CLAS12 SIDIS Program Overview

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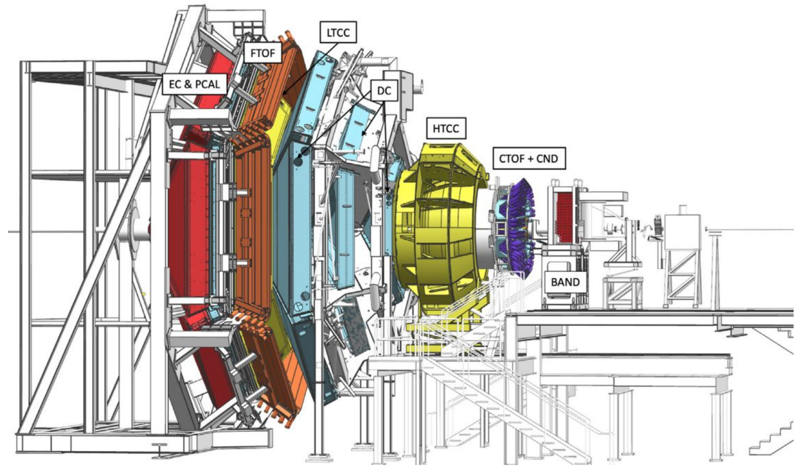
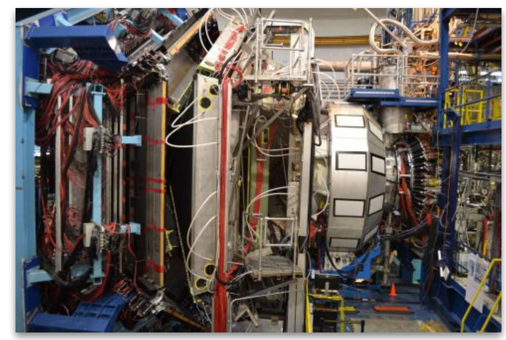
CEBAF Large Acceptance Spectrometer (CLAS)

- ★ Up to 10.6 GeV, longitudinally polarized e^- beams (~85%), fixed target experiment with near full azimuthal ϕ coverage [1]
  - ○ $2° < \theta < 5°$ forward tagger
  - ○ **$5° < \theta < 35°$ forward detector system**
  - ○ $35° < \theta < 125°$ central detector system
  - ○ $155° < \theta < 175°$ backward angle neutron detector
- ★ Comprehensive (e, π, K, p, n, γ) reconstruction
  - ○ Several AI methods developed to improve!
  - ○ 2/6 azimuthal sectors now contain a RICH (π, K)
- ★ ~2T toroidal magnetic field, 5T solenoid





Many experimental configurations (Run Groups) each with unique physics objectives (see [2])

Run Group **SIDIS** programs at a glance

Run Group A (Unpolarized LH_2 target - 10.6 GeV e^- beam)

- ★ Measurements of **unpolarized SIDIS cross section** off proton *(ex: π multiplicities)*
- ★ Access to **higher-twist PDFs** through A_{LU} beam-spin asymmetries (BSAs)
- ★ Study impact of struck quark's spin/flavor/momentum on **hadronization**
  - ○ Separate contributions from vector meson decays *(ex: direct π vs. decay π)*
- ★ Observe correlations between struck quark and target breakup

Run Group B (Unpolarized LD_2 target - 10.6 GeV e^- beam)

- ★ Complementary to RG-A → allow for ***u/d*** **quark flavor separation** of observables

Run Group C (Dynamic longitudinally polarized NH_3 and ND_3 - 10.6 GeV e^- beam)

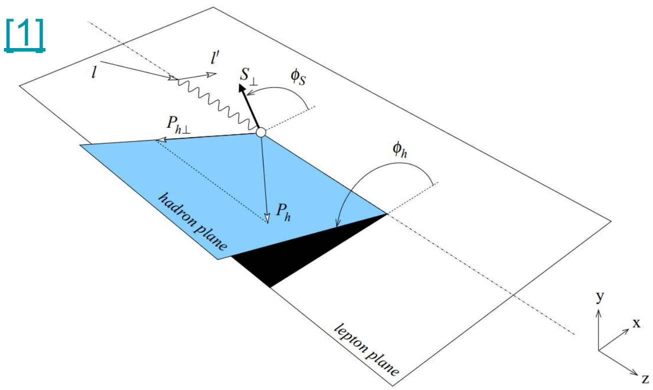
- ★ Access to $\mathbf{F_{UL}}$ and $\mathbf{F_{LL}}$ structure functions → Sensitive to different PDFs and FFs
  - ○ Dihadron SIDIS will give first measurements of **higher-twist** fragmentation functions

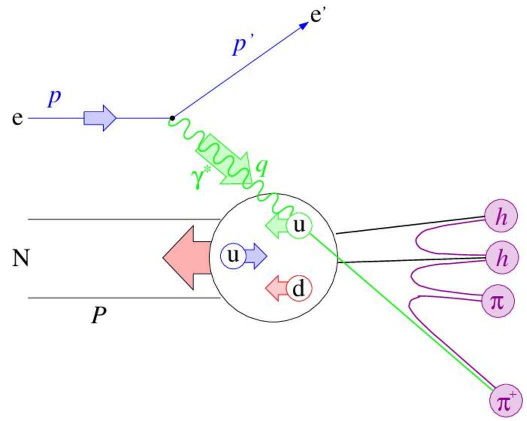
Run Group K (Unpolarized LH_2 target - 6.5, 7.5, 8.4 GeV e^- beam)

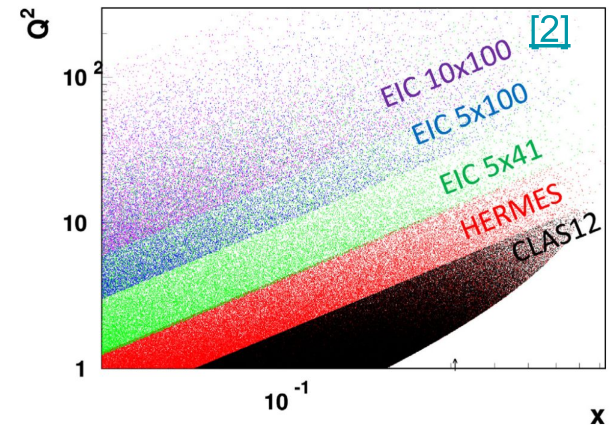
- ★ Separation of longitudinal ($F_{UU,L}$) and transverse ($F_{UU,T}$) photons from SIDIS cross section

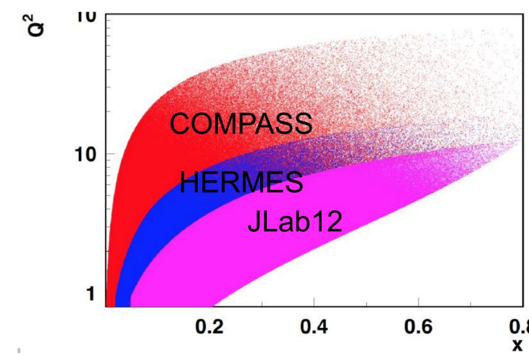
SIDIS Kinematics and Coverage

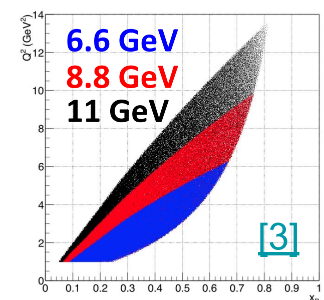
[1]











CLAS12 $\longrightarrow$ high beam polarization, high luminosity, comprehensive PID, moderate-to-large x_B physics

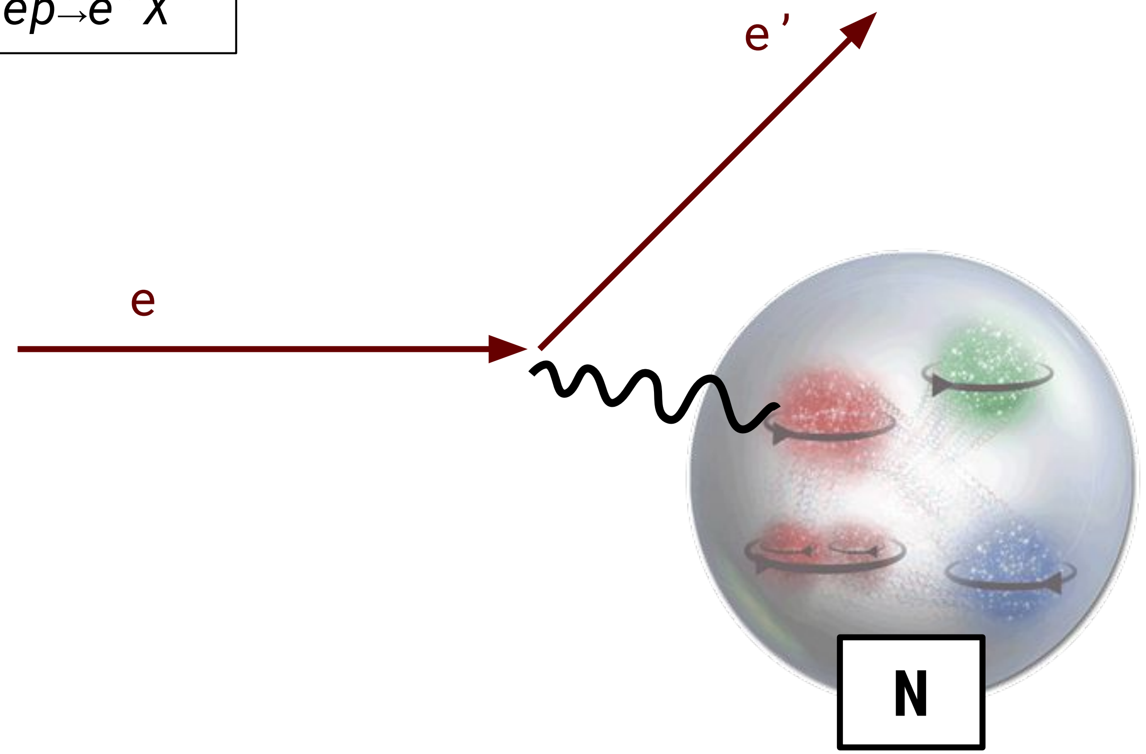
Experiments measure azimuthal dependence of the SIDIS cross section as a function of x, Q^2, p_T, z

★ 3D partonic distributions & hadronization mechanisms (fragmentation functions) reveal themselves through azimuthal modulations

★ QCD predicts only the Q^2-dependence $\longrightarrow$ Need experiment!

The DIS picture

$ep \to e'X$



Quark-quark correlator breaks into 8 independent terms using (**p**, **k**$_\perp$) and (**S**, **s**$_q$) $\longrightarrow$ TMDs

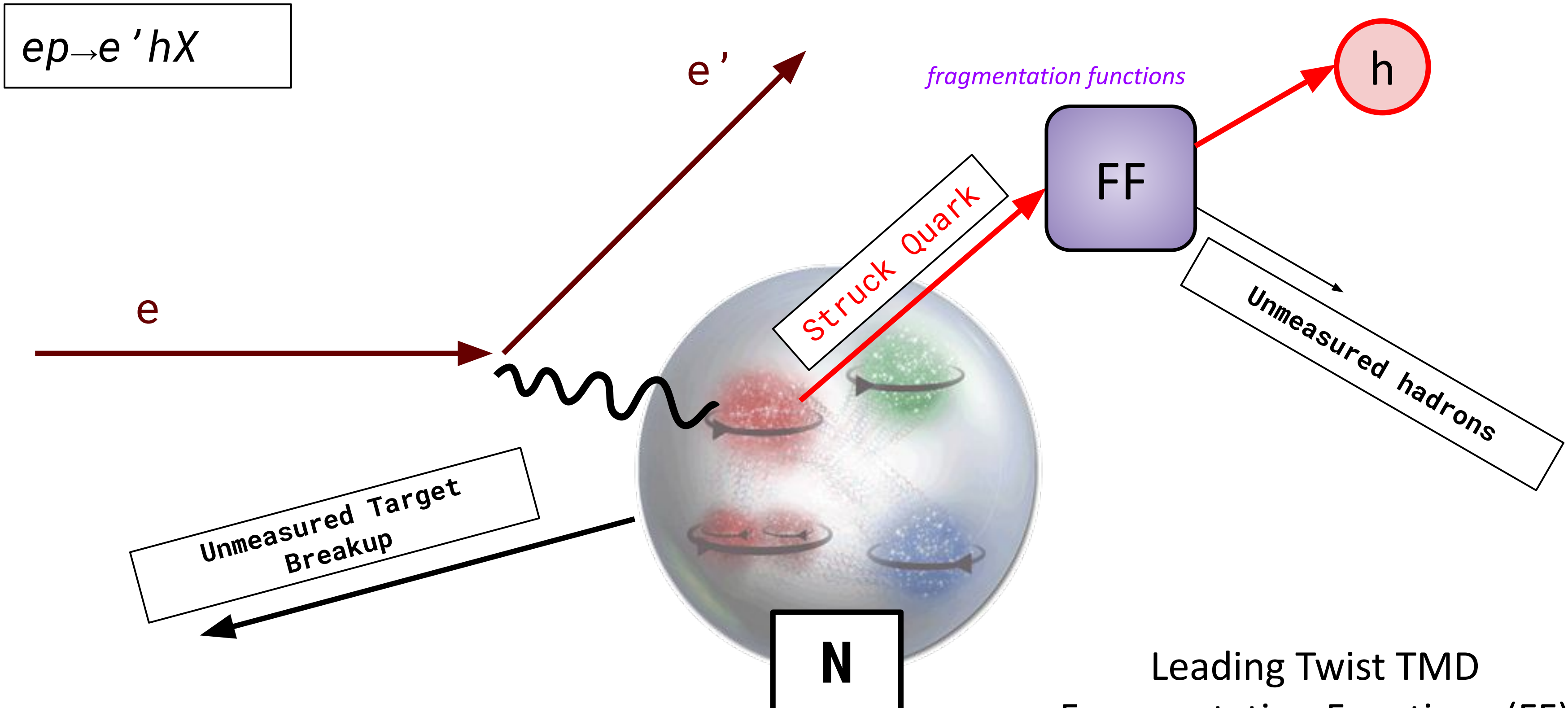
Leading Twist TMD-PDFs

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

Rich landscape of **Parton Distribution Functions** are integrated over w/o measuring hadrons (need SIDIS)

$$\sigma = \hat{\sigma} \otimes \mathrm{PDF}$$

The SIDIS picture (**Current Fragmentation)**



Leading Twist TMD
Fragmentation Functions (FF)

