TMD: from CLAS12 to EIC

Anselm Vossen

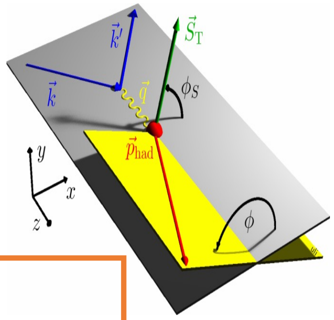
Research Supported by

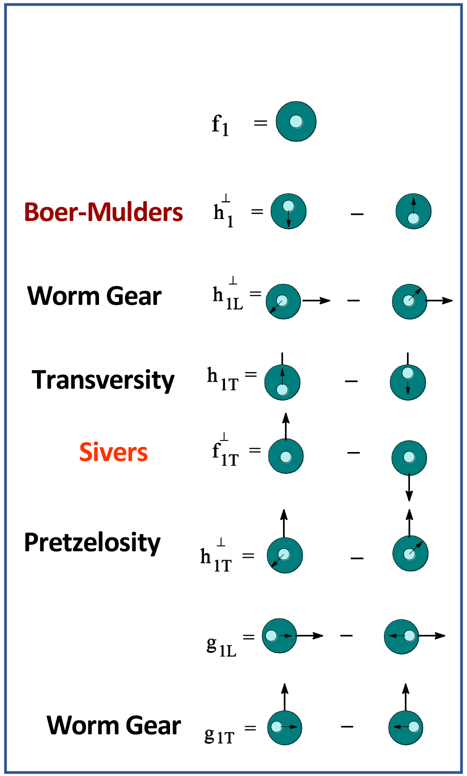
U.S. DEPARTMENT OF ENERGY | Office of Science

Duke UNIVERSITY

Jefferson Lab

SIDIS X-section in the Parton Model





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

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z, P_{h\perp}^2)$$
$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

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

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

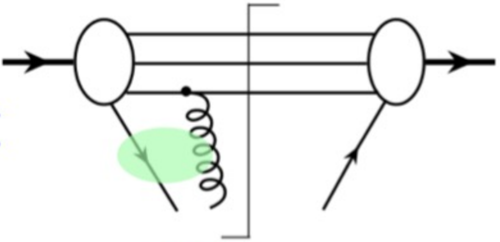
Beyond the parton picture

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

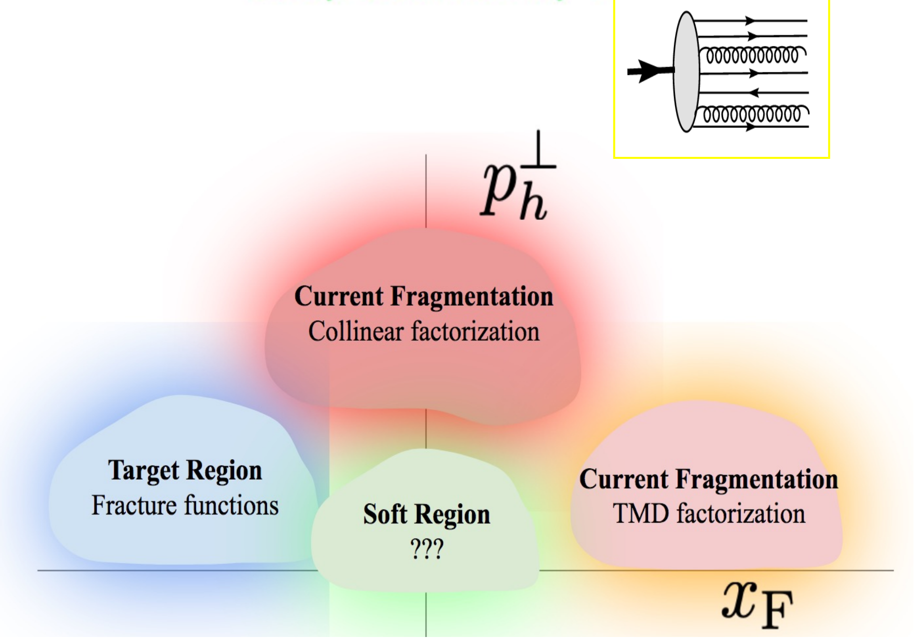
One persons ‘complication’ is another person's signal…

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

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

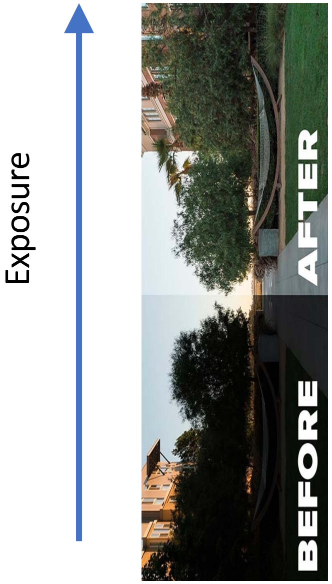


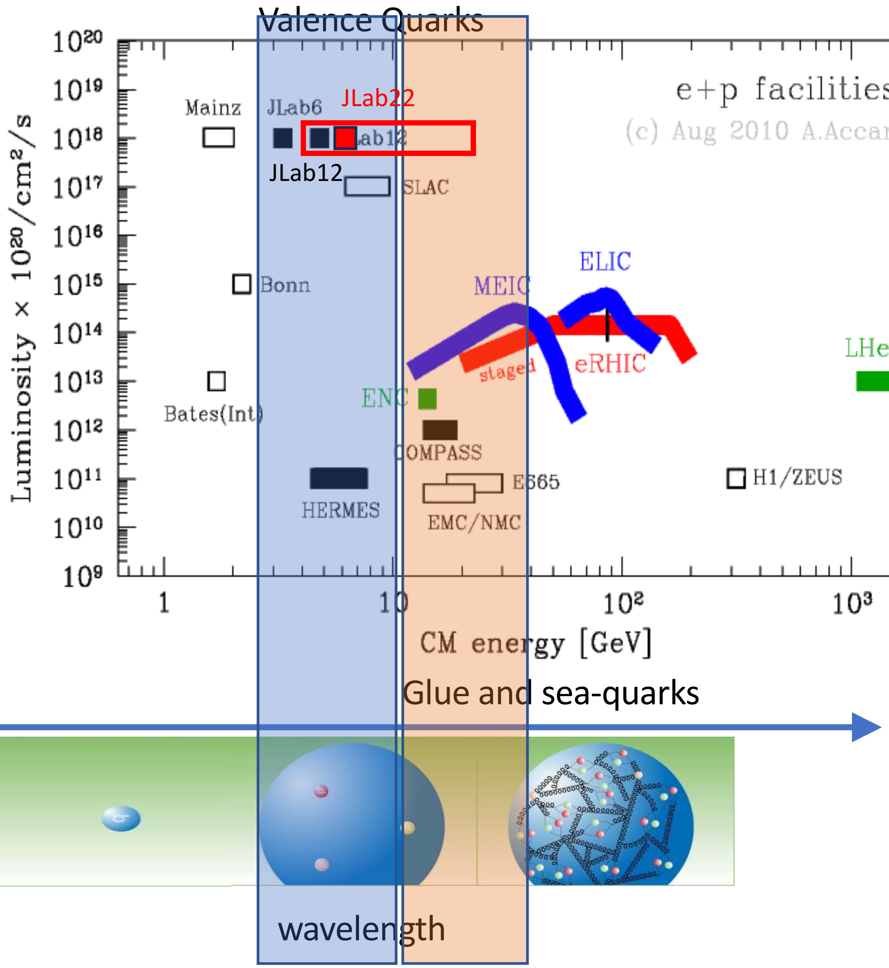
Qiu, Sterman, 1991, …



Boglione, Produkin et al

Landscape

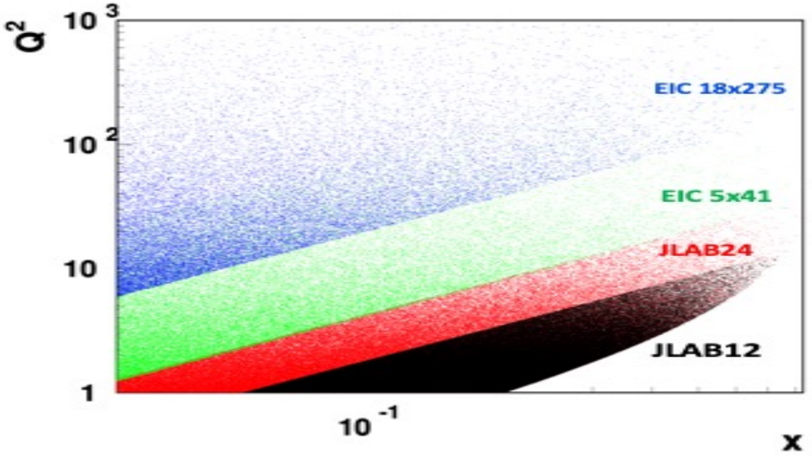


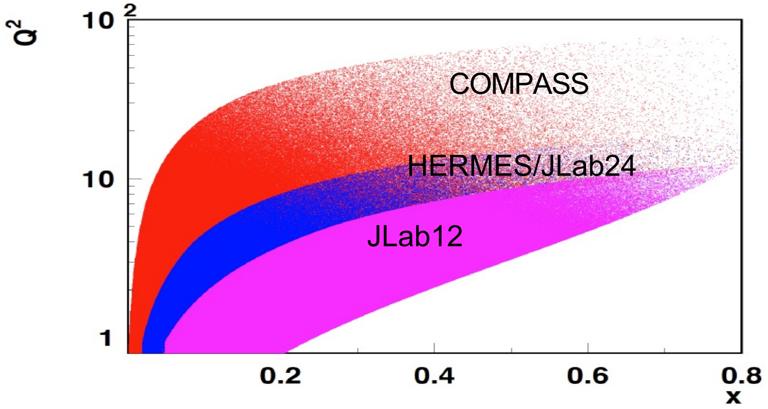


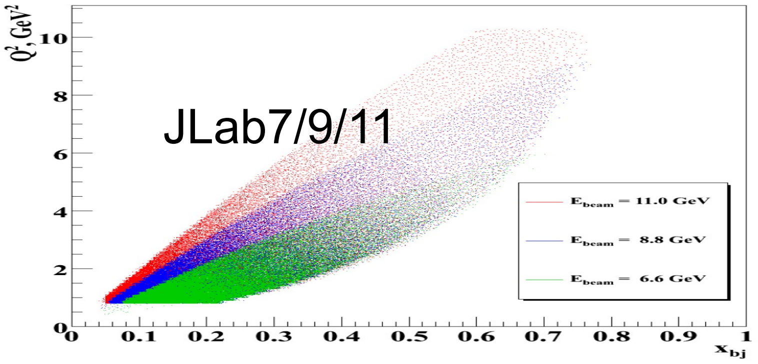
To extract 3D structure
Need luminosity

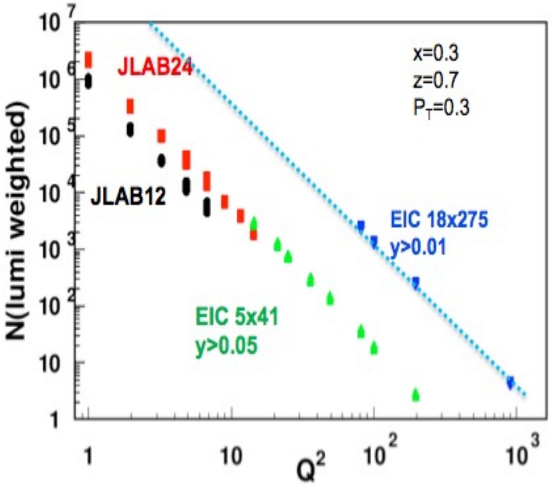
- Jlab12: 2018+
- JLab22:

Kinematic comparisons



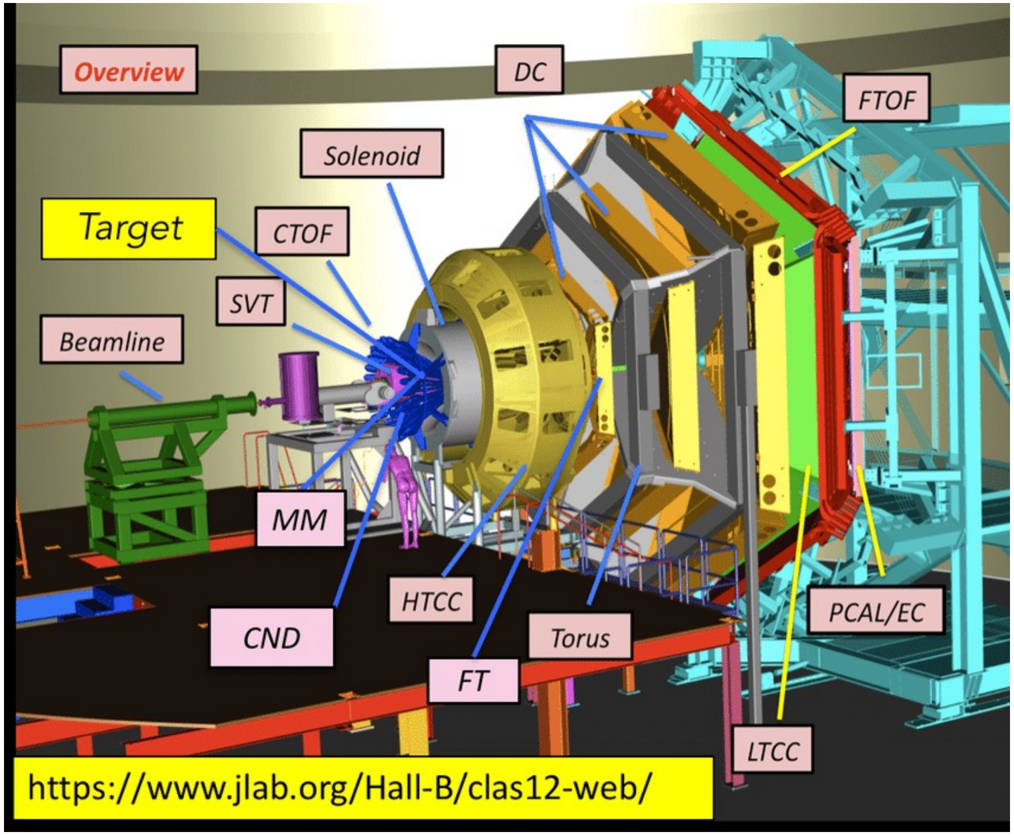






NB: Kinematic slice heavily biased towards Jlab

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



- **Longitudinally Polarized Electron Beam**
  - E = 10.6 GeV
  - P = 86–89%
- **Unpolarized Liquid H_2 Fixed Target**
- Torus magnet → electrons inbending

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)

- ★ $\mathbf{F_{UL}}$ and $\mathbf{F_{LL}}$

Run Group K (Unpolarized LH_2 target)

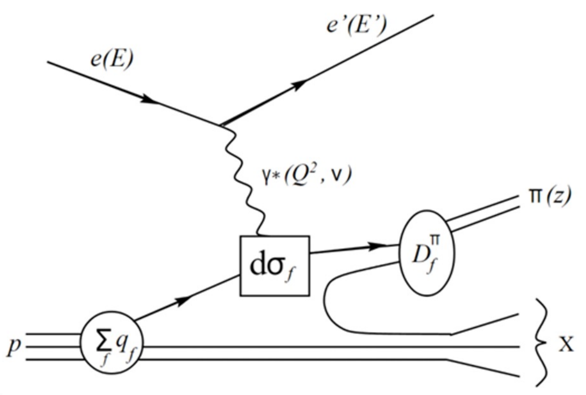
- ★ - 6.5, 7.5, 8.4 GeV e- beam
- ★ $F_{UU,L}$, $F_{UU,T}$ Separation

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

- ★ $\mathbf{F_{UT}}$ structure function

⇒should be completed before 1st Shutdown ≈ 2032

Unpolarized Multiplicities of ep→eπ^0(X)



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

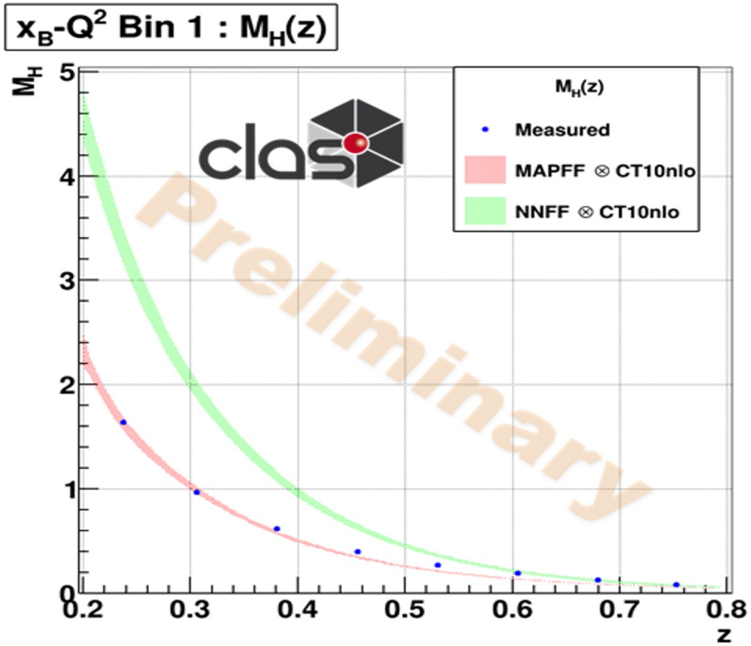
$$\boxed{\sigma^{\pi^0} \approx \sigma^{DIS} \otimes f^p(x, Q^2) \otimes D^{p\rightarrow\pi^0}(z, Q^2)}$$

- ★ Study integrates over the azimuthal ϕ_h angle

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

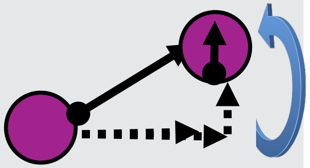
- ★ Invariant mass fits over the diphoton spectrum are performed to calculate N(π^0)

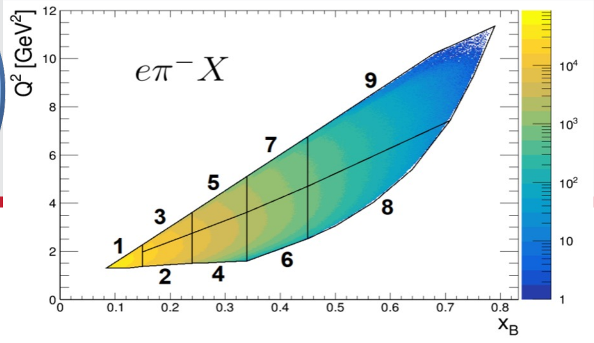
- ★ **Ongoing Work:** Bayesian unfolding, ϕ_h modulation fits

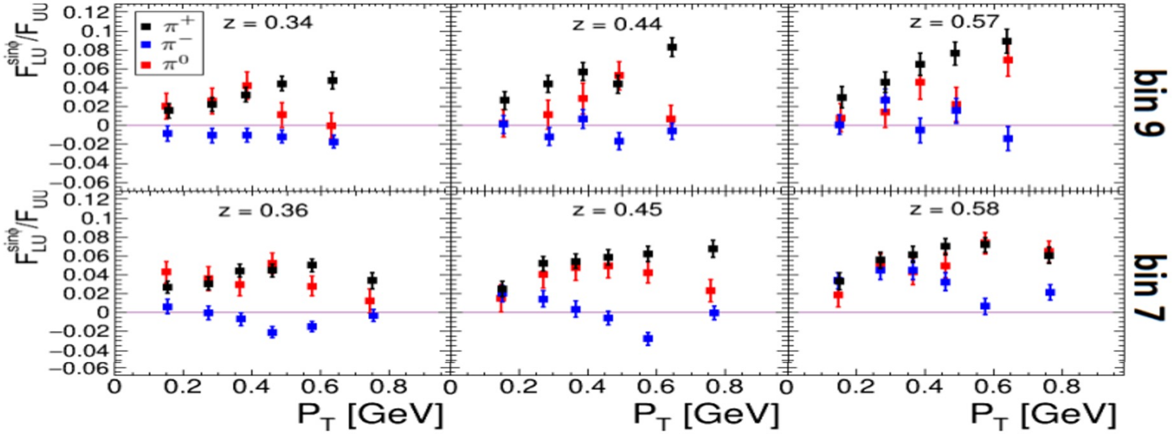


M.Scott

CLAS12 pion BSAs







S. Diehl

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

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

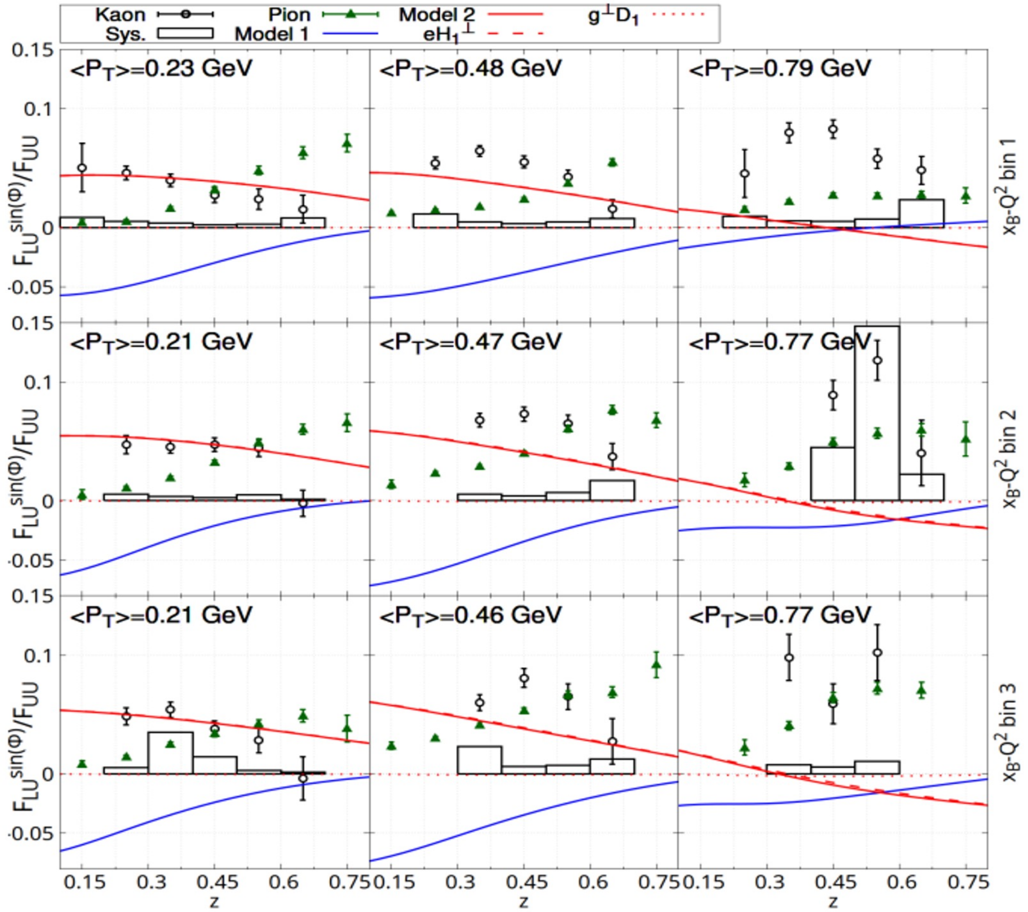
★ If Collins term only **($H_1^\perp$)** → hierarchy of the A_{LU}’s

