

Polarized SIDIS at CLAS12

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w/ input from
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Research Supported by



U.S. DEPARTMENT OF
ENERGY

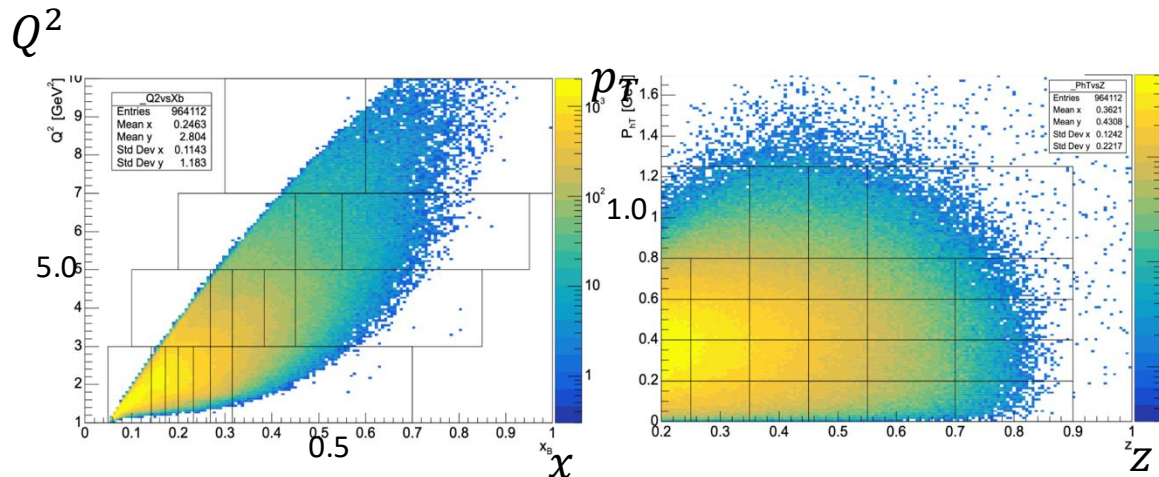
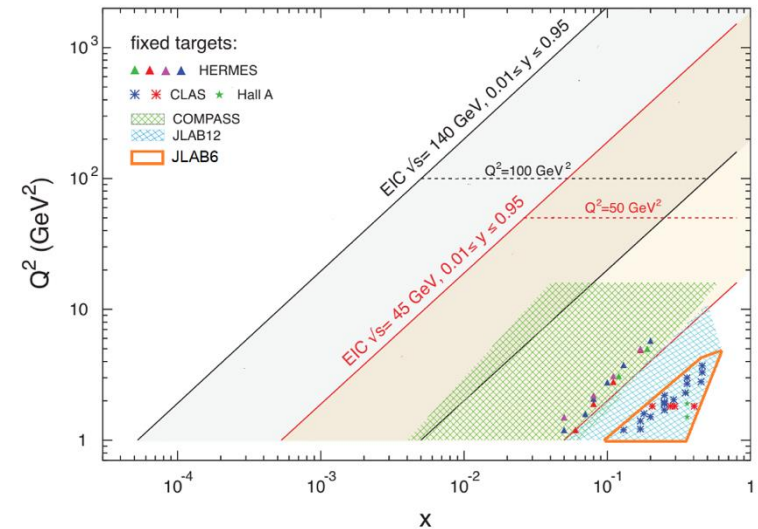
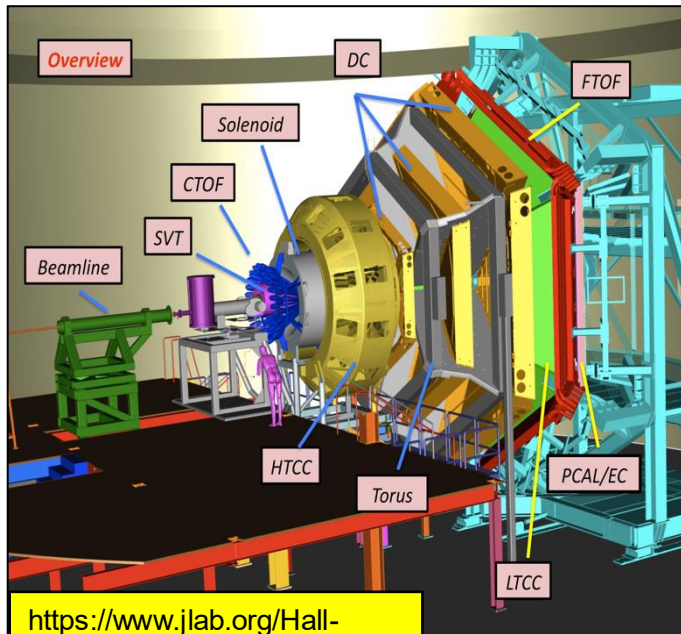
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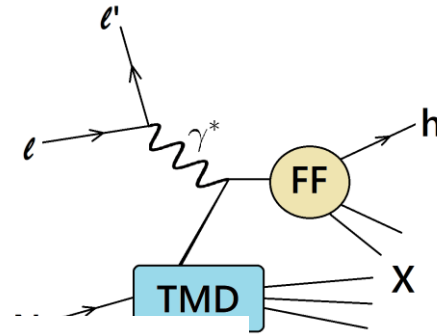
Duke
UNIVERSITY

CLAS12 Spectrometer

- CLAS12: high luminosity (10^{34}), wide acceptance, low Q^2 (higher twist measurements)
- Began data taking in Spring 2018 – many “run periods” now available: liquid H_2 , D_2 , polarized NH_3 and ND_3 etc.
- ~ 10.5 GeV electron beam, longitudinally polarized beam.



SIDIS Observables at CLAS12



Run Group A (Unpolarized LH₂ target)

- ★ unpolarized SIDIS cross section off proton
- ★ A_{LU} in Beam Spin Asymmetries

Run Group B (Unpolarized LD₂ target)

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

Run Group C (longitudinally polarized NH₃ and ND₃)

- ★ F_{UL} and F_{LL}

Run Group K (Unpolarized LH₂ target)

- ★ 6.5, 7.5, 8.4 GeV e- beam
- ★ $F_{UU,L}$, $F_{UU,T}$ Separation

Run Group H (transversely polarized NH₃)

- ★ F_{UT} structure function

→ scheduled for FY 2029

The CLAS12 physics program will have access to the full SIDIS cross section including all observables in a variety of flavors.

$$\frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right.$$

$$\left. + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} \right.$$

$$\left. + S_{\parallel} \left[\sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \right.$$

$$\left. + S_{\parallel} \lambda_e \left[\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \right.$$

$$\left. + |S_{\perp}| \left[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right. \right.$$

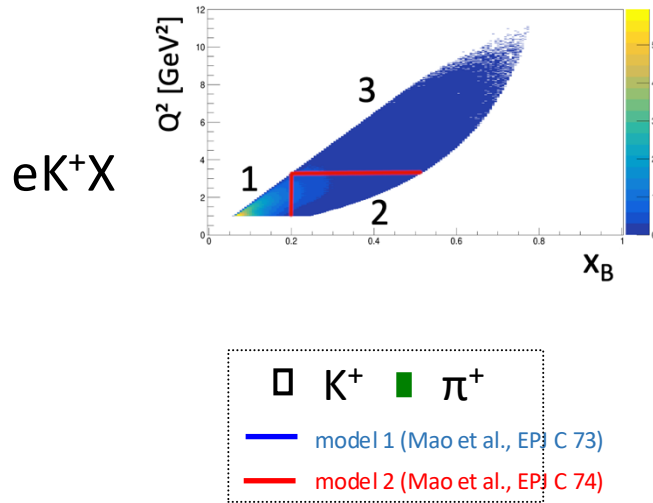
$$\left. + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \right.$$

$$\left. + \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right]$$

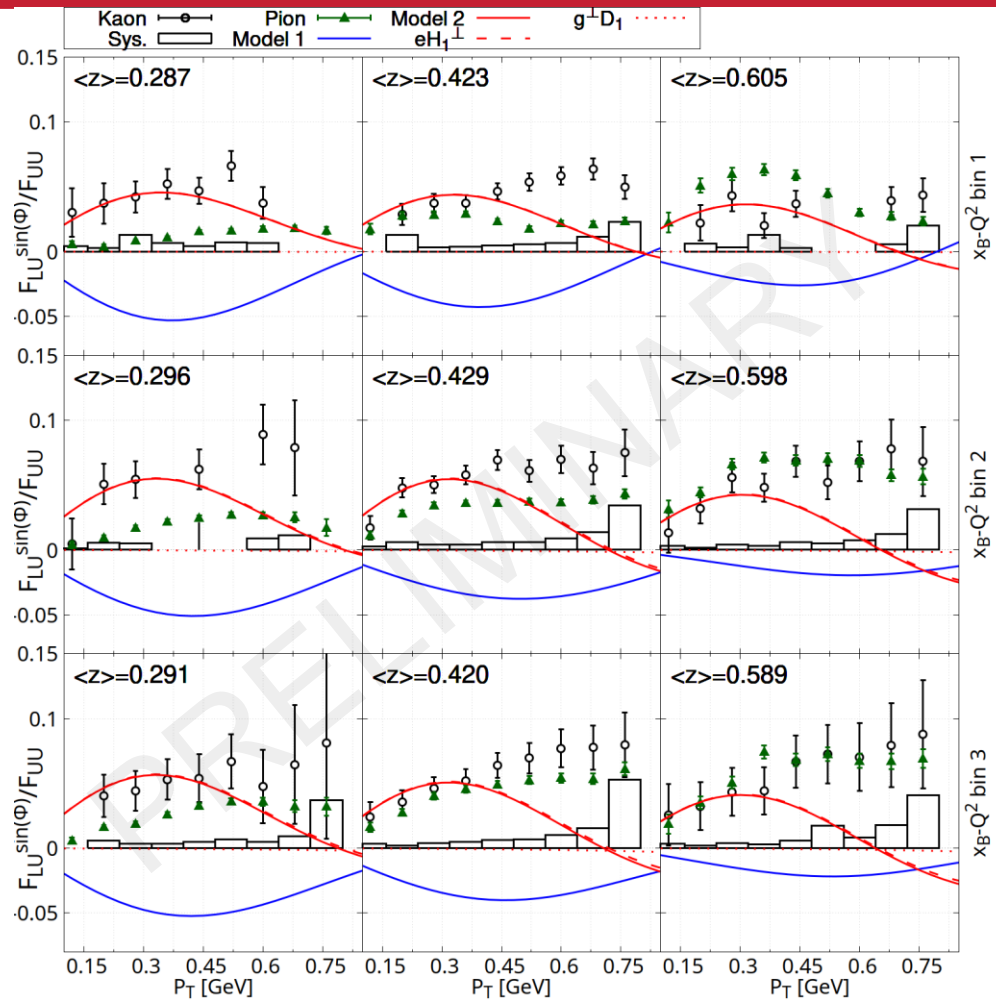
$$\left. + |S_{\perp}| \lambda_e \left[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \right. \right.$$

$$\left. + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \left. \right\}$$

Beam Spin Asymmetries of Single Hadrons



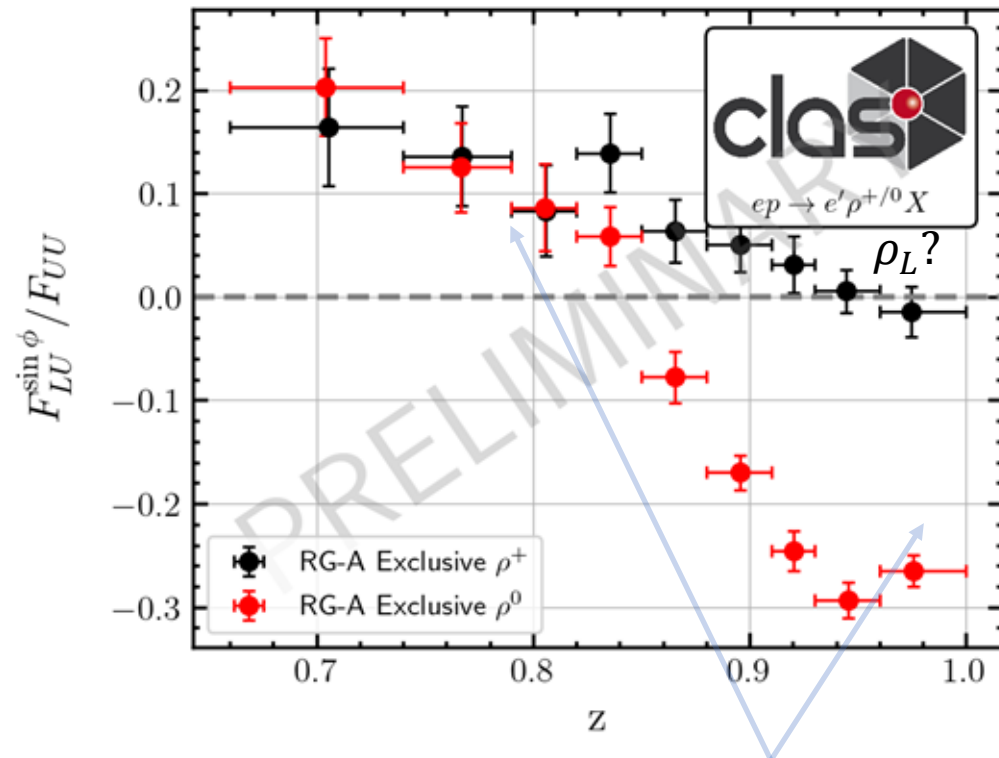
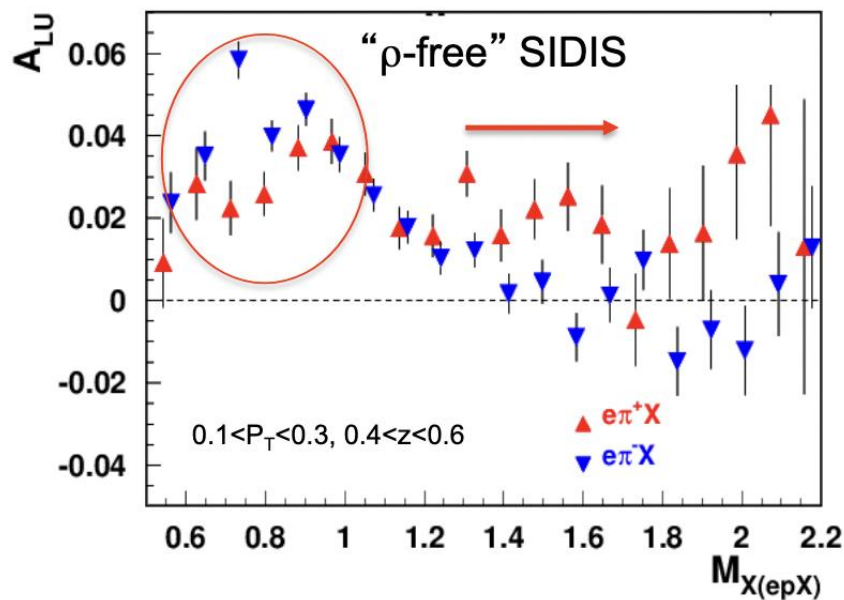
- Reasonable assumption of u-quark dominance
- Differences either from fragmentation functions or distinct VM contributions



