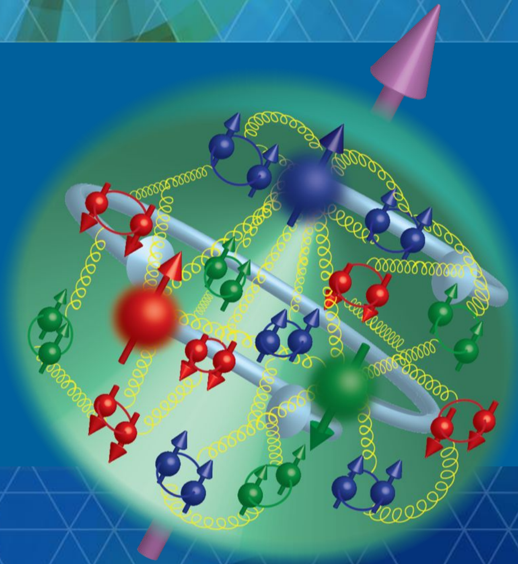
2nd workshop on advancing the understanding of non-perturbative QCD using energy flow

Stony Brook University, 6-9 November, 2023

Overview of 3D structure results at CLAS12



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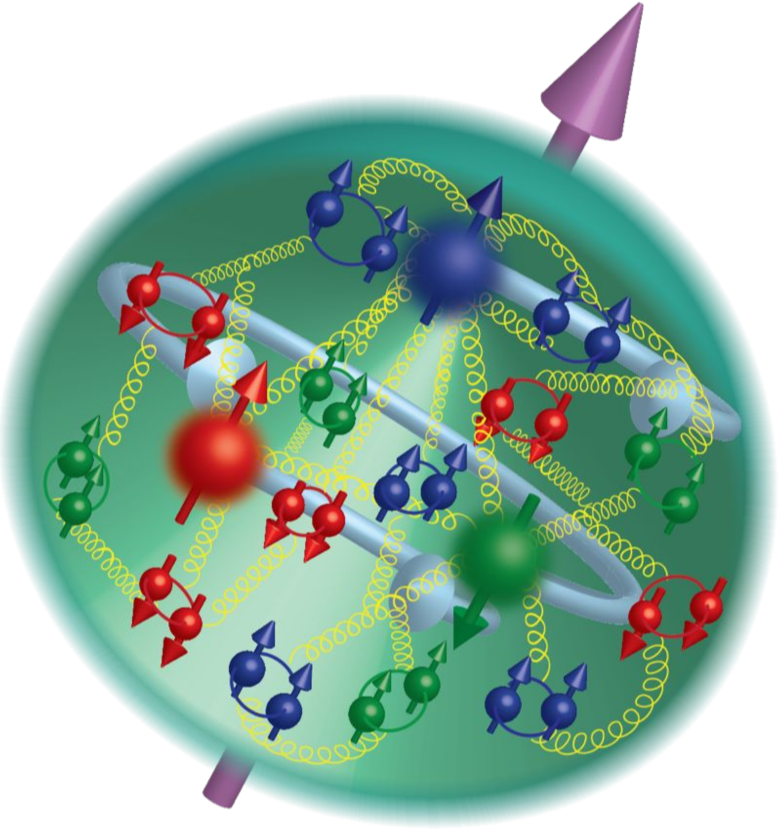
Argonne NATIONAL LABORATORY



Physics Question

How does the **spin of the nucleon originate** from its **quark, anti-quark,** and **gluon** constituents and their dynamics?

Jaffe-Manohar sum rule:

$$\underbrace{\boxed{\Delta\Sigma/2}}_{\text{Quark helicity}} + \underbrace{\boxed{\Delta G}}_{\text{Gluon helicity}} + \underbrace{\boxed{\ell_q}}_{\text{Quark canonical orbital angular momentum}} + \underbrace{\boxed{\ell_g}}_{\text{Gluon canonical orbital angular momentum}} = \hbar/2$$

- All terms have **partonic interpretation**
- In infinite-momentum frame
- **ℓq and ℓg** (Twist-3 quantities) can be extracted **from GPDs**
- Nucl. Phys. B 337, 509–546 (1990)

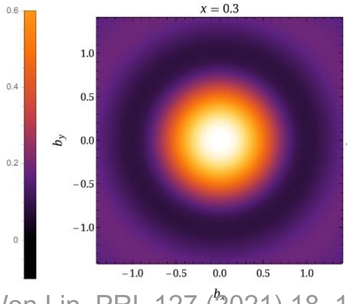
Physics Questions

How is the **nucleon spin correlated with the motion** of quarks and gluons?
How is the **nucleon spin correlated with the spatial distribution** of partons?

Nucleon tomography

Impact parameter dependent
parton distribution functions $f(x,b_T)$
Can be accessed from **GPDs:** $H(x, \xi, t) \longrightarrow f(x,b_T)$

- Extrapolation to zero skewness $\xi \rightarrow 0$
- Fourier Transformation $t \leftrightarrow b_T$

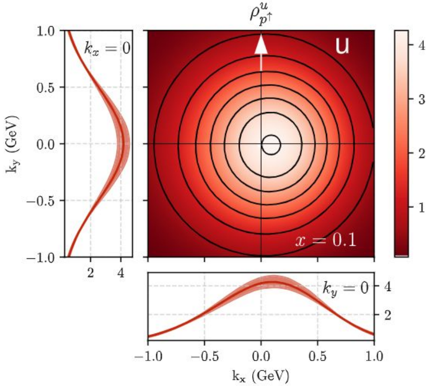


Huey-Wen Lin, PRL 127 (2021) 18, 182001, from Lattice

Position space

Momentum space

Transverse momentum dependent
parton distribution functions (TMDs) $f(x,k_T)$

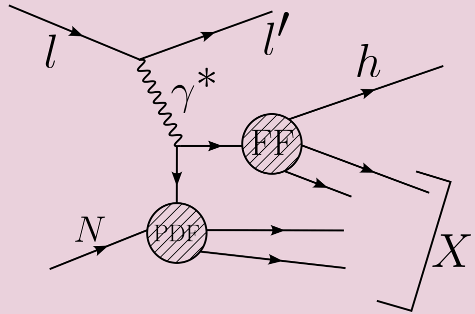


A. Bacchetta, F. Delcarro, C. Pisano, M. Radici,
PLB 827 (2022) 136961, from SIDIS and DY/W data

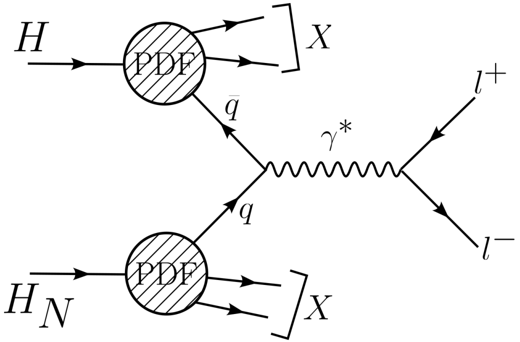
How to access proton spin structure?

