Longitudinal Target-Spin Effects in SIDIS with CLAS12

Tensor SIDIS workshop and b1/Azz Collaboration meeting

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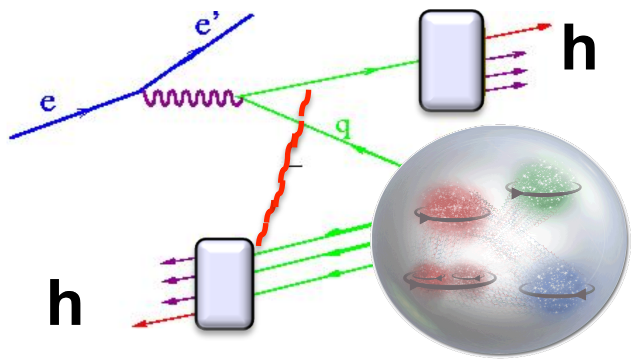
June 5, 2026

- Interconnections of Semi-Inclusive and Exclusive DIS
- Final states (π0, π+, π+π− ,…)
- What we can learn from longitudinal target measurements
- Dissecting SIDIS
- Evolution studies as validation test
- Comparing ALU with AUL
- Summary

3D PDFs: Electroproduction of hadrons

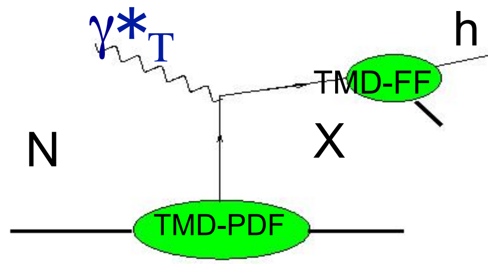
Current Fragmentation Region (CFR)

$x_F>0$



$x_F<0$

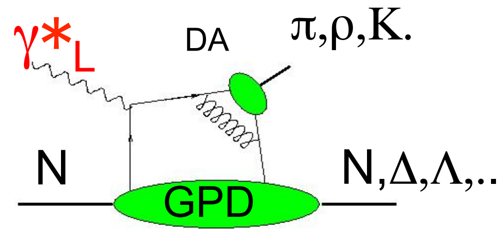
Target Fragmentation Region (TFR)



Study

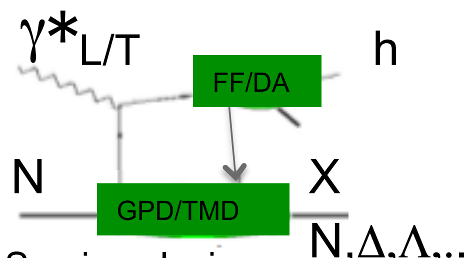
x,Q^2,z,P_T,ϕ,ϕ_S $\sim 1/Q^4$

Flavor and polarization dependence of transverse momentum distributions



$x,Q^2,t,\phi,\phi_S+\phi,\theta$ $\sim 1/Q^6$

Flavor and polarization dependence of transverse space distributions



Semi-exclusive production (Guo-Yuan)

correlations and entanglement of CFR and TFR, controlling CFR, allowing access to GPDs and GTMDs

- Different non-perturbative objects may be involved with several independent variables involved
- Cross contributions make studies based on a given set of assumptions challenging

From electron cross sections to to $\gamma^* p \rightarrow hX$

hep-ph/0611265

$$\frac{d\sigma}{dx_B\, dQ^2\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x_B Q^4} \frac{y^2}{2(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_B}\right) \left[F_{UU,T} + \varepsilon F_{UU,L} + \ldots\right]$$

subprocess $\gamma^* N \rightarrow hX$

helicity structure functions

$$F_{mn}^{ij}(x_B, Q^2, z, P_{h\perp}^2) = \frac{Q^2(1-x)}{4\pi^3\alpha} \left(1+\frac{\gamma^2}{2x_B}\right)^{-1} \frac{d\sigma_{mn}^{ij}}{dz\, dP_{h\perp}^2}$$

$$F_{UU,T} = \tfrac{1}{2}\left(F_{++}^{++} + F_{++}^{--}\right), \qquad F_{UU,L} = F_{00}^{++},$$

$(\nu+M)/\nu$

hep-ph/0503023

$$\left[\frac{\alpha_{\rm em}}{8\pi^3} \frac{y^2}{1-\varepsilon} \frac{1-x_B}{x_B} \frac{1}{Q^2}\right]^{-1} \frac{d\sigma}{dx_B\, dQ^2\, d\phi\, d\psi} \left[\frac{1}{2}\left(\sigma_{++}^{++} + \sigma_{++}^{--}\right) + \varepsilon\sigma_{00}^{++} - \varepsilon\cos(2\phi) + \ldots\right]$$

$$\sigma_T = \frac{1}{2}\left(\sigma_{++}^{++} + \sigma_{++}^{--}\right) \qquad \sigma_L = \sigma_{00}^{++}$$

$$\Gamma = \frac{4\pi^3\alpha_{\rm em}}{Q^2} \frac{x_B}{1-x_B} \qquad \frac{1}{2}\left[\frac{d\sigma_{++}^{++}}{dz\, dP_{hT}^2} + \frac{d\sigma_{++}^{--}}{dz\, dP_{hT}^2}\right] = \Gamma\, \mathcal{F}\left[f_1 D_1\right]$$

← Q^2-dependence in evolution

What happens to Q^2-dependences of $F_{UU,T}$ and $F_{UU,L}$ in exclusive limit of $z \rightarrow 1$?

Exclusive limit of SIDIS cross sections ep→e'hX

hep-ph/0611265

$$\frac{d\sigma}{dx_B\, dQ^2\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x_B Q^4} \frac{y^2}{2(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_B}\right) \left[F_{UU,T} + \varepsilon F_{UU,L} + \ldots\right] ($$

subprocess $\gamma^* N \to hX$

helicity structure functions

$$F_{mn}^{ij}(x_B, Q^2, z, P_{h\perp}^2) = \frac{Q^2(1-x)}{4\pi^3\alpha} \left(1+\frac{\gamma^2}{2x_B}\right)^{-1} \frac{d\sigma_{mn}^{ij}}{dz\, dP_{h\perp}^2}$$

$$F_{UU,T} = \tfrac{1}{2}\left(F_{++}^{++} + F_{++}^{--}\right),$$
$$F_{UU,L} = F_{00}^{++},$$

hep-ph/050617

$$z = 1 + \frac{x_B(M_P^2 - M_X^2)}{Q^2} + x_B t/Q^2 \quad \rightarrow \quad z_{\mathrm{excl}} = 1 + \frac{x_B t}{Q^2}$$

$$\frac{d\sigma}{dx_B\, dQ^2\, d\psi\, dt\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{Q^6} \frac{y^2}{2(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_B}\right) \left[F_{UU,T} + \varepsilon F_{UU,L} + \cdots\right]$$

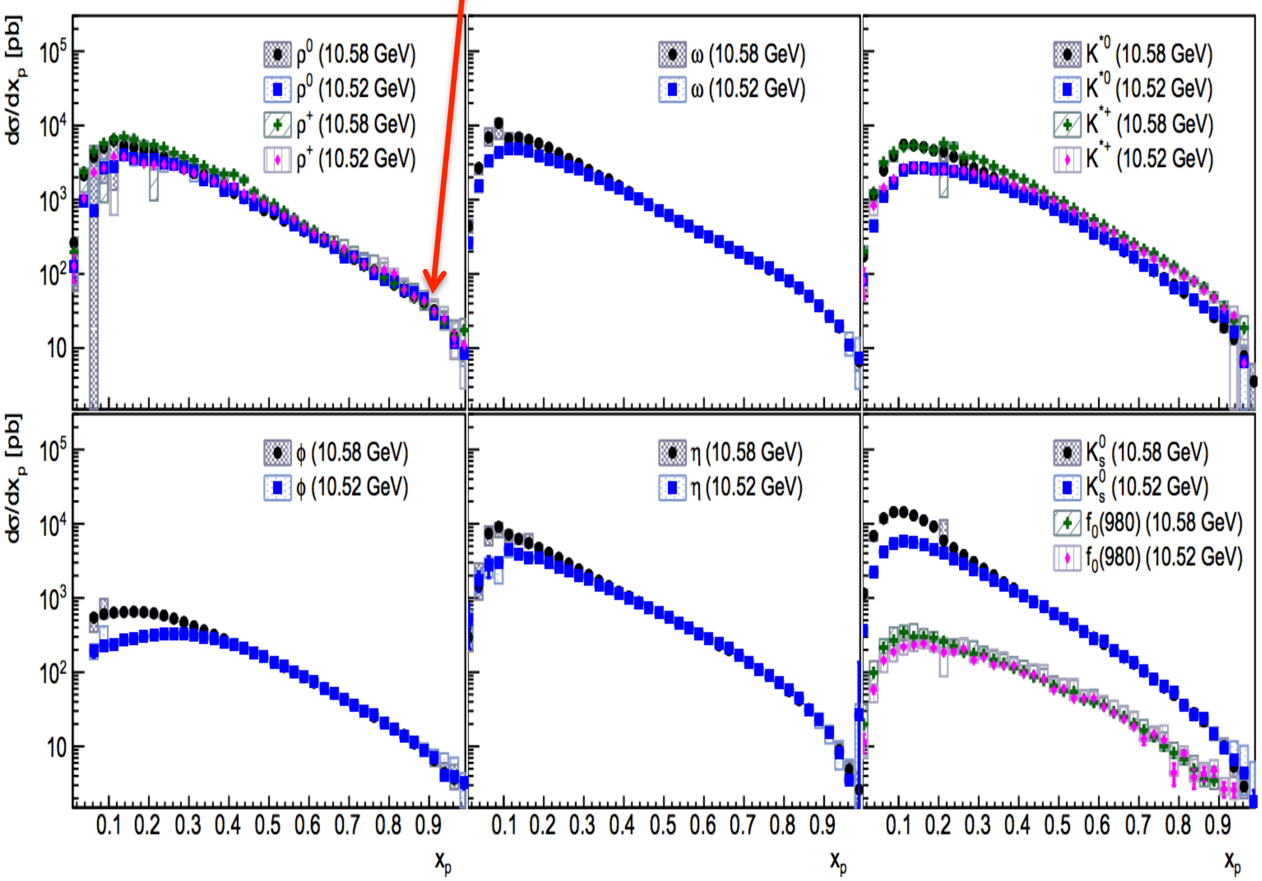
$$\frac{d\sigma}{dP_T^2} \propto \exp\left(-\frac{P_T^2}{2\sigma^2}\right) \quad \text{small t} \rightarrow \quad \frac{d\sigma}{d|t|} \propto (1-x_B)\exp\left[-\frac{(1-x_B)|t|}{2\sigma^2}\right]$$

exponential fall consistent with exclusive production

cross sections in the z→limit from e+e-

2411.12216

what is the z^{α} (1-z) $^{\beta}$



Belle: production cross sections as a function of x_p

Can we use FFs in z→1 limit to estimate the σ_T?

