JLAB HALL B NUCLEON SPIN STRUCTURE EXPERIMENTS

HiX2019
Κολυμπαρι
Κρητη

Celebrating 2000 years of spin

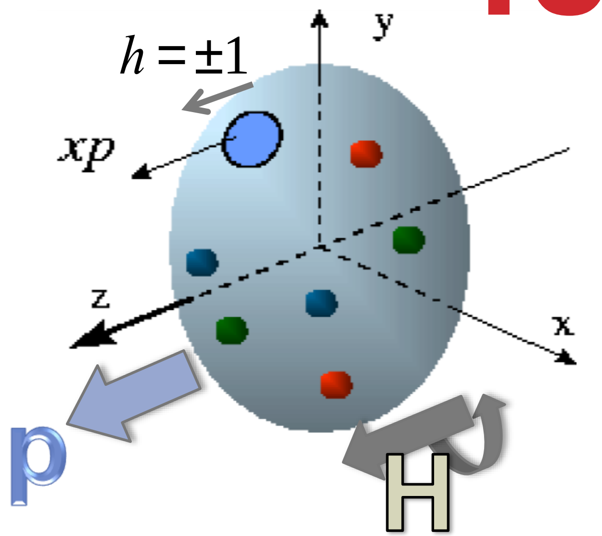
SEBASTIAN KUHN

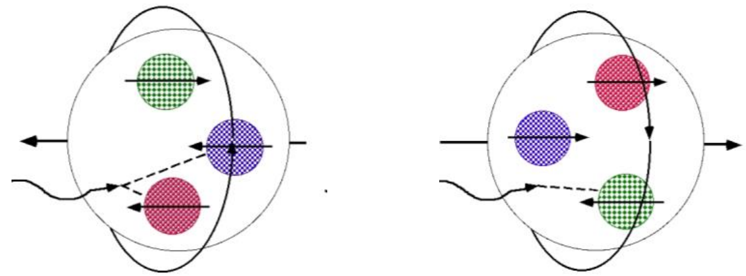
OLD DOMINION UNIVERSITY

OVERVIEW

- **SCIENTIFIC GOALS**
  - Polarized Parton Distribution Functions
  - Valence Quarks, Resonances and Duality
  - Sum Rules, Higher Twist, and χPT
- **RESULTS FROM THE 6 GEV ERA**
  - EG1
  - EG1-DVCS
  - EG4
- **THE FUTURE PROGRAM**
  - CLAS12
  - Run Group C
  - The EMC^2 Effect
- **OUTLOOK AND SUMMARY**

TOPICS TO EXPLORE





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

$$\frac{1}{2} = S_p = \frac{1}{2}\sum_q \int_0^1 \Delta q(x)\,dx + \sum_q L_q + J_G$$

$\leftarrow \Delta\Sigma \rightarrow$

$\Delta q,\ \Delta\bar{q} \quad \Delta G$

$A_1(x\text{->}1)$

Duality

OPE, twist >2

pQCD

LQCD

GDH, ChPT

CFT/AdS$_5$

PDFS

Orbital Angular Momentum

Resonance

Structure

Constituent Quark Model

(SU(6))

Sum Rules

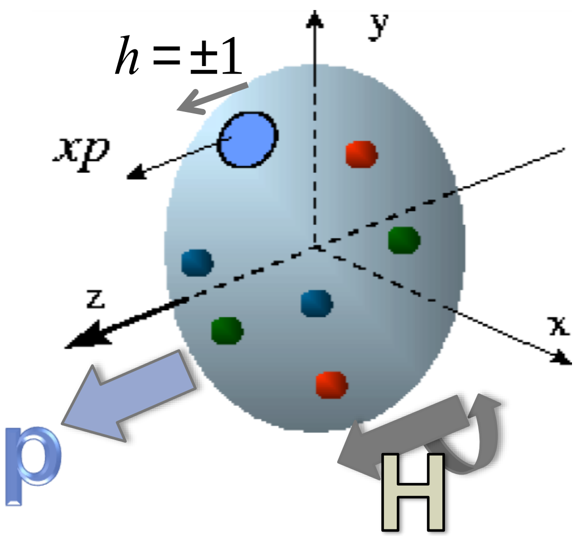
TMD

DVCS

Inclusive lepton scattering

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

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



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

Traditional “1-D” Parton Distributions (PDFs)
(integrated over many variables)

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

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

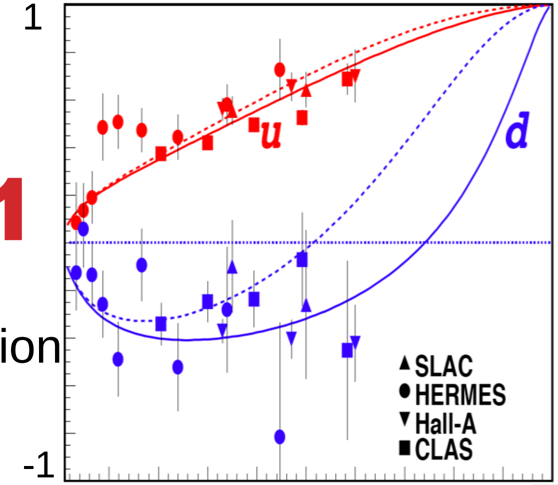
⇒ access to gluons. $\delta C_q, \delta C_G - \textit{Wilson}$ coefficient functions

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

Jefferson Lab 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 $\frac{1}{Q^n}$)

VALENCE REGION AND MODERATE Q^2: SFS FOR $X \rightarrow 1$



Valence quark polarization

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* ⇒

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

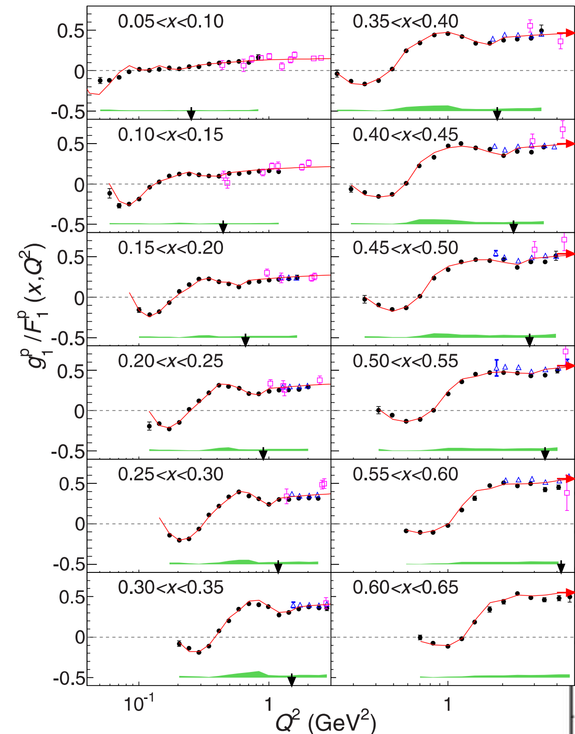
Relativistic Correction: lower component reduces axial charge, adds to orbital angular momentum (p-wave) ⇒

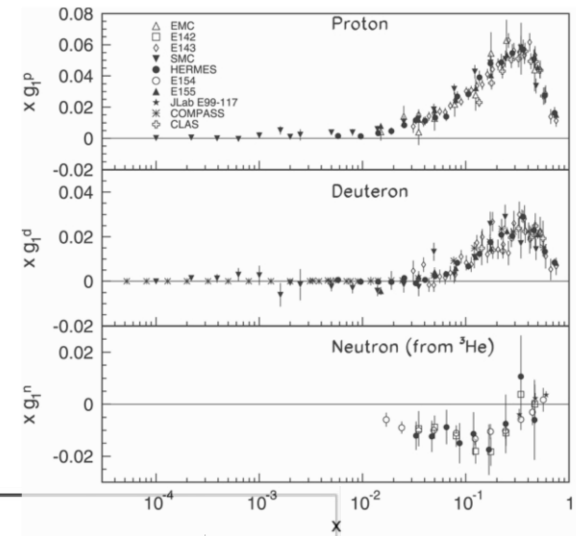
$$\sum_q \Delta q = \Delta\Sigma \approx 60\%; \quad g_A^{(3)} = \Delta u - \Delta d \approx 1.26; \quad g_A^{(8)} = \Delta u + \Delta d - 2\Delta s \approx 0.6$$

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

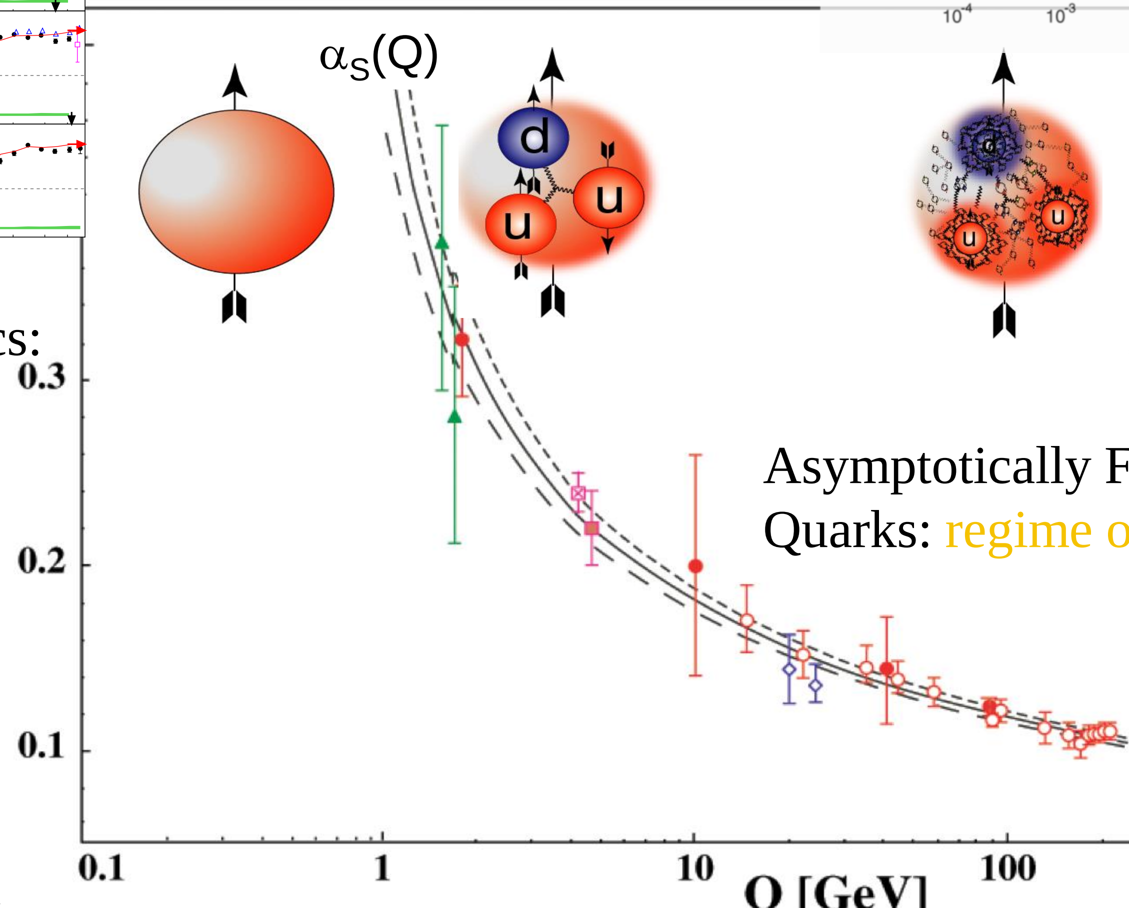
pQCD: helicity conservation (q↑↑p) => d/u =2/(9+1) = 1/5, Δu/u = 1, Δd/d = 1
for $x \longrightarrow 1$

DUALITY





Long Distance Physics:
hadronic observables



Asymptotically Free Quarks: regime of pQCD

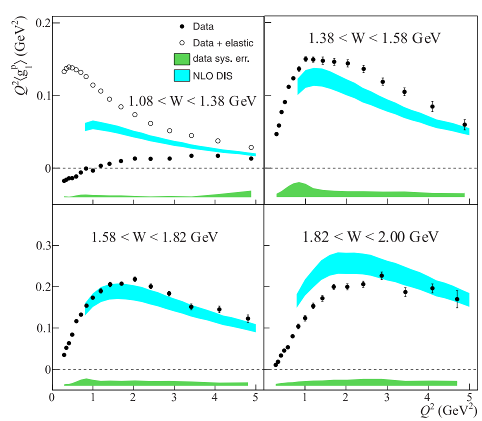


FIG. 40. Averages of $Q^2 g_1^p(x,Q^2)$ vs Q^2 over limited spans in x corresponding to prominent “resonance regions” as indicated by the ranges in W. Symbols are the same as in Fig. 39.

THE LIMIT $Q^2 \to 0$: GDH Sum Rule

$$I_{GDH} = \frac{M^2}{8\alpha\pi^2}\int_{thr}^{\infty}(\sigma_{1/2}-\sigma_{3/2})\frac{d\nu}{\nu} = -\frac{1}{4}\kappa^2$$

- relates the difference of the photo-absorption cross section for helicity 1/2 and 3/2 to the nucleon magnetic moment, i.e. a connection between dynamic and static properties

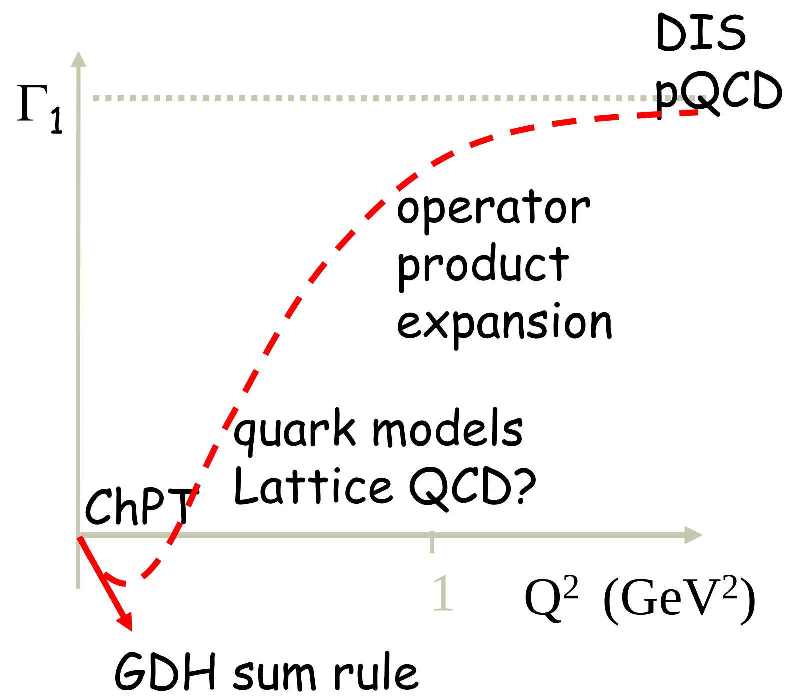
- based on very general principles, as gauge invariance, dispersion relation, low energy theorem

- at finite Q^2 can be related to the integral of the spin structure function g_1

$$\Gamma_1 = \int g_1(x,Q^2)\,dx \xrightarrow[Q^2\to 0]{} \frac{Q^2}{2M^2} I_{GDH}$$

- strong variation of nucleon spin properties as a function of Q^2

- Q^2-dependence described by Chiral Perturbation Theory (χPT) at low Q^2



The Limit $Q^2 \to 0$: **Spin Polarizability**

$$\int_{thr}^{\infty} (\sigma_{1/2} - \sigma_{3/2}) \frac{d\nu}{\nu^3} = 4\pi^2 \gamma_0$$

- γ_0 measures the response ("stiffness") of the nucleon spin against electromagnetic deformations along the spin axis

- Follows from same dispersion relation and low energy theorem (limit of forward Compton scattering) as GDH sum rule

- can also be extended to finite Q^2:

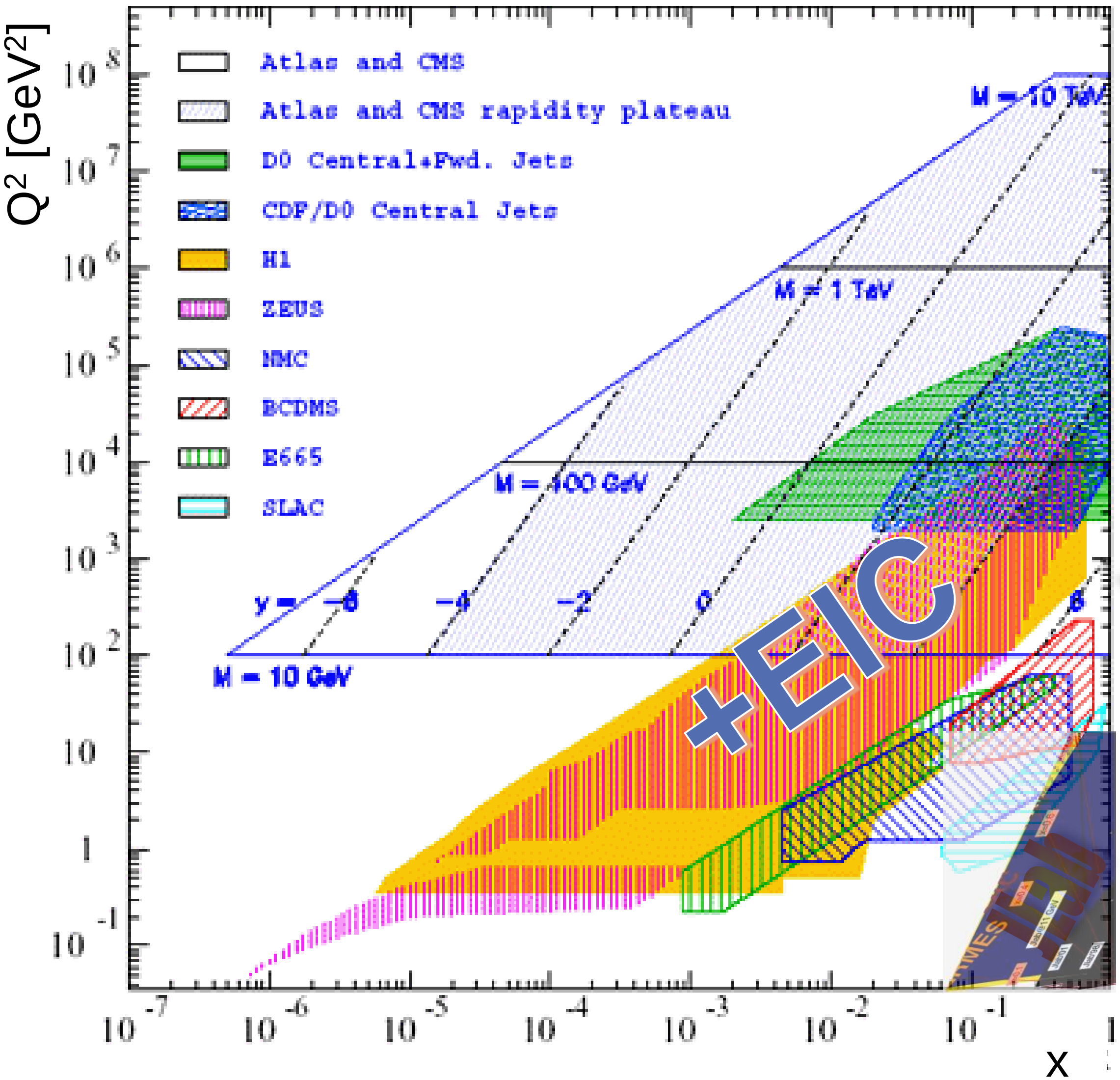
$$\Gamma_3^N = \int x^2 g_1^N(x, Q^2)\, dx \xrightarrow[Q^2 \to 0]{} \frac{Q^6}{16\alpha M^2} \gamma_0^N$$