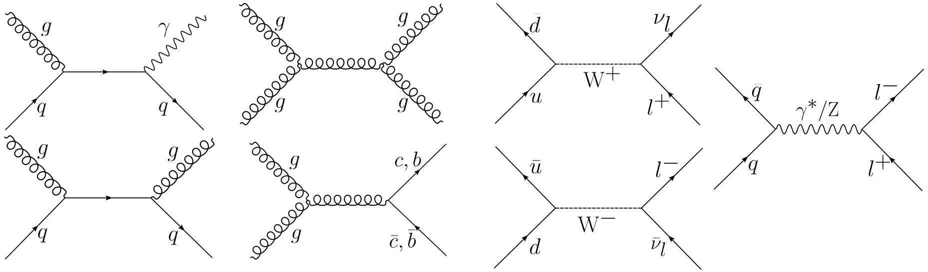
Complementarity of experimental probes

(Semi-Inclusive) Deep Inelastic Scattering

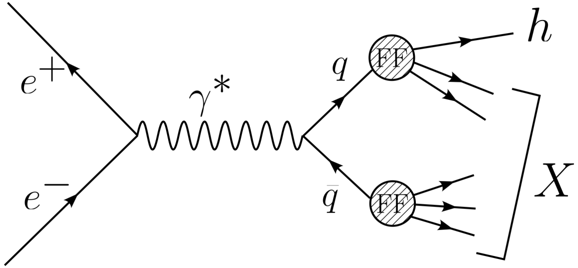


Hadron-hadron interactions



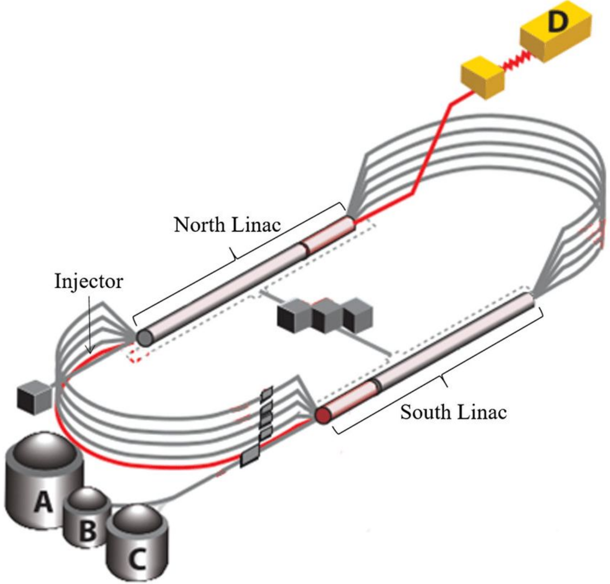


e+e- annihilation (access to FF)



CLAS12

Thomas Jefferson National Accelerator Facility



Continuous Electron Beam Accelerator Facility (CEBAF)

- 12 GeV continuous polarized electron beam
- Four experimental halls: A, B, C, D

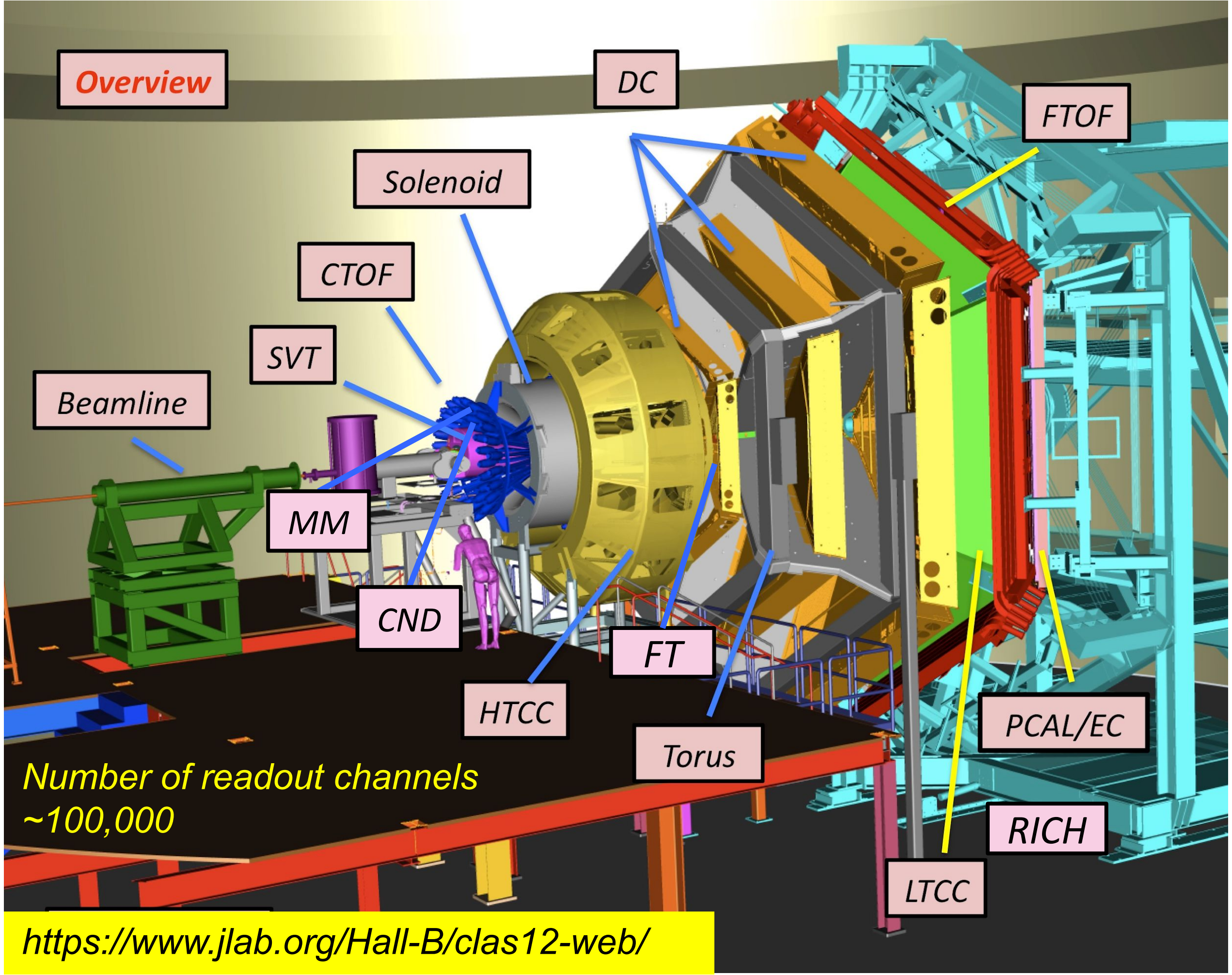
CLAS12 located in Hall B
high luminosity, wide acceptance

Began data taking in Spring 2018

- 2018-2020: unpolarized proton/deuterium target
- 2022/23 longitudinally polarized proton/deuterium target ~5 % produced

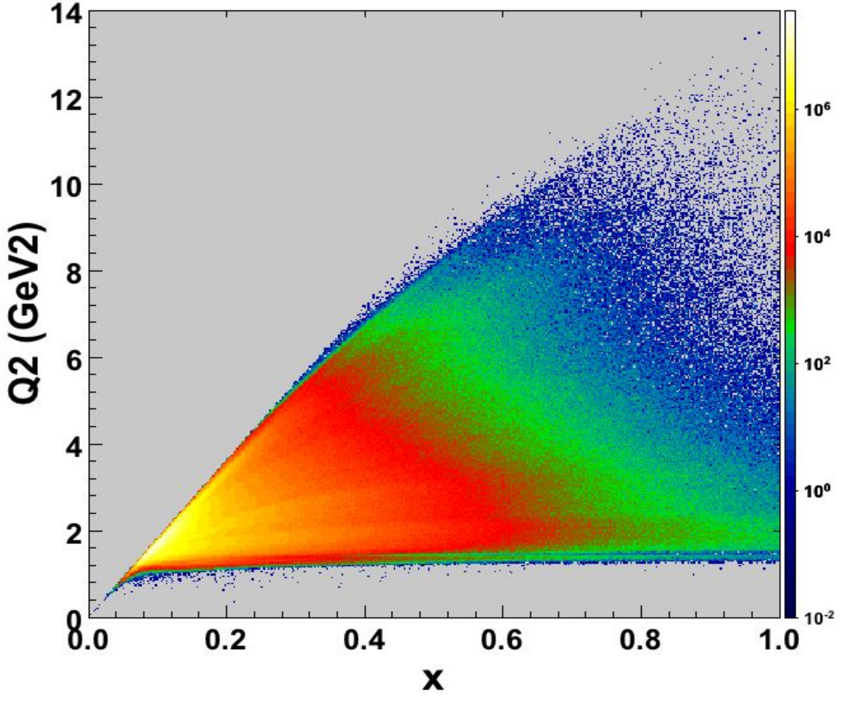
Forward Detector:
TORUS magnet
HT Cherenkov Counter
Drift chamber system
LT Cherenkov Counter
Forward ToF System
Preshower calorimeter
EM calorimeter (EC)
RICH detector
Forward Tagger