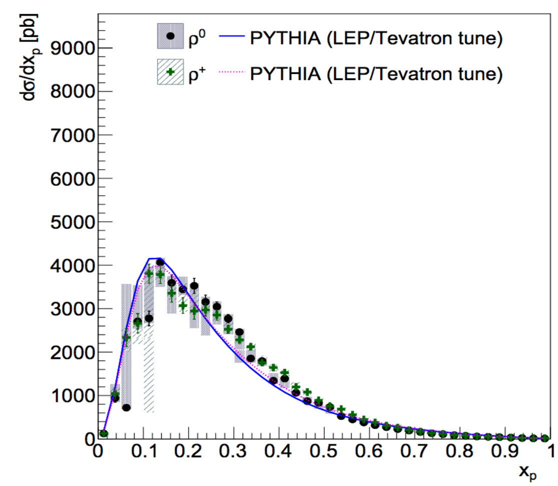
hadron momentum in e+e- CM

$$x_p = \frac{2|\vec{p}_h|}{\sqrt{s}} \quad z_h = \frac{E_h}{\nu}$$

$$z_P = \frac{\text{hadron light-cone momentum}}{\text{fragmenting parton light-cone momentum}}$$

$$z_h \approx z_P \left[1 + \frac{M_h^2 + P_T^2}{z_P^2 Q^2}\right]^{-1}$$

$$z_P \approx \frac{1}{2}\left[x_p + \sqrt{x_p^2 + \frac{4m_h^2}{s}}\right]$$



slightly more rho+!

Theory-Experiment Dialogue

$$\frac{d\sigma^{lN\to l'hX}}{dx_B dQ^2 dz dP^2_{h\perp} d\phi_h} = \frac{\pi\alpha^2 y}{x_B y Q^2(1-\epsilon)}[F_{UU,T} + \quad \ldots\ldots]$$

$lN \to l'\pi^+X$

$lN \to l'\rho^0 X$

....

$lN \to l'\pi^+X$

Fragmentation Function

→ probability to produce π+

$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

$\gamma^*_T p \to \pi^+ X(\pi^+ n, \pi^+\Delta, \pi^+\pi^- p, \pi^+\pi^0\pi^- \ldots)$

....

$\gamma^*_L p \to \pi^+ X(\pi^+ n, \pi^+\Delta, p\rho^0, \pi^+\pi^0\pi^- \ldots)$

$lN \to l'\pi^+X$

experiment

$\gamma^*_L p \to p\rho^0_L$

→ most significant

→ increases at higher energies

What type of exclusive processes should we cut out from experiment to have an adequate comparison with theory which doesn't have longitudinal photon contributions?

Observables with longitudinally pol. target

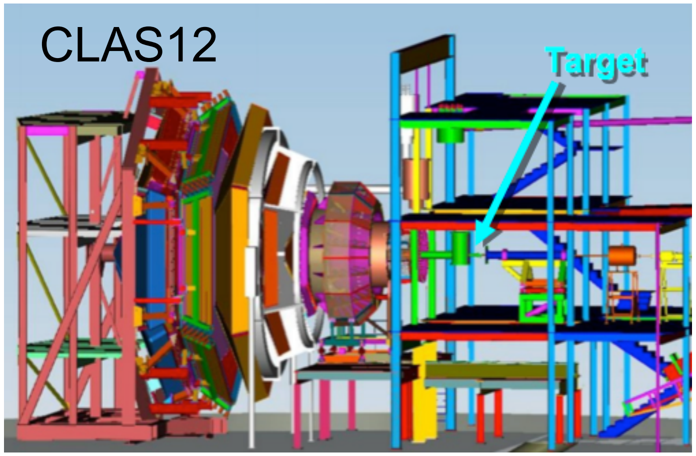
$$\sigma^{\lambda\Lambda} = \sigma_{UU} + \lambda\sigma_{LU}\sin\phi + \Lambda\sigma_{LU}\sin\phi + \lambda\Lambda(\sigma_{LL} + \sigma_{LL}^{\cos}\cos\phi)$$

λ and Λ→ helicities of e- and proton (normalizing lumi of positive and negative targets

$N^{++}+N^{-+}$ = sum of events (with +/- helicities of e-) for positive target polarization
$N^{+-}+N^{--}$ = sum of events (with +/- helicities of e-) for negative target polarization
$N^{++}+N^{+-}$ = sum of events (with +/- helicities of p) for positive e- helicity
$N^{-+}+N^{--}$ = sum of events (with +/- helicities of p) for negative e- helicity
Observables
beam SSA $(N^{++} + N^{+-} - N^{-+}-N^{--})/(N^{++} + N^{+-} + N^{-+}+N^{--})= (a_{lu}\sin\phi)/(1+b_{uu}\cos\phi)$
use the $(1+b_{uu}\cos\phi)$ containing cos from acceptance and Cahn for others
target SSA
$(N^{++} + N^{-+} - N^{+-}-N^{--})/(N^{++} + N^{+-} + N^{-+}+N^{--})= (a_{ul}\sin\phi+b_{ul}\sin2\phi)/(1+b_{uu}\cos\phi)$
Target double spin asymmetries
1) $(N^{++} - N^{-+})/(N^{++} + N^{-+}) =(a_{ul}\sin\phi+b_{ul}\sin2\phi+a_{LL}+b_{LL}\cos\phi)/(1+b_{uu}\cos\phi)$
2) $(N^{--} - N^{+-})/(N^{--} + N^{+-}) =(-a_{ul}\sin\phi-b_{ul}\sin2\phi+a_{LL}+b_{LL}\cos\phi)/(1+b_{uu}\cos\phi)$
use the same helicity
1) $(N^{++} - N^{+-})/(N^{++} + N^{+-}) =(a_{lu}\sin\phi+a_{LL}+b_{LL}\cos\phi)/(1+b_{uu}\cos\phi)$
2) $(N^{--} - N^{-+})/(N^{--} + N^{-+}) =(-a_{lu}\sin\phi+a_{LL}+b_{LL}\cos\phi)/(1+b_{uu}\cos\phi)$

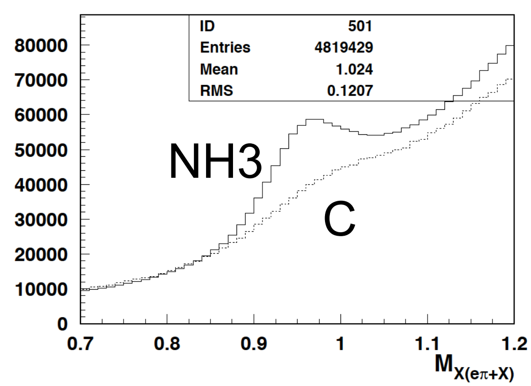
Longitudinally polarized target offers several observables critical for test

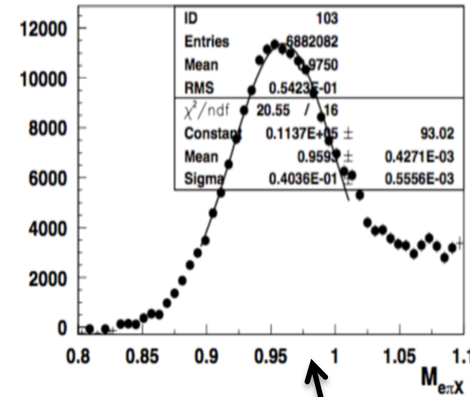
CLAS12 RGC experiment with longitudinally polarized target



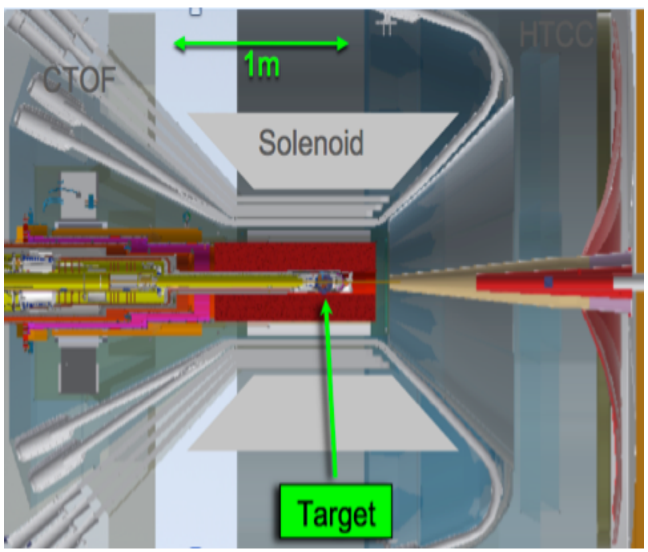
E12-06-109, E12-06-119, E12-07-107, E12-09-009

