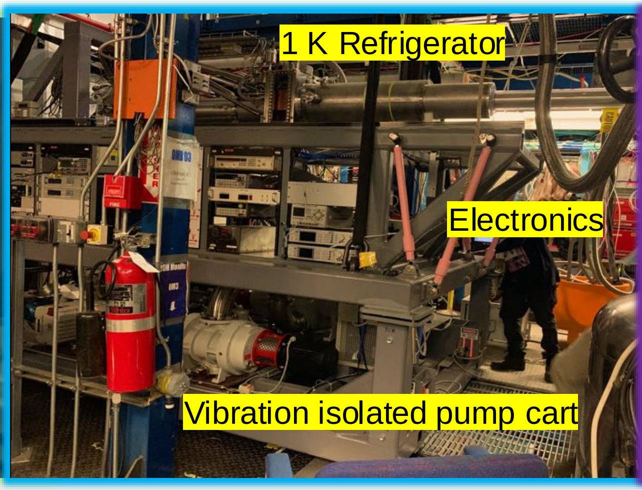
RG-C with CLAS12

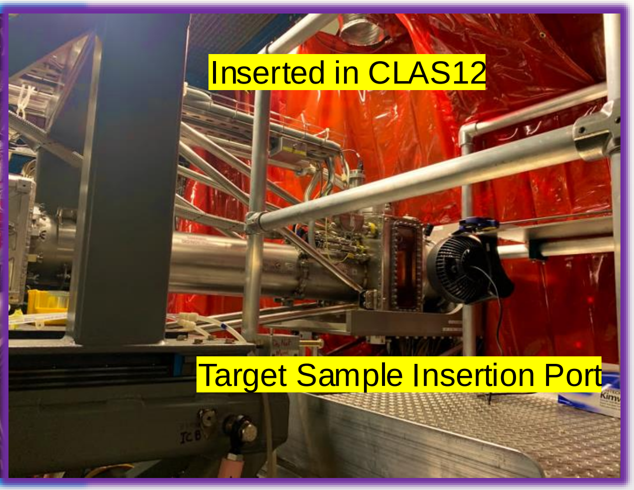
- ❑ Measure DIS inclusive spin structure functions (A_1, g_1) of the proton and deuteron.
  - ❑ Include tagging with π, K SIDIS to extract flavor-separated Δq
- ❑ Measure spin- and transverse momentum-dependent (TMD) PDFs, back-to-back hadrons, forward dihadrons,... (SIDIS).
- ❑ Deeply Virtual Compton 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) – collected data for about 2/3 of this
- 10.6 GeV, 10 nA polarized electrons on 3 g/cm^2 polarized NH_3 / ND_3 ($L = 10^{35}$)
- Dynamic Nuclear Polarization at 1 K, 5 T with 140 GHz μwave on irradiated ammonia

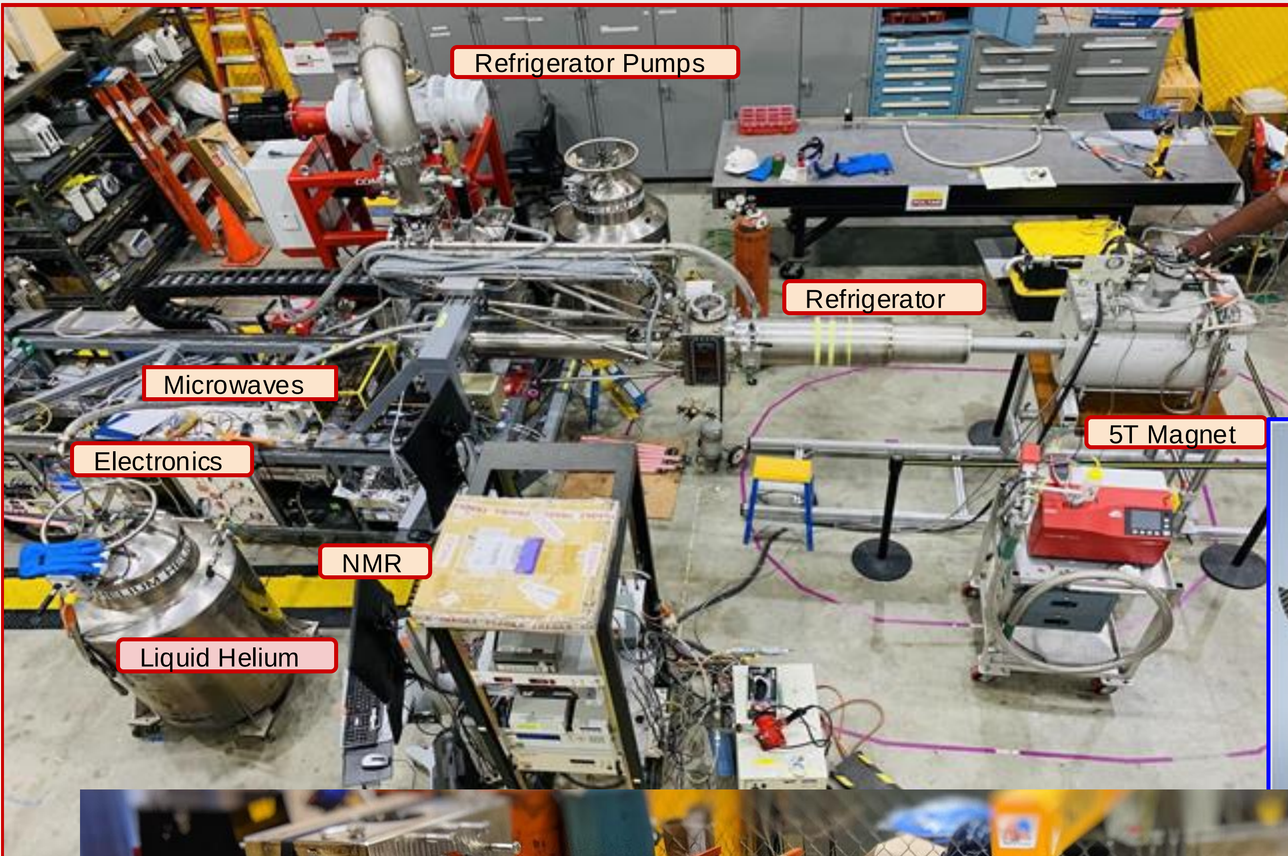
Polarized target “APOLLO”

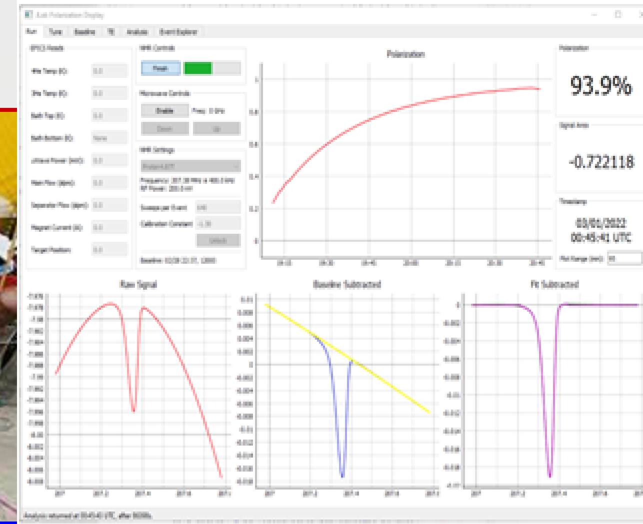


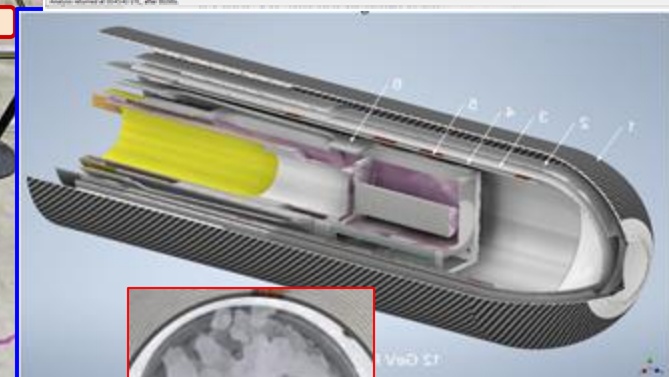




Longitudinally Polarized Target for CLAS12







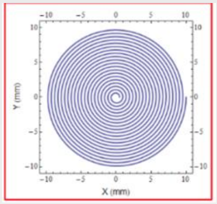
Jefferson Lab

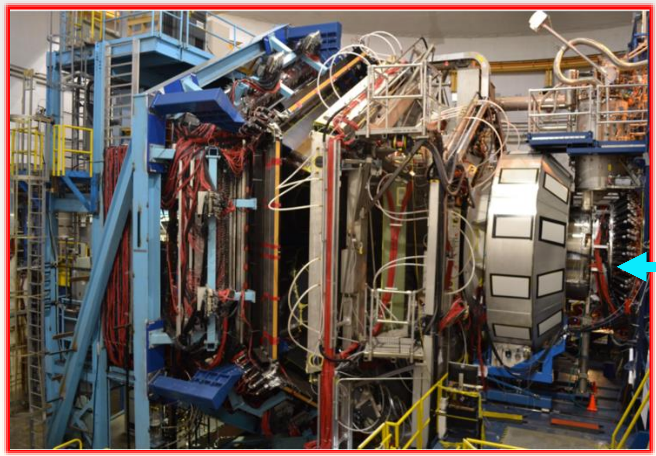
OLD DOMINION UNIVERSITY

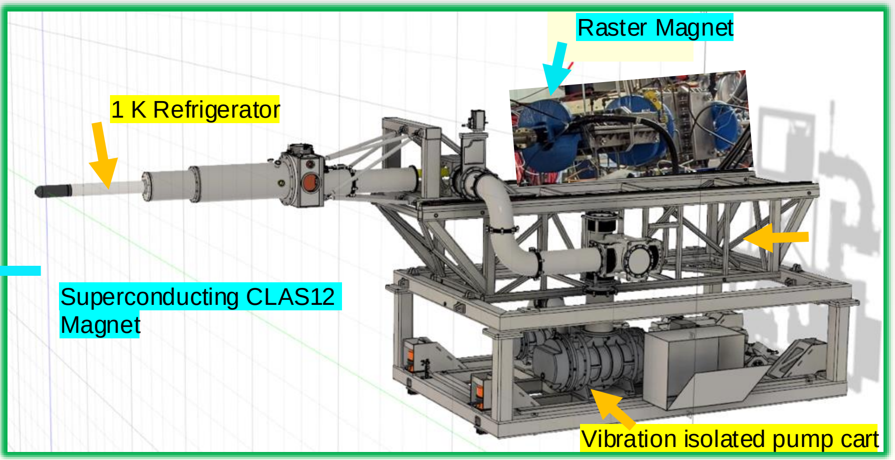
UNIVERSITY of VIRGINIA

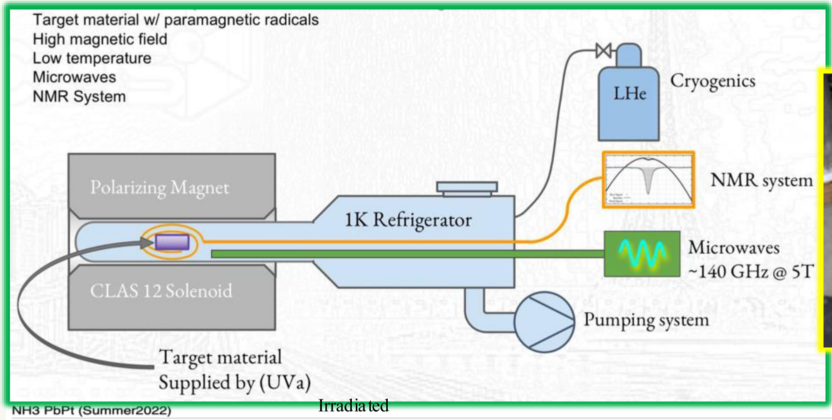
CHRISTOPHER NEWPORT UNIVERSITY

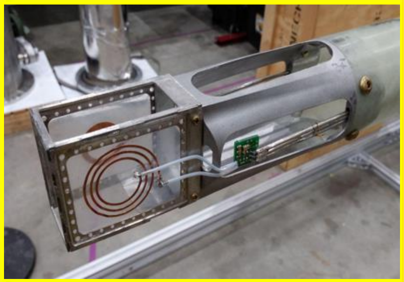
More on "APolLo"

