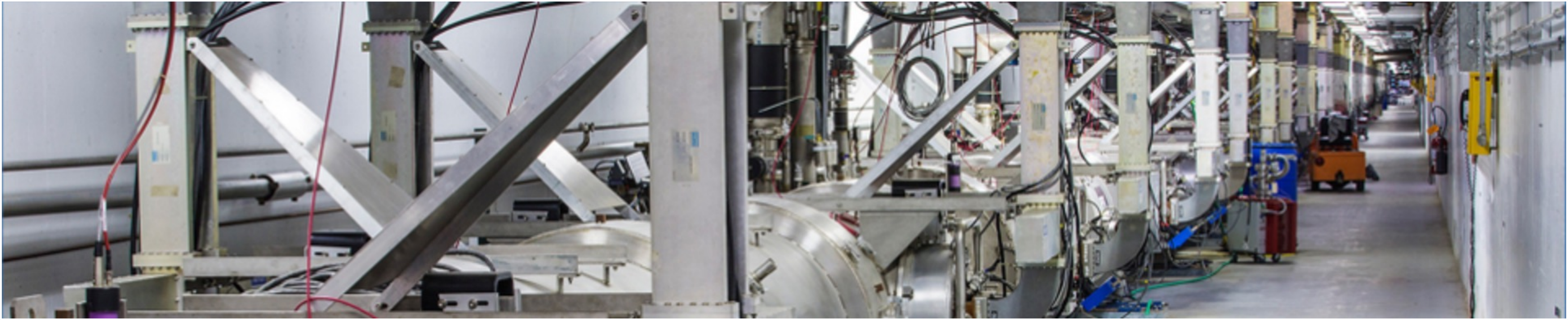
Accessing Target Fragmentation:

Prospects and Results from CLAS12(22)

Timothy B. Hayward



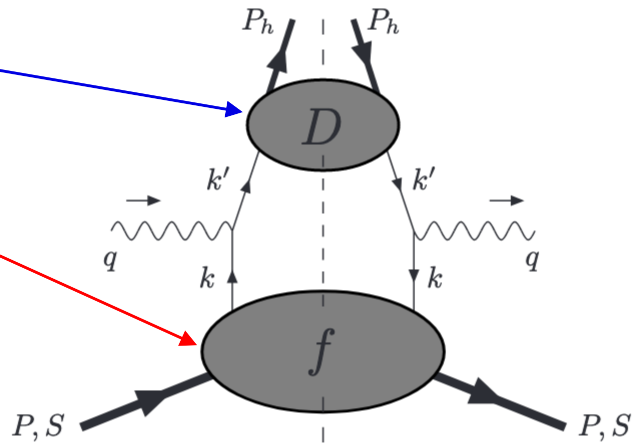
July 20, 2022

Traditional SIDIS measurements

- Decades of study have led to detailed mappings of the momentum distribution of partons in the nucleon in terms of 1-D and 3-D (TMD) parton distribution functions (PDFs).
- SIDIS measurements rely on the assumption that measured hadrons are produced in the CFR.
- Cross section factorized as a convolution of PDFs and Fragmentation Functions (FFs)[1].

$$\frac{\mathrm{d}\sigma^{\mathrm{CFR}}}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}z_h} = \sum_a e_a^2\,\boxed{f_a(x_B)}\,\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}y}\,\boxed{D_a(z_h)}$$

- PDFs
  - Confined motion of quarks and gluons inside the nucleus
  - Orbital motion of quarks, correlations between quarks and gluons
- Fragmentation Functions
  - Probability for a quark to form particular final state particles
  - Insight into transverse momenta and polarization



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

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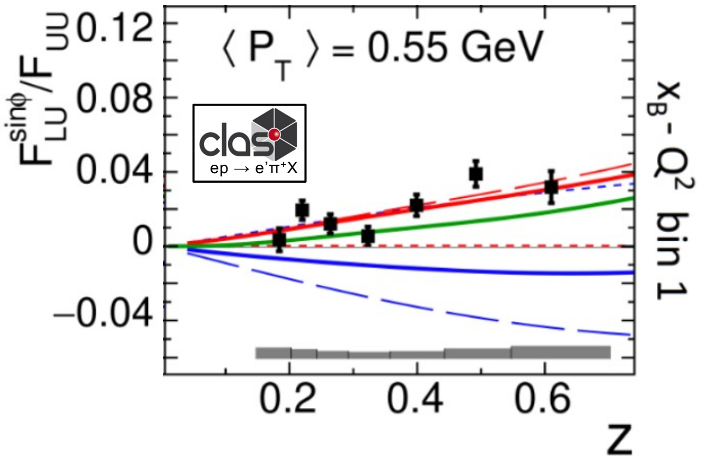
1. A. Bacchetta et al., JHEP 02 (2007) 093 [hep-ph] 0611265,

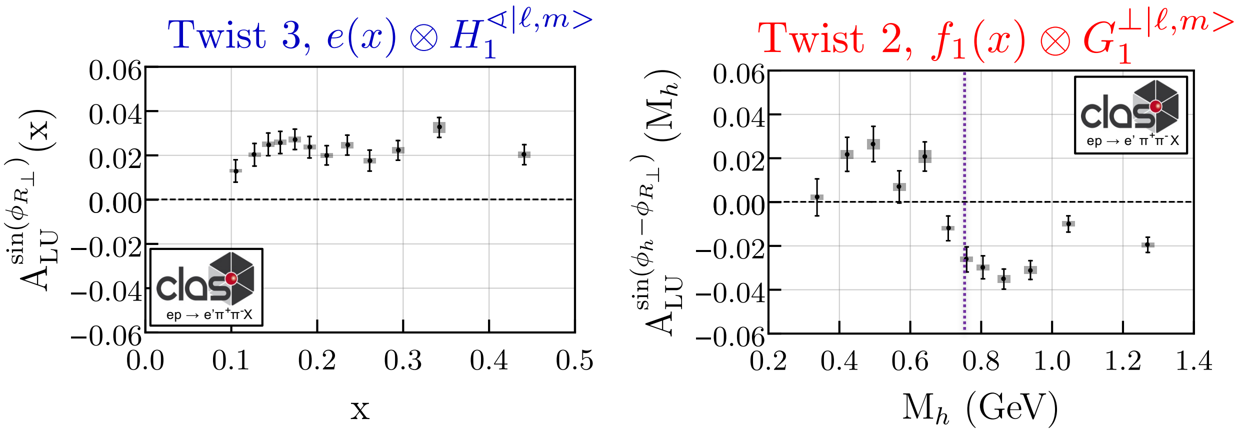
CFR Sensitive CLAS12 Measurements

- Measurements traditionally focus on factorization theorems and assumption that **hadrons are produced in current fragmentation.**

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{h}\cdot p_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$



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


Twist 3, $e(x) \otimes H_1^{\sphericalangle|\ell,m>}$

Twist 2, $f_1(x) \otimes G_1^{\perp|\ell,m>}$

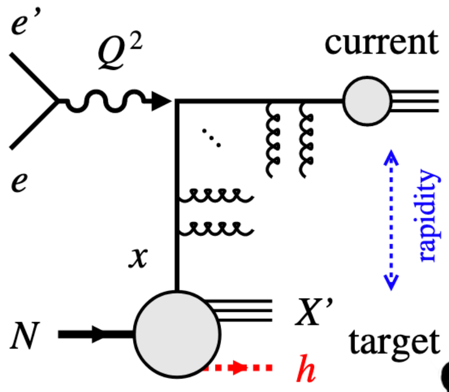
T. B. Hayward et al., *Phys. Rev. Lett.*, 126, 152501, (2021), [hep:ex] 2101.04842

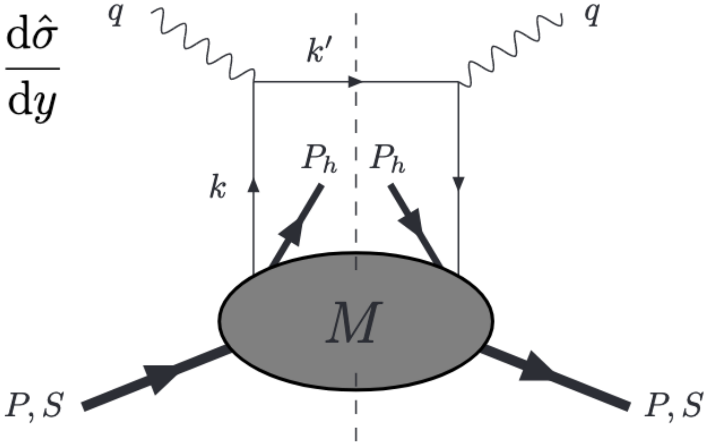
UCONN

The Neglected Hemisphere – Target Fragmentation

- Final state hadrons also form from the left-over target remnant (TFR) whose partonic structure is defined by “fracture functions”[1,2]: the probability for the target remnant to form a certain hadron given a particular ejected quark.
- In the TFR, factorization into x and z does not hold because it is not possible to separate quark emission from hadron production.

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





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

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1. L. Trentadue and G. Veneziano, Phys. Lett. B323 (1994) 201,
2. M. Anselmino et al., Phys. Lett. B. 699 (2011), 108-118, [hep-ph] 1102.4214
3. TFR/CFR Fig. from EIC Yellow Report, (2021) [physics.ins-det] 2103.05419

Potential Ambiguities

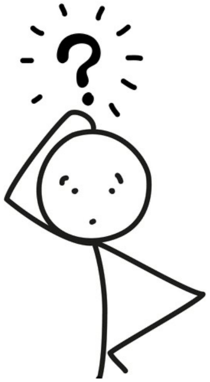
$$\frac{\mathrm{d}\sigma^{\mathrm{TFR}}}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}\zeta\,\mathrm{d}^2\boldsymbol{P}_{h\perp}\,\mathrm{d}\phi_S} = \frac{2\alpha_{\mathrm{em}}^2}{Q^2 y}\left\{\left(1-y+\frac{y^2}{2}\right)\right. \times \sum_a e_a^2\left[\hat{u}_1(x_B,\zeta,\boldsymbol{P}_{h\perp}^2) - |\boldsymbol{S}_\perp|\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,\hat{u}_{1T}^\perp(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)\,\boxed{\sin(\phi_h-\phi_S)}\right] + \lambda_l\,y\left(1-\frac{y}{2}\right)\sum_a e_a^2\left[S_\parallel\;\hat{l}_{1L}\;(x_B,\zeta,\boldsymbol{P}_{h\perp}^2) + |\boldsymbol{S}_\perp|\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\;\hat{l}_{1T}^\perp\;(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)\,\boxed{\cos(\phi_h-\phi_S)}\right]\left.\right\}.$$

M. Anselmino et al., Phys. Lett. B. 699 (2011), 108-118, [hep-ph] 1102.4214

$$\boxed{\begin{aligned}\left[F_{UT,T}^{\sin(\phi_h-\phi_S)}\right]_{\mathrm{TFR}} &= -\sum_a e_a^2\,x_B\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\hat{u}_{1T}^\perp(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)\\ \left[F_{UT,T}^{\sin(\phi_h-\phi_S)}\right]_{\mathrm{CFR}} &= \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\perp}{m_N}\,f_{1T}^\perp\,D_1\right]\end{aligned}}$$

$$\boxed{\begin{aligned}\left[F_{LT}^{\cos(\phi_h-\phi_S)}\right]_{\mathrm{TFR}} &= \sum_a e_a^2\,x_B\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\;\hat{l}_{1T}^\perp\;(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)\\ \left[F_{LT}^{\cos(\phi_h-\phi_S)}\right]_{\mathrm{CFR}} &= \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\perp}{m_N}\,g_{1T}\,D_1\right]\end{aligned}}$$

The same azimuthal asymmetries can appear in both the CFR and TFR complicating their interpretation…



… six more azimuthal asymmetries appear in the CFR at leading twist which are absent in the TFR.

Categorizing Fracture Functions

- At leading twist fracture functions exist that can be organized into tables of quark and nucleon polarizations just like the more familiar PDFs.
- Access to *both* k_T and p_T effects gives 2 x 8 = 16 FrFs.

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

CFR ⟷ TFR

Nucleon polarization	Quark polarization		
	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

Analogs to PDFs

- A direct relationship exists to the eight leading twist PDFs after the fracture functions are integrated over the fractional longitudinal nucleon momentum.

$$z(1-x) = \boxed{E_h/E = \zeta}$$

$$\sum_h \int d\zeta M_a(x_B)(x_B, k_\perp^2, \zeta) = (1-x_B) f_a(x_B, k_\perp^2)$$

M. Anselmino et al., Phys. Lett. B. 699 (2011), 108, [hep-ph] 1102.4214

Quark polarization

Nucleon polarization

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

Boer-Mulders analog

etc. etc.