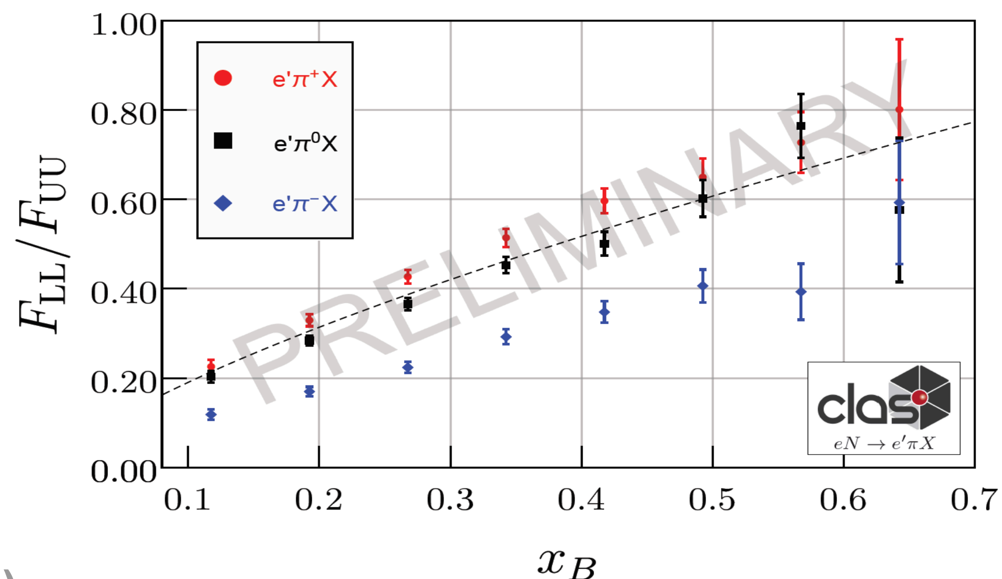
Electroproduction on longitudinally polarized NH3 and ND3





Subtracting carbon data from NH3 (nice neutron peak)

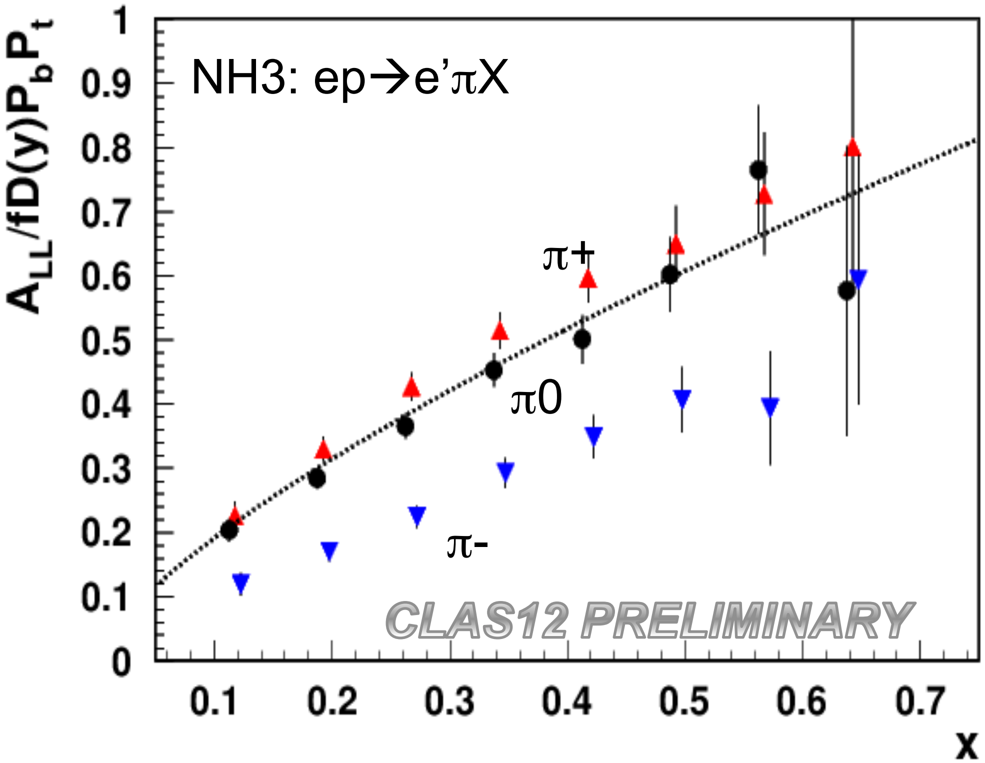


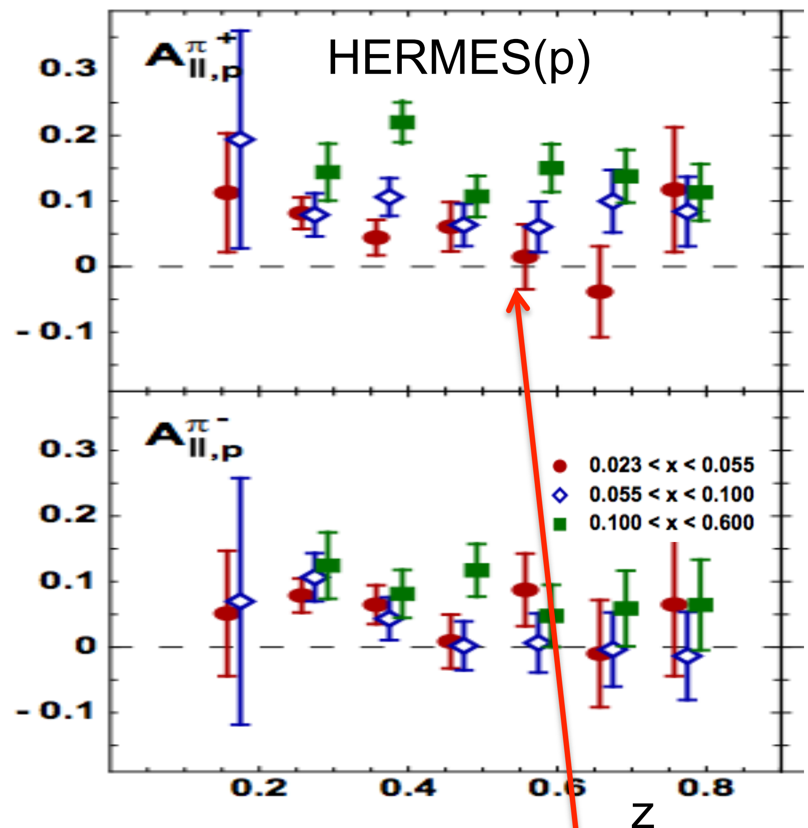


Dynamic Nuclear Polarization (DNP)

Single pion DSAs

1810.07054



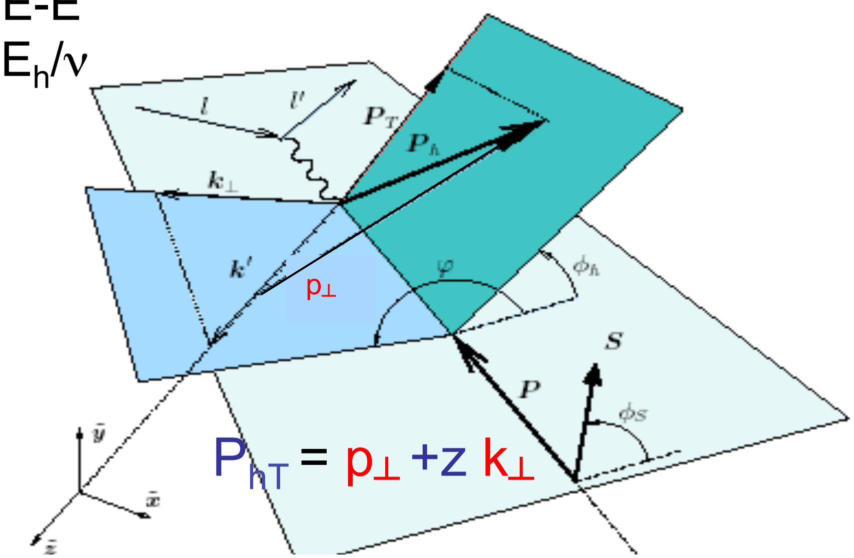


- Double spin asymmetries for ep→eπ+X seem to decrease at large z and effect more significant at low x
- The ep→eπ+X drops faster at low x than ep→eπ0X (consistent with DIS fit)
- Note: →exclusive rho contributions more significant at large z and low x

DIS kinematical coverage and observables

$\nu = E - E'$

$z = E_h/\nu$



$$\frac{d\sigma}{dx\, dy\, d\phi_S\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x\, y\, Q^2} \frac{y^2}{2(1-\varepsilon)} \Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h}$$

$$+ \lambda_e \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h} + S_L \Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} \Big]$$

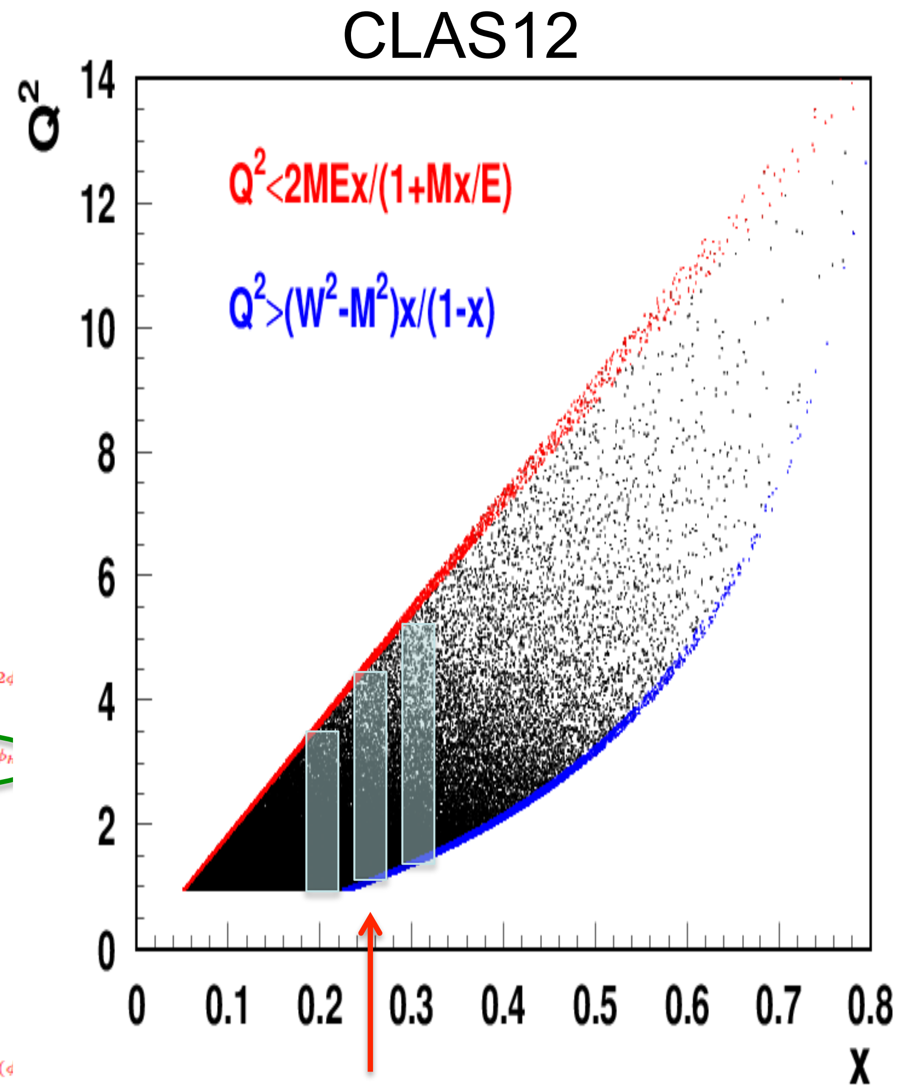
$$+ S_L \lambda_e \Big[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_h\, F_{LL}^{\cos\phi_h} \Big]$$

