Nucleon (Spin) Structure at High X

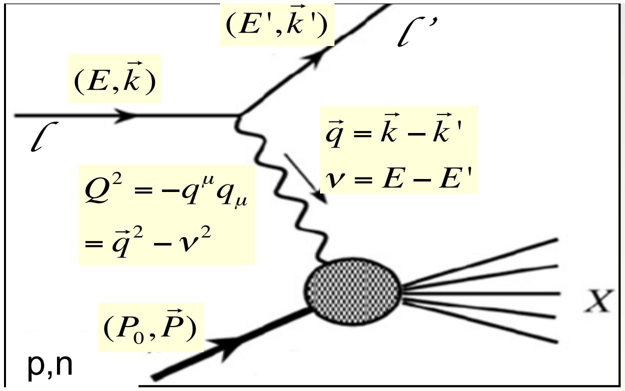
J-FUTURE

March 30, 2022

Sebastian Kuhn, *Old Dominion University*

Overview

- Valence structure of the nucleon
  - Why do we care?
  - Where are we right now?
- Spin structure at high *x*
  - Existing world data
  - Recent results (Exp. and Theory)
  - Upcoming experiments
- JLab at > 20 GeV – what more can we do?
  - General considerations
  - Example: projections for A_{1n}
- Conclusions



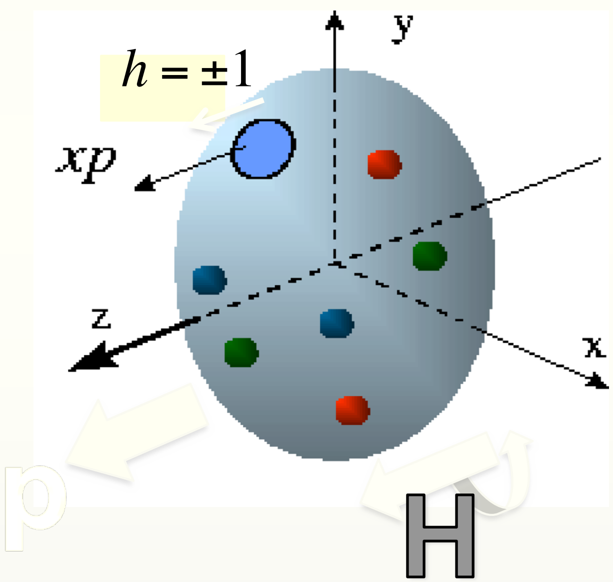
Inclusive lepton scattering

Callan-Gross

Wandzura-Wilczek

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

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



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

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

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

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

$\Rightarrow$ 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 $\Rightarrow$ separate $q_i(x,Q^2)$, $\Delta q_i(x,Q^2)$

Fixed target kinematics: $Q^2\approx M^2$ $\Rightarrow$ 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 Q^2: χPT, EFT,…

Duality?

Valence Region: Structure Functions for x→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, lower x through DGLAP -> LHC

- MANY predictions based on pQCD and quark models:

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 $x \Rightarrow$

$$\sum_q \Delta q = 1 \quad \Rightarrow \quad S_p = \frac{1}{2}\sum_q \Delta q = \frac{1}{2}\Delta\Sigma; \quad g_A^{(3)} = \Delta u - \Delta d = 5/3; \quad g_A^{(8)} = \Delta u + \Delta d - 2\Delta s = 1$$

Relativistic Correction: lower component reduces axial charge, adds to orbital angular momentum (p-wave) $\Rightarrow$

$$\sum_q \Delta q = \Delta\Sigma \approx 60\%; \quad g_A^{(3)} = \Delta u - \Delta d \approx 1.26; \quad g_A^{(8)} = \Delta u + \Delta d - 2\Delta s \approx 0.6$$

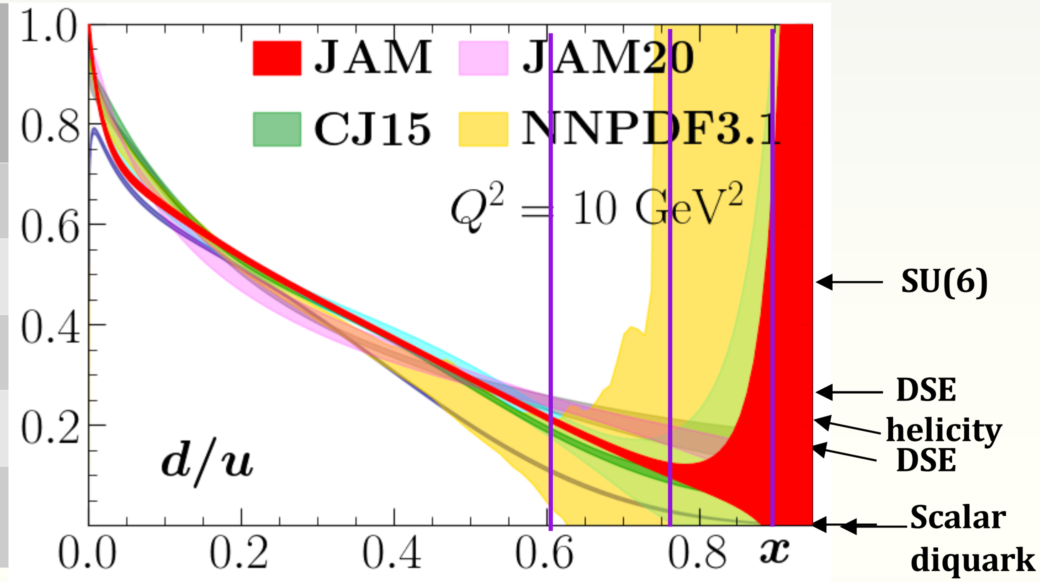
Hyperfine structure effect in QM: S=1 suppressed => d/u = 0, Δu/u = 1, Δd/d = -1/3 for $x \rightarrow 1$ => $A_{1p} = 1$, $A_{1n} = 1$, $A_{1D} = 1$

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

Other approaches: Dyson-Schwinger Equation, statistical models, …

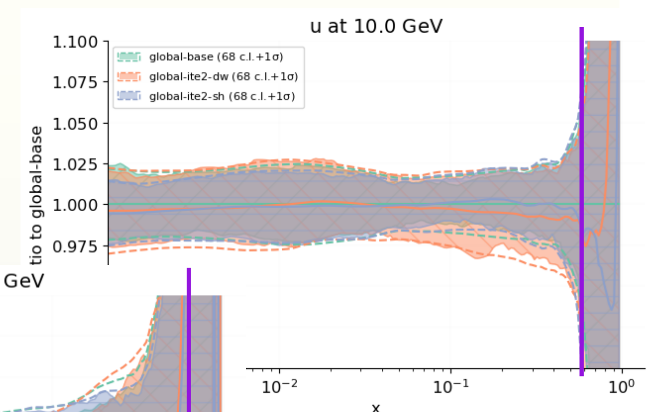
Unpolarized PDFs– high *x*

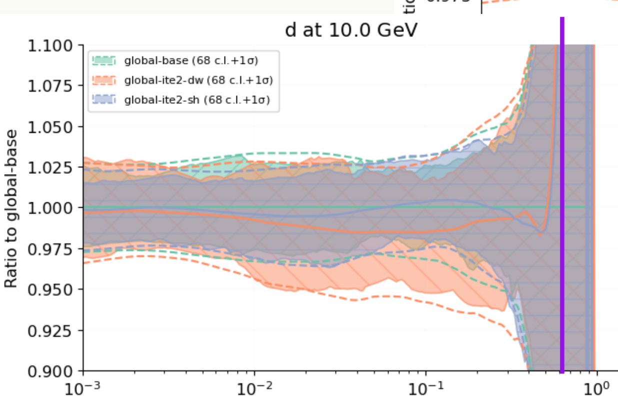
Nucleon Model	F_2^n/F_2^p $x \to 1$	d/u $x \to 1$
SU(6) Symmetry	2/3	0.5
Scalar diquark dominance	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
PQCD (helicity conservation)	3/7	0.2