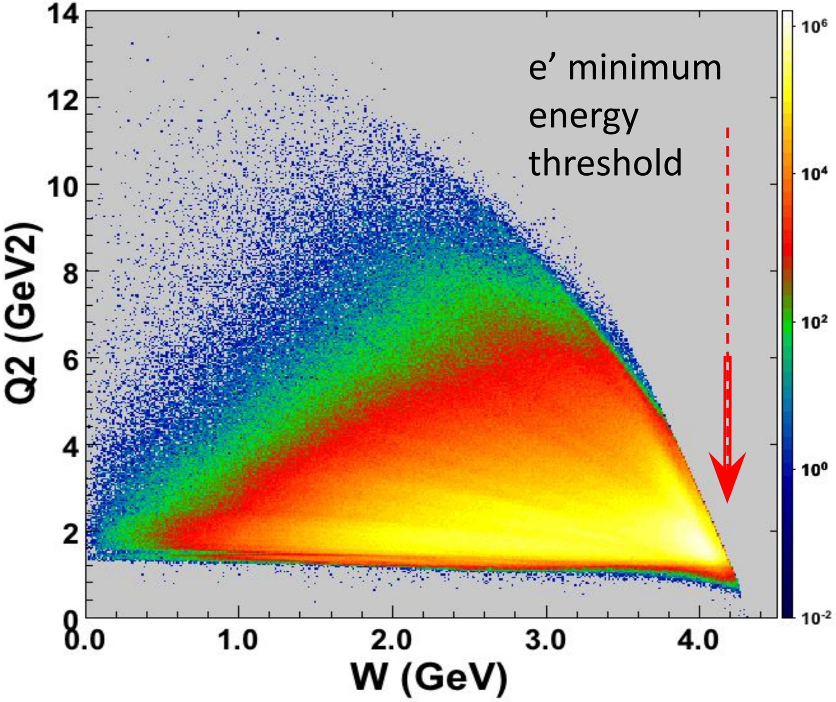
Central Detector:
Solenoid magnet
Barrel Silicon Tracker
Central Time-of-Flight
Central Neutron Detector
Micromegas Tracker



CLAS12 Kinematic Reach

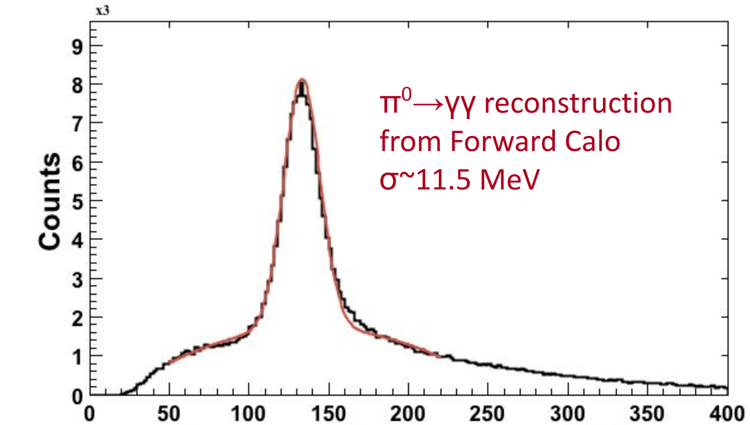
p(e,e’)X, plots based on 200 min. of data taking

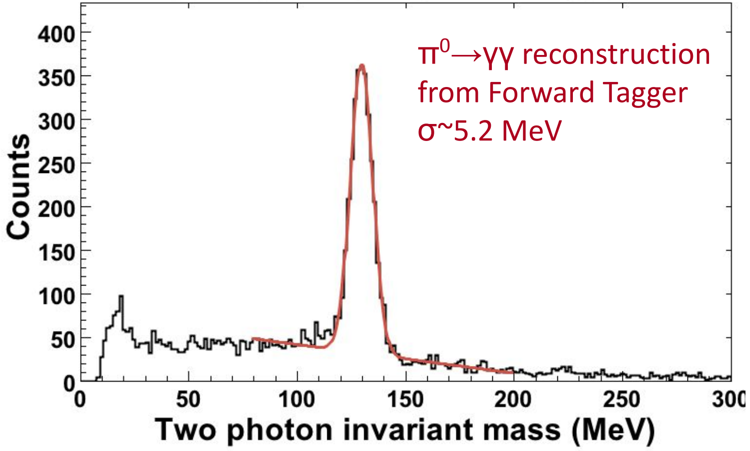


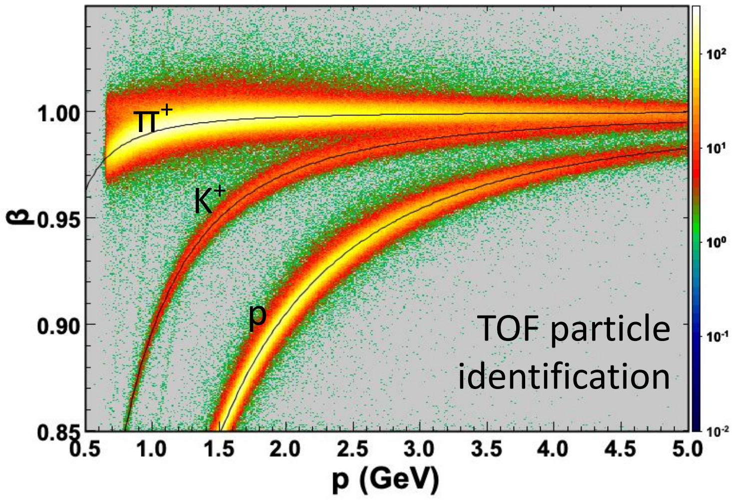


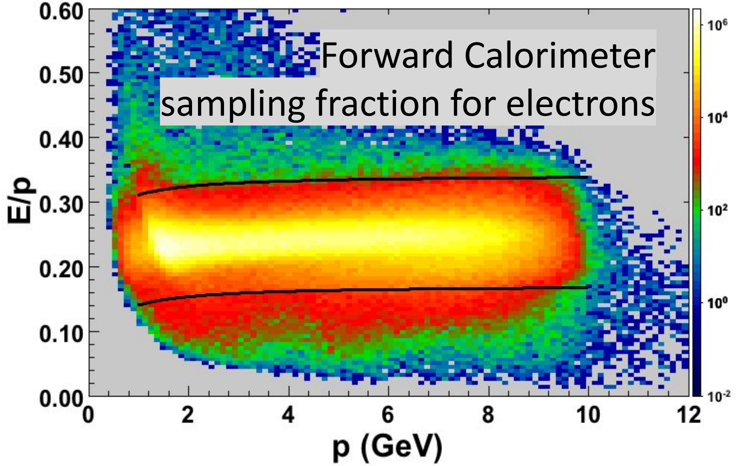
Beam energy at 10.6 GeV Torus current 3770 A, electrons in-bending, Solenoid magnet at 2416 A.

