Semi-Inclusive Physics Prospects at ePIC

Christopher Dilks

on behalf of the ePIC Collaboration

DIS 2023

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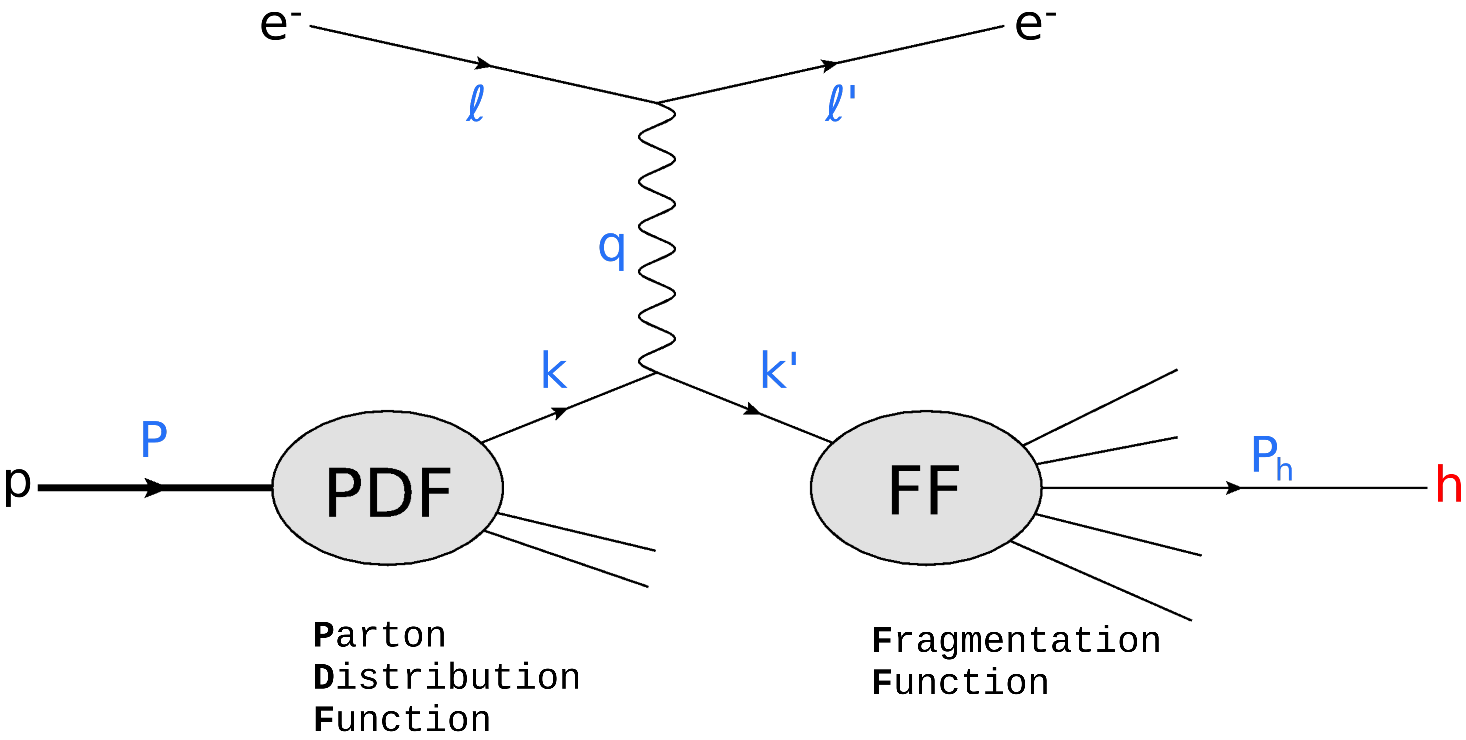
Research supported by the U.S. DEPARTMENT OF ENERGY Office of Science

Outline

- SIDIS, Observables, Kinematic Reach
- Parton Distribution Functions
- Fragmentation Functions
- Kinematic Reconstruction

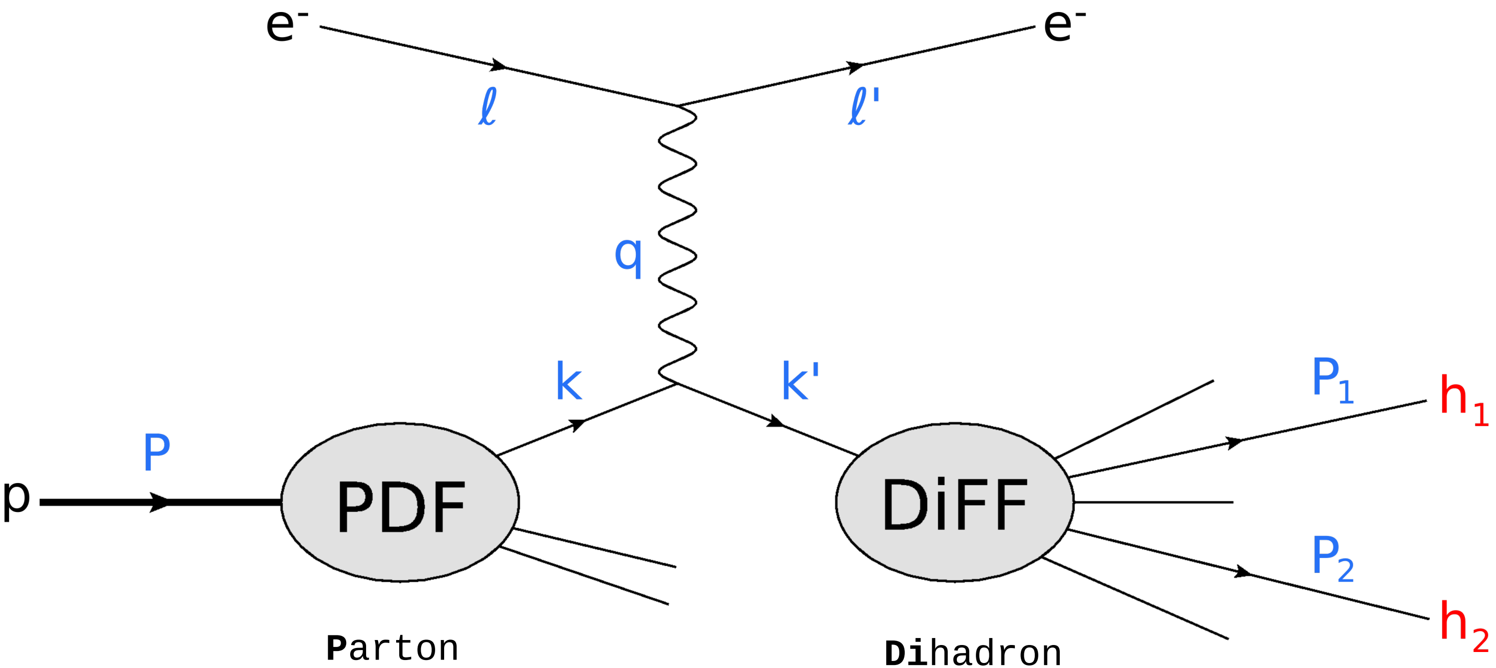
Semi-inclusive Hadron Production

$$e + p \rightarrow e + h + X$$



Semi-inclusive Dihadron Production

$$e + p \rightarrow e + h_1 + h_2 + X$$



Parton
Distribution
Function

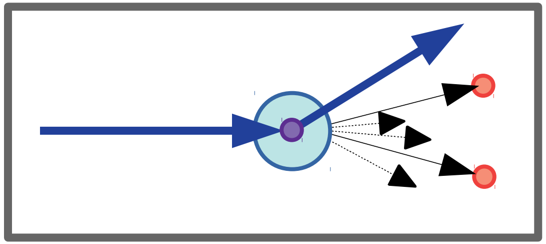
Dihadron
Fragmentation
Function

Cross Sections and Asymmetries

Cross Section

(Or Multiplicity)

$$d\sigma$$



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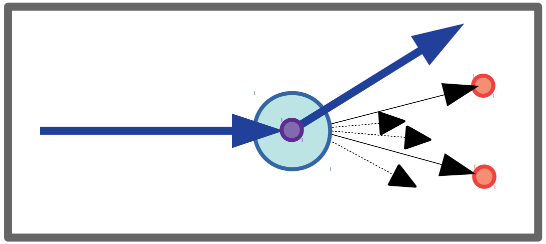
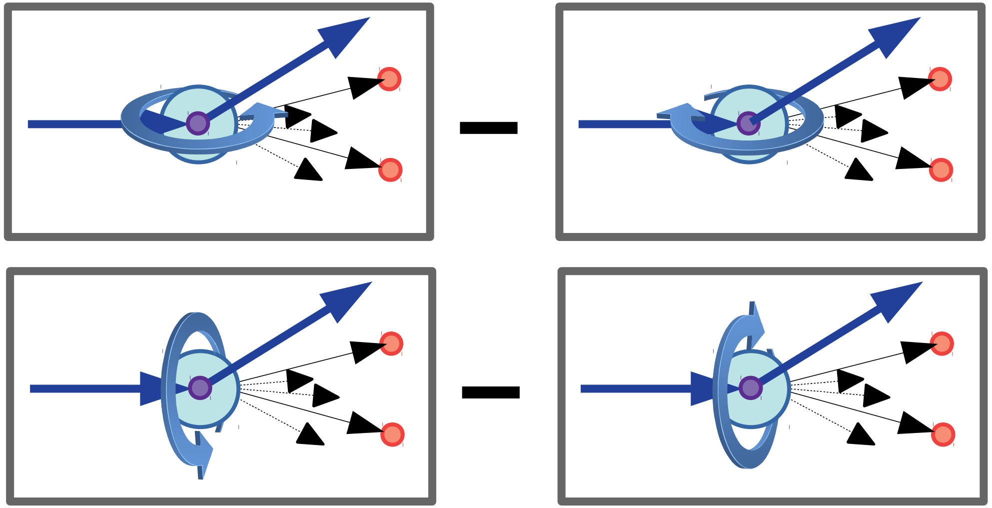


Target Spin Asymmetry

A_{UT}

A_{UL}



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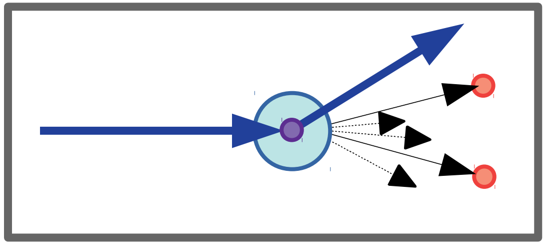

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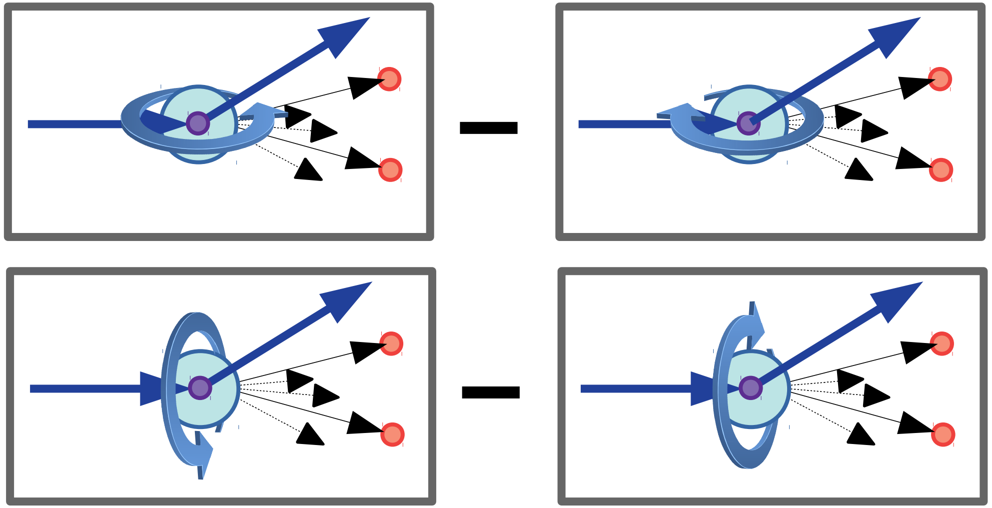
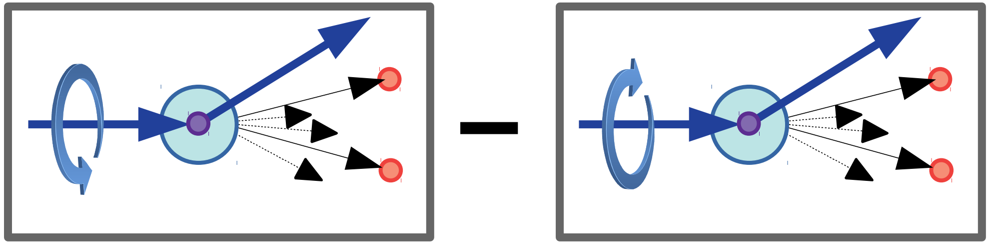


Beam Spin Asymmetry

A_{LU}



Cross Sections and Asymmetries

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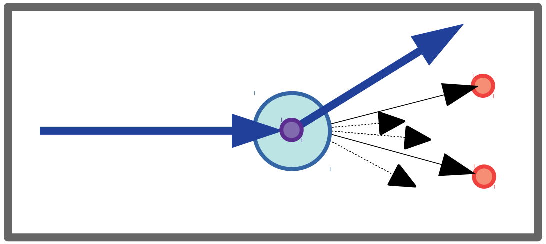

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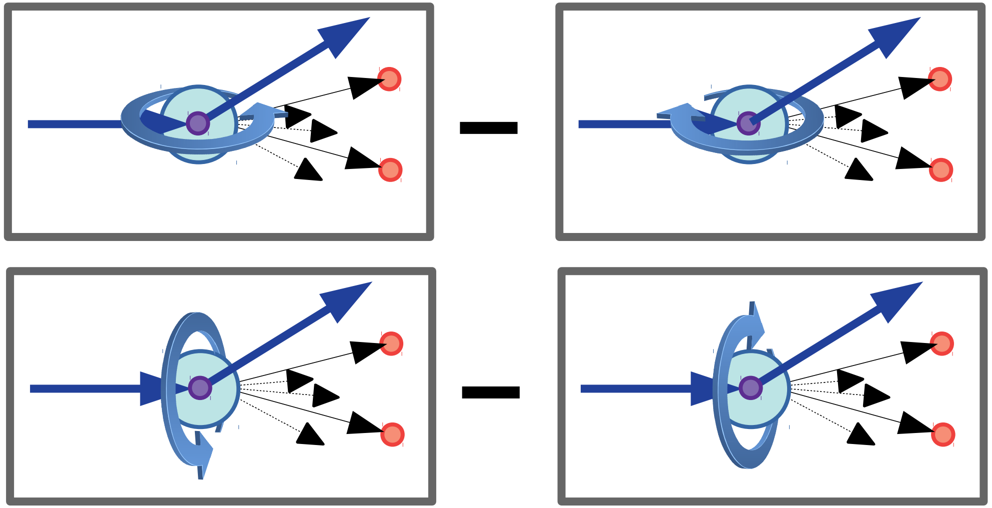

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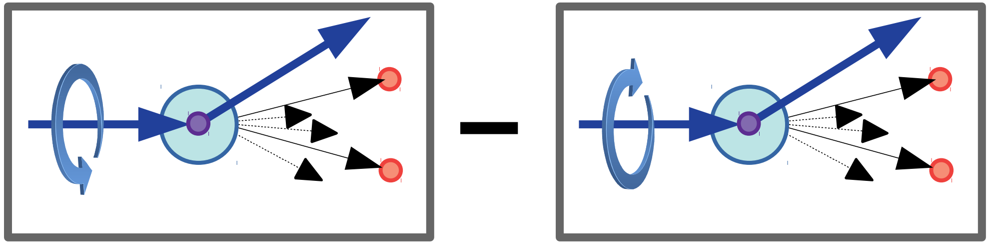


Double Spin Asymmetries

$$A_{LL}$$

$$A_{LT}$$

$$A_{LL} = \frac{(d\sigma_{++} + d\sigma_{--}) - (d\sigma_{+-} + d\sigma_{-+})}{d\sigma}$$

The Main Goal

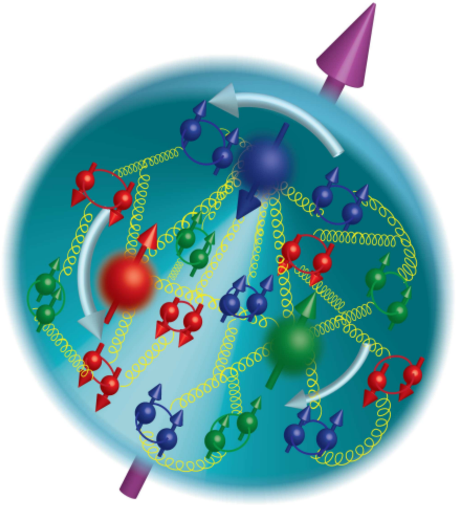
$$\mathrm{d}\sigma_{XY} \propto \text{Structure Functions} \propto \text{PDF} \otimes \text{FF}$$

(or DiFF)

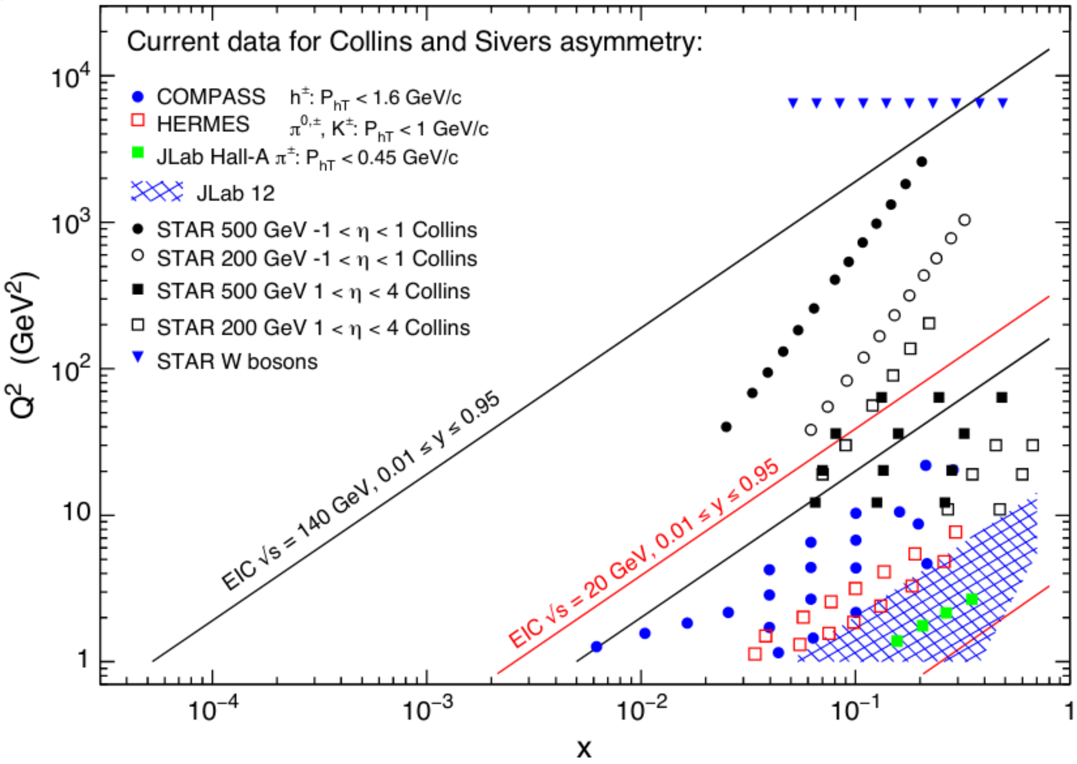
$$A_{UT} = \frac{d\sigma_{UT}}{d\sigma_{UU}} = \frac{d\sigma_{\uparrow} - d\sigma_{\downarrow}}{d\sigma}$$

Goal:

- ◆ Probe spin/orbit effects within the proton and during hadronization
- ◆ 3D Transverse Spin and Momentum Structure