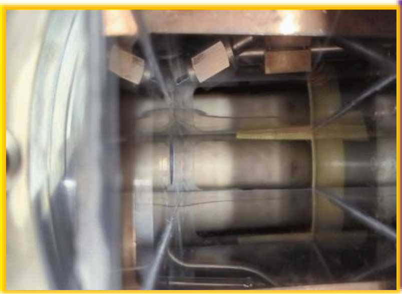


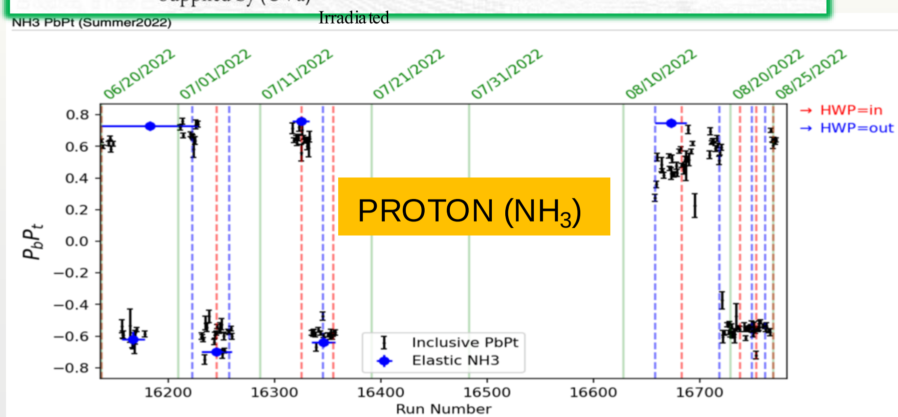


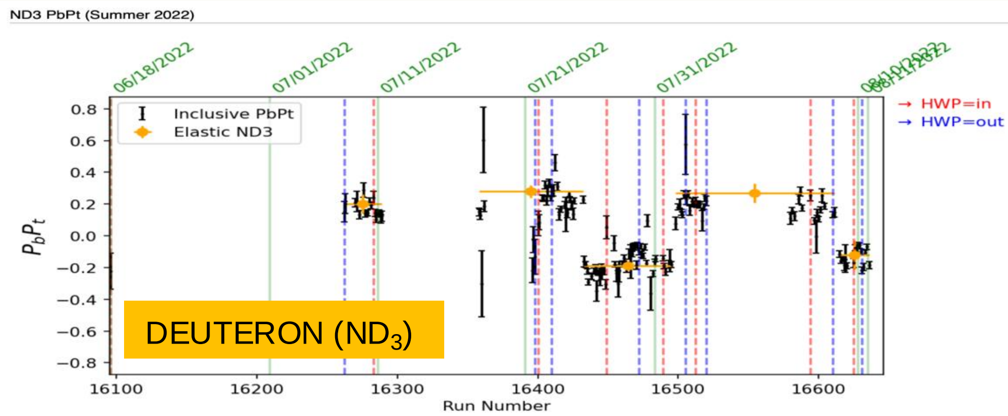










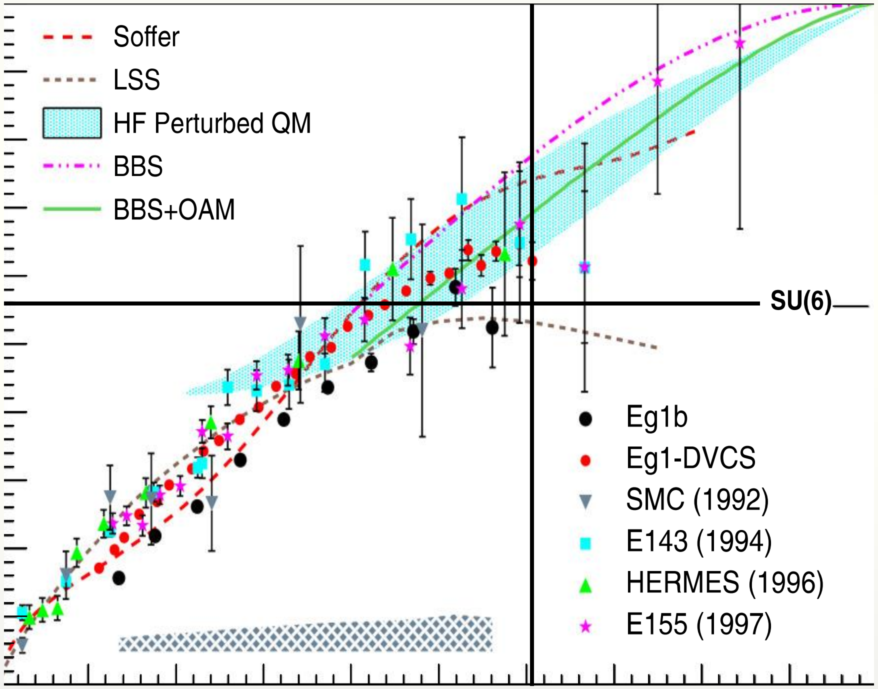


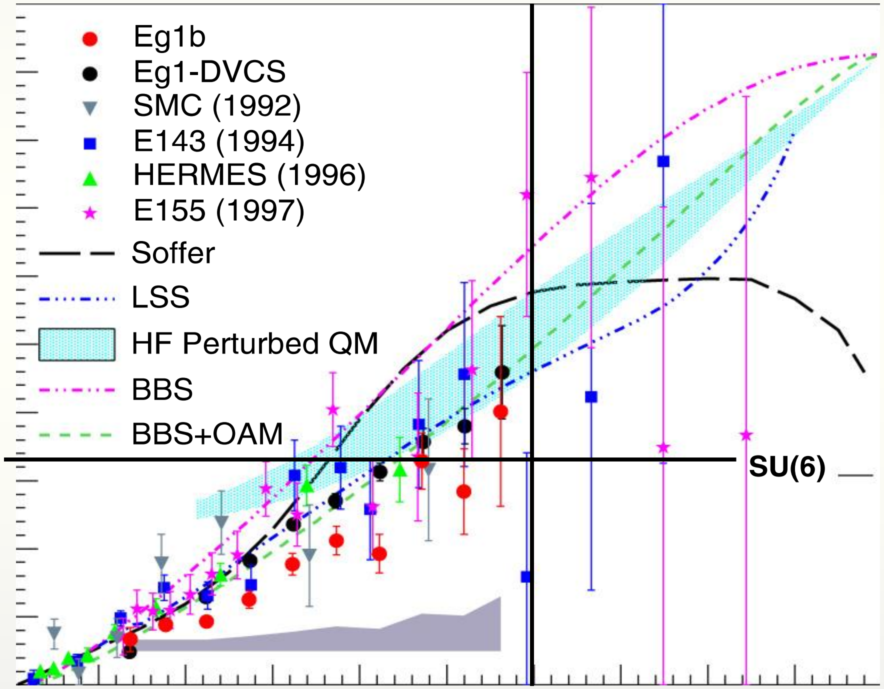
Preliminary Data from CLAS12 RG-C - DIS

Proton

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

Deuteron



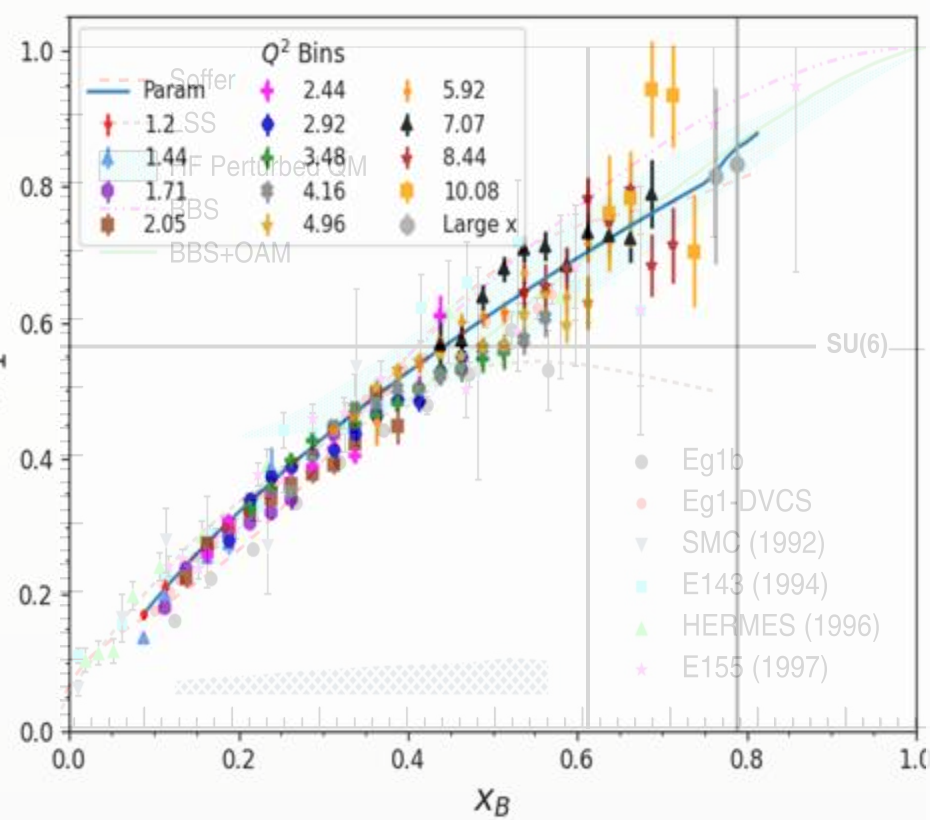


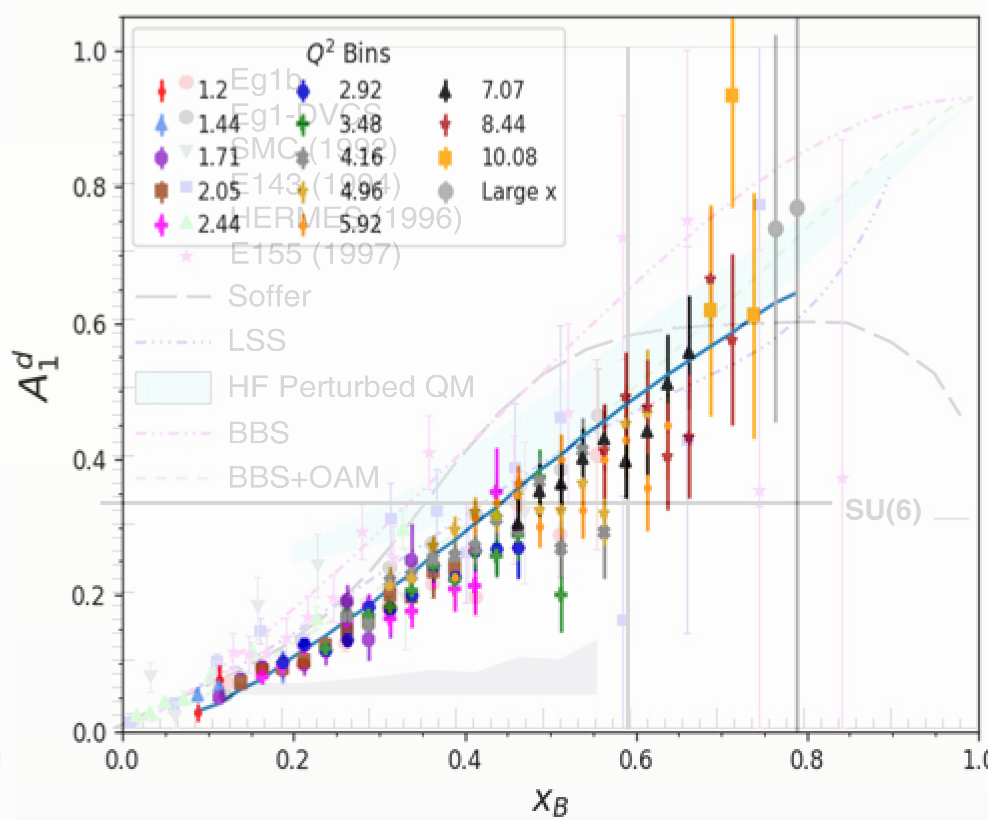
