SIDIS Dihadron Beam Spin Asymmetries at CLAS12

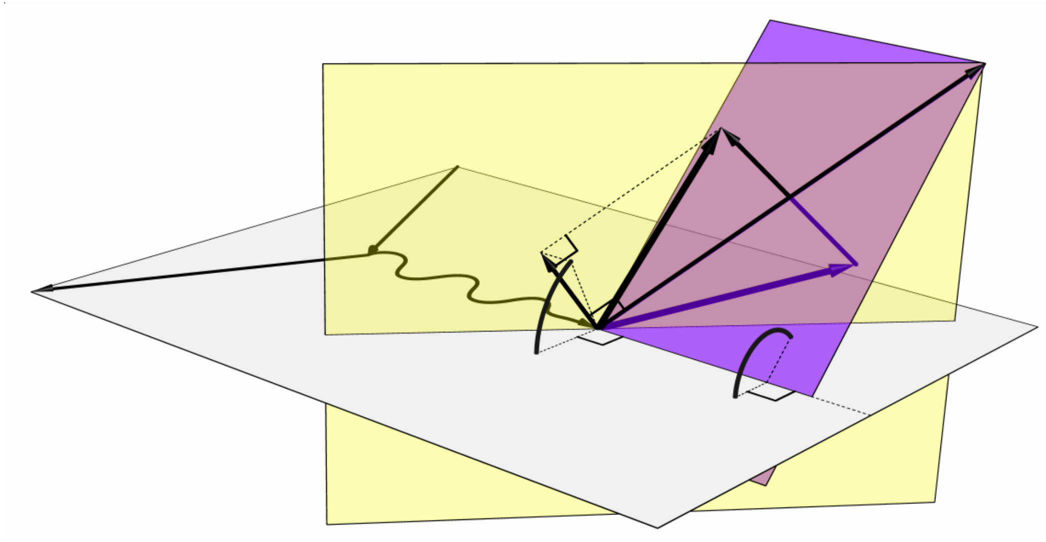
– Flavor Dependence from Proton and Deuteron Targets –

Christopher Dilks

May 2022

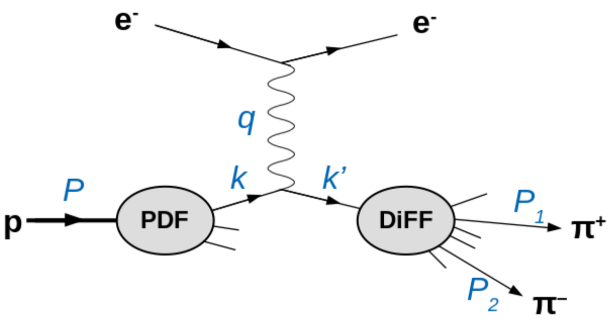
Research supported by the U.S. DEPARTMENT OF ENERGY Office of Science

Dihadrons, PDFs, and Fragmentation



Dihadron Kinematics

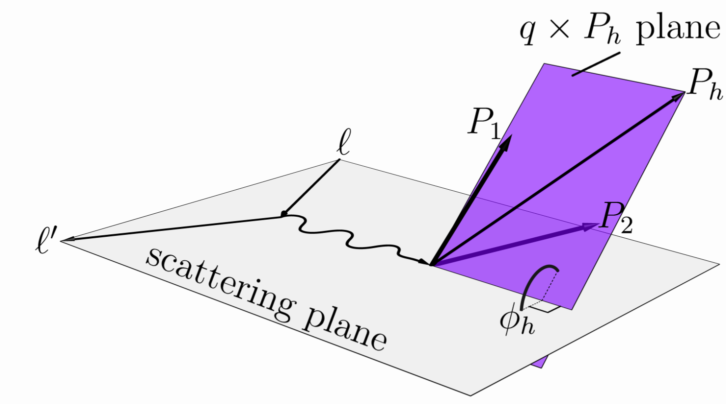
$$eN \rightarrow e + \pi^{+}(P_1) + \pi^{-}(P_2) + X$$



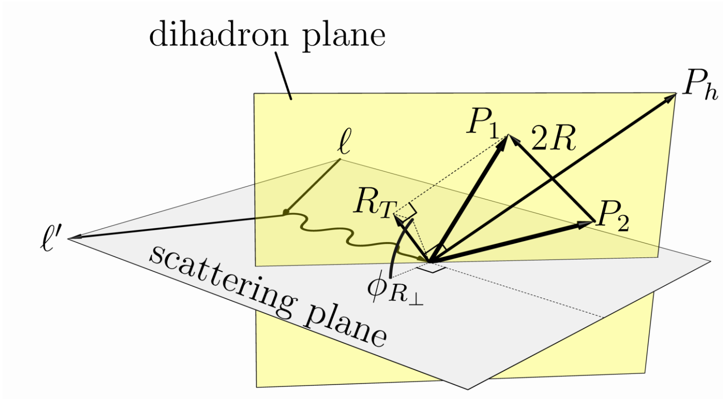
momentum: $P_h = P_1 + P_2$

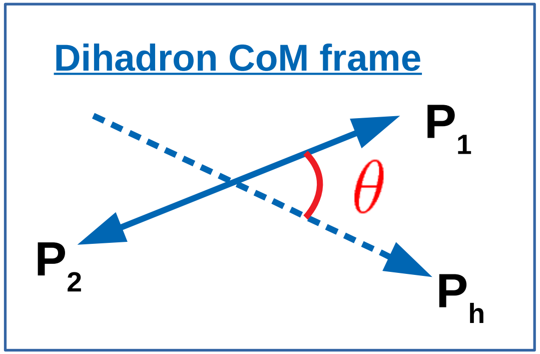
kinematics: $M_h, \; z, \; p_T$

angles: $\phi_h, \; \phi_R, \; \theta$ → **Cross Section Modulations** → $\text{PDF} \otimes \text{DiFF}$



cf. single-hadron ϕ_h





Beam Spin Asymmetry → e(x) Constraints

$$A_{LU} = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} = A_{LU}^{\sin\phi_R}\sin\phi_R + A_{LU}^{\sin\phi_h}\sin\phi_h + \dots$$

$$A_{LU}^{\sin\phi_R} \propto e(x)\cdot H_1^{\sphericalangle}$$

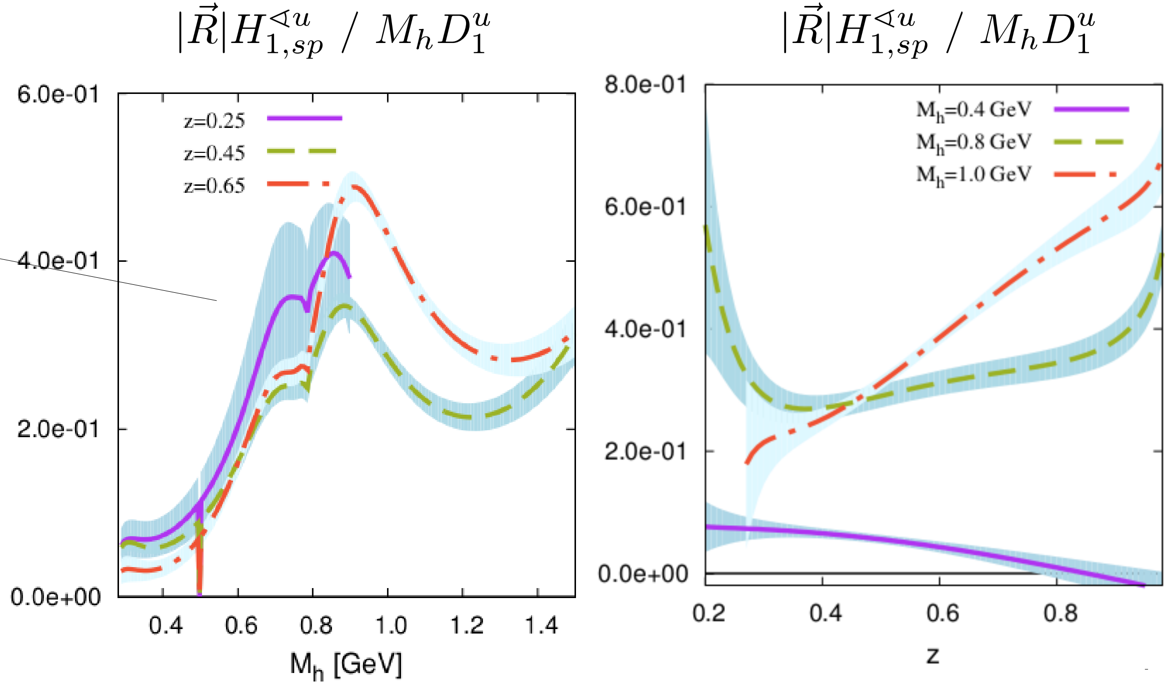
$e(x)$ collinear twist-3 PDF

$H_1^{\sphericalangle}$ dihadron fragmentation function (DiFF)

Measurement of A_{LU}

+ Extraction of $H_1^{<}$ from Belle Data

= **access to e(x)**



Phys.Rev.D 85 (2012) 114023

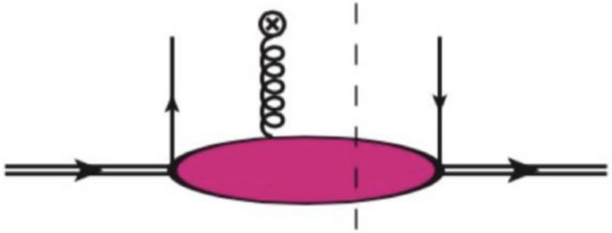
C. Dilks

Twist-3 Collinear PDFs

Collinear PDFs
– **Twist-2**
– **Twist-3**

Nucleon Polarization \ Quark Polarization	U	L	T
U	f_1		e
L		g_1	h_L
T		g_T	h_1

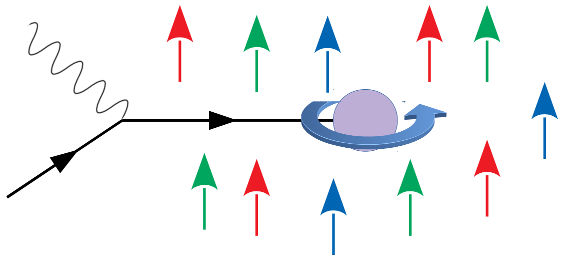
- Twist-3 TMDs are expressible in terms of multi-parton correlators
- Fundamental to understanding TMDs in general
- Physical interpretation through *x-moments*



e(x) accessible in Beam Spin Asymmetry A_{LU}

- Physical interpretation via moments:
  - Pion-nucleon σ term: $m_q \rightarrow m_N$
  - "Boer-Mulders Force": Transverse force exerted by color field on q↑ after scattering, in an unpolarized nucleon

Phys.Rev.D 88 (2013) 114502

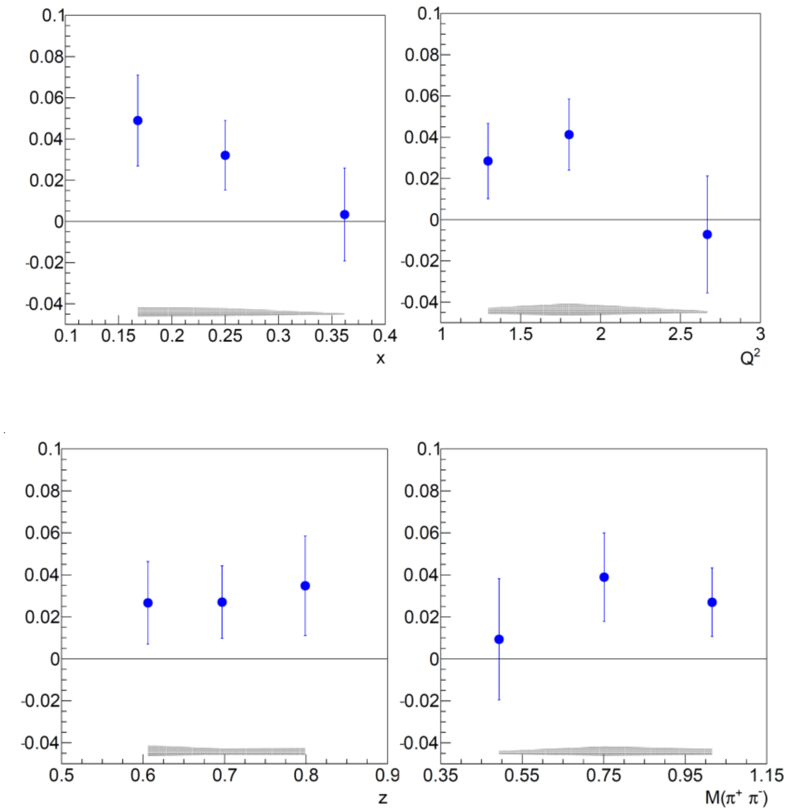


Target Spin Asymmetry A_{UL}

A proposed measurement for Run Group C

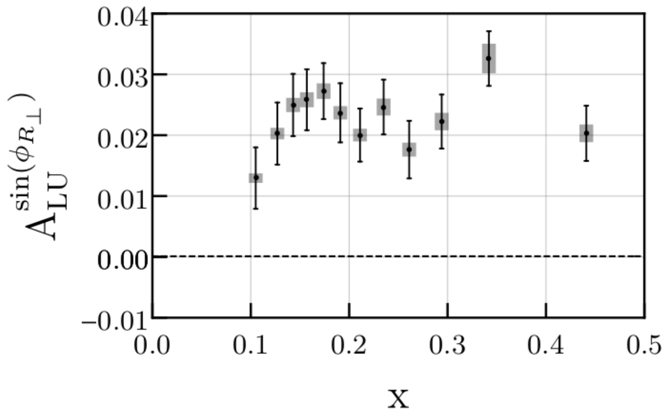
Dihadron A_{LU} Measurements – Proton Target

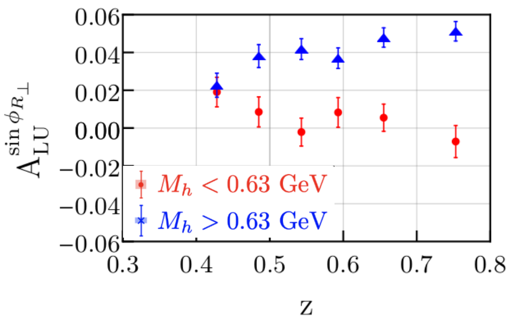
CLAS6 $\pi^+\pi^-$ $A_{LU}^{\sin\phi_R}$