$$F_{LU}^{\sin \phi_h} = \frac{2M}{Q} \mathcal{C} \left[-\frac{\hat{h} \cdot k_T}{M_h} \left(x \underbrace{e \boxed{H_1^\perp}}_{\text{Collins FF}} + \frac{M_h}{M} \underbrace{f_1 \boxed{\tilde{G}^\perp}}_{\text{twist-3 FF}} \right) + \frac{\hat{h} \cdot p_T}{M} \left(x \underbrace{g^\perp \boxed{D_1}}_{\text{unpolarized FF}} + \frac{M_h}{M} \underbrace{h_1^\perp \boxed{\tilde{E}}}_{\text{Boer-Mulders}} \right) \right]$$

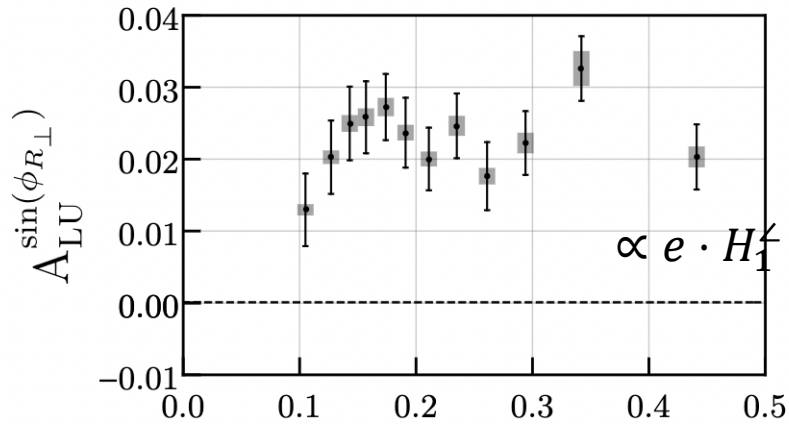
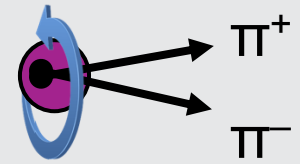
twist-3 chiral odd PDF
 twist-3 t-odd PDF
 Boer-Mulders

Background from Exclusive Vector Meson Production

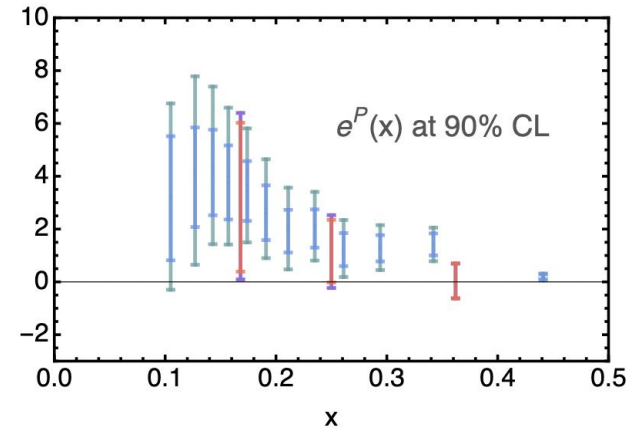


- ρ contribution depends on SDMEs
- Highly dependent on experimental acceptance

Better: di-hadrons



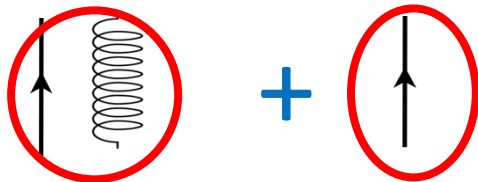
Phys.Rev.Lett. 126 (2021) 152501



Phys.Rev.D 106 (2022) 1, 014027

$$F_{LU}^{\sin\phi_R} \propto \frac{M}{m_{hh}} \mathbf{x} e(\mathbf{x}) \mathbf{H}^\perp(z, \cos\theta, m_{hh}) + \frac{1}{z} f_1 \tilde{G}^\perp(z, \cos\theta, m_{hh})$$

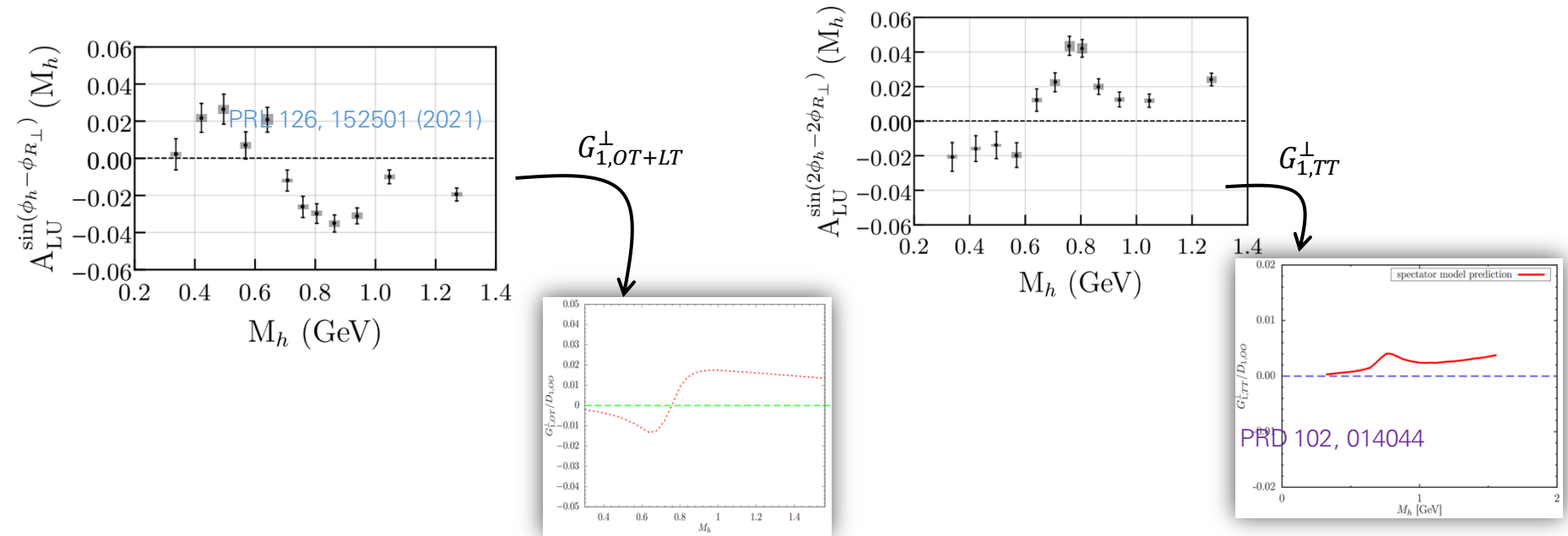
- First extraction of chiral odd $e(x) \rightarrow$ point-by-point! -



First Measurement of $G_1^\perp \rightarrow$ no 1h equivalent

- $d\sigma_{LU} \propto f_1 \otimes G_1^\perp$
- Fragmentation sensitive to quark helicity

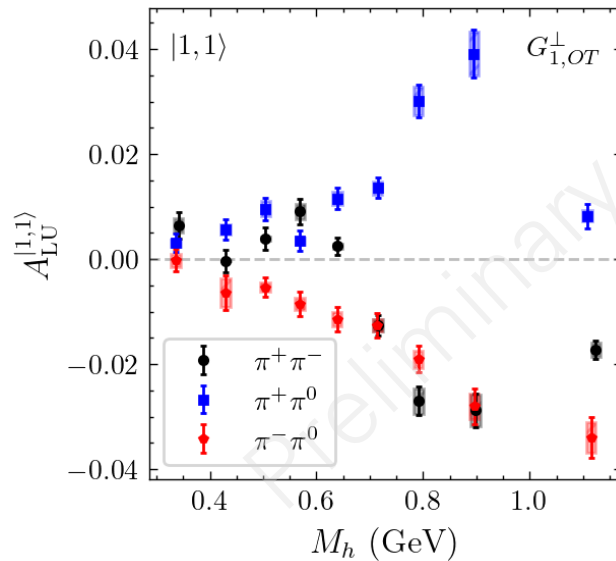
$d\sigma_{LU}$



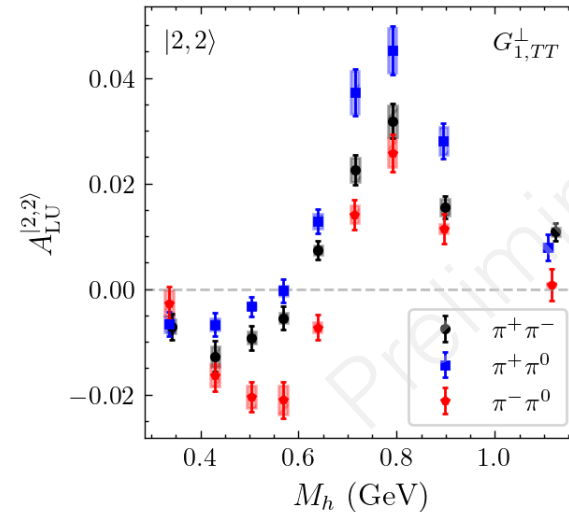
- First nonzero $G_1^\perp$ signal
- Resonance structure **predicted** by spectator models and **verified** at CLAS12

PRD 101, 054020

Flavor dependence of Different Partial Waves



$$A_{LU}^{[1,1]} \propto f_1(x) \otimes G_{1,OT}^\perp$$

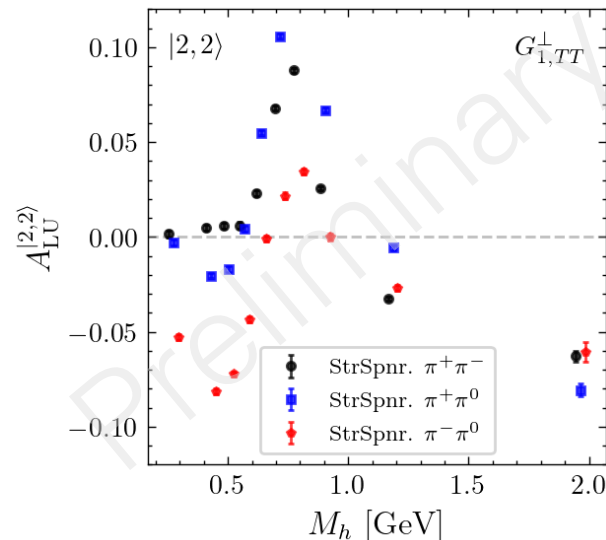
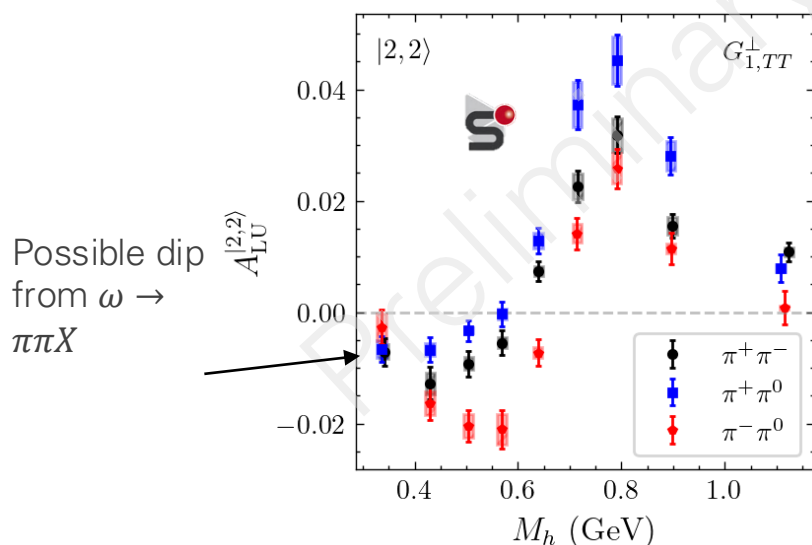


$$A_{LU}^{[2,2]} \propto f_1(x) \otimes G_{1,TT}^\perp$$

- Partial Waves are Flavor dependent
 - Different Decay Channels contribute to different PWs

Reproduction in Event Generator Models

- **StringSpinner** introduces *spin-dependent* fragmentation into PYTHIA8 based on the string+ $^3P_0$ model of hadronization ($q\bar{q}$ produced in $L = S = 1, J = 0$ quantum state)
- Pythia allows to extrapolate beyond validity of factorized QCD framework
- With parameter tuning, StringSpinner can replicate several of our dihadron beam-spin asymmetries across multiple $\pi\pi$ channels → huge step for phenomenology!

