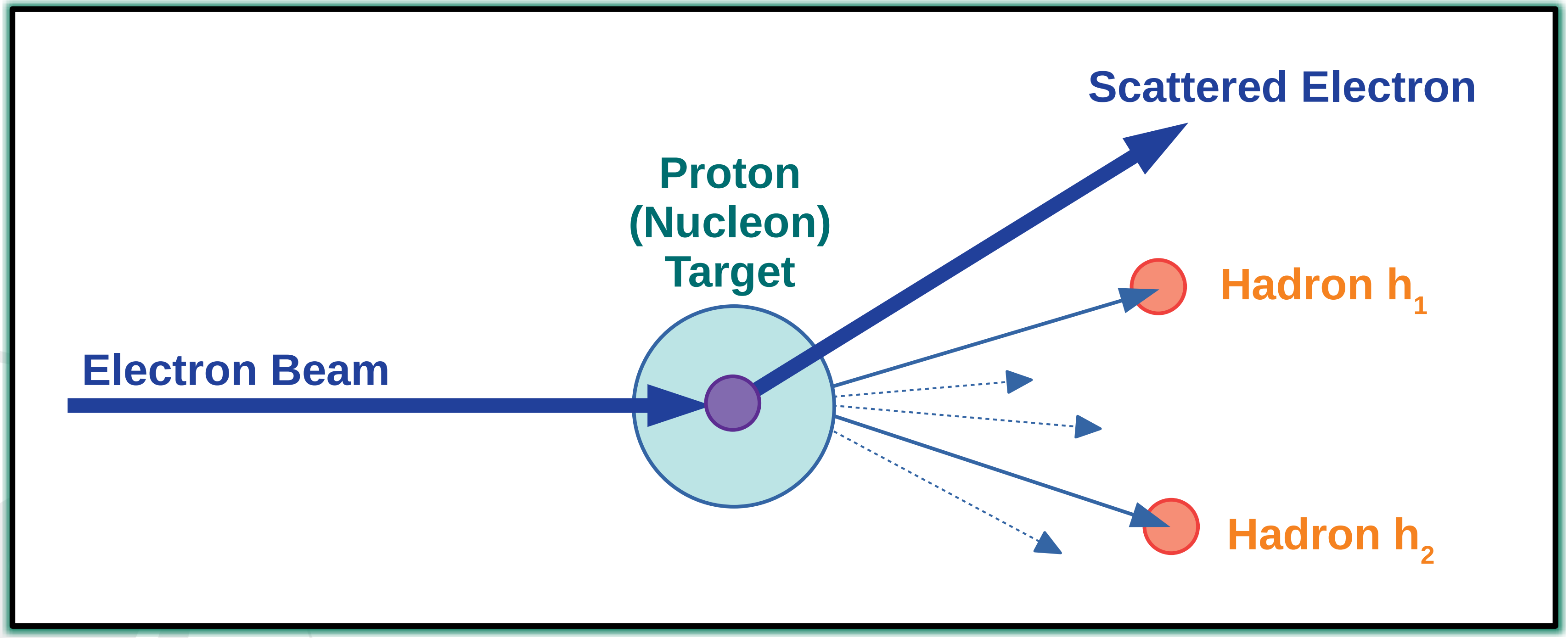
Future Studies of Dihadron Production in SIDIS



25TH INTERNATIONAL SPIN PHYSICS SYMPOSIUM

September 24 – 29, 2023
Durham Convention Center
Durham, NC, USA

Christopher Dilks

September 2023

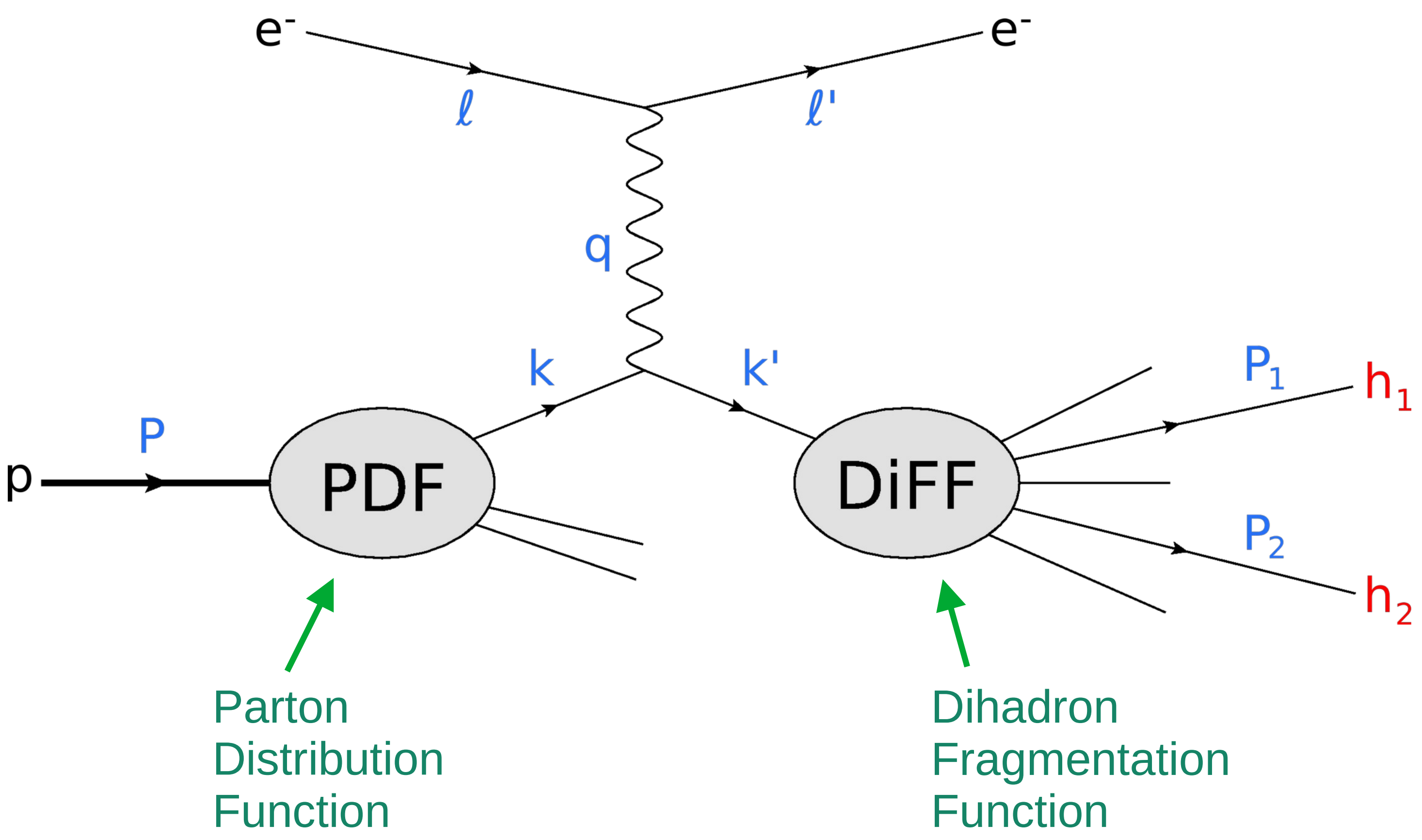
Outline

- **Kinematics and Cross Section for SIDIS Dihadrons**
- **Distribution and Fragmentation Functions**
- **Partial Waves, Vector Mesons, Fracture Functions**
- **Ongoing and Future Studies**

Disclaimer: Focusing on CLAS and ePIC

SIDIS Dihadrons

$$e^-(\ell) + p(P) \rightarrow e^-(\ell') + h_1(P_1) + h_2(P_2) + X$$

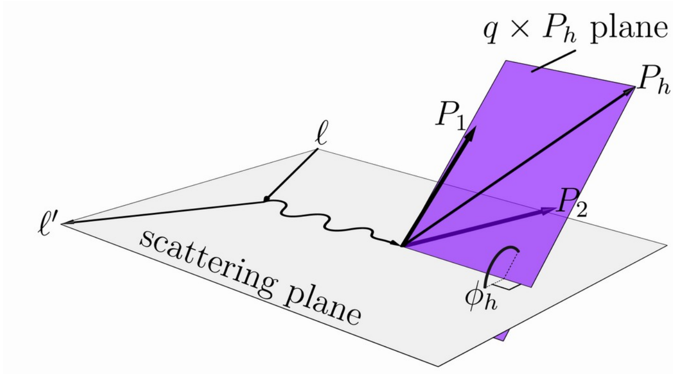


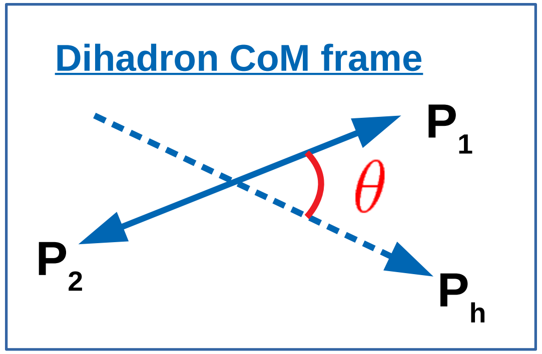
Dihadron Kinematics

Inclusive:

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

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



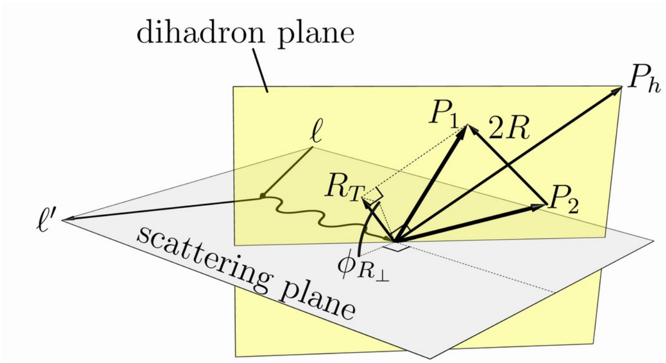


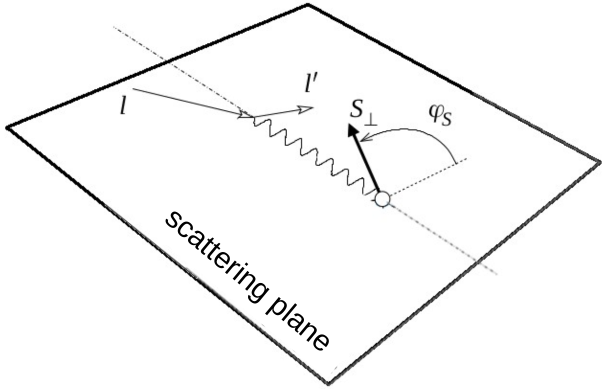
Dihadrons:

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

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

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





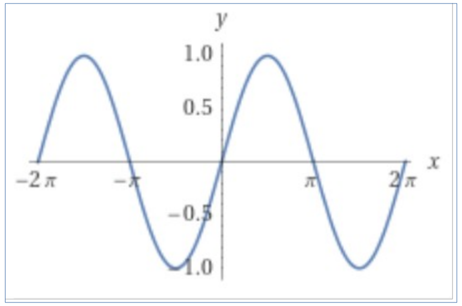
ϕ_h, ϕ_R, and θ figures produced from CD, c-dilks/diagrams (Github repository)
ϕ_S figure adapted from A. Bachetta, et al., Phys.Rev.D 70 (2004) 117504

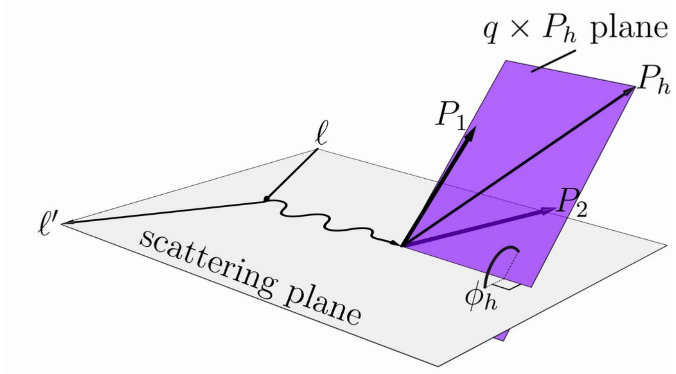
Jefferson Lab

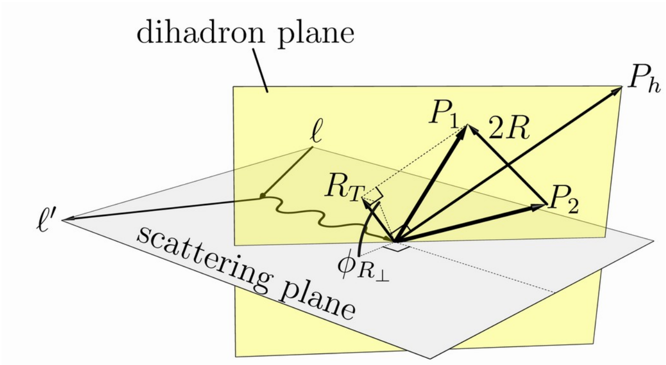
Dihadron Kinematics

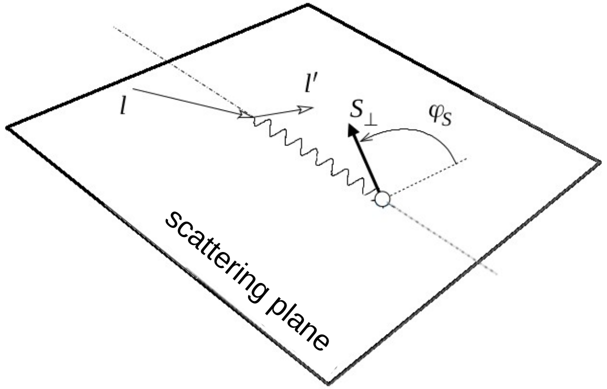
Azimuthal modulations of cross section (and asymmetries)

