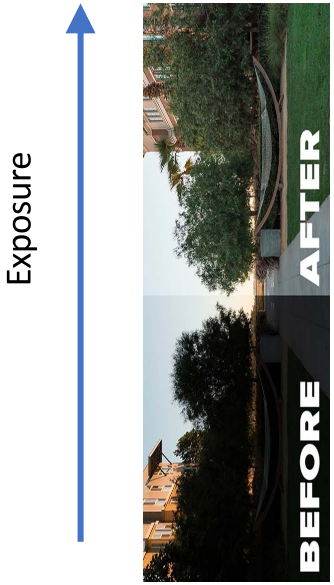
Opportunities for SIDIS in 12 GeV era at Jlab

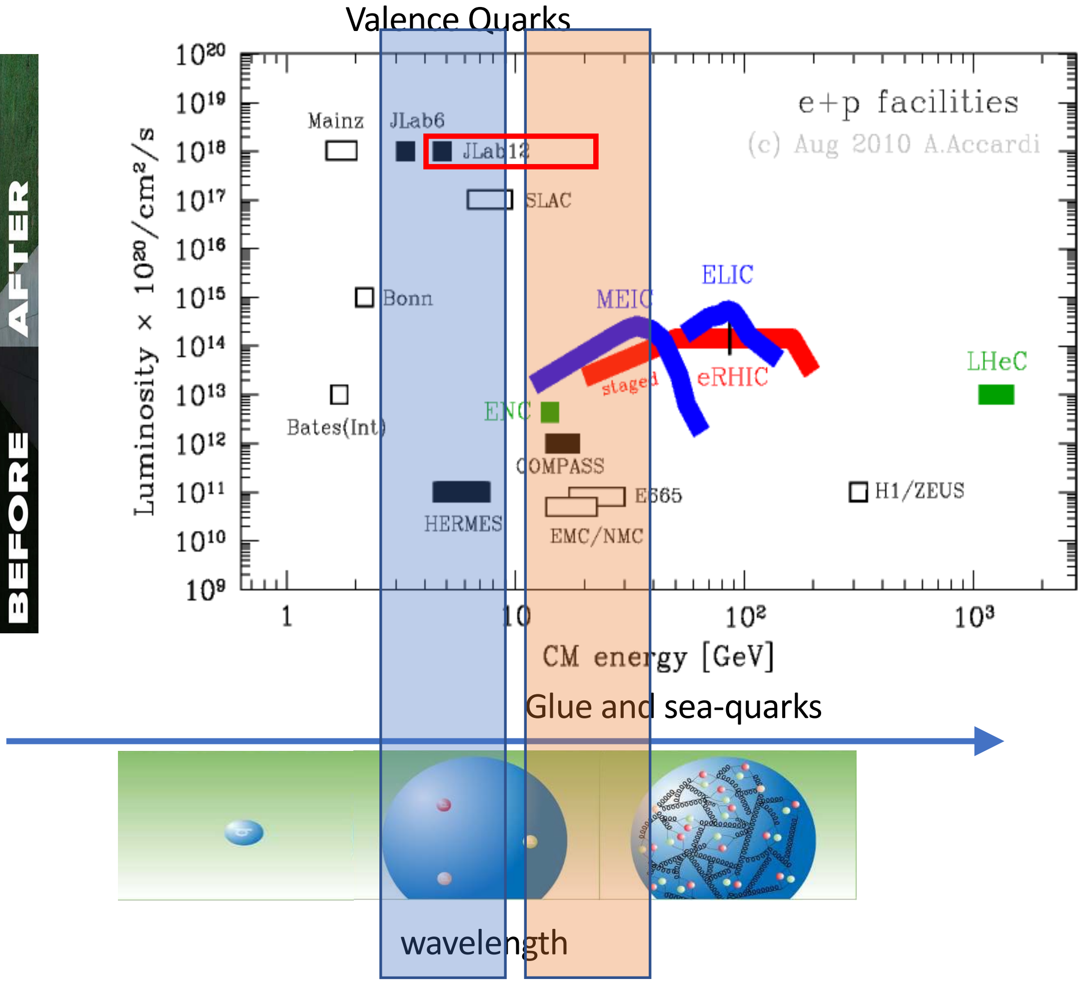
Anselm Vossen

Duke
UNIVERSITY

Jefferson Lab

What makes the 12 GeV era?



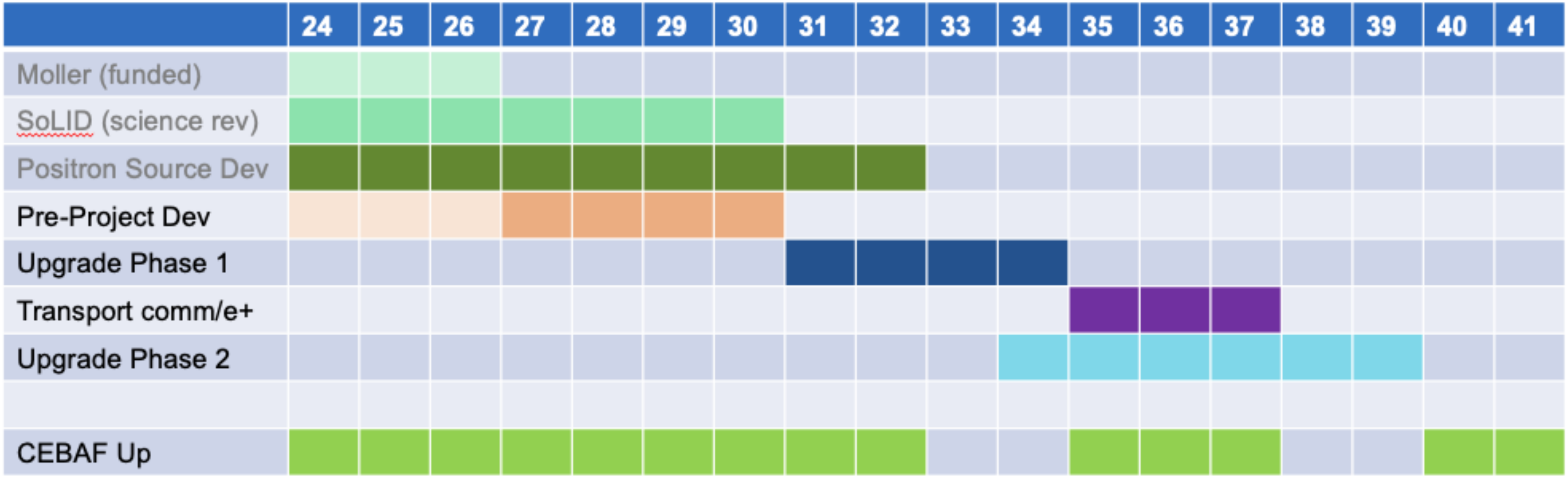


To extract 3D structu
Need luminosity

Luminosity + DIS Kinematics =
Precision tests of QCD, 3D structure of the nucleon

Notional CEBAF & upgrade schedule (FY24 – FY42)

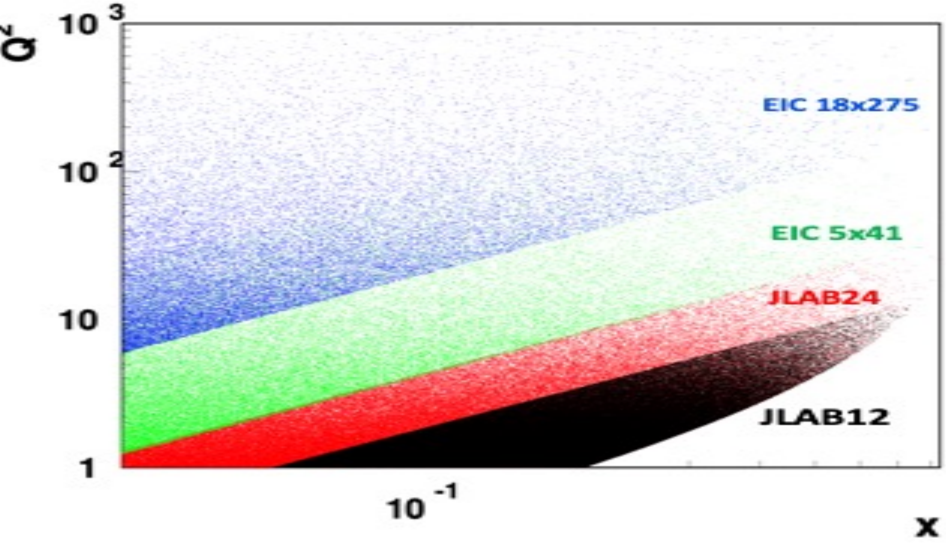
- Accelerator and engineering team have worked up an early schedule and cost estimate
  - Schedule assumptions based on a notional timing of when funds might be available (near EIC ramp down based on EIC V3 profile)
  - For completeness, Moller and SoLID (part of 12 GeV program) are shown; positron source development also shown

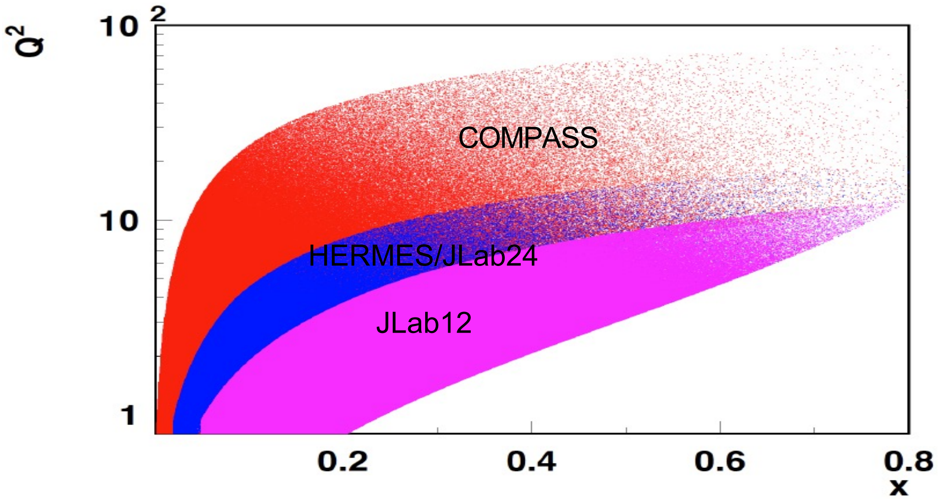


	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Moller (funded)	🟩	🟩	🟩															
SoLID (science rev)	🟩	🟩	🟩	🟩	🟩	🟩	🟩											
Positron Source Dev	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩									
Pre-Project Dev	▨	▨	▨	🟧	🟧	🟧	🟧											
Upgrade Phase 1								🟦	🟦	🟦	🟦							
Transport comm/e+												🟪	🟪	🟪				
Upgrade Phase 2											🟦	🟦	🟦	🟦	🟦	🟦		
CEBAF Up	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			🟩	🟩	🟩			🟩	🟩

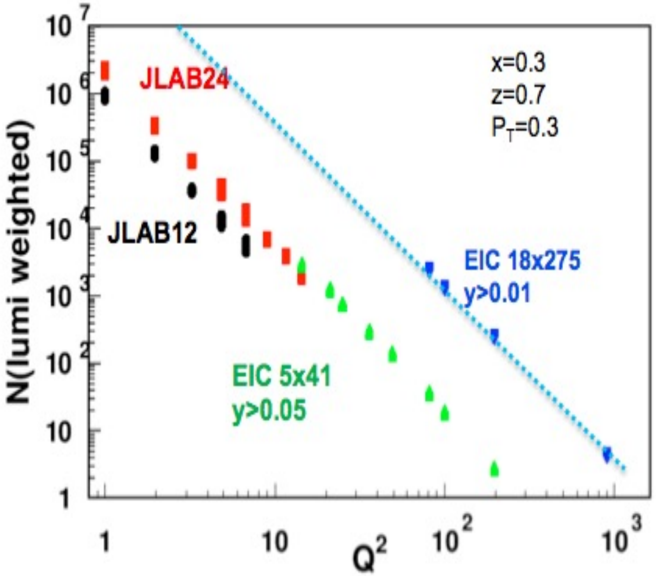
Tia Keppel at

Kinematic comparisons



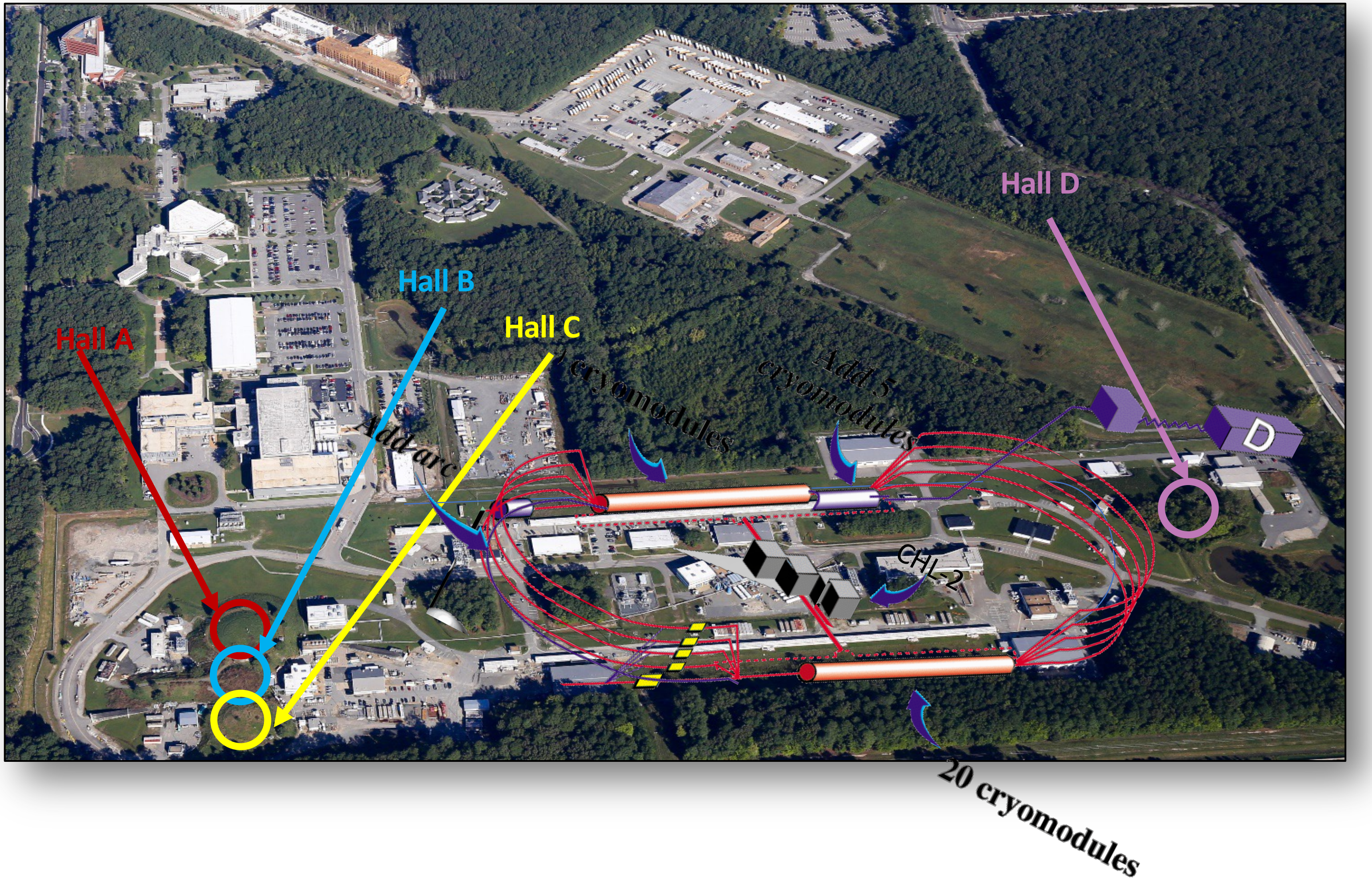


Plot by H. Avakian

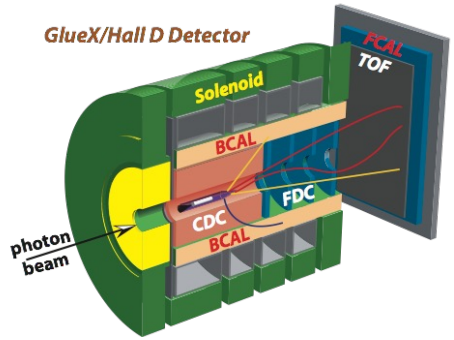


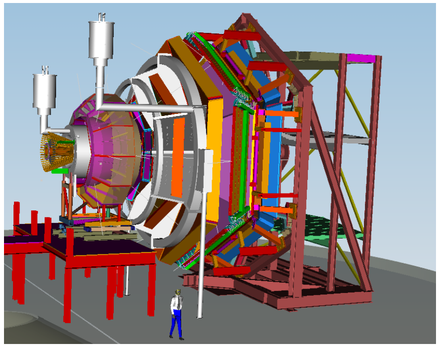
NB: Kinematic slice heavily biased towards Jlab

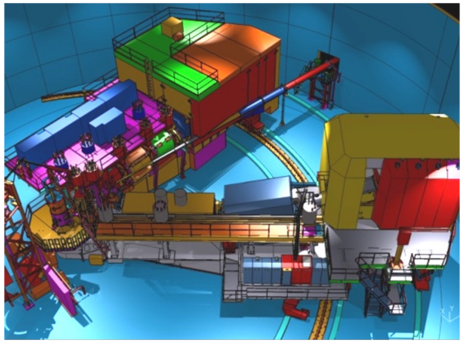
Jefferson Lab with CEBAF at 12 GeV

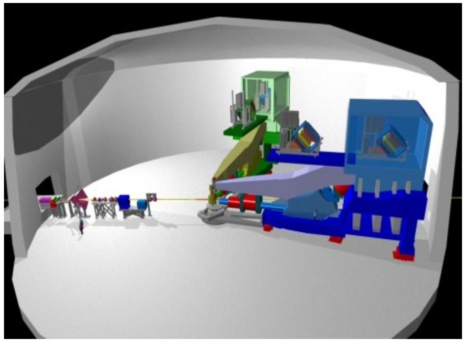


Detector Requirements: Complementarity









Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	Hermeticity	precision	
E_{γ}~8.5-9 GeV	11 GeV beamline		
10^{8} photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction		luminosity up to 10^{38}	
particle ID			

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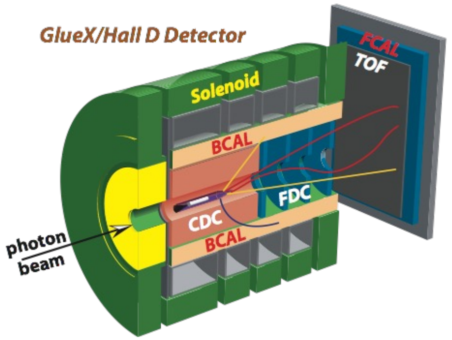