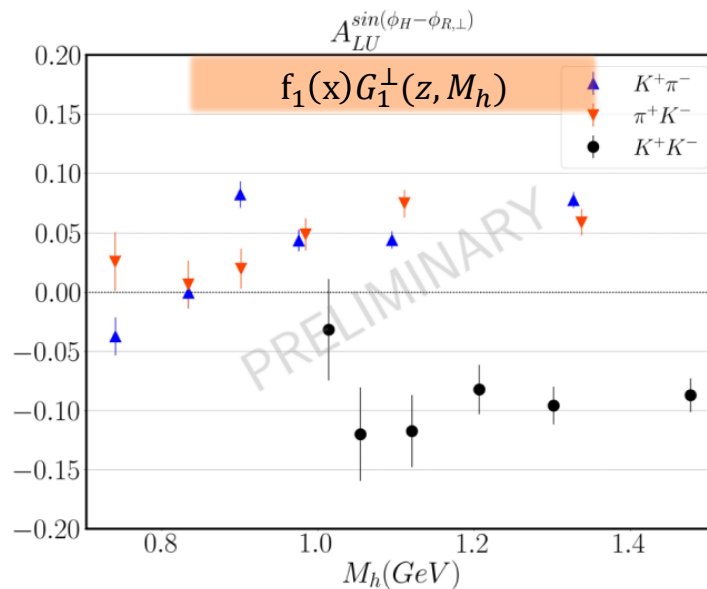
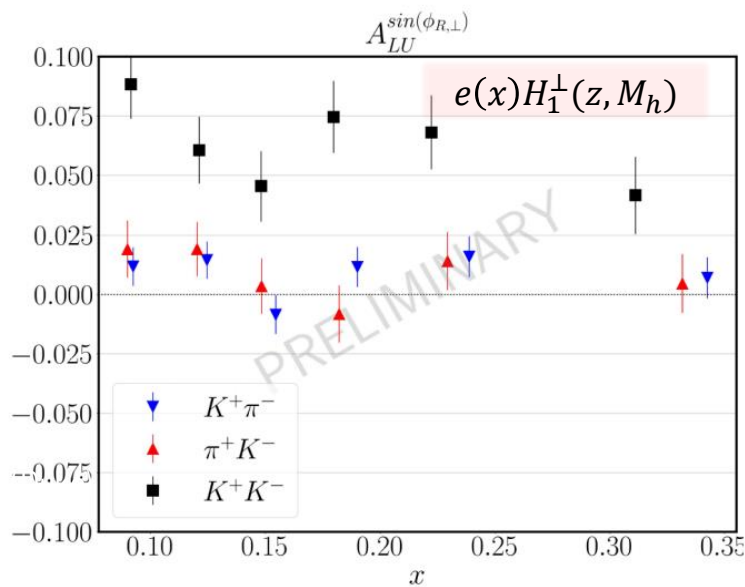


StringSpinner
Modeling

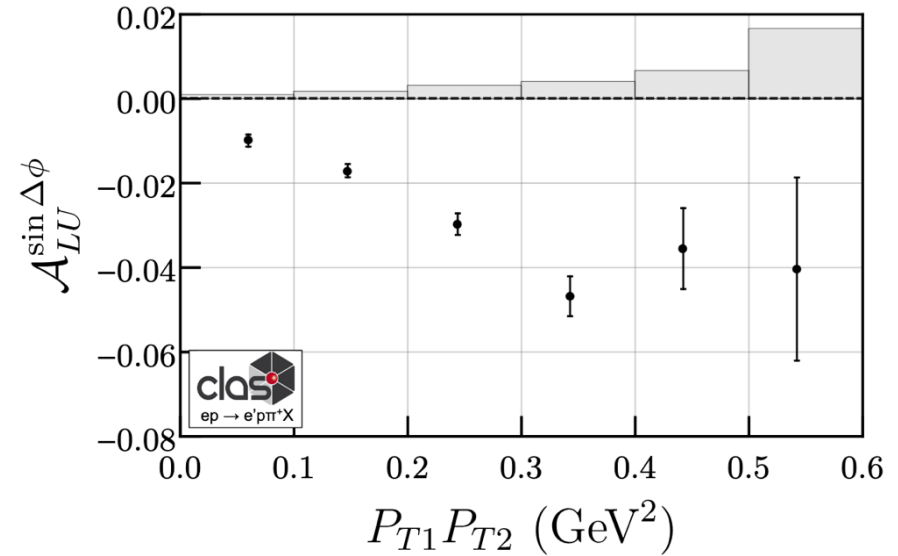
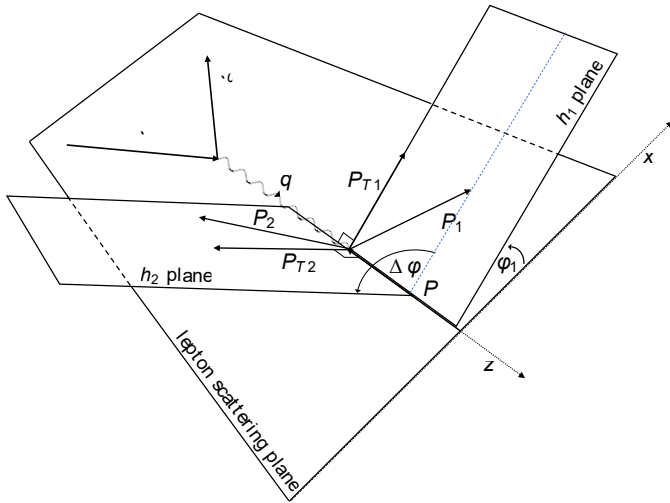


Large Kaon Asymmetries Currently not understood

- Large asymmetries observed in K^+K^- dihadrons $\rightarrow$ larger than $\pi^+\pi^-$ dihadrons! (compare to large A_C at BaBar)
- Correlations of πK appear absent in $H_1^\perp$ DiFF (left plot) yet large in $G_1^\perp$ (right plot)
- Access to K^* and ϕ vector meson contributions to single hadron SIDIS



First observation of correlations between Current and target region



- “back-to-back” configuration h_1 in the CFR h_2 in TFR → convolution of a **fracture function** and a **fragmentation function**.
- Unique access to longitudinally polarized quarks in unpolarized nucleons... no corresponding PDF!
- Make use of different asymmetries in CFR and TFR to distinguish regions

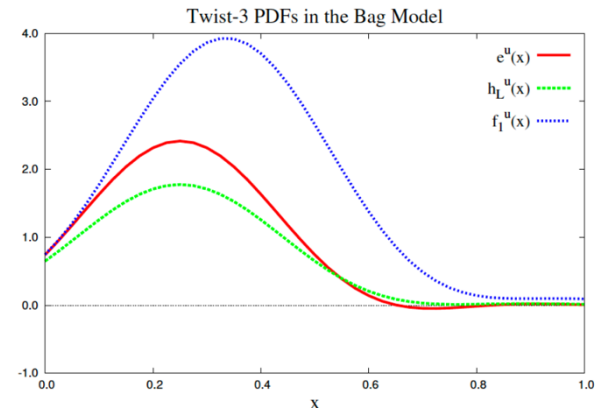
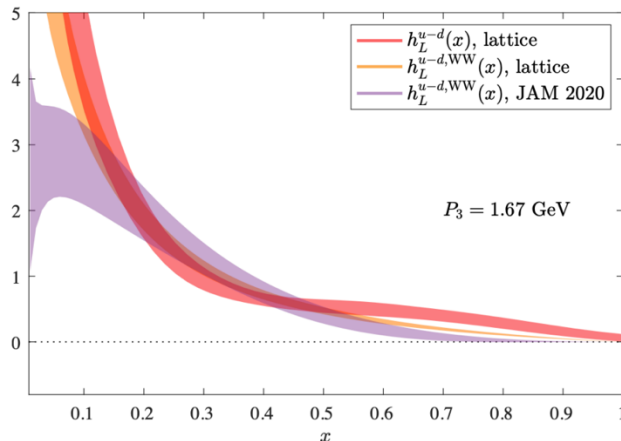
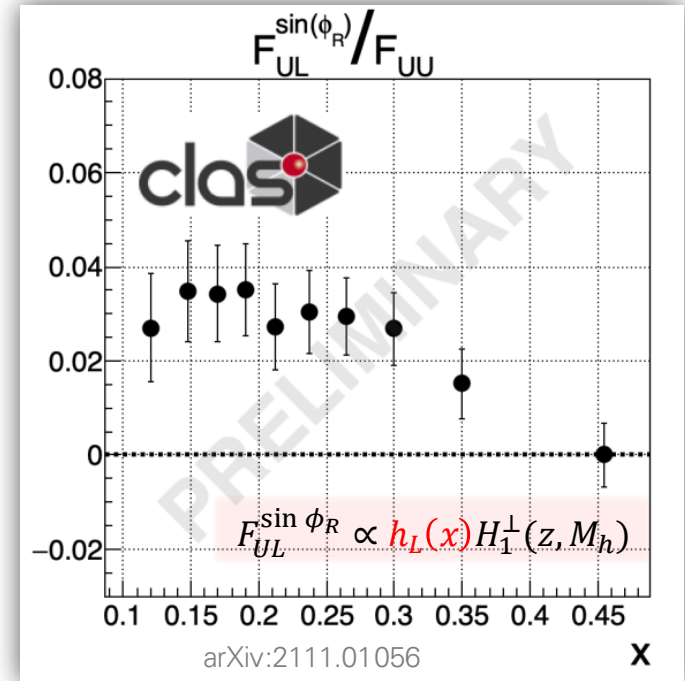
$$A_{LU} = -k(\epsilon) \frac{P_{T1} P_{T2}}{m_1 m_2} \frac{\mathcal{C} \left[w_5 \hat{l}_1^{\perp h}(x, \zeta_2, P_{T2}) D_1(z_1, P_{T1}) \right]}{\mathcal{C} \left[\hat{u}_1(x, \zeta_2, P_{T2}) D_1(z_1, P_{T1}) \right]} \sin(\Delta\phi)$$

		Quark polarization		
		U	L	T
Nucleon polarization	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	$\hat{u}_{1T}^h, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^h, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}^h, \hat{t}_{1T}^{\perp}$

New: Longitudinal Target SSAs

$$d\sigma_{UL}$$

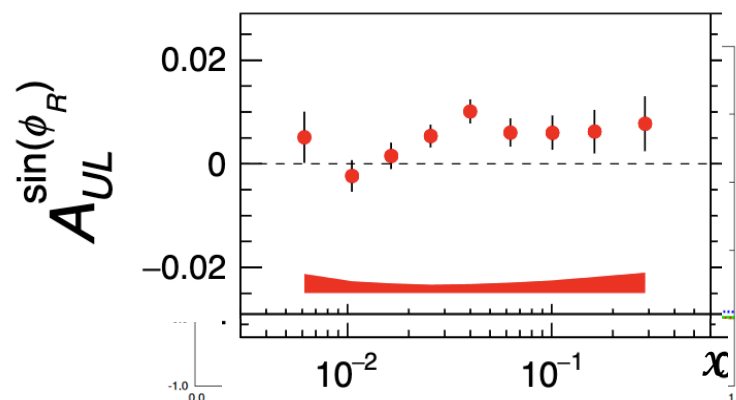
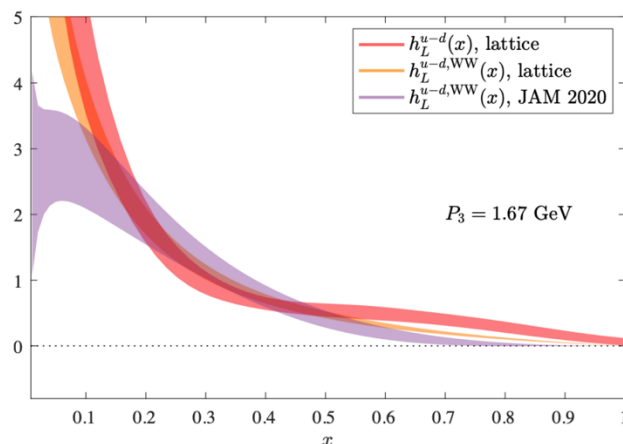
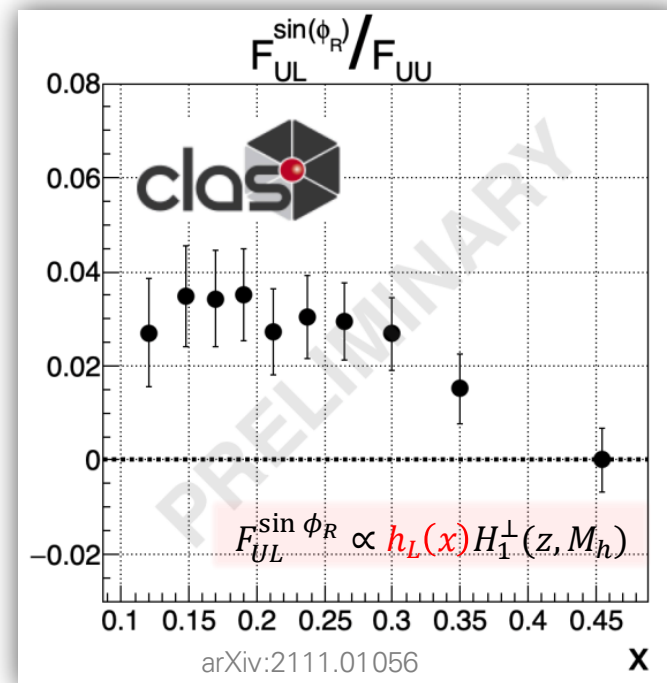
- No published results on chiral odd twist-3 $h_L(x)$, only lattice and phenomenological models
 - x^3 moment connected to average longitudinal gradient of the transverse force on T. pol. Quarks in L proton (Phys. B375, 527 (1992))
- Sign of gradient will help to study correlations of nucleon spin and color magnetic field