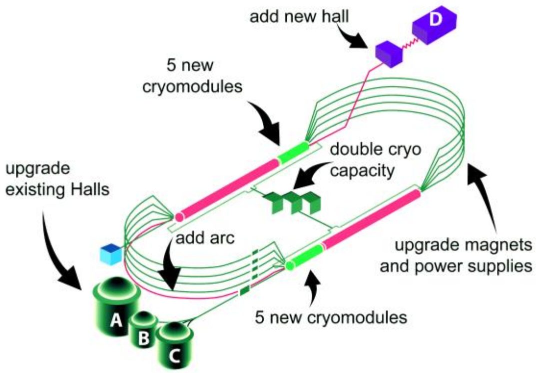
- much more sensitive to low-energy (high x) part of the integral -> ideal for Jlab

- plus other polarizabilities: δ_{LT}

- $\Rightarrow$ Chiral Perturbation Theory should be able to predict $\gamma_0(Q^2)$, $\delta_{LT}(Q^2)$ and **b** in $\Gamma_1(Q^2) = -\frac{\kappa^2}{8M^2} Q^2 + \boxed{b} Q^4 \ldots$

JEFFERSON LAB IN PERSPECTIVE





JLab DIS

Now: 12 GeV

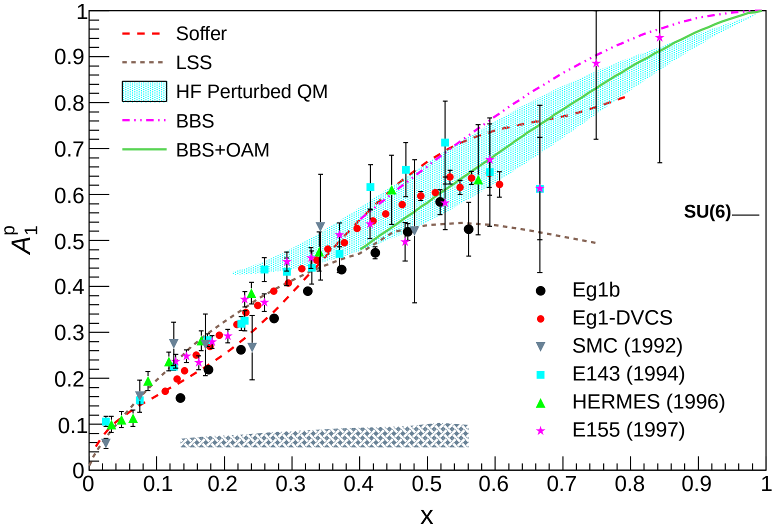
$Q^2 = 1 \ldots 13$ GeV^2

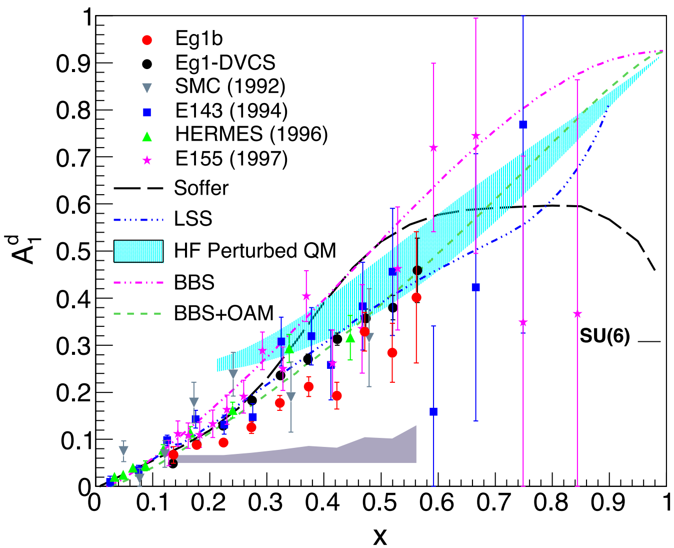
$x = 0.06 \ldots 0.8$

$W < 4$ GeV

SPIN STRUCTURE FUNCTIONS IN THE LAST 40 YEARS

SATO, MELNITCHOUK, KUHN, ETHIER, and ACCARDI PHYSICAL REVIEW D **93,** 074005 (2016)





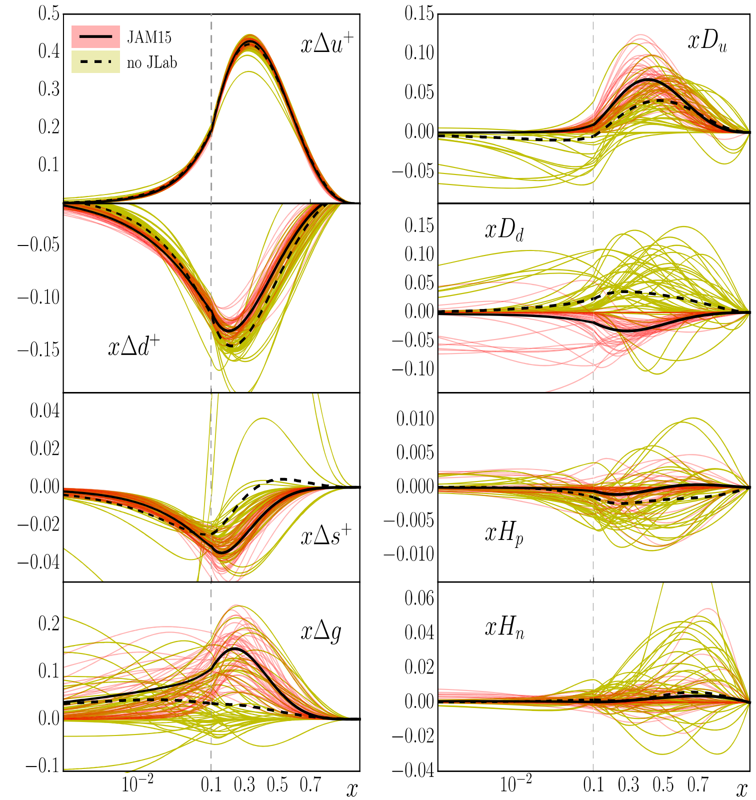


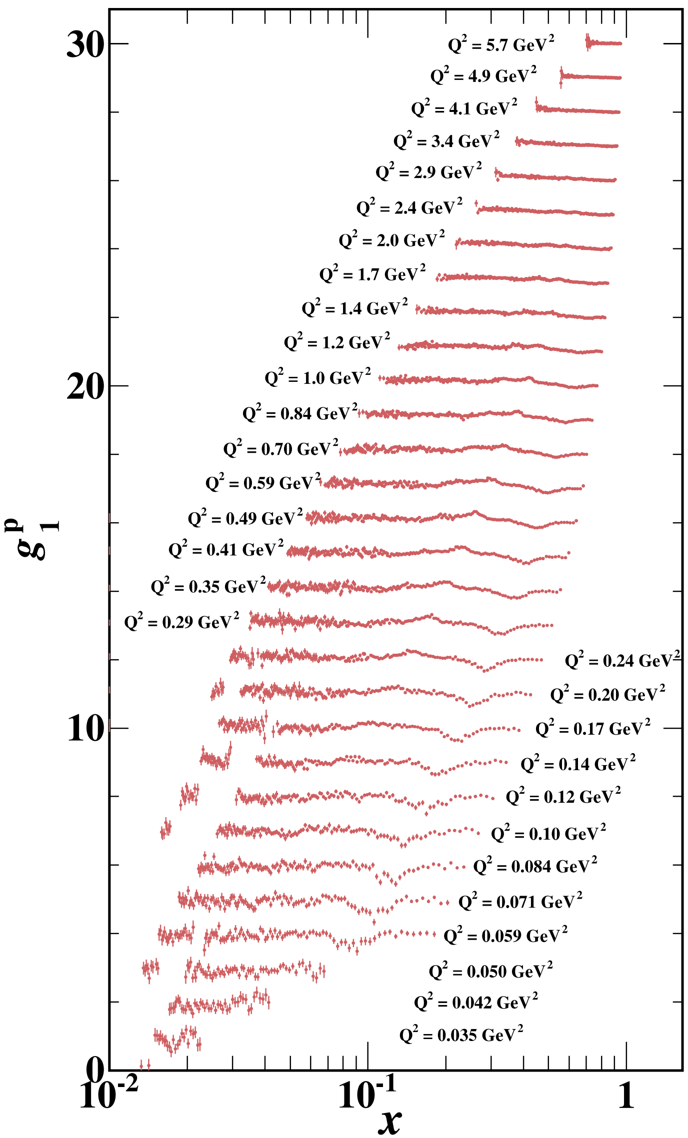
FIG. 15. Comparison of the JAM15 IMC fits (red curves, with the average indicated by the black solid curve) with corresponding fits excluding all Jefferson Lab data (yellow curves, with the average given by the black dashed curve) for the twist-2 PDFs Δu^+, Δd^+, Δs^+ and Δg, the twist-3 distributions D_u and D_d, and the twist-4 functions H_p and H_n at $Q^2 = 1$ GeV^2. Note that x times the distribution is shown. For illustration each distribution is represented by a random sample of 50 fits.

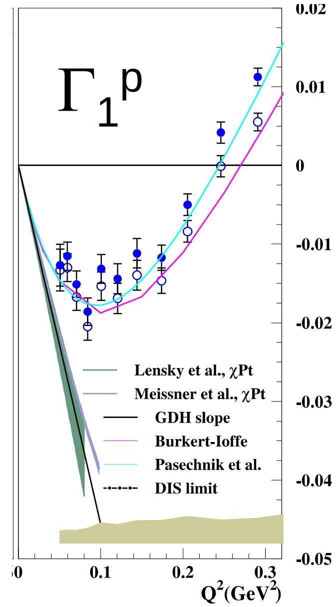
-ex/0205020.

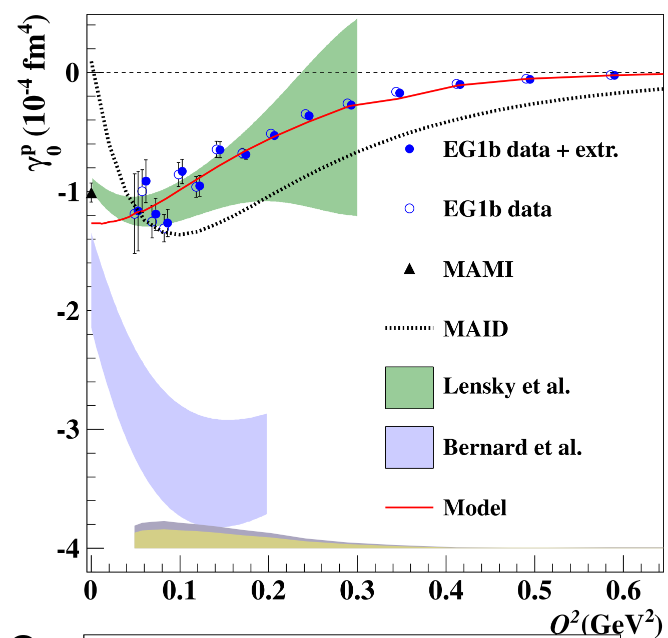
Nobuo Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier, and A. Accardi:"Iterative Monte Carlo analysis of spin-dependent parton distributions", Phys. Rev. D **93**, 074005 (5 April 2016).

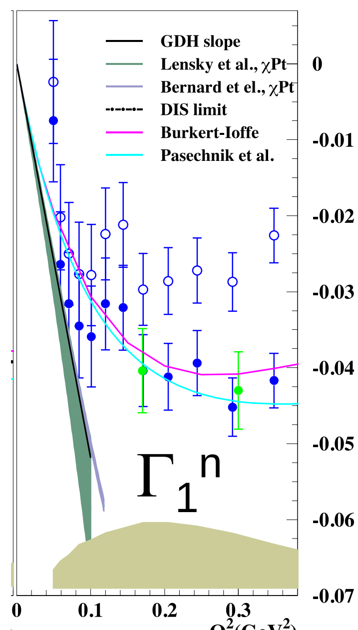
A. Deur, Y. Prok, V. Burkert, D. Crabb, F.-X. Girod, K. A. Griffioen, N. Guler, S. E. Kuhn, and N. Kvaltine: "High precision determination of the Q² evolution of the Bjorken sum", Phys. Rev. C **90**, 012009 (July 2014).