$$f\left(\phi_h, \phi_{R_\perp}, \phi_S\right)$$









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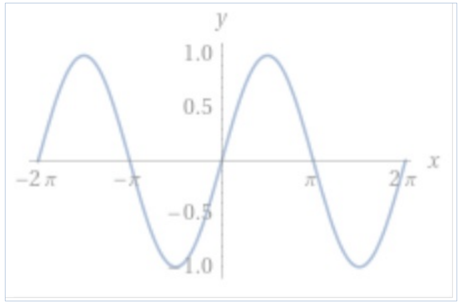
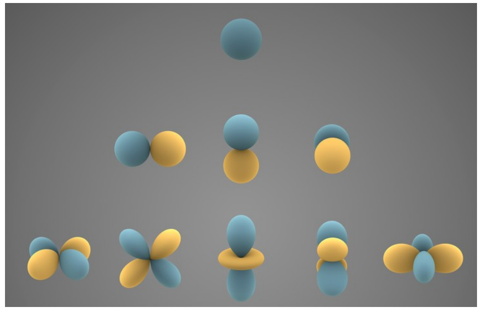
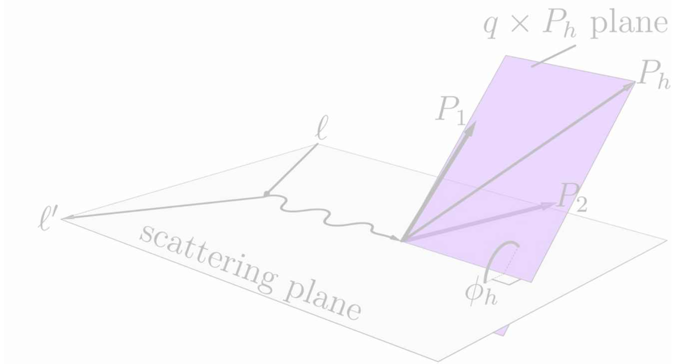


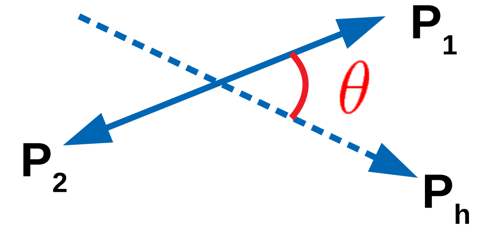
Partial Wave Expansion

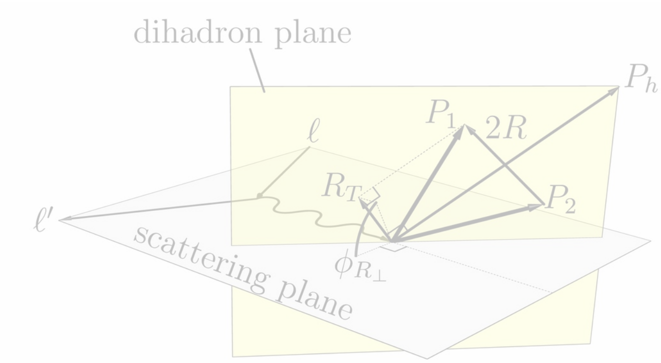
$$P_{\ell,m}\left(\cos\theta\right)$$

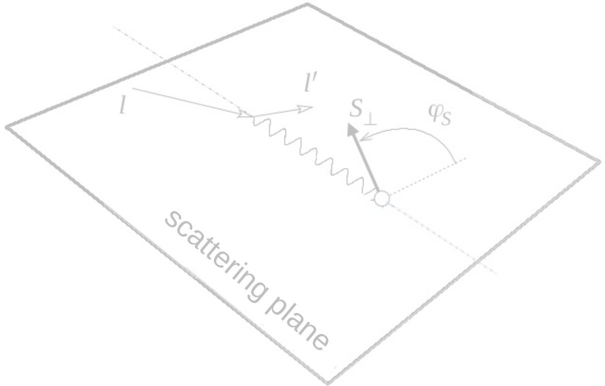




Dihadron CoM frame



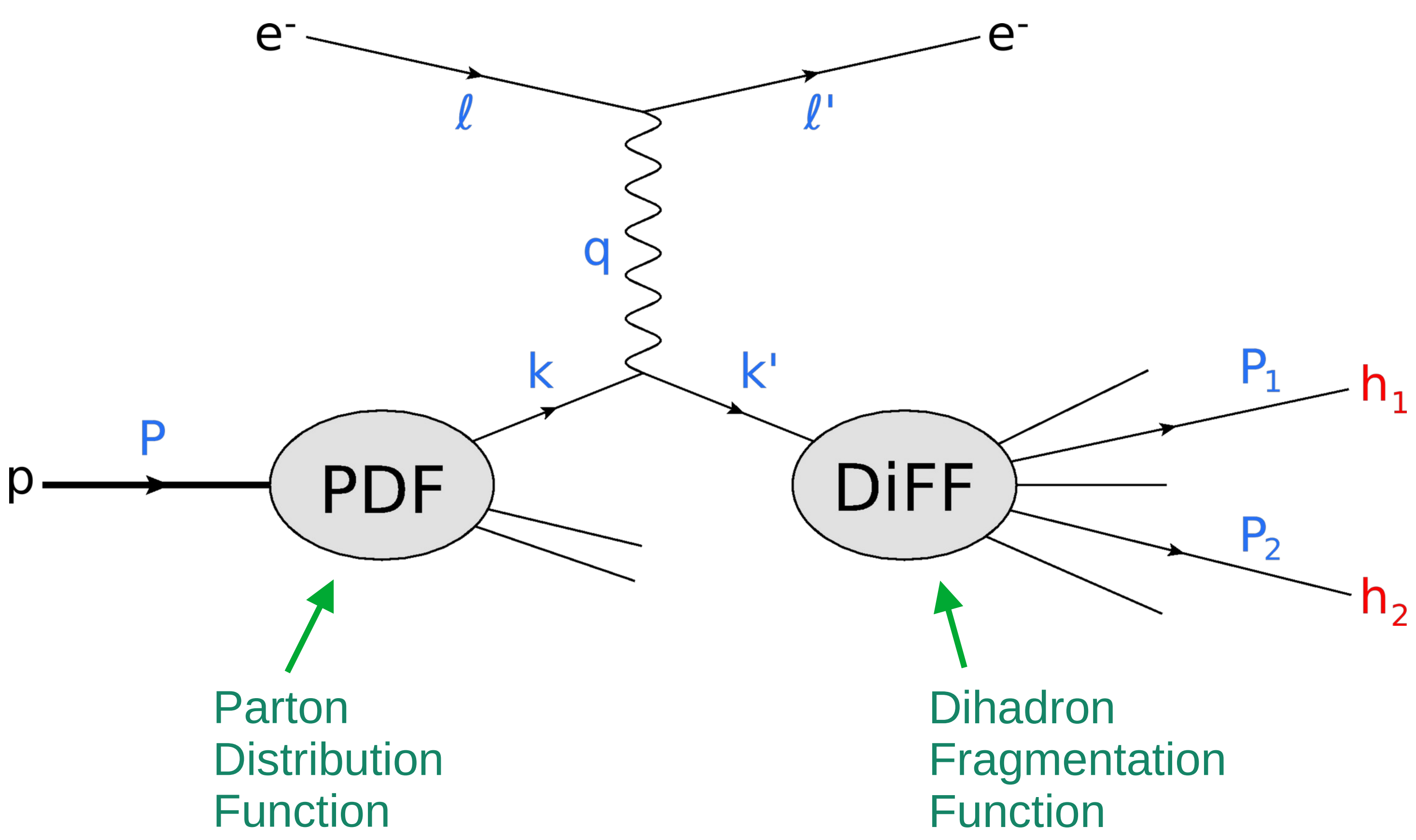




ϕ_h, ϕ_R, and θ figures produced from CD, c-dilks/diagrams (Github repository)
ϕ_S figure adapted from A. Bachetta, et al., Phys.Rev.D 70 (2004) 117504

Jefferson Lab

Dihadron Structure Functions → TMD PDF x DiFF



Beam and Target Polarization:

$$X, Y \in \{U, L, T\}$$

Modulations:

$$P_{\ell,m}(\cos\theta)\ f(\phi_h, \phi_{R_\perp}, \phi_S)$$

$$F_{XY}^{P_{\ell,m}\cdot f} \propto \mathrm{TMD\ PDF} \otimes \mathrm{DiFF}$$

Dihadron Structure Functions → TMD PDF x DiFF

Twist 2

Target Polarization (columns), Beam Polarization (rows)

	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 (columns), Beam Polarization (rows)

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

Bacchetta, Alessandro, and Marco Radici. "Partial-Wave Analysis of Two-Hadron Fragmentation Functions." Physical Review D 67, no. 9 (May 6, 2003): 094002. https://doi.org/10.1103/PhysRevD.67.094002.

Bacchetta, Alessandro, and Marco Radici. "Two-Hadron Semi-Inclusive Production Including Subleading Twist." Physical Review D 69, no. 7 (April 27, 2004): 074026. https://doi.org/10.1103/PhysRevD.69.074026.

Gliske, Stephen, Alessandro Bacchetta, and Marco Radici. "Production of Two Hadrons in Semi-Inclusive Deep Inelatic Scattering." Physical Review D 90, no. 11 (December 23, 2014): 114027. https://doi.org/10.1103/PhysRevD.90.114027.

Outline

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Transverse Momentum Dependent (TMD) PDFs

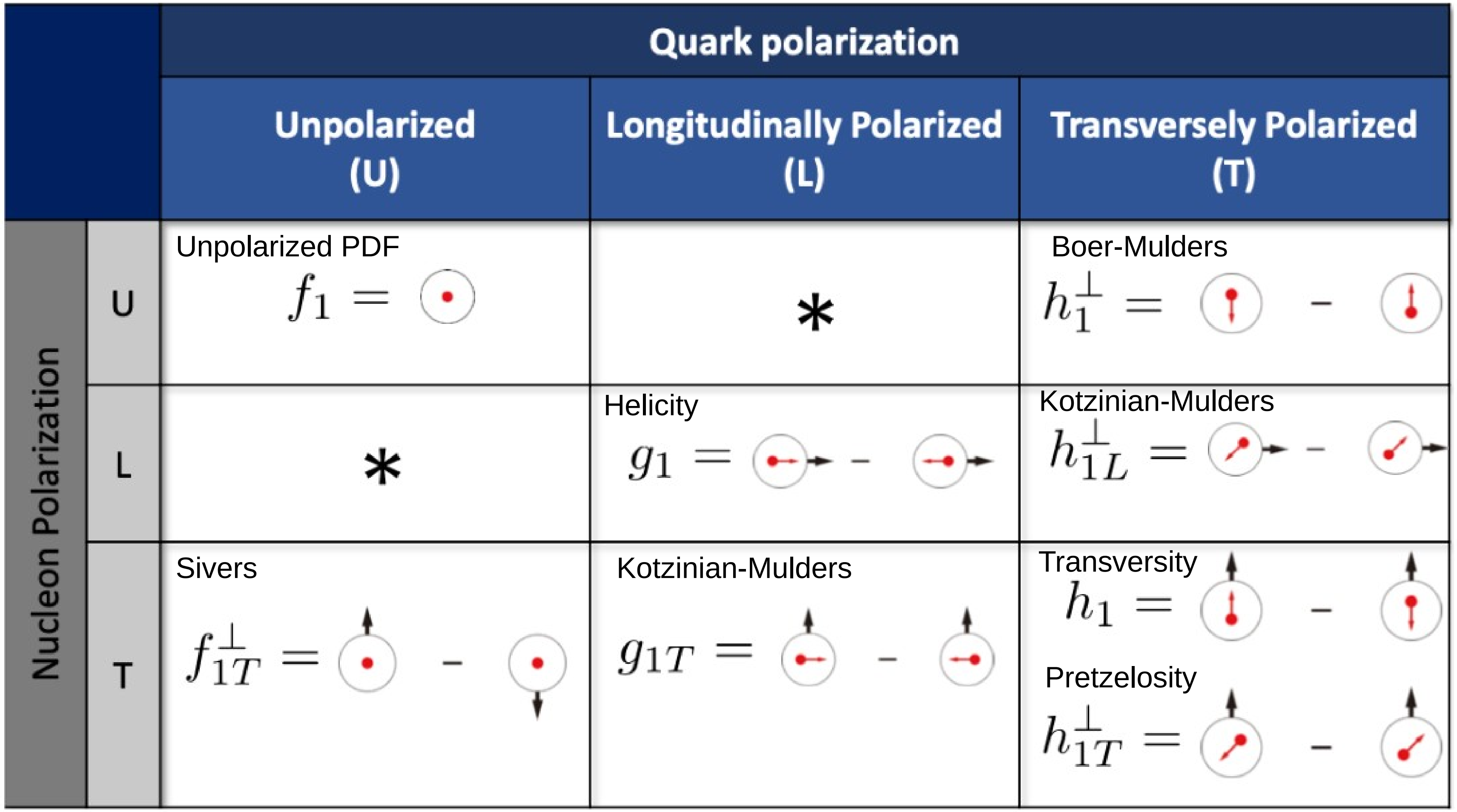


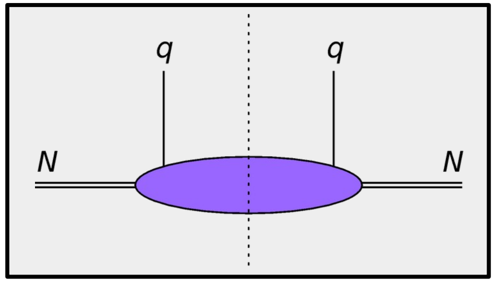
Figure from S.J. Brodsky, et al., Int.J.Mod.Phys.E 29 (2020) 08, 2030006