Kinematic Phase Space



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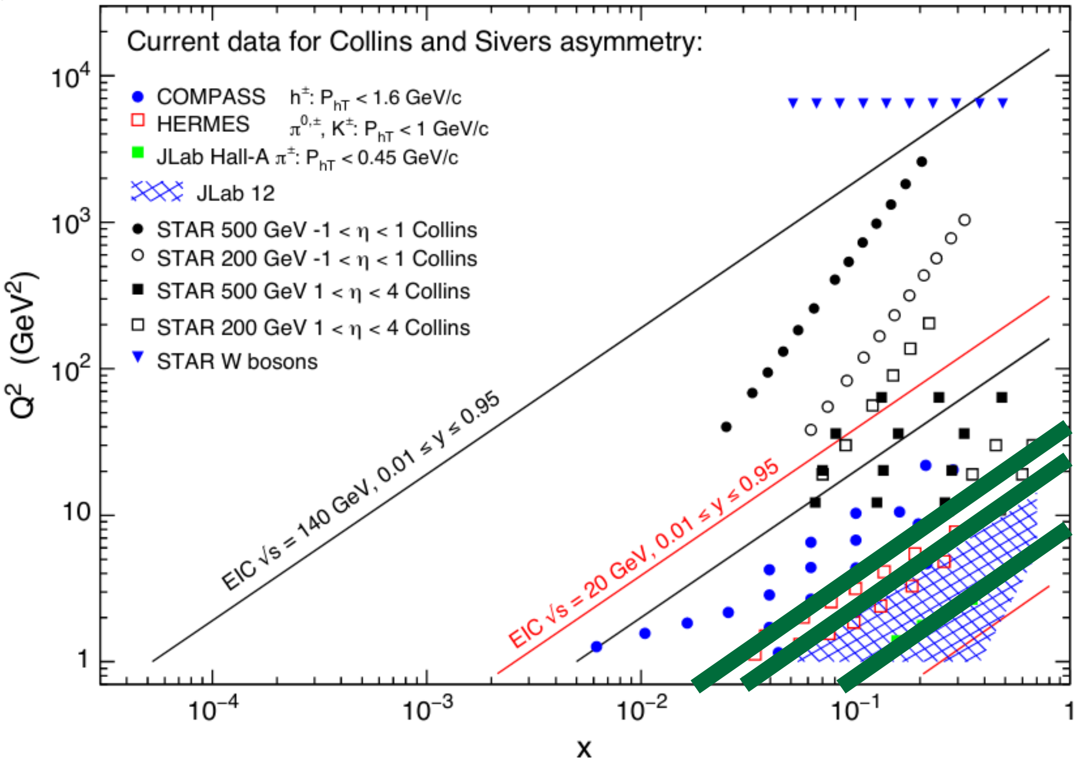

y=0.05

y=0.03

y=0.01

EIC y_{min}

5 x 41 GeV
√s = 28.65 GeV

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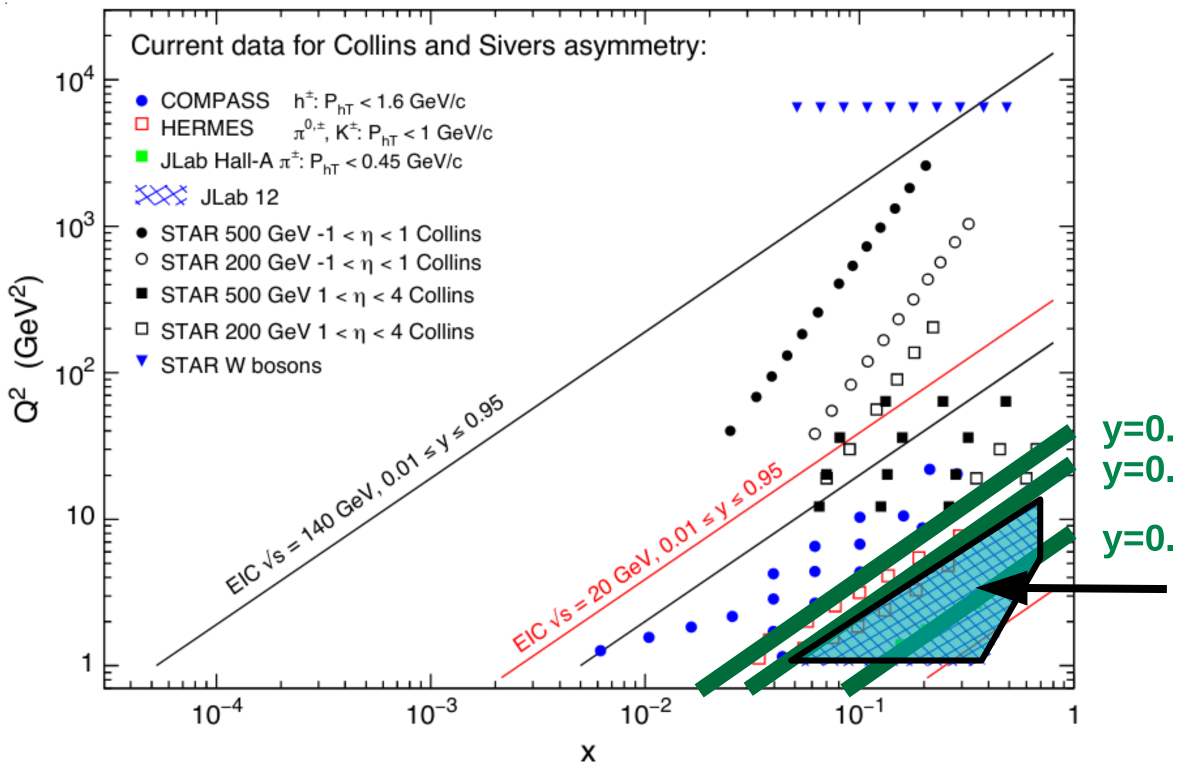

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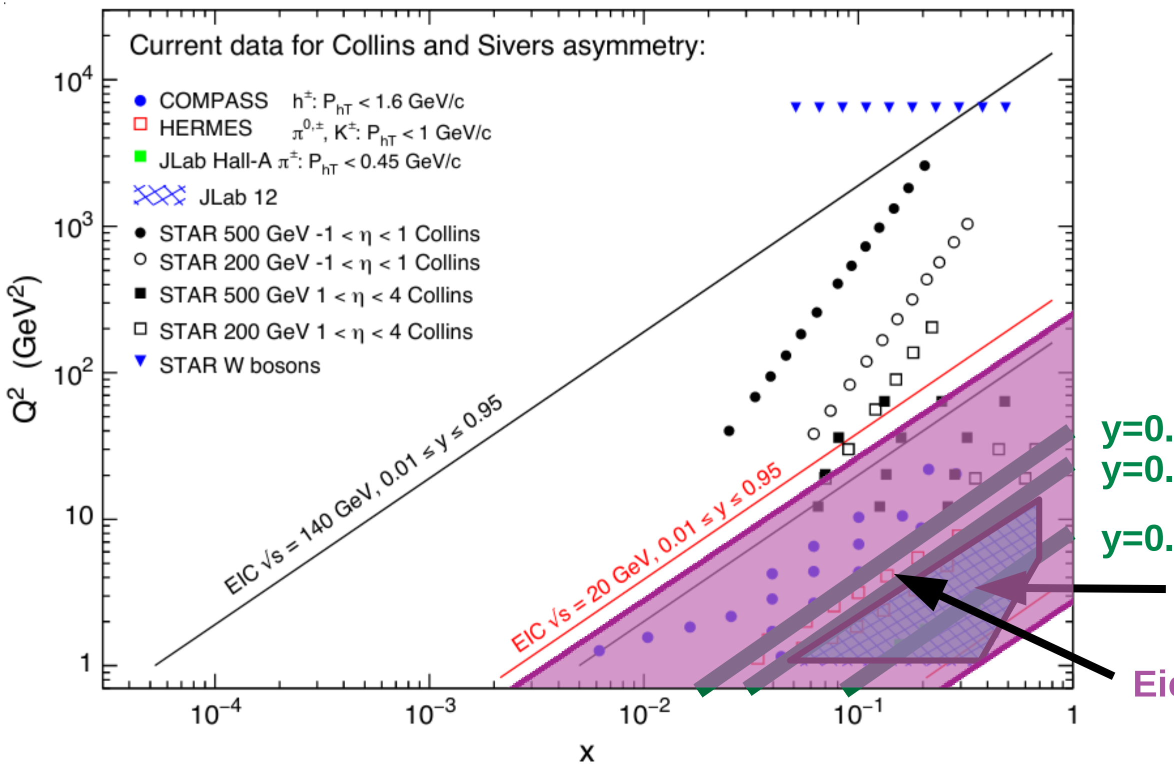

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EicC (3.5x20 GeV)

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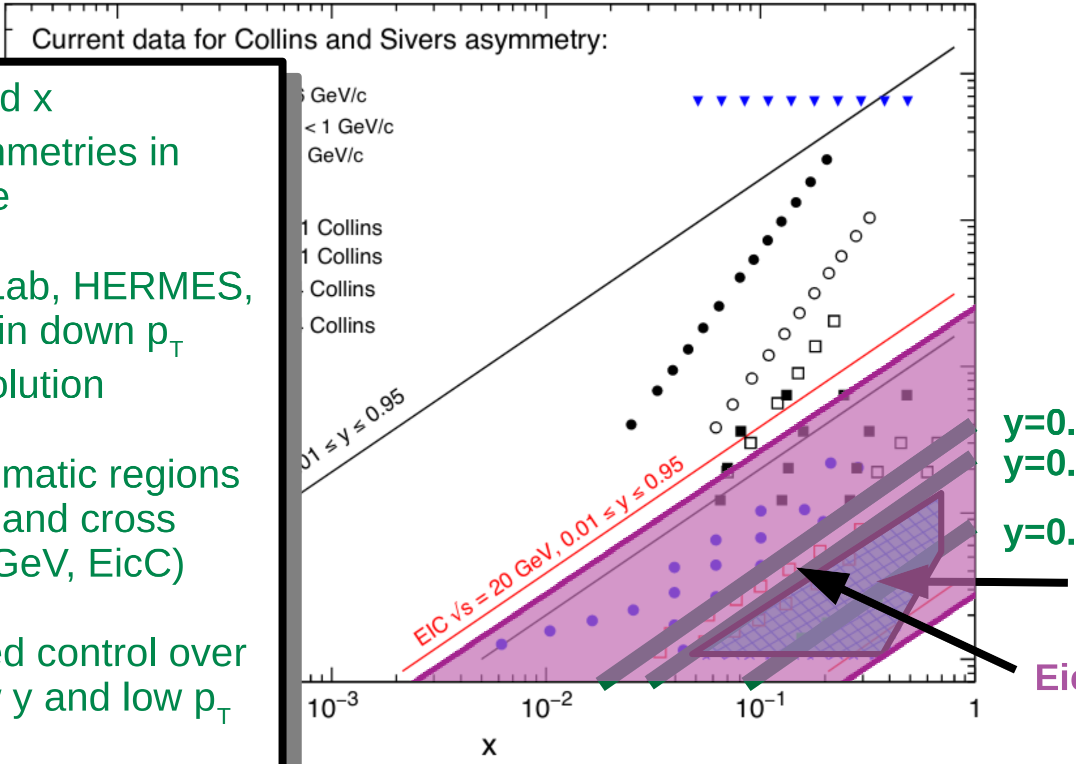
Kinematic Phase Space

- EIC: study p_T, Q^2, and x dependence of asymmetries in wide kinematic range
- Comparisons with JLab, HERMES, and COMPASS, to pin down p_T dependence and evolution
- Need overlap of kinematic regions for evolution studies and cross checks (JLab @ 22 GeV, EicC)
- For EIC overlap, need control over reconstruction at low y and low p_T



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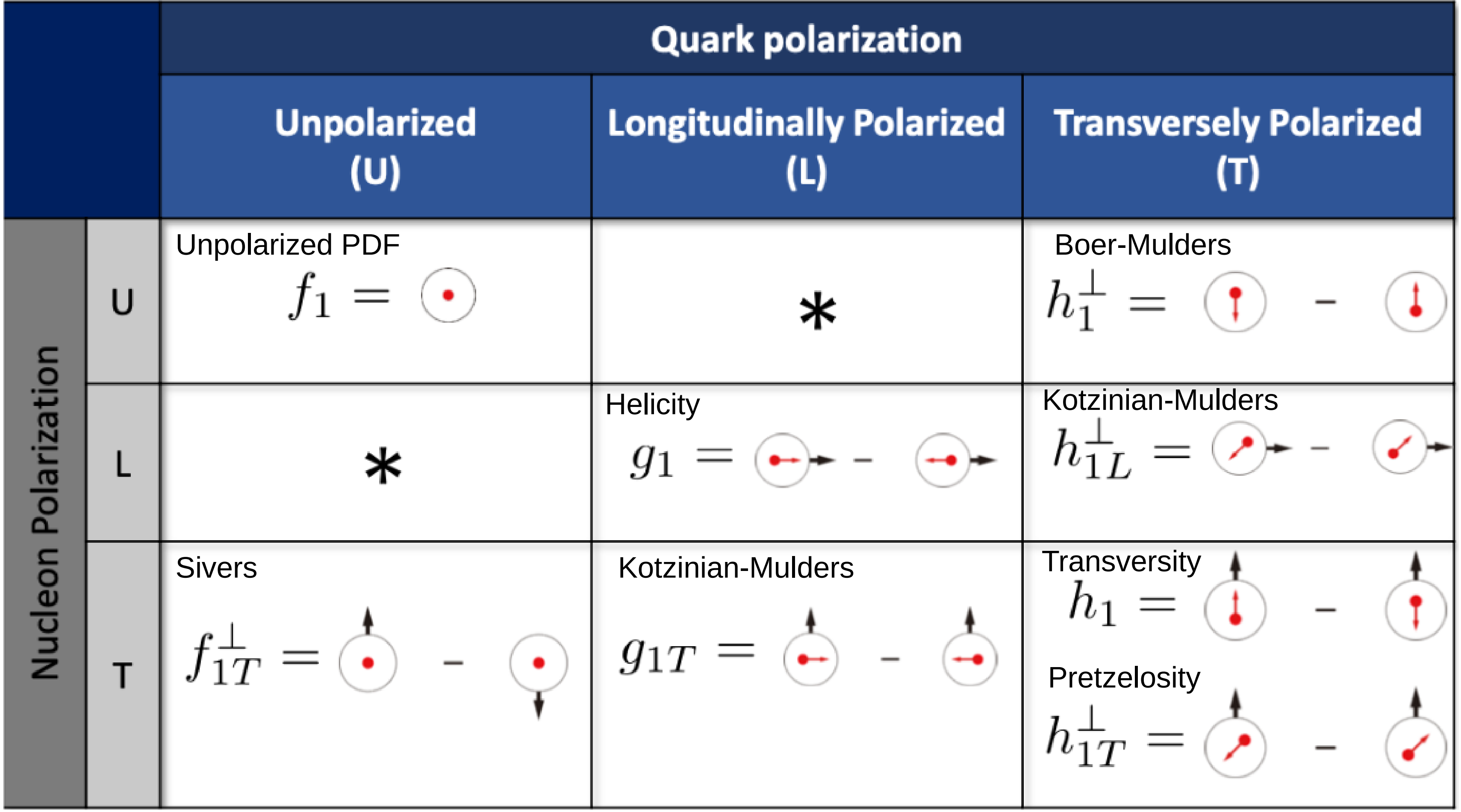
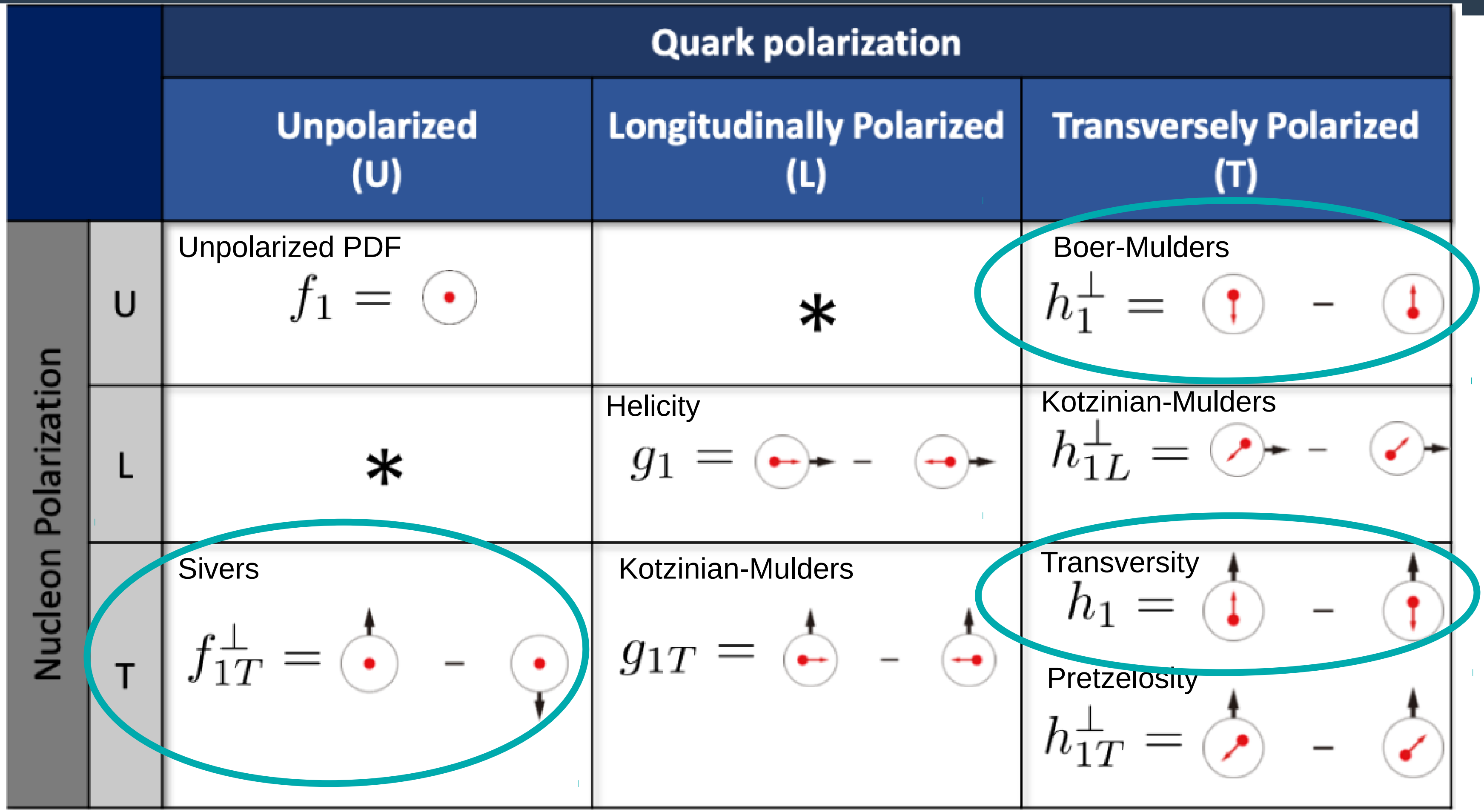
Transverse Momentum Dependent (TMD) PDFs



		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	Unpolarized PDF $f_1 =$	*	Boer-Mulders $h_1^\perp = \quad - \quad$
	L	*	Helicity $g_1 = \quad - \quad$	Kotzinian-Mulders $h_{1L}^\perp = \quad - \quad$
	T	Sivers $f_{1T}^\perp = \quad - \quad$	Kotzinian-Mulders $g_{1T} = \quad - \quad$	Transversity $h_1 = \quad - \quad$ Pretzelosity $h_{1T}^\perp = \quad - \quad$

Figure from S.J. Brodsky, et al., Int.J.Mod.Phys.E 29 (2020) 08, 2030006

Transverse Momentum Dependent (TMD) PDFs



Nucleon Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
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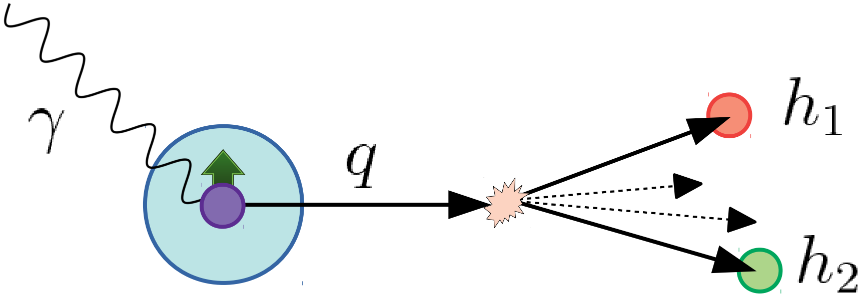
Figure from S.J. Brodsky, et al., Int.J.Mod.Phys.E 29 (2020) 08, 2030006

Unpolarized Nucleons

Unpolarized SIDIS:

- **Cahn Effect**: quark transverse momentum leads to azimuthal modulations of SIDIS cross section
- **Boer-Mulders Effect:** Non-collinear quarks in an unpolarized proton can have transverse polarization, also contributing azimuthal modulations

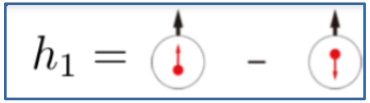


- **Boer-Mulders and Cahn effects are comparable in single hadron production**
  - HERMES and COMPASS data, e.g. Phys.Rev.D 81 (2010) 114026
- **Dihadrons can help decouple BM from Cahn**
  - Extra degree of freedom in dihadrons
    - Cahn effect impacts dihadron total momentum direction P_h
    - Utilize azimuthal angle about P_h, in addition to the azimuth about the virtual photon
- **Advantages from a broader and higher Q^2 range at ePIC**
  - Broader Q^2 range probes evolution effects
  - Higher Q^2 suppresses Cahn effect in single-hadron asymmetries (Cahn is twist-4)
  - Lower Q^2 for overlap with other SIDIS experiments

