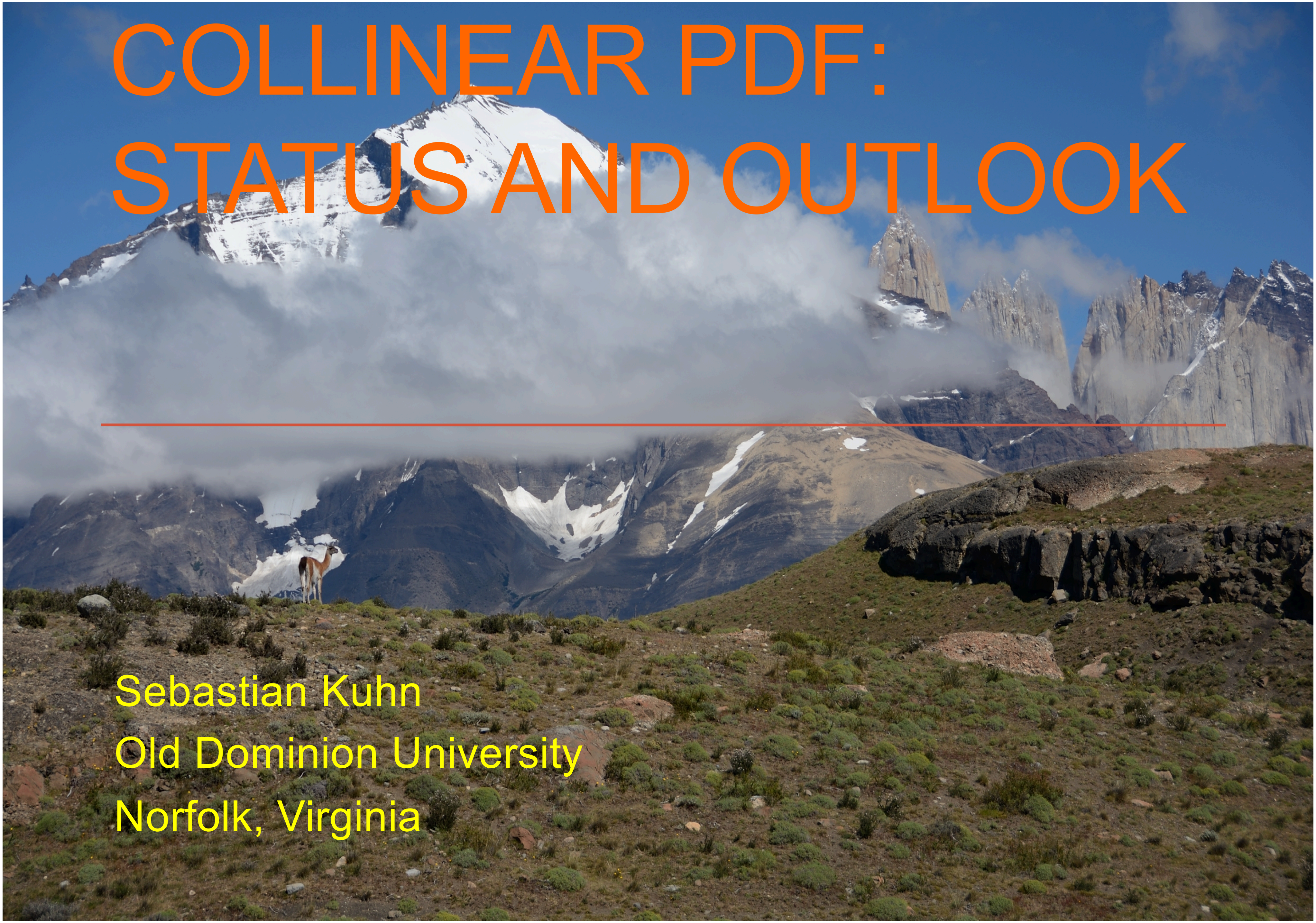


COLLINEAR PDF: STATUS AND OUTLOOK

Sebastian Kuhn
Old Dominion University
Norfolk, Virginia

Overview

PDFs

- Collinear Structure of the Nucleon -
- Polarized and Unpolarized PDFs
- Recent Results
  - Spin-Averaged PDFs
  - Spin-Dependent PDFs
- Outlook
  - Future Experiments
  - EIC

ChPT

Resonance Structure

CQM

Duality
OPE, twist >2

$\Delta\Sigma$

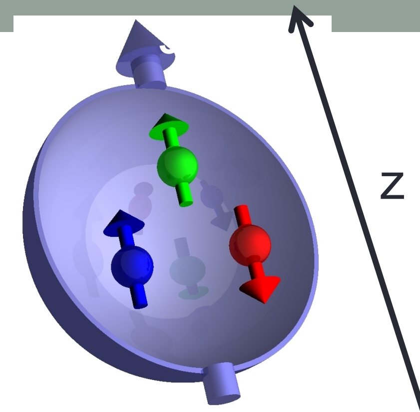
ΔG

d/u, $\Delta q/q$

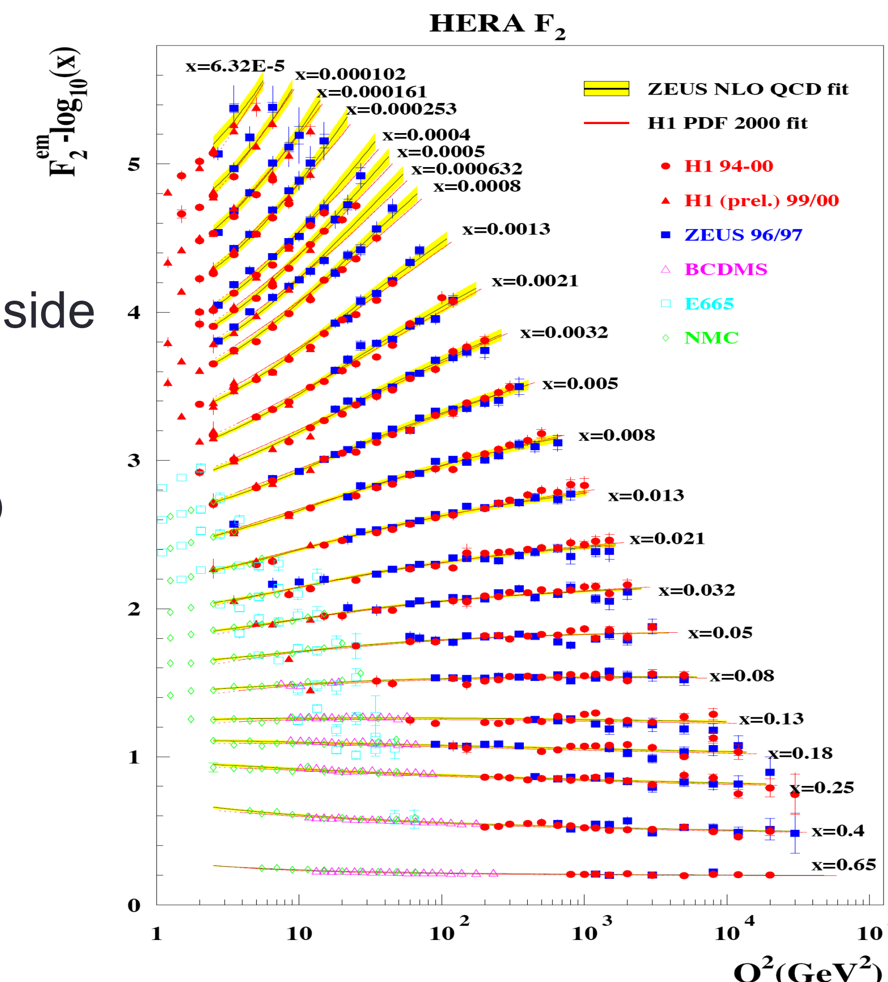
$x \to 1$

Sum Rules

Collinear Parton Distribution Functions - (still) highly relevant!



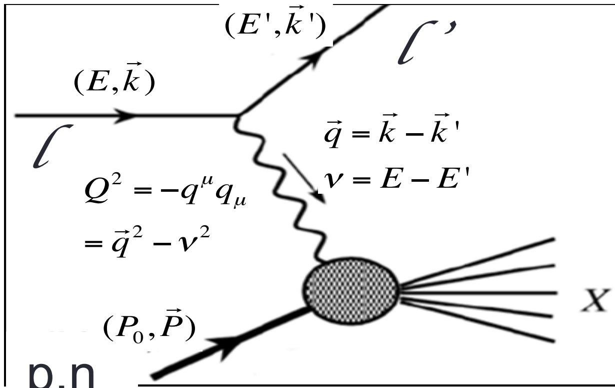
- The 1D world of nucleon collinear structure:
  - Take a nucleon
  - Move it real fast along z
    ⇒ light cone momentum
    $P_+ = P_0 + P_z$ (>>M)
  - Select a "parton" (quark, gluon) inside
  - Measure **its** l.c. momentum
    $p_+ = p_0 + p_z$ ($m \approx 0$)
  - ⇒ Momentum Fraction x = p_+/P_+ $^{*)}$
  - In DIS $^{**)}$: $p_+/P_+ \approx \xi = (q_z - \nu)/M$
    $\approx x_{Bj} = Q^2/2M\nu$
  - Probability: $f_1^i(x), i = u, d, s, \ldots, G$



In the following, will often write "$q_i(x)$" for $f_1^i(x)$

$^{*)}$ Advantage: Boost-independent along z

$^{**)}$ DIS = "Deep Inelastic (Lepton) Scattering; here assuming target rest frame

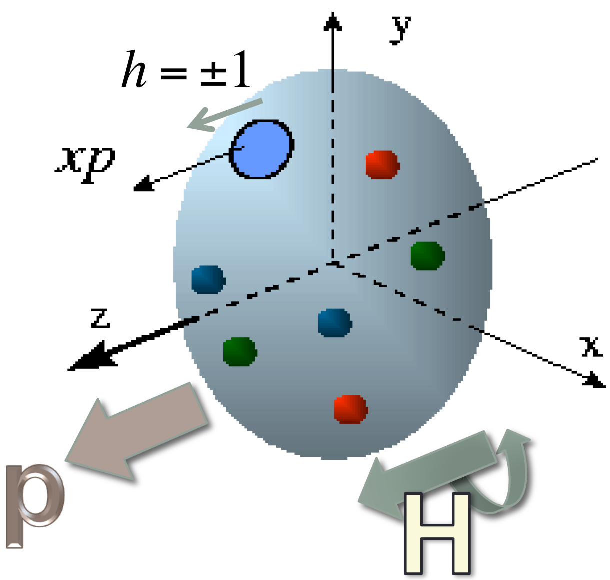


Inclusive lepton scattering

Callan-Gross   Wandzura-Wilczek

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

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



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

"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?

Moments of Structure Functions

Importance of *high* x!

Related to matrix elements of local operators (OPE) - in principle accessible to lattice QCD calculations

Sum rules relate moments to the total spin carried by quarks in the nucleon (and β-decay matrix elements), sea quark asymmetries etc.

At low Q^2: Higher Twist, Parton-Hadron Duality, Chiral Perturbation Theory, GDH Sum Rule all make predictions for moments

Gottfried Sum Rule:

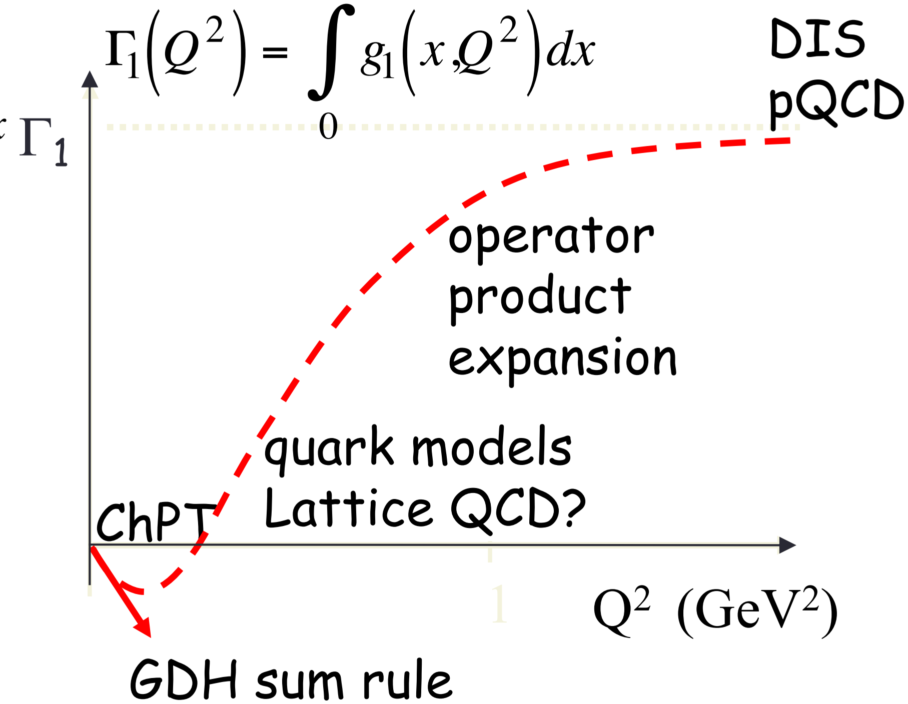
$$\int_0^1 \left[F_2^p(x,Q^2) - F_2^n(x,Q^2)\right]\frac{dx}{x} = \frac{1}{3} - \frac{2}{3}\int_0^1 \left[\bar{d}(x,Q^2) - \bar{u}(x,Q^2)\right]dx$$

Bjorken Sum Rule: $\Gamma_1^p - \Gamma_1^n = \dfrac{g_A}{6} + \text{ QCD corr.}$

GDH Sum Rule: $\Gamma_1\left(Q^2 \to 0\right) \to -\dfrac{Q^2}{2M^2}\dfrac{\kappa^2}{4}$