Preliminary Data from CLAS12 RG-C - DIS

Proton

W > 2; Q^2 > 1

Deuteron



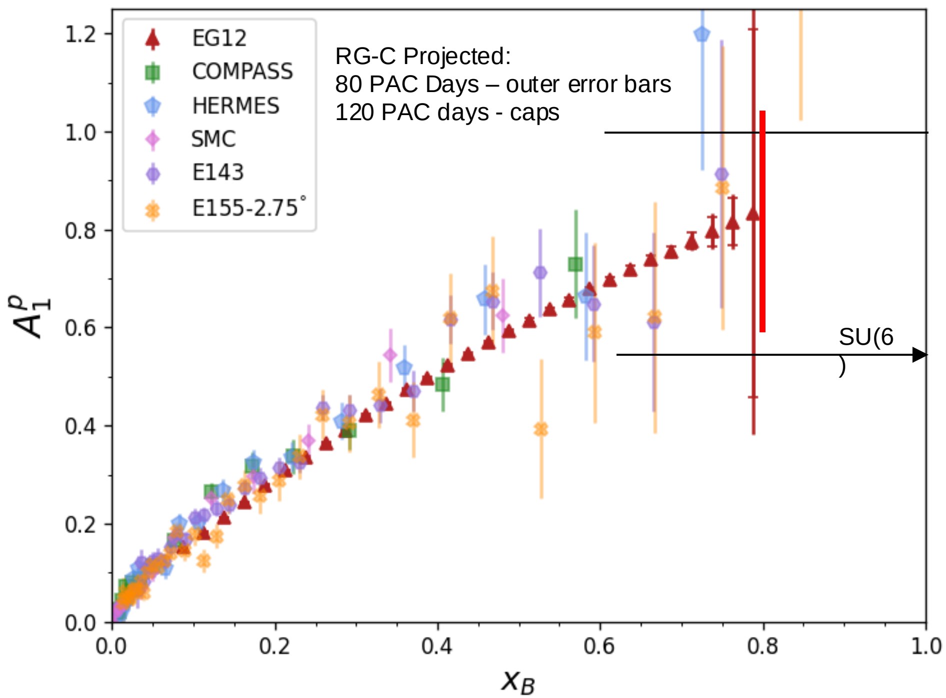


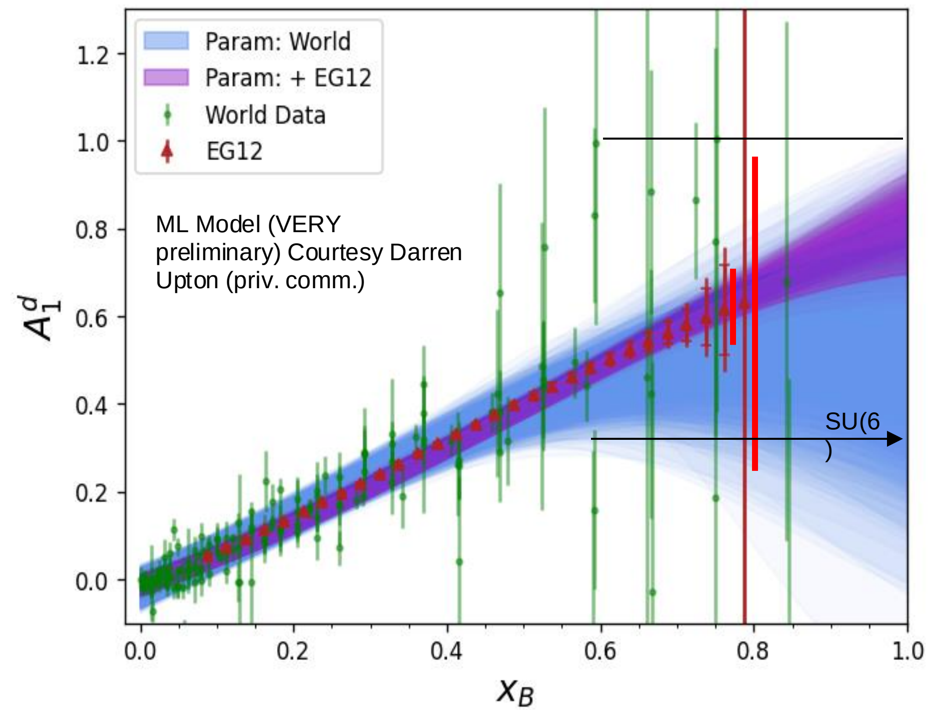
Preliminary Data from CLAS12 RG-C - DIS

Proton

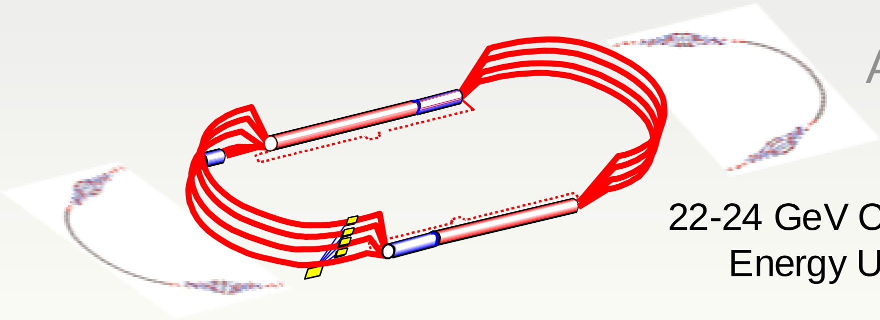
W > 2; Q^2 > 1

Deuteron





Future: JLab at 20+ GeV?



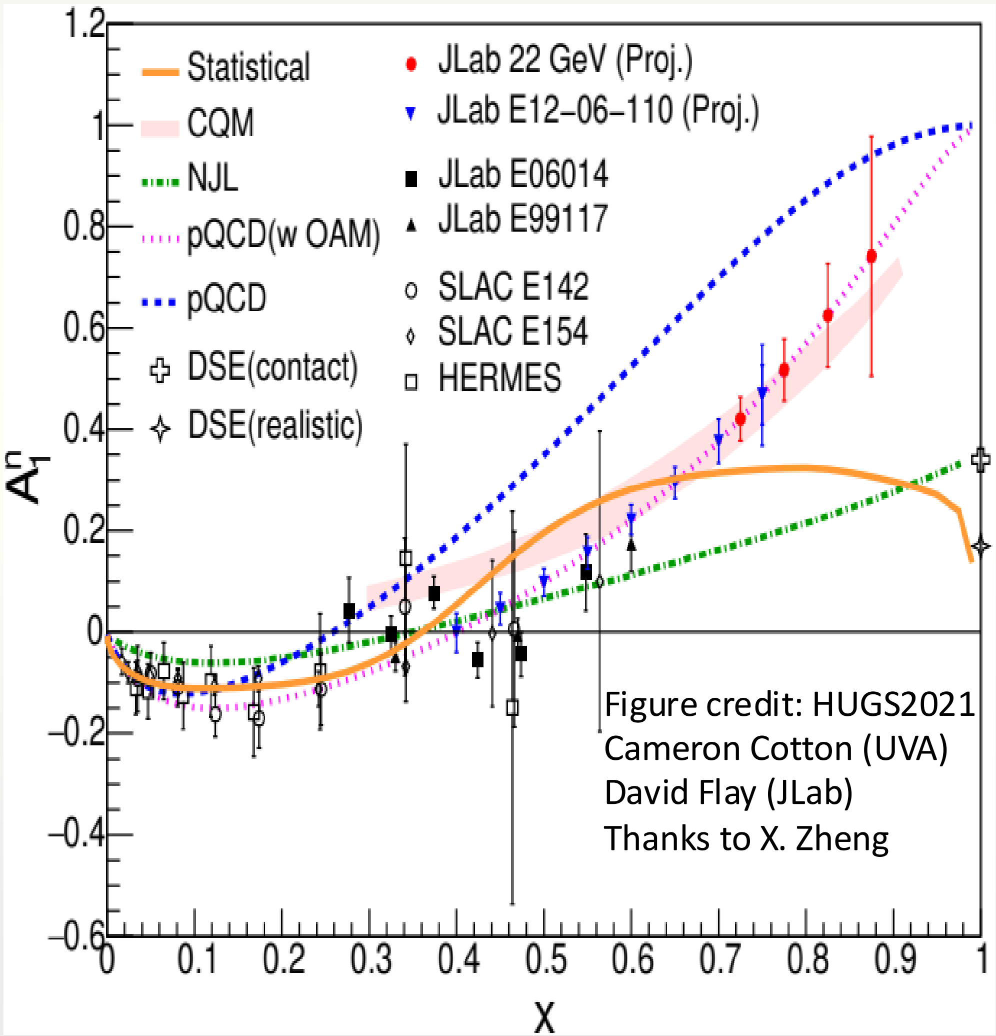
Alex Bogacz J-FUTURE Workshop
Jefferson Lab / Messina University