Sivers analog

Quark polarization

Nucleon polarization

	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

Extension to (collinear) twist-3

- Twist-3 fracture functions defined through quark-quark, quark-gluon and pure gluonic correlators.

$$\int \frac{d\lambda}{2\pi} e^{-ix\lambda P^+} \sum_X \langle h_A \,|\bar{\psi}_j(\lambda n)\mathcal{L}_n^\dagger(\lambda n)|h_B(P_h), X\rangle\langle X, h_B(P_h)|\mathcal{L}_n(0)\psi_i(0)|\, h_A\rangle \Big|_{\text{twist}-3,\ U,L-\text{target}}$$

$$= \frac{1}{2N_c P^+}\Big[(\gamma_\perp \cdot P_{h\perp})_{ij} \boxed{\hat{u}_2^{\perp h}(x,\xi,P_{h\perp})} + (\gamma_5\gamma_\perp \cdot \tilde{P}_{h\perp})_{ij} \boxed{\hat{l}_2^{\perp h}(x,\xi,P_{h\perp})}\Big]$$

$$+ \frac{S_L}{2N_c P^+}\Big[(\gamma_\perp \cdot \tilde{P}_{h\perp})_{ij} \boxed{\hat{u}_{2L}^{\perp h}(x,\xi,P_{h\perp})} + (\gamma_5\gamma_\perp \cdot P_{h\perp})_{ij} \boxed{\hat{l}_{2L}^{\perp h}(x,\xi,P_{h\perp})}\Big] + \cdots,$$

K.B. Chen, J.B. Ma, X.B. Tong (Private correspondence)
c.f. JHEP, vol 11 (2021), [hep-ph] 2108.13582

Additional contributions from quark and quark-gluon correlators with transverse momentum derivatives…

q N	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	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

Twist-2

Already accessible with data collected at CLAS12.

q N	U	L	T
U	$\tilde{u}_2^{\perp h}$	$\tilde{l}_2^{\perp h}$	$\tilde{t}_2, \tilde{e}_2$
L	$\tilde{u}_{2L}^{\perp h}$	$\tilde{l}_{2L}^{\perp h}$	$\tilde{t}_{2L}, \tilde{e}_{2L}$
T	$\tilde{u}_{2T}^{\perp\prime h}, \tilde{u}_{2T}^{\perp h}$	$\tilde{l}_T, \hat{l}_{2T}^{\perp h}$	$\tilde{t}_{2T}^h, \tilde{e}_{2T}^h, \tilde{t}_{2T}^{\perp h}, \tilde{e}_{2T}^{\perp h}$

Collinear twist-3

Twist-3 Observables

$$\int \frac{d\lambda}{2\pi} e^{-ix\lambda P^+} \sum_X \langle h_A \,|\bar{\psi}_j(\lambda n)\mathcal{L}_n^\dagger(\lambda n)|h_B(P_h), X\rangle\langle X, h_B(P_h)|\mathcal{L}_n(0)\psi_i(0)|\, h_A\rangle \Big|_{\text{twist}-3,\ U,L-\text{target}}$$
$$= \frac{1}{2N_cP^+}\left[\boxed{(\gamma_\perp \cdot P_{h\perp})_{ij}\hat{u}_2^{\perp h}(x,\xi,P_{h\perp})} + \boxed{(\gamma_5\gamma_\perp \cdot \tilde{P}_{h\perp})_{ij}\hat{l}_2^{\perp h}(x,\xi,P_{h\perp})}\right]$$
$$+ \frac{S_L}{2N_cP^+}\left[\boxed{(\gamma_\perp \cdot \tilde{P}_{h\perp})_{ij}\hat{u}_{2L}^{\perp h}(x,\xi,P_{h\perp})} + \boxed{(\gamma_5\gamma_\perp \cdot P_{h\perp})_{ij}\hat{l}_{2L}^{\perp h}(x,\xi,P_{h\perp})}\right] + \cdots,$$

K.B. Chen, J.B. Ma, X.B. Tong (Private correspondence)
c.f. JHEP, vol 11 (2021), [hep-ph] 2108.13582

Target-spin Asymmetry

$$\boxed{A_{UL} \propto S_L\sqrt{2\epsilon(1+\epsilon^2)}F_{UL}^{\sin\phi_h}\sin\phi_h}$$

$$F_{UU}^{\cos\phi_h} \sim \tilde{u}_2^{\perp h} + \cdots,\ F_{LU}^{\sin\phi_h} \sim \tilde{l}_2^{\perp h} + \cdots,\ F_{UL}^{\sin\phi_h} \sim \tilde{u}_{2L}^{\perp h} + \cdots,\ F_{LL}^{\cos\phi_h} \sim \tilde{l}_{2L}^{\perp h} + \cdots$$

Beam-spin Asymmetry

$$\boxed{A_{LU} \propto S_L\sqrt{2\epsilon(1-\epsilon^2)}F_{LU}^{\sin\phi_h}\sin\phi_h}$$

$$\frac{d\sigma}{dxdyd\zeta dP_T^2 d\phi_h} = \hat{\sigma}_U\Big[F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\boxed{F_{UU}^{\cos\phi_h}\cos\phi_h} + \varepsilon F_{UU}^{\cos 2\phi_h}\cos(2\phi_h) +$$
$$\lambda_\ell\sqrt{2\varepsilon(1-\varepsilon)}\boxed{F_{LU}^{\sin\phi_h}\sin\phi_h} + S_L\sqrt{2\varepsilon(1+\varepsilon)}\boxed{F_{UL}^{\sin\phi_h}\sin\phi_h} +$$
$$\lambda_\ell S_L\sqrt{1-\varepsilon^2}F_{LL} + \lambda_\ell S_L\sqrt{2\varepsilon(1-\varepsilon)}\boxed{F_{LL}^{\cos\phi_h}\cos\phi_h} + S_L\varepsilon F_{UL}^{\sin 2\phi_h}\sin(2\phi_h)\Big]$$

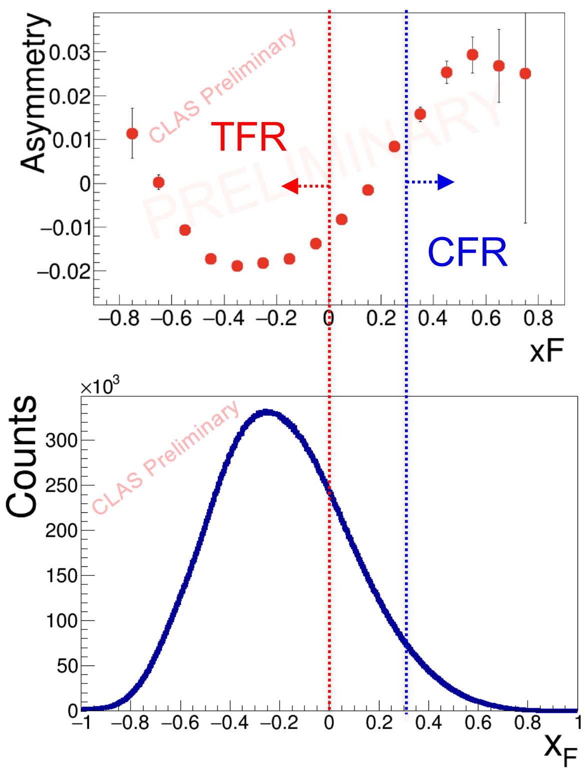
In the TFR the sin(2ϕ) and cos(2ϕ) modulations appear at twist-4 because there are no appropriate FrFs to generate the correct tensor structure.

Why fracture functions?

- Sometimes possible to kinematically separate CFR and TFR (some jets, high energy DY, etc) … but not always clear (fixed target experiments).
- Without an understanding of the signals we expect from target fragmentation we may misinterpret results that we expect are from the current.
- Studying the TFR tests our complete understanding of the SIDIS production mechanism while also providing access to information not available in the CFR.
- Access to more familiar TMD/PDFs through momentum sum rules, but with different systematics.

Can We Separate Target and Current?

ep → e'pX



Feynman variable

$$x_F = \frac{p_h^z}{p_h^z\,(\mathrm{max})} \quad \text{in CM frame } \mathbf{p} = -\,\mathbf{q}, \qquad -1 < x_F < 1$$

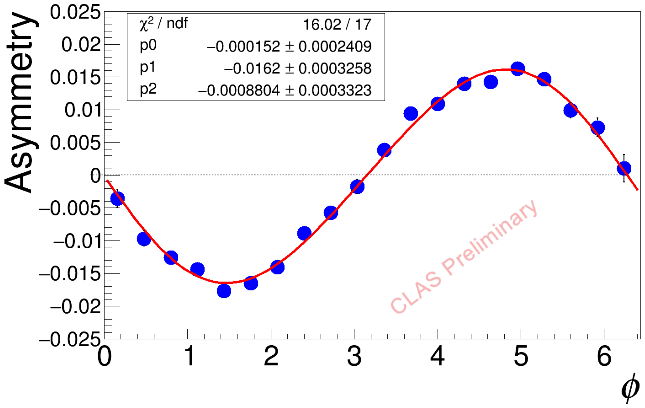
Rapidity

$$y = \frac{1}{2}\log\frac{p_h^+}{p_h^-} = \frac{1}{2}\log\frac{E_h + p_h^z}{E_h - p_h^z}$$

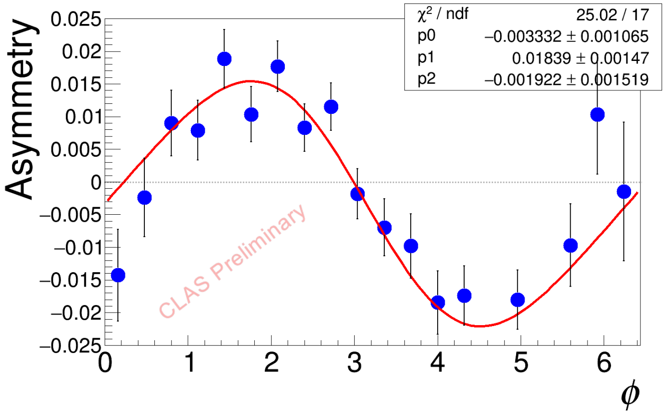
- No clear *experimental* definition of what constitutes current production versus target production.
- Structure functions, with different production mechanisms in both regions, give a possible clue.
- Protons (as opposed to mesons) at CLAS12 kinematics give a unique opportunity because they have extensive coverage in both regions.

Separate Signals

TFR



CFR



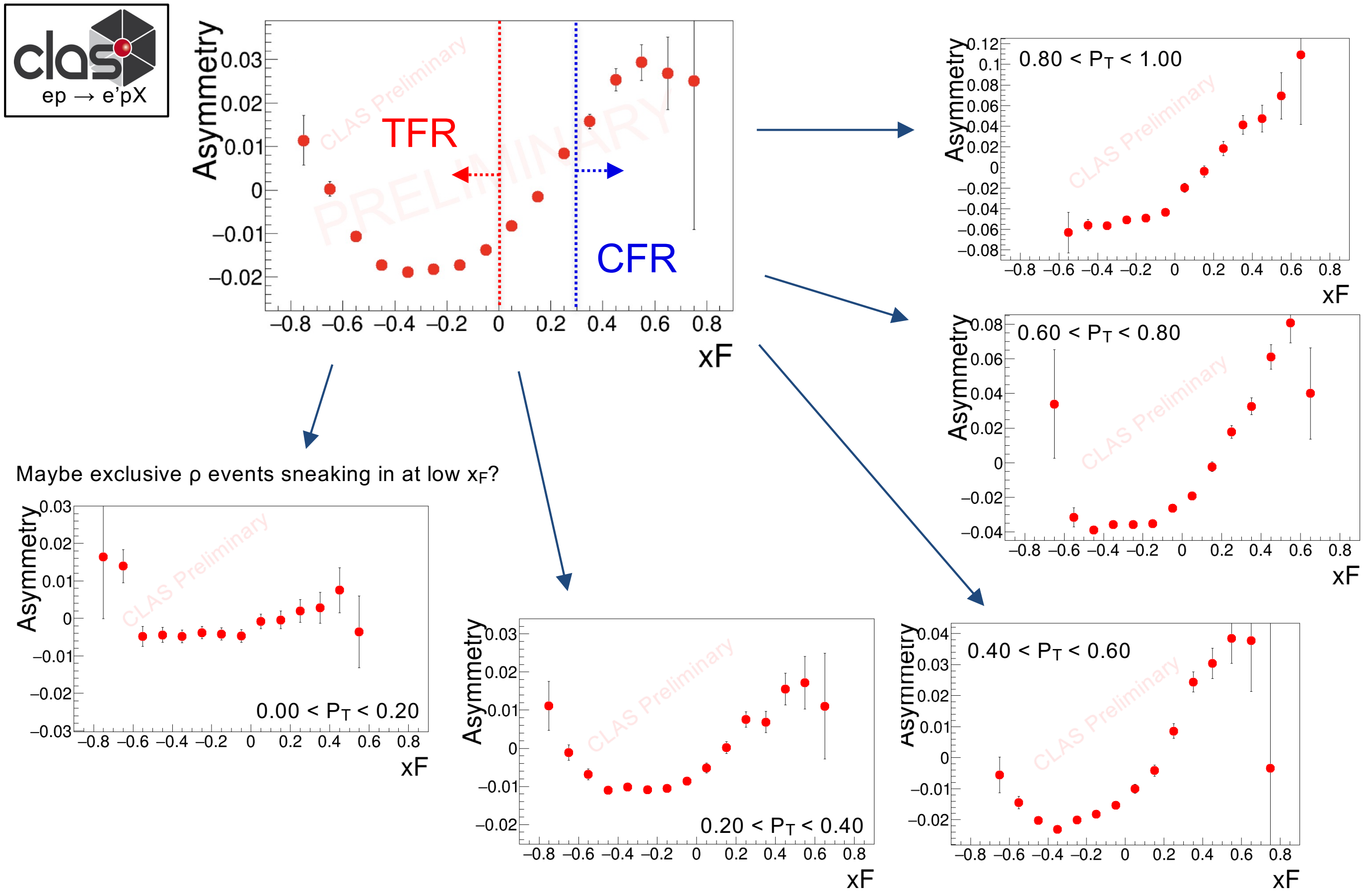
$$F_{LU}^{\sin\phi} \propto \frac{2M}{Q}\left[\tilde{l}_2^{\perp h} + \dots \qquad\qquad\right]$$

