Dihadrons at CLAS12

CPHI 2022

Christopher Dilks
March 2022

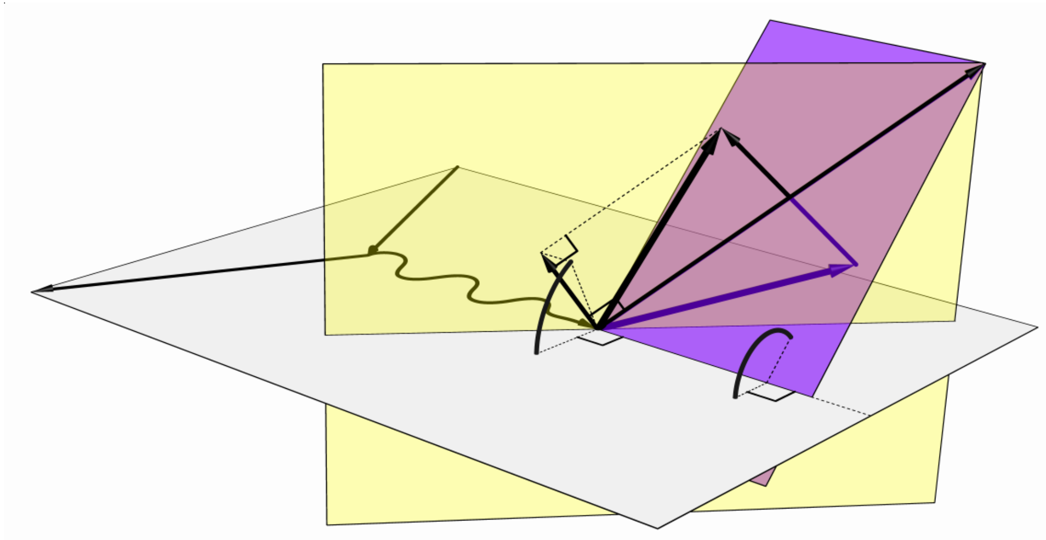
Duke
UNIVERSITY

clas

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

- **Longitudinally Polarized Electron Beam**
  - Energy = 10.2–10.6 GeV
  - Polarization = 86–89%
- **Fixed Targets (H, ^{2}H, NH$_3$, …)**

Dihadrons, PDFs, and Fragmentation



Dihadron Kinematics

$$eN \to e + {\color{red} h_1(P_1)} + {\color{red} h_2(P_2)} + X$$

momentum: $P_h = P_1 + P_2$

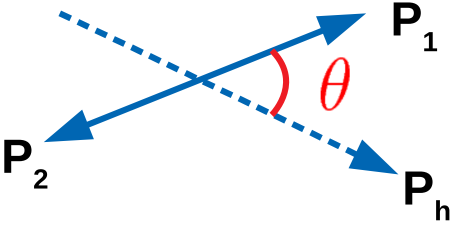
kinematics: $M_h,\ z,\ p_T$

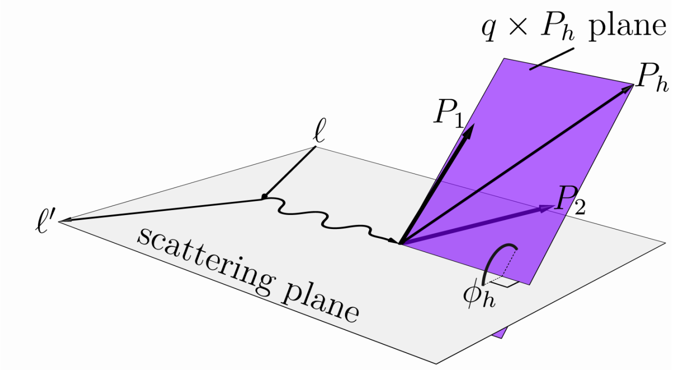
angles: $\phi_h,\ \phi_R,\ \phi_S,\ \theta$ →

Structure Function Modulations

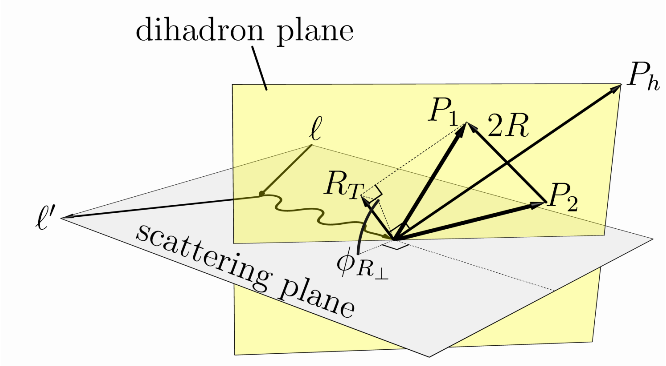
$\mathrm{PDF} \otimes \mathrm{DiFF}$

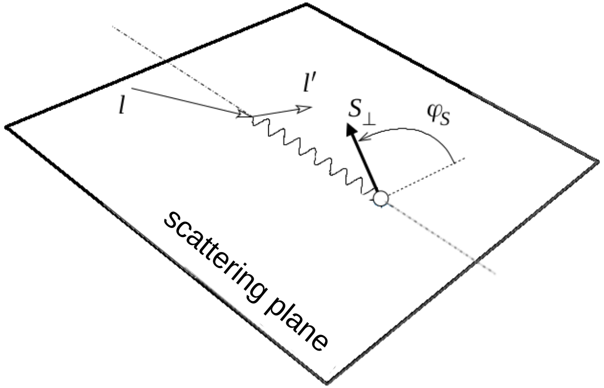
Dihadron CoM frame





cf. single-hadron ϕ_h





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Beam Spin Asymmetry → e(x) Constraints