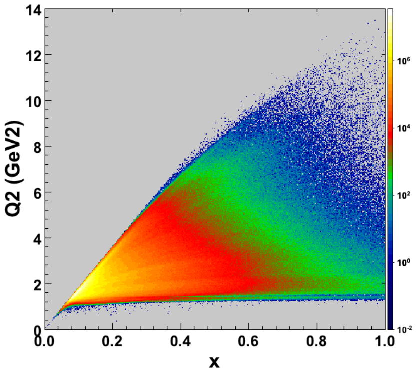

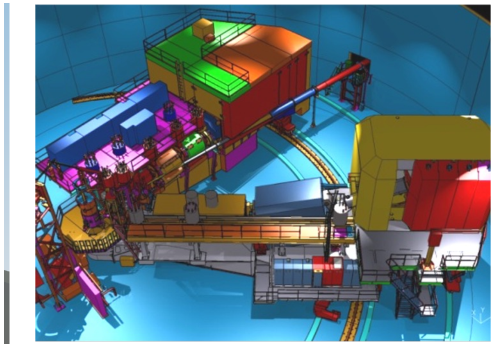

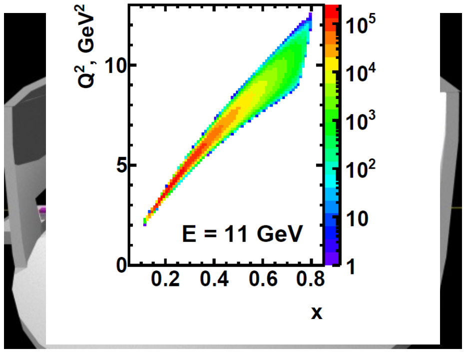

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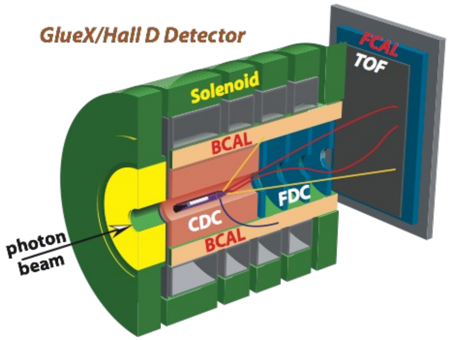

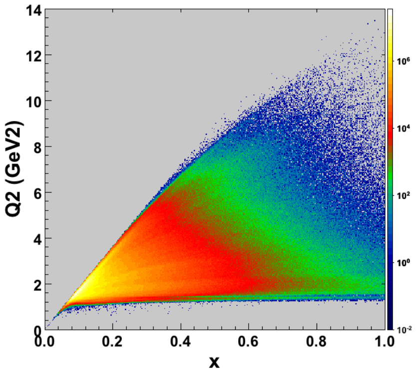

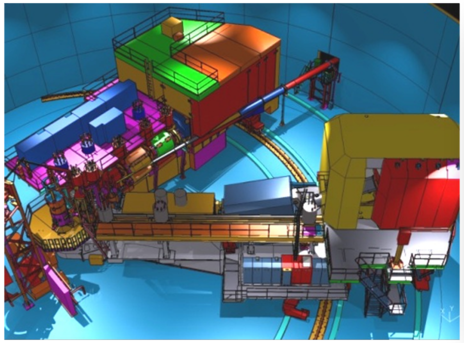

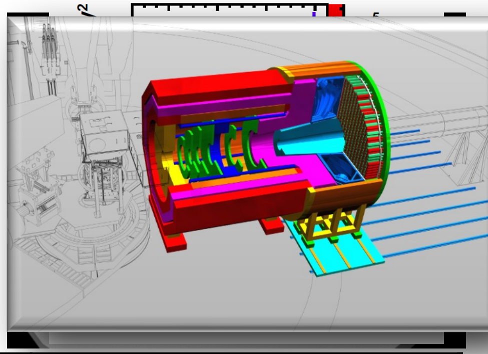

<table>
<tr><th>Hall D</th><th>Hall B</th><th>Hall C</th><th>Hall A</th></tr>
<tr><td>excellent hermeticity</td><td>luminosity 10^{35}</td><td>energy reach</td><td>SoLID ≈ 2028</td></tr>
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</table>

SIDIS Datasets, present and future

CLAS12 in Hall B

Run Group A (Unpolarized LH$_2$ target

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

Run Goup B (Unpolarized LD$_2$ target)

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

Run Group C (**longitudinally** polarized NH$_3$ and ND$_3$)

- ★ **F$_{UL}$** and **F$_{LL}$**

Run Group K (Unpolarized LH$_2$ target)

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

Run Group H (**transversely** polarized NH$_3$)

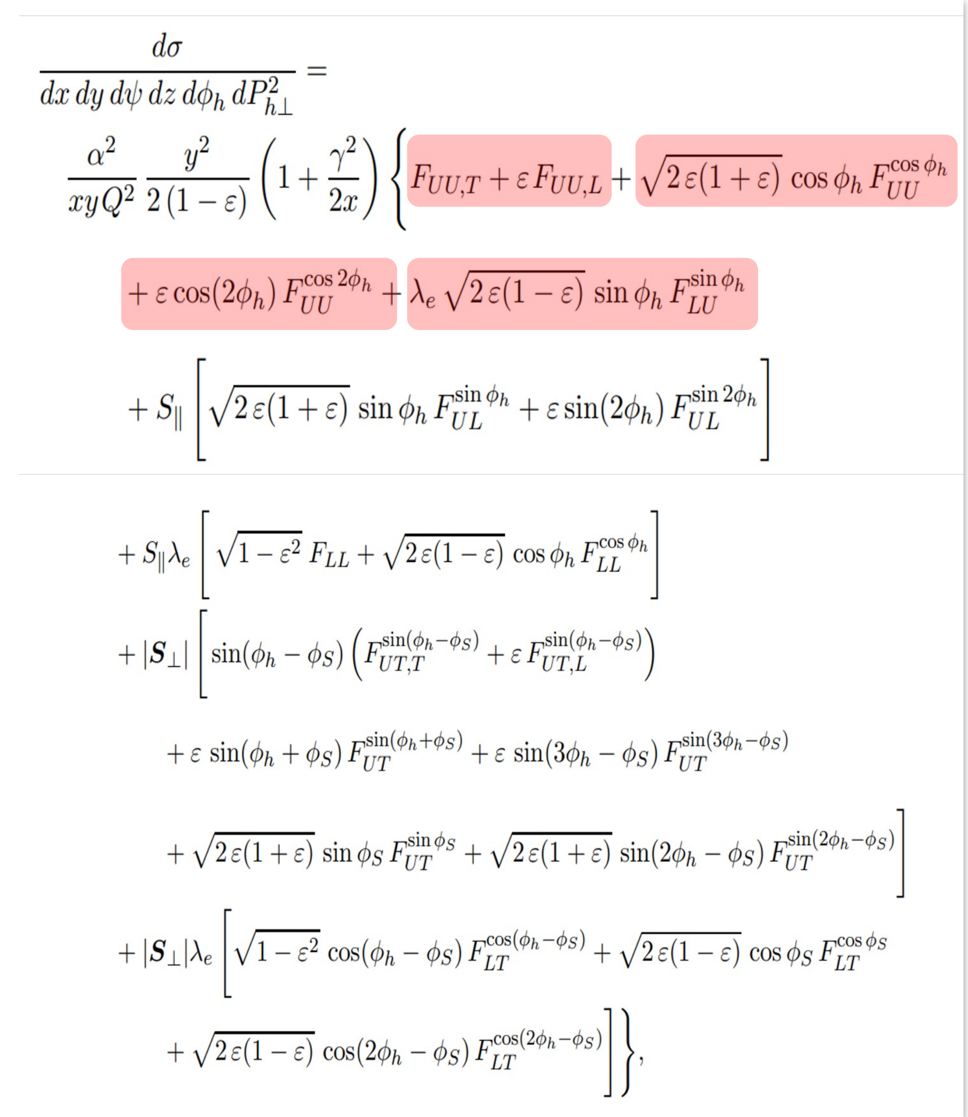
- ★ **F$_{UT}$** structure function

Hall A

- ≈2028 SoLID with He3/proton target (long/transverse)

⇒should be completed before 1st Shutdonw ≈ 2032

CLAS12: Full access to SIDIS cross-section



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

Run Group A (Unpolarized LH_2 target

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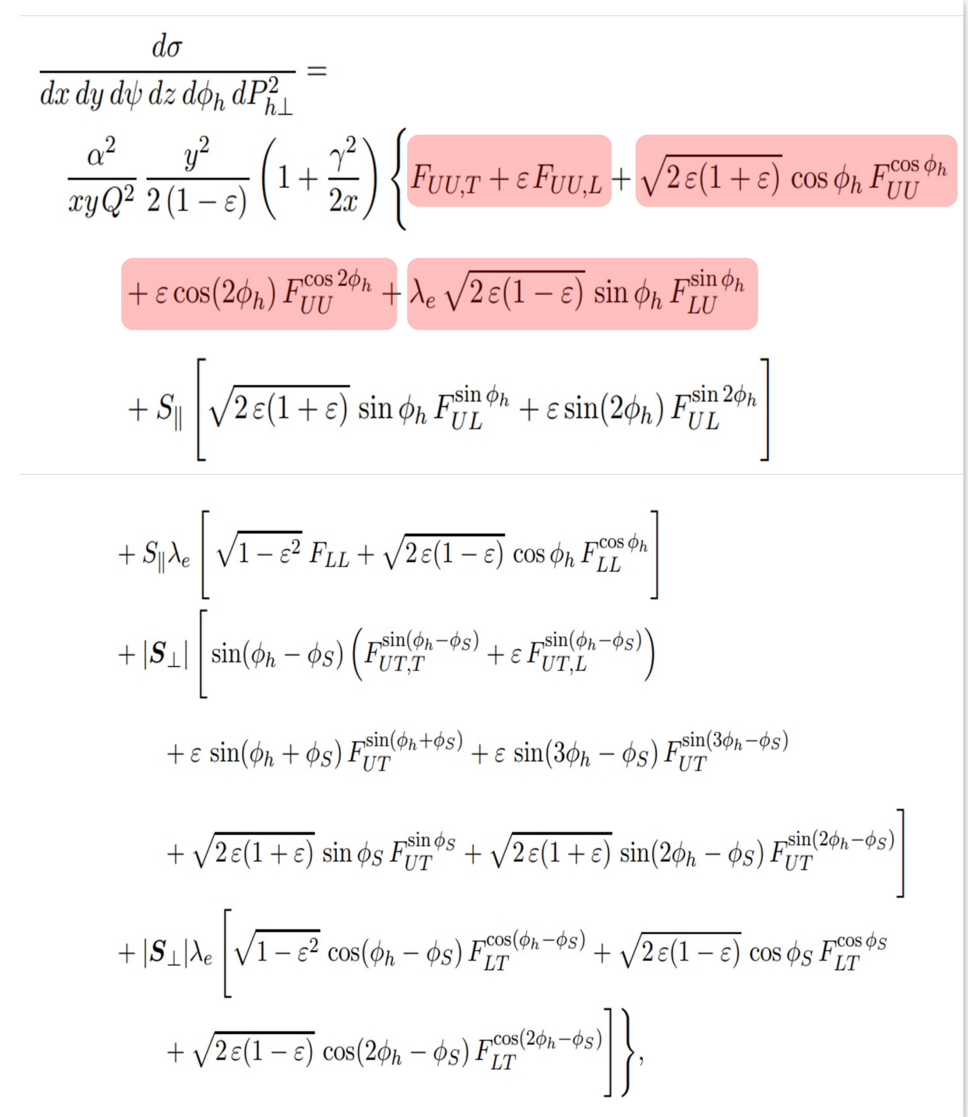

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

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

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

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

$$+\,|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

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

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

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

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

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Run Goup B (Unpolarized LD_2 target)

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

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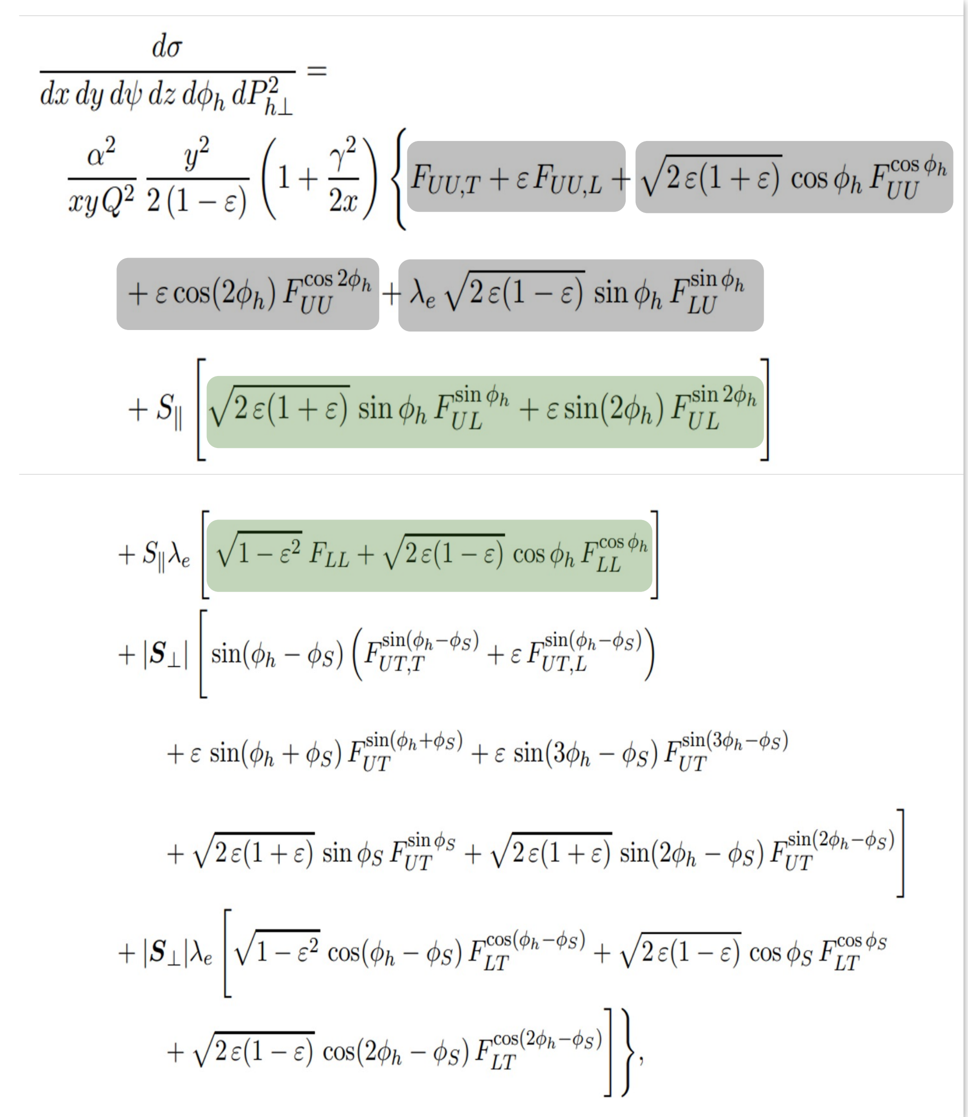

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$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

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

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

$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

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

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

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

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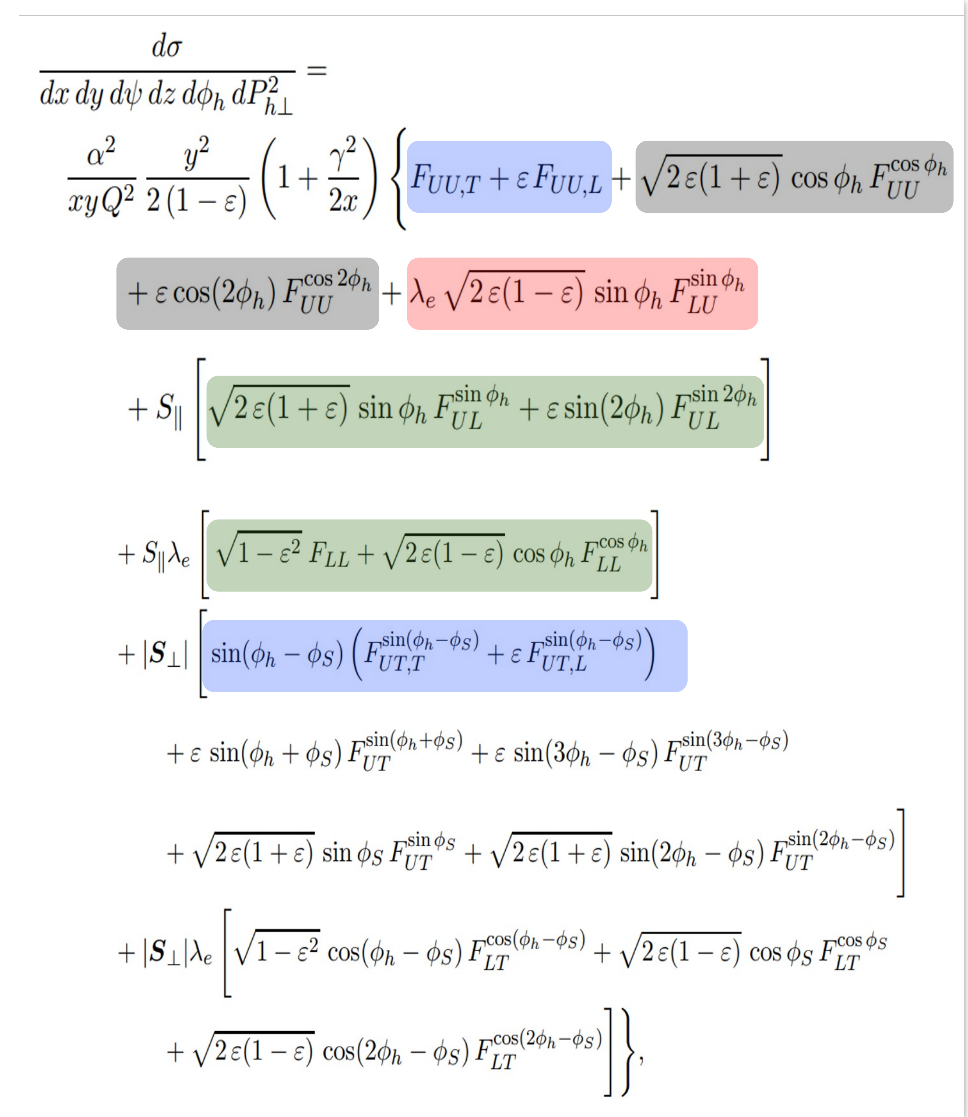

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$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

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

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

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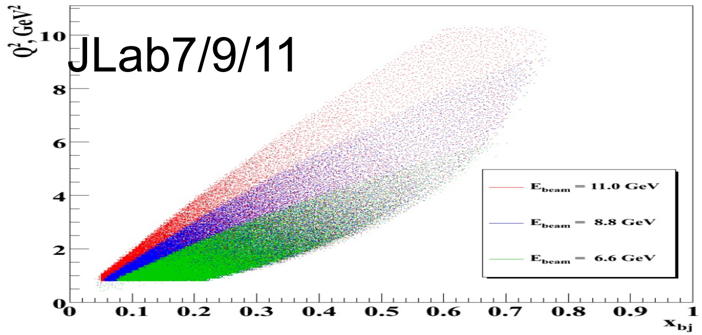