H \ q	U	L	T
U	$D_1^{h/q}$		$H_1^{\perp\, h/q}$
L		$G_1^{h/q}$	$H_{1L}^{\perp\, h/q}$
T	$D_{1T}^{\perp\, h/q}$	$G_{1T}^{h/q}$	$H_1^{h/q}$ $H_{1T}^{\perp\, h/q}$

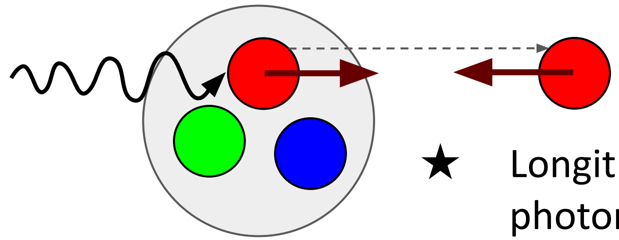
PDF ⊗ FF - produce **azimuthal modulations** of the final-state hadron which we measure in SIDIS

$$\sigma = \hat{\sigma} \otimes \mathrm{PDF} \otimes \mathrm{FF}$$

Sensitivity to Twist-3 effects

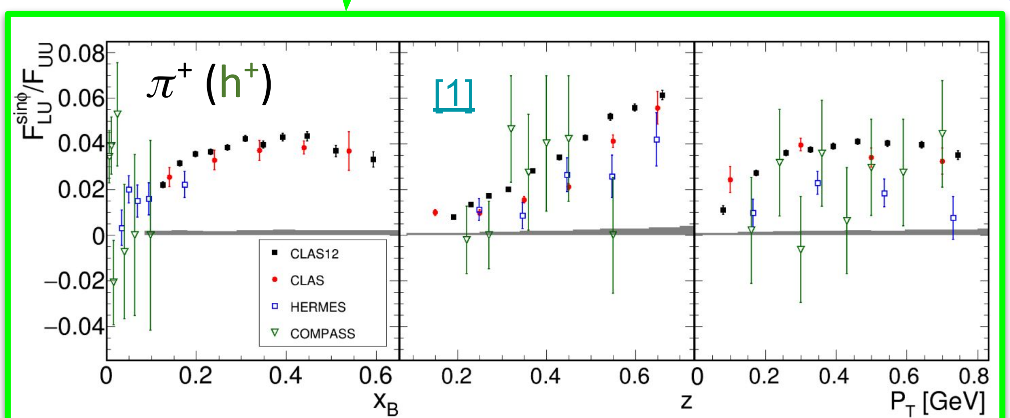
TMD-PDFs at Twist-3

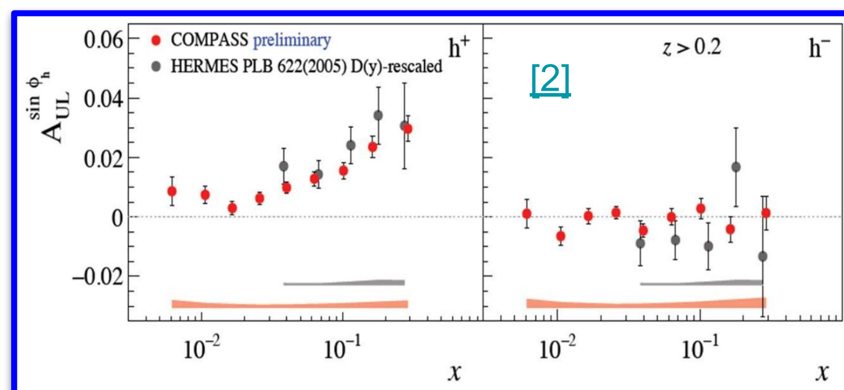
N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$



★ Longitudinally polarized photons “pick out” longitudinally polarized quarks

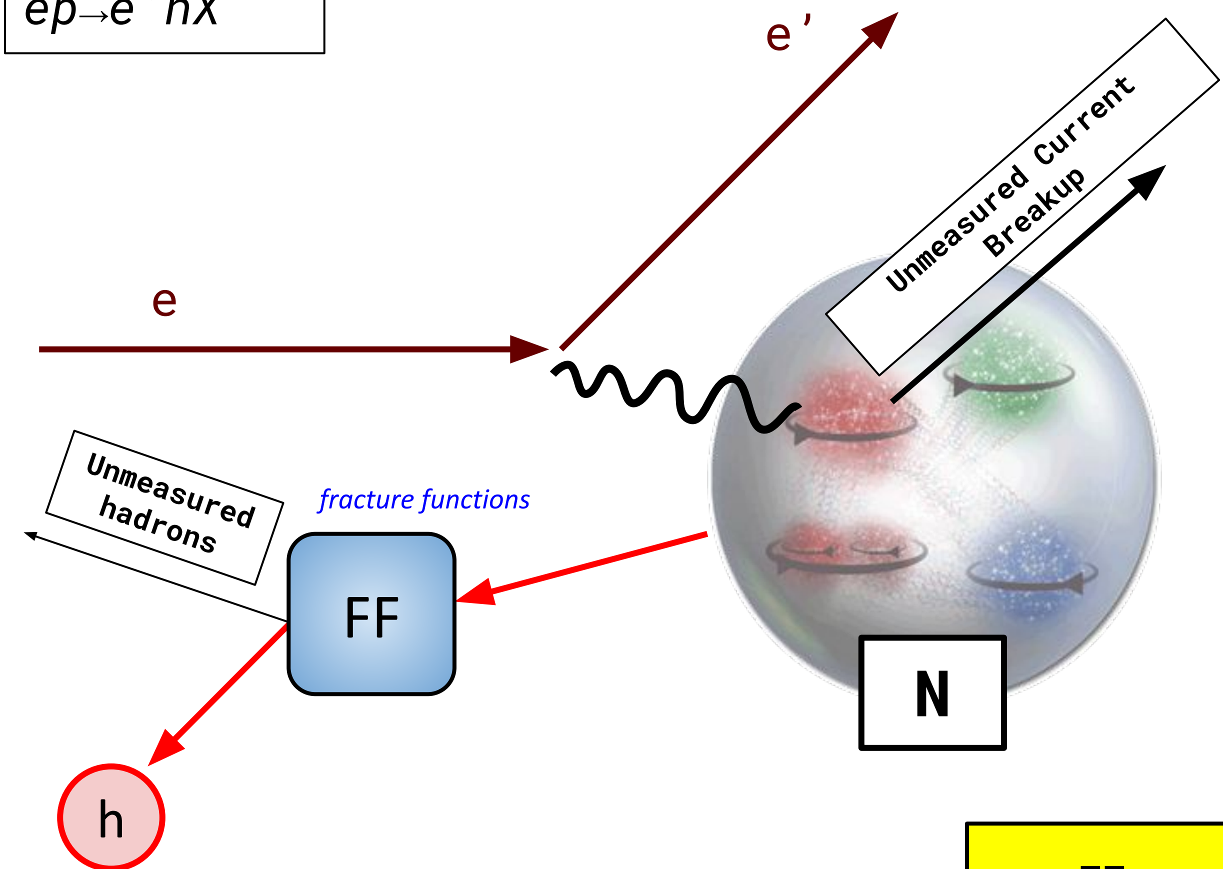
PDFs at higher twist (1/Q suppression) give rise to new A_{LU}, A_{UL}. Correspond to novel quark-gluon dynamics within the proton → Measure(d) at CLAS, COMPASS, HERMES





The SIDIS picture (**Target Fragmentation**)

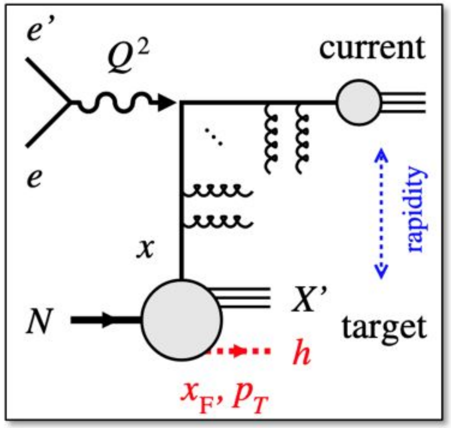
$ep \to e'hX$



$$\sigma = \hat{\sigma} \otimes \mathrm{FF}$$

FF $\longrightarrow$ Fracture Functions give the conditional probability for the target remnant to form a hadron given ejected quark q

The SIDIS picture (**Target Fragmentation**)



"What physics can we learn from the target remnant (TFR)?"

- **Fracture Functions** → probability for the target (p/n) remnant to form a hadron *given* ejected quark q_f
  - No hard/soft energy scale separation

$$\frac{d\sigma^{\mathrm{TFR}}}{dx_B\, dy\, dz} = \sum_a e_a^2 (1 - x_B) \boxed{M_a(x_B, (1 - x_B)z)} \frac{d\hat{\sigma}}{dy}$$

- Direct relationship to traditional **PDFs** by integrating over fractional longitudinal nucleon momentum ζ

$$\boxed{\Sigma_h \int_0^{1-x} d\zeta\, \zeta\, \hat{\boldsymbol{u}}_{\boldsymbol{1}}(\boldsymbol{x}, \boldsymbol{\zeta}) = (1 - x) \boldsymbol{f}_{\boldsymbol{1}}(\boldsymbol{x})}$$

$$\boxed{\Sigma_h \int_0^{1-x} d\zeta\, \zeta\, \hat{\boldsymbol{l}}_{\boldsymbol{1L}}(\boldsymbol{x}, \boldsymbol{\zeta}) = (1 - x) \boldsymbol{g}_{\boldsymbol{1L}}(\boldsymbol{x})}$$

- Key for understanding how to separate *current* vs. *target* fragmentation

CFR ⟷ TFR [1]

Quark polarization (columns) / Nucleon polarization (rows) — CFR:

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

Quark polarization (columns) / Nucleon polarization (rows) — TFR:

	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

Separating **CFR** and **TFR**

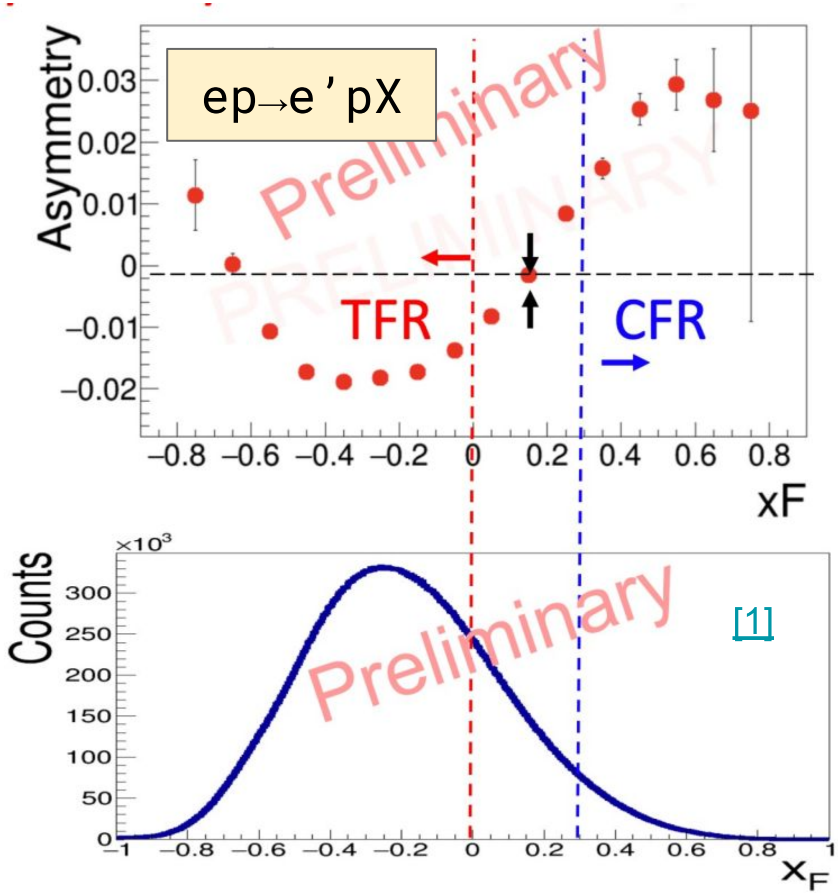
ep→e′hX

*"So we measured a hadron … how do we know it came from the **struck quark**? **Target remnant?**"*

x-Feynman (x_F) : Value between [-1,1] , measures degree of **target**/**current** fragmentation