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

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

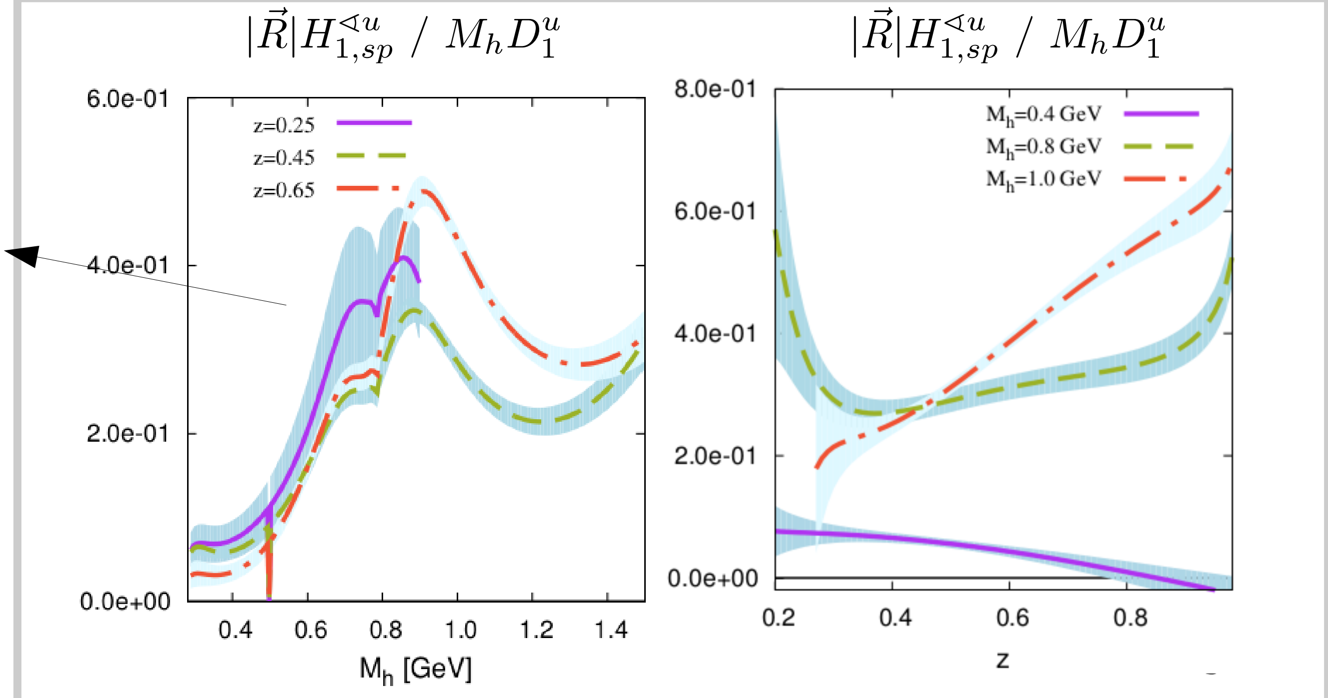
$e(x)$ collinear twist-3 PDF

$H_1^{\sphericalangle}$ 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

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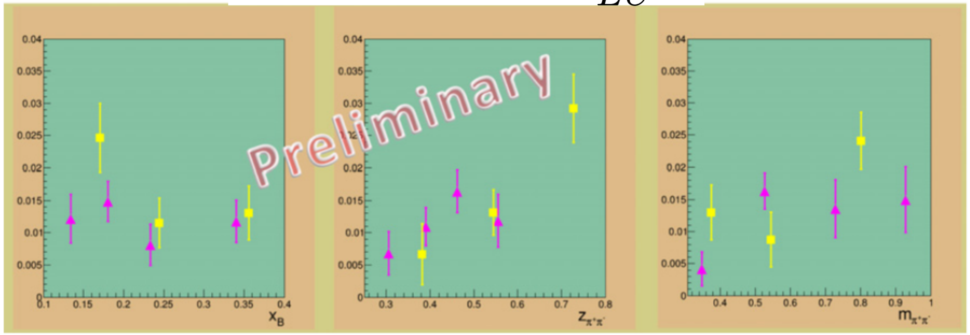
Beam Spin Asymmetry Measurements

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



yellow squares: H_2

magenta triangles: NH_3

EPJ Web Conf. 73 (2014) 02008

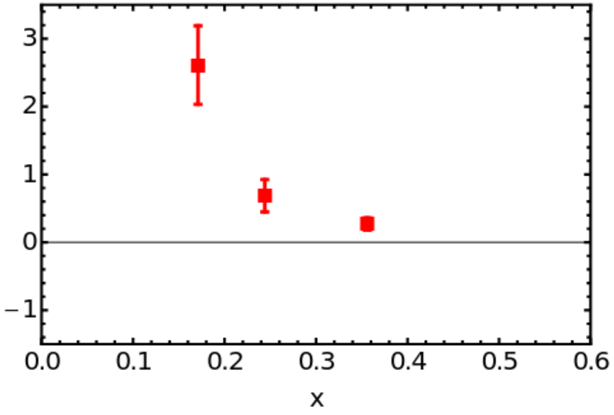
PoS DIS2014 (2014) 231

see also single-pion A_{LU}

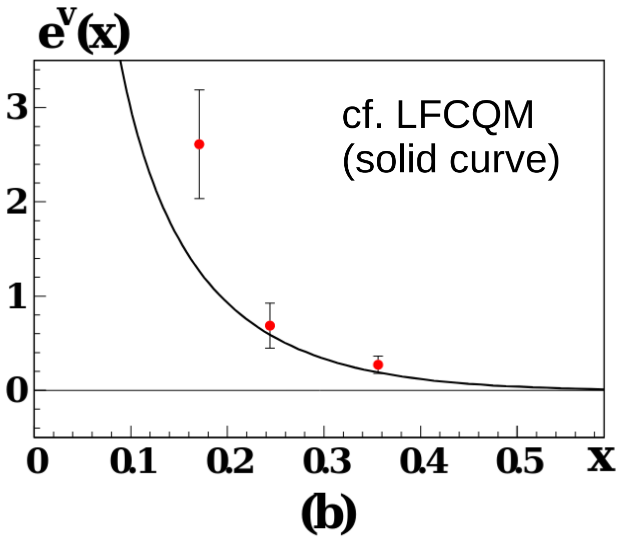
CLAS6 A_{LU}

→ $e^V(x)$ extraction

$$e^V = \frac{4}{9}e^{u_V} - \frac{1}{9}e^{d_V}$$



arXiv: 1405.7659 [hep-ph]