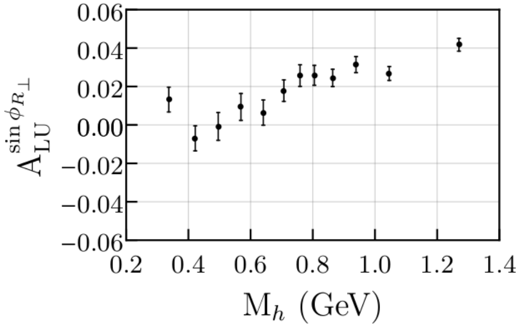


Phys.Rev.Lett. 126 (2021) 6, 062002

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







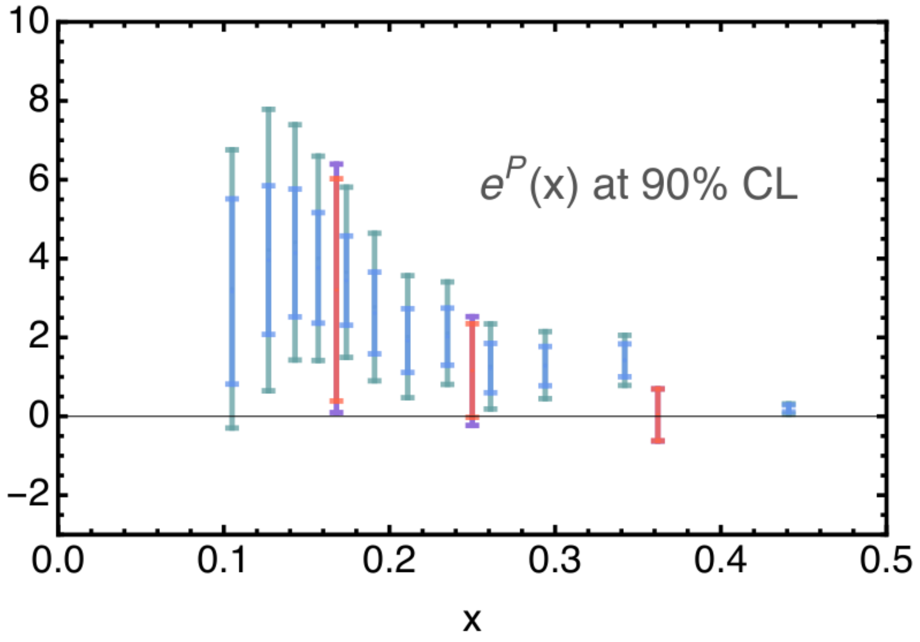
Phys.Rev.Lett. 126 (2021) 152501

New e(x) Extraction – Proton Flavor Combination

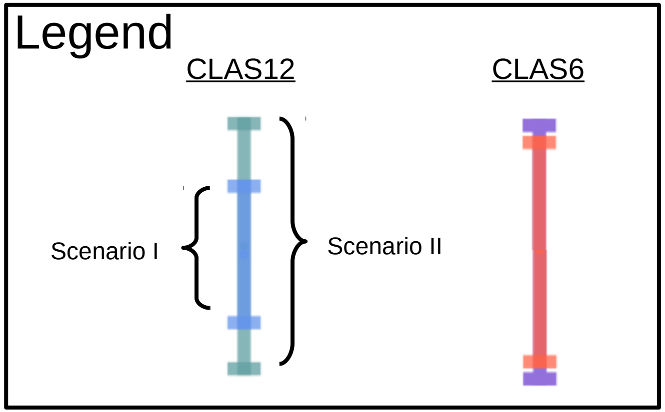
See Aurore's talk (NEXT)

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

twist-3 DiFF



- **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}

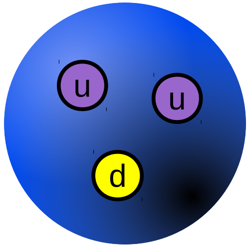


Courtoy, Aurore, et al. e-Print: 2203.14975 [hep-ph]
Courtoy, Aurore – CPHI 2022

Accessing Flavor Dependence of e(x)

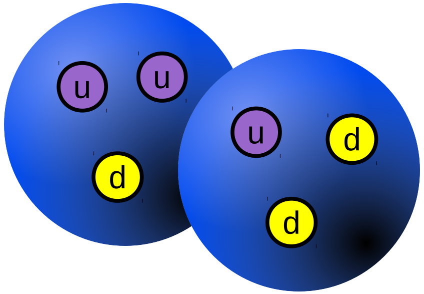
Different targets → flavor dependence

Proton Target



$$A_{LU,\mathbf{p}}^{\text{twist 3}} \propto 4xe^{u_V}(x) - xe^{d_V}(x)$$

Deuteron Target

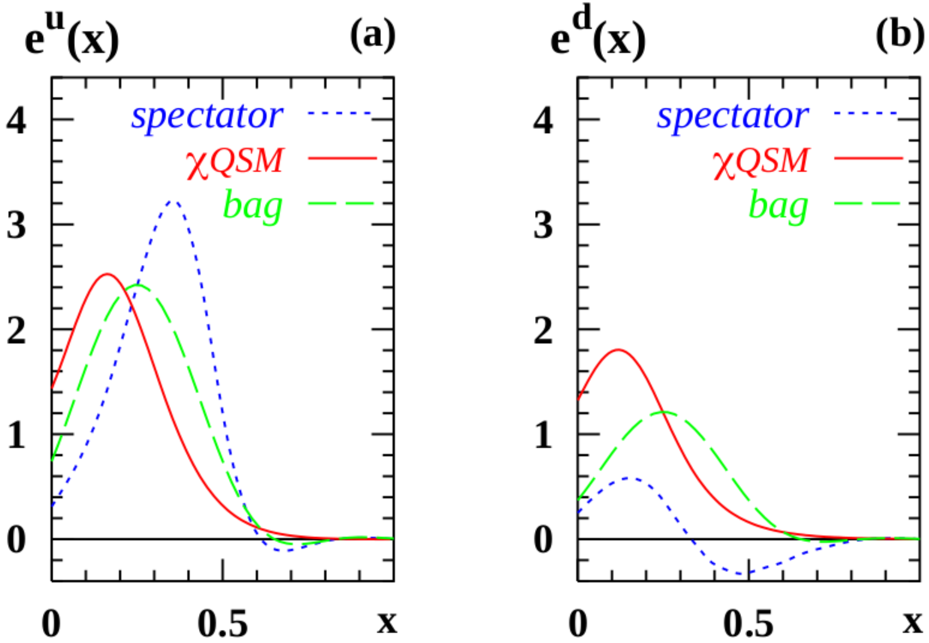


$$A_{LU,\mathbf{d}}^{\text{twist 3}} \propto xe^{u_V}(x) + xe^{d_V}(x)$$

2 equations and 2 unknowns: decouple flavor dependence of e(x) → $\boldsymbol{e^{uv}(x)}$ **and** $\boldsymbol{e^{dv}(x)}$

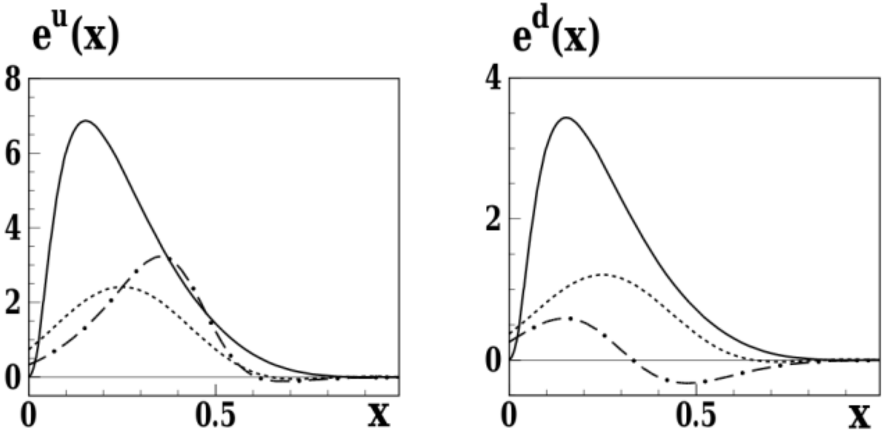
e(x) Model Predictions

- Several model predictions available
- Some differences, but mind the scale:
  - Bag: 0.4 GeV
  - Spectator: 0.5 GeV
  - χQSM: 0.6 GeV
- $e^u(x)$ and $e^d(x)$ significant for $x<0.5$



Bag Model: Nucl.Phys.B 375 (1992) 527-560
Nucl.Phys.B 497 (1997) 415-434
Spectator Model: Nucl.Phys.A 626 (1997) 937-965
Chiral Quark Soliton Model (χQSM): Acta Phys.Polon.B 39 (2008) 609-640

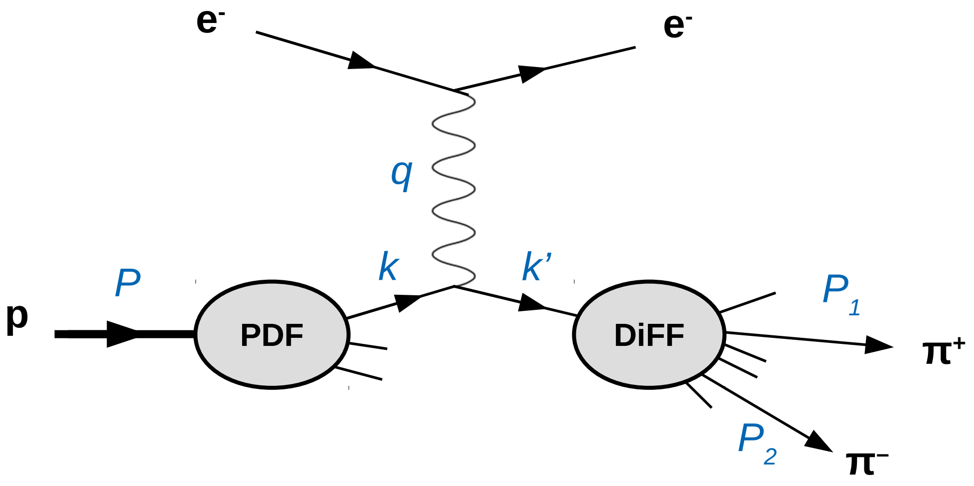
Light-Front Constituent Quark Model



JHEP 01 (2015) 103
Solid: LFCQM model
Dot-Dashed: spectator model
Dashed: bag model

- Relatively larger magnitude partly due to mass effects

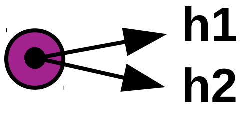
Factorization

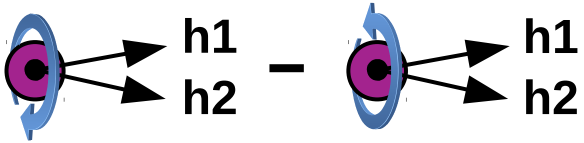


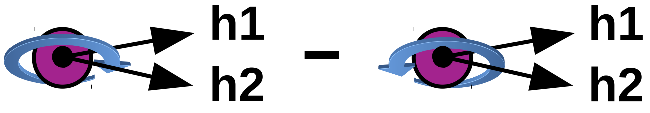
$$\text{Structure Function} \propto \text{PDF} \otimes \text{DiFF}$$

Dihadron Fragmentation Functions (DiFFs)

Twist 2

$D_1 =$ 

$G_1 =$ 

$H_1 =$ 

(notation):

$G_1 = G_1^{\perp}$

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

Twist 3

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

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

small ?
see, for example,

PoS DIS2014 (2014) 231

Phys.Rev.D 99 (2019) 5, 054003

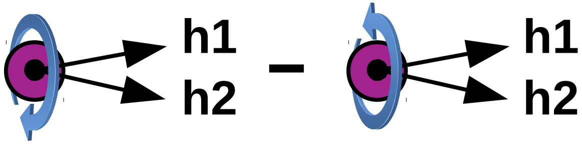
arXiv: 1405.7659 [hep-ph]