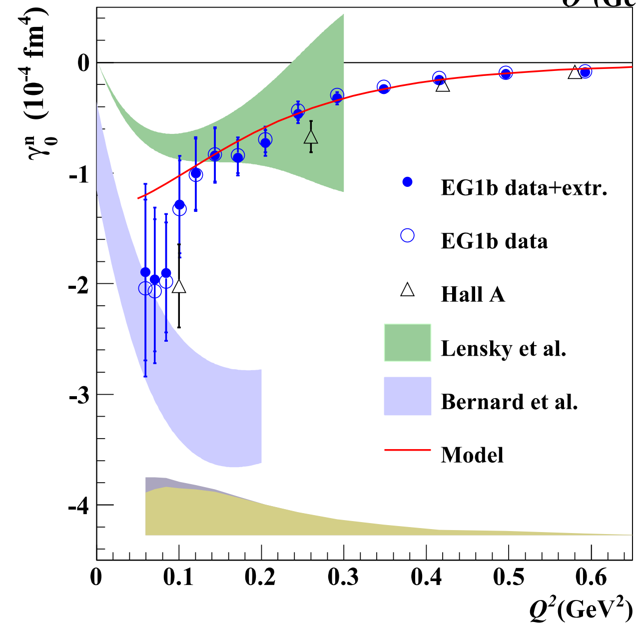
RESULTS FROM EG1B



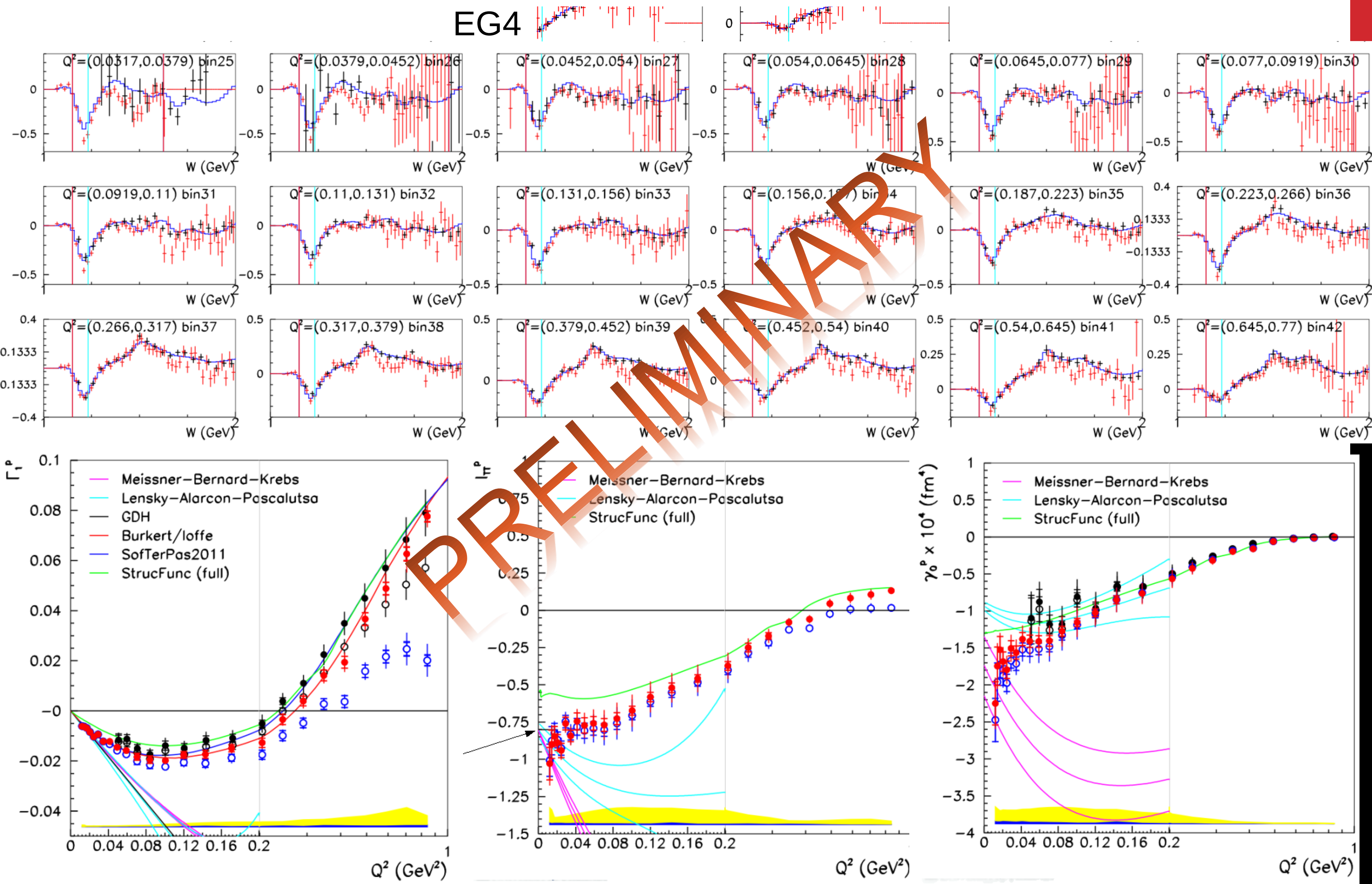






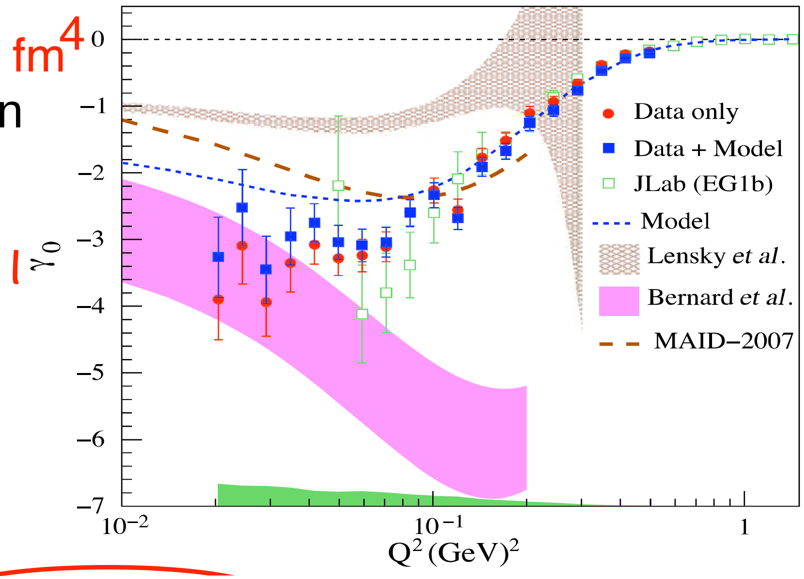


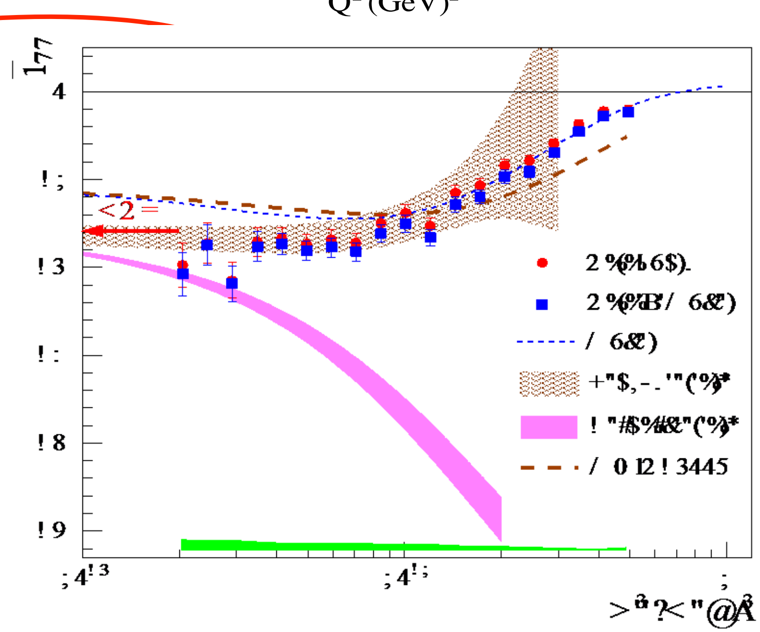
The SF g_{1p} – recent results at low Q^2

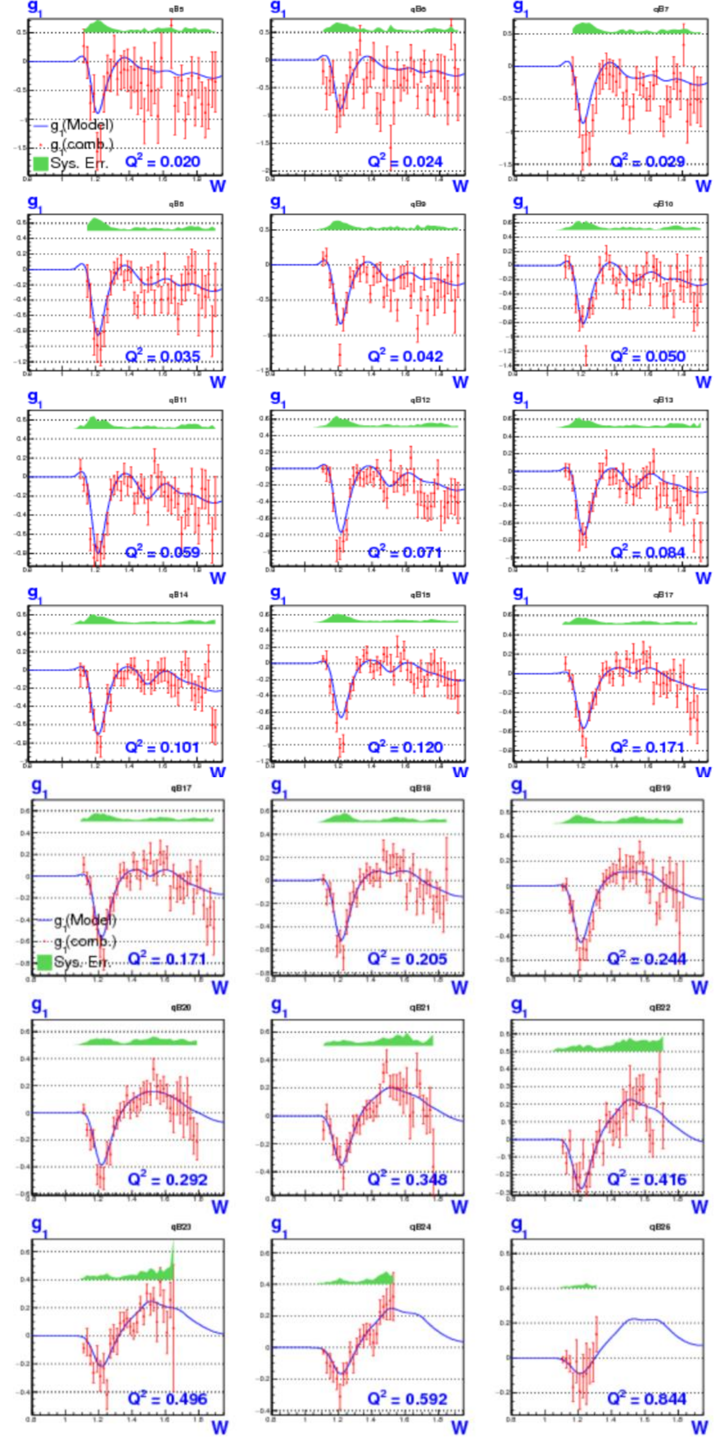


The SF g_{1d} – recent results at low Q^2

EG4
deuteron

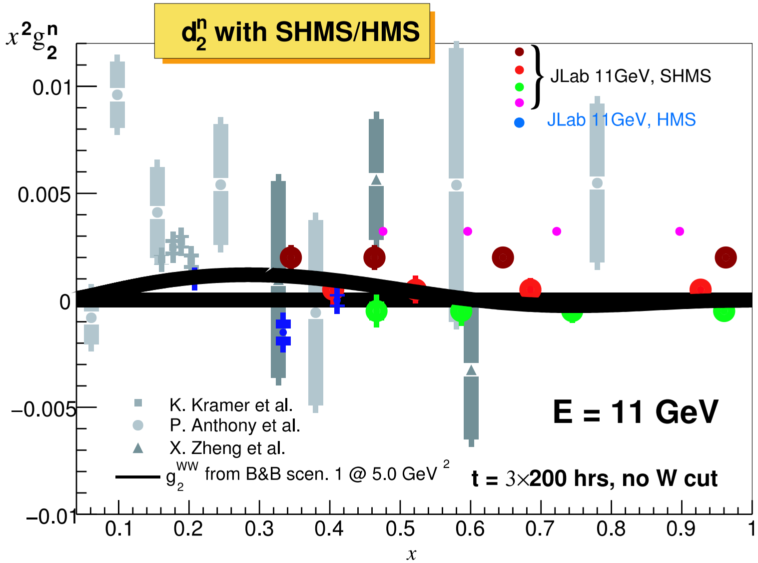


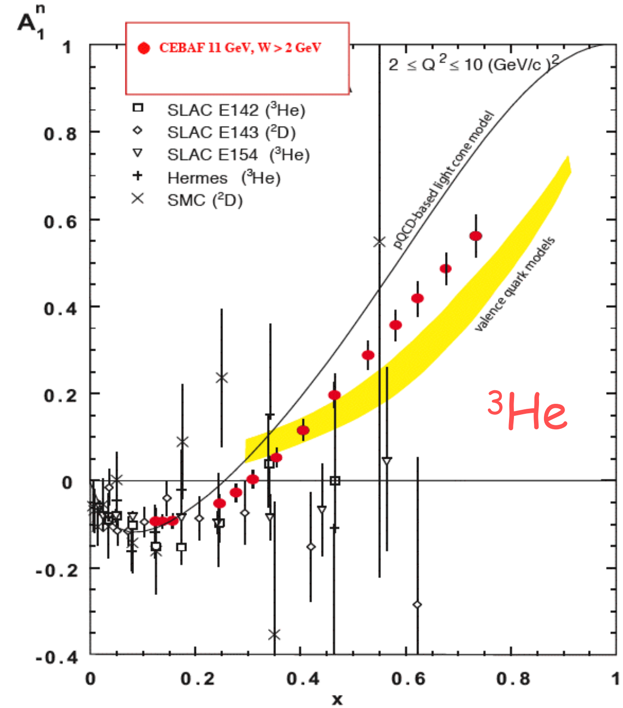




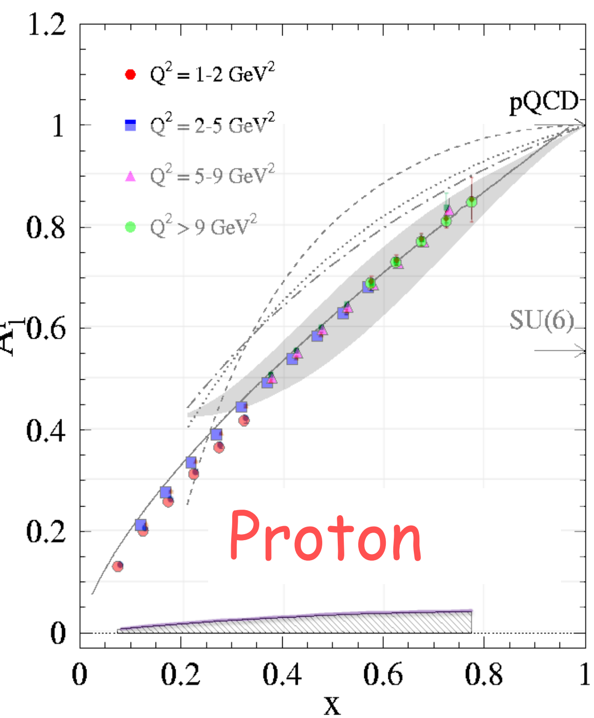
THE FUTURE

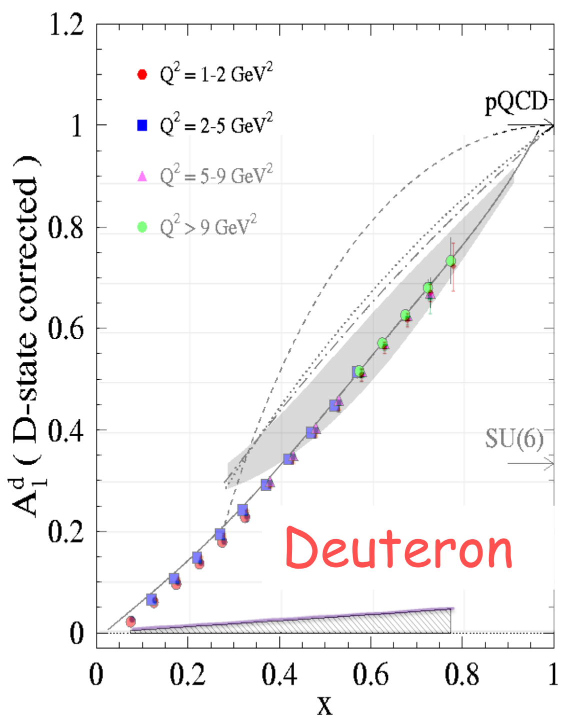
High precision inclusive SSFs on p, d, n in the region $0.05 < x < 0.8$