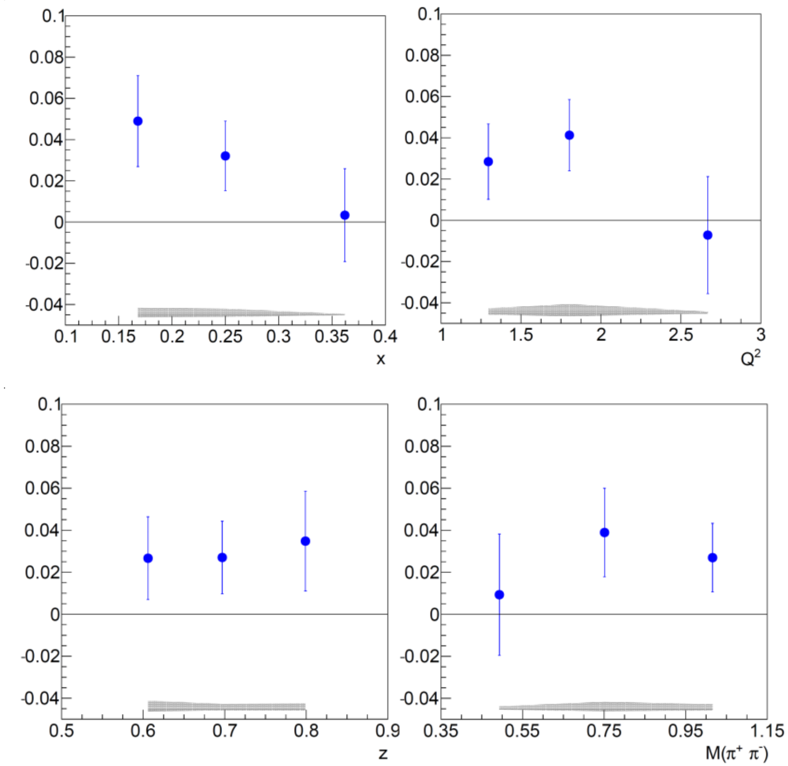


cf. LFCQM (solid curve)

JHEP 01 (2015) 103

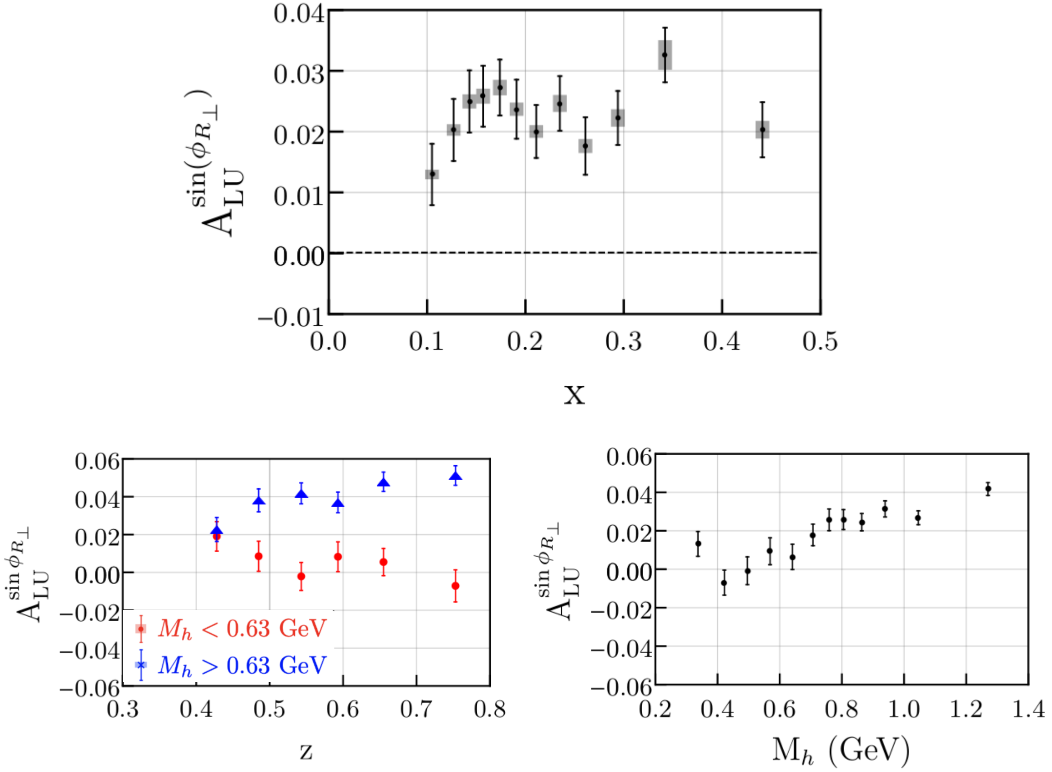
Beam Spin Asymmetry Measurements

Updated 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

1st CLAS12 Publication!

