Overview of Nucleon Spin and 3-d structure program at JLab

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DIS 2024, Grenoble, France, April 8-12, 2023

- Introduction/Overview
- Highlights of JLab 1-d Spin Program
    - Spin Moments (Sum Rules and Polarizabilities) @ Low-Q^2
    - Spin Moments (d2n) @ medium-high Q^2
    - Spin structure (A1n/A1p) in high-x (valence quark) region
- Highlights of JLab 3-d Structure Program
    - CLAS12 (RGC): DVCS, SIDIS
    - Hall A/C: DVCS, SIDIS
- Future
    - SoLID Program: precision multi-d mapping
    - Tensor-TMD

Acknowledgment: Thanks to C. Camacho, J. Chen, M. Chen, A. Deur, E. Kinney, S Kuhn, G. Matousek, J. Poudel, D. Ruth, N. Santiesteban, K. Slifer, X. Zheng, … and collaborators for the work in this talk and for providing slides

Introduction and Overview

Nucleon Spin and 3-D Structure
JLab Program Summary

Nucleon Spin Structure Study

- 1980s: EMC (CERN) + early SLAC
  quark contribution to proton spin is very small
  $\Delta\Sigma$ = (12+-9+-14)% ! ‘spin crisis’

- 1990s-2000s: SLAC, SMC (CERN), HERMES (DESY)
  $\Delta\Sigma$ = 20-30%, the rest: gluon and quark orbital angular momentum
  Jaffe and Manohar: $(½)\Delta\Sigma + L_q + \Delta G + L_G = 1/2$
  Ji (gauge invariant): $(½)\Delta\Sigma + \mathcal{L}_q + J_G = 1/2$
  Bjorken Sum Rule verified to <10% level

- 2000s-2020s: COMPASS (CERN), HERMES (DESY), RHIC-Spin, JLab, …

$\Delta\Sigma$ ~ 30%; ΔG ~ 20-50% (RHIC-Spin); orbital angular momentum significant

OAM → needs transverse coordinate and momentum → **GPDs, TMDs**

spin moments (sum rules/polarizabilities) → test of QCD theoretic approaches

full spin-flavor separation: **valence quarks** and sea quarks

Reviews: Sebastian, Chen, Leader, arXiv:0812.3535, PPNP 63 (2009) 1;
Chen, arXiv:1001.3898, IJMPE 19 (2010) 1893; …

Summary/Highlights of JLab Spin/3-d Experiments

- 1-d Spin
  - Low-Q spin moments (sum rules and polarizabilties)

    Hall A g2p (trans. p), Hall B EG4 (long. p and d), SAGDH (trans. and long. ^{3}He/n)
  - JLab12

    Hall C A1n and d2n (long. and trans. 3He/n), Hall B (CLAS12) RGC (long. p and d)

    …
- 3-d
  - Hall B (CLAS12) RGC SIDIS and DVCS with long. p and d
  - Hall A/C DVCS (unpolarized p and d)
  - Hall C SIDIS (unpolarized p and d)

    …
- Future:
  - SoLID TMD and GPD program (trans. and long. ^{3}He/n; trans. p)
  - Tensor Spin and TMD (tensor polarized deuteron)

    …

Spin Sum Rules and Polarizabilities

Sum Rules

Nucleon Structure ←→ Global Properties

mass, spin, magnetic moment, polarizabilities, …

How is nucleon structure related (gives rise) to global properties?

→ Help understand Strong QCD (LQCD, χEFT, …)

Bjørken Sum Rule, GDH Sum Rule, Generalized Sum Rule

Bjørken Sum Rule (high Q^2)

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \int \{g_1^p(x,Q^2) - g_1^n(x,Q^2)\}dx = \frac{1}{6} g_A C_{NS}$$

GDH Sum Rule
Real photon (Q^2=0)

$$\int_{\nu_{in}}^{\infty} \left(\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)\right)\frac{d\nu}{\nu} = -\frac{2\pi^2\alpha_{EM}}{M^2}\kappa^2$$

Generalized GDH Sum Rule

$$S_1(Q^2) = 4\int_{el}^{\infty}\frac{G_1(Q^2,\nu)d\nu}{\nu}$$

- Q^2-dependence of GDH Sum Rule provides **a bridge linking strong QCD to pQCD**
  - Bjorken and GDH sum rules are two limiting cases

    High Q^2, Operator Product Expansion : S_1(p-n) ~ g_A → Bjorken

    Q^2 → 0, Low Energy Theorem: $S_1 \sim \kappa^2$ → GDH

  - High Q^2: pQCD, Operator Product Expansion
  - All Q^2 region: Lattice QCD calculations
  - Low Q^2 region (< ~0.1 GeV^2): Chiral Effective Field Theory (χEFT)

Spin Polarizabilities (higher moments)

- **Polarizibilities @ low Q^2**

Generalized forward spin polarizability:

$$\gamma_0 = \frac{4e^2M^2}{\pi Q^6} \int x^2 (g_1 - \frac{4M^2}{Q^2} x^2 g_2) dx$$

Longitudinal-Transverse polarizability:

$$\delta_{LT} = \frac{4e^2M^2}{\pi Q^6} \int x^2 (g_1 + g_2) dx$$

They can be calculated with χEFT and Lattice QCD (4-point functions)

- **Polarizibilities @ Intermediate-to-high Q^2**

Color polarizability (X. Ji)
Color Lorentz force (M. Burkardt)

$$\int_0^1 x^2 \{2g_1 + 3g_2\} dx = d_2$$

Dynamic twist-3 matrix element: quark-gluon correlations
Lattice QCD calculations

Low-Q Spin Experiments @ JLab

- **Hall B EG4: proton g_1:** Spokespeople: M. Ripani, M. Battaglieri, A. Deur, R. de Vita
  Students: H. Kang, K. Kovacs
  X. Zheng et al., Nature Physics, vo. 17 736-741 (2021)
- **Hall A g2p: proton g_2:** Spokespeople: K. Slifer, J. P. Chen, A. Camsonne, D. Crabb
  Students: D. Ruth, R. Zielinski, C. Gu, M. Allada (Cummings), T. Badman, M. Huang, J. Liu, P. Zhu
  D. Ruth et al, Nature Physics 18, 1441 (2022)
- **Hall A SAGDH: neutron g_1 and g_2 with L/T polarized ^{3}He**

Spokespeople: J. P. Chen, A. Deur, F. Garibaldi.

Students: V. Sulkosky, C. Peng, J. Singh,V. Laine, N. Ton, J. Yuan.

V. Sulkosky et al., Nature Phys., 17 687 (2021)
V. Sulkosky et al., PLB 805 135428 (2020)

Combining EG4 and SAGDH to form Bjorken Sum**: A. Deur et al., Phys. Lett. B 825 (2022) 136878**
Extracting effective coupling α_{g1}: A. Deur, et al., Particles, 5-171 (2022)

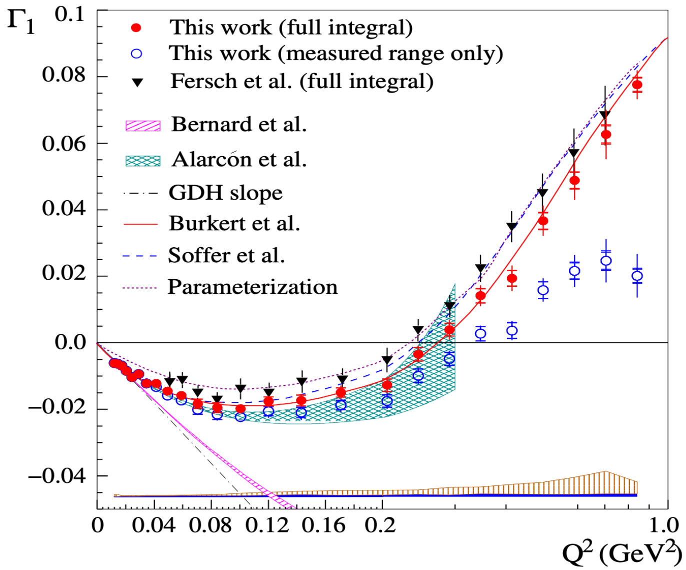
JLab low-Q data on Γ_1, Γ_2 for proton and neutron

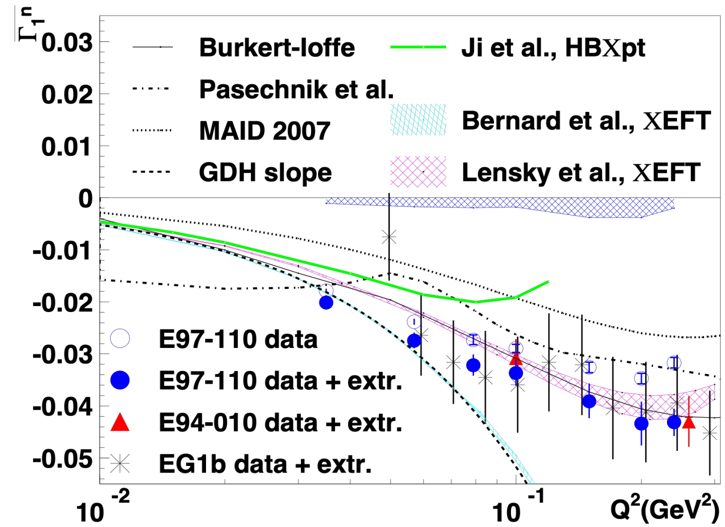
proton

neutron

Γ_1

Nature Physics, 17, 736-741 (2021)



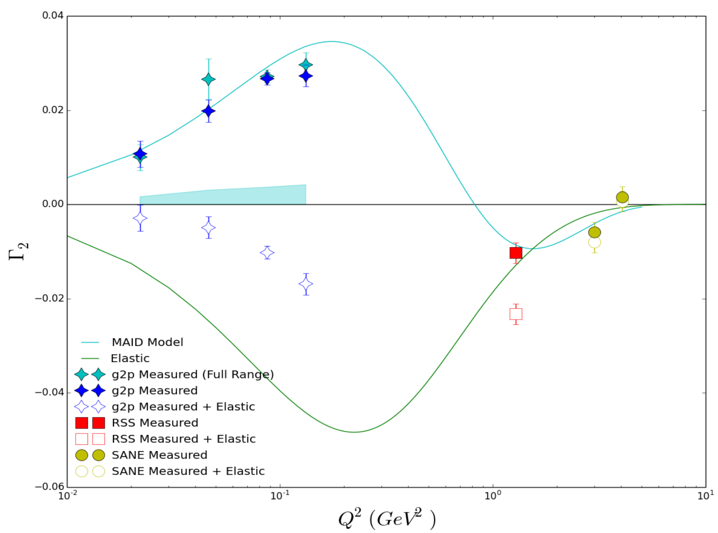


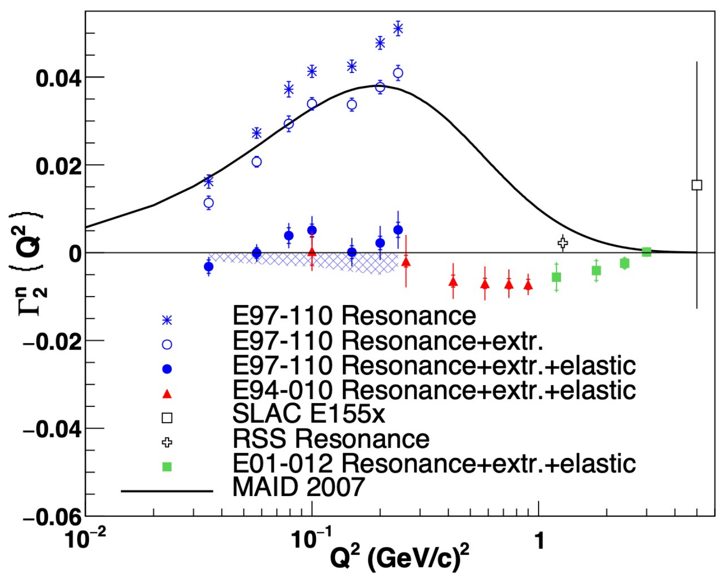
Physics Letter B 805, 135428 (2020)