Transversely Polarized Nucleons

Transversely polarized SIDIS:

- Access to several additional **TMDs**:
  - **Transversity** → Tensor Charge

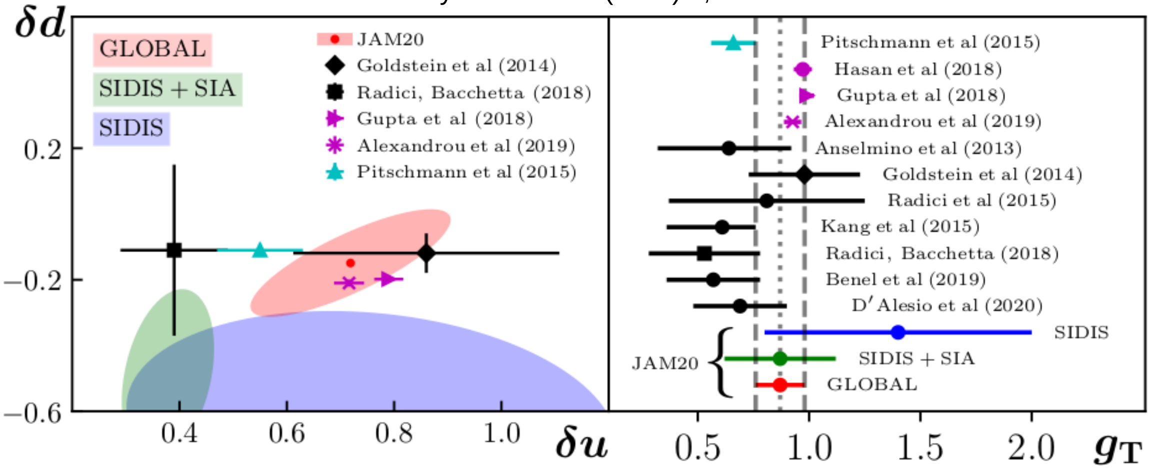


- Quark EDM contribution to nucleon EDM
- Comparisons with lattice QCD calculation

$$\delta q = \int_{-1}^{1} dx h(x) = \int_{0}^{1} dx \left[h(x) - \bar{h}(x) \right]$$

$$g_T = \delta u - \delta d$$

Phys.Rev.D 102 (2020) 5, 054002



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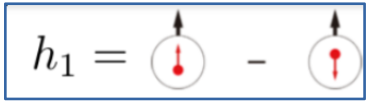

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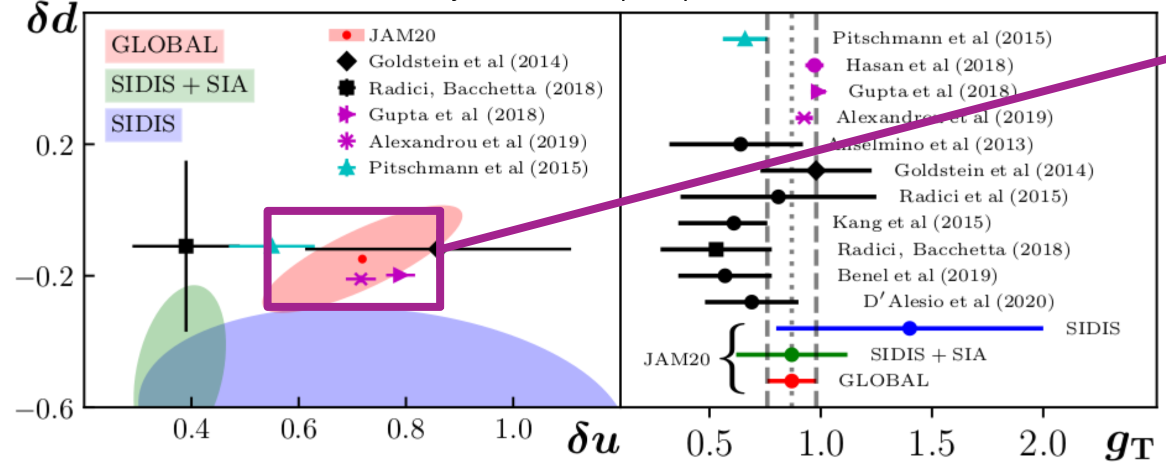
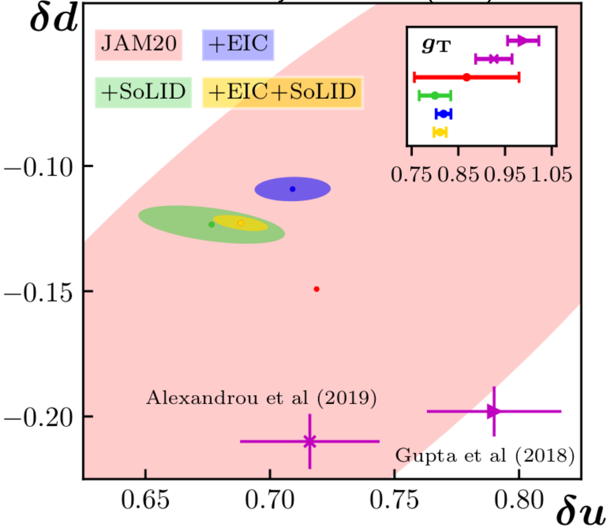
ePIC Impact $ep + e^3\mathrm{He}$

Phys.Rev.D 102 (2020) 5, 054002

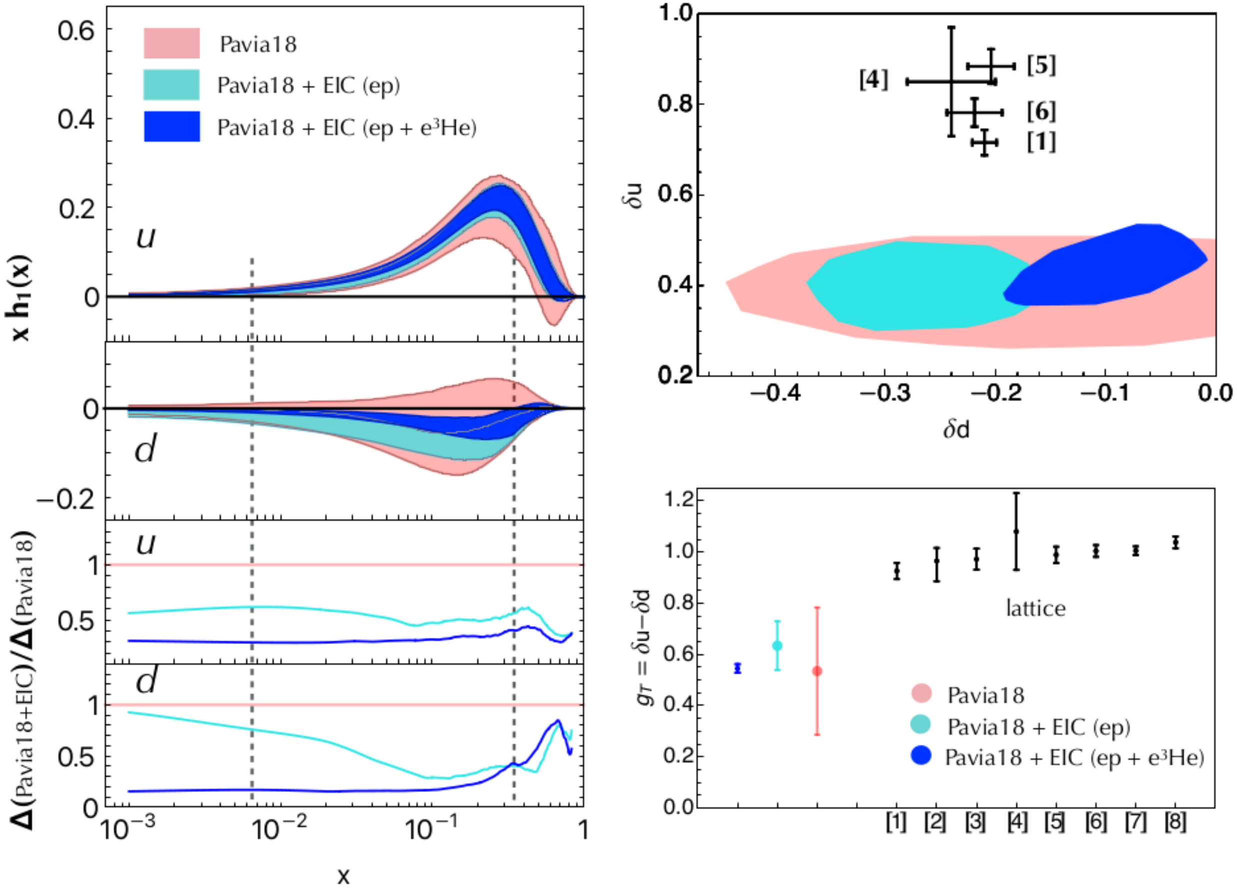


Phys.Lett.B 816 (2021) 136255



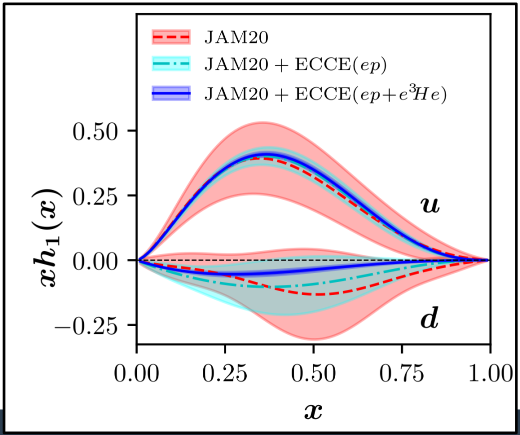
Dihadron Impact on Transversity

- Complementary to single-hadron SIDIS and hadrons in jets
- Complementarity reduces systematic uncertainties overall
- Additional advantages from dihadrons:
  - Expect little contribution from twist-3 FFs
  - Acceptance effects tend to “average out” between the two hadrons, which is especially good for F_{UU} measurements (Boer-Mulders function)



EIC Yellow Report

cf. single-hadron impact →



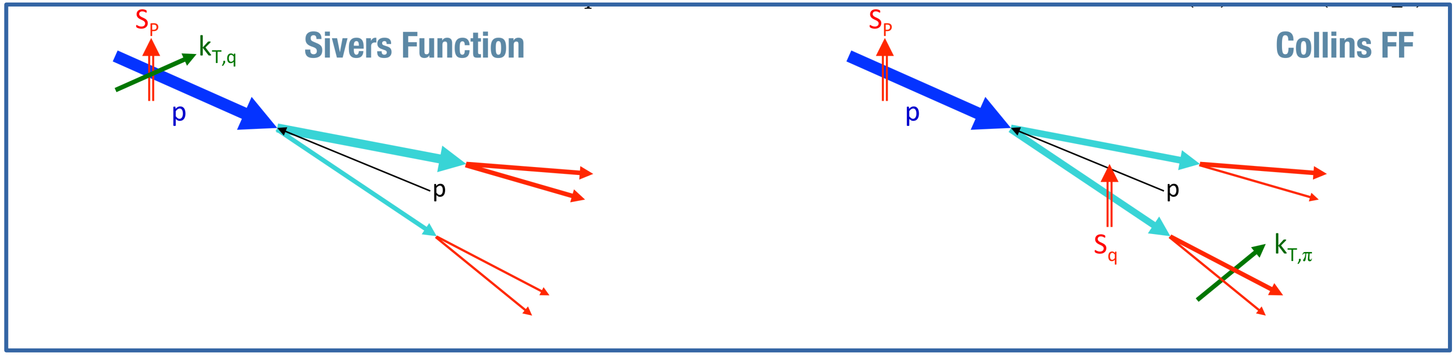
ECCE Proposal

Transversely Polarized Nucleons

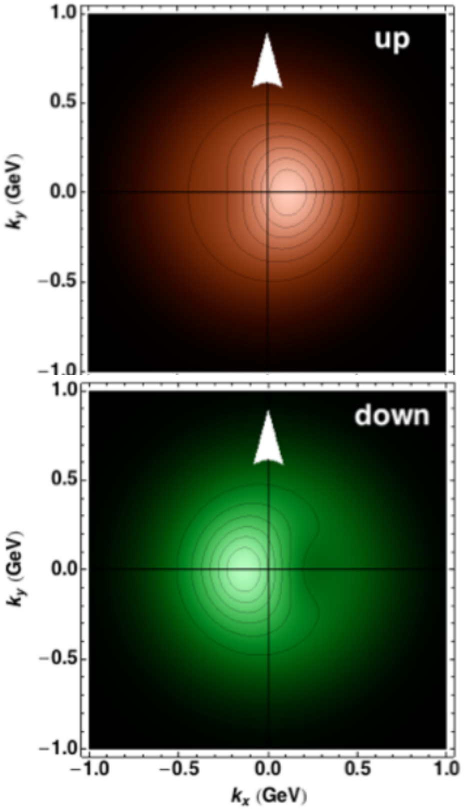
Transversely polarized SIDIS:

- Access to several additional **TMDs**:
  - **Sivers Function** $A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$
  - **Collins Fragmentation** $A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1 \otimes H_1^{\perp}$

A. Bacchetta, et al., JHEP 02 (2007) 093



EIC Impact on the Sivers Function

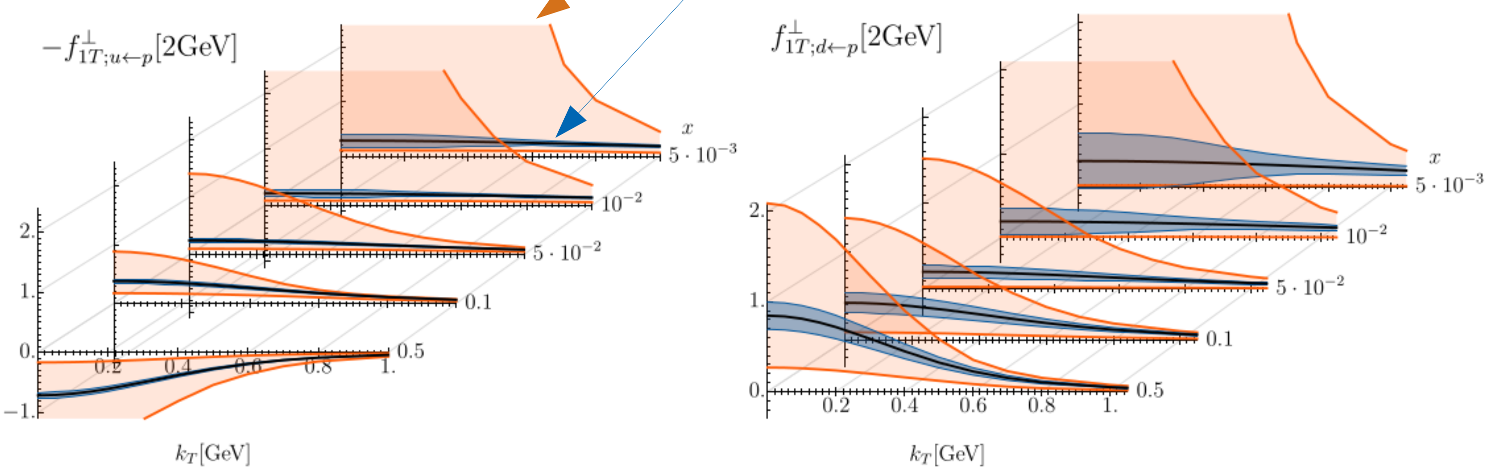


A. Bacchetta and M. Radici, Phys.Rev.Lett. 107 (2011) 212001

M. Radici, AIP Conference Proceedings 1735, 020003 (2016)

Distorted Momentum distribution from Sivers, for transversely polarized (y) proton

u and *d* quark Sivers impact



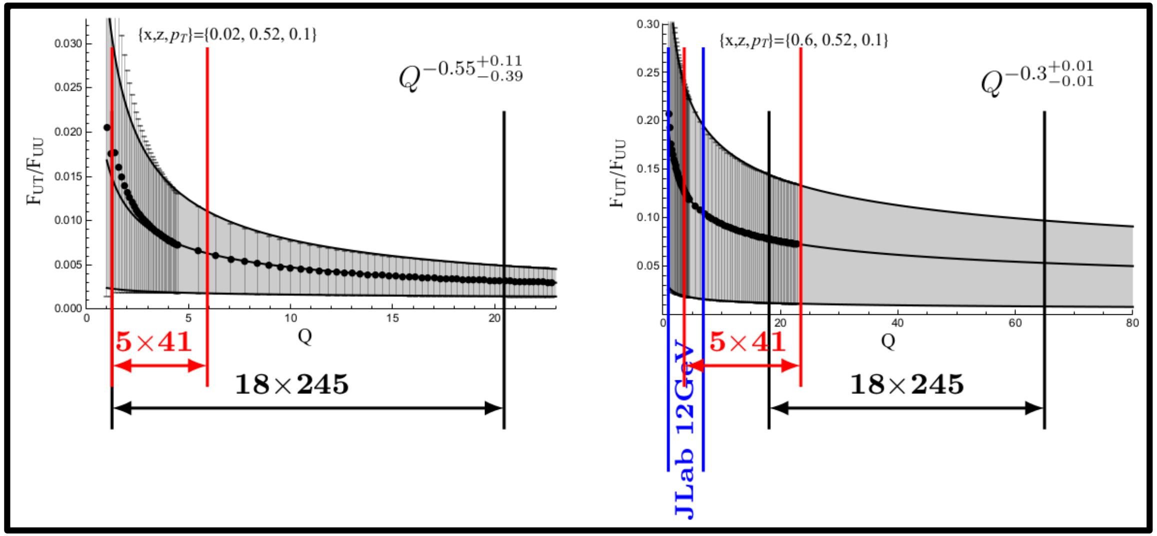
Present Uncertainty

Expected uncertainty with ePIC (ECCE) pseudo-data

R. Seidl, et al., Nucl.Instrum.Meth.A 1049 (2023) 168017, Nucl.Instrum.Meth.A 1049 (2023) 168017

TMD Evolution

- **Expect logarithmic decrease, but asymmetries don't "disappear"**
- **Larger asymmetries expected at higher x**
- **Wide (x,Q2) range at ePIC → probe evolution**
- **Study sea and gluons at lower x**



A. Vladimirov, IR2@EIC workshop, Mar 2021

Collinear Twist-3 PDFs

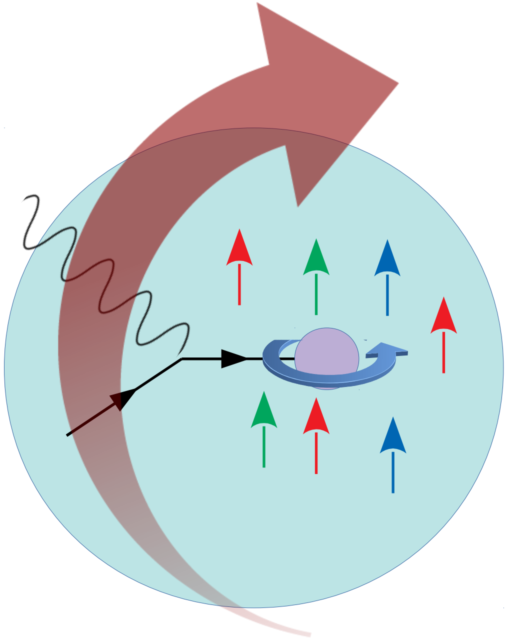
Semi-classical interpretation via x-moments

$h_L(x)$

- Average longitudinal gradient of the transverse force on a **transversely** polarized struck quark in a **longitudinally** polarized nucleon

$$\mathcal{L}^q_{\mathrm{JM}} - L^q_{\mathrm{Ji}} = \Delta L^q_{\mathrm{FSI}}$$

Expressible in terms of the change in quark OAM as it leaves the target



- M. Abdallah, M. Burkardt, Phys.Rev.D 94 (2016) 9, 094040
- M. Burkardt, Phys.Rev.D 66 (2002) 114005
- P.J. Mulders, R.D. Tangerman, Nucl.Phys.B 461 (1996) 197-237

$e(x)$

M. Burkardt, Phys.Rev.D 88 (2013) 114502

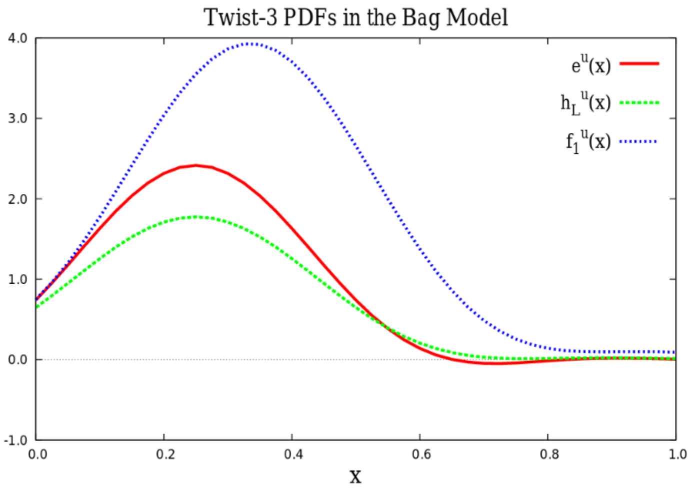
$g_T(x)$

M. Abdallah, M. Burkardt, Phys.Rev.D 94 (2016) 9, 094040

EIC Impact on Collinear Twist-3 PDFs: $h_L(x)$

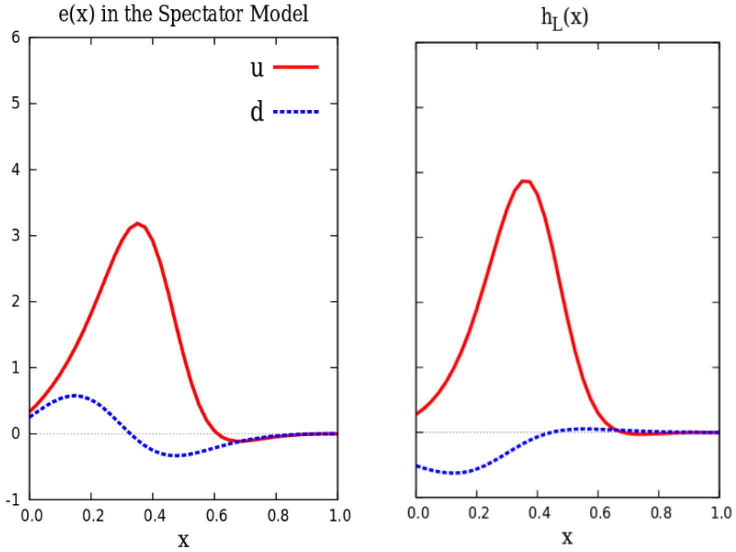
- Accessible in target spin asymmetry A_{UL}
  - Depolarization <u>allows</u> for broad coverage
  - cf. Ongoing experiment at CLAS12 → evolution!