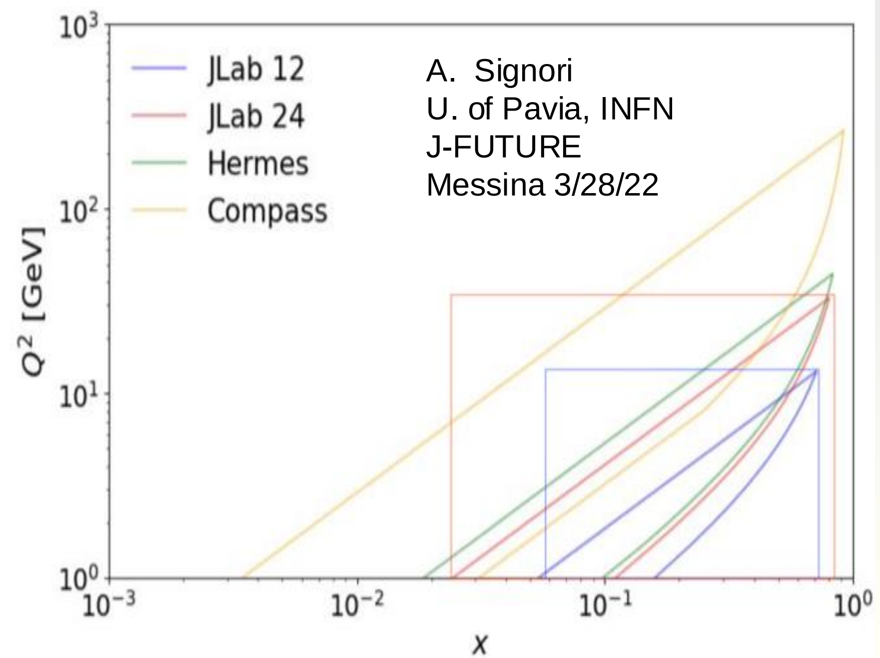
22-24 GeV CEBAF FFA
Energy Upgrade

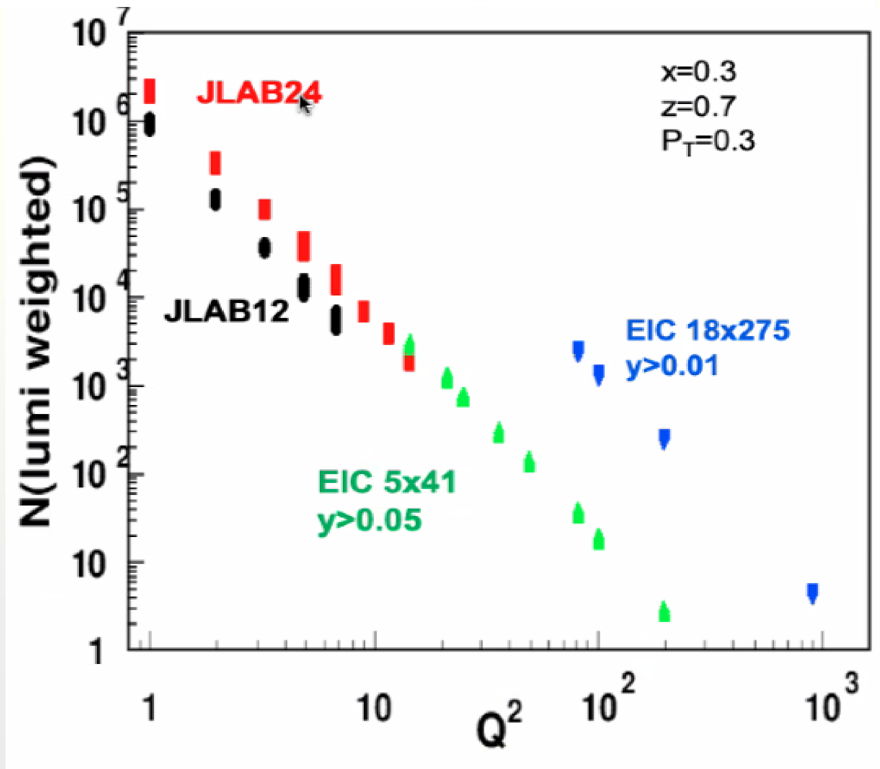
- Halve distance to $x = 1$, higher Q^2: Definite determination of asymptotic limit… *)
- …AND to $x = 0$ => Study "valence" sea quarks (pion cloud)
- Increase Q^2 range for all x -> DGLAP => Study "valence" gluon helicity
- Even for same x, Q^2: higher energy -> higher rates -> better statistics
- *(Super)Rosenbluth* – 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

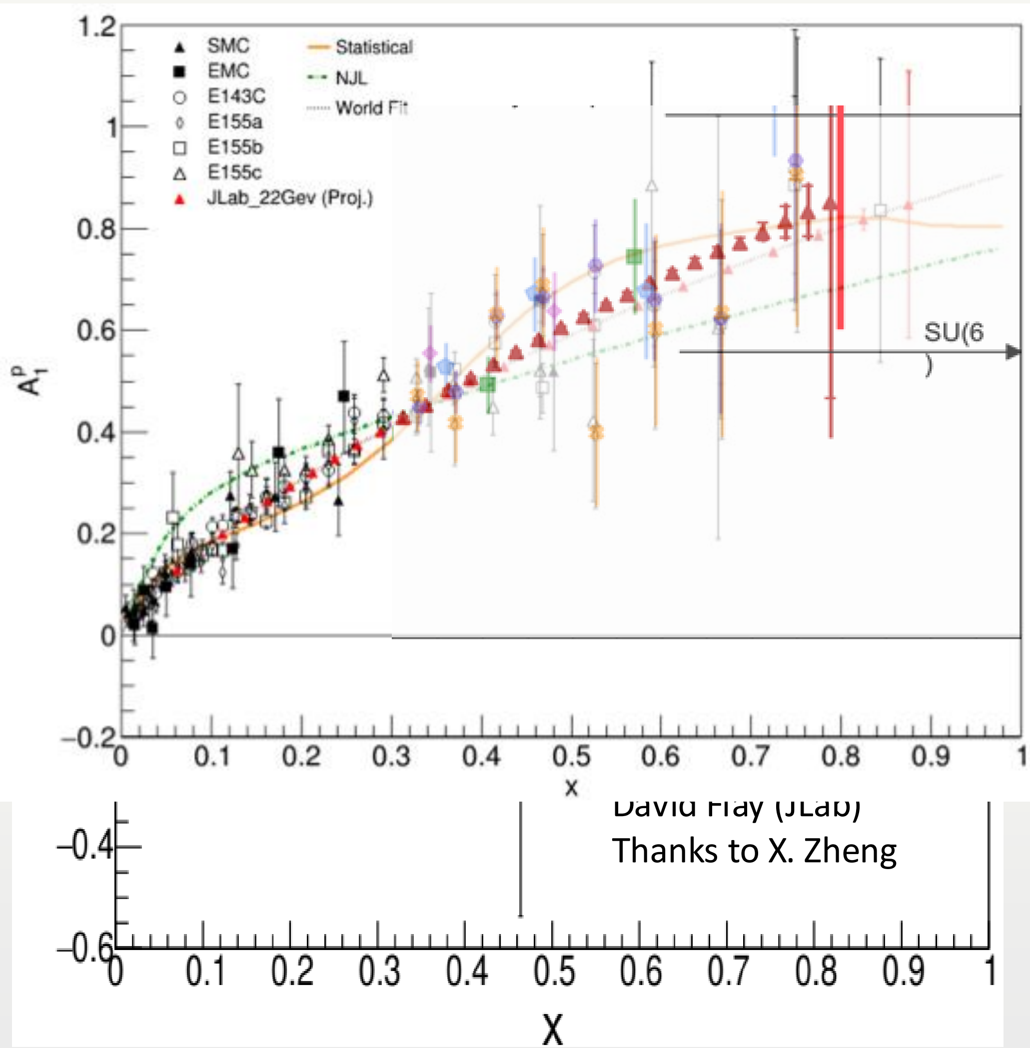
From JLab at 12 to 22 GeV… and to the EIC

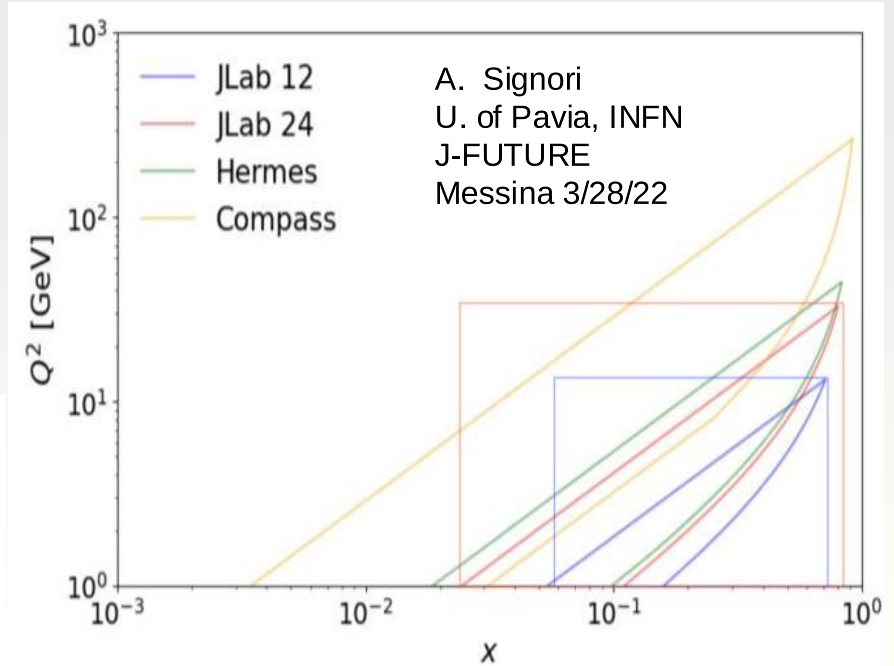


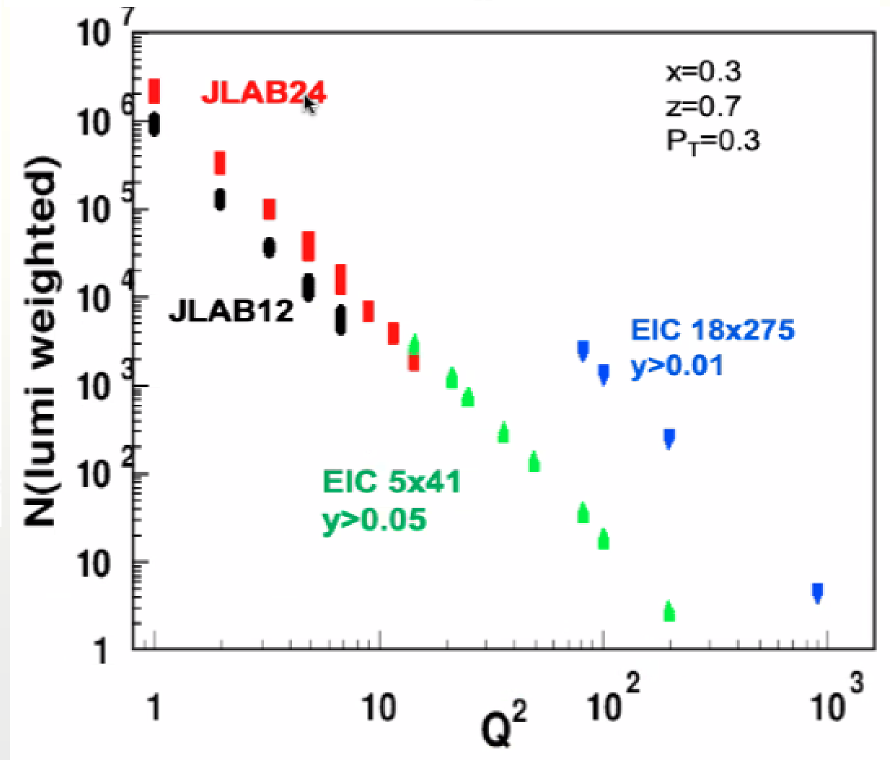




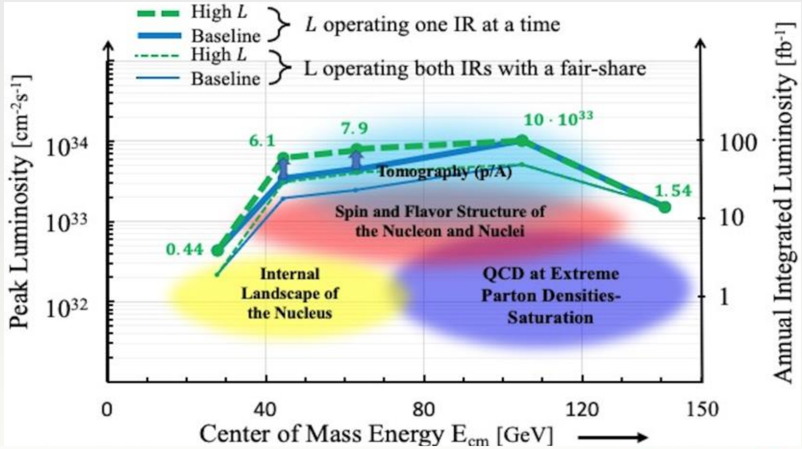
From JLab at 12 to 22 GeV… and to the EIC