Fraction of COM energy carried by the hadron in the direction of the virtual photon

$$x_F = \frac{2P_h \cdot q}{W|q|}$$



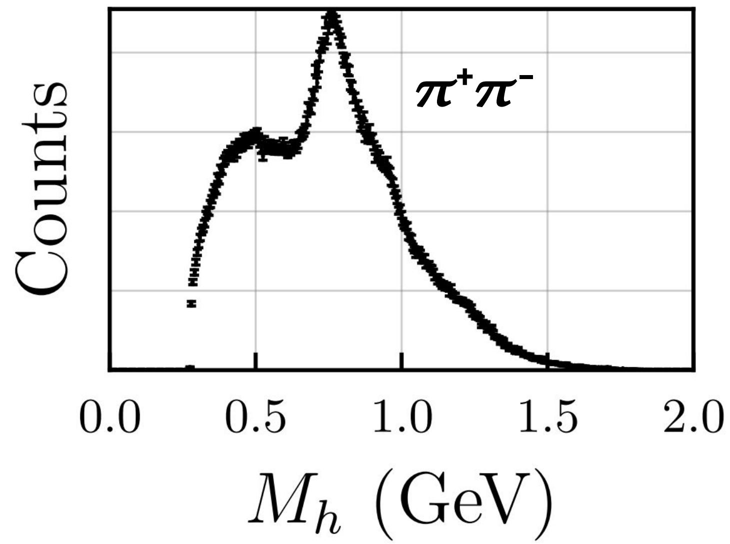
Clear sign difference between **x_F < 0** and **x_F > 0** in the beam-spin asymmetries for SIDIS protons *(What framework for in-between?)*

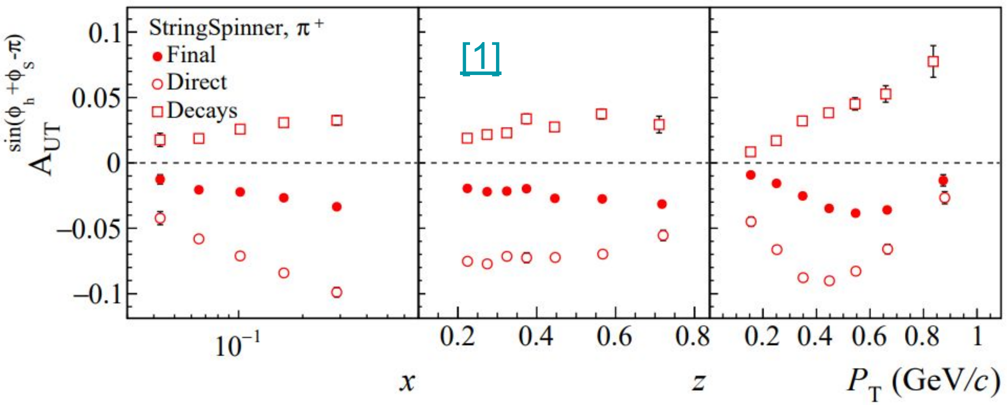
Separating **Resonant** and **Non-resonant**

$ep \rightarrow e'\pi^+X$

*"So we measured a π^+ … how do we know it came from **direct fragmentation? Meson decay?***

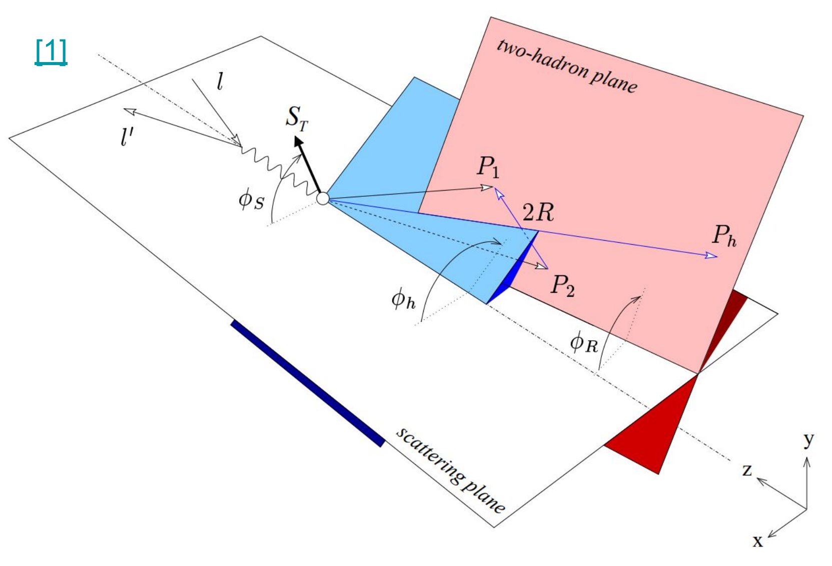
Suppose: The ϱ^0 has a large BSA
Result: The π^+ from the ϱ^0 decay are background to our $\sigma = \hat{\sigma} \otimes \text{PDF} \otimes \text{FF}$ framework





Several efforts at CLAS12 look to constrain **resonant** and **nonresonant** contributions by measuring **VM** and/or **Dihadron** asymmetries

$\gamma p \rightarrow h_1 h_2 X$ Dihadron SIDIS Observables

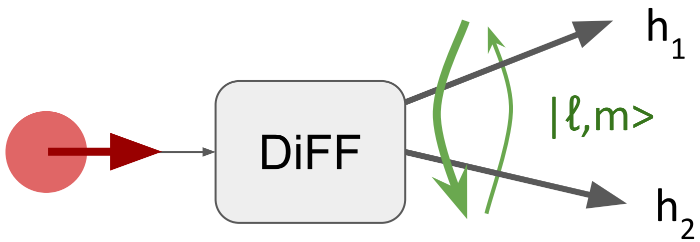


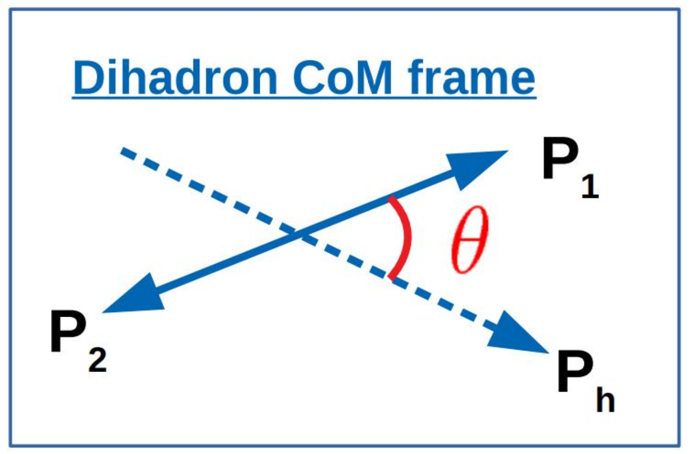
$$\sigma = \hat{\sigma} \otimes \text{PDF} \otimes \text{DiFF}$$

★ Correlations between **two** hadrons fragmented from the **struck quark**

★ More degrees of freedom → More azimuthal modulations than 1h SIDIS

- ϕ_h, ϕ_R, θ





Hadron pair *relative angular momentum* allows for **new,** and at times **simpler** couplings with **PDFs** and **Dihadron Fragmentation Functions (DiFFs)** than with traditional 1h SIDIS

Comparing **1h** and **2h** SIDIS

*How can **dihadrons** help us better interpret our SIDIS results?*

*Suppose we want to measure the **twist-3 PDF** **e(x)***

Single Hadron BSAs

$$d\sigma_{LU} \propto c\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h}\left(x_B e H_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M}\left(x_B g^{\perp} D_1 + \frac{M_h}{M} h_1^{\perp} \frac{\tilde{E}}{z}\right)\right]\sin\phi_h$$

- ★ e(x) appears over a convolution of transverse momentum space
  - ○ k_T → initial quark
  - ○ p_T → final hadron
- ★ 4 other **PDF ⊗ FF** pairs appear
  - ○ Need $g^{\perp}$ (assuming twist-3 FF's are small [1])

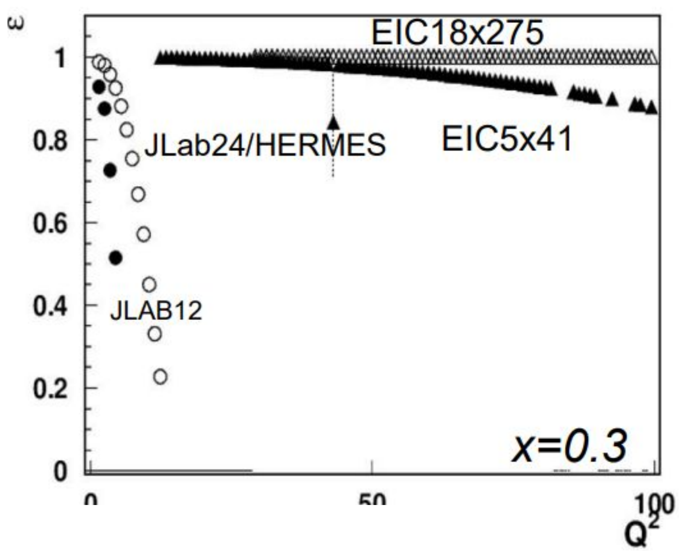
Dihadron BSAs

$$d\sigma_{LU} \propto \left[\frac{M}{M_h}\, x\, e(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x)\, \widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)\right]\sin\phi_R$$

- ★ e(x) accessible **without convolution**
  - ○ Quark spin couples to angular momentum of the hadron pair instead of p_T
- ★ **Run Group C** F_{UL}'s can help us measure simultaneously measure the twist-3 DiFF

Structure Functions and Depolarization Factors @ CLAS12

- ★ Fixed target (CLAS, COMPASS) are sensitive to ALL structure functions
- ★ At higher energies (EIC), only **F$_{UU}$** , **F$_{UL}$** , and **F$_{UT}$** survive ($\varepsilon \longrightarrow 1$)



[1]

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = {} & \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{\boxed{F_{UU,T}+\varepsilon F_{UU,L}} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
& + S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
& + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
& + |\boldsymbol{S}_\perp|\bigg[\sin(\phi_h-\phi_S)\boxed{\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)} \\
& + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\bigg] \\
& + |\boldsymbol{S}_\perp|\lambda_e\bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
& + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\bigg]\Bigg\},
\end{aligned}
$$

Separation of **F$_{UU,L}$** & **F$_{UU,T}$** (as well as **F$_{UT,L}$** and **F$_{UT,T}$**) require measurements at different ε
$\longrightarrow$ **CLAS12 Run Group K, Hall C Measurements, etc.**

Painting the SIDIS picture with CLAS12

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$
$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h}$$
$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}$$
$$+S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]$$
$$+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$
$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$
$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}$$
$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

The experimental programs at CLAS12 are designed to give us **full access** to the SIDIS cross section

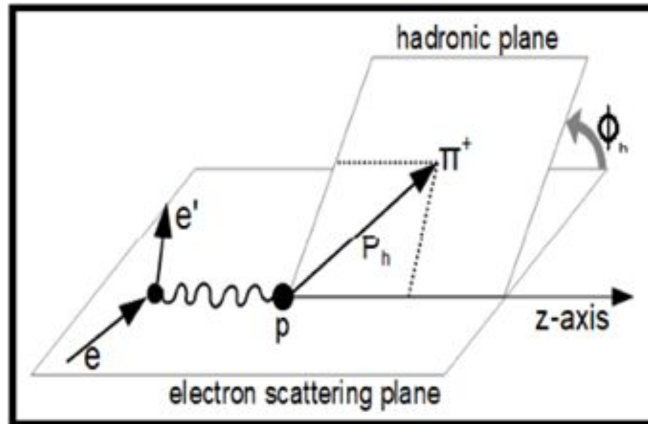
- ★ Variety of beam energies (~5-11 GeV)
- ★ Multiple targets (*p*, *d* , NH_3 , ND_3 , …)
- ★ All target spin configurations (unpolarized, longitudinal, transverse)

Run Group Sensitivities	RG-K	Any	RG-A, RG-B	RG-C	RG-H

Unpolarized Modulations of ep→eπ^+(X)

4-d measurements of the cos(ϕ) and cos(2ϕ) moments of single pion SIDIS [x, Q^2, p_T, z]

- ★ Sensitive to the **Cahn Effect**
  - ○ Quark $k_T \longrightarrow$ Unpolarized modulations
- ★ Sensitive to the **Boer Mulders Effect**
  - ○ Quark k_T & $S_T \longrightarrow$ Unpolarized modulations
- ★ Study performs 5-D bayesian unfolding (acceptance corrections)



Reaction Studied: ep→eπ^+(X)

$$\frac{d^5\sigma}{dy\,dQ^2\,dz\,d\phi_h\,dP_{h\perp}^2} = \underbrace{\frac{x_B}{y}\frac{2\pi\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\epsilon)}(1+\frac{\gamma^2}{2x_B})(F_{UU,T}+\epsilon F_{UU,L})}_{A_0}\left\{1+\underbrace{\frac{\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos\phi_h}}\cos\phi_h+\underbrace{\frac{\epsilon F_{UU}^{\cos 2\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\right\}$$

leading twist

$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}h_1^\perp H_1^\perp+\dots\right]$$

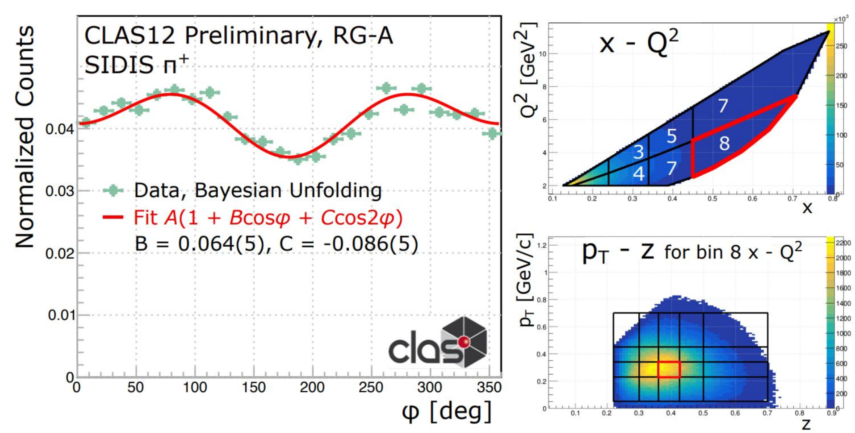
BOER-MULDERS EFFECT

CAHN EFFECT

next to leading twist

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M_h}x\,h\,H_1^\perp-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M}f_1D_1+\dots\right]$$