Γ_2

Preliminary results from JLab g2p experiment

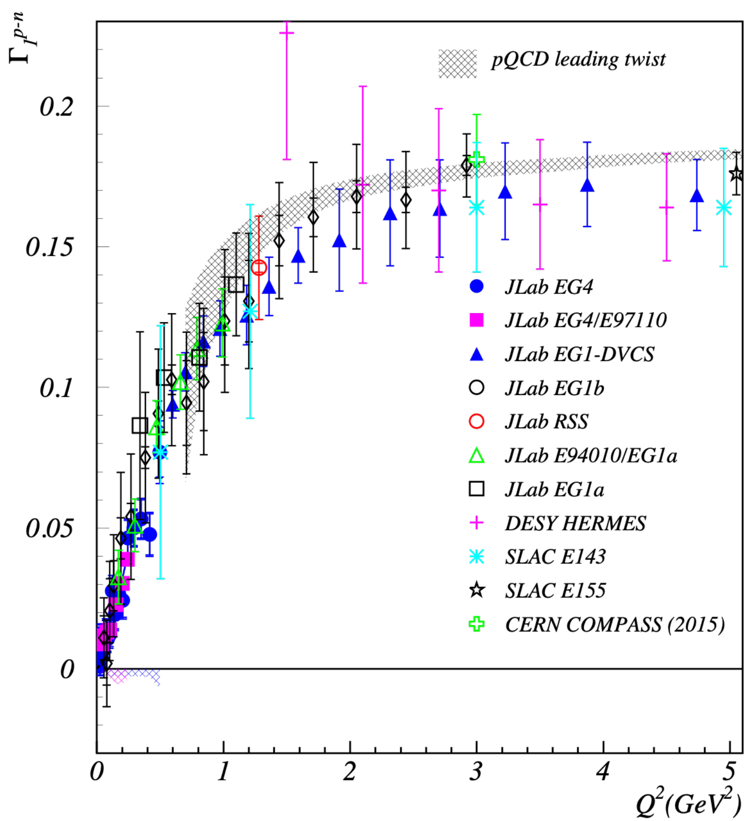
D. Ruth





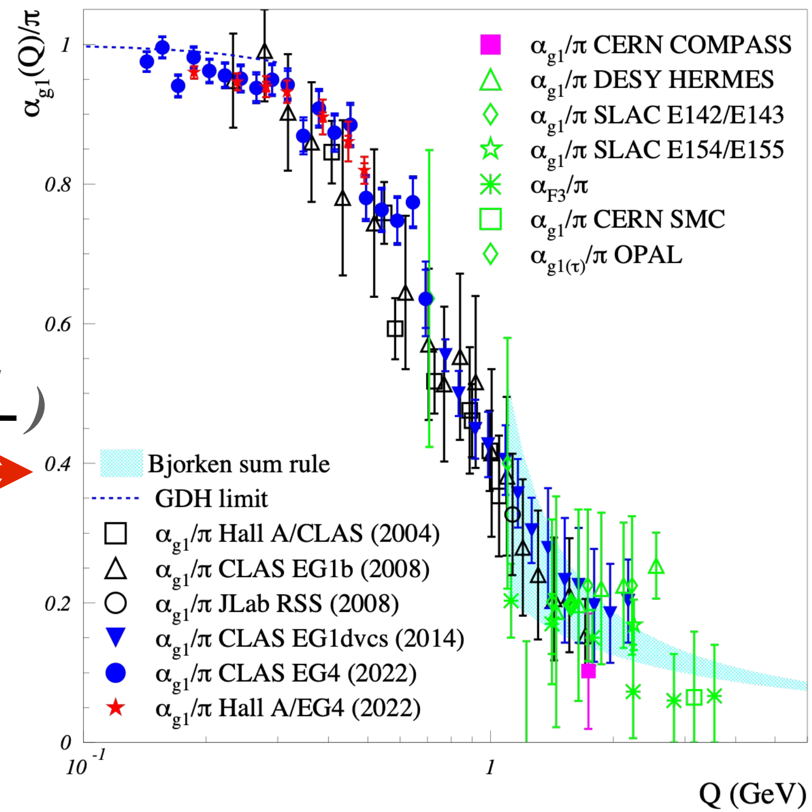
α_{g1} Extracted from the Bjorken Sum data

Bjorken sum Γ_1^{p-n} measurements



Effective coupling α_{g1}

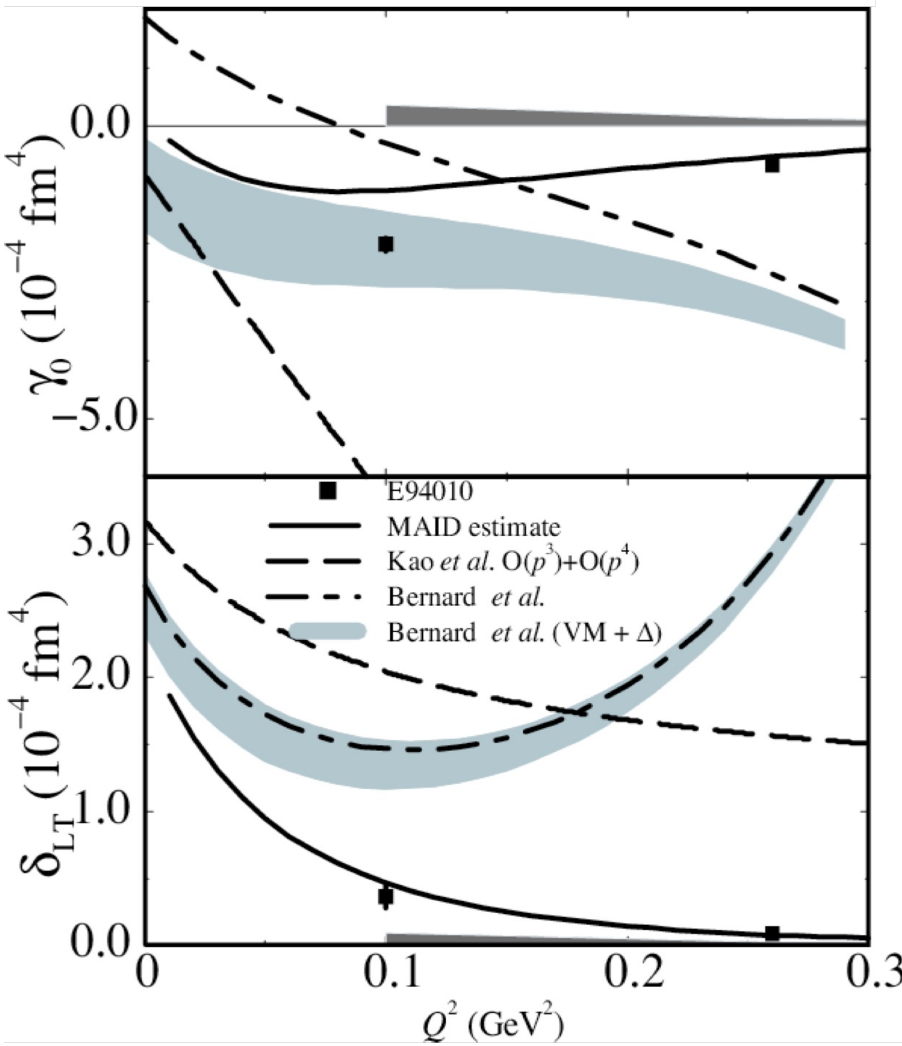
$$\Gamma_1^{p-n} \triangleq \frac{1}{6} g_A\left(1-\frac{\alpha_{g1}}{\pi}\right)$$

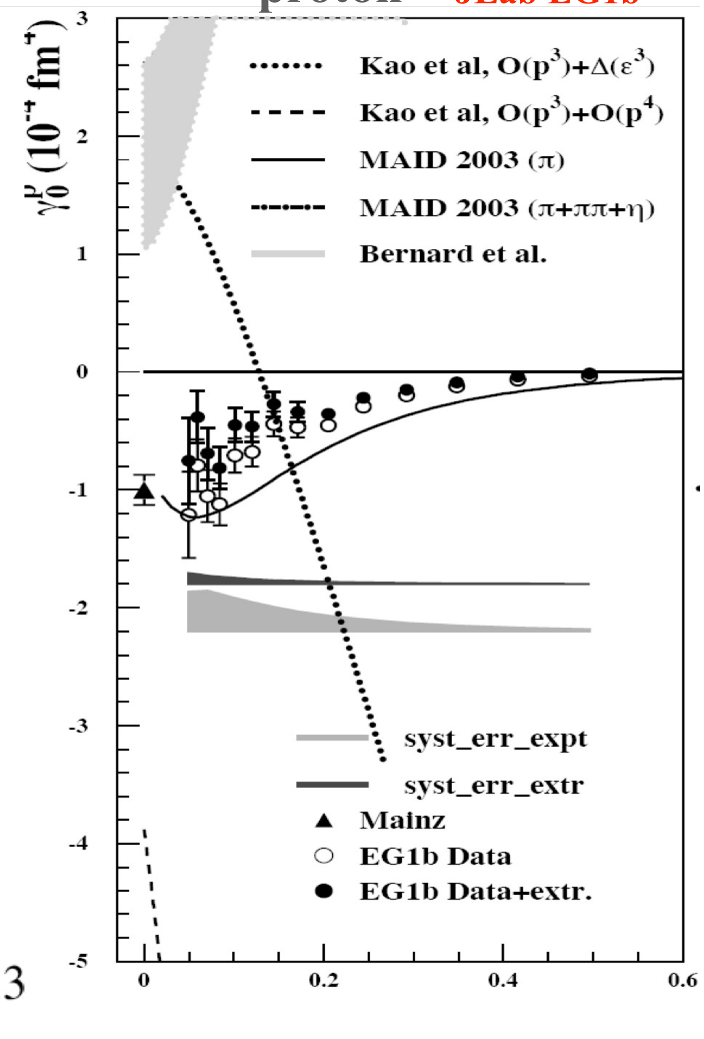


A. Deur, *et al.*
Physics Letter B
825 (2022) 136878

A. Deur, V. Burkert, J. P. Chen and W. Korsch
Particles, 5-171 (2022)

Previous JLab spin polarizabilities data before low-Q experiments





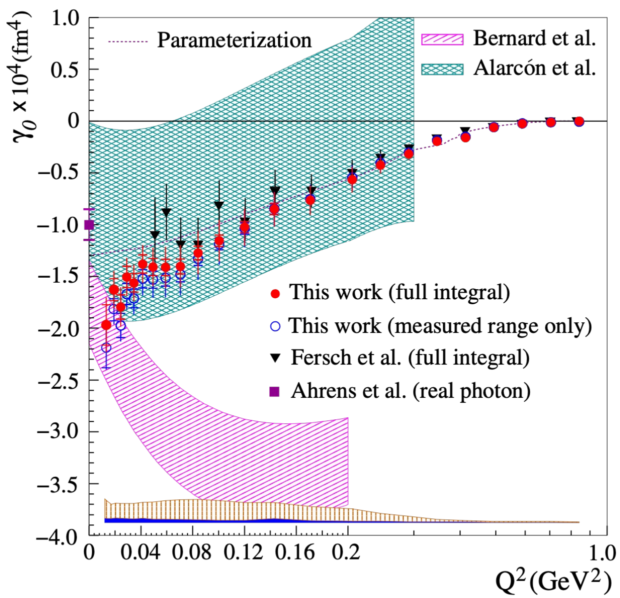
Strong disagreement with χEFT predictions available at that time: **"δ_{LT} puzzle"**

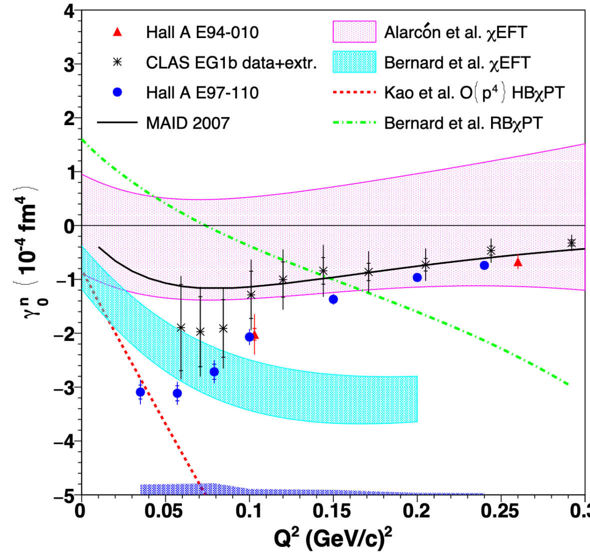
Spin Polarizabilities $\gamma_0(Q^2)$, $d_{LT}(Q_2)$ for proton and neutron

proton **neutron**

γ_0

Nature Physics, 17, 736-741 (2021)