Dihadron $A_{LU} \rightarrow$ PDF · DiFF

Twist 2

$$A_{LU}^{\text{twist 2}} \propto f_1 G_1$$

$$G_1 =$$

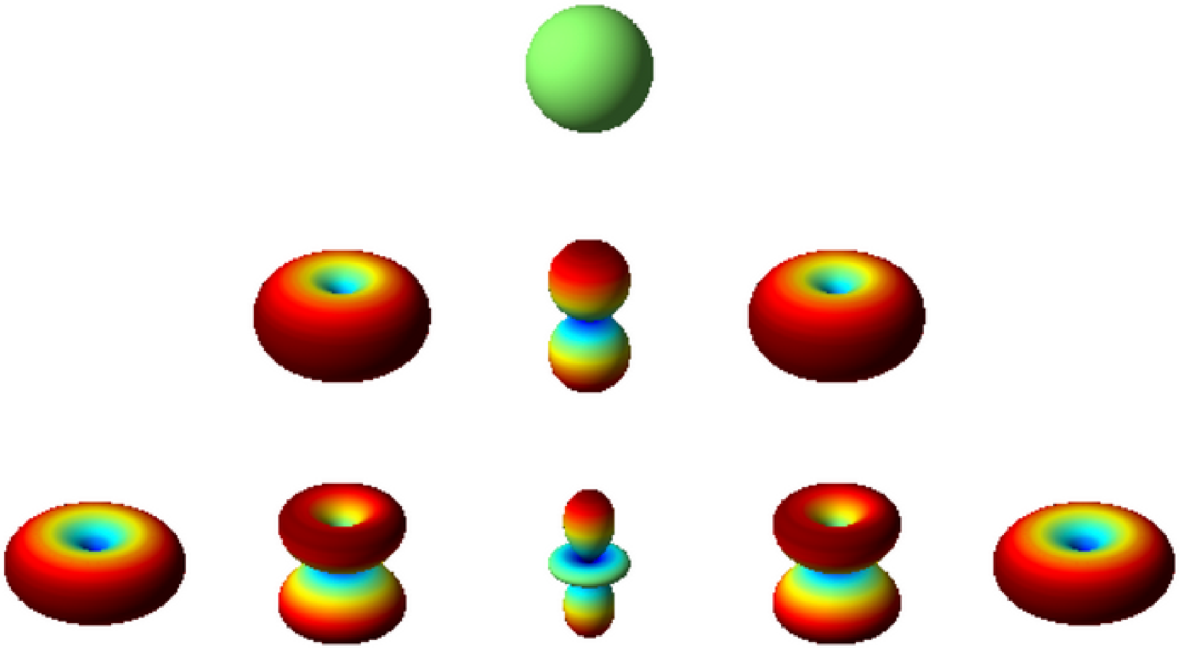


Twist 3

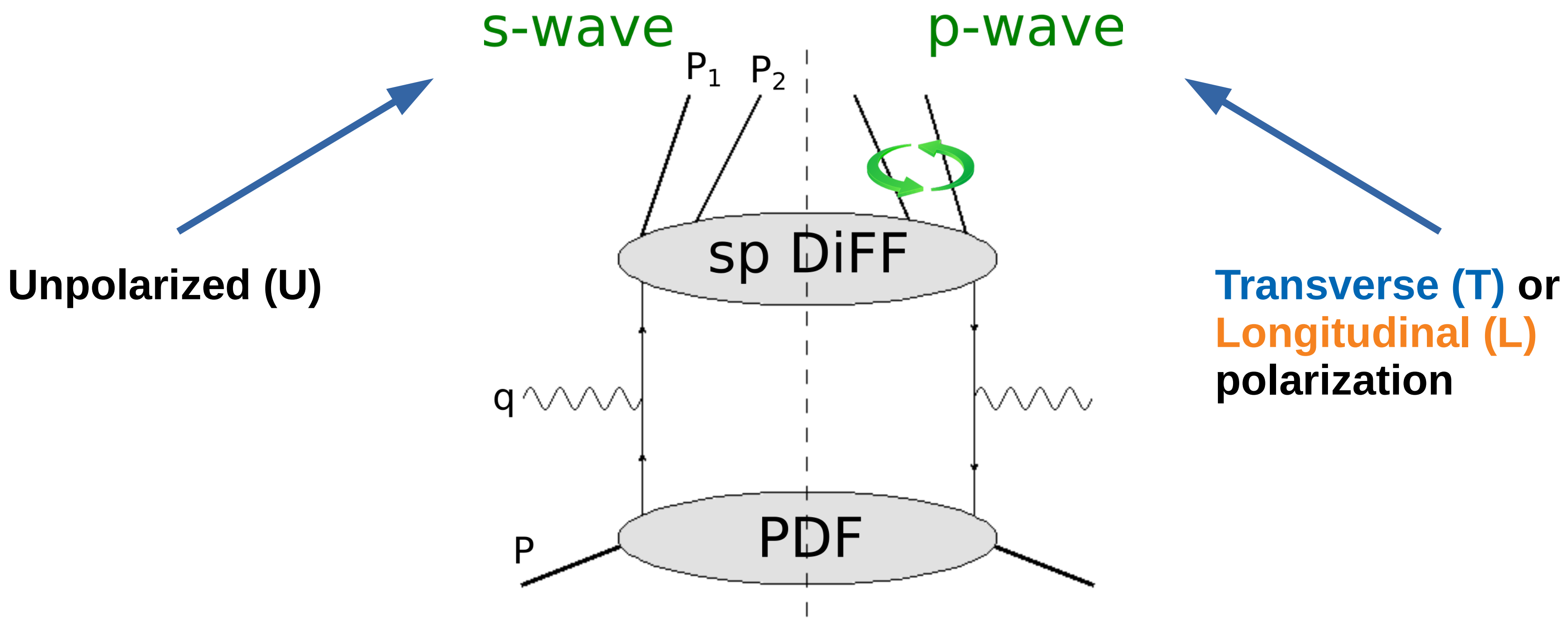
$$A_{LU}^{\text{twist 3}} \propto e H_1$$

$$H_1 =$$

Partial Waves



Partial Wave Expansion



- DiFFs expand on a basis of spherical harmonics
- Angular momentum eigenvalues | ℓ, m >
- Explore dihadron fragmentation depending on relative angular momentum

$$H_1^{\perp} = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\vartheta)\, e^{im(\phi_{R_\perp}-\phi_p)}\, H_1^{\perp|\ell,m\rangle}$$

Partial Waves

$\ell = 0$

ss

$|0,0\rangle$

U U

$m = 0$

Partial Waves

ℓ = 0 *ss*		$\vert 0,0\rangle$ U U	
ℓ = 1 *sp*	$\vert 1,-1\rangle$ U T	$\vert 1,0\rangle$ U L	$\vert 1,1\rangle$ U T
	m = -1	*m = 0*	*m = +1*

Partial Waves

	m = -2	m = -1	m = 0	m = +1	m = +2
ℓ = 0 ss			$\vert 0,0\rangle$ U U		
ℓ = 1 sp		$\vert 1,-1\rangle$ U T	$\vert 1,0\rangle$ U L	$\vert 1,1\rangle$ U T	
ℓ = 2 pp	$\vert 2,-2\rangle$ T T	$\vert 2,-1\rangle$ L T	$\vert 2,0\rangle$ L L	$\vert 2,1\rangle$ L T	$\vert 2,2\rangle$ T T

Partial Waves

	m = -2	m = -1	m = 0	m = +1	m = +2
ℓ = 0 ss			$\|0,0\rangle$ **U U** $G_{1,OO}^{\perp}$ $H_{1,OO}^{\perp}$		
ℓ = 1 sp		$\|1,-1\rangle$ **U T** $G_{1,OT}^{\perp}$ $H_{1,OT}^{\perp}$	$\|1,0\rangle$ **U L** $G_{1,OL}^{\perp}$ $H_{1,OL}^{\perp}$	$\|1,1\rangle$ **U T** $G_{1,OT}^{\perp}$ $H_{1,OT}^{\sphericalangle}$	
ℓ = 2 pp	$\|2,-2\rangle$ **T T** $G_{1,TT}^{\perp}$ $H_{1,TT}^{\perp}$	$\|2,-1\rangle$ **L T** $G_{1,LT}^{\perp}$ $H_{1,LT}^{\perp}$	$\|2,0\rangle$ **L L** $G_{1,LL}^{\perp}$ $H_{1,LL}^{\perp}$	$\|2,1\rangle$ **L T** $G_{1,LT}^{\perp}$ $H_{1,LT}^{\sphericalangle}$	$\|2,2\rangle$ **T T** $G_{1,TT}^{\perp}$ $H_{1,TT}^{\sphericalangle}$

Partial Waves

12 Parameter Simultaneous Fit

Twist 2

3 params

$$G_1^{\perp,|\ell,0\rangle}=0$$

$$G_1^{\perp,|\ell,m\rangle}=G_1^{\perp,|\ell,-m\rangle}$$

	$\|1,1\rangle$ $G_{1,OT}^{\perp}$	
	$\|2,1\rangle$ $G_{1,LT}^{\perp}$	$\|2,2\rangle$ $G_{1,TT}^{\perp}$

Twist 3

9 params

		$\|0,0\rangle$ $H_{1,OO}^{\perp}$		
	$\|1,-1\rangle$ $H_{1,OT}^{\perp}$	$\|1,0\rangle$ $H_{1,OL}^{\perp}$	$\|1,1\rangle$ $H_{1,OT}^{\sphericalangle}$	
$\|2,-2\rangle$ $H_{1,TT}^{\perp}$	$\|2,-1\rangle$ $H_{1,LT}^{\perp}$	$\|2,0\rangle$ $H_{1,LL}^{\perp}$	$\|2,1\rangle$ $H_{1,LT}^{\sphericalangle}$	$\|2,2\rangle$ $H_{1,TT}^{\sphericalangle}$

m=0 terms:

- Included in fit, excluded from figures
- Large uncertainties
- |0,0> and |2,0> correlation
- |1,0> suppressed

Partial Waves

A_{LU} Result Figure Layouts

Twist 2

$$G_1^{\perp,|\ell,0\rangle} = 0$$

$$G_1^{\perp,|\ell,m\rangle} = G_1^{\perp,|\ell,-m\rangle}$$

$\lvert 1,1\rangle$ $G_{1,OT}^{\perp}$	
$\lvert 2,1\rangle$ $G_{1,LT}^{\perp}$	$\lvert 2,2\rangle$ $G_{1,TT}^{\perp}$

Twist 3

	$\lvert 1,-1\rangle$ $H_{1,OT}^{\perp}$	$\lvert 1,1\rangle$ $H_{1,OT}^{\measuredangle}$	
$\lvert 2,-2\rangle$ $H_{1,TT}^{\perp}$	$\lvert 2,-1\rangle$ $H_{1,LT}^{\perp}$	$\lvert 2,1\rangle$ $H_{1,LT}^{\measuredangle}$	$\lvert 2,2\rangle$ $H_{1,TT}^{\measuredangle}$

- **Longitudinally Polarized Electron Beam**
  - Energy = 10.2–10.6 GeV
  - Polarization = 86–89%

- **Fixed Targets:**
  - **Proton** (liquid hydrogen)
  - **Deuteron** (liquid deuterium)

Event Selection Criteria

General Cuts

- $Q^2 > 1$ GeV^2
- $W > 2$ GeV
- $y < 0.8$
- $5° < \theta < 35°$ (applied to $e^-,\pi^\pm$)

Pion and Dihadron Cuts

- $x_F(\pi^\pm) > 0$
- $p(\pi^\pm) > 1.25$ GeV
- $z_{pair} < 0.95$
- $M_{miss} > 1.5$ GeV