Interaction dependent terms neglected

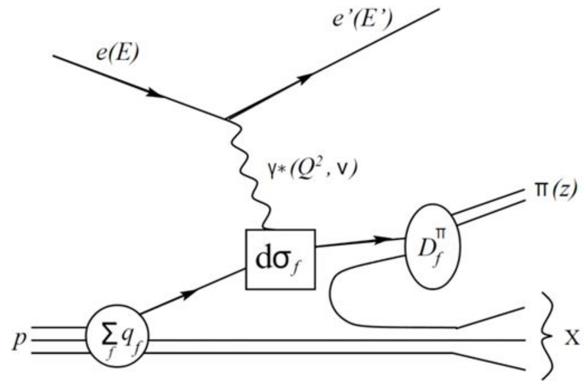


Richard Capobianco

Unpolarized Cross Section of ep→eπ^0(X)

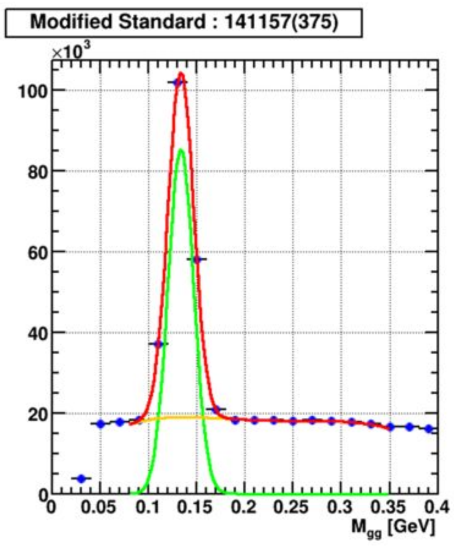
- Measurements of neutral pion multiplicities
  - π^0 yields normalized by number of DIS electrons

$$\sigma^{\pi^0} \approx \sigma^{DIS} \otimes f^p(x,Q^2) \otimes D^{p\rightarrow\pi^0}(z,Q^2)$$



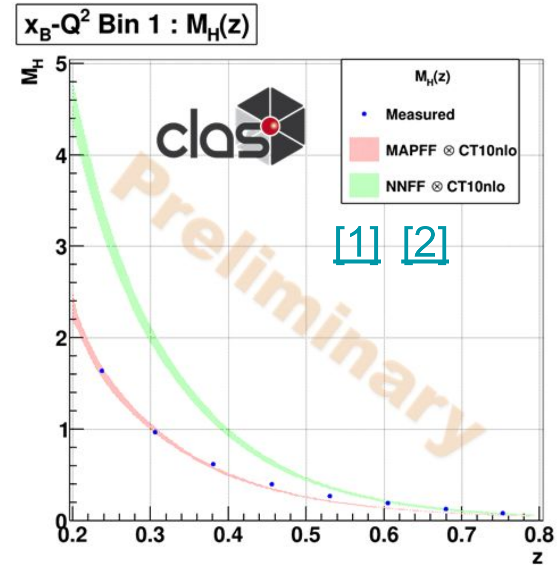
- Study integrates over the azimuthal ϕ_h angle

$$F_{UU,T} = \mathcal{C}[f_1 D_1] \qquad D_1^{\pi^0/q} = \frac{1}{2}\left(D_1^{\pi^+/q} + D_1^{\pi^-/q}\right)$$



- Invariant mass fits over the diphoton spectrum are performed to calculate N(π^0)

- **Ongoing Work:** Bayesian unfolding, ϕ_h modulation fits



Marshall Scott

Multidimensional **BSAs** of ep→eπ(X)

★ Preliminary 4-dimensional (x, Q^2, z, p_T) measurements of π^+, π^0 and π^- SIDIS BSAs

- W > 2 [GeV] ⟶ Deep inelastic
- M_X > 1.5 [GeV] ⟶ Non-exclusive (ex: ep→eπ^0p)

$$A_{LU}(x_B, Q^2, z, P_T, \phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$
$$= \frac{\sqrt{2\epsilon(1-\epsilon)}\,\frac{F_{LU}^{\sin\phi}}{F_{UU}}\sin\phi}{1 + \sqrt{2\epsilon(1+\epsilon)}\,\frac{F_{UU}^{\cos\phi}}{F_{UU}}\cos\phi + \epsilon\,\frac{F_{UU}^{\cos 2\phi}}{F_{UU}}\cos 2\phi},$$

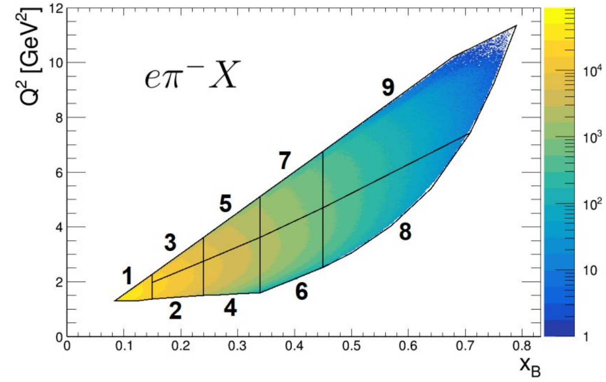
★ If Collins term only **($H_1^\perp$)** ⟶ hierarchy of the A_{LU}'s

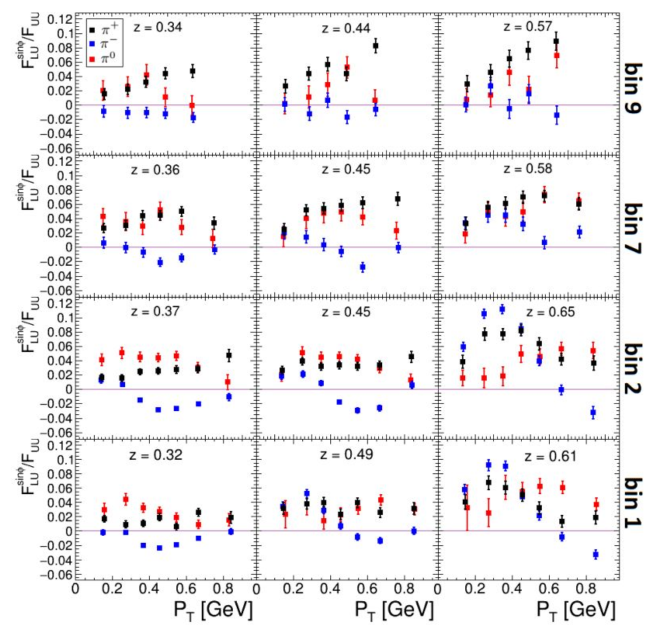
$A_{LU}(\pi^-) < A_{LU}(\pi^0) = 0 < A_{LU}(\pi^+)$

★ Observed is more **Sivers-like ($g^\perp$)**, asymmetry comes from struck u-quark

$A_{LU}(\pi^-) < A_{LU}(\pi^0) = A_{LU}(\pi^+)$

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h}\left(x_B e H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M}\left(x_B g^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z}\right)\right],$$





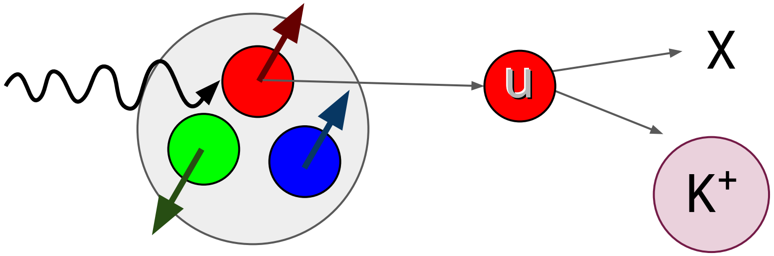
Stefan Diehl

Multidimensional **BSAs** of ep→eK(X)

★ Valence region (moderate x_B) measurements of Kaon F_{LU}'s give us access to… $D_1^{K^+/u}$

$H_1^{\perp\, K^+/u}$

… etc



★ Sensitivity to twist-3 PDFs **e(x)** and **$g^{\perp}$(x)**

★ Assumes twist-3 FFs are small (Wandzura-Wilczek Approximation [1])

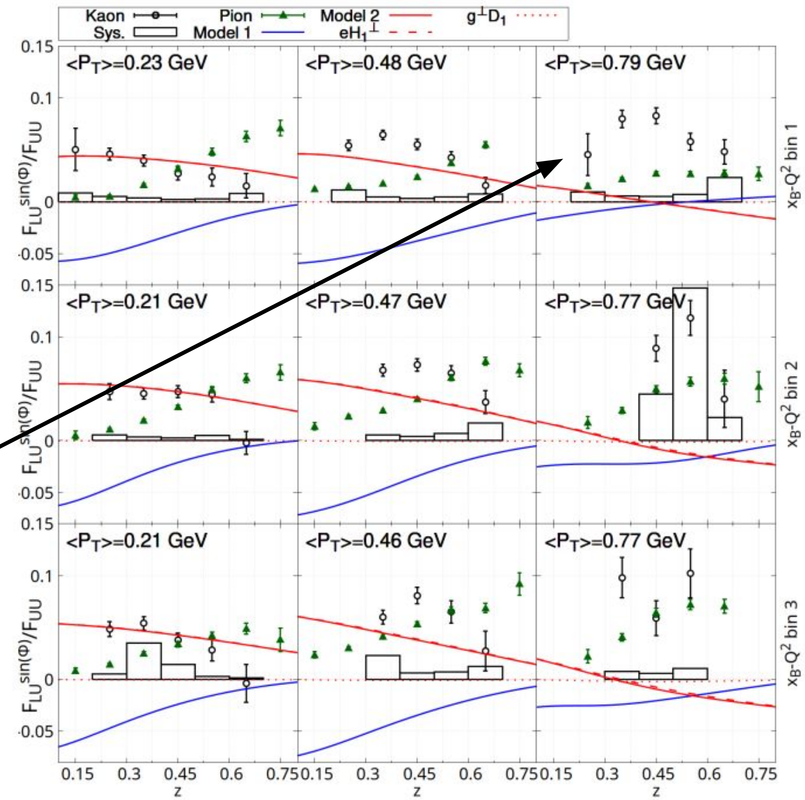
★ M_X > 1.6 GeV ⟶ Remove exclusives

★ Deep Neural Net was developed to improve $K^{\pm}$ purity (50% ⟶ 90%) at high p

To theorists: Why do we measure stronger asymmetries in **Kaon SIDIS** than **Pion SIDIS?**

- Contributions from the K^* ?

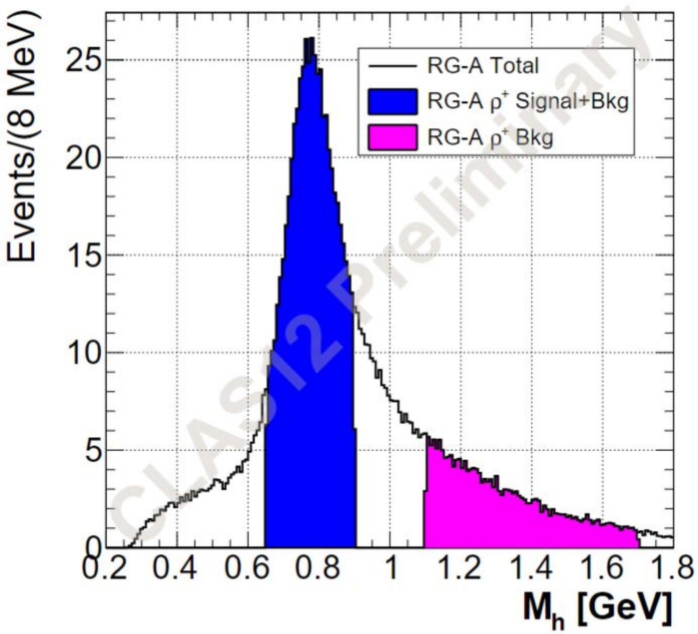
$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h}\left(x_B e H_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M}\left(x_B g^{\perp} D_1 + \frac{M_h}{M} h_1^{\perp} \frac{\tilde{E}}{z}\right)\right],$$

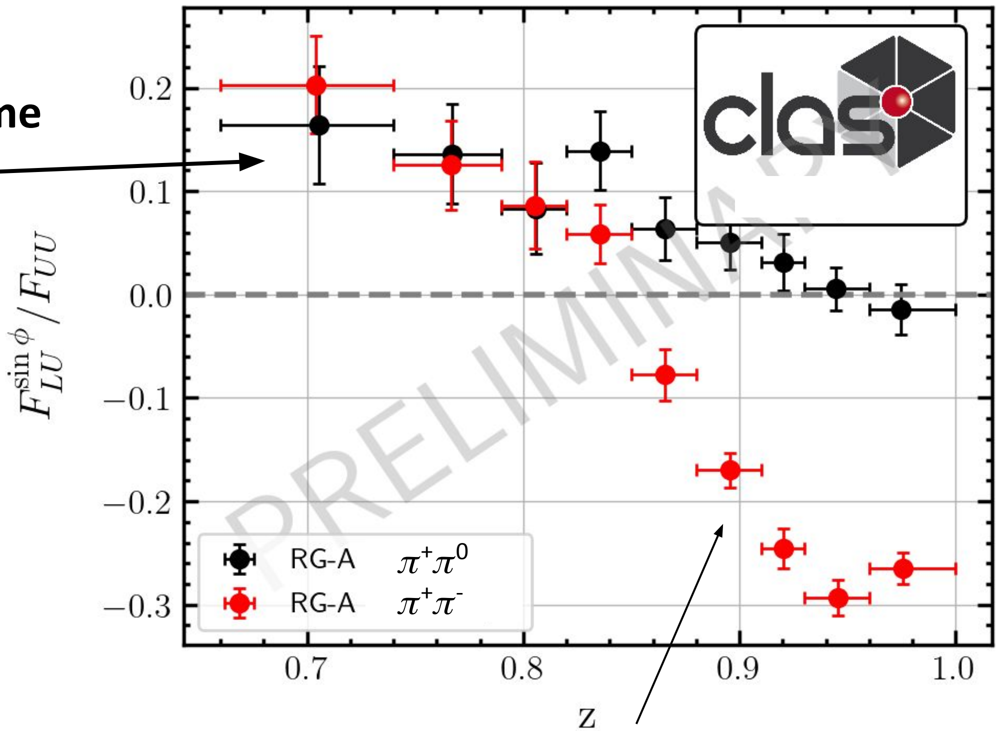


Near-exclusive $\pi^+\pi^-$, $\pi^+\pi^0$ production

★ We can constrain/better understand the contribution of ϱ^0, ϱ^+ decays on our single hadron asymmetries by looking at near-exclusive (M_X < 1.1 GeV) channels