Subleading Twist

Twist 2

("Leading Twist")

$$d\sigma \propto \frac{1}{Q^2}$$

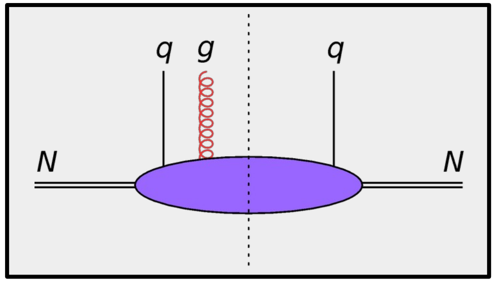


- TMD PDFs from previous slide are all twist-2
- Probabilistic interpretations
- Quark-quark correlators
- PDFs and FFs are better constrained

Twist 3

("Sub-leading Twist")

$$d\sigma \propto \frac{1}{Q^3}$$



- Harder to interpret probabilistically
- Semi-classical interpretation via x-moments
- Multi-parton correlators
- Not as well known

- There is also Twist 4 and beyond
- JLab kinematic phase space is *ideal* for studying subleading-twist effects

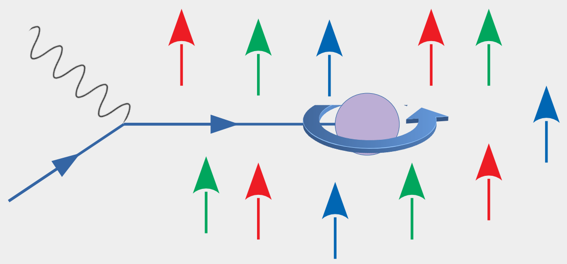
Collinear Twist-3 Distributions

Semi-classical interpretation via x-moments

e(x)

- Pion-nucleon σ term: $m_q \rightarrow m_N$
- "Boer-Mulders Force": Transverse force exerted by color field on a **transversely** polarized struck quark in an **unpolarized** nucleon

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



$g_T(x)$

- Average transverse force on an **unpolarized** struck quark in a **transversely** polarized nucleon

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

$h_L(x)$

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

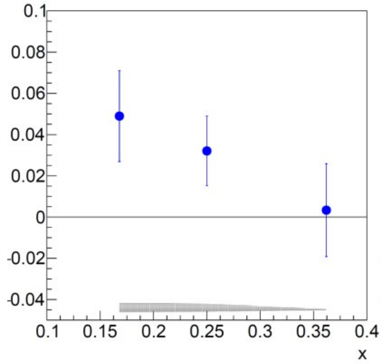
$$\mathcal{L}^q_{\mathrm{JM}} - L^q_{\mathrm{Ji}} = \Delta L^q_{\mathrm{FSI}}$$

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

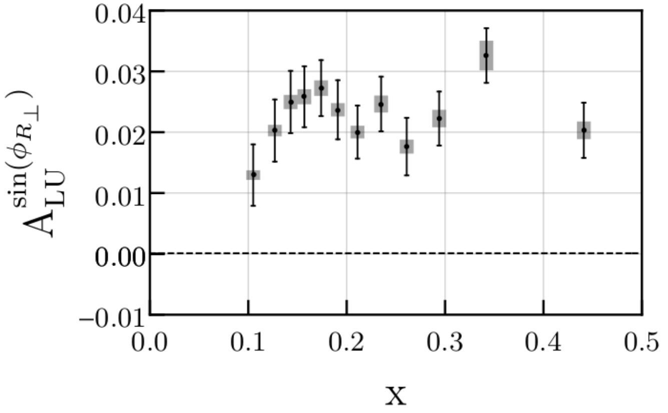
CLAS Beam Spin Asymmetry → e(x) Extraction

CLAS6 $\pi^+\pi^-$ $A_{LU}^{\sin\phi_R}$



M. Mirazita, et al., Phys.Rev.Lett. 126 (2021) 6, 062002

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

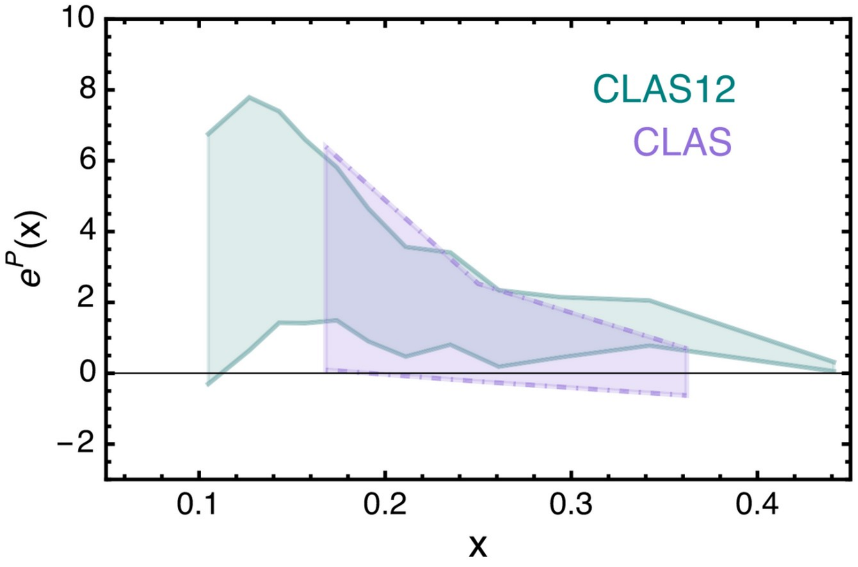


Error bars: stat. unc.
Shaded boxes: sys. unc.

T.B. Hayward, C. Dilks, et al., Phys.Rev.Lett. 126 (2021) 152501

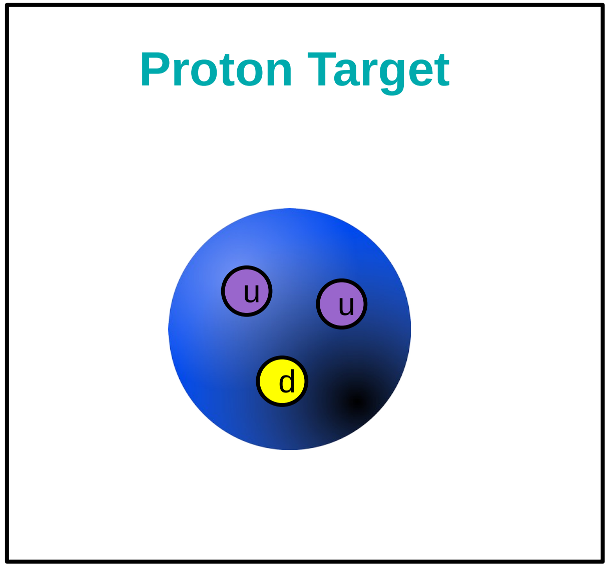
$$F_{LU}^{\sin\phi_{R\perp}} \propto eH_1 + \ldots$$

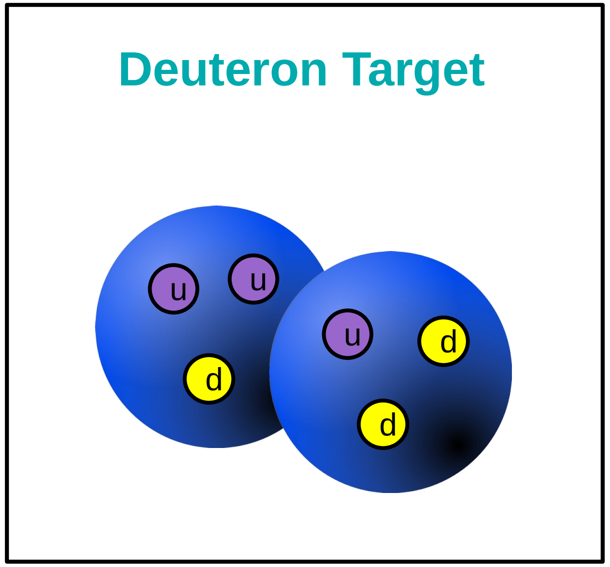
$e^P(x)$ → Proton (valence) combination



A. Courtoy, et al., Phys.Rev.D 106 (2022) 1, 014027

Flavor Separation from Different Targets





$$e^{u_V}(x)$$

2 equations and 2 unknowns: decouple flavor dependence of e(x)

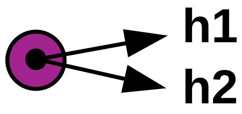
$$e^{d_V}(x)$$

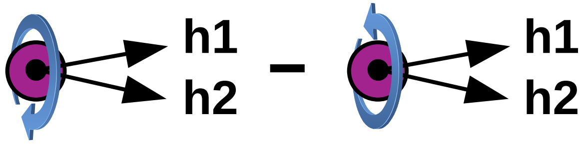
CLAS12 Analysis in Progress

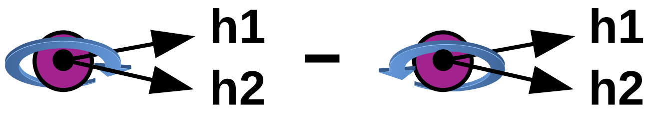
CD, Transversity 2022

Dihadron Fragmentation Functions (DiFFs)

Twist 2

$D_1 =$ 

$G_1 =$ 

$H_1 =$ 

Twist 3

$\tilde{D}^{\perp}$ $\tilde{G}^{\perp}$

$\tilde{H}$ $\tilde{E}$

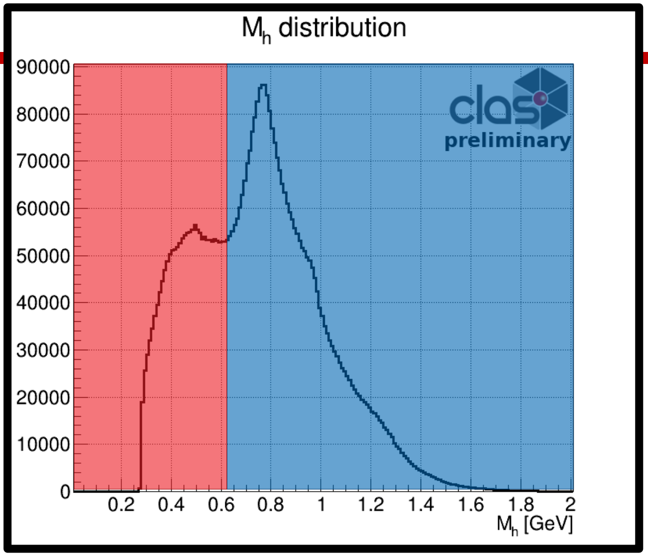
Thought to be small…
see, for example:

W. Yang, et al., Phys.Rev.D 99 (2019) 5, 054003

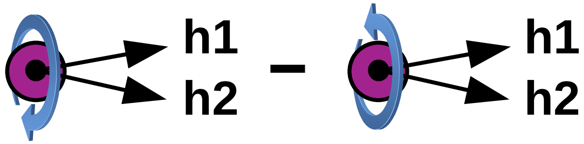
S. Pereira, PoS DIS2014 (2014) 231

A. Courtoy, e-Print: 1405.7659 [hep-ph]

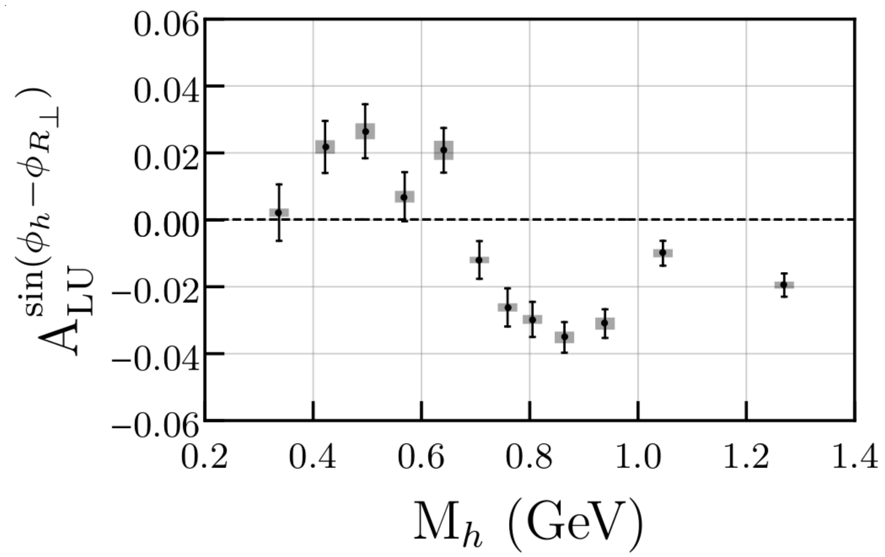
Beam Spin Asymmetry → Access to $G_1^\perp$