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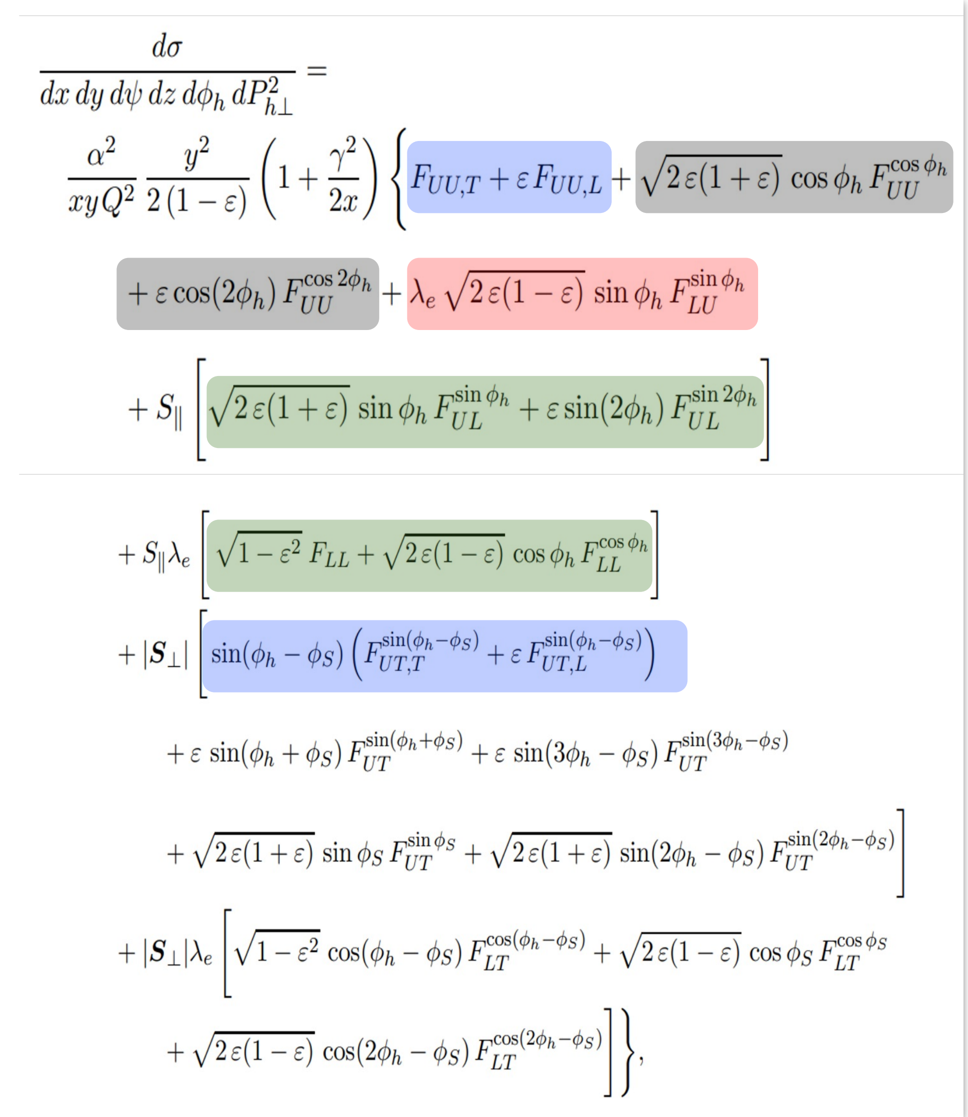

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$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

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

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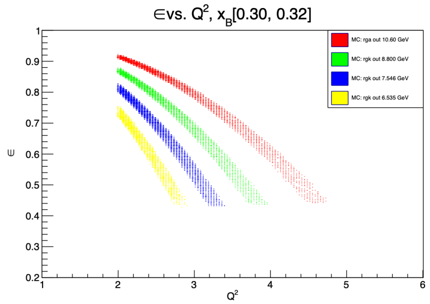
JL



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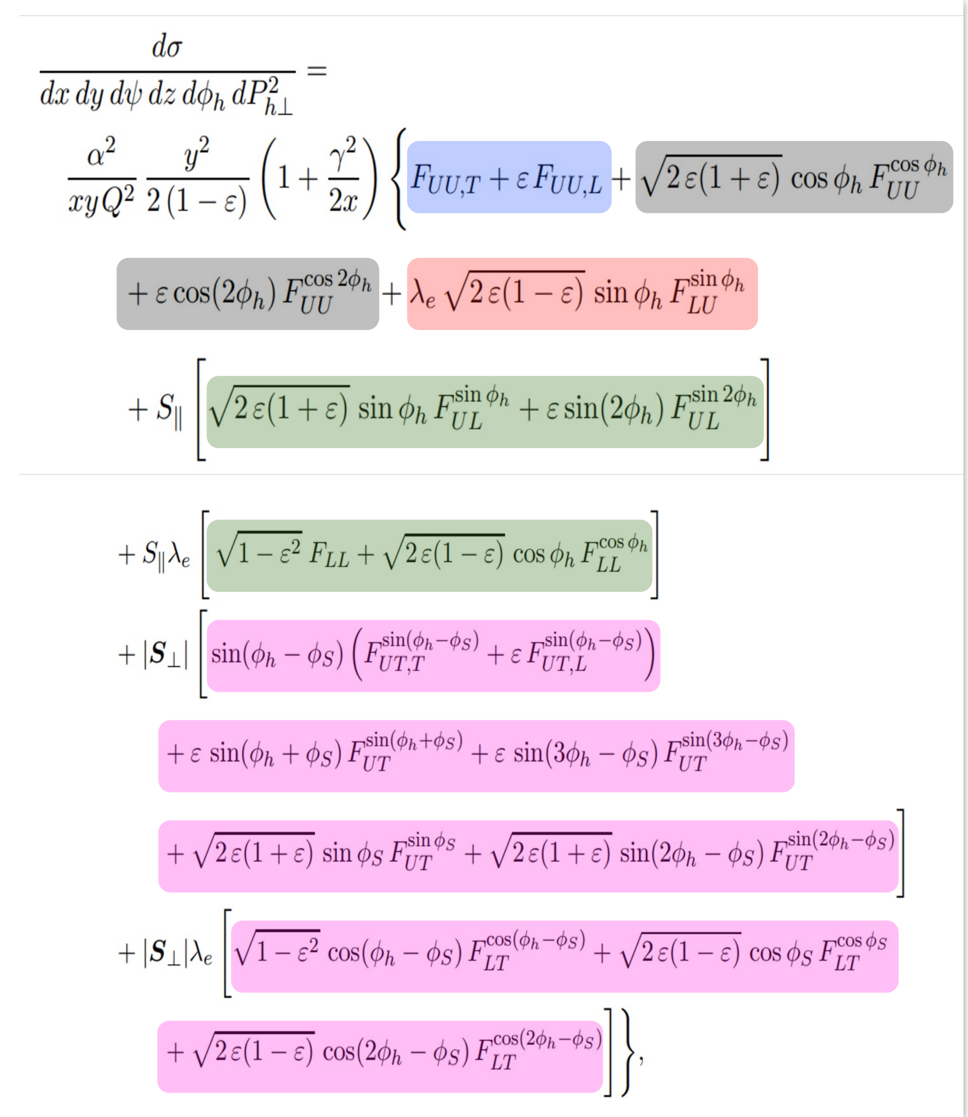


$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

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

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

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

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

$$+\,|\boldsymbol{S}_\perp|\bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

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

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

$$+\,|\boldsymbol{S}_\perp|\lambda_e\bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

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

Run Group A (Unpolarized LH_2 target)

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

Run Goup B (Unpolarized LD_2 target)

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

Run Group C (**longitudinally** polarized NH_3 and ND_3)

- ★ **F_{UL}** and **F_{LL}**

Run Group K (Unpolarized LH_2 target)

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

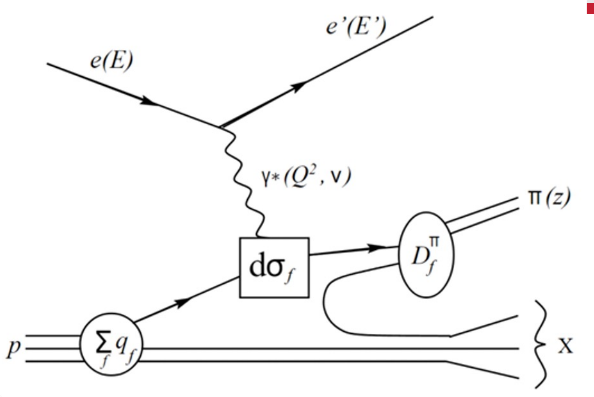
Run Group H (**transversely** polarized NH_3)

- ★ **F_{UT}** structure function

Unpolarized Multiplicities of ep→eπ^0(X)

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

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

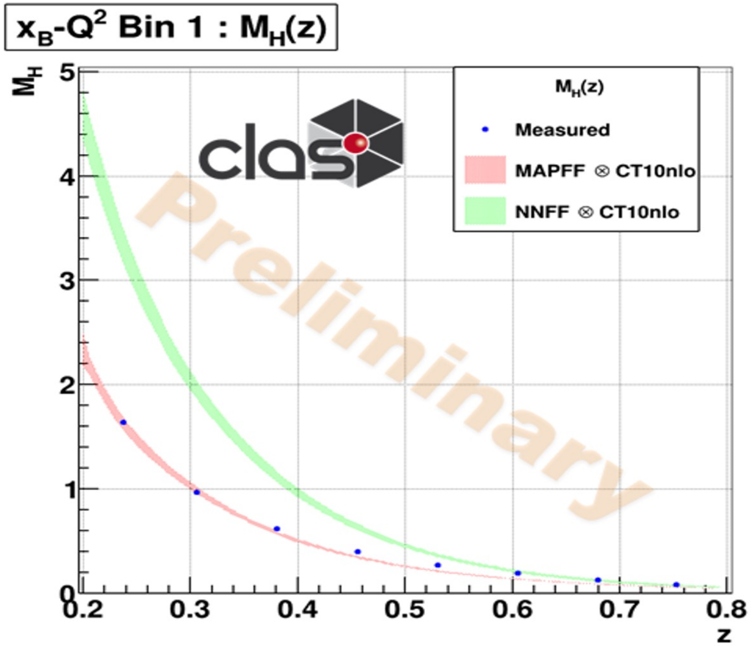


- ★ Study integrates over the azimuthal ϕ_h angle

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

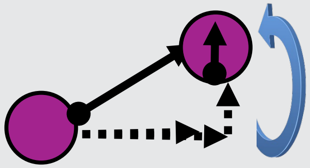
- ★ Invariant mass fits over the diphoton spectrum are performed to calculate N(π^0)

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

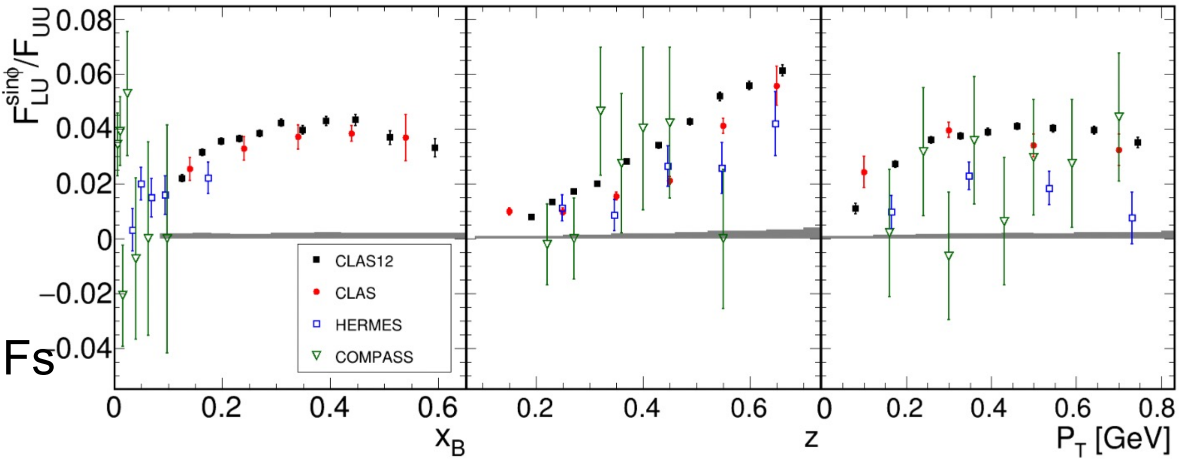


M.Scott

CLAS12 pion BSAs



Phys.Rev.Lett. 128 (2022) 6, 062005



Higher Twist PDFs

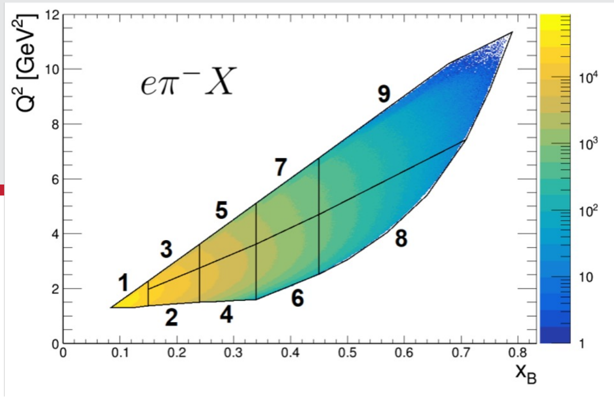
N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

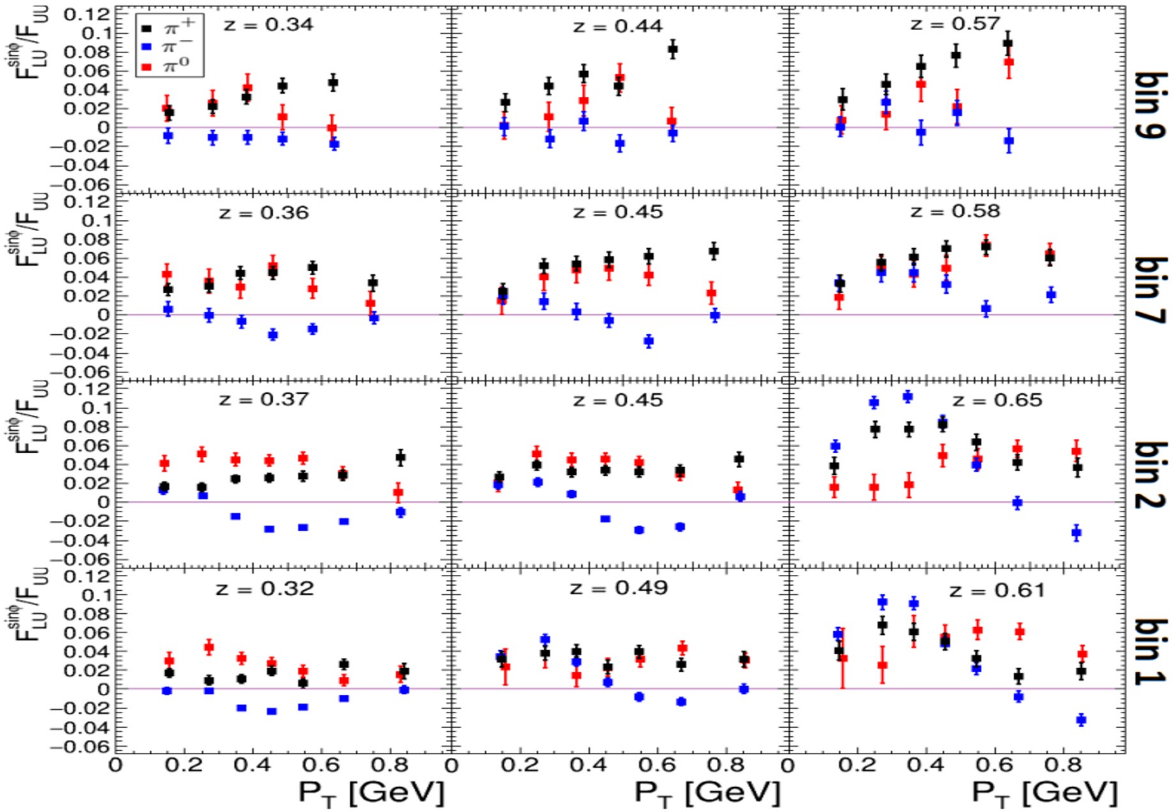
S. Diehl

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

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

Collins FF twist-3 FF unpolarized FF





S. Diehl

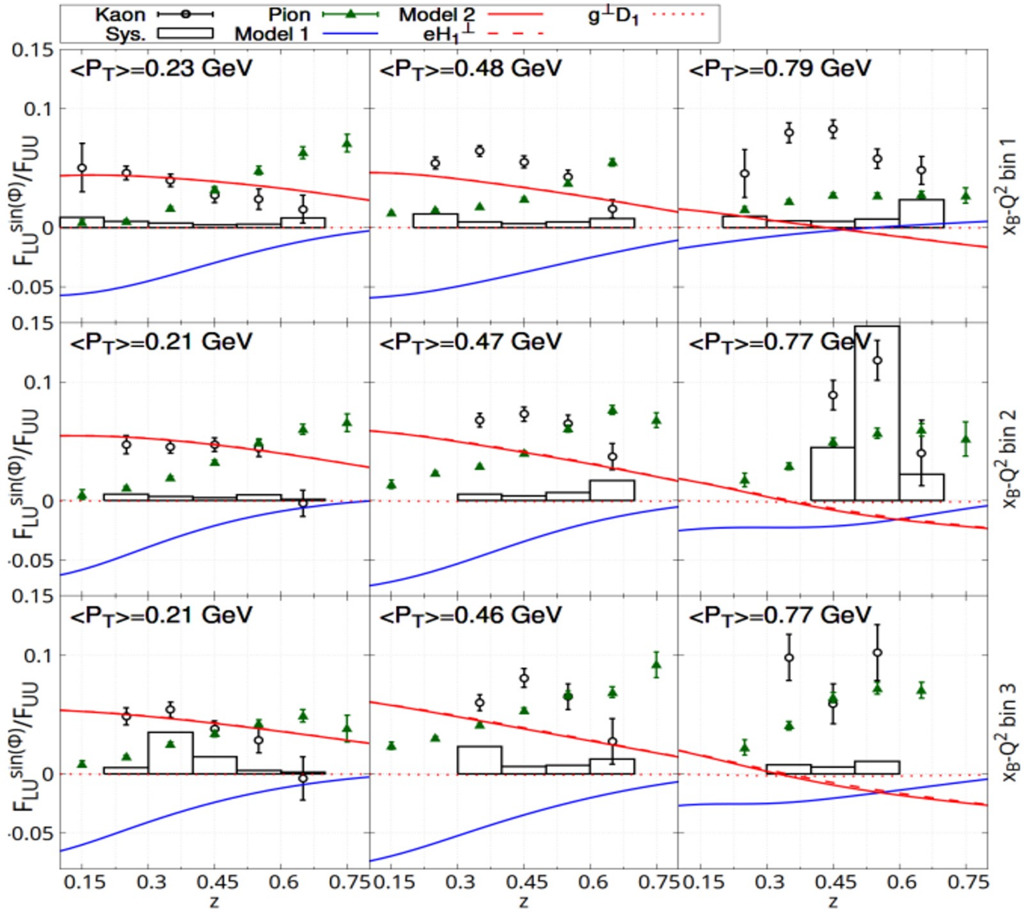
- ★ If Collins term only **($H_1^{\perp}$)** → hierarchy of the A_{LU}'s

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

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

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

Kaon Asymmetries are larger



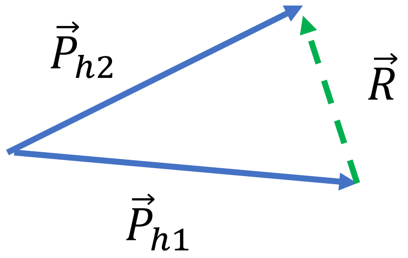
A. Kripko

- Reasonable Assumption
  - u quark dominance

➔Difference due to $D_1^{K^+/u}$,$H_1^{\perp K^+/u}$

Models by Mao/Lu
using different models
of $e(x), g^\perp$
EPJC 73, 2557 (2013) and 74, 2910 (2014)

Better: Dihadron Fragmentation Functions



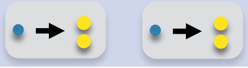
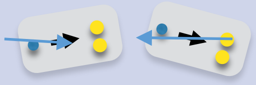
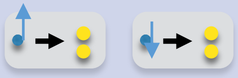
Additional Observable:

$\vec{R} = \overrightarrow{P_1} - \overrightarrow{P_2}$:

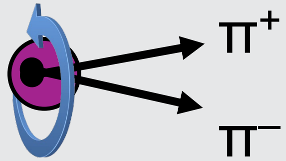
The relative momentum of the hadron pair is an additional degree of freedom:

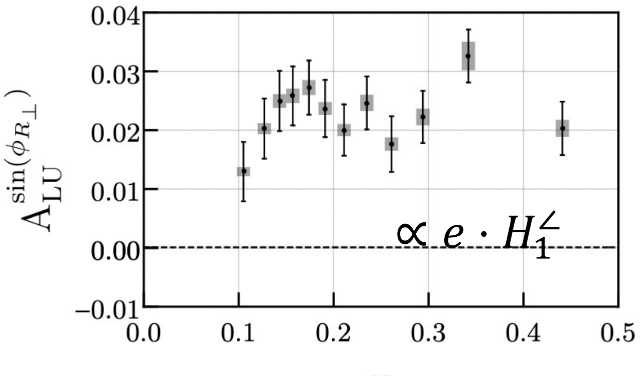
More degrees of freedom→More information about correlations in final state

Additional FFs that do not exist in single-hadron case $G_1^{\perp}$ →related to jet handedness

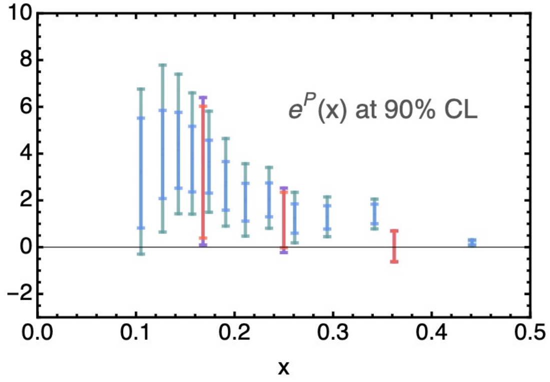
Parton polarization → Hadron Polarization ⇣	**Spin averaged**	**longitudinal**	**transverse**
spin averaged	$D_1^{h/q}(z,M)$ 		$\boldsymbol{H_1^{\perp h/q}(z,p_T}$**M, (Ph),**$\theta)$ 'Di-hadron Collins'
longitudinal			
Transverse		**G₁$^{\perp}$(z,M,P$_h$,θ)=**  T-odd, chiral-even →jet handedness QCD vaccum strucuture	**H₁$^{\sphericalangle}$(z,M, (P$_h$),θ)=.** T-odd, chiral-odd Colinear 

Better: di-hadrons





Phys.Rev.Lett. 126 (2021) 152501

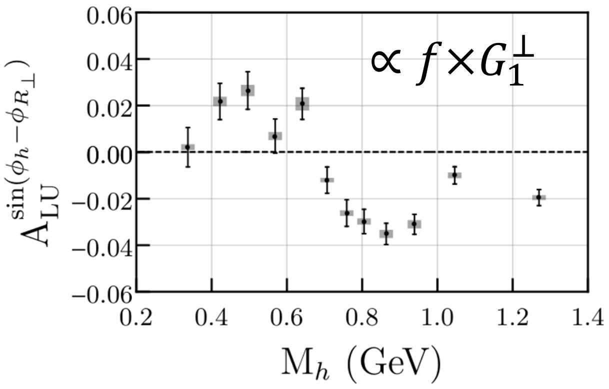


Phys.Rev.D 106 (2022) 1, 014027

C. Dilks/T. Hayward

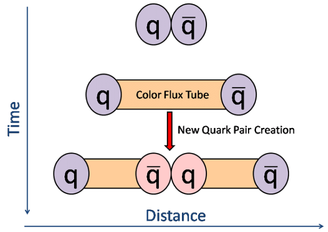
$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{m_{hh}}\,x\,e^q(x)\,H_1^{\triangleleft q}(z,\cos\theta,m_{hh}) + \frac{1}{z}\,f_1^q(x)\,\widetilde{G}^{\triangleleft q}(z,\cos\theta,m_{hh})\right],$$

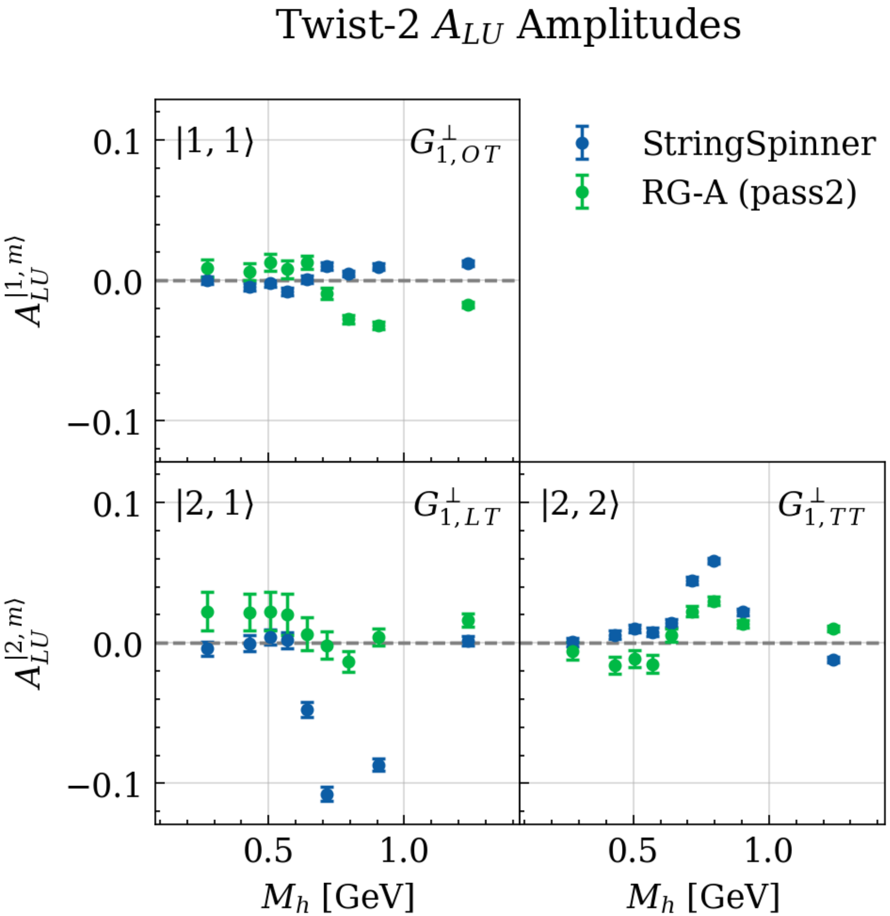
- First extraction of $e(x)$
- Further constrains from F_{UL} and F_{LL}
- First signal for $G_1^{\perp}$
  - Interesting resonance structure consistent with models
    (e.g. Luo, Sun, Xie, *Phys.Rev.D* 101 (2020) 5, 054020)

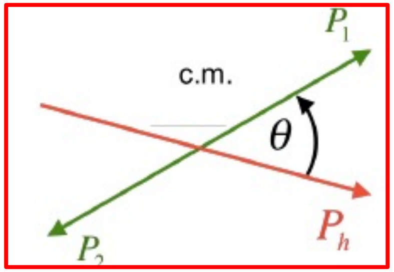


Compare Partial Wave Decomposition in MC and Data

- Comparing to Polarized Lund model here (StringSpinner $3P_0$ *model*, A. Kerbizi et al, *Comput.Phys.Commun.* 272 (2022))





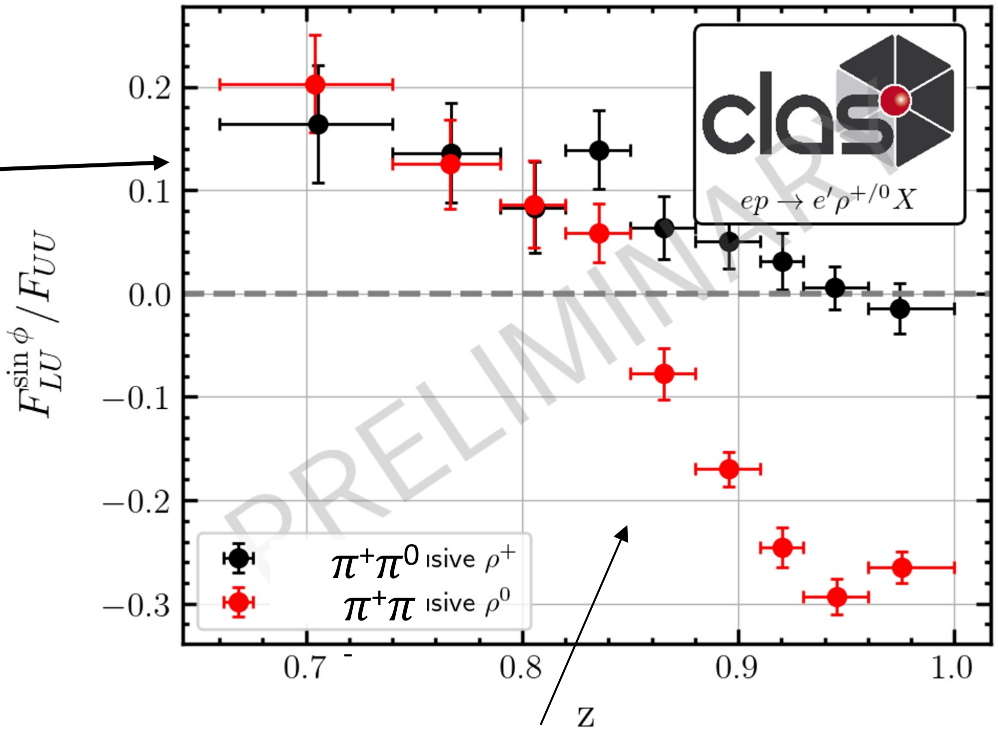


G Matousek

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

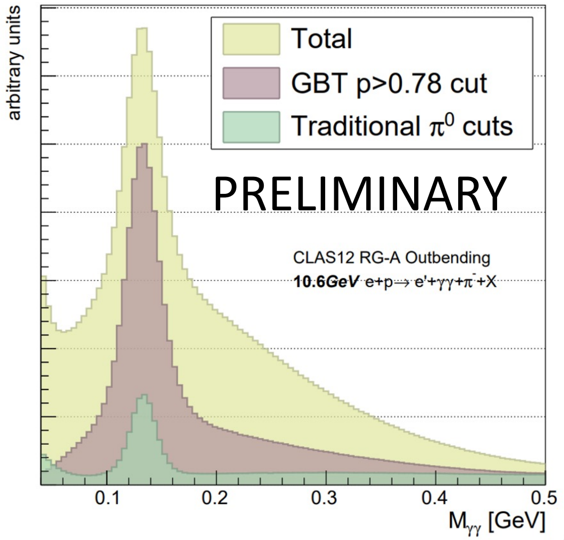
- ★ We can constrain/better understand the contribution of ρ^0, ρ^+ decays on our single hadron asymmetries by looking at near exclusive (M_X < 1.1 GeV) channels
  - ★ Strong yet similar asymmetries observed **(both productions came from struck *u* quark)**

→See talk by K. Joo



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

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



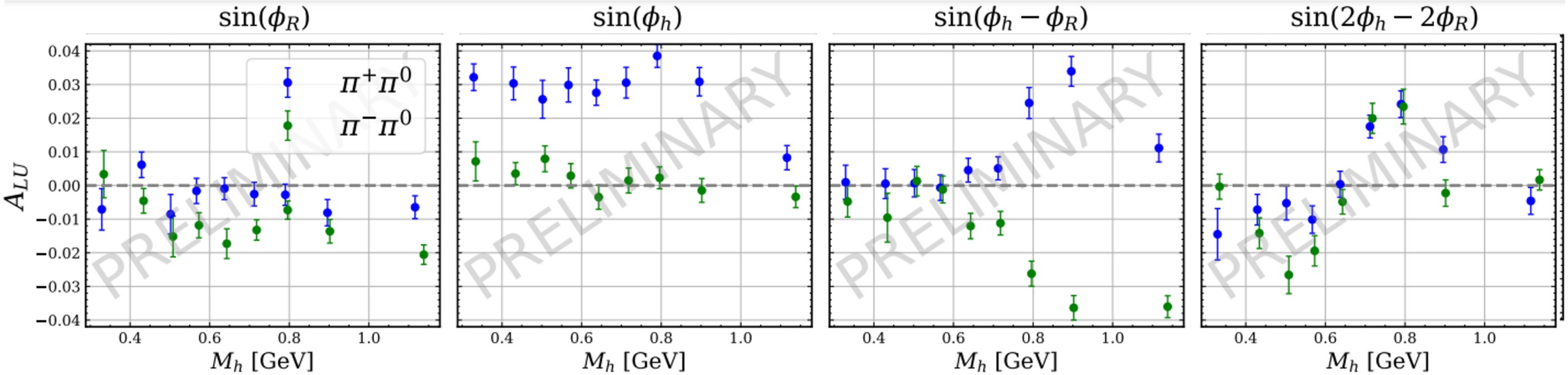
- ★ Nearest-neighbor GBDT model to reduce γ background

- ★ 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

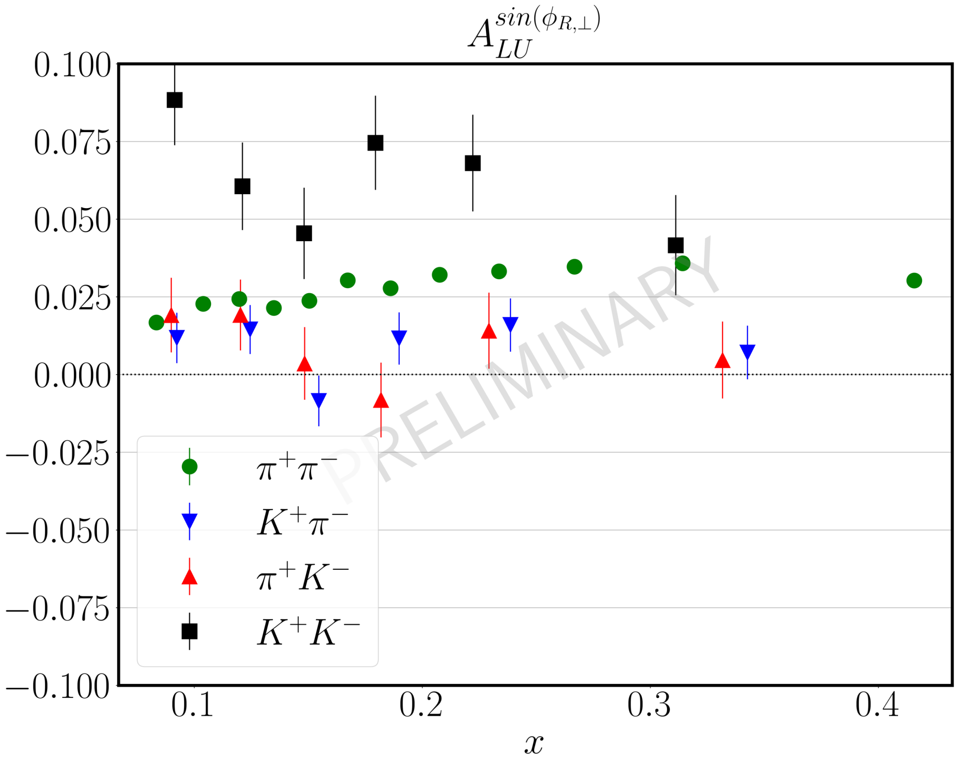
$$e \otimes H_1^{\perp|\ell,m>}$$

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



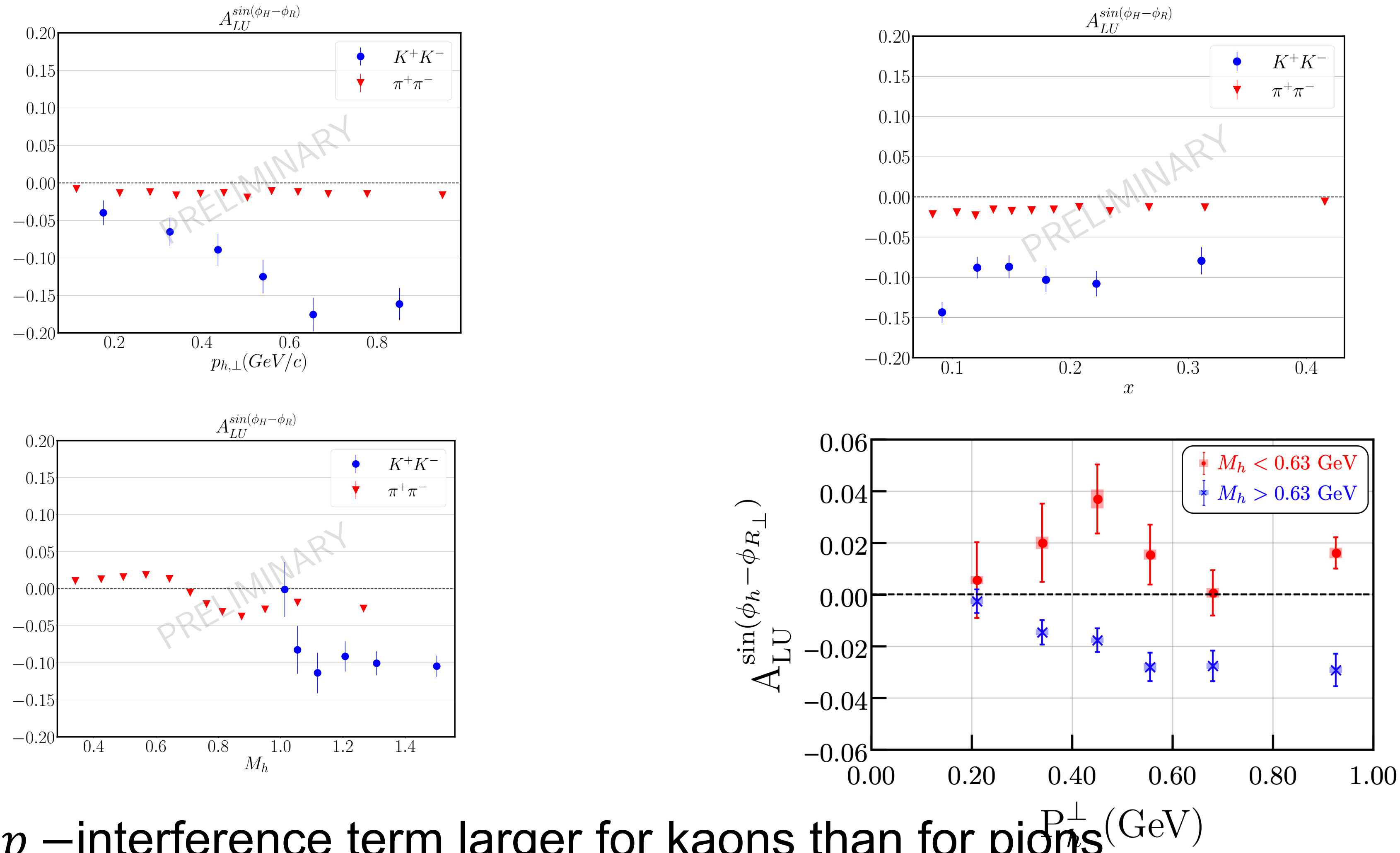
Slide by G. Matousek

Kaons



- Kaon ≫ Pions
  - Assuming u −quark dominance →FF effect?
  - Twist3 FF relevant?
  - Or $e(x)$ for strange quarks