Bag Model



Jaffe and Ji, Nucl.Phys. B375 (1992) 527-560

Spectator Model



Jakob, Mulders, and Rodrigues, Nucl.Phys. A626 (1997) 937-965

Figures from JLab Proposal E12-06-112B/E12-09-008B

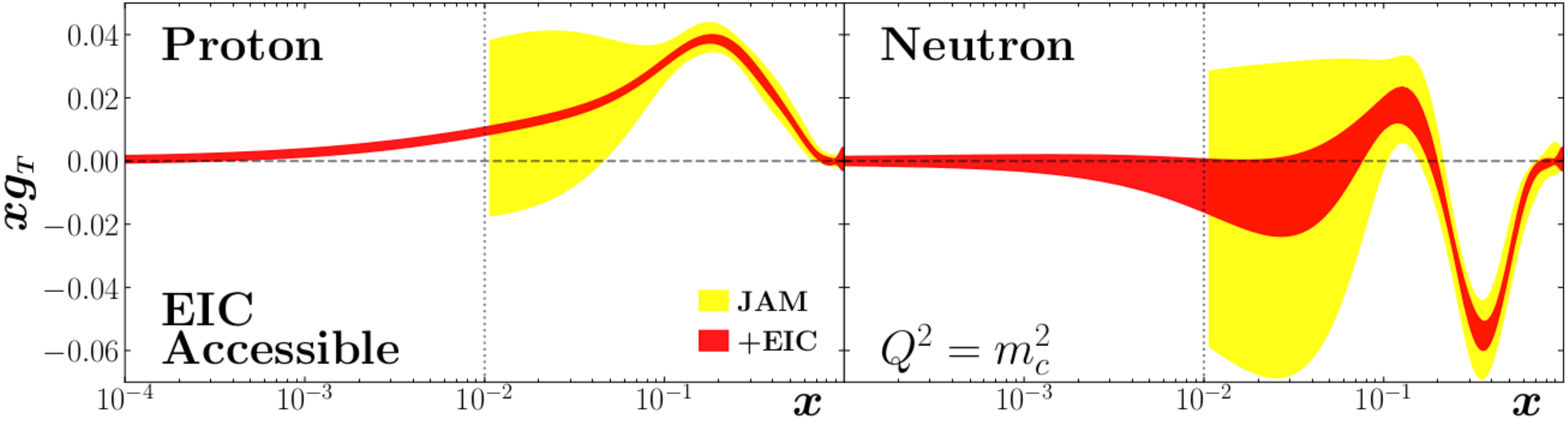
See also:

– Chiral Quark Soliton Model	Cebulla et al., Acta Phys.Polon. B39 (2008) 609-640
– Light Front Constituent Quark Model	Lorcé , Pasquini, Schweitzer, JHEP 1501 (2015) 103

EIC Impact on Collinear Twist-3 PDFs: $g_T(x)$

- x-Moment → semi-classical interpretation: Average transverse force on an **unpolarized** struck quark in a **transversely** polarized nucleon

M. Abdallah, M. Burkardt, Phys.Rev.D 94 (2016) 9, 094040



EIC Yellow Report

- Accessible in inclusive measurements: $\vec{e}p^{\uparrow} \to e'X$
- $g_T(x)$ is also accessible in double spin asymmetry A_{LT} in semi-inclusive dihadrons
  - Caveat: depolarization for A_{LT} favors high y…

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- **Fragmentation Functions**
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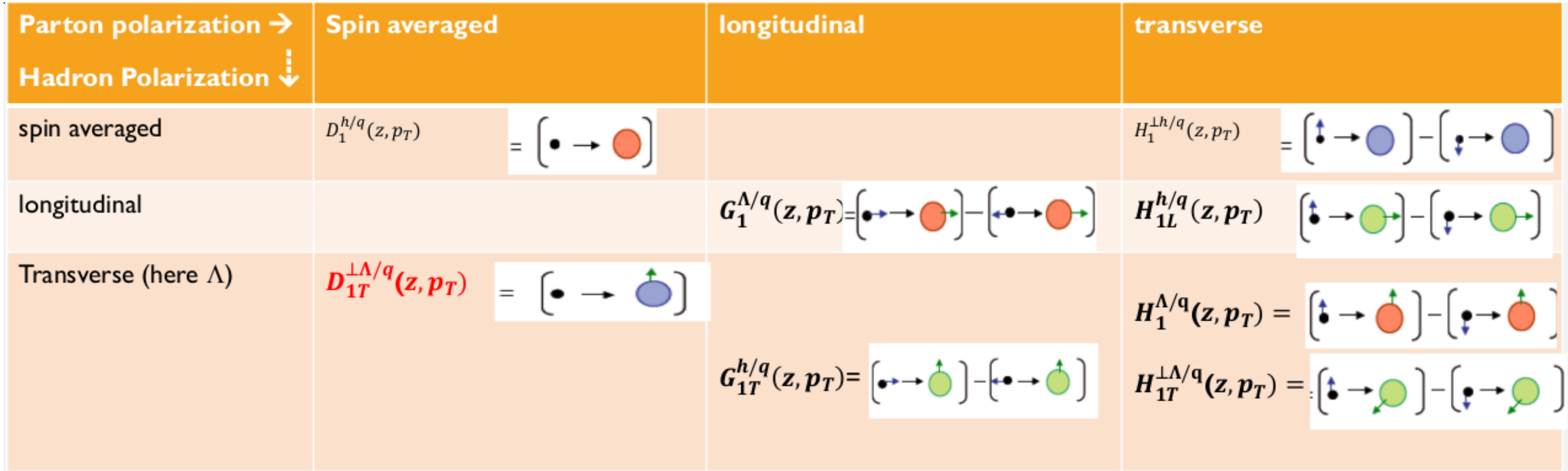
Fragmentation Functions (leading twist)

Single-hadron Fragmentation Functions



Parton polarization → Hadron Polarization ↓	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z,p_T)$ =		$H_1^{\perp h/q}(z,p_T)$ =
longitudinal		$G_1^{\Lambda/q}(z,p_T)$=	$H_{1L}^{h/q}(z,p_T)$
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z,p_T)$ =	$G_{1T}^{h/q}(z,p_T)$=	$H_1^{\Lambda/q}(z,p_T) =$ $H_{1T}^{\perp\Lambda/q}(z,p_T) =$

Table from A. Vossen, INT-18-3

Fragmentation Functions (leading twist)

Single-hadron Fragmentation Functions

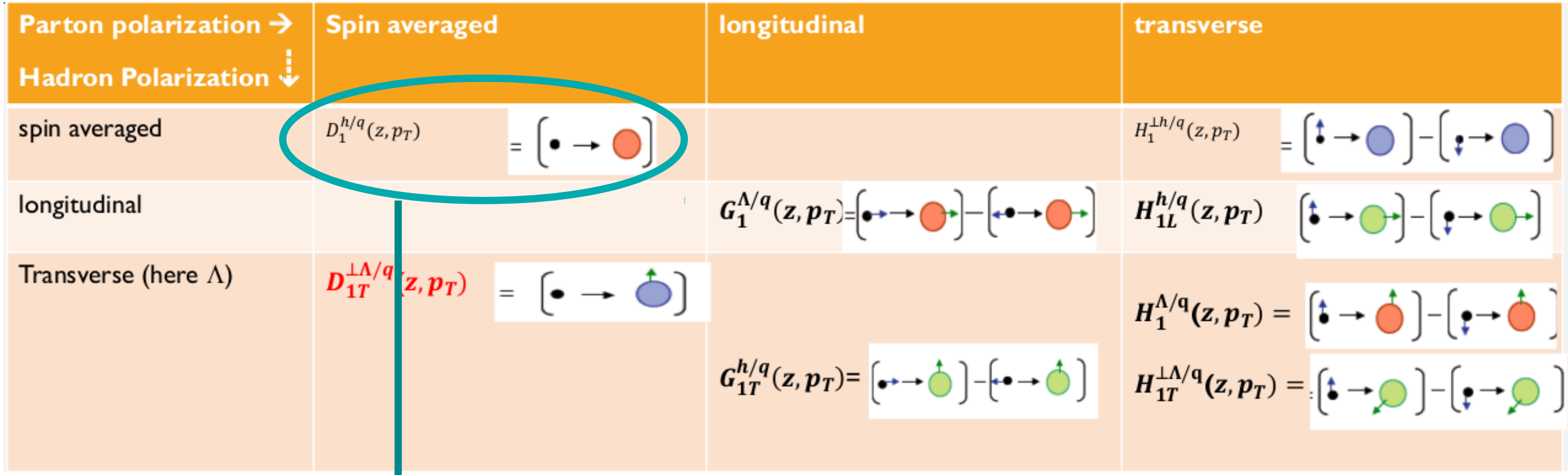


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Table from A. Vossen, INT-18-3

“well known” unpolarized FFs

Fragmentation Functions (leading twist)

Single-hadron Fragmentation Functions

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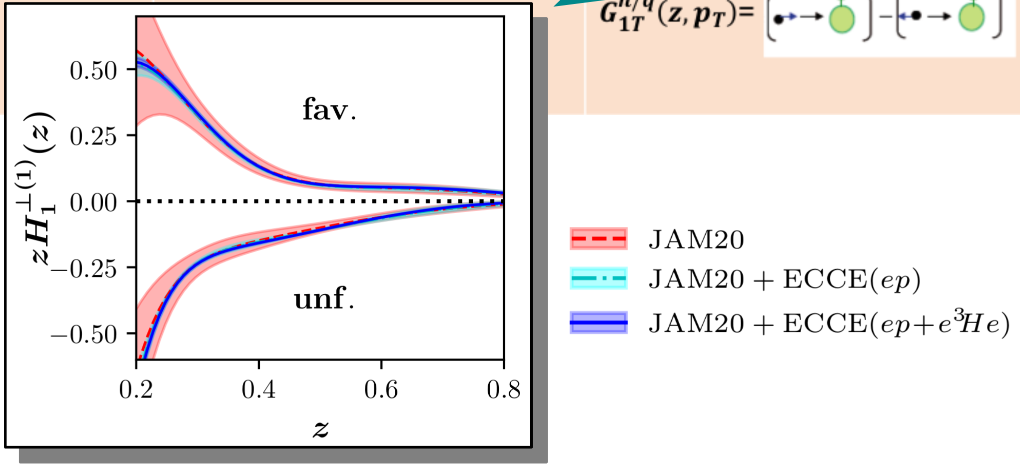
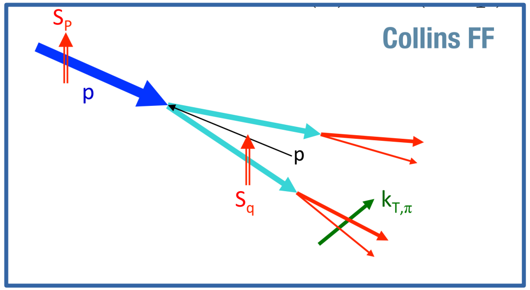
Table from A. Vossen, INT-18-3

Impact on Collins FF →

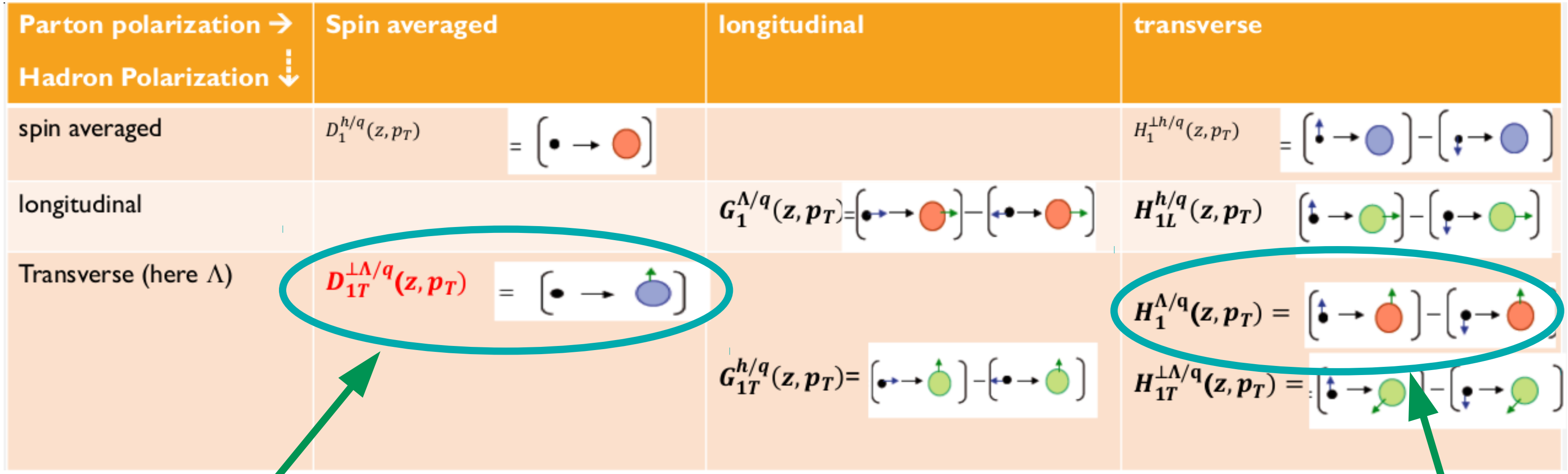




ECCE consortium. (2022). EIC Comprehensive Chromodynamics Experiment Collaboration Detector Proposal.

Fragmentation Functions (leading twist)

Single-hadron Fragmentation Functions



Parton polarization → Hadron Polarization ↓	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z,p_T)$ =		$H_1^{\perp h/q}(z,p_T)$ =
longitudinal		$G_1^{\Lambda/q}(z,p_T)$=	$H_{1L}^{h/q}(z,p_T)$
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z,p_T)$ =	$G_{1T}^{h/q}(z,p_T)$=	$H_1^{\Lambda/q}(z,p_T)$ = $H_{1T}^{\perp\Lambda/q}(z,p_T)$ =

Table from A. Vossen, INT-18-3

Access via spontaneous polarization

$$P_\Lambda = \frac{F_{UT}^{\sin(\phi_S-\phi_\Lambda)}}{F_{UU}}$$

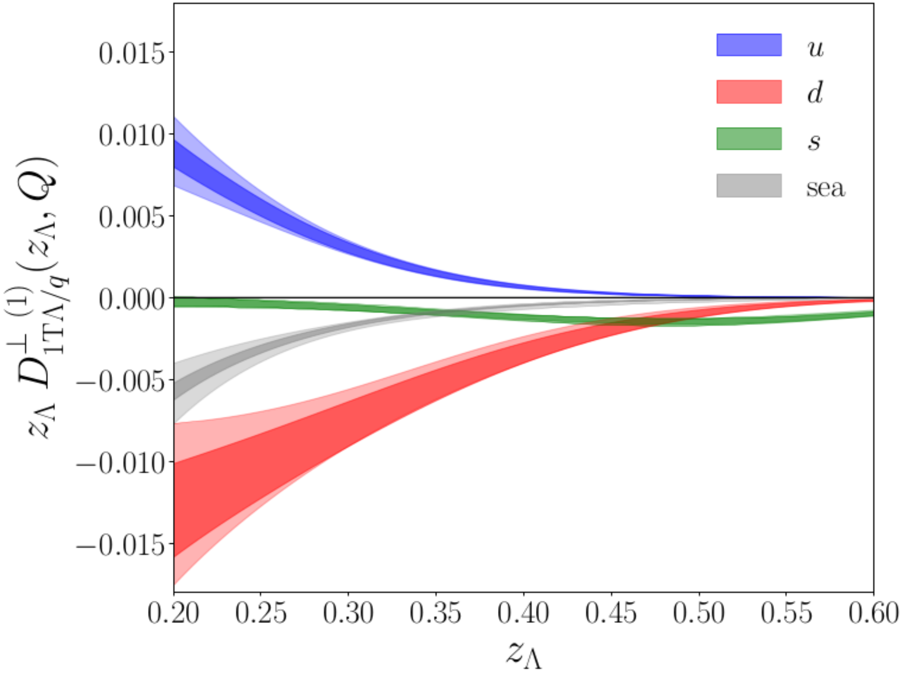
Transversely polarized Λs
“Self-analyzing” decay → pπ
→ Final state polarization!