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

★ 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

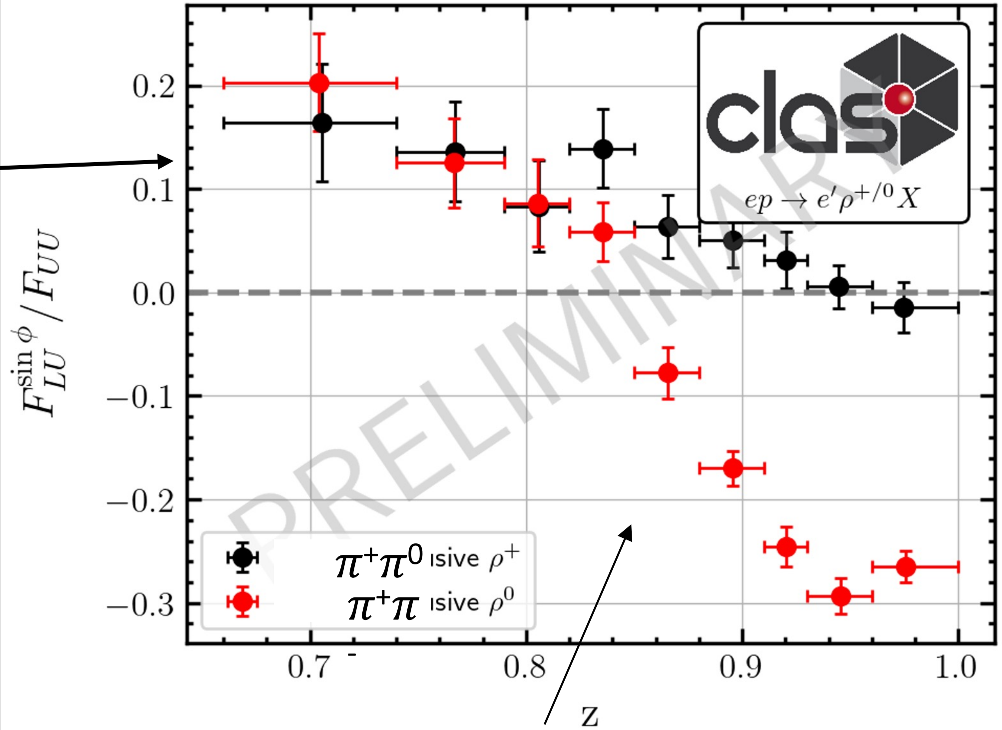
➔Difference due to $D_1^{K^+/u}$,$H_1^{\perp K^+/u}$

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

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

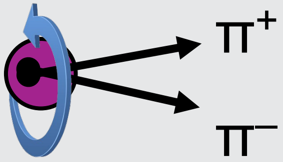
- ★ We can constrain/better understand the contribution of ρ^0, ρ^+ decays on our single hadron asymmetries by looking at near exclusive (M_X < 1.1 GeV) channels
  - ★ Strong yet similar asymmetries observed **(both productions came from struck *u* quark)**

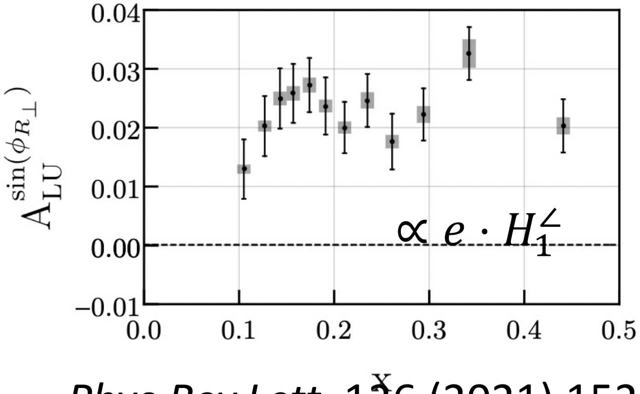
→See talk by K. Joo



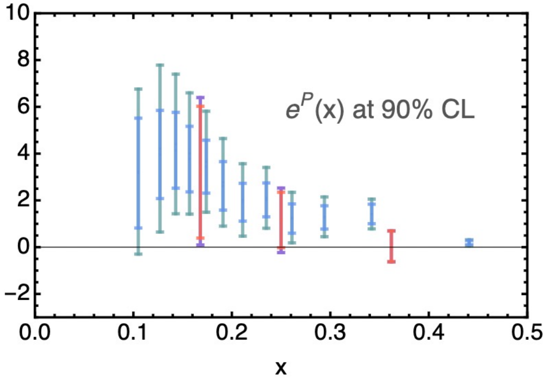
- ★ Different mechanism for neutral ρ^0 at high z (low |t|) → GPDs, gluon contributions

Better: di-hadrons

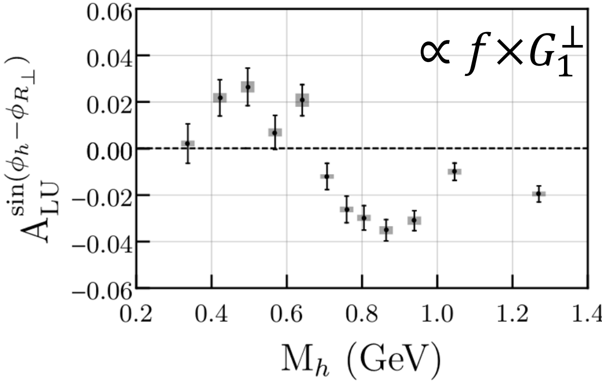




Phys.Rev.Lett. 126 (2021) 152501



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

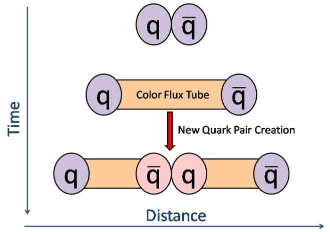


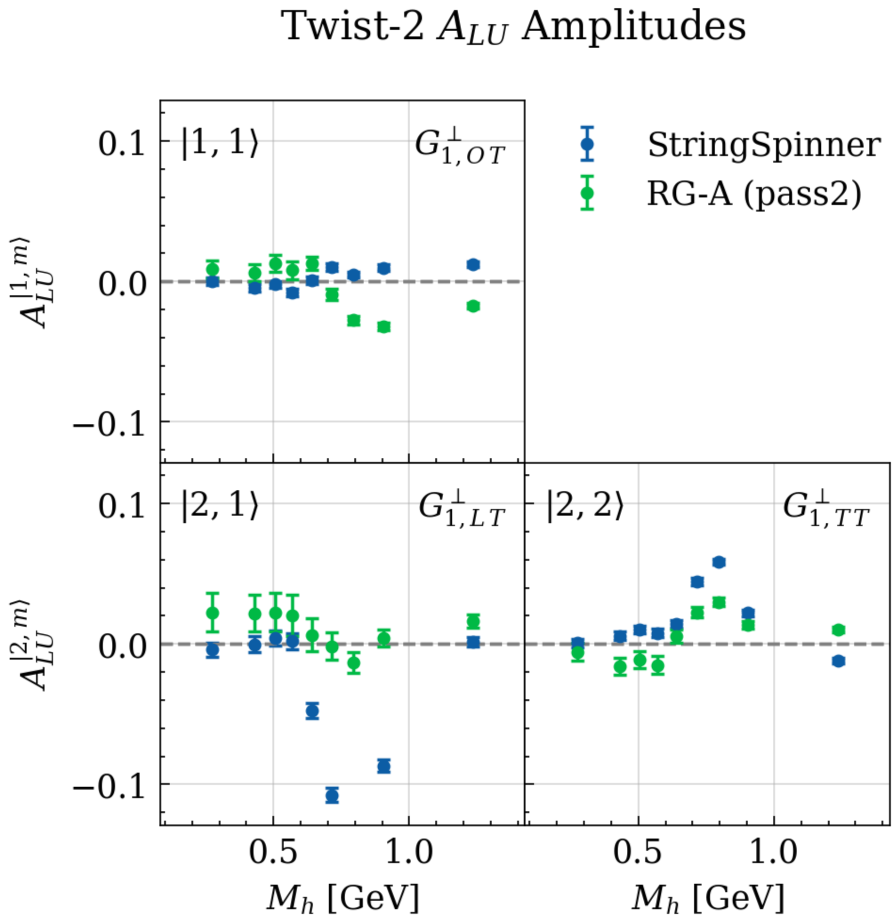
$$F_{LU}^{\sin\phi_R} = -x \frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{m_{hh}} x\, e^q(x)\, H_1^{\sphericalangle q}(z, \cos\theta, m_{hh}) + \frac{1}{z} f_1^q(x)\, \widetilde{G}^{\sphericalangle q}(z, \cos\theta, m_{hh})\right],$$

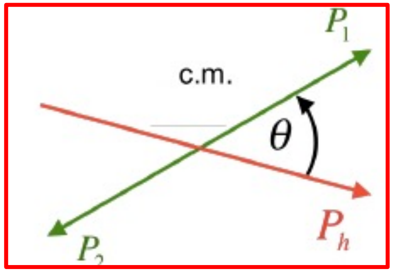
- First extraction of $e(x)$
- Further constrains from F_{UL} and F_{LL}

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))





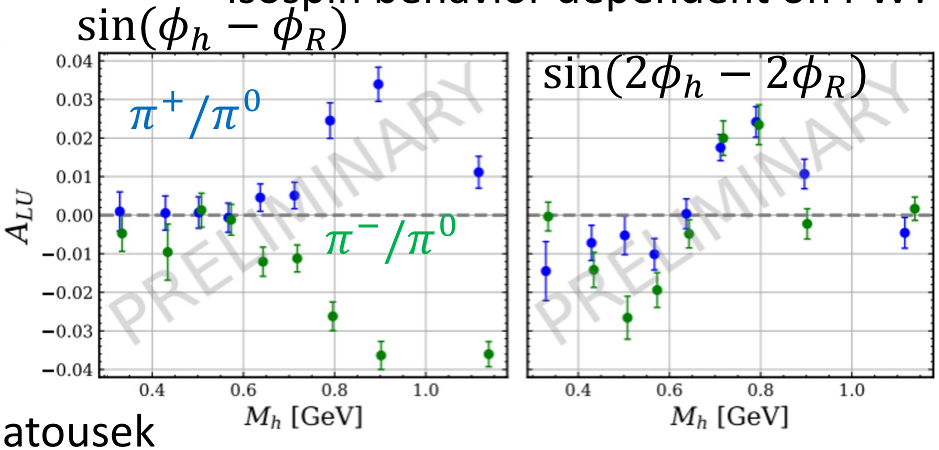


- See more MC tuning studies in QCD whitepaper
- E.g. charge, flavor correlations (Phys.Rev.D 105 (2022) 5, L051502)

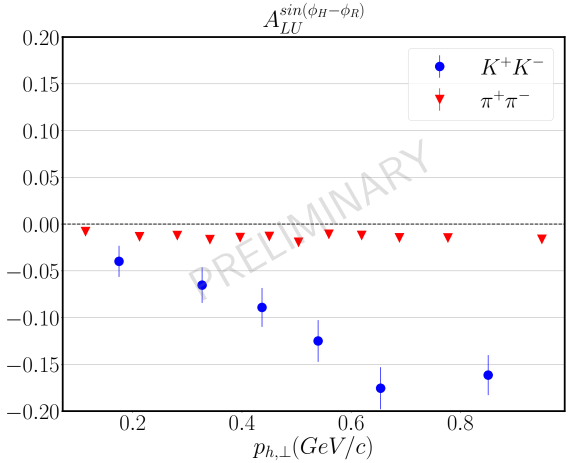
G Matousek

π^0 and Kaon combinations (SIDIS@CLAS12)

Isospin behavior dependent on PW?



G Matousek



C Pecar

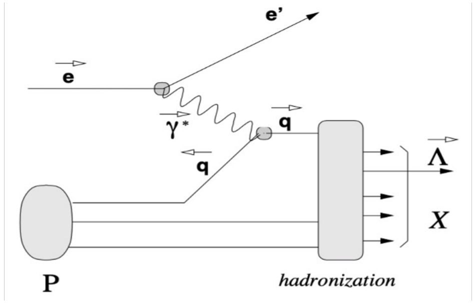
- $A_{LU} \propto \frac{f(x,k_t)G_1^\perp(z,p_t)}{f(x,k_t)D(z,p_t)} \approx \frac{G_1^\perp}{D_1}$
- Kaon ≫ Pions for sp interference (not all PW terms)
  - FF effect?
  - $\pi^\pm/\pi^0$ ordering dependent on PW

Lambda Program at CLAS12

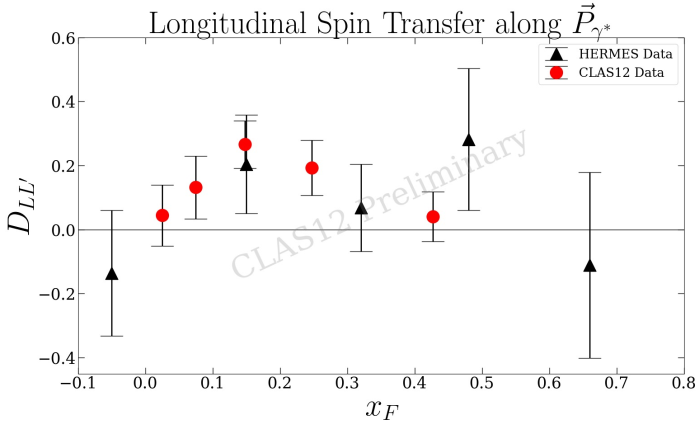
- **Constituent Quark Model (CQM)**
  - Predicts *s* quark carries 100% of the *Λ* hyperon spin
- "Do polarized *u*-quarks from current fragmentation transfer their longitudinal spin to the lambda?" → Test spin structure

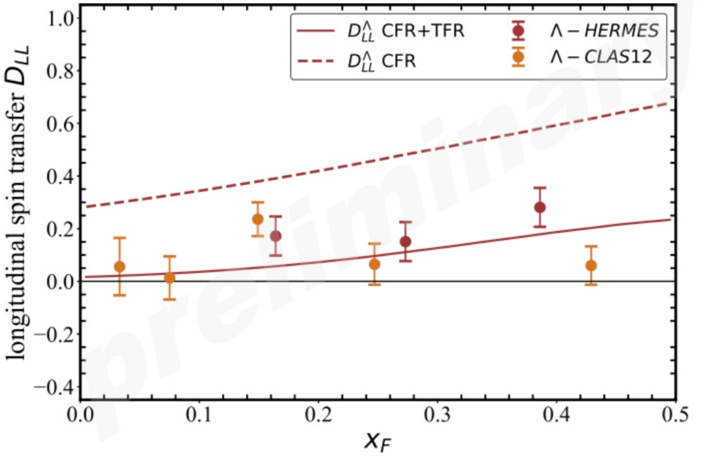
$$P_\Lambda = P_b D(y) \boxed{D^{\Lambda}_{LL'},}$$

longitudinal spin-transfer



Xiaoyan Zhao at



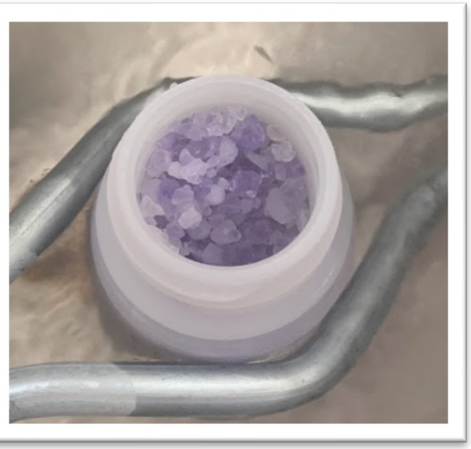


M. McEneaney

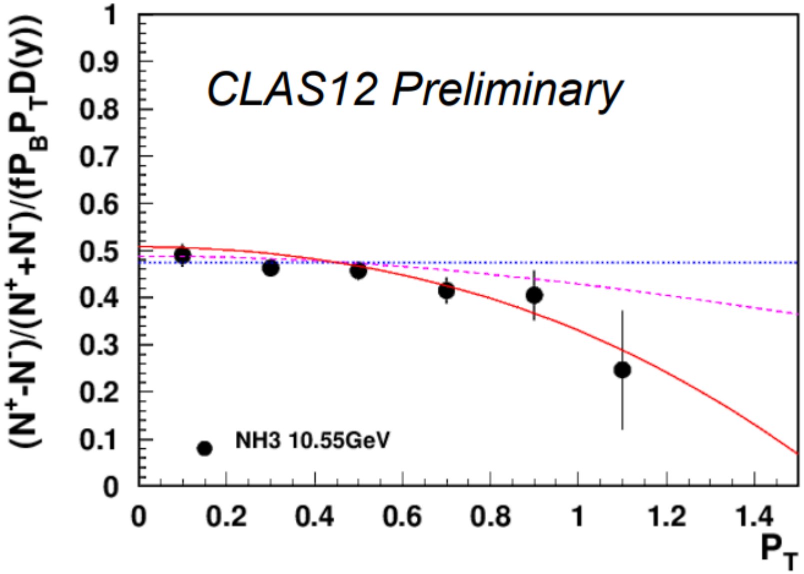
Part of planned extensive Lambda program with larger statistics: Transverse, polarizing…

Longitudinal target results with RGC

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



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



Sensitive to the k_T width of f_1 and g_1

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

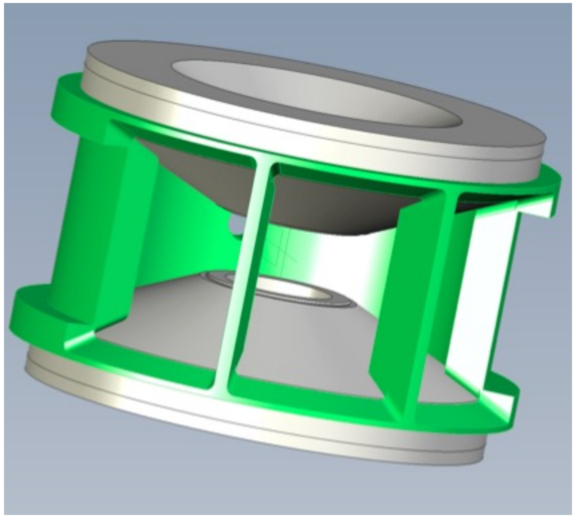
Convolution over transverse momentum space

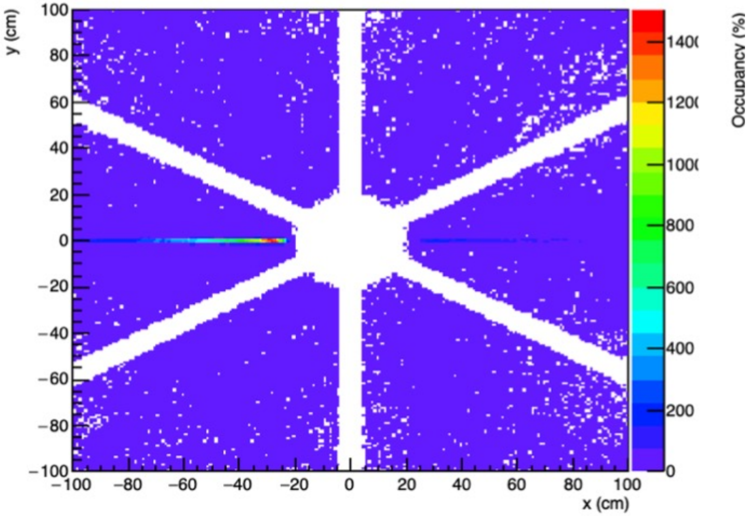
- Rich program underway

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 $5\times10^{33}cm^{-2}s^{-1}$ (about $\frac{1}{50}$ of ‘regular’ CLAS12)