Asymmetries sensitive to $G_1^\perp$



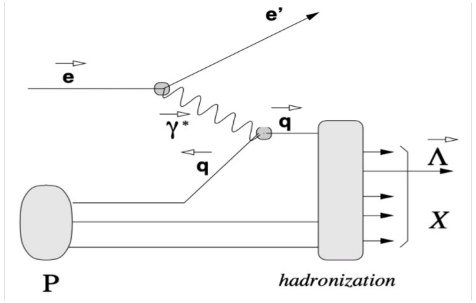
- sp −interference term larger for kaons than for pions
- Not true for all interference terms (not shown)
- $M_{KK} > m_\phi$ can account for $p_\perp$ dependence

Lambda Program at CLAS12

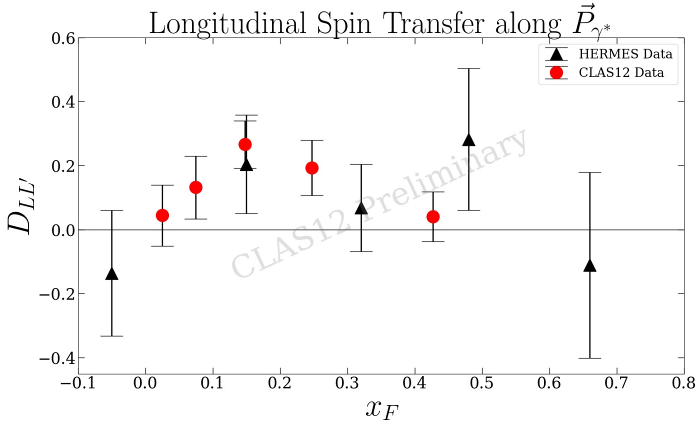
- **Constituent Quark Model (CQM)**
  - Predicts *s* quark carries 100% of the *Λ* hyperon spin
- “Do polarized *u*-quarks from current fragmentation transfer their longitudinal spin to the lambda?” → Test spin structure

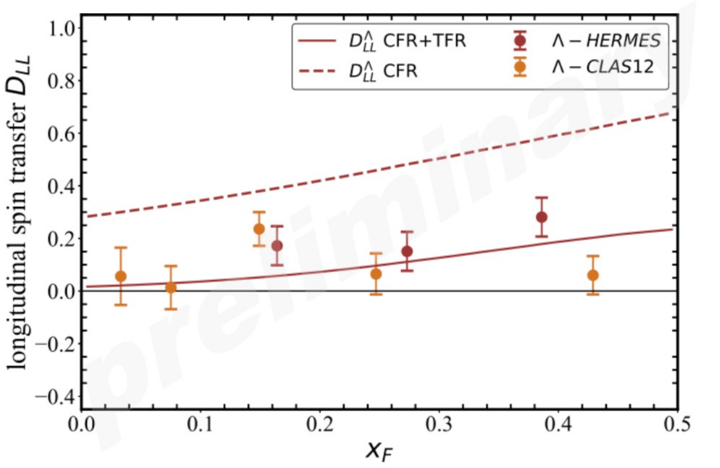
$$P_\Lambda = P_b D(y) \boxed{D^{\Lambda}_{LL'}},$$

longitudinal spin-transfer



Xiaoyan Zhao at



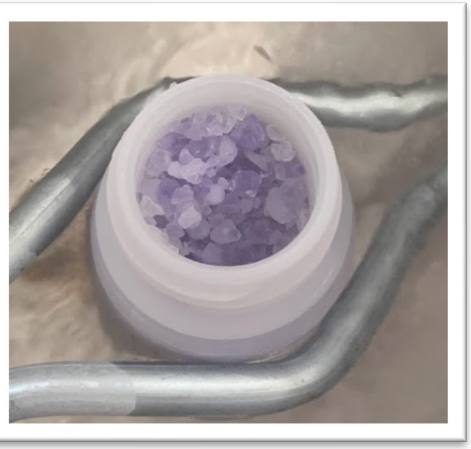


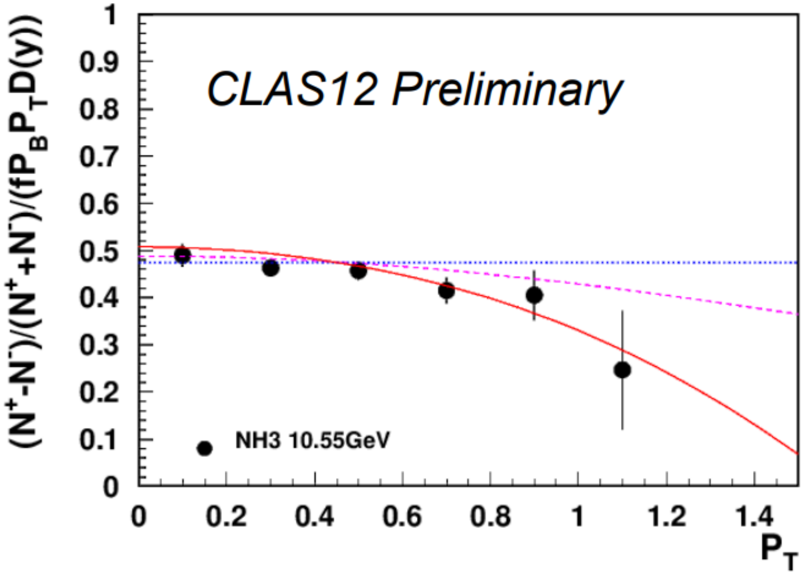
M. McEneaney

Part of planned extensive Lambda program with larger statistics: Transverse, polarizing…

Longitudinal target results with RGC

- Results represent 5% proton target (Ammonia, NH_3)





Sensitive to the k_T width of f_1 and g_1

- Dilution factor $\approx \frac{3}{17}$
- Polarization $\approx 85\%$

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

Convolution over transverse momentum space

- Rich program underway

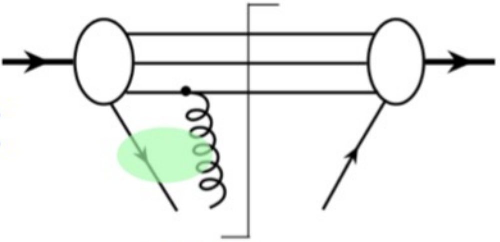
Beyond the parton picture

- Higher Twist Contributions
- Overlap of regions that are not captured by factorized TMD picture
- VM Meson decays
- Radiative corrections
- Assumption of suppressed long photon contributions

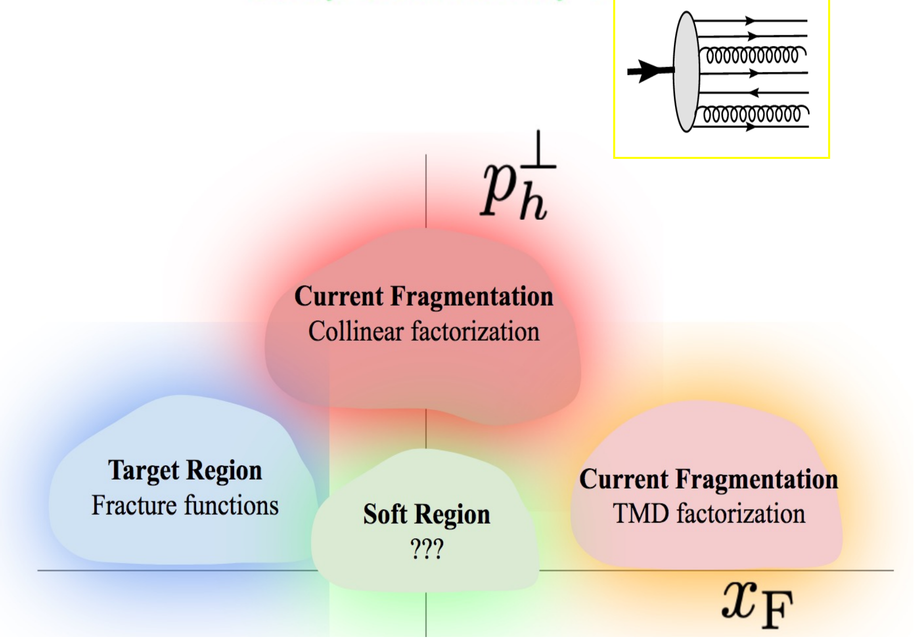
One persons ‘complication’ is another person's signal…

➔Need high lumi, leverarm in kinematics to disentangle various contributions

$T^{(3)}(x,x) \propto$

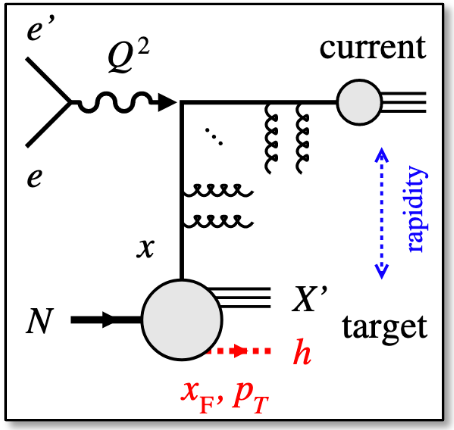


Qiu, Sterman, 1991, ...



Boglione, Produkin et al

Fracture Functions to describe Target Region



- probability for the target (p/n) remnant to form a hadron *given* ejected quark

  No hard/soft energy scale separation

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

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

$$\boxed{\sum_h \int_0^{1-x} d\zeta\,\zeta\,\hat{u}_1(x,\zeta) = (1-x)f_1(x)}$$

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

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

$$\sum_h \int_0^{1-x} d\zeta\zeta M_a(x,\zeta) = (1-x)f_a(x)$$

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}	$h_1, h_{1T}^\perp$

Unpolarized PDF analog

helicity PDF analog

etc. etc.

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

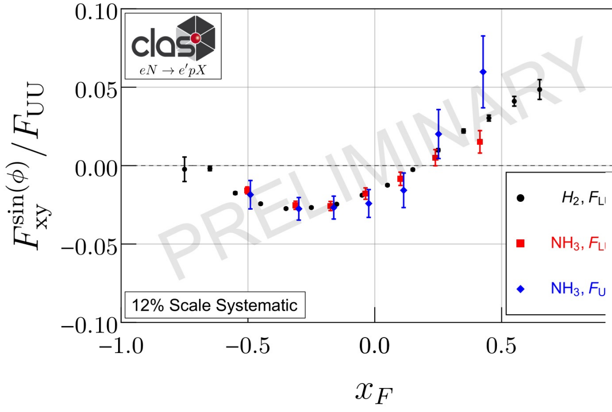
M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

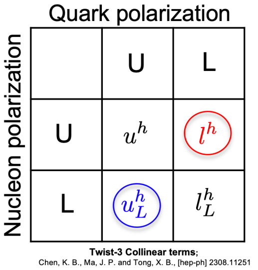
CFR

TFR

Preliminary Analysis: Fracture Functions

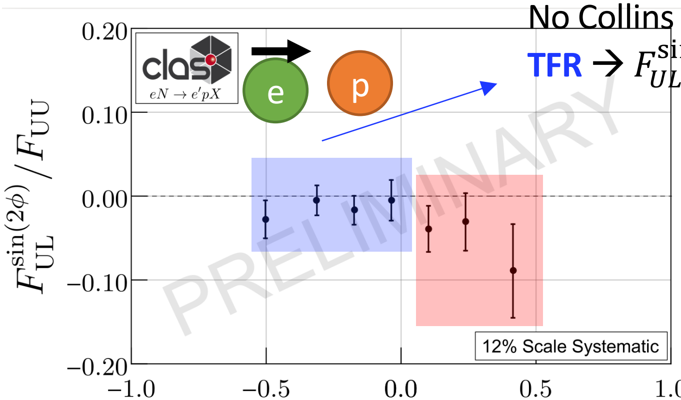
- First observation of correlations between Current and target region
- Visible separation between TFR ($x_F < 0$) and CFR ($x_F > 0$)





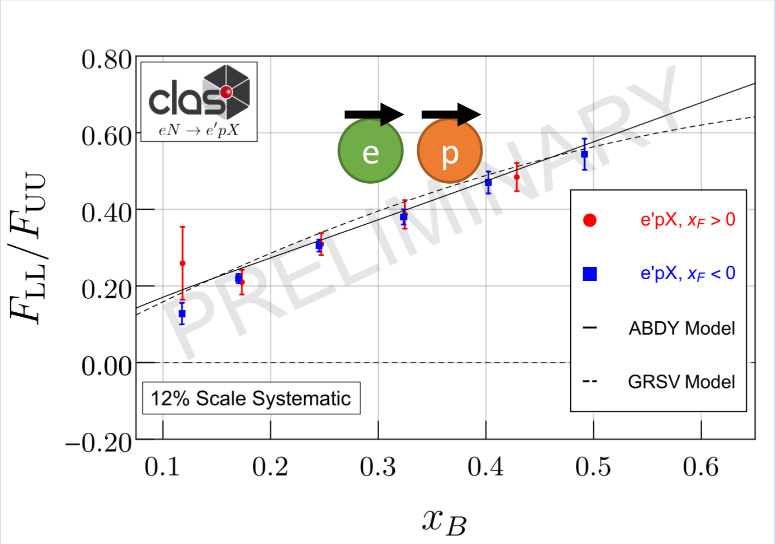
Nucleon polarization	Quark polarization U	Quark polarization L
U	u^h	l^h
L	u_L^h	l_L^h

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



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

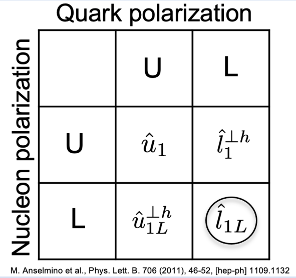
$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1L}^{\perp} H_1^{\perp}\right]$$



TFR Access to helicity distribution g_{1L}

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

Integral relation holds!



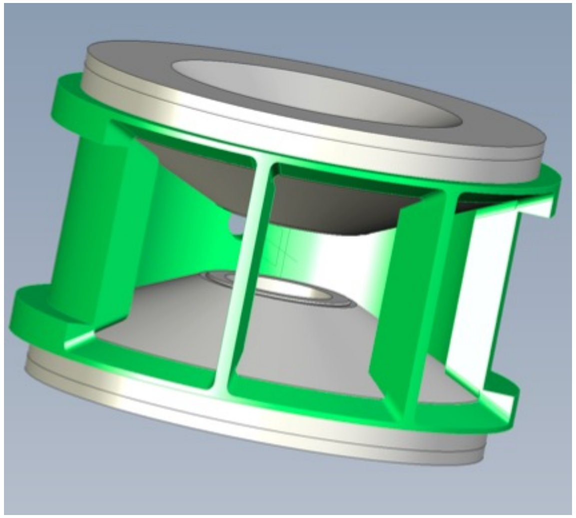
Nucleon polarization	Quark polarization U	Quark polarization L
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$

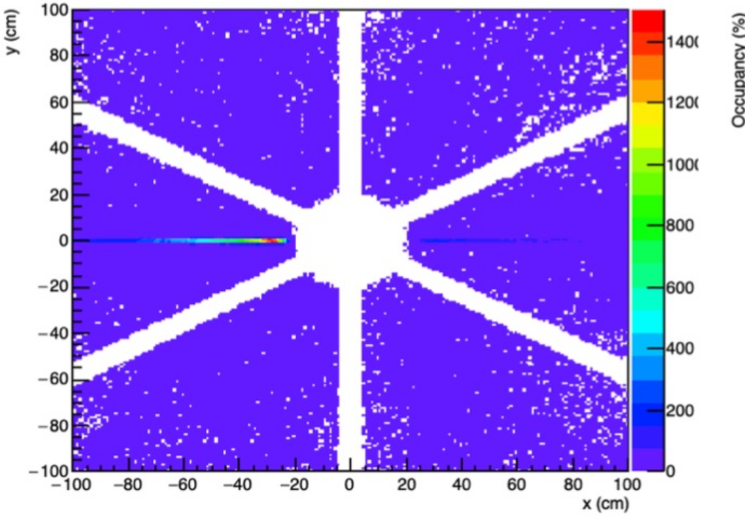
M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

CLAS future: Transverse Spin NH_3 target (RGH)

- Add ”conventional” NH_3 target to CLAS
- Similar to longitudinal target, dilution $3/17$, Polarization $\approx 85\%$
- Transverse Holding field: Moeller Scattering limits luminosity

➔For proposal use **very** conservative $5{\times}10^{33}cm^{-2}s^{-1}$ (about $\frac{1}{50}$ of ‘regular’ CLAS12)

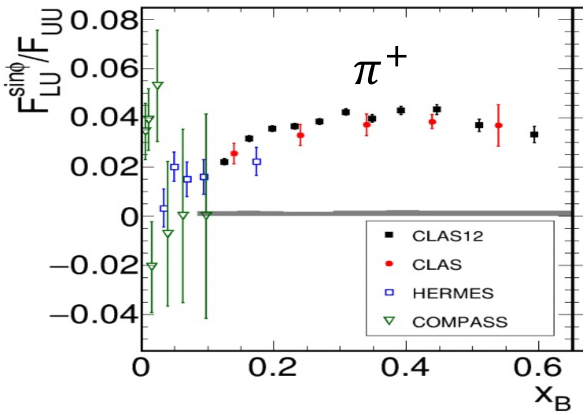


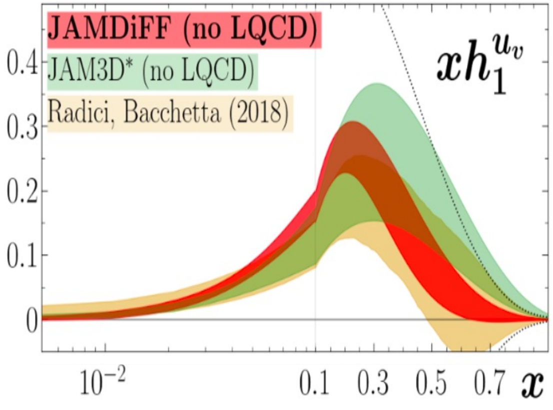


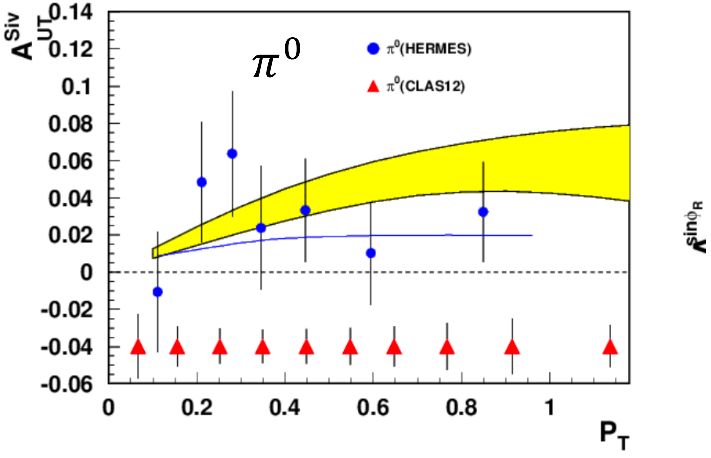
Physics with a transverse Target: Example Transversity