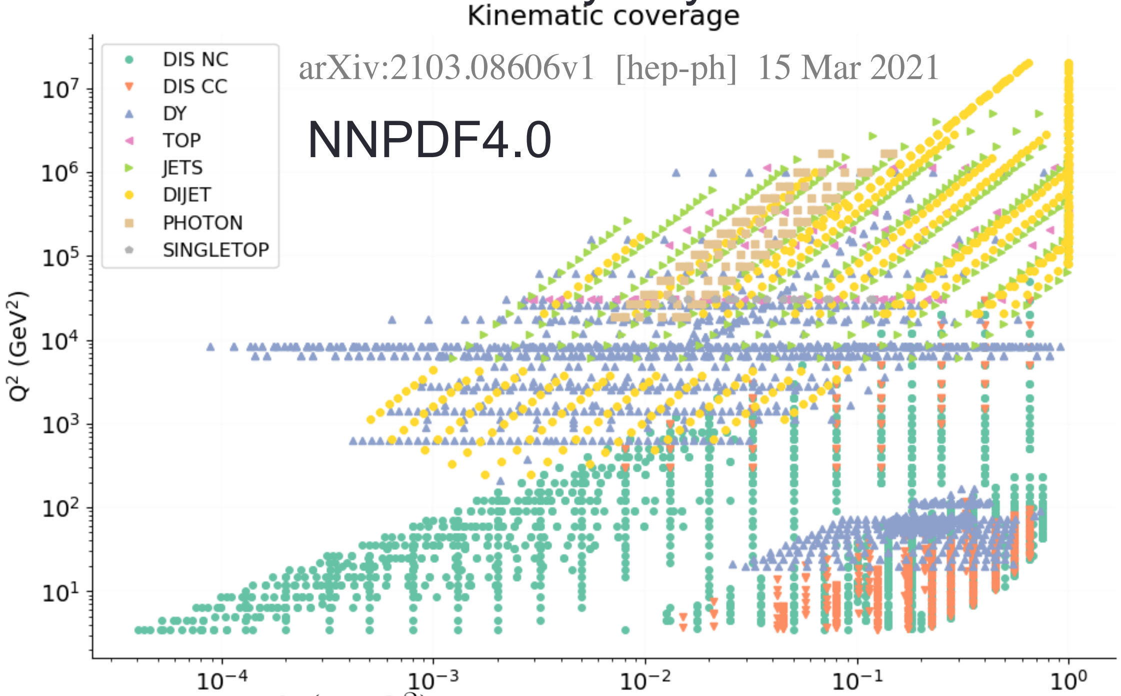
…and γ_0, δ_{LT}

$$\Gamma_1\left(Q^2\right) = \int_0^1 g_1\left(x,Q^2\right)dx$$

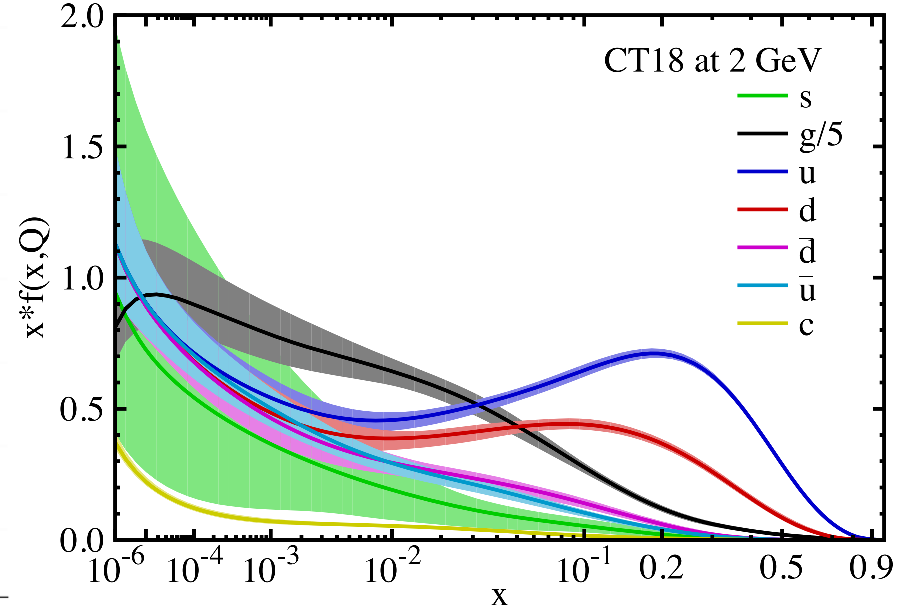


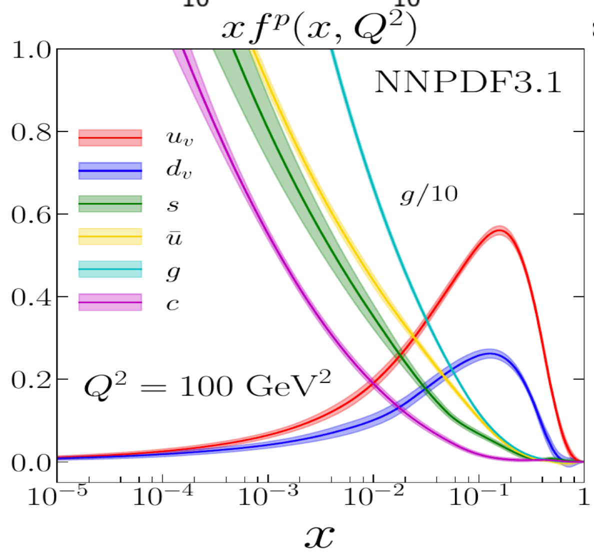
Unpolarized PDFs

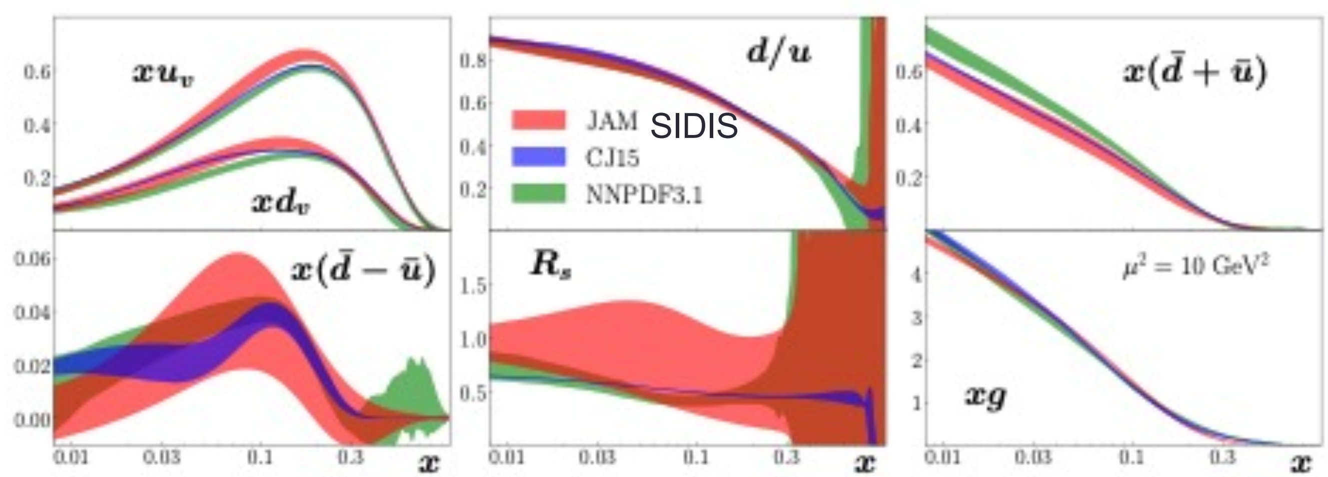
World Data Coded by Physics Process



PHYS. REV. D 103, 014013 (2021)