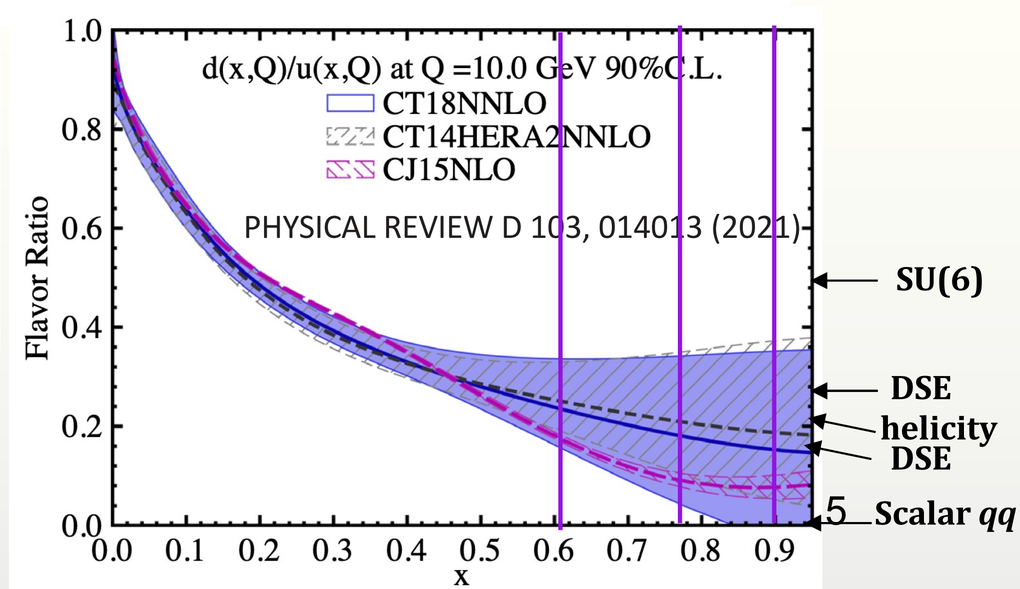


NNPDF3.1

arXiv:2011.00009



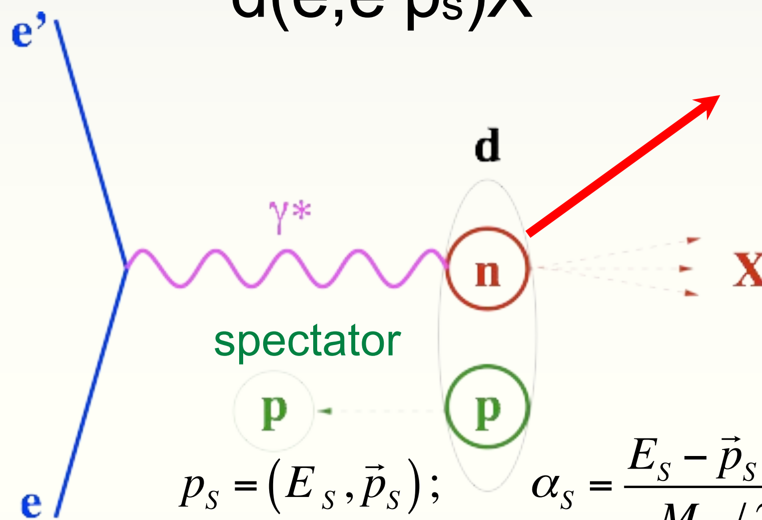




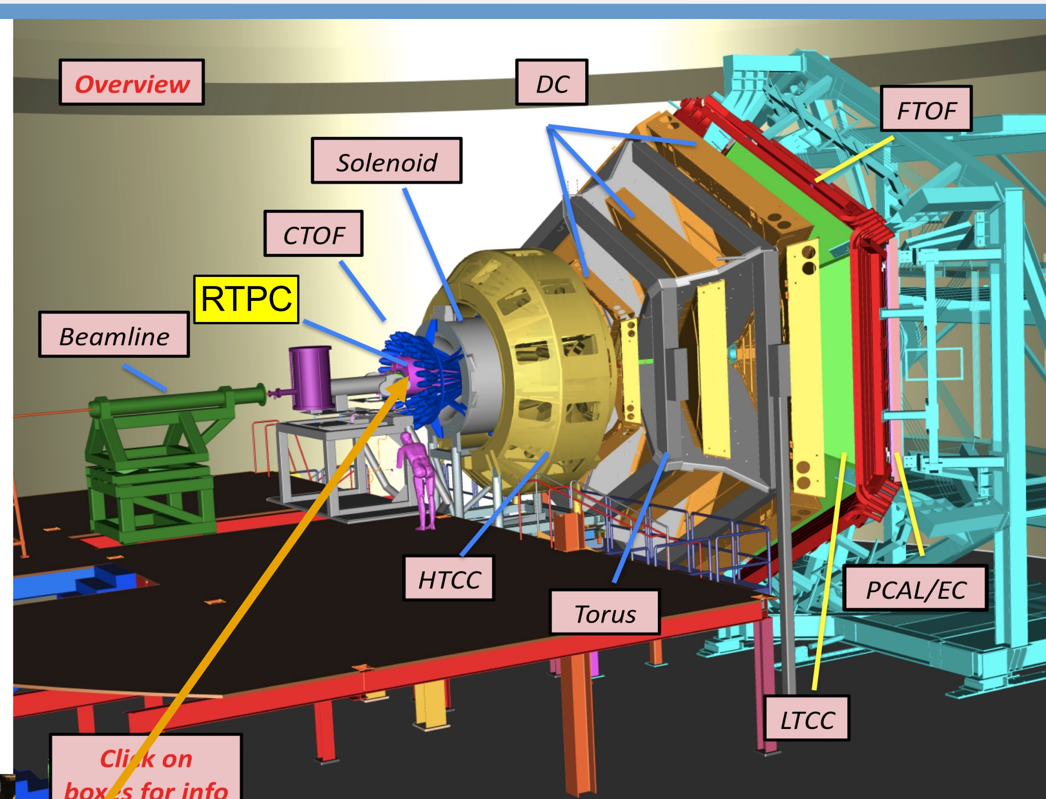
BONuS12 with CLAS12

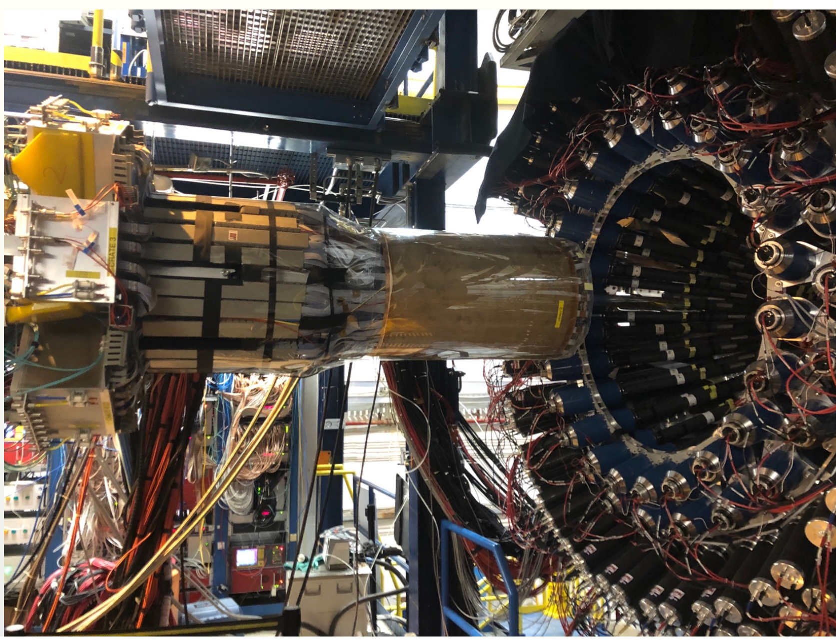
F_{2n}/F_{2p} through spectator tagging

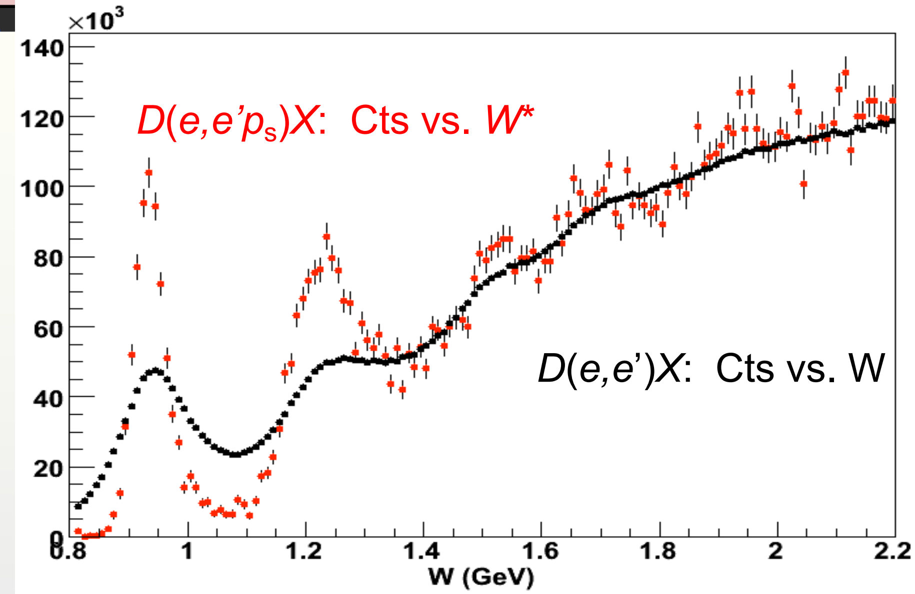
$d(e,e'p_s)X$



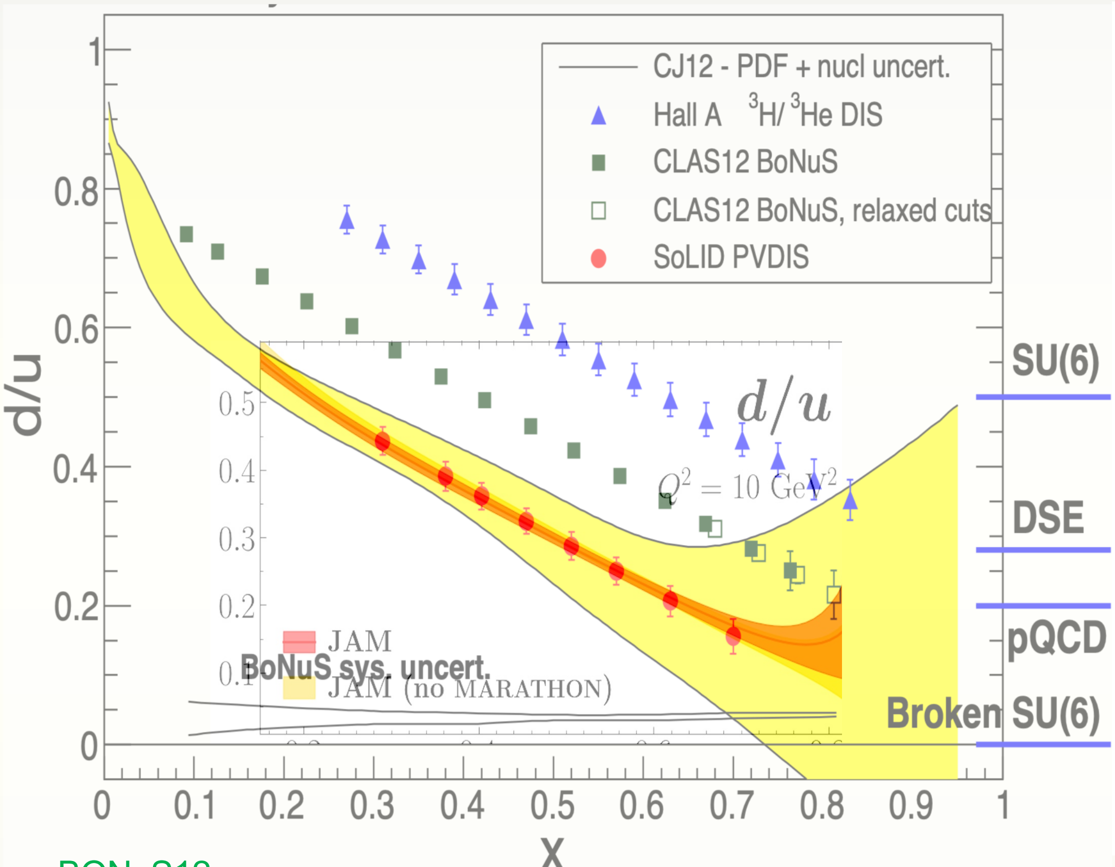
$$p_S = (E_S, \vec{p}_S); \qquad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D / 2}$$



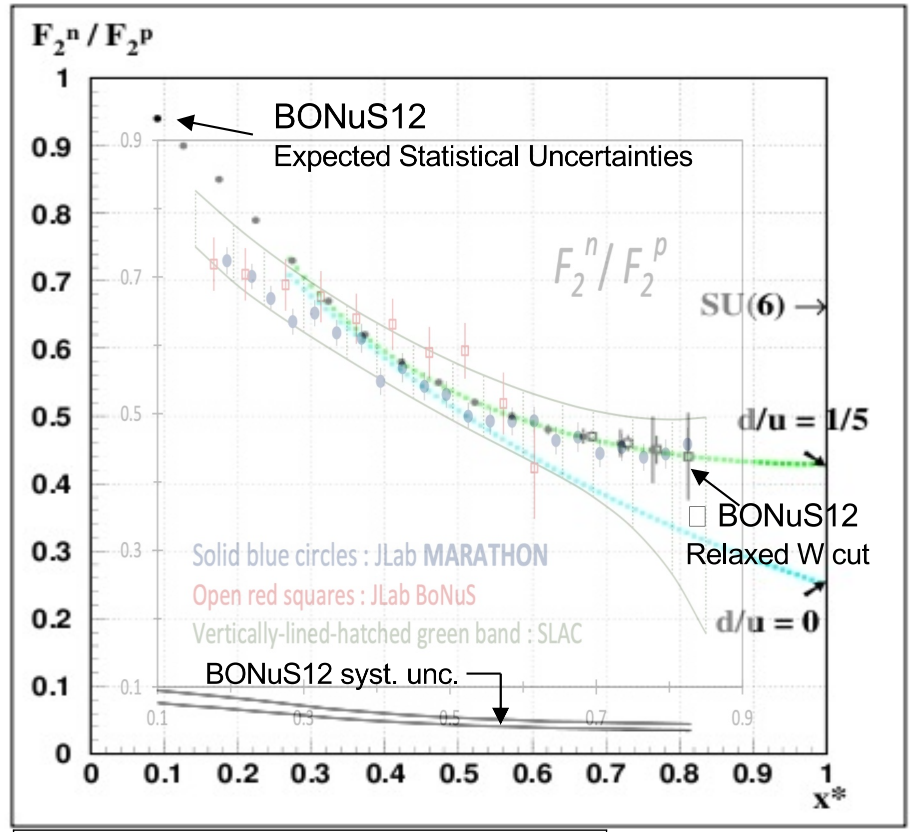




Projected JLab@12 GeV d/u Extractions



Marathon and BONuS12

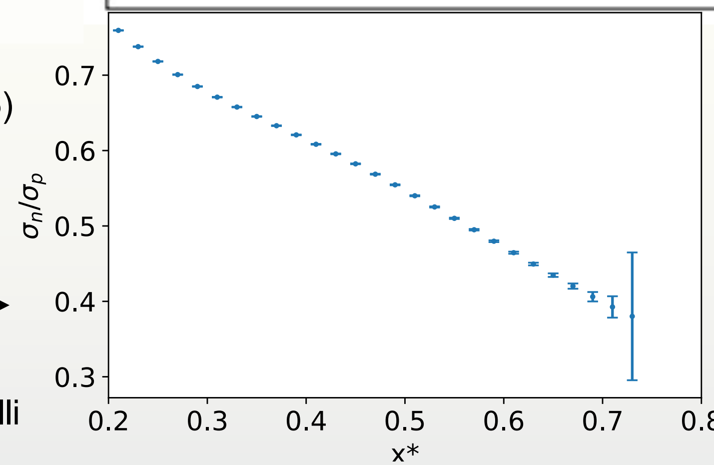


BONuS12:

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

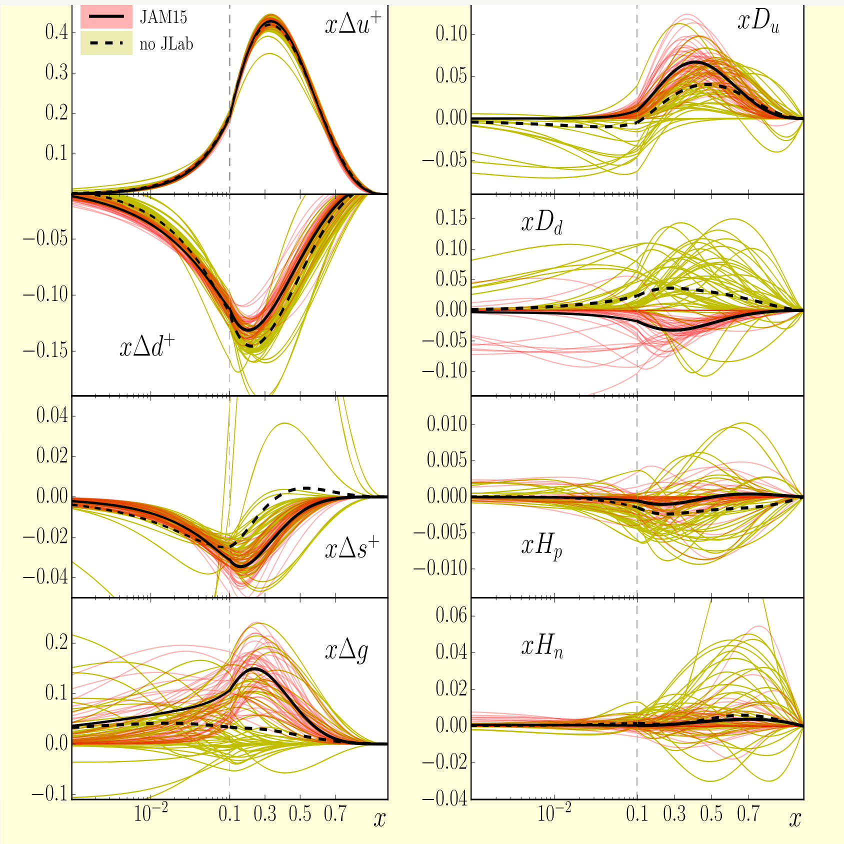
Open Symbols: “Relaxed cut” W* > 1.8 GeV (x* up to 0.83)

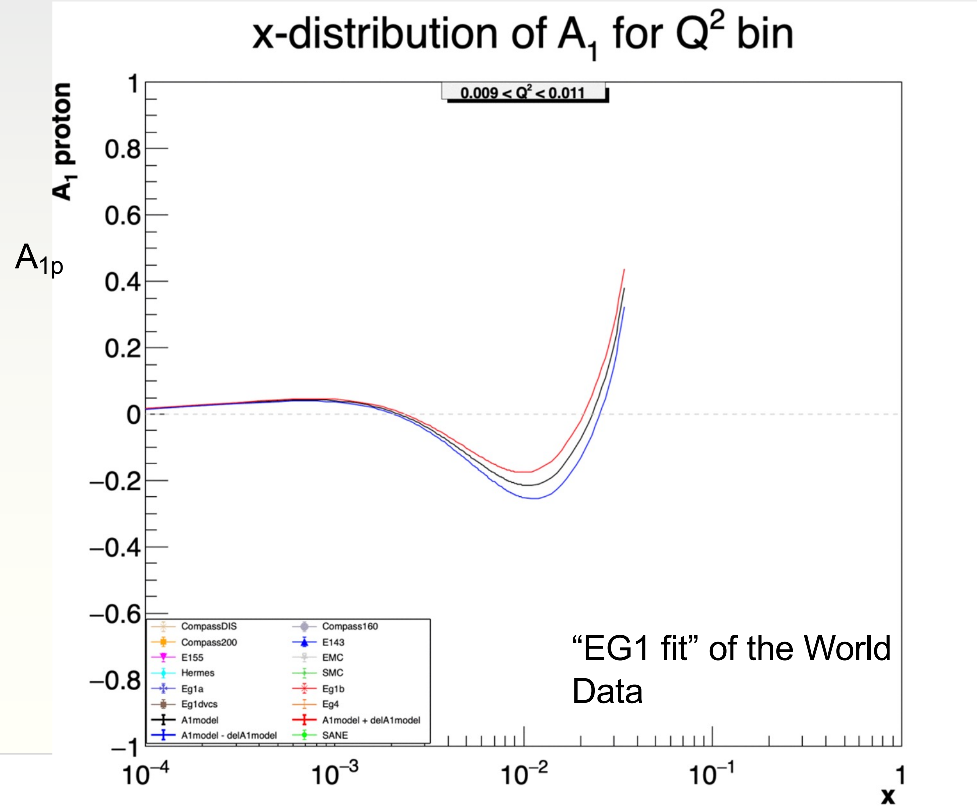
…also: Additional data from ALERT and TDIS →