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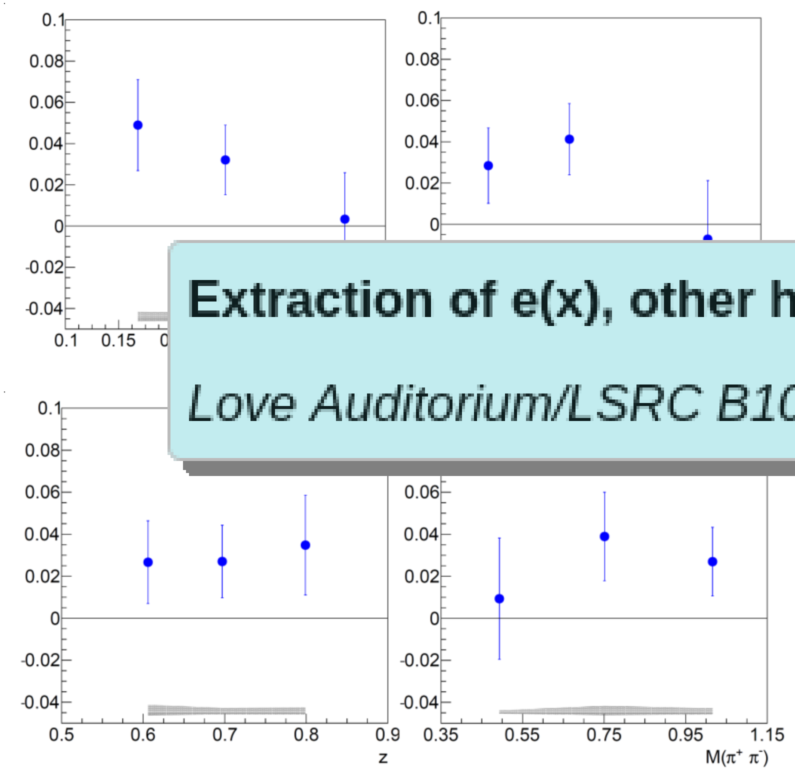
Beam Spin Asymmetry Measurements

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

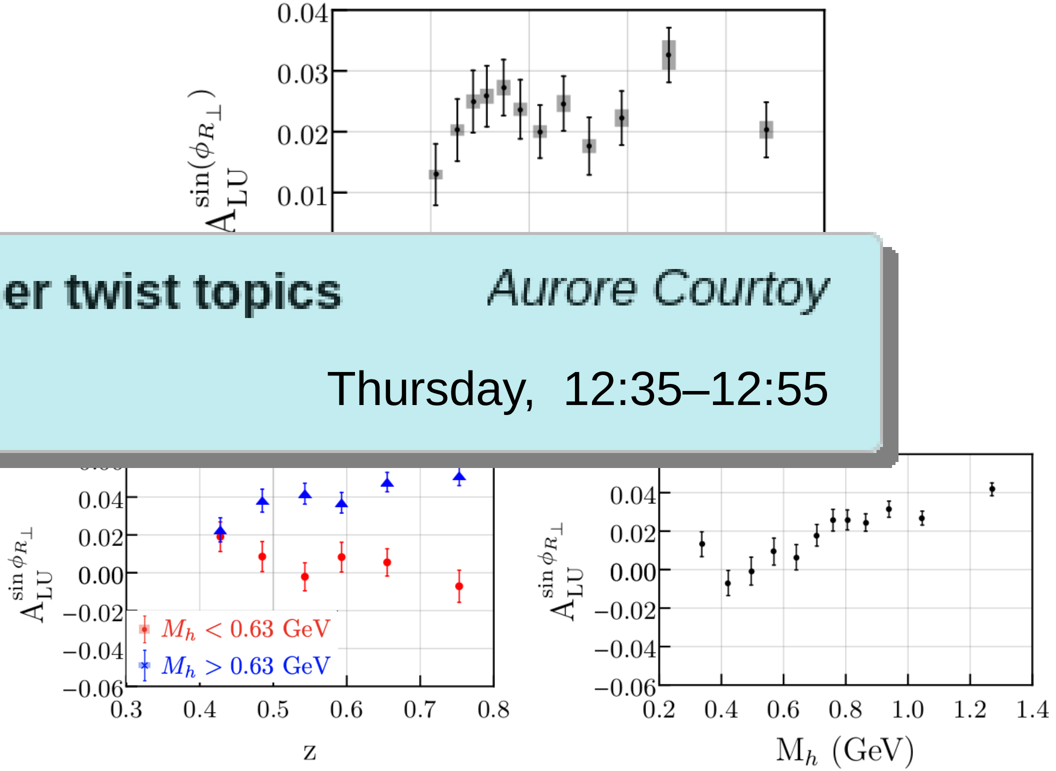


Phys.Rev.Lett. 126 (2021) 6, 062002

Extraction of e(x), other higher twist topics *Aurore Courtoy*

Love Auditorium/LSRC B101 Thursday, 12:35–12:55

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



Phys.Rev.Lett. 126 (2021) 152501

1st CLAS12 Publication!

Twist-3 PDF Interpretations

e(x)

- 1st moment → pion-nucleon σ term, representing the contribution to the nucleon mass from the finite quark masses
- 2nd moment → proportional to quark mass and number of valence quarks
- 3rd moment → transverse polarization dependence of the transverse color-Lorentz force experienced by a struck quark, in an unpolarized nucleon

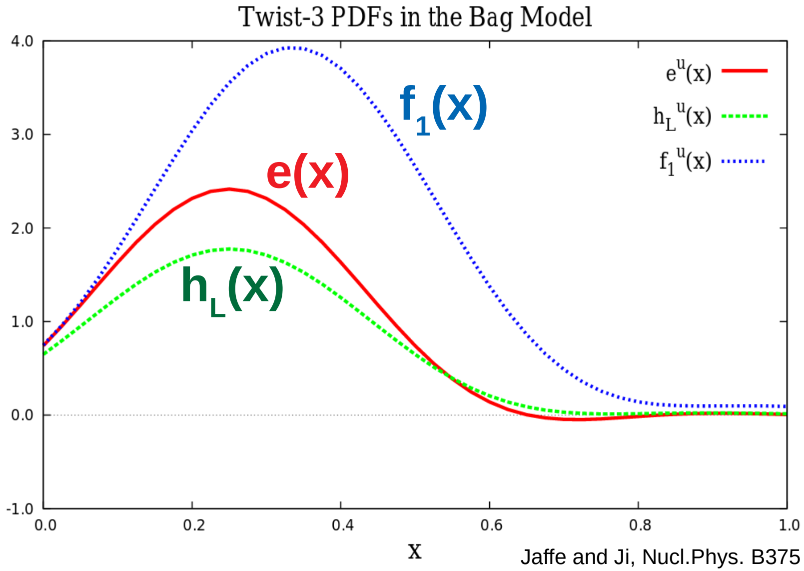
Efremov and Schweitzer, JHEP 0308 (2003) 006
Courtoy, arXiv:1405.7659
Burkardt, Phys.Rev. D88 (2013) 114502