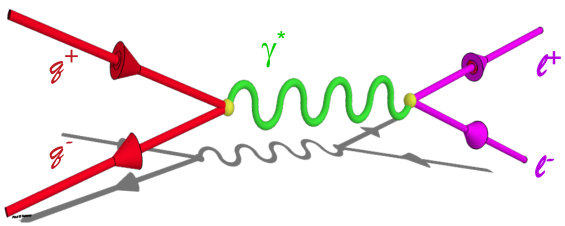


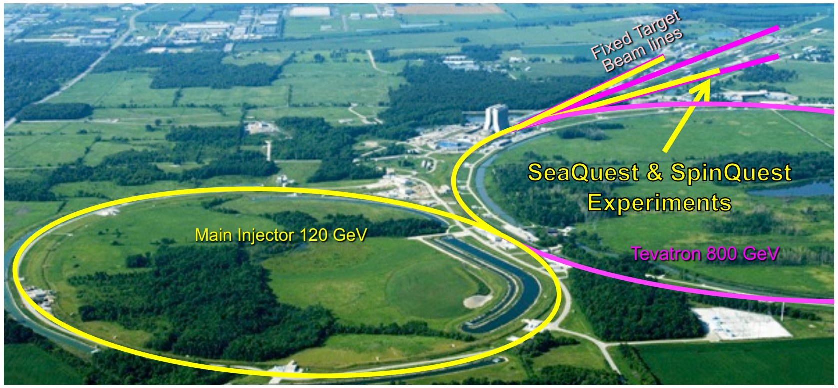


arXiv:2101.04664v1 [hep-ph] 12 Jan 2021

Unpolarized PDFs

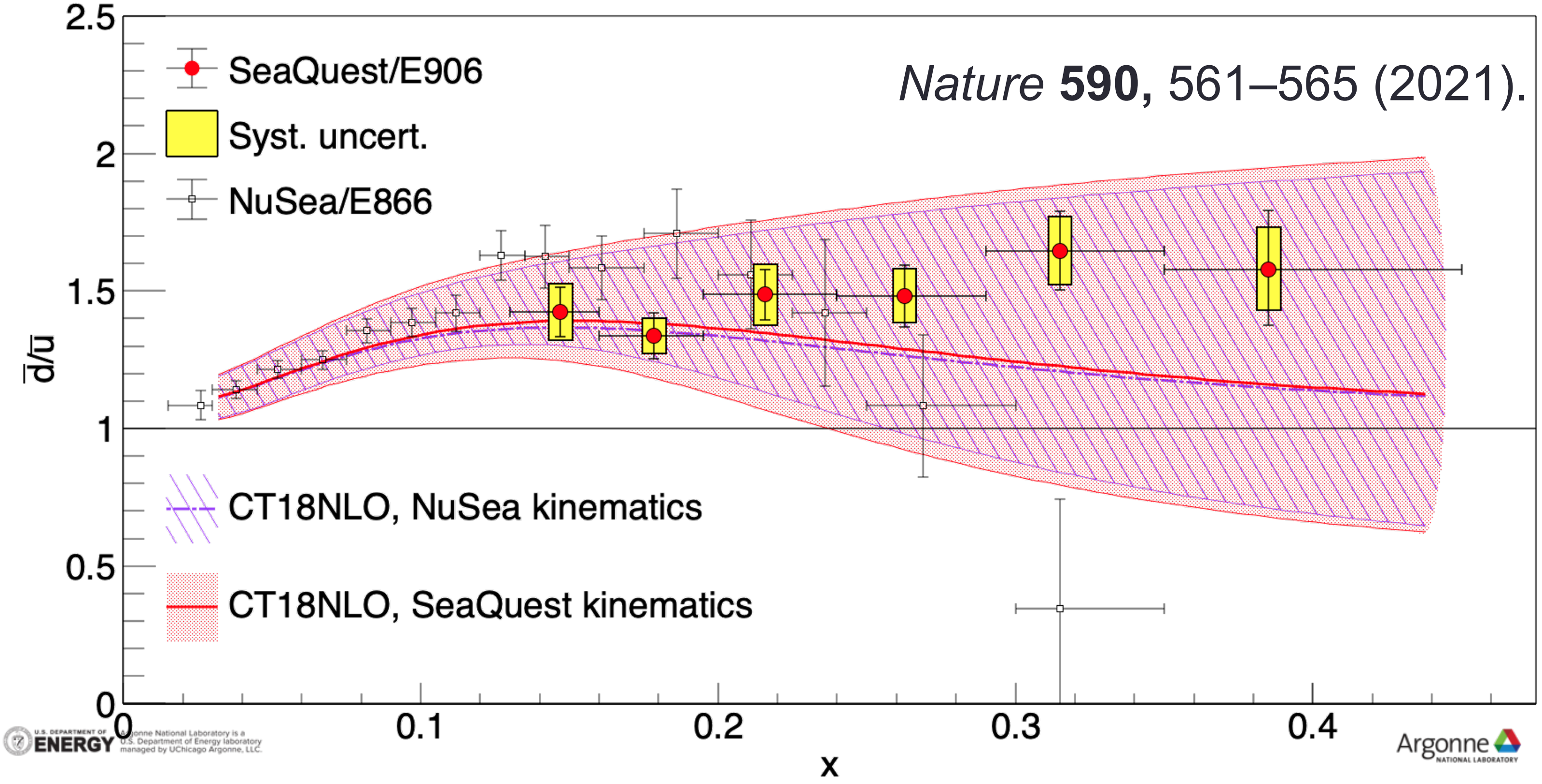
Drell-Yan in pp-collisions at FermiLab





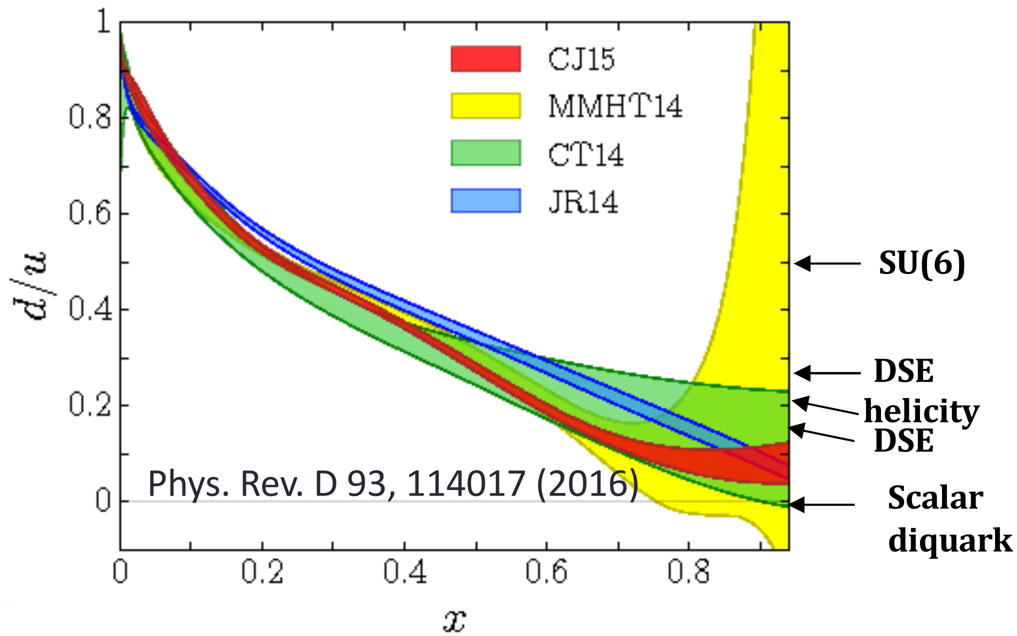
SeaQuest compared with Global Fits

Courtesy Paul Reimer, ANL



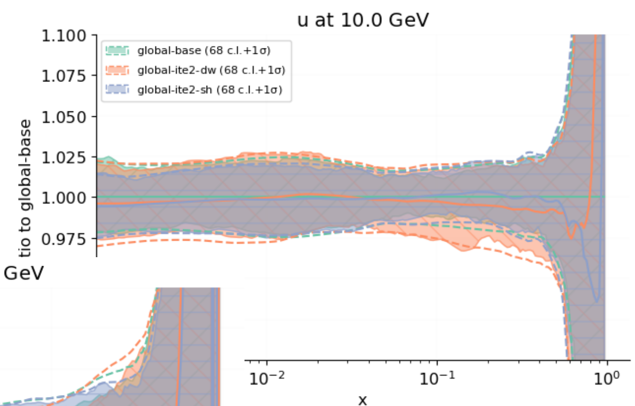
Unpolarized PDFs– high *x*

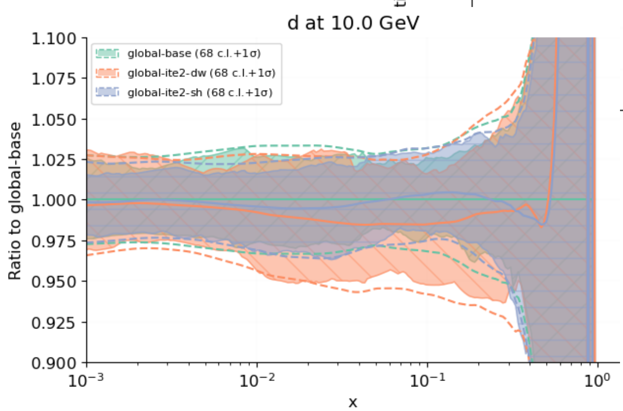
Nucleon Model	F_2^n/F_2^p $X \to 1$	d/u $X \to 1$
SU(6) Symmetry	2/3	0.5
Scalar diquark dominance	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
PQCD (helicity conservation)	3/7	0.2



NNPDF3.1

[arXiv:2011.00009](https://arxiv.org/abs/2011.00009)





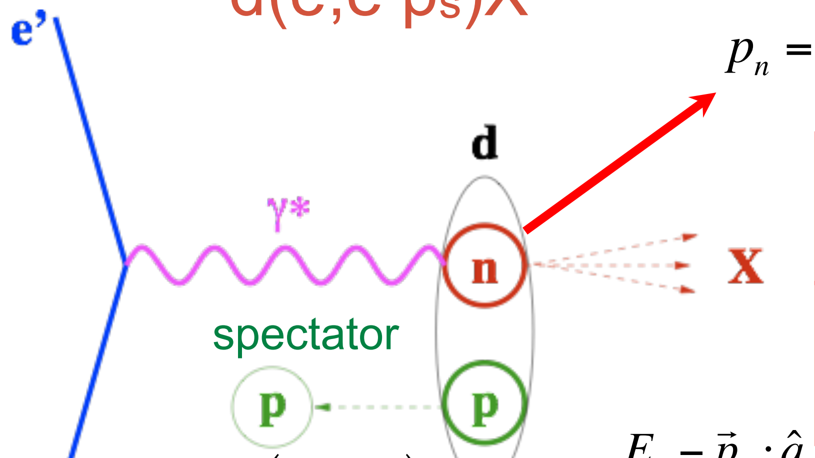
d/u from…

- F_{2n}/F_{2p}, but
  - Free neutron targets don't exist
  - Extraction from D data complicated by Binding, Fermi Motion, FSI
- 3H/3He, but
  - Still only smeared SF ratios
  - Requires assumptions about isospin-dependence of EMC effect
- PVDIS, but limited by statistics

Spectator Tagging – BONuS12

SLOW, backward spectator – minimize FSI, Offshell effects, target fragmentation

d(e,e′p$_s$)X

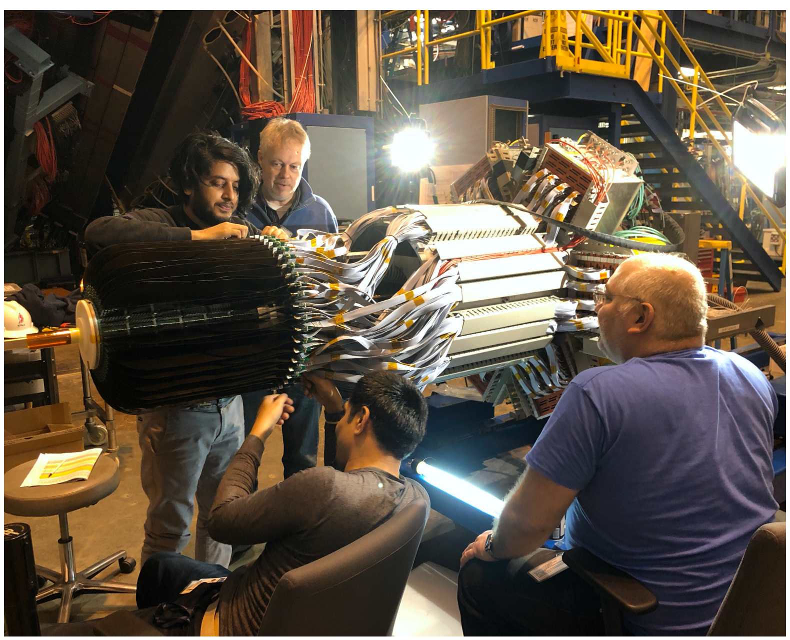


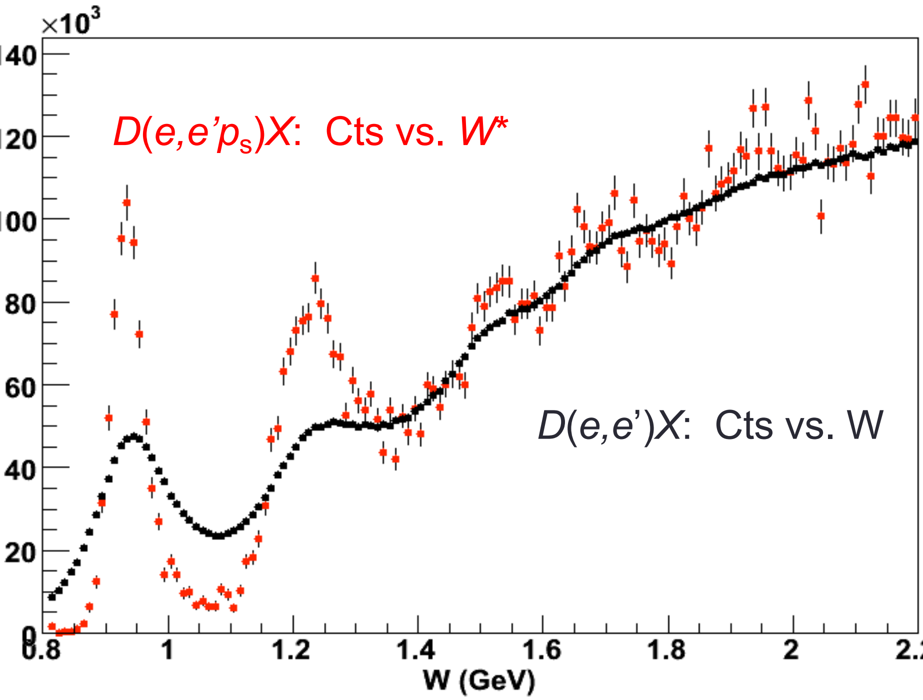
$$p_S = (E_S, \vec{p}_S); \qquad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D/2}$$

$$p_n = (M_D - E_S, -\vec{p}_S); \alpha_n = 2 - \alpha_S \qquad M^{*2} = p_n^{\mu} p_{n\mu}$$

$$\boxed{x^* = \frac{Q^2}{2 p_n{}^{\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2-\alpha_S)}}$$

$$\boxed{\begin{aligned} W^{*2} &= (p_n + q)^2 = M^{*2} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2 \\ &\approx M^{*2} + 2M\nu(2-\alpha_s) - Q^2 \end{aligned}}$$

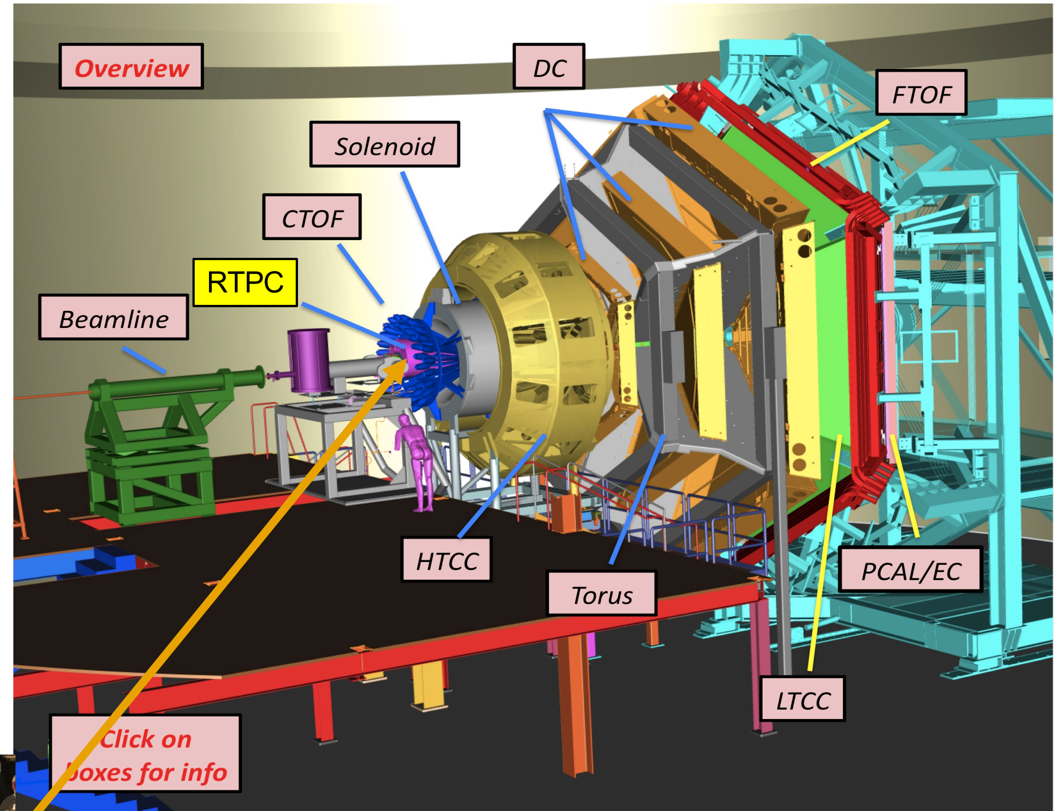


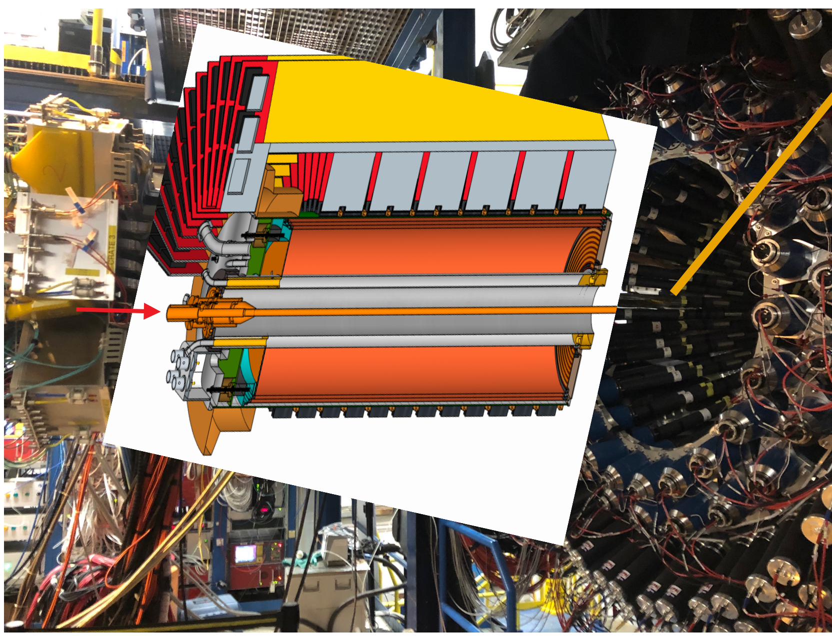


BONuS12

- CLAS12 Forward Detector:
→ Superconducting Torus magnet.
→ 6 independent sectors:
- → HTCC
- → 3 regions of DCs
- → LTCC /RICH
- → FTOF Counters
- → PCAL and ECs