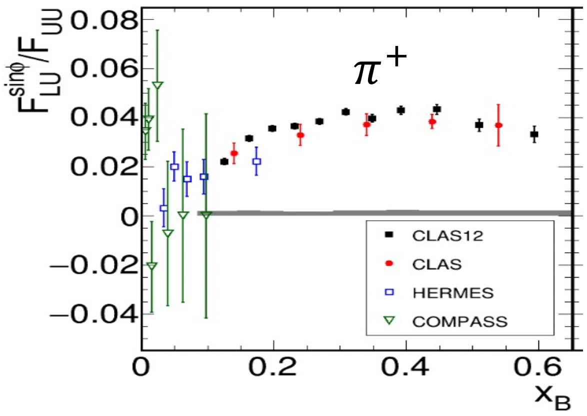


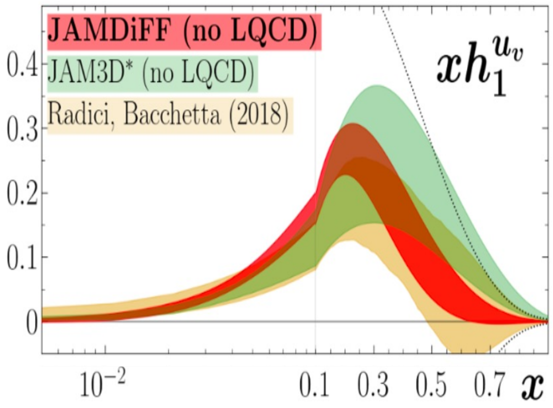


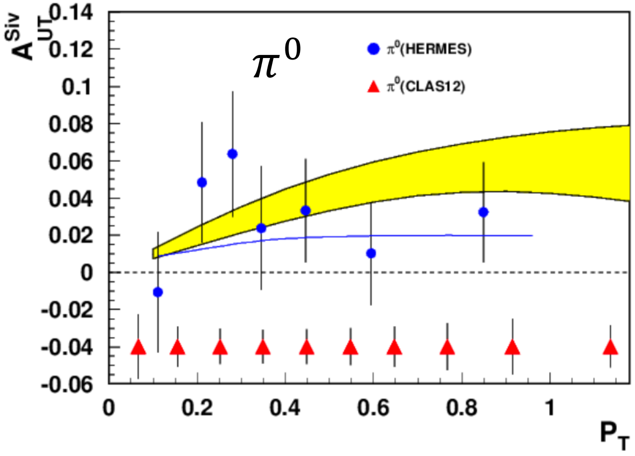
Physics with a transverse Target: Example Transversity

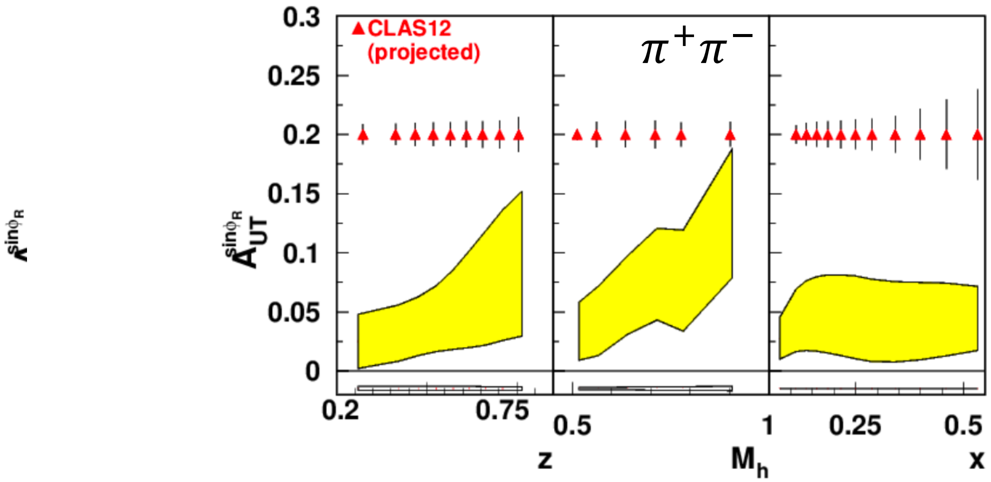
- Data $x > 0.2$ very sparse

→Models diverge



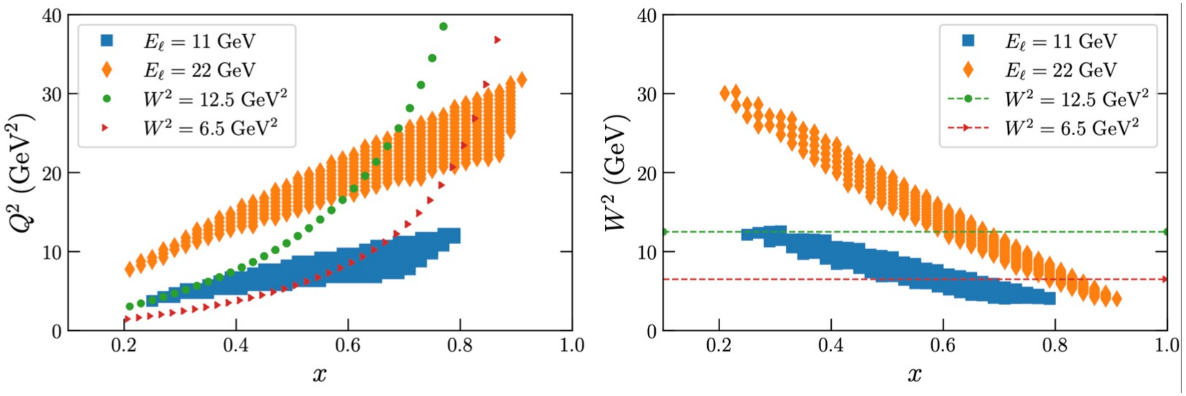


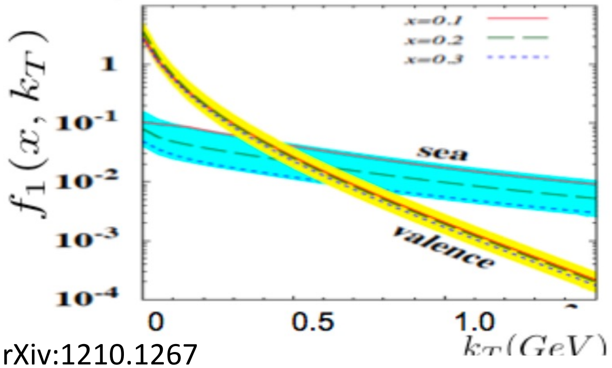




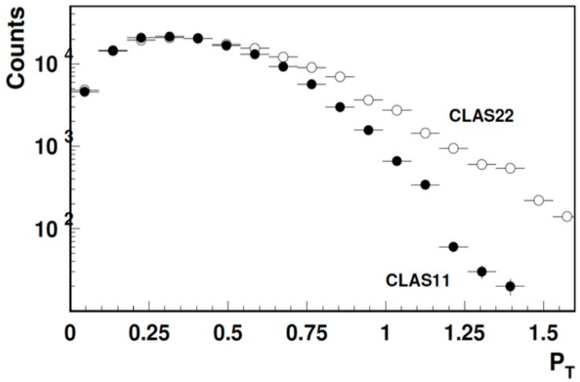
≈ 2035

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

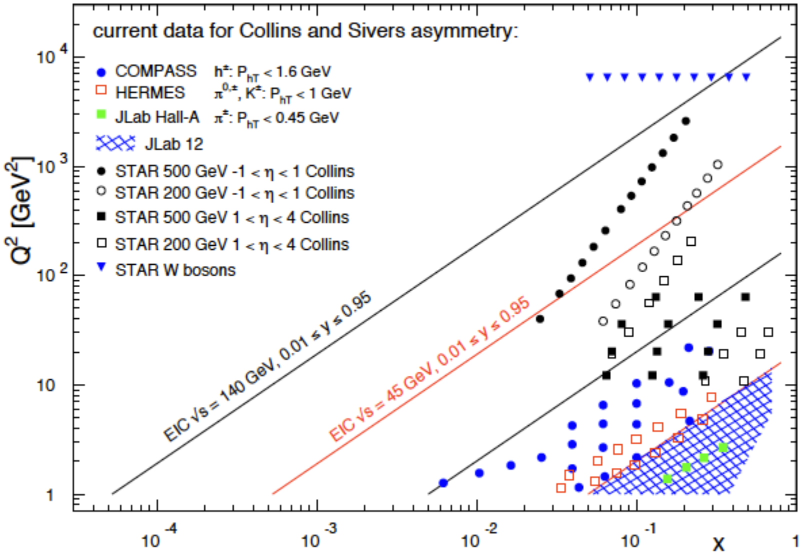
t: 2306.09360 [nucl-ex]

- ≈doubling beam energy significantly increases phase space
- Pin down valence structure of the proton
- Integration in global analyses (e.g, strange distributions, CS Kernel)

SIDIS physics at an EIC: Coverage

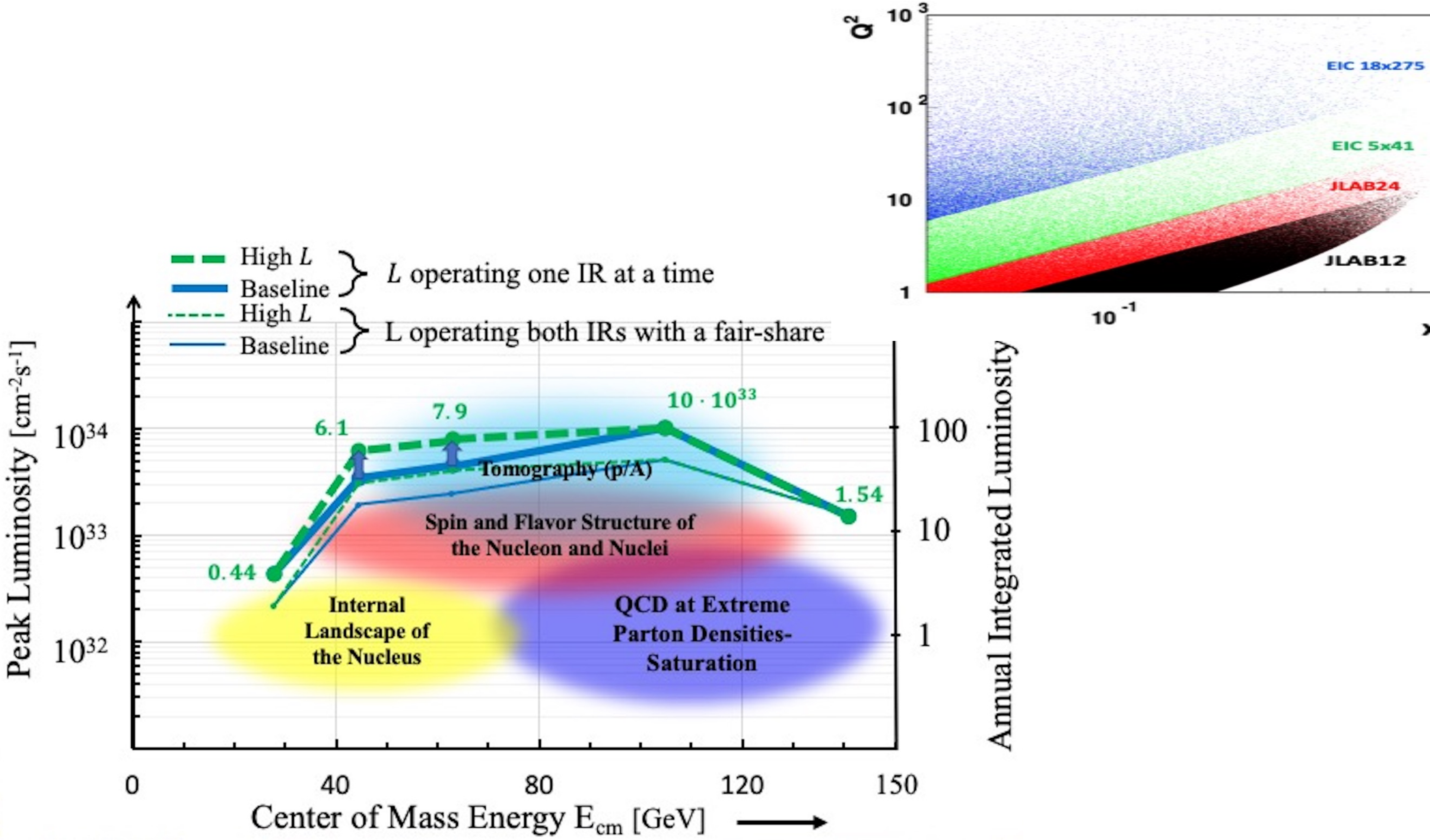
- Common theme on EIC impact
  - Extended kinematic coverage and precision, along with polarization and possible beam charge degrees of freedom allow multi-pronged approach →needed to extract multidimensional objects
  - TMD factorization is valid

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



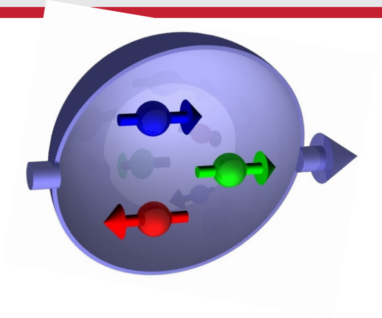
Coverage to low x: access sea and gluon distributions

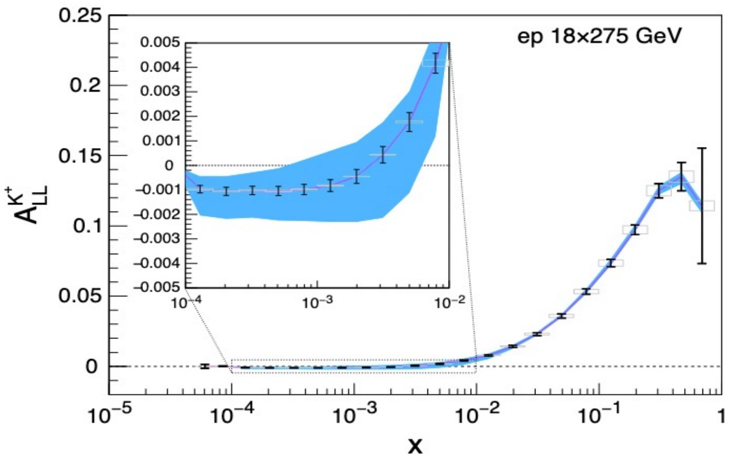
Order of magnitude in luminosity depending on $\sqrt{s}$ (beware of projections with fixed $\int L$)

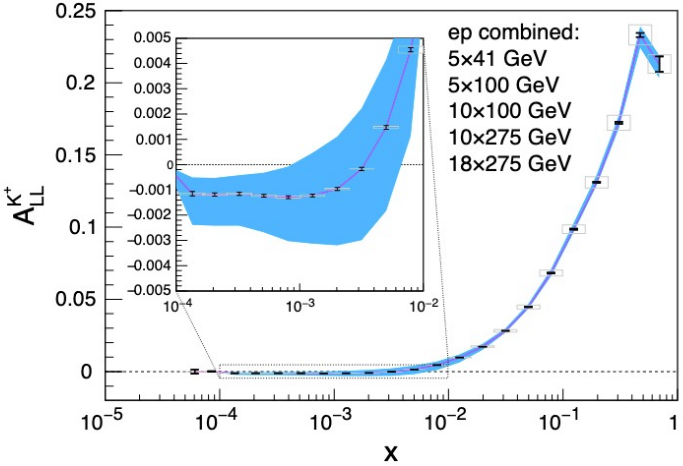


Longitudinal double spin asymmetries

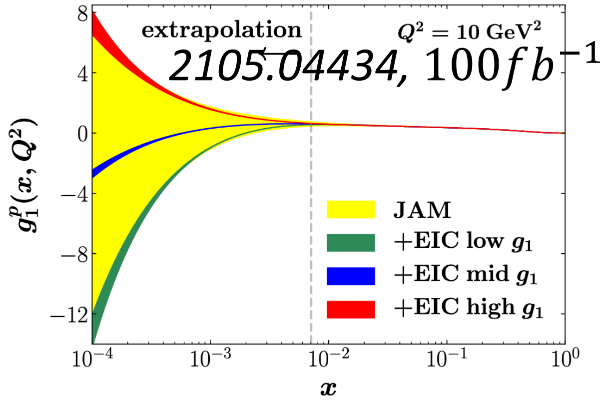
- $A_{LL} = \frac{\sigma^{\uparrow\Uparrow}-\sigma^{\uparrow\Downarrow}}{\sigma^{\uparrow\Uparrow}+\sigma^{\uparrow\Downarrow}} \propto g_1$







- Projections for Athena (2022 *JINST* **17** P10019)
- 3% point-to-point, 2% scale uncertainties (from Hera experience)
- $z > 0.2$
- $15.5\ fb^{-1}$ at $18x275$, other datasets scaled accordingly