Need more theory calculations!

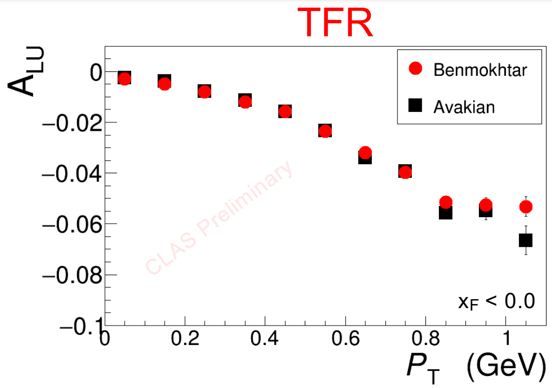
$$F_{LU}^{\sin\phi} \propto \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{h}\cdot p_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

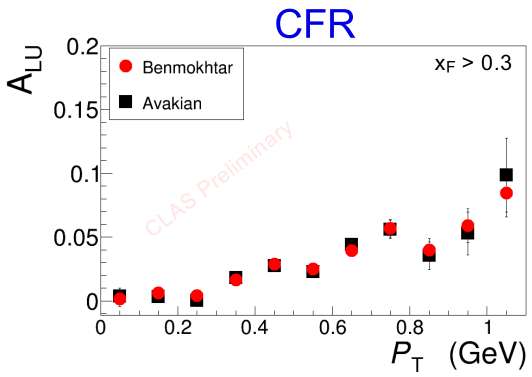
- Sinusoidal modulations (that are probably) coming from the struck quark and the spectator partons appear with roughly equal amplitudes but opposite signs.

Transverse Momentum Effects



Maybe exclusive ρ events sneaking in at low x_F?



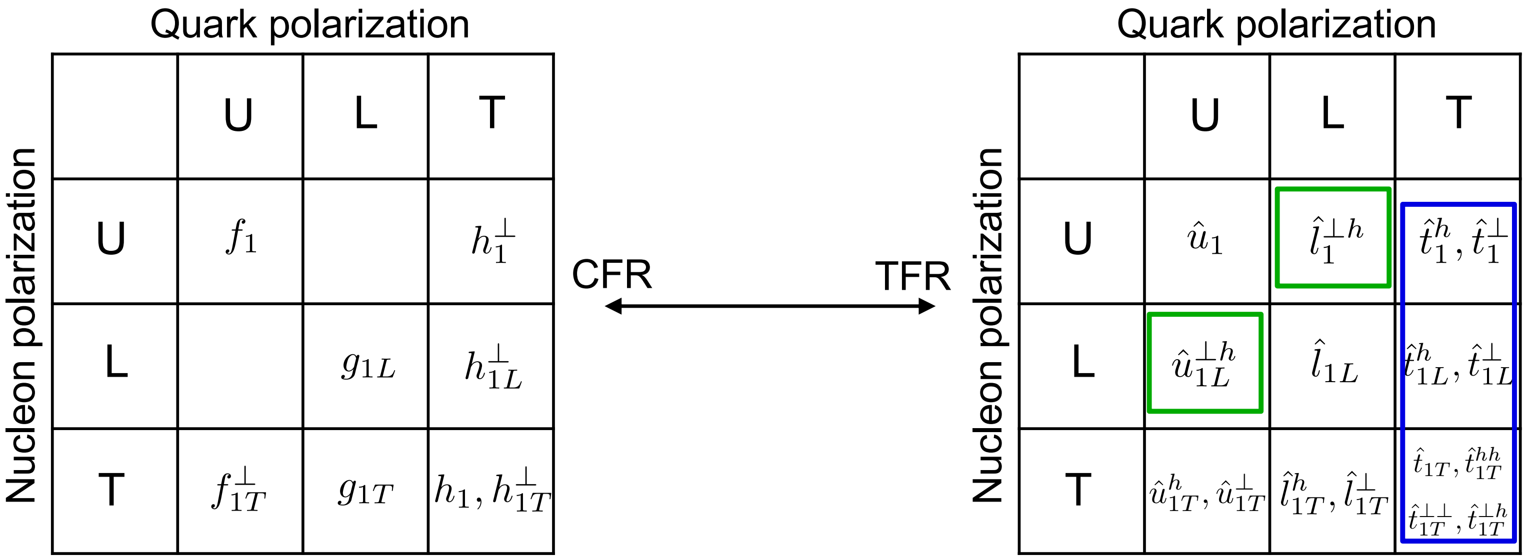


Strong linear dependence on P_T.

UCONN

Single hadron limitations

- FrFs describing transversely polarized quarks are chiral odd and inaccessible in TFR single hadron production where there is no access to a chiral odd FF.
- Functions with double superscripts containing h and ⊥ have give the unique possibility of measuring longitudinal polarized quarks in unpolarized nucleons (and vice versa) but disappear after integration over either momentum.



Quark polarization

Nucleon polarization

	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

Nucleon polarization

	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

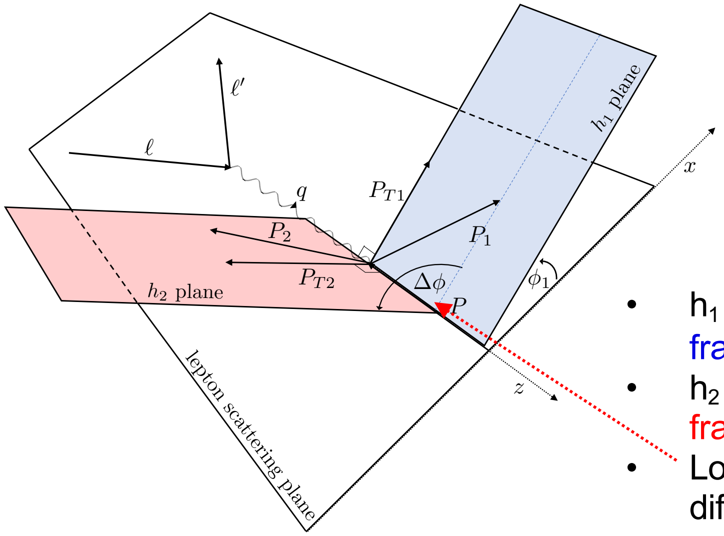
UCONN

Back-to-back (dSIDIS) Formalism

- When two hadrons are produced “back-to-back”[1,2] with one in the CFR and one in the TFR the structure function contains a convolution of a fracture function and a fragmentation function.
- Leading twist beam(target)-spin asymmetry.

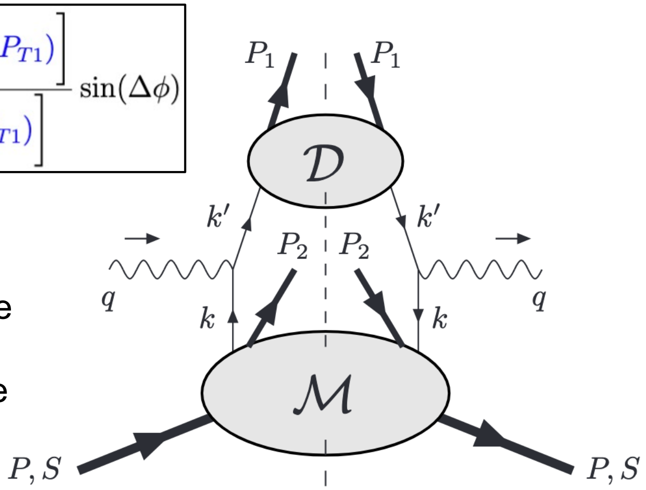
$\hat{l}_1^{\perp h}$ Unique access to longitudinally polarized quarks in unpolarized nucleon… no corresponding PDF!

$$A_{LU} = -k(\epsilon)\frac{P_{T1}P_{T2}}{m_1 m_2}\frac{\mathcal{C}\left[w_5 \hat{l}_1^{\perp h}(x,\zeta_2,P_{T2})D_1(z_1,P_{T1})\right]}{\mathcal{C}\left[\hat{u}_1(x,\zeta_2,P_{T2})D_1(z_1,P_{T1})\right]}\sin(\Delta\phi)$$



Kinematic plane for b2b dihadron production.

- h_1 in the CFR with production dictated by the fragmentation function
- h_2 in the TFR with production dictated by the fracture function
- Long range correlation depends on the difference in azimuthal angles of both hadrons



Handbag diagram for dihadron production; lower blob contains FrFs and upper blob contains the FFs.

1. M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132
2. M. Anselmino et al., Phys. Lett. B. 713 (2012), 317-320, [hep-ph] 1112.2604

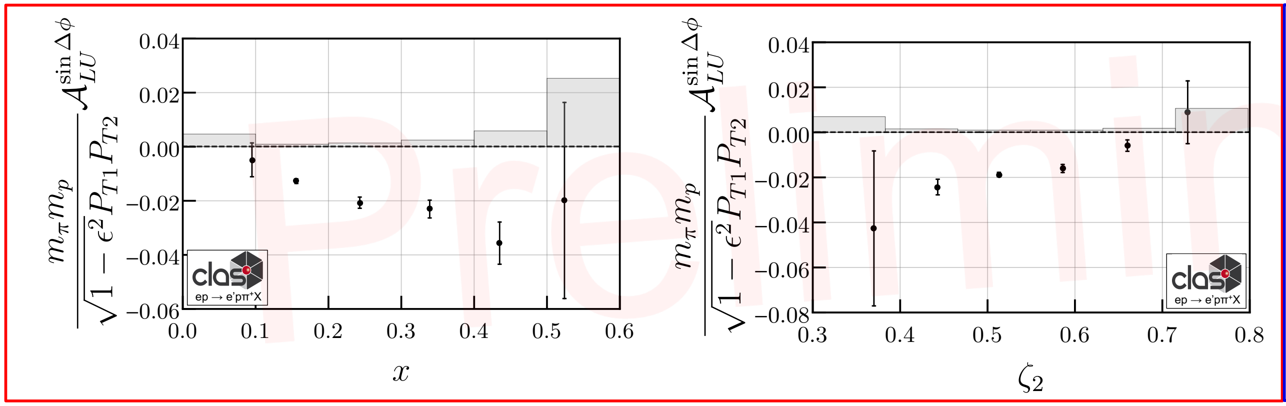
Access to unmeasured fracture functions

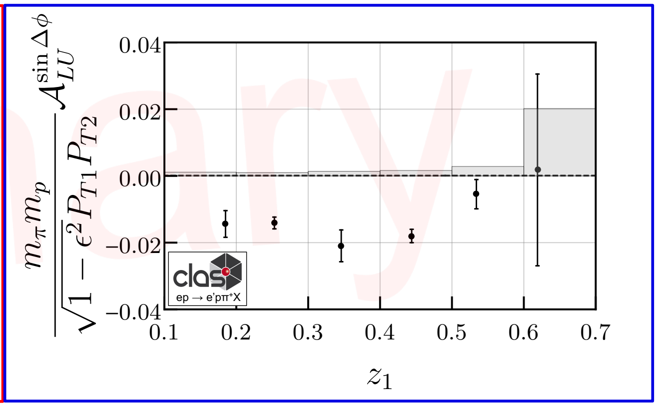
- x-dependence increases in magnitude in the valance quark region.
- ζ_2-dependence shows decreasing amplitude with increasing momenta. Possibly due to correlations with x.
- Relatively flat as a function of z_1, possibly due to cancellation of fragmentation functions.
- First observation of TMD fracture functions and long-range correlations between current and target. Already working on follow up (negative pion, deuteron target, more statistics etc.)

ep → e'pπ⁺X

$$A_{LU} \propto \frac{\mathcal{C}\left[w_5 \hat{l}_1^{\perp h}(x,\zeta_2,P_{T2})D_1(z_1,P_{T1})\right]}{\mathcal{C}\left[\hat{u}_1(x,\zeta_2,P_{T2})D_1(z_1,P_{T1})\right]}$$

Paper submitted in few weeks!