- Central Detector:
→ Solenoid (3.5 - 4 T)
→ Target: D gas @ 6 atm, 293 K
→ BONuS12 RTPC
→ FMT
→ CTOF, and CND

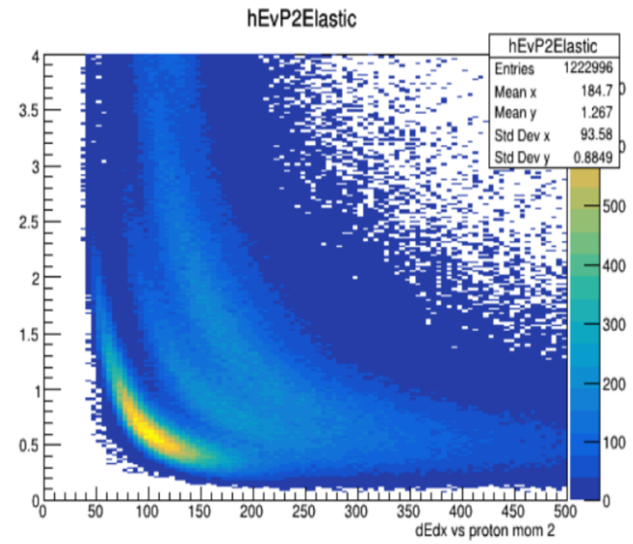


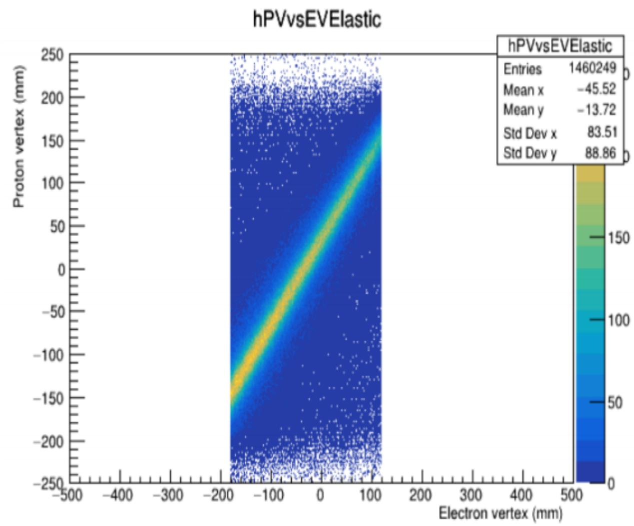


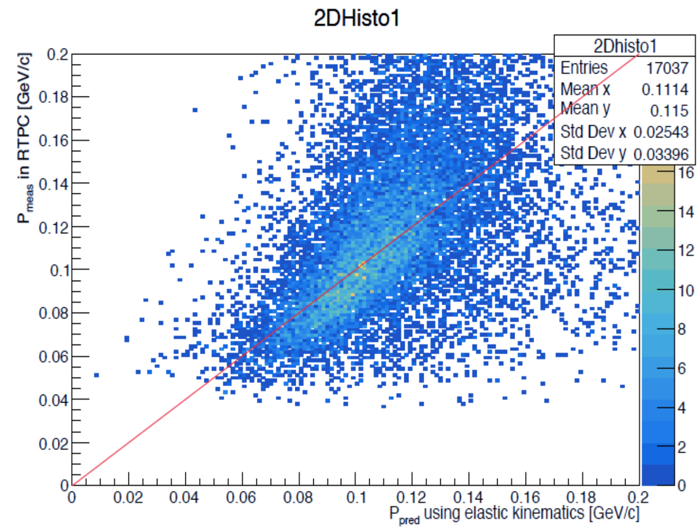
Beam Energy	Target	Spring 2020	Summer 2020
1 Pass Data	H2	81M	185M
	D2	37M	45M
	4He	19M	44M
	Empty	1M	22M
	Total	138M	296M
5 Pass Data	H2	151M	266M
	D2	2275M	2355M
	4He	77M	51M
	Empty	21M	45M
	Total	2524M	2717M