Access via spin transfer

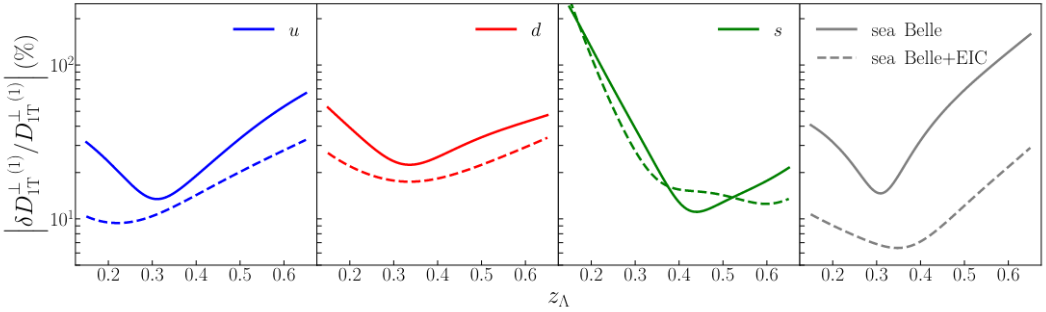
$$S_\Lambda = D(y)\frac{F_{TT}^{\cos(\varphi_S-\phi_S)}}{F_{UU}}$$

Impact on TMD Polarizing Fragmentation Function

Extracted TMD PFF moment



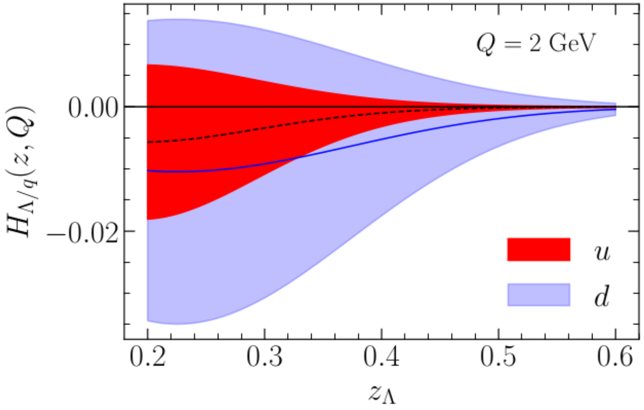
Theoretical Uncertainty Impact



Figures from
Phys.Rev.D 105 (2022) 9, 094033

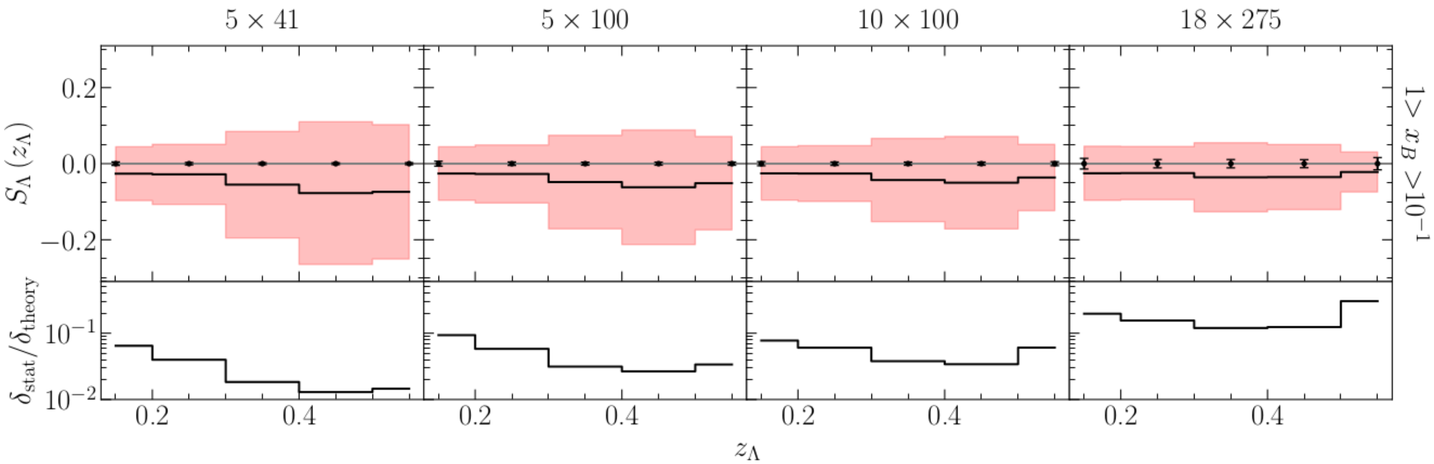
- Larger bands: from Belle [Phys.Rev.D 102 (2020) 9, 096007]
- Smaller bands: Belle + EIC pseudodata

Impact on Transversity TMD FF & Spin Transfer



- Transversity FF extracted from COMPASS [Phys.Lett.B 824 (2022) 136834]

- EIC Impact on Spin Transfer
  - Red bands: theoretical uncertainty
  - Black error bars: projected statistical uncertainty (40 fb^{-1})

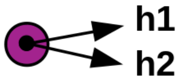


Figures from
Phys.Rev.D 105 (2022) 9, 094033

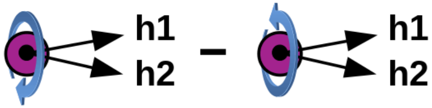
Fragmentation Functions (leading twist)

Dihadron Fragmentation Functions

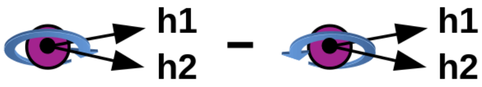
$D_1 =$

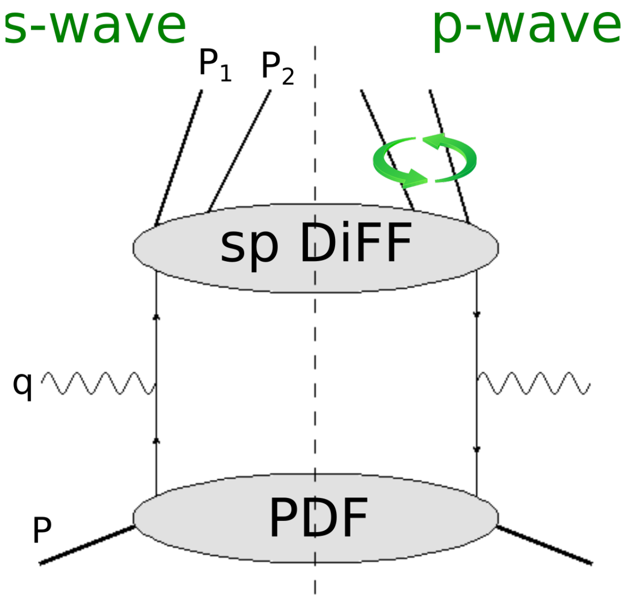


$G_1^\perp =$



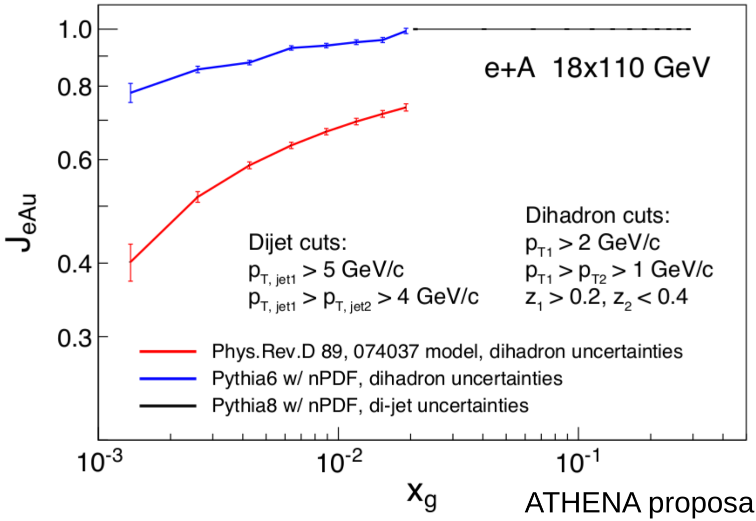
$H_1^\perp,\ H_1^\sphericalangle =$



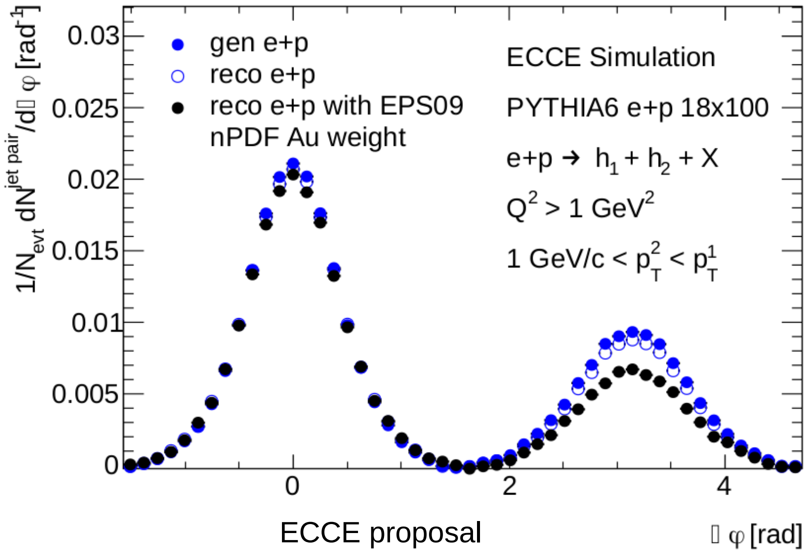


Dihadron polarization dependence → partial waves…

Dihadrons for Gluon Saturation



ATHENA proposal



ECCE proposal

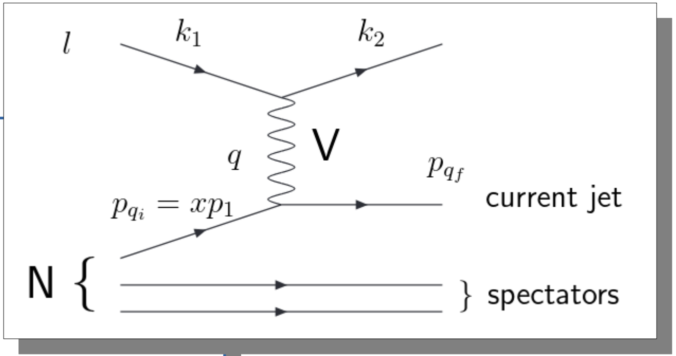
- Away-side peak in Δϕ de-correlates when non-linear QCD effects set in
- Sensitive to gluon TMDs
- Measure suppression J_{eAu}, the relative e+Au to e+p back-to-back dihadron yields
  - Scaled by $A^{1/3}$
  - J_{eAu}~1 if no collective nuclear effects

Outline

- SIDIS, Observables, Kinematic Reach
- Parton Distribution Functions
- Fragmentation Functions
- **Kinematic Reconstruction**

Kinematics Reconstruction

- **Study SIDIS in a *particle collider* context**
- **Need to develop tools for accurate reconstruction of event kinematics**

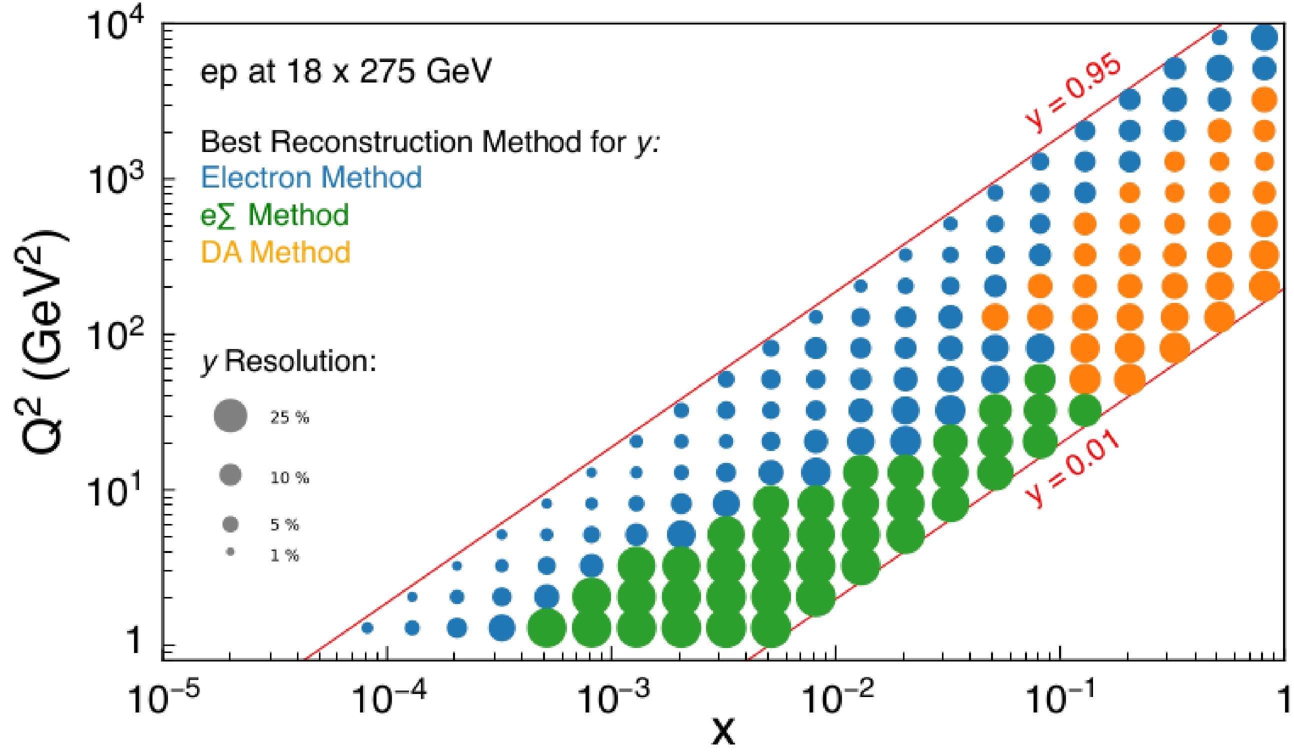


i)	*Leptonic variables*	$q \equiv q_l = k_2 - k_1, \quad y_l = p_1.(k_1 - k_2)/p_1.k_1$
ii)	*Hadronic variables* [81]	$q \equiv q_h = p_2 - p_1, \quad y_l = p_1.(p_2 - p_1)/p_1.k_1$
iii)	*Jacquet-Blondel variables* [82]	$Q^2_{JB} = (\vec{p}_{2,\perp})^2/(1 - y_{JB}), \quad y_{JB} = \Sigma/(2E(k_1))$ $\Sigma = \sum_h (E_h - p_{h,z})$
iv)	*Mixed variables* [81]	$q = q_l, y_m = y_{JB}$
v)	*Double angle method* [83]	$Q^2_{DA} = \frac{4E(k_2)^2 \cos^2(\theta(k_2)/2)}{\sin^2(\theta(k_2)/2) + \sin(\theta(k_2)/2)\cos(\theta(k_2)/2)\tan(\theta(p_2)/2)},$ $y_{DA} = 1 - \frac{\sin(\theta(k_2)/2)}{\sin(\theta(k_2)/2) + \cos(\theta(k_2)/2)\tan(\theta(p_2)/2)},$
vi)	*θy method* [84]	$Q^2_{\theta y} = 4E(k_2)^2(1 - y_{JB})\frac{1 + \cos(\theta(k_2))}{1 - \cos(\theta(k_2))}, \quad y_{\theta y} = y_{JB}$
vii)	*Σ method* [85]	$Q^2_{\Sigma} = \frac{(\vec{k}_{2,\perp})^2}{1 - y_{\Sigma}}, \quad y_{\Sigma} = \frac{\Sigma}{\Sigma + E(k_2)[1 - \cos(\theta(k_2))]}$
viii)	*$e\Sigma$ method* [85]	$Q^2_{e\Sigma} = Q^2_l, \quad y_{e\Sigma} = \frac{Q^2_l}{sx_{\Sigma}}$

Prog.Part.Nucl.Phys. 69 (2013) 28-84, 1208.6087 [hep-ph]

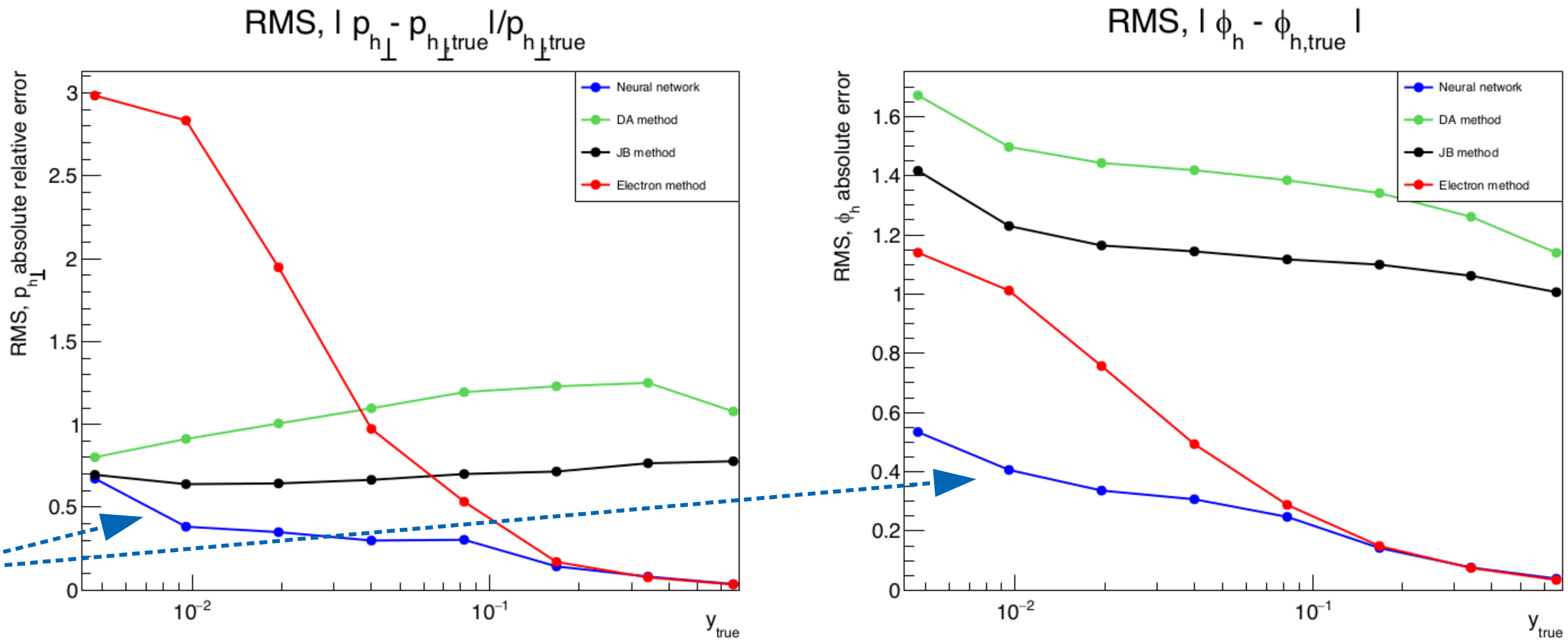
Difficulties at low y

ATHENA, best method for y-reconstruction



ATHENA Detector Proposal, JINST 17 (2022) 10, P10019

Neural Network Approaches



Particle Flow Network

AI for kinematics reconstruction shows promising results!

C. Pecar, 2nd Workshop on AI for the EIC (Oct. 2022)

See also M. Diefenthaler, et al., Eur.Phys.J.C 82 (2022) 11, 1064

Summary

- **SIDIS Cross Sections and Asymmetries probe a wide range of functions**
  - Transverse Momentum Dependent PDFs
    - Sivers, Collins, Boer-Mulders, Twist-3, …
  - Fragmentation Functions
    - Collins, Transverse spin-dependent (Λs), …
  - Dihadron Fragmentation functions
- **ePIC will have *significant* impact**
  - Uncertainty reduction
  - Evolution studies & complementarity with other experiments

Many analysis opportunities will be available, for both experiment and theory!