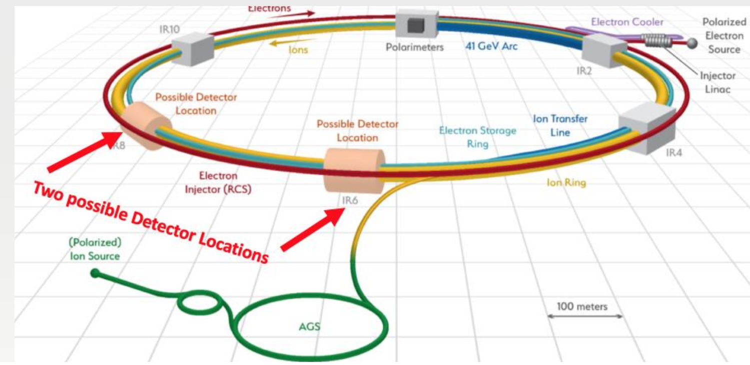


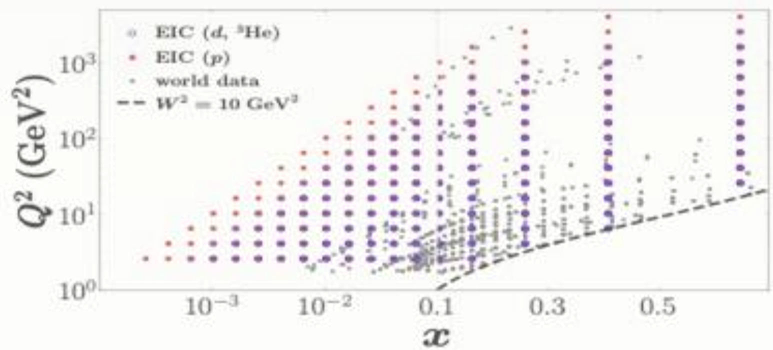




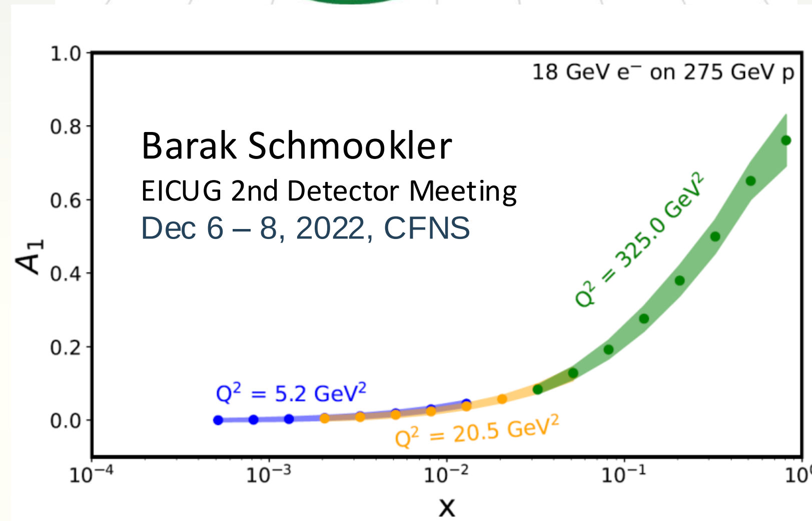
EIC



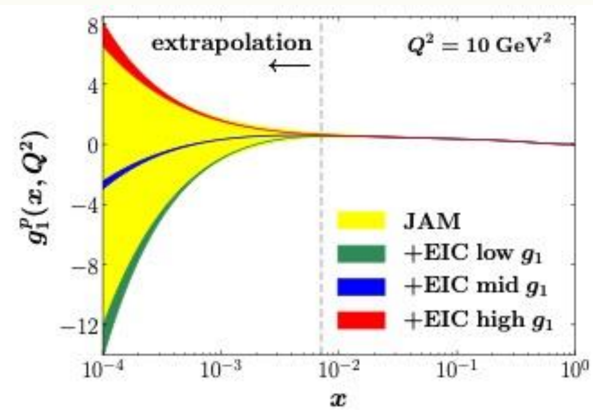




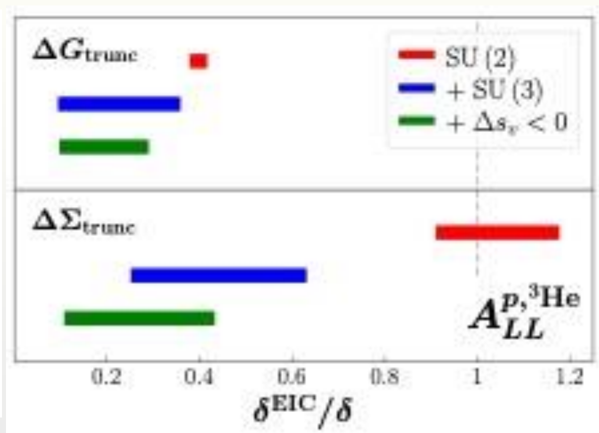
Y. Zhou et al., Phys. Rev. D **104**(2021)034028 arXiv:2105.04434v1



Expected reduction of present SSF uncertainties from EIC



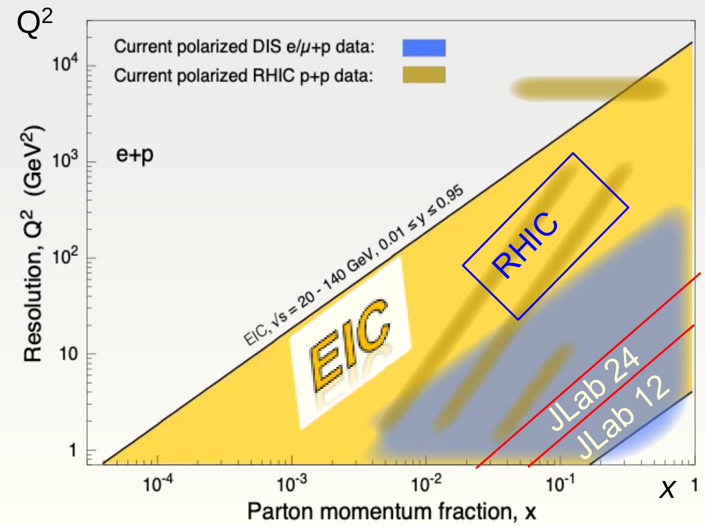
Inclusive p A_{LL}, enforce SU(3)



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* ?**
- **Nuclear effects on nucleon structure**

JLab @ 12 -> 22 GeV

- **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 22 GeV can expand the coverage in *x* from 0.8 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.

Backup Slides

More on Nuclear Corrections

HAGUE, ARRINGTON, LI, AND SANTIESTEBAN
PHYSICAL REVIEW C 110, L041302 (2024)

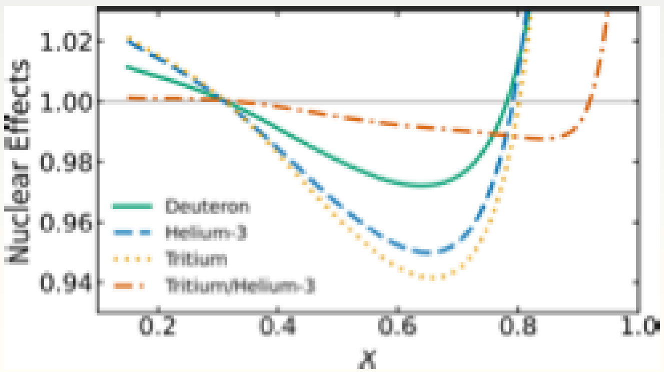


FIG. 1. The nuclear effects, $F_{2A}/(ZF_{2p}+NF_{2n})$, from the KP model [11] for ^{2}H (solid line), ^{3}He (dashed), ^{3}H (dotted), and the correction $\mathcal{R}_{th}$ (dash-dotted). The corrections to the h/t extraction are smaller than for the d/p case, and the larger effects and rapid x dependence occur at larger x values.

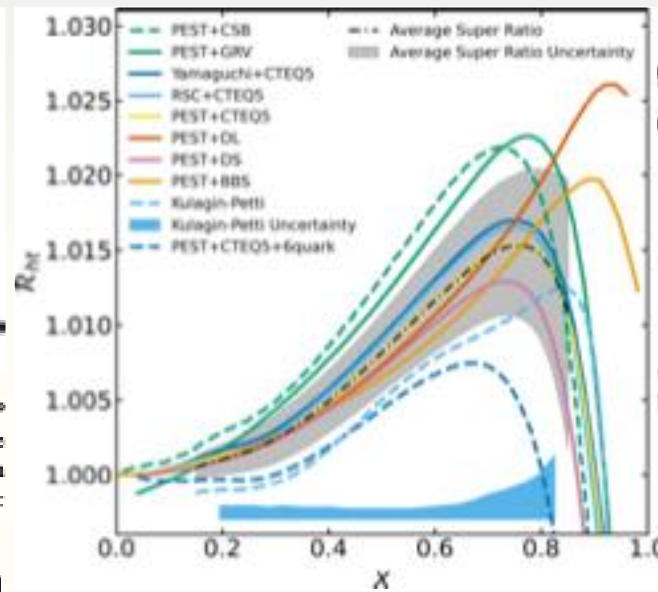


FIG. 2. Selected calculations of $\mathcal{R}_{ht}$ from Ref. [7] alongside the KP model [10,11] that was used by the MARATHON experiment. Also shown is the average of all plotted models with a 1σ-rms band with a dash-dotted line. Models that include effects beyond smearing and off-shell effects are shown with dashed lines. The legend is ordered by descending values of the model evaluated at $x = 0.6$. The blue band shows the uncertainty from the KP model used in Ref. [9].

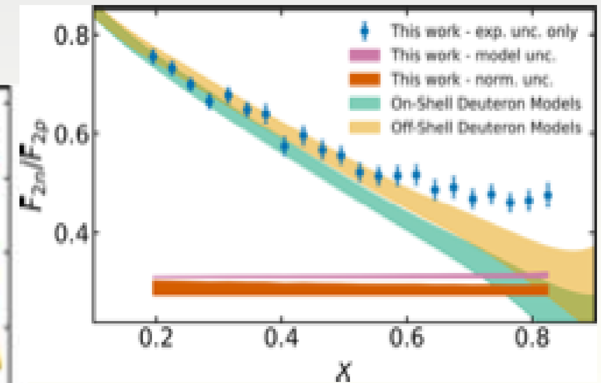


FIG. 4. Comparison of this work (circles) and F_{2n}/F_{2p} extractions from d/p measurements with (top band) and without (bottom band) the inclusion of off-shell effects [5].

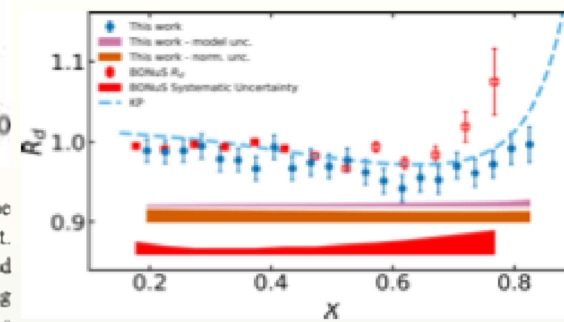


FIG. 5. R_d extracted from the comparison of F_{2n}/F_{2p} from the h/t measurement discussed here and a compilation of world d/p measurements [1]. Filled points indicate kinematics with large invariant mass ($W^2 > 3$ GeV^2), for which we expect to see behavior consistent with DIS [23].

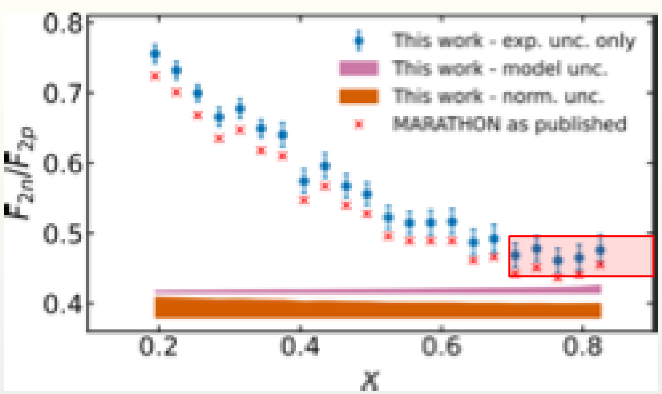


FIG. 3. F_{2n}/F_{2p} from this analysis, compared to the original extraction [9]. The error bars include statistical and point-to-point systematic uncertainties. The model uncertainty is the impact of the 1σ uncertainty on $\mathcal{R}_{ht}$ and the normalization band shows the correlated shift associated with the 1.25% normalization uncertainty in F_{2n}/F_{2p}.