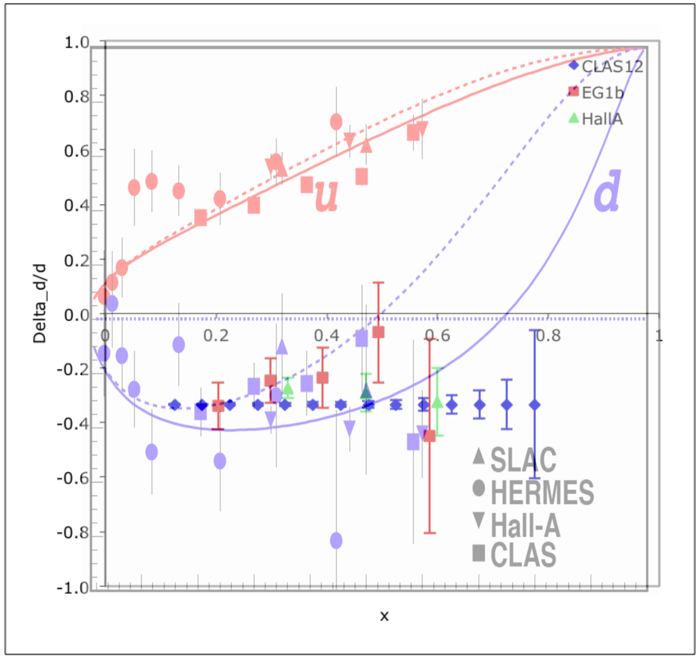




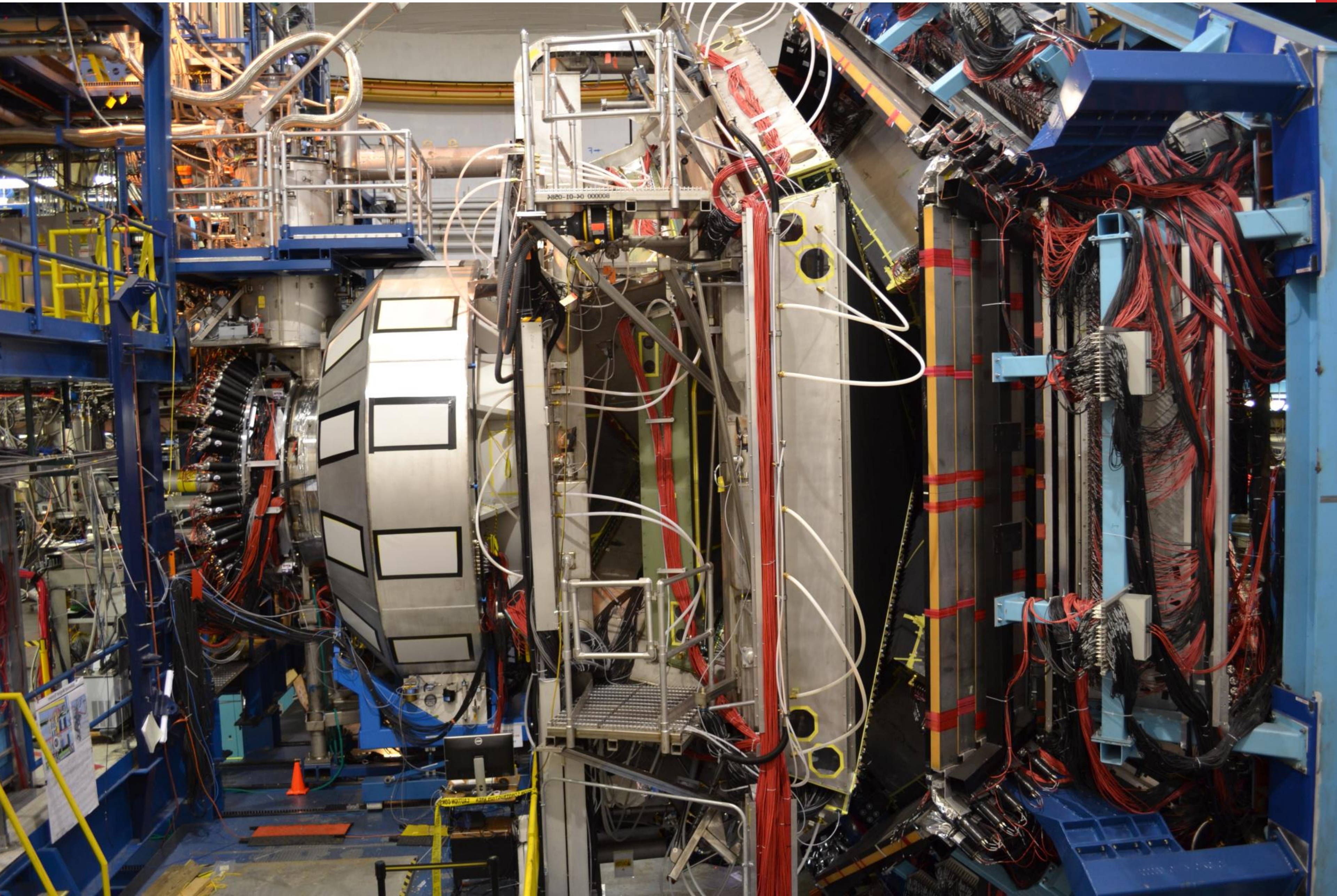
W > 2; Q^2 > 1







CLAS12



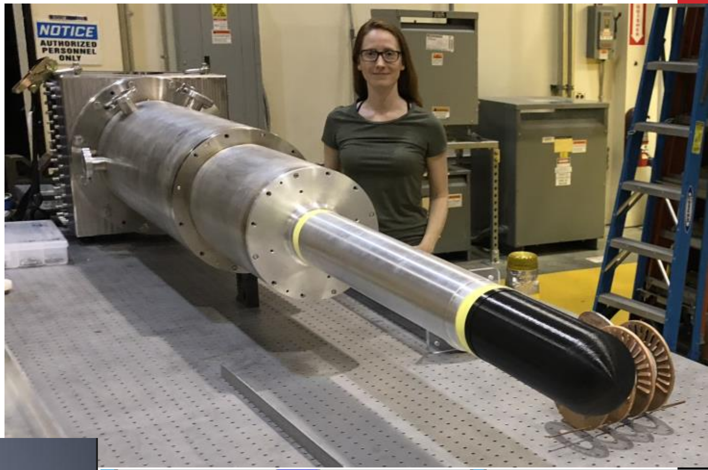
RUN GROUP C

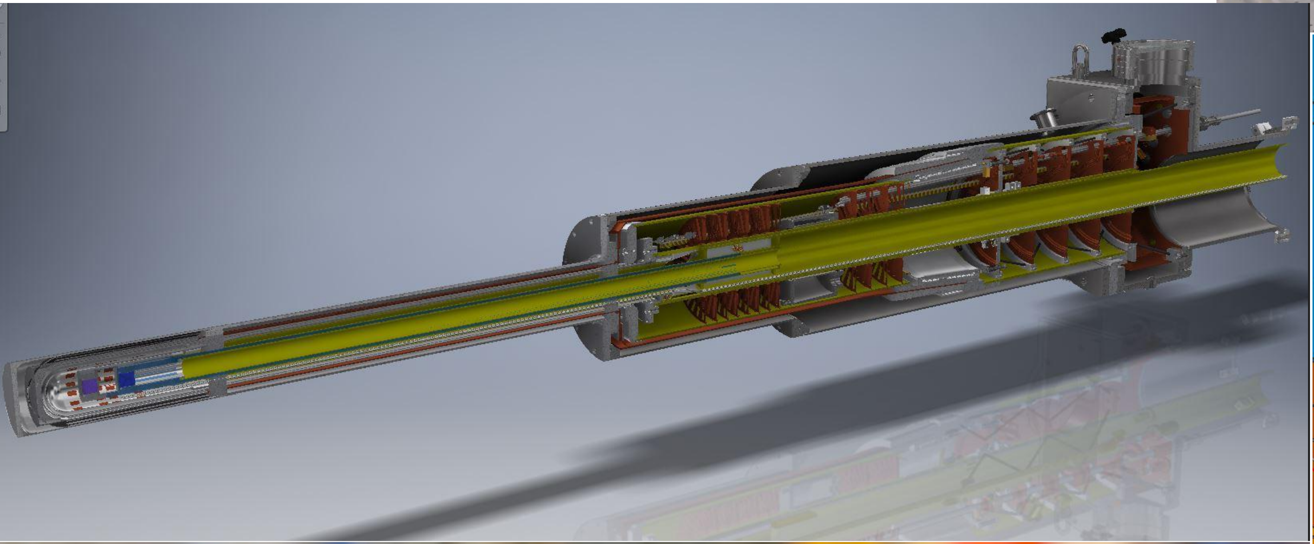
- Experiments with CLAS12 and a longitudinally polarized p/d target
- Tentatively scheduled for 6 months in 2021-2022 (First Installment)
- Just passed Experimental Readiness Review
- Comprises 6 approved experiments

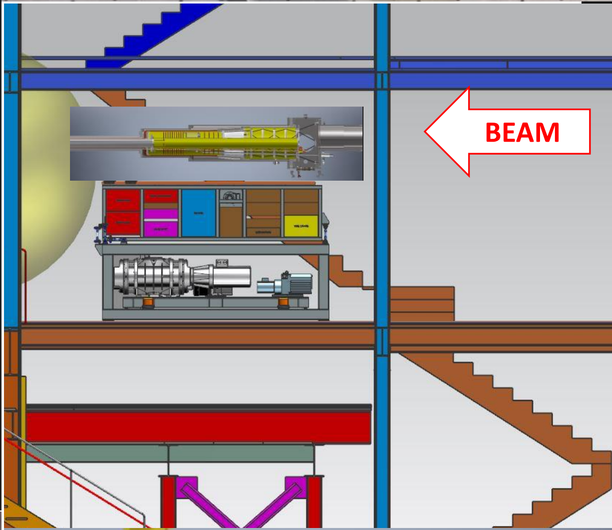
Proposal ID	Title	Contact Person	PAC Rating	Awarded Days
E12-06-109	Longitudinal Sping Structure of the Nucleon	Kuhn	A	80
E12-06-109A	DVCS on the neutron with polarized deuterium target	Niccolai	RG proposal	(60)
E12-06-119(b)	DVCS on longitudinally polarized proton target	Sabatie	A	120
E12-07-107	Spin-Orbit Correlations with longitudinally polarized target	Avakian	A-	103
E12-09-007(b)	Study of partonic distributions using SIDIS K production	Hafidi	A-	80
E12-09-009	Spin-Orbit correlations in K production with polarized targets	Avakian	B+	103

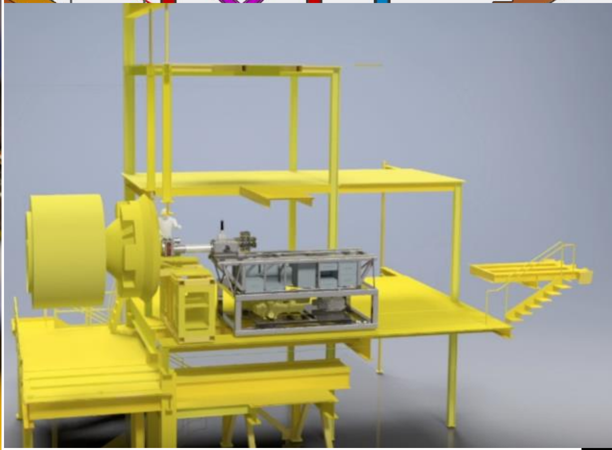
Total number of approved beam (PAC) days: 185 (120 p, 60 d, 5 auxiliary)

POLARIZED TARGET –
FROZEN AMMONIA AND DEUTERATED AMMONIA IN 1K LIQUID HE BATH AND 5 T MAGNETIC FIELD, IRRADIATED WITH 140 GHZ MICROWAVES





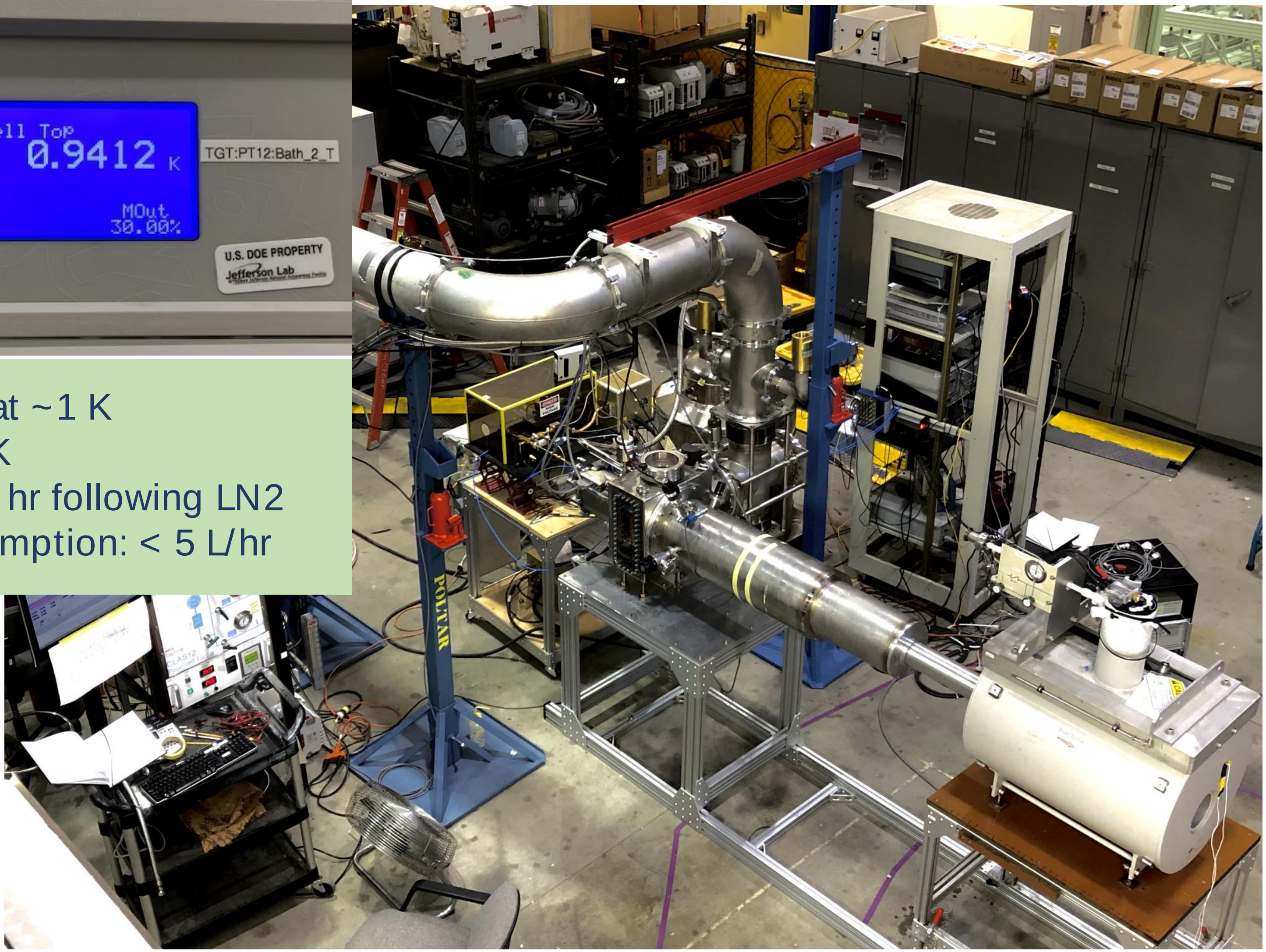




Photos courtesy of J. Brock

1 K Refrigerator

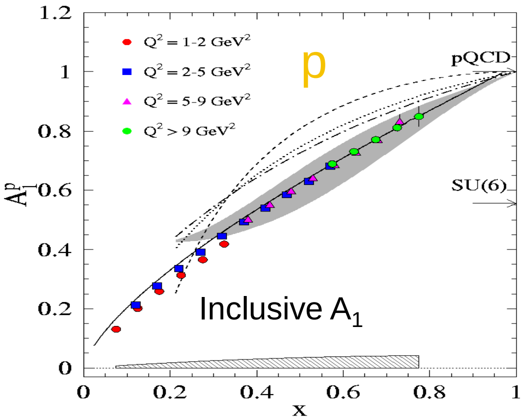
Stable operation at ~1 K
Heat shield < 28 K
Fast cool-down: 3 hr following LN2
Low helium consumption: < 5 L/hr

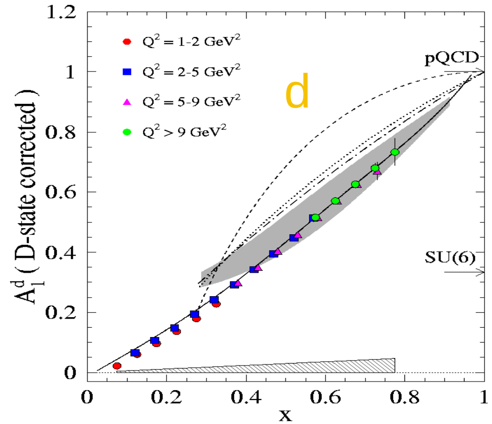


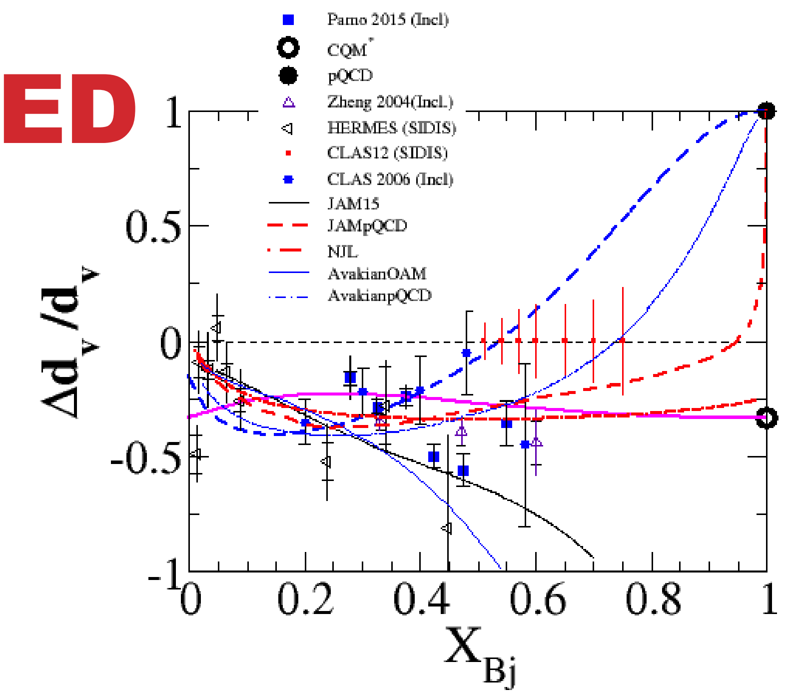
Passed Experimental Readiness Review 6/19