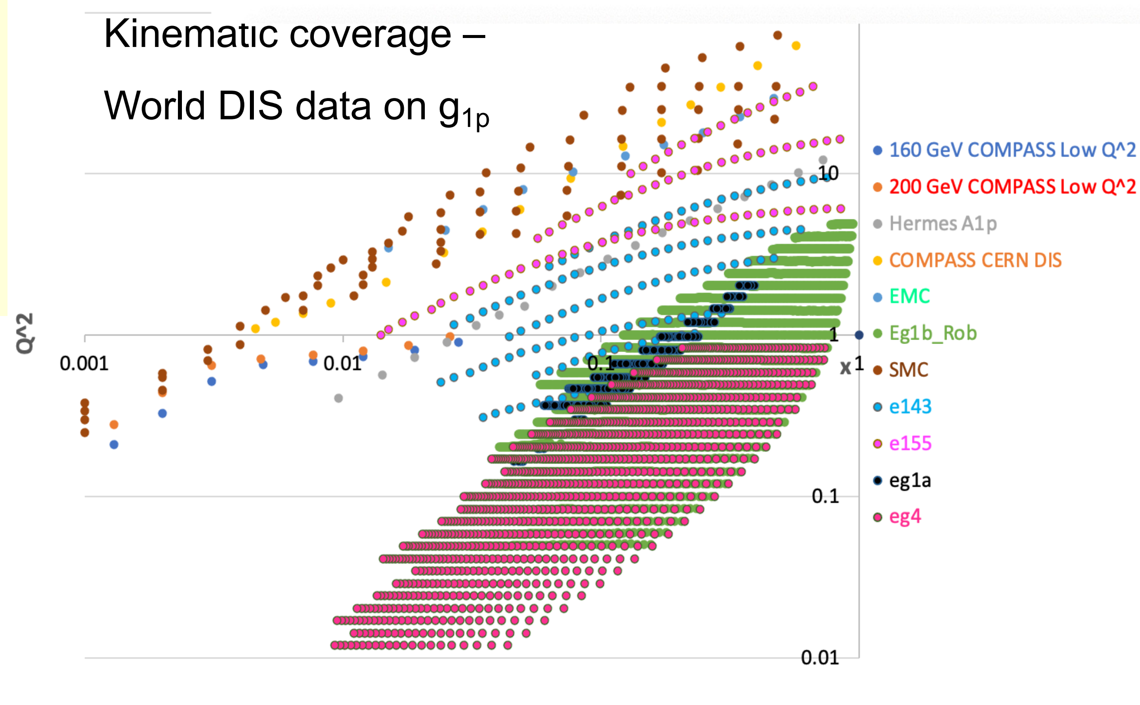


Courtesy Arun Tadepalli

Spin Structure Functions in the last 40 years



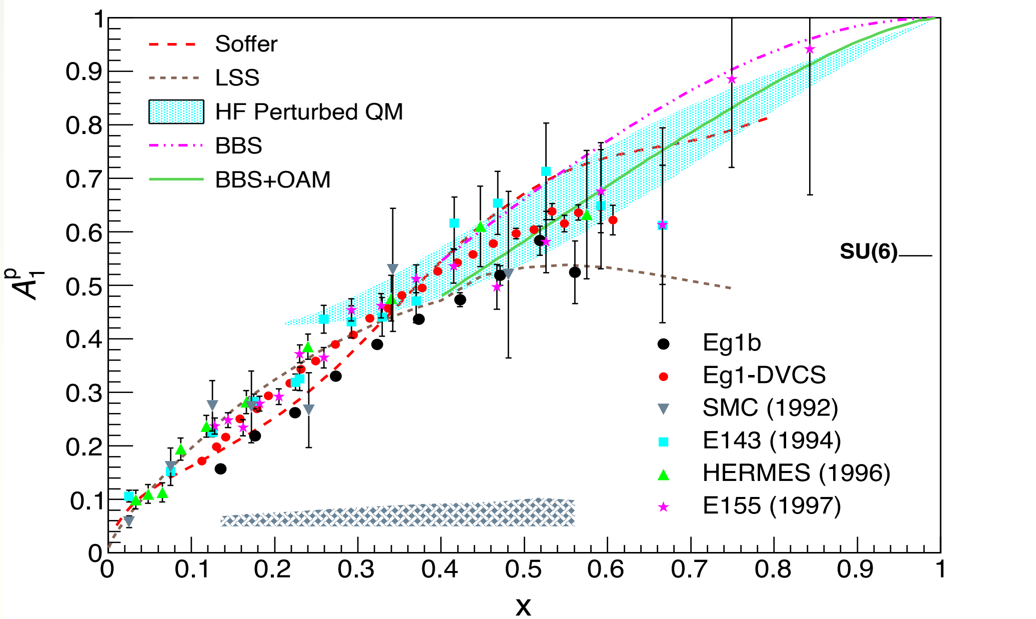


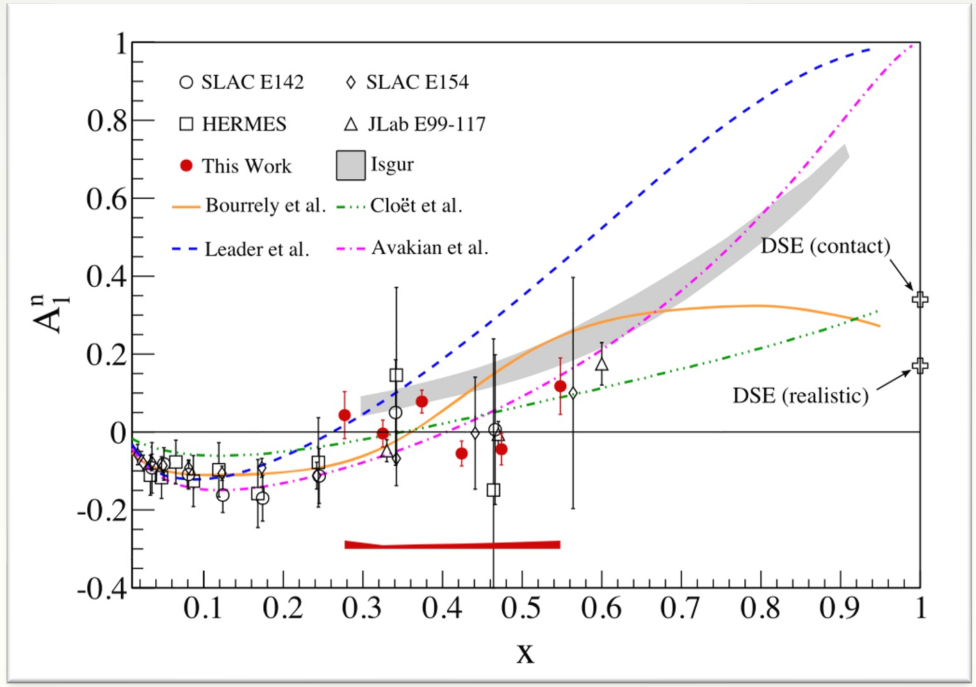


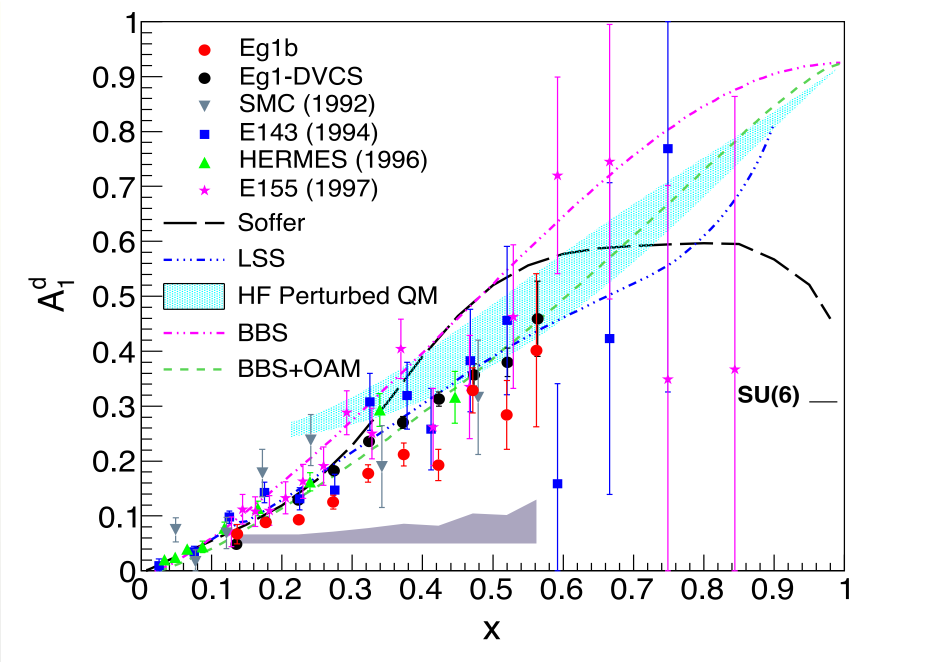
Nobuo Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier, and A. Accardi:"Iterative Monte Carlo analysis of spin-dependent parton distributions", Phys. Rev. D **93**, 074005 (5 April 2016).

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).

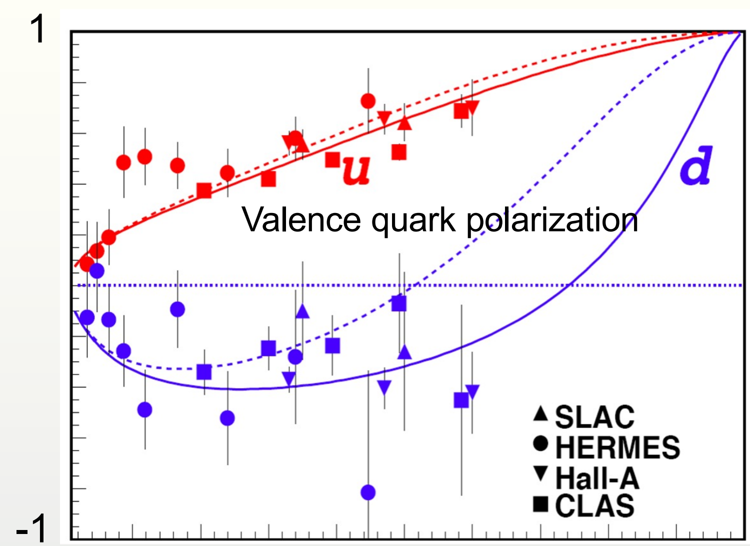
Existing Spin Structure Functions at high *x*





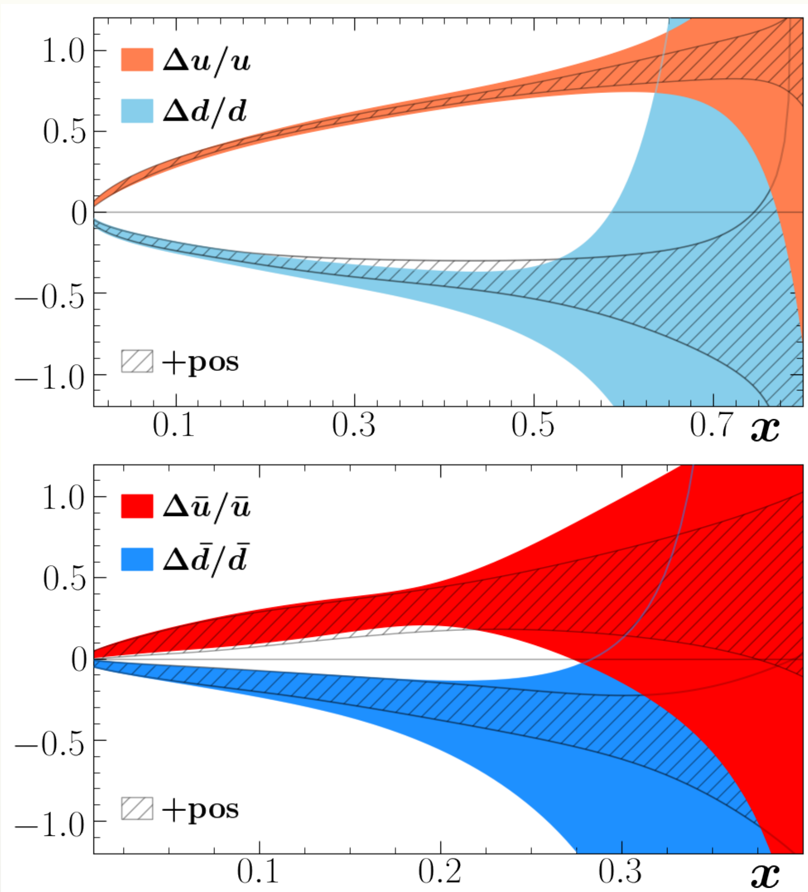


Parno et al., Phy Let B DOI: 10.1016/j.physletb.2015.03.067
X. Zheng et al., PRL 92, 012004 (2004); PRC 70, 065207 (2004)