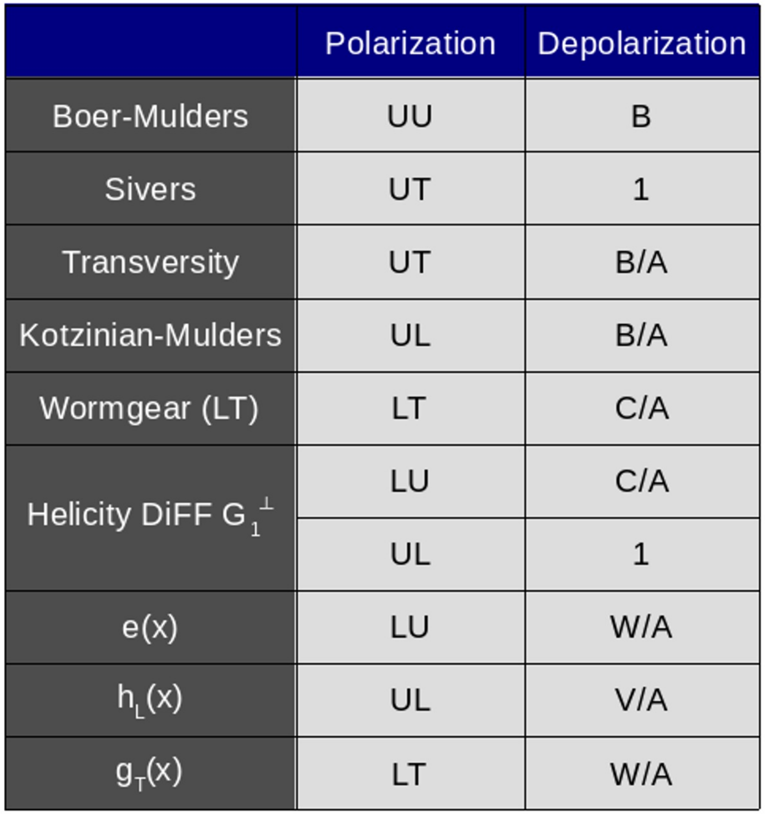


2105.04434, $100 fb^{-1}$

Access to TMDs: Kinematic factors

Twist 2

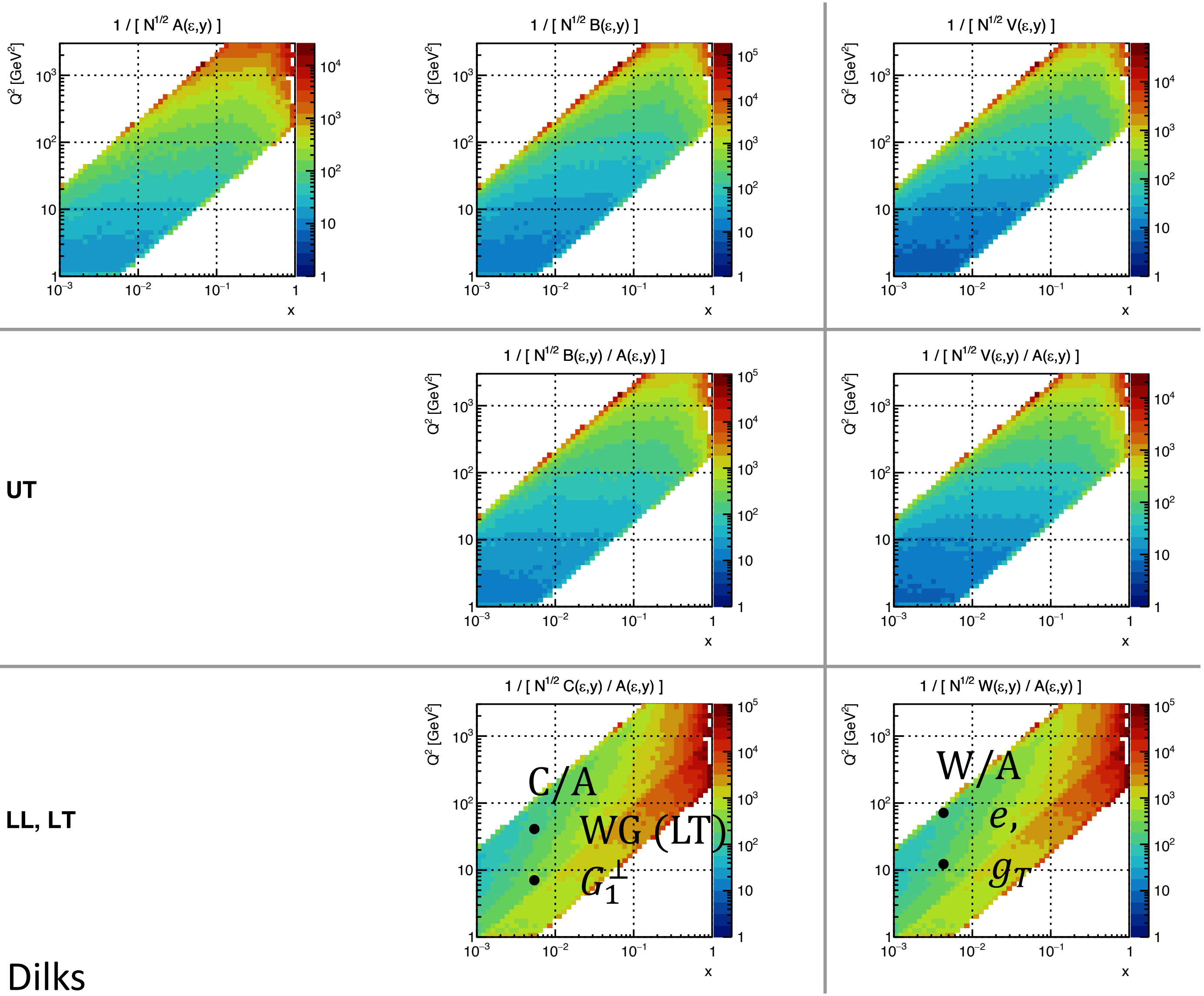
Twist 3



	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

Slide from C. Dilks

Statistical uncertainty scaling factor for $18x275$



UU

UL, UT

LU, LL, LT

Slide from C. Dilks

Depolarization Factors

Twist 2

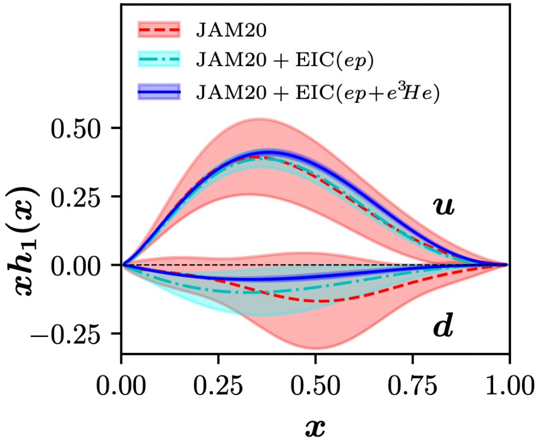
Twist 3

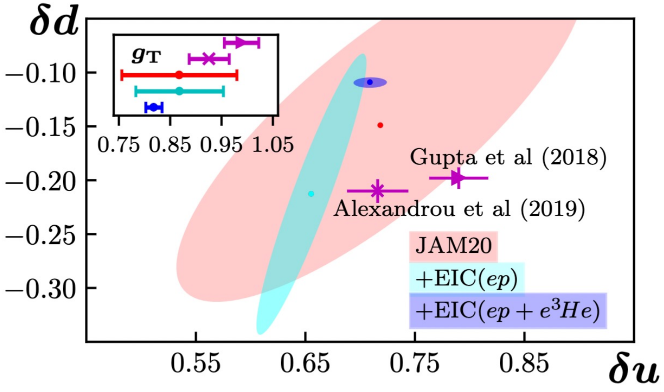
	Polarization	Depolarization
Boer-Mulders	UU	B
Sivers	UT	1
Transversity	UT	B/A
Kotzinian-Mulders	UL	B/A
Wormgear (LT)	LT	C/A
Helicity DiFF $G_1^\perp$	LU	C/A
	UL	1
e(x)	LU	W/A
h_L(x)	UL	V/A
g_T(x)	LT	W/A

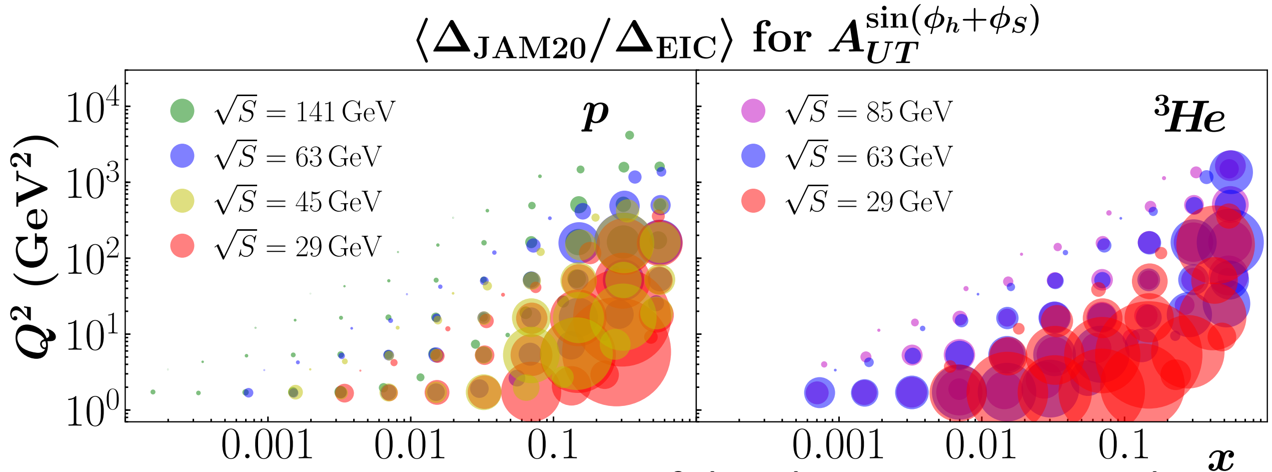
Suppressed at EIC

Slide from C. Dilks

Example: transversity extraction from Jlab and the EIC







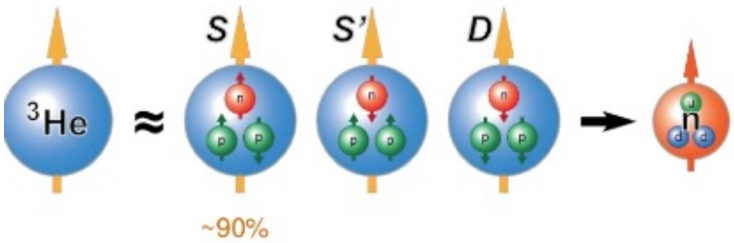
But careful with parametrization bias…

Phys.Lett.B 816 (2021) 136255

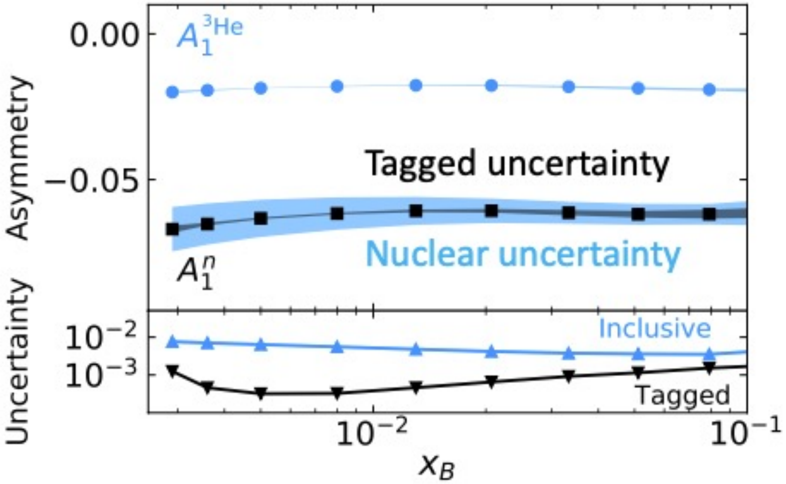
Simulations w/o radiative effects
Fixed $\mathcal{L} = 10$^fb^{-1} for each energy (unrealistic)

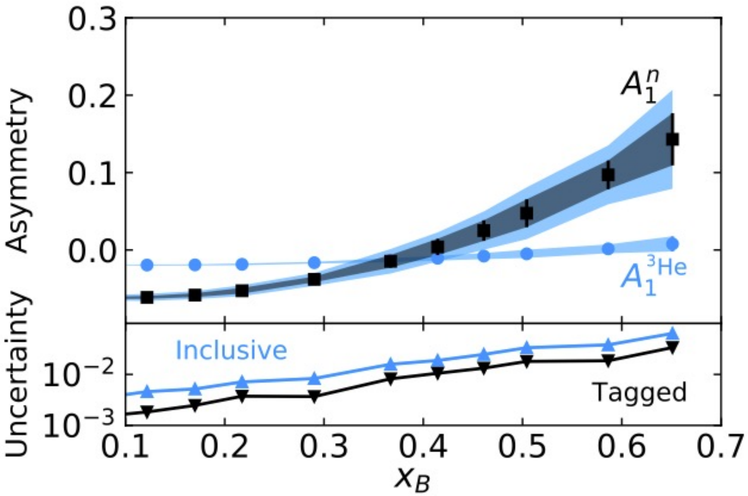
He^3 Double Tagging at the EIC allows clean neutron measurement

- Neutron is to 87% polarized
- Double tagged events thus provide access to polarized neutron beam



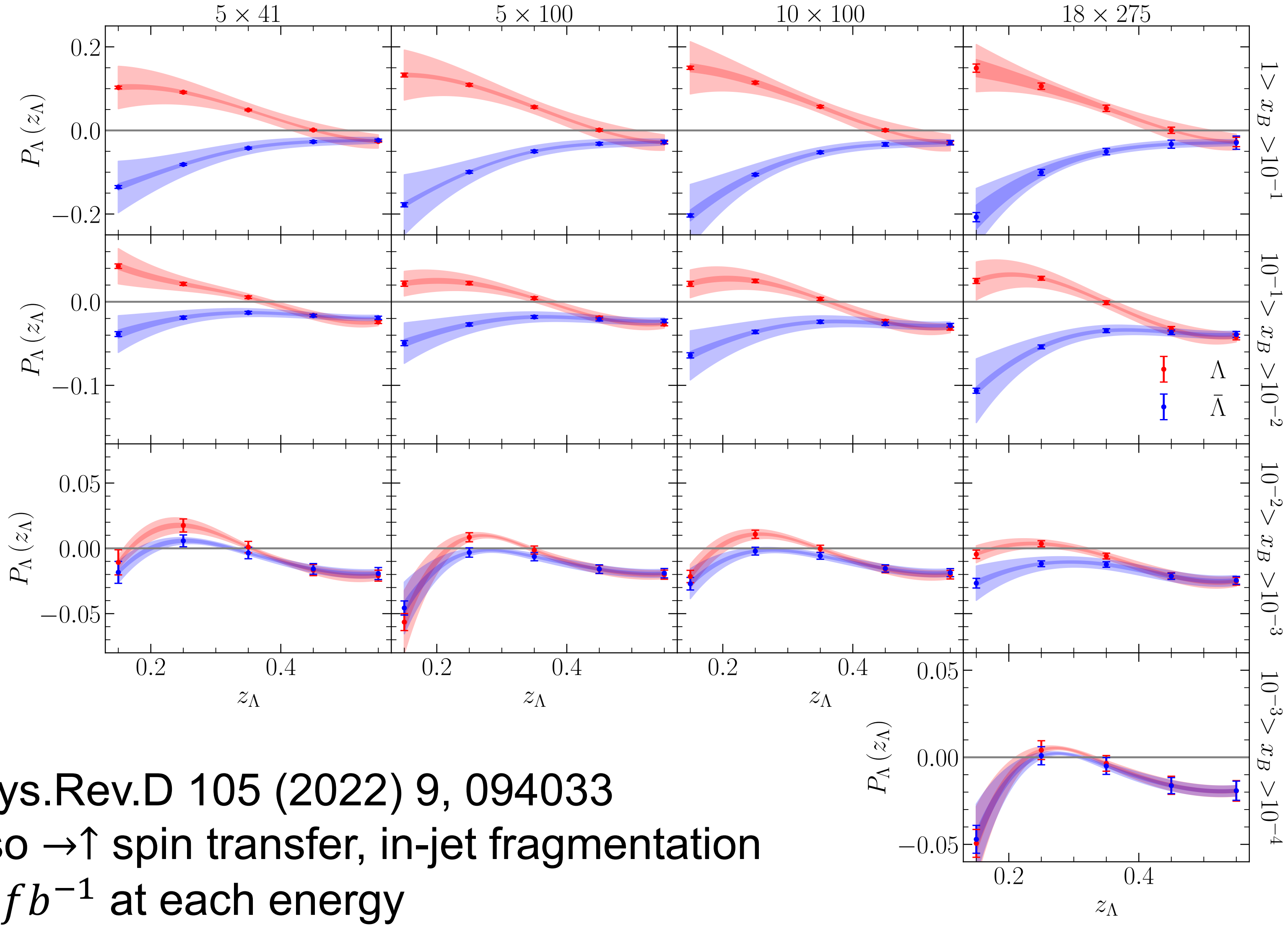
- Reconstruction of initial neutron momentum from tagged protons allows reduction of uncertainties from nuclear corrections





Friščić, I, Nguyen, D, Pybus, JR, Jentsch et al

Precision Λ physics at the EIC

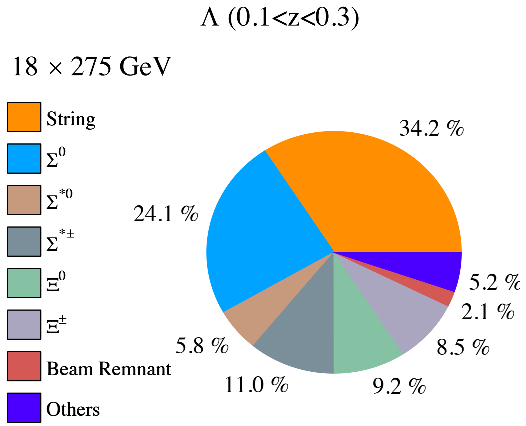


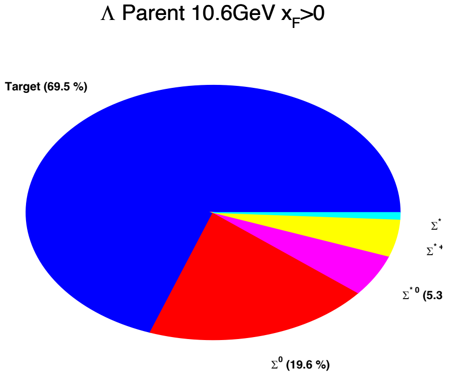
- Phys.Rev.D 105 (2022) 9, 094033
- Also →↑ spin transfer, in-jet fragmentation
- 40 fb^{-1} at each energy
- Significant impact of low $\sqrt{s}$ data

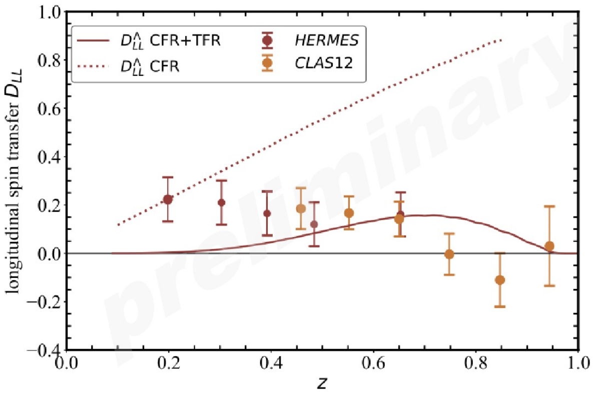
Lambda feed-down composition vs JLab20

EIC

JLAB12







Xiaoyan Zhao at S

Study by M. McEneaney(Duke)
JLab22 similar

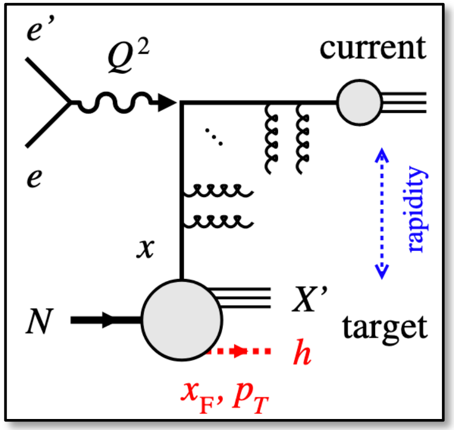
- Possible to unfold at the EIC (not so much at Jlab)
- ML methods might help

Summary/Conclusion/Outlook

- Broad and diverse SIDIS program
  - Present: JLab12, COMPASS
  - Future: JLab22, EIC
- Wide kinematic reach enabling us to understand the full QCD picture
- Jlab: unprecendented precision in valence quark regime
- Already exiting results, e.g. kaon final states
- EIC: new frontiers

- What is missing in this talk:
  - Target Fragmentation/Fracture Functions
  - Exclusive limit
  - TMDs in medium
  - Charged current at the EIC
  - Details on JLab12, 22 and EIC programs can be found in review papers and detector proposals
    - Yellow Report, Athena, ECCE, CORE proposals, PSQ report…
  - …(and a lot more)

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

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

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

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

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

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

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

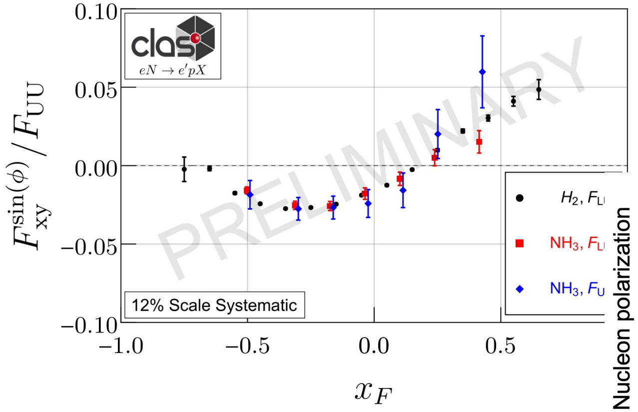
	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}$ $\hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp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

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 ($x_F > 0$)

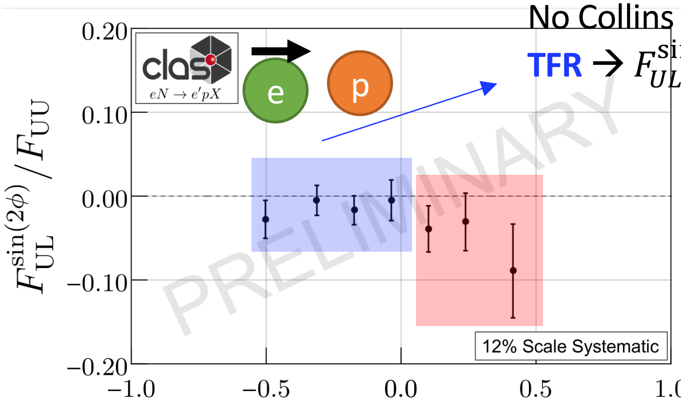


Quark polarization

Nucleon polarization

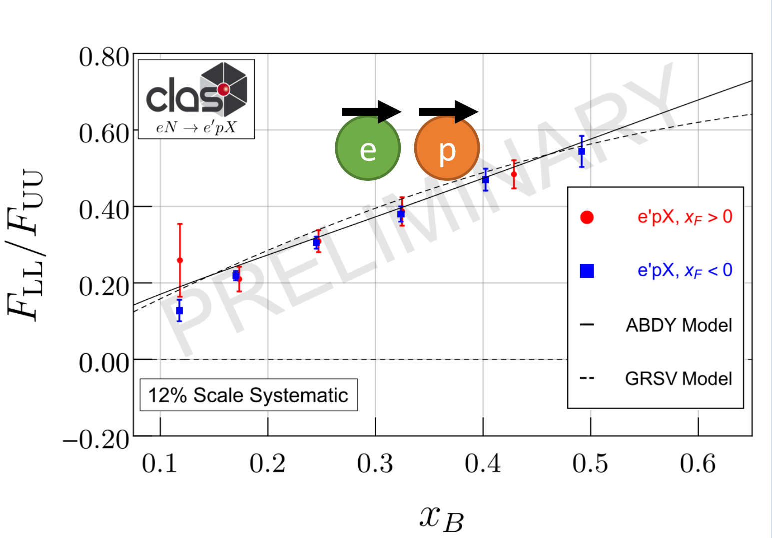
	U	L
U	u^h	l^h
L	u_L^h	l_L^h

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



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

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



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!