CLAS12 Particle ID



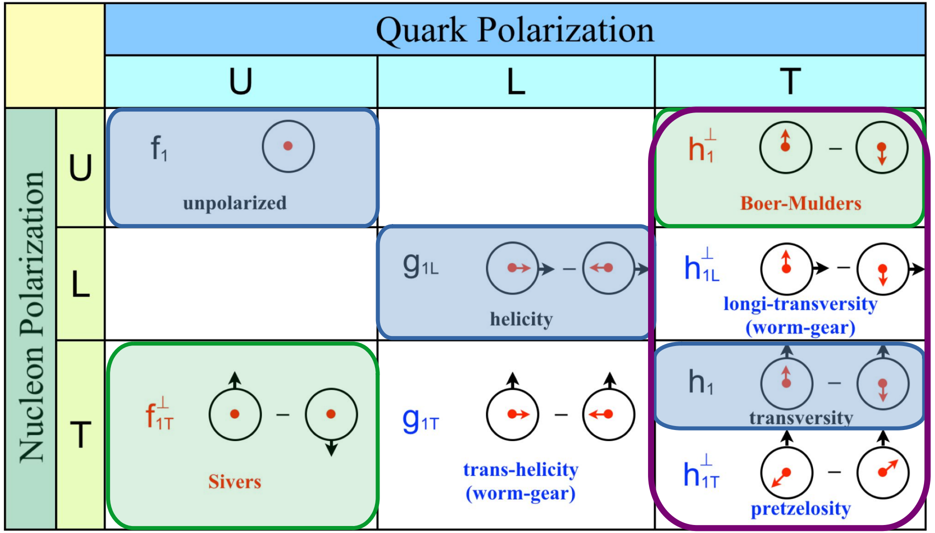






Selected TMD results

TMDs and Spin-Orbit Correlations



TMDs surviving integration over k_T

Naive time-reversal odd TMDs describing strength of **spin-orbit correlations**

Chiral odd TMDs

Off-diagonal part vanishes without parton's transverse motion

TMDs describing strength of spin-orbit correlations non-zero → indication of parton OAM

- No quantitative relation between TMDs & OAM identified yet

- **Sivers:** correlations of transverse-spin direction and the parton transverse momentum
- **Boer-Mulders:** correlations of parton transverse spin and parton transverse momentum
- **Collins:** fragmentation of a transversely polarized parton into a final-state hadron

Access to TMDs from the SIDIS Cross Section

Unpolarized and Longitudinally Polarized Targets

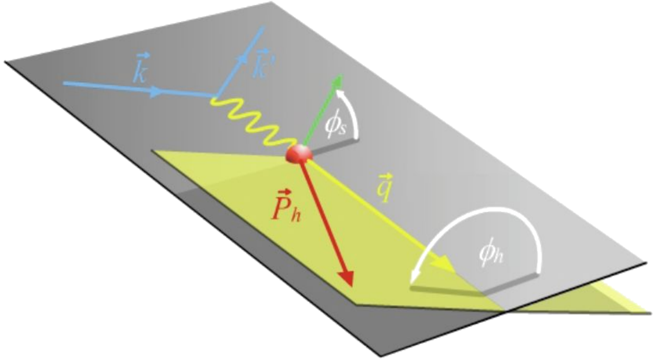
$$\frac{d^6\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_T^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\cdot$$

$$\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h$$

$$+\lambda\left(\sqrt{2\varepsilon(1-\varepsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h\right)$$

$$+S_L\left(\sqrt{2\varepsilon(1+\varepsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h + \varepsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right)$$

$$+S_L\lambda\left(\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\right)$$



Leading twist formalism
(higher-twist terms can be included)

$$F_{UU,T} = \mathcal{C}\left[f_1 D_1\right]$$

Unpolarized PDF ⊗ Unpolarized fragmentation function

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp) - \boldsymbol{k}_T\cdot\boldsymbol{p}_\perp}{zMM_h}h_1^\perp H_1^\perp\right]$$

Boer-Mulders ⊗ Collins Fragmentation Function

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp) - \boldsymbol{k}_T\cdot\boldsymbol{p}_\perp}{zMM_h}h_{1L}^\perp H_1^\perp\right]$$

Worm-gear ⊗ Collins Fragmentation Function

$$F_{LL} = \mathcal{C}\left[g_{1L} D_1\right]$$

Helicity ⊗ Unpolarized fragmentation function

Access to TMDs from the SIDIS Cross Section

Transversely Polarized Target

$$\frac{d^6\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_T^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\cdot$$

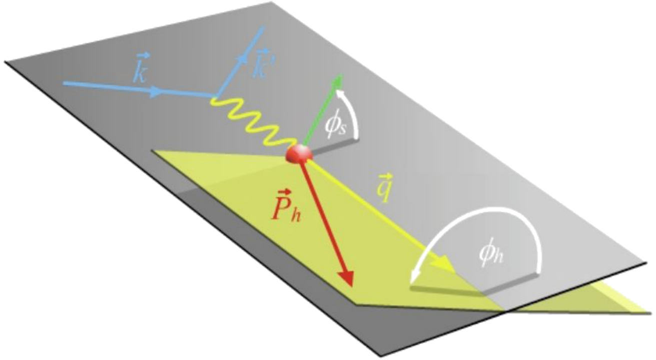
$$\Big\{ S_T\Big(\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)\sin(\phi_h-\phi_S)$$

$$+\varepsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \varepsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big)$$

$$+S_T\lambda\Big(\sqrt{1-\varepsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\varepsilon(1-\varepsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big)\Big\}$$



Leading twist formalism

(higher-twist terms can be included)

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}f_{1T}^{\perp}D_1\right]$$

Sivers ⊗ Unpolarized fragmentation function

$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp}{zM_h}h_1H_1^{\perp}\right]$$

Transversity ⊗ Collins Fragmentation Function

$$F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\boldsymbol{k}_T\cdot\boldsymbol{p}_\perp)+k_T^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp)-4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp\right)}{2zM^2M_h}h_{1T}^{\perp}H_1^{\perp}\right]$$

Pretzelosity ⊗ Collins Fragmentation Function

$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}g_{1T}D_1\right]$$

Worm Gear ⊗ Unpolarized fragmentation function

Single Pion Beam Spin Asymmetries

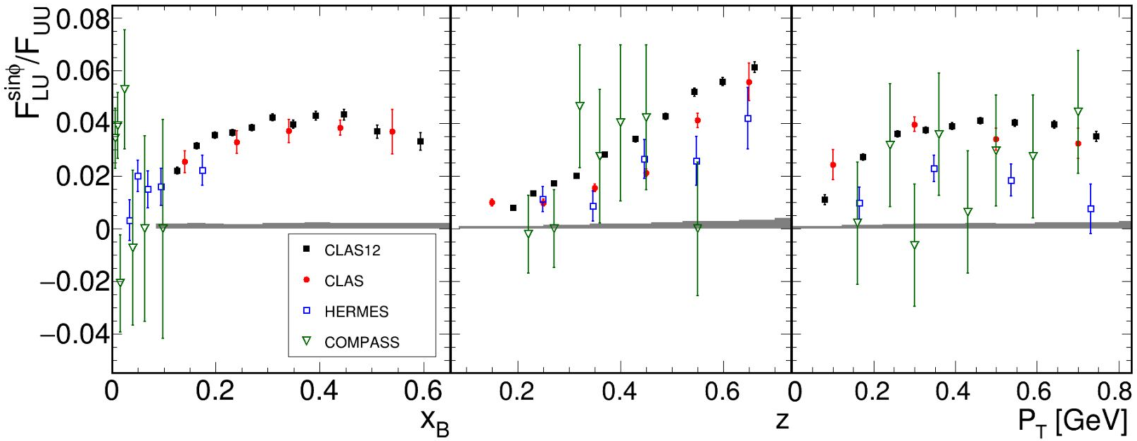
twist-3 pdf   unpolarized PDF   twist-3 t-odd PDF   Boer-Mulders

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(x\boxed{e}\boxed{H_1^{\perp}}+\frac{M_h}{M}\boxed{f_1}\frac{\boxed{\tilde{G}^{\perp}}}{z}\right)+\frac{\hat{h}\cdot p_T}{M}\left(x\boxed{g^{\perp}}\boxed{D_1}+\frac{M_h}{M}\boxed{h_1^{\perp}}\frac{\boxed{\tilde{E}}}{z}\right)\right]$$

Collins FF   twist-3 FF   unpolarized FF   twist-3 FF

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	$h, \mathbf{e}$
L	$f_L^{\perp}$	$g_L^{\perp}$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^{\perp}$	$\mathbf{g_T}, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

CLAS12, S. Diehl et al., Phys. Rev. Lett., 128, 062005, (2022), [hep:ex] 2101.03544



Multidimensional analysis performed

Data sensitive to the $eH^{\perp}_1$ (DCSB) and $g^{\perp}D_1$ (quark gluon correlation)