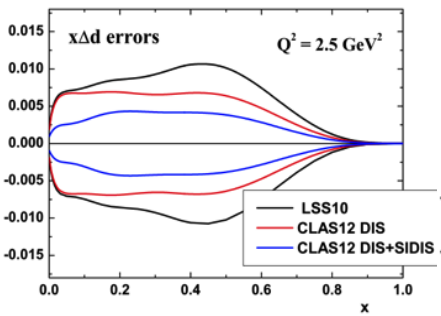
Jefferson Lab
Target Group

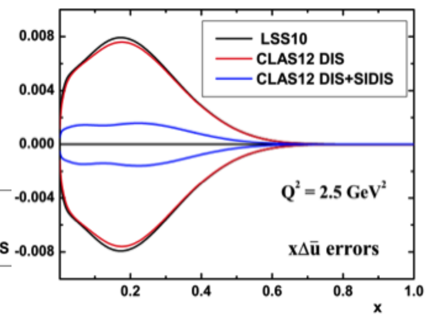
INCLUSIVE + TAGGED SSF – HALL B

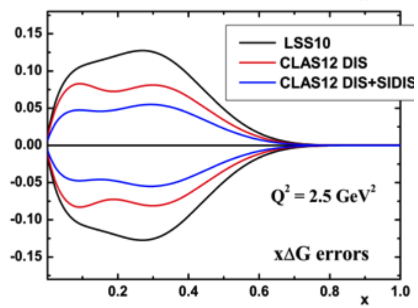


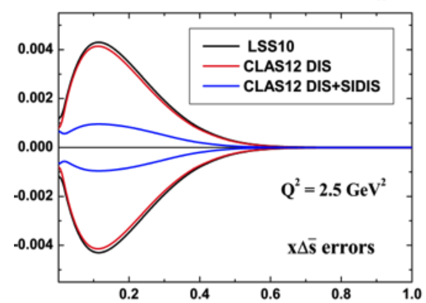




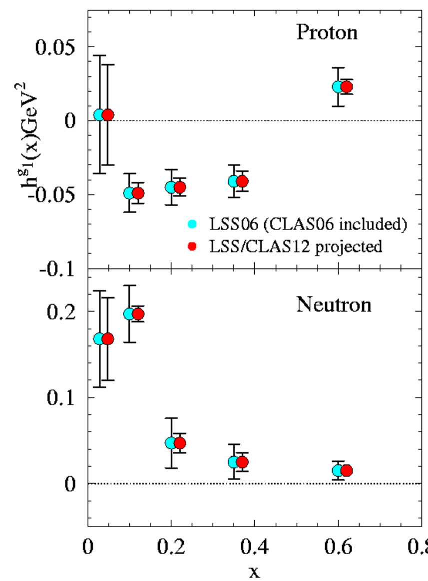




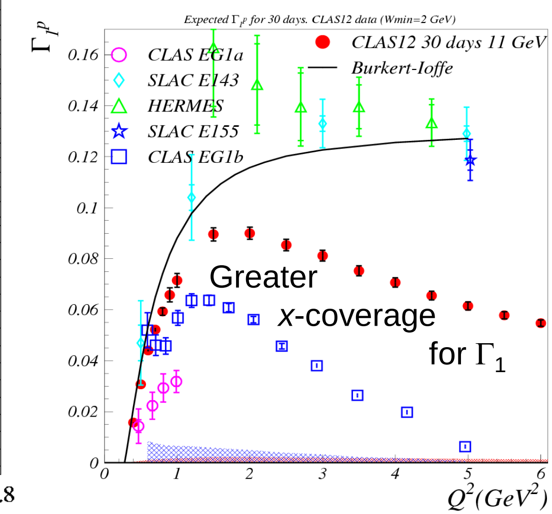




Improved PDFs from NLO analyses

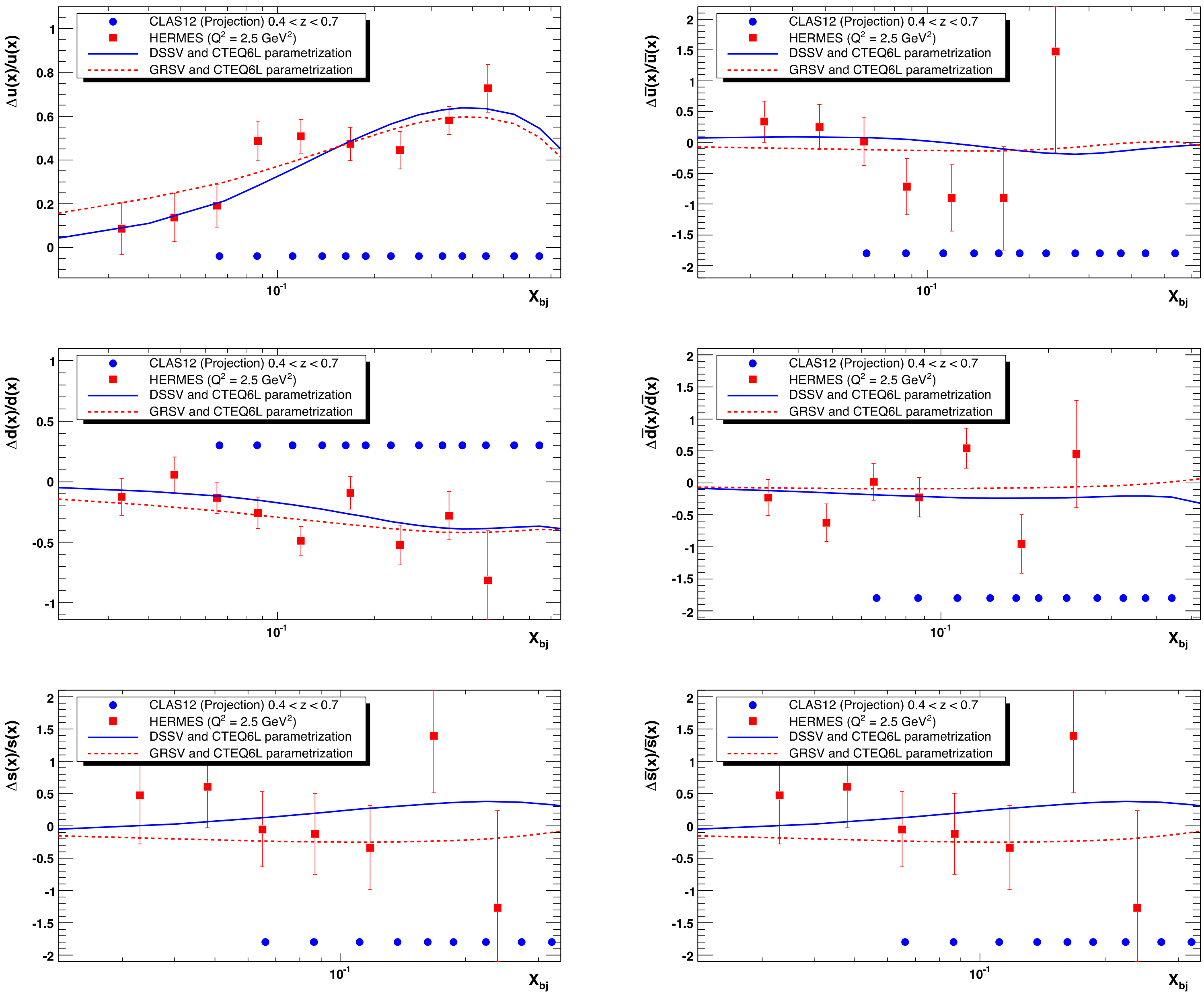


Better determination of Higher Twist vs. x



Improved coverage to evaluate moments

QUARK POLARIZATION FROM KAON SIDIS



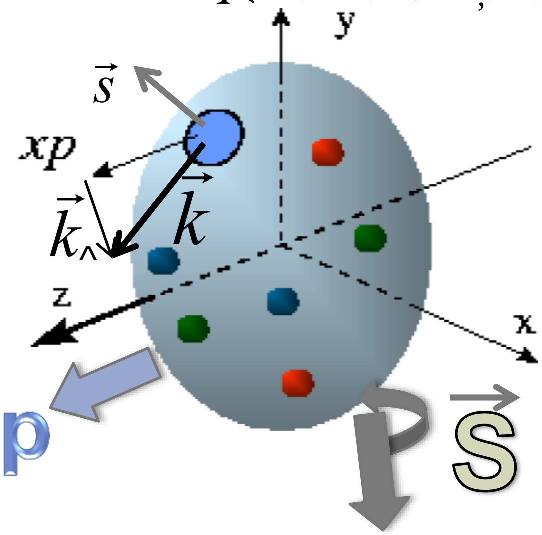
See talk by K. Hafidi Tuesday morning

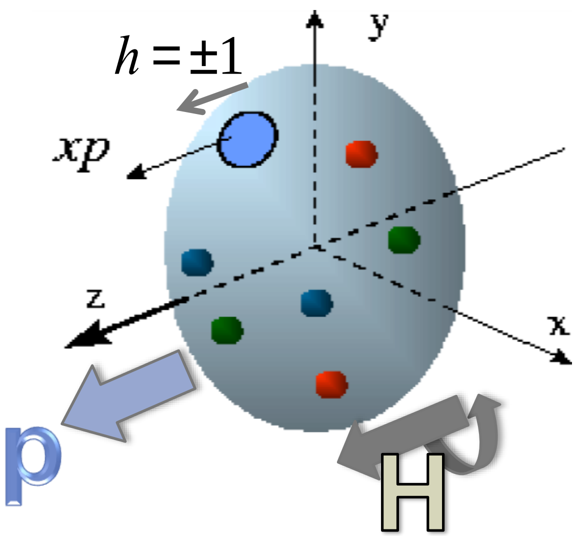
3D Partonic Structure

3-D Picture of parton flavor, spin and momentum (TMDs)

$$q(H, \vec{S}_\perp, x, \vec{k}_\perp, h, \vec{s}_\perp; Q^2)$$

From 1-D to 3-D:

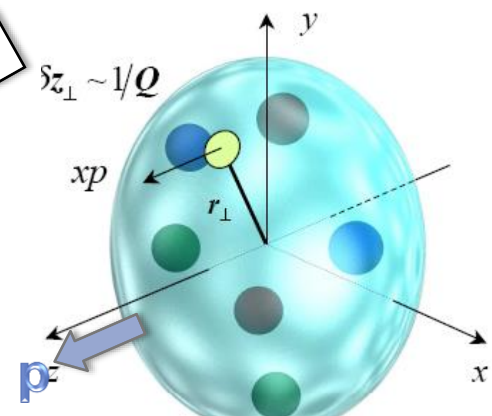


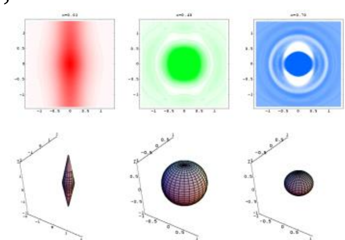


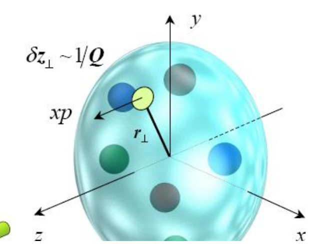
$$q(x;Q^2), \langle h \times H \rangle q(x;Q^2)$$

Traditional “1-D” Parton Distributions (PDFs)
(inclusive, integrated over many variables)

$$q(\vec{S}, x, \vec{r}_\perp, \vec{s}; Q^2)$$





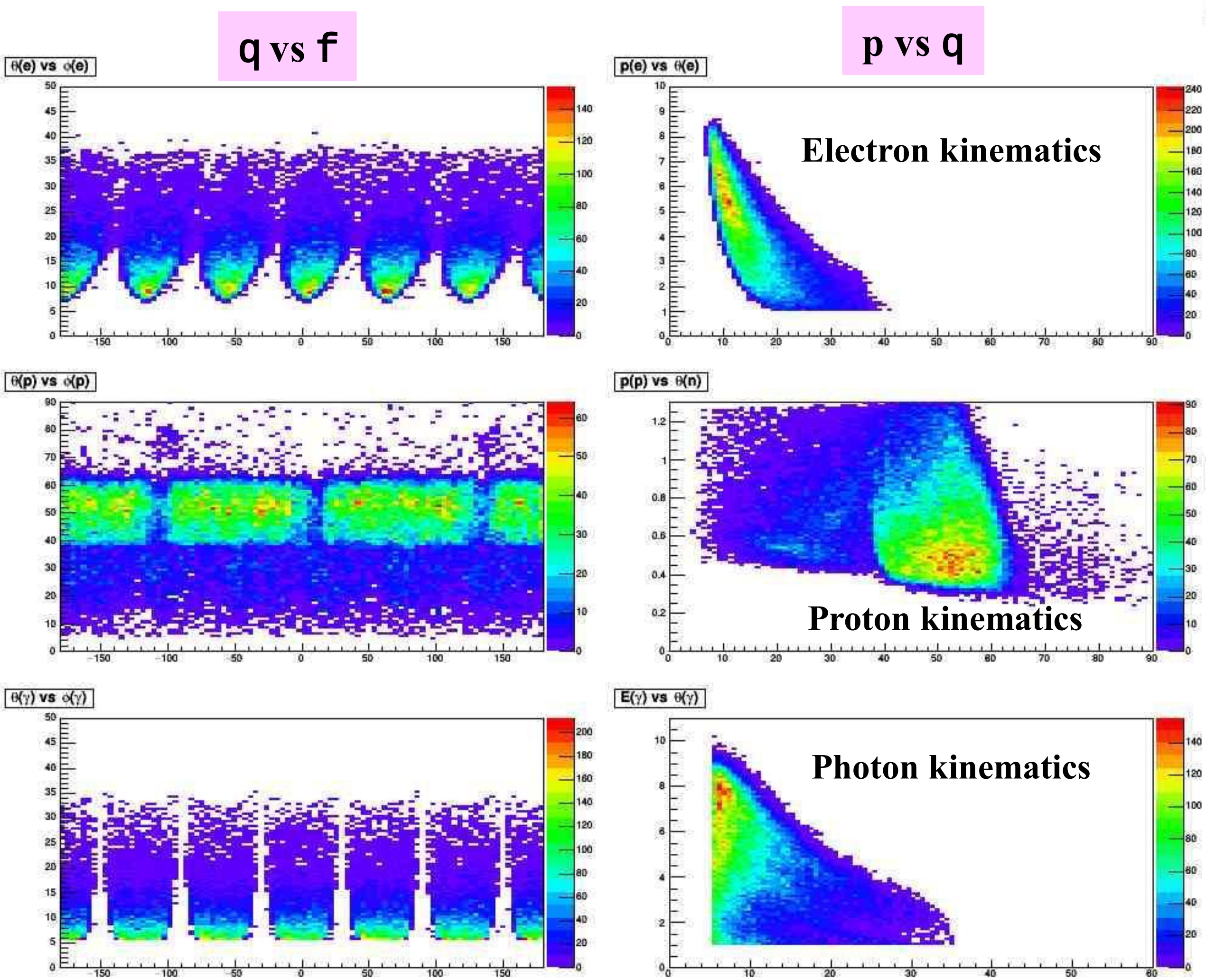


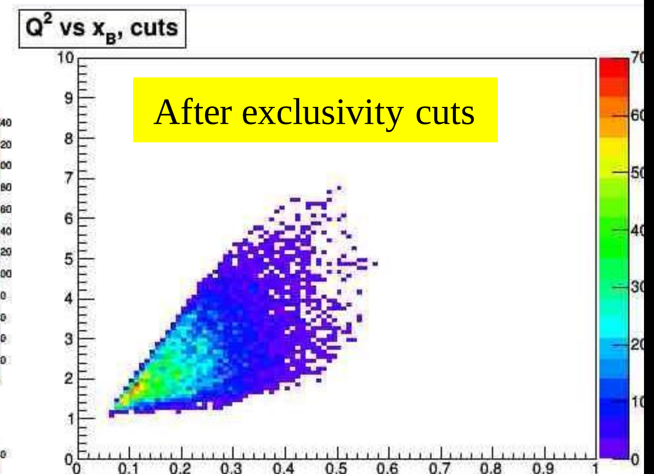
3-D parton orbits (GPDs)

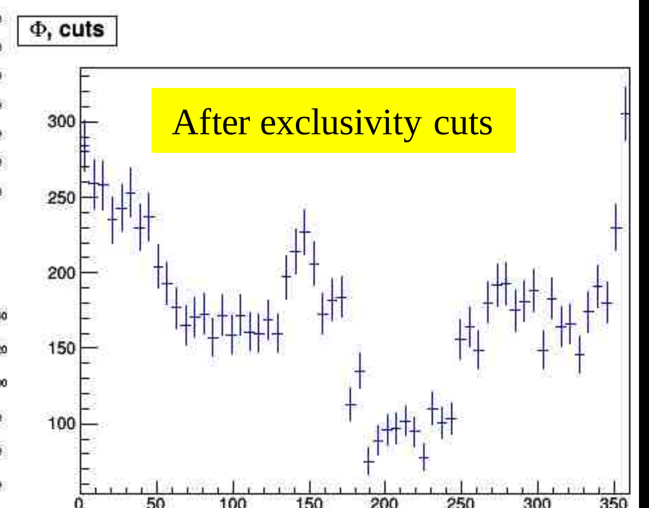
pDVCS simulations with RGC setup

pDVCS event generator (GENEPI): DVCS-BH on proton target, $t<-1.2$ GeV^2

- cell target, NH_3, noFT configuration
-
- analysis (PID + channel selection cuts)







n DVCS Target Spin and Double Spin Asymmetries

First time measurement of longitidunal target-spin asymmetry and double (beam-target) spin asymmetry

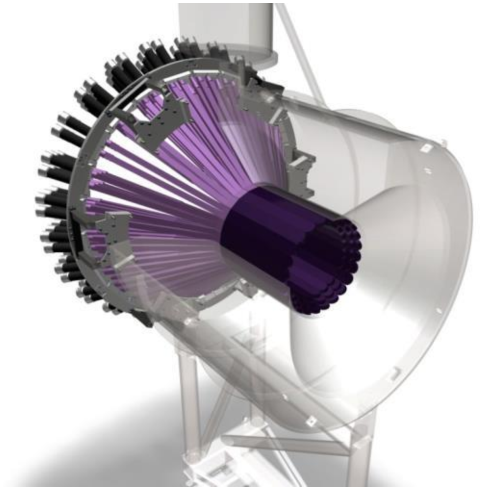
$\Delta\sigma_{UL} \sim \mathbf{\sin\phi}\ \mathbf{Im}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\mathcal{E})-\xi k F_2\tilde{\mathcal{E}}+\ldots\}$

$\Delta\sigma_{LL} \sim (\mathbf{A+B\cos\phi})\ \mathbf{Re}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\mathcal{E})-\xi k F_2\tilde{\mathcal{E}}+\ldots\}$

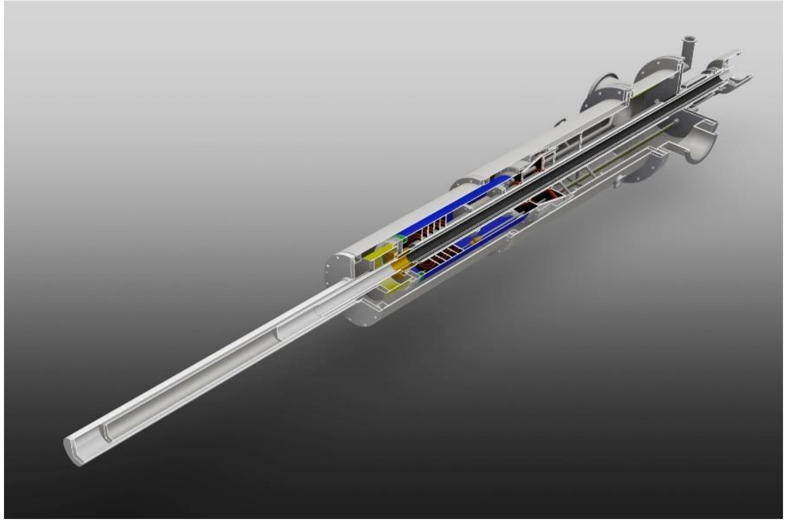
→ 3 observables (including BSA), constraints on real and imaginary CFFs of various neutron GPDs

$L = 3/20\cdot10^{35}cm^{-2}s^{-1}$
Run time = 40 days
$P_t = 0.4$; $P_b = 0.85$

$eND_3 \rightarrow e(p)n\gamma$
CLAS12 + Longitudinally polarized target + **CND**



Will run in 2021



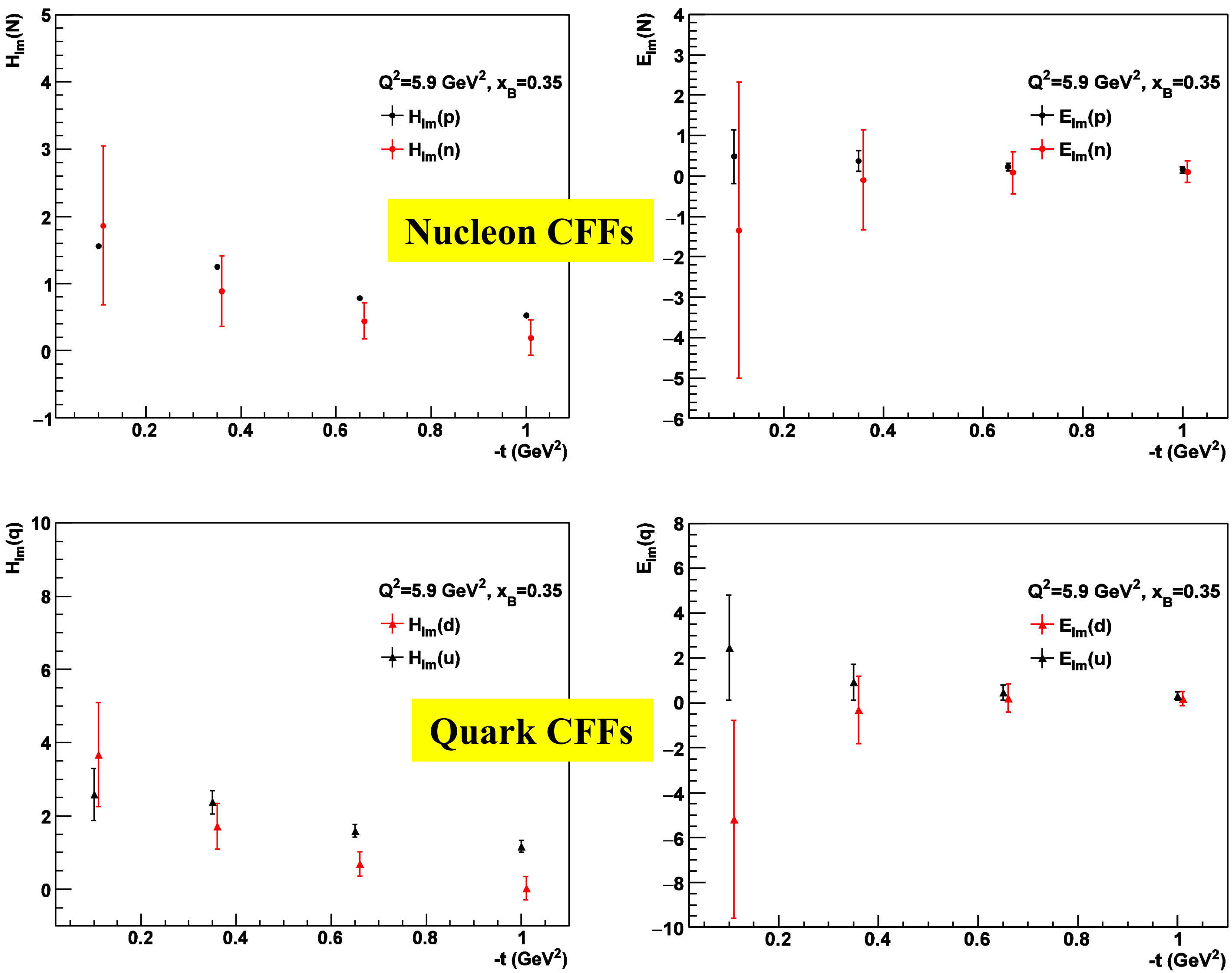
CLAS12: projections for flavor separation ($Im\mathcal{H}$, $Im\mathcal{E}$)

$$(H,E)_u(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$

$$(H,E)_d(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

$$\frac{1}{2}\int_{-1}^{1} x dx \left(H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right) = J^q$$