UCONN

A_{LL} – The Best of Both Worlds

$$\frac{d\sigma}{dx\,dy\,d\zeta\,dP_T^2} = 2\pi\hat{\sigma}_U \sum_q e_q^2 \left[F_{UU,T} + \lambda S_L \sqrt{1-\varepsilon^2} F_{LL} \right]$$

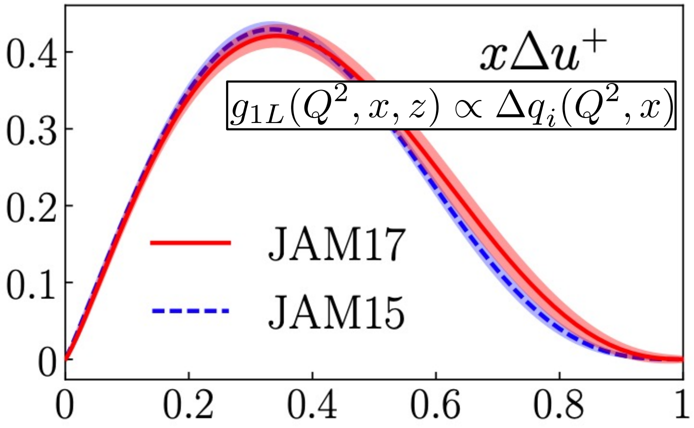
M. Anselmino et al., Phys. Lett. B. 699 (2011), 108, [hep-ph] 1102.4214

At leading twist for the case of a longitudinally polarized target and a single hadron produced in the TFR, only two terms appear:

$$F_{UU,T} \propto \tilde{u}_1(x,\zeta,P_T^2) = \int d^2k_T \hat{u}_1$$

$$F_{LL} \propto \tilde{l}_{1L}(x,\zeta,P_T^2) = \int d^2k_T \hat{l}_{1L}$$

J.J. Ethier et al., *Phys. Rev. Lett.*, 119, (2017), [hep:ph 1705.05889]



Double Spin Asymmetry: $A_{LL} = \lambda_\ell S_L \dfrac{\sqrt{1-\epsilon^2}F_{LL}}{F_{UU,T}}$

1. Single hadron → Highest statistics
2. Leading twist → Simple interpretation
3. Linked to g_1 → easiest test of FrF prediction

$$\sum_h \int \zeta d\zeta \int d^2P_T \underbrace{\hat{l}_{1L} = (1-x)}\, g_{1L}(x,k_T^2)$$

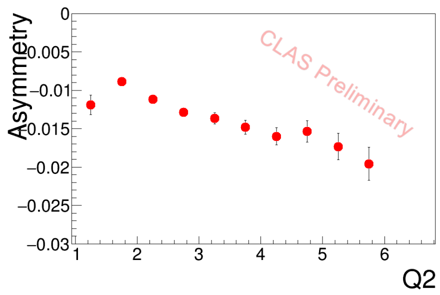
Motivations for JLAB22

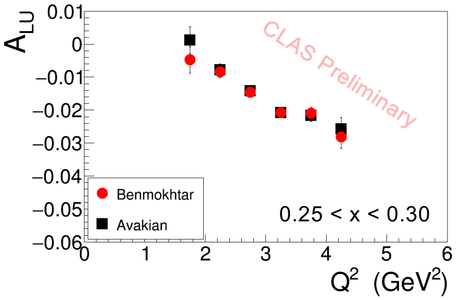
- 1) Identify “flagship” measurements that can only be done with 22 GeV
- 2) Identify measurements at 22 GeV that can extend and improve upon those done at 12 GeV
- 3) Identify measurements that can help bridge the gap between JLab12 and EIC

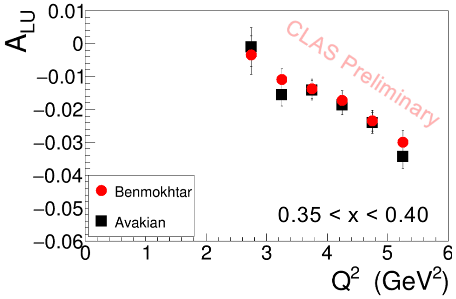
Mapping the Q^2 dependence

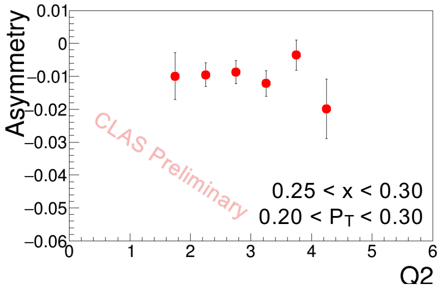
- SSAs in single hadron production are twist-3 (M/Q suppression).
- ”Twist 3” asymmetries not behaving as expected (EMC, COMPASS, CLAS12 etc!)
- Proper interpretation of the Q^2 dependence is crucial for our understanding of the underlying dynamics.

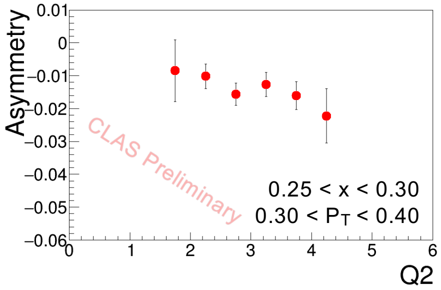
ep → e’pX

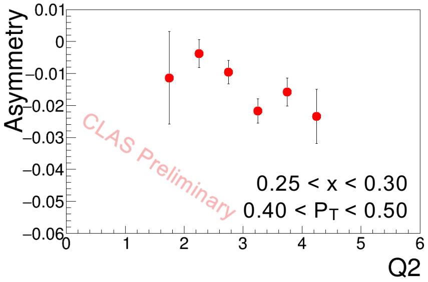












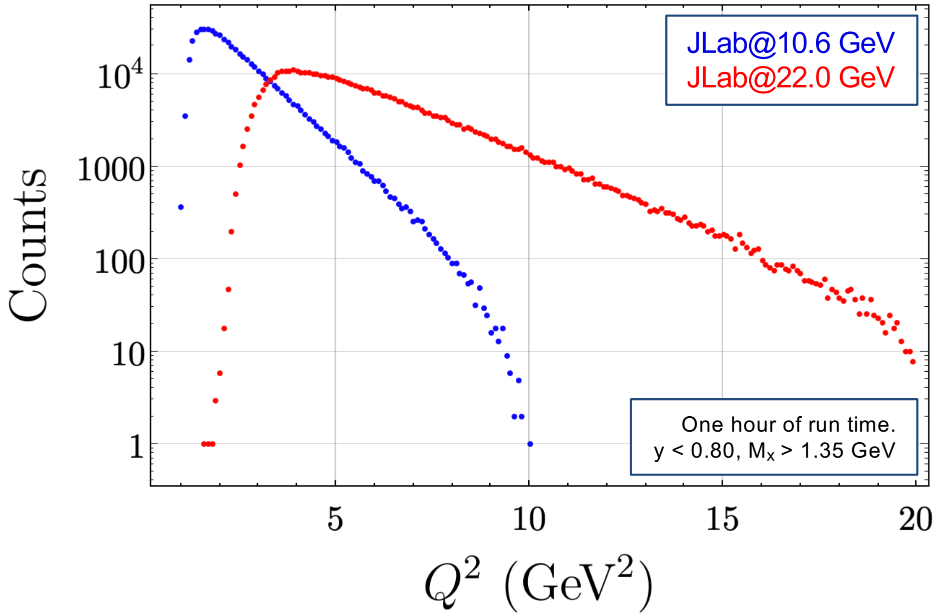
Onward to 4D

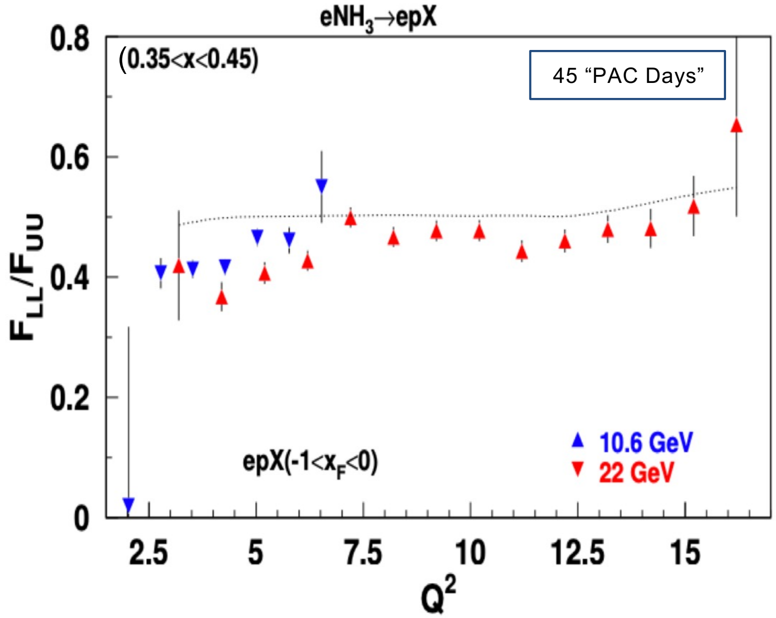
All plots $x_F < 0$.

Observing the expected Q^2 behavior for subleading twist objects may require high precision multidimensional bins… or maybe our theory is wrong.

Only about 1/3(1/6) of statistics collected(approved) on H_2 with CLAS12!

Q^2 Extension at JLab22





- Studies of the evolution of asymmetries will be critical for validating QCD predictions.
- Further range while maintaining the cutting edge luminosity of CLAS will be crucial for pinning down the Q^2 dependence of observables.

Kinematic Suppression at EIC

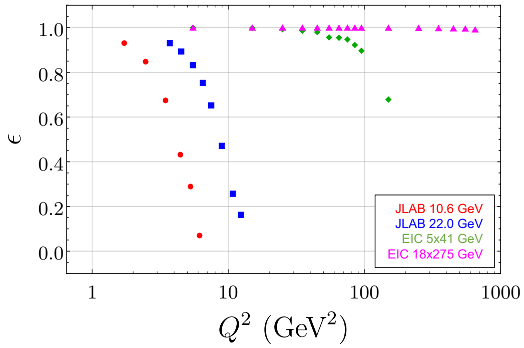
$F_{UU,L}$

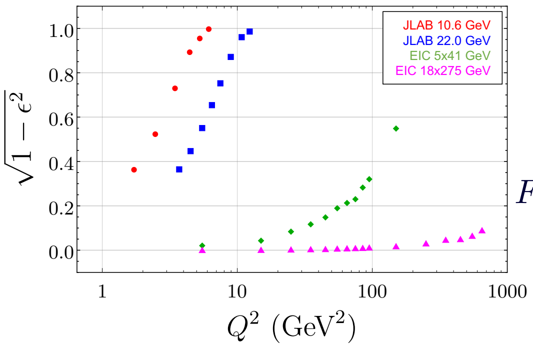
$F_{UU}^{\cos 2\phi}$

$F_{UT}^{(3\phi-\phi_S)}$

$F_{UT,L}^{\sin(\phi-\phi_S)}$

etc



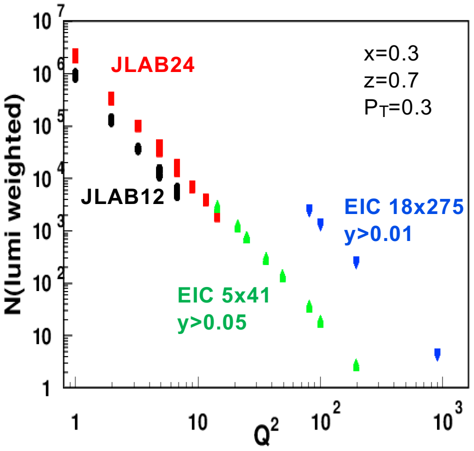


F_{LL}

$F_{LU}^{\sin\Delta\phi}$

$F_{LU}^{\sin(\phi_h-\phi_{R_\perp})}$

etc



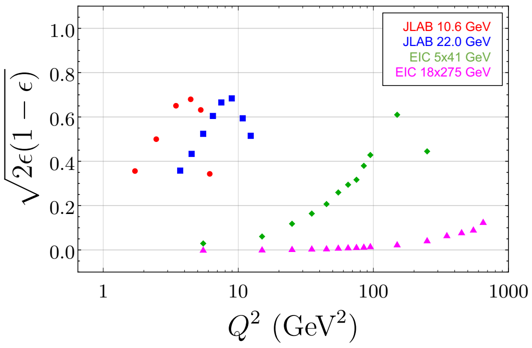
At the premier EIC luminosity of 10x275 many observables are **heavily** suppressed.