February – March 2020 | MEDCON6 | August-September 2020

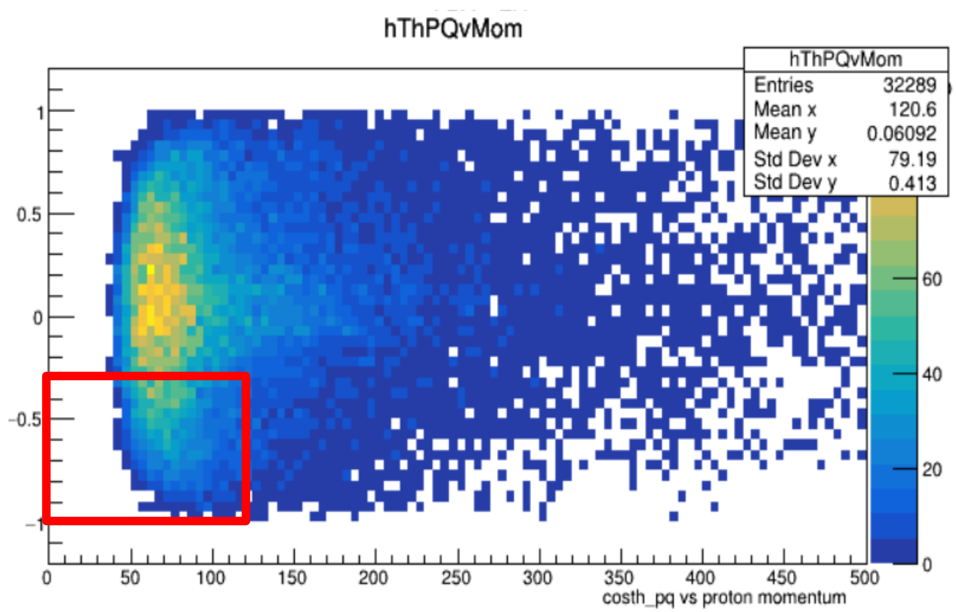
BONuS12 - 2.1 GeV Data

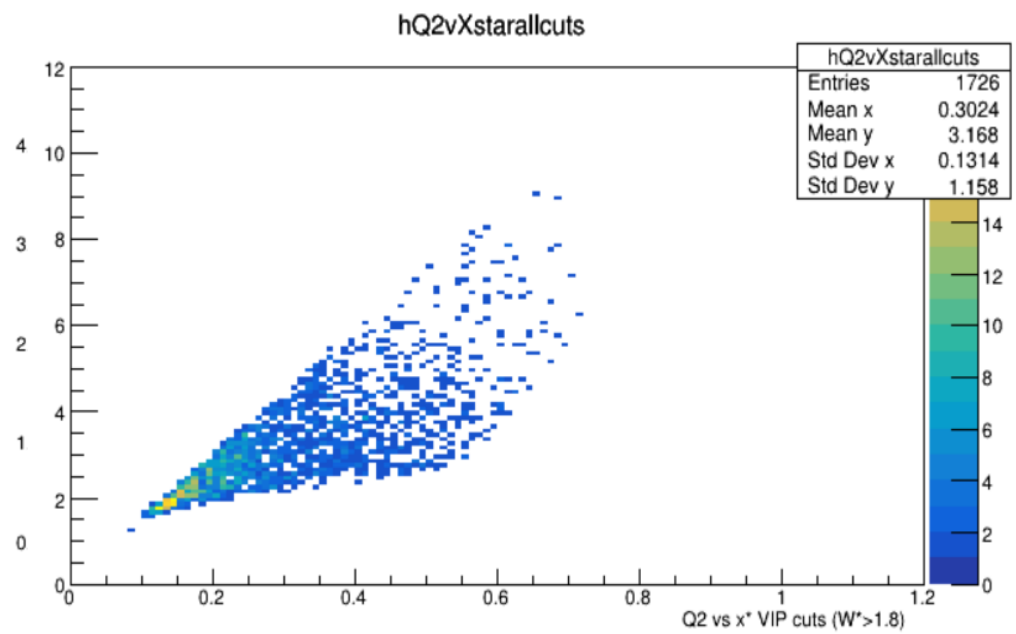




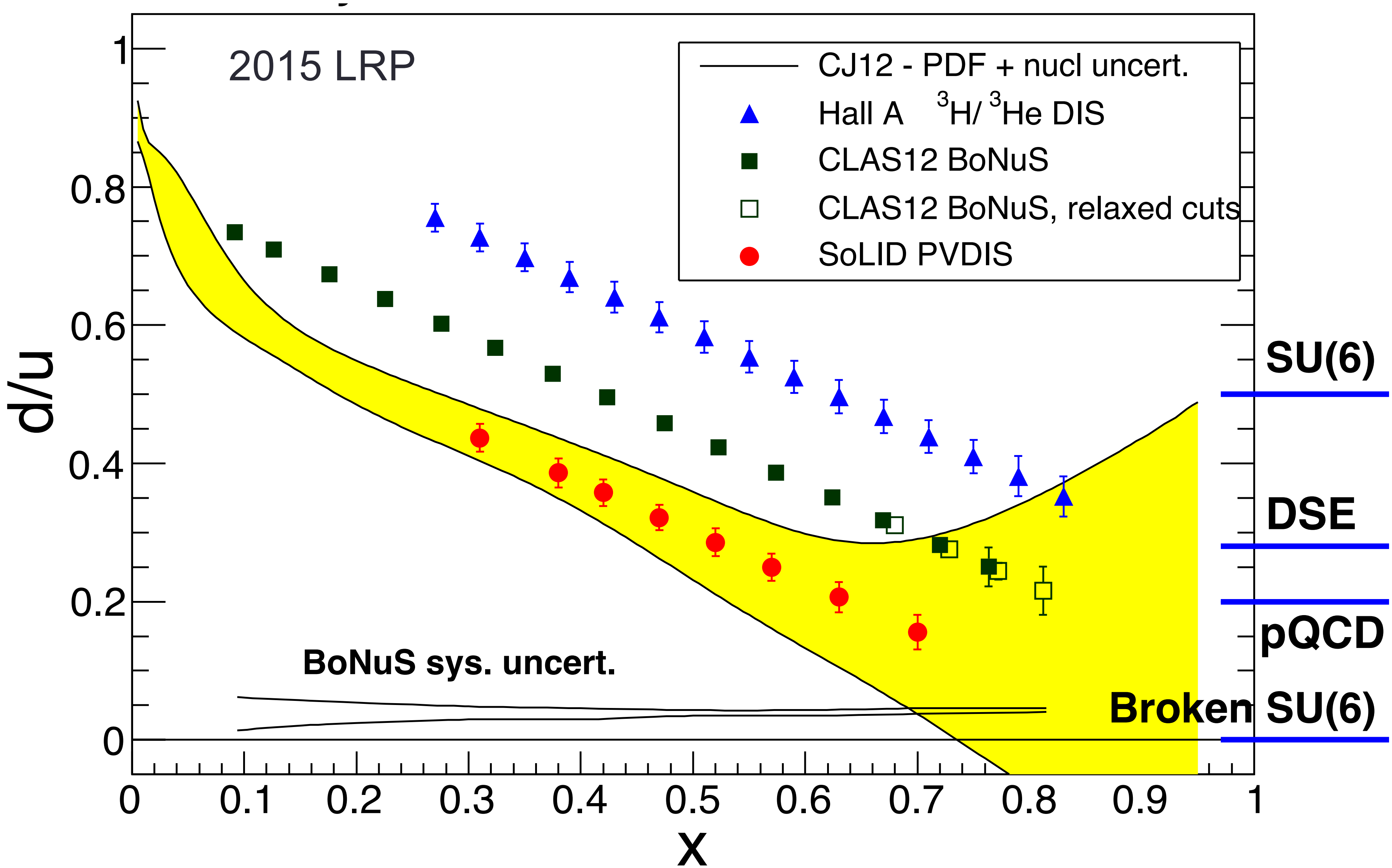


BONuS12 – 10.4 GeV Data

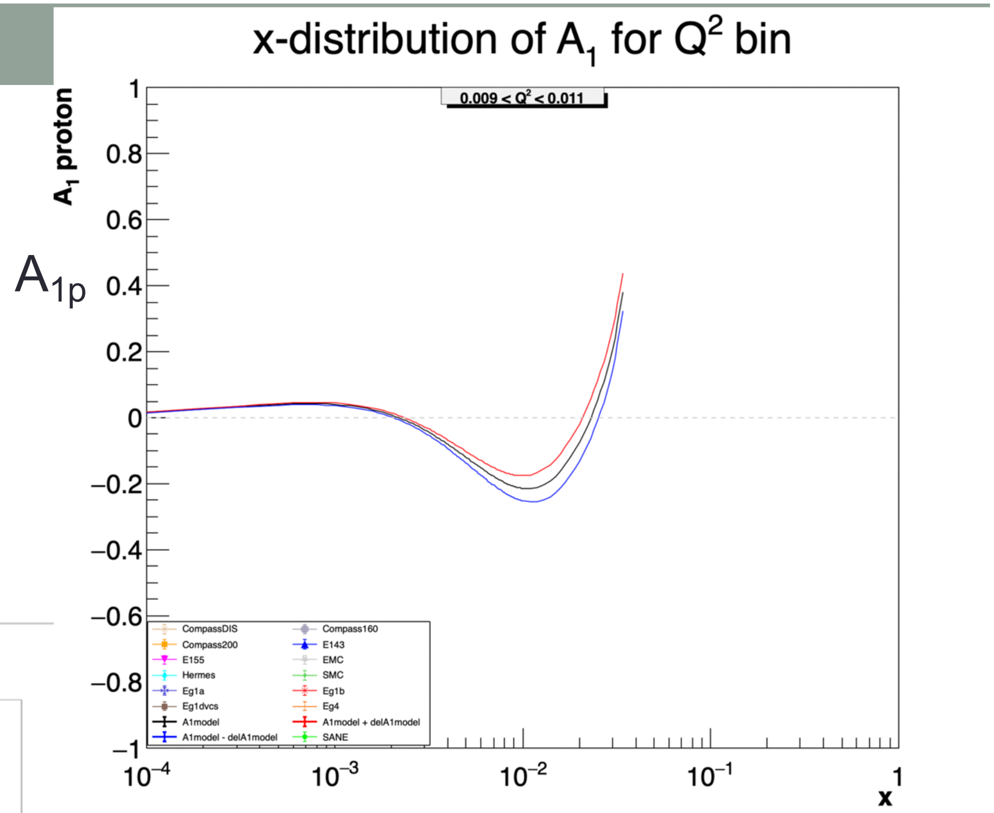




Projected JLab@12 GeV d/u Results

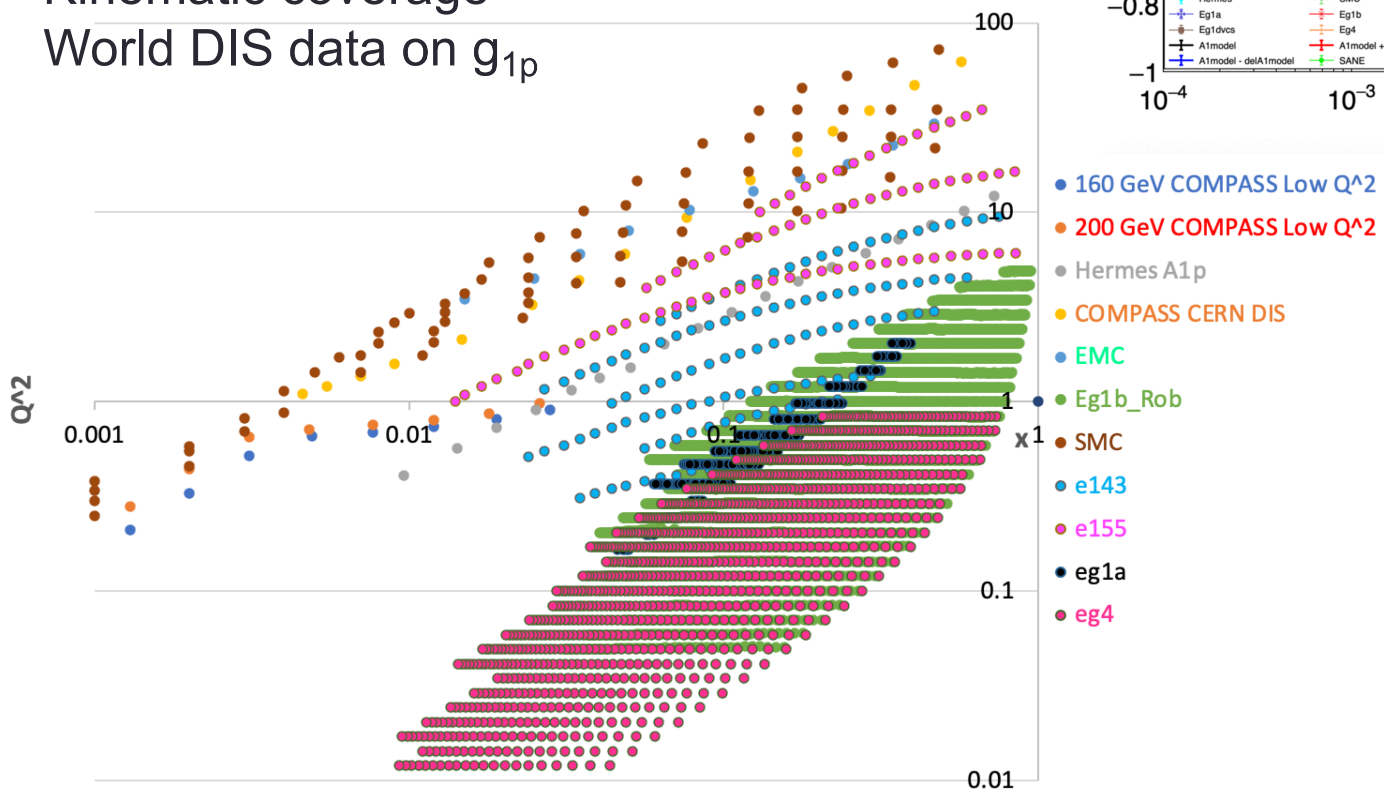


Polarized Structure Functions



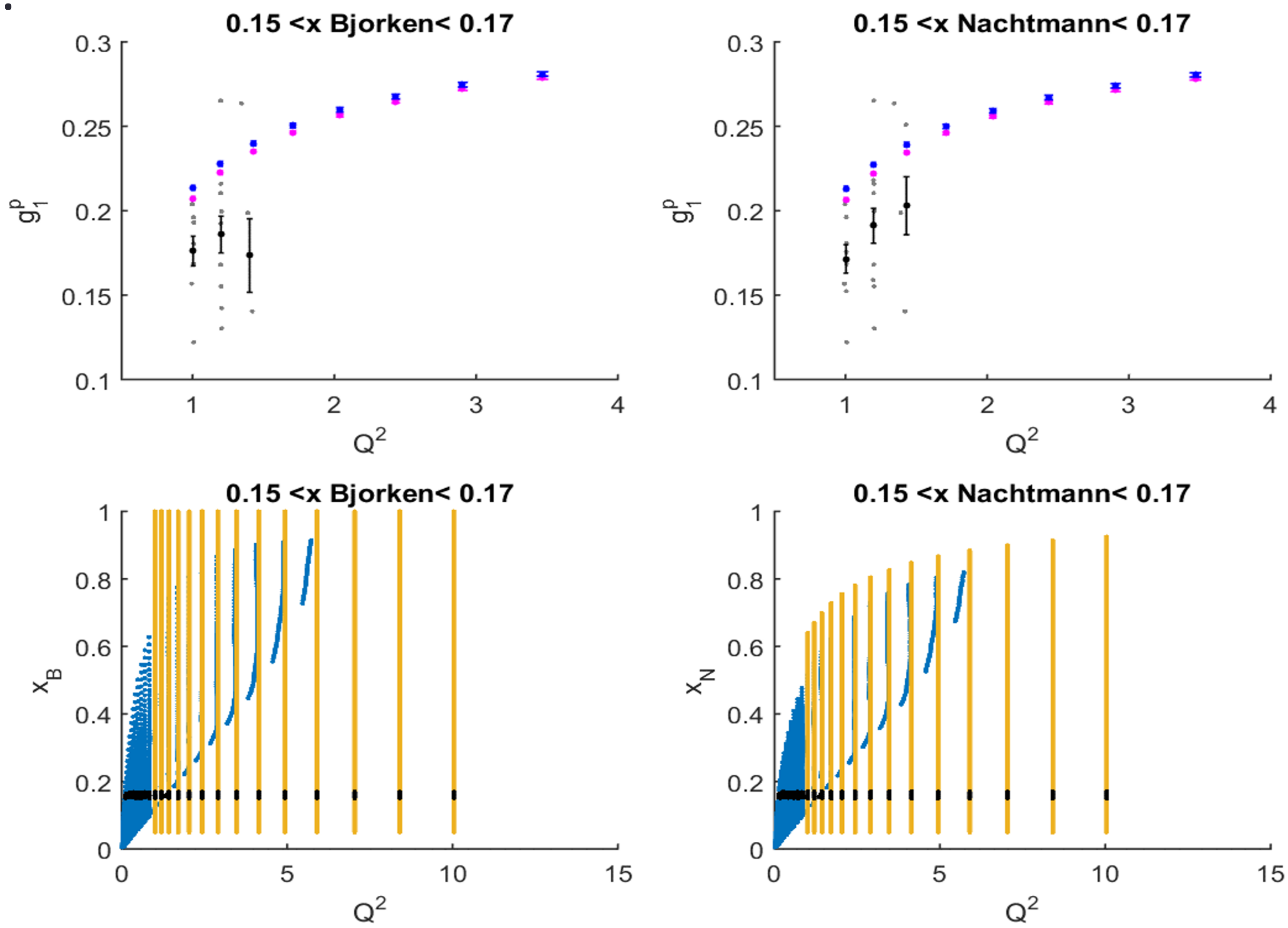
"EG1 fit" of the World Data

Kinematic coverage –
World DIS data on g_{1p}

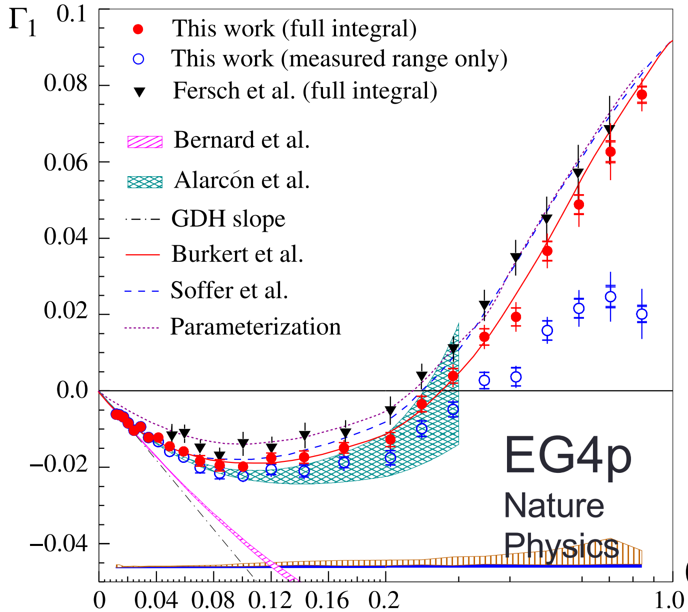


Polarized Structure Functions - Duality

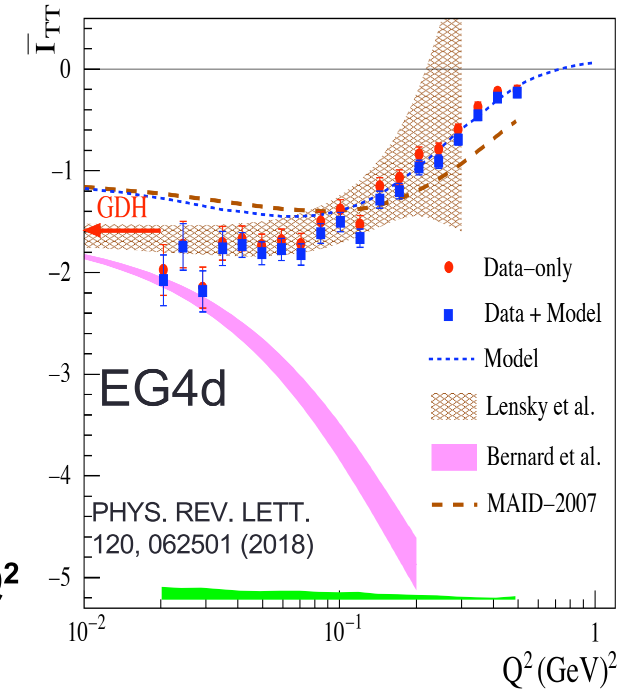
Compare 4-6 GeV g_{1p} data (eg1b) to JAM DGLAP fits in the DIS region (W>2).