Present Status on polarized PDFs

- Newest JAM analysis including RHIC and COMPASS data



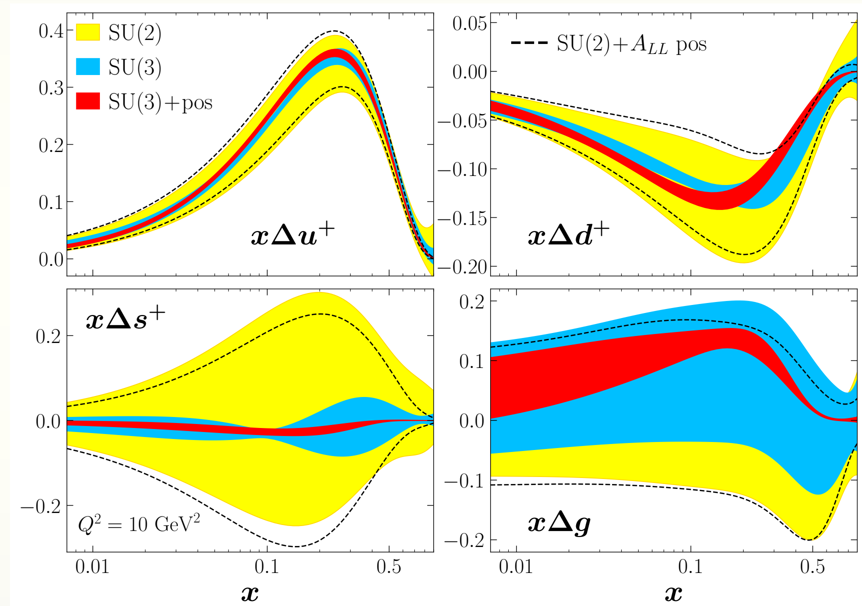


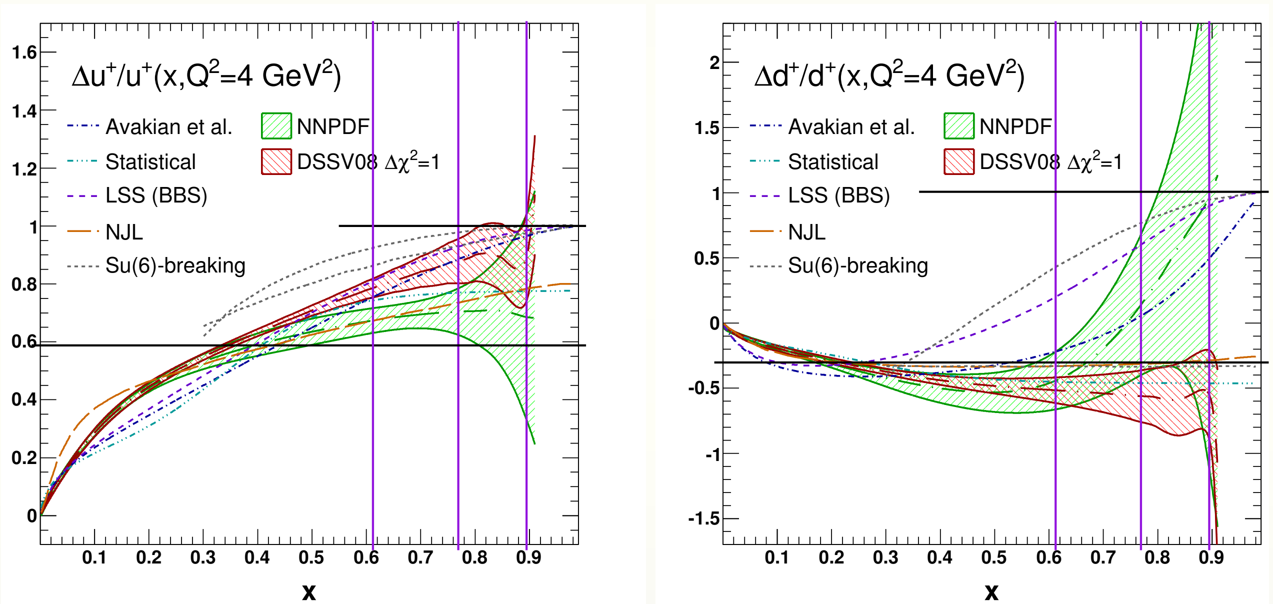
FIG. 6. Expectations values for spin-dependent Δu^+, Δd^+, Δs^+, and Δg PDFs at $Q^2 = 10$ GeV^2 fitted under various theory assumptions according to the SU(2) (yellow 1σ bands), SU(3) (blue 1σ bands) and SU(3)+positivity (red 1σ bands) scenarios, as well as with the SU(2) scenario but filtered to ensure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

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

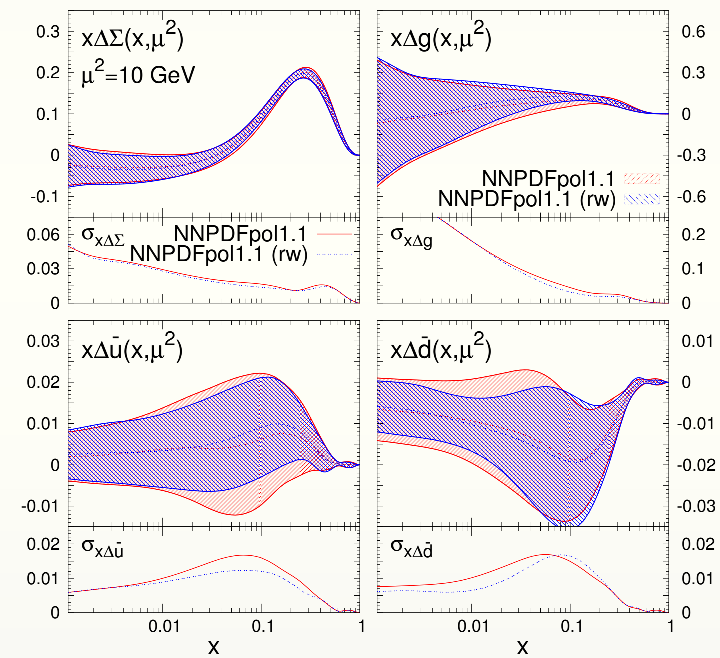
arXiv:2201.02075v1 [hep-ph] 6 Jan 2022

Present Status on polarized PDFs

- NNDPFpol1.1+RHIC W data analysis

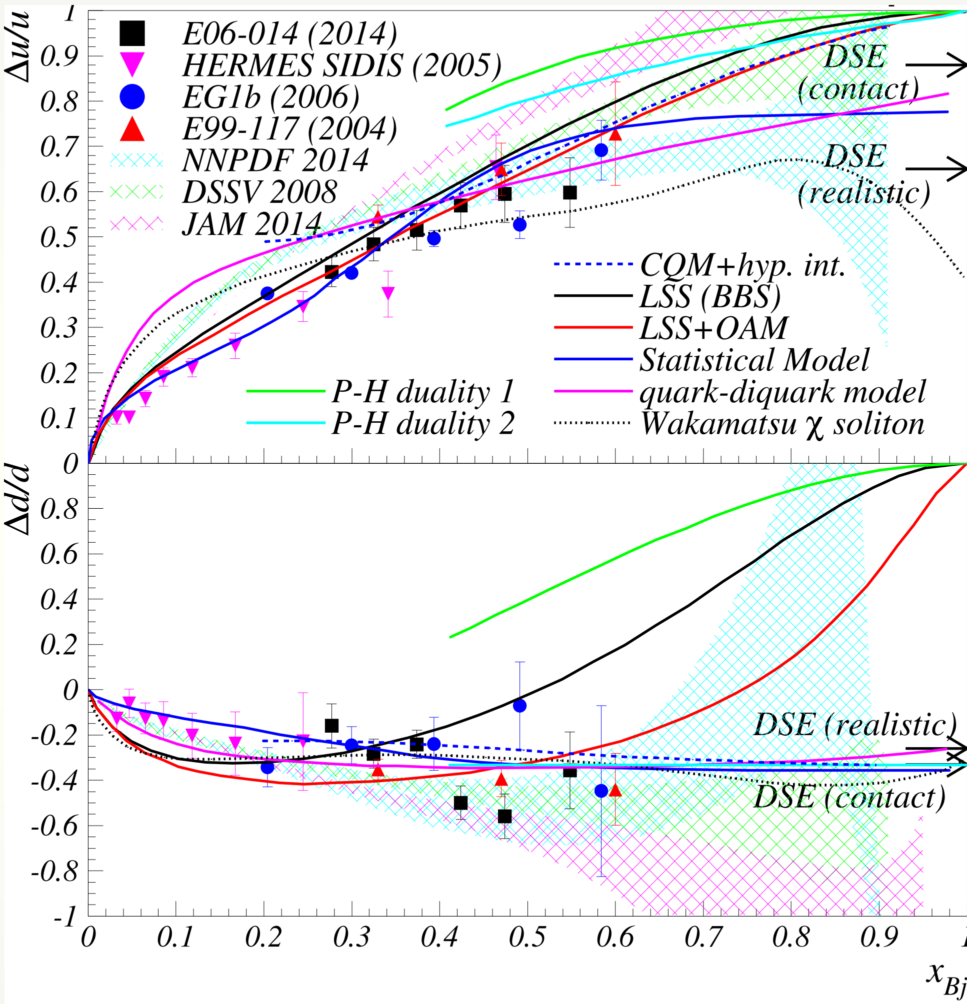


arXiv:1410.7290v2 [hep-ph] 23 Jan 2015



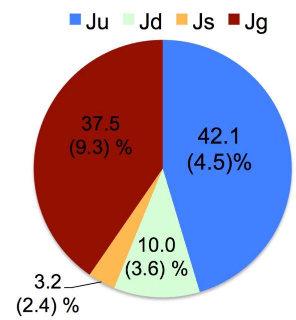
arXiv:1702.05077v1 [hep-ph] 16 Feb 2017

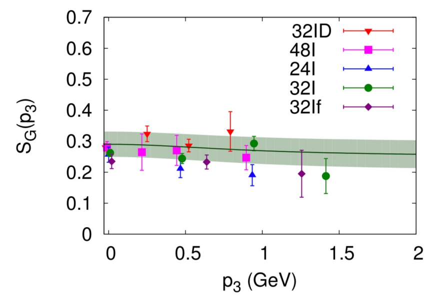
Recent theoretical predictions



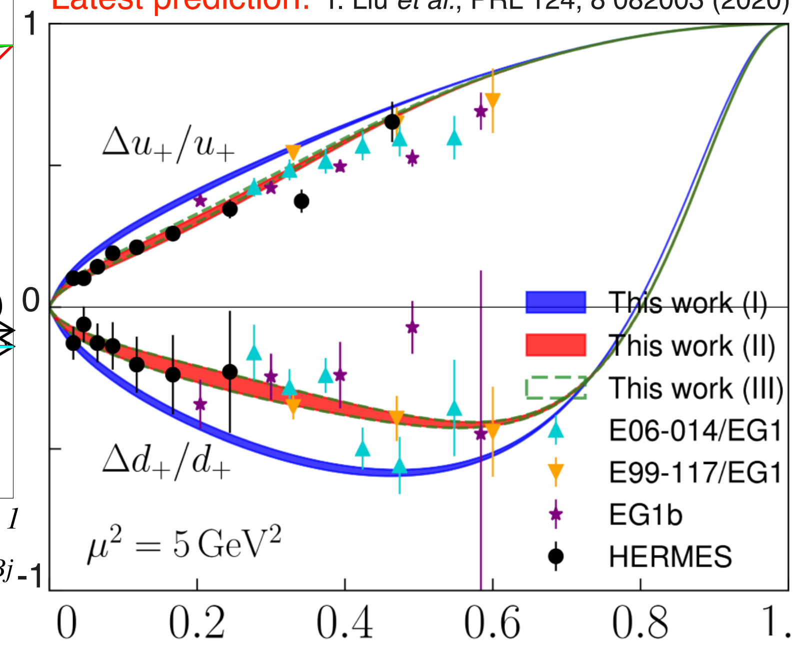
Full 12 GeV Data set will significantly constrain valence + sea quark and gluon PDF fits, higher twist effects and sum rules

Ji, Yuan and Zhao: arXiv2009.01291 [hep-ph] 2 Sep 2020





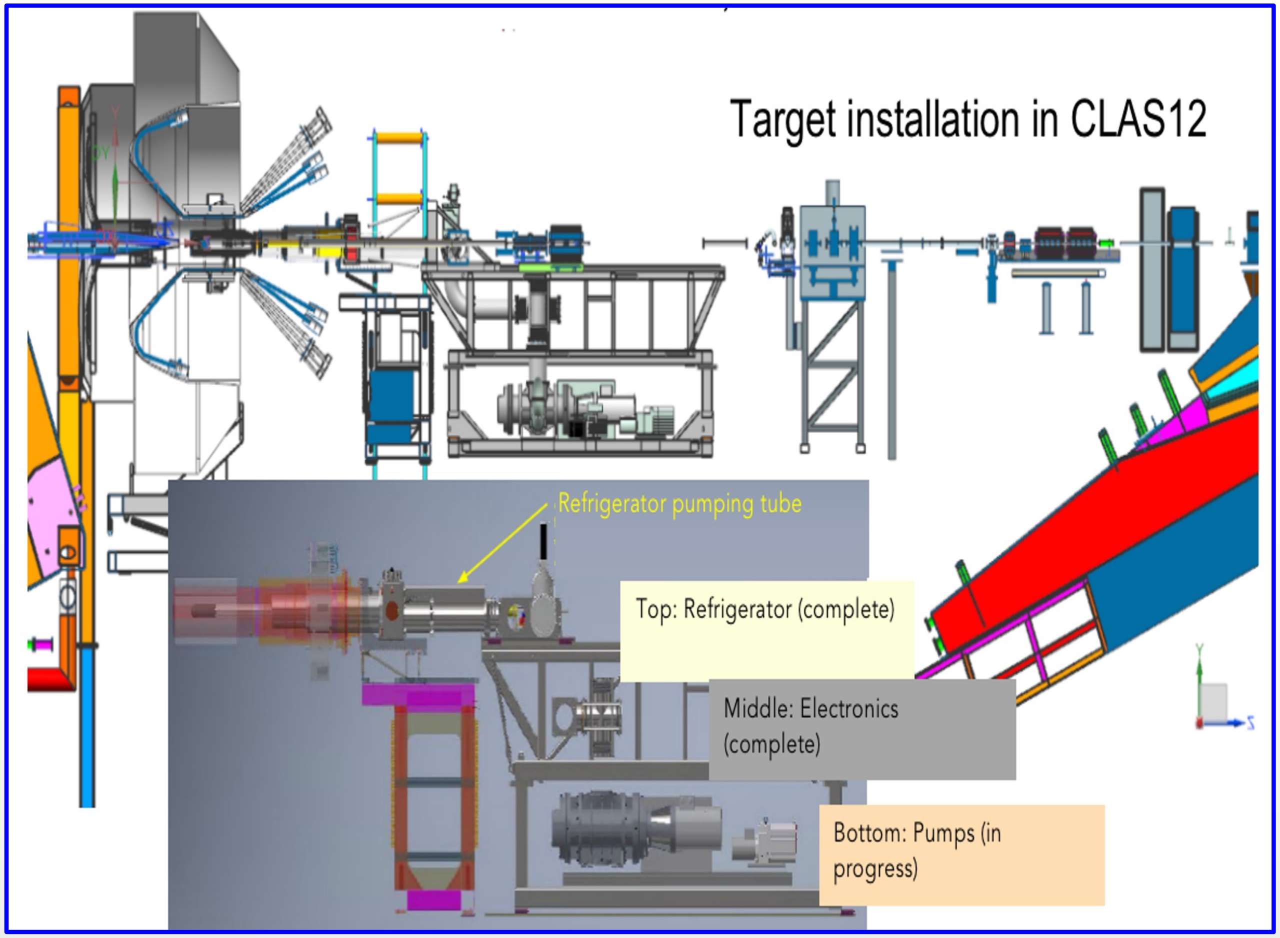
Latest prediction: T. Liu *et al.*, PRL 124, 8 082003 (2020)



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.