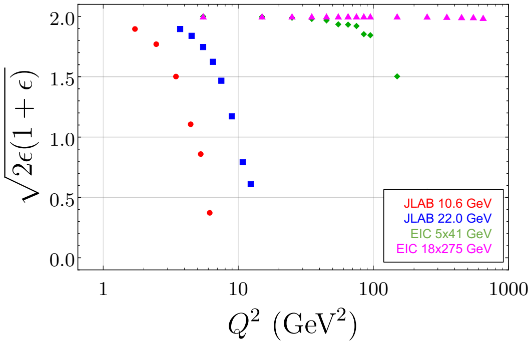
$F_{LU}^{\sin\phi}$

$F_{LU}^{\sin\phi_{R_\perp}}$

$F_{LL}^{\cos\phi}$

etc





$F_{UL}^{\sin\phi}$

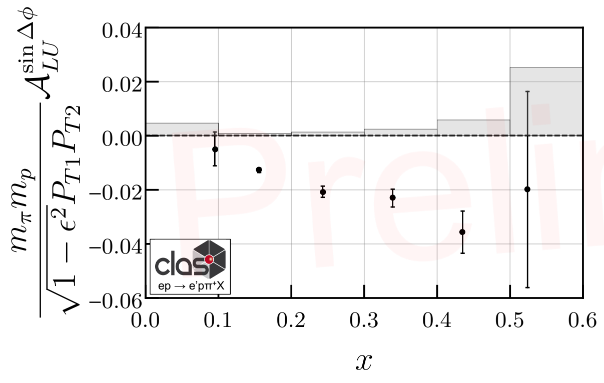
$F_{UU}^{\cos\phi}$

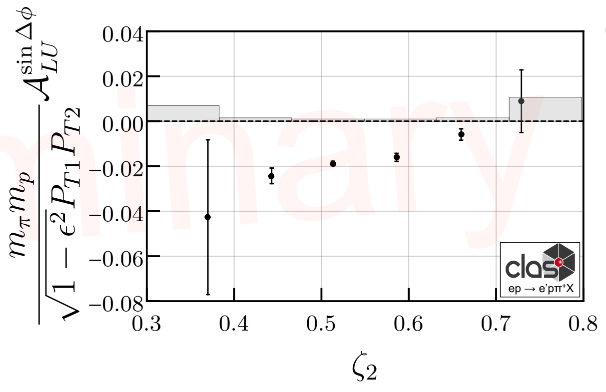
$F_{UT}^{\sin\phi_S}$

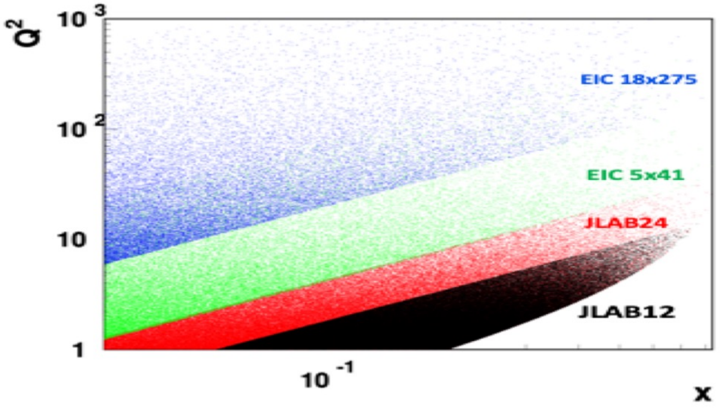
$F_{UT}^{\sin\phi_S}$

etc

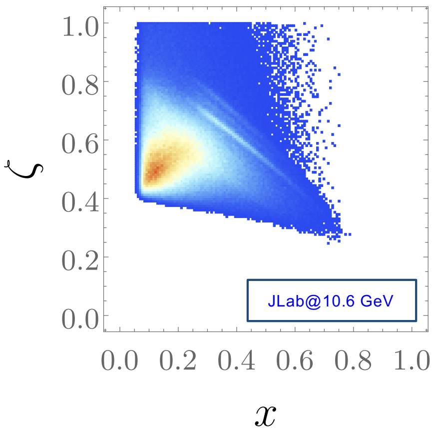
EIC suppression… JLab22 Enhancement

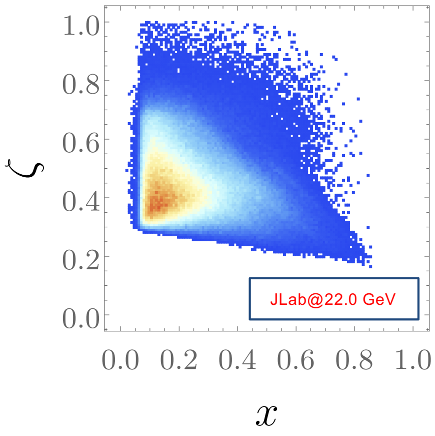


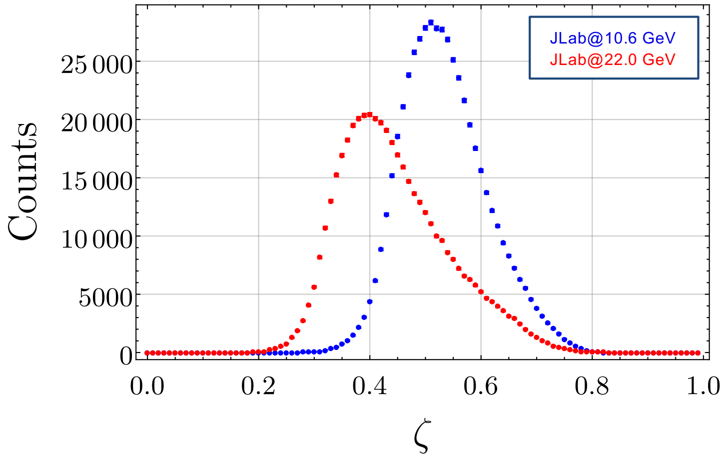




In addition to ε-dependent suppression, many of these observables are most enhanced in the high-x valence quark region.







UCONN

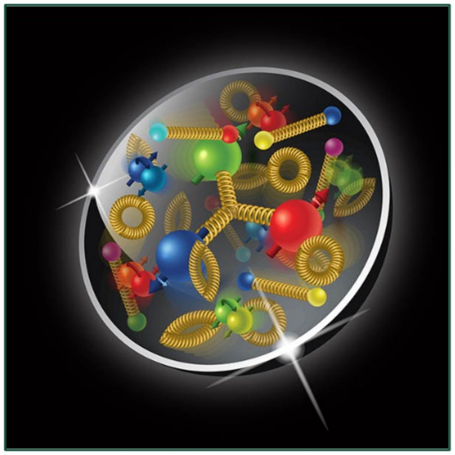
Conclusions

- Studies of the transverse momentum dependence of partons by analyzing target fragmentation is just beginning.
- Variety of measurements with access to leading and subleading-twist observables already available with CLAS12.
- JLab22 would present a significant opportunity to extend coverage to different kinematics, most critically higher Q^2, while maintaining CLAS12 luminosity.
- Many TMD measurements at EIC are heavily suppressed and even the ones that aren’t suffer from decreased luminosity.

Thank you!

Back up

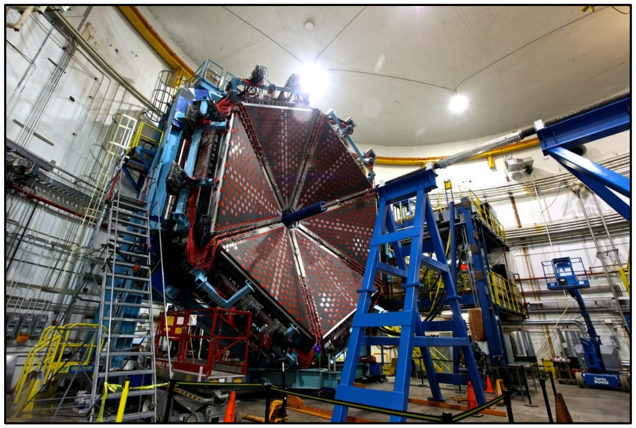
CLAS12 (Hall B) Physics Program



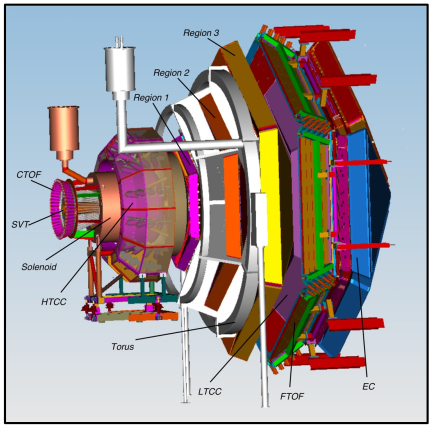
Stony Brook University News, August 2017

- International collaboration with more than 40 member institutions and 200 full members.

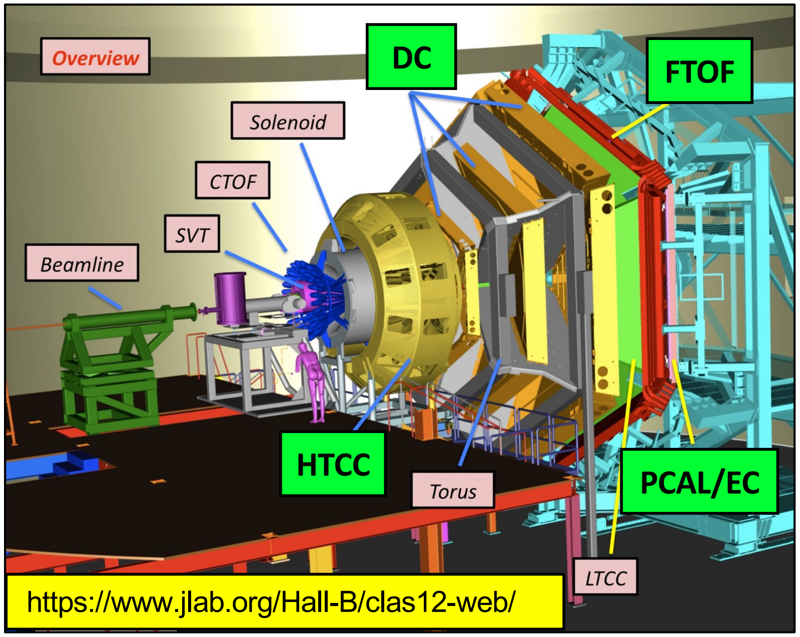
- CLAS(12) is the world's only large acceptance and high luminosity spectrometer for fixed target lepton scattering experiments.