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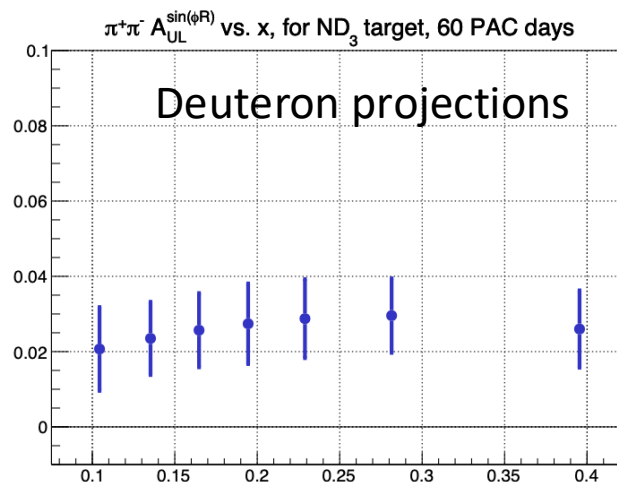
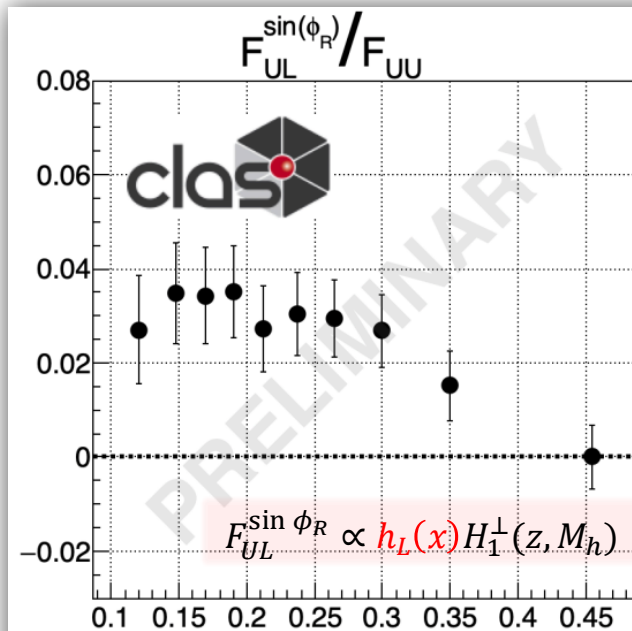
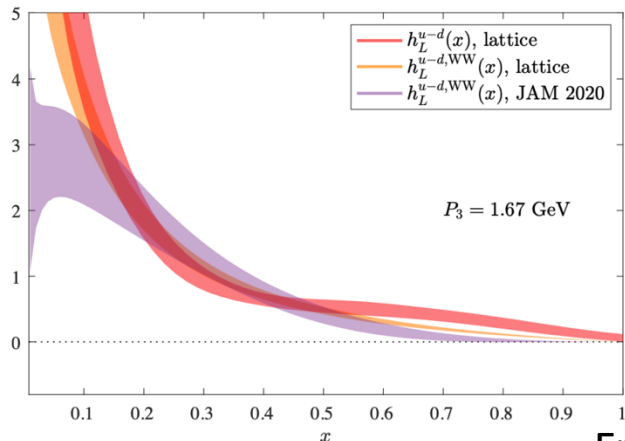
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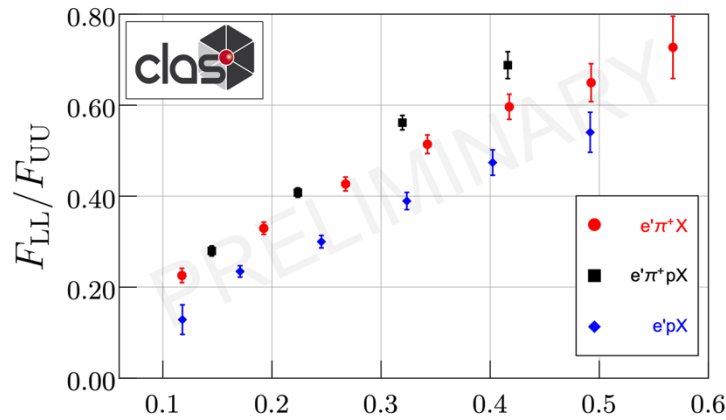
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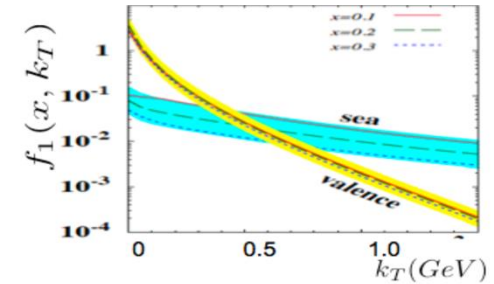
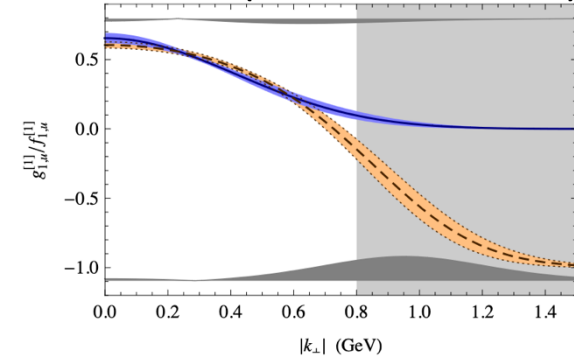
Longitudinal DSAs for single hadrons

- Explore p_T dependence of $A_{LL} \propto f_1(x, k_T)/g_1(x, k_T)$
- Sensitive to spin dynamics
- Relativistic dynamics (Melosh rotation)

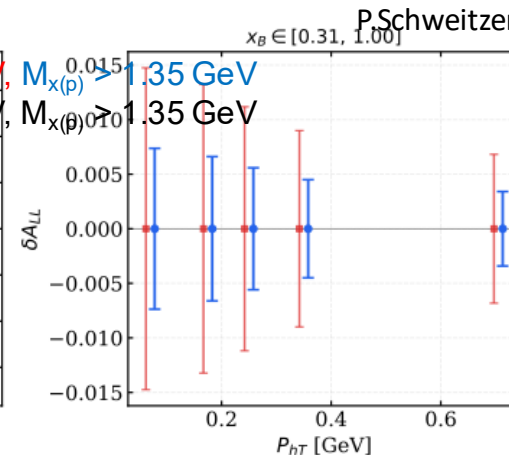
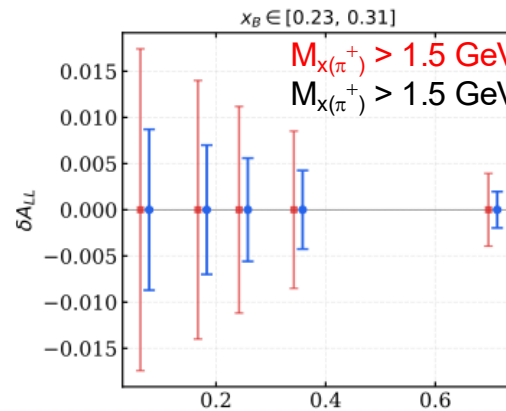
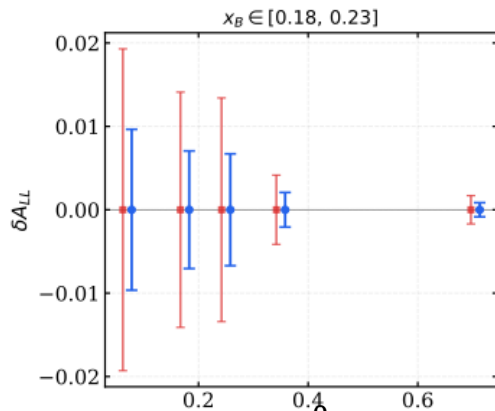
B. Musch et al (arxiv 1011.1213)



$M_{x(\pi^+)} > 1.5 \text{ GeV}$, $M_{x(p)} > 1.35 \text{ GeV}$
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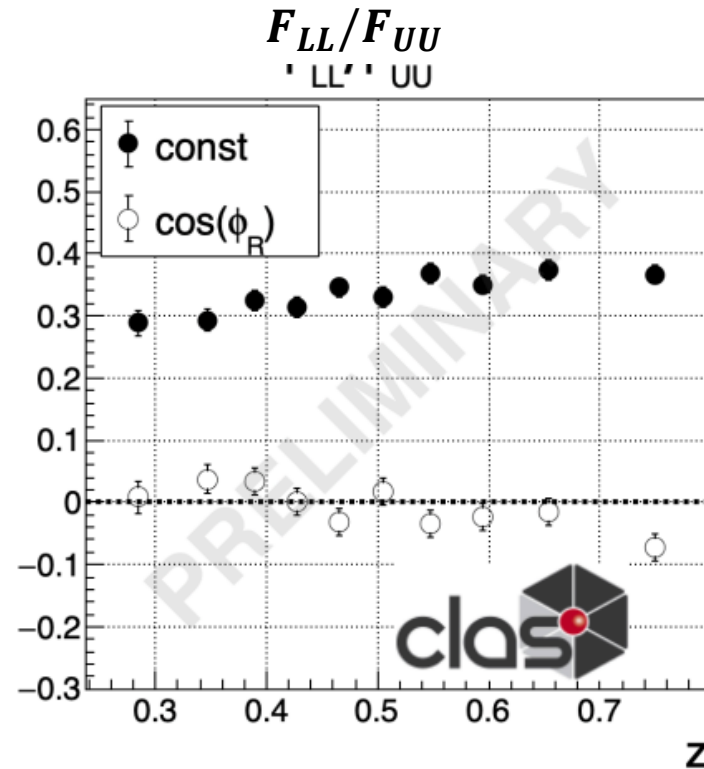
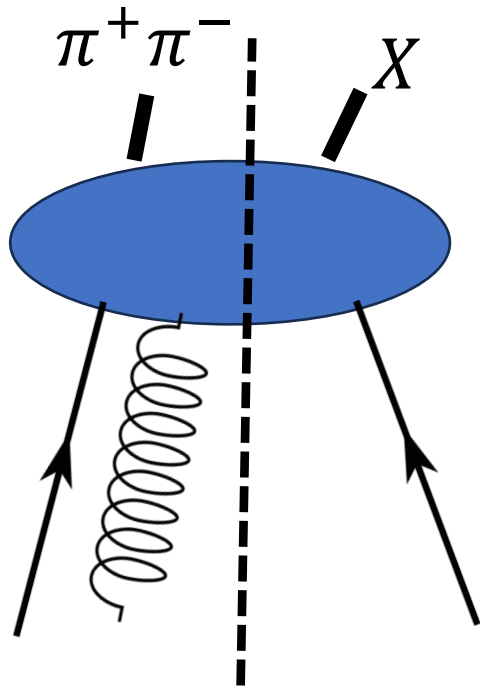
A_{LL} Precision vs p_{hT} in x_B bins — x_B Weighted Average (NH_3)