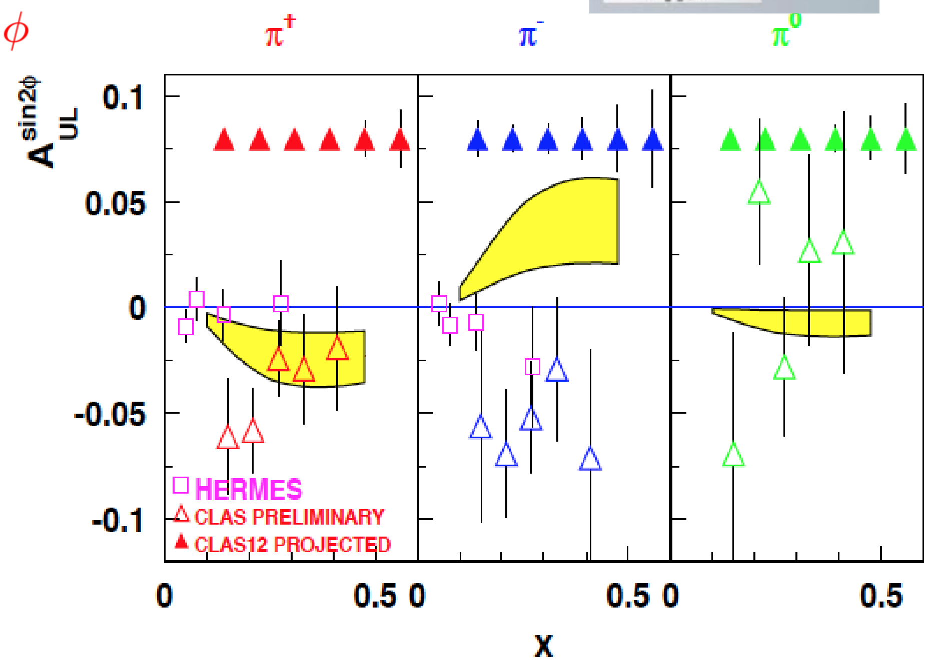
Fits done to all the projected observables for **pDVCS** (BSA, lTSA, lDSA, tTSA, CS, DCS) and **nDVCS** (BSA,lTSA, lDSA) of the CLAS12 program



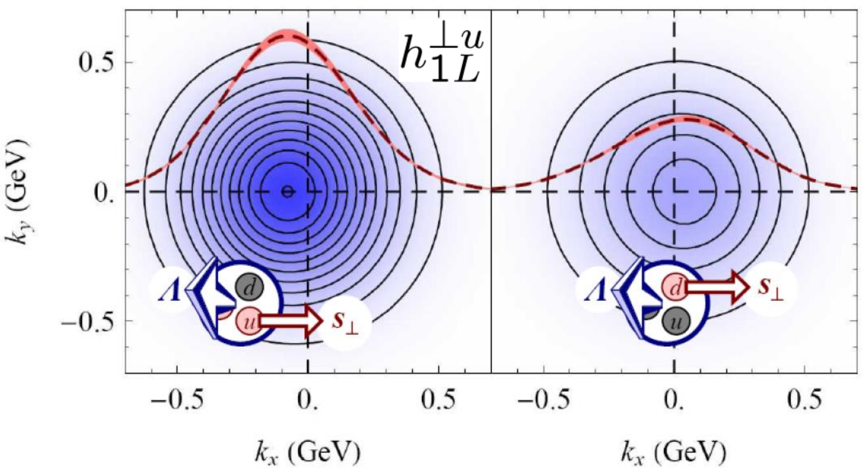
KOTZINIAN-MULDERS ASYMMETRIES

$$A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp} H_1^{\perp} \sin 2\phi$$

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$\boxed{h_{1L}^{\perp}}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$



A.V. Efremov, K. Goeke and P. Schweitzer, Czech. J. Phys. 55 (2005) A189, hep-ph/0412420.

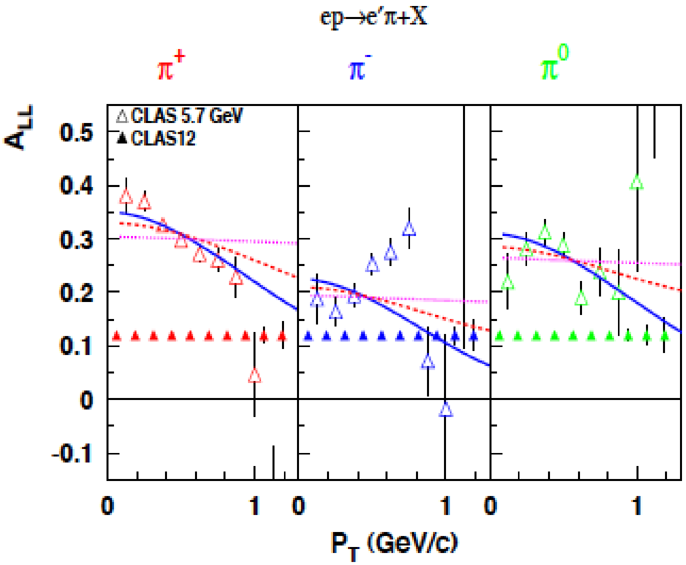


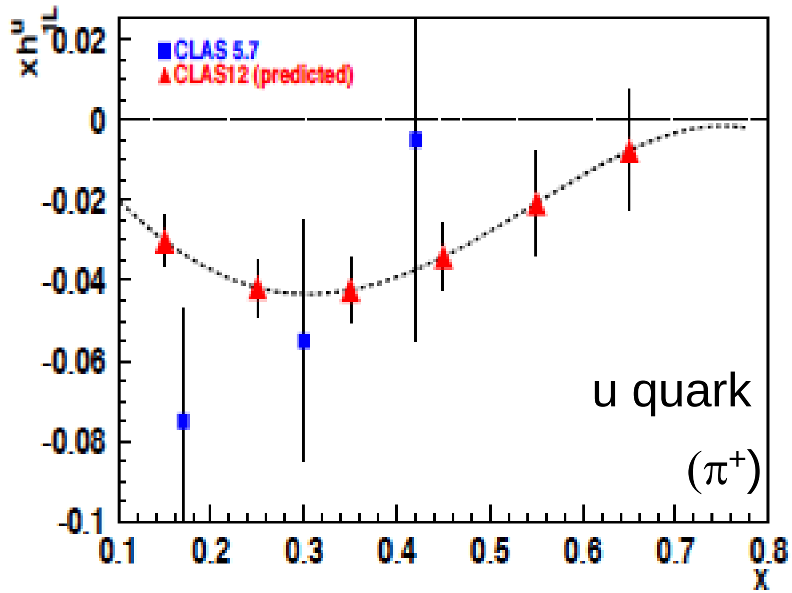
B.Musch arXiv:0907.2381

Worm gear TMDs are unique (no analog in GPDs)

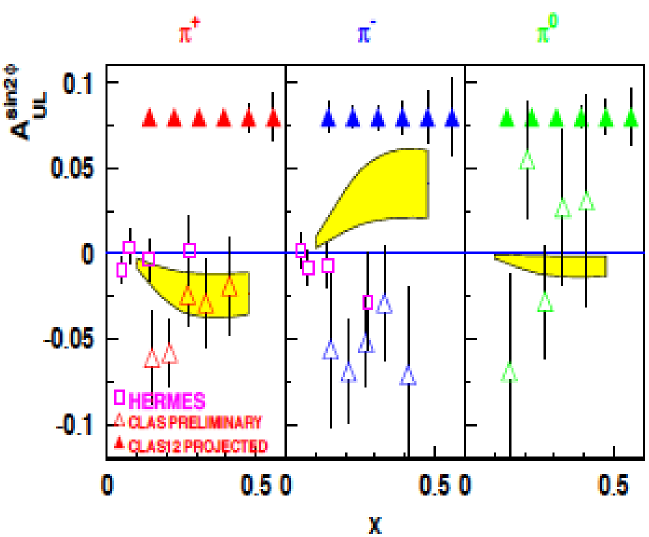
TMDS – CLAS12 (LONG. POL. P,D)

A_1 p_T distr.

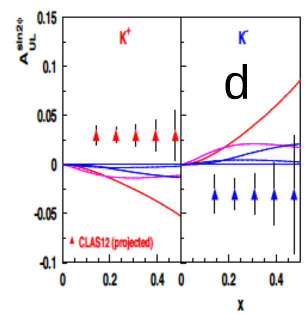


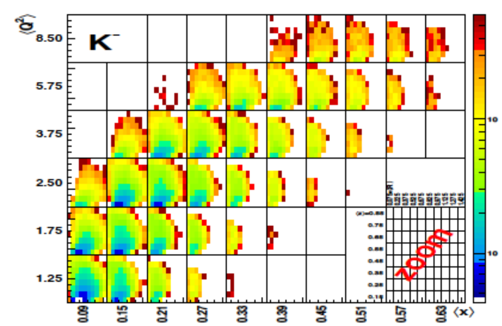


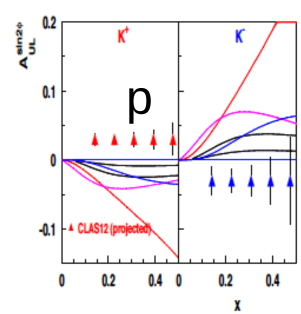
Worm Gear

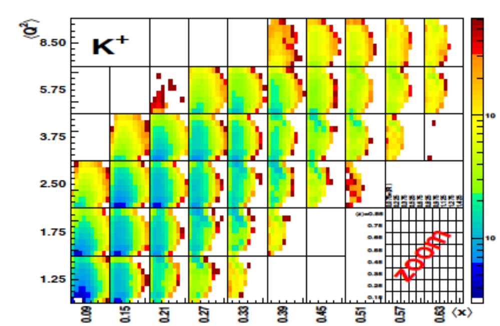


…+sinϕ (Higher Twist)

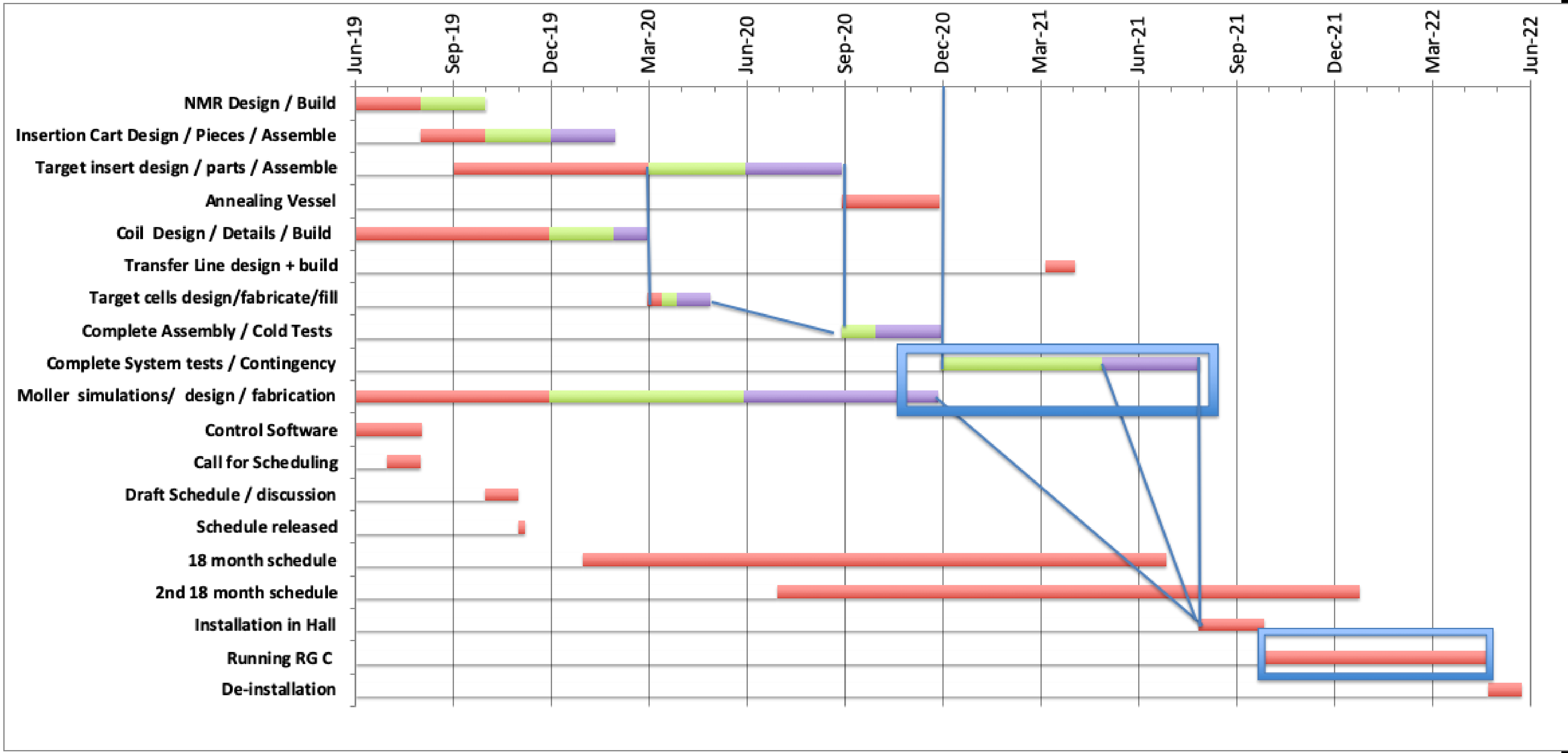






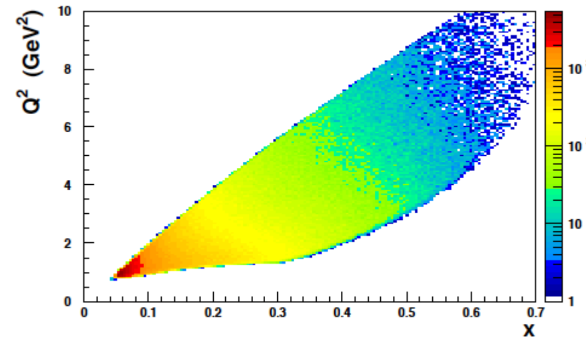


TIMELINE RUN GROUP C

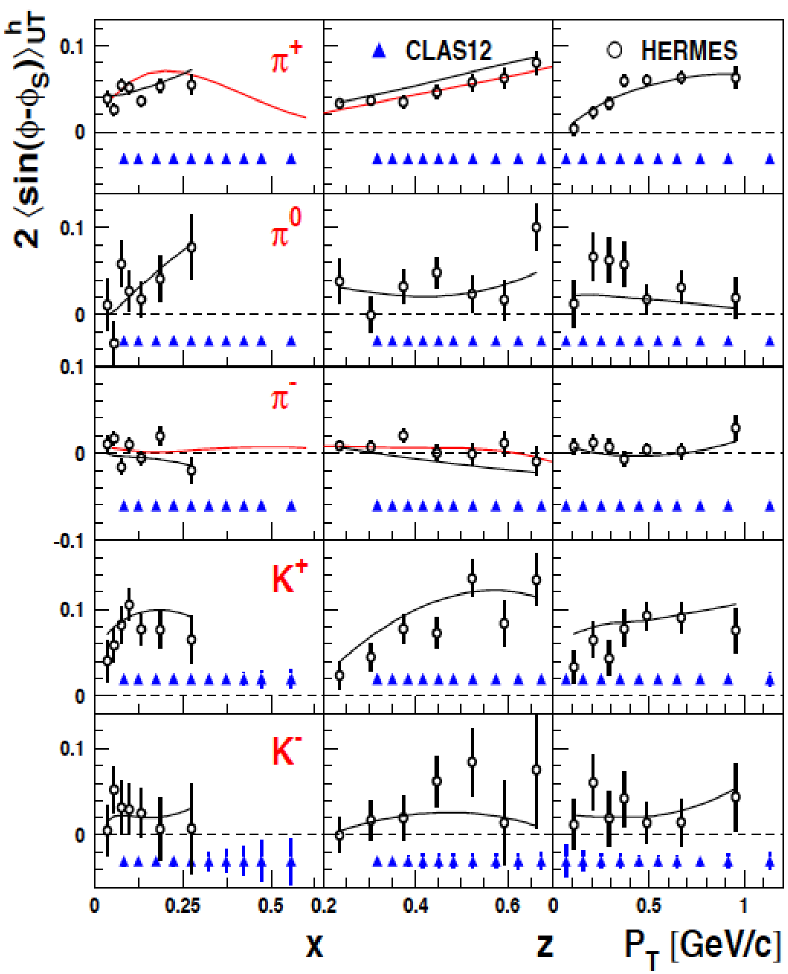


…followed by experiment with transversely polarized p target (HD-ICE)

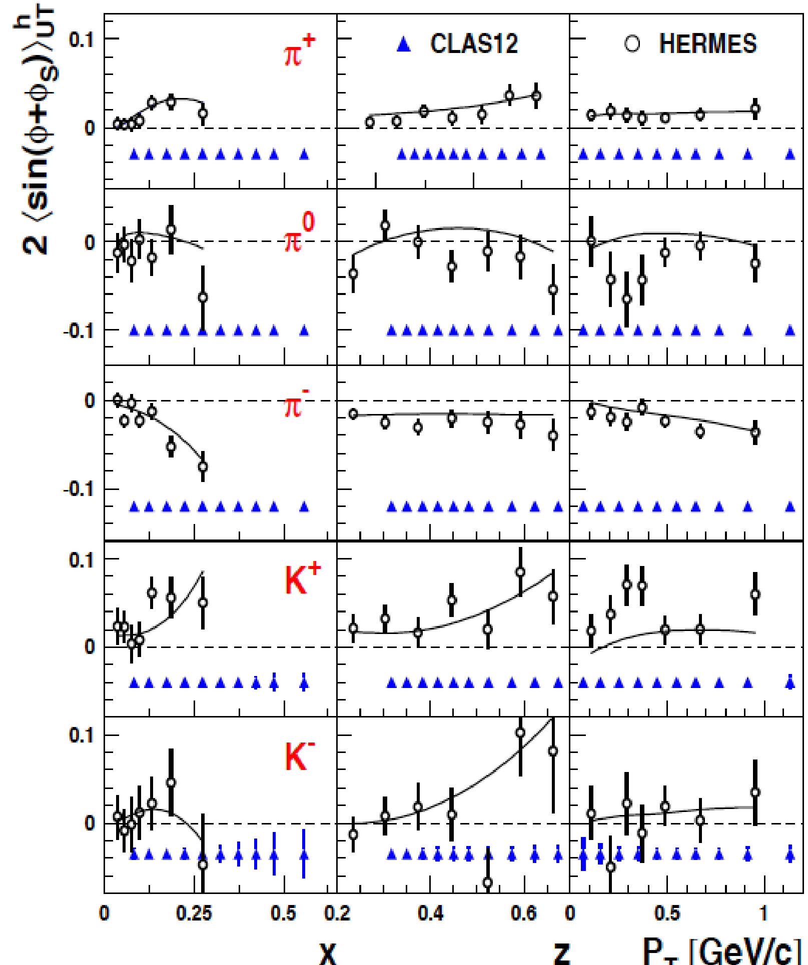
TMDS – CLAS12 TRANSVERSE HD-ICE (?)