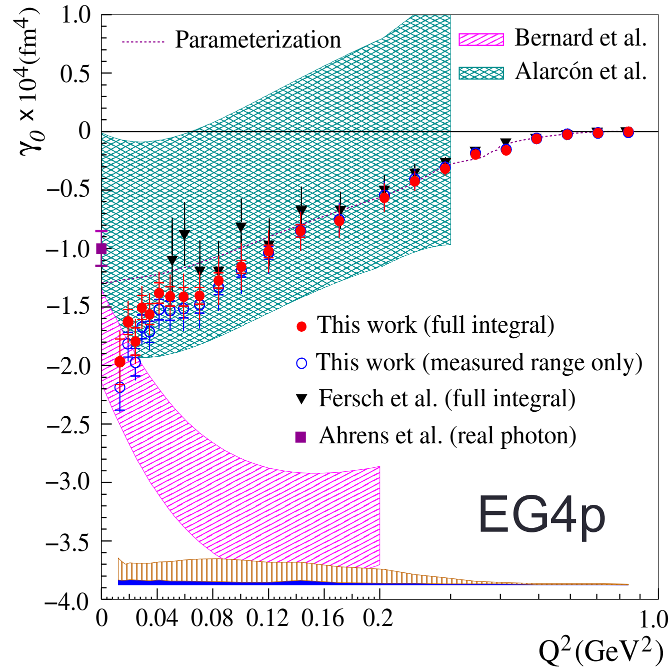


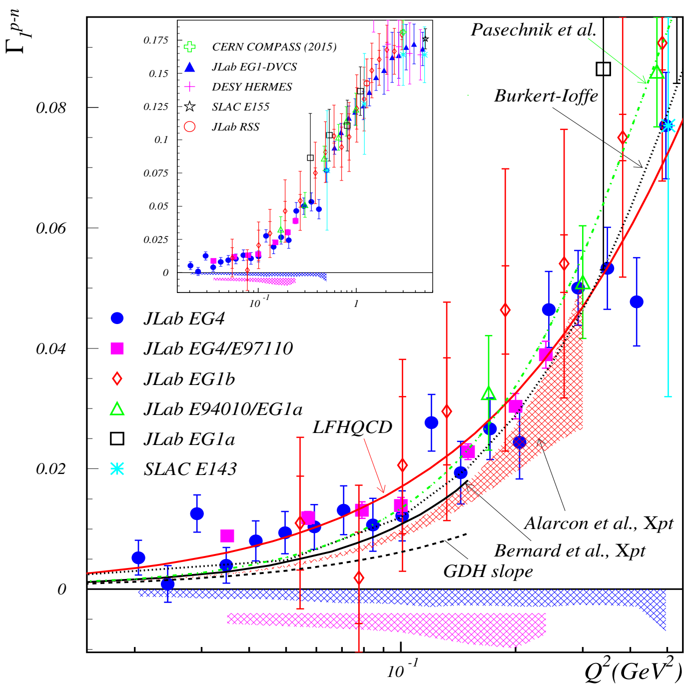
Low Q^2 – testing χPT

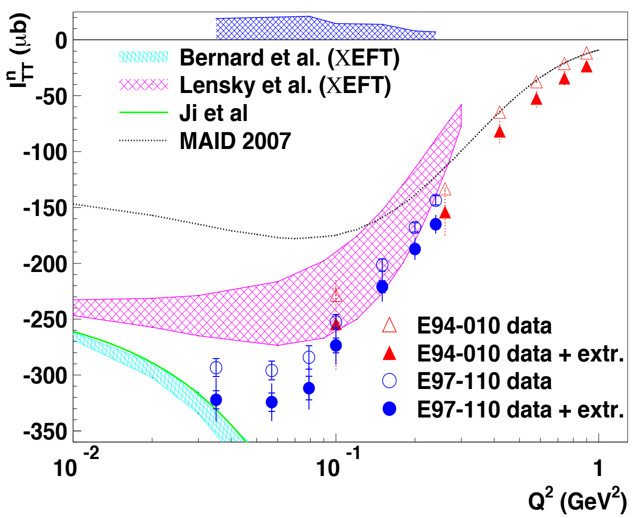


Q2

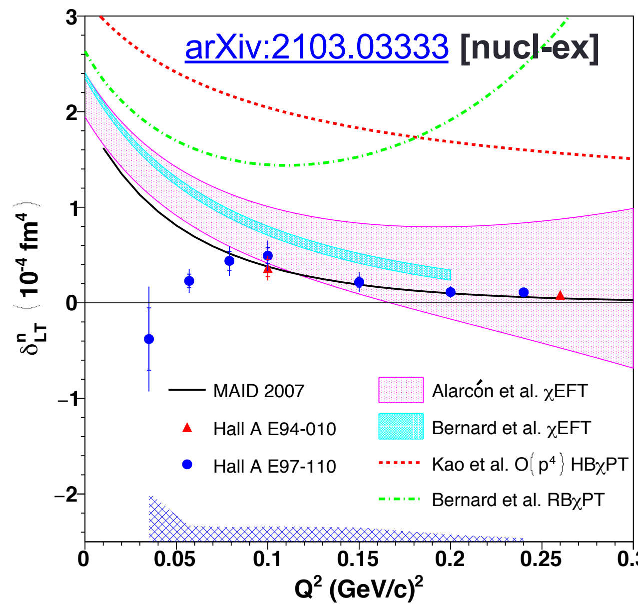




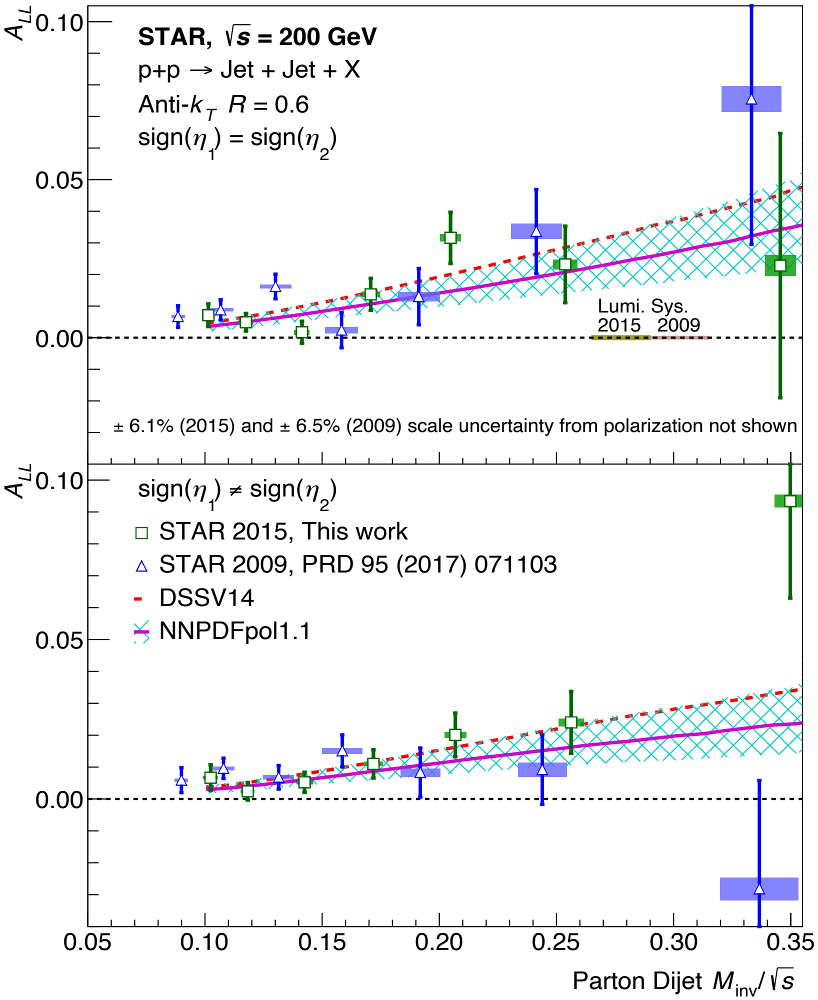




Phys. Lett. B 805 (2020) 135428



Polarized PDFs – pp collisions



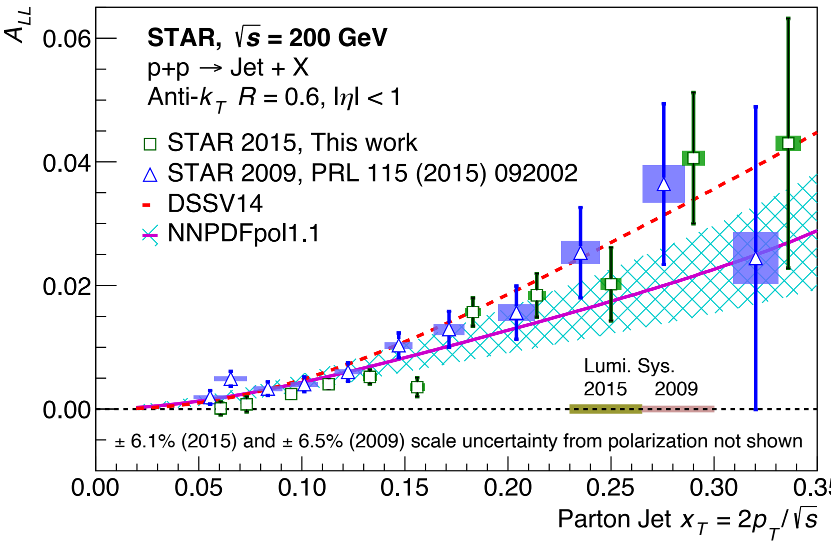
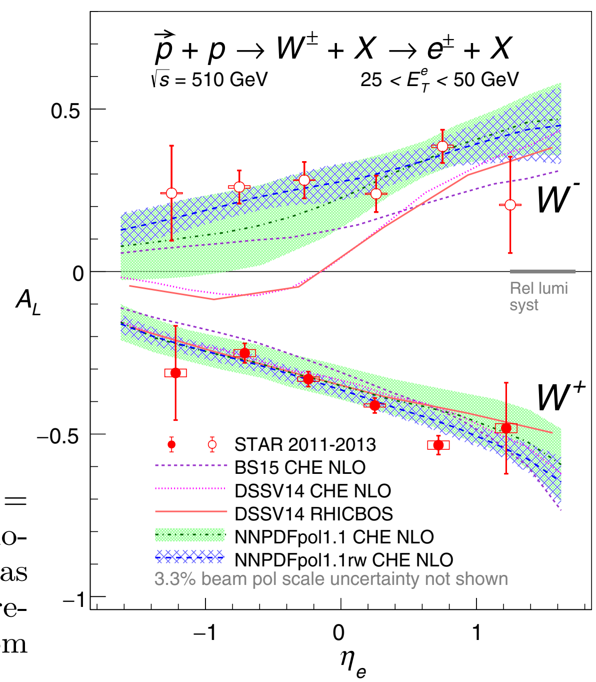
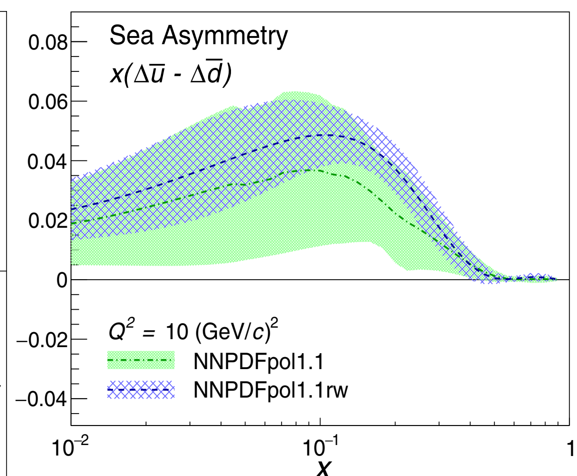


FIG. 4. A_{LL} versus $M_{inv}/\sqrt{s}$ for dijets with the sign(η_1) = sign(η_2) (top) and sign(η_1) ≠ sign(η_2) (bottom) event topologies. The square markers show the present data, whereas the triangle markers show the data of Ref. [46]. The results are compared to theoretical predictions for dijets from DSSV14 [18] and NNPDFpol1.1 [20] with its uncertainty.





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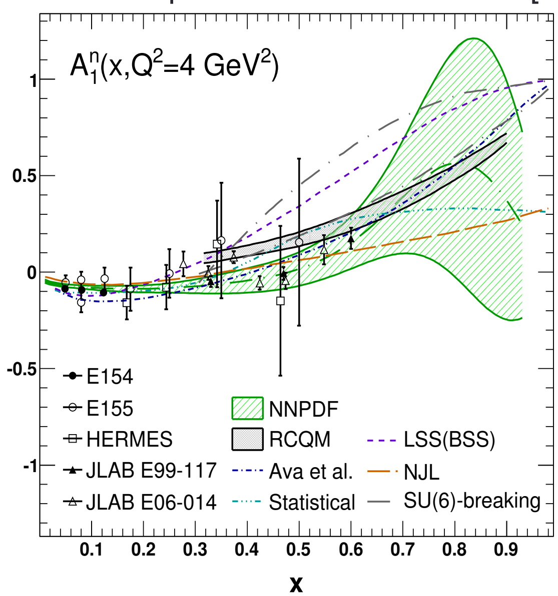
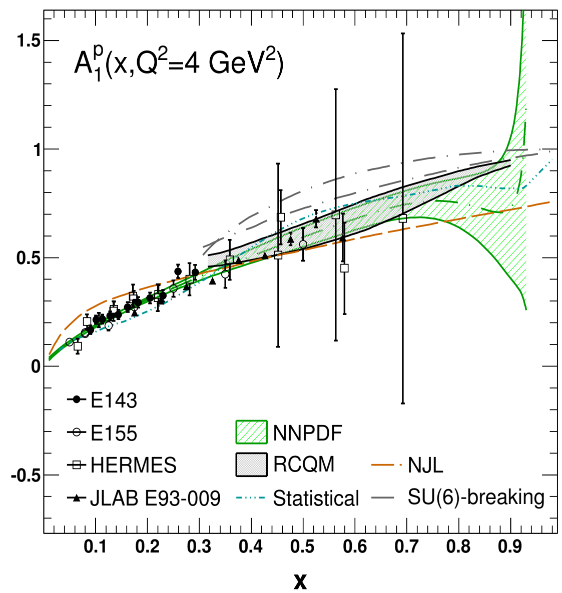
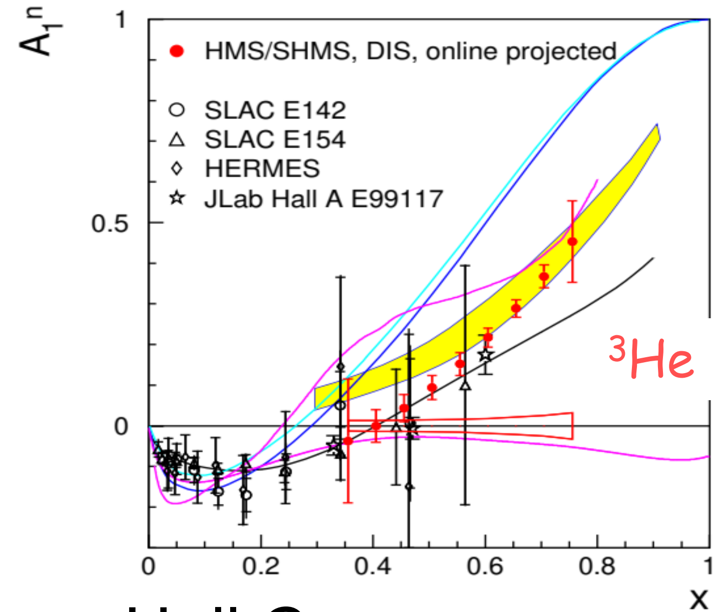
Future PDFs: What's left to do for Jefferson Lab?