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

SIDIS Datasets, present and future

CLAS12 in Hall B

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)

★ $\mathbf{F_{UL}}$ and $\mathbf{F_{LL}}$

Run Group K (Unpolarized LH_2 target)

★ - 6.5, 7.5, 8.4 GeV e- beam

★ $F_{UU,L}$, $F_{UU,T}$ Separation

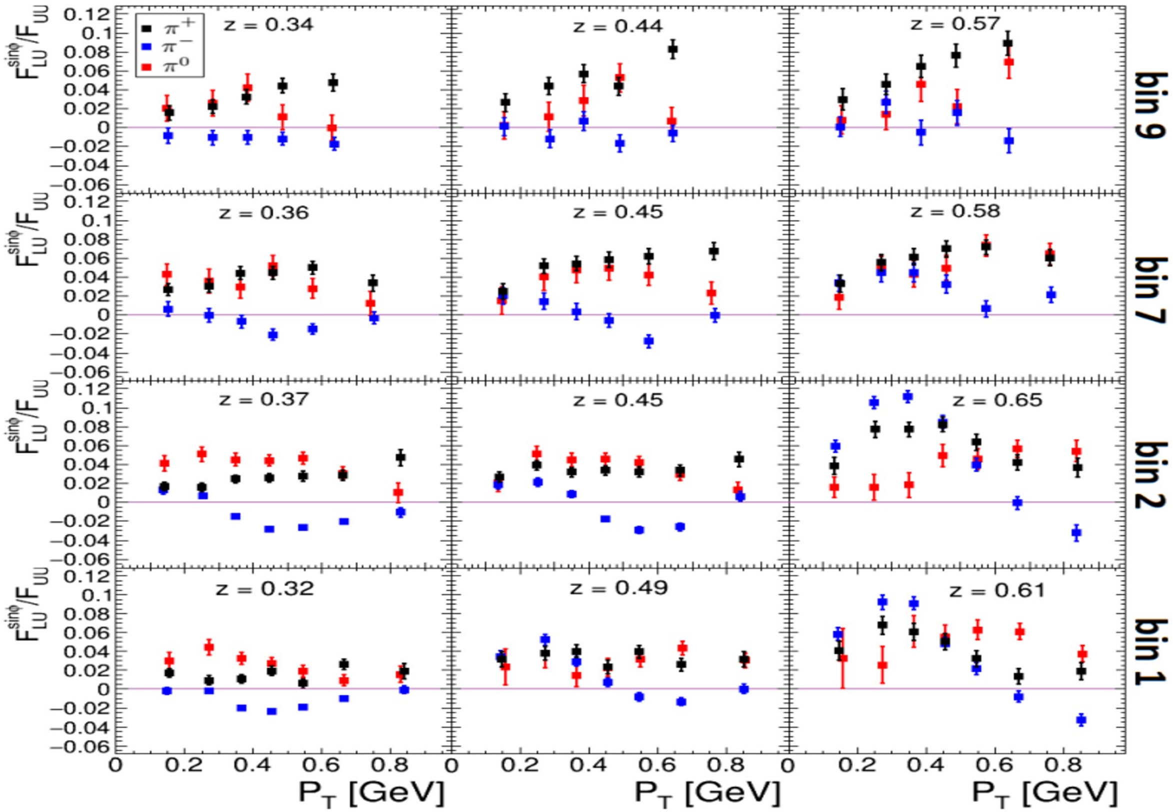
Run Group H (**transversely** polarized NH_3)

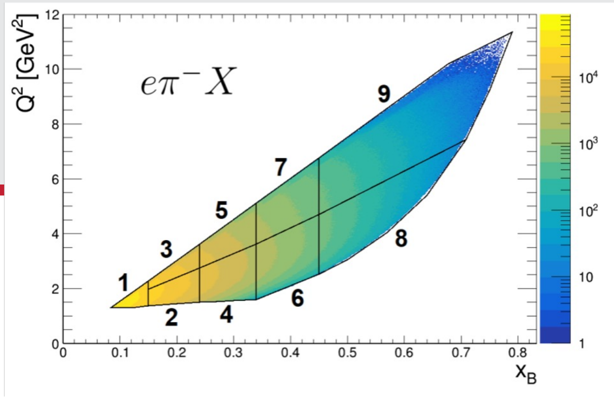
★ $\mathbf{F_{UT}}$ structure function

Hall A

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

⇒should be completed before 1st Shutdonw ≈ 2032





S. Diehl

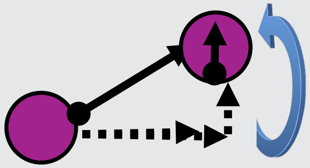
★ If Collins term only **($H_1^\perp$)** → hierarchy of the A_{LU}'s

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

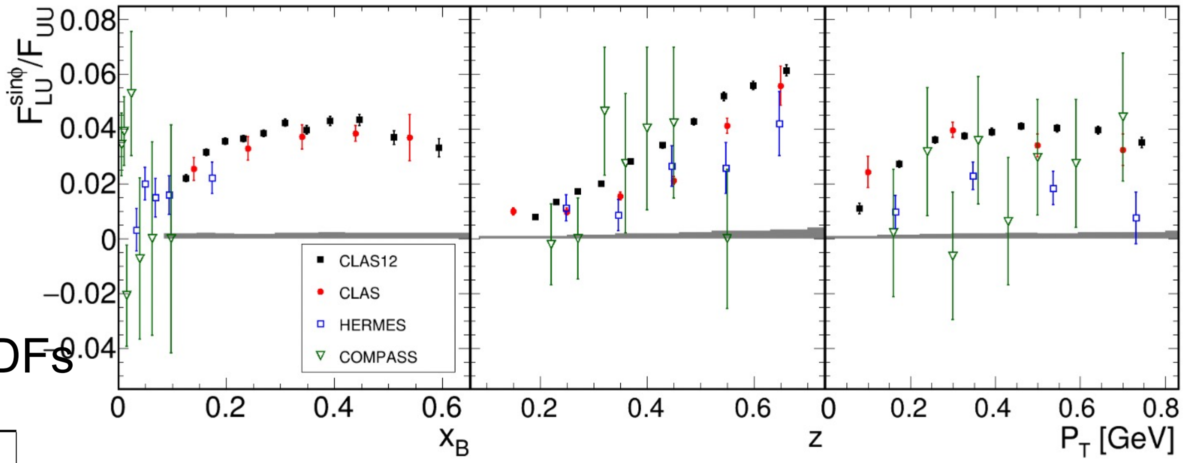
★ Observed is more **Sivers-like ($g^\perp$)**, asymmetry comes from struck u-quark

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

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

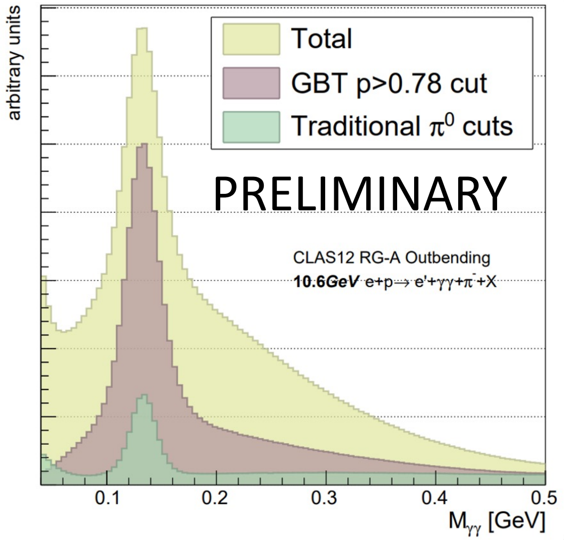
S. Diehl

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

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



★ Nearest-neighbor GBDT model to reduce γ background

★ Negative **sin(ϕ_R)** asymmetry for **π-π**0 → e(x) extraction

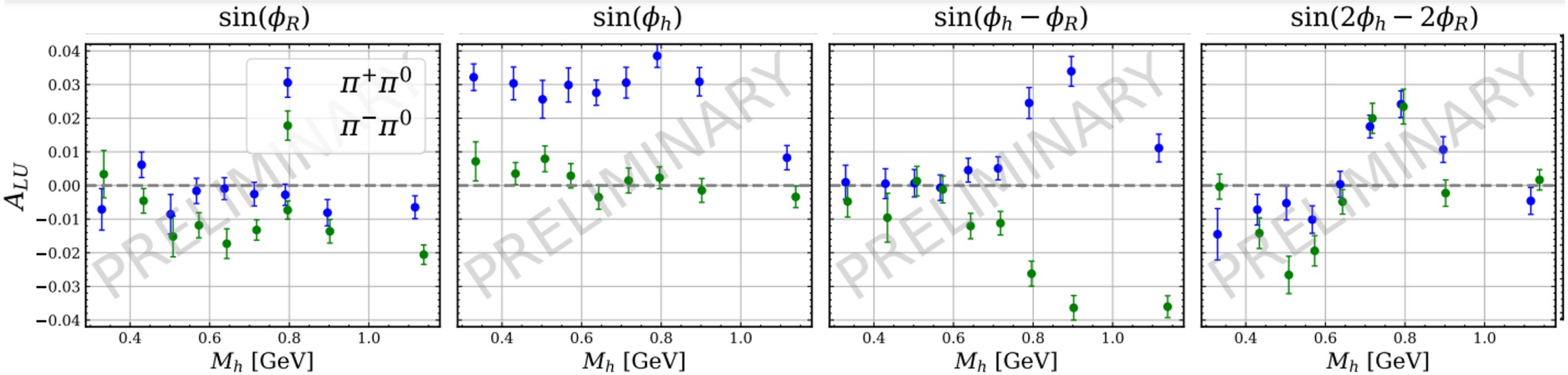
★ Strong positive **sin(ϕ_h)** asymmetry for **π+π**0 → u quark dominated channels (seen in 1h SIDIS frequently)

★ Isospin symmetries of G_1 DiFF observed in **sin(ϕ_h - ϕ_R)**

★ Strong enhancement near resonant region

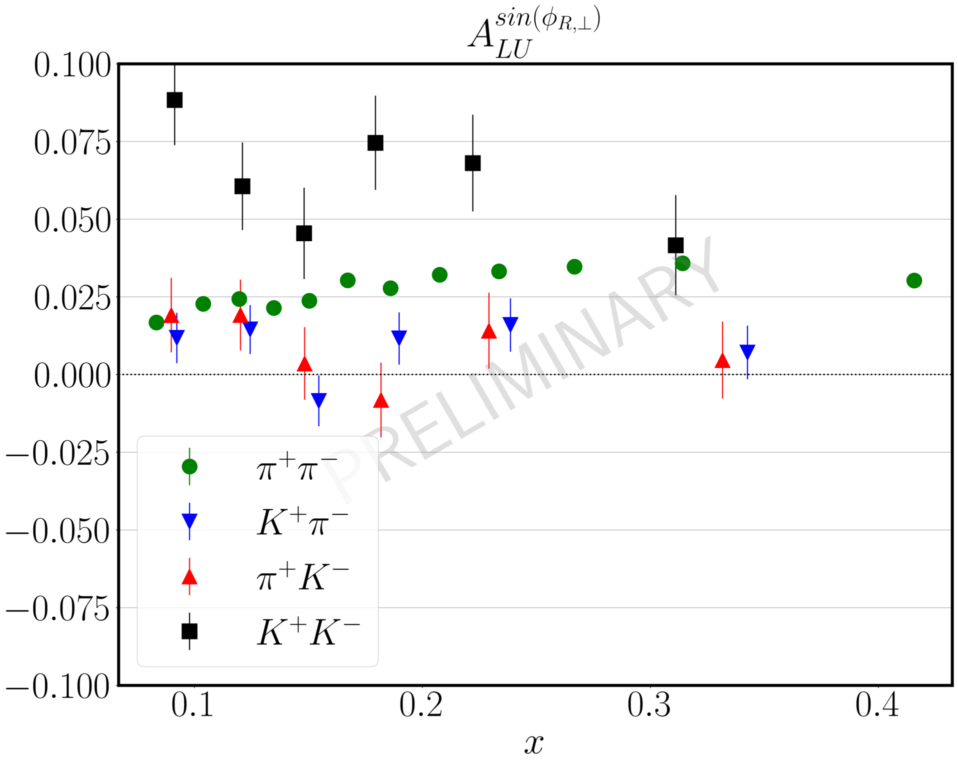
$$e \otimes H_1^{\perp|\ell,m>}$$

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



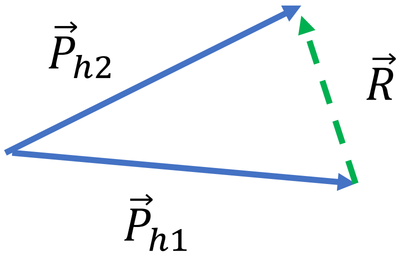
Slide by G. Matousek

Kaons



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

Better: Dihadron Fragmentation Functions



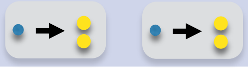
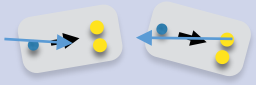
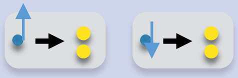
Additional Observable:

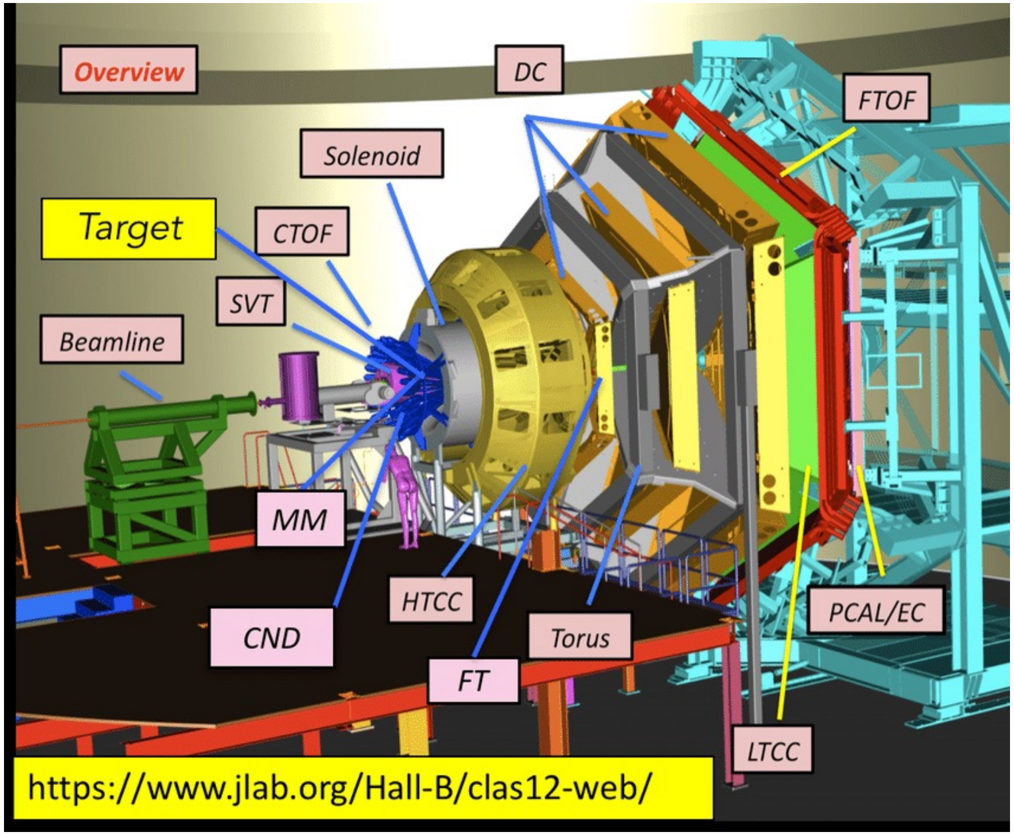
$\vec{R} = \overrightarrow{P_1} - \overrightarrow{P_2}$:

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	$D_1^{h/q}(z, M)$ 		$\boldsymbol{H_1^{\perp h/q}}(\boldsymbol{z}, \boldsymbol{p_T}\mathbf{M}, \mathbf{(Ph)}, \theta)$ 'Di-hadron Collins'
longitudinal			
Transverse		**$G_1^{\perp}(z,M,P_h,\theta)$=**  T-odd, chiral-even →jet handedness QCD vaccum strucuture	**$H_1^{\sphericalangle}(z,M, (P_h),\theta)$=.** T-odd, chiral-odd Colinear 



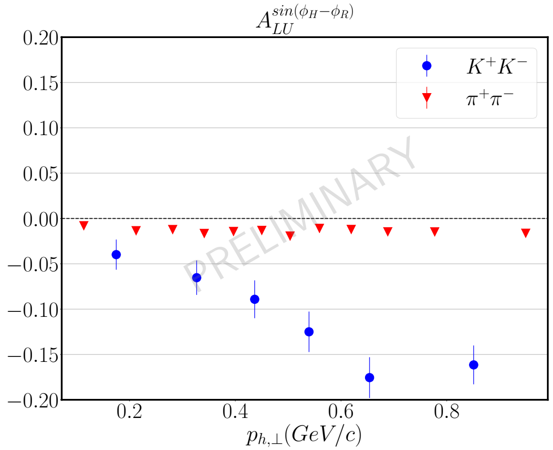
Forward Detector

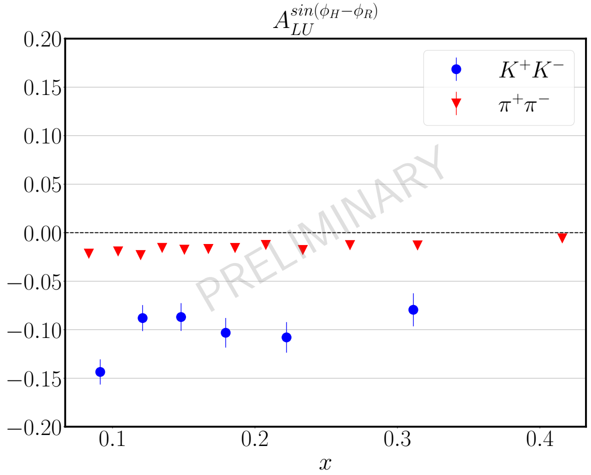
- Torus Magnet
- Drift Chamber (DC)
- Forward Time of Flight (FTOF)
- High-threshold Cherenkov Counter (HTCC)
- Low-threshold Cherenkov Counter (LTCC)
- Ring Imaging Cherenkov Detector (RICH)
- Preshower + Electromagnetic Calorimeter (PCAL/EC)
- Forward Tagger (FT)

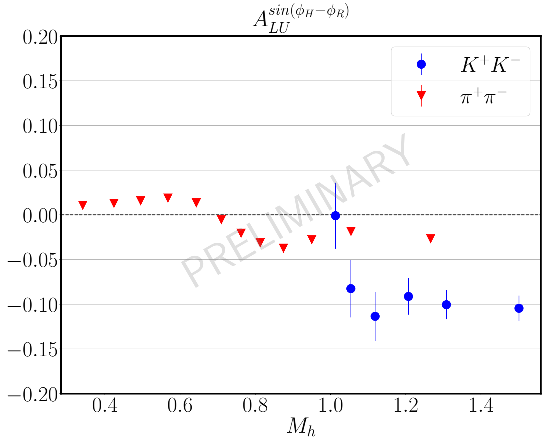
- **Longitudinally Polarized Electron Beam**
  - E = 10.6 GeV
  - P = 86–89%
- **Unpolarized Liquid H_2 Fixed Target**
- Torus magnet → electrons inbending

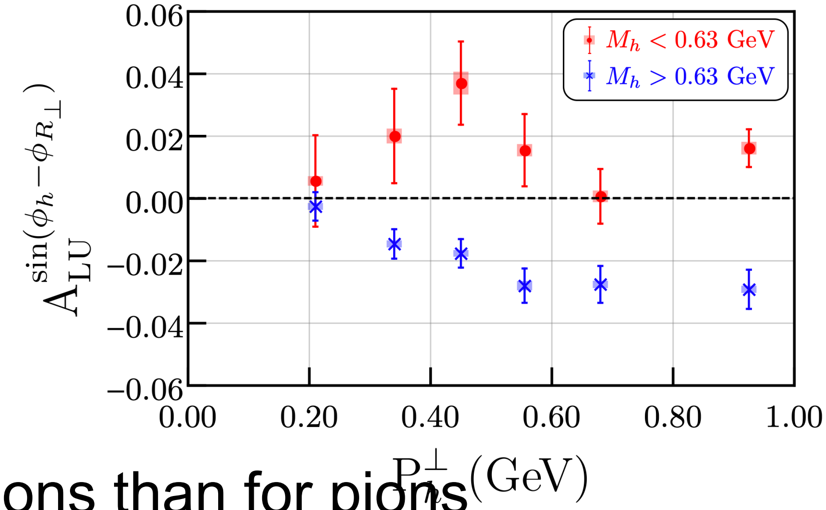
V. Burkert et al., Nucl.Instrum.Meth.A 959 (2020) 163419