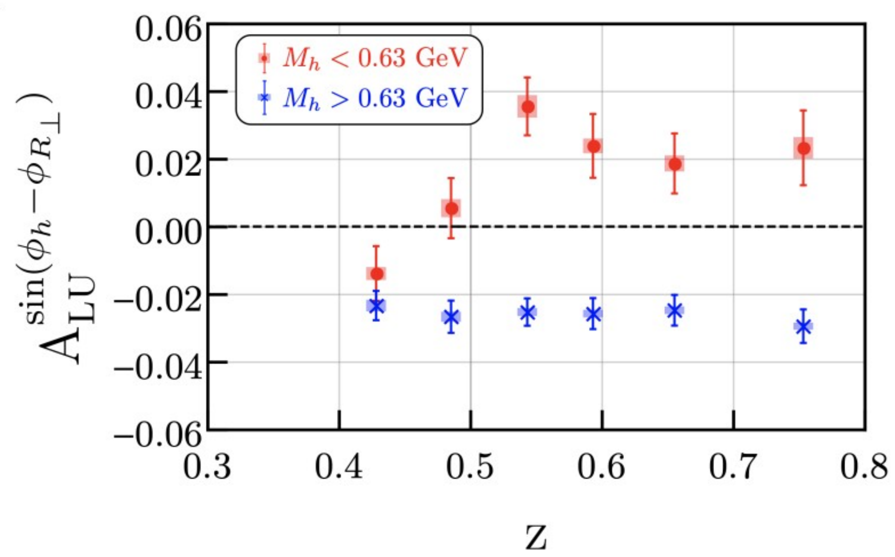


$G_1^\perp(z, M_h, p_T) =$



$$F_{LU}^{\sin(\phi_h - \phi_{R_\perp})} \propto f_1 \otimes G_1^\perp$$





T.B. Hayward, C. Dilks, et al., Phys.Rev.Lett. 126 (2021) 152501

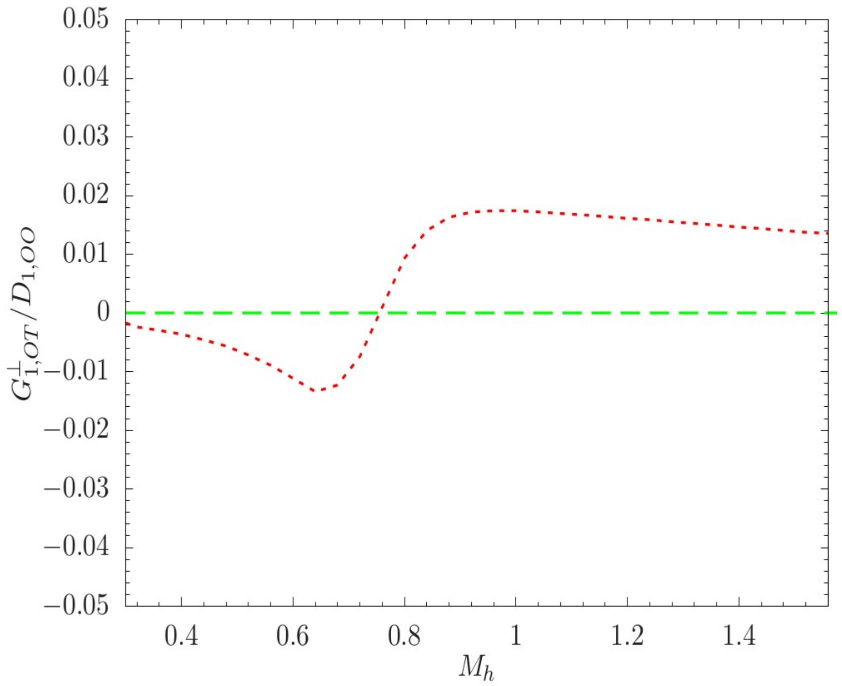
The M_ρ Sign Change

$$|\pi^+\pi^- X\rangle = e^{i\delta_s}|(\pi\pi)_s X\rangle + e^{i\delta_p}|(\pi\pi)_p X\rangle + \ldots$$

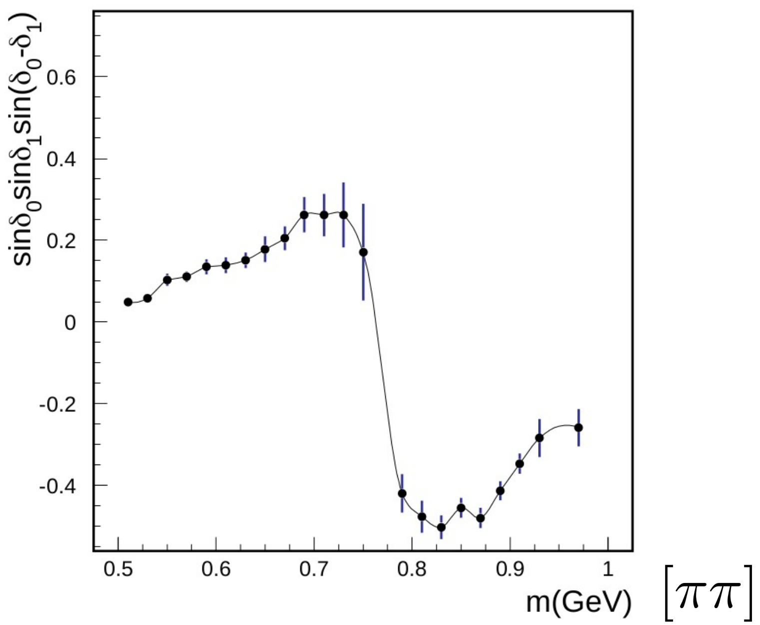
Partial Wave Amplitudes: $f_s \propto \sin\delta_s$, $f_p \propto \sin\delta_p$, $f_{sp} \propto \sin(\delta_s - \delta_p)$

"*s*- and *p*-wave production channels interfere strongly in the mass region around the *ρ*, *K**, and *ϕ* resonances"

Spectator Model Prediction



X. Luo, H. Sun, Y.L. Xie, Phys.Rev.D 101 (2020) 5, 054020



R.L. Jaffe, Can Transversity Be Measured?
2nd Topical Workshop on Deep Inelastic Scattering off Polarized Targets: Theory Meets Experiment (SPIN 97)

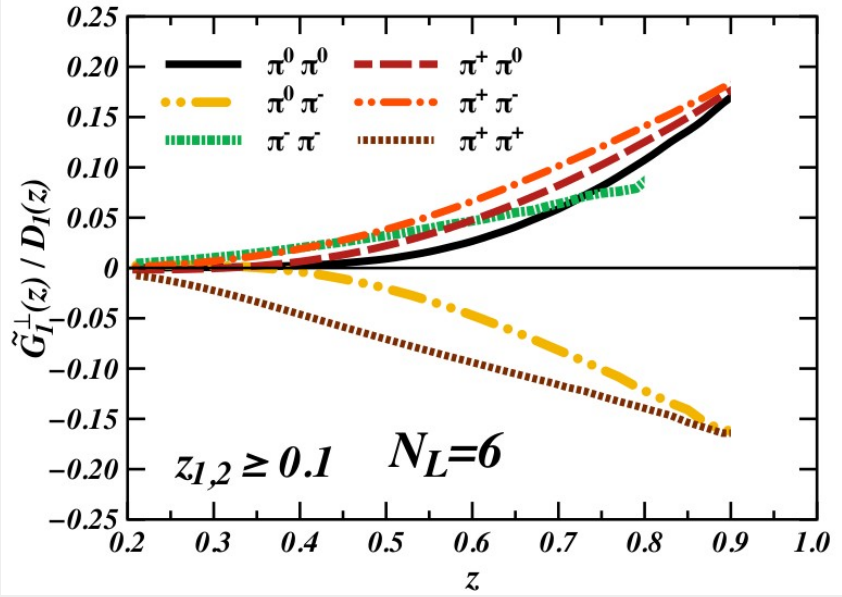
Fragmentation Channel Dependence

Channel dependence of DiFFs

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

Also... $\pi K,\ KK,$ like sign, $\ldots$

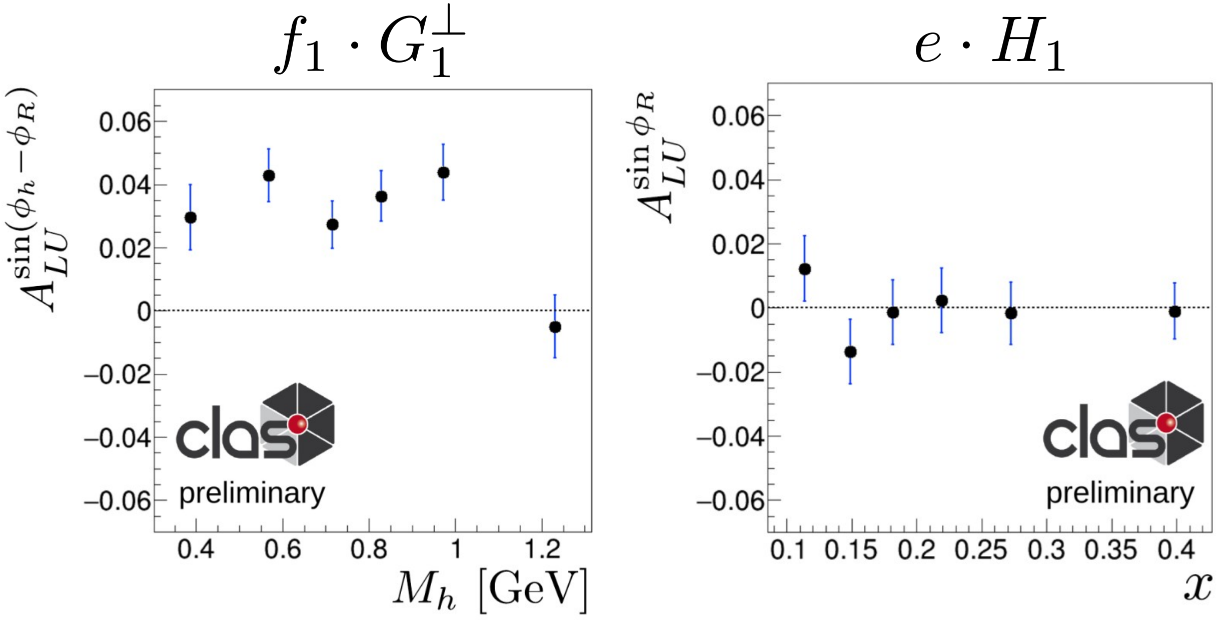
Example model predictions (quark-jet model)



H.H. Matevosyan, A. Kotzinian, A. Thomas, Phys.Rev.D 96 (2017) 7, 074010

$\pi^+\pi^0$

Asymmetries



CD, JPS Conf.Proc. 37 (2022) 020109, SPIN2021

→ Analysis continuing by G. Matousek (Duke U.)

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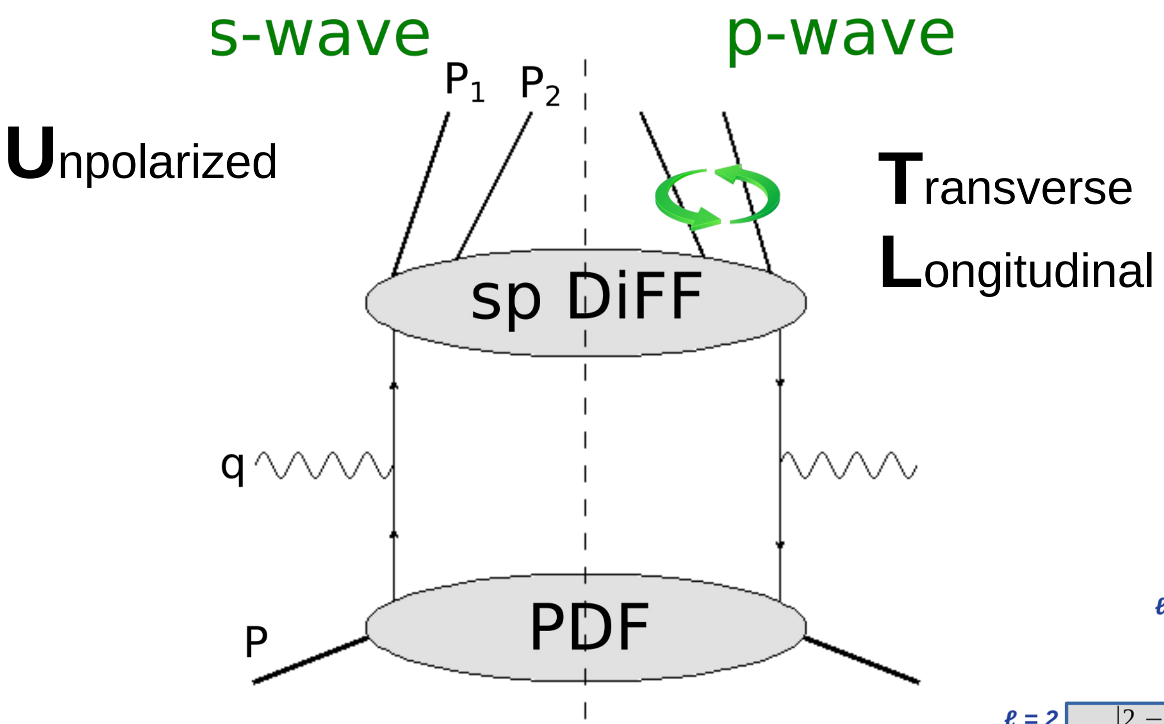
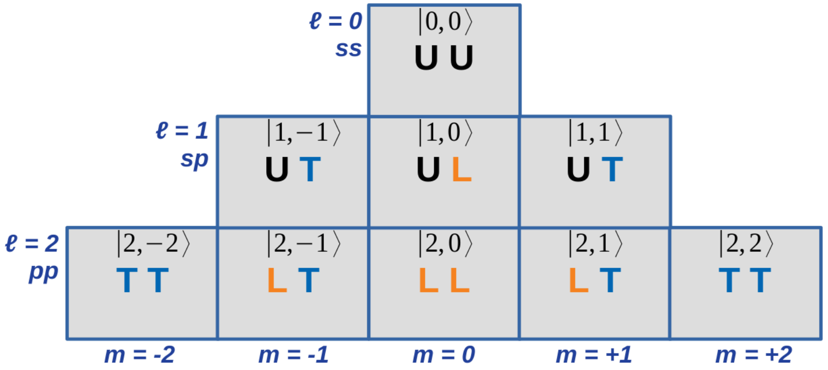
Partial Waves