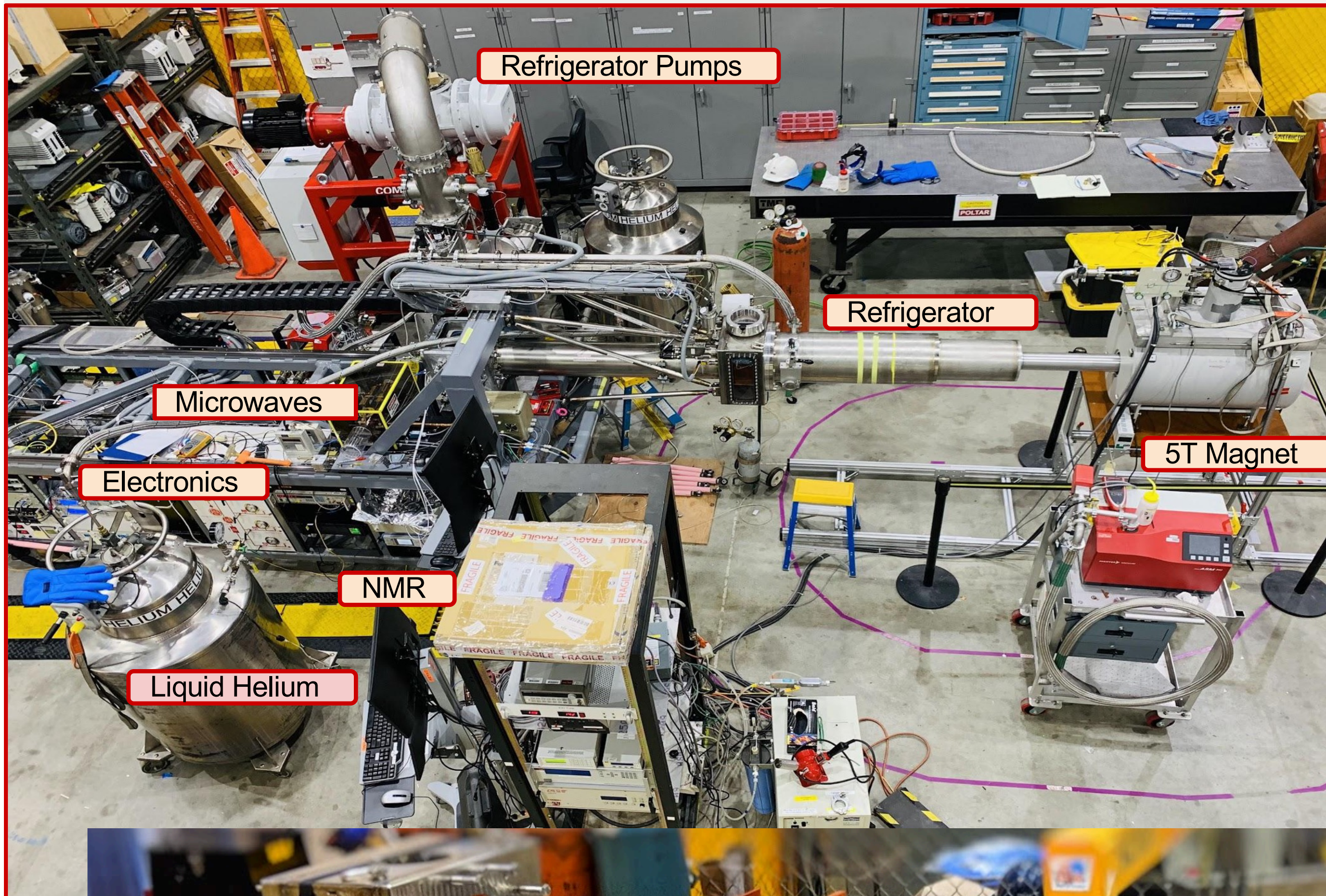
RG-C with CLAS12

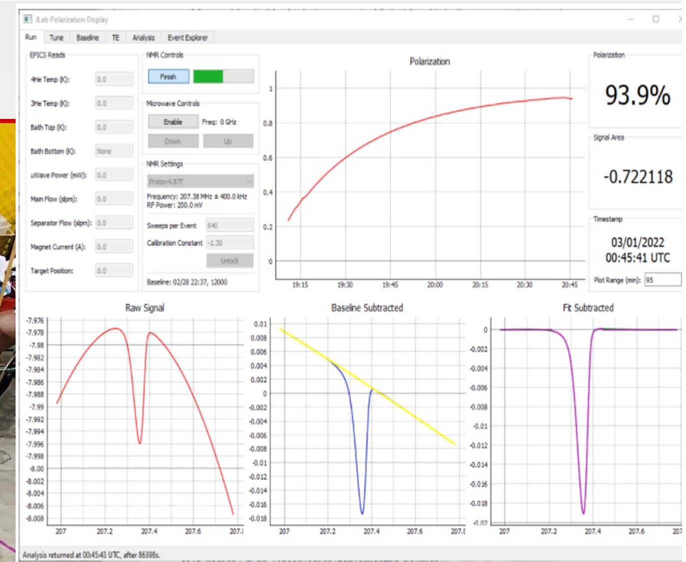
- ❑ Measure DIS inclusive spin structure functions (A_1, g_1) of the proton and deuteron.
  - ❑ Include tagging with π, K SIDIS to extract flavor-separated Δq
- ❑ Measure spin- and transverse momentum-dependent (TMD) PDFs (SIDIS).
- ❑ Deeply Virtual Compton Scattering (DVCS) to access Generalized Parton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

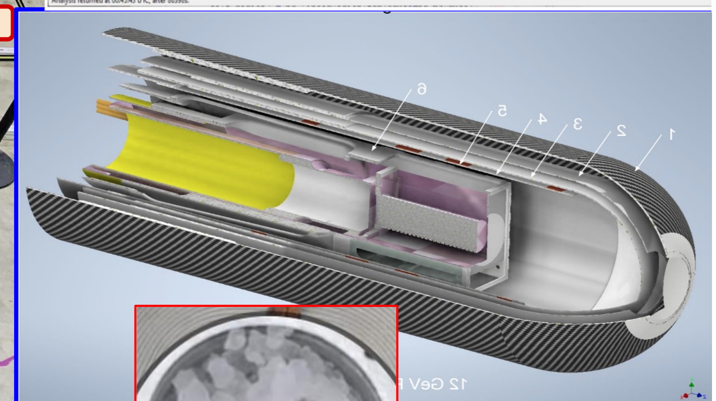


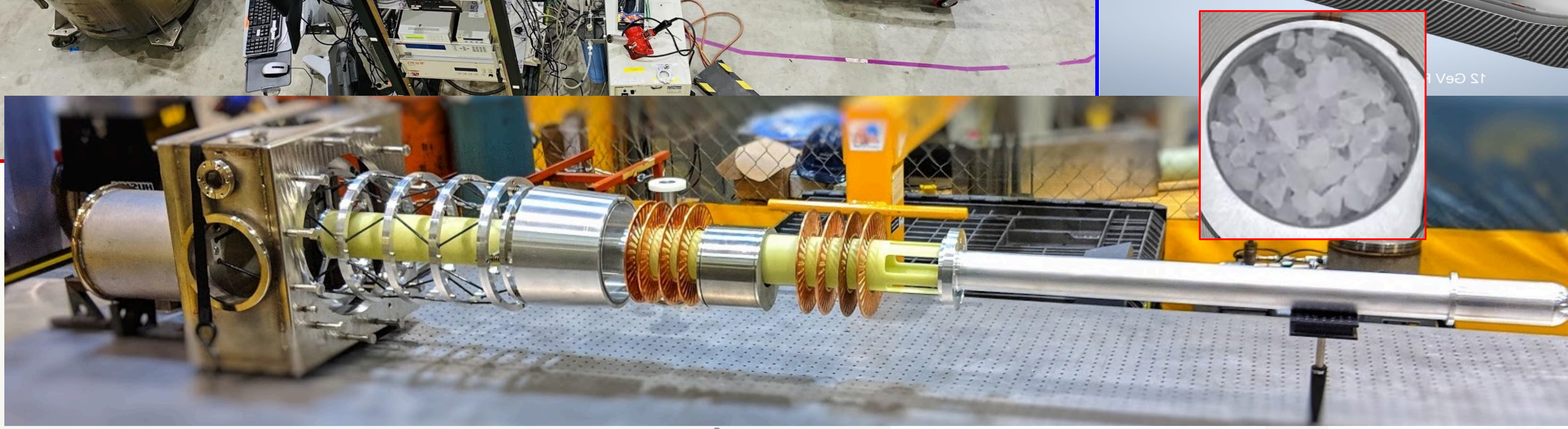
- Scheduled from June 2022 through March 2023 (240 Calendar Days)
- 10.6 GeV, 10 nA polarized electrons on 3 g/cm^2 polarized NH_3 / ND_3 ($\mathcal{L}$ = 10^{35})
- Dynamic Nuclear Polarization at 1 K, 5 T with 140 GHz µwave on irradiated ammonia
- Continuation of EG1, EG1-dvcs, EG4 to 12 GeV era
- Could in principle run at 24 GeV with somewhat higher luminosity (2x)