Asymmetries sensitive to $G_1^\perp$





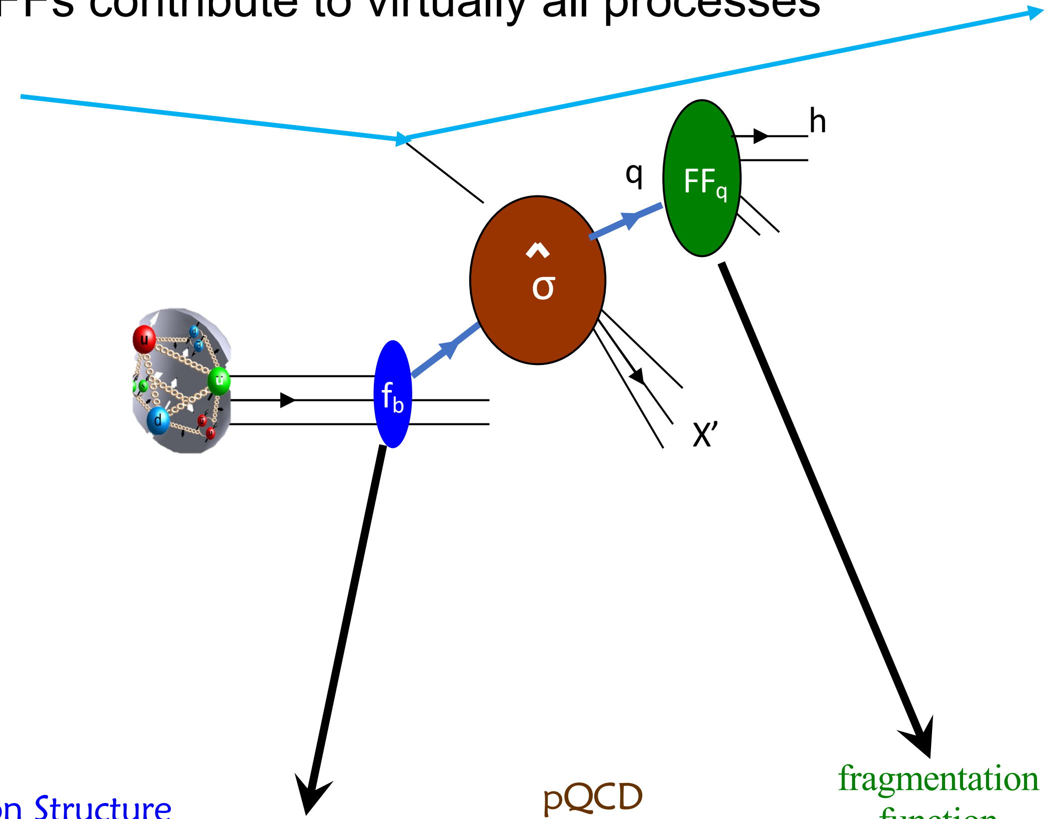


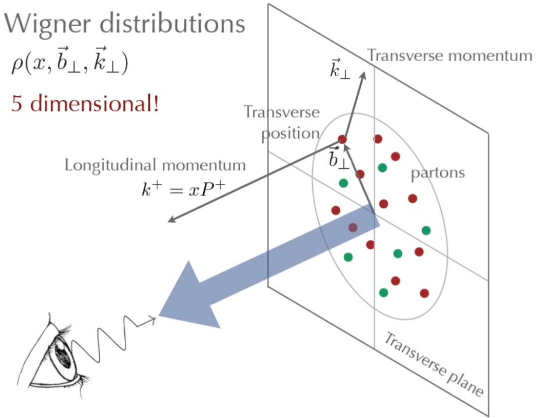


- sp −interference term larger for kaons than for pions
- Not true for all interference terms (not shown)
- $M_{KK} > m_\phi$ can account for $p_\perp$ dependence

Hard Scattering is a premier tool to probe the quark and gluon degrees of freedom

- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes





- Q^2 "scale" of the probe, "resolution"
- x: bjorken **scaling variable**, in partonic picture momentum fraction of the struck parton, "shutter speed"
- z fractional quark momentum carried by hadron
- p_T

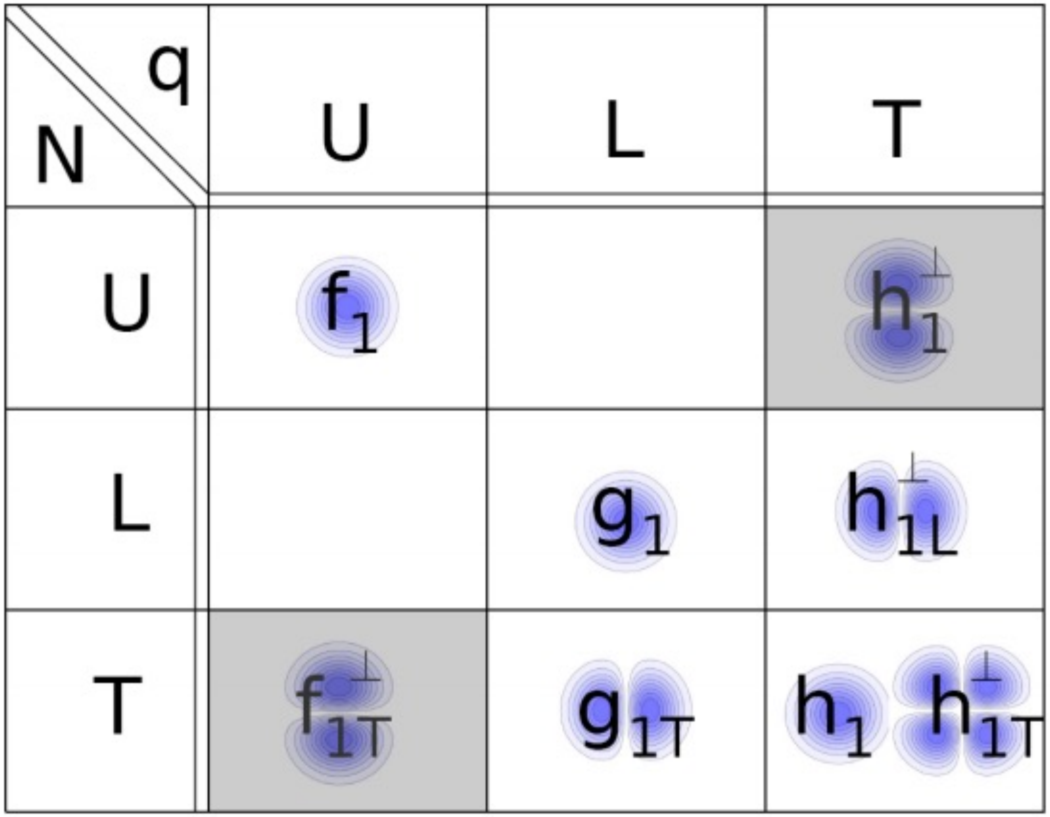
Proton Structure

pQCD

fragmentation function

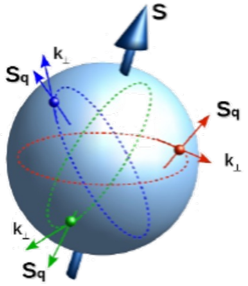
$$\frac{d^2\sigma(ep \to \pi X)}{dx\, dz\, p_{hT}} \propto \boxed{q(x, k_T)\times} \boxed{\frac{d\sigma^2(e\, q \to e' q')}{dx}} \times FF(z, p_T)\, \delta(p_{hT} - (k_T + p_T))$$

Momentum structure in the parton model parametrized by TMDs (spin ½)



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

- In addition to the spin-spin correlations can have spin momentum correlations!



Spin-orbit correlations

Run Group **SIDIS** programs at a glance

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

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

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

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

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

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

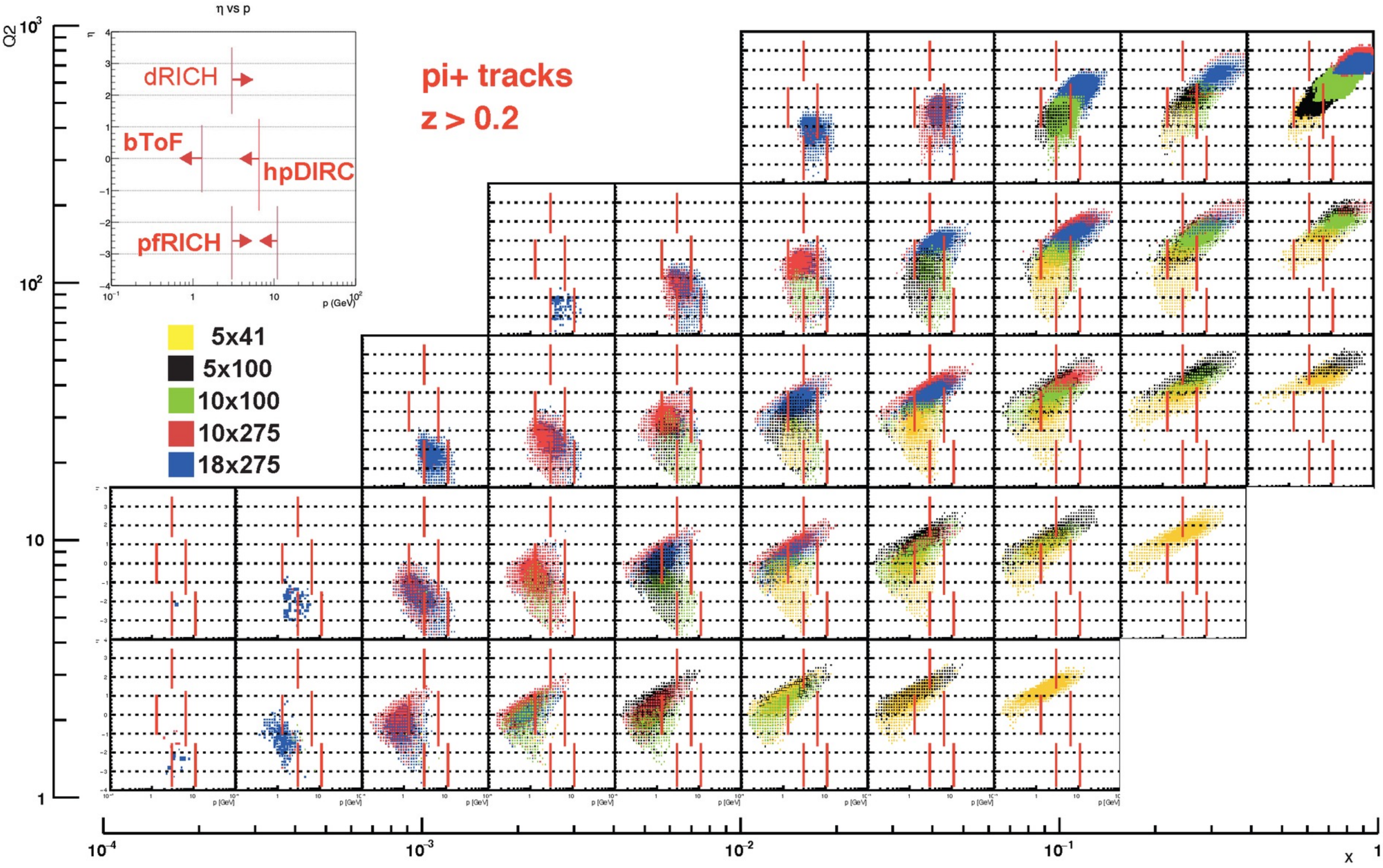
Run Group K (Unpolarized LH_2 target - 6.5, 7.5, 8.4 GeV e^- beam)

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

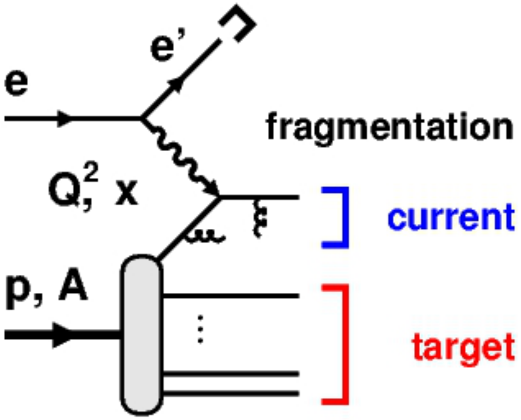
Run Group H (Dynamic **transversely** polarized NH_3 - 10.6 GeV e^- beam)

- ★ Access to $\mathbf{F_{UT}}$ structure function → Transverse spin structure at high (essentially unmeasured) x

Wide Coverage



Target Fragmentation → Fracture Functions

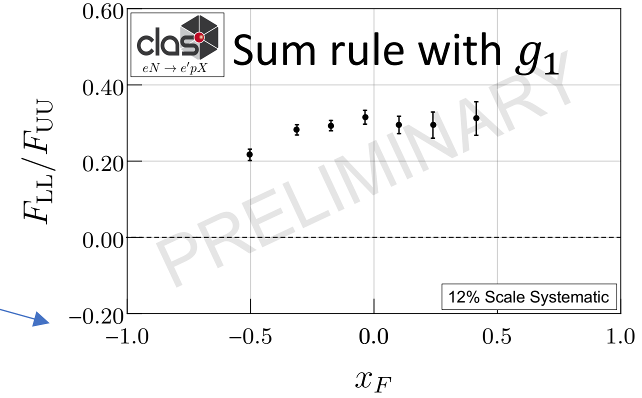


- Correlations between CFR-TFR allows to extract fracture functions coupled to FFs

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

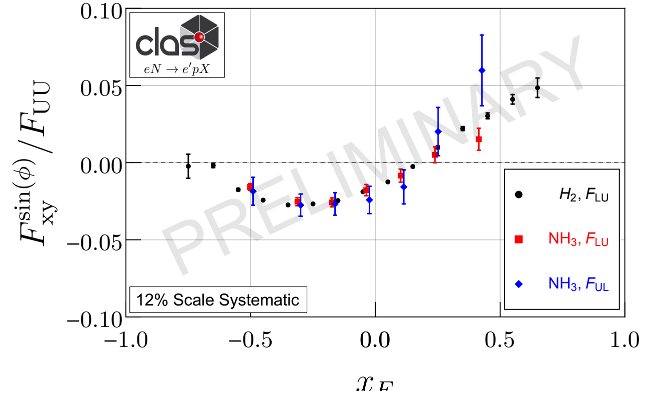
M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132



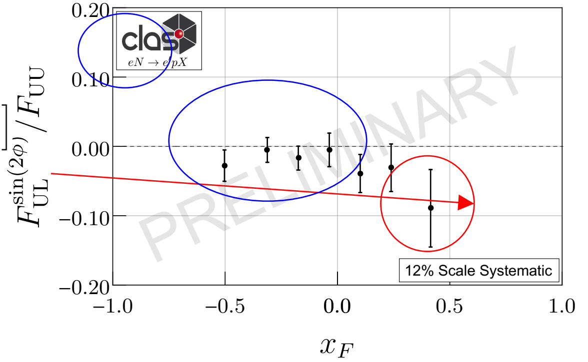
Quark polarization / Nucleon polarization

	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

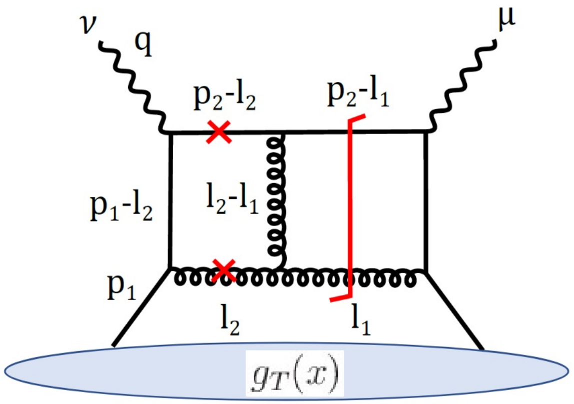


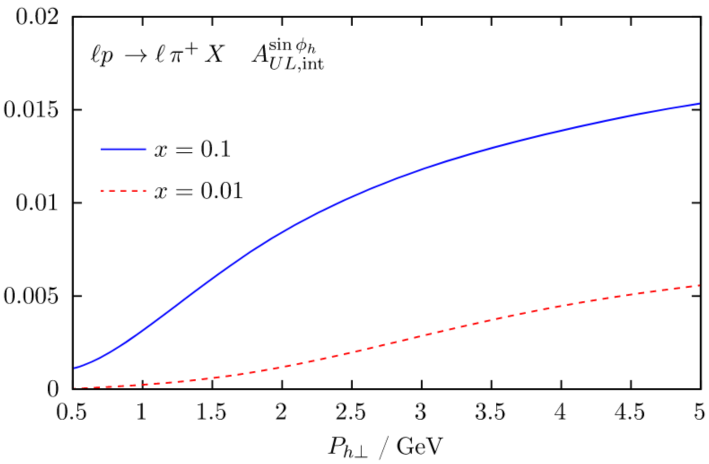
$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{MM_h}h_{1L}^{\perp}H_1^{\perp}\right]$$



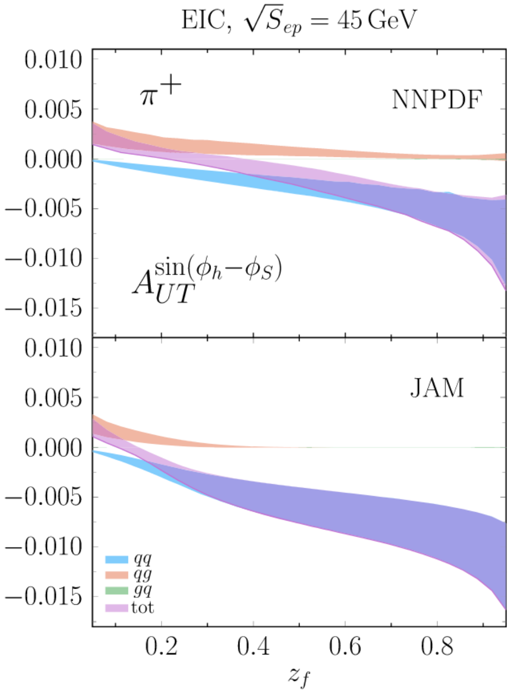
Appearance of perturbative asymmetries

- Additionally: perturbative generation of asymmetries from g_T
- What about di-hadron correlations?





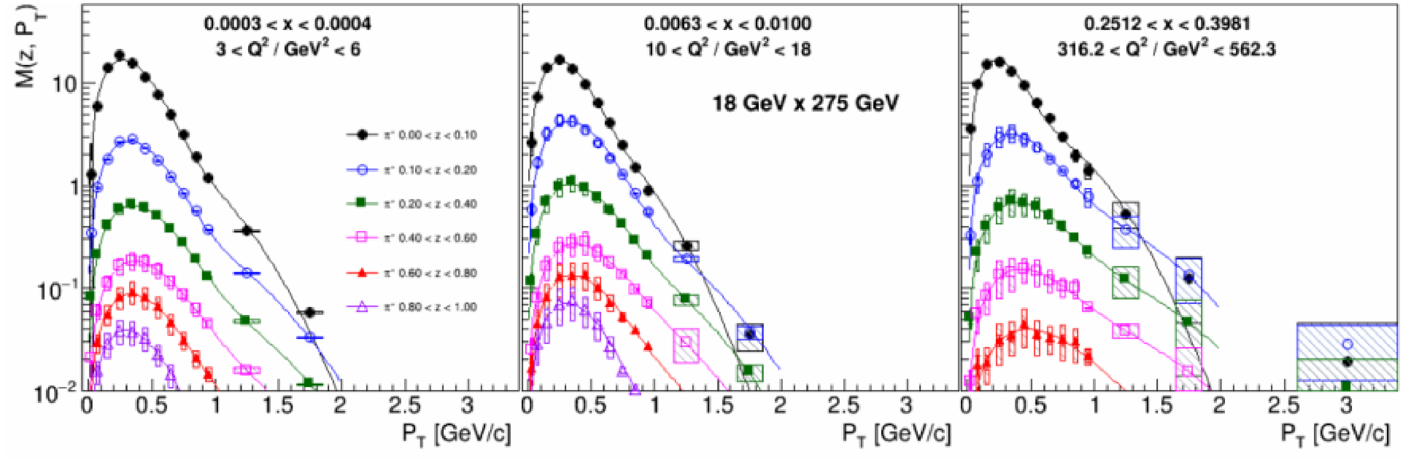
Abele, Aicher, Piacenza, Schafer, Vogelsang (2022)



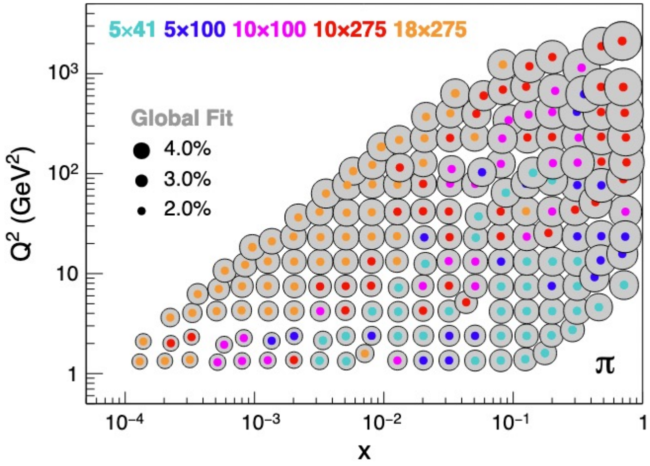
Benic et al. Phys. Rev. D 104, 094027

Unpolarized TMDs

- Top: Explicit z dependence of select pion multiplicities in 3 x-Q^2 bins, including the double-Gaussian fits