- Expand DiFFs into spherical harmonics
- Correlations of angular momentum of dihadrons with that of fragmenting quark
- Infinitely many terms (typically truncate ℓ≤2)



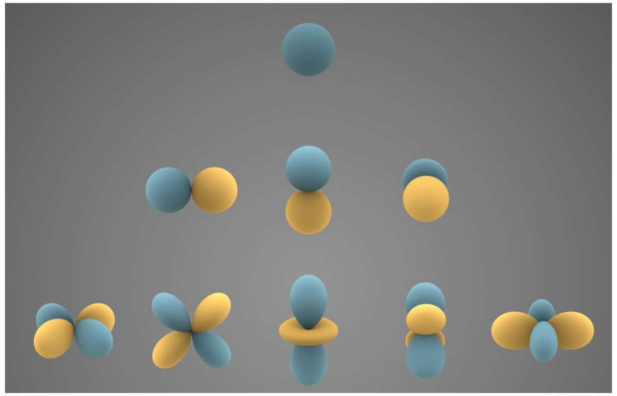


Image from Wikipedia: Spherical Harmonics

Bacchetta, Alessandro, and Marco Radici. “Partial-Wave Analysis of Two-Hadron Fragmentation Functions.” Physical Review D 67, no. 9 (May 6, 2003): 094002. https://doi.org/10.1103/PhysRevD.67.094002.

Gliske, Stephen, Alessandro Bacchetta, and Marco Radici. “Production of Two Hadrons in Semi-Inclusive Deep Inelatic Scattering.” Physical Review D 90, no. 11 (December 23, 2014): 114027. https://doi.org/10.1103/PhysRevD.90.114027.

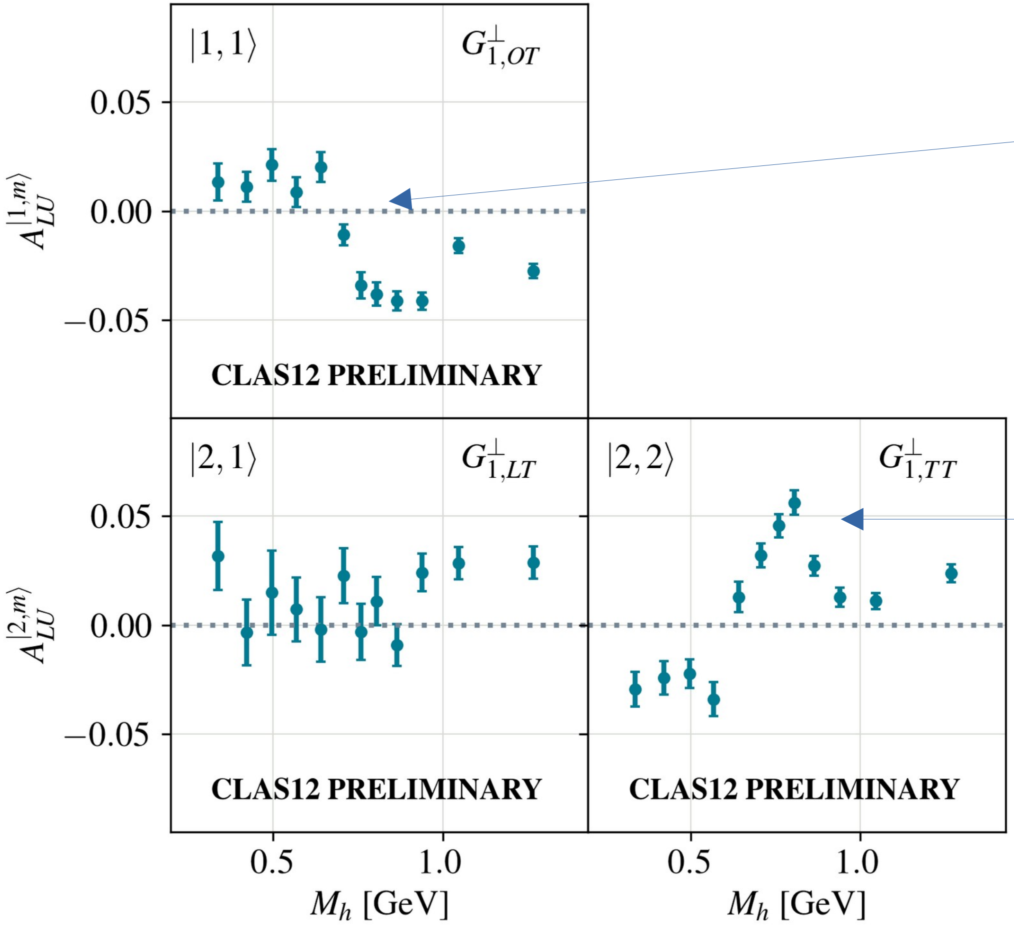
CLAS12 Partial Waves in Beam Spin Asymmetries

Twist 2

Sensitive to
$f_1 \bullet G_1^{\perp}$

sp-interference

pp-interference

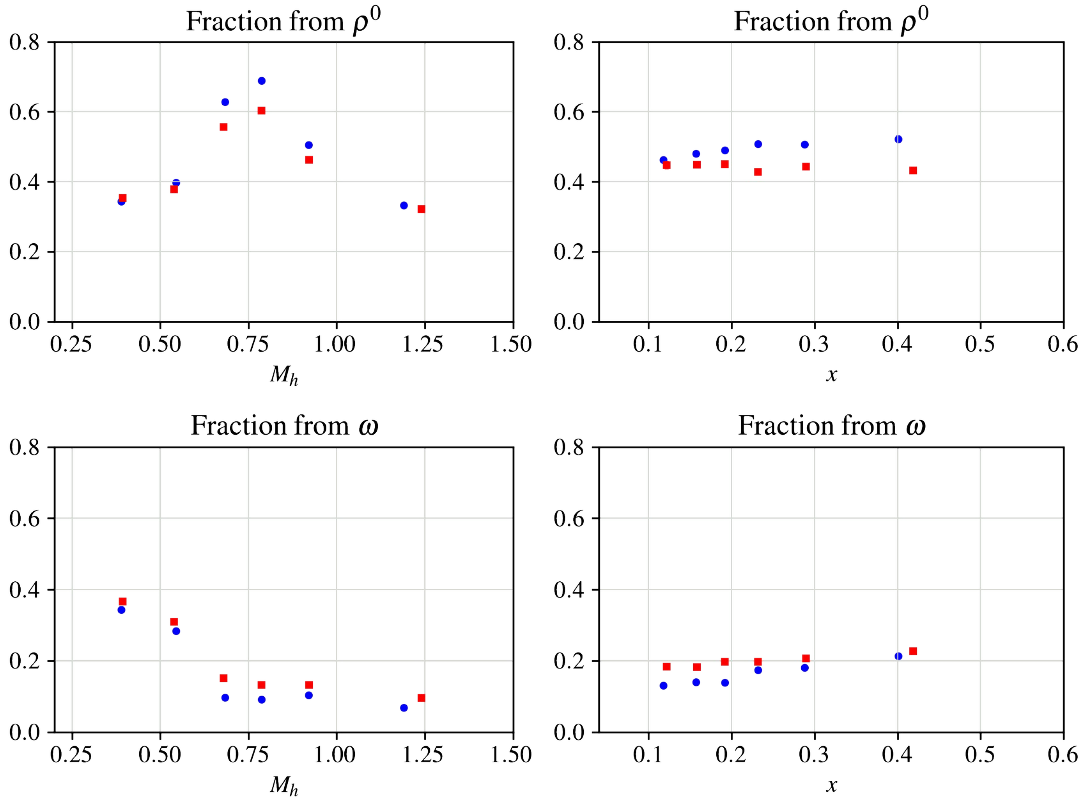


Aforementioned sign change

Enhancement at ρ mass
Spin-1 Fragmentation Function * Breit Wigner?

CD, 2107.12965 [hep-ex]