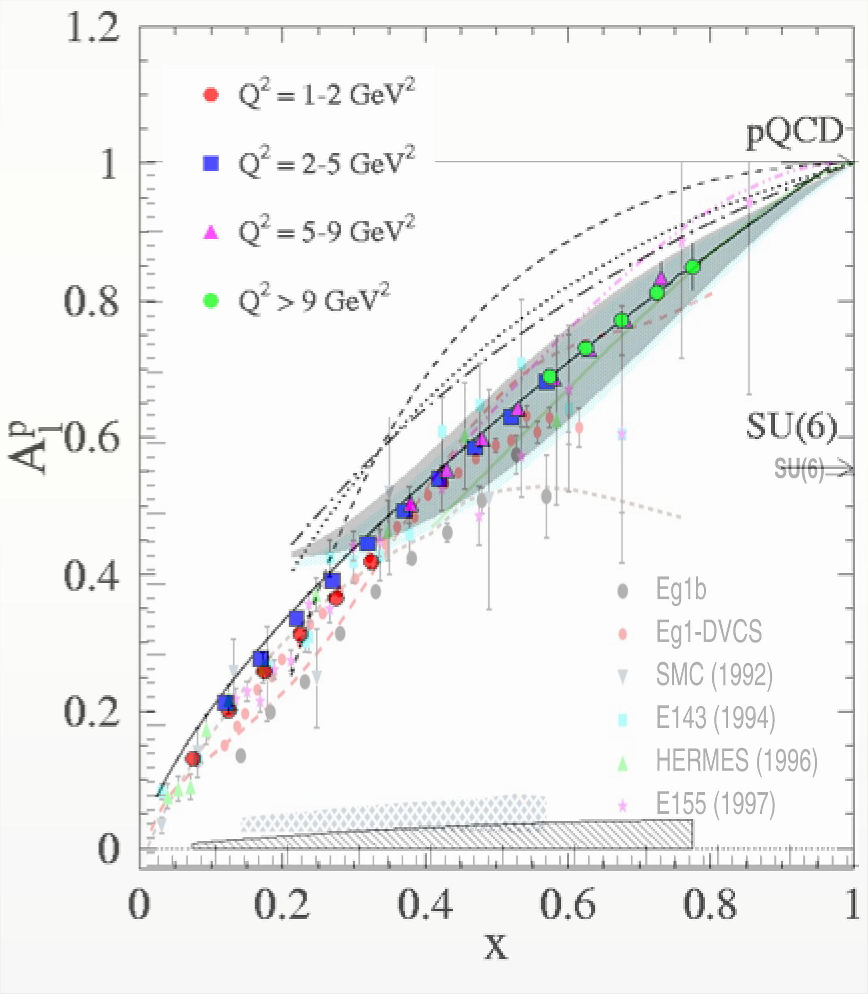
a) Marathon points have normalization uncertainty up 0.02.
b) Last Marathon point gets significant contributions from smeared SF in the resonance and even elastic region, as well as much lower x
c) In general, Marathon data are all Fermi-smeared (Contributions from x* = x/(1±0.15).)
d) Nuclear Modifications are partially additive; no reason to assume that they affect p and n the same (isospin-dependence).

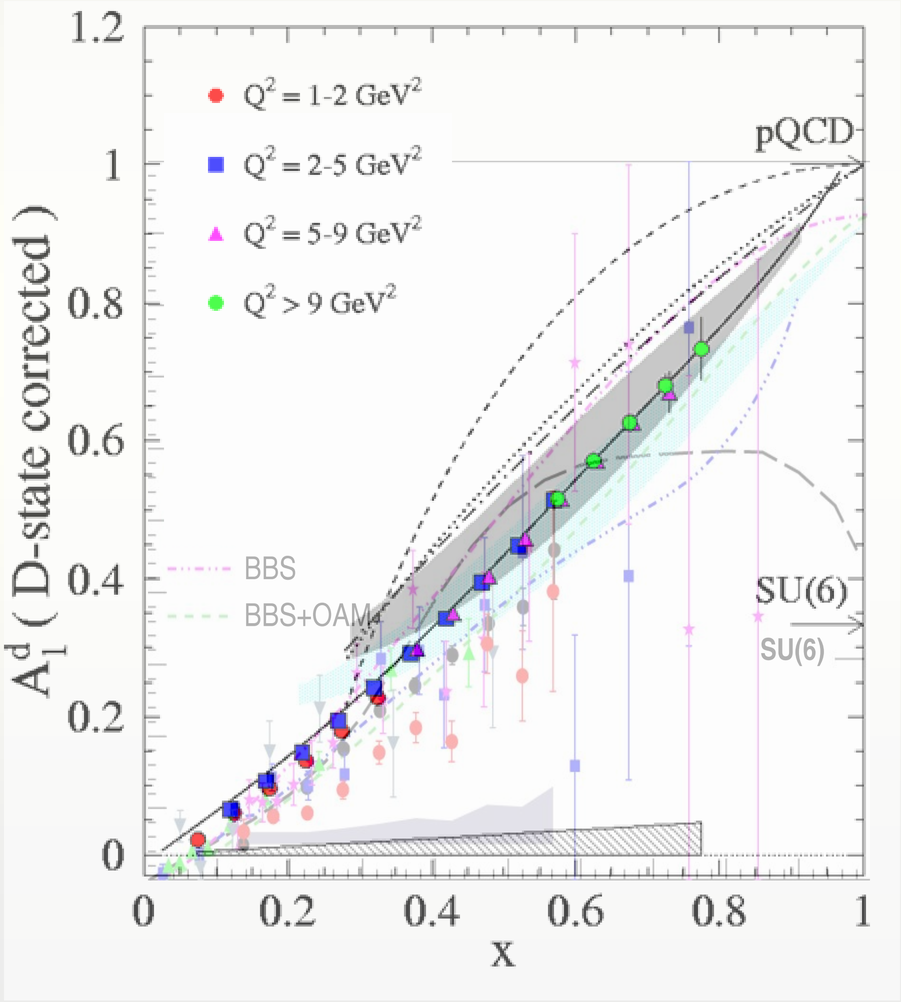
Predicted Data from CLAS12 - DIS

Proton

W > 2; Q^2 > 1

Deuteron





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)

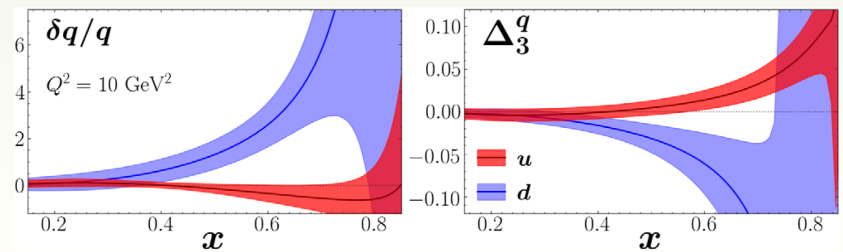
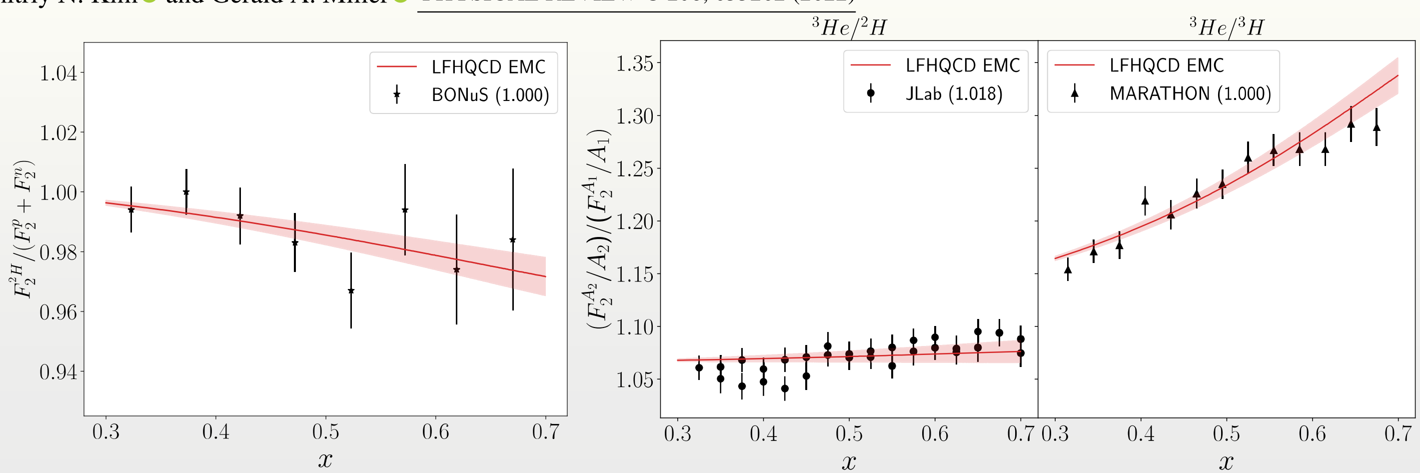
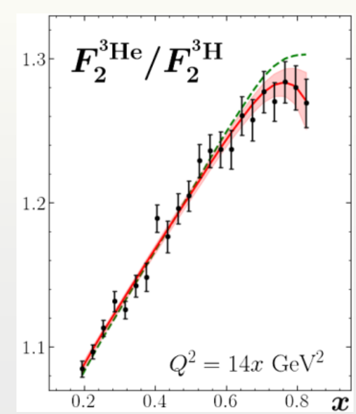


FIG. 3. Ratio of off-shell to on-shell PDFs $\delta q/q$ (left) and the difference between proton valence quarks in ^{3}He and ^{3}H normalized to the sum, Δ_3^q (right), for valence u (red bands) and d (blue bands) quarks, at $Q^2 = 10$ GeV^2.