★ Strong yet similar asymmetries observed **(both productions came from struck *u* quark)**





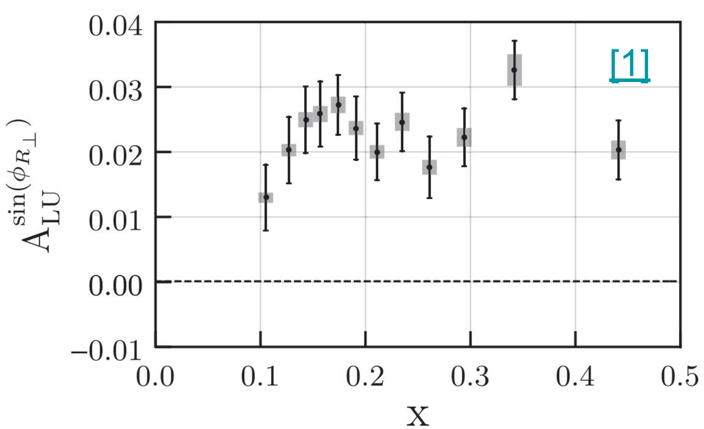
★ Different mechanism for neutral ϱ^0 at high z (low |t|) → GPDs, gluon contributions

Dihadron Production $ep \to e\pi^+\pi^-(X)$

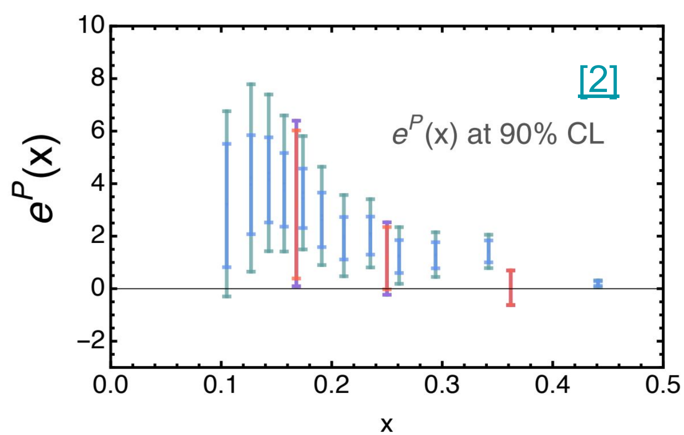
Dihadron BSAs

$$d\sigma_{LU} \propto \left[\frac{M}{M_h} x\, e(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x)\, \widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)\right] \sin\phi_R$$

- ★ Dihadron SIDIS is a clean probe for **twist-3 PDFs** such as **e(x)**
- ★ First point-by-point extraction of a **twist-3 PDF** ever performed was made using **CLAS** data (see below)



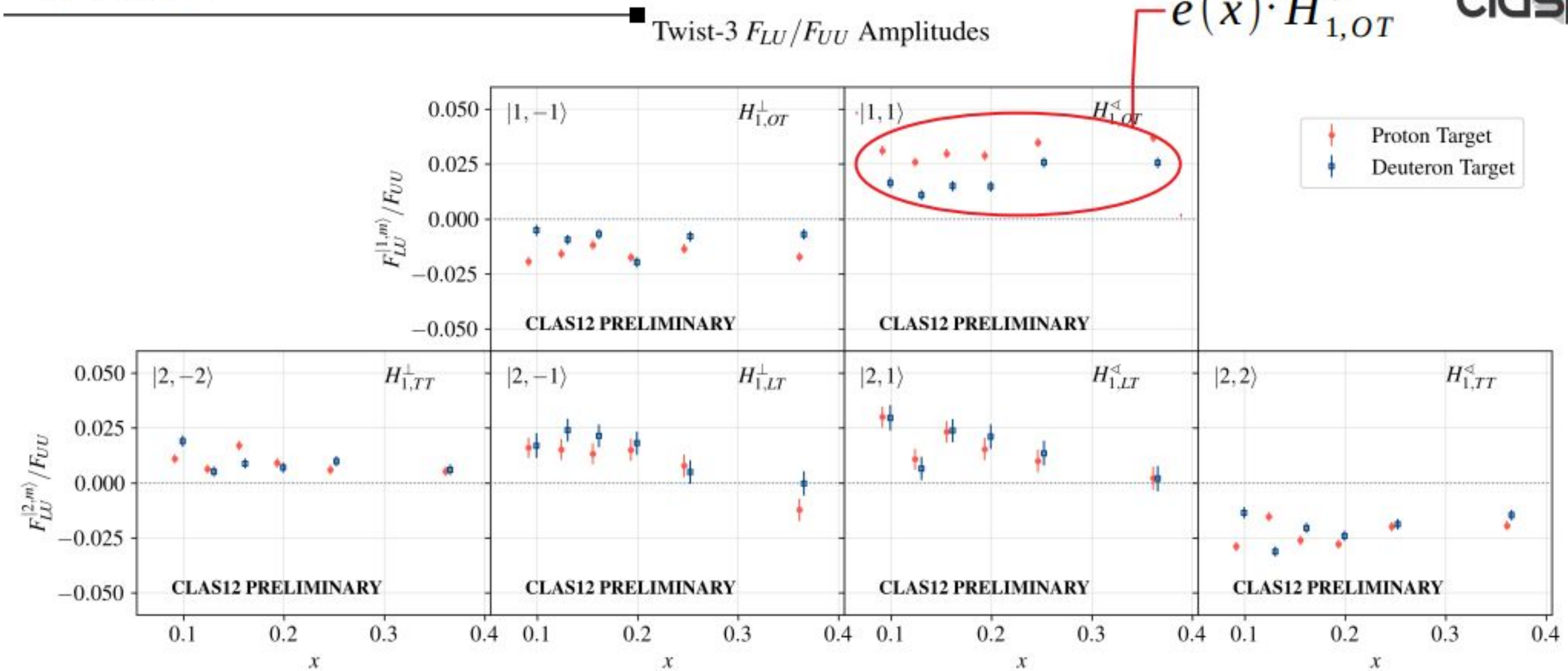
Extraction from **CLAS12** data



But can we do flavor separation? $e^u(x)$? $e^d(x)$?

Dihadron Production $ep \to e\pi^+\pi^-(X)$

x Bins

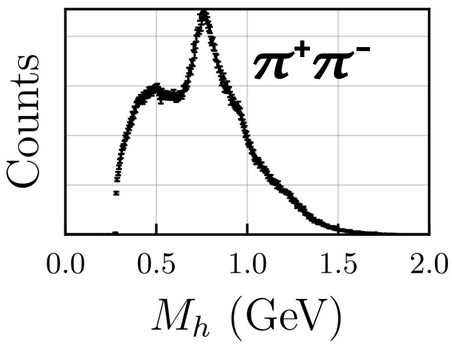


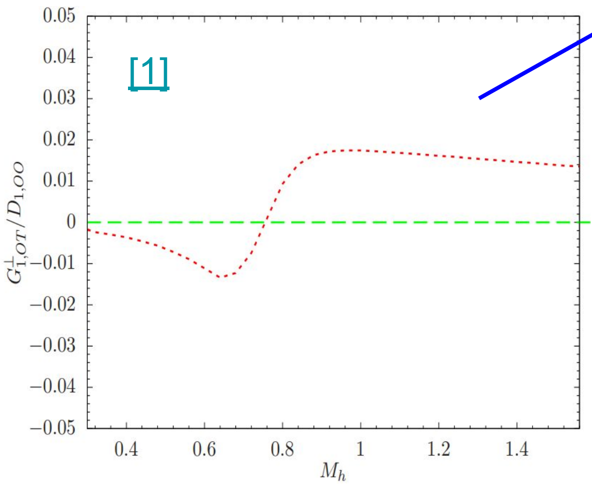
$$A^{|\ell,m\rangle}_{LU,\mathbf{p}} \propto \left(4xe^{u_V} - xe^{d_V}\right) H_1^{\perp|\ell,m\rangle}$$

$$A^{|\ell,m\rangle}_{LU,\mathbf{d}} \propto \left(xe^{u_V} + xe^{d_V}\right) H_1^{\perp|\ell,m\rangle}$$

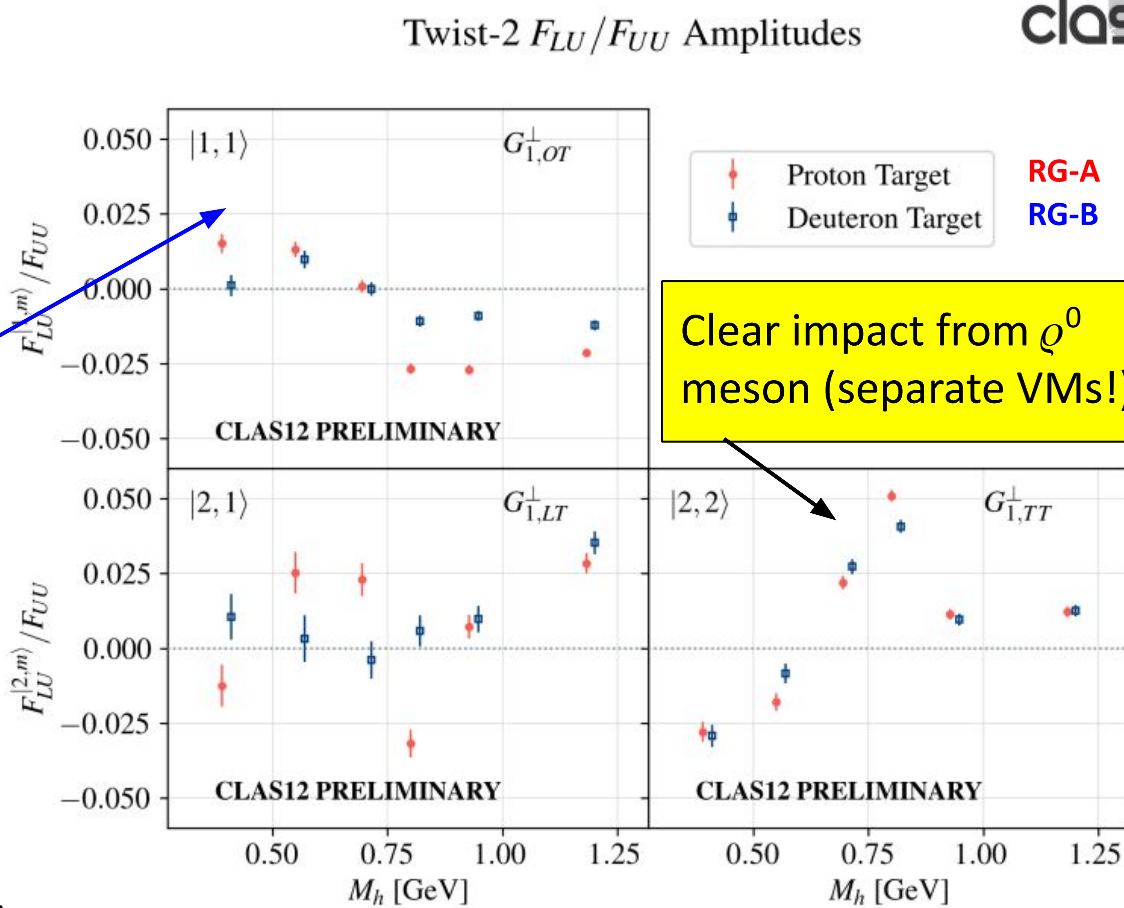
Flavor decomposition of twist-3 PDFs possible with **Run Group A** (ep) and **Run Group B** (ed) datasets at CLAS12

Dihadron Production $ep \rightarrow e\pi^+\pi^-(X)$





Spectator model predictions → observation of DiFF sign change in partial wave decomposition

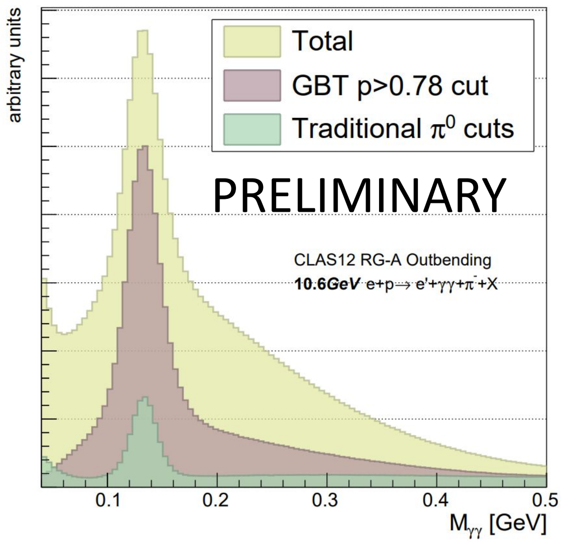


Clear impact from ρ^0 meson (separate VMs!)