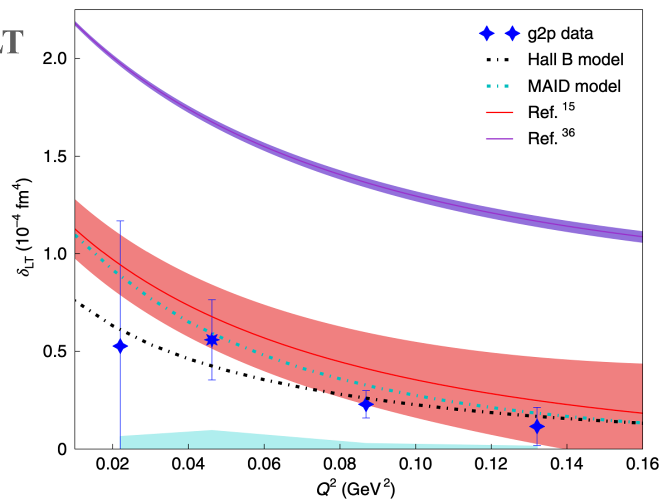


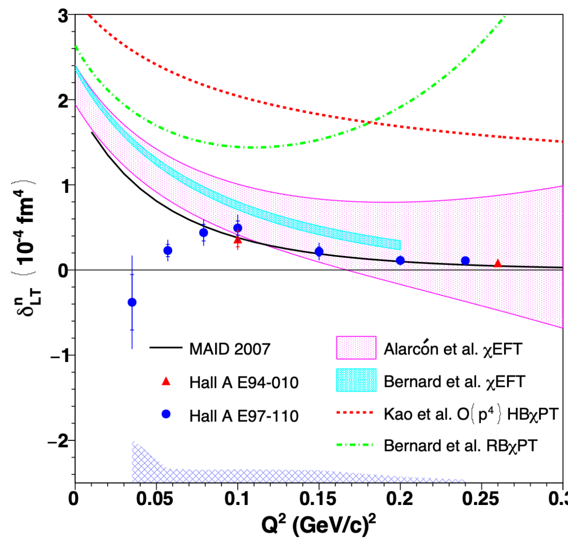


Nature Physics, 17, 687 (2021)

Nature Physics 18, 1441 (2022)

δ_{LT}





Comparisons with χEFT calculations: favor Alarcon *et al.*, strong disagreement with Bernard *et al.*

"$\delta^n_{LT}(Q^2)$ puzzle" remains!

Highlights of JLab12 Spin Program
Spin Moments @ Intermediate Q^2
Spin Structure in Valence Quark Region

- Preliminary results from d2n(^{3}He) in Hall C
  color polarizability/color Lorentz force
- Preliminary results from A1n(^{3}He)@high-x:
  spin structure in valence region
- Overview of RGC@CLAS12: A1p (A1d) @high-x
  spin structure with longitudinally polarized p and d

6 GeV Results for d2 Moment

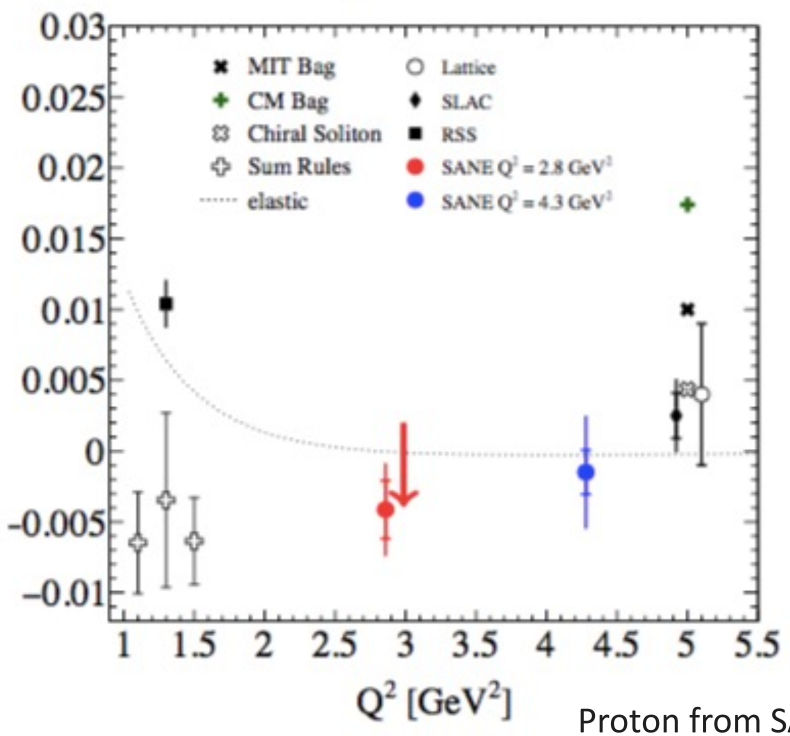
Dynamic twist-3 matrix element

$$\int_0^1 x^2\{2g_1 + 3g_2\}dx = d_2$$

Interpretations of d_2

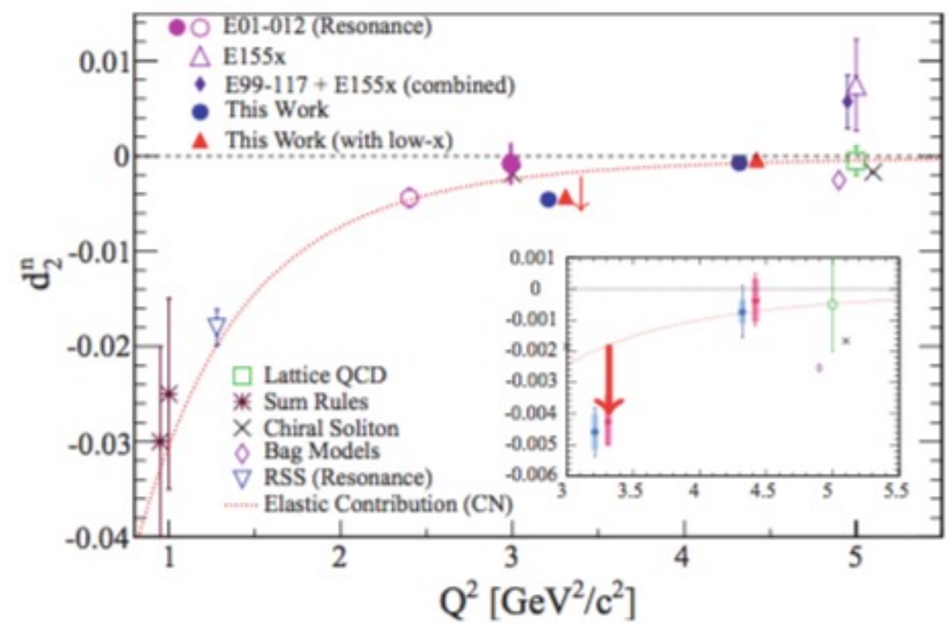
- Color Polarizabilities (X.Ji 95, E. Stein et al. 95)
- **Average Color Lorentz force** (M.Burkardt)

proton



Proton from SANE, PRL 122, 022002 (2019)

neutron



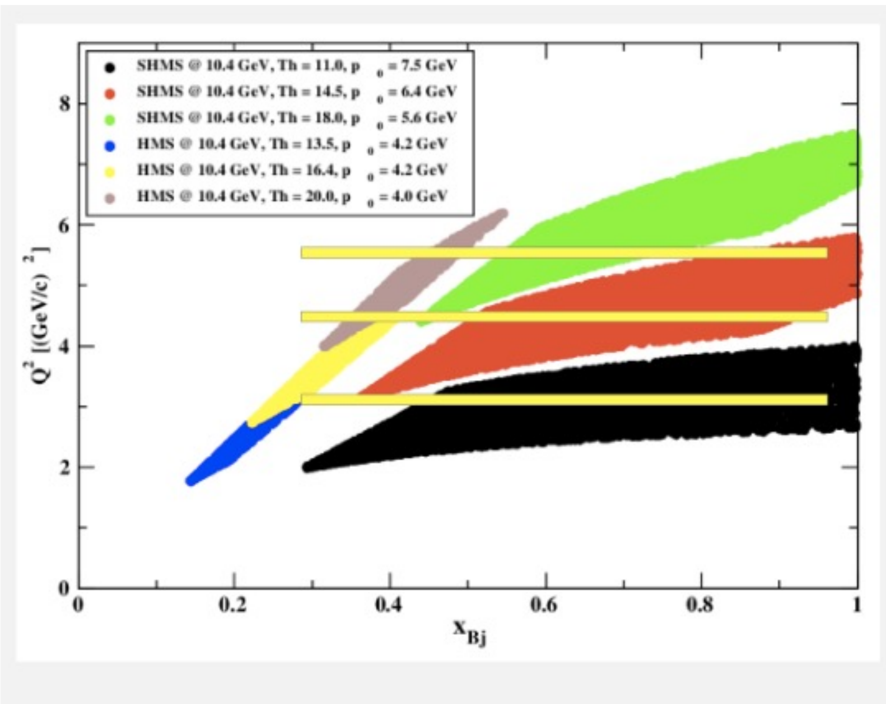
Neutron from d_2^n experiment: D.Flay, et.al. PRD.94(2016)no.5,052003

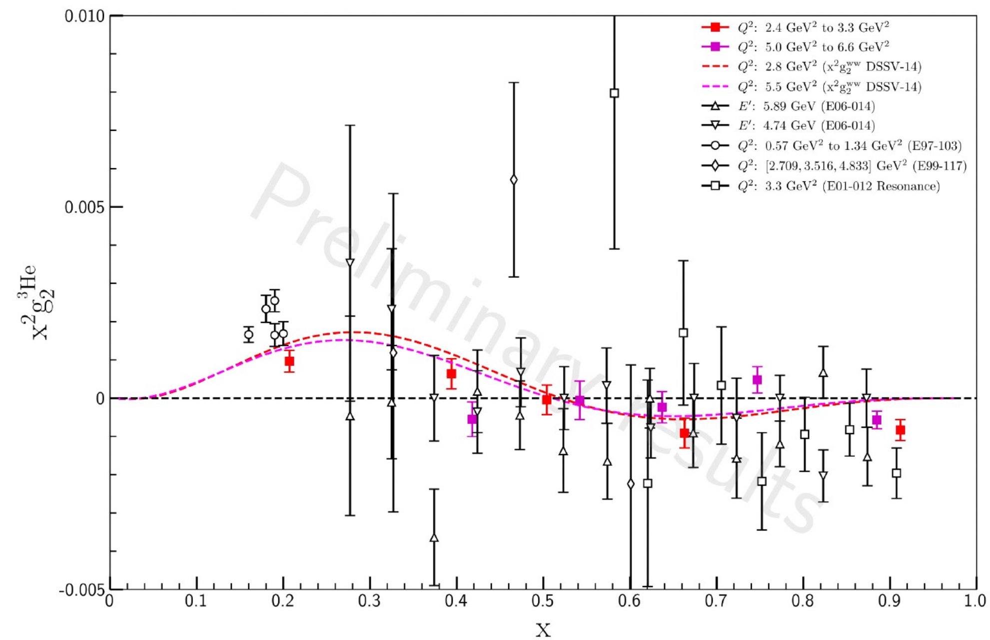
12 GeV d_2^n

12 GeV d_2^n: Color Polarizability/Lorentz Force

- Measurement of g_1 and g_2 structure functions and d_2 moments at 3 GeV^2 < Q^2 < 5.5 GeV^2 for the neutron using a polarized ^{3}He target
- Study quark-gluon correlations (twist-3) and provide a benchmark test of LQCD calculations.
- Completed data taking in 2020