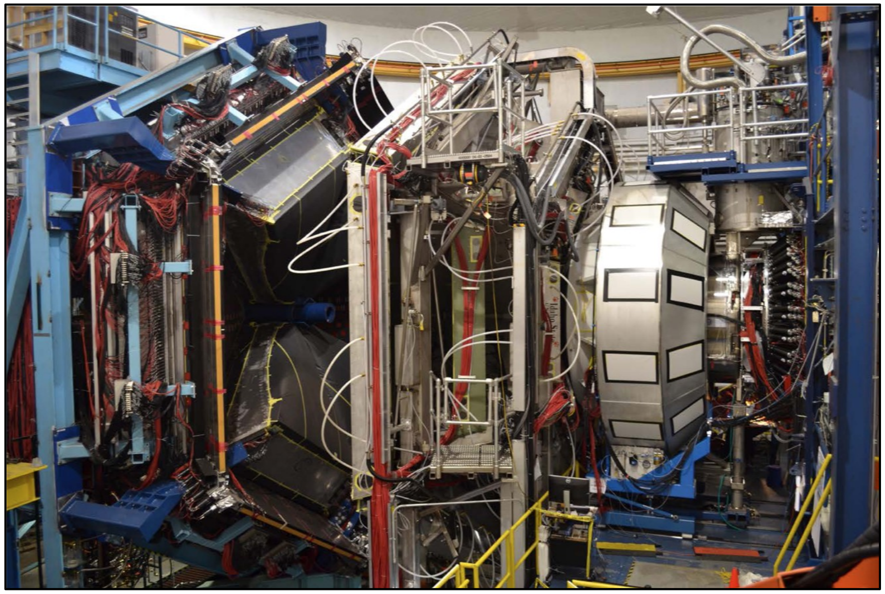
1. Study of the nucleon resonance structure at photon virtualities from 2.0 to 12 GeV^2
2. Study of Generalized Parton Distributions (GPDs), (2 +1) D imaging of the proton and the study of its gravitational and mechanical structure.
3. Study of the Transverse Momentum Dependence (TMDs) and the of 3D structure in momentum space.
4. Study of J/ψ Photoproduction, LHCb Pentaquarks and Timelike Compton Scattering.
5. Study of meson spectroscopy in search of hybrid mesons
6. Much more!



CLAS12 Spectrometer



https://www.jlab.org/Hall-B/clas12-web/

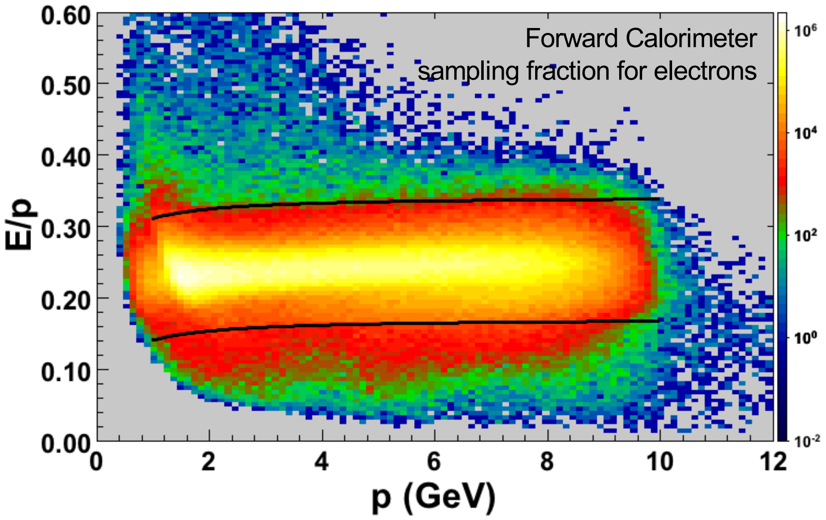


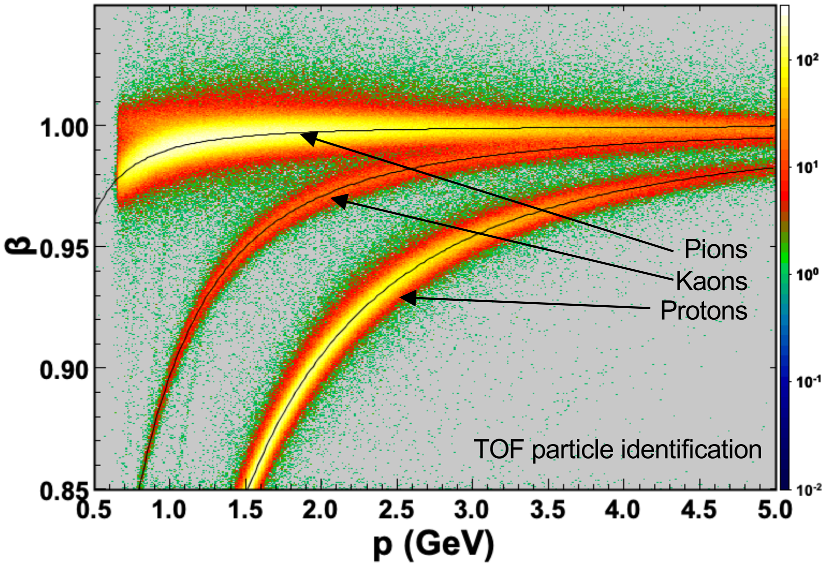
V. Burkert et al., Nucl. Instrum. Meth. A 959 (2020) 163419

- CLAS12: very high luminosity, wide acceptance, low Q^2
- Began data taking in Spring 2018 – many “run periods” now available.
- 10.6 GeV electron beam, longitudinally polarized beam

Particle ID

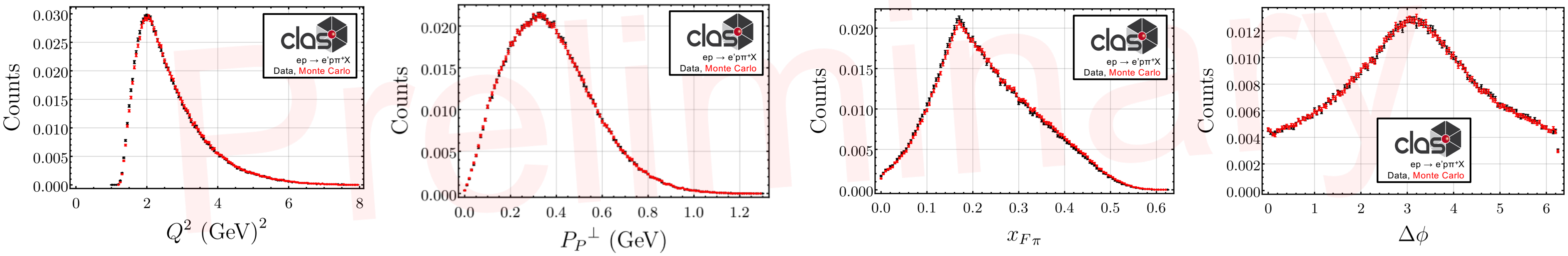
- Electron
  - Electromagnetic calorimeter.
  - Cherenkov detector.
  - Vertex and fiducial cuts.
- Hadron
  - β vs p comparison between vertex timing and event start time.
  - Vertex and fiducial cuts..





Monte Carlo

- SIDIS MC “clasdis”[1] based on PEPSI[2] generator, the polarized version of the well-known LEPTO[3] generator.
- Parameters changed to reproduce observed distributions include average transverse momentum, fraction of spin-1 light mesons and fraction of spin-1 strange mesons.
- CLAS12 detector system described in “GEMC”[4], a detailed GEANT4 simulation package.
- Excellent agreement between data and MC!



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1. H. Avakian, “clasdis.” https://github.com/JeffersonLab/clasdis, 2020.
2. L. Mankiewicz, A. Schafer, and M. Veltri, “Pepsi: A monte carlo generator for polarized leptoproduction,” Comput. Phys. Commun., vol. 71, pp. 305–318, 1992.
3. G. Ingelman, A. Edin, and J. Rathsman, “LEPTO 6.5: A Monte Carlo generator for deep inelastic 912 lepton - nucleon scattering,” Comput. Phys. Commun., vol. 101, pp. 108–134, 1997.
4. M. Ungaro et al., “The CLAS12 Geant4 simulation,” Nucl. Instrum. Meth. A, vol. 959, p. 163422, 2020.

z? z_h?? ζ??? TFR Hadronic Variables

- Traditional CFR SIDIS measurements describe the hadronic variables in terms of transverse momenta and the ratio of hadronic energy to virtual photon energy, $\boxed{z_h = P \cdot P_h / P \cdot q}$
- In the γ*N center-of-mass z_h does not discriminate between soft hadron emission (E_h = 0) and collinear target fragmentation (θ_h = 0),

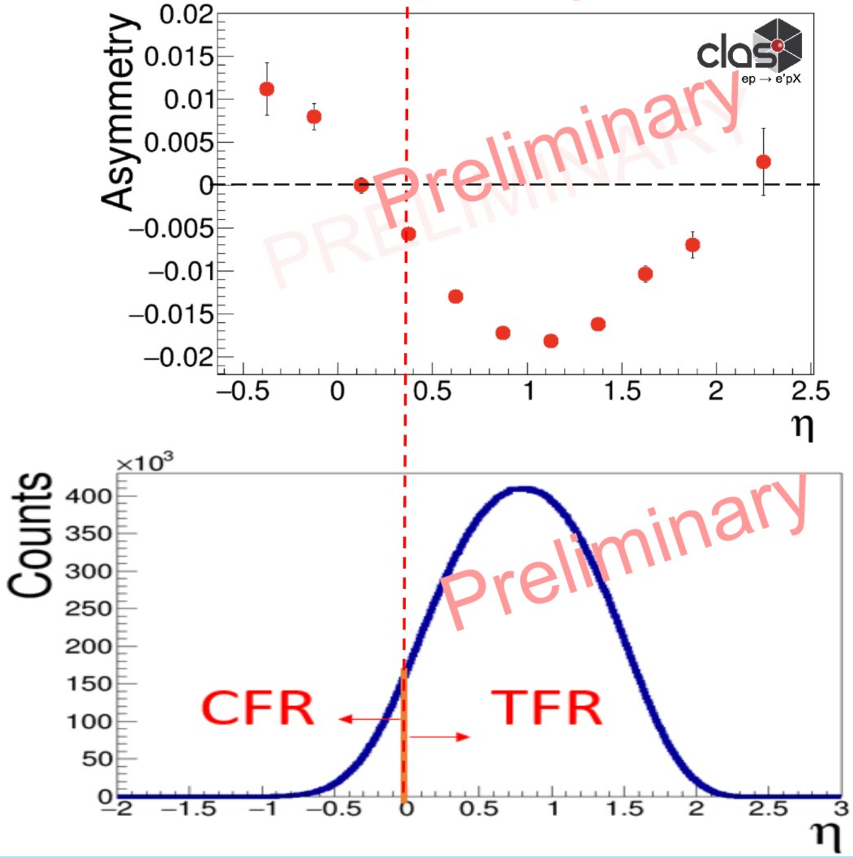
$$z_h = \frac{E_h}{E(1-x_B)} \frac{(1-\cos\theta_h)}{2}$$

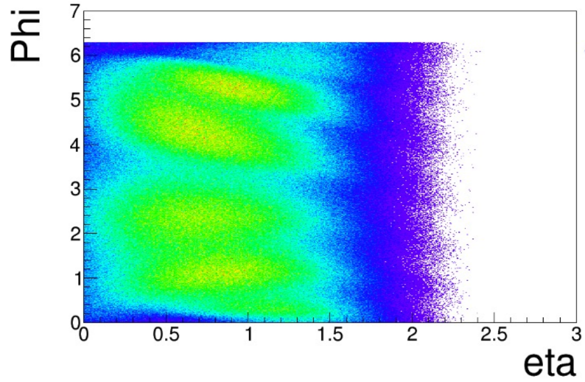
- Define a new variable, $\boxed{z = E_h/E(1-x)}$, which is 0 only in the case of soft hadron emission. Hadron momentum becomes $z(1-x) = \boxed{E_h/E = \zeta}$.
- Cross section parameterized in terms of ζ:

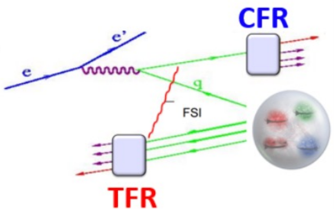
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}\zeta\;\mathrm{d}^2\boldsymbol{P}_{h\perp}\,\mathrm{d}\phi_S} = \frac{\alpha_{\mathrm{em}}^2}{4\,Q^4}\,\frac{y}{\zeta}\,L_{\mu\nu}W^{\mu\nu}$$

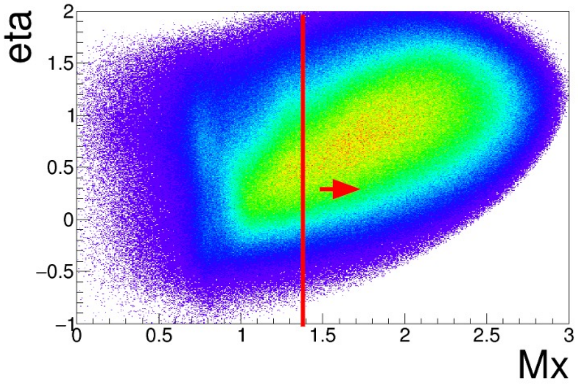
M. Anselmino et al., Phys. Lett. B. 699 (2011), 108-118, [hep-ph] 1102.4214