For single-pion SIDIS - e(x) is accessible only when the transverse momentum of the final hadron is not integrated out

Di-hadron Beam Spin Asymmetries

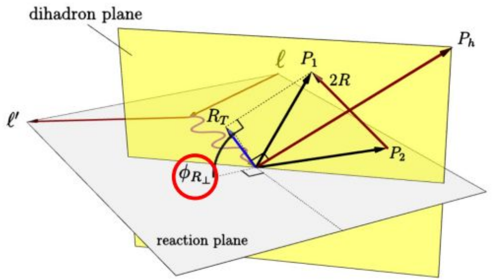
twist-3 pdf

unpolarized pdf

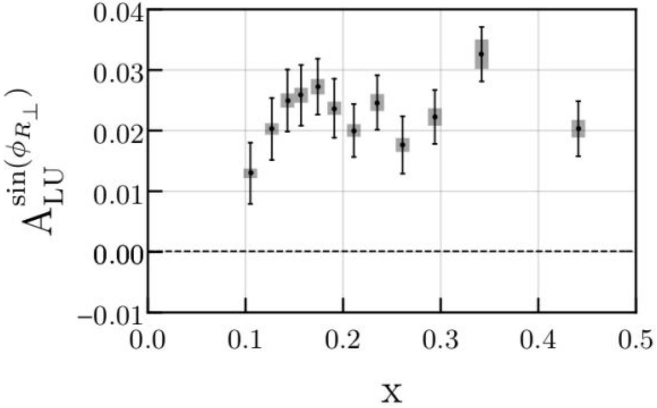
$$F_{LU}^{\sin\phi_{R_\perp}} = -x\frac{\vec{R}\sin\theta}{Q}\left[\frac{M}{M_h}x\boxed{e^q(x)}\boxed{H_1^{\sphericalangle q}(z,\cos\theta,M_h)} + \frac{1}{z}\boxed{f_1^q(x)}\boxed{\tilde{G}(z,\cos\theta,M_h)}\right]$$

"Interference Fragmentation Function"

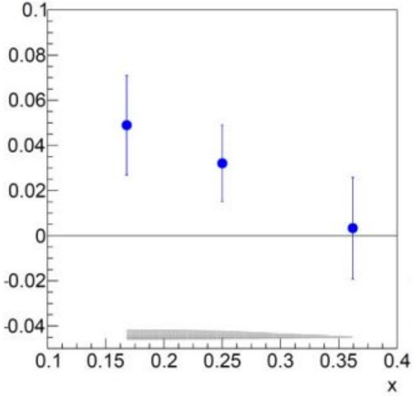
twist-3 FF



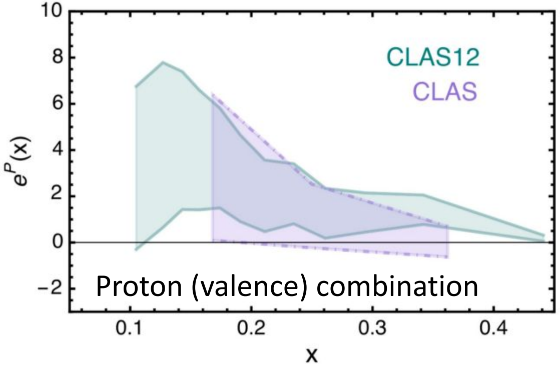
CLAS12, T. Hayward, et al., PRL 126 (2021) 152501



CLAS6, M. Mirazita, et al., PRL 126 (2021) 6, 062002



A. Courtoy, et al., Phys.Rev.D 106 (2022) 1, 014027

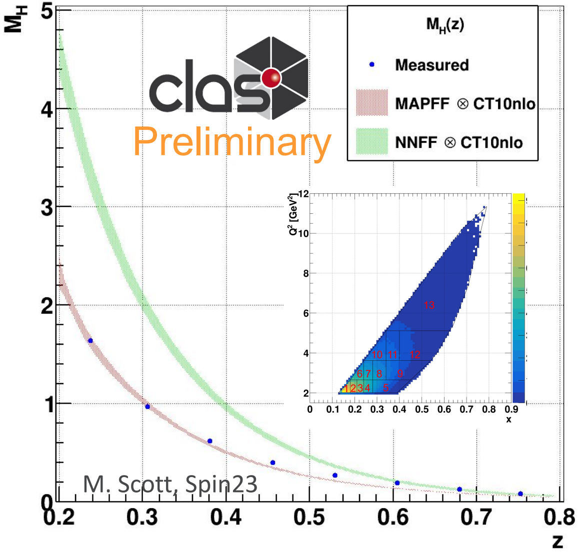


- First measurement of dihadron A_{LU} and extraction of e(x): IFF measured at Belle combined with CLAS results
- Twist-3 PDF (quark gluon correlations): related to quark contributions to nucleon mass
- Boer-Mulders force: ⊥ force exerted by color field on a ⊥ polarized struck quark in an unpolarized nucleon

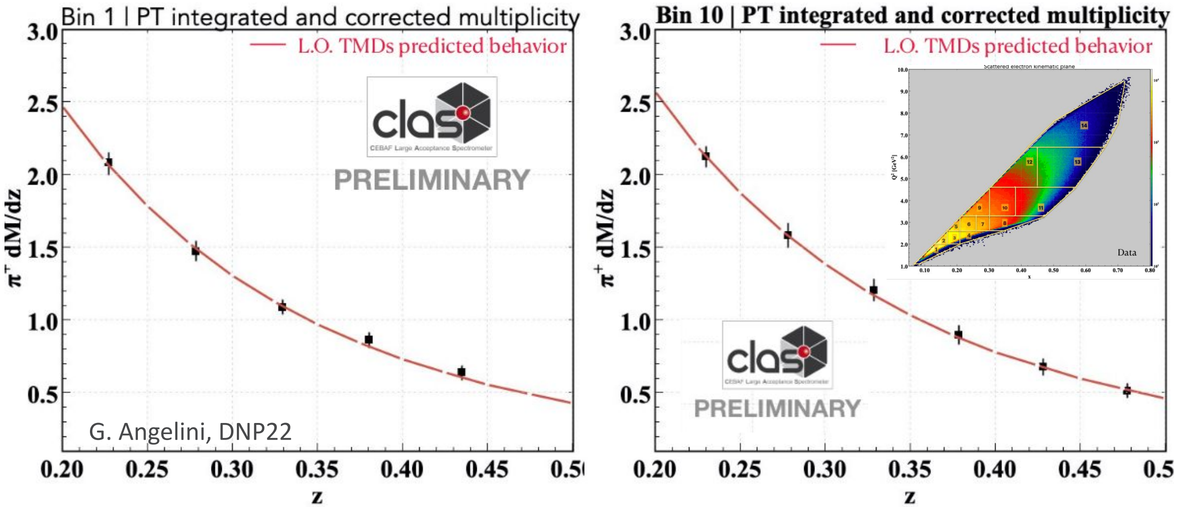
Pion Multiplicities

- Pion multiplicities describe the number of produced pions in the five-dimensional SIDIS phase space $(x, Q^2, z, p_T^2, \varphi_h)$ per number of DIS events in (x, Q^2) phase space.
- Directly related to the $D_1(z)$ FF $$m_N^h(x,z,\boldsymbol{P}_{hT}^2) = \frac{\pi}{\sum_a e_a^2 f_1^a(x)} \sum_a e_a^2 f_1^a(x)\, D_1^{a\to h}(z)\, \frac{e^{-\boldsymbol{P}_{hT}^2/\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}}{\pi\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}$$
- Neutral pion results further serve as a test on the isospin symmetry between neutral and charged pion FF

Example p_T^2 integrated π^0 multiplicity for x-Q^2 Bin 1 with LO 1σ theory curves