J. Chen

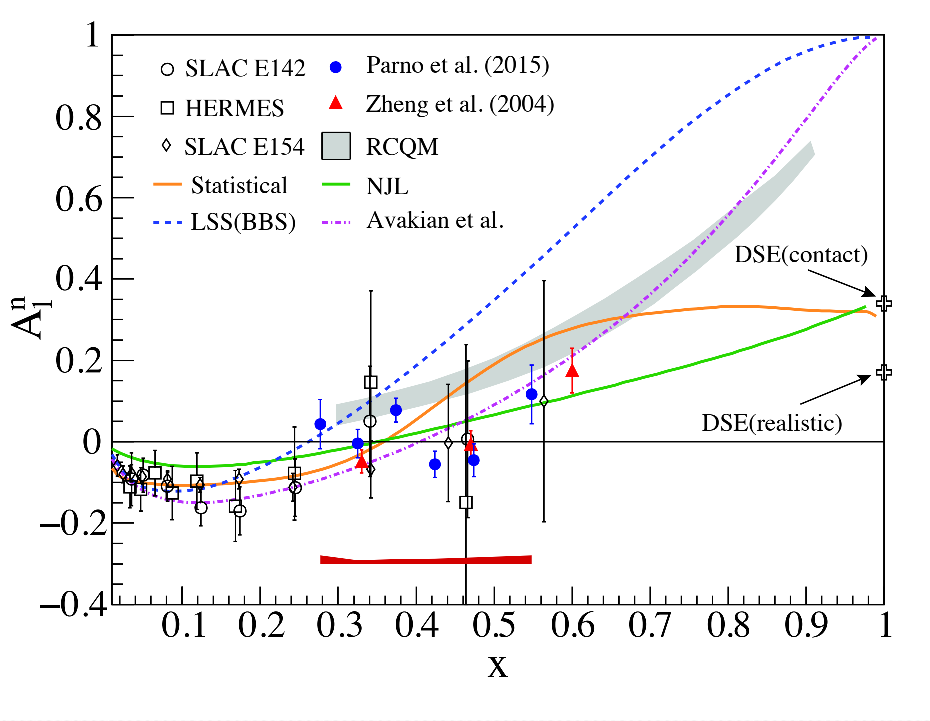


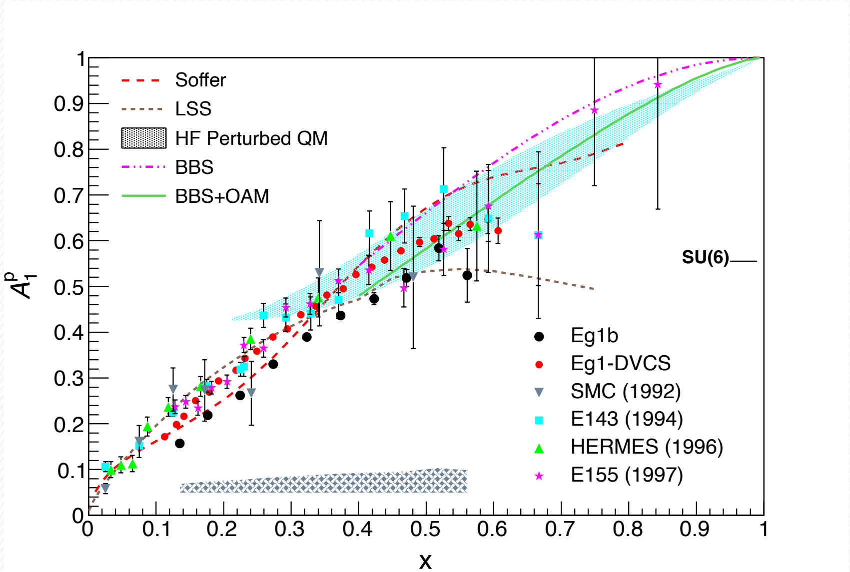


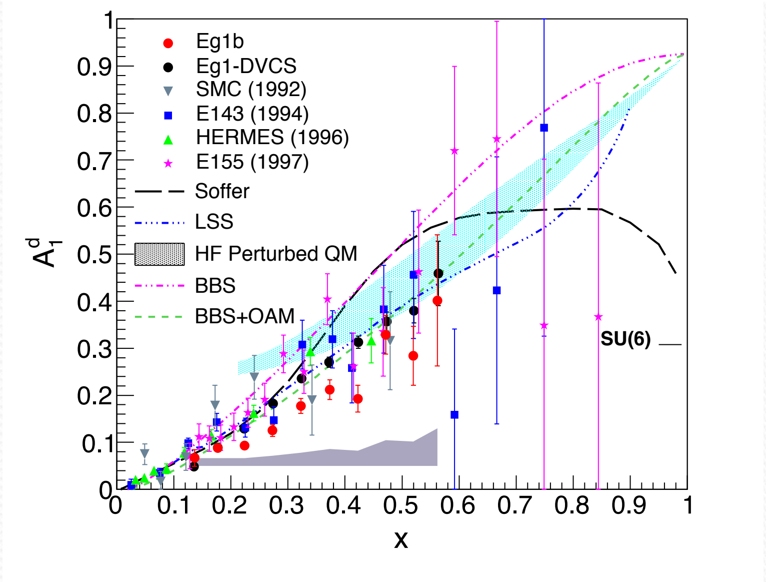
Preliminary Results on g2n

A_1 at High-x: World Data

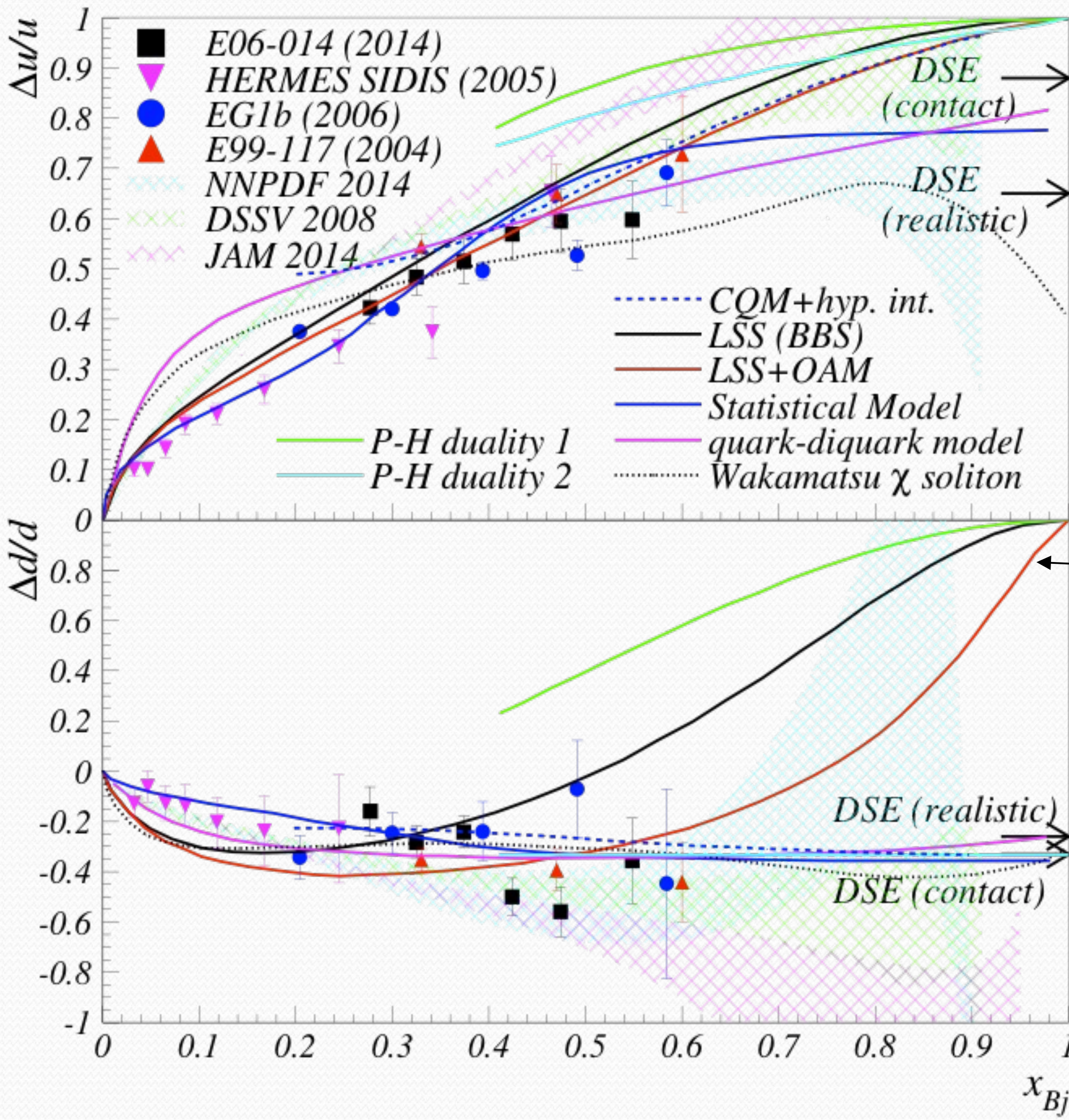
- a clean domain where QCD (and many other models) can make predictions for (the ratio of) structure functions
- ratios of pol/unpol pdfs at x→ 1 provide unambiguous, scale invariant, non-perturbative features of QCD







Simple Spin-flavor Decomposition at High-x



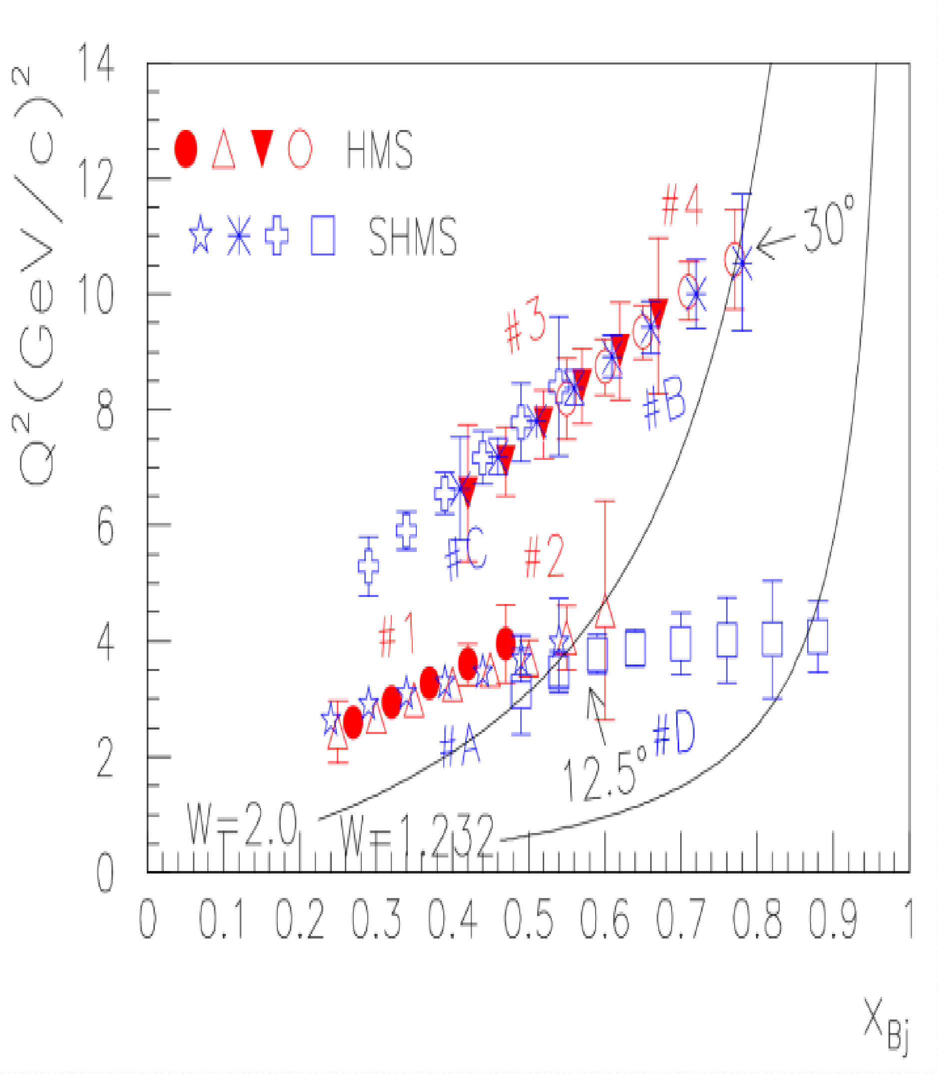
$$\frac{\Delta u+\Delta\bar{u}}{u+\bar{u}}=\frac{4}{15}\frac{g_1^p}{F_1^p}(4+R^{du})-\frac{1}{15}\frac{g_1^n}{F_1^n}(1+4R^{du})$$

$$\frac{\Delta d+\Delta\bar{d}}{d+\bar{d}}=\frac{-1}{15}\frac{g_1^p}{F_1^p}\left(1+\frac{4}{R^{du}}\right)+\frac{4}{15}\frac{g_1^n}{F_1^n}\left(4+\frac{1}{R^{du}}\right)$$