Asymmetry vs η Prel. Results, Mx > 1.35 (and appropriate cuts)



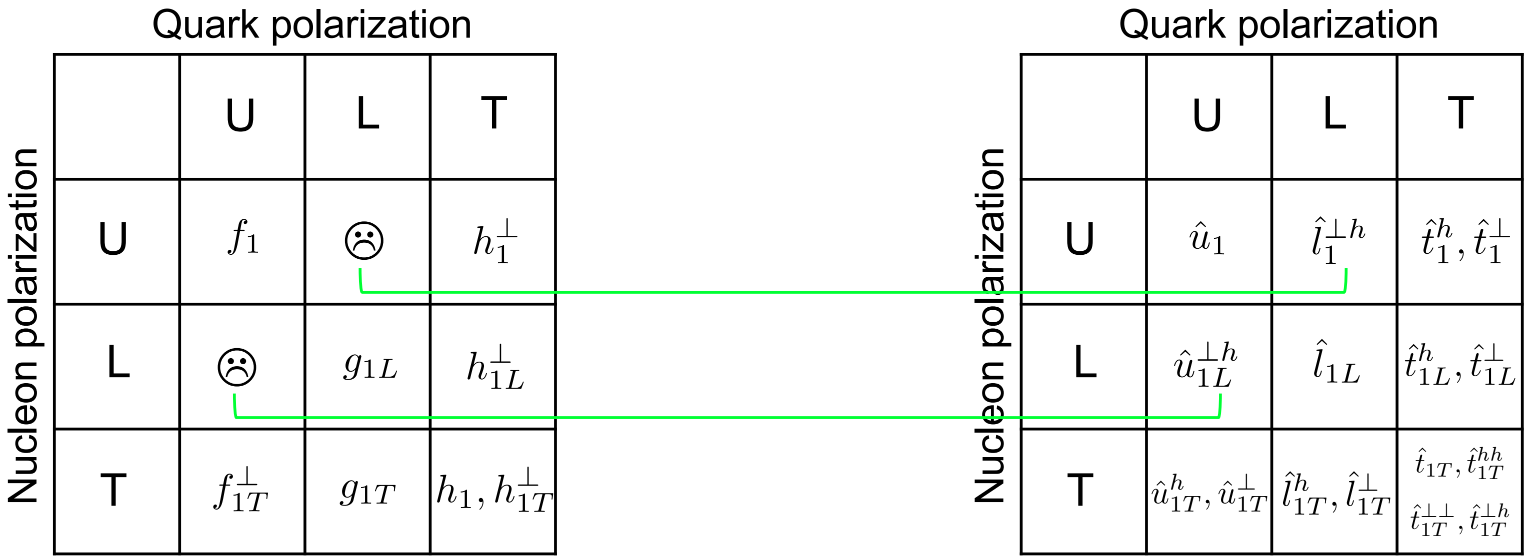






Accessing longitudinal polarization

- TFR studies provide unique access to longitudinally polarized quarks in unpolarized nucleons and unpolarized quarks in longitudinally polarized nucleons.



Quark polarization

Nucleon polarization

	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

Nucleon polarization

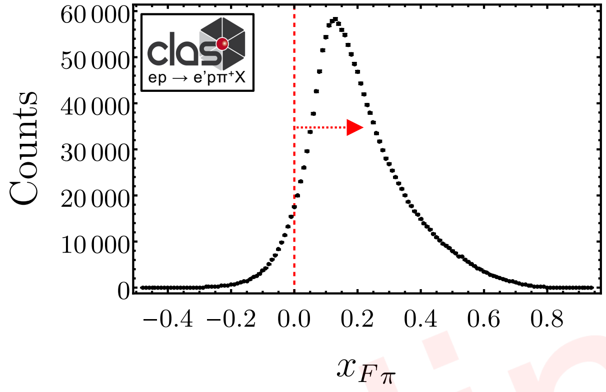
	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^{\perp}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^{\perp}$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^h, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}$ $\hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp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

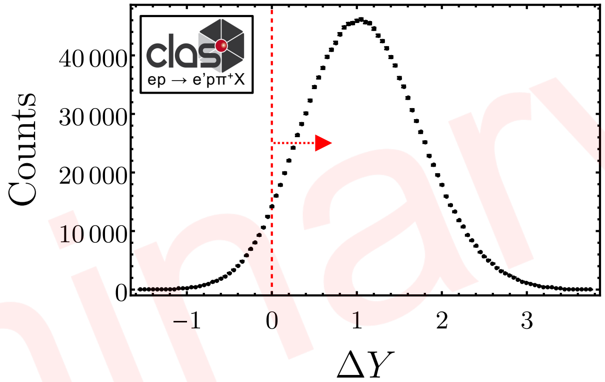
M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

UCONN

Selecting back-to-back events

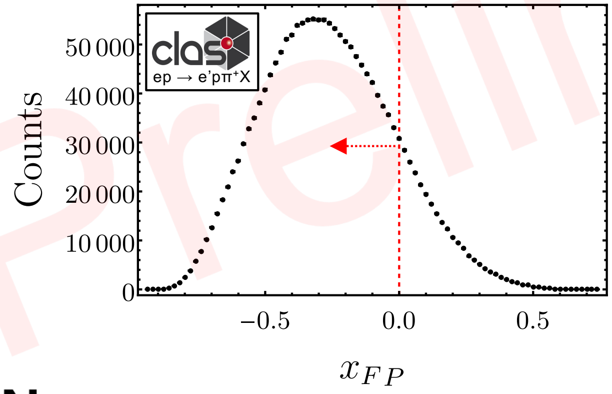
- A natural choice for a first analysis are events with a pion (CFR biased) and proton (TFR biased).

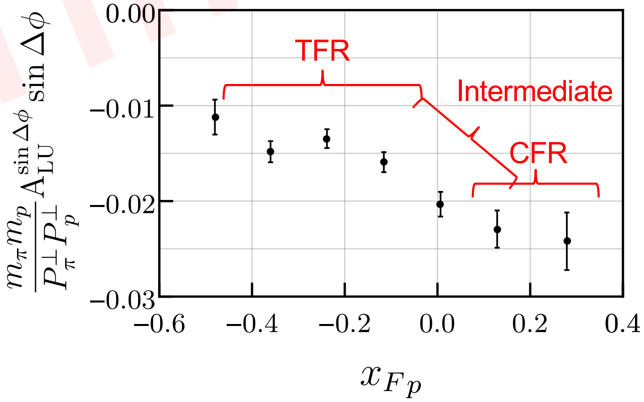




$$x_F = \frac{2p \cdot q}{|q|W}$$

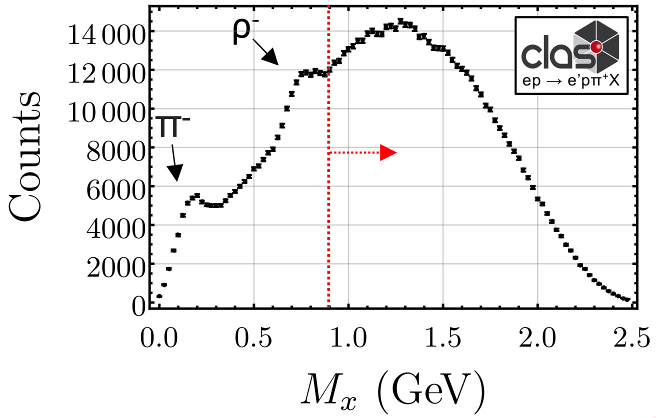
$$Y = \frac{1}{2}\log\left[\frac{E_h + p_z}{E_h - p_z}\right]$$



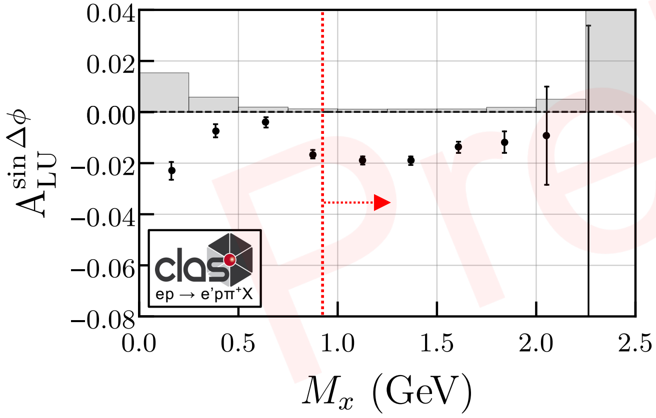


Early signs of separate signatures in both interaction regions. Need more statistics.

Removing background

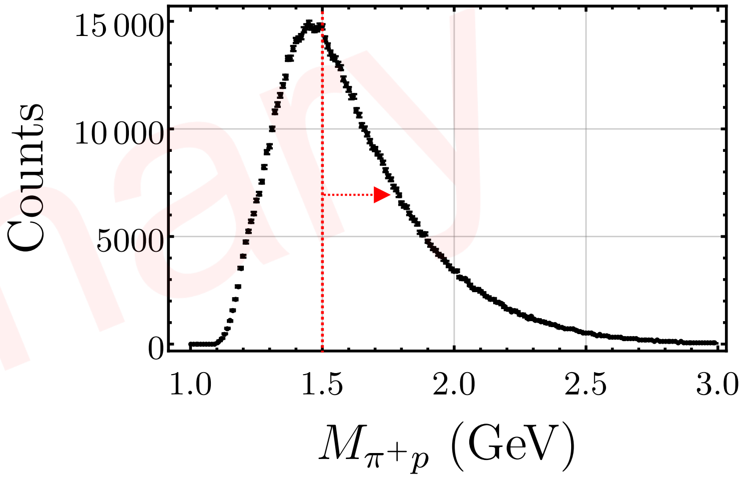


- Exclusive pion and rho production clearly visible.



- Different amplitudes at low M_x are generated from separate physics than our signal.

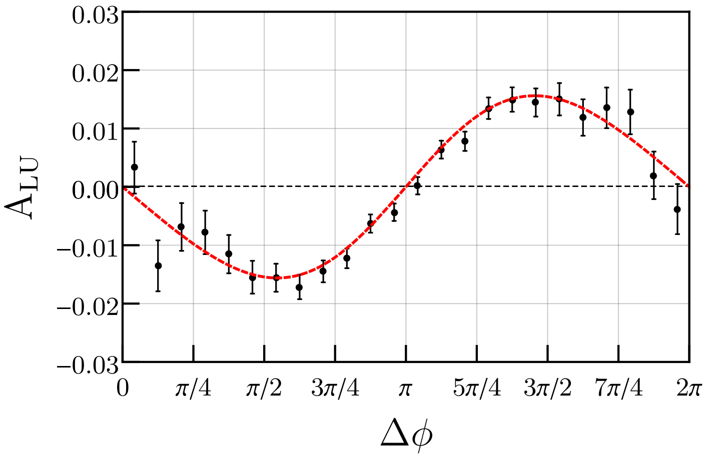
$\Delta^{++} \rightarrow p\pi^+$ Contamination?

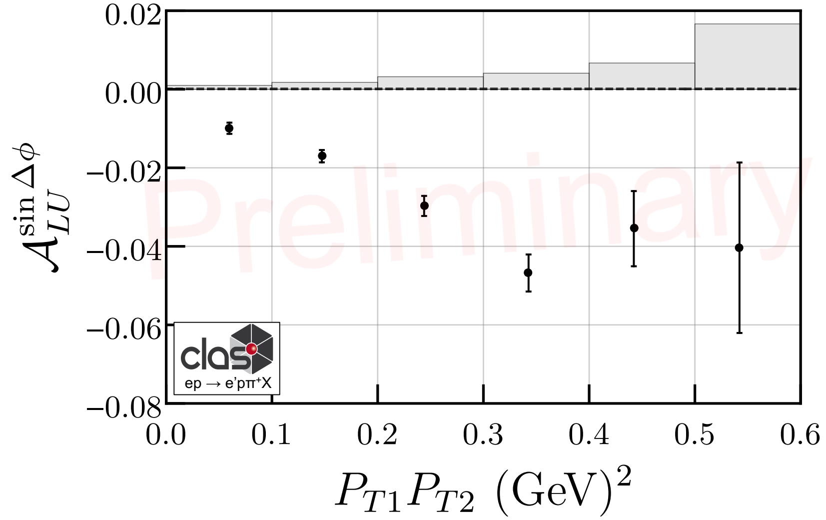


- Little sign of Δs; cut on mass > 1.5 GeV for safety.
- Estimate remaining contribution from MC.