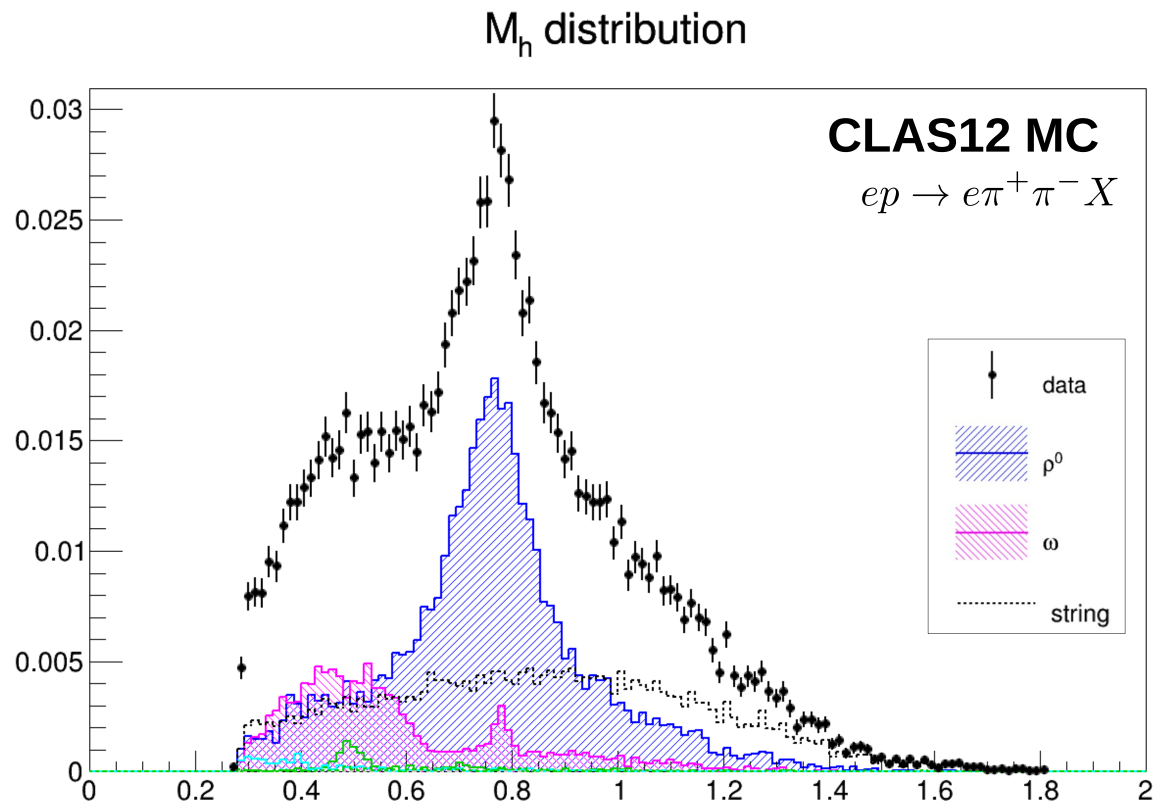
Vector Meson Contributions



Fractions where one or both hadrons originate from a ρ or ω

22 GeV

10.6 GeV



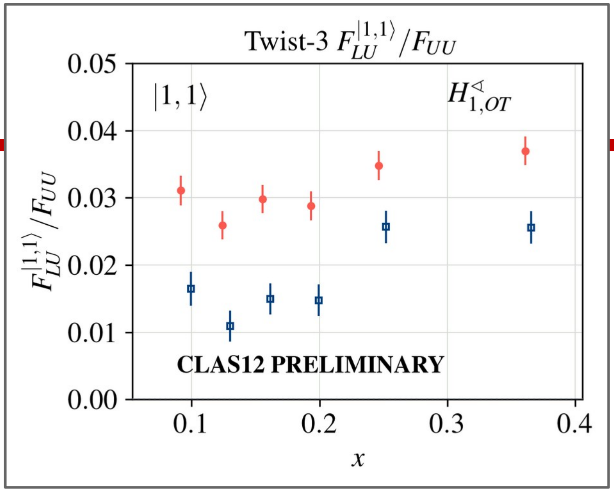
Jefferson Lab

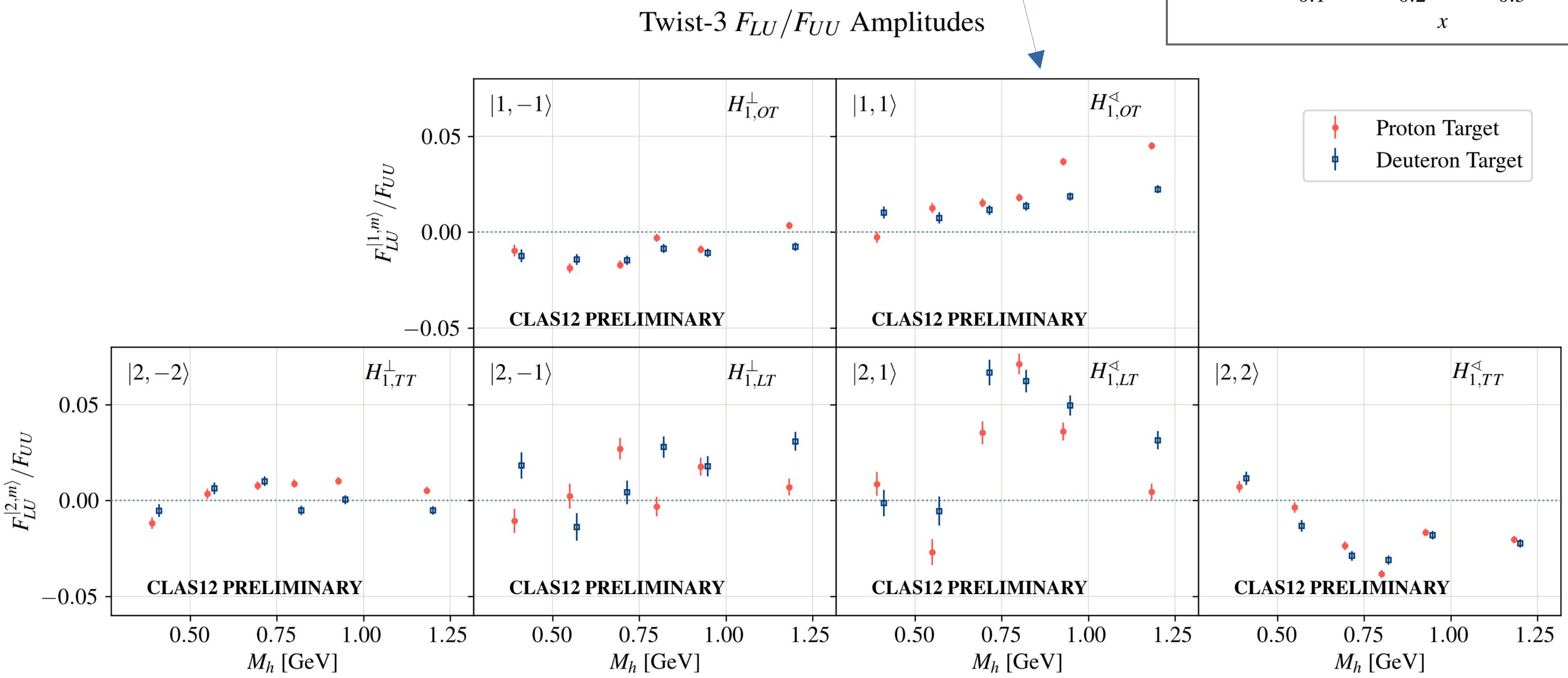
CLAS12 Partial Waves in Beam Spin Asymmetries

Twist 3

Sensitive to
e ● H_1

Flavor dependence of e(x)





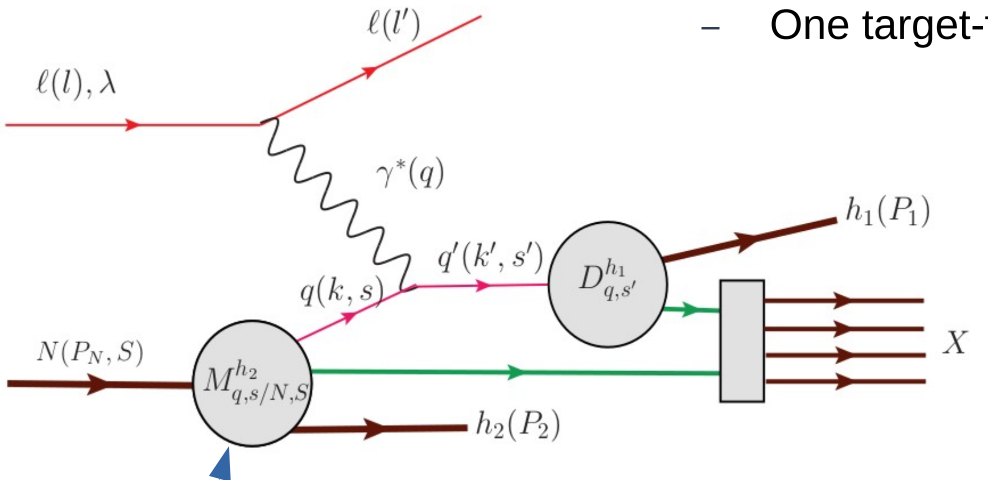
sp-interference

pp-interference

CD, Transversity 2022

Current and Target Fragmentation Region Correlations

- Fracture functions accessible in “Double SIDIS” a.k.a. “Back-to-Back” production
  - One current-fragmentation region (CFR) hadron h_1
  - One target-fragmentation region (TFR) hadron h_2



A. Kotzinian, et al., Nuovo Cim.C 036 (2013) 05, 127-130

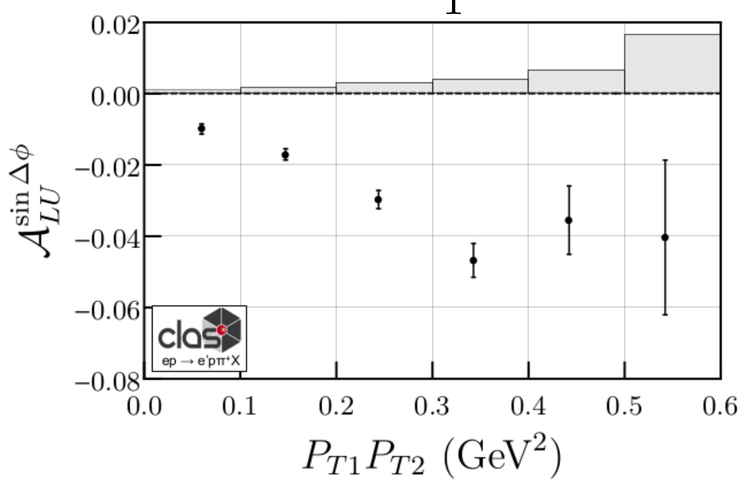
Fracture Functions:

- Conditional probability to produce a target-fragmentation hadron
- Similar to TMDs, different fracture functions for different combinations of quark and nucleon polarizations

H. Avakian, T.B. Hayward, et al., Phys.Rev.Lett. 130 (2023) 2, 022501

CFR pion, TFR proton → $\hat{l}_1^{\perp p}$ (L quark, U nucleon)

→ $\hat{u}_1^{p}$ (unpolarized)



See T. Hayward’s talk

Exploring fracture functions with semi-inclusive target- and double-spin asymmetries in the target fragmentation region with CLAS12

Outline

- Kinematics and Cross Section for SIDIS Dihadrons
- Distribution and Fragmentation Functions
- Partial Waves, Vector Mesons, Fracture Functions
- **Ongoing and Future Studies**

CLAS12 Opportunities with a Longitudinally Polarized Target

Target Spin Asymmetry A_{UL}

- Access twist-3 distribution $h_L(x)$
- Kotzinian-Mulders (wormgear) TMD PDF
- Other twist-3 TMDs (or at least their integrals)?

Double Spin Asymmetry A_{LL}

- Unpolarized DiFF D_1 partial waves
  - *cf.* access from multiplicity modulations
- Constrain twist-3 DiFFs
  - Maybe small; needed for e(x) and $h_L(x)$ extraction
  - Additional leverage from A_{LU} / A_{UL}

TFR/CFR Correlations (DSIDIS)

- More Fracture Functions

$h_L(x)$

- 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

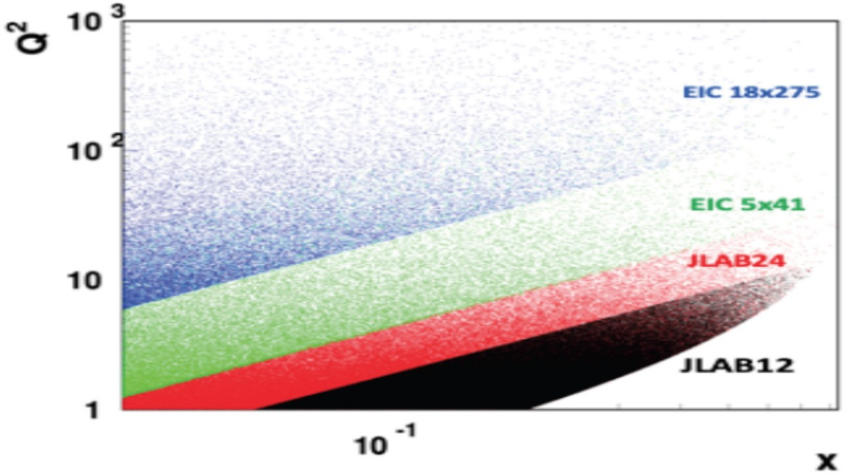
- M. Abdallah, M. Burkardt, Phys.Rev.D 94 (2016) 9, 094040
- M. Burkardt, Phys.Rev.D 66 (2002) 114005
- P.J. Mulders, R.D. Tangerman, Nucl.Phys.B 461 (1996) 197-237

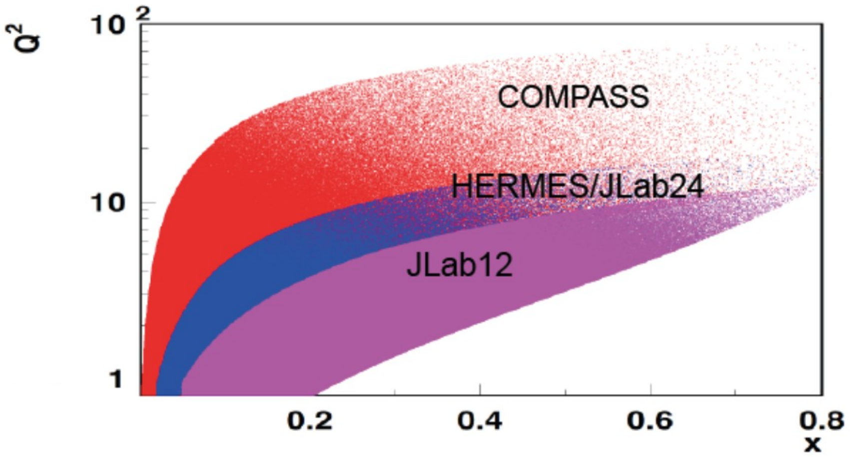
See G. Matousek's talk:
Spin observables in Deep Processes with CLAS12 at Jefferson Lab

H. Avakian, C. Dilks, O. Soto, et al., E12-09-007A (PAC 48 Proposal)

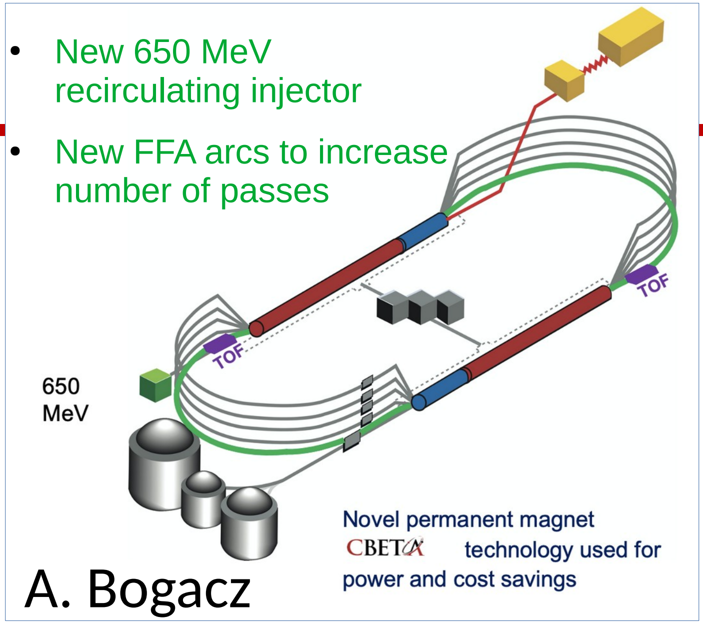
Opportunities with Future Experiments: CLAS at 22 GeV

- CLAS has the ideal phase space for studying twist-3 effects: $e(x)$, $h_L(x)$, $g_T(x)$
  - Especially asymmetries that require a *longitudinally* polarized electron beam
- Improve overlap in the region between EIC and CLAS12
  - Wide range in Q^2 and p_T combined with high luminosity and superior resolution
  - Evolution studies, complementary to other experiments