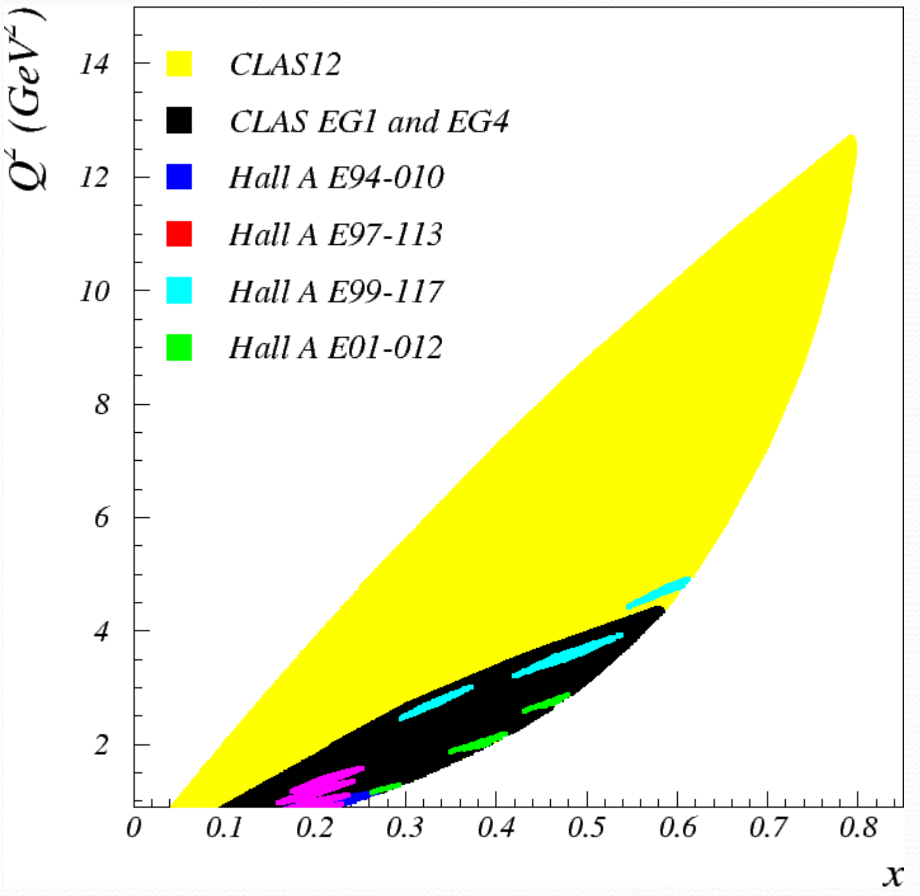
pQCD with quark OAM,

Reaching Deeper Valence Quarks Region with 12 GeV

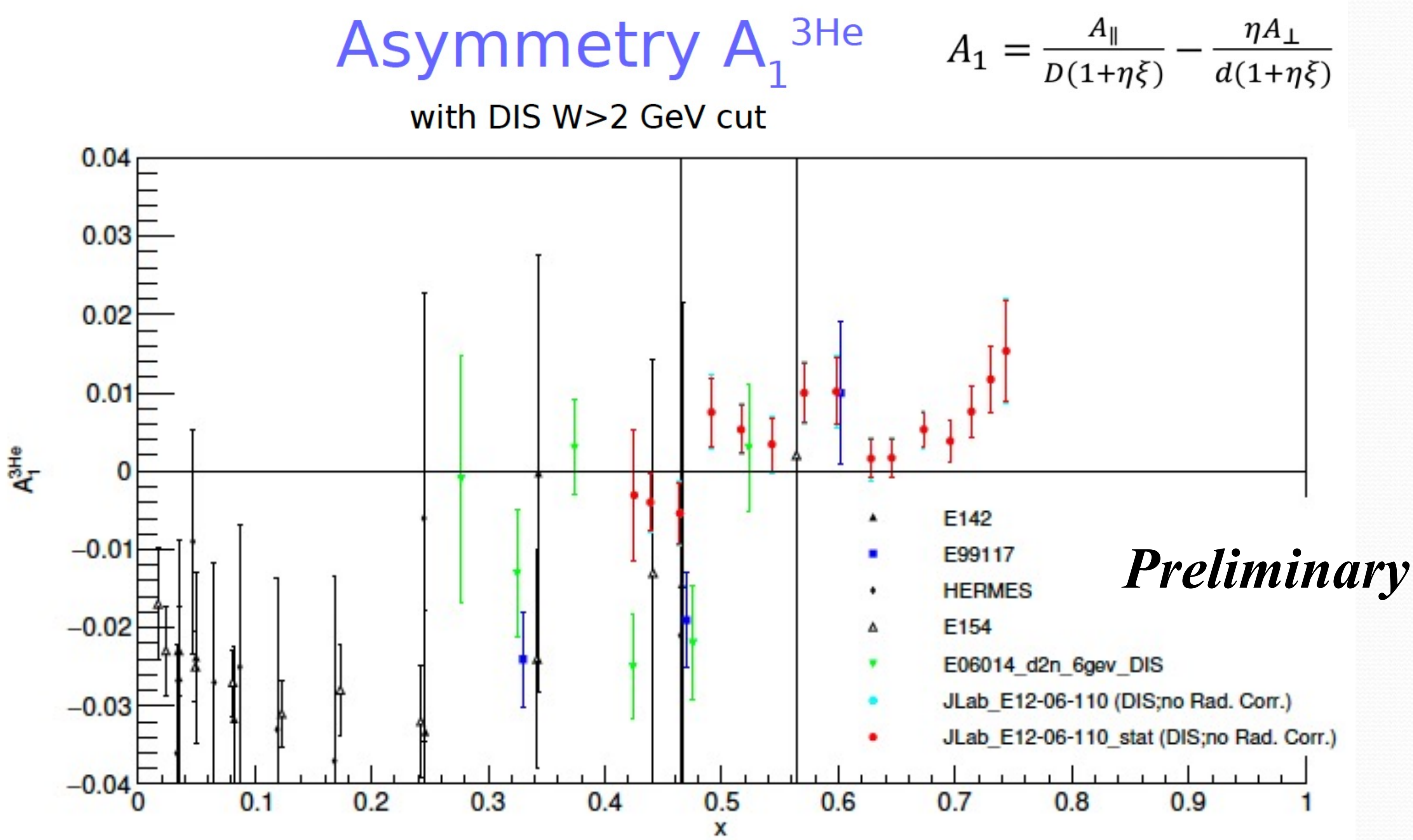
Hall C A_1^n Kinematics



CLAS12 Kinematics



A1n@High-x: Preliminary Results ($A_1{}^3He$)

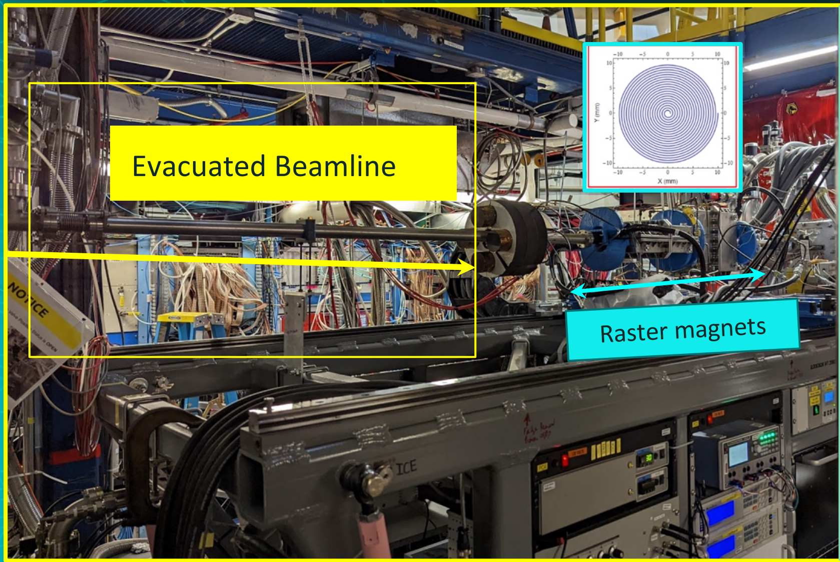


M. Chen

- Credit to Mingyu Chen (UVA)

RGC@CLAS12 with Longitudinally Polarized proton/deuteron Targets

P. Pandey



RGC scheduled for 9 calendar months (240 calender days), data collected for 190 days, 80% of allotted beam time.

Collected data from 06/11/2022 to 03/20/2023 with some breaks due to Magnet power supply failure (firmware issue) and configuration changes.

Proposal ID	Title
E12-06-109	Longitudinal Spin Structure of the Nucleon
E12-06-109A	DVCS on the Neutron with Polarized Deuterium Target
E12-06-119(b)	DVCS on Longitudinally Polarized Proton Target
E12-07-107	Spin-Orbit Correlations with Longitudinally Polarized Target
E12-09-007(b)	Study of Partonic Distributions using SIDIS K Production
E12-09-009	Spin-Orbit Correlations in K Production with Polarized Targets

See G. Matousek's talk

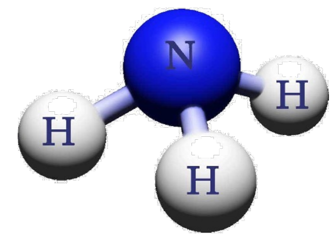
3-d Structure Study @ CLAS12

RG-C Run Group Experiments
DVCS with L. Pol. Proton
SIDIS with L. Pol. Proton

Run Group C @ CLAS12

G. Matousek

- Polarized fixed target experiment (June 2022 – March 2023)
  - Dynamically polarized NH_3 **(proton)** and ND_3 **(deuteron)** targets
  - Calibration targets **C**, CH_2 and CD_2



- <u>Physics Goals</u>

DIS inclusive and flavor-tagged **spin structure functions**

Semi-inclusive DIS (SIDIS) to access **Transverse Momentum Distributions** (TMDs), dihadron production and backward baryon production

Deeply Virtual Compton Scattering (DVCS) & Timelike Compton Scattering (TCS) to access **Generalized Parton Distributions** (GPDs) - Measure target single and beam/target double spin asymmetries in proton and neutron DVCS.

★ Longitudinal beam & target polarizations

Spin direction changes every 33ms (CEBAF)

Polarization configurable run-by-run

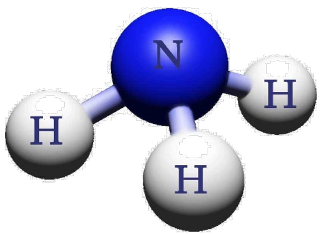
List of RG-C Experiments

G. Matousek

Experiment Title	Key Observables	Preliminary
Longitudinal Spin Structure of the Nucleon	Polarized parton distributions, gluon helicity, higher twist	---
DVCS on the neutron with polarized deuterium target	Neutron Compton Form Factors	---
DVCS on longitudinally polarized proton target	Helicity dependent cross sections, upgrade precision and coverage of previous CLAS DVCS measurements	√
Study of partonic distributions using SIDIS K production	Hadron multiplicities, flavor decomposition of nucleon spin dependent quark PDFs	---
Spin-Orbit Correlations with longitudinally polarized target	Transverse momentum dependence of valence quark T/L spin distributions, pion SIDIS	√
Spin-Orbit correlations in K production with polarized targets	Strange sea p_T distributions, kaon SIDIS (complement above)	---
Studies of Dihadron Electroproduction in DIS with Longitudinally Polarized Hydrogen and Deuterium Targets	Spin-orbit correlations in hadronization, dihadron fragmentation functions, fracture functions, twist-3 PDFs	---
Studies of Single Baryon Production in the Target Fragmentation Region with a Longitudinally Polarized Target	Fracture functions, separation of current/target hadronization	√

Preliminary Analysis: **Pion SIDIS**

G. Matousek



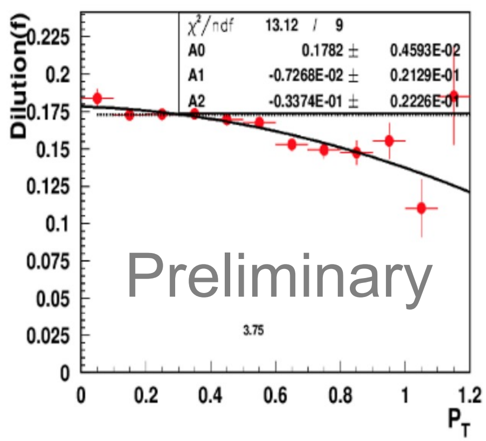
$$A_{LL} = \frac{N^+ - N^-}{N^+ + N^-} \rightarrow \left(\frac{1}{f \times P_b \times P_t \times D(y)}\right) \frac{N^+ - N^-}{N^+ + N^-}$$