$h_L(x)$

- Accessible via **Target Spin Asymmetries**
  - CLAS12 longitudinally polarized target
- 3rd moment → "Average longitudinal gradient of the transverse force that acts on transversely polarized [struck] quark"

  – M. Abdallah and M. Burkardt

  - Phys.Rev.D 94 (2016) 9, 094040
  - Phys.Rev.D 66 (2002) 114005
  - Nucl.Phys.B 461 (1996) 197-237

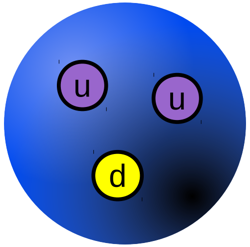

Twist-3 PDFs in the Bag Model

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

Accessing Flavor Dependence of e(x)

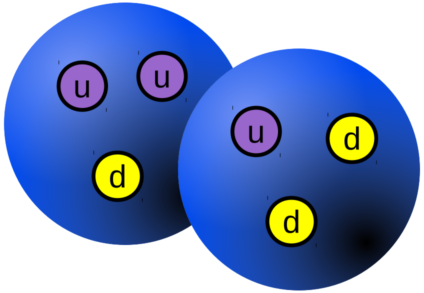
Different targets → flavor dependence

Proton Target



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

Deuteron Target



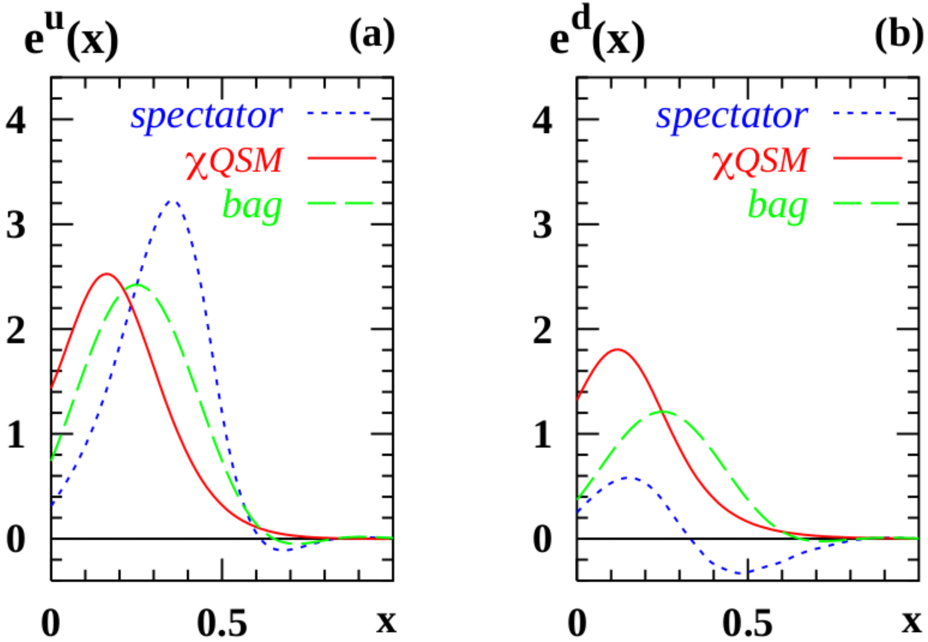
$$A_{LU,\mathbf{d}}^{\text{twist 3}} \propto xe^{u_V}(x) + xe^{d_V}(x)$$

2 equations and 2 unknowns: decouple flavor dependence of e(x) → $\boxed{e^{u_V}(x) \text{ and } e^{d_V}(x)}$