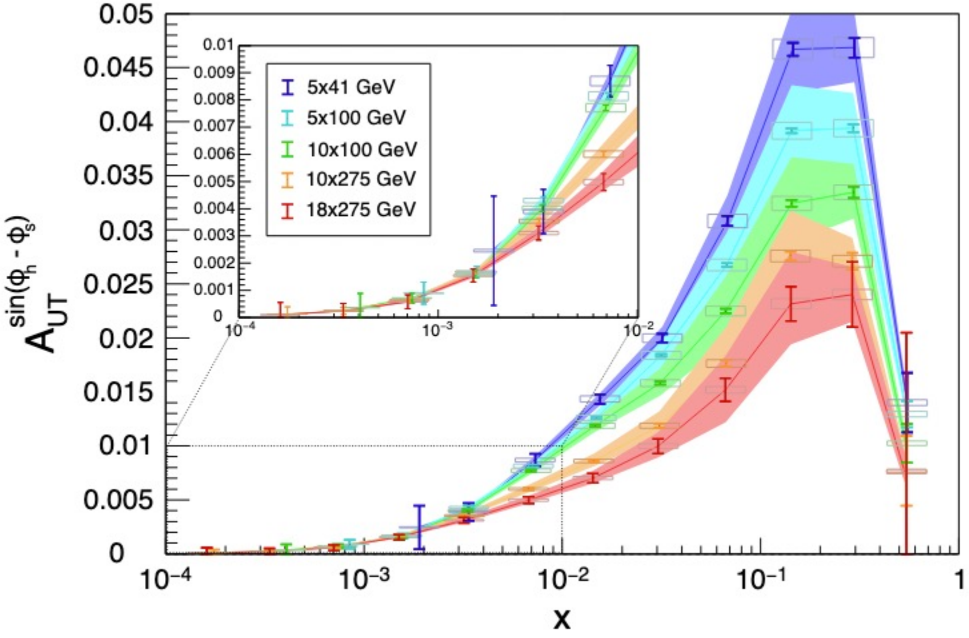


hep-ex:2207.10893



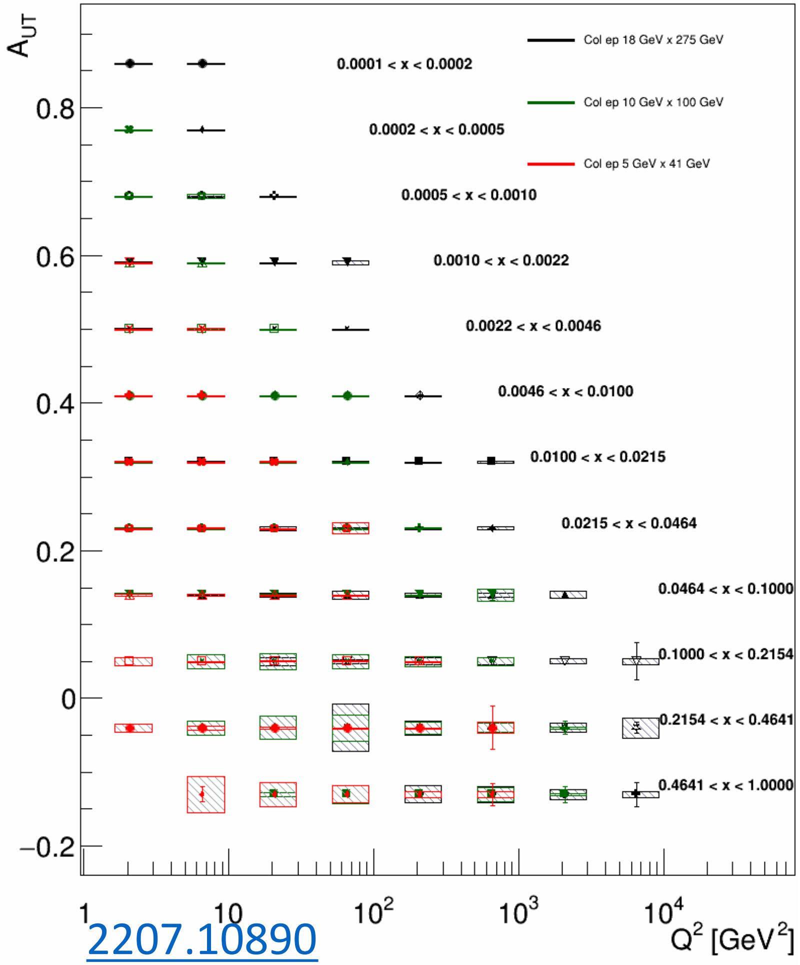
- Impact on $f(x, k_T)$ from Athena proposal
- $\frac{q_T}{Q} < 1.0, y > 0.01$
- Experimental uncertainties dominated by 2% $p2p$, 3% scale, theoretical uncertainties driven by uncertainties on evolution

Projection of transverse TSSAs



Athena projections for the measurement of Sivers asymmetries

$$0.2 < z < 0.7, Q^2 > 1.0, y > 0.05, \frac{qT}{Q} < 1.0$$



2207.10890

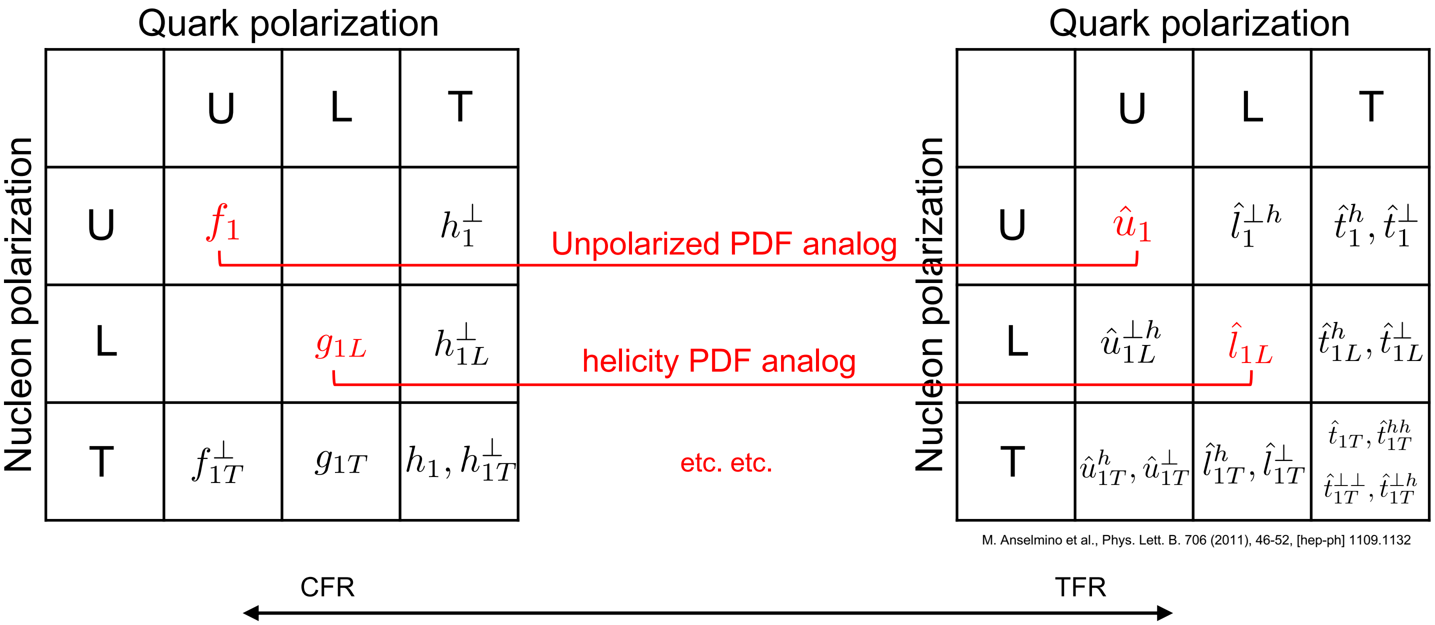
Projected uncertainties on Collins Asymmetries by ECCE

Analog to PDFs; Momentum Sum Rules

- A direct relationship exists to the eight leading twist PDFs after the fractional 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 (rows: Nucleon polarization)

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

Quark polarization (rows: 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	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}$ $\hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

Unpolarized PDF analog

helicity PDF analog

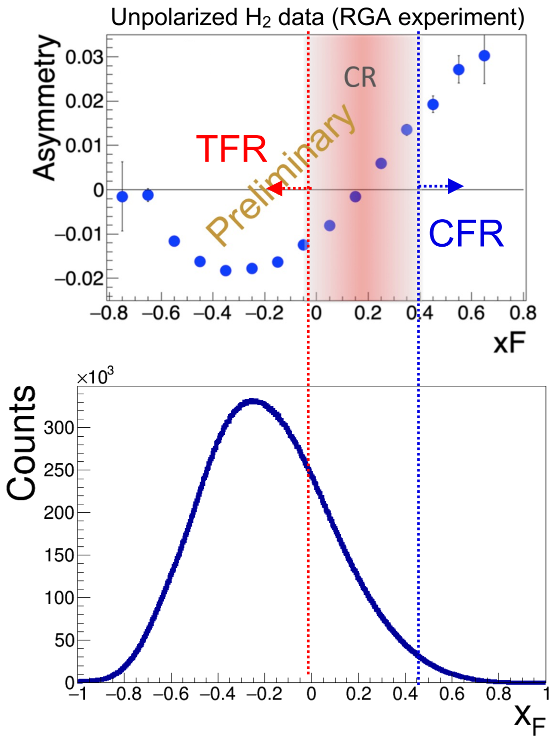
etc. etc.

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

CFR ← → TFR

Can We Separate Target and Current?

ep → e'pX



Feynman variable

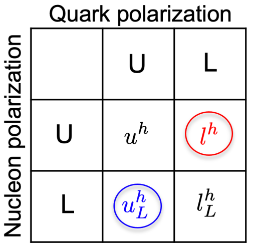
$$x_F = \frac{p_h^z}{p_h^z(\mathrm{max})} \quad \text{in CM frame } \mathbf{p} = -\mathbf{q}, \qquad -1 < x_F < 1$$

Rapidity

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

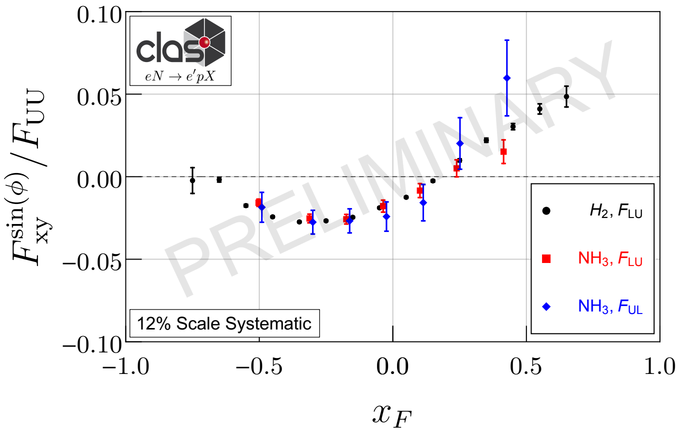
- No clear *experimental* definition of what constitutes current production versus target production.
- Odd structure functions, with different production mechanisms in both regions, give a possible clue.
- Protons (as opposed to mesons) at CLAS12 kinematics give a unique opportunity because they have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

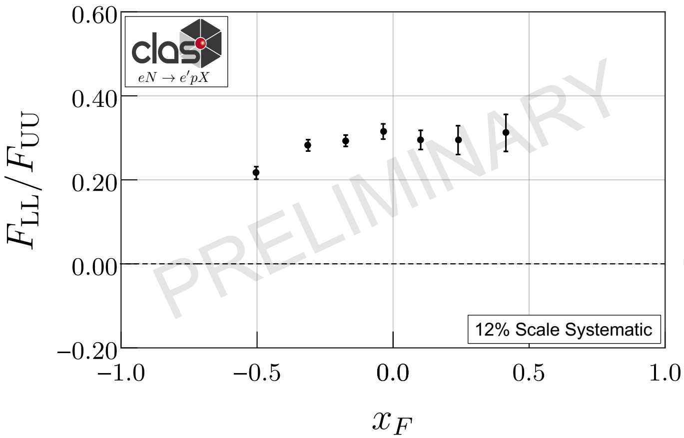
Current and Target Separation

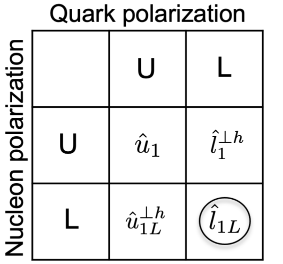


Nucleon polarization \ Quark polarization	U	L
U	u^h	l^h
L	u^h_L	l^h_L

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





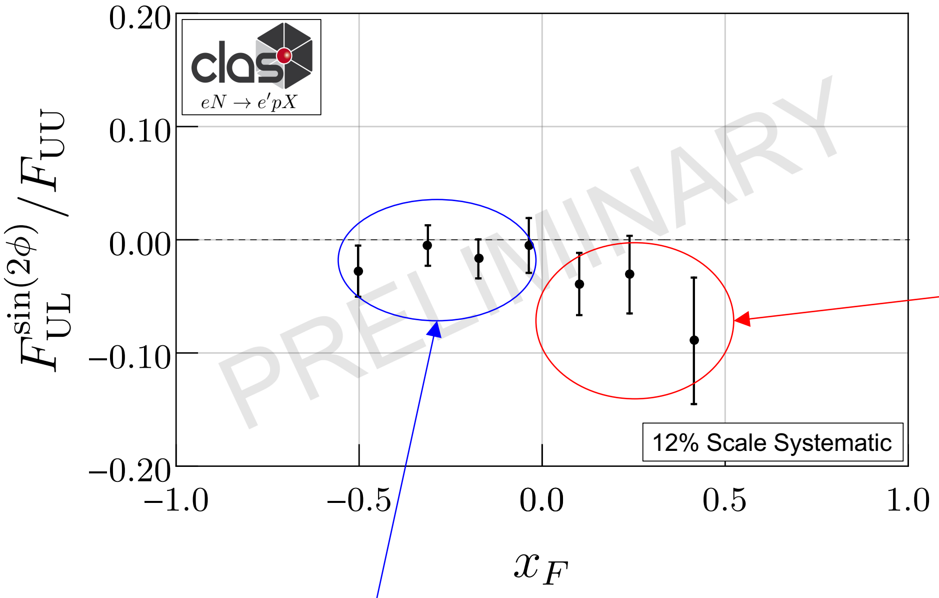


Nucleon polarization \ Quark polarization	U	L
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$

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.

Kotzinian-Mulders Asymmetry



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

- The $F_{UL}^{\sin 2\varphi}$ asymmetry is purely generated by the Collins mechanism – whereby a transversely polarized quark flips orientation during hadronization and produces an asymmetric distribution in the transverse plane.
- Hadronization in the TFR is more isotropic – there is no additional chiral-odd quantity like the Collins function to pair with the Kotzinian-Mulders TMD because factorization into separate soft and hard scale processes does not hold.

- No Collins mechanism in the TFR so $F_{UL}^{\sin 2\varphi}$ (and $F_{UU}^{\cos 2\varphi}$) are pure twist-4. We would expect small magnitude at $-x_F$.

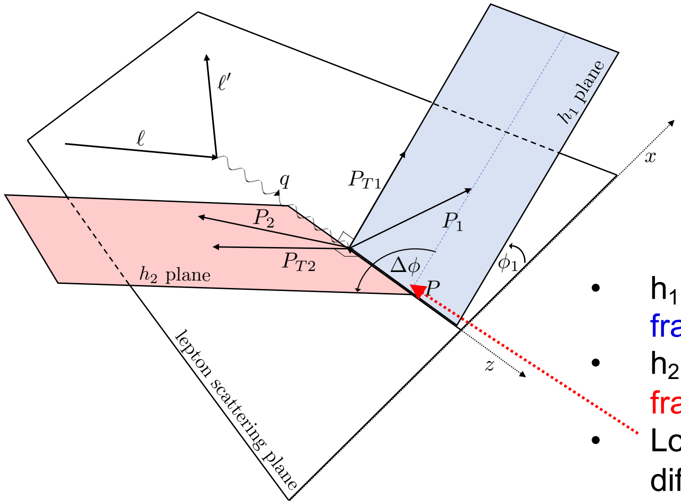
Early signs give a *possible* hint but need more statistics!

Back-to-back (dSIDIS) Formalism

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

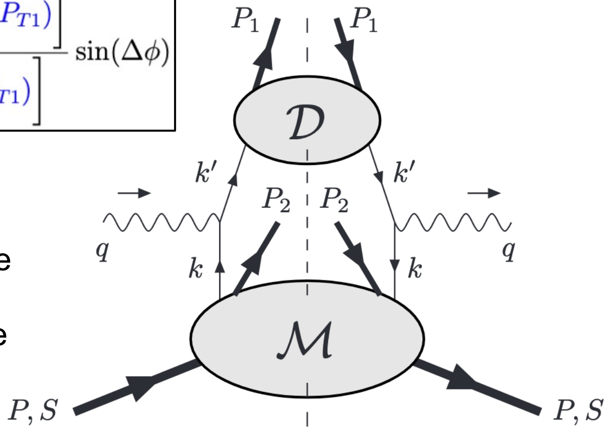
$\hat{l}_1^{\perp h}$ Unique access to longitudinally polarized quarks in unpolarized nucleon… no corresponding PDF!

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



Kinematic plane for b2b dihadron production.

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



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

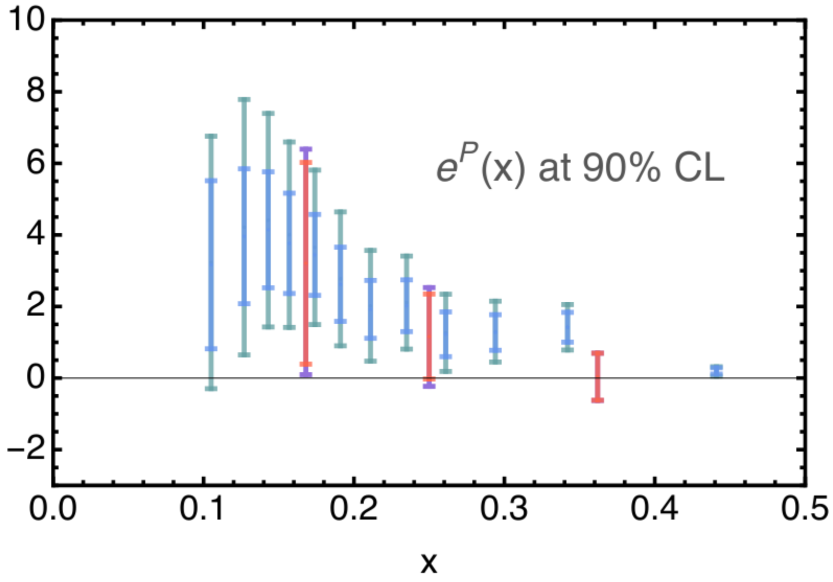
---

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

New e(x) Extraction – Proton Flavor Combination

$$A_{LU}^{\sin\phi_R} \propto \frac{M}{Q}\,\frac{\sum_q e_q^2\left[xe^q(x)\,H_{1,sp}^{\sphericalangle,q}(z,m_{\pi\pi})+\frac{m_{\pi\pi}}{zM}\,f_1^q(x)\,\tilde{G}_{sp}^{\sphericalangle,q}(z,m_{\pi\pi})\right]}{\sum_q e_q^2\,f_1^q(x)\,D_{1,ss+pp}^q(z,m_{\pi\pi})}$$

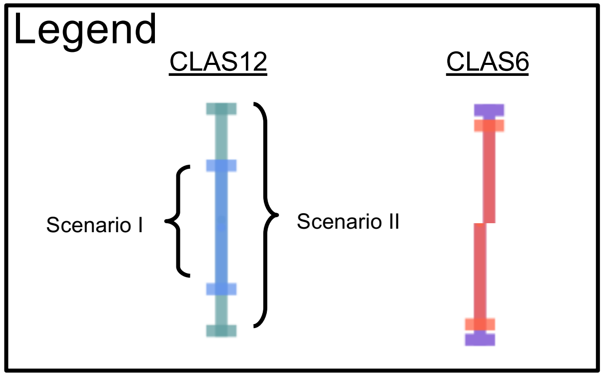
twist-3 DiFF



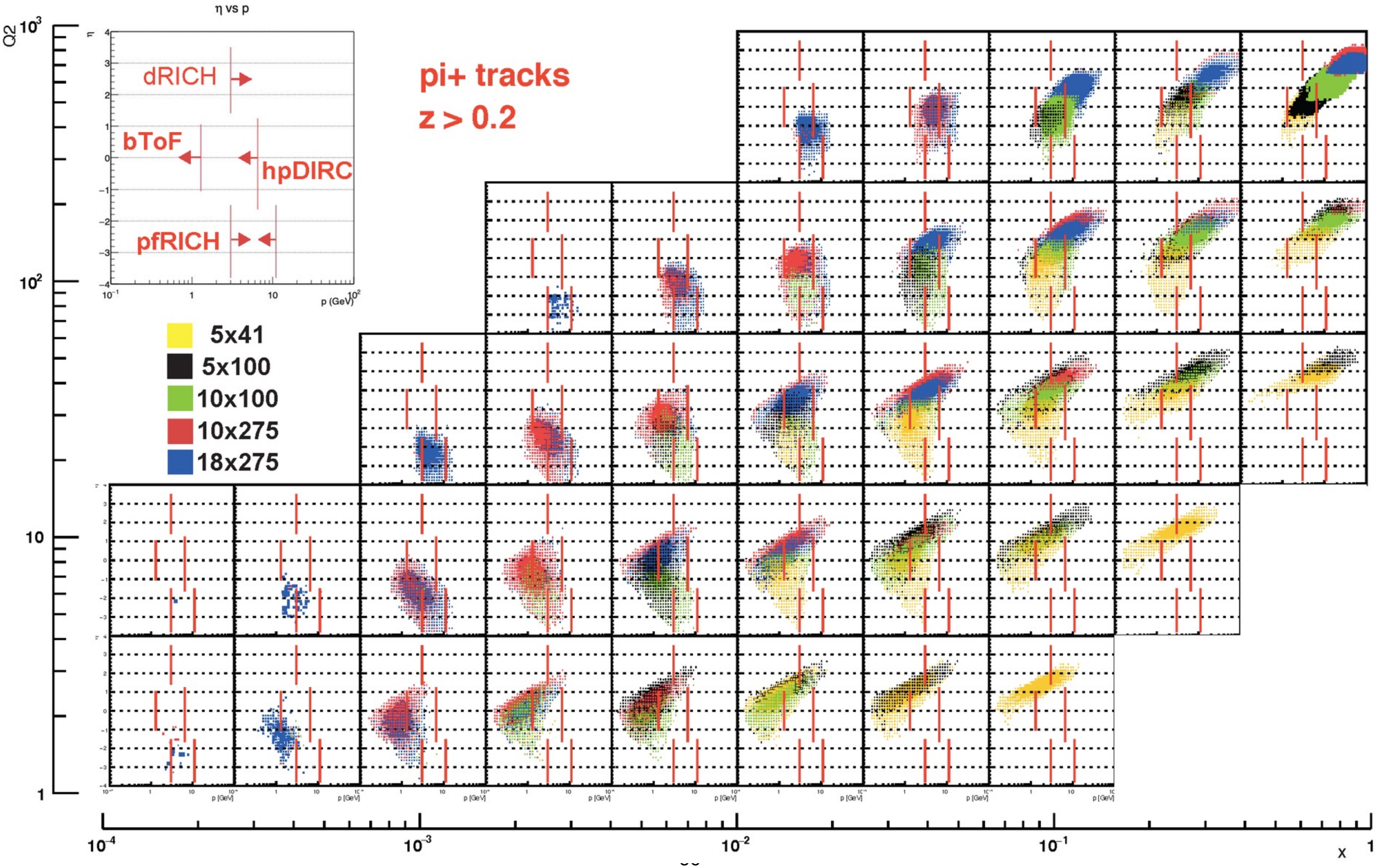
Courtoy, Aurore, et al. *Phys.Rev.D* 106 (2022)