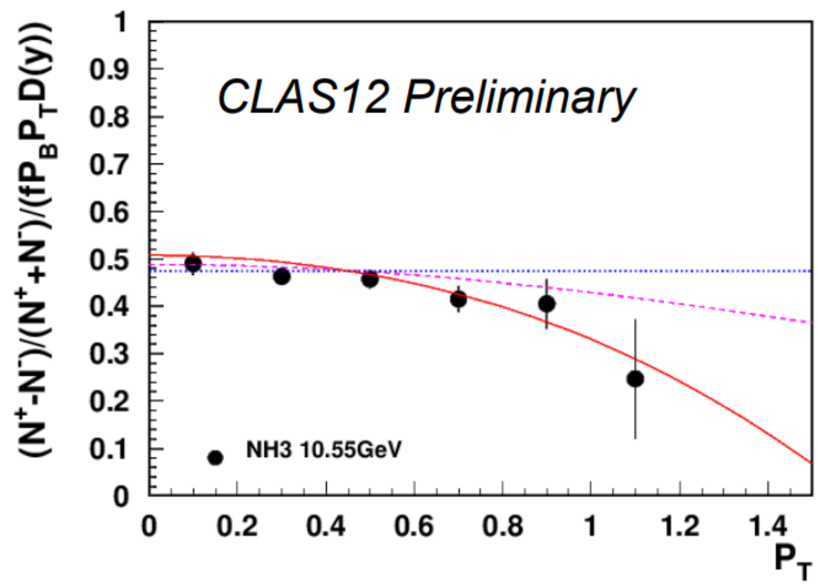
Beam/target polarization

Depolarization factor

- Bin-by-bin determination of dilution factors
  - Analyze NH_3 vs. C yields
  - Calculate %-age of proton cross section contribution to NH_3

$$f = 1 - \frac{N_C}{N_{NH_3}}$$

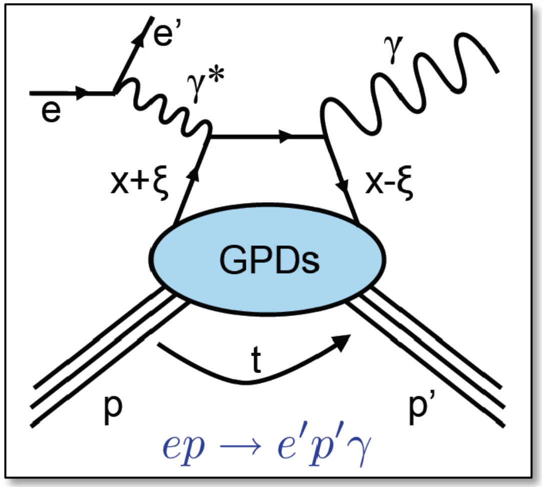




H.Avakian

Preliminary Analysis: pDVCS on NH_3

G. Matousek

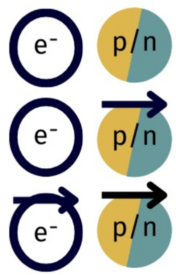


$$\mathcal{F}_p(\xi,t) = \frac{4}{9}\mathcal{F}_u(\xi,t) + \frac{1}{9}\mathcal{F}_d(\xi,t)$$

$$\mathcal{F}_n(\xi,t) = \frac{4}{9}\mathcal{F}_d(\xi,t) + \frac{1}{9}\mathcal{F}_u(\xi,t)$$

★ *Flavor Decomposition* ★

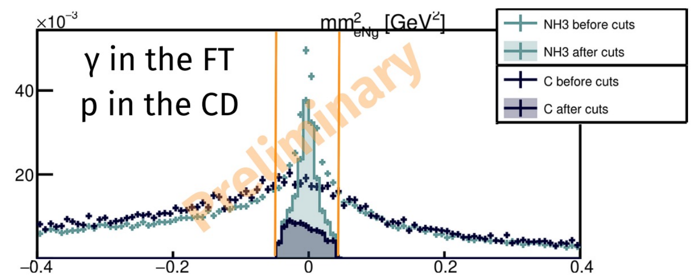
- GPDs give a 3-d partonic picture in terms of longitudinal momentum, transverse spatial position, and their correlations
- **pDVCS (NH_3)** measurements at RG-C give access to A_{LU}, A_{UL}, A_{LL}
- With **nDVCS (ND_3)** → Separation of u, d Compton Form Factors



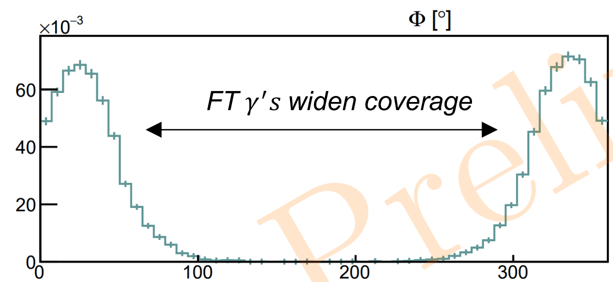
$$\Delta\sigma_{LU} \simeq sin(\phi)\Im\left[F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \xi\frac{t}{4M^2}F_2\mathcal{E}\right]$$

$$\Delta\sigma_{UL} \simeq \sin(\phi)\Im\left[F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_{bj}}{2}\mathcal{E}) - \xi(\frac{x_{bj}}{2}F_1 + \frac{t}{4M^2}F_2)\tilde{\mathcal{E}}\right]$$

$$\Delta\sigma_{LL} \simeq (A+B\cos(\phi))\Re[F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+\frac{x_{bj}}{2}\mathcal{E})-\xi(\frac{x_{bj}}{2}F_1+\frac{t}{4M^2}F_2)\tilde{\mathcal{E}}]$$



$(e'\gamma p')$ Missing Mass (exclusivity)



Forward-Tagger Photon Φ distribution

Talk by N. Pilleux

3-d Structure Study @ Hall A/C

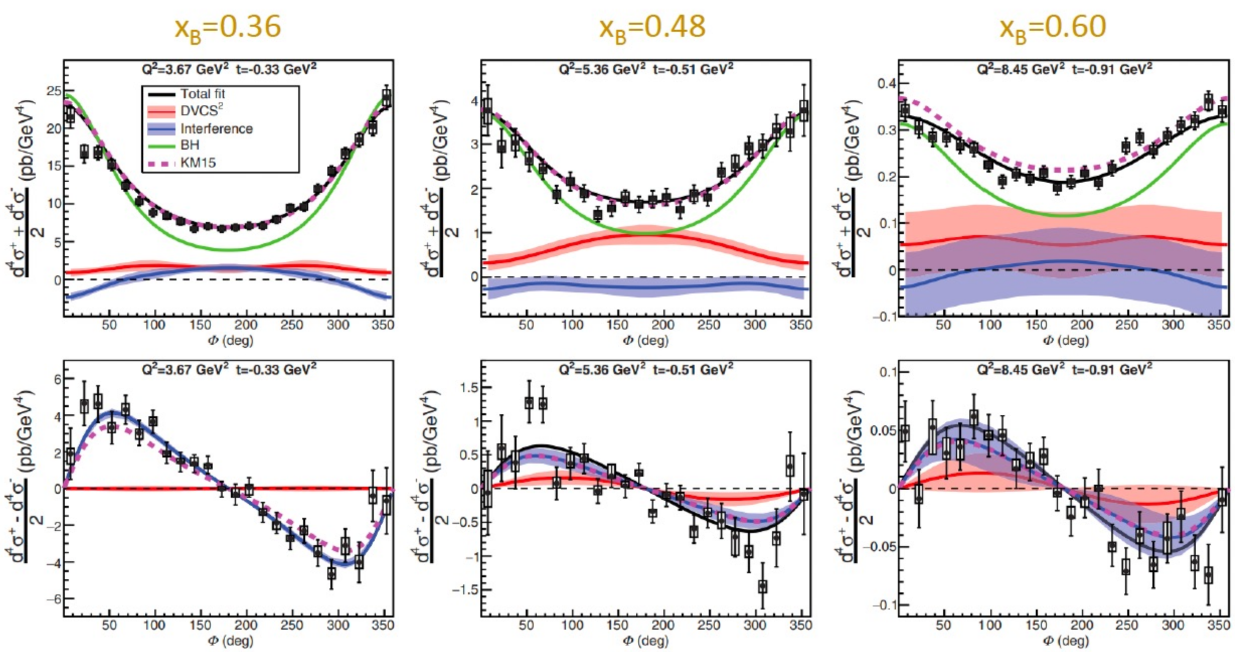
DVCS in Hall A/C
SIDIS in Hall C

C. Camacho

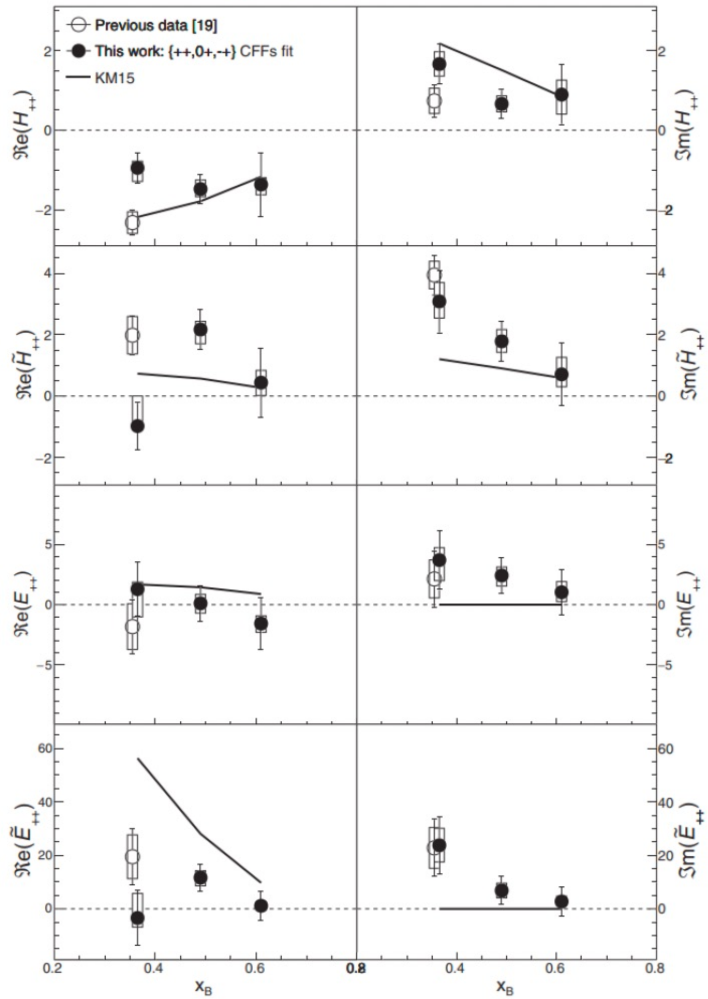
DVCS high precision cross-section measurements

- High precision program of nucleon 3D structure in Hall A and Hall C
- Q^2 scans of the cross-section up to high values of x_B
- Beam-energy dependence measurements further contraints Compton Form Factors extraction