BACKUP

Transversely Polarized Nucleons

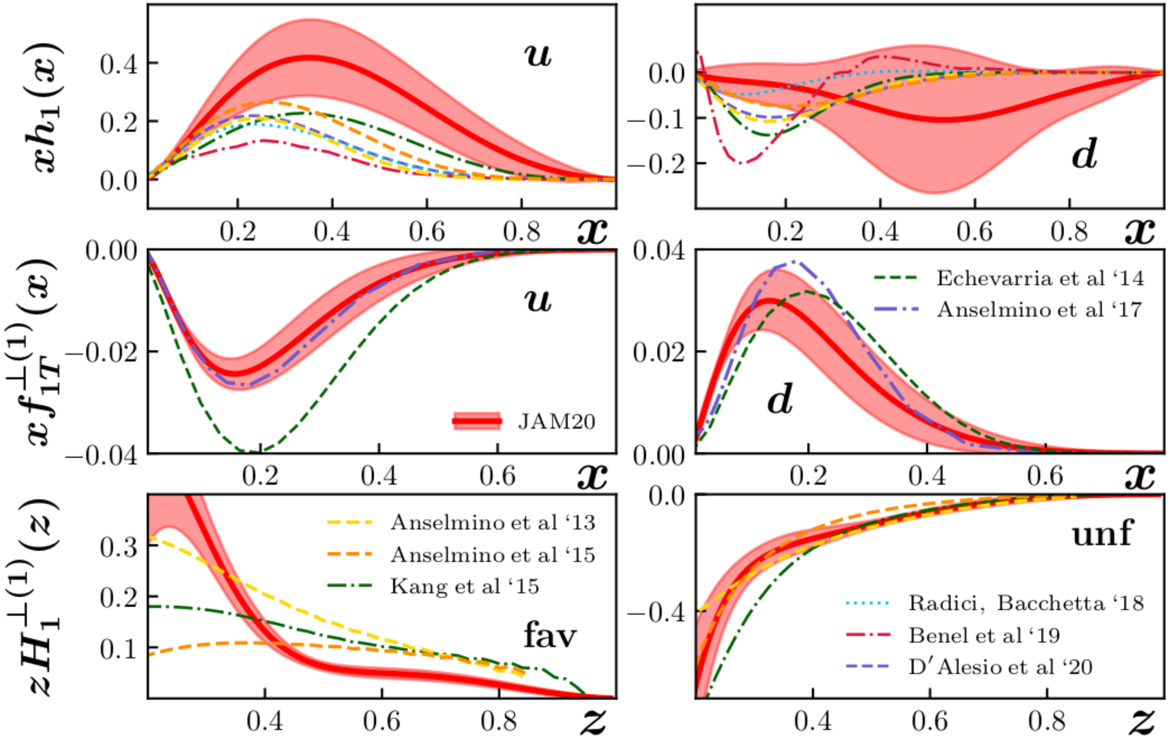
Transversely polarized SIDIS:

- Access to several additional **TMDs**:

Transversity

Sivers Function

Collins Fragmentation Function

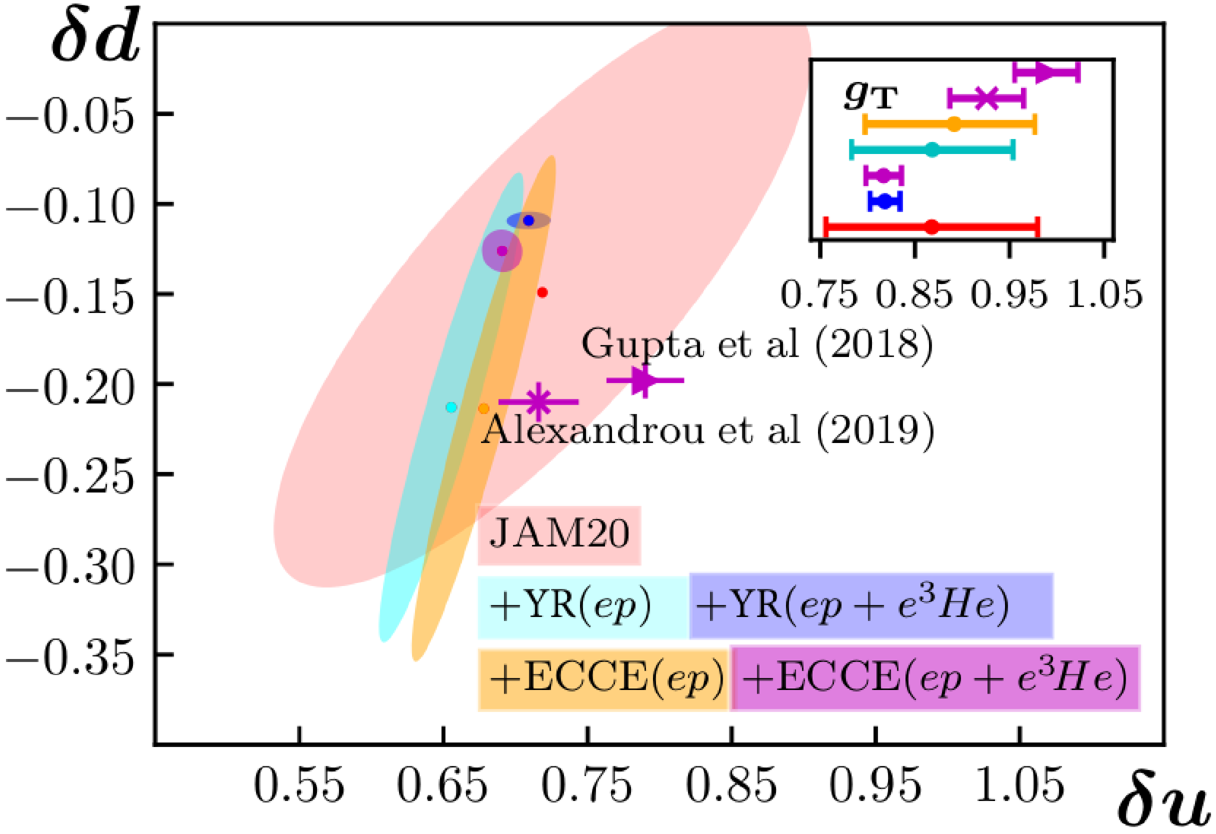


Phys.Rev.D 102 (2020) 5, 054002

Only valence quarks known, within 0.01<x<0.3

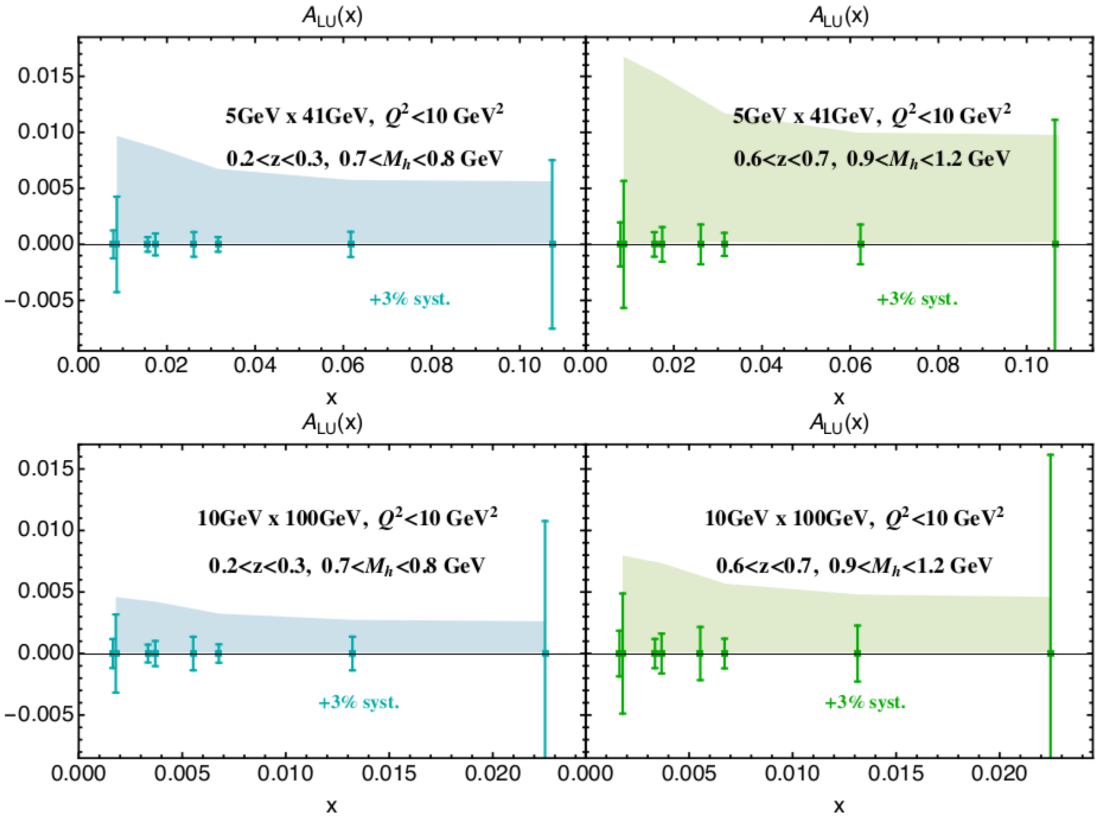
Currently no sensitivity to sea quarks and low x

ePIC Impact on Tensor Charge



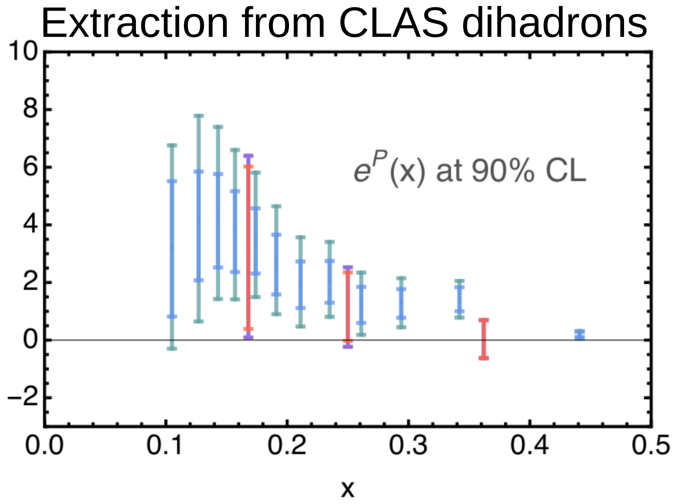
ECCE consortium. (2022). EIC Comprehensive Chromodynamics Experiment Collaboration Detector Proposal.

EIC Impact on Collinear Twist-3 PDFs: e(x)



EIC Yellow Report

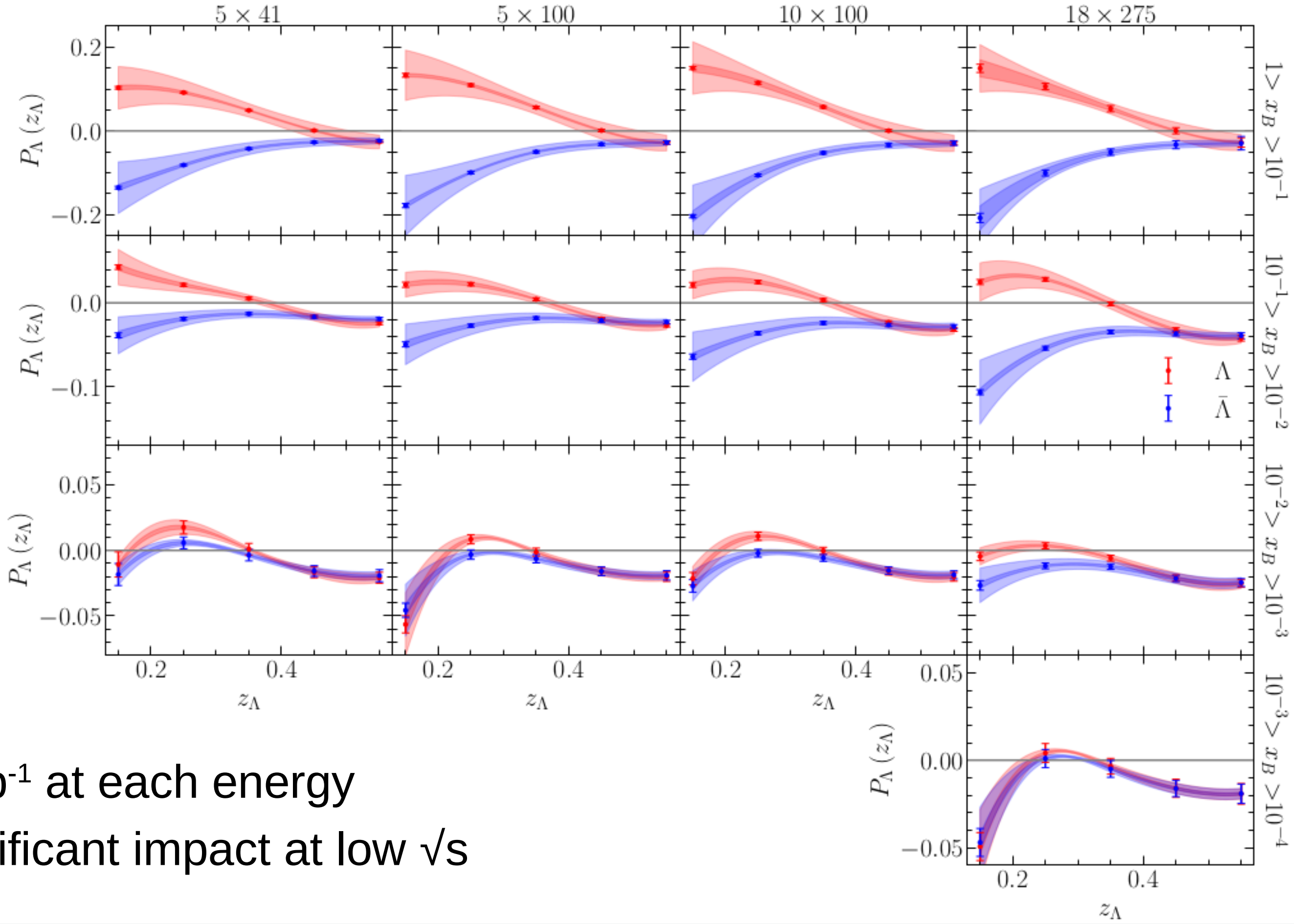
- e(x) is accessible in beam spin asymmetry A_{LU}
- Cleaner access in dihadrons, compared to single-hadron SIDIS (which involves additional unknowns)
- Caveat: depolarization for A_{LU} favors high y



Courtoy, Aurore, et al. e-Print: 2203.14975 [hep-ph]

Courtoy, Aurore – CPHI 2022

Impact on Spontaneous Polarization



- 40 fb^{-1} at each energy
- Significant impact at low √s

Dihadron Access to PDFs x DiFFs

Twist 2

Target Polarization

Beam Polarization

	U	**L**	**T**
U	$f_1 D_1$ $h_1^\perp H_1$	$h_{1L}^\perp H_1$ $g_{1L} G_1$	$f_{1T}^\perp D_1$ $g_{1T} G_1$ $h_1 H_1$ $h_{1T}^\perp H_1$
L	$f_1 G_1$	$g_{1L} D_1$	$g_{1T} D_1$ $f_{1T}^\perp G_1$

Twist 3

Target Polarization

Beam Polarization

	U	**L**	**T**
U	$h H_1 \quad f_1 \tilde{D}$ $f^\perp D_1 \quad h_1^\perp \tilde{H}$	$h_L H_1 \quad g_{1L} \tilde{G}$ $f_L^\perp D_1 \quad h_{1L}^\perp \tilde{H}$	$f_T D_1 \quad h_1 \tilde{H}$ $h_T H_1 \quad g_{1T} \tilde{G}$ $h_T^\perp H_1 \quad f_{1T}^\perp \tilde{D}$ $f_T^\perp D_1 \quad h_{1T}^\perp \tilde{H}$
L	$e H_1 \quad f_1 \tilde{G}$ $g^\perp D_1 \quad h_1^\perp \tilde{E}$	$e_L H_1 \quad g_{1L} \tilde{D}$ $g_L^\perp D_1 \quad h_{1L}^\perp \tilde{E}$	$g_T D_1 \quad h_1 \tilde{E}$ $e_T H_1 \quad g_{1T} \tilde{D}$ $e_T^\perp H_1 \quad f_{1T}^\perp \tilde{G}$ $g_T^\perp D_1 \quad h_{1T}^\perp \tilde{E}$

Dihadron Access to PDFs x DiFFs

Twist 2

Target Polarization

Beam Polarization

	U	L	T
U	**A** $f_1 D_1$ **B** $h_1^\perp H_1$	**B** $h_{1L}^\perp H_1$ **A** $g_{1L} G_1$	**A** $f_{1T}^\perp D_1$ **A** $g_{1T} G_1$ **B** $h_1 H_1$ **B** $h_{1T}^\perp H_1$
L	**C** $f_1 G_1$	**C** $g_{1L} D_1$	**C** $g_{1T} D_1$ $f_{1T}^\perp G_1$

Depolarization Factors

Twist 3

Target Polarization

Beam Polarization

	U	L	T
U	**V** $h H_1$ $f_1 \tilde{D}$ $f^\perp D_1$ $h_1^\perp \tilde{H}$	**V** $h_L H_1$ $g_{1L} \tilde{G}$ $f_L^\perp D_1$ $h_{1L}^\perp \tilde{H}$	**V** $f_T D_1$ $h_1 \tilde{H}$ $h_T H_1$ $g_{1T} \tilde{G}$ $h_T^\perp H_1$ $f_{1T}^\perp \tilde{D}$ $f_T^\perp D_1$ $h_{1T}^\perp \tilde{H}$
L	**W** $e H_1$ $f_1 \tilde{G}$ $g^\perp D_1$ $h_1^\perp \tilde{E}$	**W** $e_L H_1$ $g_{1L} \tilde{D}$ $g_L^\perp D_1$ $h_{1L}^\perp \tilde{E}$	**W** $g_T D_1$ $h_1 \tilde{E}$ $e_T H_1$ $g_{1T} \tilde{D}$ $e_T^\perp H_1$ $f_{1T}^\perp \tilde{G}$ $g_T^\perp D_1$ $h_{1T}^\perp \tilde{E}$

Depolarization Factors

- Depolarization factors depend on (x,y,Q^2)
- Asymmetry denominator:

$$\int d\sigma_{UU} \sim A$$

Depolarization Factors

	Twist 2	**Twist 3**
Unpolarized Beam	***A, B***	***V***
Longitudinal Beam	***C***	***W***

Asymmetry, for modulation $M(\theta, \phi_h, \phi_R, \phi_S)$

$D \in \{A, B, C, V, W\}$

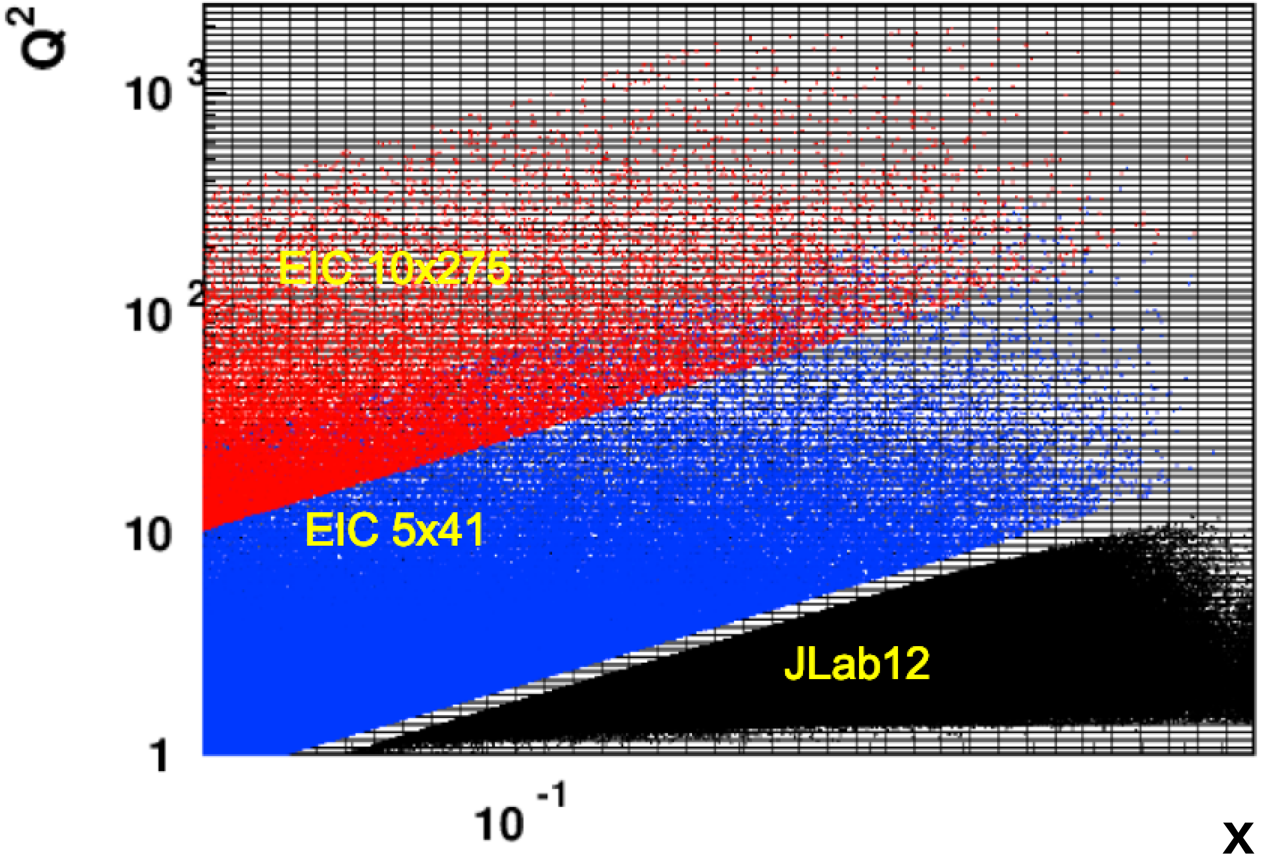
Structure Functions

$$A_{XY}^{M} \propto \frac{D_{XY}^{M}}{A} \cdot \frac{F_{XY}^{M}}{F_{UU,T}^{\text{const}} + \epsilon F_{UU,L}^{\text{const}}}$$