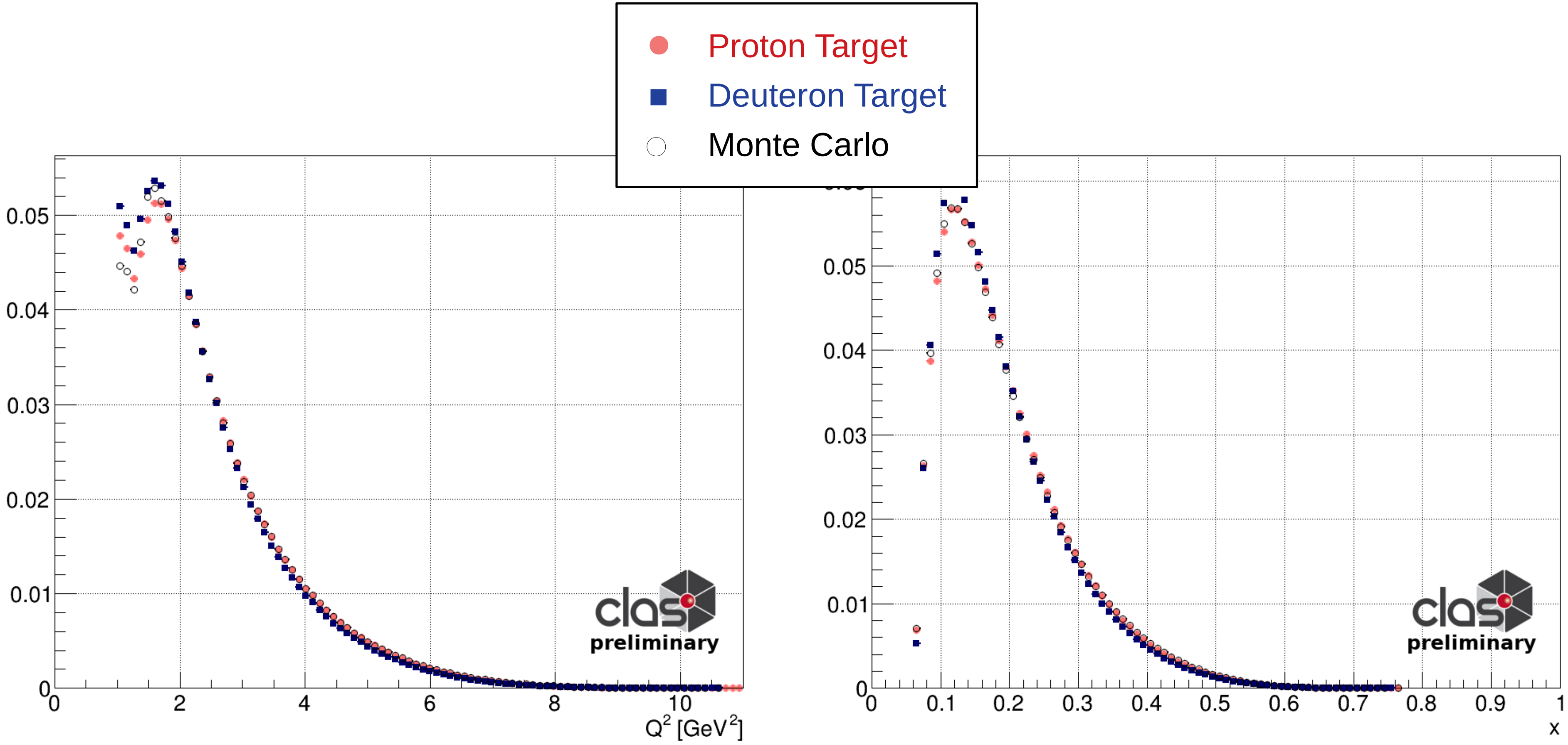
Additional Cuts

- PID Refinement
- Vertex
- Fiducial volume

Data Sets

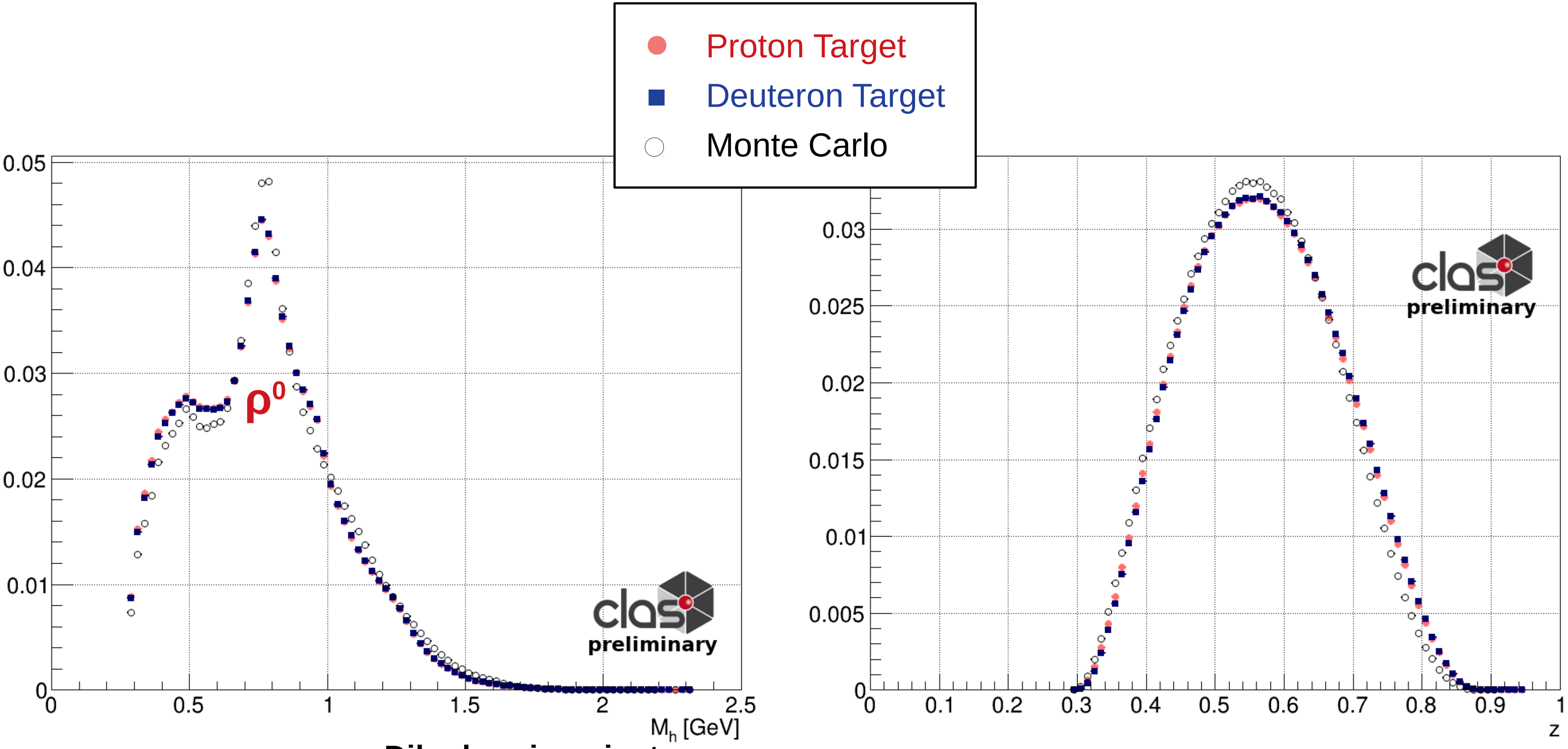
- CLAS12 Fall 2018 – Spring 2020
- Includes Both Torus Polarities

$\pi^+\pi^-$ Kinematic Distributions



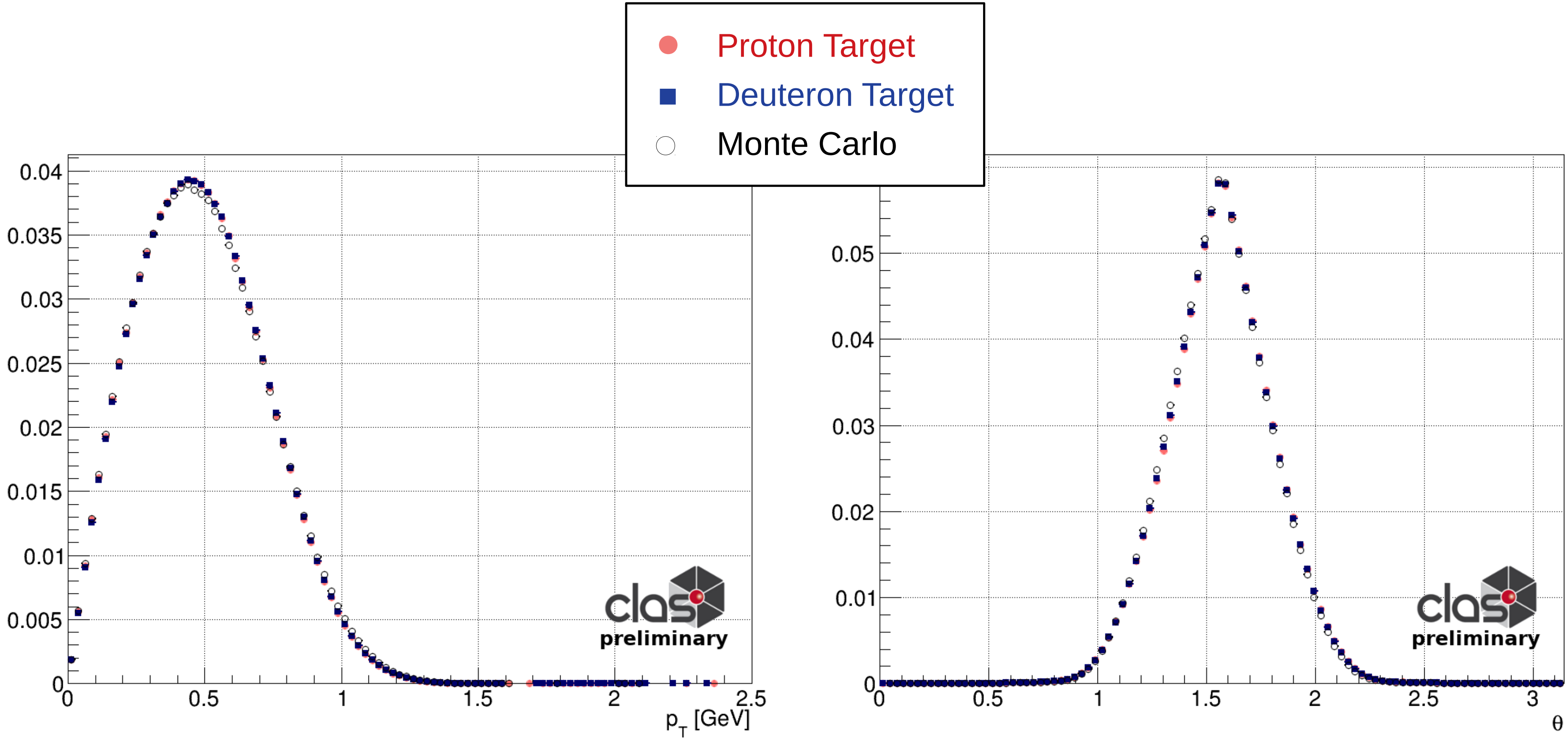
* distributions normalized by dihadron yield

$\pi^+\pi^-$ Kinematic Distributions

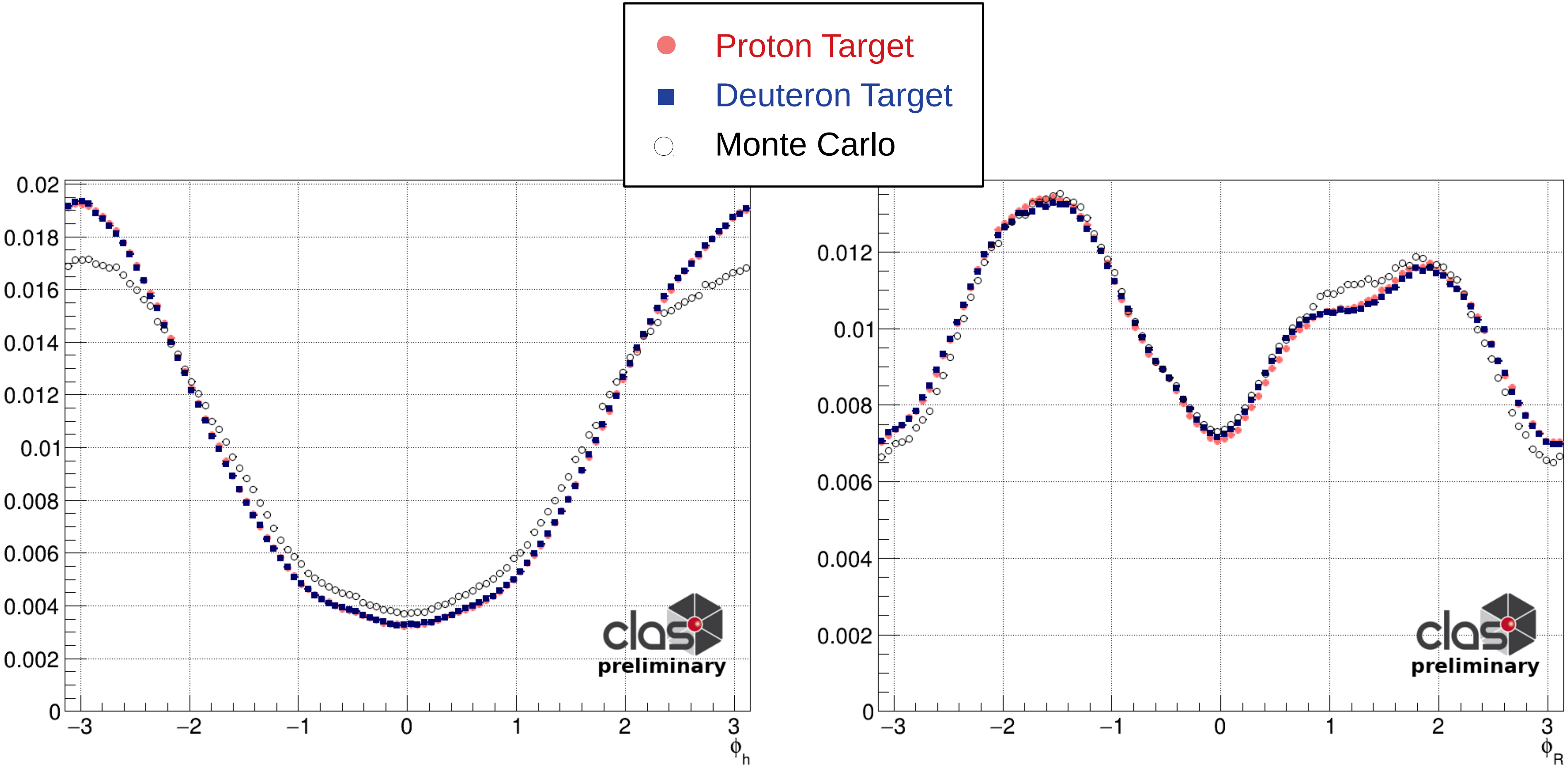


Dihadron invariant mass

$\pi^+\pi^-$ Kinematic Distributions



$\pi^+\pi^-$ Kinematic Distributions



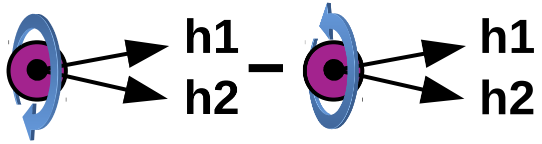
Beam Spin Asymmetries

Twist 2

Presenting F_{LU} / F_{UU}
(= A_{LU} / depolarization)

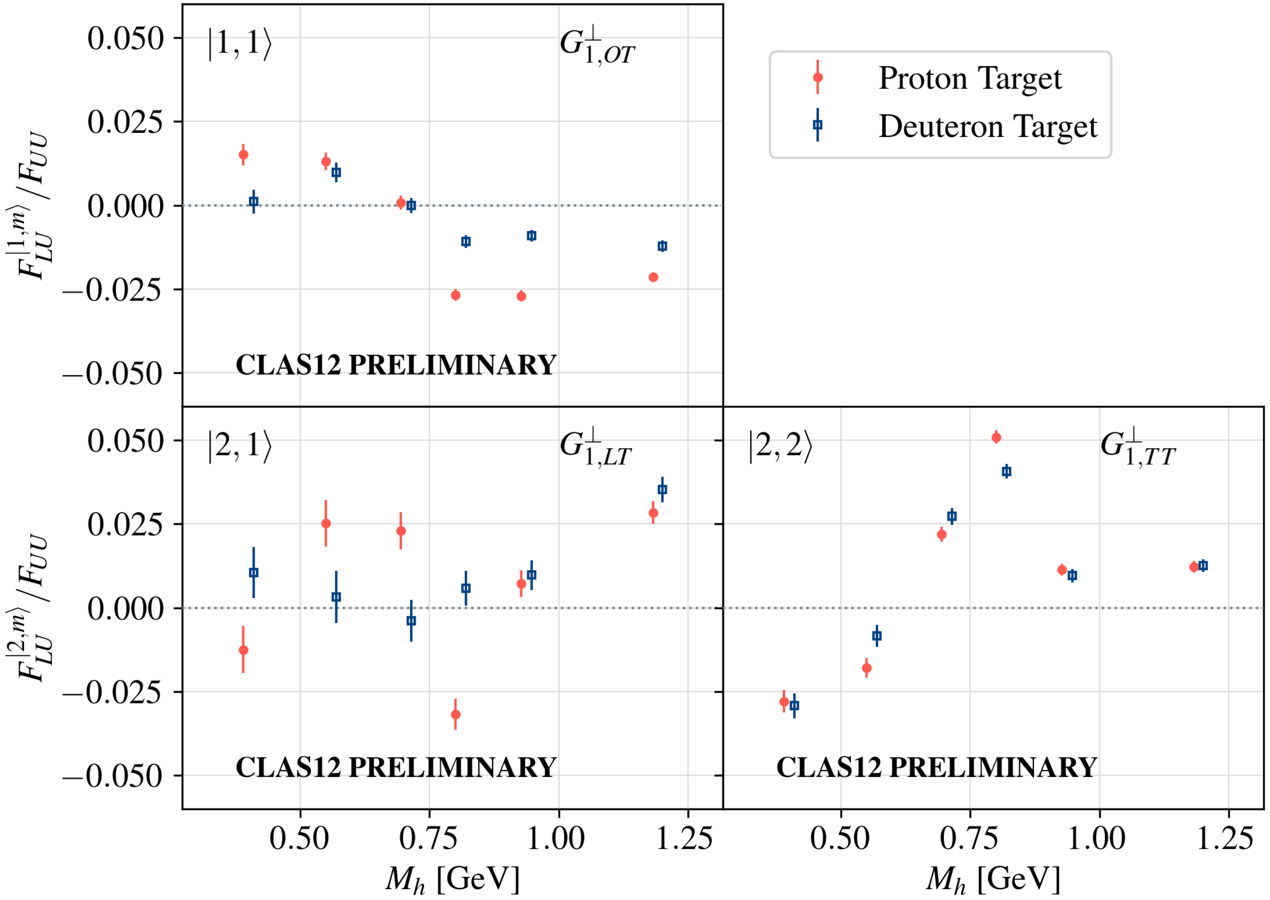
$$F_{LU,T} \sim f_1 \otimes G_1^{\perp|\ell,m\rangle}$$