Helicity-dependent DVCS cross sections



Real and Imaginary parts of CFFs H, $\tilde{H}$, E and $\tilde{E}$

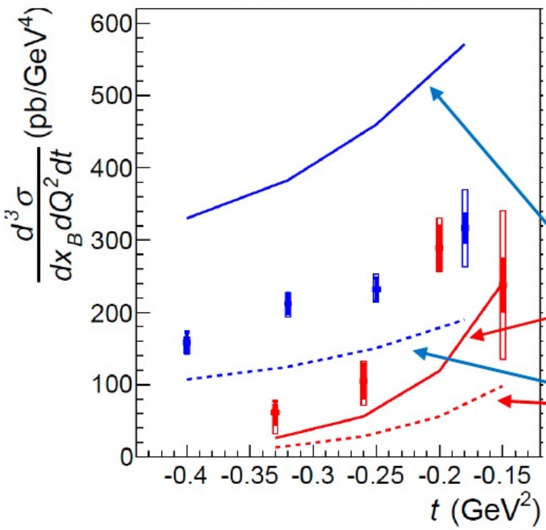


F. Georges et al. PRL **128** (2022)

DVCS off the neutron

C. Camacho

Neutron & deuteron
DVCS cross sections

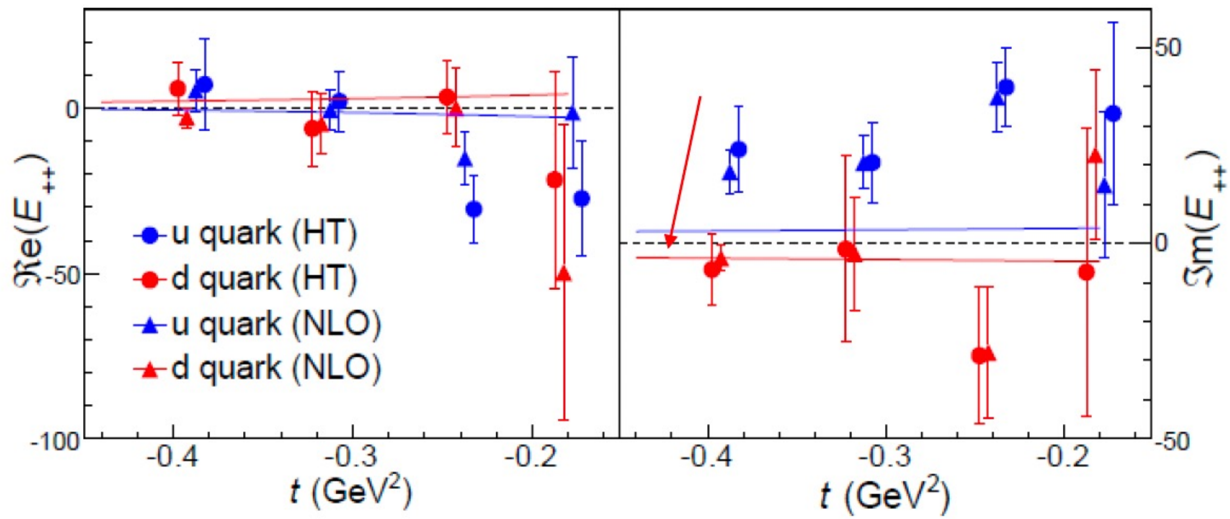


- DVCS experiment E08-025 in Hall A at Jefferson Lab
- Coherent deuteron & quasi-free neutron DVCS cross sections off deuteron target as a function of the momentum transfer t
- 1st observation of DVCS signal off the neutron
- Unique sensitivity to Generalized Parton Distribution (GPD) ***E***

1st flavor separation of GPD integrals when combined with proton DVCS

NLO and high twist (HT) analyses performed

Real part of GPD integral ***E*** Imaginary part of GPD integral ***E***

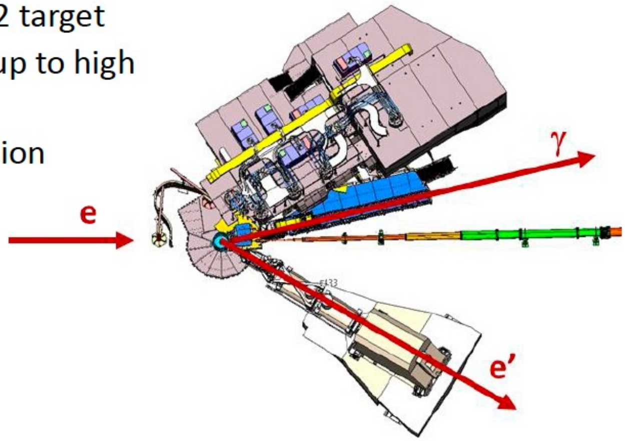


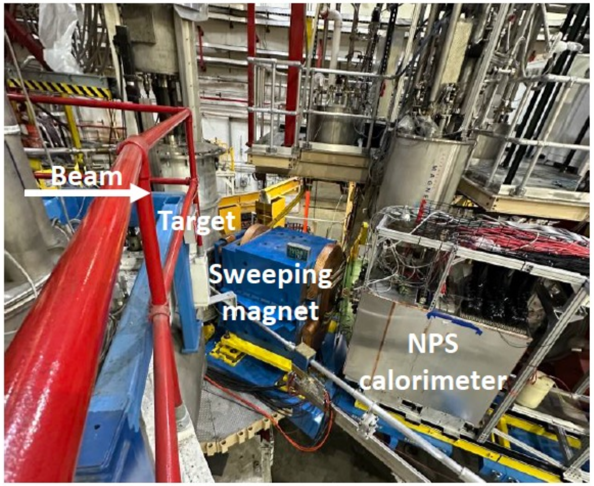
M. Benali et al., Nature Physics **16**, 191 (2020)

C. Camacho

Running experiment in Hall C

- Current run (Sep 2023 – May 2024): both LH2 and LD2 target
- Beam-energy dependence of the DVCS cross section up to high values of x_B
- Stronger constraints in Compton Form Factors extraction

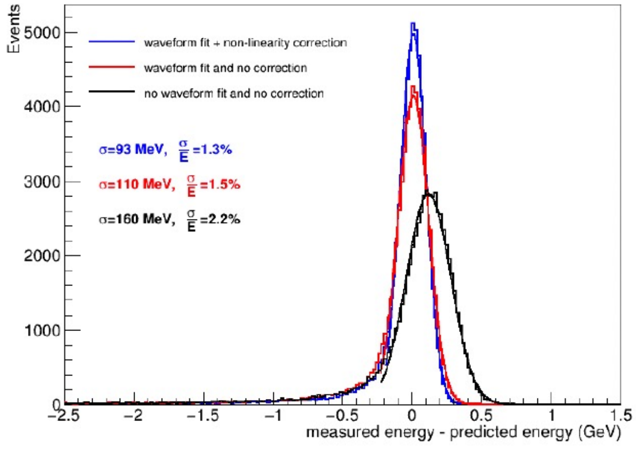




Neutral Particle Spectrometer (NPS) in Hall C:

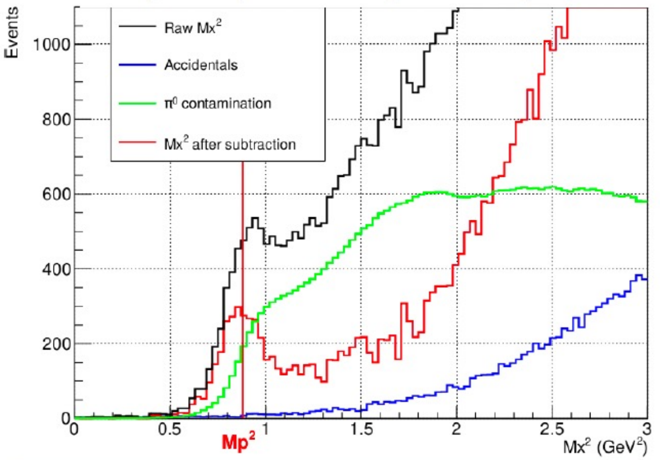
- 1080 $PbWO_4$ crystals
- 0.6 Tm sweeping magnet
- F250ADC sampling electronics

- Higher energy resolution calorimeter than previous experiments
- Higher luminosity thanks to the addition of a sweeping magnet



1.3% energy resolution at 7.3 GeV

$ep \rightarrow e\gamma X$ missing mass squared

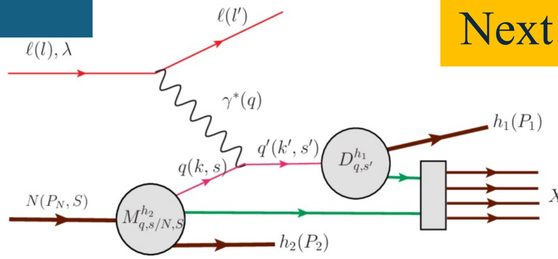


Clean identification of exclusive channel

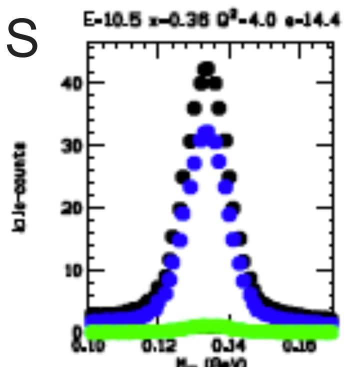
Overview of SIDIS Experiments in Hall C

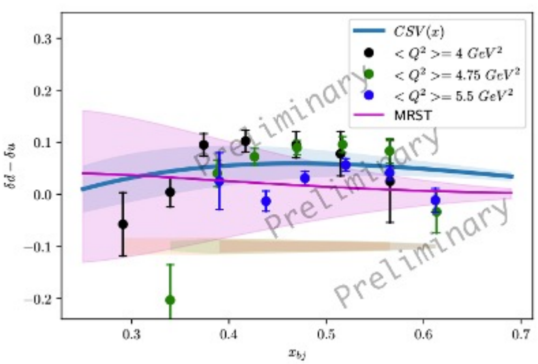
E. Kinney
Next talk

Precision studies using the spectrometers and the high available luminosity of Hall C



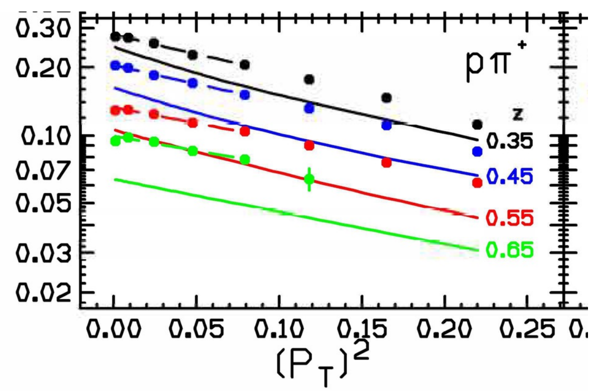
- Study of p_T dependence of charged pion and kaon SIDIS (2018)
- Study of charge symmetry violation in charged pion SIDIS (2018)
- Longitudinal/transverse cross sections of neutral pion SIDIS (2023-2024)
- Longitudinal/transverse cross sections of charged pion SIDIS (2025 tent.)
- Tagged DIS from meson (conditionally approved)



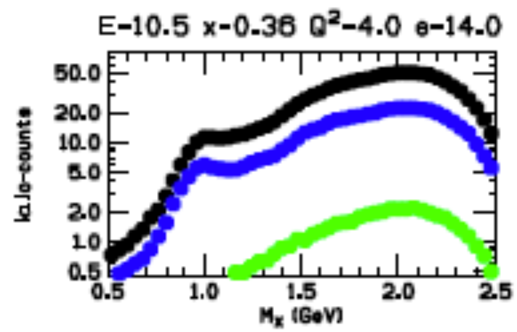


$CSV x \equiv \delta d - \delta u = x^a(1-x)^b(x-c)$

CSV



p_T SIDIS



π^0 SIDIS (online)

Future Precision 3-d Study with SoLID

SIDIS-TMD Multi-d Mapping

Deep-Exclusive Meson Production

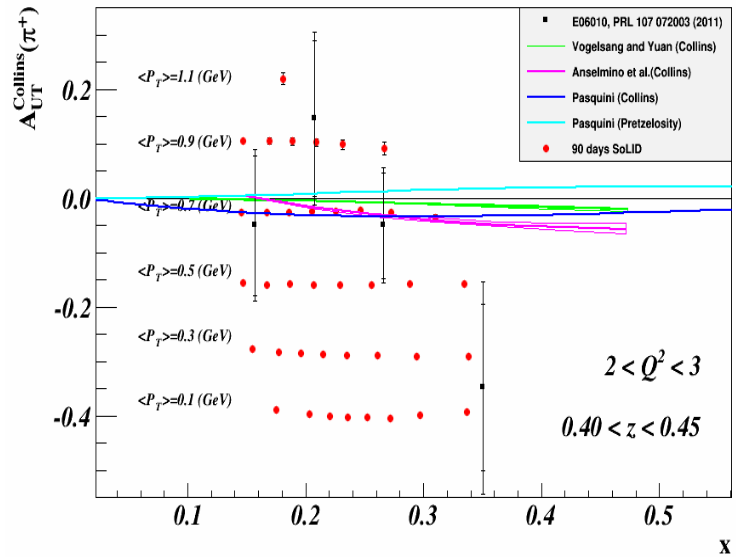
DDVCS

SoLID-SIDIS: Precision Mapping in Multi-Dimension

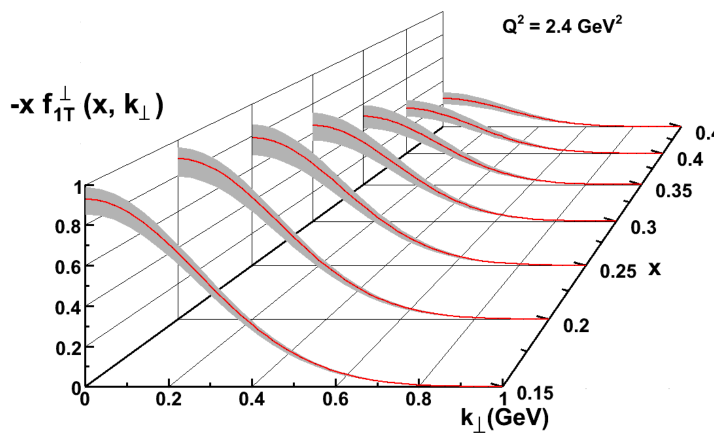
SoLID-SIDIS program: Large acceptance, Full azimuthal coverage + High luminosity
- 4-D mapping of asymmetries with precision
- Constrain models and forms of TMDs, Tensor charge, …
- Lattice QCD, QCD dynamics

4-D binning for the first time!