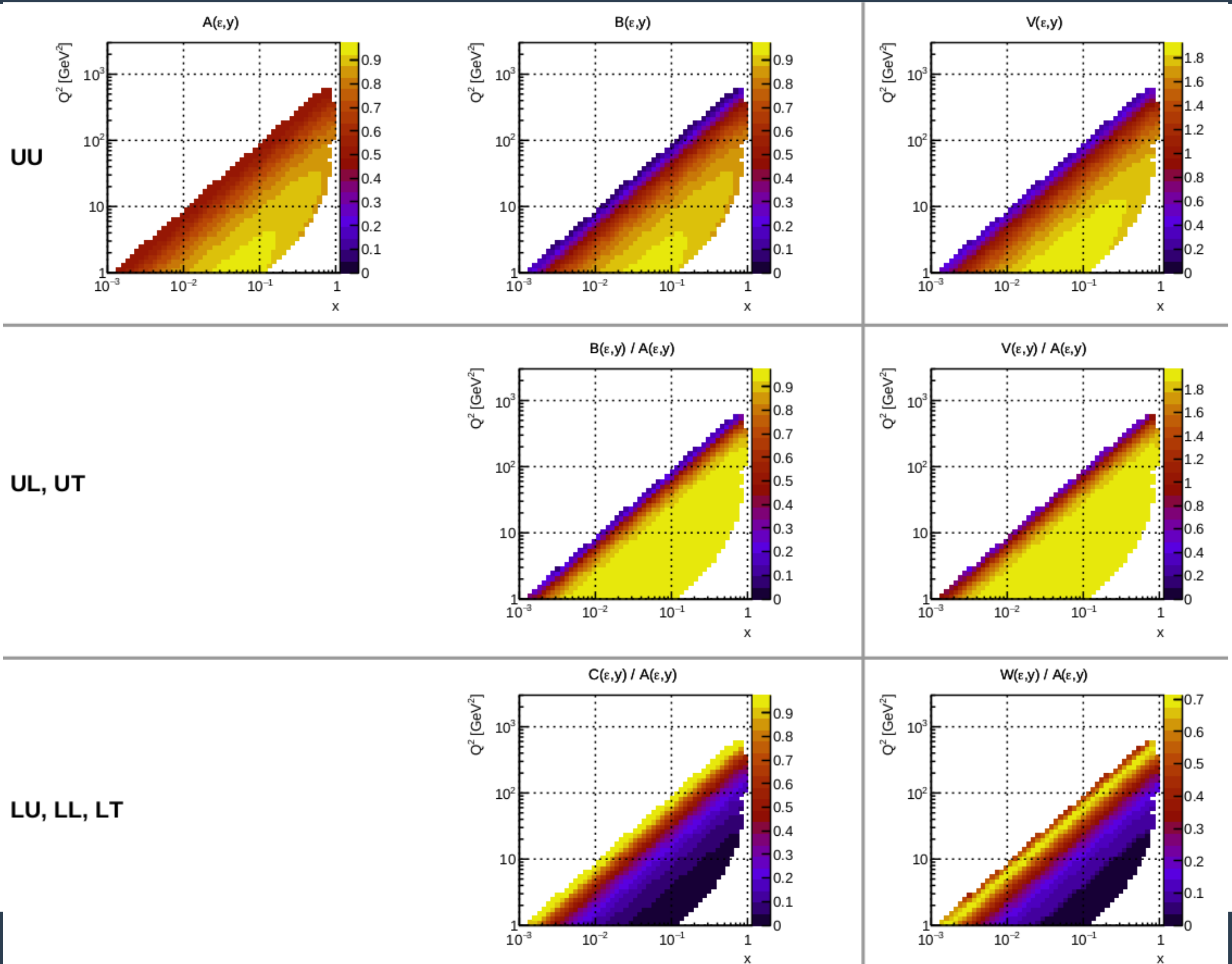
Depolarization Factors

		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
Twist 3	e(x)	LU	W/A
	$h_L(x)$	UL	V/A
	$g_T(x)$	LT	W/A

Kinematic Coverage

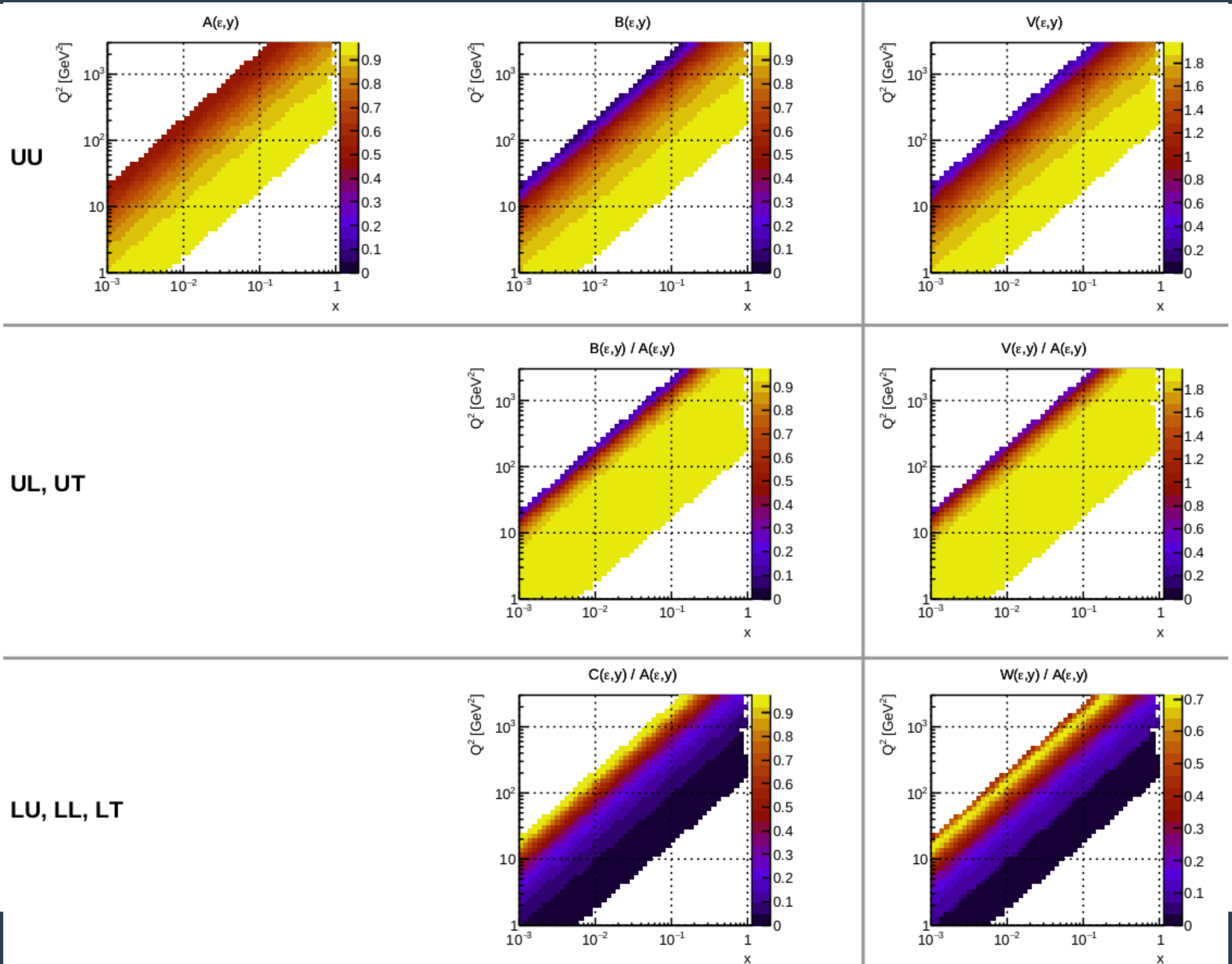


Depolarization Factors



C. Dilks

Depolarization Factors

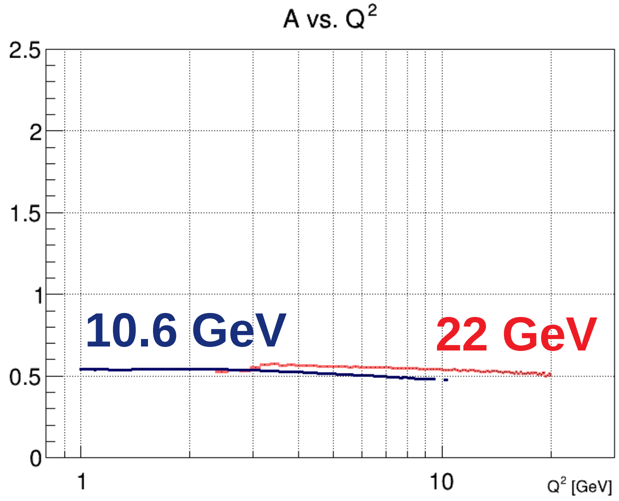


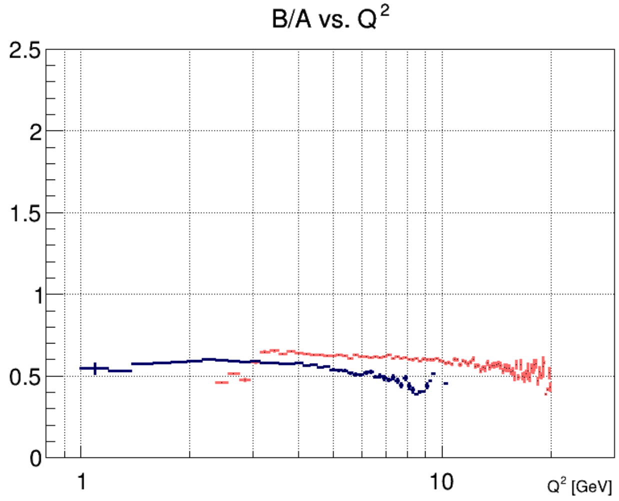
UU

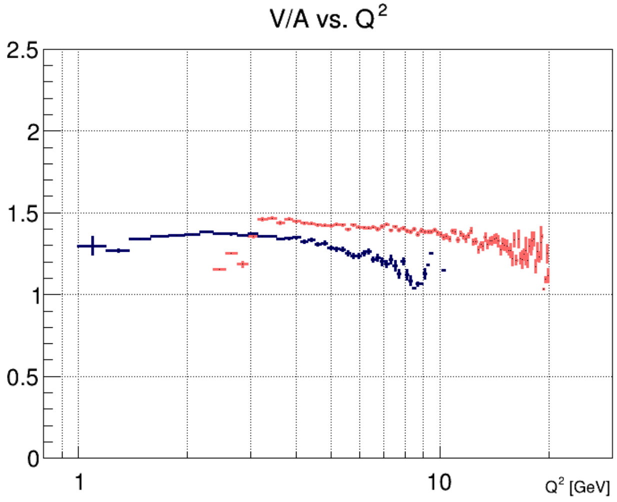
UL, UT

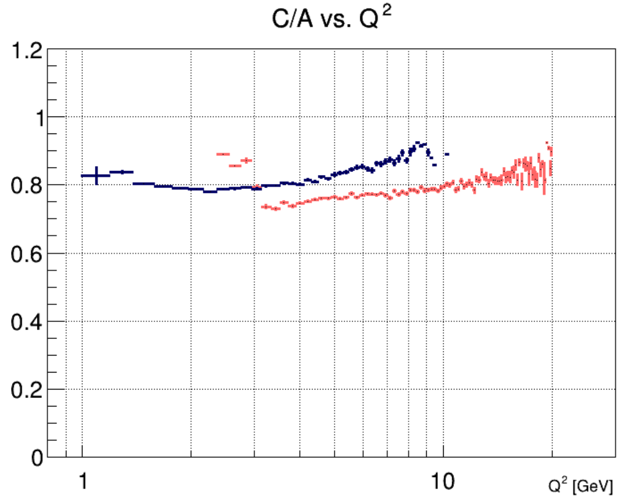
LU, LL, LT

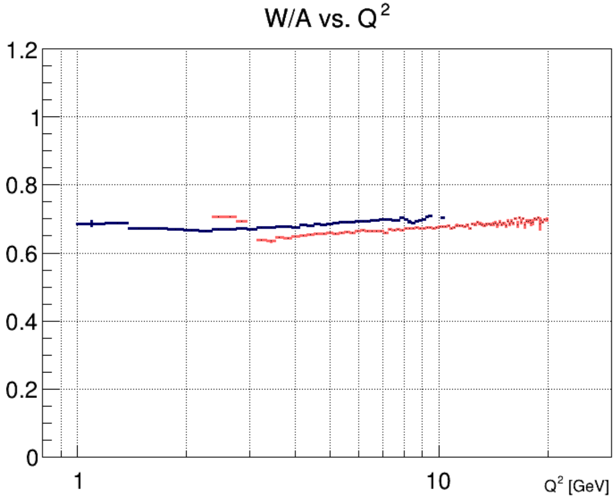
Depolarization at CLAS







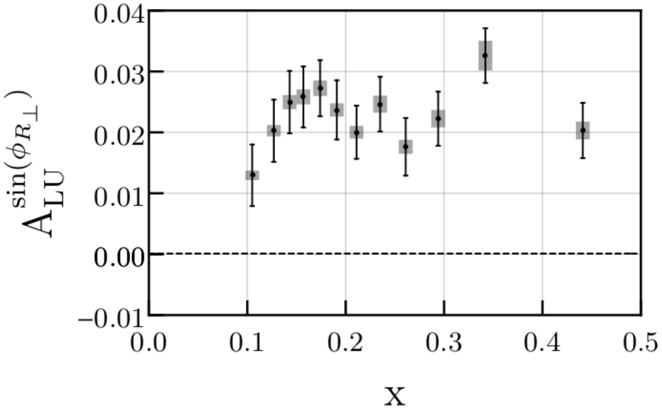




C. Dilks

CLAS Dihadron A_{LU} Measurements for e(x)

$\mathrm{CLAS12}\ \pi^+\pi^-\ A_{LU}^{\sin\phi_R}$



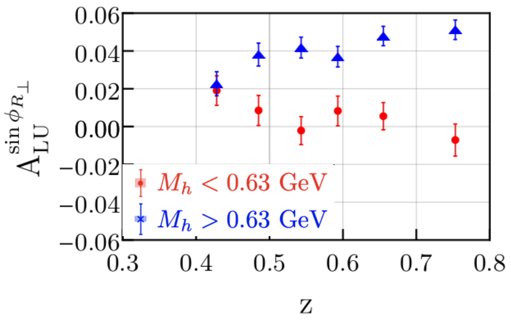
$$A_{LU}^{\sin\phi_R} \propto \frac{M}{Q}\,\frac{\sum_q e_q^2\left[x e^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,m_{\pi\pi}) + \frac{m_{\pi\pi}}{zM}\, f_1^q(x)\, \tilde{G}_{sp}^{\sphericalangle,q}(z,m_{\pi\pi})\right]}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,m_{\pi\pi})}$$

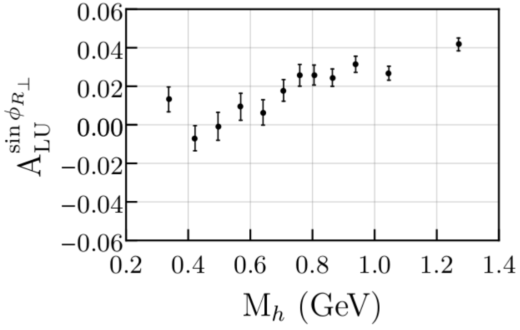
twist-3 DiFF

Extraction of $H_1^<$ from Belle Data

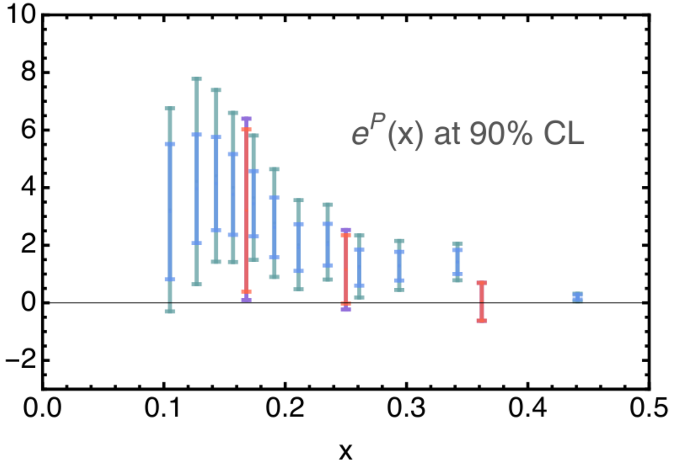
→ point-by-point extraction of e(x)

Phys.Rev.D 85 (2012) 114023





Phys.Rev.Lett. 126 (2021) 152501



Courtoy, Aurore, et al. e-Print: 2203.14975 [hep-ph]

Courtoy, Aurore – CPHI 2022

Dihadron Kinematics

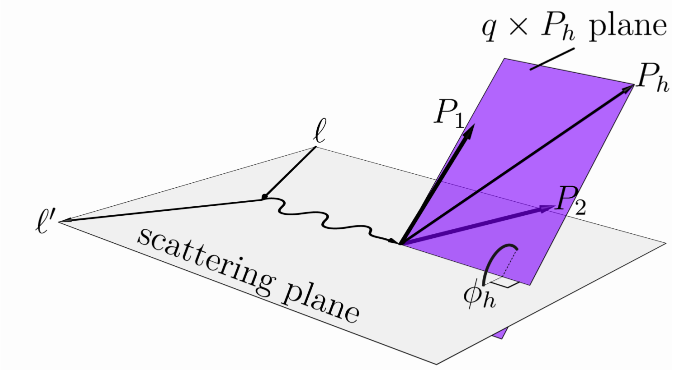
$$eN \to e + h_1(P_1) + h_2(P_2) + X$$

Dihadrons:

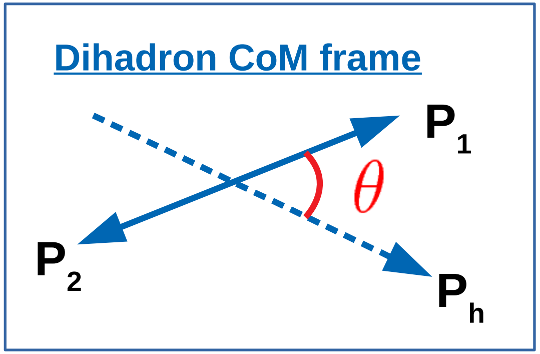
$$\text{momentum:}\;\; P_h = P_1 + P_2$$

$$\text{kinematics:}\;\; M_h,\;\; z,\;\; p_T$$

$$\text{angles:}\;\; \phi_h,\;\; \phi_R,\;\; \phi_S,\;\; \theta$$



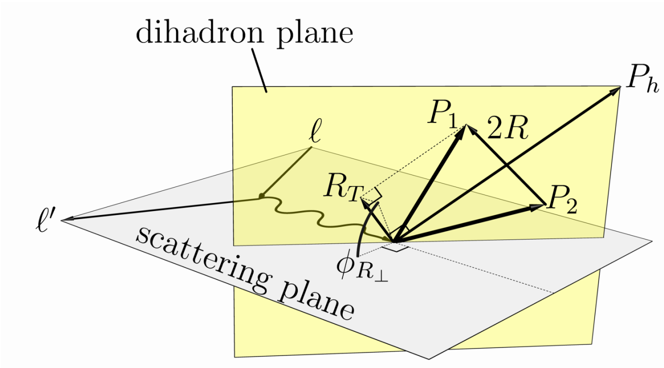
cf. single-hadron ϕ_h

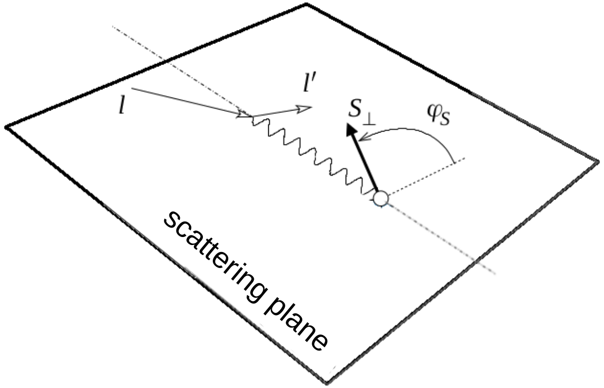


Inclusive:

$$x_B = \frac{Q^2}{2\,P \cdot q}, \quad y = \frac{P \cdot q}{P \cdot l}$$

$$\gamma = \frac{2Mx_B}{Q}$$





Online 3D View:

https://c-dilks.github.io/dihadronAngleDefs/dihadronAngleDefs.html

SIDIS Dihadron Cross Section

UU

$$\begin{aligned} d\sigma_{UU} &= \frac{\alpha^2}{4\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right) \\ &\times \sum_{\ell=0}^{\ell_{\max}} \Bigg\{ A(x,y) \sum_{m=0}^{\ell} \left[P_{\ell,m} \cos(m(\phi_h - \phi_{R_\perp})) \left(F_{UU,T}^{P_{\ell,m} \cos(m(\phi_h - \phi_{R_\perp}))} + \epsilon F_{UU,L}^{P_{\ell,m} \cos(m(\phi_h - \phi_{R_\perp}))} \right) \right] \\ &+ B(x,y) \sum_{m=-\ell}^{\ell} P_{\ell,m} \cos((2-m)\phi_h + m\phi_{R_\perp}) F_{UU}^{P_{\ell,m} \cos((2-m)\phi_h + m\phi_{R_\perp})} \\ &+ V(x,y) \sum_{m=-\ell}^{\ell} P_{\ell,m} \cos((1-m)\phi_h + m\phi_{R_\perp}) F_{UU}^{P_{\ell,m} \cos((1-m)\phi_h + m\phi_{R_\perp})} \Bigg\} . \end{aligned}$$

LU

$$\begin{aligned} d\sigma_{LU} &= \frac{\alpha^2}{4\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right) \lambda_e \\ &\times \sum_{\ell=0}^{\ell_{\max}} \Bigg\{ C(x,y) \sum_{m=1}^{\ell} \left[P_{\ell,m} \sin(m(\phi_h - \phi_{R_\perp}))\, 2 \left(F_{LU,T}^{P_{\ell,m} \cos(m(\phi_h - \phi_{R_\perp}))} + \epsilon F_{LU,L}^{P_{\ell,m} \cos(m(\phi_h - \phi_{R_\perp}))} \right) \right] \\ &+ W(x,y) \sum_{m=-\ell}^{\ell} P_{\ell,m} \sin((1-m)\phi_h + m\phi_{R_\perp}) F_{LU}^{P_{\ell,m} \sin((1-m)\phi_h + m\phi_{R_\perp})} \Bigg\} . \end{aligned}$$