H. Avakian,
JLab at 22 GeV Workshop



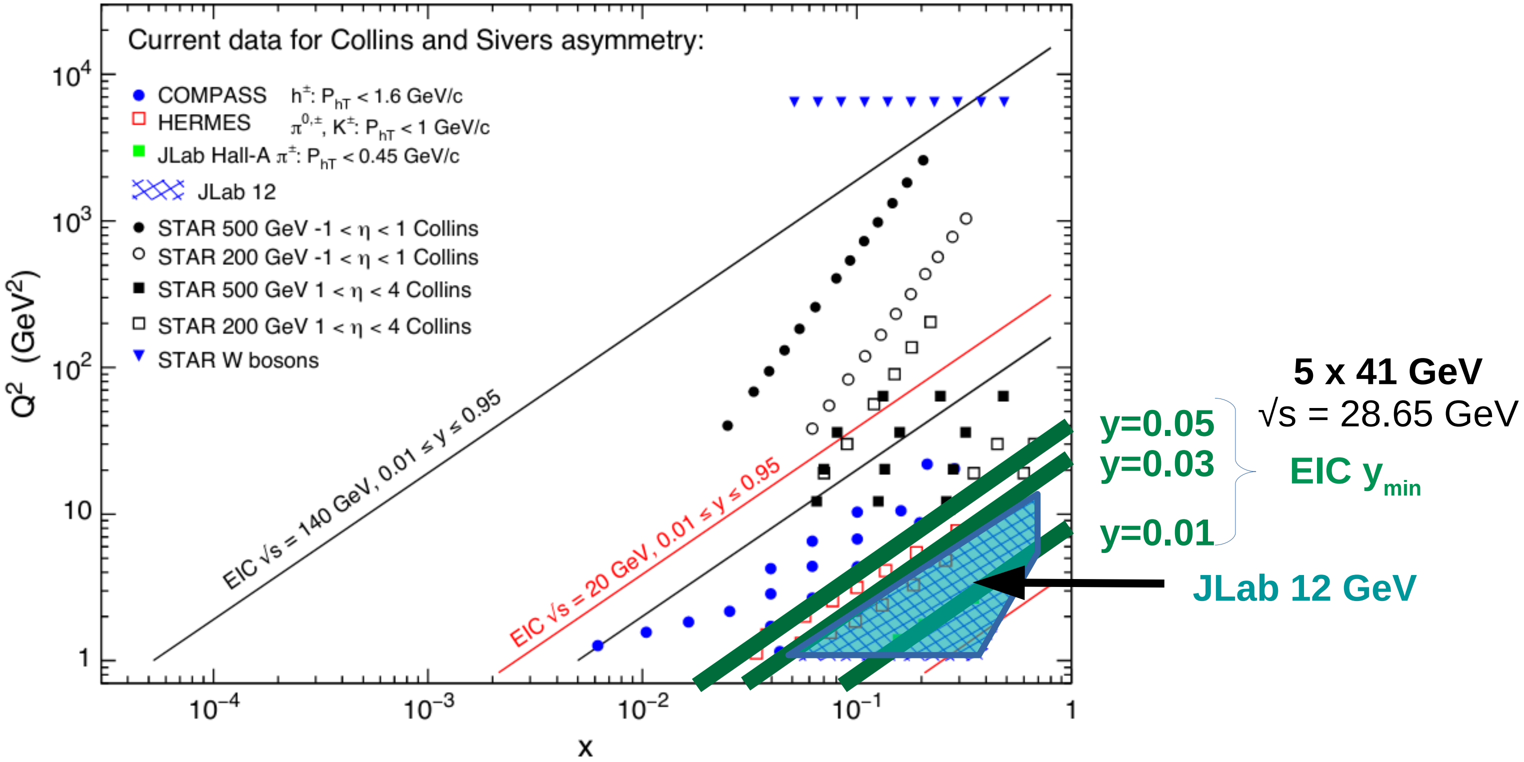
See A. Bogacz's talk
22 GeV CEBAF with Novel FFA Design

See C. Keppel's talk
New Opportunities with Jefferson Lab at 22 GeV
Sep 29, 2023, 5:00 PM

Opportunities with Future Experiments: Electron-Ion Collider (EIC)

- A_{UT} and A_{UL} at higher Q^2 and lower x → evolution studies
  - Transversity, Sivers, $h_L(x)$, DiFF partial waves, and more
  - Back-to-back suppression in *ep* vs. *eA*: probe saturation effects

- 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



e-Print: 2302.00605 [nucl-ex]

Complementary between all the experiments is critical to continue to broaden our understanding of the nucleon (and nuclei)

Opportunities with Future Experiments: Electron-Ion Collider (EIC)

Proton Spin at EIC

Sep 25, 2023, 4:00 PM

[M. Zurek]

The ePIC Detector and Physics

Sep 28, 2023, 12:00 PM

[B. Schmookler]

Measuring Transversity in Di-Hadron Correlations with the ePIC Detector

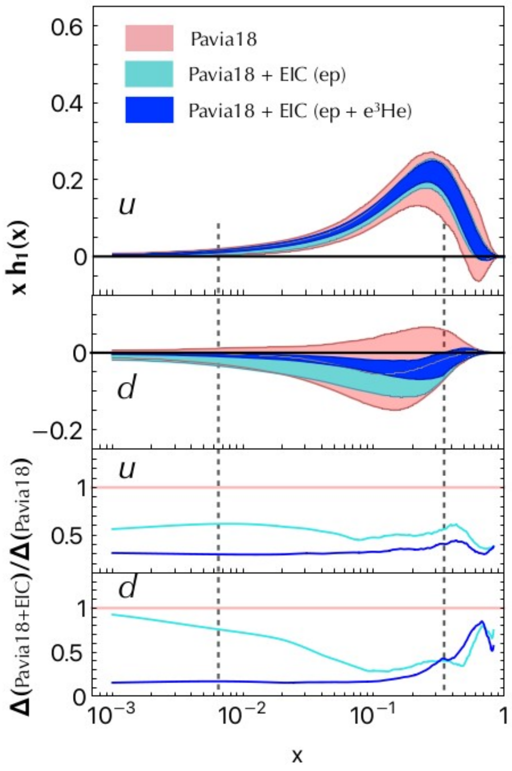
Sep 28, 2023, 7:00 PM

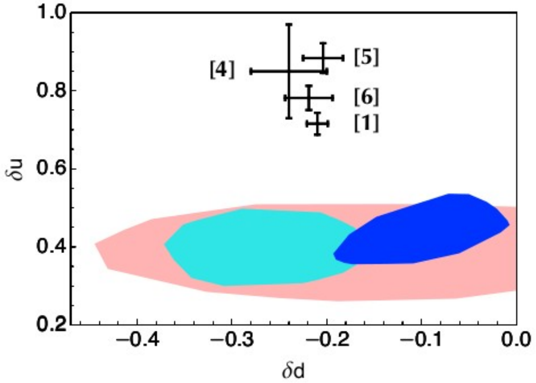
[S. Reiman]

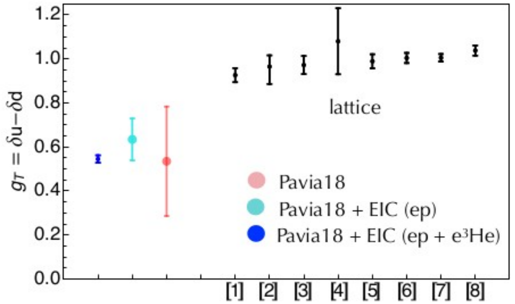
(poster)

Dihadron Impact on Transversity at the EIC

- 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)



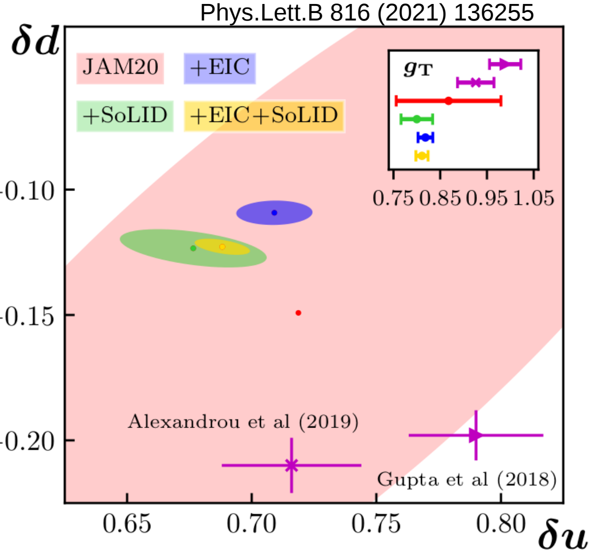




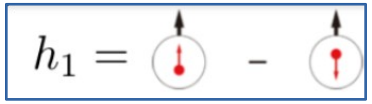
EIC Yellow Report

cf. single-hadron impact

Phys.Lett.B 816 (2021) 136255



Transversity



Tensor Charge

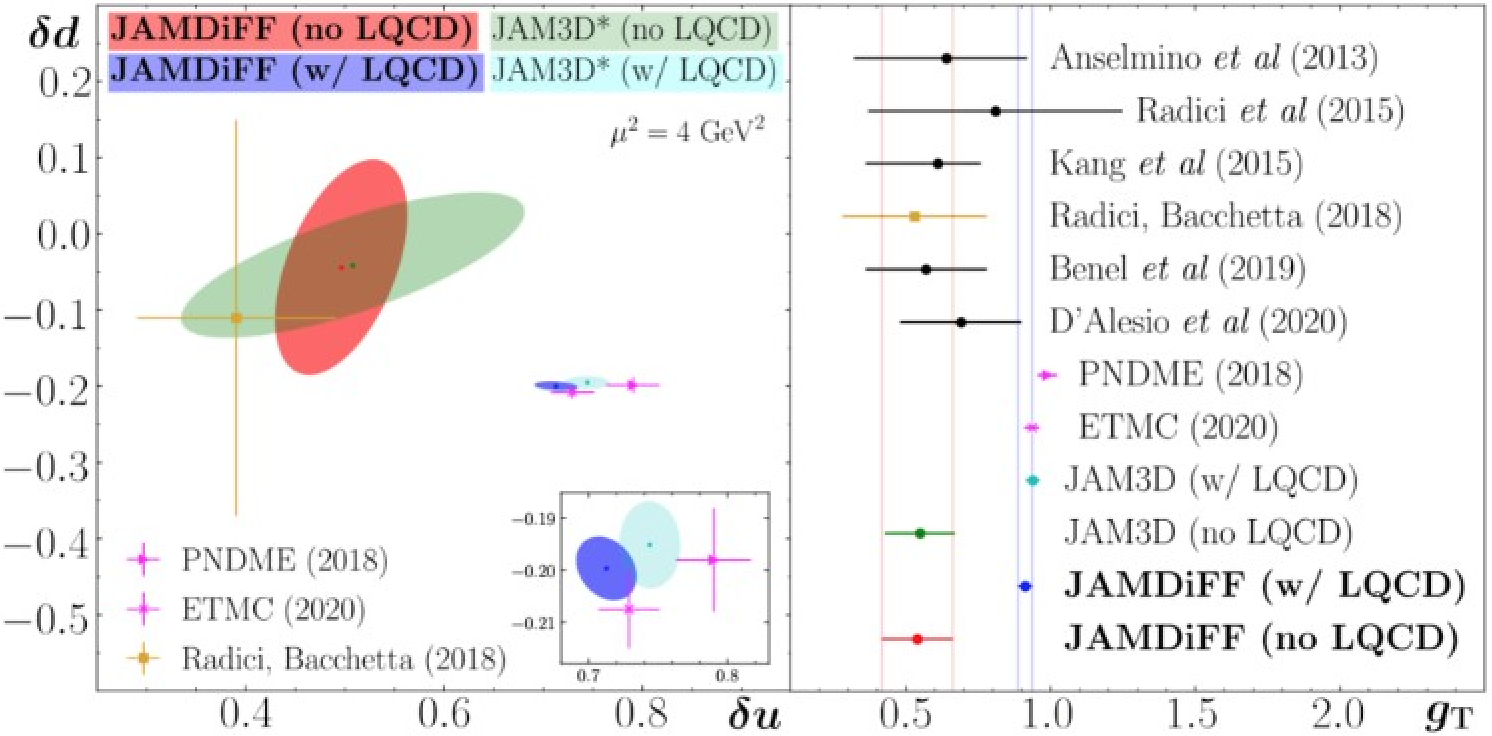
$$\delta q = \int_{-1}^{1} dx h(x) = \int_{0}^{1} dx\left[h(x) - \bar{h}(x)\right]$$

Dihadron Impact on Transversity

Need for New Data

- Unpolarized data for di-hadron production in SIDIS and pp collision would help to constrain $D_1^{\pi^+\pi^-/a}$
- (Precise) data for A_{UT} at any x would better constrain $h_1^{q_v}(x)$, $h_1^{\bar{q}}(x)$
- For the tensor charge δq, (new) data for $x \gtrsim 0.2$ seems most important

$$A_{UT}^{\mathrm{SIDIS}} = c(y)\frac{\sum_{q,\bar{q}} e_q^2\, h_1^q(x)\, H_1^{\sphericalangle,q}(z, M_h)}{\sum_{q,\bar{q}} e_q^2\, f_1^q(x)\, D_1^q(z, M_h)}$$