P. Schweitzer et al. arXiv:1210.1267

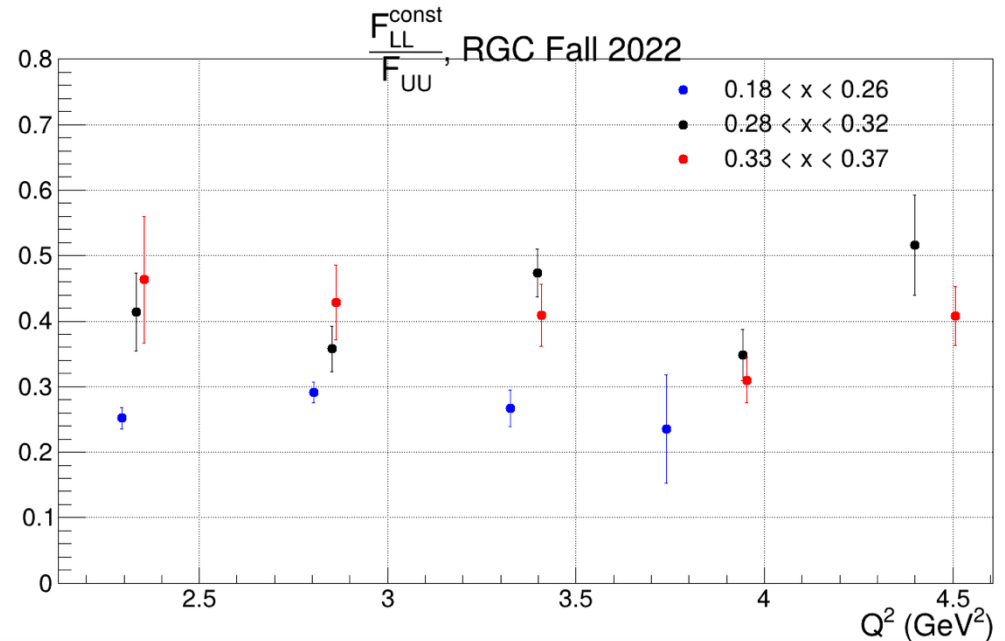
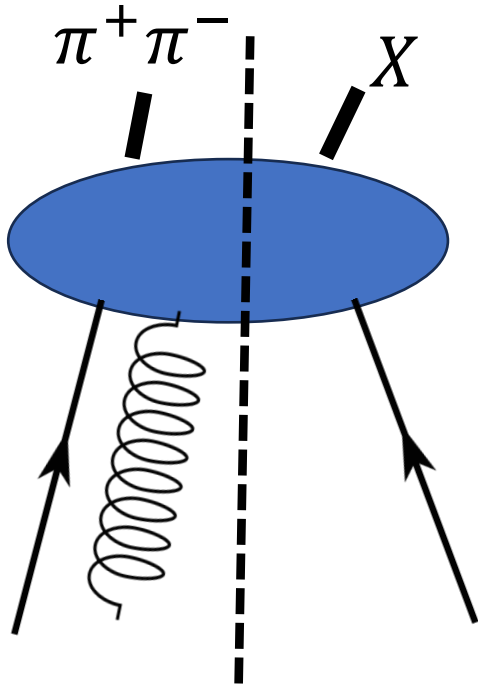
Projections of $A_{LL}^{\pi^0}$ current data 4x statistics

Access to Twist3 FFs in Longitudinal Double Spin Asymmetries



- $F_{LL}^{\text{const}}/F_{LL}^{\text{cos } \phi_R}$ sensitive to $g_{1L}D_1/g_{1L}\tilde{D}$
 $\rightarrow$ probe of twist-3 DiFF $\tilde{D}$ size
- Preliminary results indicate $\tilde{D}$ is roughly one order of magnitude smaller than D_1
 - Different than PDFs!

Access to Twist3 FFs in Longitudinal Double Spin Asymmetries



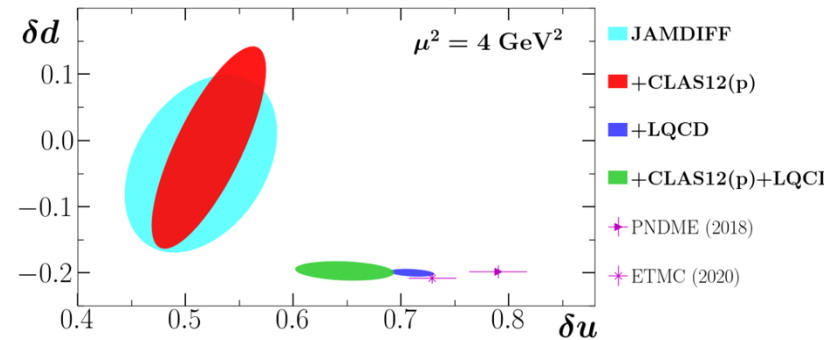
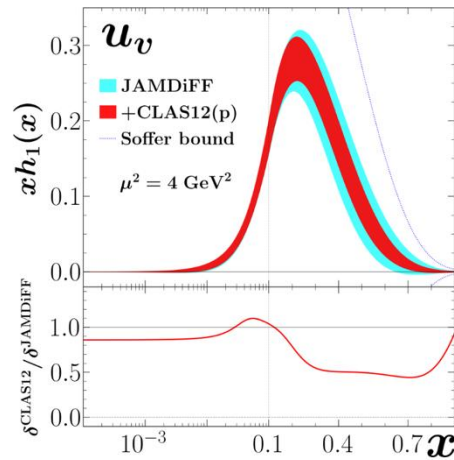
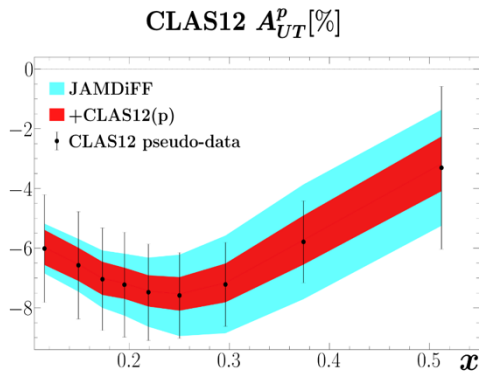
- $F_{LL}^{\text{const}} / F_{LL}^{\text{cos } \phi_R}$ sensitive to $g_{1L} D_1 / g_{1L} \tilde{D}$
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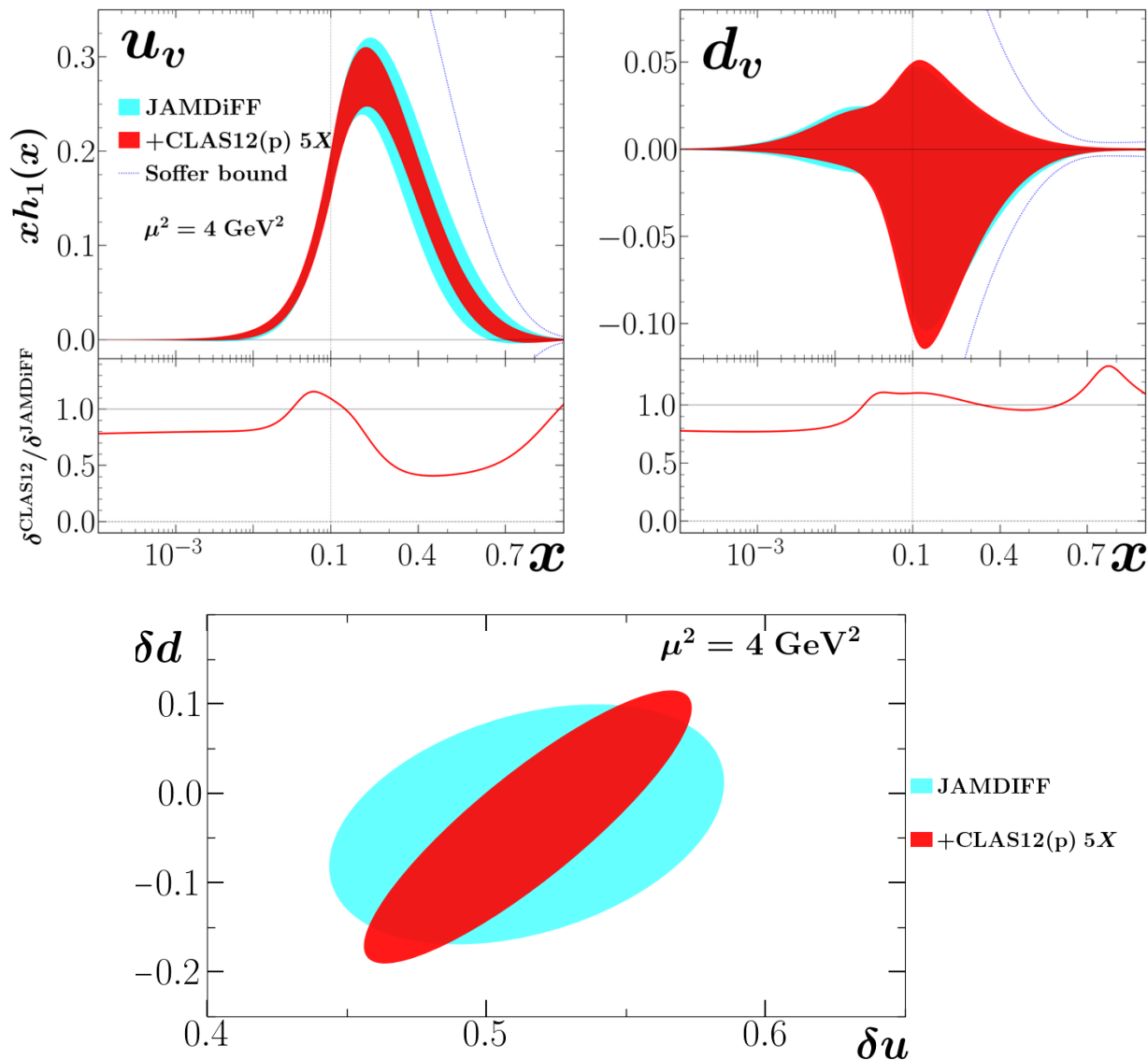
□ Different than PDFs!

$$e^-p \rightarrow e^- \pi^+ \pi^- X$$

- **Run Group H:** 1st transversely polarized target experiment at CLAS12
- Recently approved with rating **A** by the Program Advisory Committee (PAC) – awaiting beam-time
- Recent projections from the JAM group show **RG-H** will be competitive with lattice efforts to constrain the tensor charge [8]



Impact with 5x Statistics



Yorgo Sawaya
(Temple)

Polarized Λ 's as a tool to Learn about Spin Structure

Leading Quark TMDFFs



Hadron Spin

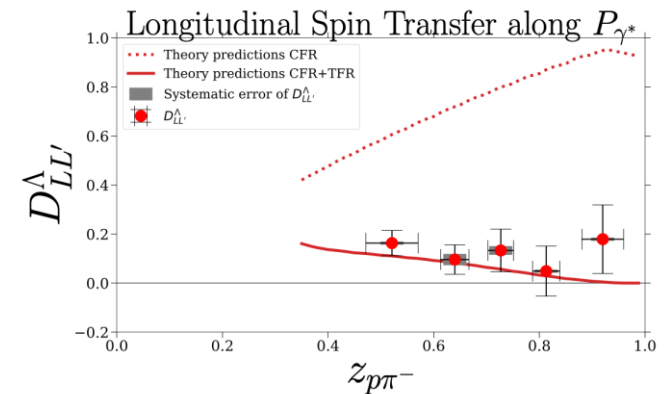
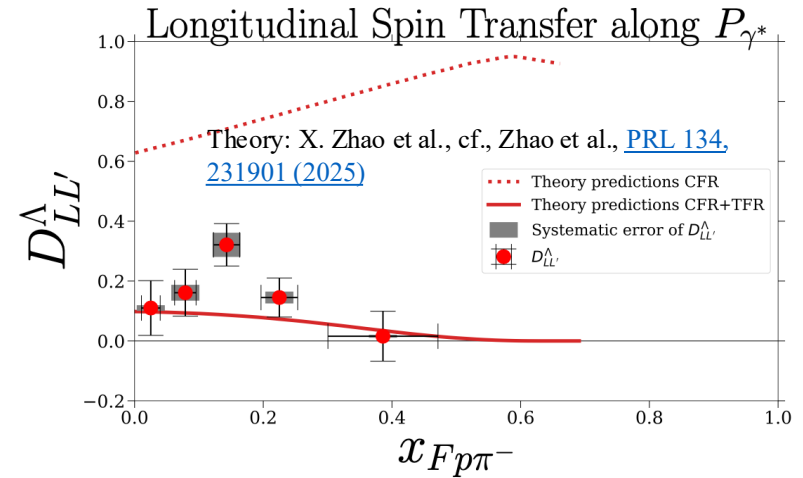


Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		$D_1 = \text{Unpolarized}$		$H_1^\perp = \text{Collins}$
Polarized Hadrons	L		$G_1 = \text{Helicity}$	$H_{1L}^\perp$
	T	$D_{1T}^\perp = \text{Polarizing FF}$	$G_{1T}^\perp$	$H_{1T}^\perp = \text{Transversity}$

- First measurement of A_{LUT}
- Future:
 - Precision Λ program at CLAS12
 - Comparison with MC models