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

$$+ \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S}$$

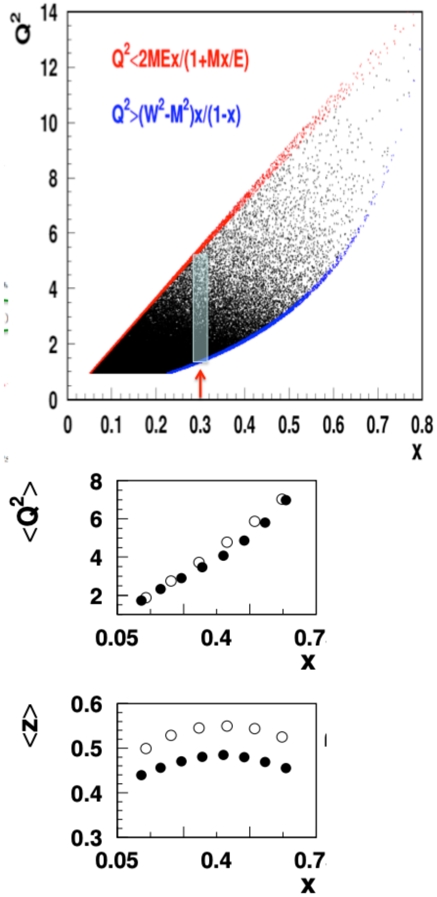
$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big] + S_T \lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)}$$

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

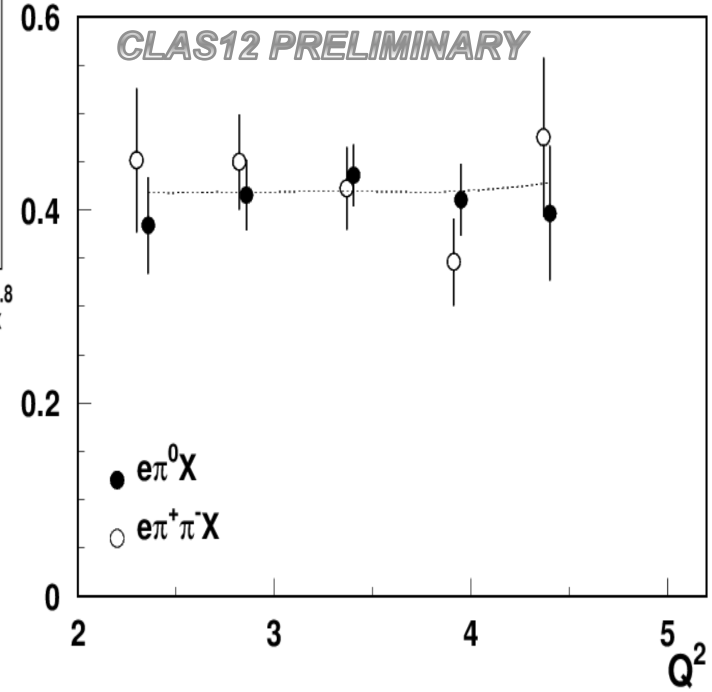


x-slices to study Q^2-dependence

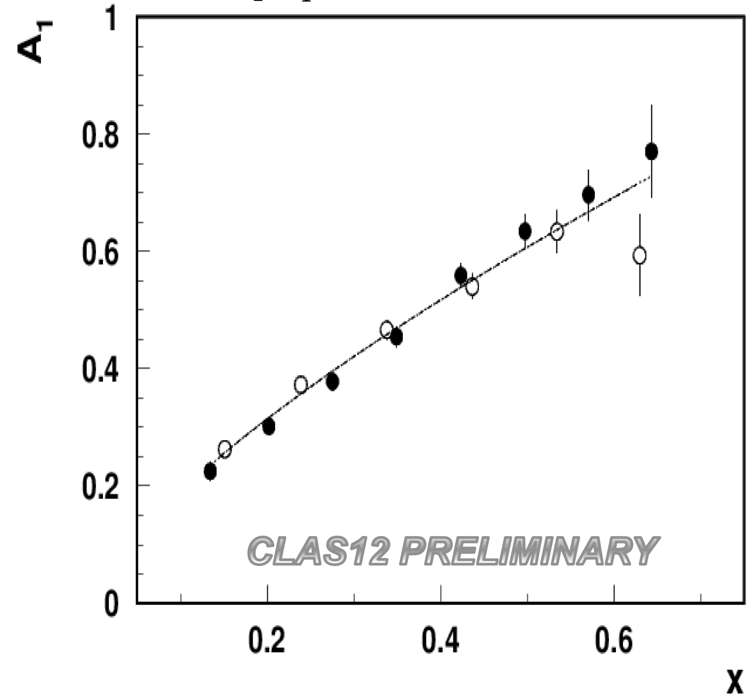
A_1 x-dependence for ep→e'π^0X vs ep→e'π+π−X



0.3<z<0.8, y<0.75



$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$



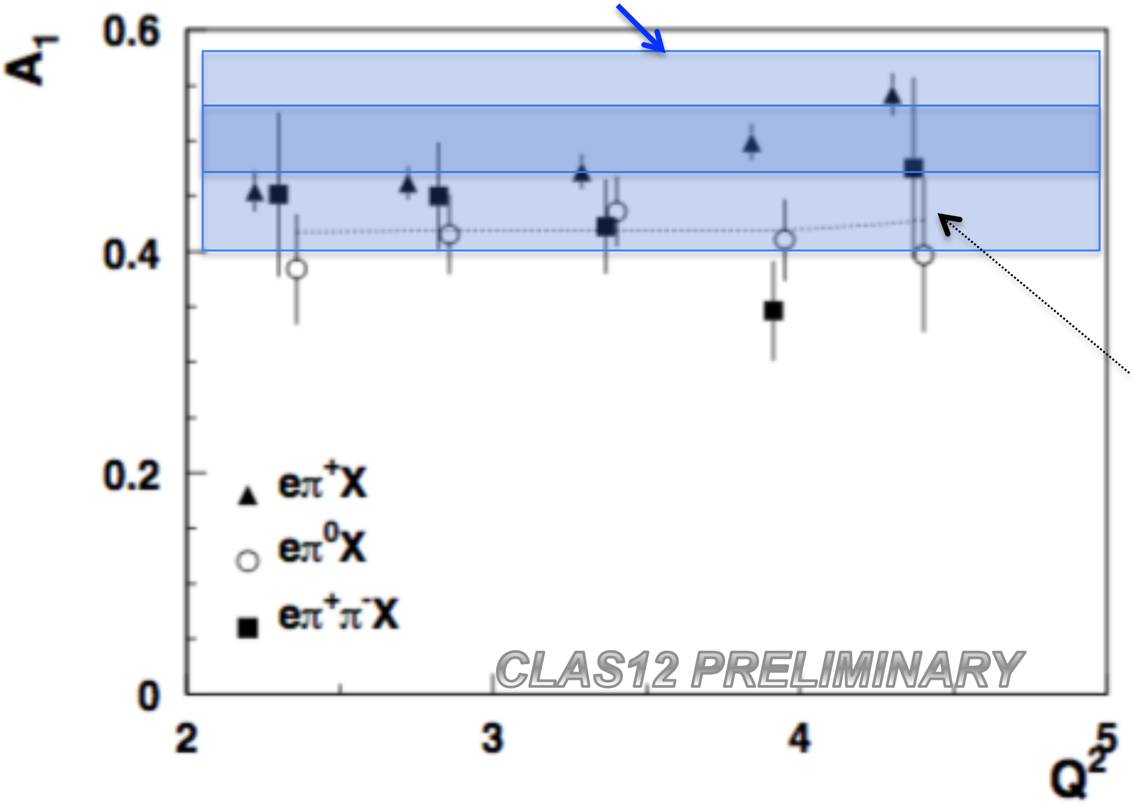
the line $x^{0.72}$(DIS)

- DSA extracted for ep→e'π^0X (filled) and ep→e'π+π−X for 0.3<z<0.8(empty circles) consistent
- No contributions from exclusive ep→e'ρ^0X
- Consistent with simple fit to world data (no major Q^2-dependence)