Longitudinally Polarized Target for CLAS12









Jefferson Lab

OLD DOMINION UNIVERSITY

UNIVERSITY of VIRGINIA

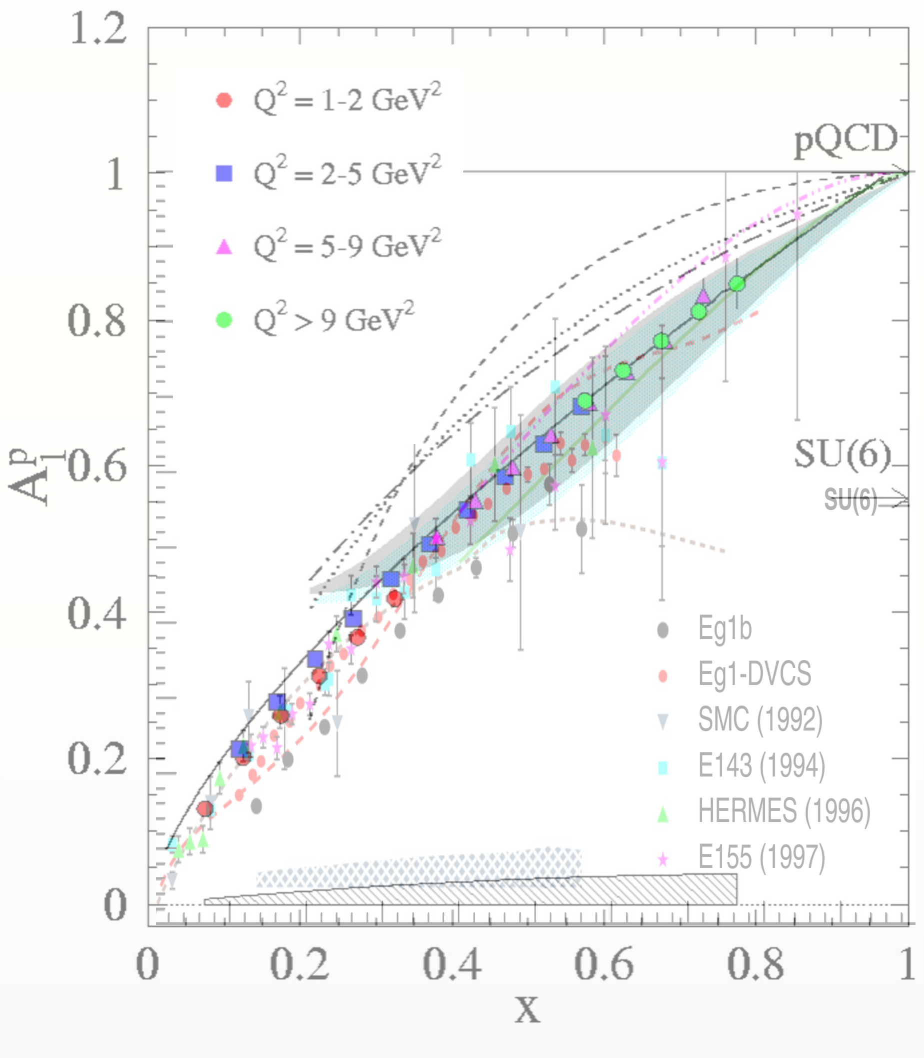
CHRISTOPHER NEWPORT UNIVERSITY

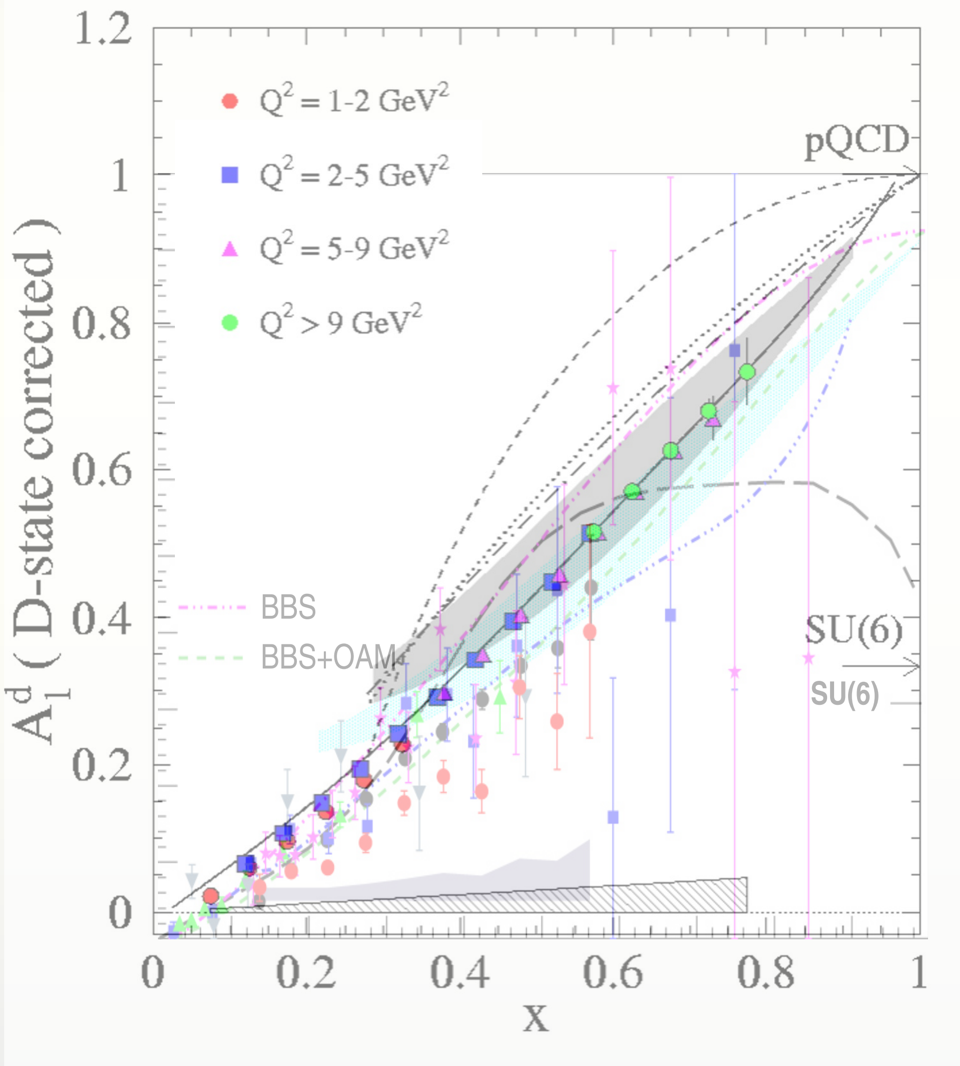
Predicted Data from CLAS12 - DIS

Proton

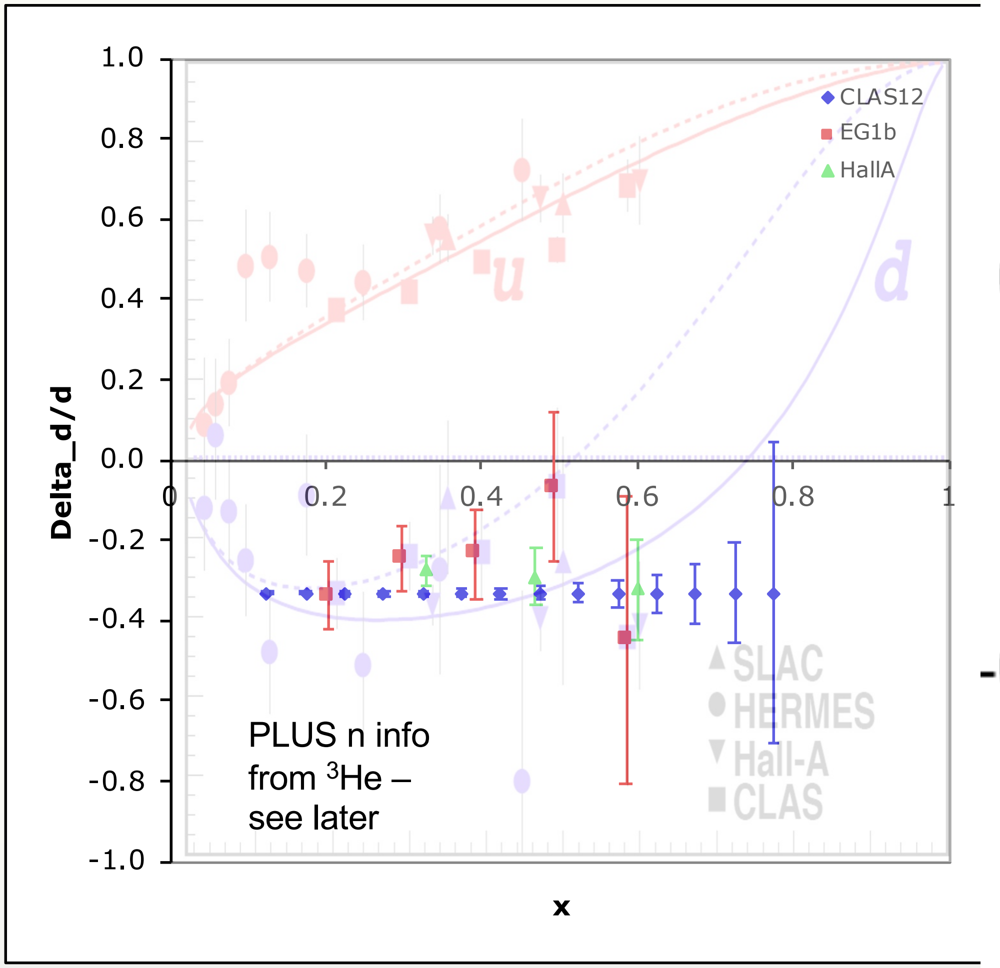
W > 2; Q^2 > 1

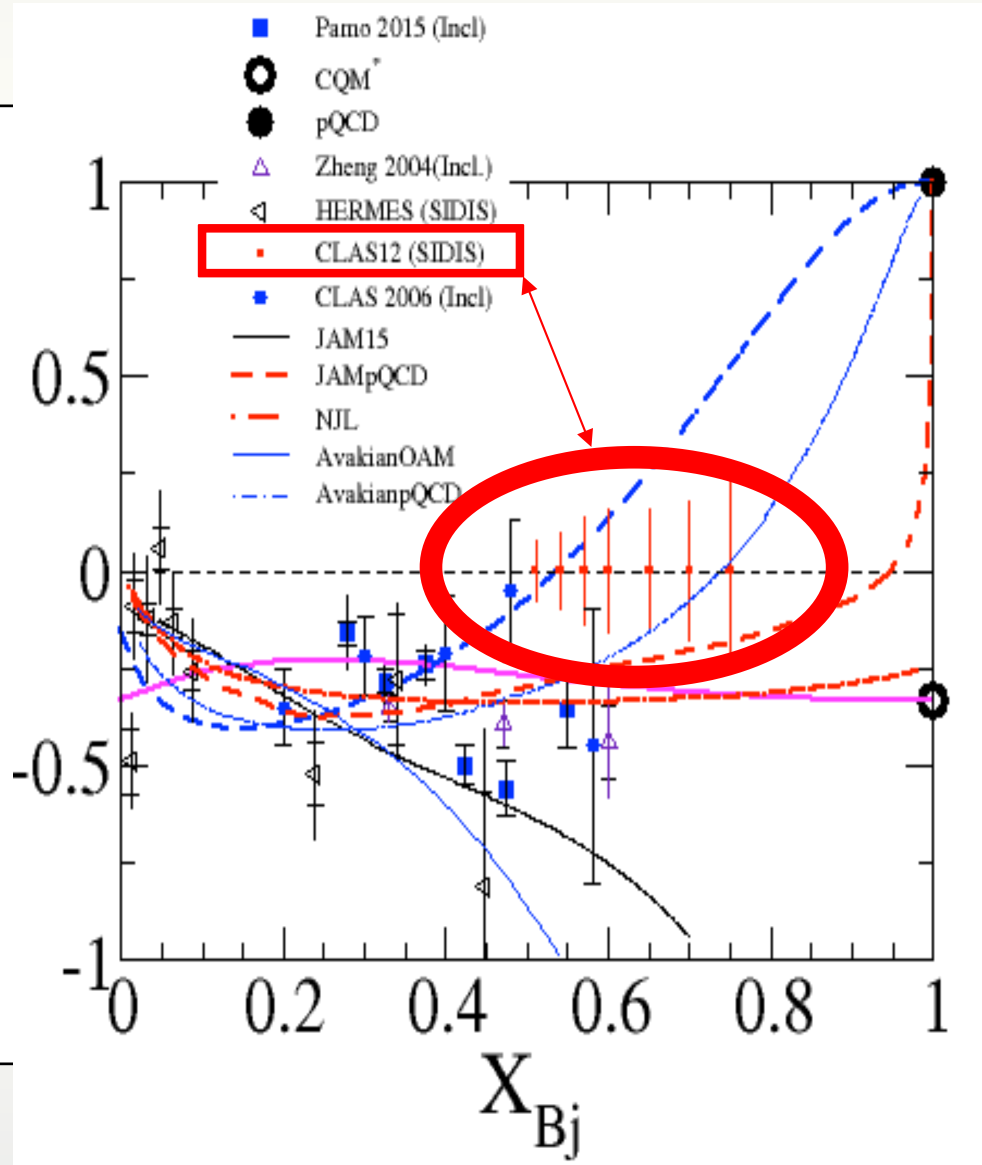
Deuteron





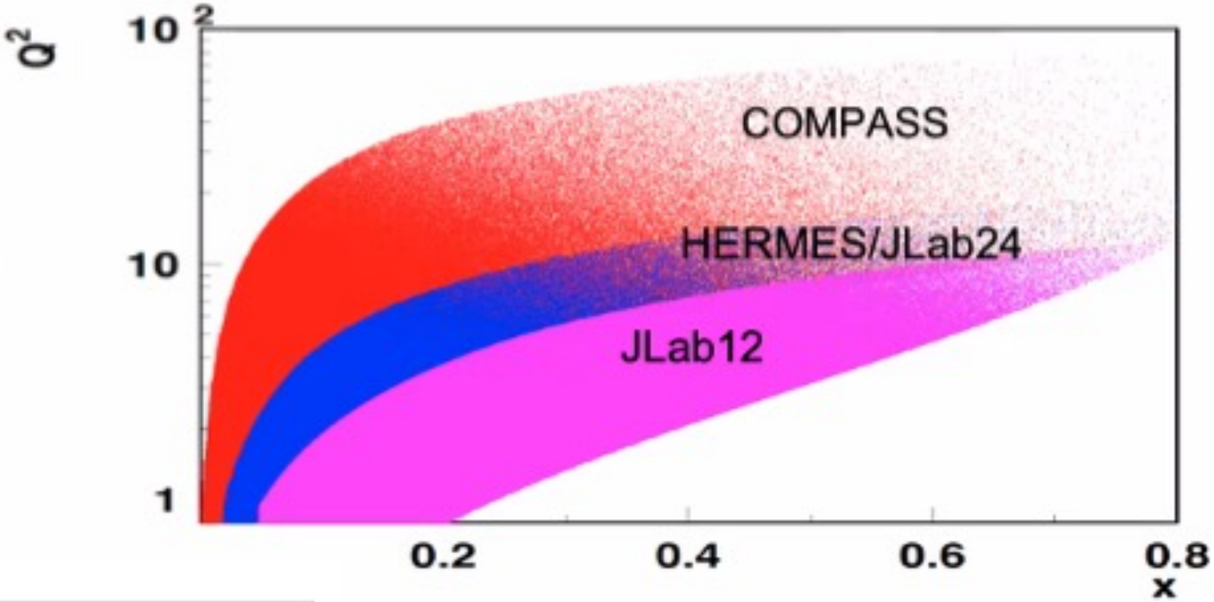
Example: Δd/d

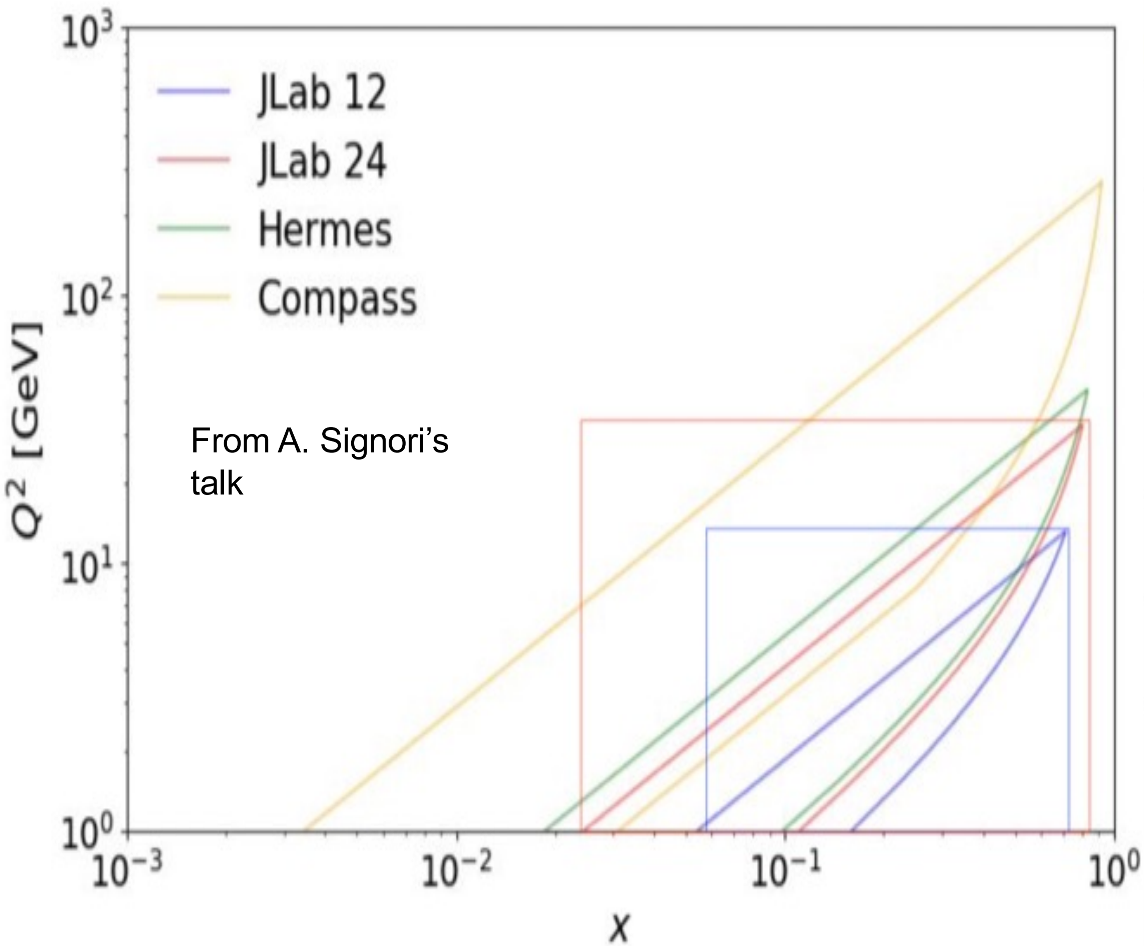




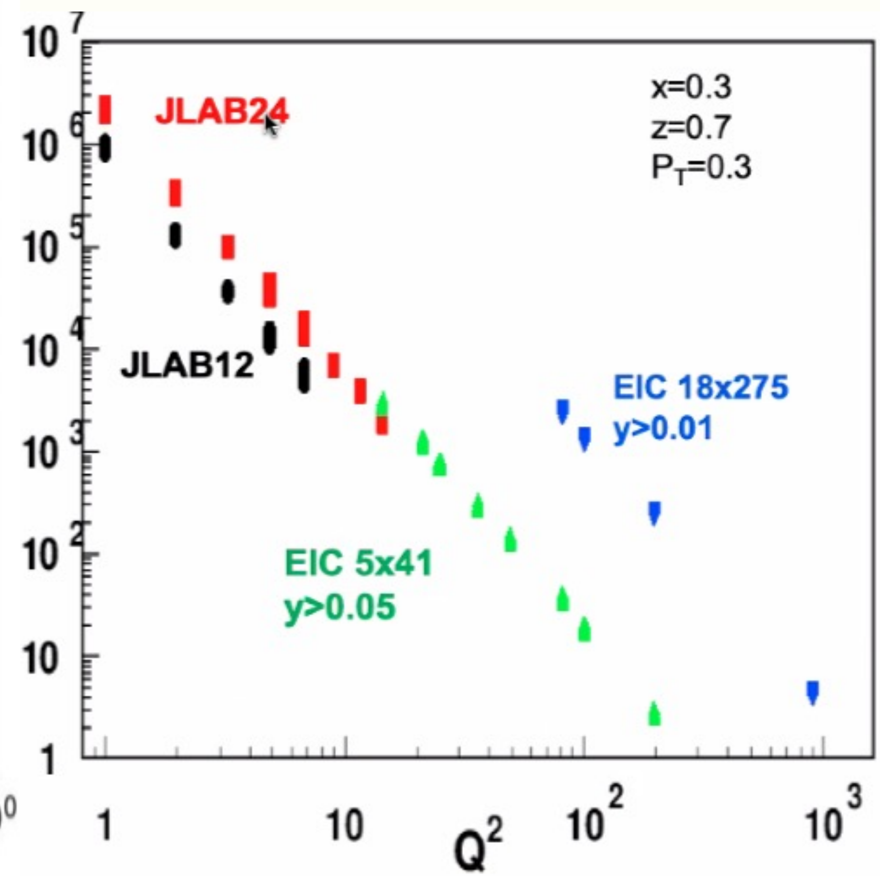
Up-to-date estimate RG-C
Inclusive and semi-inclusive data

From 12 to 24 GeV





From A. Signori's talk



24 GeV

- Halve distance to $x = 1$ AND to $x = 0$
- Increase Q^2 range for all x -> DGLAP
- Even for same x, Q^2: higher energy -> higher rates -> better statistics
- *”SuperRosenbluth”* – expand range in ε for fixed x, Q^2
- Higher Q^2: Suppress higher twist, study logarithmic resummation
- Extend SIDIS to higher x, Q^2:
  high-x sea quarks, gluons,…
- Issues: Still need to avoid nuclear uncertainties.
- Example: A_{1n} at 24 GeV

A_{1n}

- Projection using Hall C's
  - HMS @ 30 deg, 4.6 GeV