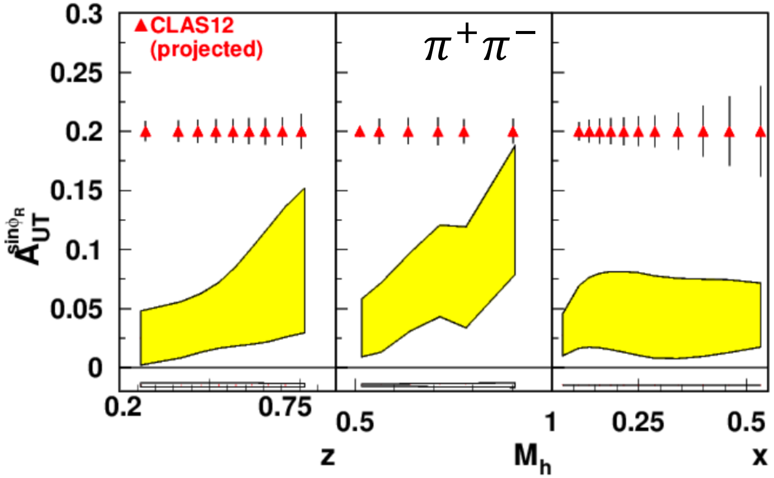
- Data $x > 0.2$ very sparse

→Models diverge



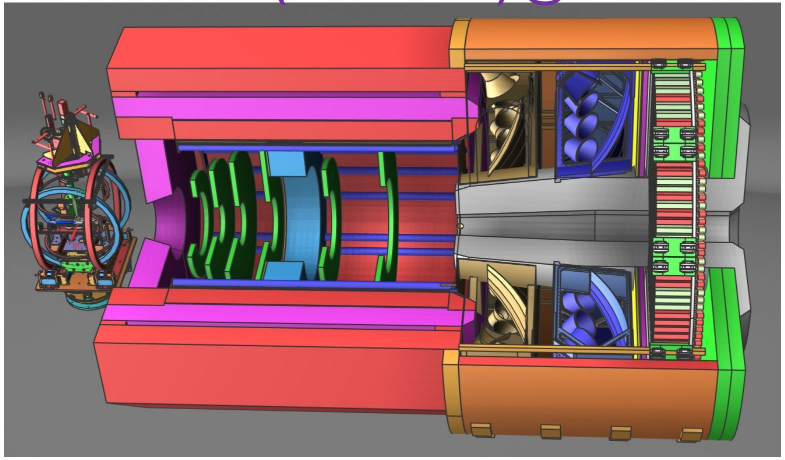




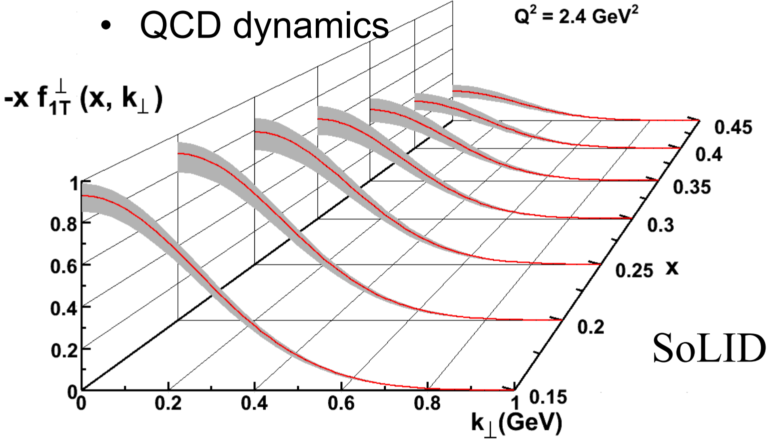


SoLID provides *unique* capability combining high luminosity ($10^{37\text{-}39}$ /cm^2/s) (>100 of CLAS12; >1000 times of EIC) and **large acceptance** with full ϕ coverage to maximize the science return of the 12-GeV CEBAF upgrade

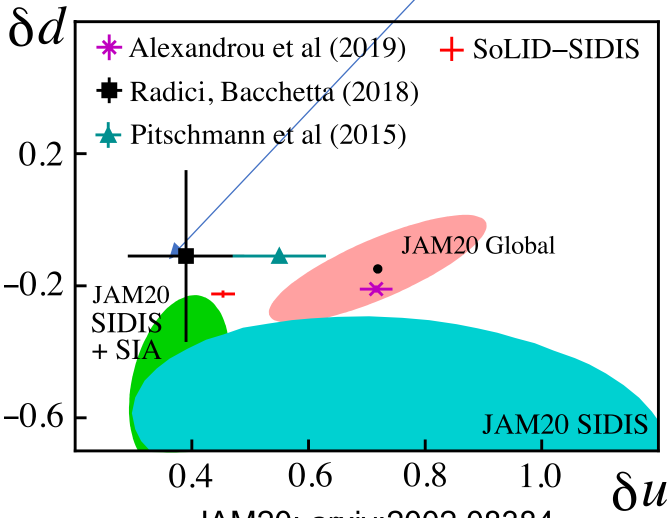
Polarized ^{3}He (``neutron") @ SoLID



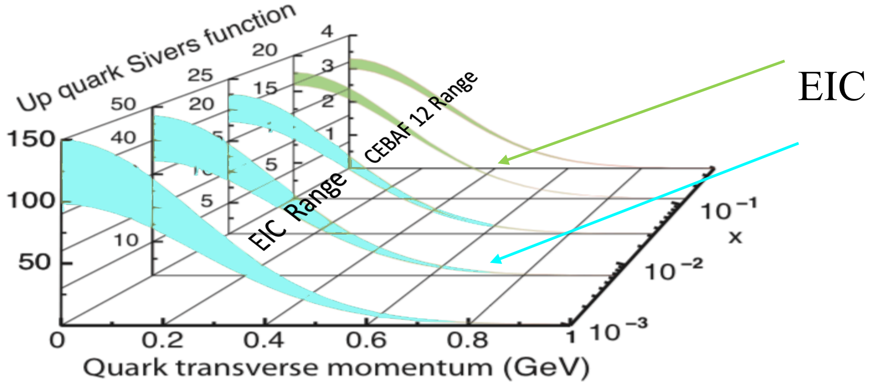
- Sivers: an example of TMDs
- Quantum correlations between nucleon spin and quark motion
- QCD dynamics



SoLID impact on tensor charge

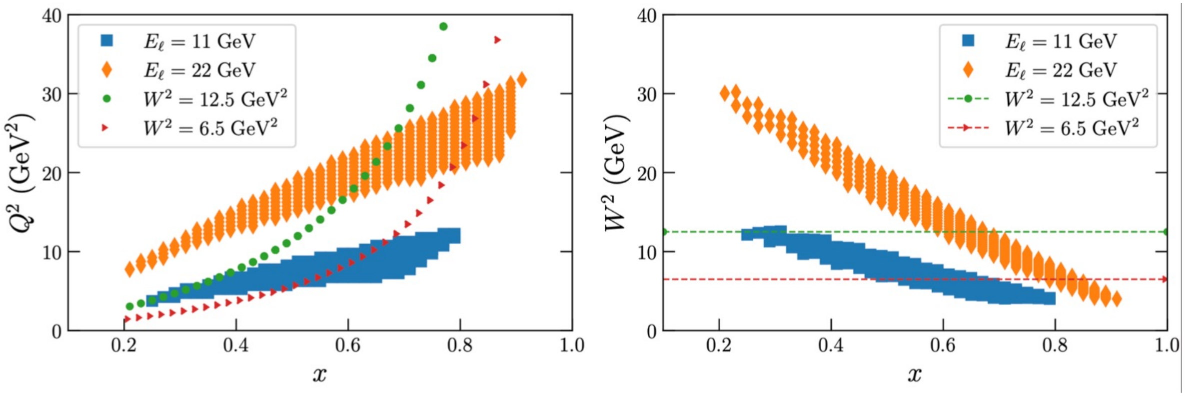


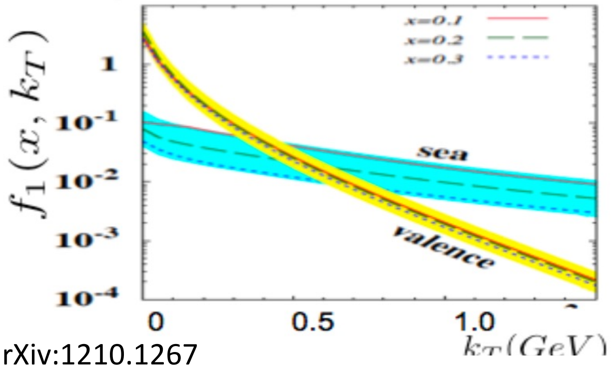
JAM20: arxiv:2002.08384



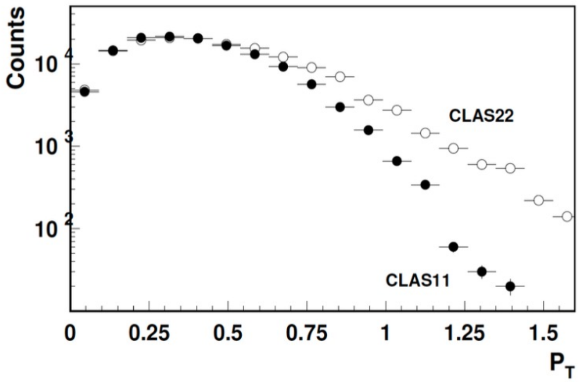
- Tensor charge: a fundamental QCD quantity to test lattice QCD
- Probe new physics combined with EDMs

High x at Jlab 22





P.Schweitzer et al. arXiv:1210.1267



Strong Interaction Physics at the Luminosity Frontier
with 22 GeV Electrons at Jefferson Lab

t: 2306.09360 [nucl-ex]

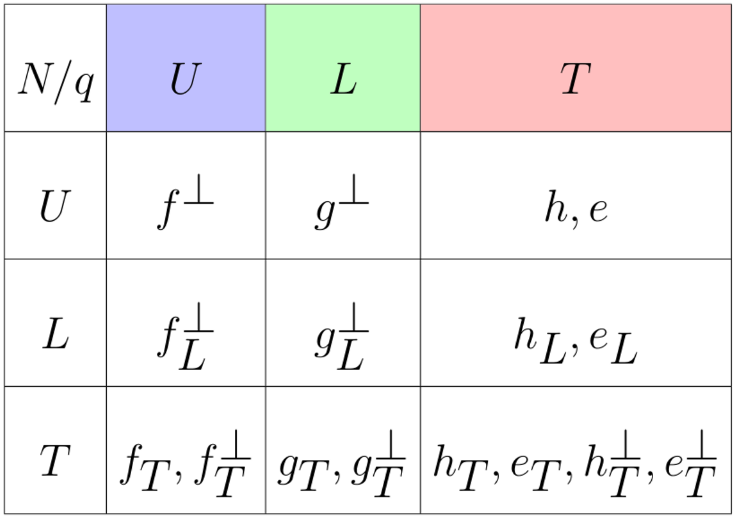
- ≈doubling beam energy significantly increases phase space
- Pin down valence structure of the proton
- Integration in global analyses (e.g. strange distributions, CS Kernel)
- Kinematic phase space opens up for TMD analysis ($\frac{q_T}{z}$ cut), $\sigma_{L/T}$ Separation etc

Summary and Outlook

- **JLAB12 provides several orders of magnitude higher luminosity than any other lepton scattering facility!**
- **High precision data in the valence region**
  - Proton, deuteron, helium targets
  - Beam spin, longitudinal/transverse target polarizations
  - Multidimensional measurements
  - Analyses beyond leading twist/CFR regime
- **First results from BSAs and longitudinal spin asymmetries**
  - Precision data to extract TMDs
  - New target-current correlations
  - Intriguing flavor dependencies
  - Insights into spin-orbit correlations in hadronization using partial wave decomposition

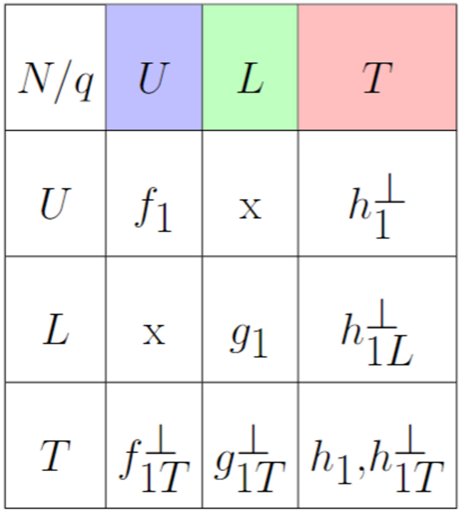
- **Future at CLAS12 and SoLID**
  - Full program with data with longitudinal target(s)
  - Transverse target
  - Modulations of the unpolarized cross-section
  - …
- EIC Complementarity
  - Phase space
  - Depolarization factors

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	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

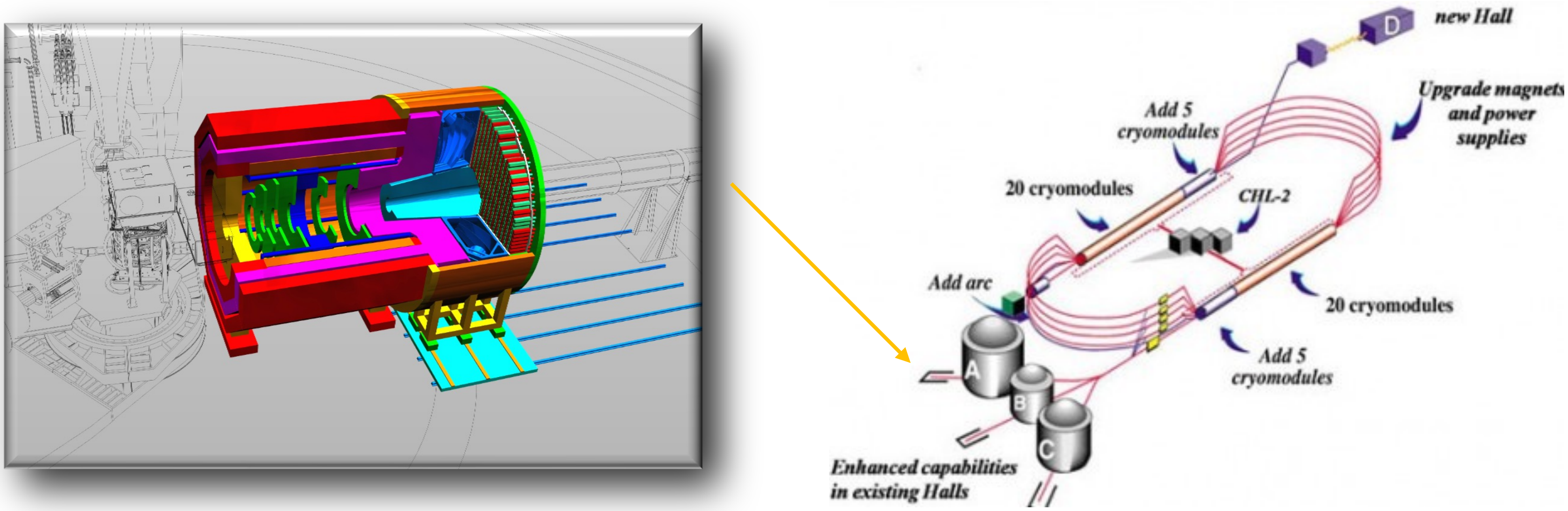
Leading Twist TMD-PDFs



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

SoLID@12-GeV JLab: QCD at the intensity frontier

SoLID provides *unique* capability combining high luminosity ($10^{37\text{-}39}$ /cm^2/s) (>100 of CLAS12; >1000 times of EIC) and **large acceptance** with full ϕ coverage to maximize the science return of the 12-GeV CEBAF upgrade



SoLID with unique capability for rich physics programs

✓ Pushing the phase space in the search of new physics and of hadronic physics

✓ 3D momentum imaging of a relativistic strongly interacting confined system (nucleon spin)

✓ Superior sensitivity to the differential electro- and photo- production cross section of J/ψ near threshold (proton mass)

SoLID physics complementary and synergistic with the EIC science (proton spin and mass, two important EIC science questions) – high-luminosity SoLID unique for valence quark tomography (separation of structure from collision) and precision J/ψ production near the threshold

EIC complementarity

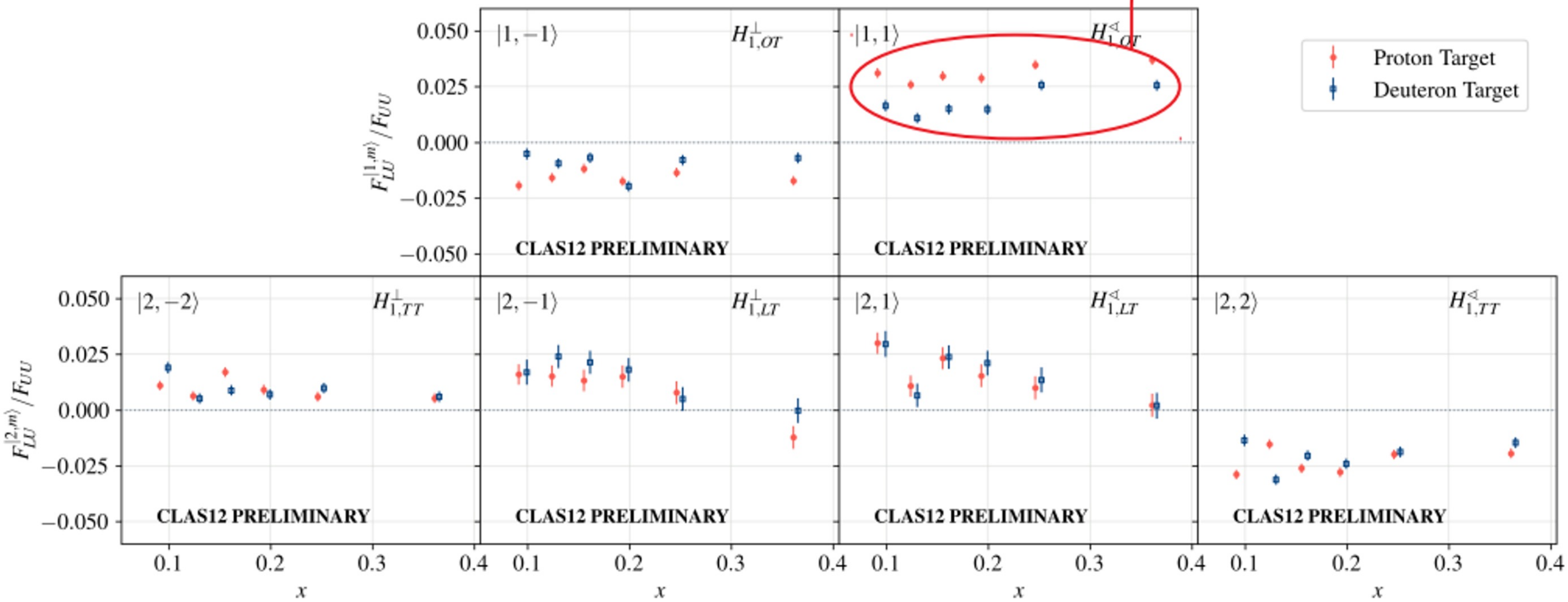
- Some approximations also relevant at EIC
- Valence region, statistics

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

x Bins

Twist-3 F_{LU}/F_{UU} Amplitudes

$e(x) \cdot H_{1,OT}^{\sphericalangle}$



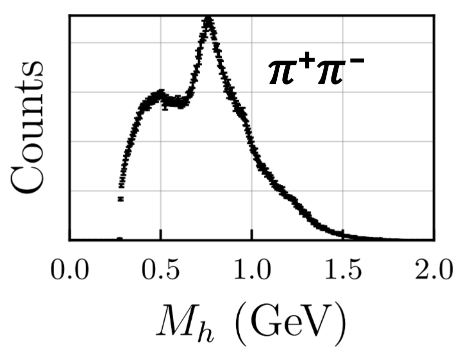
$$A_{LU,\mathbf{p}}^{|\ell,m\rangle} \propto \left(4xe^{u_V} - xe^{d_V}\right) H_1^{\perp|\ell,m\rangle}$$