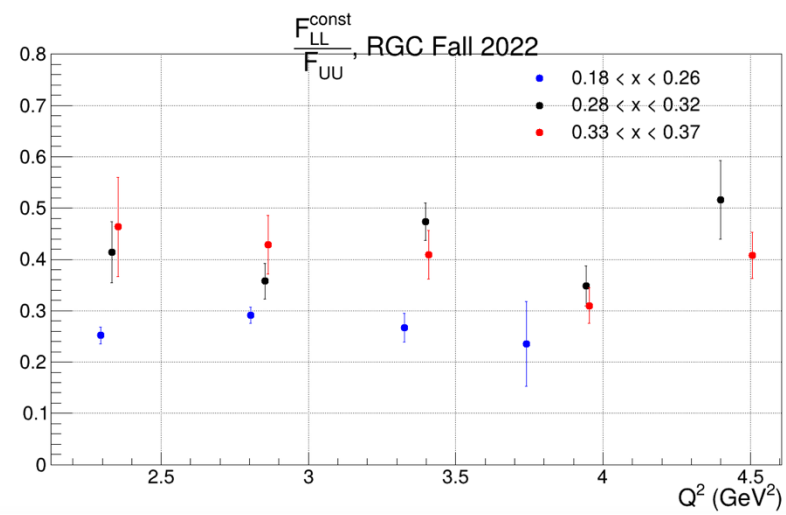
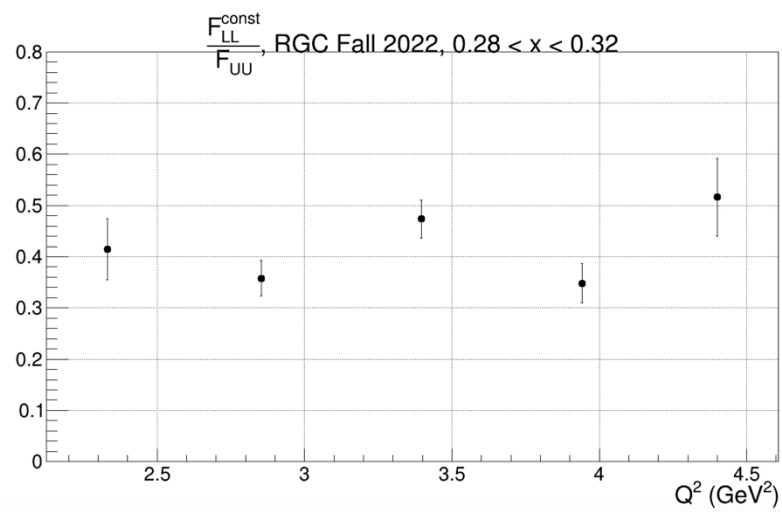
Phys.Rev.D 113 (2026) 9, 092019



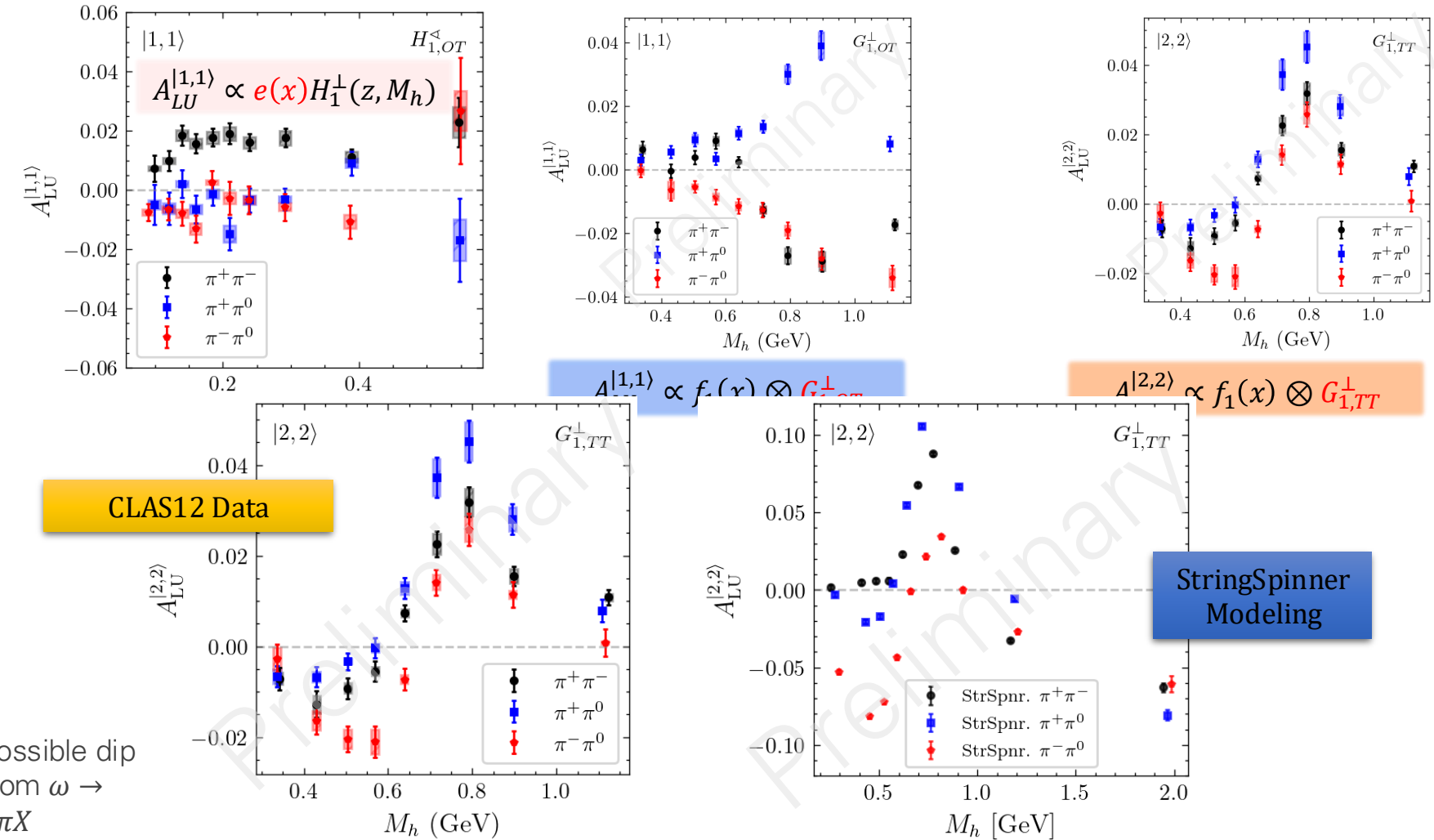
$$\mathcal{A}_{LUT}^{\cos \phi_{S\Lambda}} = \frac{F_{LUT}^{\cos \phi_{S\Lambda}}}{F_{UUU}} = - \frac{\sum_a e_a^2 \left[\frac{Mx}{Q} e^a(x) H_1^a(z_h) + \frac{M_h}{zQ} f_1^a(x) \tilde{G}^a(z_h) \right]}{\sum_a e_a^2 f_1^a(x) D_1^a(z_h)}$$

Summary & Conclusion

- CLAS12 has a rich program to study TMDs
- Large acceptance makes correlation studies possible
- Large acceptance enable program to explore correlations in hadronization
- “High Luminosity” would help extend p_T, Q^2 reach
- Will increase impact of RGH
- Additional deuterium data will be helpful for flavor separation
 - Possibly helpful to explain surprising Kaon results
- Improvements enabling higher luminosity in software might have disproportional effect on Λ reconstruction → rich program on polarized Λ in SIDIS



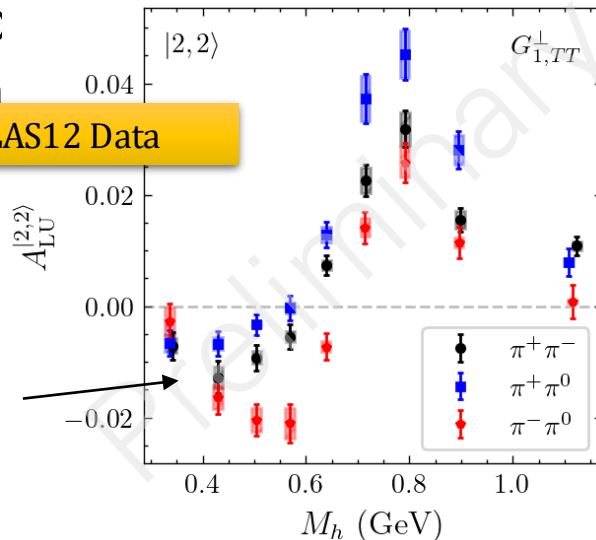
Flavor dependence + String Spinner



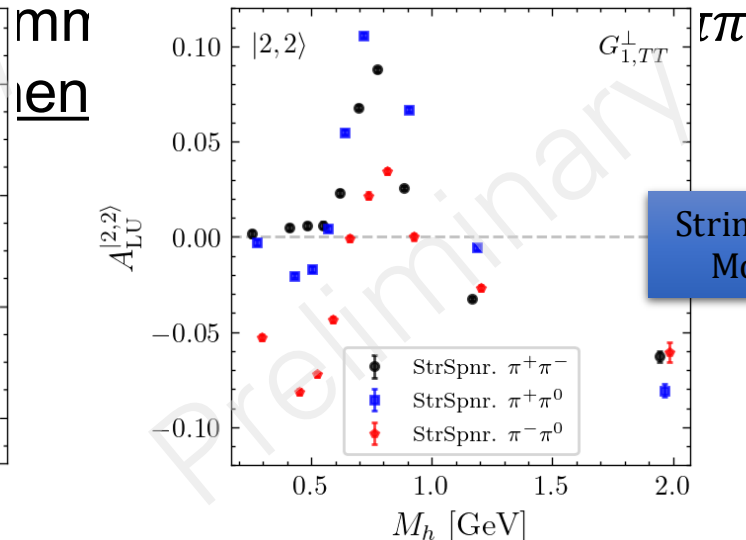
$$e^- p \rightarrow e^- \pi^\pm \pi^0 X$$

$d\sigma_{LU}$

- **StringSpinner** introduces *spin-dependent* fragmentation into PYTHIA8 based on the string+ $^3P_0$ model of hadronization ($q\bar{q}$ produced in $L = S = 1, J = 0$ quantum state) [6]
1
- With parameter tuning, StringSpinner can replicate several of our channels



Possible dip from $\omega \rightarrow \pi\pi X$



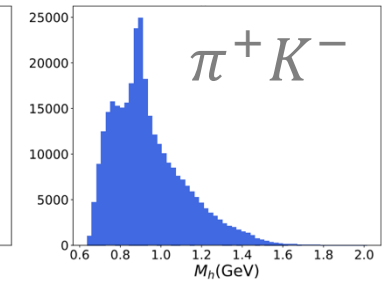
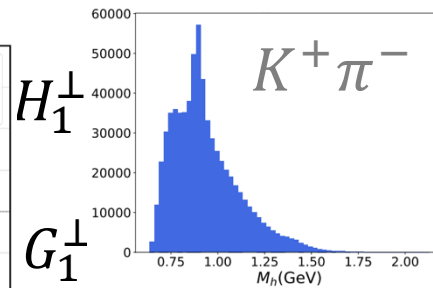
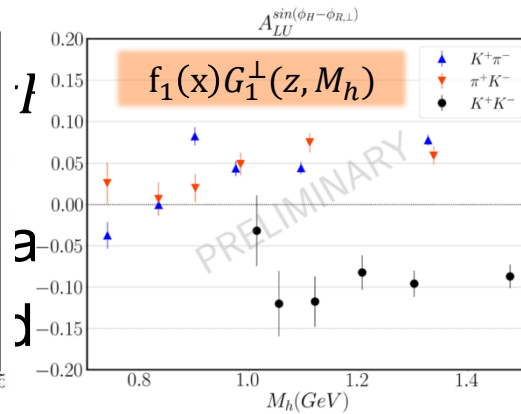
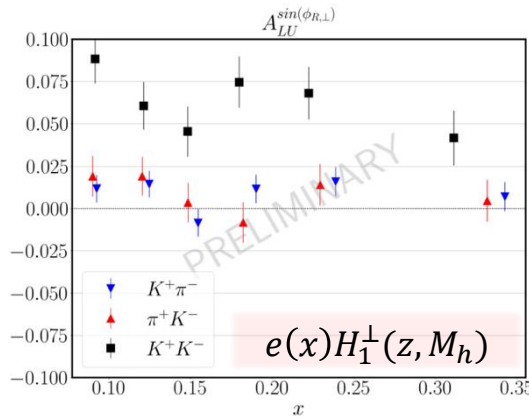
Note that $e(x)$ is also reproduced... unclear now