  - SHMS @ 20 deg, 7.8 GeV
- "F1F2-21 fit" for $^3He \rightarrow$ neutron "nuclear correction"
- 30 days beam time, latest polarized 3He target performance (40cm, 50%, 30uA)
- projections (12 and 24 GeV) plotted on pQCD

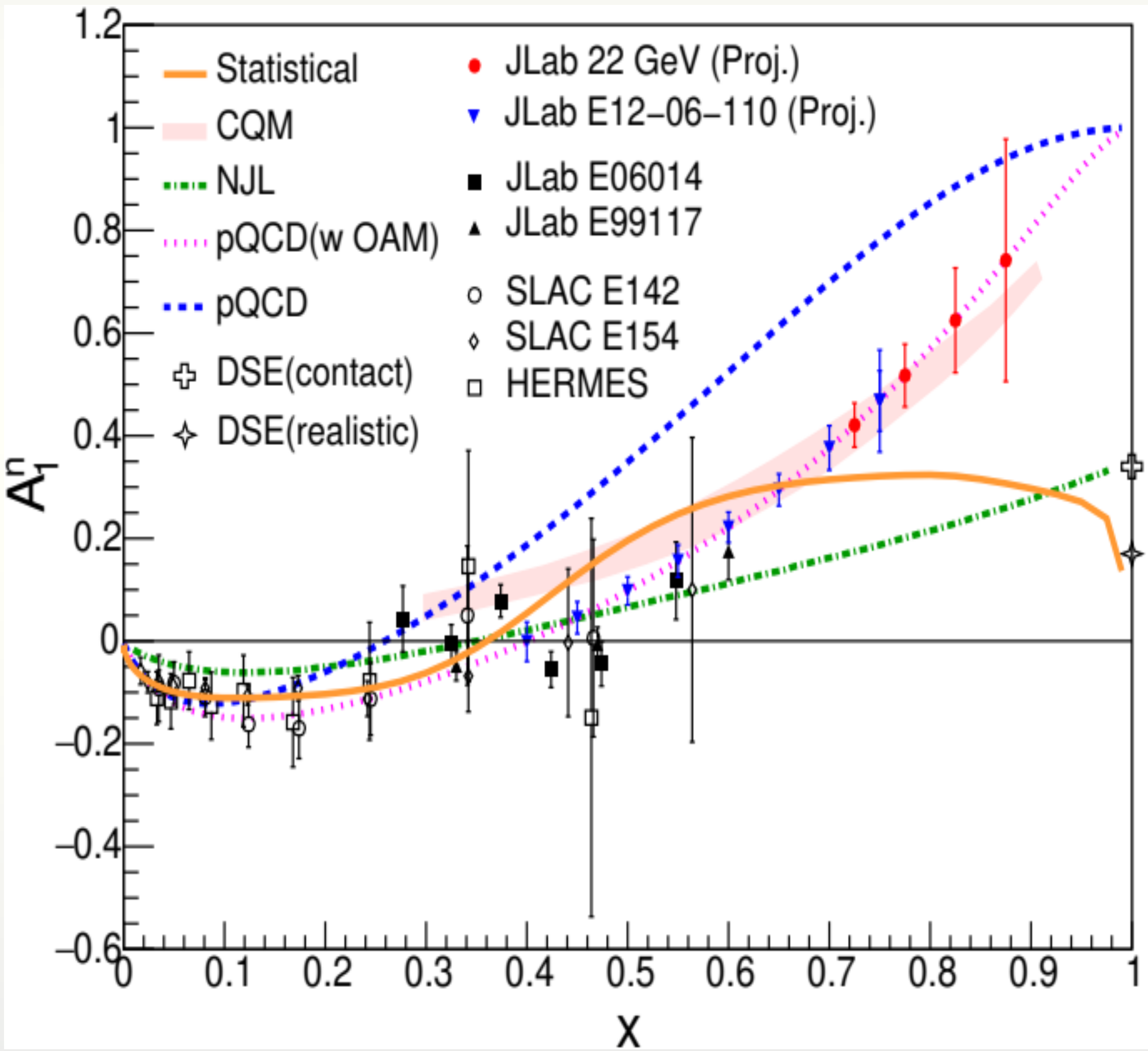
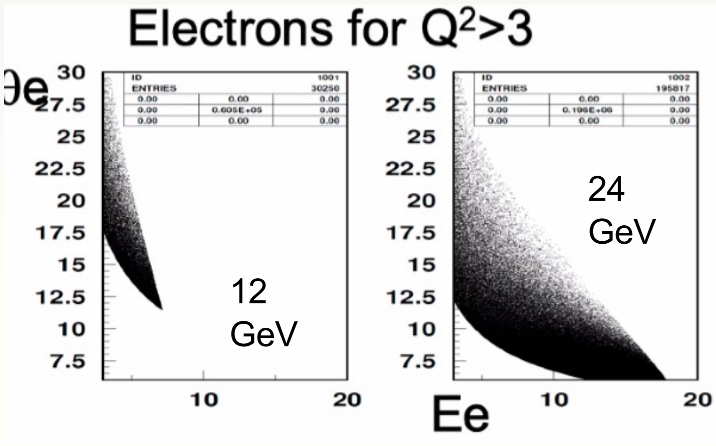
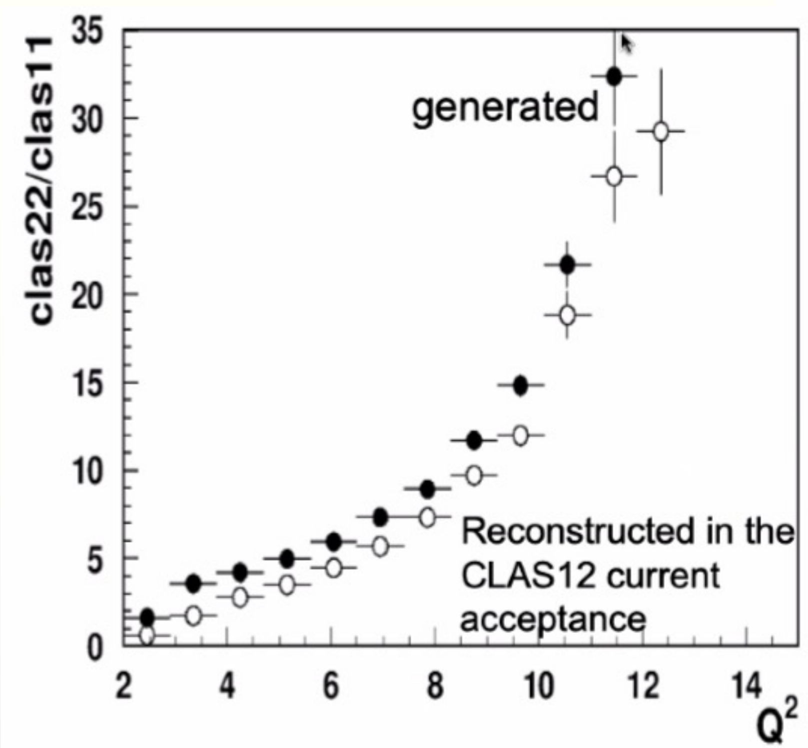


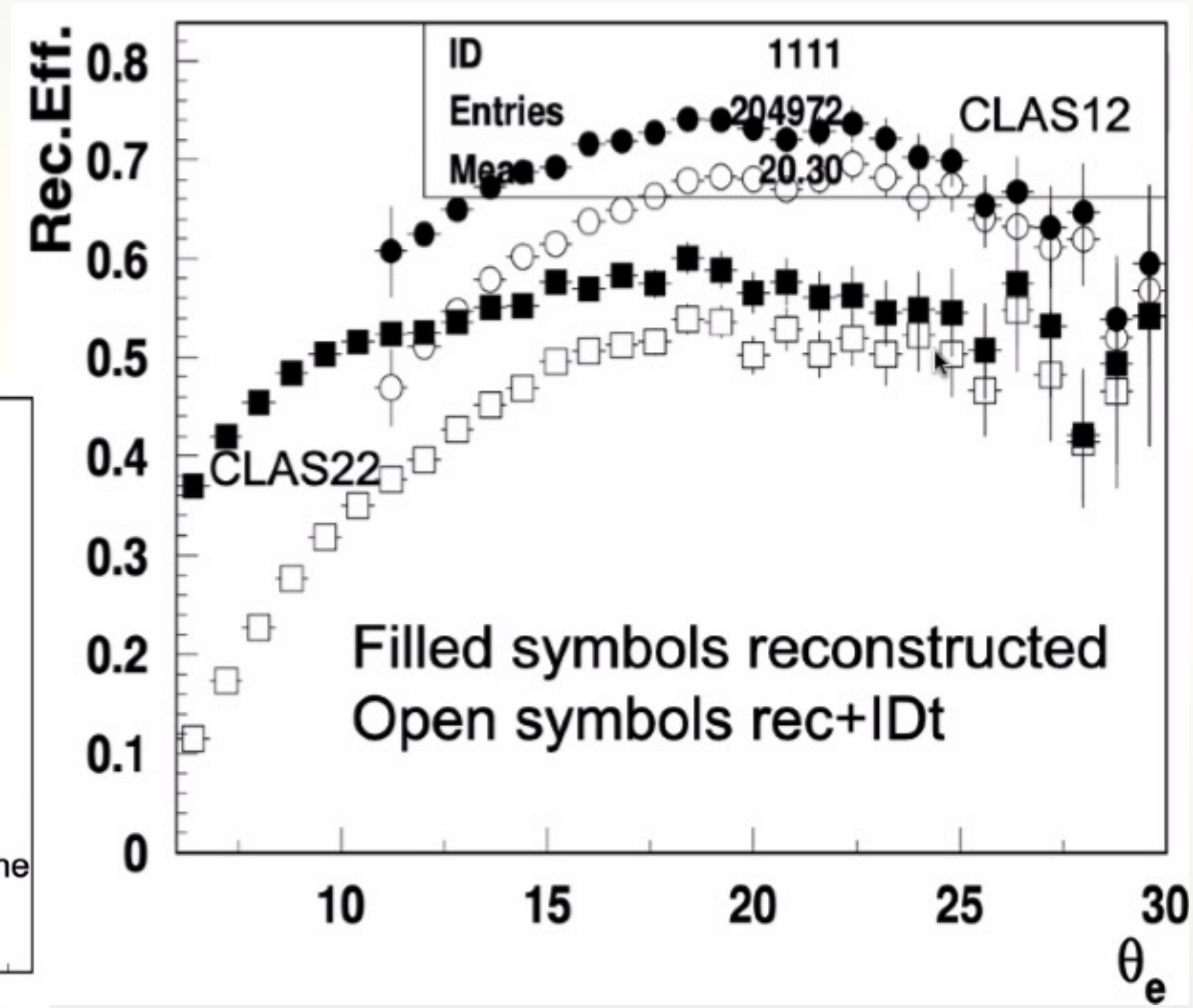
Figure credit:
Cameron Cotton (UVA/HUGS2021)
David Flay (JLab)
Thanks to X. Zheng

Kinematic Reach with CLAS12

Credit: H. Avakian





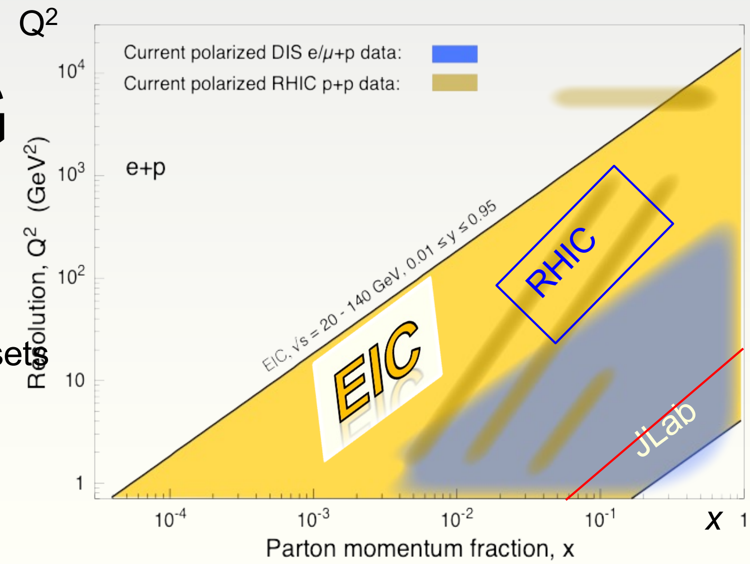


Conclusions

- Structure functions in the valence region remain of high interest
- Jefferson Lab at 12 GeV will make significant impact on our understanding of this region
- 24 GeV can expand the coverage in x from 0.75 to 0.9, thereby minimizing the extrapolation to x -> 1.
- Larger range in Q^2 and higher count rates -> minimize theoretical uncertainties and increase statistics even at lower x.
- 24 GeV necessary to close the gap with EIC
- Remaining issues: extracting neutron (polarized) structure functions from measurements on nuclei (d, ^{3}He).