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

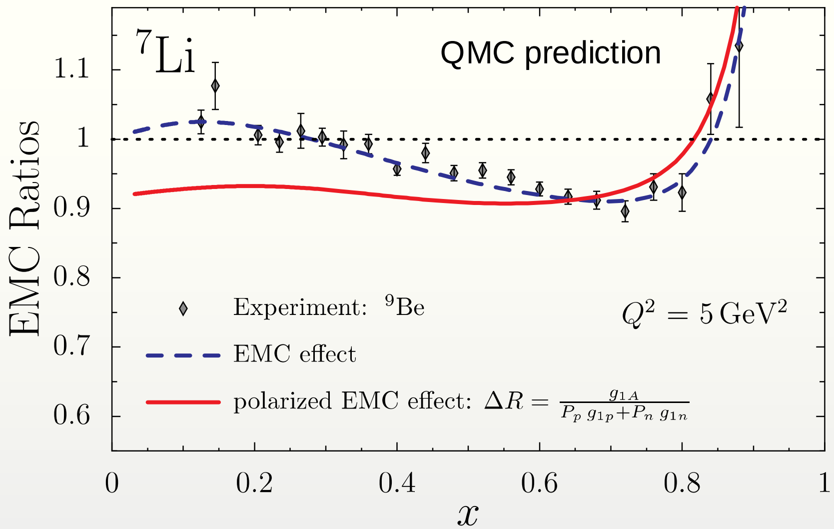




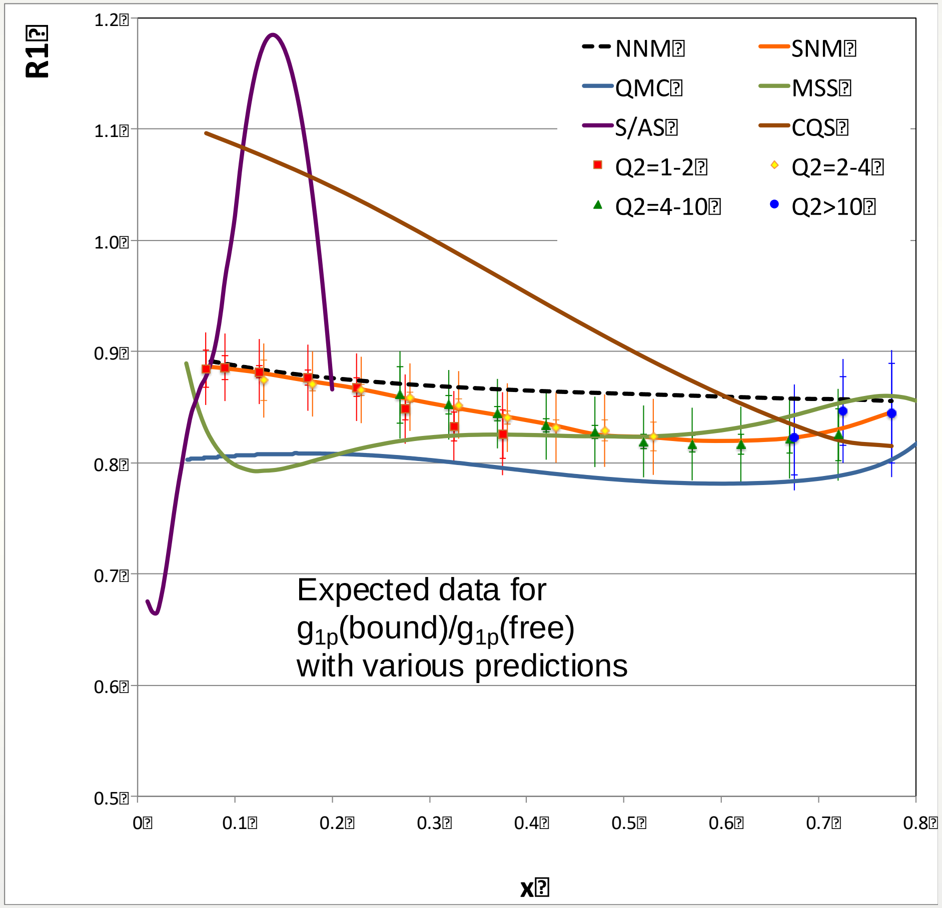
Polarized EMC effect

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

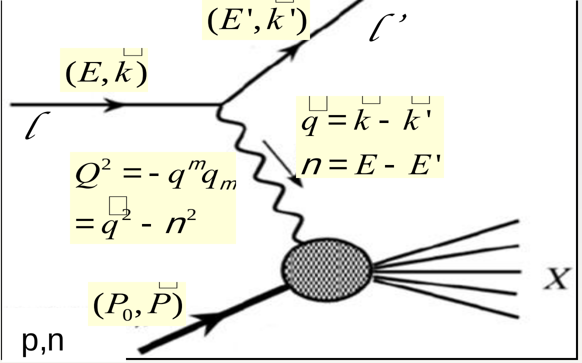
- A large number of experiments is studying modifications of bound nucleon structure function F_2 on a wide range of nuclei – data average over ALL nucleons!
- Unique test of EMC models: Measure modification of **polarized** structure function g_{1p} on a single valence nucleon!



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



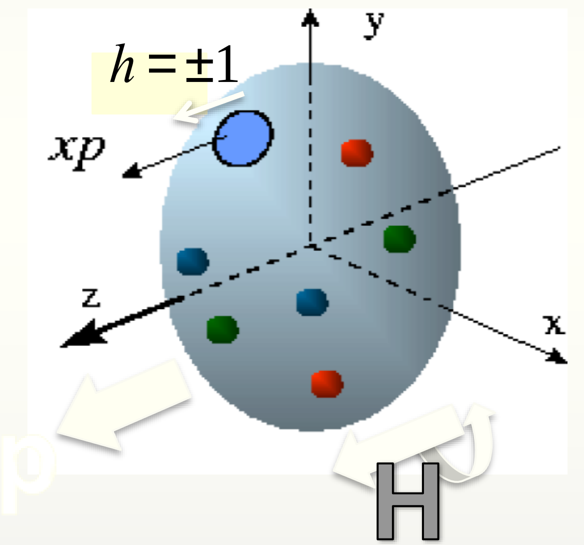
Inclusive lepton scattering

Callan-Gross

Wandzura-Wilczek

Parton model: DIS can access $F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x)$ $\left(\text{and } F_2(x) \approx 2xF_1(x)\right)$

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x) \quad \left(\text{and } g_2(x) \approx -g_1(x) + \int_x^1 \frac{g_1(y)}{y}dy\right)$$



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

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

At finite Q²: pQCD evolution ($q(x,Q^2)$, $\Delta q(x,Q^2)$ ⇒ DGLAP equations), and gluon radiation

$$g_1(x,Q^2)_{pQCD} = \frac{1}{2}\sum_q^{N_f} e_q^2[(\Delta q + \Delta\bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \otimes \frac{\delta C_G}{N_f}]$$

⇒ access to gluons. $\delta C_q, \delta C_G$ – *Wilson* coefficient functions

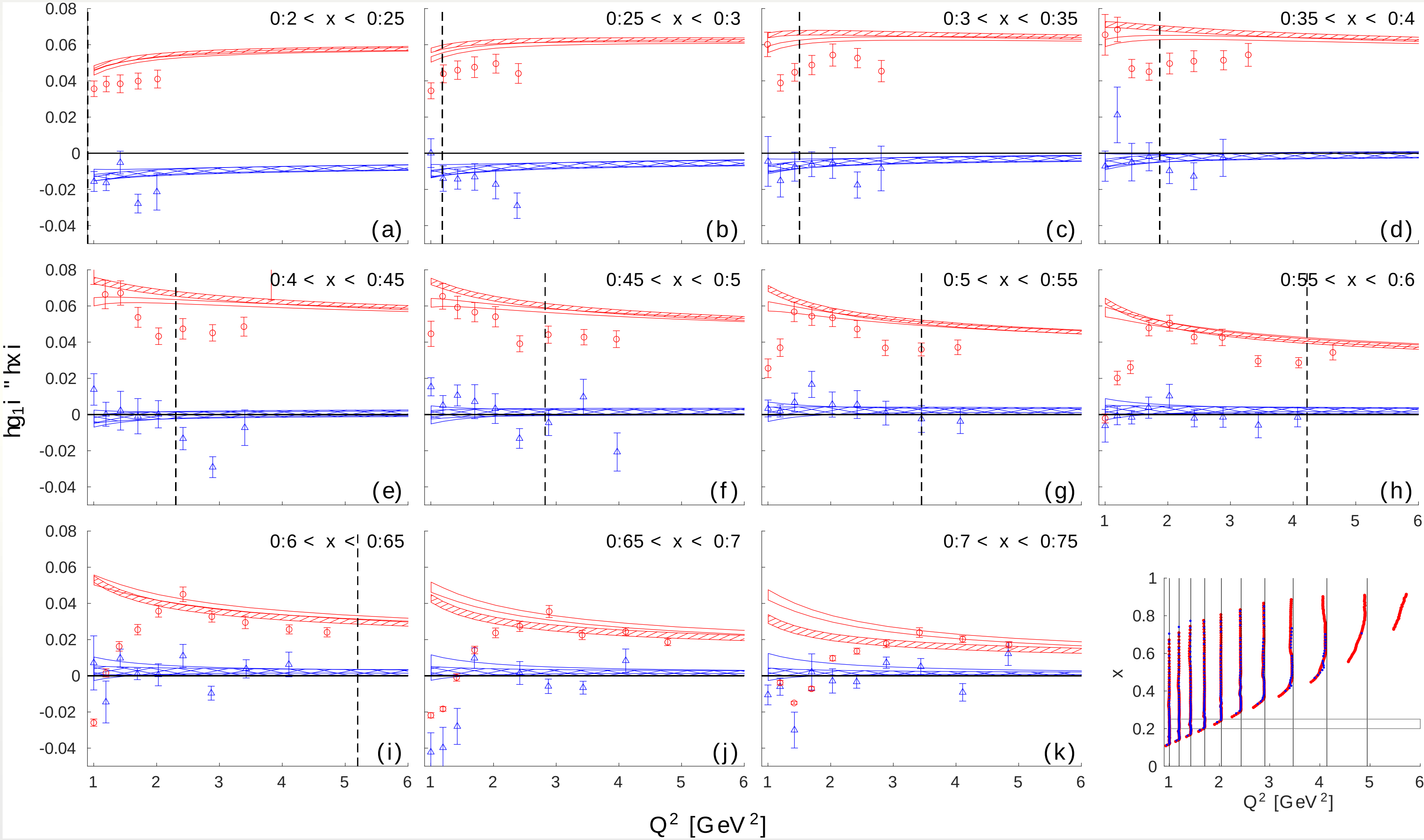
SIDIS: Tag the flavor of the struck quark with the leading FS hadron ⇒ separate $q_i(x,Q^2)$, $\Delta q_i(x,Q^2)$

Fixed target kinematics: $Q^2 \approx M^2$ ⇒ target mass effects, higher twist contributions and resonance excitations

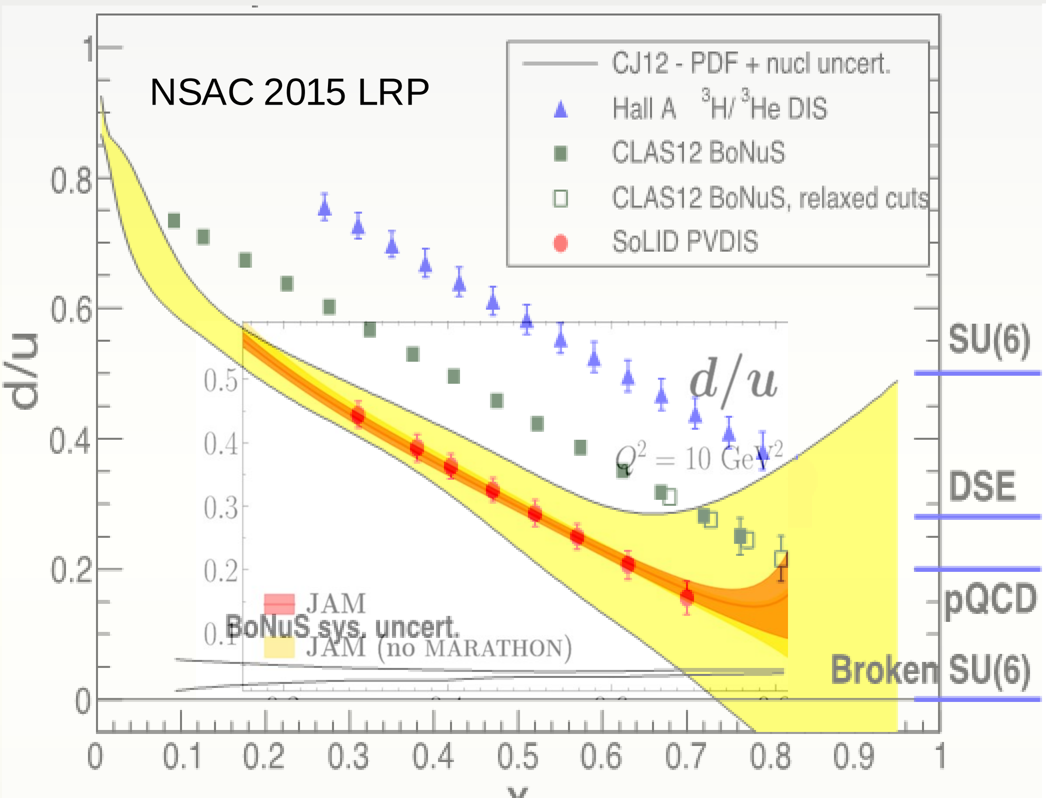
- Non-zero $R = \frac{F_2}{2xF_1}\left(\frac{4M^2x^2}{Q^2}+1\right) - 1$, $g_2^{HT}(x) = g_2(x) - g_2^{WW}(x)$
- Further Q^2-dependence (power series in $\frac{1}{Q^n}$)
- Ultra-low Q²: χPT, EFT,…

Duality?