UL

$$\begin{aligned} d\sigma_{UL} &= \frac{\alpha^2}{4\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right) S_L \\ &\times \Bigg\{ A(x,y) \sum_{\ell=1}^{\ell_{\max}} \sum_{m=1}^{\ell} P_{\ell,m} \sin(-m\phi_h + m\phi_{R_\perp}) F_{UL}^{P_{\ell,m} \sin(-m\phi_h + m\phi_{R_\perp})} \\ &+ B(x,y) \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} P_{\ell,m} \sin((2-m)\phi_h + m\phi_{R_\perp}) F_{UL}^{P_{\ell,m} \sin((2-m)\phi_h + m\phi_{R_\perp})} \\ &+ V(x,y) \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} P_{\ell,m} \sin((1-m)\phi_h + m\phi_{R_\perp}) F_{UL}^{P_{\ell,m} \sin((1-m)\phi_h + m\phi_{R_\perp})} \Bigg\} . \end{aligned}$$

LL

$$\begin{aligned} d\sigma_{LL} &= \frac{\alpha^2}{4\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right) \lambda_e S_L \\ &\times \sum_{\ell=0}^{\ell_{\max}} \Bigg\{ C(x,y) \sum_{m=0}^{\ell} 2^{2-\delta_{m0}}\, P_{\ell,m} \cos(m(\phi_h - \phi_{R_\perp})) F_{LL}^{P_{\ell,m} \cos(m(\phi_h - \phi_{R_\perp}))} \\ &+ W(x,y) \sum_{m=-\ell}^{\ell} P_{\ell,m} \cos((1-m)\phi_h + m\phi_{R_\perp}) F_{LL}^{P_{\ell,m} \cos((1-m)\phi_h + m\phi_{R_\perp})} \Bigg\} . \end{aligned}$$

UT

$$\begin{aligned} d\sigma_{UT} &= \frac{\alpha^2}{4\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right) |\boldsymbol{S}_\perp| \\ &\times \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} \Bigg\{ A(x,y) \Big[P_{\ell,m} \sin((m+1)\phi_h - m\phi_{R_\perp} - \phi_S)) \\ &\quad \times \left(F_{UT,T}^{P_{\ell,m} \sin((m+1)\phi_h - m\phi_{R_\perp} - \phi_S)} + \epsilon F_{UT,L}^{P_{\ell,m} \sin((m+1)\phi_h - m\phi_{R_\perp} - \phi_S)} \right) \Big] \\ &+ B(x,y) \Big[P_{\ell,m} \sin((1-m)\phi_h + m\phi_{R_\perp} + \phi_S) F_{UT}^{P_{\ell,m} \sin((1-m)\phi_h + m\phi_{R_\perp} + \phi_S)} \\ &\quad + P_{\ell,m} \sin((3-m)\phi_h + m\phi_{R_\perp} - \phi_S) F_{UT}^{P_{\ell,m} \sin((3-m)\phi_h + m\phi_{R_\perp} - \phi_S)} \Big] \\ &+ V(x,y) \Big[P_{\ell,m} \sin(-m\phi_h + m\phi_{R_\perp} + \phi_S) F_{UT}^{P_{\ell,m} \sin(-m\phi_h + m\phi_{R_\perp} + \phi_S)} \\ &\quad + P_{\ell,m} \sin((2-m)\phi_h + m\phi_{R_\perp} - \phi_S) F_{UT}^{P_{\ell,m} \sin((2-m)\phi_h + m\phi_{R_\perp} - \phi_S)} \Big] \Bigg\} . \end{aligned}$$

LT

$$\begin{aligned} d\sigma_{LT} &= \frac{\alpha^2}{4\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right) \lambda_e |\boldsymbol{S}_\perp| \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} \Bigg\{ \\ & C(x,y)\, 2\, P_{\ell,m} \cos((1-m)\phi_h + m\phi_{R_\perp} - \phi_S)) F_{LT}^{P_{\ell,m} \cos((1-m)\phi_h + m\phi_{R_\perp} - \phi_S))} \\ &+ W(x,y) \Big[P_{\ell,m} \cos(-m\phi_h + m\phi_{R_\perp} + \phi_S) F_{LT}^{P_{\ell,m} \cos(-m\phi_h + m\phi_{R_\perp} + \phi_S)} \\ &\quad + P_{\ell,m} \cos((2-m)\phi_h + m\phi_{R_\perp} - \phi_S) F_{LT}^{P_{\ell,m} \cos((2-m)\phi_h + m\phi_{R_\perp} - \phi_S)} \Big] \Bigg\} . \end{aligned}$$

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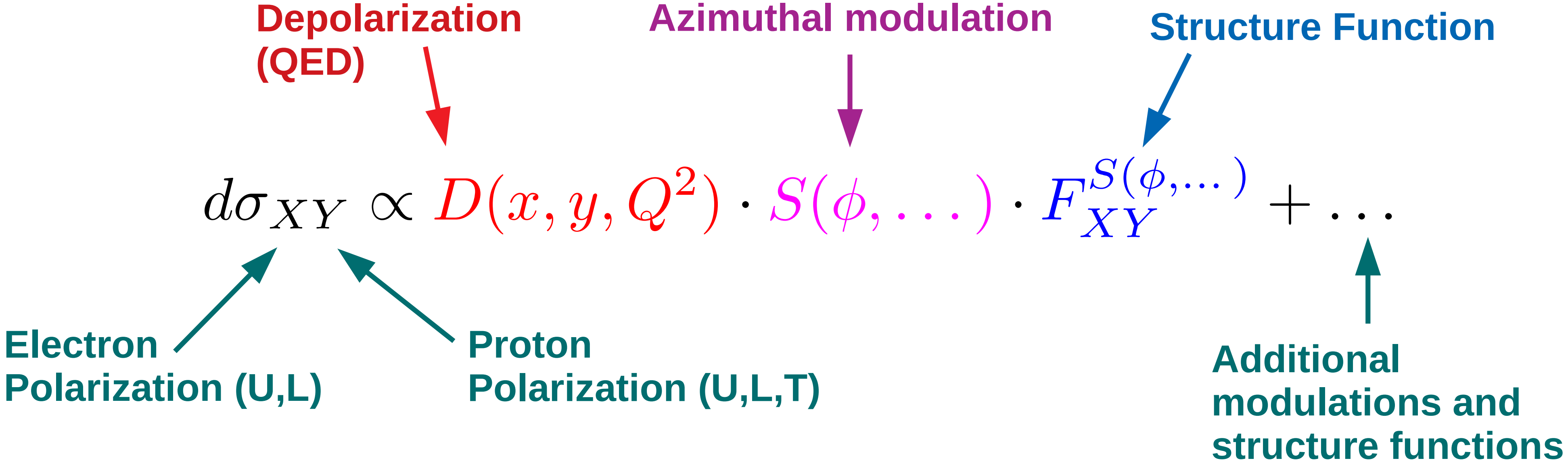
SIDIS Cross Section

$$A_{UT} = \frac{d\sigma_{UT}}{d\sigma_{UU}} = \frac{d\sigma_{\uparrow} - d\sigma_{\downarrow}}{d\sigma}$$

General form of each term:



Depolarization (QED)

Azimuthal modulation

Structure Function

$$d\sigma_{XY} \propto D(x, y, Q^2) \cdot S(\phi, \ldots) \cdot F_{XY}^{S(\phi,\ldots)} + \ldots$$

Electron Polarization (U,L)

Proton Polarization (U,L,T)

Additional modulations and structure functions

Dihadron Access to PDFs x DiFFs

Twist 2

Nucleon Polarization

Electron Polarization

	U	L	T
U	$f_1 D_1$ $h_1^\perp H_1$	$h_{1L}^\perp H_1$ $g_{1L} G_1$	$f_{1T}^\perp D_1$ $g_{1T} G_1$ $h_1 H_1$ $h_{1T}^\perp H_1$
L	$f_1 G_1$	$g_{1L} D_1$	$g_{1T} D_1$ $f_{1T}^\perp G_1$

Twist 3

Nucleon Polarization

Electron Polarization

	U	L	T
U	$h H_1 \quad f_1 \tilde{D}$ $f^\perp D_1 \quad h_1^\perp \tilde{H}$	$h_L H_1 \quad g_{1L} \tilde{G}$ $f_L^\perp D_1 \quad h_{1L}^\perp \tilde{H}$	$f_T D_1 \quad h_1 \tilde{H}$ $h_T H_1 \quad g_{1T} \tilde{G}$ $h_T^\perp H_1 \quad f_{1T}^\perp \tilde{D}$ $f_T^\perp D_1 \quad h_{1T}^\perp \tilde{H}$
L	$e H_1 \quad f_1 \tilde{G}$ $g^\perp D_1 \quad h_1^\perp \tilde{E}$	$e_L H_1 \quad g_{1L} \tilde{D}$ $g_L^\perp D_1 \quad h_{1L}^\perp \tilde{E}$	$g_T D_1 \quad h_1 \tilde{E}$ $e_T H_1 \quad g_{1T} \tilde{D}$ $e_T^\perp H_1 \quad f_{1T}^\perp \tilde{G}$ $g_T^\perp D_1 \quad h_{1T}^\perp \tilde{E}$

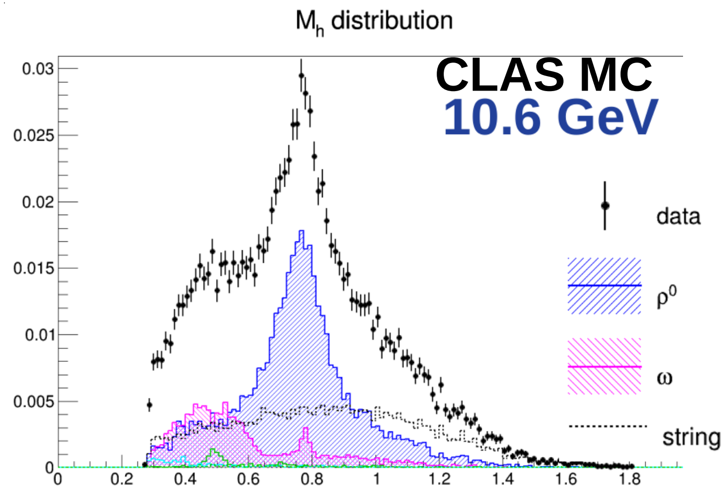
Even more from Dihadrons...

Vector Mesons: a significant fraction of dihadrons

$$\rho \to \pi\pi$$

$$K^* \to \pi K$$

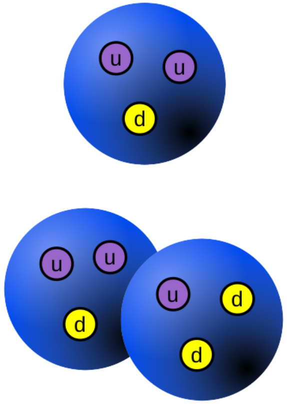
$$\phi \to KK$$



Flavor-dependence of twist-3 PDFs

Proton Target

Deuteron Target



Channel dependence of DiFFs

$$\begin{matrix} D_1^{q/\pi^+\pi^-} \\ G_1^{q/\pi^+\pi^-} \\ H_1^{q/\pi^+\pi^-} \end{matrix} \neq \begin{matrix} D_1^{q/\pi^\pm\pi^0} \\ G_1^{q/\pi^\pm\pi^0} \\ H_1^{q/\pi^\pm\pi^0} \end{matrix}$$

Transverse Lambdas

Spontaneous Polarization: $P_\Lambda = \dfrac{F_{UT}^{\sin(\phi_S-\phi_\Lambda)}}{F_{UU}}$

Spin Transfer: $S_\Lambda = D(y)\,\dfrac{F_{TT}^{\cos(\varphi_S-\phi_S)}}{F_{UU}}$

F_{XY} X = proton polarization
Y = Λ polarization

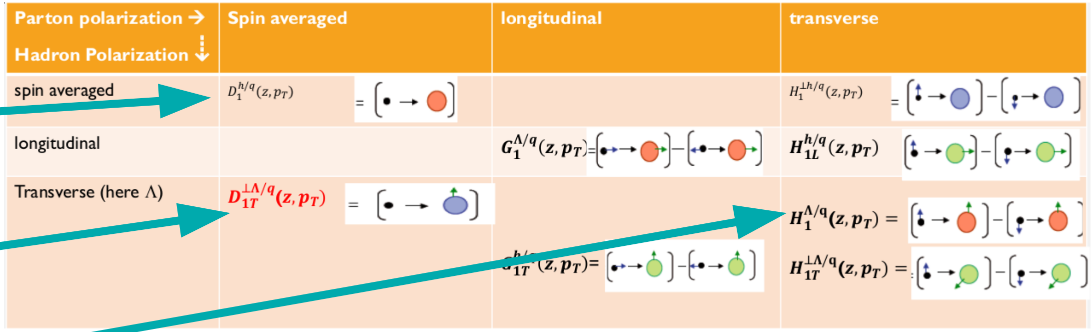
Accessible via cosθ distribution of protons in Λ → pπ

$$\frac{\mathrm{d}N_{\mathrm{p}(\bar{\mathrm{p}})}}{\mathrm{d}\cos\theta} \propto 1 + \alpha_{\Lambda(\bar{\Lambda})} P_{\Lambda(\bar{\Lambda})} \cos\theta$$

$$F_{UU} \sim f^{q/p} \otimes D_1^{\Lambda/q}$$

$$F_{UT}^{\sin(\phi_S-\phi_\Lambda)} \sim f^{q/p} \otimes D_{1T}^{\perp\Lambda/q}$$

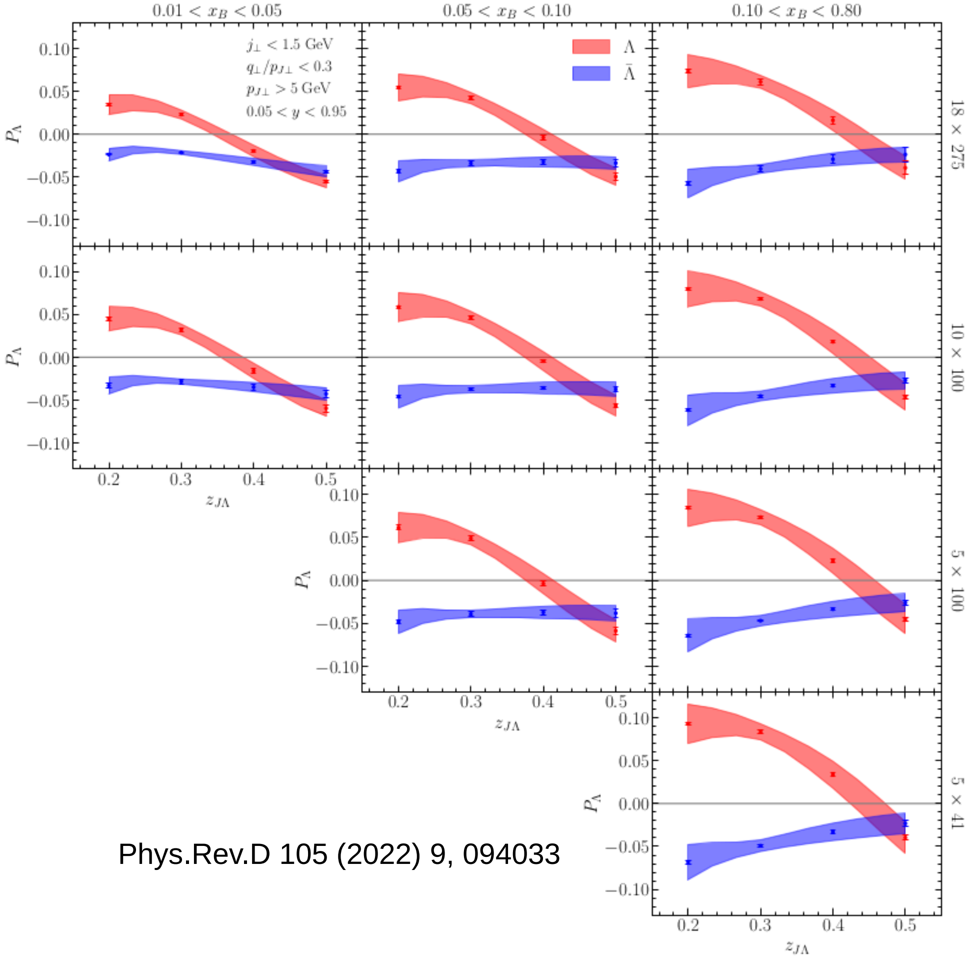
$$F_{TT}^{\cos(\varphi_S-\phi_S)} \sim h^{q/p} \otimes H_1^{\Lambda/q}$$



Parton polarization → Hadron Polarization ↓	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z,p_T)$ =		$H_1^{\perp h/q}(z,p_T)$ =
longitudinal		$G_1^{\Lambda/q}(z,p_T)$=	$H_{1L}^{h/q}(z,p_T)$
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z,p_T)$ =	$G_{1T}^{h/q}(z,p_T)$=	$H_1^{\Lambda/q}(z,p_T)$ = $H_{1T}^{\perp\Lambda/q}(z,p_T)$ =

Spontaneous Polarization Impact from Λs in Jets

- Measuring Λs in jets provides another probe for TMD FFs
- Distribution of hadrons relative to jet axis allows for decorrelation of TMD FFs and PDFs
- Impact on spontaneous polarization:
  - Bands: theoretical uncertainty
  - Error bars: projection from 100 fb^{-1}



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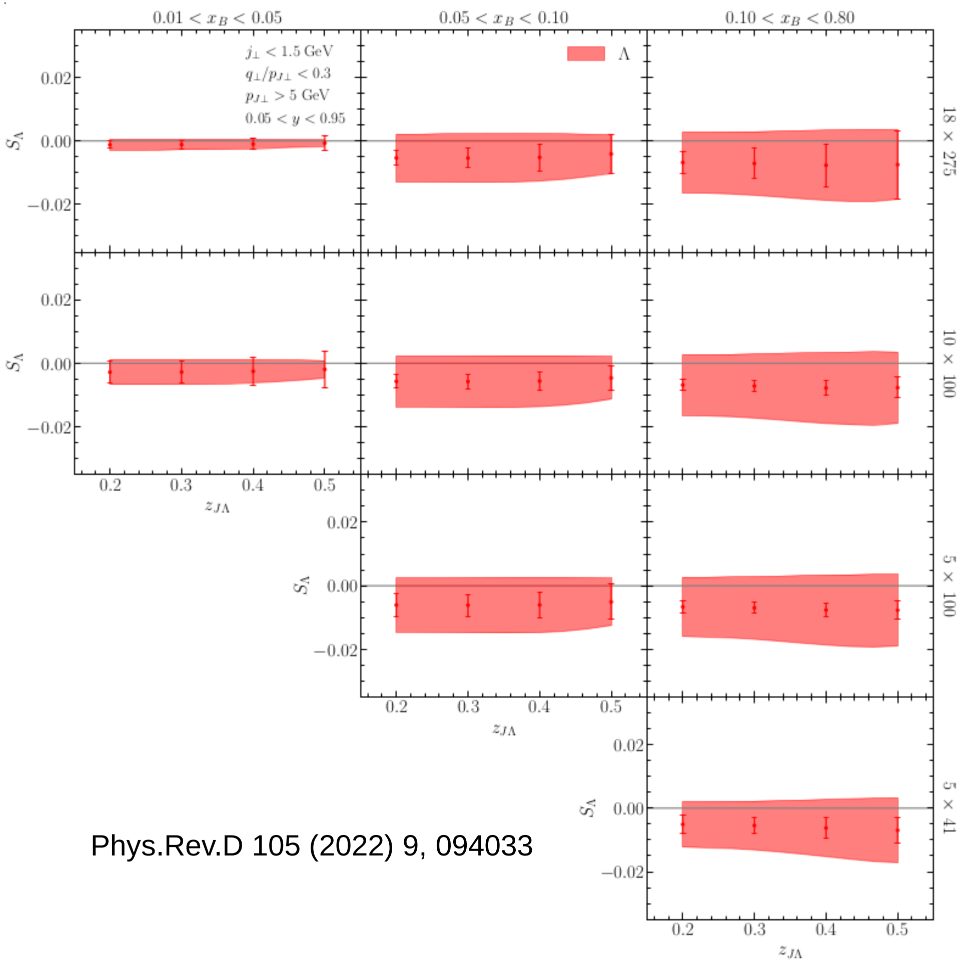
Spin Transfer Impact from Λs in Jets

- Impact on spin transfer:
  - Bands: theoretical uncertainty
  - Error bars: projection from 100 fb^{-1}



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