CLAS12 data taken 2018–2020

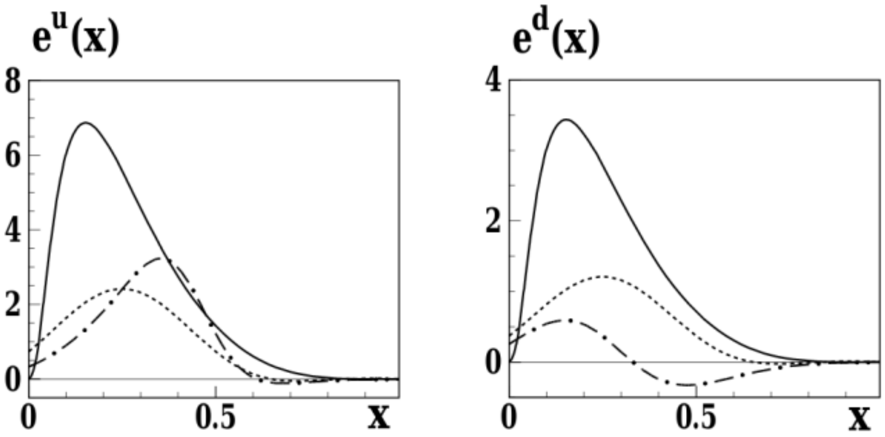
e(x) Model Predictions

- 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

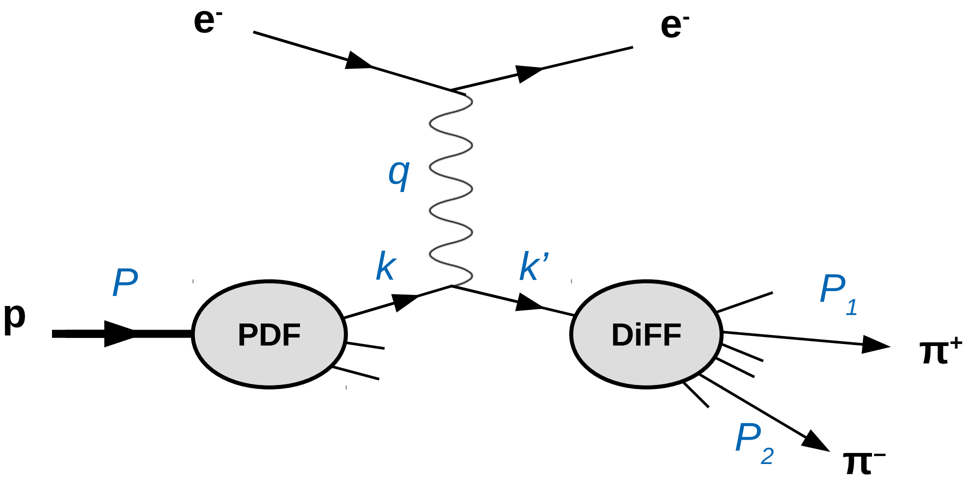


JHEP 01 (2015) 103

Solid: LFCQM model
Dot-Dashed: spectator model
Dashed: bag model

- Relatively larger magnitude partly due to mass effects

Factorization

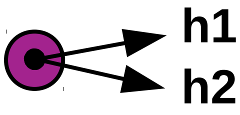


$$\text{Structure Function} \propto \text{PDF} \otimes \text{DiFF}$$

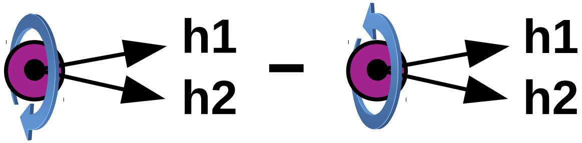
Dihadron Fragmentation Functions (DiFFs)

Twist 2

$D_1 =$



$G_1 =$



$H_1 =$

(notation):

$$G_1 = G_1^{\perp}$$
$$H_1 = \left\{H_1^{\perp}, H_1^{\sphericalangle}\right\}$$

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]

Accessing Flavor Dependence of DiFFs

$$D_1^{u/\pi^+\pi^-} = D_1^{\bar{d}/\pi^+\pi^-} = D_1^{d/\pi^+\pi^-} = D_1^{\bar{u}/\pi^+\pi^-}$$

$$G_1^{u/\pi^+\pi^-} = G_1^{\bar{d}/\pi^+\pi^-} = G_1^{d/\pi^+\pi^-} = G_1^{\bar{u}/\pi^+\pi^-}$$

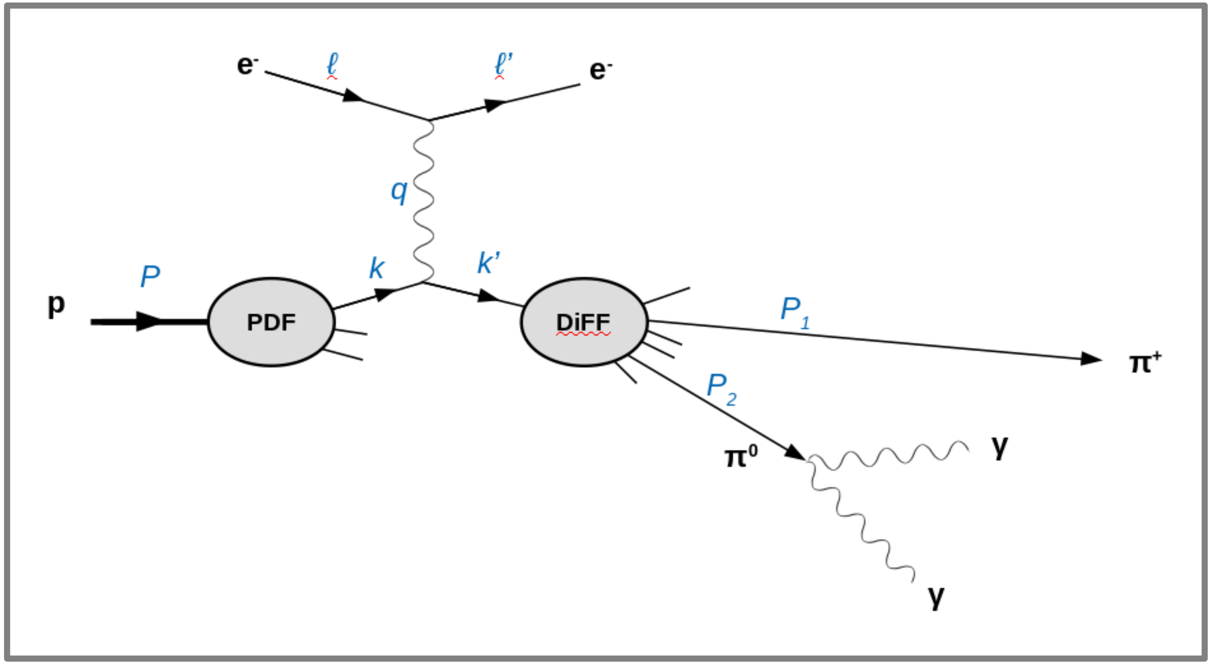
$$H_1^{u/\pi^+\pi^-} = H_1^{\bar{d}/\pi^+\pi^-} = -H_1^{d/\pi^+\pi^-} = -H_1^{\bar{u}/\pi^+\pi^-}$$