DSAs: comparing different processes

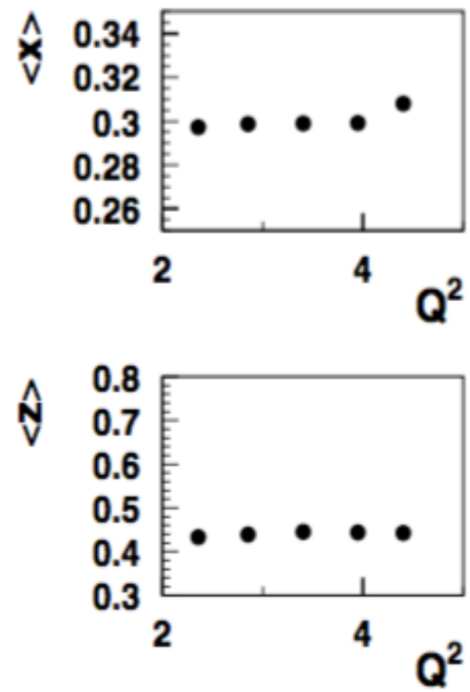
$0.28<x<0.32$, $0.3<z<0.8$, $y<0.75$

A. Bongallino(ep→e'π+X)



the DIS line $x^{0.72}$

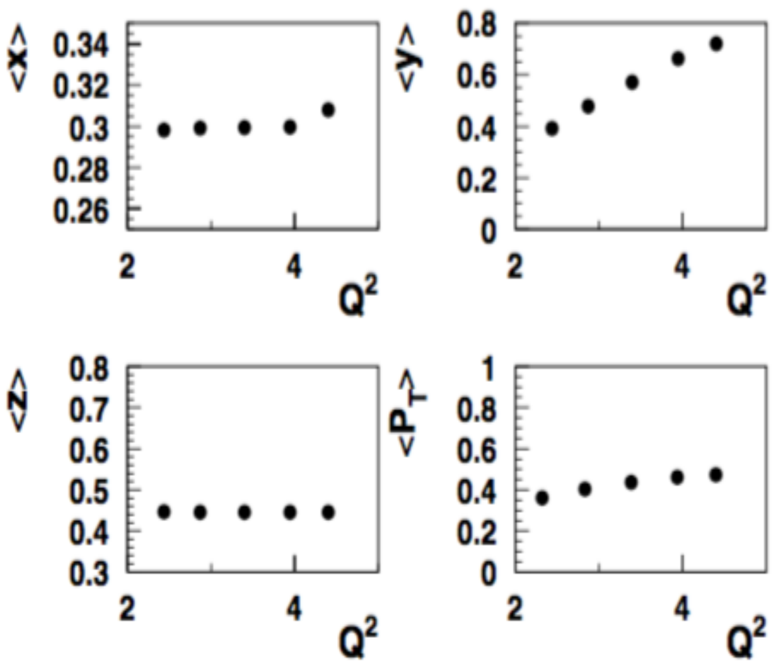
ep→e'π+X



- DSA for ep→e'π+X vs ep→e'π0X and ep→e'π−π+X consistent
- No major Q^2-dependence apart from for ep→e'π+X

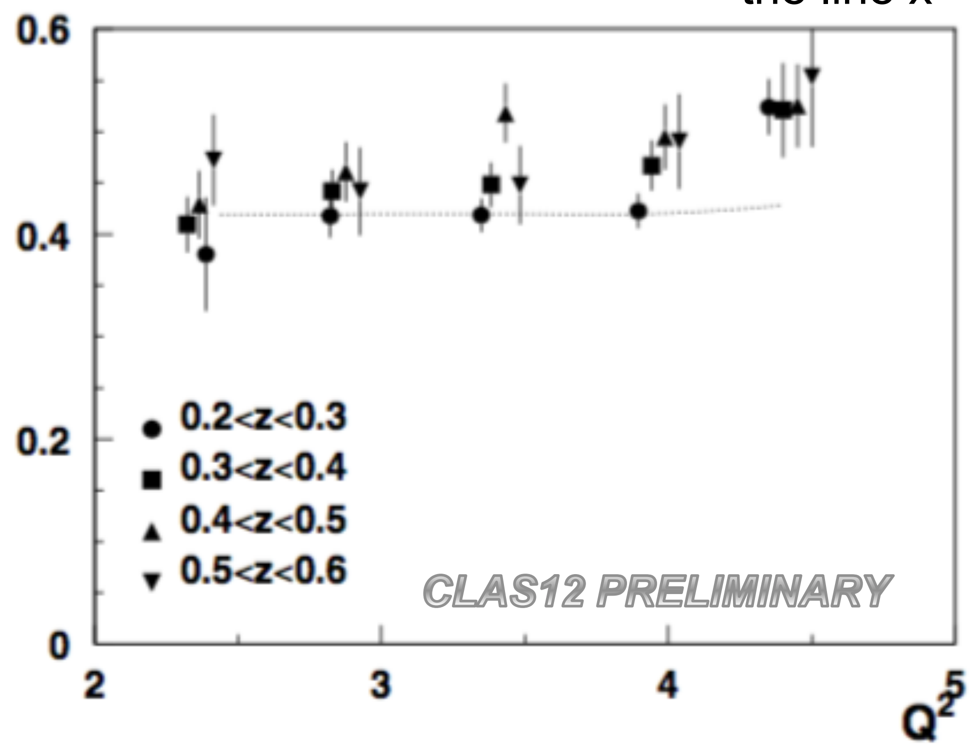
DSAs: Q^2-dependence in z-bins

0.28<x<0.32, y<0.75



ep→eπ+X

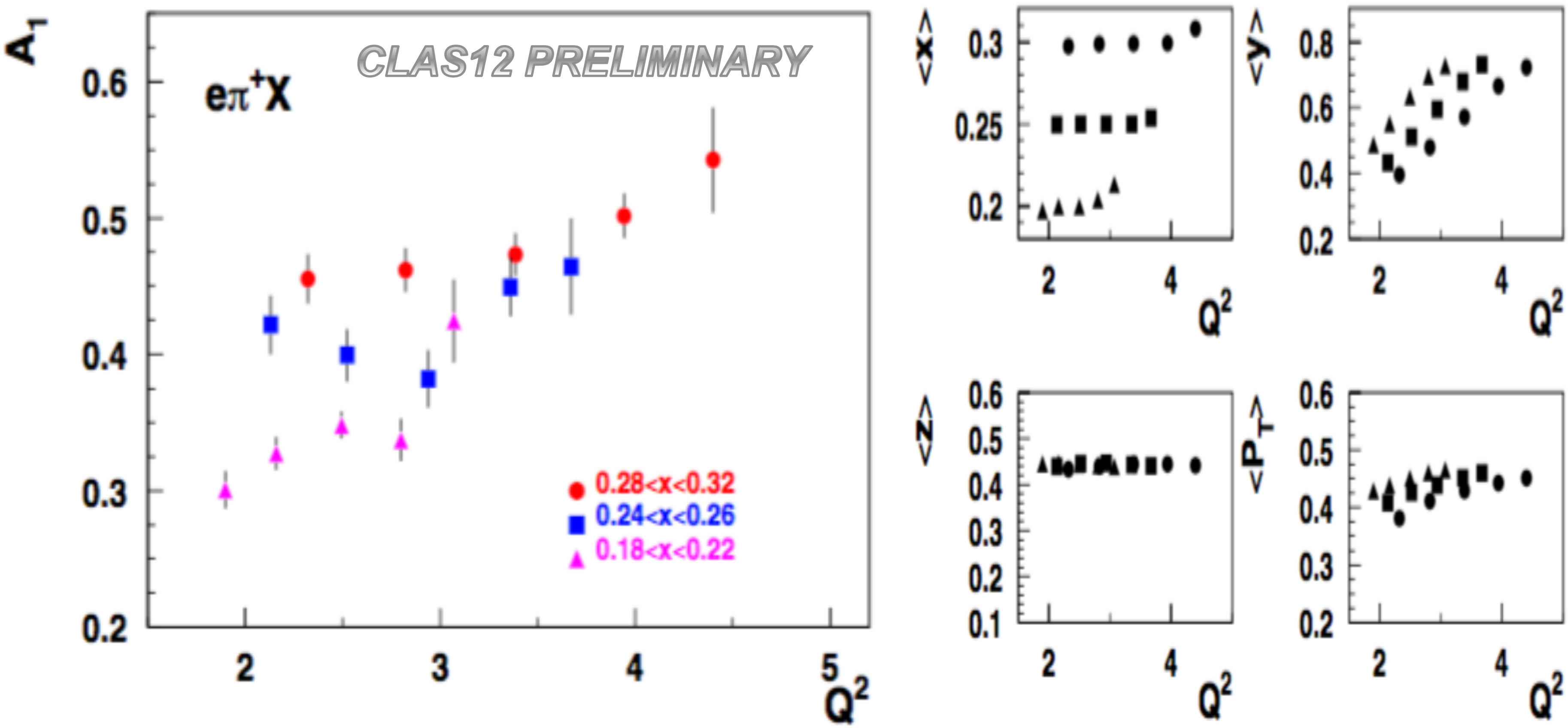
the line $x^{0.72}$



- DSA for ep→e'π+X for z-bins
- Tendency to increase with Q^2 stays for bins in z