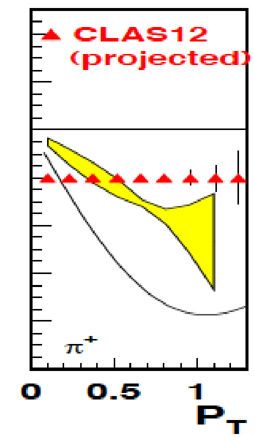
Sivers



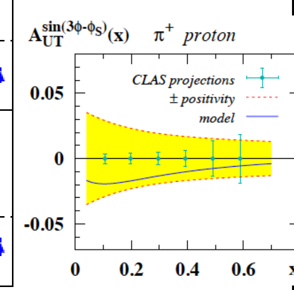
Collins



+ worm gear,

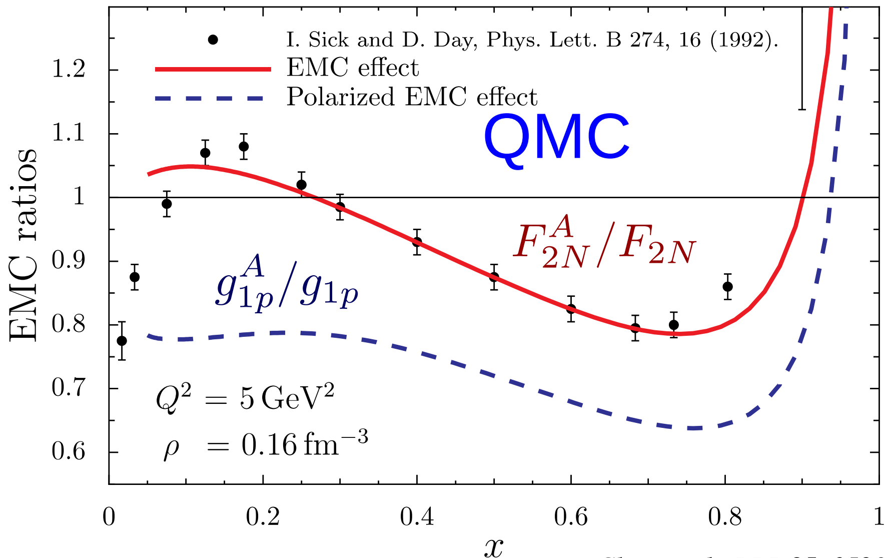


pretzelosity

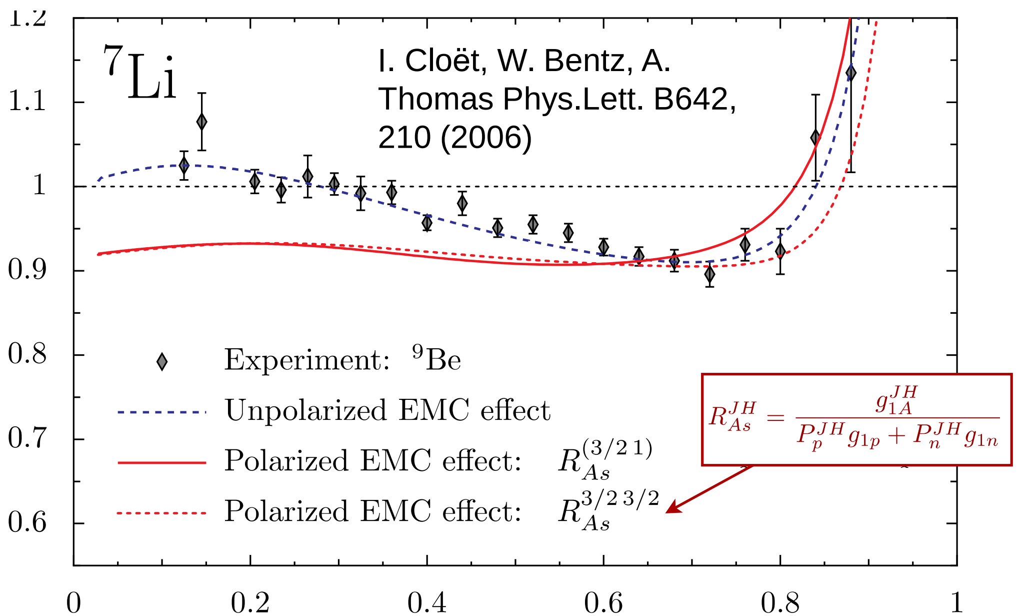


POLARIZED EMC EFFECT?

Quark-Meson Coupling Model (QMC

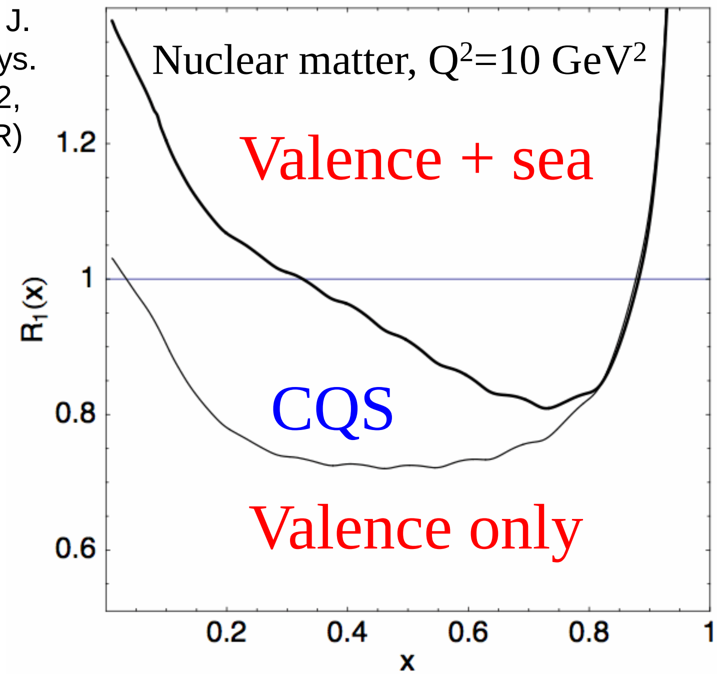


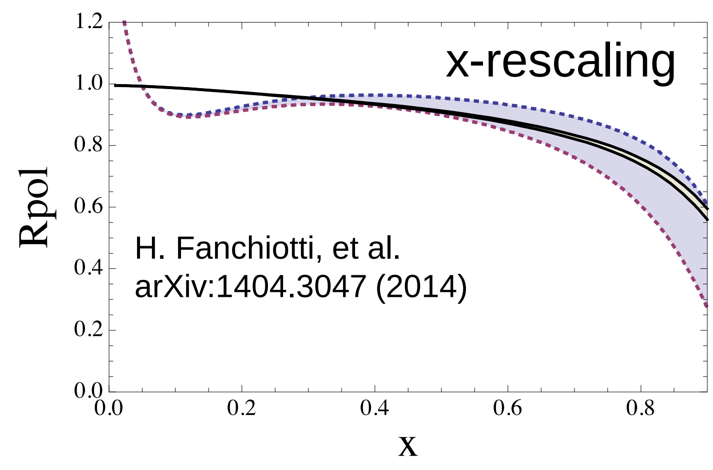
*Cloet et al., PRL **95**, 052302*



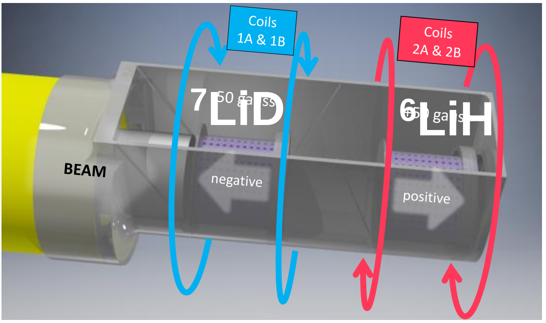
Chiral Quark Soliton Model (CQS)

J. Smith, J. Miller Phys. Rev. C 72, 022203(R) (2005)

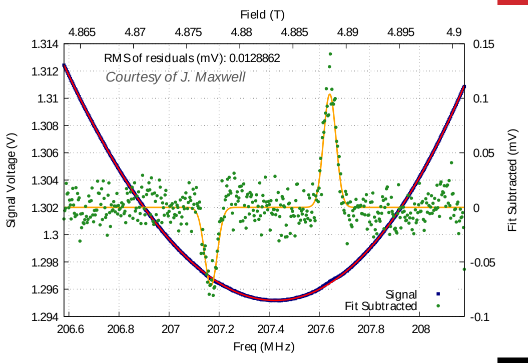


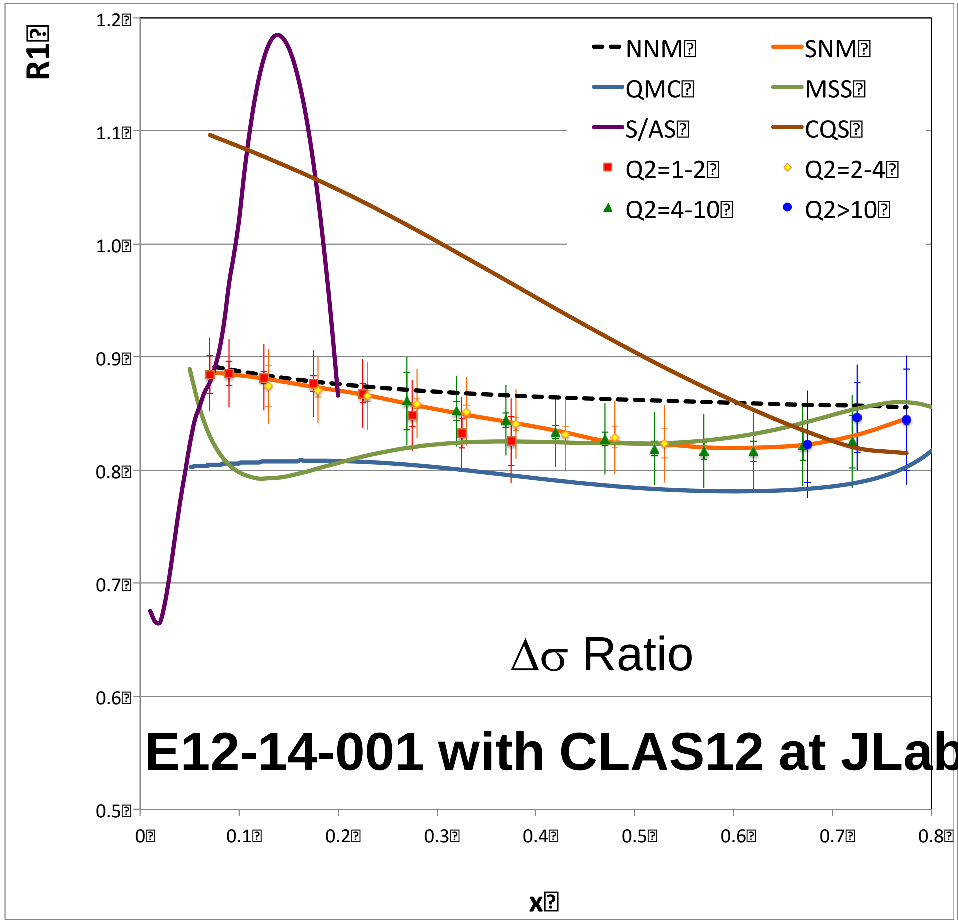


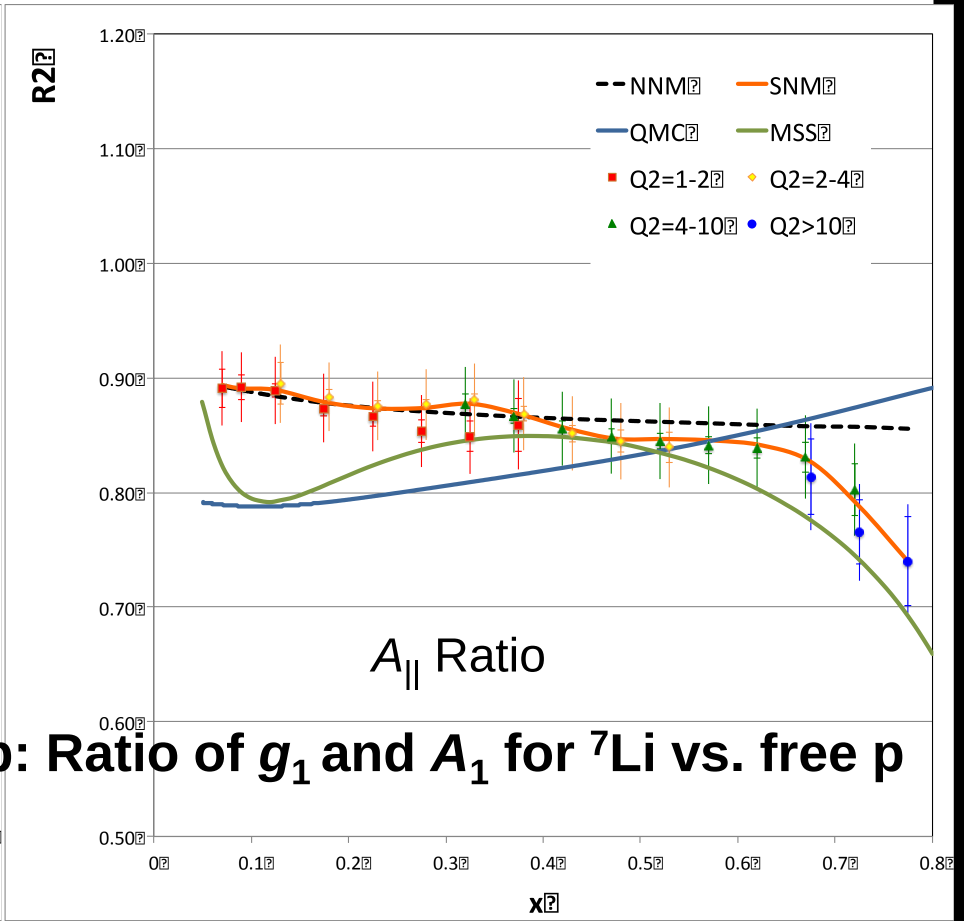
POLARIZED EMC EFFECT?