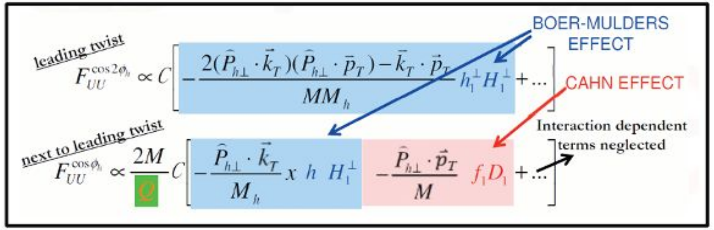
Example p_T^2 integrated π^+ multiplicity for x-Q^2 Bin 1 and 10 with LO theory curves (CTEQ and Sassot)

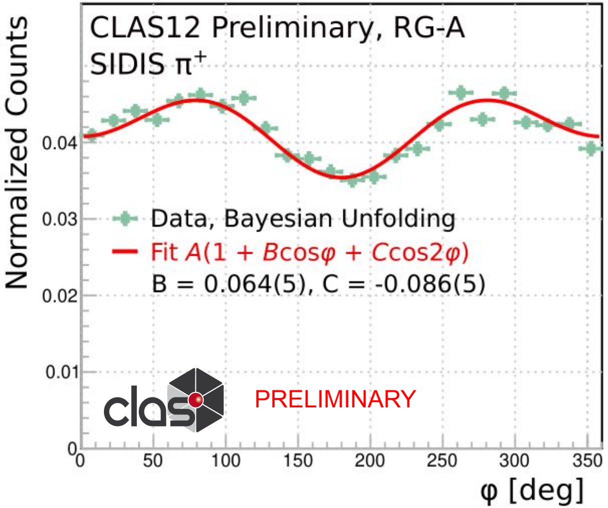


Cosφ$_h$ and Cos2φ$_h$ Moments of the SIDIS cross section

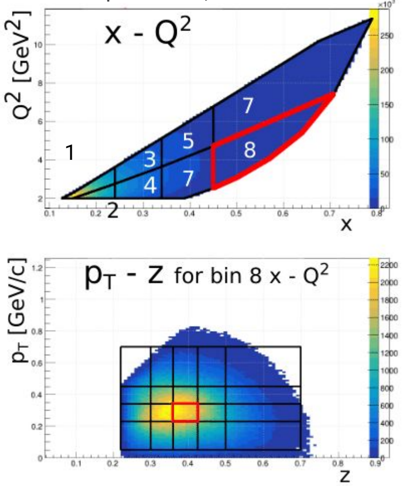
- cos(φ$_h$) and cos(2φ$_h$) moments of unpolarized SIDIS cross-section for π$^+$ using hydrogen target
- High-precision study of the moments which probe the Boer-Mulders function and Cahn effect
- The high-statistics data will, for the first time, enable a multidimensional analysis over a large kinematic range of Q^2, y, z, and P_T.

Structure functions connection
to Boer-Mulders and Cahn effects:

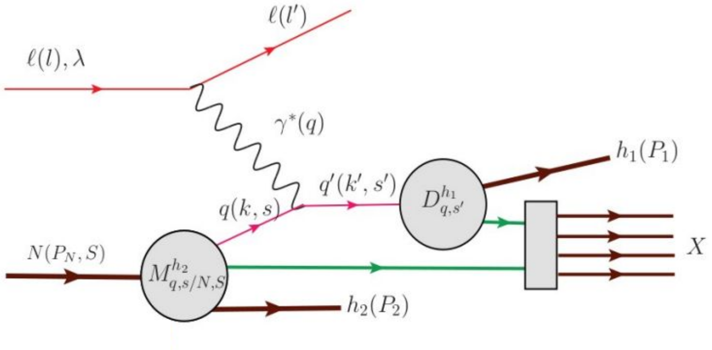




R. Capobianco, DNP22



Current and Target Fragmentation Region Correlations



Fracture functions accessible in “Back-to-Back” production

- One current-fragmentation region (CFR) hadron h_1
- One target-fragmentation region (TFR) hadron h_2

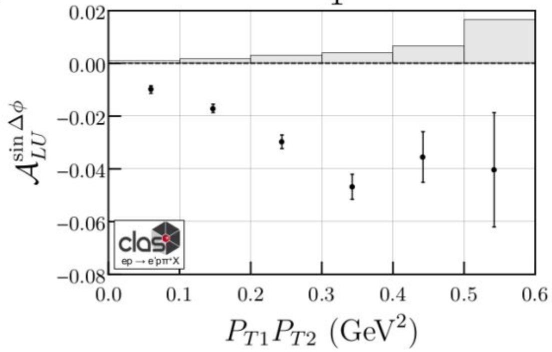
Fracture functions: the probability for the target remnant to form a certain hadron given a particular ejected quark

CLAS12, H. Avakian, et al., Phys.Rev.Lett. 130 (2023) 2, 022501

CLAS12 Preliminary, T. Hayward, Spin23

CFR pion, TFR proton → $\hat{l}_1^{\perp p}$ (L quark, U nucleon)

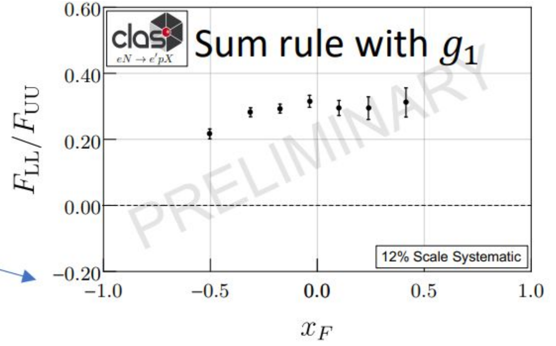
→ $\hat{u}_1^p$ (unpolarized)



Quark polarization (columns); Nucleon polarization (rows)

	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132



Selected GPD results

GPDs and Angular Orbital Momentum

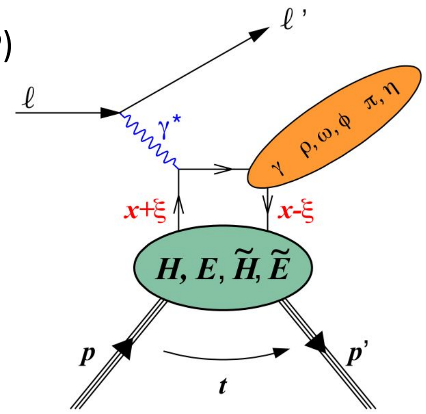
Connection to the **proton spin**: $J_{\rm q} = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x \, x \left[H^{\rm q}(x, \xi, t) + E^{\rm q}(x, \xi, t) \right]$ $\quad J_q = \frac{1}{2}\Delta\Sigma + L_q$

N / q	U	L	T
U	H		E_T
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T \quad \tilde{H}_T$

4 chiral-even and 4 chiral-odd quark **GPDs at leading twist** for a spin-½ hadron

Accessed via hard exclusive processes: cross section and asymmetries

- Deep virtual Compton scattering (**DVCS**) and hard exclusive meson production (**HEMP**)
- H, E accessed in vector meson production, all 4 chiral-even GPDs accessed in DVCS



DVCS and access to GPDs

- Experimental access to GPDs via Compton Form Factors
- Different configurations: p and e polarization, beam charge → different CFFs
- proton + neutron DVCS → flavor separation of GPDs

$$\mathcal{H}(\xi, t) = \sum_q e_q^2 \int_{-1}^{1} dx \, H^q(x, \xi, t) \left(\frac{1}{\xi - x - i\varepsilon} - \frac{1}{\xi + x - i\varepsilon} \right)$$

GPDs and Angular Orbital Momentum

Connection to the **proton spin**: $J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$ $\quad J_q = \frac{1}{2}\Delta\Sigma + L_q$

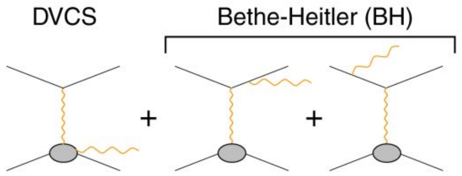
N / q	U	L	T
U	H		E_T
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T \quad \tilde{H}_T$