DSA ep→e'π+X: more bins in x

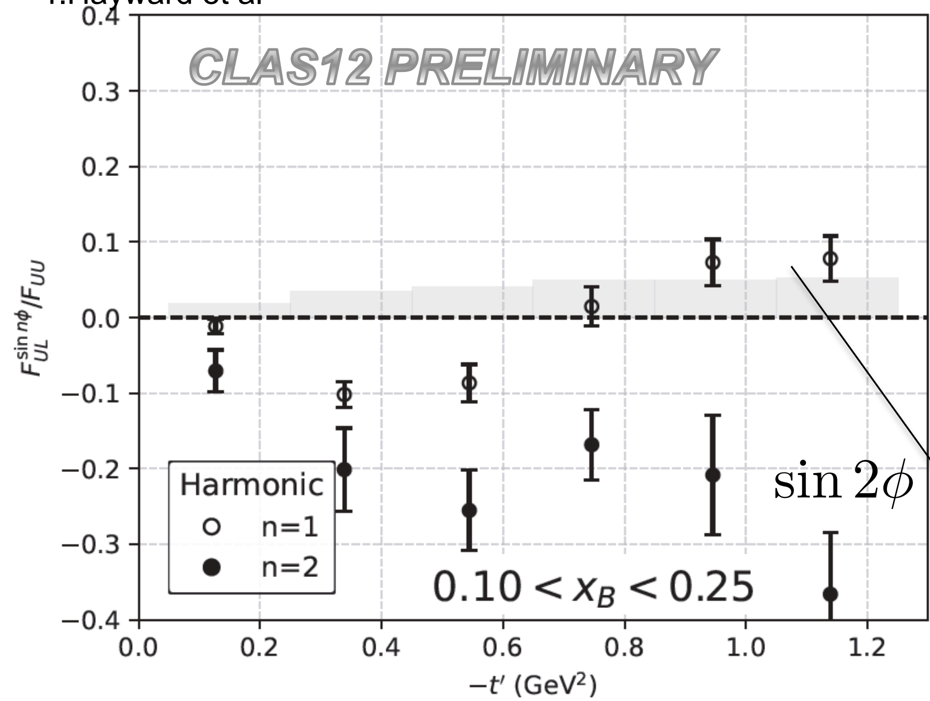
0.28<x<0.32, 0.3<z<0.8, y<0.75

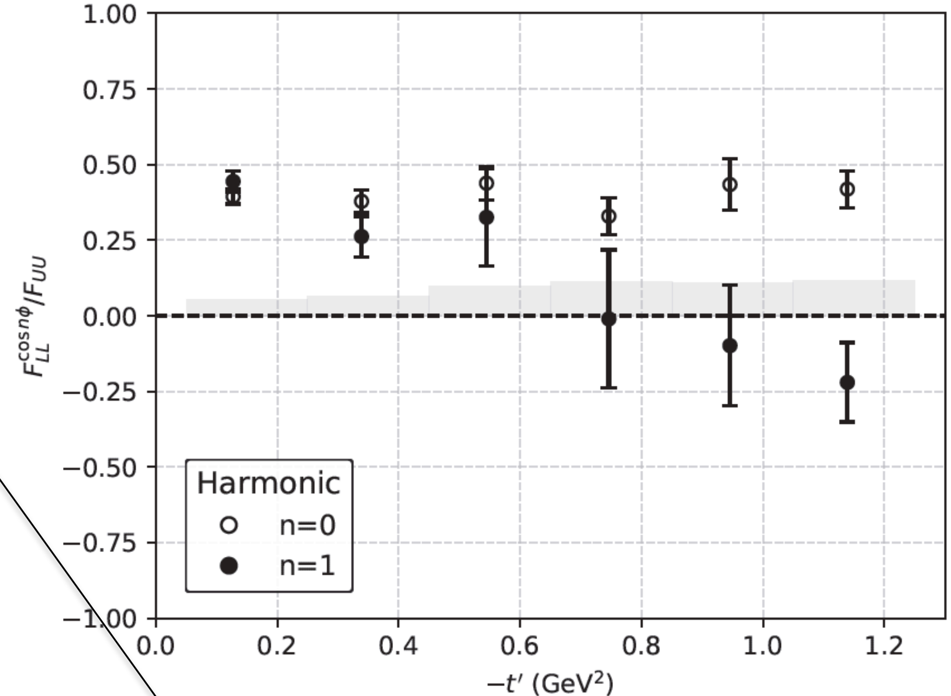


Inclusive (in progress) and π+ samples may have significant contributions from longitudinal photons (VMs)
Behavior of the double spin asymmetry for π+ is consistent with increase with Q^2

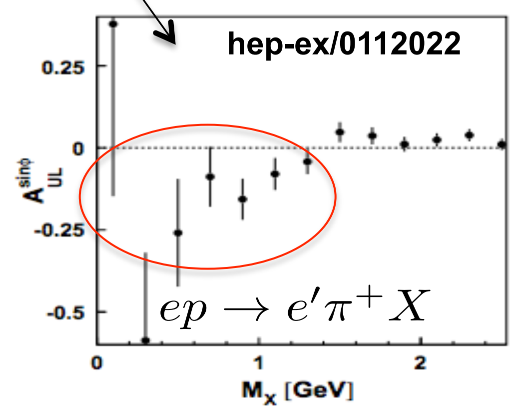
ep→e'π+X: exclusive limit for SSA and DSA

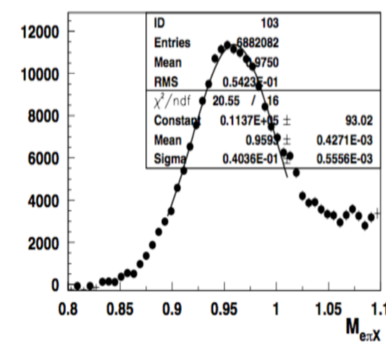
T.Hayward et al



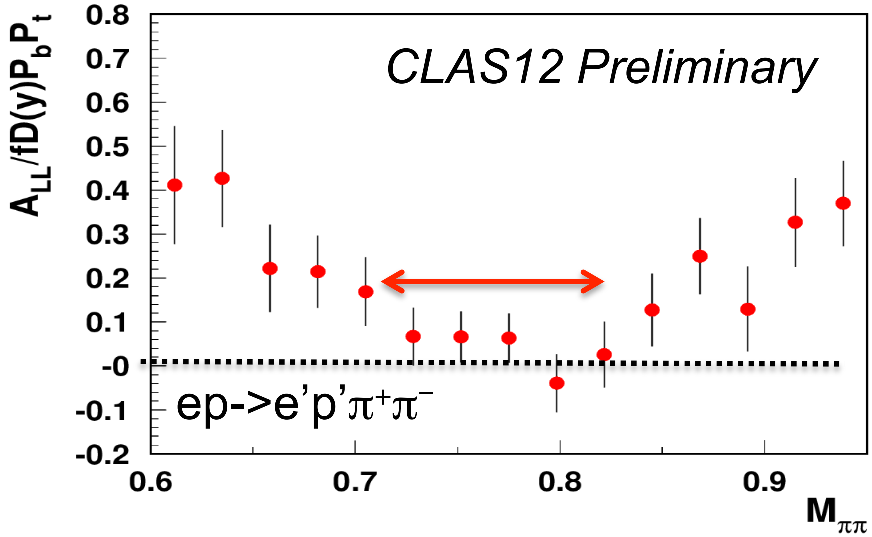


At low *x (low t)* CLAS12 observes negative <sinϕ> consistent with HERMES
The <sin2ϕ> observed by CLAS12 may provide direct access to GTMDs
(S. Bhattacharya et al hep-ph: 2312.01309)



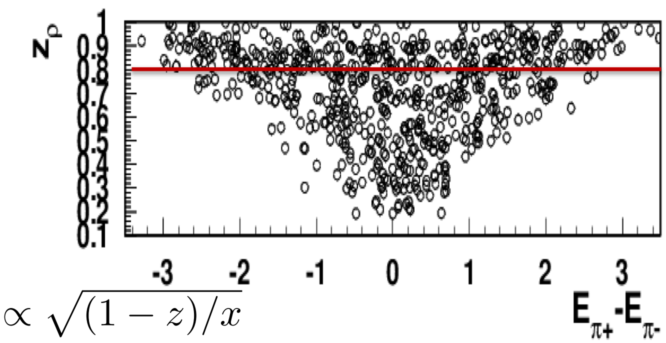


Studies of ρ^0 impact with longitudinally polarized NH_3 target

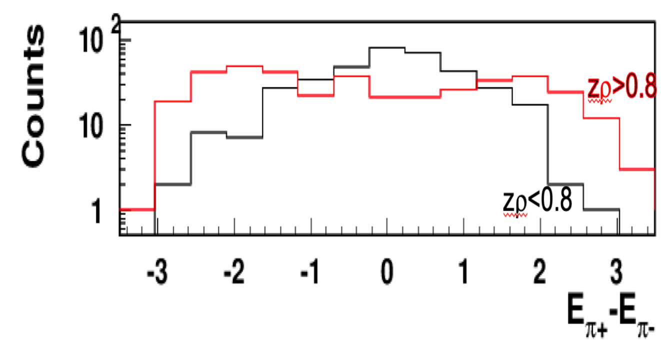


Need clear separation of hydrogen from NH_3
and "diffractive" exclusive ρ0s from exclusive π+π−