Very interesting resonant behavior observed in **Dihadron Fragmentation Functions!** (no 1h analog)

C. Dilks (Transversity 2022)

Dihadron Production ep→e$\pi^{\pm}\pi^{0}$(X)



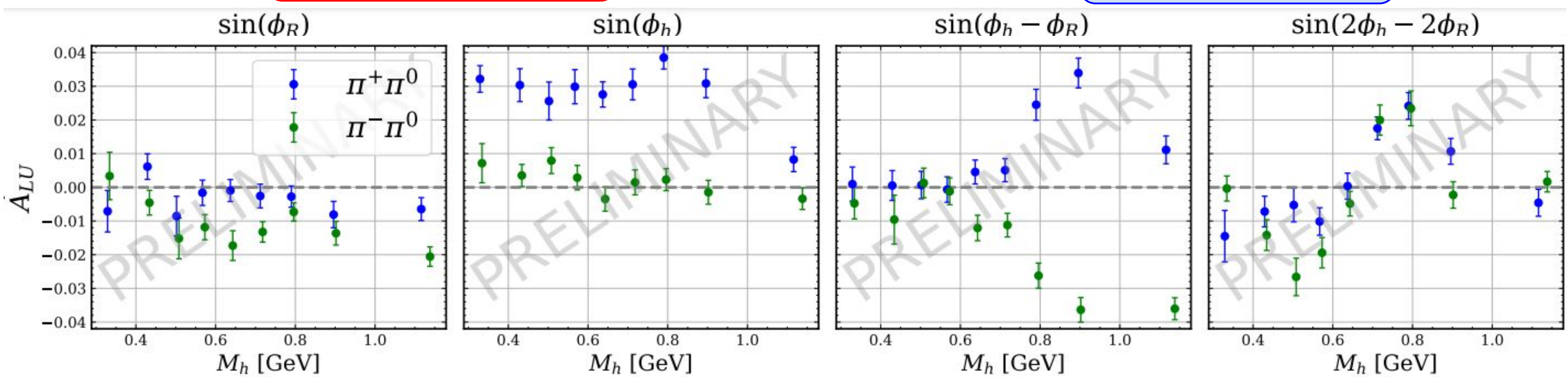
- ★ Nearest-neighbor GBDT model to reduce γ background

- ★ Negative **sin(ϕ_R)** asymmetry for **π-π0** → e(x) extraction
- ★ Strong positive **sin(ϕ_h)** asymmetry for **π+π0** → u quark dominated channels (seen in 1h SIDIS frequently)

- ★ Isospin symmetries of G_1 DiFF observed in **sin(ϕ_h - ϕ_R)**
- ★ Strong enhancement near resonant region

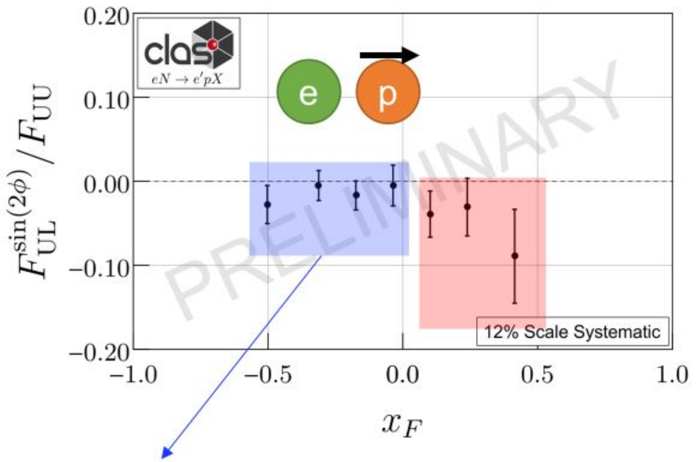
$$e \otimes H_1^{\perp|\ell,m>}$$

$$f_1 \otimes G_1^{\perp|\ell,m>}$$



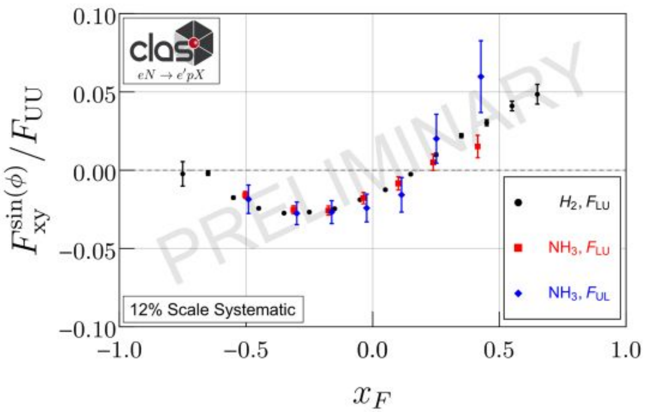
Preliminary Analysis: **Fracture Functions**

$$ep \rightarrow e'p\,X$$



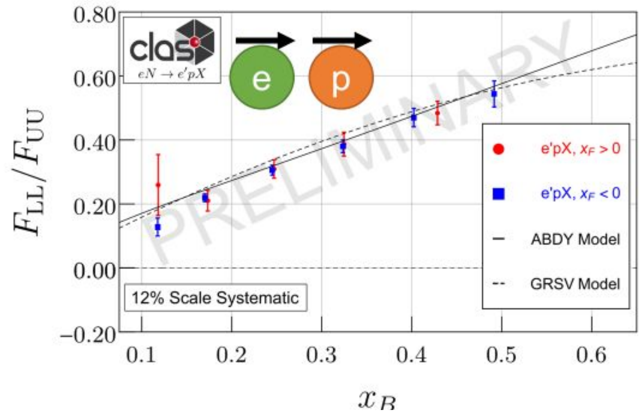
No Collins mechanism in **TFR** → $F_{UL}^{\sin 2\phi} \approx 0$

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



Visible separation between TFR ($x_F < 0$) and CFR ($x_F > 0$) contributions

Minimal nuclear medium modification

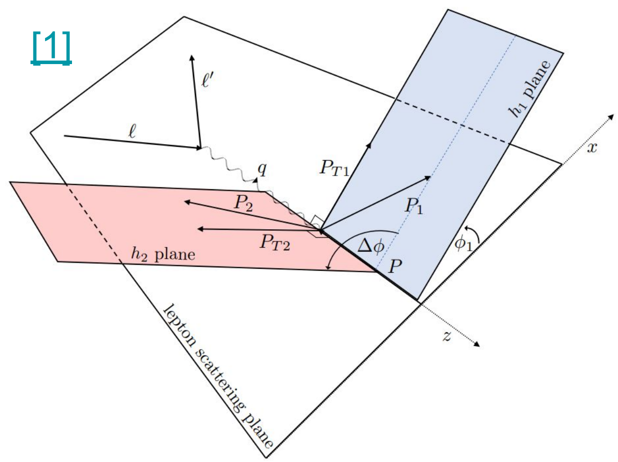


TFR Access to helicity distribution g_{1L}

$$A_{LL} = \lambda_\ell S_L \frac{\sqrt{1-\epsilon^2}F_{LL}}{F_{UU,T}}$$

Full processing of Run Group C (**longitudinally polarized target**) is underway! Expect more SIDIS results from them soon!

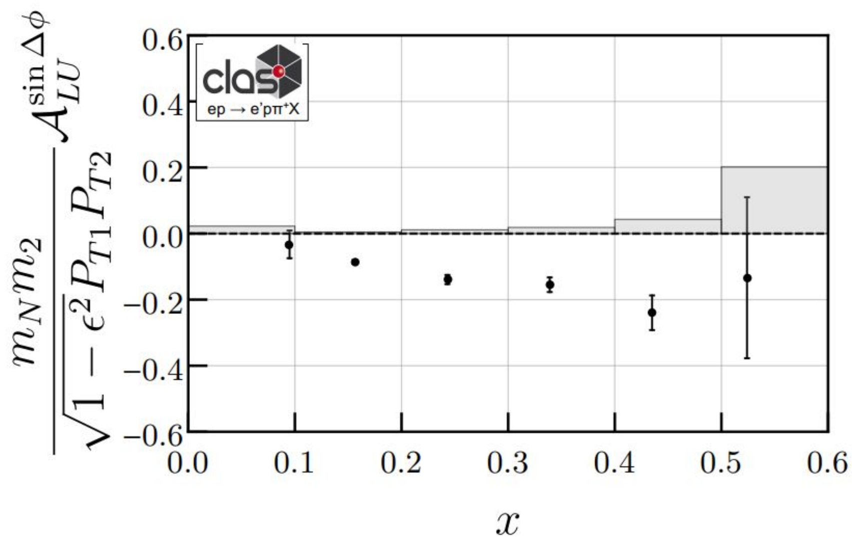
Back-to-Back Dihadrons ep→epπ^+(X)



Single π^+ from struck quark fragmentation ($x_F > 0$)
Single p from target breakup ($x_F < 0$)

★ **Fracture Functions** for the **TFR**
★ **Fragmentation Functions** for the **CFR**

$$\mathcal{A}_{LU} = -\sqrt{1-\epsilon^2}\,\frac{|\vec{P}_{T1}||\vec{P}_{T2}|}{m_N\, m_2}\,\frac{\mathcal{C}[w_5\,\hat{l}_1^{\perp h}\,D_1]}{\mathcal{C}[\hat{u}_1\,D_1]}\sin\Delta\phi.$$



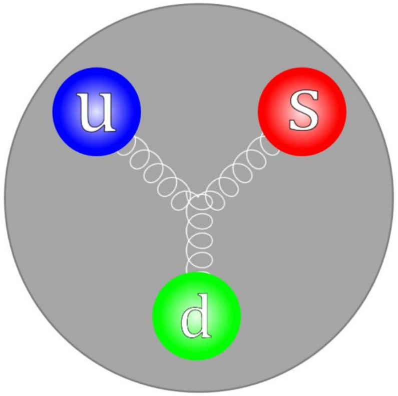
Long-range correlations between current/target breakup is more prominent in valence region

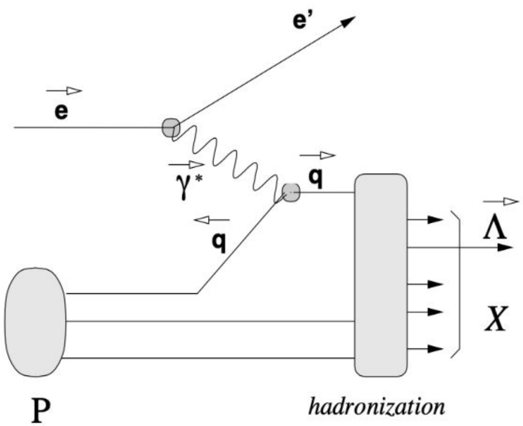
Future Studies (M. McEneaney):

Correlations between **TFR Λ's** and **CFR hadrons (π, K).** Study strangeness in the already under-explored fracture function formalism.

Lambdas: The quark polarimeter

- ★ **Constituent Quark Model (CQM)** [1]
  - ○ Predicts s quark carries 100% of the Λ hyperon spin
- ★ "Do polarized u-quarks from current fragmentation transfer their longitudinal spin to the lambda?" → Test spin structure

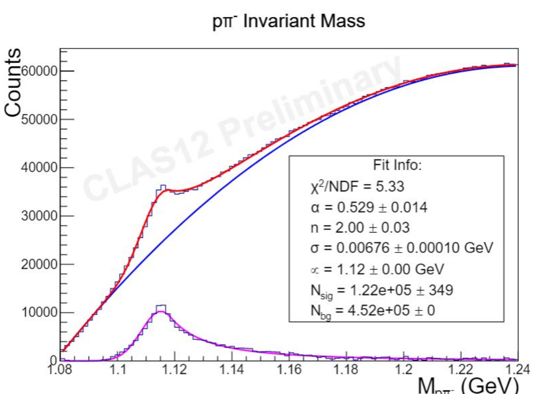




$$P_\Lambda = P_b D(y) D^{\Lambda}_{LL'},$$

Polarization of Λ depends on longitudinal spin-transfer from struck quark (w/ beam pol + depolarization)

- ★ **Domain Adversarial GNNs** developed to identify events as containing a Λ → reduction of backgrounds



Preliminary Helicity Balance

$\cos\theta_{pL'}$ along $\vec{p_\Lambda}$	$\cos\theta_{pL'}$ along $\vec{p_\gamma}$
0.0618 ± 0.0963	0.118 ± 0.107

Most precise measurement to date!

D_{LL} results consistent with HERMES and NOMAD

Summary

★ High luminosity, high beam polarization fixed-target program, pushing the frontier of valence region physics and hadronization

★ Active community. Looking into many channels + multidimensional

- Capable of probing current and target fragmentation
- Broadening our interpretation of single hadron SIDIS results (ex: higher twist effects) through dihadron/vector meson channels

★ **"In the Works"/Future Experiments** → Longitudinally (Run Group C) + Transversely polarized targets (Run Group H)

★ Many more results to come soon! Stay tuned!