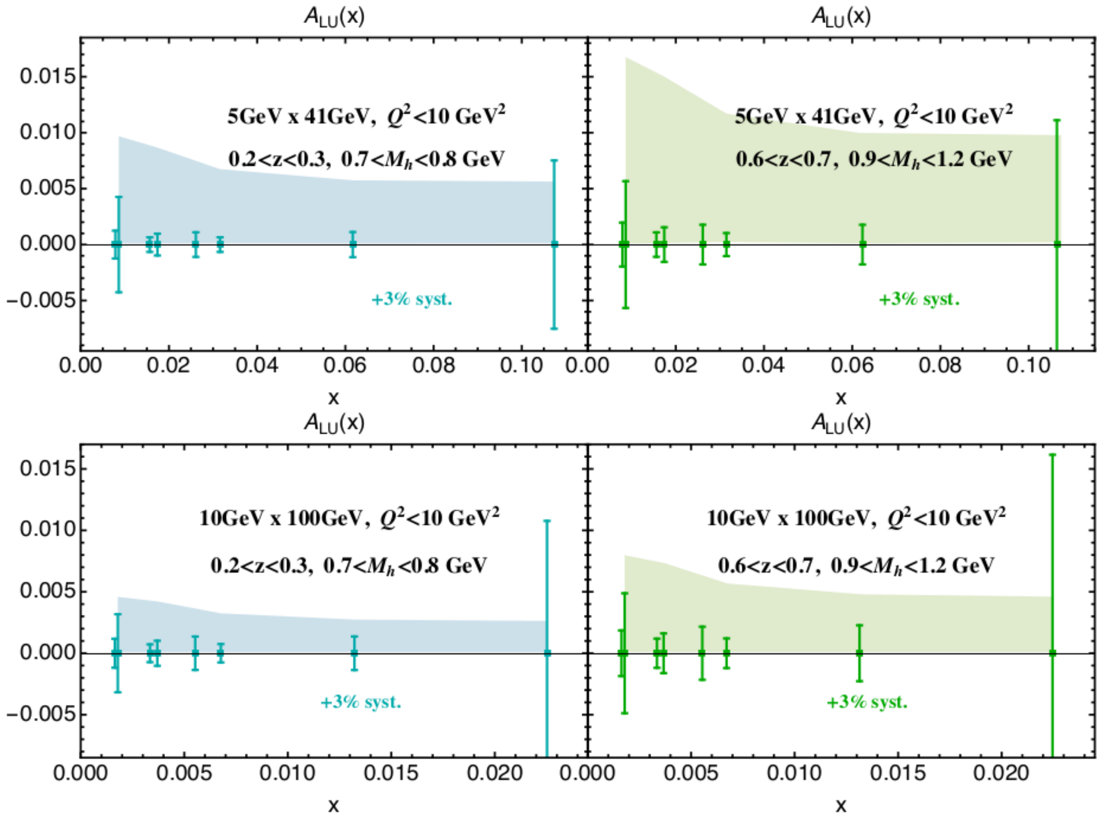


From A. Metz's talk:

New Developments in Di-Hadron Theory and Phenomenology

(Andreas Metz, Temple University)

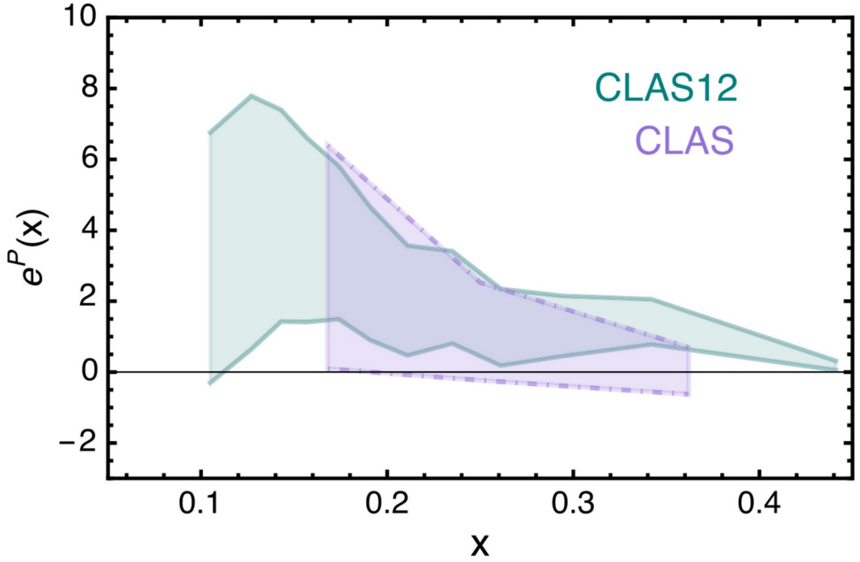
Dihadron Impact on Collinear Twist-3 e(x) at the EIC



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

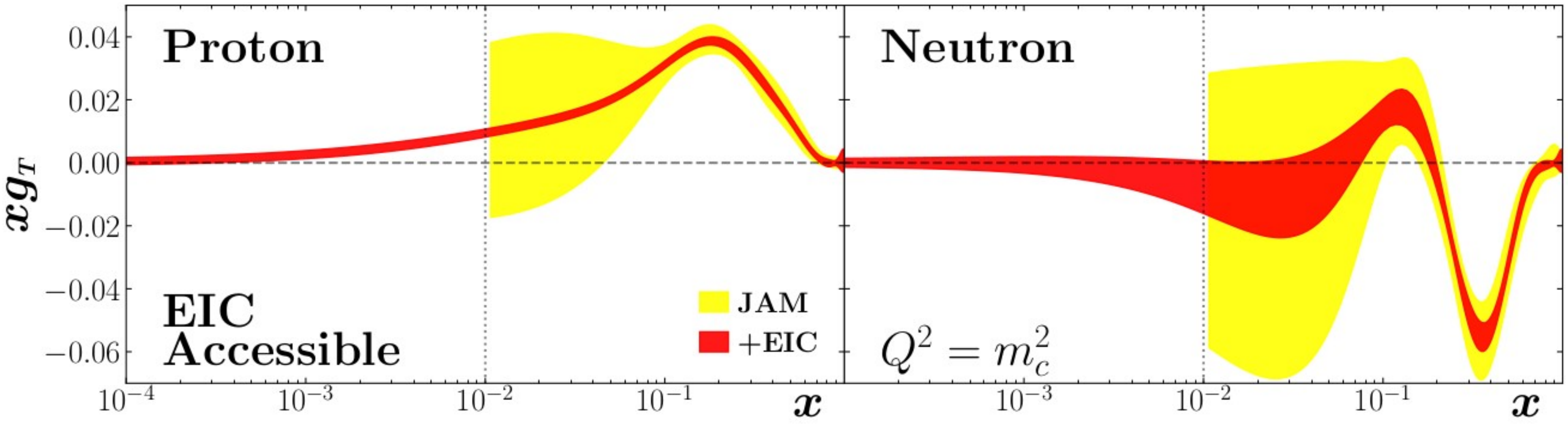
Extraction from CLAS dihadrons



A. Courtoy, et al., Phys.Rev.D 106 (2022) 1, 014027

Jefferson Lab

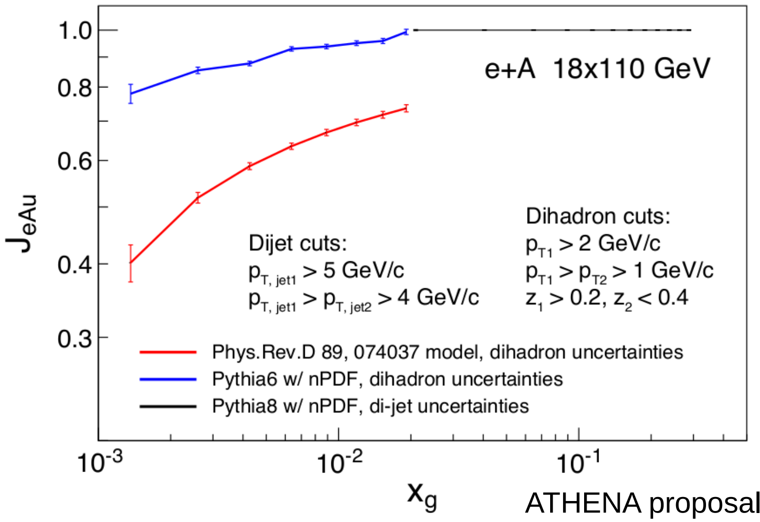
Dihadron Impact on Collinear Twist-3 $g_T(x)$ at the EIC



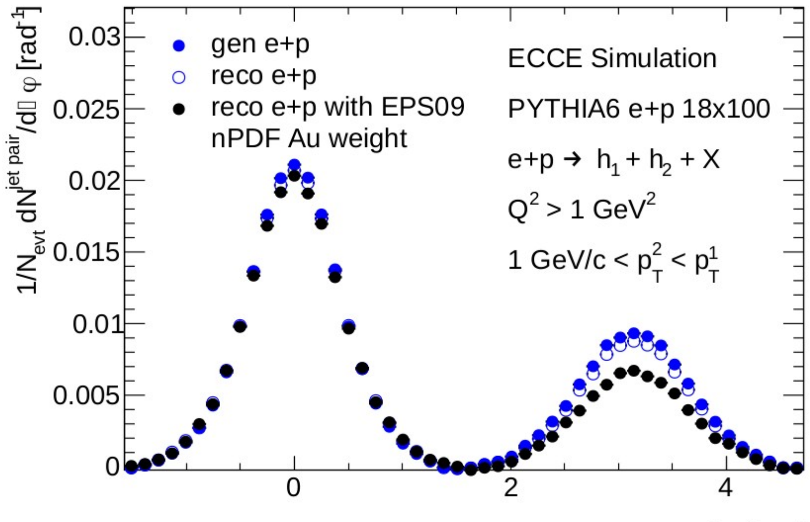
EIC Yellow Report

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

Dihadrons for Gluon Saturation at the EIC



ATHENA proposal



ECCE proposal

- Away-side peak in $\Delta\phi$ 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

So much to measure…

Asymmetries & Multiplicity
(different combinations of PDFs and DiFFs)

Vector Mesons
(Spin-1 effects)

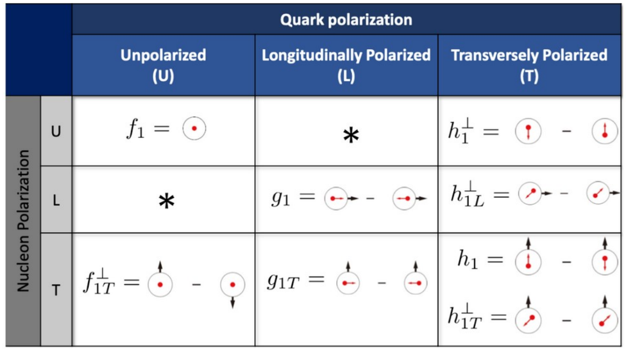
Partial Waves
(Spin/Orbit effects in Fragmentation)

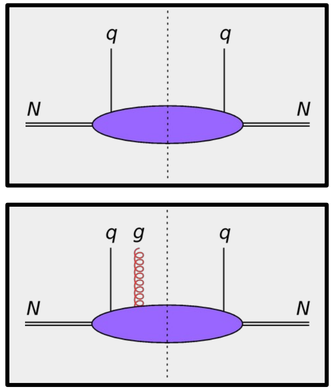
TFR / CFR Correlations
(Fracture Functions)

Dihadron Channels
(DiFFs for each Hadron Pair)

Proton vs. Deuteron Target
(Flavor separation of PDFs)

… and so much to learn!

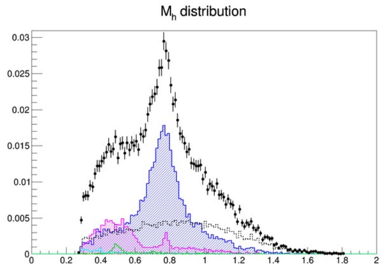


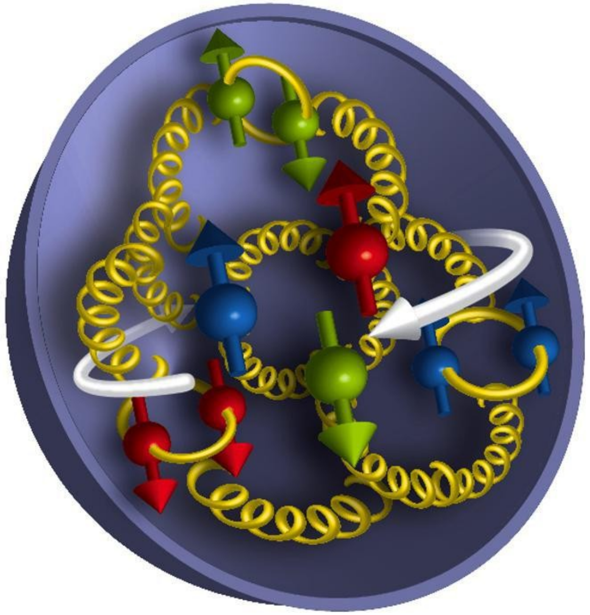


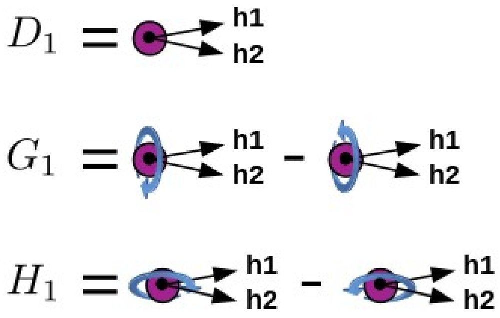
e

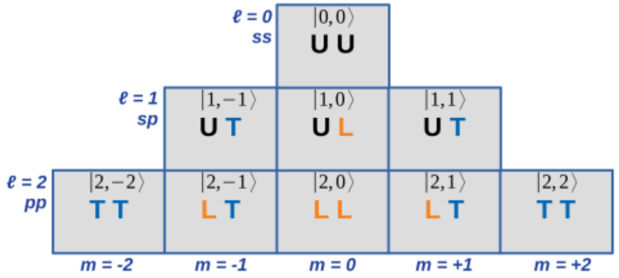
g_T

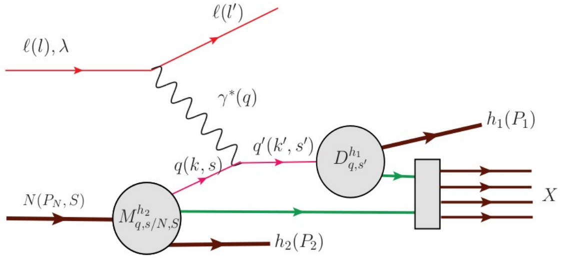
h_L











… and possibly more to discover