NNPDFpol1.1 arXiv:1410.7290v2 [hep-ph]

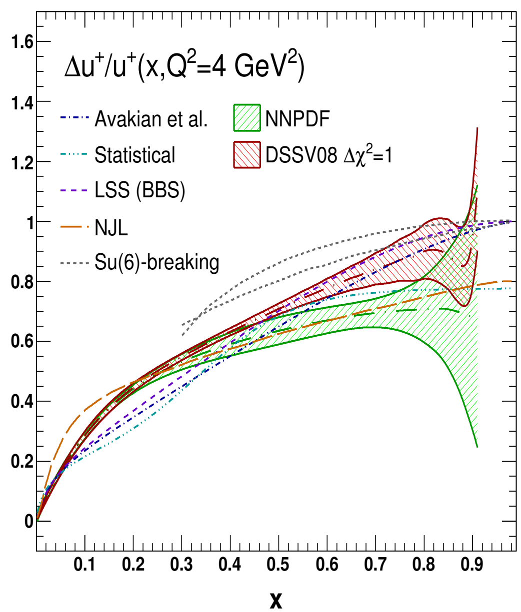


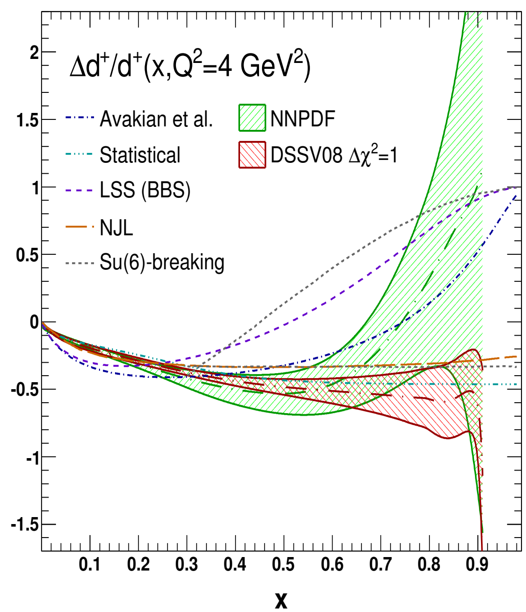


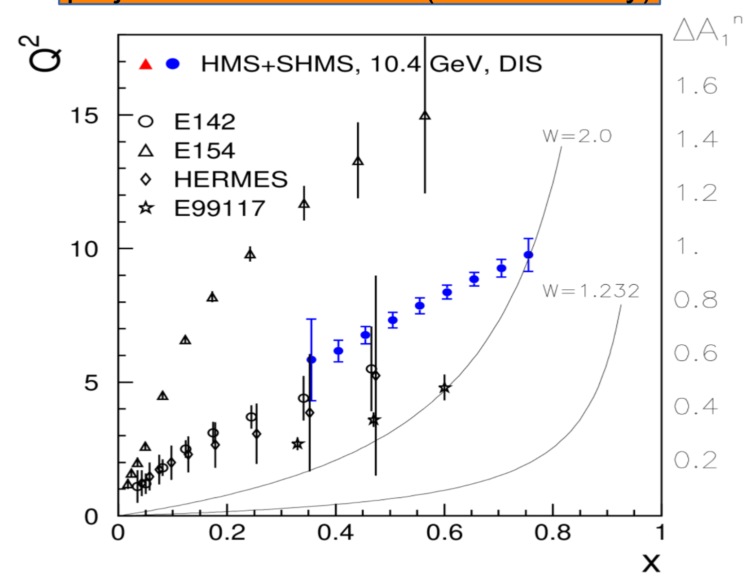


Hall C

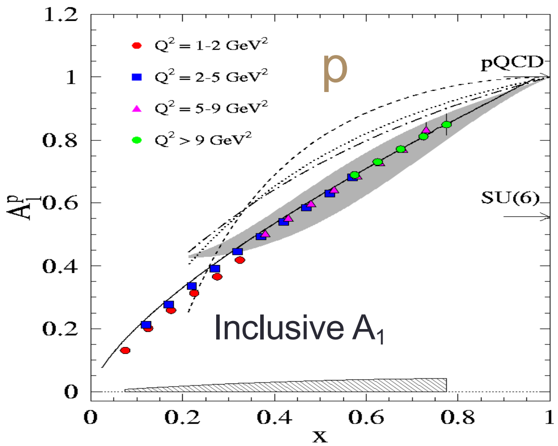
projected online results (stat error only)

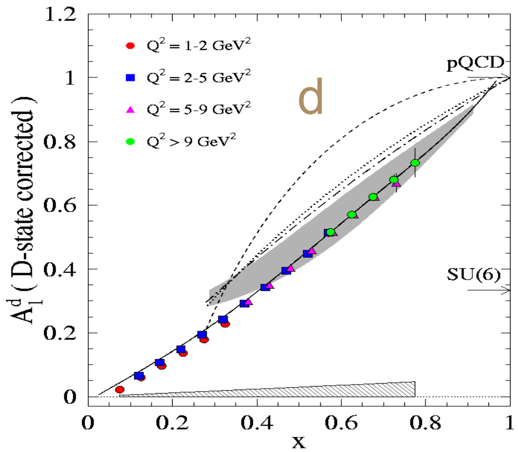




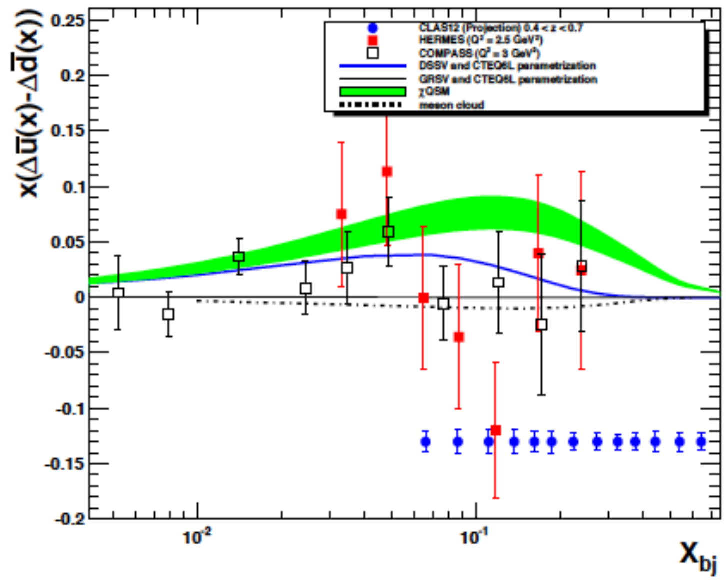


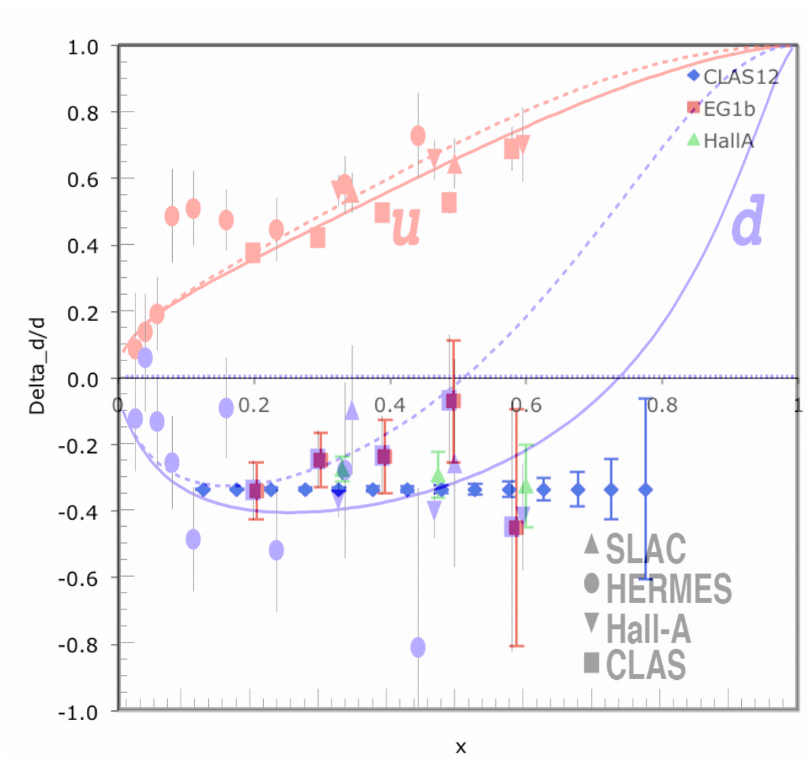
Future Spin PDFs: Hall B

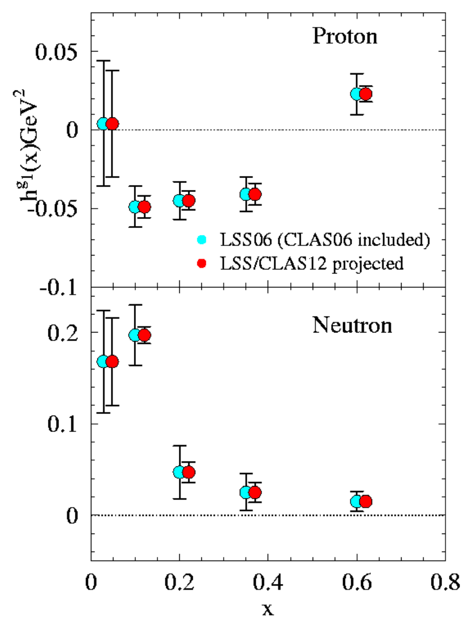




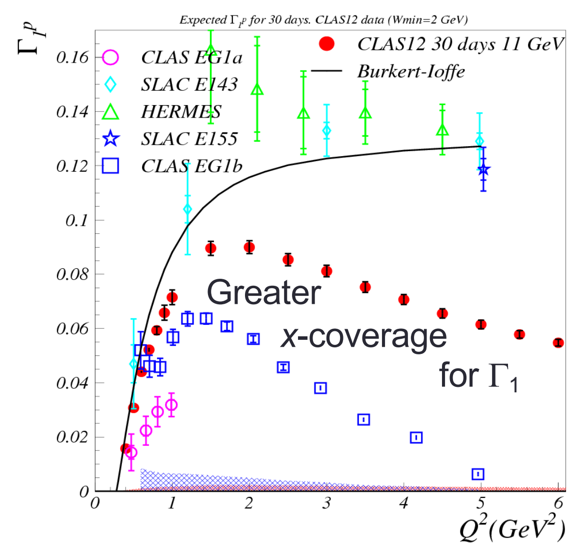
SIDIS A_1







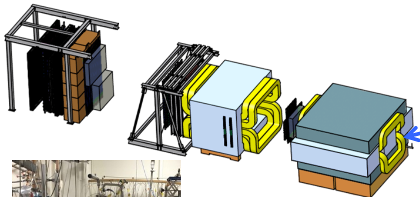
Better determination of Higher Twist vs. x