Polarization of rho



$$\gamma_T^* \to \rho_L \propto \sqrt{(1-z)/x}$$

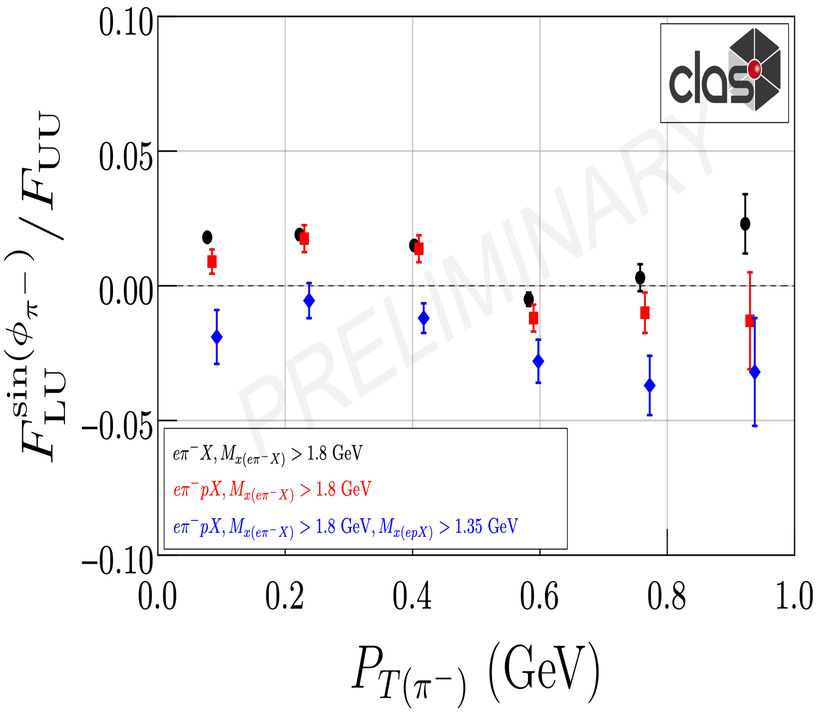


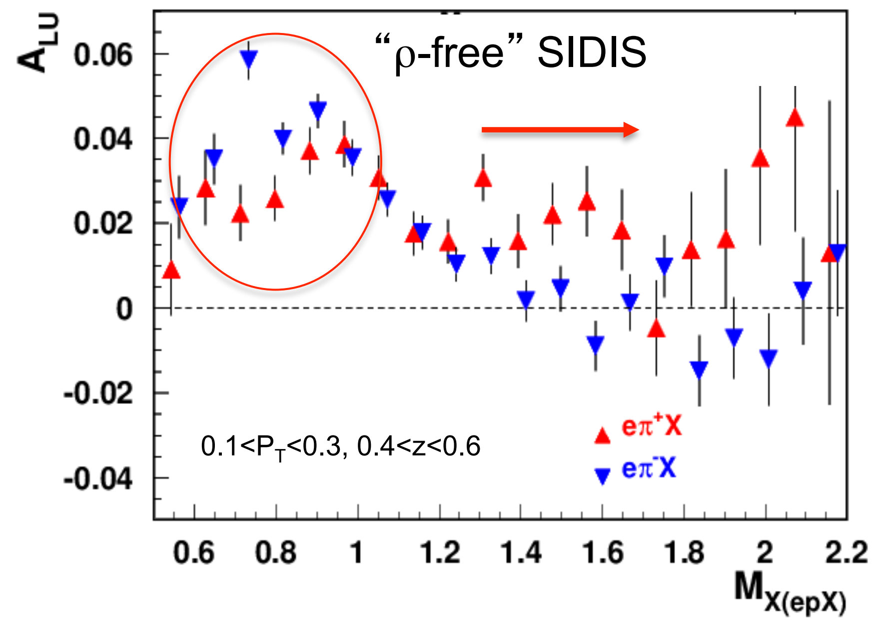
- DSA is P-even, SSA is P-odd
- longitudinal photon cross section is P-odd

→ contribution appears only in the SSA, a P-odd observable, and does not appear in DSA(→significant dilution in DSA)

At large z (small t) the shapes of distributions (getting asymmetric) clearly indicate dominance of longitudinal rho

Exclusive ρ contributions to π: P_T-dependence





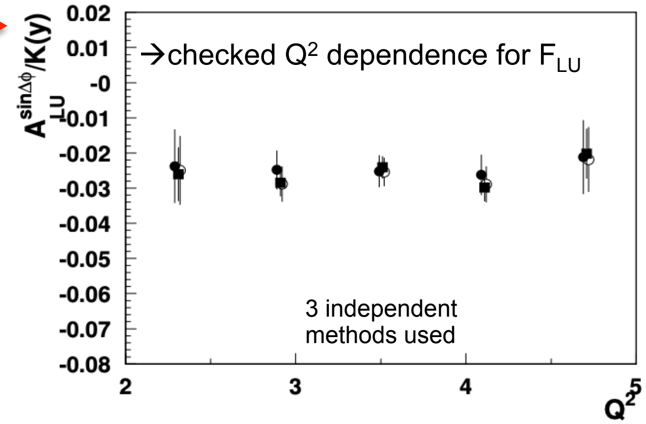
- Can change the pion SSAs, in particular at small PT
- The same sign and size of π+ and π- SSA indicates the rho0 may not be properly subtracted(require detailed MC studies, which require proper SDMEs)
- While VM contributions are ~20% in multiplicities in SSA they can be >100%
- Detection of the target proton introduces much smaller bias on the inclusive charged pion SSA, than the exclusive rho contributions

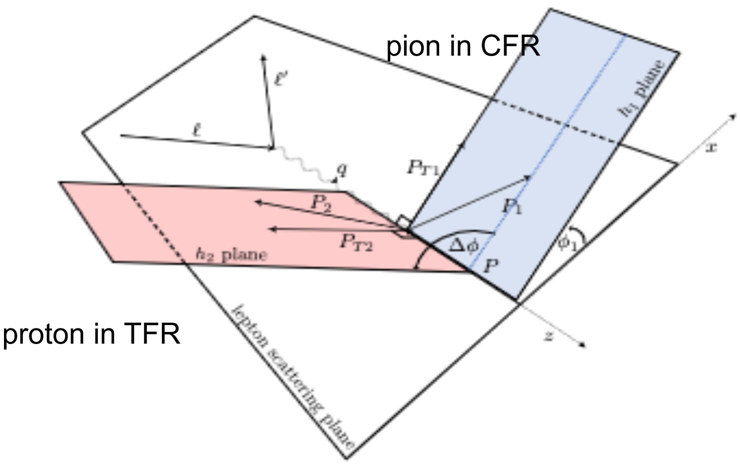
Azimuthal modulations in B2B production

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

$$\sigma_{LU} = -\frac{P_{T1}P_{T2}}{m_N m_2} F_{k1}^{l_1^{\perp h} \cdot D_1} \sin(\Delta\phi),$$

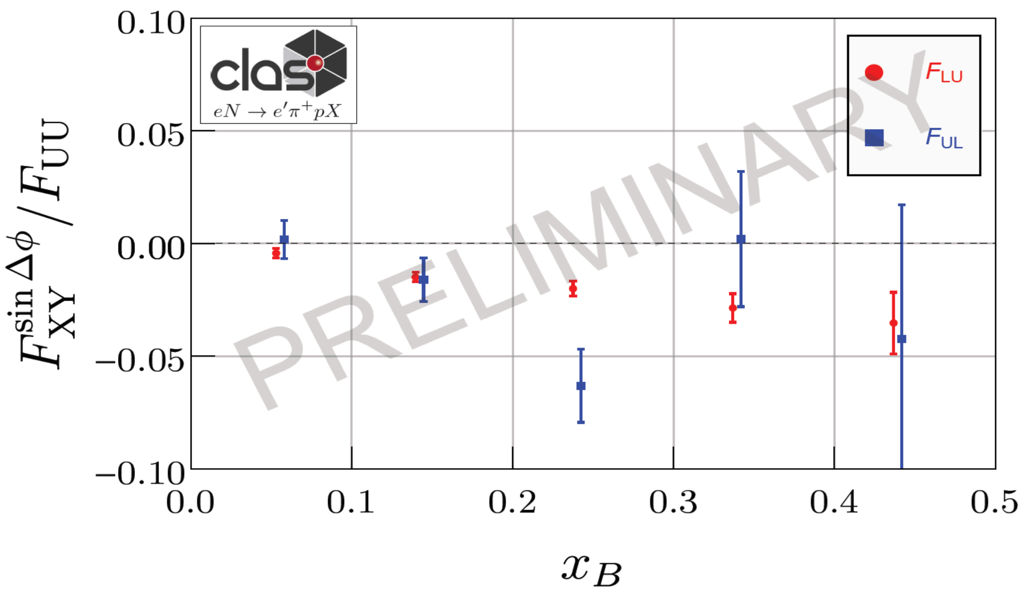
$$\sigma_{UL} = -\frac{P_{T1}P_{T2}}{m_N m_2} F_{k1}^{\hat{u}_{1L}^{\perp h} \cdot D_1} \sin(\Delta\phi)$$





→ F_{UL} and F_{LU} comparable (consistent with epX))

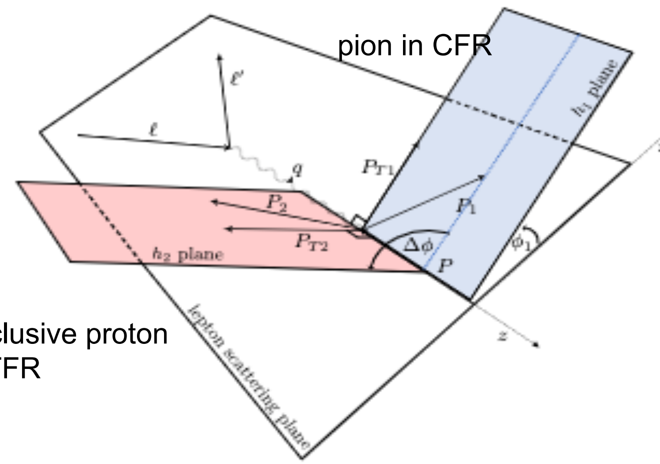
→ No suppression at higher energies for F_{UL}



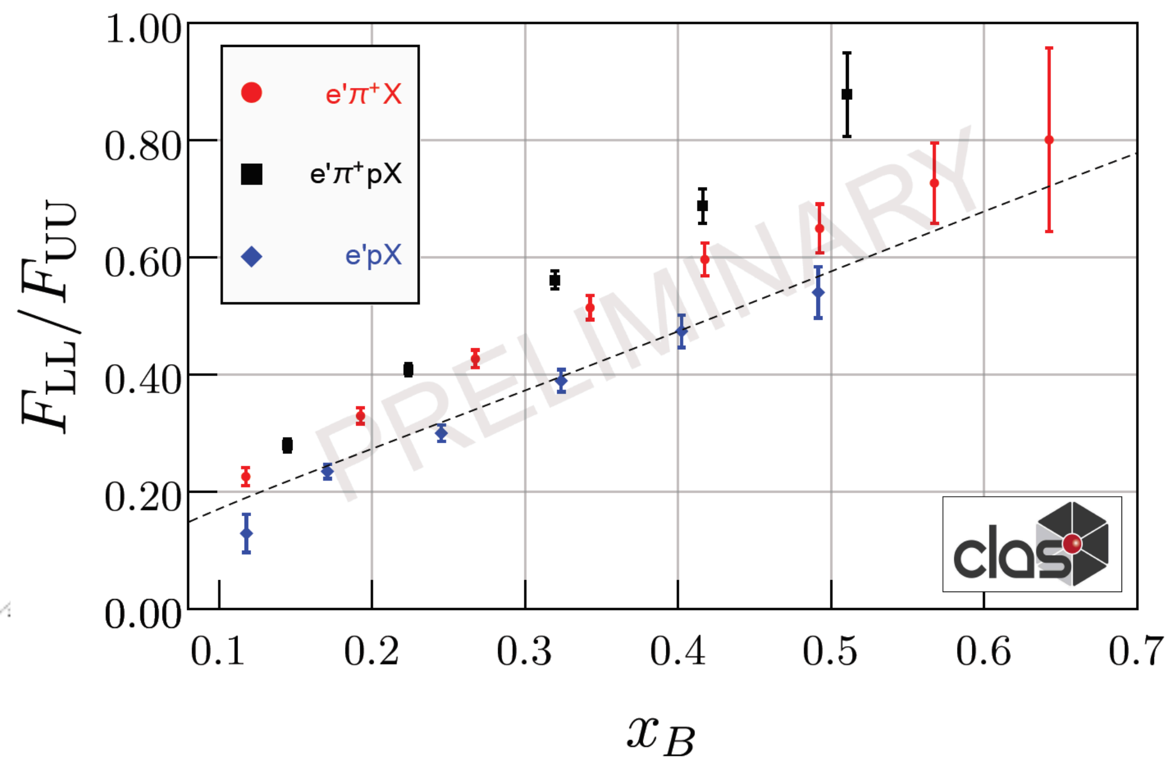
Full CLAS12 longitudinally polarized target set (x4) will provide a significant measurement of the target single spin asymmetry $A_{UL}^{\sin\Delta\phi}$, which has no suppression at higher energies and can be measured at colliders!