$$e^- p \rightarrow e^- K \pi X$$

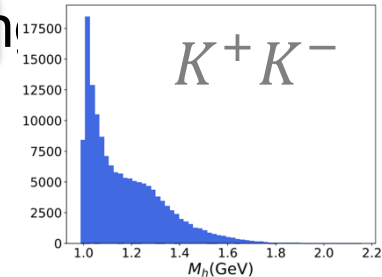
$$e^- p \rightarrow e^- K^+ K^- X$$

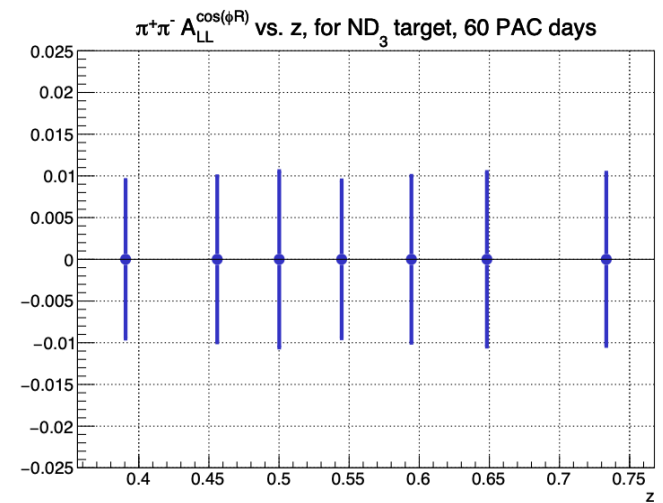
$d\sigma_{LU}$

- Large asymmetries observed in $K^+ K^-$ dihadrons $\rightarrow$ larger than



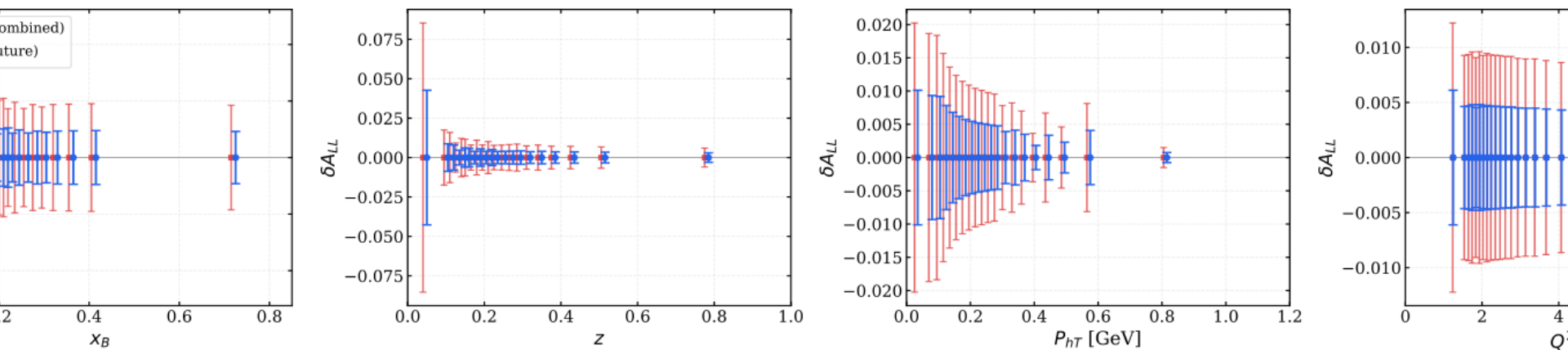
Invariant Masses



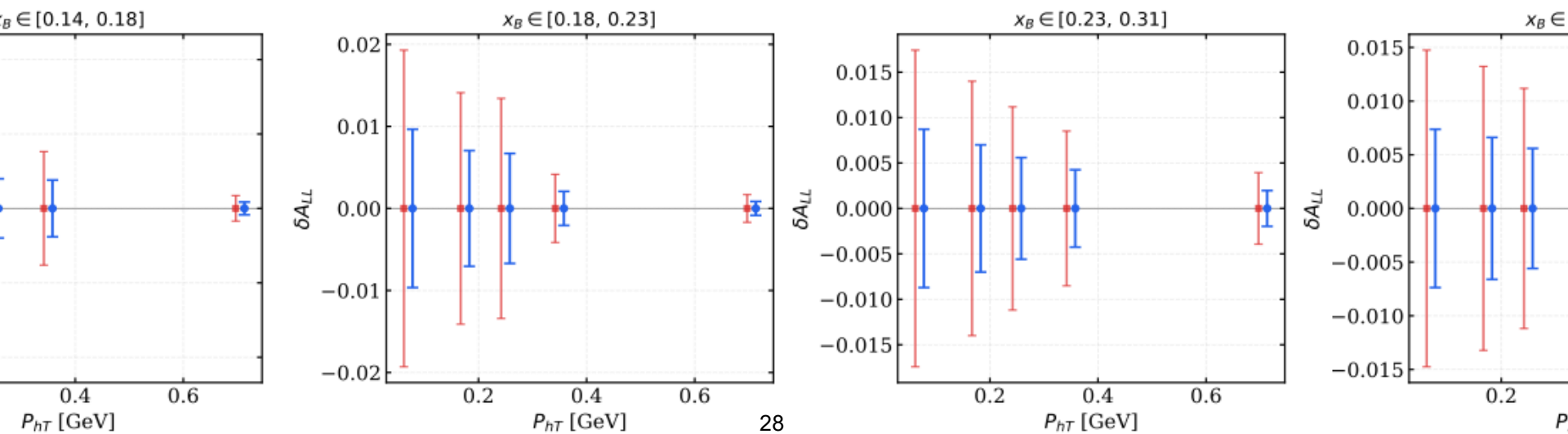


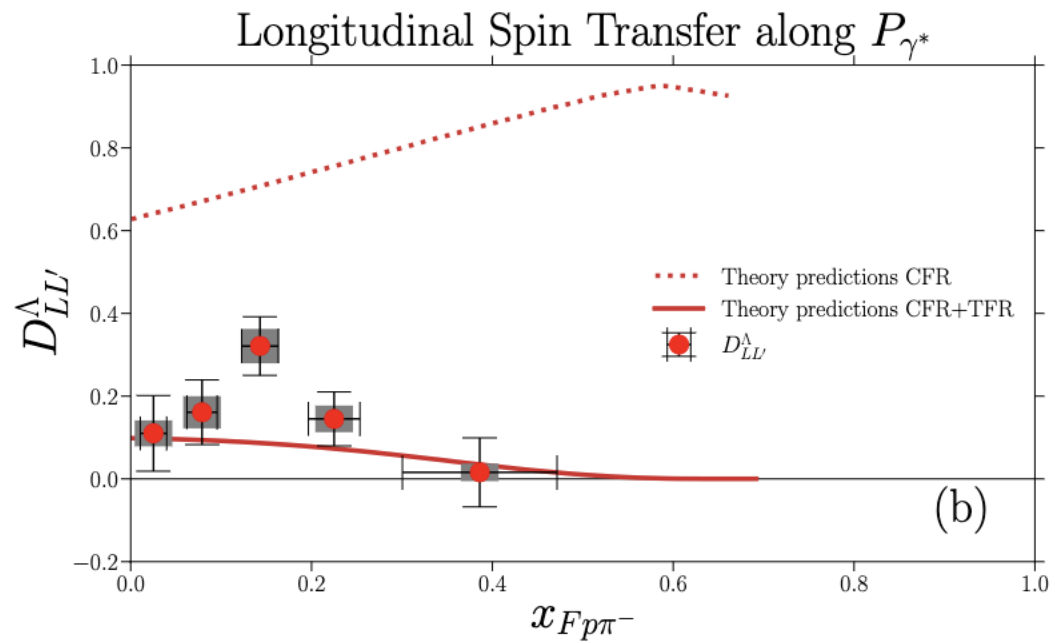
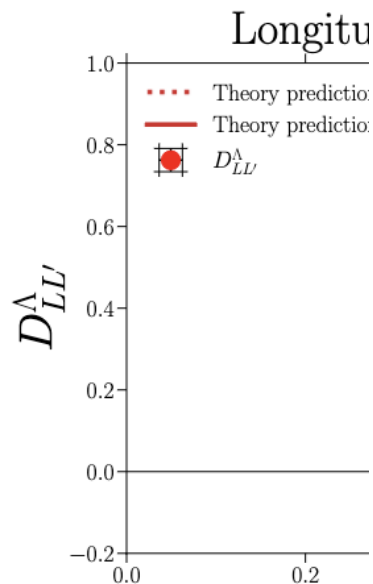
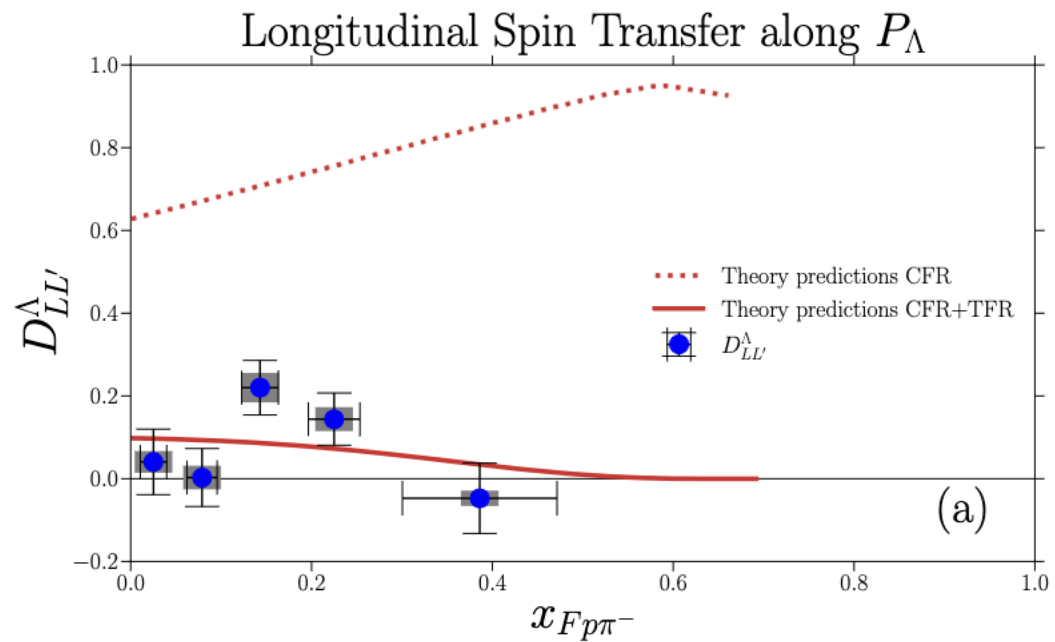
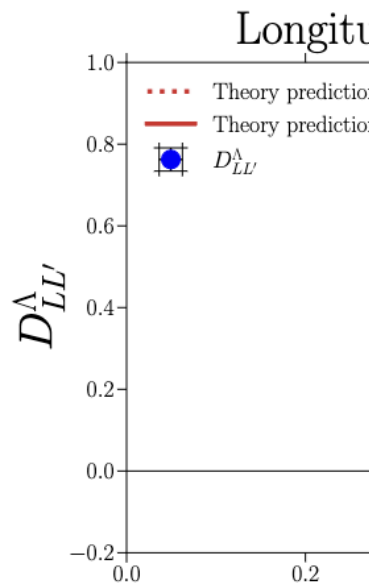
From the proposal for the RG Addition to PAC48 (C. Dilks)

π^0 SIDIS A_{LL} Statistical Precision — CLAS12 RG-C (Weighted Average, NH_3)



π^0 SIDIS A_{LL} Precision vs p_{hT} in x_B bins — Weighted Average (NH_3)

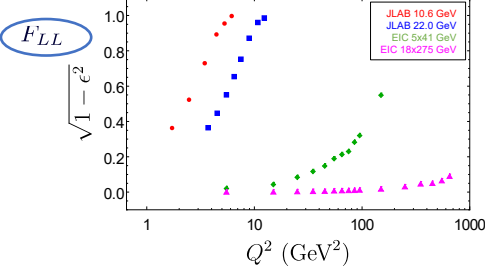




Helicity TMD (and the effect from ρ^0)

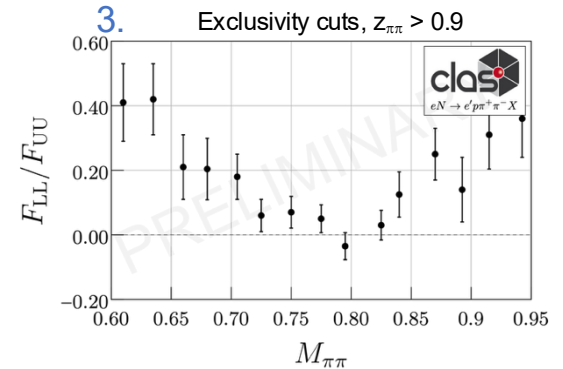
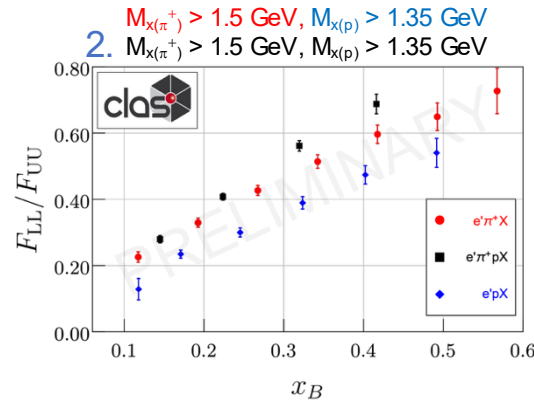
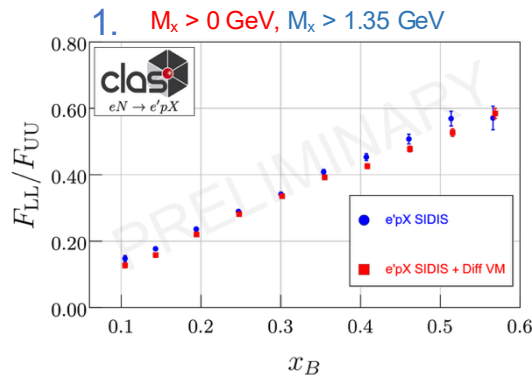
- $g_1(x, k_T)$ will be heavily kinematically suppressed at EIC.
- JLab22, with extension to higher P_T , would be critical for studies of g_1 in the valance quark region.