Extra Slides

$\gamma p \rightarrow h_1 h_2 X$ Dihadron SIDIS Observables

★ Traces of the fragmentation correlator produce *infinite* number of dihadron fragmentation functions (DiFFs) [1]

- $h_1 h_2$ produced in relative $|\ell, m\rangle$ states, interfere in amplitude →

$$D_1 = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\vartheta) \cos\left(m\left(\phi_{R_\perp} - \phi_p\right)\right) D_1^{|\ell,m\rangle}(z, M_h, |\boldsymbol{p}_T|),$$

$$G_1 = \sum_{\ell=1}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\vartheta) \sin\left(m\left(\phi_{R_\perp} - \phi_p\right)\right) G_1^{|\ell,m\rangle}(z, M_h, |\boldsymbol{p}_T|),$$

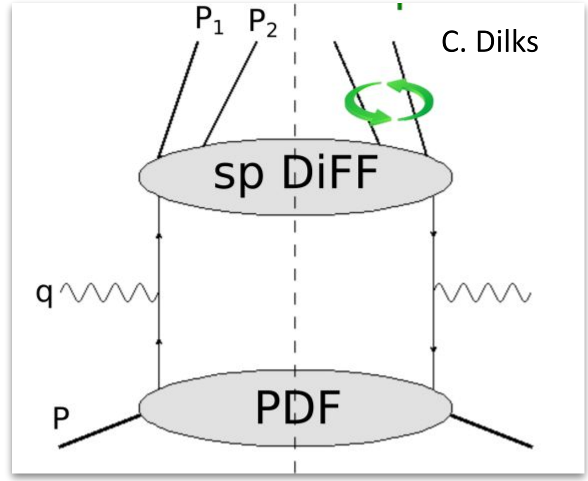
$$H_1^\perp = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\vartheta)\, e^{im\left(\phi_{R_\perp} - \phi_p\right)}\, H_1^{\perp|\ell,m\rangle}(z, M_h, |\boldsymbol{p}_T|)\ ,$$

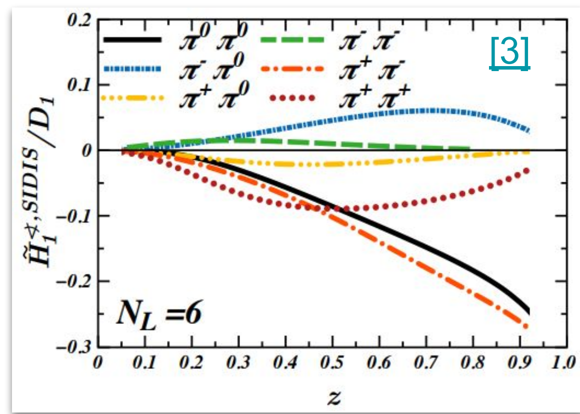
★ Structure functions allow for more *targeted extraction* of twist-3 PDFs like $e(x)$ [2]

- CLAS12 flavor separation! **Proton** vs. **Deuteron** targets

$$A_{LU,\mathbf{p}}^{\text{twist }3} \propto 4xe^{u_V}(x) - xe^{d_V}(x)$$

$$A_{LU,\mathbf{d}}^{\text{twist }3} \propto xe^{u_V}(x) + xe^{d_V}(x)$$





Test theoretical modeling of DiFFs with isospin symmetries

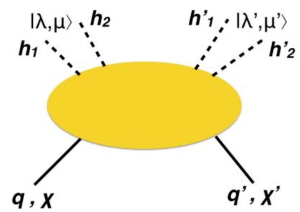
$\gamma p \rightarrow h_1 h_2 X$ Dihadron SIDIS Observables

At CLAS12 energies (ℓ_{max} = 2) and by integrating over the partial wave θ one can arrive at 7 distinct modulations

$$d\sigma_{LU} \propto \lambda_e \left[\sum_{m=1}^{2}\left(A_{LU}^{\sin(m(\phi_h-\phi_{R_\perp}))}\sin(m(\phi_h-\phi_{R_\perp}))\right) + \sum_{m=-2}^{2}\left(A_{LU}^{\sin((1-m)\phi_h+m\phi_{R_\perp})}\sin((1-m)\phi_h+m\phi_{R_\perp})\right)\right]$$

Twist-2

2 modulations



Twist-3

5 modulations

Sensitive to $f_1 \otimes G_1^{\perp|\ell,m>}$

f_1 → Unpolarized Parton distribution function

G_1 → Dihadron fragmentation function sensitive to the longitudinal spin of the fragmenting quark

★ Has no 1h SIDIS counterpart ★

★ Interference of T-polarized dihadron with U,L or T in amplitude ★

Sensitive to $e \otimes H_1^{\perp|\ell,m>}$

e → Twist-3 collinear PDF (transversely polarized quarks in unpolarized proton)

H_1 → Dihadron fragmentation function sensitive to the transverse spin of the fragmenting quark

★ Interference of U,L,T polarized dihadron with U,L or T in amplitude ★

Dihadron Cross Section

$$d\sigma_{LU} = \frac{\alpha^2}{4\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right)\lambda_e$$
$$\times \sum_{\ell=0}^{\ell_{\max}} \Bigg\{ C(x,y)\sum_{m=1}^{\ell}\left[P_{\ell,m}\sin(m(\phi_h-\phi_{R_\perp}))\,2\,\underline{\left(F_{LU,T}^{P_{\ell,m}\cos(m(\phi_h-\phi_{R_\perp}))}+\epsilon F_{LU,L}^{P_{\ell,m}\cos(m(\phi_h-\phi_{R_\perp}))}\right)}\right]$$
$$+\,W(x,y)\sum_{m=-\ell}^{\ell}P_{\ell,m}\sin((1-m)\phi_h+m\phi_{R_\perp})\underline{F_{LU}^{P_{\ell,m}\sin((1-m)\phi_h+m\phi_{R_\perp})}}\Bigg\}\,.$$

$$\boxed{F_{LU}^{P_{\ell,m}\sin((1-m)\phi_h+m\phi_{R_\perp})}} = \frac{2M}{Q}\mathcal{I}\Bigg[-\frac{|\boldsymbol{p}_T|}{M_h}\cos\left((1-m)\left(\phi_p-\phi_h\right)\right)$$
$$\times\left(xe\,H_1^{\perp|\ell,m\rangle}+\frac{M_h}{M}f_1\frac{\tilde{G}^{\perp|\ell,m\rangle}}{z}\right)$$
$$+\frac{|\boldsymbol{k}_T|}{M}\cos\left((m-1)\phi_h+\phi_k-m\phi_p\right)$$
$$\times\left(xg^\perp D_1^{|\ell,m\rangle}+\frac{M_h}{M}h_1^\perp\frac{\tilde{E}^{|\ell,m\rangle}}{z}\right)\Bigg]\,.$$

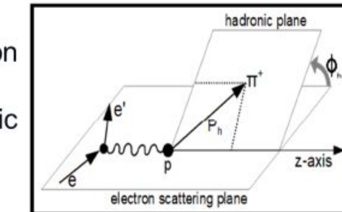
$$\boxed{F_{LU,L}^{P_{\ell,m}\sin(m(\phi_h-\phi_{R_\perp}))}} = 0\,,$$
$$\boxed{F_{LU,T}^{P_{\ell,m}\sin(m(\phi_h-\phi_{R_\perp}))}} = -\mathcal{I}\left[2\cos\left(m(\phi_h-\phi_p)\right)f_1 G_1^{|\ell,m\rangle}\right]\,,$$

Unpolarized Modulations of ep→eπ^+(X)

Measurements of the Cosϕ_h and Cos2ϕ_h Moments of the Unpolarized SIDIS π+ Cross-section at CLAS12

Richard Capobianco
(UCONN/Argonne)

- Working towards the extraction of the cos(ϕ_h) and cos(2ϕ_h) moments of unpolarized SIDIS cross-section for charged pions using RG-A data
- The collected statistics enable a high-precision study of these azimuthal moments which probe the Boer-Mulders function and Cahn effect
- The high statistics data will, for the first time, enable a multidimensional analysis of both moments over a large kinematic range of Q^2, y, z, and P_T.
- Current Ongoing Objectives:
  - ➢ Complete the switch to using Pass 2 version of data
  - ➢ Introduce Radiative Effects into my Monte Carlo Simulation
  - ➢ Complete the Multidimensional (5D) Unfolding Acceptance Corrections
    - Have performed up to 3D unfolding of z, P_T, and ϕ_h in different Q^2-y Bins
    - Investigating residual modulations after corrections that might not be related to the cos(ϕ_h) and cos(2ϕ_h) moments



Reaction Studied: ep→eπ^+(X)

The lepton-hadron Unpolarized SIDIS Cross-Section:

$$\frac{d^5\sigma}{dy\,dQ^2\,dz\,d\phi_h\,dP_{h\perp}^2} = \underbrace{\frac{x_B}{y}\frac{2\pi\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)(F_{UU,T}+\epsilon F_{UU,L})}_{A_0}\left\{1+\underbrace{\frac{\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos\phi_h}}\cos\phi_h+\underbrace{\frac{\epsilon F_{UU}^{\cos 2\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\right\}$$

The Boer-Mulders and Cahn effects are present in the Structure Functions:

leading twist

$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}h_1^\perp H_1^\perp+\ldots\right]$$

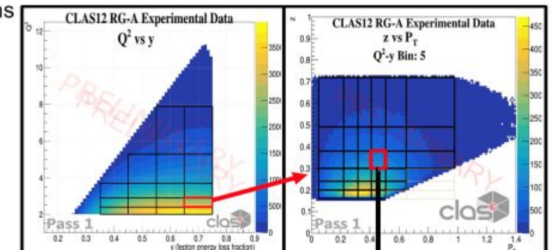
next to leading twist

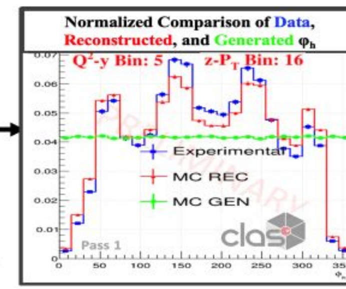
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M_h}x\,h\,H_1^\perp-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M}f_1D_1+\ldots\right]$$

BOER-MULDERS EFFECT

CAHN EFFECT

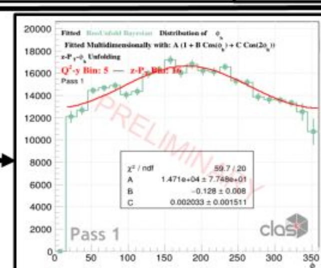
Interaction dependent terms neglected





Reconstructed

Unfolded (Example)



Unfold the data using Simulated and Experimental data and fit the new distribution with the function:
$A(1+B\cos\phi_h+C\cos 2\phi_h)$
Where A, B, and C will then be used to calculate the azimuthal moments from the cross-section equation

Do for every Q^2-y and z-P_T bin to get A, B, and C as functions of all 4 variables

Link to latest Analysis Note: https://clas12-docdb.jlab.org/cgi-bin/DocDB/private/ShowDocument?docid=1017

Unpolarized Cross Section of ep→eπ^0(X)

SIDIS MULTIPLICITIES

- **Goal**
  - Measure neutral pion multiplicities

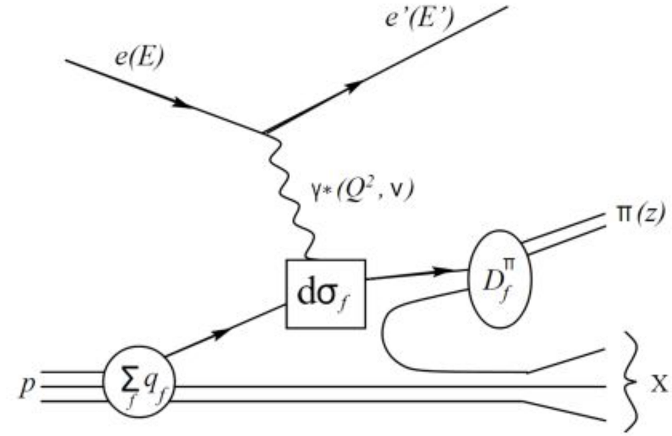
$$M_h = \frac{d\sigma^h}{dx dQ^2 dz dp_T^2} \Big/ \frac{d\sigma^{DIS}}{dx dQ^2}$$

  - Related to the non-perturbative proton structure, i.e., PDFs and FFs

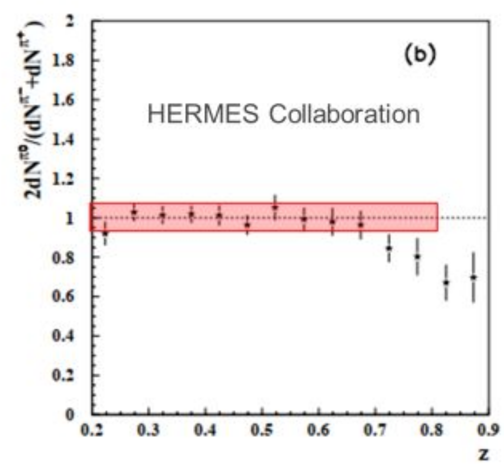
$$\sigma^{\pi^0} \approx \sigma^{DIS} \otimes f^p(x, Q^2) \otimes D^{p\to\pi^0}(z, Q^2)$$