$$G_1^{\perp|\ell,m\rangle} =$$



M_h Bins

Twist-2 F_{LU}/F_{UU} Amplitudes

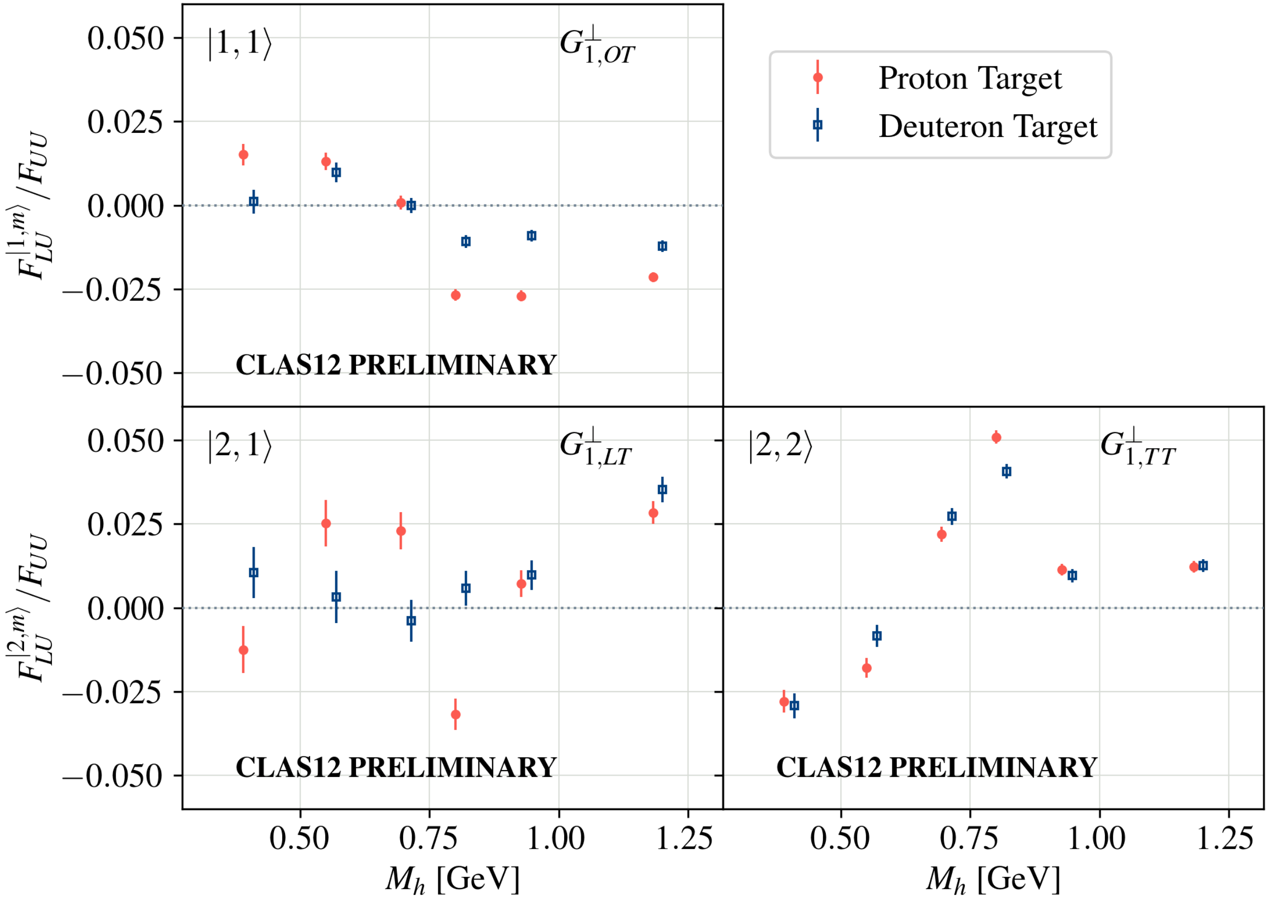


M_h Bins

Different targets → f_1 flavors

$$A_{LU,\mathbf{p}}^{|\ell,m\rangle} \propto \left(4xf^{u_V} - xf^{d_V}\right) G_1^{|\ell,m\rangle}$$
$$A_{LU,\mathbf{d}}^{|\ell,m\rangle} \propto \left(xf^{u_V} + xf^{d_V}\right) G_1^{|\ell,m\rangle}$$

Twist-2 F_{LU}/F_{UU} Amplitudes



M_h Bins

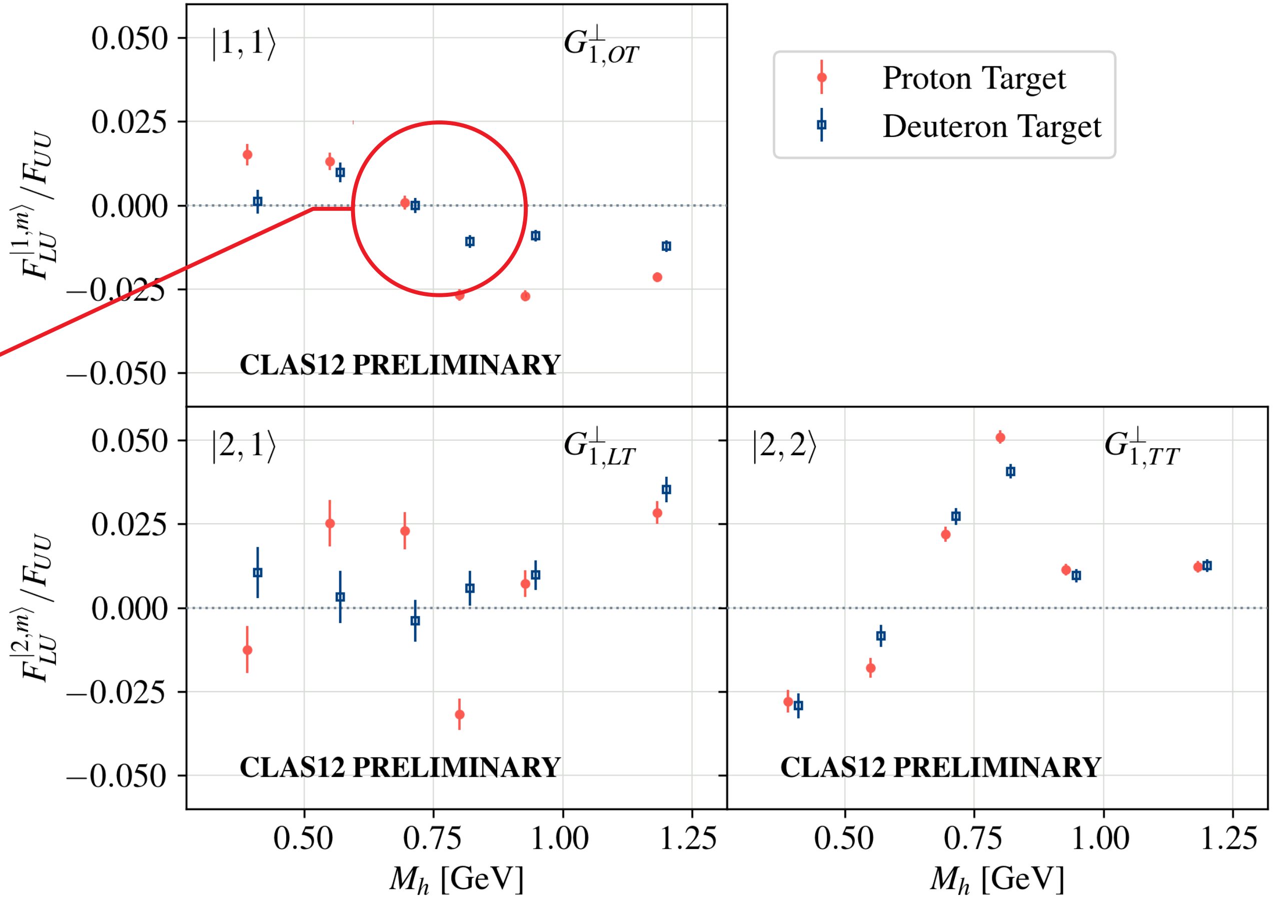
Different targets → f_1 flavors

$$A_{LU,\mathbf{p}}^{|\ell,m\rangle} \propto \left(4xf^{u_V} - xf^{d_V}\right) G_1^{|\ell,m\rangle}$$

$$A_{LU,\mathbf{d}}^{|\ell,m\rangle} \propto \left(xf^{u_V} + xf^{d_V}\right) G_1^{|\ell,m\rangle}$$

Sign change near ρ mass

Twist-2 F_{LU}/F_{UU} Amplitudes



M_h Bins

Different targets → f_1 flavors

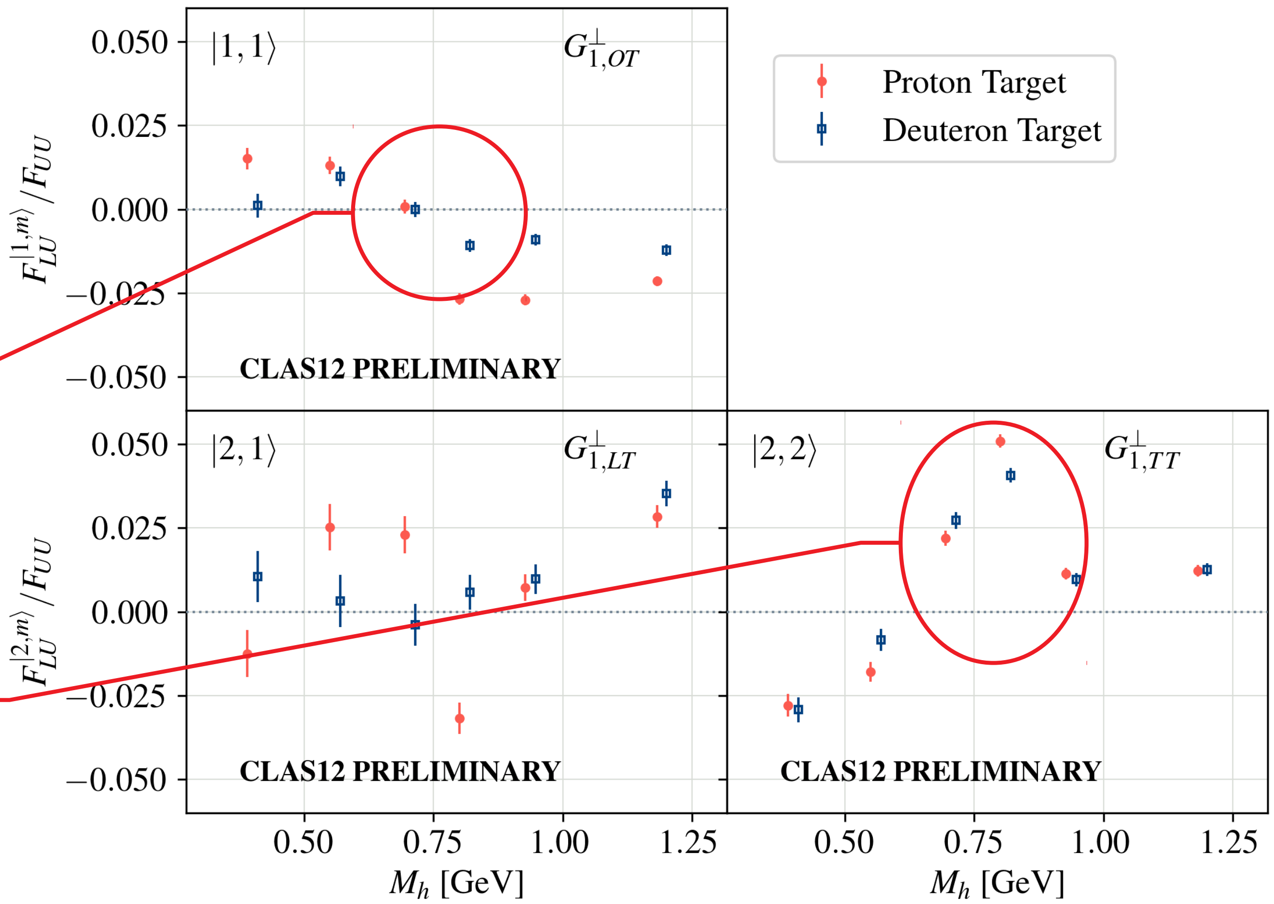
$$A_{LU,\mathbf{p}}^{|\ell,m\rangle} \propto \left(4xf^{u_V} - xf^{d_V}\right) G_1^{|\ell,m\rangle}$$
$$A_{LU,\mathbf{d}}^{|\ell,m\rangle} \propto \left(xf^{u_V} + xf^{d_V}\right) G_1^{|\ell,m\rangle}$$

Sign change near ρ mass

Enhancement at ρ mass (and a sign change)