B2B production: exclusive baryon in TFR

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



Exclusive proton in TFR



Detection of proton allows implementation of the “rho free” SIDIS. The same DSA ep→eπ+X with detection of proton, allowing to cut out the exclusive rho is higher.

theory

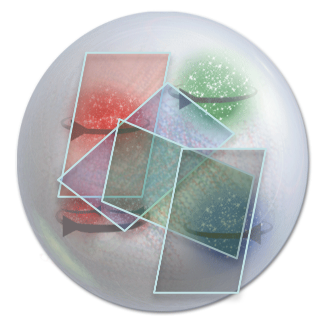
•Semi-exclusive processes, involving GPDs/ GTMDs on proton side (TFR) and FFs on pion side (CFR) Yuan and Guo

Theory-Experiment Dialogue: How to proceed

1. Keeping the formalism the same, including the input data where it works well, and try to get a better description using more sophisticated TMD models for TMD PDFs, and TMD FFs.

2. Try to extend the theory adding contributions assumed irrelevant in existing phenomenology, including also accounting of NLO terms. Note that all kinds of perturbative calculations for azimuthal moments (sin,cos, F_UU,L,...) in perturbative approaches were order of magnitude less than non-perturbative quantities (ex. Cahn)

3. Try to extend the theory coverage by eliminating from the input data set the contributions that are not accounted for in the phenomenology, most importantly the longitudinal photon contributions



Measurements of Q^2-dependence of observables is key for validation!!!

summary

Huge amount of semi-inclusive and exclusive hadron production data accumulated by CLAS12 allowing detailed studies of variety of contributions, critical for providing adequate data for QCD phenomenology for 3D studies (TMDs and GPDs/GTMDs?)

- First data from longitudinally polarized target, confirms importance of sorting out longitudinal photon contributions in general, and longitudinal rho0s, in particular
- Studies of evolution properties of all relevant observables has been shown to be a critical validation test
- *SIDIS in exclusive limit, may provide important info on transverse photon contributions in exclusive processes, the neutral pions (both exclusive and semi-inclusive), ready for phenomenological studies!!!*

Support slides

Connecting M_X, t, P_T and z

ep→e'π^0X (M_X=M_P, t=(γ^*-$p_{\pi 0}$)^2)

exclusive limit M_X=M_P ↗

$$z(t) = z_0 + at, \qquad a = \frac{x_B}{Q^2}, \qquad z_0 = 1 + \frac{x_B(M_P^2 - M_X^2)}{Q^2}$$

$$P_T^2(t) = z^2\nu^2 - m_\pi^2 - \frac{(t + Q^2 - m_\pi^2 + 2z\nu^2)^2}{4(\nu^2 + Q^2)}.$$

$$P_T^2(t) = \nu^2\left(1 + \frac{x_B t}{Q^2}\right)^2 - m_\pi^2 - \frac{\left[Q^2 - m_\pi^2 + 2\nu^2 + t\left(1 + \frac{2\nu^2 x_B}{Q^2}\right)\right]^2}{4(\nu^2 + Q^2)}$$

In the small-$|t|/Q^2$ limit and neglecting m_π^2,

$$P_T^2(t) \simeq -(1 - x_B)t = (1 - x_B)|t|.$$

→ $$\frac{d\sigma}{d|t|} \propto (1 - x_B)\exp\left[-\frac{(1 - x_B)|t|}{2\sigma^2}\right]$$

$$\frac{d^5\sigma^{\ell p \to \ell h X}}{dx_B\, dQ^2\, dz_h\, d^2\mathrm{P}_T} = \frac{2\pi\alpha^2}{Q^4}\frac{y^2}{1-\epsilon}\sum_q e_q^2 f_q(x_B)\, D_q^h(z_h)\frac{1}{\pi\langle P_T^2\rangle}e^{-P_T^2/\langle P_T^2\rangle}$$

$$\langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle = 2\sigma^2,$$

Correlated slopes in P_T and t

$ep \rightarrow e'\pi^0 X$ ($M_X = M_P$, $t = (\gamma^* - p_{\pi 0})^2$)

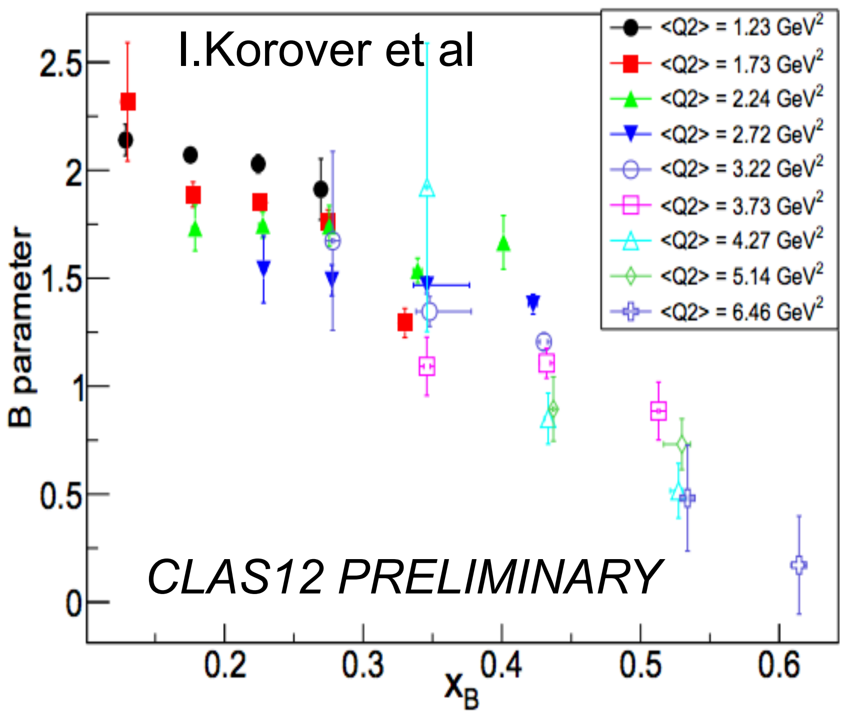
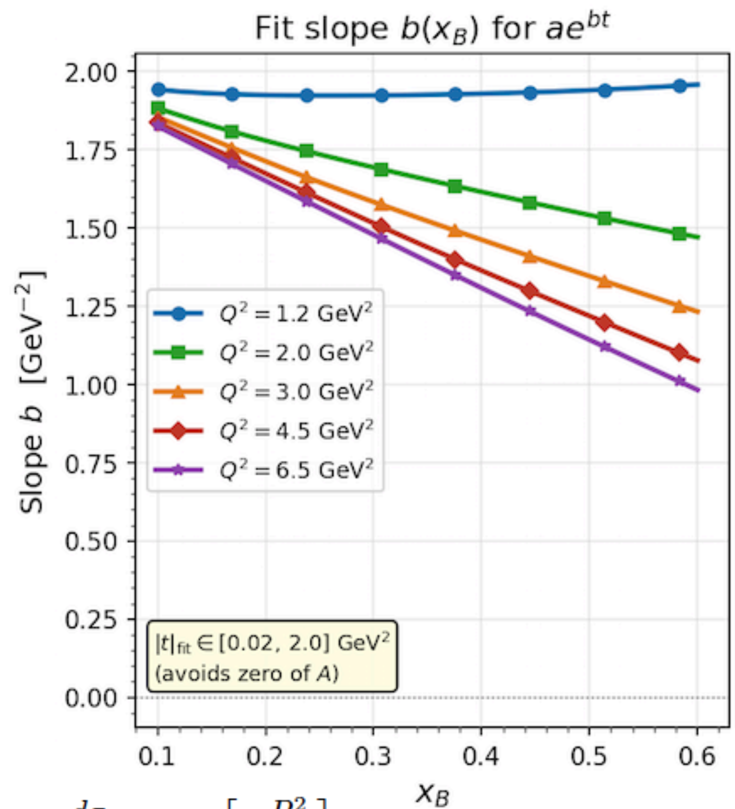


Figure 68: The extracted B parameters for multiple Q^2 bins as function of x_B. The Q^2 value is average value of the Q^2 value that was used to extract the structure function at the relevant bin.



$$\frac{d\sigma}{d^2 P_T} \propto \exp\left[-\frac{P_T^2}{2\sigma^2}\right]$$

$$\frac{d\sigma}{dt} \propto \left|\frac{dP_T^2}{dt}\right| \exp\left[\frac{z_{\rm excl} t + z_{\rm excl}(1 - z_{\rm excl})Q^2 + (1 - z_{\rm excl})m_\pi^2}{2\sigma^2}\right]$$

$$z_{\rm excl} = 1 + \frac{x_B t}{Q^2}$$