Courtoy, Aurore – CPHI 2022

- **Scenario I: Wandzura-Wilczek (WW) Approximation**
  - Drop twist-3 DiFF
- **Scenario II: Beyond WW approximation**
  - Estimate max integrated twist-3 DiFF from COMPASS A_{UL} and A_{LL}



Wide Coverage



Depolarization Factors

Twist 2

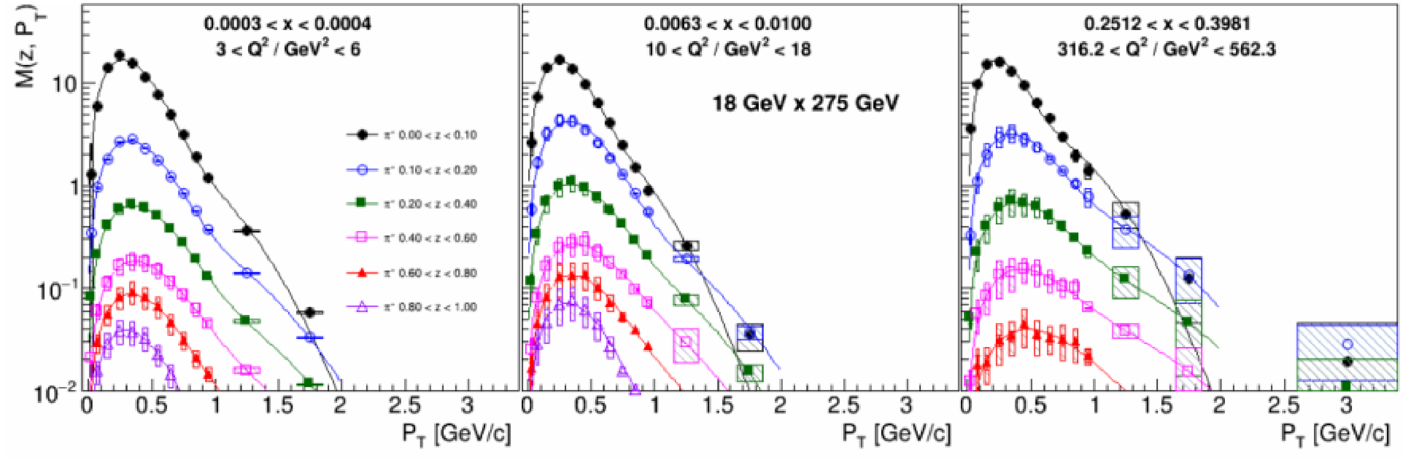
Twist 3

	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

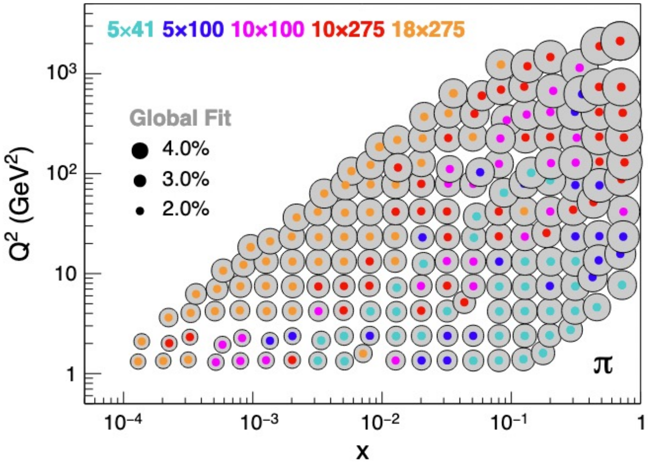
Slide from C. Dilks

Unpolarized TMDs

- Top: Explicit z dependence of select pion multiplicities in 3 x-Q^2 bins, including the double-Gaussian fits

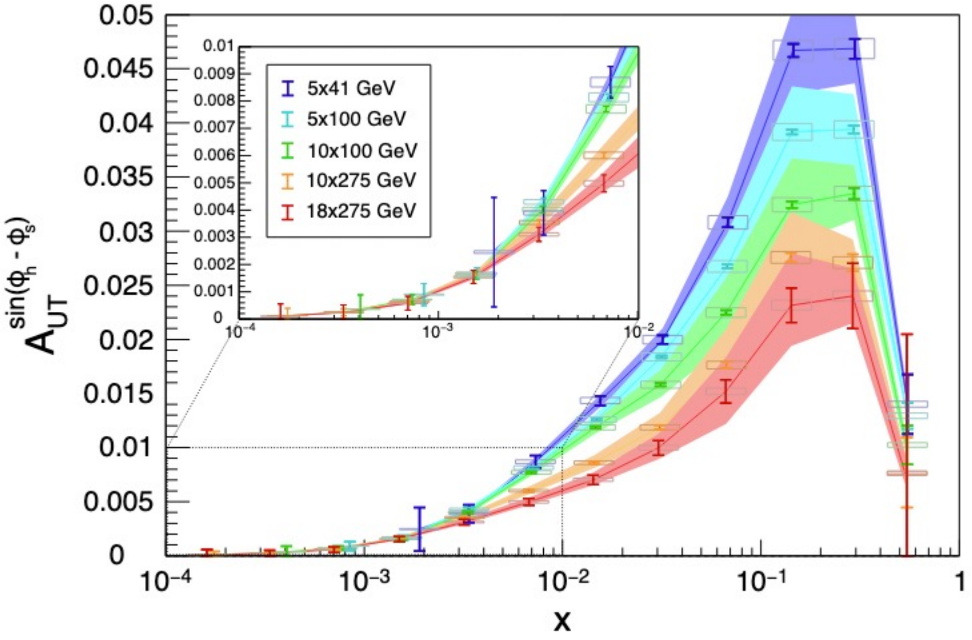


hep-ex:2207.10893



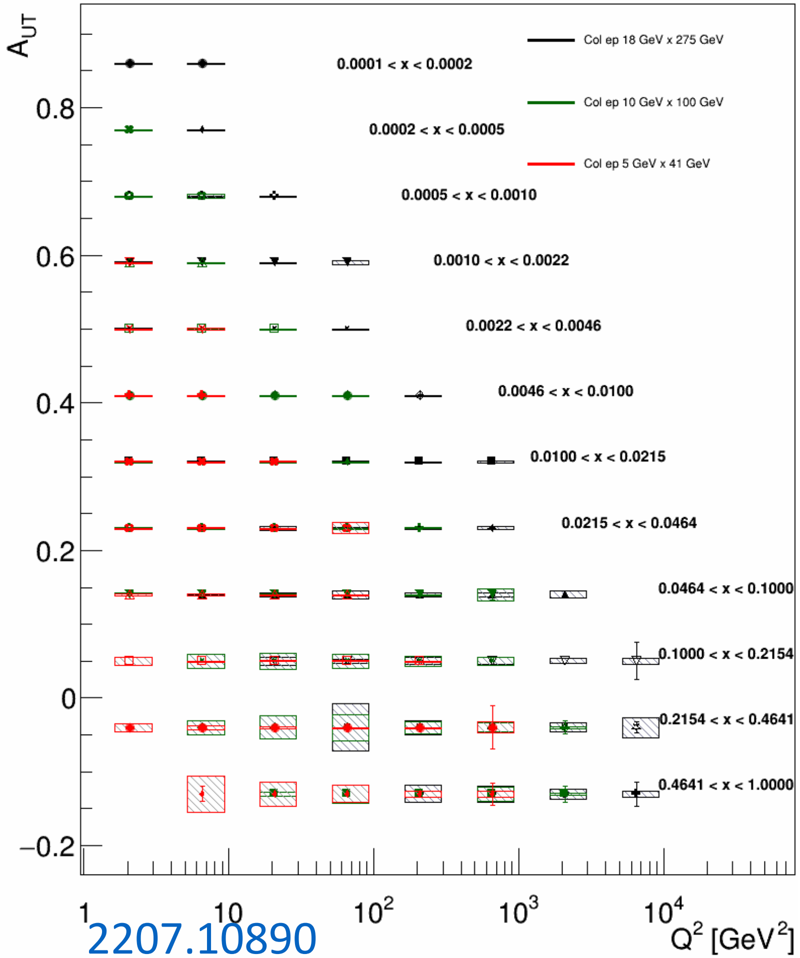
- Impact on $f(x, k_T)$ from Athena proposal
- $\frac{q_T}{Q} < 1.0, y > 0.01$
- Experimental uncertainties dominated by 2% $p2p$, 3% scale, theoretical uncertainties driven by uncertainties on evolution

Projection of transverse TSSAs



Athena projections for the measurement of Sivers asymmetries

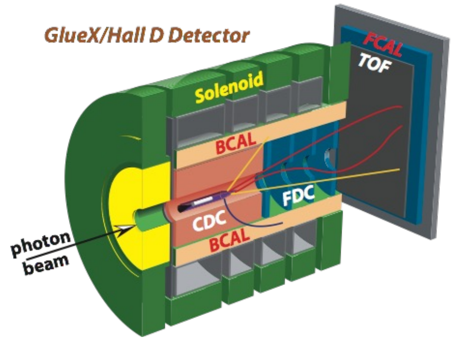
$$0.2 < z < 0.7, Q^2 > 1.0, y > 0.05, \frac{qT}{Q} < 1.0$$

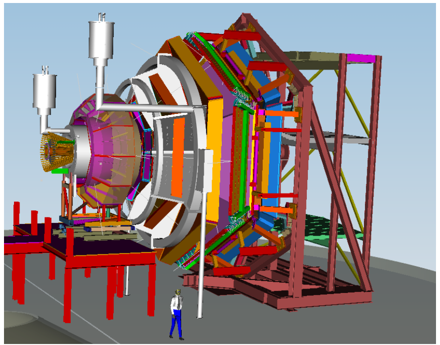


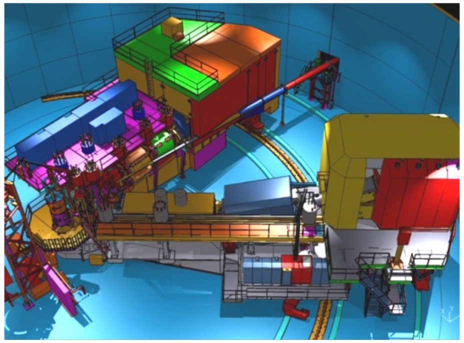
2207.10890

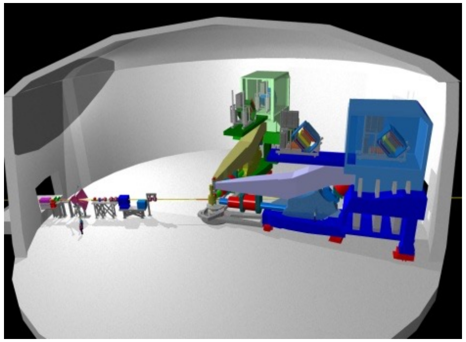
Projected uncertainties on Collins Asymmetries by ECCE

Detector Requirements: Complementarity



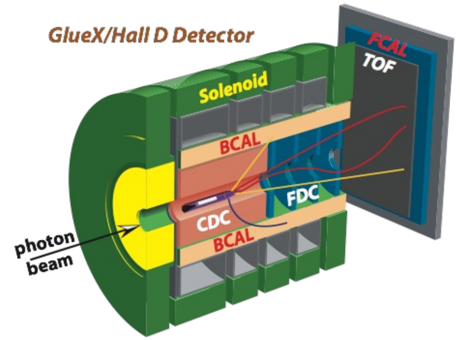


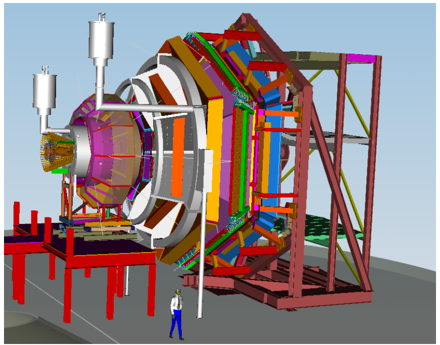


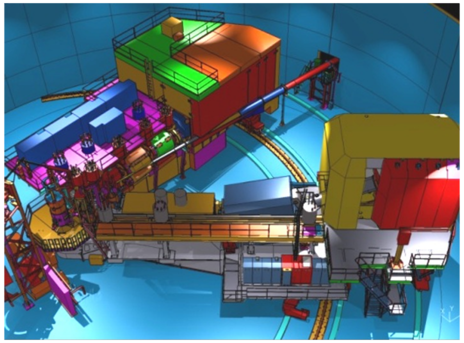


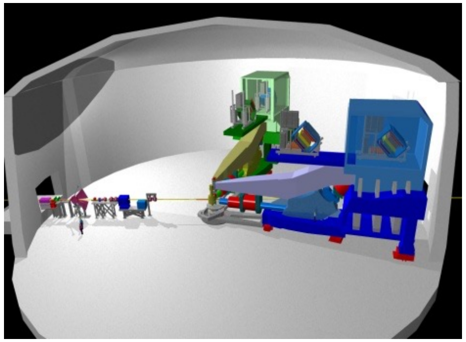
Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction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

Detector Requirements: Complementarity



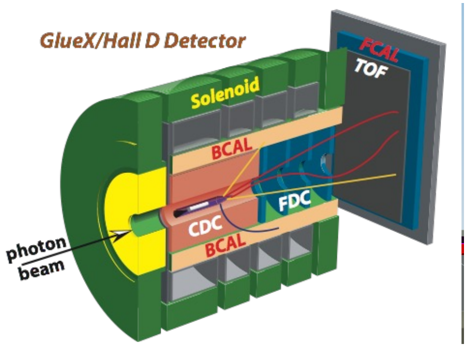


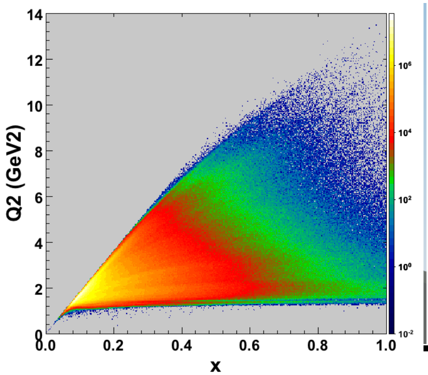


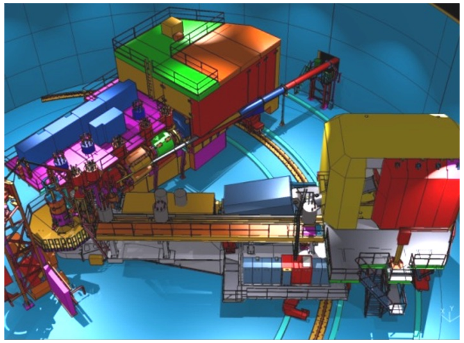


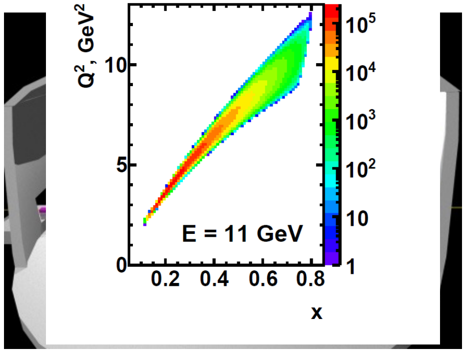
Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent moment	
high multiplicity reconstruction		luminosity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

Detector Requirements: Complementarity



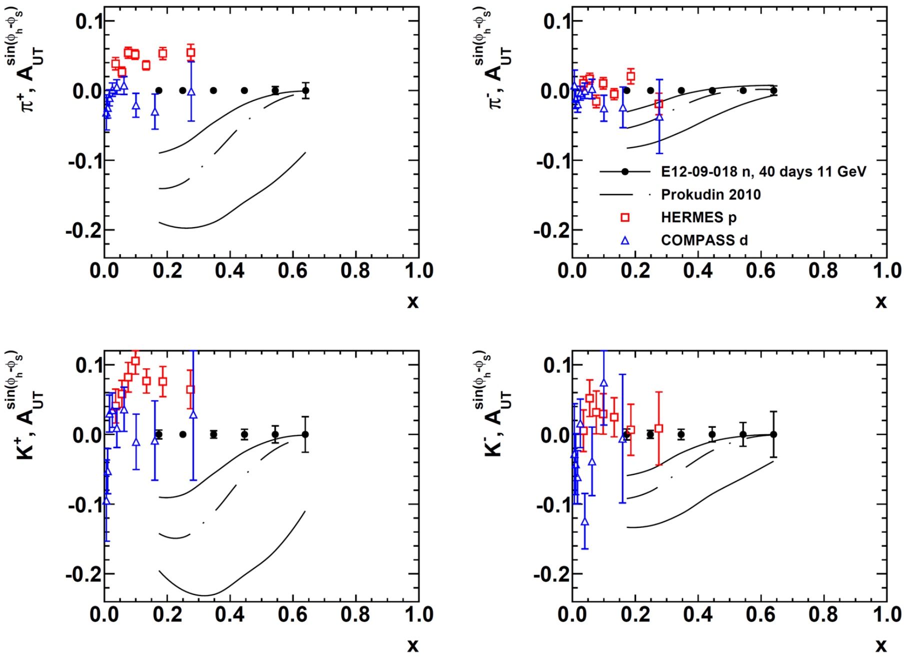




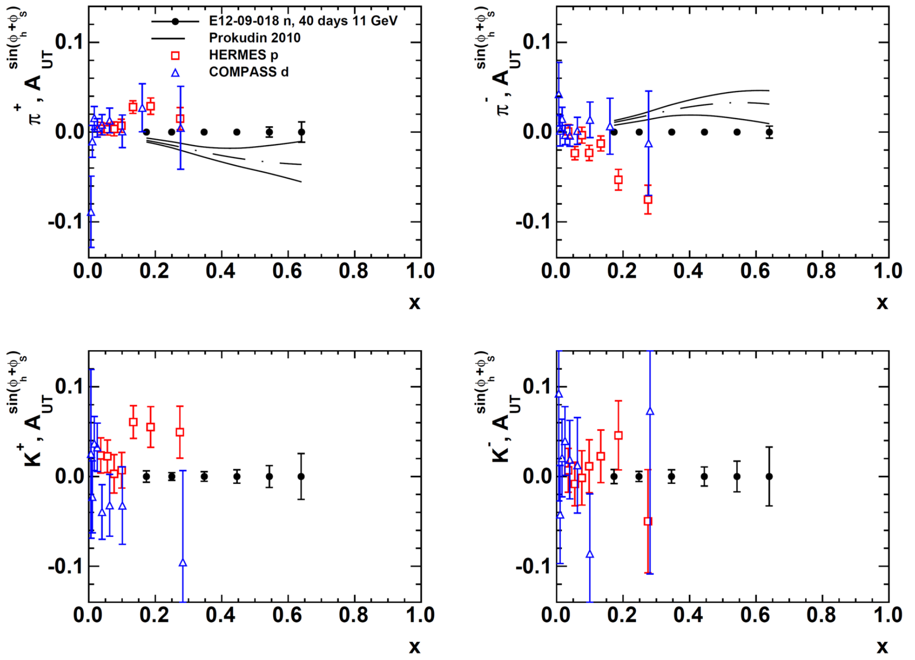


Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction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

SBS+BB Projected Results: Collins and Sivers SSAs



Projected A_{UT}^{Sivers} vs. x (11 GeV data only)



Projected $A_{UT}^{Collins}$ vs. x (11 GeV data only)

- E12-09-018 will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than Hall A E06-010 neutron data. *Near-future more precise COMPASS deuteron data will sharpen expected impacts, urgency of E12-09-018*
- SBS installation starts 2020. E12-09-018 could run as early as 2022; 2023 more likely.