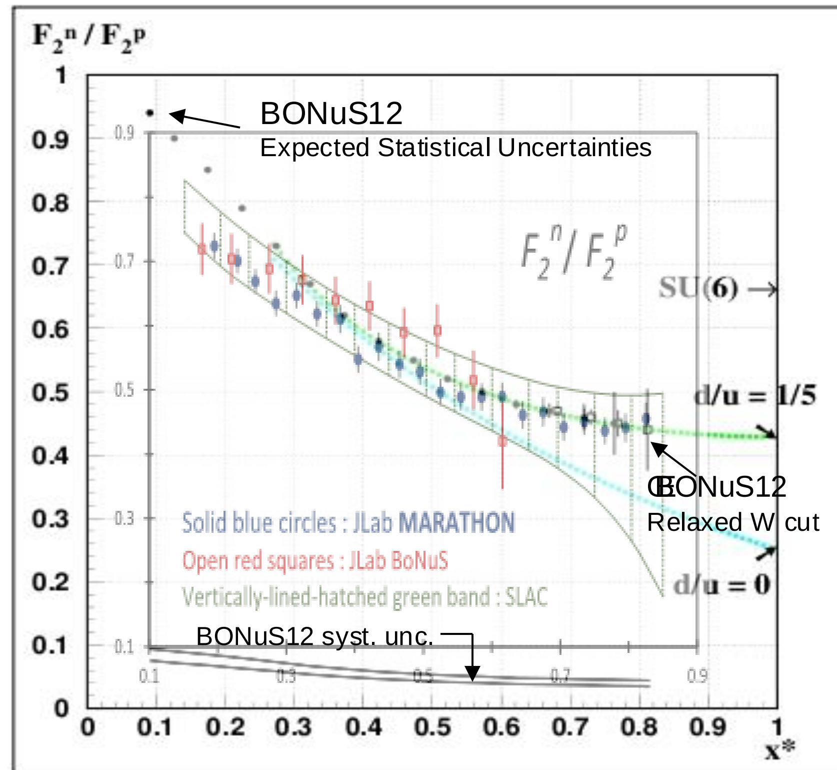
Duality in Spin Structure Functions



Projected JLab@12 GeV d/u Extractions



Marathon and BONuS12

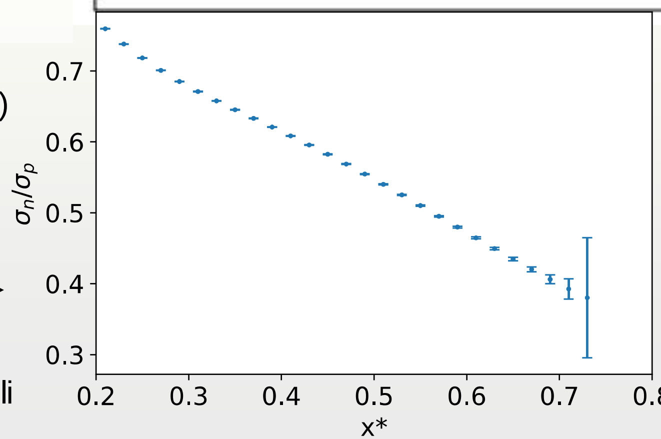


BONuS12:

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

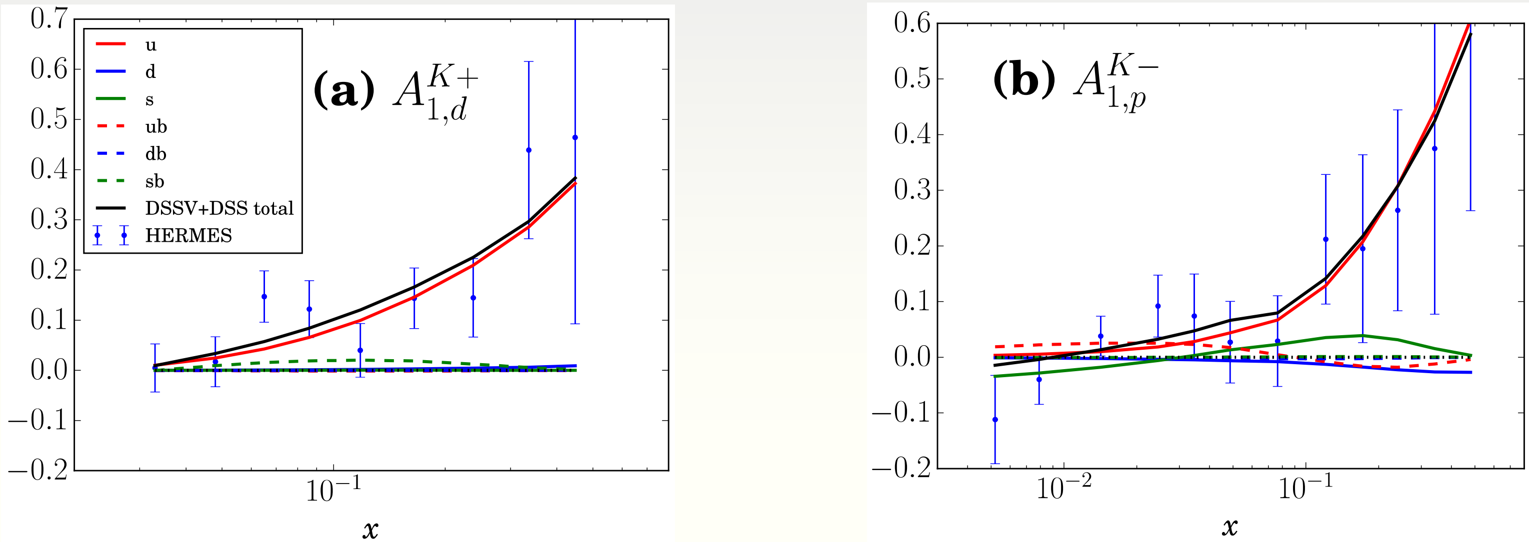
Open Symbols: "Relaxed cut" W* > 1.8 GeV (x* up to 0.83)

…also: Additional data from ALERT and TDIS →

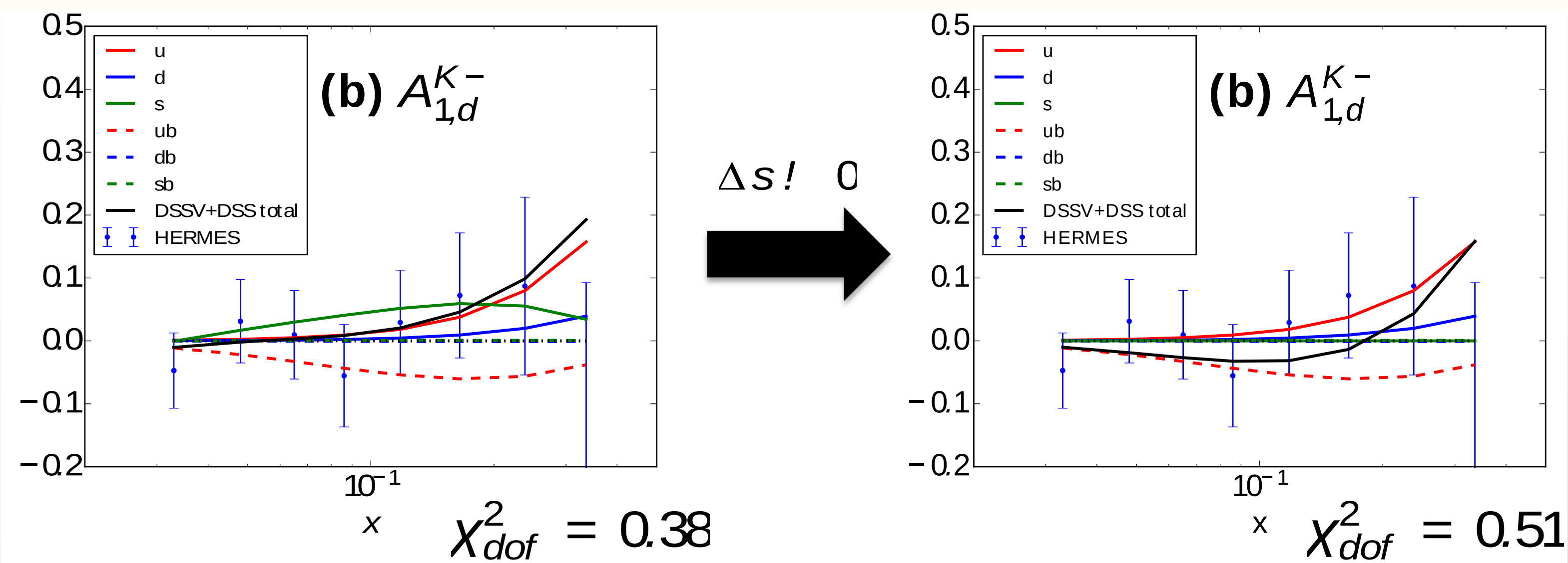


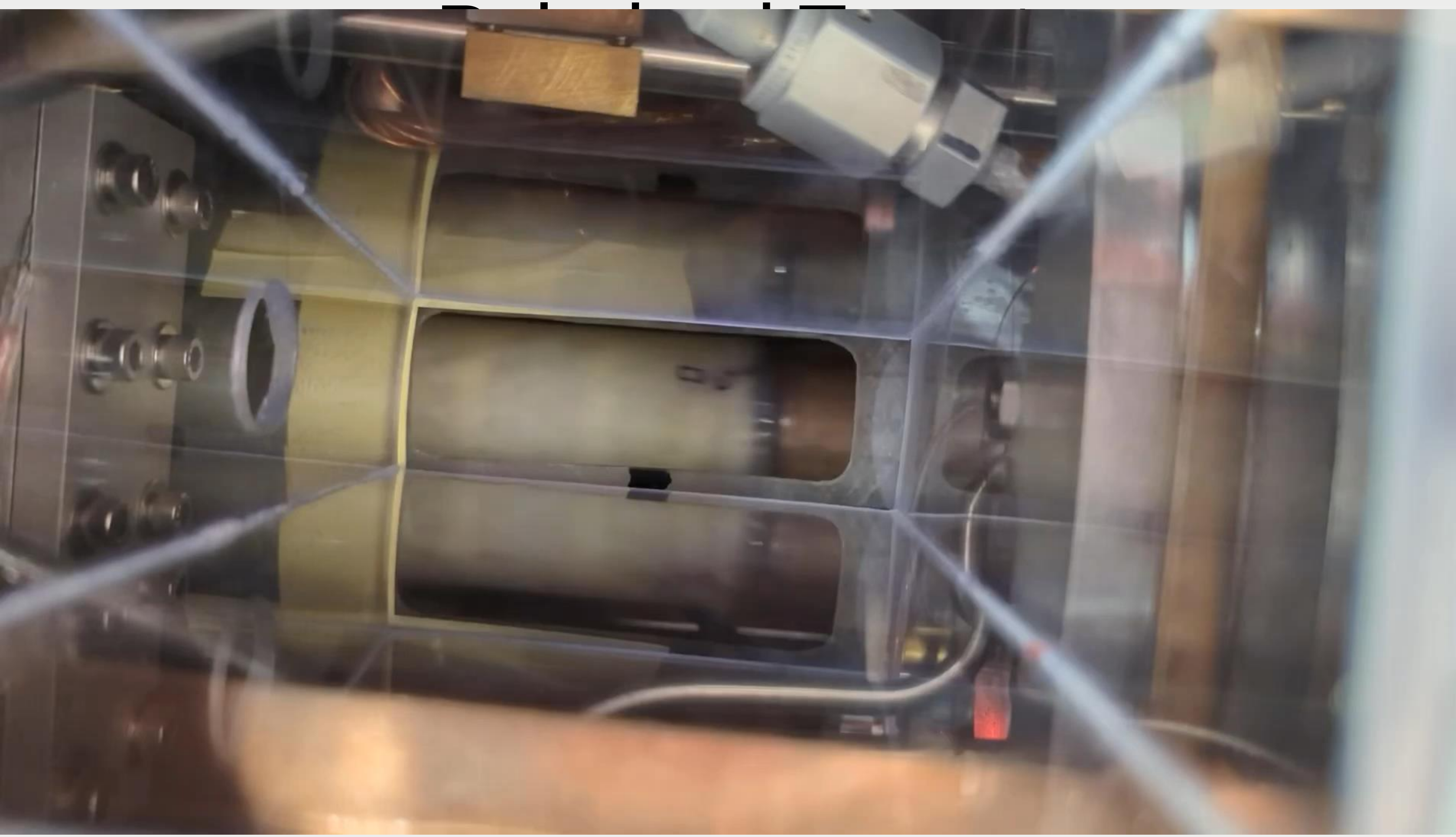
Courtesy Arun Tadepalli

PDFs from SEMI-inclusive RG-C data



Only K⁻ production on D is uniquely sensitive to Δs (Δu and Δd largely cancel)





Kinematic Reach with CLAS12

Credit: H. Avakian