Shim coils (4)
32 AWG (0.20 mm) copper wire
Outer coils: 4 layers, 32 windings @2 amps
Inner coils: 4 layers, 43 windings @5 amps

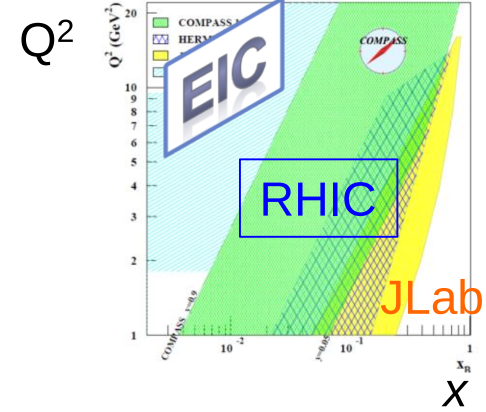






E12-14-001 with CLAS12 at JLab: Ratio of g_1 and A_1 for ^{7}Li vs. free p

OUTLOOK: COMPLETING THE PICTURE



- $\Delta u/u$ and $\Delta d/d$ at high x ?
- Nuclear effects on nucleon structure

JLab @ 12 GeV

EIC

- Understanding the sea – Δs, $\bar{u}$ - $\bar{d}$, $\Delta\bar{u}$ - $\Delta\bar{d}$? JLab, FNAL, RHIC, COMPASS
- Orbital angular momentum? -> GPDs in 3D
- Axial and Tensor charges of the nucleon
- Full mapping of all TMD PDFs in the valence and sea region EIC

COMPASS, JLab

- Gluon helicity distribution at large x and a small x? What is the integral ΔG? JLab + COMPASS (NLO), RHIC, COMPASS SIDIS EIC
- Test of universality RHIC, COMPASS, FNAL
- Test of prediction that time-odd TMDs (e.g., Sivers asymmetry) change sign in Drell-Yan processes

RHIC, COMPASS, FNAL, FAIR, JPARC vs. JLab

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

EIC

ENERGY LEVELS IN A HYDROGEN-LIKE ATOM

Putting it all together – example HFS (courtesy K. Griffioen, W&M):

$$E_{\mathrm{HFS}}(e^- p) = 1.42040575177667(9)\mathrm{GHz} = (1 + \Delta_{QED} + \Delta_R^p + \Delta_S) E_F^p \quad + \ldots$$

(21 cm)

Recoil

$$\Delta_S = \Delta_Z + \Delta_{\mathrm{pol}}$$

Zemach: $\Delta_Z = -2\alpha m_e \langle r \rangle_Z (1 + \delta_Z^{\mathrm{rad}})$

$$\langle r \rangle_Z = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left[G_E(Q^2) \frac{G_M(Q^2)}{1+\kappa} - 1 \right]$$

$$\delta_Z^{\mathrm{rad}} = \frac{\alpha}{3\pi} \left[2 \ln \frac{\Lambda^2}{m^2} - \frac{4111}{420} \right]$$

$$\Delta_{\mathrm{pol}} = \frac{\alpha m_e}{2\pi(1+\kappa)M} (\Delta_1 + \Delta_2)$$

$$\Delta_1 = \frac{9}{4} \int_0^\infty \frac{dQ^2}{Q^2} \left\{ F_2^2(Q^2) + \frac{8m_p^2}{Q^2} B_1(Q^2) \right\}$$

$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

$$B_1 = \int_0^{x_{\mathrm{th}}} dx\, \beta(\tau) g_1(x, Q^2)$$

$$B_2 = \int_0^{x_{\mathrm{th}}} dx\, \beta_2(\tau) g_2(x, Q^2)$$

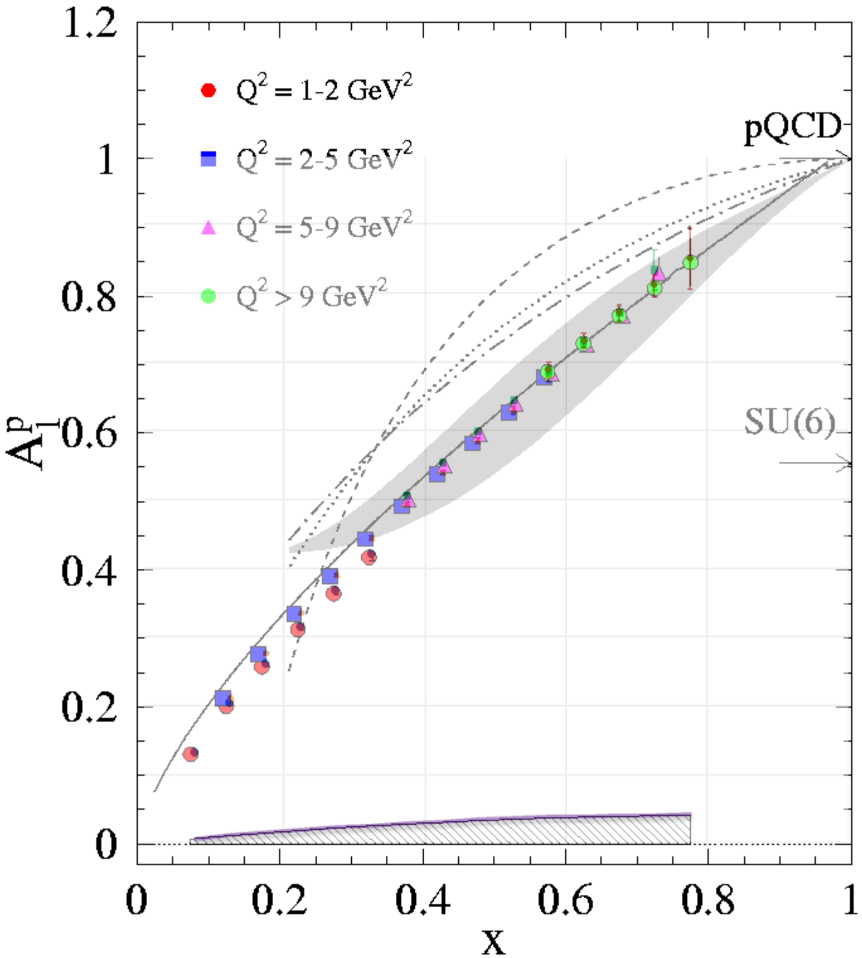
$$\beta(\tau) = \frac{4}{9} \left(-3\tau + 2\tau^2 + 2(2-\tau)\sqrt{\tau(\tau+1)} \right)$$

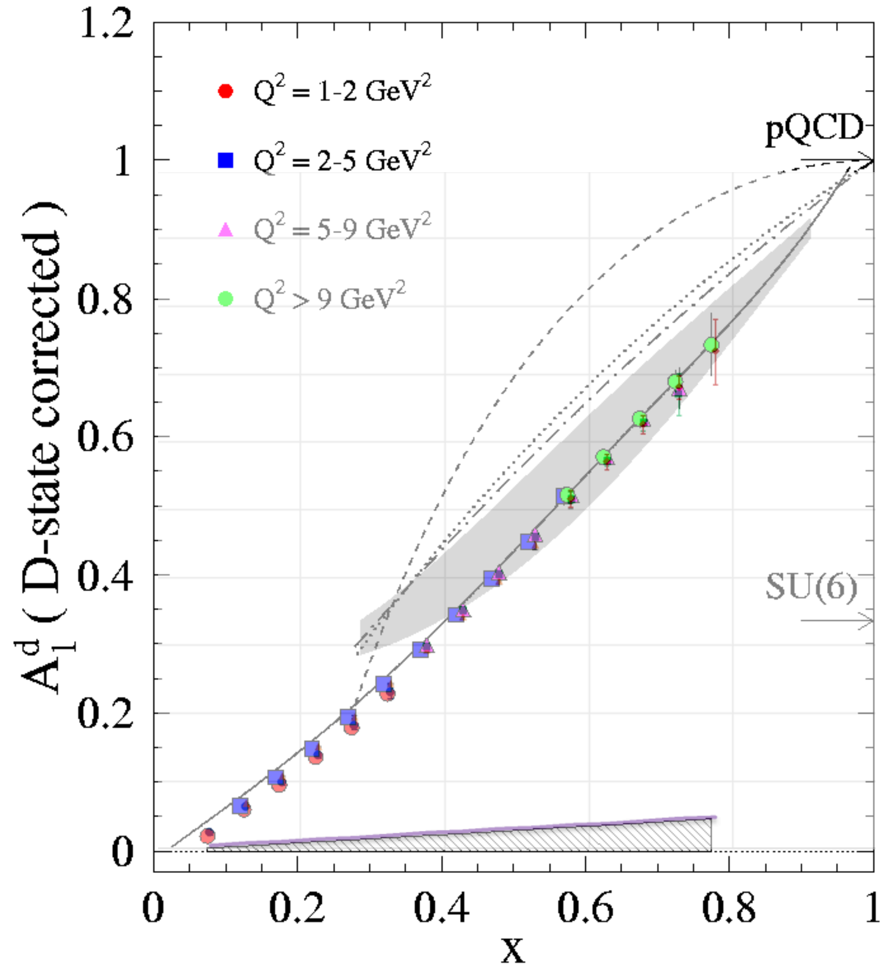
$$\beta_2(\tau) = 1 + 2\tau - 2\sqrt{\tau(\tau+1)},$$

Measurements of form factors, (generalized) polarizabilities and (spin) structure functions **at small Q^2** are crucial.

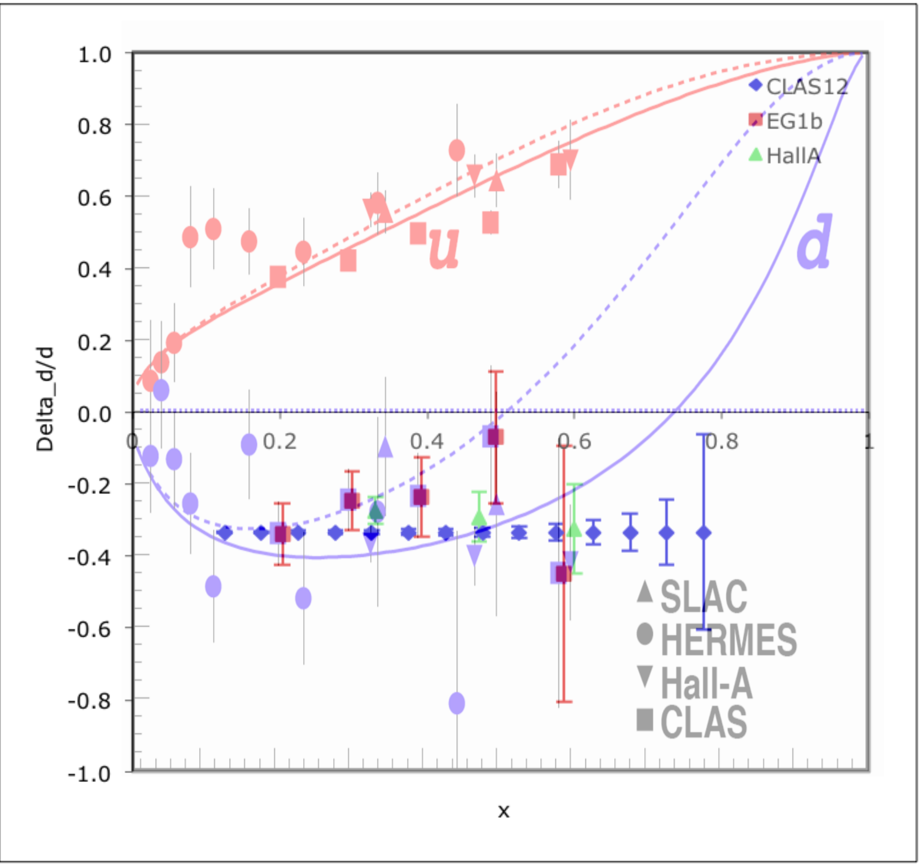
PREDICTED DATA FROM CLAS12 - DIS

Proton W > 2; Q^2 > 1 Deuteron

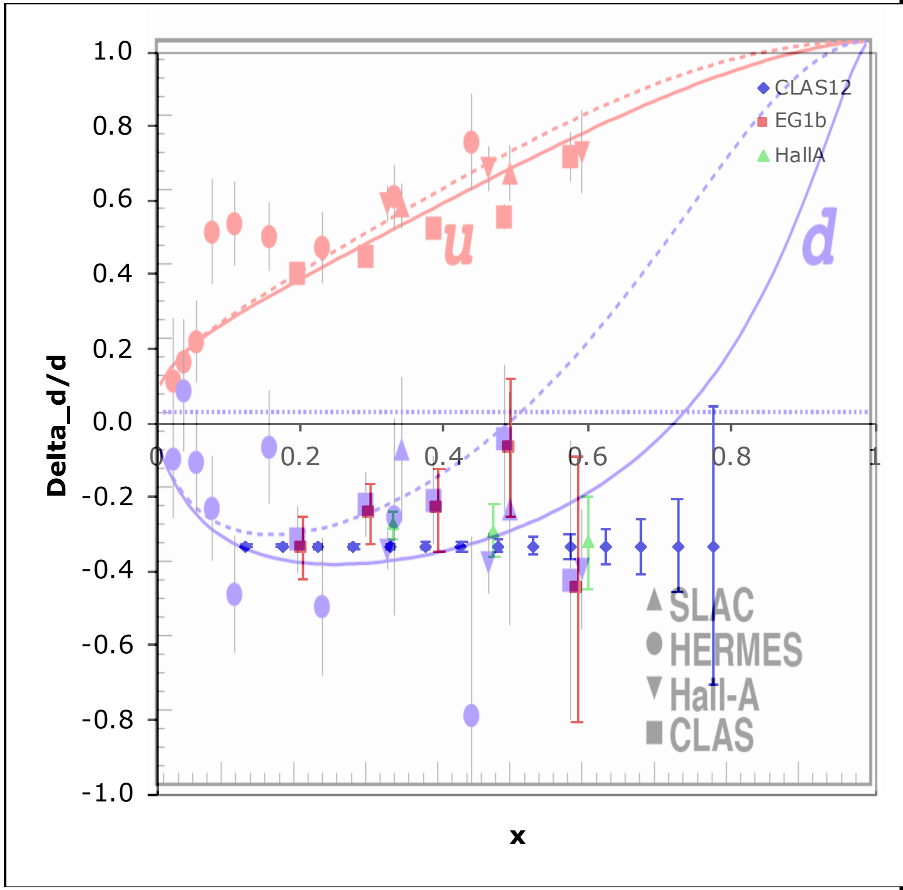




ΔD/D FROM DIS

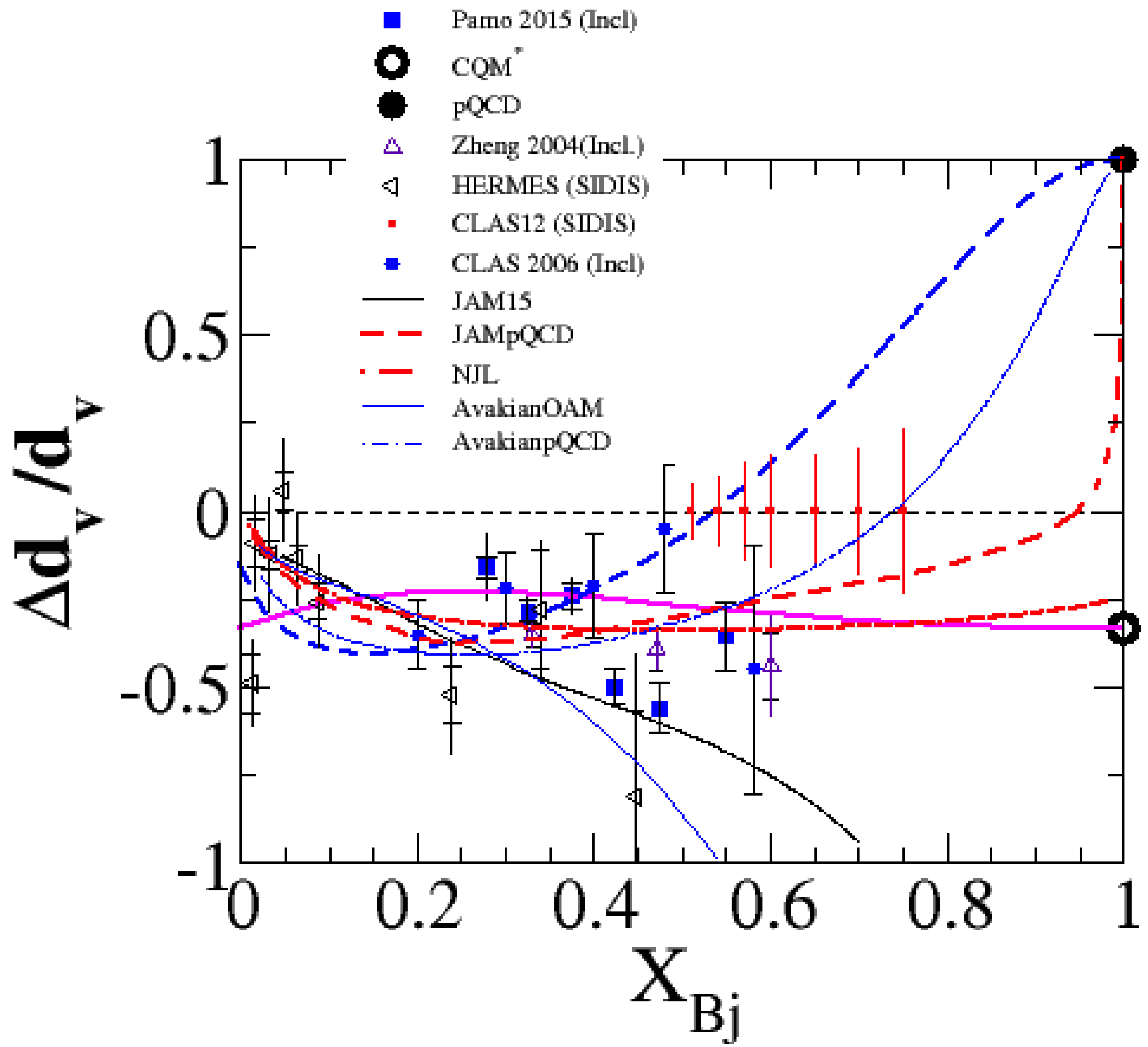


As proposed

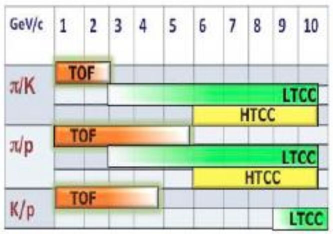


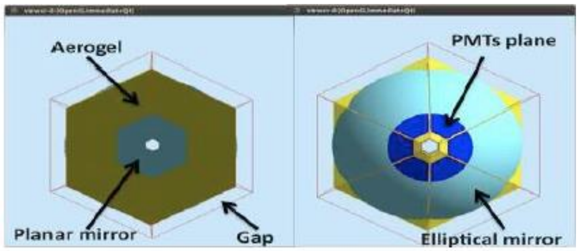
Up-to-date estimate for 1st run of RGC

ΔD/D INCLUDING SIDIS



TMDS – CLAS12





Comprehensive Program with **Longitudinal** and **Transverse** H, D targest

	Experiment	Quantity	Physics	Target	particle species	Kinematics	beam request	run group
Worm gear, HT	E12-07-107	$A_{UL}^{\sin\varphi}$ $A_{UL}^{\sin 2\varphi}$		NH_3 ND_3	π^+, π^-, π^0	x= 0.1-0.7 P_T=0.1-1.2	30 days 50 days	
Flavor tagging (Δq); pT dep.	E12-09-007b	Δu, Δd, Δs Δu, Δd, Δs	x(Δu-Δd)	NH_3 ND_3	π^+, π^-, π^0 K^+, K^-, K^0_s	x=0.1-0.7	30 days 50 days	**170 days**
Kaons Worm gear	E12-09-009	A_1 $A_{UL}^{\sin\varphi}$ $A_{UL}^{\sin 2\varphi}$		NH_3 ND_3	π^+, π^-, π^0 K^+, K^-, K^0_s	Q^2= 1 - 9 x=0.1-0.7 P_T= 0.1-1.2	30 days 50 days	
Two-Hadron (Deferred)	PR12-11-109b	A_{UL}	h_L	NH_3 ND_3	ππ, KK	x=0.05-0.6	30 days 50 days	

Transversity, Sivers, Worm Gear, Pretzelosity	PR12-11-111	SIDIS A_{UT}	Sivers, Transversity Pretzelosity	HD	π^+,π^-,π^0 K^+, K^-, K^0_s	Q^2=1-10GeV^2 x=0.1-0.7 P_T=0.2-1.5	100 days	**100 days**