Initial Observation

- Observed linear dependence on the product of transverse momenta is consistent with expectations (linear, goes to zero at zero transverse momenta, etc.)
- Non-zero asymmetries are the first experimental observation of possible spin-orbit correlations between hadrons produced simultaneously in the CFR and TFR.



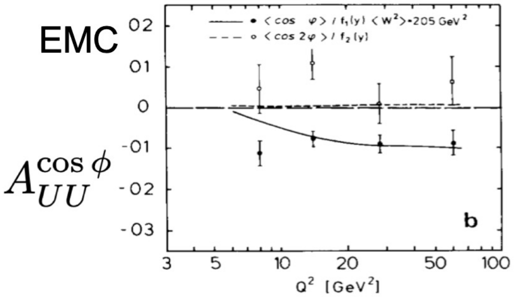


$$\mathcal{A}_{LU} = -\boxed{\sqrt{1-\epsilon^2}\,\frac{|\vec{P}_{T1}||\vec{P}_{T2}|}{m_N\, m_2}}\,\frac{\mathcal{C}[w_5\,\hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}\sin\Delta\phi$$

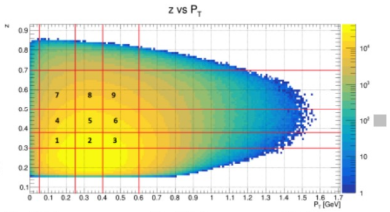
Divide out the kinematic factors for clearer description of fracture and fragmentation function dependence…

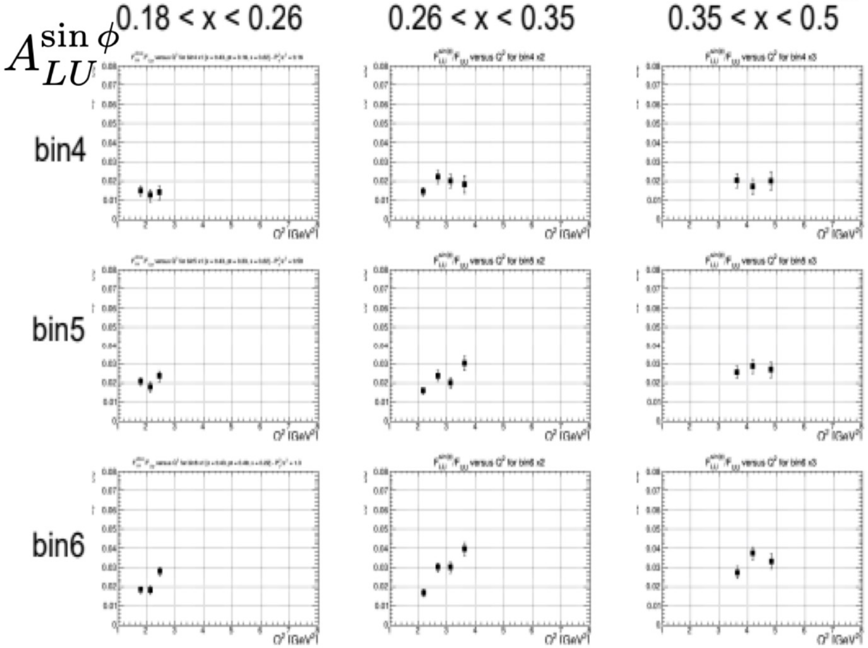
Attempts to understand Q^2-dependence of HT

EMC

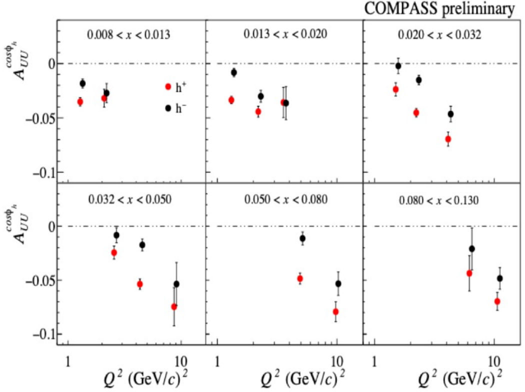


CLAS12(preliminary)

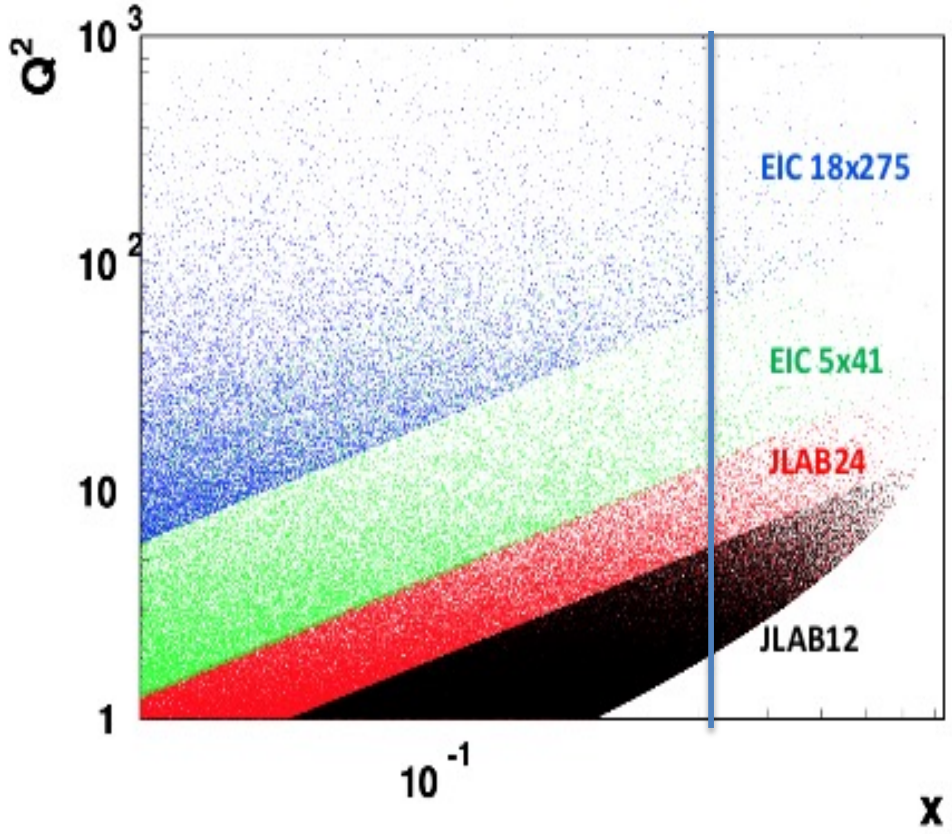


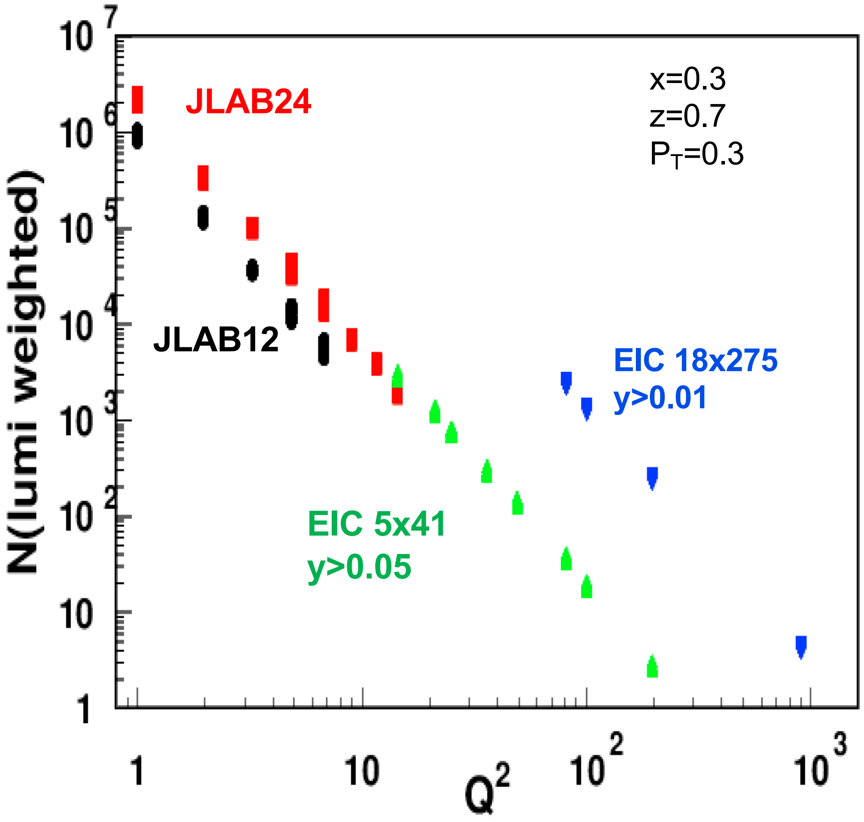


COMPASS

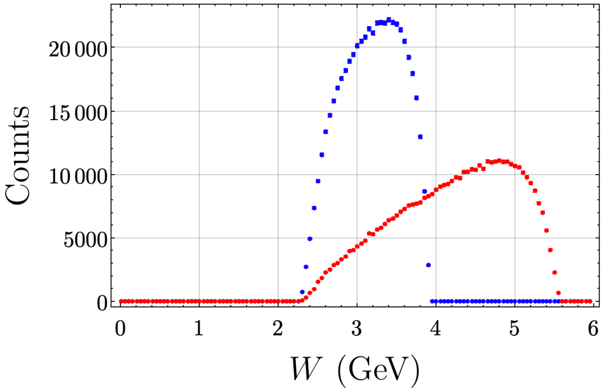


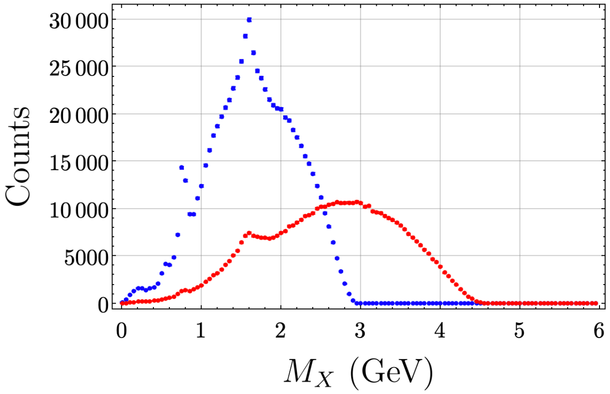
The ratios of SFs (to F_{UU}) are not decreasing with Q!!!
The HT observables, don’t look much like HT observables, something missing in understanding
Understanding of these behavior can be a key to understanding of other inconsistencies


Q^2
10^3
10^2
10
1
10^-1
x
EIC 18x275
EIC 5x41
JLAB24
JLAB12

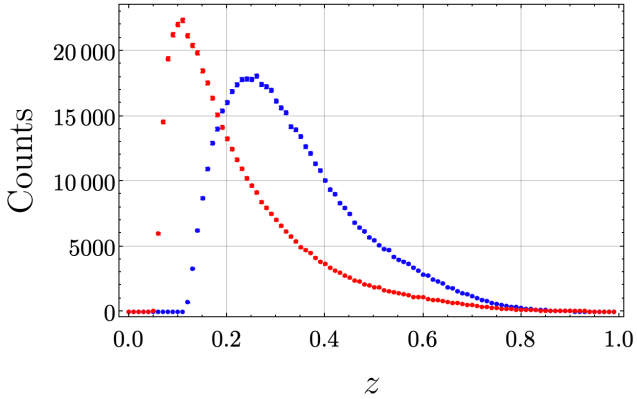

N(lumi weighted)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
1
10
10^2
10^3
Q^2
x=0.3
z=0.7
P_T=0.3
JLAB24
JLAB12
EIC 18x275
y>0.01
EIC 5x41
y>0.05

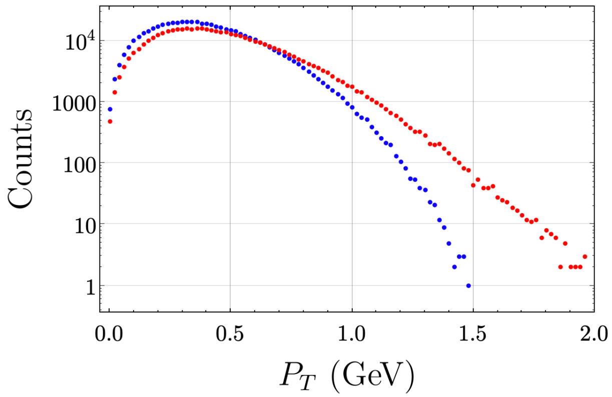
Phase Space





Higher W and M_x, less radiative effects from exclusive processes?





Higher P_T is critical, see Harut's talk!

UCONN