$$\neq$$

$$D_1^{q/\pi^\pm\pi^0}$$

$$G_1^{q/\pi^\pm\pi^0}$$

$$H_1^{q/\pi^\pm\pi^0}$$



$\pi^+\pi^-$

$\pi^+\pi^0$

$\pi^-\pi^0$

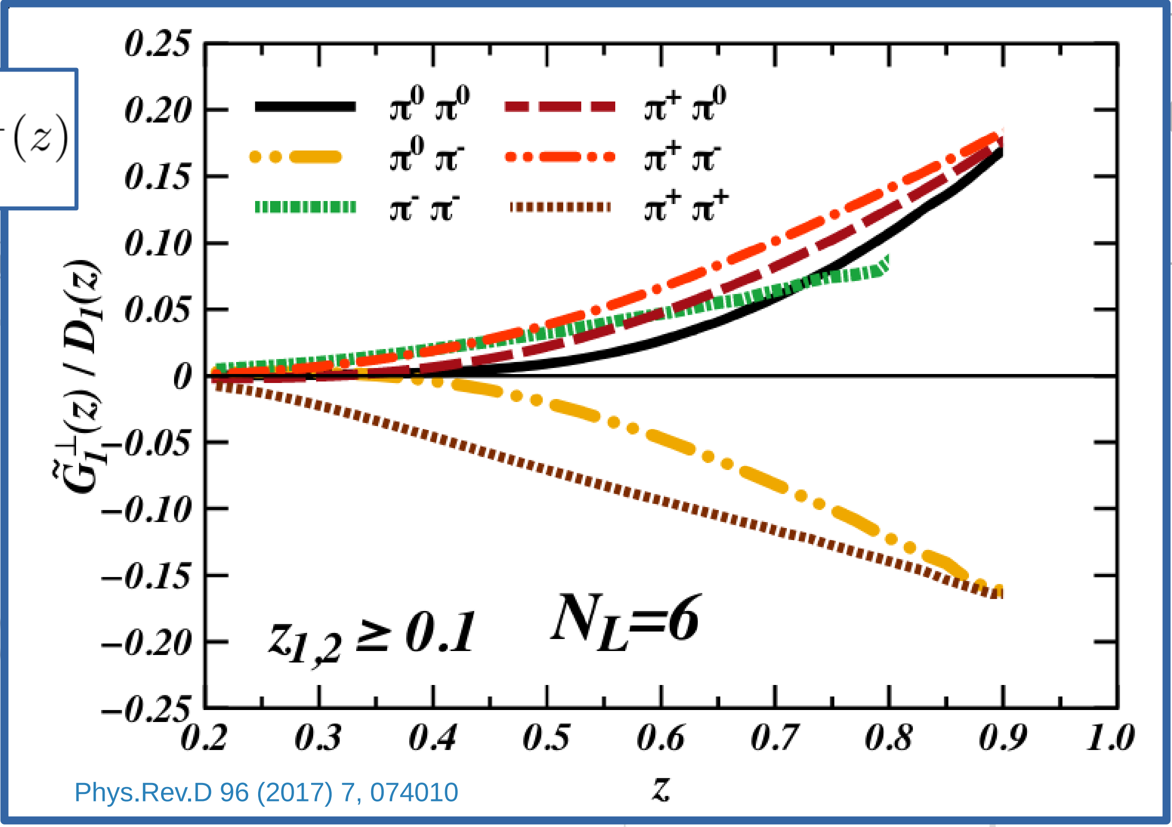
$\ldots$

Accessing Flavor Dependence of DiFFs

$D_1^{u/\pi^+\pi^-} = D_1^{\bar{d}/\pi^+\pi^-} = D_1^{d/\pi^+\pi^-} = D_1^{\bar{u}/\pi^+\pi^-}$

$$\tilde{G}_1^{\perp}(z) \equiv \frac{1}{M_1 M_2} G_1^{\perp}(z)$$

$H_1^{u/\pi^+\pi^-} = H$



Phys.Rev.D 96 (2017) 7, 074010

$D_1^{q/\pi^\pm\pi^0}$

$G_1^{q/\pi^\pm\pi^0}$

$H_1^{q/\pi^\pm\pi^0}$

$\pi^+\pi^-$

$\pi^+\pi^0$

$\pi^-\pi^0$

$\cdots$

Full Dihadron Cross Section

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

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

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

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

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

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

Phys.Rev.D 90 (2014) 11, 114027

Full Dihadron Cross Section

Twist 2

		Target Polarization		
		U	**L**	**T**
Beam Polarization	**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		
		U	**L**	**T**
Beam Polarization	**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	$e H_1 \quad f_1 \tilde{G}$ $g^\perp D_1 \quad h_1^\perp \tilde{E}$	$e_L H_1 \quad g_{1L} \tilde{D}$ $g_L^\perp D_1 \quad h_{1L}^\perp \tilde{E}$	$g_T D_1 \quad h_1 \tilde{E}$ $e_T H_1 \quad g_{1T} \tilde{D}$ $e_T^\perp H_1 \quad f_{1T}^\perp \tilde{G}$ $g_T^\perp D_1 \quad h_{1T}^\perp \tilde{E}$

Full Dihadron Cross Section

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	$f_1 G_1$	$g_{1L} D_1$	$g_{1T} D_1$ $f_{1T}^\perp G_1$

- **2018-2020**

Twist 3

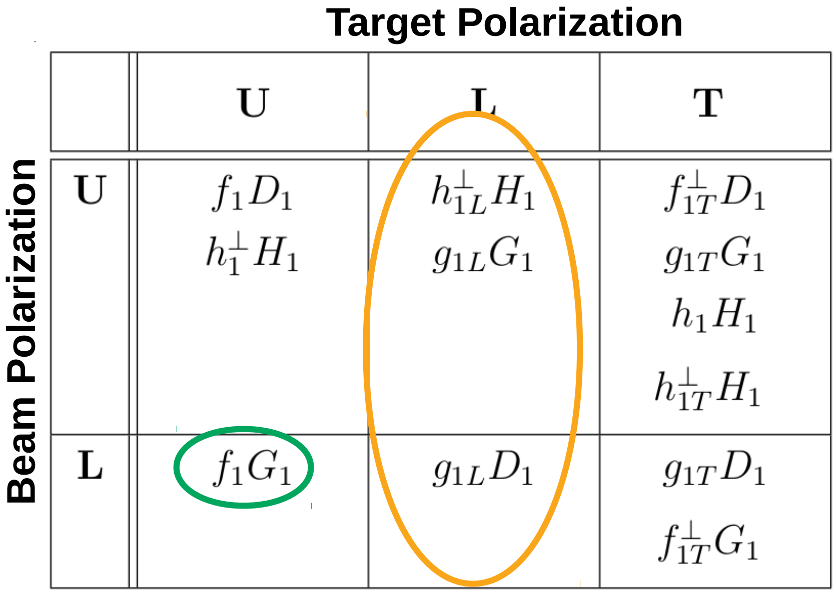
Target Polarization

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	$e H_1 \quad f_1 \tilde{G}$ $g^\perp D_1 \quad h_1^\perp \tilde{E}$	$e_L H_1 \quad g_{1L} \tilde{D}$ $g_L^\perp D_1 \quad h_{1L}^\perp \tilde{E}$	$g_T D_1 \quad h_1 \tilde{E}$ $e_T H_1 \quad g_{1T} \tilde{D}$ $e_T^\perp H_1 \quad f_{1T}^\perp \tilde{G}$ $g_T^\perp D_1 \quad h_{1T}^\perp \tilde{E}$