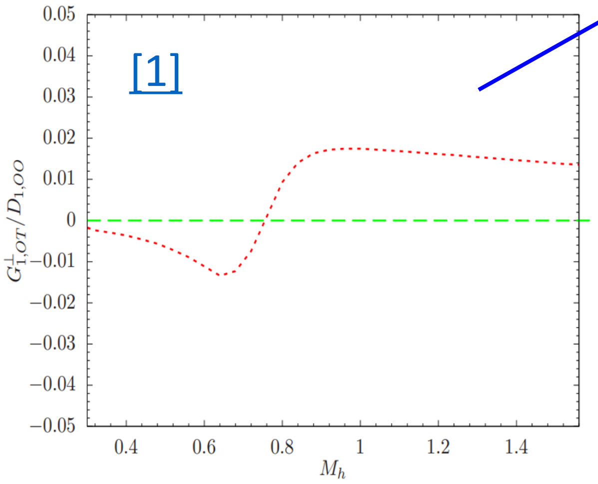
$$A_{LU,\mathbf{d}}^{|\ell,m\rangle} \propto \left(xe^{u_V} + xe^{d_V}\right) H_1^{\perp|\ell,m\rangle}$$

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

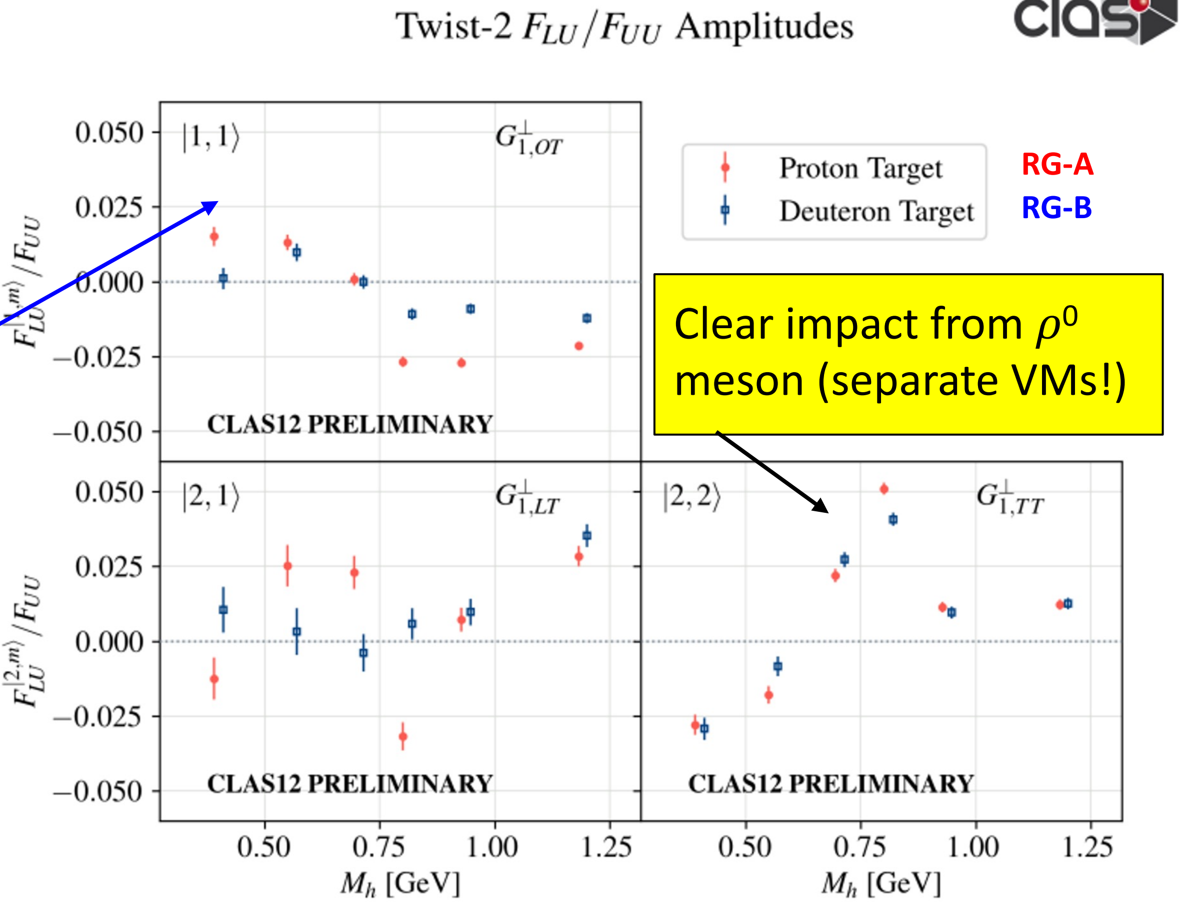
C. Dilks
(Transversity 2022)

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





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

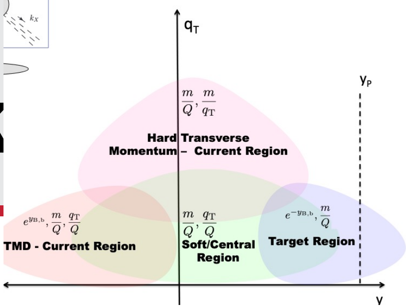


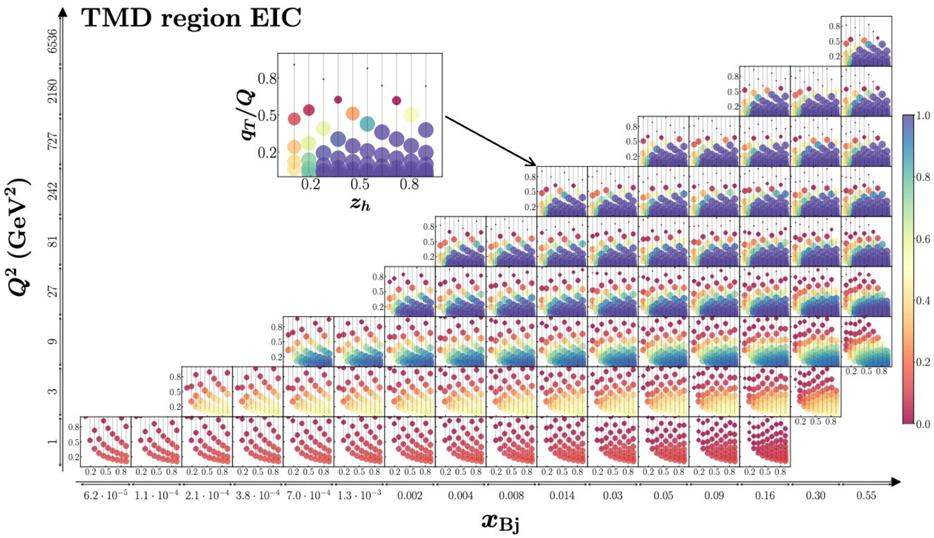
Clear impact from ρ^0 meson (separate VMs!)

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

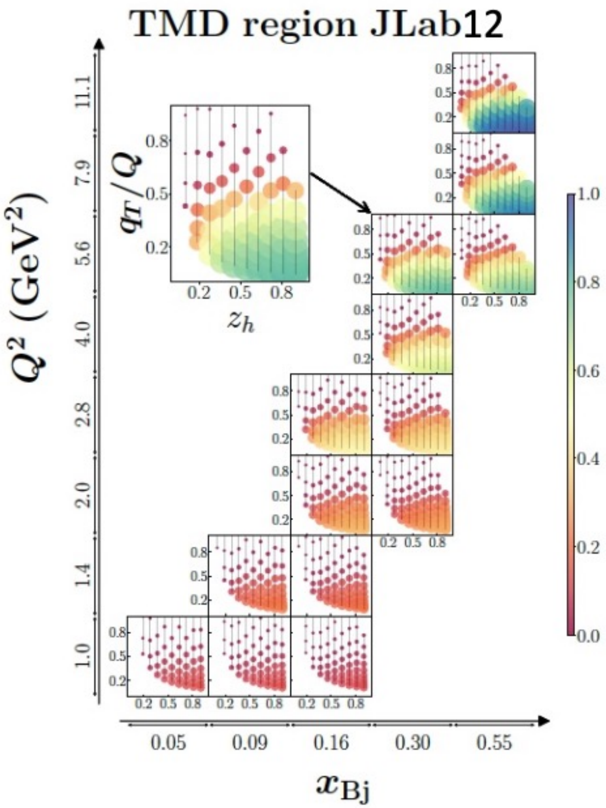
C. Dilks
(Transversity 2022)

Applicability of TMD Framework





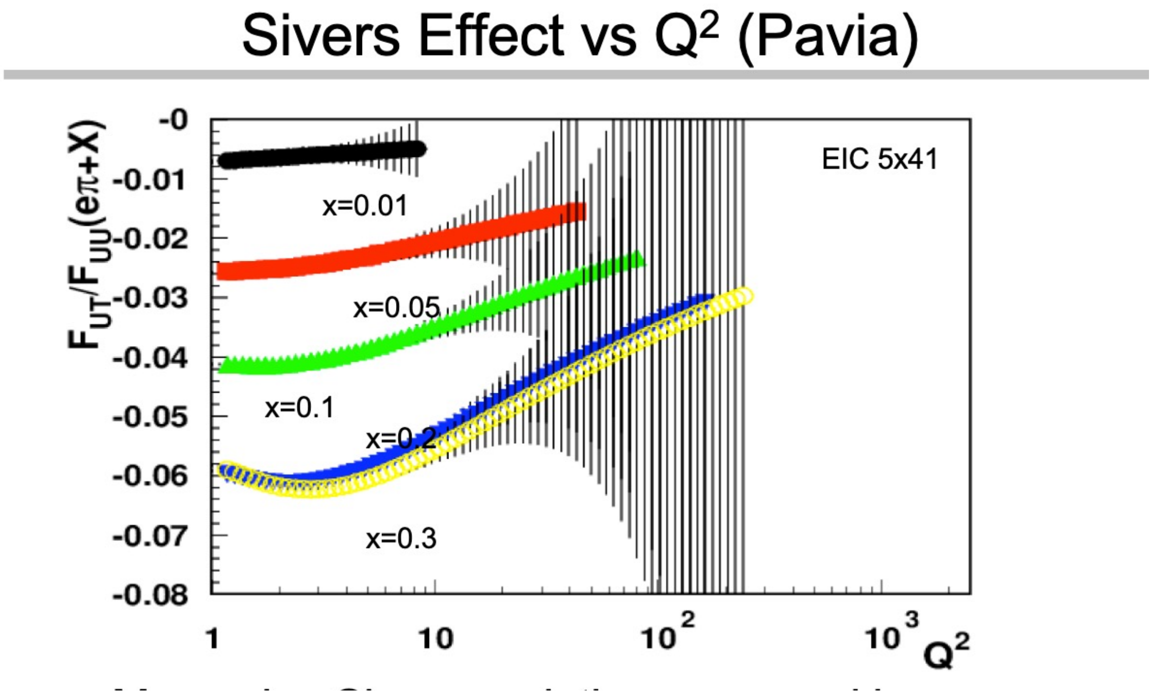
JHEP 04 (2022) 084



- EIC also larger, overlapping phase space for colinear and matching region
- Less correction from TMD expectations framework

  →Challenges and opportunities at JLab

Expected TMD signal →Q^2 dependence



Sivers Effect vs Q² (Pavia)

From A Signori by way of Harut

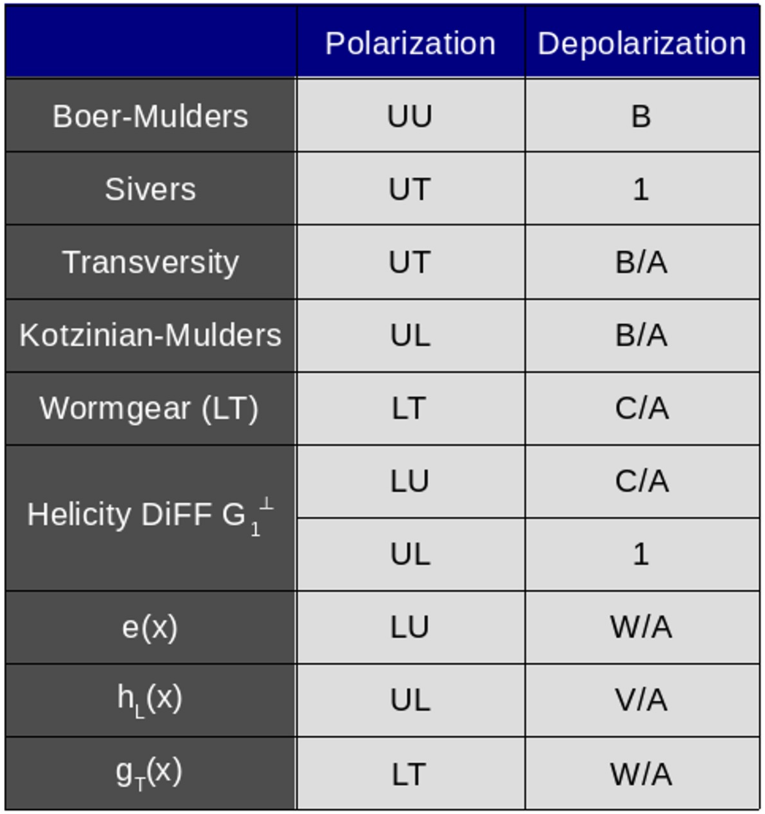
Evolution doesn’t quite cancel.

- Also confirmed by STAR W results

➔TMDs might give largest signal at low y

➔Evolution effects best measured at large x, low y, wide range of Q^2

Access to TMDs: Kinematic 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 (from $e(x)$ onward)

Slide from C. Dilks

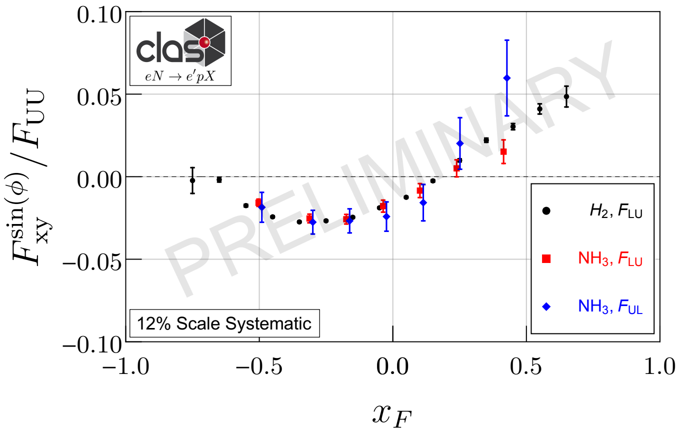
Current and Target Separation

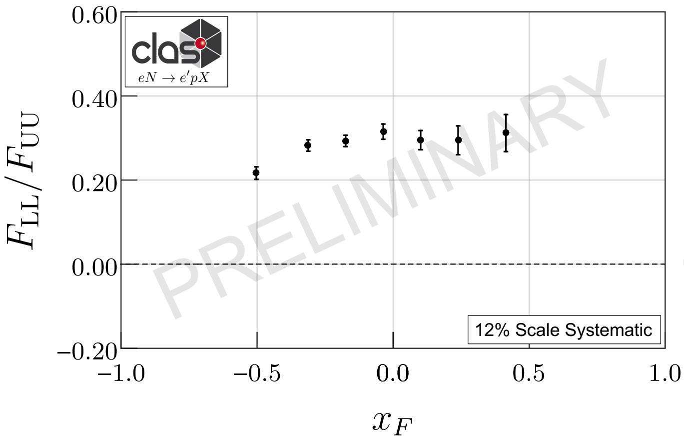
Quark polarization

Nucleon 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





Quark polarization

Nucleon polarization

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

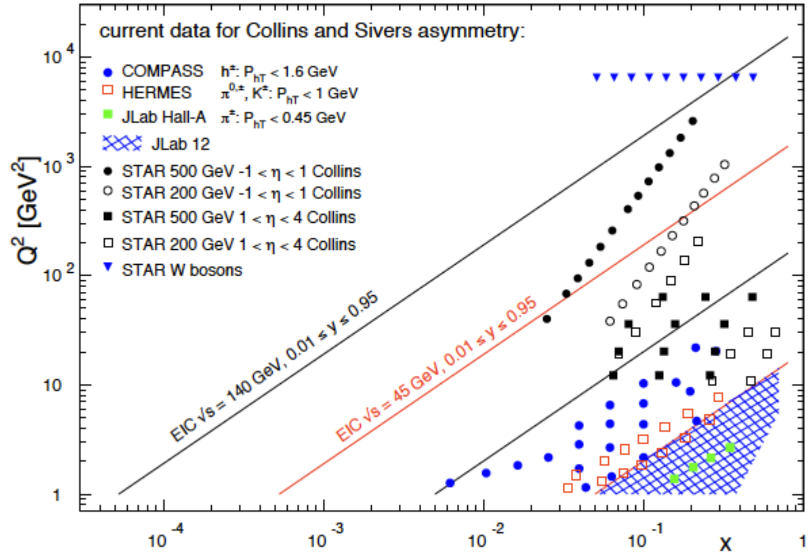
M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

- Odd-function (sine) modulations exhibit a sign flip around the transition from target to current fragmentation. Interestingly, we observe F_{LU} ~ F_{UL}.
- Even-function (cosine) behavior of double-spin asymmetry does not show a sign flip; possible signs decreasing F_{LL} as $x_F \to \pm 1$ (x_B decreasing but likely not the only cause).
- Consistent beam-spin asymmetries in unpolarized H_2 and polarized NH_3 indicates minimal nuclear medium modification.