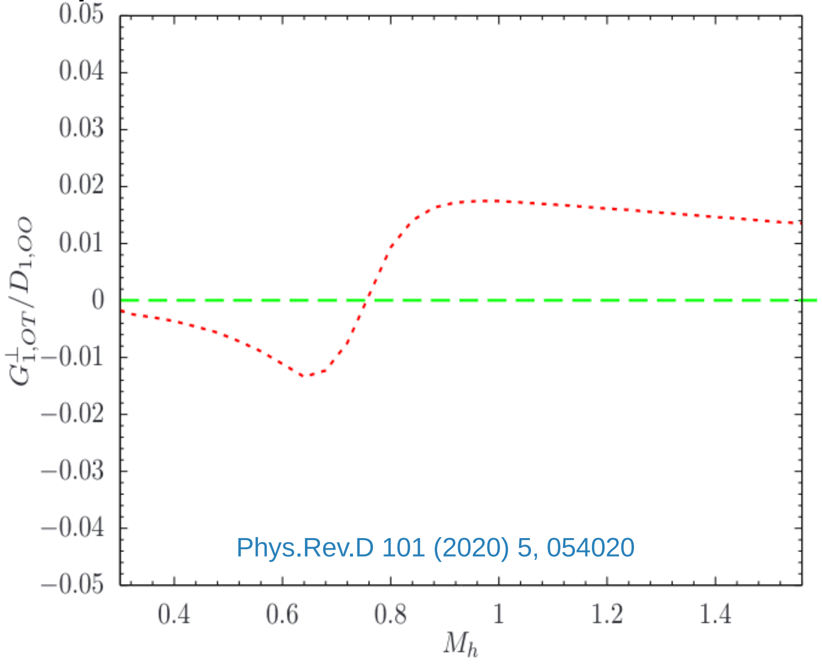
ρ meson → p-wave $\pi^+\pi^-$

Twist-2 F_{LU}/F_{UU} Amplitudes

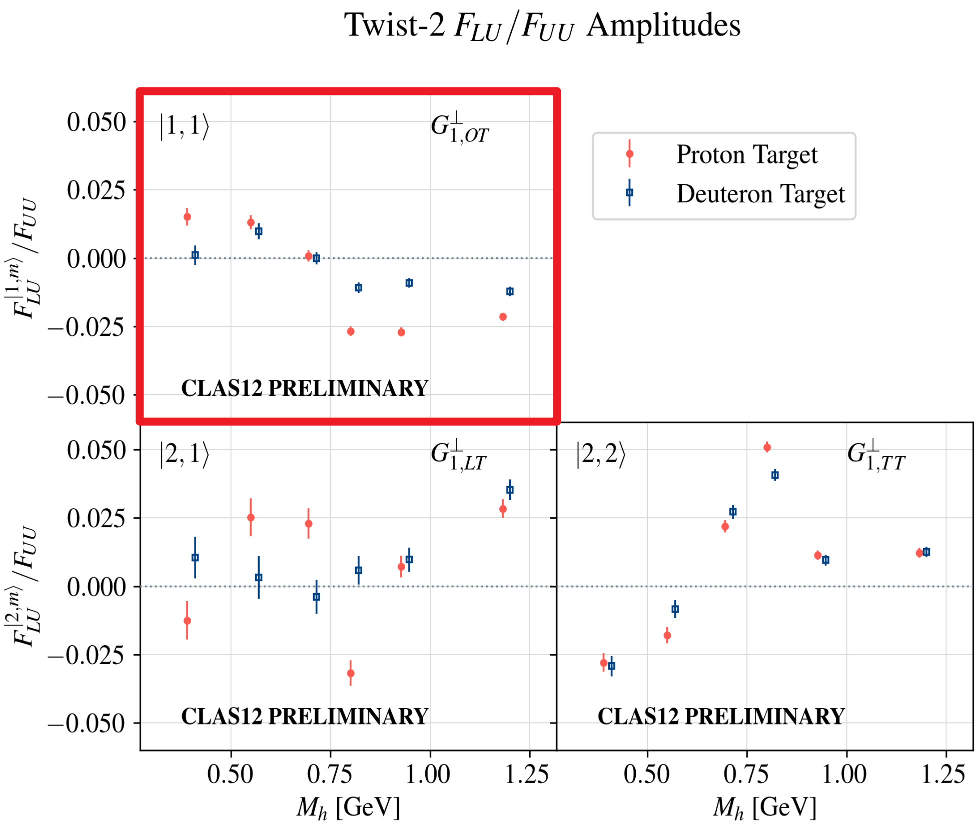


Sign Change near M_ρ

Spectator Model Prediction



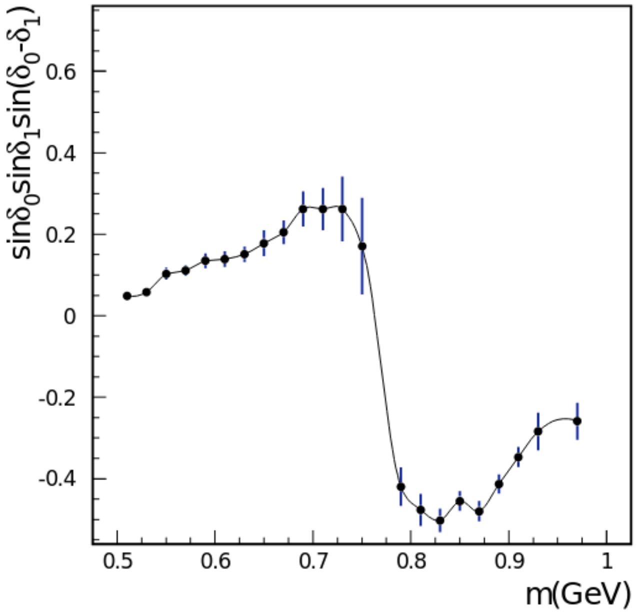
Sign change near ρ mass



Sign Change near M_ρ

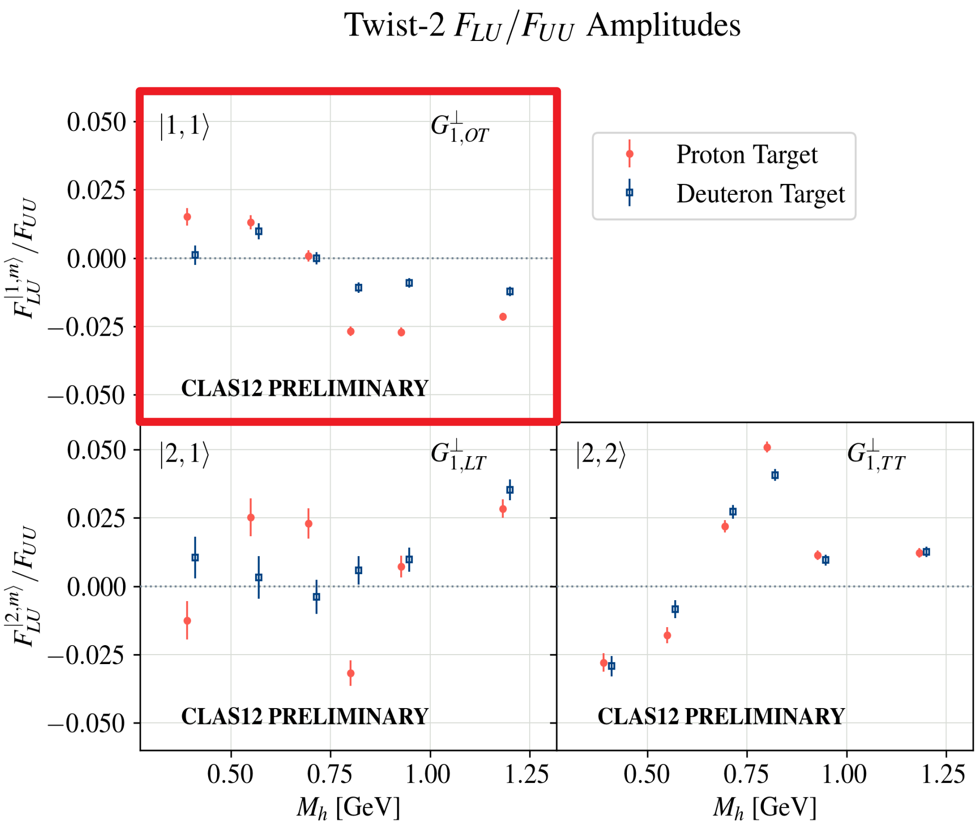
$$|\pi^+\pi^- X\rangle = e^{i\delta_0}|(\pi\pi)_{\ell=0}X\rangle + e^{i\delta_1}|(\pi\pi)_{\ell=1}X\rangle + \ldots$$

Figure Of Merit (for transversity x IFF)