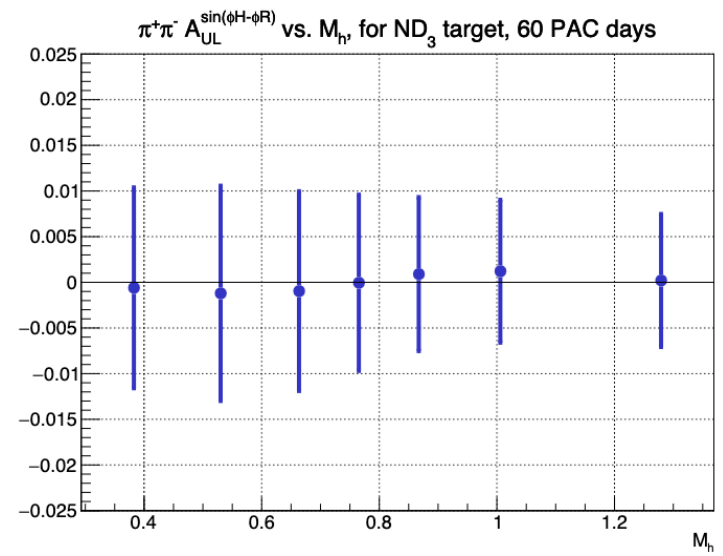
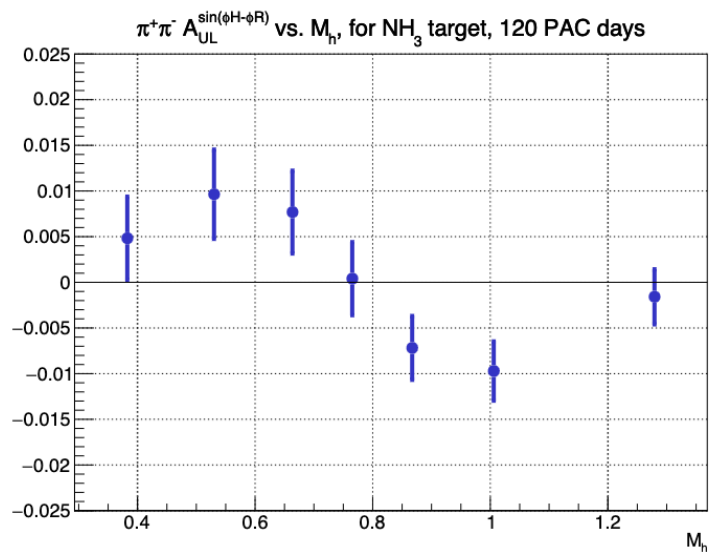
$$F_{LL} \propto g_1(x, k_T) \otimes D_1(z, p_T)$$



1. Measurements of epX A_{LL} systematically higher after M_x cut to remove VMs
2. Semi-exclusive $e'\pi^+pX$ with ρ removed larger than $e'\pi^+X$ double-spin asymmetries
3. Measurements of A_{LL} for “diffractive” ρ^0 indicate very small values (probably negative)

Contributions from VM may have caused underestimations of g_1 !

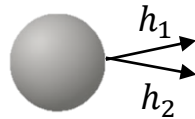




Better: Dihadron Fragmentation Functions

- Correlations in h_1 and h_2 as functions of z, M_h and p_T^2 accumulated during fragmentation
- Couple to fragmenting quark properties – ex: $\vec{S}_q, \vec{k}_T$
- DiFF's expand into *partial waves* $|\ell, m\rangle$ w.r.t θ

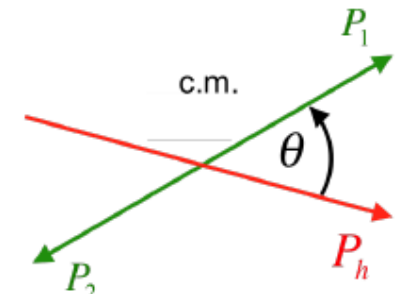
Unpolarized
 $D_1(z, M_h, p_T^2)$



Helicity-dependent
 $G_1^\perp(z, M_h, p_T^2)$



S_{qT}/k_T -dependent
 $H_1^\perp(z, M_h, p_T^2)$

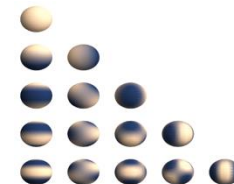


2-Point Correlations

In phase space

→ insight into hadronization

→ connection to models

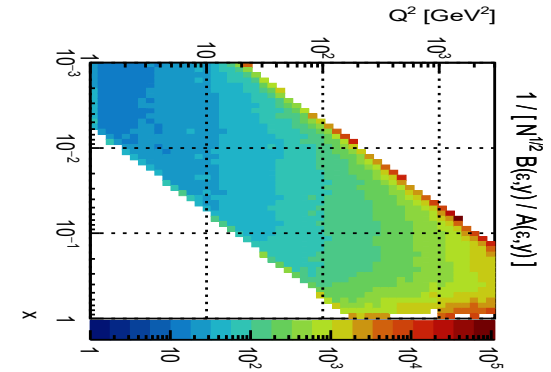


Depolarization Factors

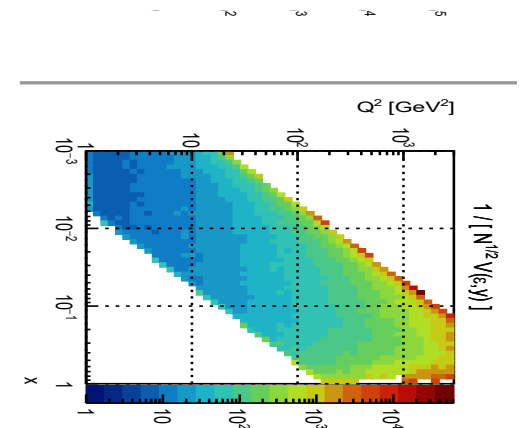
Twist 2

	Polarization	Depolarization
Boer-Mulders	UU	B
Sivers	UT	1
Transversity	UT	B/A
Kotzinian-Mulders	UL	B/A
Wormgear (LT)	LT	C/A
Helicity DiFF $G_1^\perp$	LU	C/A
	UL	1
$e(x)$	LU	W/A
$h_L(x)$	UL	V/A
$g_T(x)$	LT	W/A

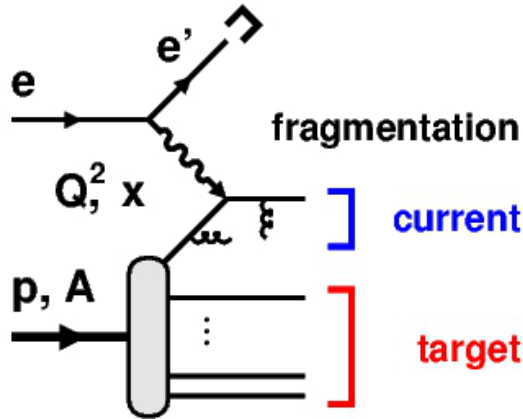
Twist 3



Suppressed at EIC



Target Fragmentation → Fracture Functions



- Correlations between CFR-TFR allows to extract fracture functions coupled to FFs

Quark polarization

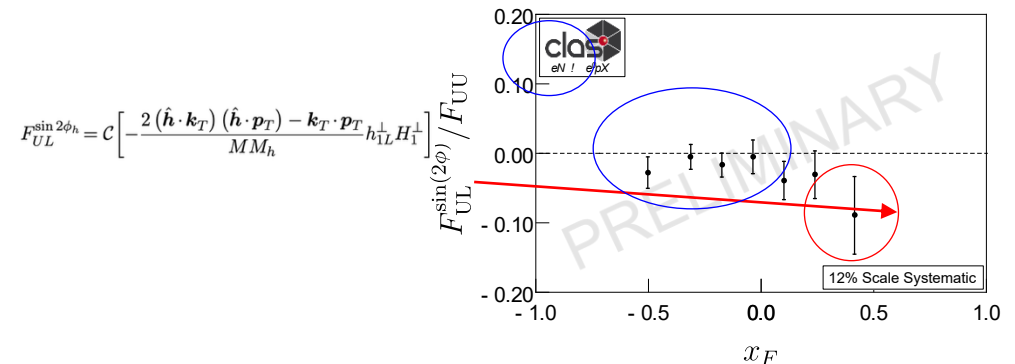
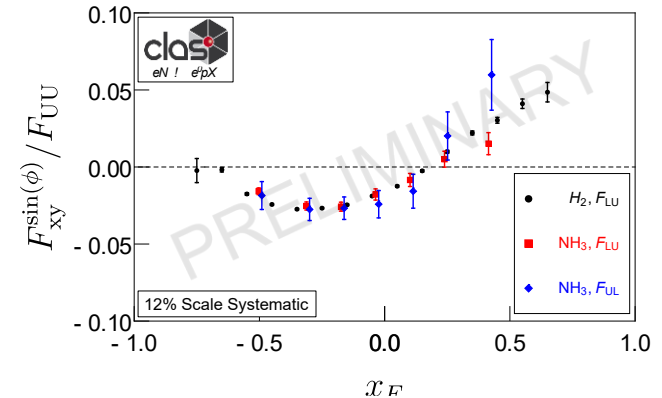
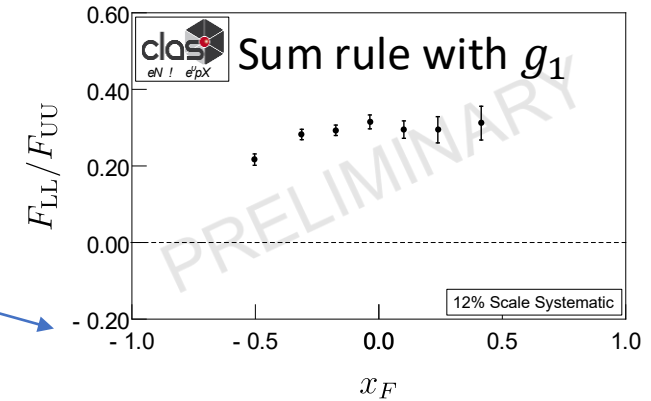
	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^h$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^\perp$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}^h, \hat{t}_{1T}^\perp$

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

Quark polarization

	U	L
U	u^h	l^h
L	u_L^h	l_L^h

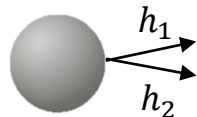
Twist-3 Collinear terms:
Chen, K. B., Ma, J. P. and Tong, X. B., [hep-ph/2308.11251]



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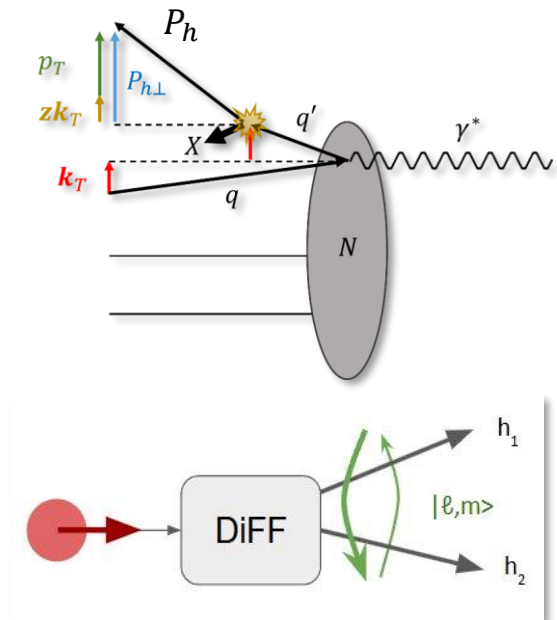
Unpolarized
 $D_1(z, M_h, p_T^2)$



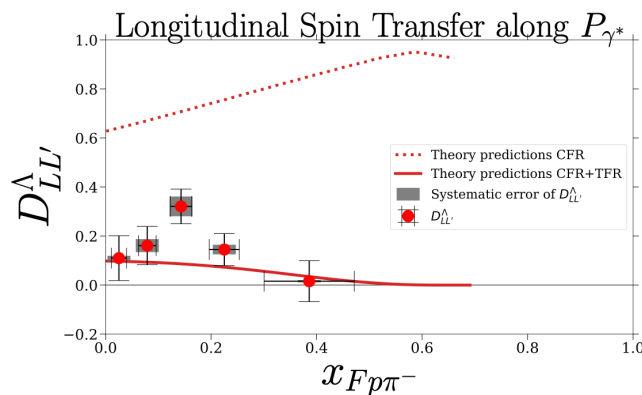
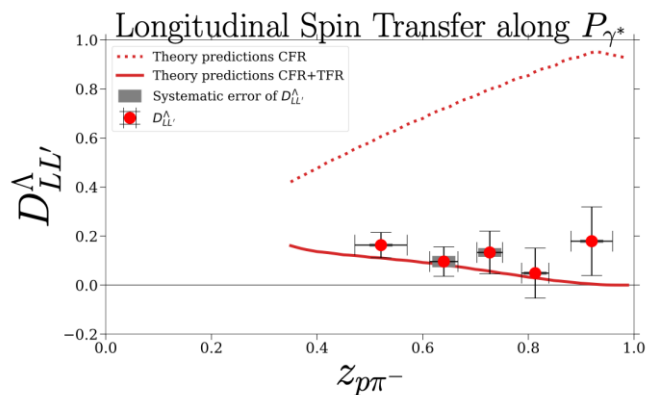
Helicity-dependent
 $G_1^\perp(z, M_h, p_T^2)$



S_{qT}/k_T -dependent
 $H_1^\perp(z, M_h, p_T^2)$



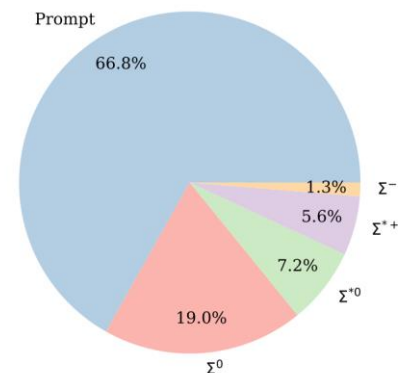
Comparison with Theory



Predictions by X. Zhao et al., cf.,
Zhao et al., [PRL 134, 231901 \(2025\)](#)

- CFR predictions come from pQCD fits to e^+e^- data
- TFR predictions come from a spectator quark-diquark model calculation

- Lambda also Spin transfer to Lambda
- Also additional vector in final state
- azimuthal asymmetries
- Future: More lambda program at CLAS...



Also Stringspinner