4 chiral-even and 4 chiral-odd quark **GPDs at leading twist** for a spin-½ hadron

Interference between DVCS and Bethe-Heitler amplitude plays key role

- Allows to determine both magnitude and phase of the DVCS amplitude

$$\sigma = |\mathcal{T}_{DVCS}|^2 + (\mathcal{T}_{DVCS}\mathcal{T}_{BH} + \mathcal{T}_{DVCS}\mathcal{T}_{BH}) + |\mathcal{T}_{BH}|^2$$



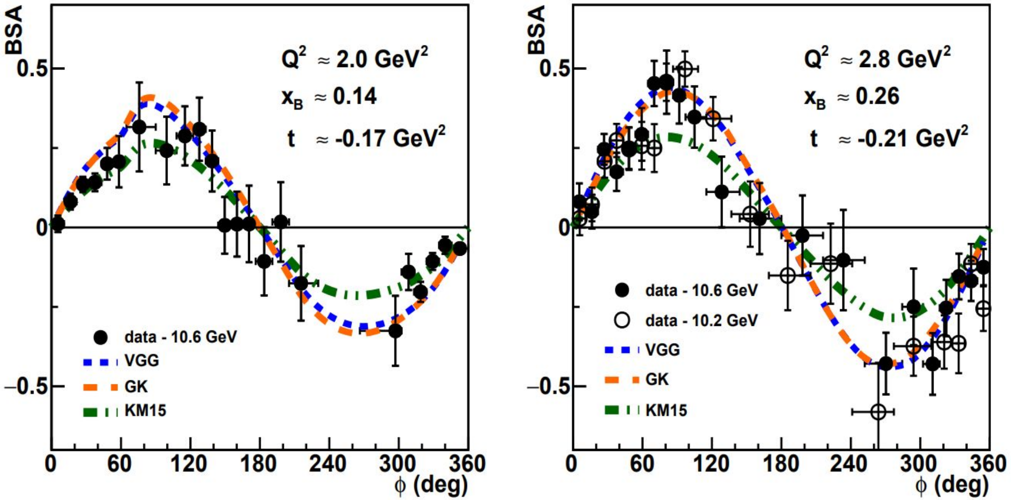
$$\frac{d\sigma^{DVCS}}{dt} \propto e^{-b|t|}$$

Slope of DVCS dσ/dt - determination of **transverse extension of partons**

DVCS AND TCS AT CLAS12

G. Christiaens et al. (CLAS), Phys. Rev. Lett. 130 (2023)

Beam spin asymmetry for DVCS on the proton



Beam-spin asymmetries in the extended valence region

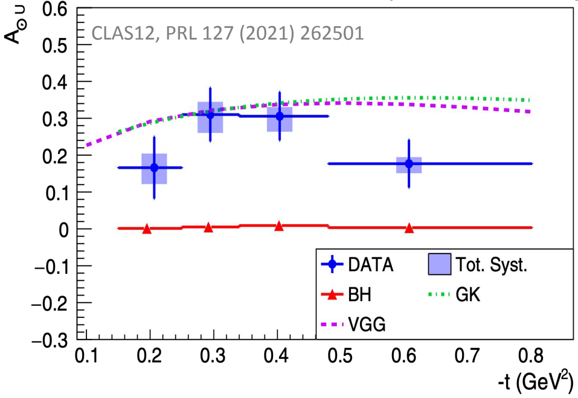
- Many kinematics never covered before
- In previously measured kinematics, the new data are shown to be in good agreement with existing data and improve the precision of GPD fits

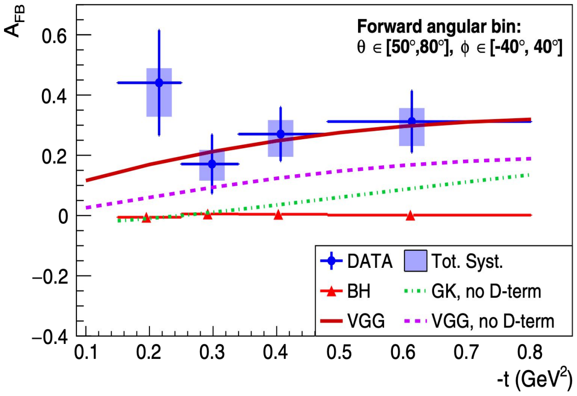
- Sensitivity to Im $\mathcal{H}$, the imaginary part of the CFF
- corresponding to the GPD H

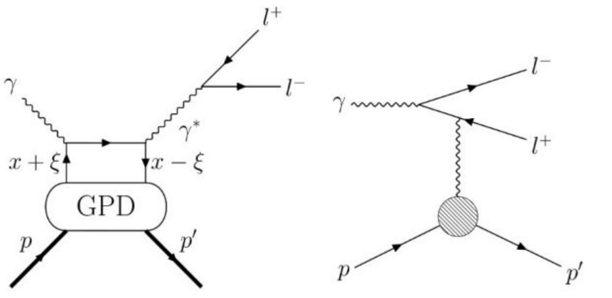
First-time measurement of nDVCS with detection of the active neutron in progress

DVCS AND TCS AT CLAS12

Timelike Compton Scattering: time reversal to DVCS







(Timelike) Compton Scattering is the time reversal process of DVCS and allows us to test the universality of GPDs.

Photon polarization asymmetry

- Sensitive to Im(CFF)
- Comparison to DVCS allows to test the universality of GPDs - especially the imaginary part of H

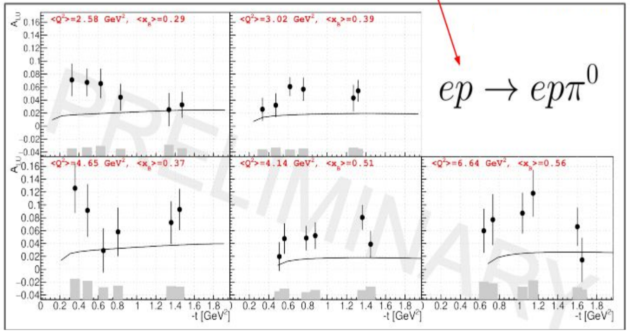
Forward-backward asymmetry

- Real part of the CFF and nucleon D-term
- Relates to mechanical properties of the nucleon (quark pressure distribution)

HARD EXCLUSIVE MESON PRODUCTION

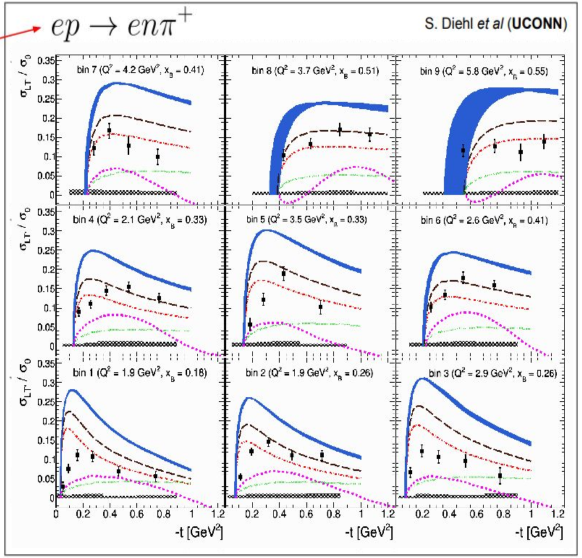
π^+/π^0 beam spin asymmetries

$$\sigma_{LT'} = \xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\times \\ \times\ \mathrm{Im}\left[\boxed{\langle H_T\rangle^*\langle\tilde{E}\rangle} + \boxed{\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle}\right]$$



A. Kim, CLAS12 Preliminary, APCTP 22

CLAS12, PLB 839, 137761 (2023)



$$\frac{d^2\sigma_{\gamma^* p}^{\leftrightarrows}}{dt\,d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{\epsilon(1+\epsilon)}\cos\phi\frac{d\sigma_{LT}}{dt} \mp |P_l|\sqrt{\epsilon(1-\epsilon)}\sin\phi\frac{d\sigma'_{LT}}{dt}\right]$$

	Meson	Flavor
$\mathcal{H}_T, \mathcal{E}_T$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	g

- DVMP offers access to the chiral-odd GPDs with separate psueodscalar and vector meson measurements providing information on the flavor dependence.
- Chiral odd GPDs provide access to information on proton anomalous tensor magnetic moment, proton tensor charge and more.