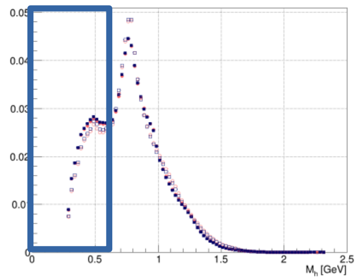


Jaffe, Can transversity be measured?, 1997

Sign change near ρ mass

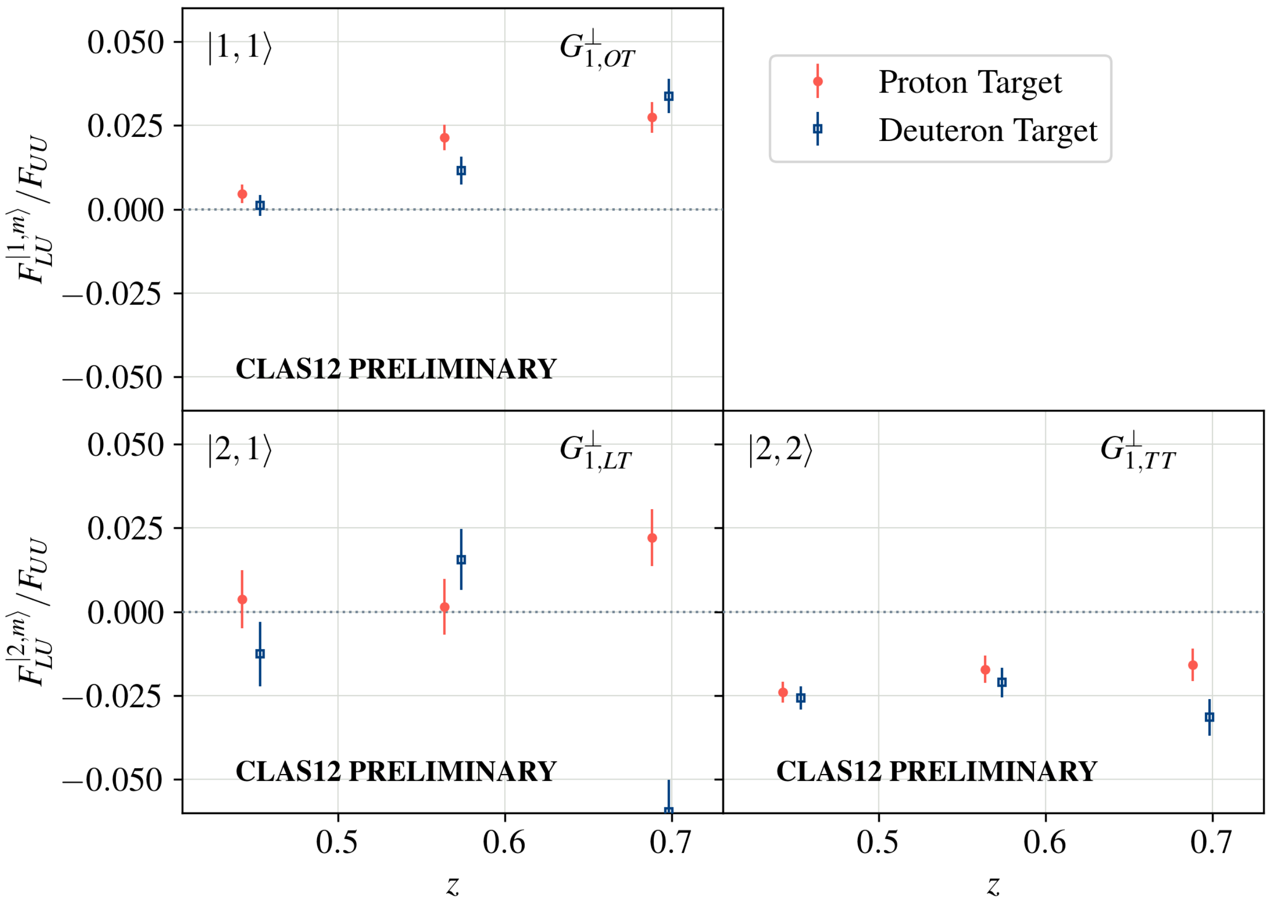


z Bins

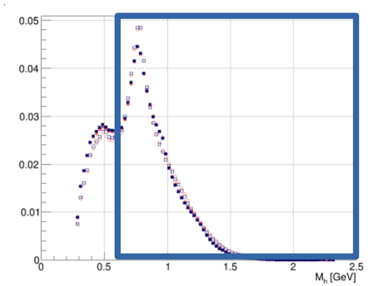


Below M_ρ

Twist-2 F_{LU}/F_{UU} Amplitudes, $M_h < 0.63$ GeV

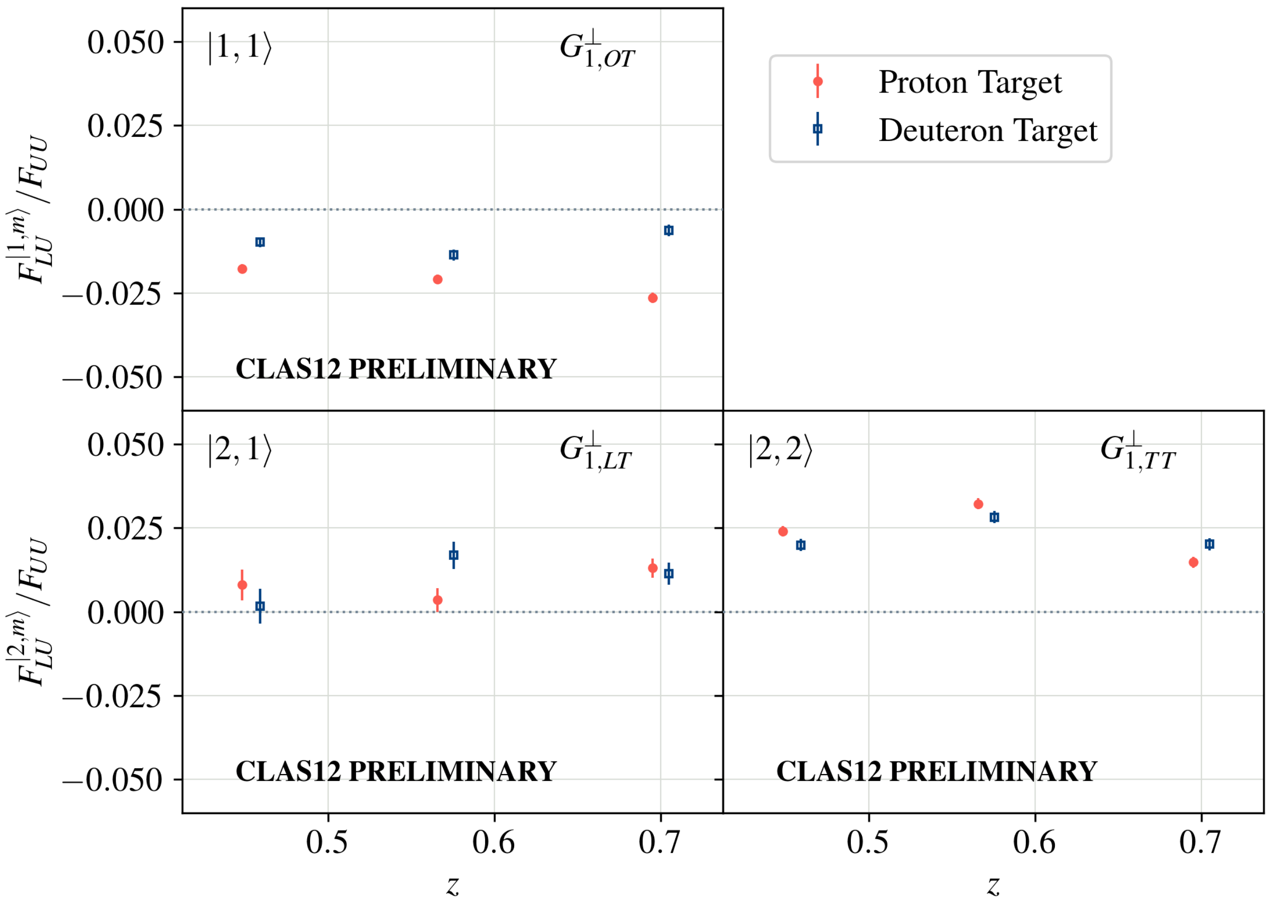


z Bins



Including and Above M_ρ

Twist-2 F_{LU}/F_{UU} Amplitudes, $M_h > 0.63$ GeV



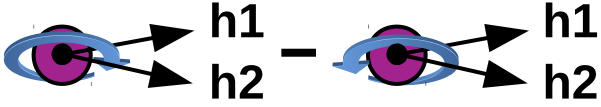
Beam Spin Asymmetries

Twist 3

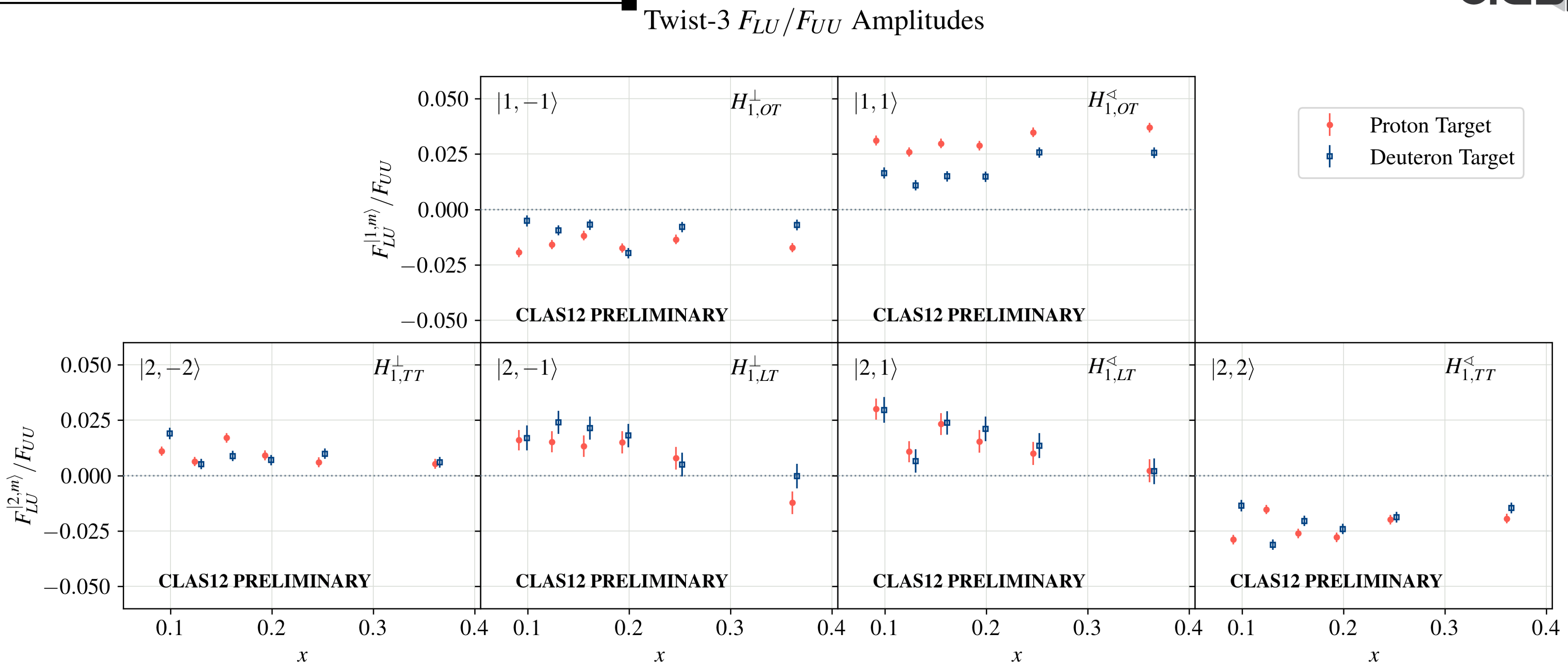
Presenting F_{LU} / F_{UU}
(= A_{LU} / depolarization)

$$F_{LU} \sim e \otimes H_1^{\perp|\ell,m\rangle}$$

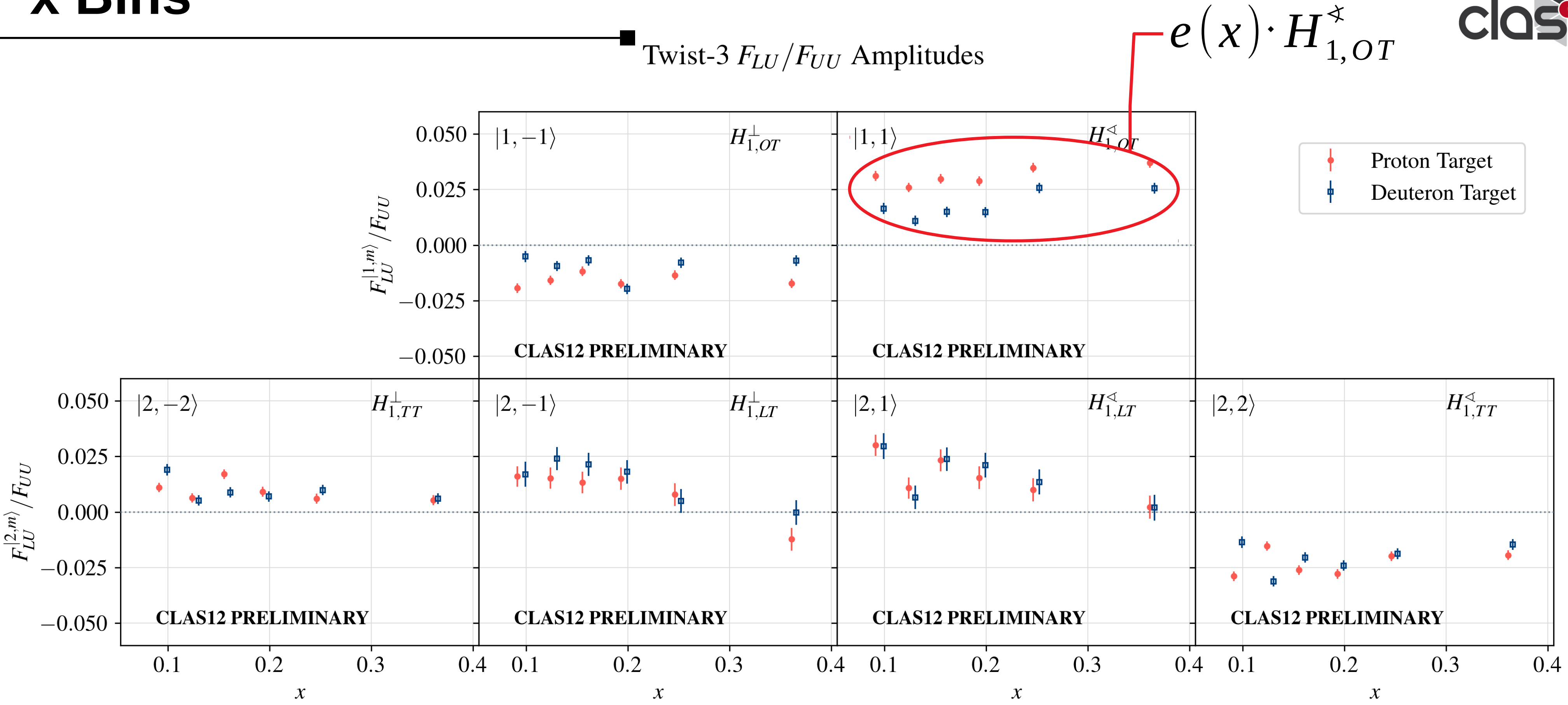
$$H_1^{\perp|\ell,m\rangle} =$$



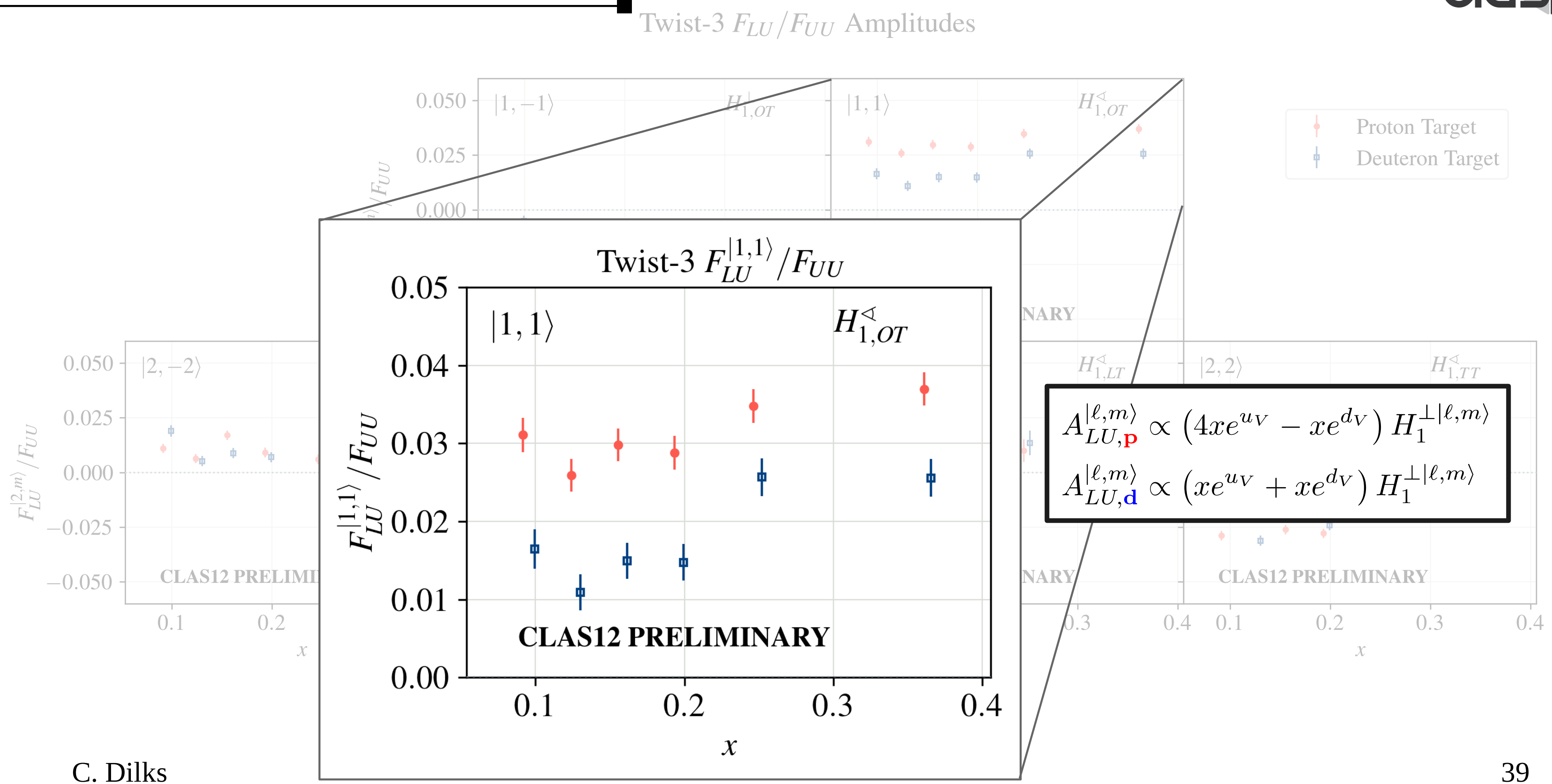
x Bins


Twist-3 F_{LU}/F_{UU} Amplitudes
$|1,-1\rangle$
$H^{\perp}_{1,OT}$
$|1,1\rangle$
$H^{\sphericalangle}_{1,OT}$
$|2,-2\rangle$
$H^{\perp}_{1,TT}$
$|2,-1\rangle$
$H^{\perp}_{1,LT}$
$|2,1\rangle$
$H^{\sphericalangle}_{1,LT}$
$|2,2\rangle$
$H^{\sphericalangle}_{1,TT}$
CLAS12 PRELIMINARY
Proton Target
Deuteron Target
$F_{LU}^{|1,m\rangle}/F_{UU}$
$F_{LU}^{|2,m\rangle}/F_{UU}$
x
0.050
0.025
0.000
−0.025
−0.050
0.1
0.2
0.3
0.4

x Bins


Twist-3 F_{LU}/F_{UU} Amplitudes
$e(x) \cdot H_{1,OT}^{\sphericalangle}$
$|1,-1\rangle$
$H_{1,OT}^{\perp}$
$|1,1\rangle$
$H_{1,OT}^{\sphericalangle}$
$|2,-2\rangle$
$H_{1,TT}^{\perp}$
$|2,-1\rangle$
$H_{1,LT}^{\perp}$
$|2,1\rangle$
$H_{1,LT}^{\sphericalangle}$
$|2,2\rangle$
$H_{1,TT}^{\sphericalangle}$
$F_{LU}^{|1,m\rangle}/F_{UU}$
$F_{LU}^{|2,m\rangle}/F_{UU}$
0.050
0.025
0.000
−0.025
−0.050
0.1
0.2
0.3
0.4
x
CLAS12 PRELIMINARY
Proton Target
Deuteron Target