Backup Slides

SUMMARY: COMPLETING THE 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 high *x* ?**
- **Nuclear effects on nucleon structure**

JLab @ 12 -> 24 GeV

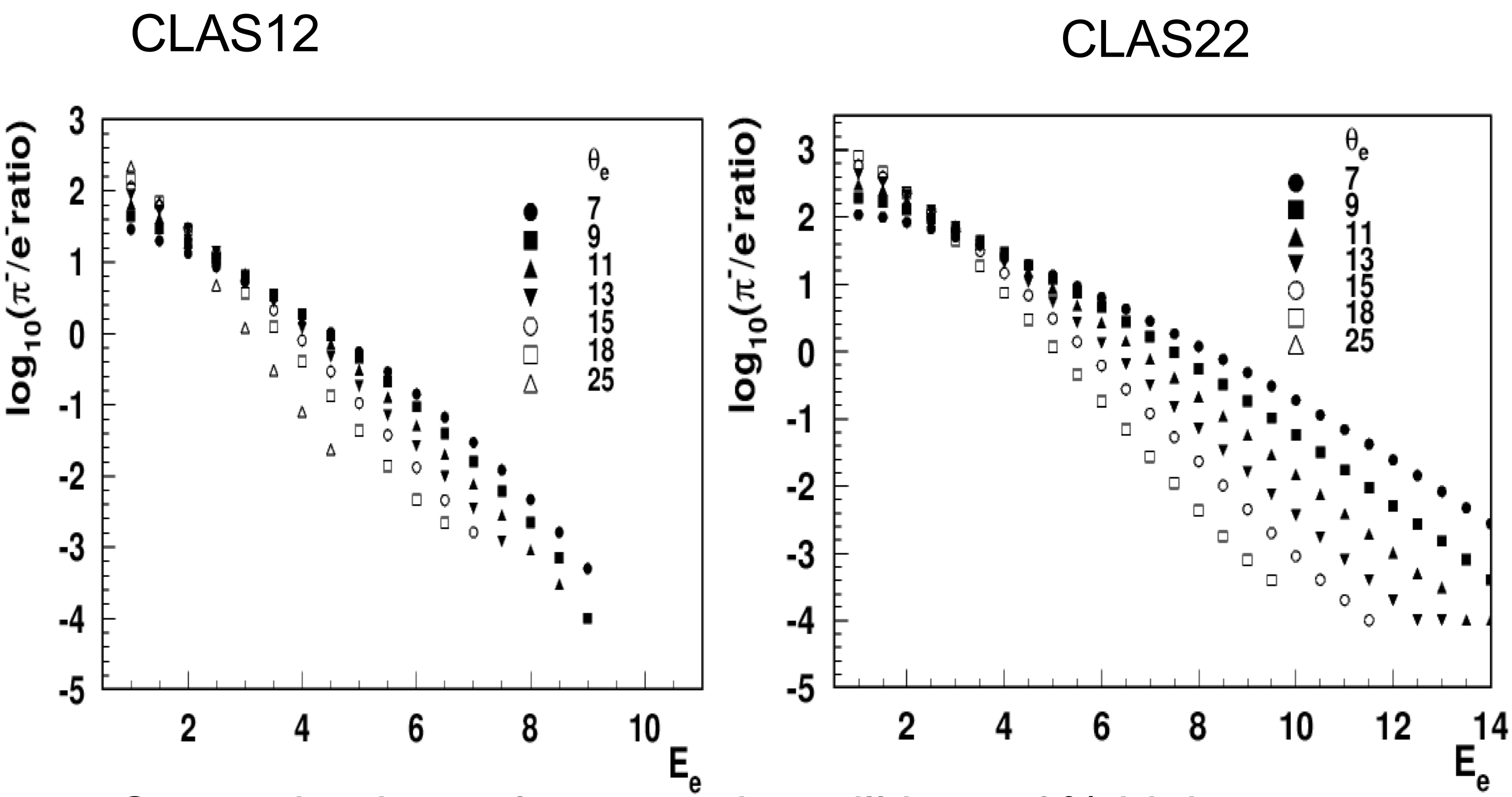
- **Understanding the sea – Δs, $\bar{u}$ - $\bar{d}$, Δ$\bar{u}$ - Δ$\bar{d}$?** JLab, FNAL, RHIC, AMBER, LHC
- **Axial and Tensor charges of the nucleon** COMPASS, JLab
- **Gluon helicity distribution at large *x* AND at small *x*?**
  What is the integral ΔG?
  Total contribution of parton helicity to proton spin?

JLab + DGLAP, RHIC, COMPASS

EIC

- **What happens at really small x << 0.01?**

Relative fluxes: e- vs pi-



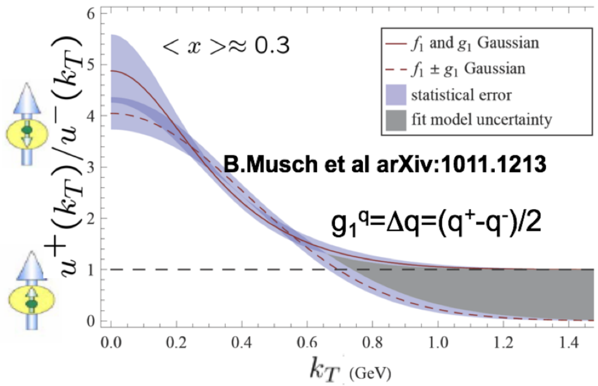
Contamination at low energies will be ~50% higher
(electrons <2 GeV may not be much useful anyway)

Unknown "known" f_1,g_1 TMDs

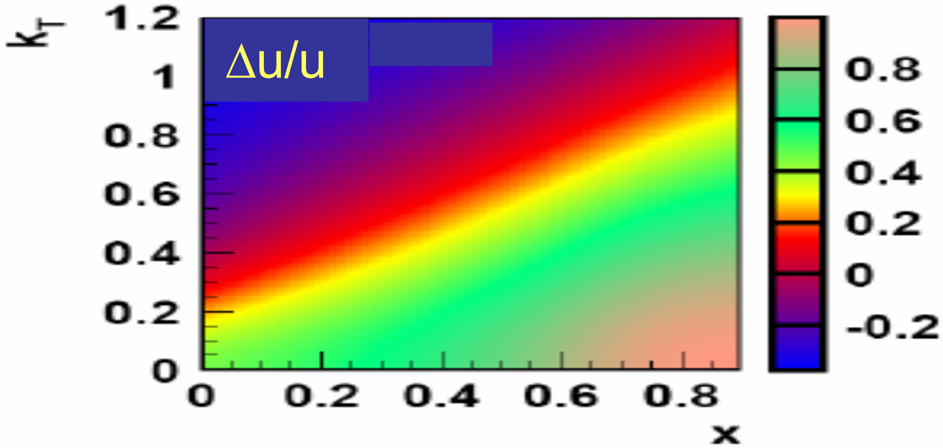
	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$

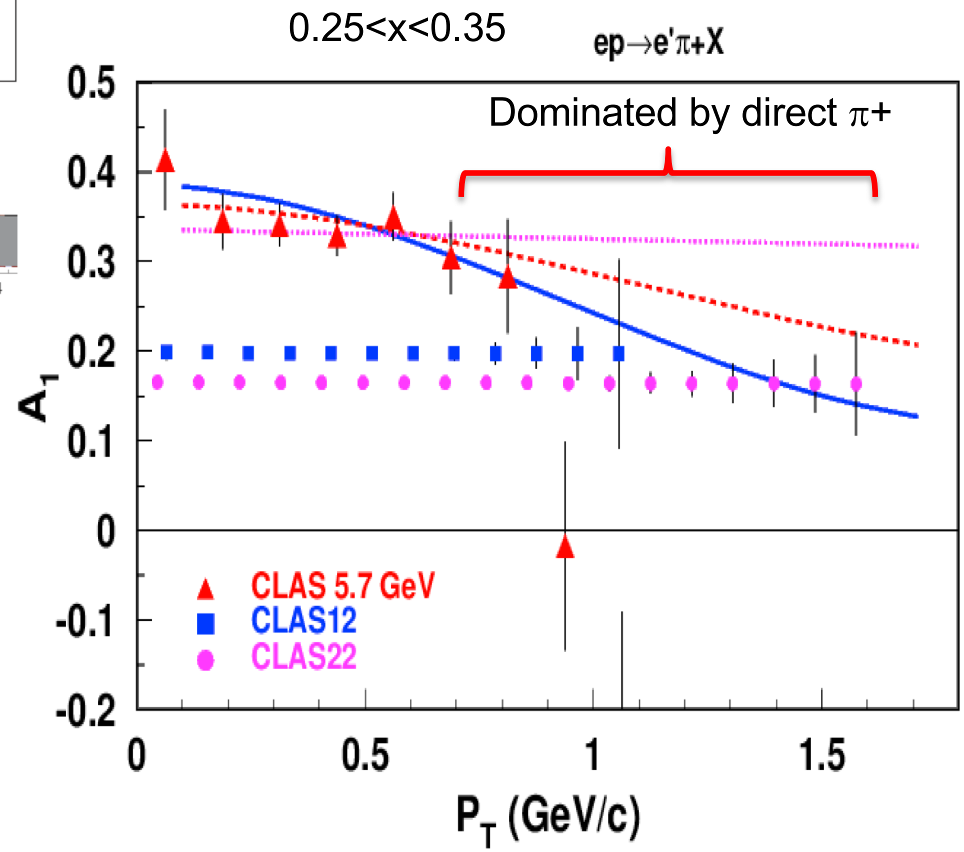
$$u^+(x,k_T) = f_1^u(x,k_T^2) + g_1^u(x,k_T^2)$$

$$u^-(x,k_T) = f_1^u(x,k_T^2) - g_1^u(x,k_T^2)$$



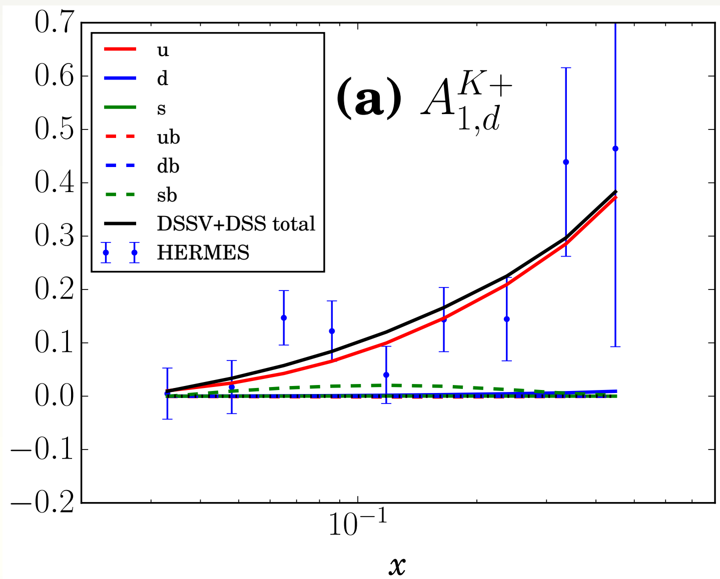
(dipole formfactor), J.Ellis, D-S.Hwang, A.Kotzinian

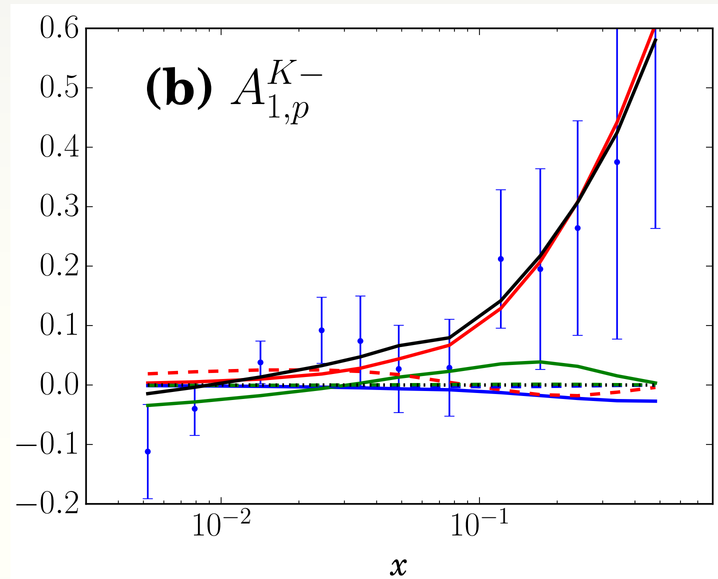




- Models and lattice predict very significant spin and flavor dependence for TMDs
- Large transverse momenta are crucial to access the large k_T of quarks
- Several CLAS12 proposals dedicated to $g_1(x,k_T)$-studies CLAS12
- Understanding of k_T-dependence of g_1 will help in modeling of f_1

PDFs from SEMI-inclusive RG-C data





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