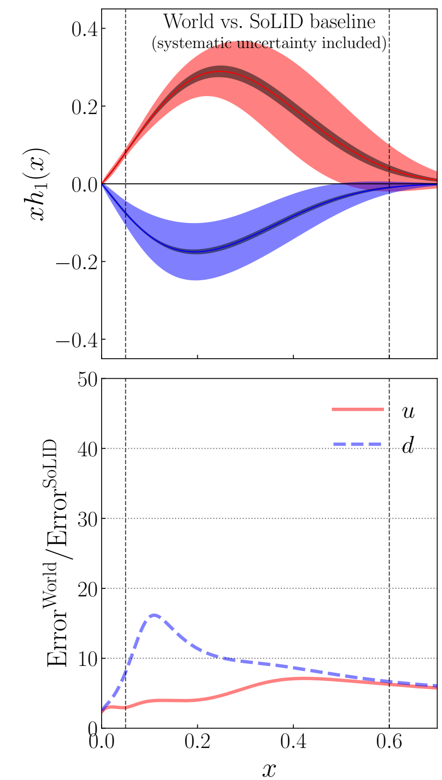
- **More than 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.**



- **Sivers:** Confined quark motion
- Quantum correlations between nucleon spin and quark motion
- QCD dynamics



Transversity



SoLID Impact on Tensor Charge

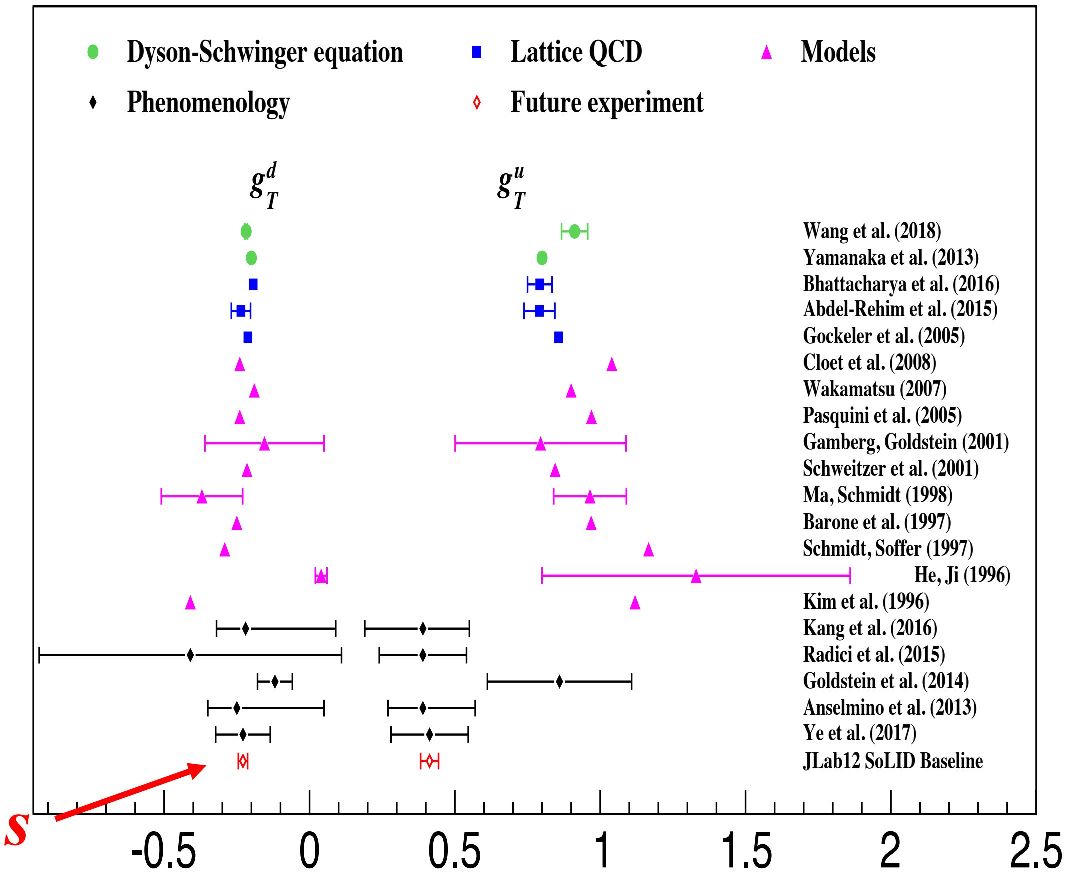
Definition

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = g_T^q\,\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S) \quad g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

- ***A fundamental QCD quantity: matrix element of local operators.***
- ***Moment of transversity distribution***
- ***Valence quark dominant.***
- ***Precision calculations available from lattice QCD.***

- ***Probe new physics combined with EDMs***

$$d_n = g_T^d\, d_u + g_T^u\, d_d + g_T^s\, d_s$$



SoLID Projections

Expansion Study of Nucleon to Deuteron

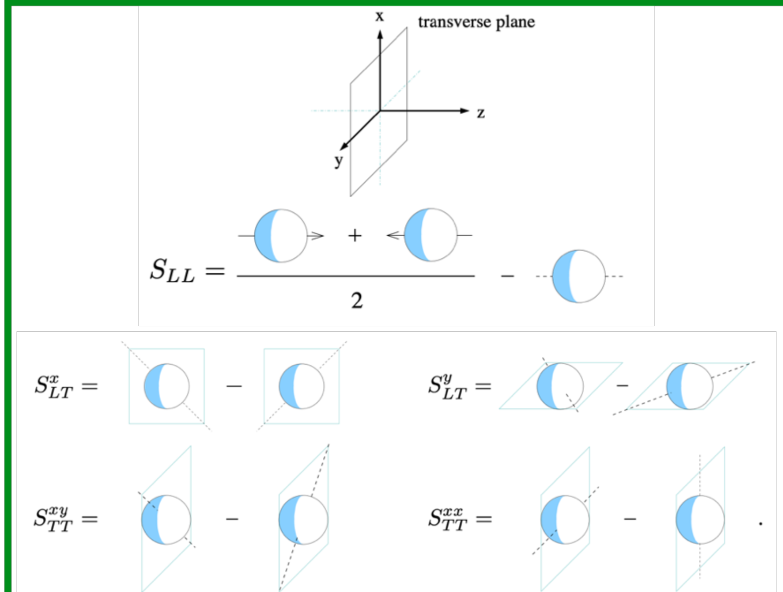
Tensor-TMD: Exploration and Precision Study
3-d Study with JLab Upgrade

N. Santiesteban

Spin 1: Leading twist transverse momentum dependent distributions (TMDs)

Never measured before

Hadron \ Quark	U (γ^+) T-even	U (γ^+) T-odd	L ($\gamma^+\gamma_5$) T-even	L ($\gamma^+\gamma_5$) T-odd	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-even	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-odd
U	f_1					$[h_1^\perp]$
L			g_{1L}		$[h_{1L}^\perp]$	
T		$f_{1T}^\perp$	g_{1T}		$[h_1], [h_{1T}^\perp]$	
LL	f_{1LL}					$[h_{1LL}^\perp]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}], [h_{1LT}^\perp]$
TT	f_{1TT}			g_{1TT}		$[h_{1TT}], [h_{1TT}^\perp]$



After integrating over the transverse momentum:

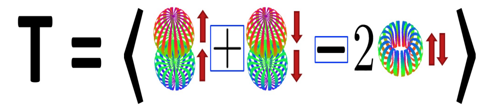
b1 measured by HERMES and soon at JLab

Hadron \ Quark	U (γ^+) T-even	U (γ^+) T-odd	L ($\gamma^+\gamma_5$) T-even	L ($\gamma^+\gamma_5$) T-odd	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-even	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-odd
U	f_1					
L			$g_{1L}\,(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}\,(b_1)$					
LT						*1
TT						

A. Bacchetta and P.J. Mulders, Phys. Rev. D 62 (2000), 114004

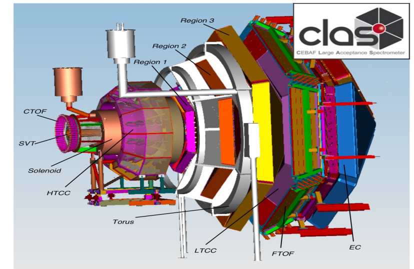
J. Poudel

Spin-1 Tensor TMDs at Jefferson Lab

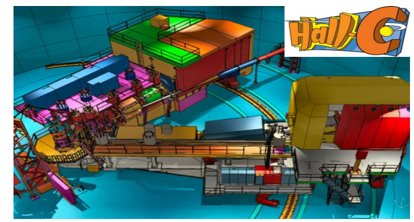


Courtesy of A. Bacchetta (private communication) 2023

- SIDIS Cross-section considering longitudinal polarization of target



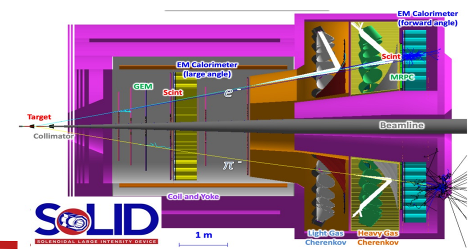
$$\frac{d\sigma}{dx\ dy\ d\psi\ dz\ d\phi_h\ dP_{h\perp}^2} = \frac{y^2\alpha^2}{2(1-\epsilon)xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h\ F_{UU}^{\cos\phi_h} + \epsilon\cos(2\phi_h)\ F_{UU}^{\cos(2\phi_h)} + \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h\ F_{LU}^{\sin\phi_h}$$



Vertical polarization:

$$+ S_{\|}\left\{\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h\ F_{UL}^{\sin\phi_h} + \epsilon\sin(2\phi_h)\ F_{UL}^{\sin 2\phi_h}\right\}$$

$$+ S_{\|}\lambda_e\left\{\sqrt{1-\epsilon^2}\ F_{LL} + \sqrt{2\epsilon(1-\epsilon}\cos\phi_h\ F_{LL}^{\cos\phi_h}\right\}$$



Tensor Polarization:

$$+ T_{\|\|}\left\{F_{U(LL),T} + \epsilon\ F_{U(LL),L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h\ F_{U(LL)}^{\cos\phi_h}\right.$$

$$\left. + \epsilon\cos(2\phi_h)\ F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h\ F_{L(LL)}^{\sin\phi_h}\right\}\Big]$$

$$F_{U(LL),T} = C[f_{1LL}D_1]$$

$$F_{U(LL)}^{\cos 2\phi_h} = C\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)(\hat{\mathbf{h}}\cdot\mathbf{p}_T) - \mathbf{k}_T\cdot\mathbf{p}_T}{MM_h}h_{1LL}^{\perp}H_1^{\perp}\right]$$

1. Use CLAS12 existing data (RG-C) to find the upper limit of $F_{U(LL),T}$ (data mining)
2. Dedicated measurement of $F_{U(LL),T}$ in Hall C
3. Precise measurement of $F_{U(LL),T}$, $F_{U(LL)}^{\cos\phi_h}$ and $F_{U(LL)}^{\cos 2\phi_h}$ in SoLID

Summary

- ❑ Highlights of Spin Structure Study @ JLab:
- Exciting results from 3 JLab low-Q spin experiments (spin moments)

  Γ_1, Γ_2, γ_0, δ_{LT} for p and n: 3 *nature physics*, 1 *PRL*, 2 *PLB,* + *more* (α_{g1})
- Preliminary results on d2n in Hall C: twist-3, q-g correlations, LQCD calculations
- Preliminary results on A1n @ high-x in Hall C: valence behavior
- A1p@CLAS12: data taken 2022

- ❑ Highlights of 3-d Structure Study @ JLab:
- SIDIS and DVCS with long. pol p/d @ CLAS12 RGC
- DVCS @Hall A/C with JLab12
- SIDIS @Hall C with JLab12
- Future: Precision mapping of 3-d structure @SoLID

  New: Experimental study of tensor-TMDs

  …