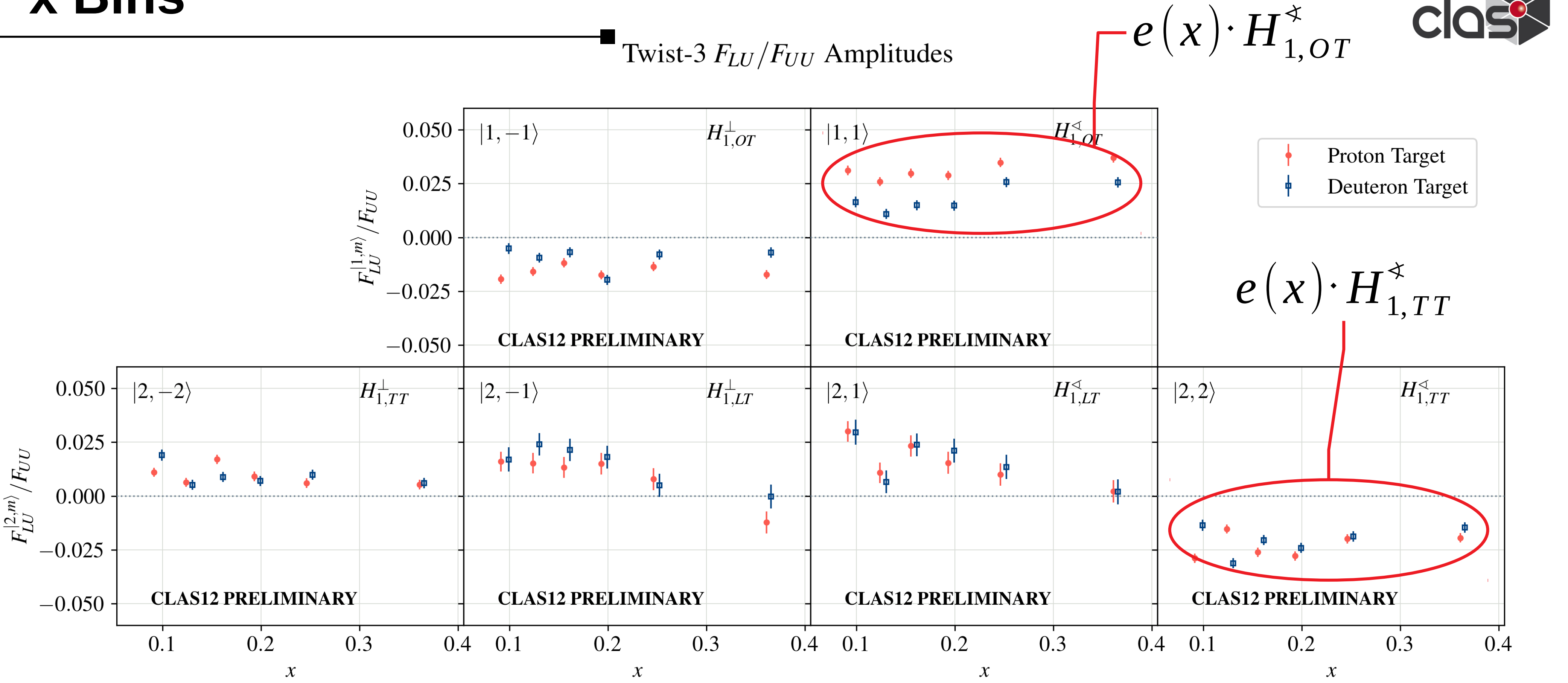
x Bins



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

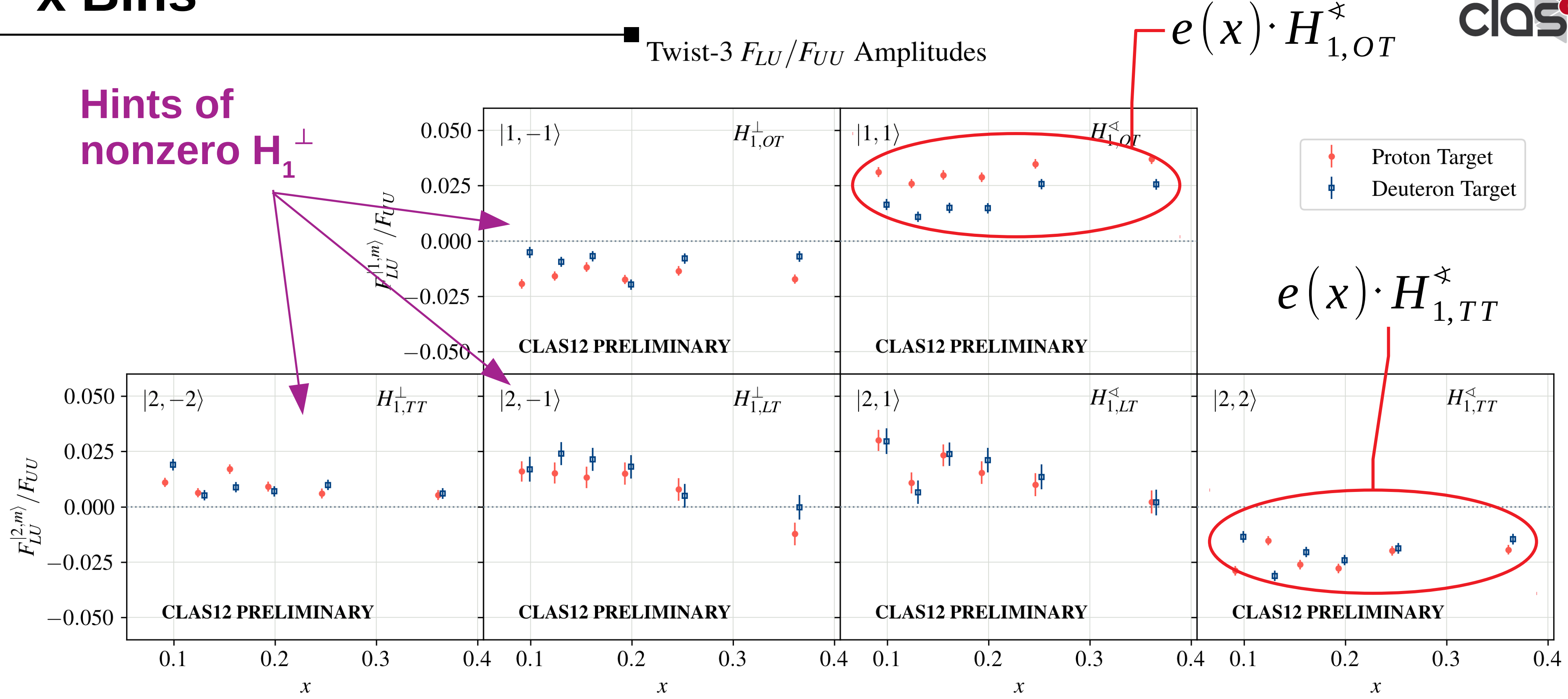
$$A_{LU,\mathbf{d}}^{|\ell,m\rangle} \propto \left(xe^{u_V} + xe^{d_V}\right) H_1^{\perp|\ell,m\rangle}$$

x Bins



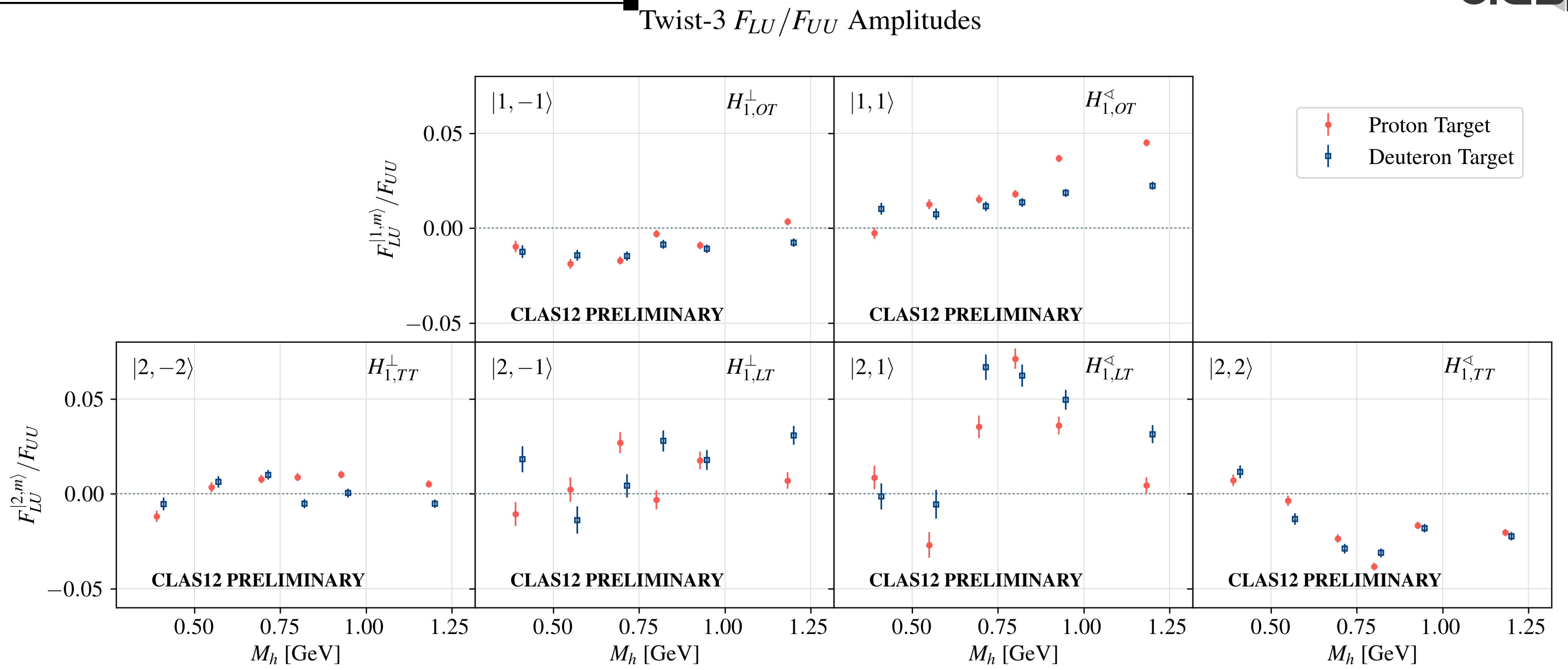
Twist-3 F_{LU}/F_{UU} Amplitudes
$e(x) \cdot H_{1,OT}^{\sphericalangle}$
$e(x) \cdot H_{1,TT}^{\sphericalangle}$
$|1,-1\rangle$ $H_{1,OT}^{\perp}$
$|1,1\rangle$ $H_{1,OT}^{\sphericalangle}$
$|2,-2\rangle$ $H_{1,TT}^{\perp}$
$|2,-1\rangle$ $H_{1,LT}^{\perp}$
$|2,1\rangle$ $H_{1,LT}^{\sphericalangle}$
$|2,2\rangle$ $H_{1,TT}^{\sphericalangle}$
Proton Target
Deuteron Target
CLAS12 PRELIMINARY
$F_{LU}^{|1,m\rangle}/F_{UU}$
$F_{LU}^{|2,m\rangle}/F_{UU}$
0.050
0.025
0.000
−0.025
−0.050
0.1
0.2
0.3
0.4
x

x Bins



Twist-3 F_{LU}/F_{UU} Amplitudes
$e(x) \cdot H_{1,OT}^{\sphericalangle}$
$e(x) \cdot H_{1,TT}^{\sphericalangle}$
Hints of nonzero $H_1^{\perp}$
$|1,-1\rangle$
$H_{1,OT}^{\perp}$
$|1,1\rangle$
$H_{1,OT}^{\sphericalangle}$
Proton Target
Deuteron Target
$|2,-2\rangle$
$H_{1,TT}^{\perp}$
$|2,-1\rangle$
$H_{1,LT}^{\perp}$
$|2,1\rangle$
$H_{1,LT}^{\sphericalangle}$
$|2,2\rangle$
$H_{1,TT}^{\sphericalangle}$
$F_{LU}^{|1,m\rangle}/F_{UU}$
$F_{LU}^{|2,m\rangle}/F_{UU}$
CLAS12 PRELIMINARY
0.050
0.025
0.000
−0.025
−0.050
0.1
0.2
0.3
0.4
x

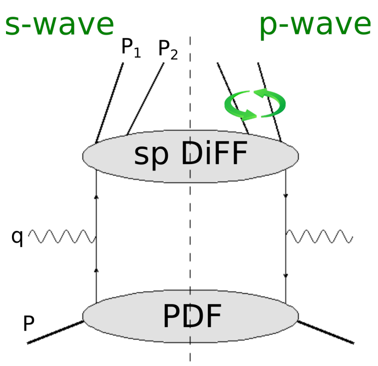
M_h Bins



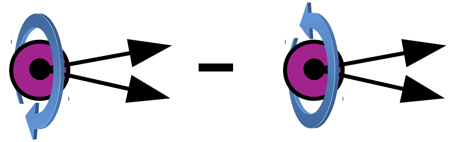
Target differences enhanced at higher M_h

Summary and Outlook

- **SIDIS dihadron spin asymmetries are sensitive to:**
  - Dihadron fragmentation function $G_1^{\perp}$ and H_1
  - Twist-3 parton distribution functions e(x) and $h_L(x)$
  - Different targets → flavor dependence of e(x) and $h_L(x)$
  - Future: Different channels → channel dependence of DiFFs



- **Partial waves expansions provide:**
  - Dependence on dihadron polarizations
  - Refined access to $G_1^{\perp}$
  - Better understanding of $H_1^{<}$
  - Hints at nonzero $H_1^{\perp}$



- **Stay tuned for data with a longitudinally polarized target!**