  - Connected to charged pion multiplicities

$$D_1^{\pi^0/q} = \frac{1}{2}\left(D_1^{\pi^+/q} + D_1^{\pi^-/q}\right)$$



https://doi.org/10.1007/s100520100765



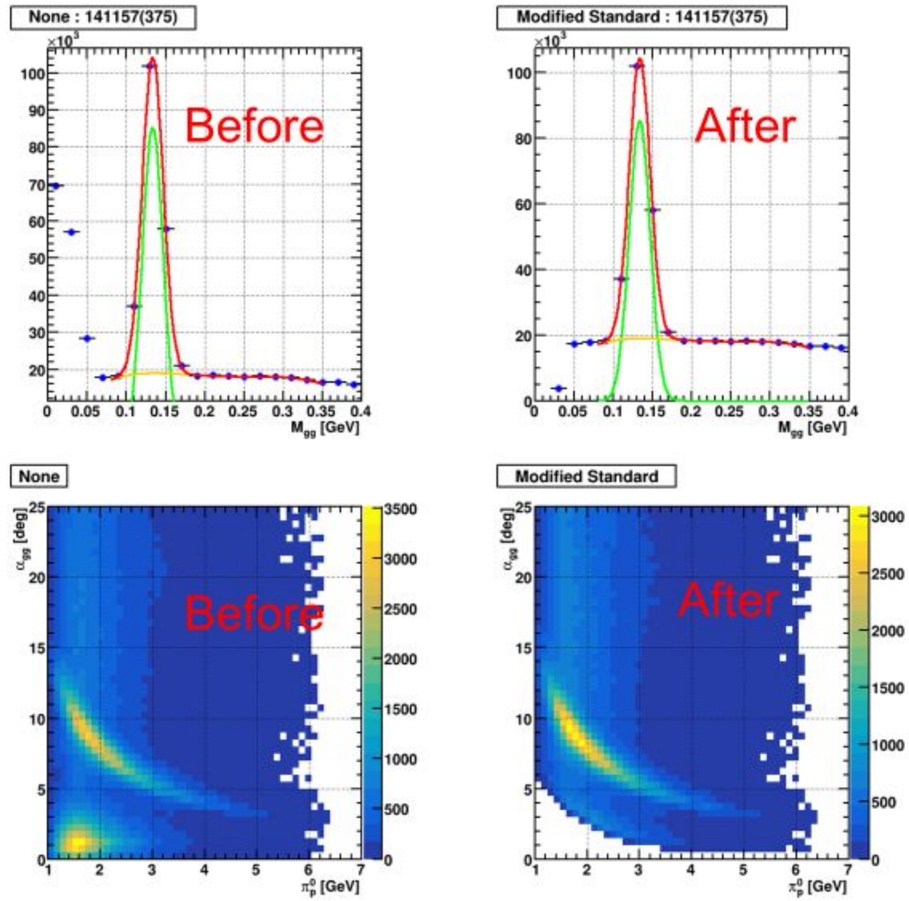
https://doi.org/10.1007/s100520100765

ENERGY Jefferson Lab 3 M. B. C. Scott Argonne

Unpolarized Cross Section of $ep \to e\pi^0(X)$

SELECTION CUTS FOR NEUTRAL PIONS

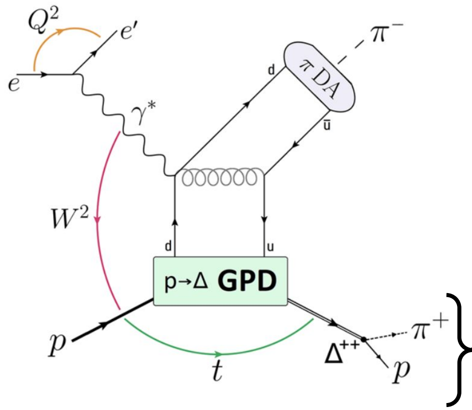
- π^0 candidates are reconstructed from photon pairs.
- The resulting invariant mass distribution shows a characteristic peak around the π^0 mass of 0.135 GeV.
- **Cuts**
  - $x_F > 0$ [$x_F = 2P_{h,L}/\sqrt{s}$] : current fragmentation region
  - $M_x > 1.5$ GeV [$M_x = |q + P - P_h|$] : remove exclusive events
  - $\alpha_{\gamma\gamma} > 6 \cdot \mathrm{Exp}(1 - p_\pi) + 0.5$ deg : background removal

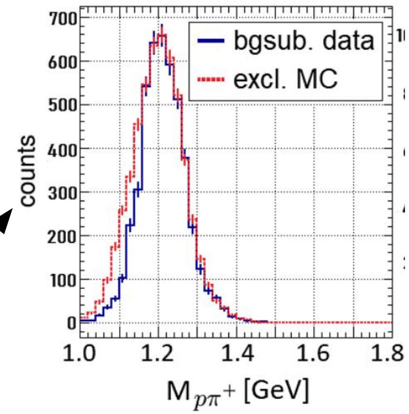


ENERGY Jefferson Lab 8 M. B. C. Scott Argonne

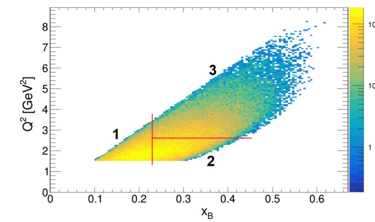
Exclusive Measurements off Proton (RG-A)

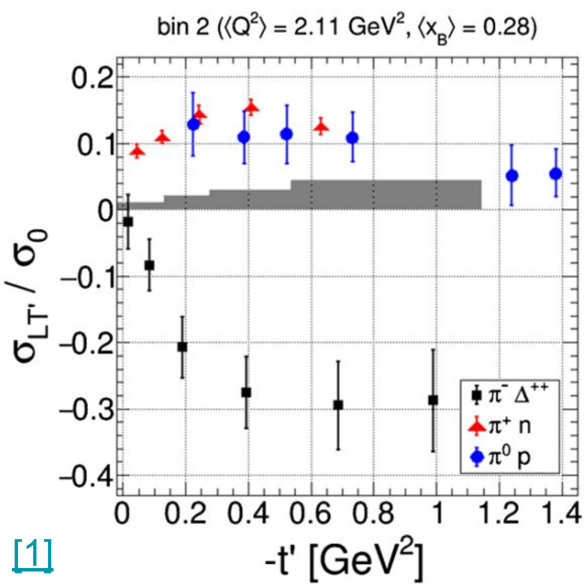
★ How do we know our π^- comes from struck *d* quark? … Exclusive $ep \to e\pi^-\Delta^{++}$! ★





Very clean polarized *d* probe, can be compared with similar baryon resonances (bottom left)





[1]

Observe nearly ***double*** the BSA for **struck *d*** than **struck *u***

Need to turn to transition GPDs for explanation

Positive BSAs for **struck *u*** channels is a hallmark in several other SIDIS analyses…

$\pi^-\Delta^{++}$ → Struck longitudinally polarized *d* quark

π^+n → Struck longitudinally polarized *u* quark

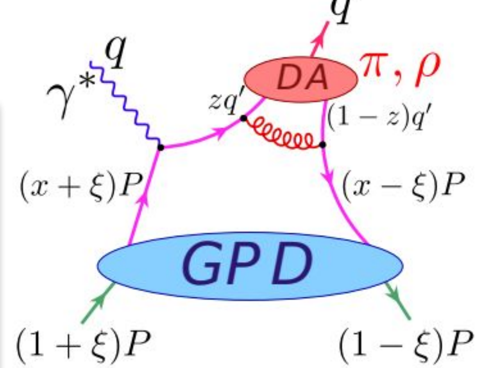
π^0p → Struck longitudinally polarized *u*/*d* quark

Exclusive ρ^0, ρ^+ production

★ DVCS only sensitive to *chiral-even* GPDs → DVMP a probe for T. polarized quarks

$$\frac{2\pi}{\Gamma(Q^2,x_B,E)}\frac{d^4\sigma}{dQ^2dx_Bdtd\phi} = \sigma_0\left[1 + A_{TT}^{\cos 2\phi}\cos 2\phi + A_{LT}^{\cos\phi}\cos\phi + \boxed{P_b A_{LU}\sin\phi}\right]$$

[1]



$$\begin{aligned}\mathcal{A}_{\rho^0} : \mathcal{A}_{\rho^+} : \mathcal{A}_{\rho^-} = & \int_{-1}^{1}\frac{dx}{\xi - x - i\epsilon}\left(\frac{2\boxed{F^{u(+)}}+\boxed{F^{d(+)}}}{\sqrt{2}} + \frac{9}{8\sqrt{2}}\frac{\boxed{F^g}}{x}\right)\\ : & \int_{-1}^{1}\frac{dx}{\xi - x - i\epsilon}\left(\frac{\boxed{F^{u(+)}}-\boxed{F^{d(+)}}}{2} + \frac{\boxed{3F^{u(-)}-3F^{d(-)}}}{2}\right)\\ : & \int_{-1}^{1}\frac{dx}{\xi - x - i\epsilon}\left(\frac{\boxed{F^{u(+)}}-\boxed{F^{d(+)}}}{2} - \frac{\boxed{3F^{u(-)}-3F^{d(-)}}}{2}\right).\end{aligned}$$

[2]

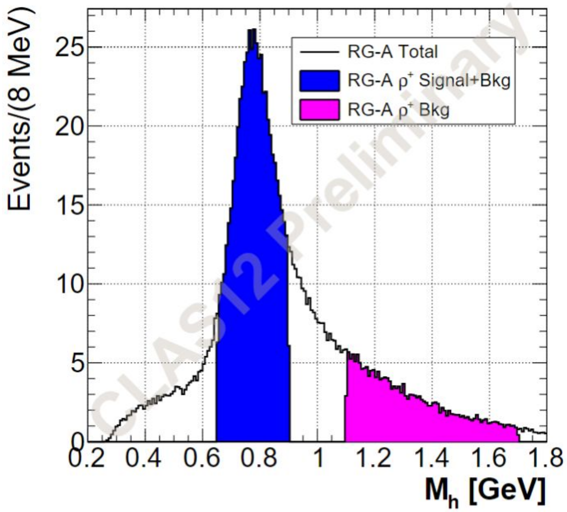
N/q	U	L	T
U	H	x	$\mathcal{E}_T$
L	x	$\tilde{H}$	x
T	E	x	H_T,$\tilde{H}_T$

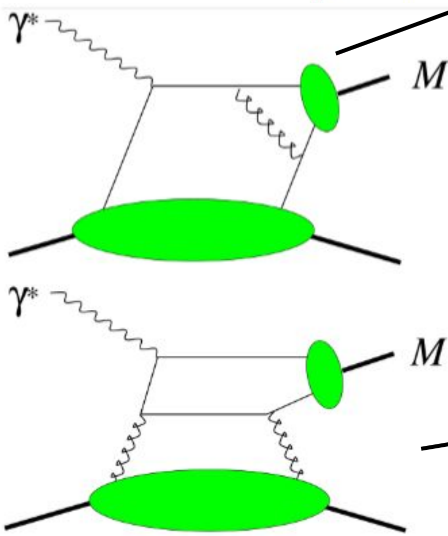
- Isospin symmetries let us build ratios between vector meson amplitudes in terms of the generalized parton distributions (within $F^{q/g}$'s)
- In combination with the ratios for $\rho^0 : \omega$, one can decouple the 4 separate components… $F^{u(+)}$ $F^{d(+)}$ F^g $F^{u(-)} - F^{d(-)}$
- Gives prediction of relative multiplicities (assuming $F^u = 2F^d$)
  - $d\sigma(\rho^0) / d\sigma(\omega) \sim 25/9$
  - $d\sigma(\rho^{+/-}) / d\sigma(\rho^0) < 1$

[3]

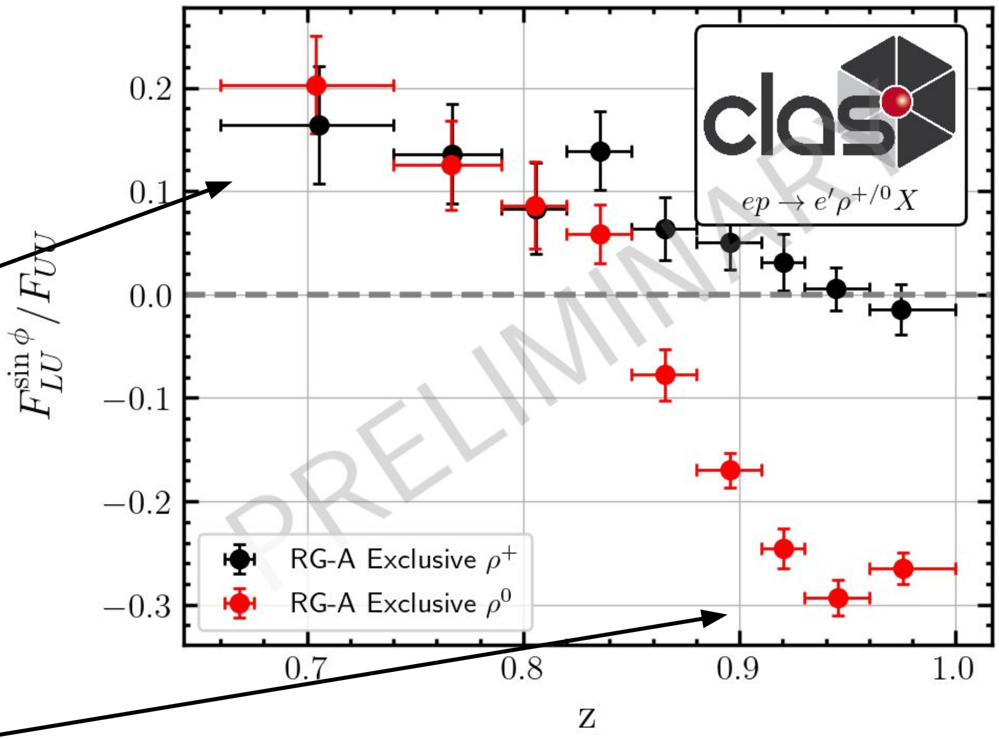
$$A_{LU} \sim [H_T E - E_T H]$$

Exclusive ϱ^0, ϱ^+ production





- ★ Sideband subtraction utilized to isolate the beam spin asymmetries of the resonance (ϱ^0, ϱ^+)

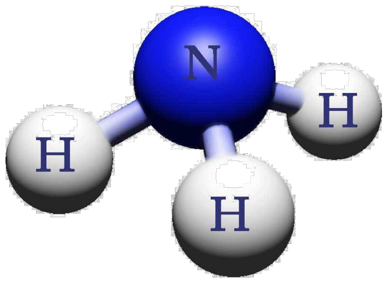


- ★ CLAS can measure all final state in exclusive production (ϱ, ω, ϕ, π^0 …)

Run Group C @ CLAS12

★ 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**
- ~27mC combined polarized target data @ 85% e^- polarization (10.5 GeV)
- Target raster, live-NMR, 2/6 RICH sectors

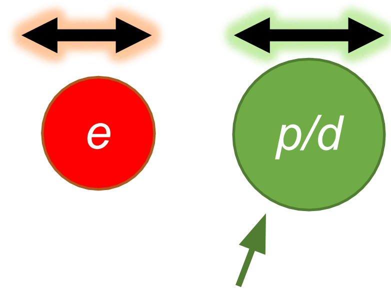


Physics Goals

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.



Polarization configurable run-by-run