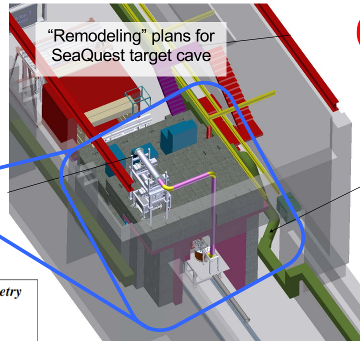


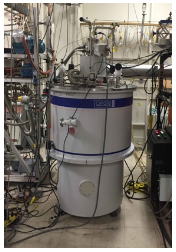
Improved coverage to evaluate moments

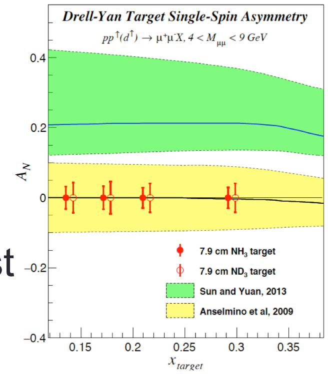
Other Future Experiments

SEAQUEST E1039 STATUS

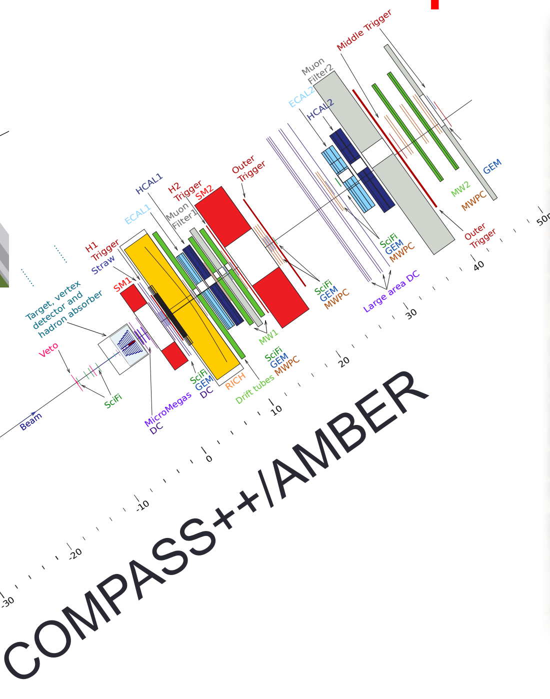


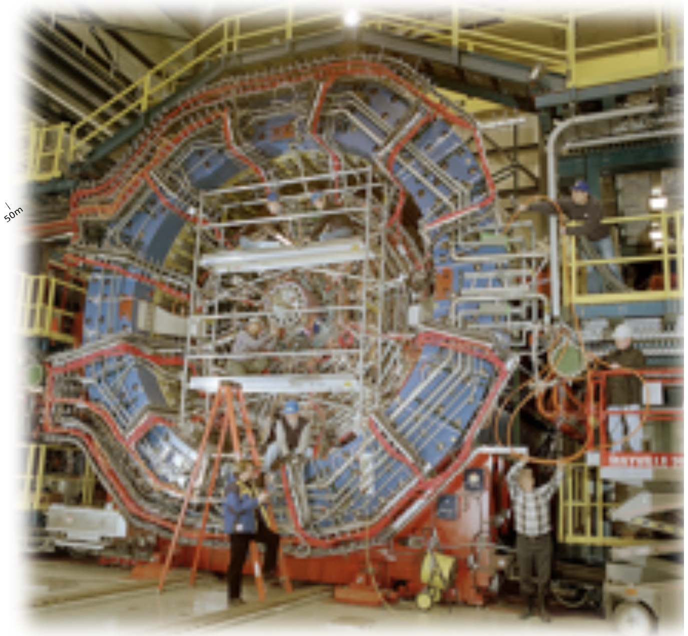




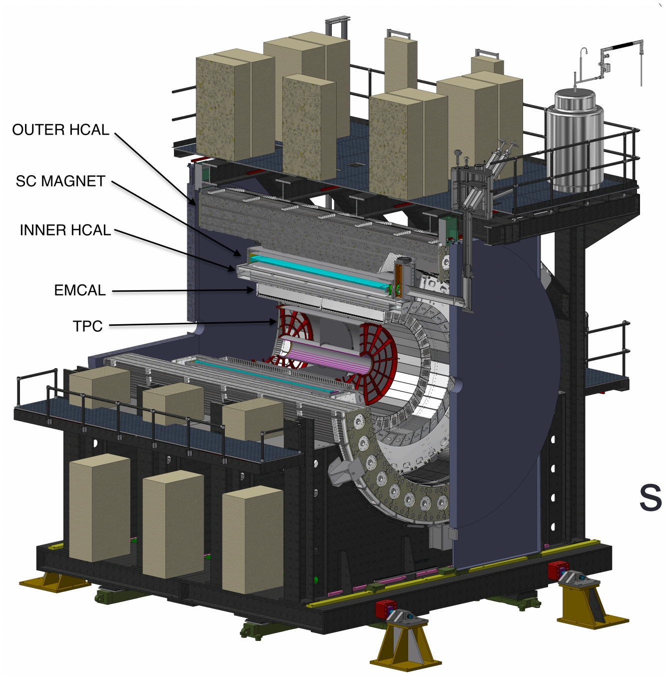


SpinQuest
at FNAL

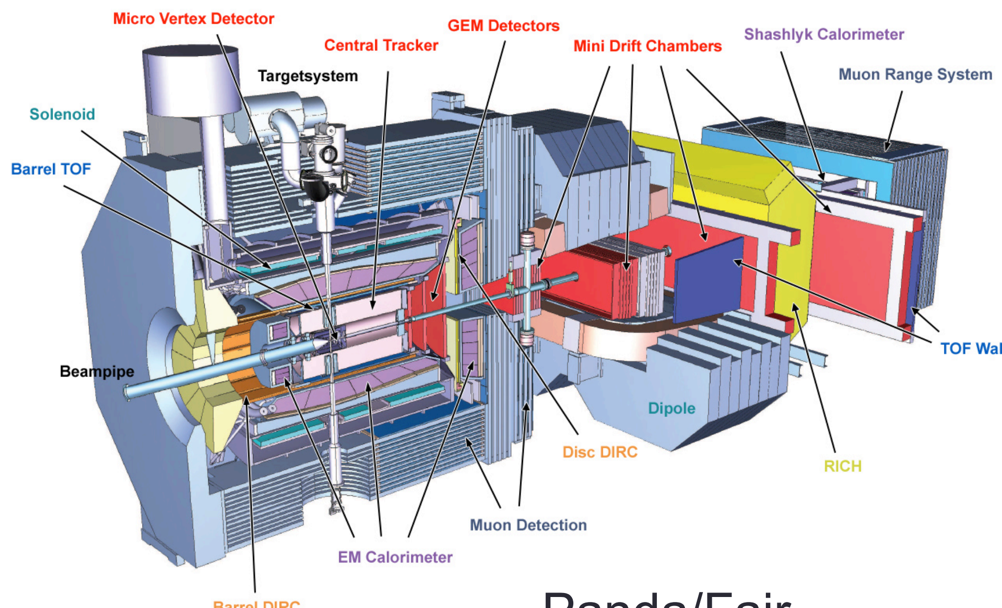




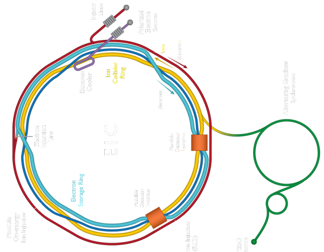
STAR



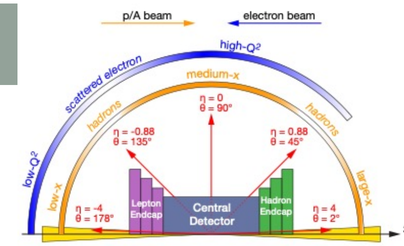
sPHENIX



Panda/Fair



EIC (Yellow Report)



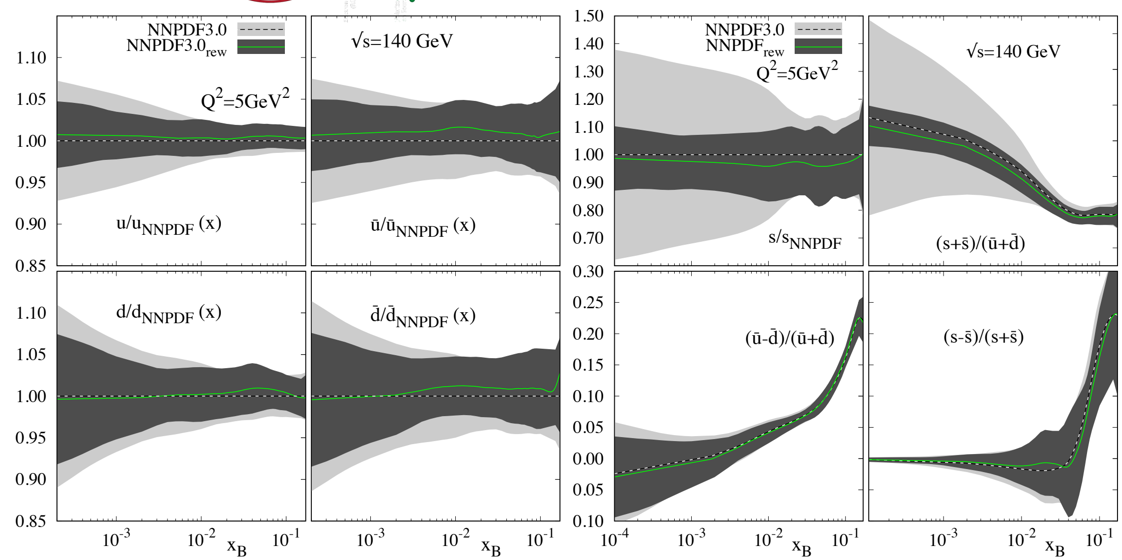
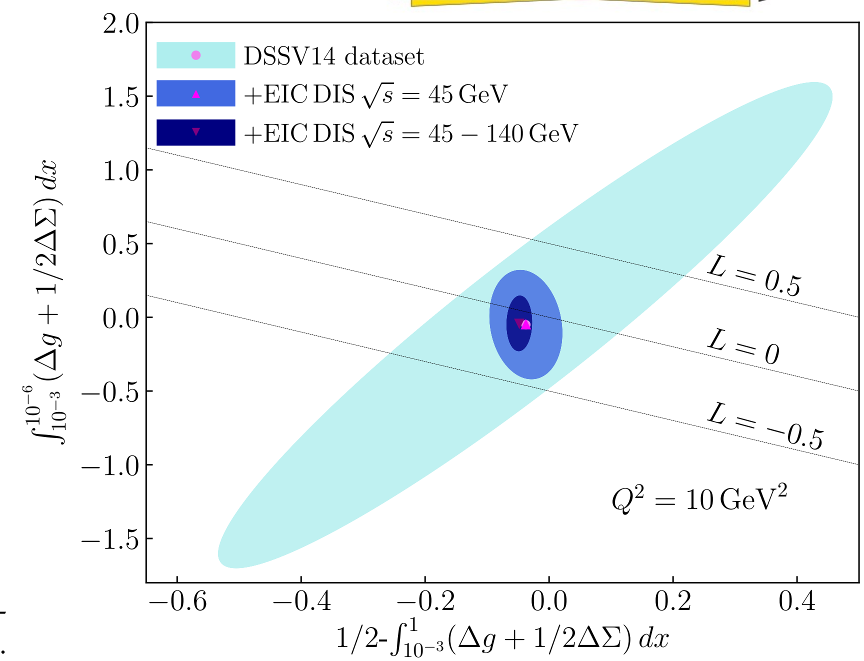
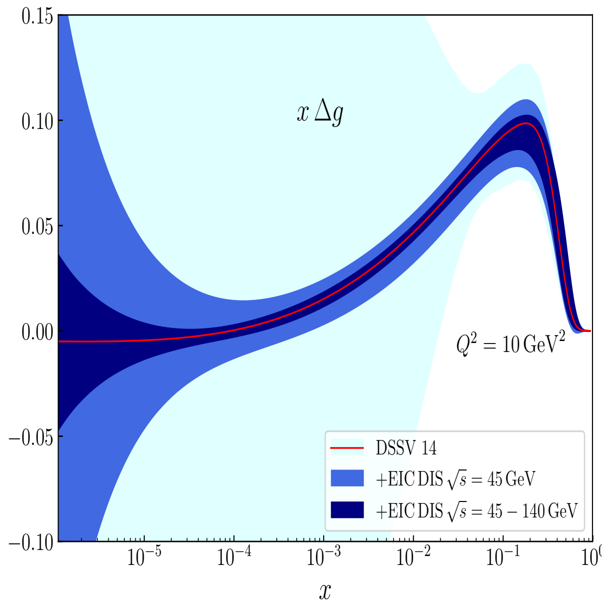
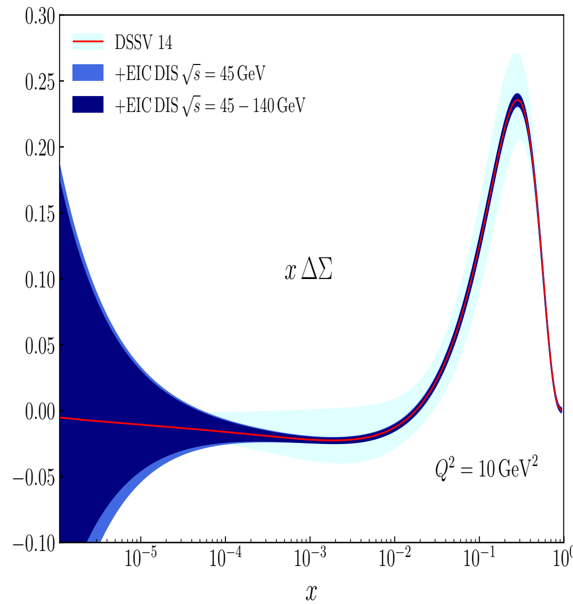
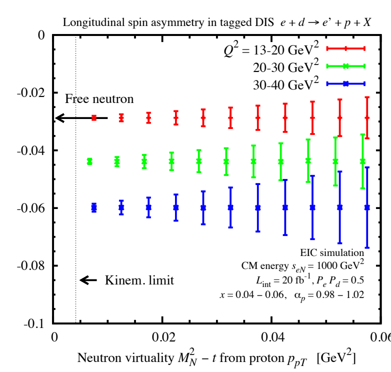


Figure 7.8: Expected impact on the unpolarized (sea) quark PDFs when adding SIDIS information from pions and kaons in *ep* collisions. The baseline NNPDFs were take from Ref. [79].









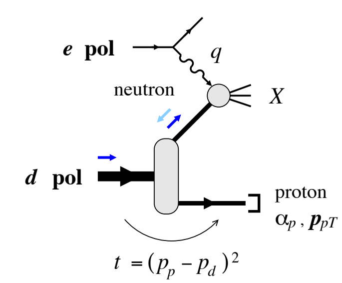
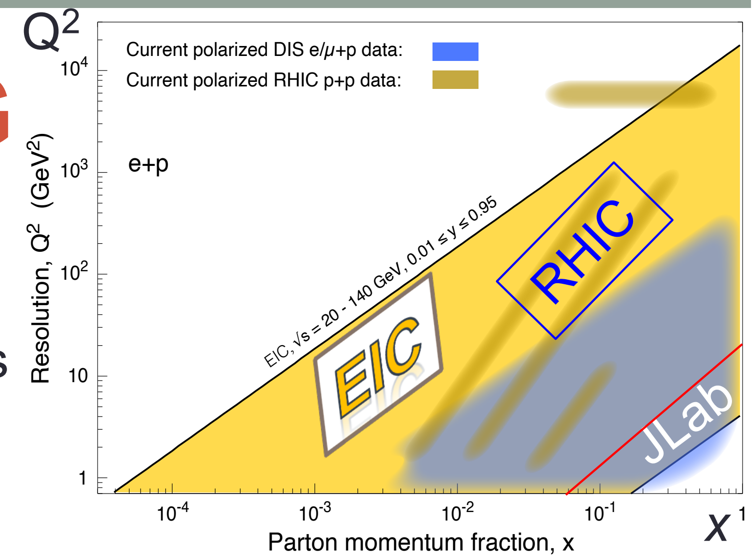


Figure 7.16: Simulated EIC measurements of the longitudinal double-spin asymmetry $A_{\parallel}$ in polarized deuteron DIS with proton tagging $e + d \to e' + X + p$. The asymmetry is shown as a function of the neutron virtuality $t - M_N^2$, which is kinematically fixed by the tagged proton momentum (light-cone momenta α_p and $\boldsymbol{p}_{pT}$). In the limit $t - M_N^2 \to 0$ (on-shell extrapolation) the tagged spin asymmetry coincides with the free neutron spin asymmetry $A_{\parallel n}$ [108, 109]. The uncertainties shown are statistical ($L_{\rm int}$ = 20 fb^{-1}, P_eP_d = 0.5).

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 GeV

- **Understanding the sea – Δs, $\bar{u} - \bar{d}$, $\Delta\bar{u} - \Delta\bar{d}$?** 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?**