SIDIS physics at an EIC: Coverage

- Common theme on EIC impact
  - Extended kinematic coverage and precision, along with polarization and possible beam charge degrees of freedom allow multi-pronged approach →needed to extract multidimensional objects
  - TMD factorization is valid

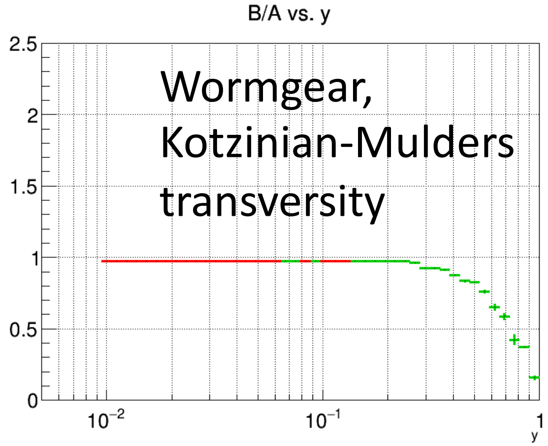
Large Q^2 lever arm: probe evolution, disentangle contributions to σ



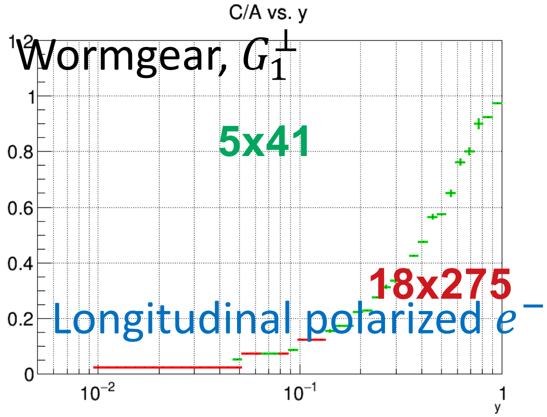
Coverage to low x: access sea and gluon distributions

Depolarization factors for some TMDs are suppressed at EIC kinematics

$$ep \to e\pi^+ X$$



Wormgear, Kotzinian-Mulders transversity

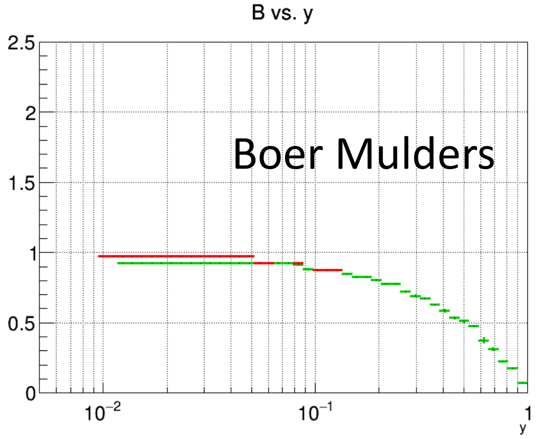


Wormgear, $G_1^\perp$

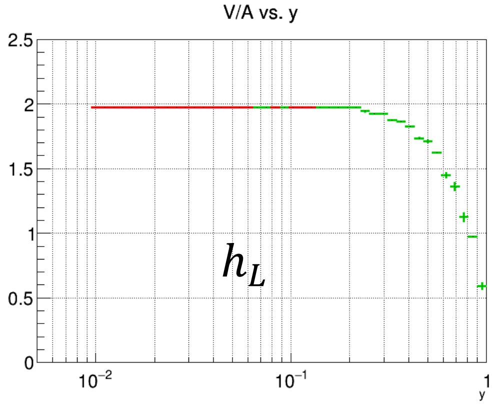
5x41

18x275

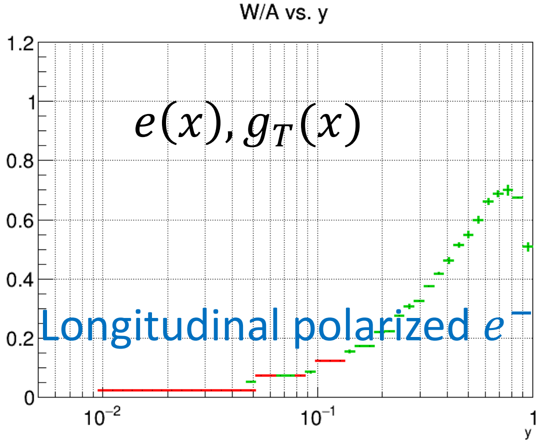
Longitudinal polarized e^-



Boer Mulders



h_L



$e(x), g_T(x)$

Longitudinal polarized e^-

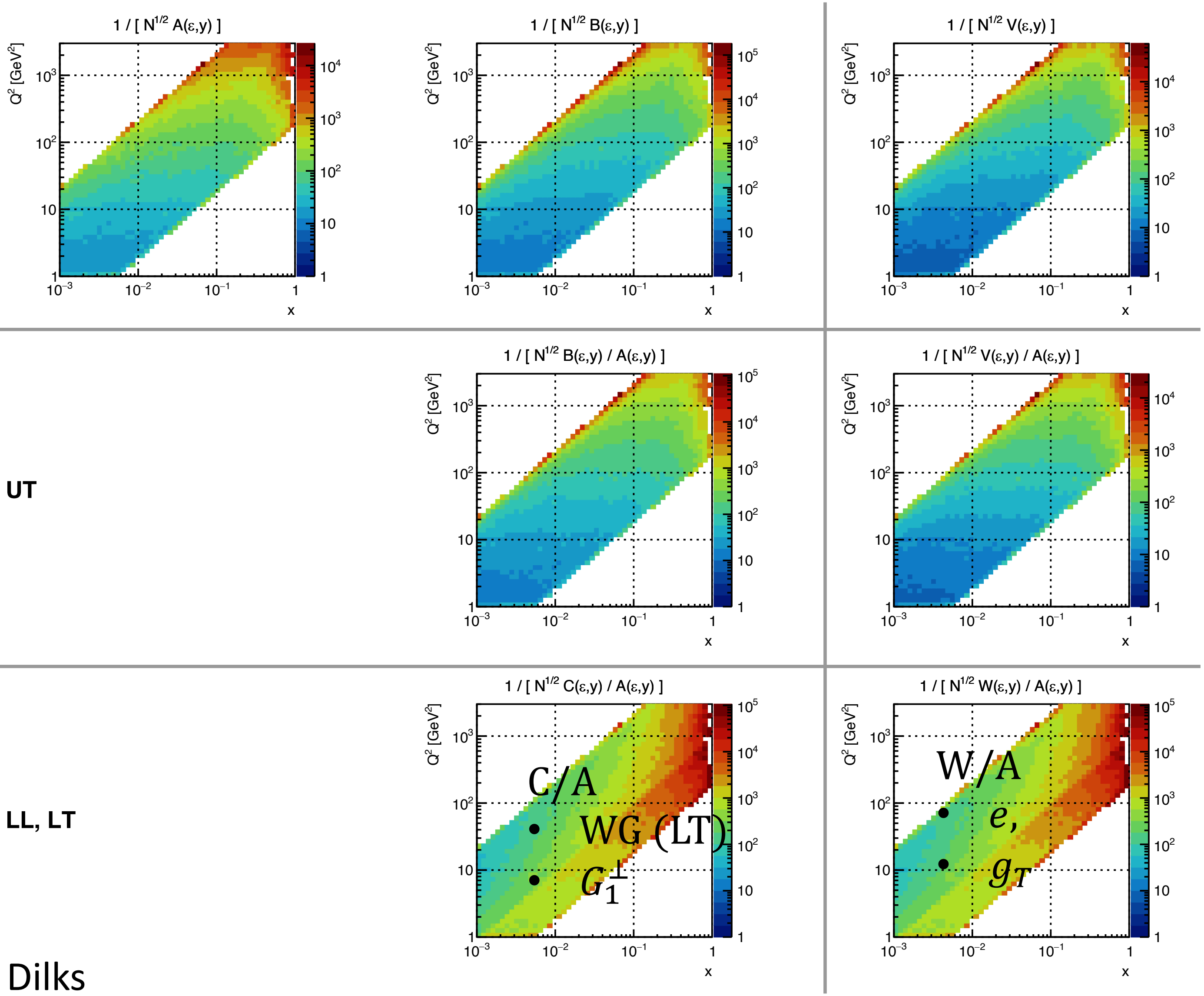
EIC (Athena) Fast Simulation, C.Dilks, Duke

Statistical uncertainty scaling factor for $18x275$

UU

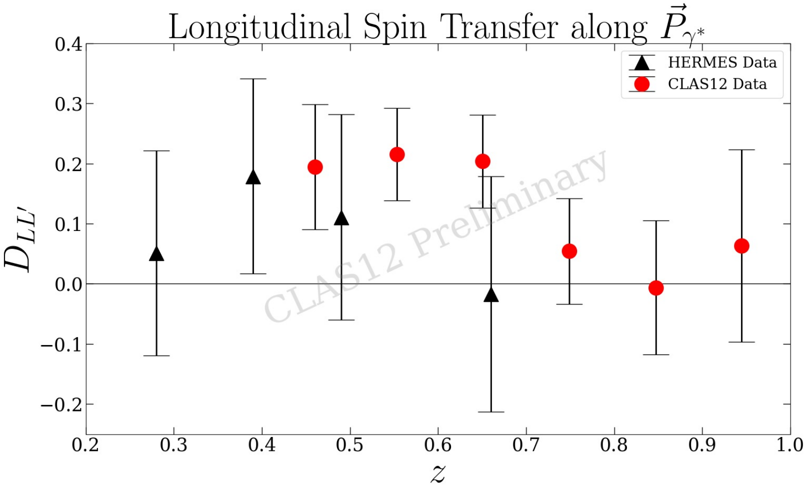
UL, UT

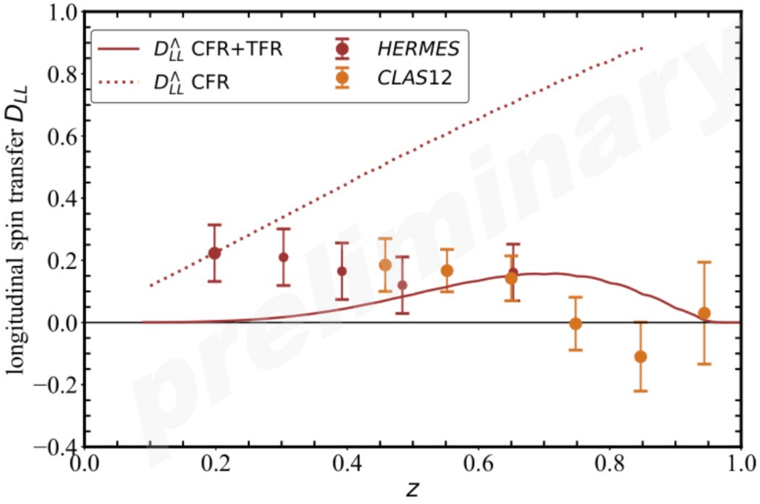
LU, LL, LT

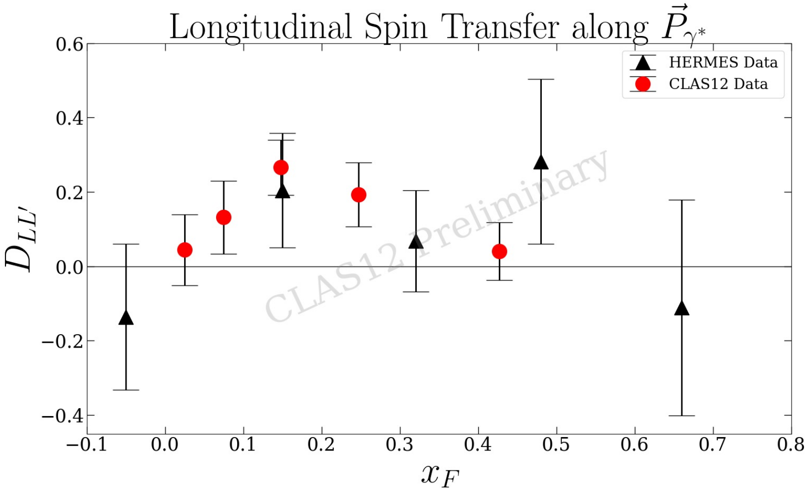


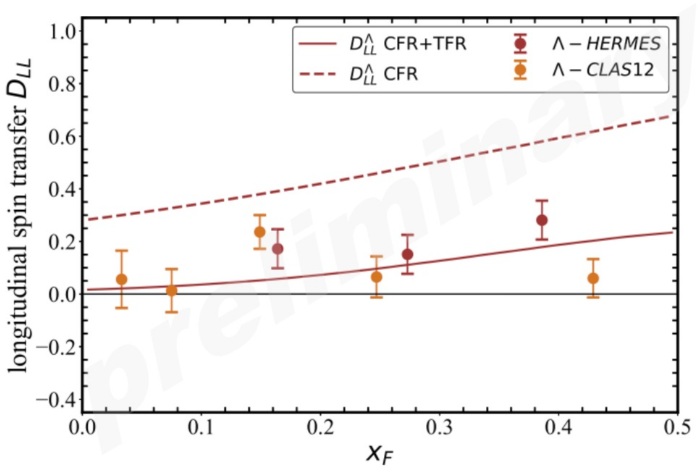
Slide from C. Dilks

Lambda


Longitudinal Spin Transfer along $\vec{P}_{\gamma^*}$
HERMES Data
CLAS12 Data
$D_{LL'}$
z
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
CLAS12 Preliminary


D_{LL}^{Λ} CFR+TFR
D_{LL}^{Λ} CFR
HERMES
CLAS12
longitudinal spin transfer D_{LL}
z
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
0.0
0.2
0.4
0.6
0.8
1.0
preliminary

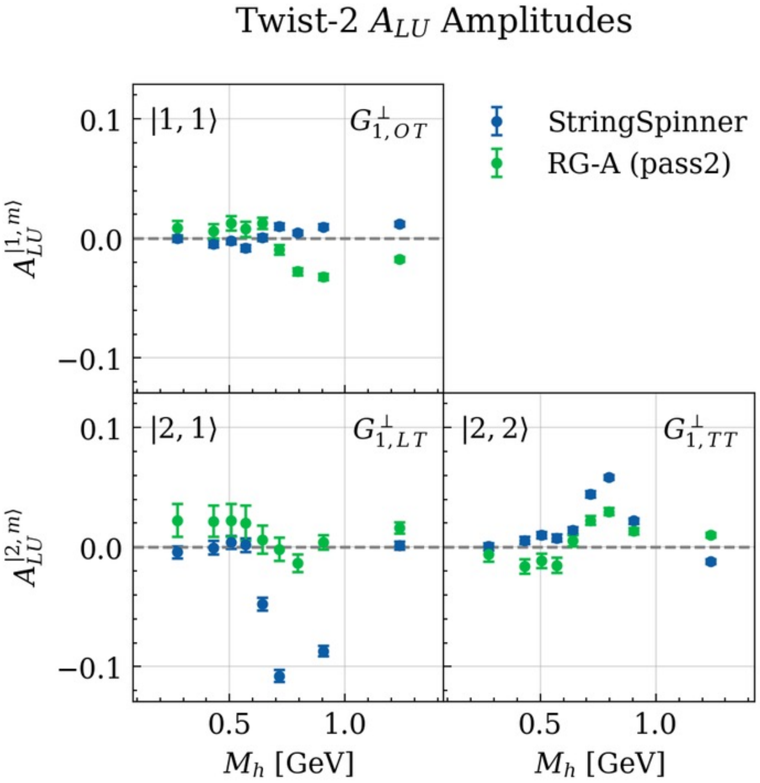

Longitudinal Spin Transfer along $\vec{P}_{\gamma^*}$
HERMES Data
CLAS12 Data
$D_{LL'}$
x_F
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
CLAS12 Preliminary


D_{LL}^{Λ} CFR+TFR
D_{LL}^{Λ} CFR
Λ − HERMES
Λ − CLAS12
longitudinal spin transfer D_{LL}
x_F
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
0.0
0.1
0.2
0.3
0.4
0.5
preliminary

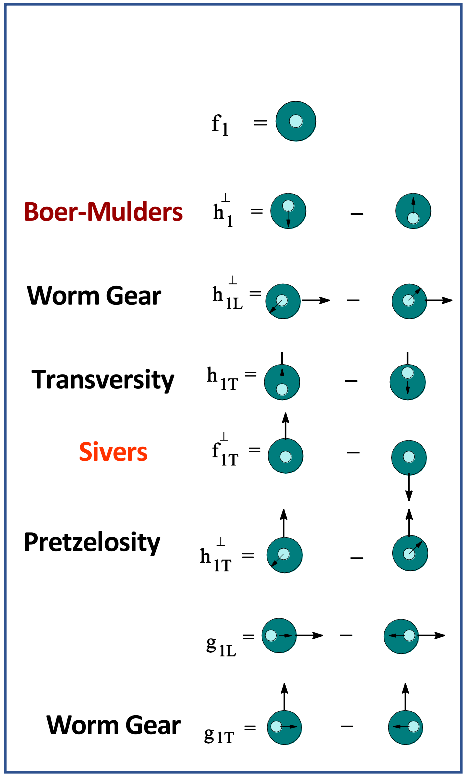
Depolarization Factors

		Polarization	Depolarization	
Twist 2	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	Suppressed at EIC
Twist 3	e(x)	LU	W/A	
	$h_L(x)$	UL	V/A	
	$g_T(x)$	LT	W/A	

Slide from C. Dilks


Twist-2 A_{LU} Amplitudes
$|1,1\rangle$
$G_{1,OT}^{\perp}$
StringSpinner
RG-A (pass2)
$A_{LU}^{|1,m\rangle}$
0.1
0.0
−0.1
$|2,1\rangle$
$G_{1,LT}^{\perp}$
$|2,2\rangle$
$G_{1,TT}^{\perp}$
$A_{LU}^{|2,m\rangle}$
0.1
0.0
−0.1
0.5
1.0
M_h [GeV]
0.5
1.0
M_h [GeV]

SIDIS X-section in the Parton Model



f_1 =

Boer-Mulders $h_1^{\perp}$ = −

Worm Gear $h_{1L}^{\perp}$ = −

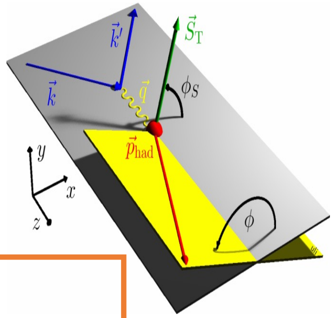
Transversity h_{1T} = −

Sivers $f_{1T}^{\perp}$ = −

Pretzelosity $h_{1T}^{\perp}$ = −

g_{1L} = −

Worm Gear g_{1T} = −



$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4} \times$$

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z, P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z, P_{h\perp}^2)$$

Polarized target

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z, P_{h\perp}^2)\}$$

Polarzied beam and target

S_L and S_T: Target Polarizations; λe: Beam Polarization

x: momentum fraction carried by struck quark, z: fractional energy of hadron

SIDIS cross-section

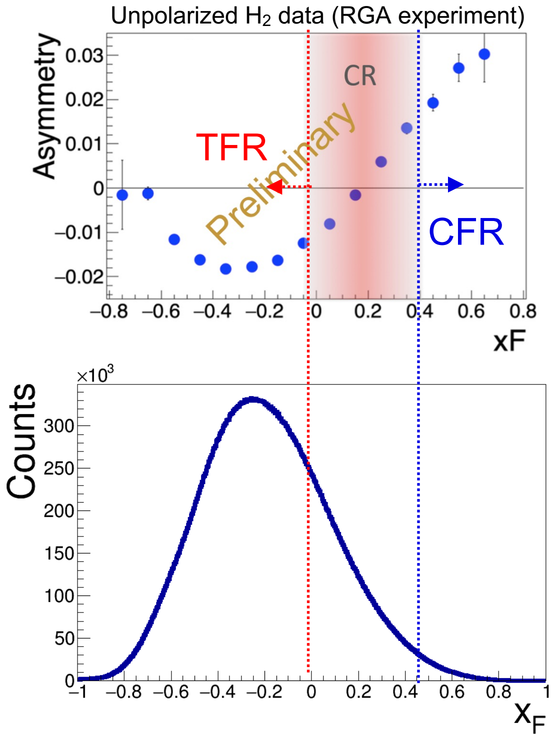
$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)} \Bigg\{ F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h} + S_L \left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} \right] \\
&\quad + S_L\,\lambda_e \left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\, F_{LL}^{\cos\phi_h} \right] \\
&\quad + S_T \Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) + \varepsilon\,\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Bigg] + S_T\lambda_e \Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Bigg] \Bigg\}
\end{aligned}
$$

- Disentangling the different contributions is not trivial
- Ratio of T to L flux
  - At fixed x e.g. change Q

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}, \qquad \gamma = \frac{2Mx}{Q}.$$

Can We Separate Target and Current?

ep → e'pX



Feynman variable

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

Rapidity

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

- No clear *experimental* definition of what constitutes current production versus target production.
- Odd 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.

Analog to PDFs; Momentum Sum Rules

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

$$\sum_h \int_0^{1-x} d\zeta \zeta M_a(x,\zeta) = (1-x) f_a(x)$$

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}	$h_1, h_{1T}^{\perp}$

Unpolarized PDF analog

helicity PDF analog

etc. etc.

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

CFR ← → TFR