Summary

- The CLAS12 facility at JLab offers an exceptional platform for conducting studies that are sensitive to nucleonic structure. This is primarily attributed to its impressive luminosity and comprehensive 4π coverage.
- Within the initial years of operation, CLAS12 has released several publications based on unpolarized H_2 data. Notably, many these publications introduced groundbreaking measurements for the first time.
- As we transition into the second phase of operations, we anticipate an exciting array of diverse measurements. This phase will encompass various aspects such as asymmetries, cross sections, differing energy levels, and a wide range of target materials and polarizations.

Backup

Longitudinal Spin Structure

- Decades of studies in **Deep Inelastic Scattering**, as well as **Semi-Inclusive Deep Inelastic Scattering** and **proton-proton** collisions
- **Polarized DIS cross section** studied at **SLAC, CERN, DESY, JLab** encodes information about **helicity structure of quarks** inside the proton (double spin asymmetries)

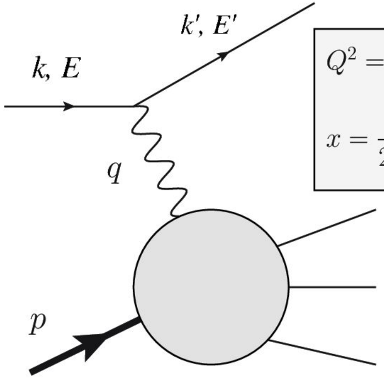
$$\frac{\mathrm{d}^2\sigma_{\mathrm{LL}}(x,Q^2)}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{8\pi\alpha^2 y}{Q^4}\left[\left(1-\frac{y}{2}-\frac{y^2}{4}\gamma^2\right)\boxed{g_1(x,Q^2)} - \frac{y}{2}\gamma^2 g_2(x,Q^2)\right]$$

$$\nu = E - E'$$
$$y = \nu/E,\ \gamma^2 = Q^2/\nu^2$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\ \Delta q(x)$$

In (LO QCD) Quark Parton Model

Quark helicity distribution



$$Q^2 = -q^2$$
$$x = \frac{Q^2}{2\,p\cdot q}$$

Experimental access through double spin asymmetries

$$A_{\parallel} = \frac{\sigma_{\mathrm{LL}}}{\sigma_{\mathrm{UU}}} = \frac{1}{P_{\mathrm{B}}P_z}\cdot\frac{\sigma^{\rightarrow}_{\Leftarrow} - \sigma^{\rightarrow}_{\Rightarrow}}{\sigma^{\rightarrow}_{\Leftarrow} + \sigma^{\rightarrow}_{\Rightarrow}} = D(1+\eta\gamma)\ A_1$$

D - Depolarization factor
η - kinematic fator
A_1 - photon-nucleon asymmetry

$$A_1 = \frac{g_1}{F_1}$$

Longitudinal Spin Structure

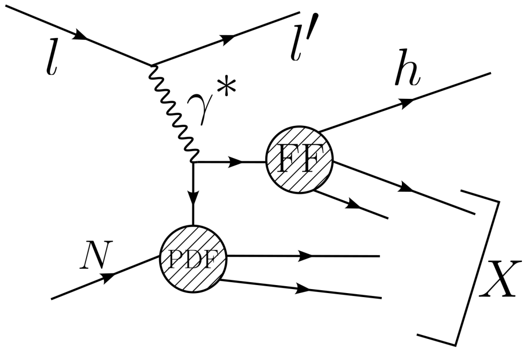
- Decades of studies in **Deep Inelastic Scattering**, as well as **Semi-Inclusive Deep Inelastic Scattering** and **proton-proton** collisions
- **Semi-Inclusive Deep Inelastic Scattering** with charged pions and kaons adds **sensitivity to flavor-separated quark helicities** via the fragmentation functions $D_q^h(z,Q^2)$
  - valence parton content of h relates to the fragmenting parton flavor, particularly at high z
    z - fractional energy of the final-state hadron $z = E^h/\nu$

Photon-nucleon asymmetry for SIDIS

$$A_1^h = \frac{\boxed{\sigma^h_{1/2}} - \boxed{\sigma^h_{3/2}}}{\sigma^h_{1/2} + \sigma^h_{3/2}} \xrightarrow{\text{LO}} \boxed{\frac{d^3\sigma^h_{1/2(3/2)}}{dx\,dQ^2\,dz}} \propto \sum_q e_q^2\, q^{+(-)}(x,Q^2)\, D_q^h(z,Q^2)$$

$$A_1^h(x,Q^2,z) = \frac{\sum_q e_q^2\, \Delta q(x,Q^2)\, D_q^h(z,Q^2)}{\sum_{q'} e_{q'}^2\, q'(x,Q^2)\, D_{q'}^h(z,Q^2)}$$

Experimental access through double spin asymmetries (analogous to DIS)

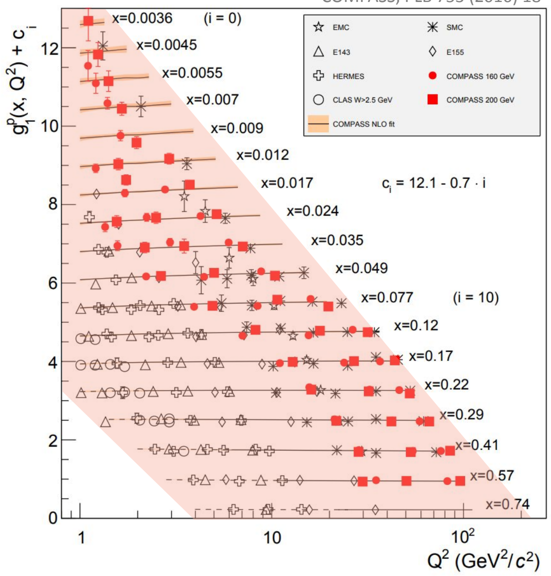


- Sensitivity to sea quarks at low x from $A_1^{\pi^-}$ ($\Delta\bar{u}$), $A_1^{\pi^+}$ ($\Delta\bar{d}$), A_1^{K} (Δs)

$\sigma^{SIDIS} = \hat{\sigma} \otimes \text{PDF} \otimes \text{FF}$

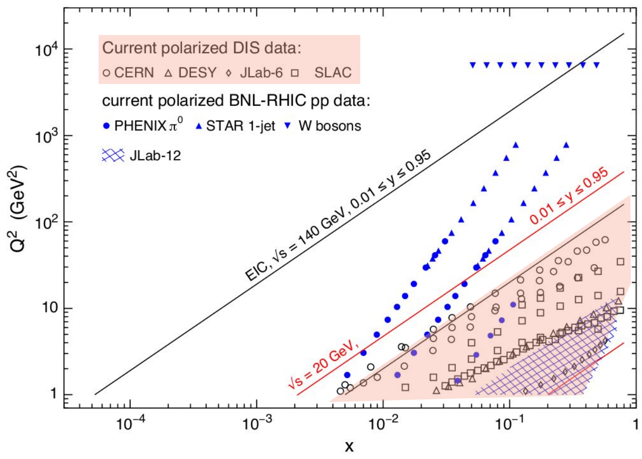
Longitudinal Spin Structure - Where Are We Going?

COMPASS, PLB 753 (2016) 18



Current DIS Data:
Down to x ≈ 0.005
Q^2 ≈ 1-100 GeV^2

EIC, Yellow Report



EIC:
Down to x ≈ 10^{-4}
Q^2 ≈ 1-10^3 GeV^2 !

- Access to gluon spin through g_1 scaling violation
- different √s settings to maximize kinematic coverage