Full Dihadron Cross Section

Twist 2



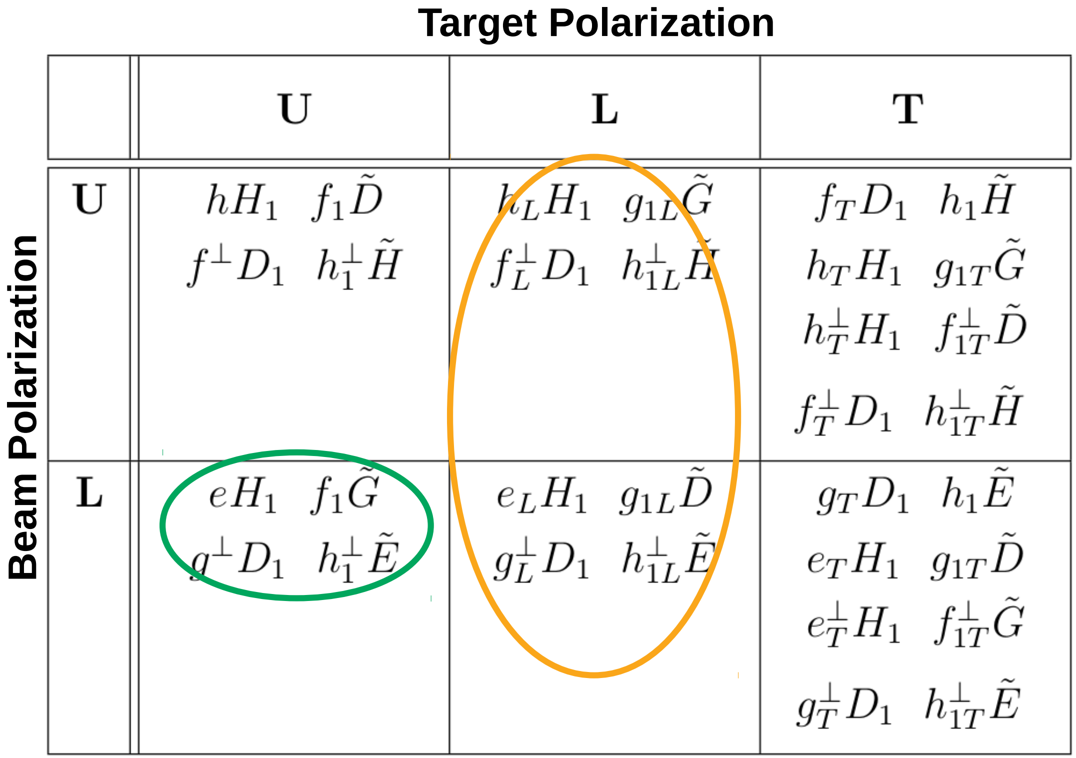
Target Polarization

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	$f_1 G_1$	$g_{1L} D_1$	$g_{1T} D_1$ $f_{1T}^\perp G_1$

- **2018-2020**
- **2022-2023**

Twist 3



Target Polarization

Beam Polarization

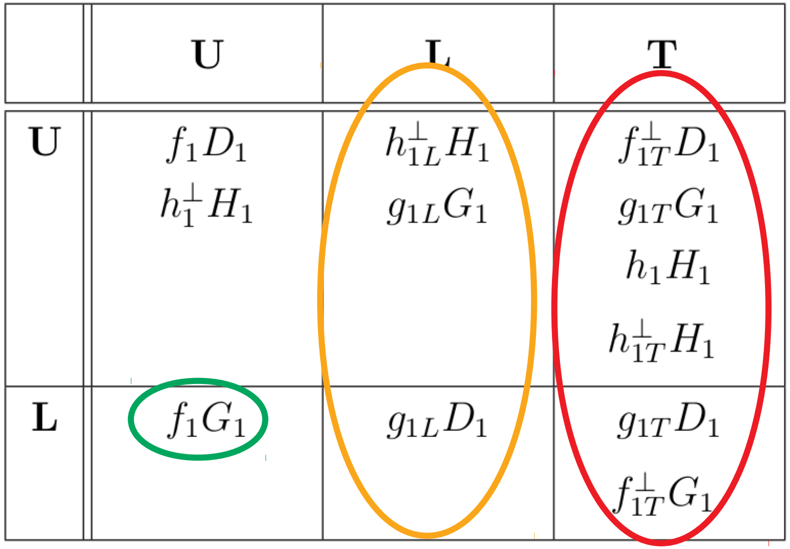
	U	L	T
U	$h H_1 \quad f_1 \tilde{D}$ $f^\perp D_1 \quad h_1^\perp \tilde{H}$	$h_L H_1 \quad g_{1L} \tilde{G}$ $f_L^\perp D_1 \quad h_{1L}^\perp \tilde{H}$	$f_T D_1 \quad h_1 \tilde{H}$ $h_T H_1 \quad g_{1T} \tilde{G}$ $h_T^\perp H_1 \quad f_{1T}^\perp \tilde{D}$ $f_T^\perp D_1 \quad h_{1T}^\perp \tilde{H}$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

Full Dihadron Cross Section

Twist 2

Target Polarization

Beam Polarization



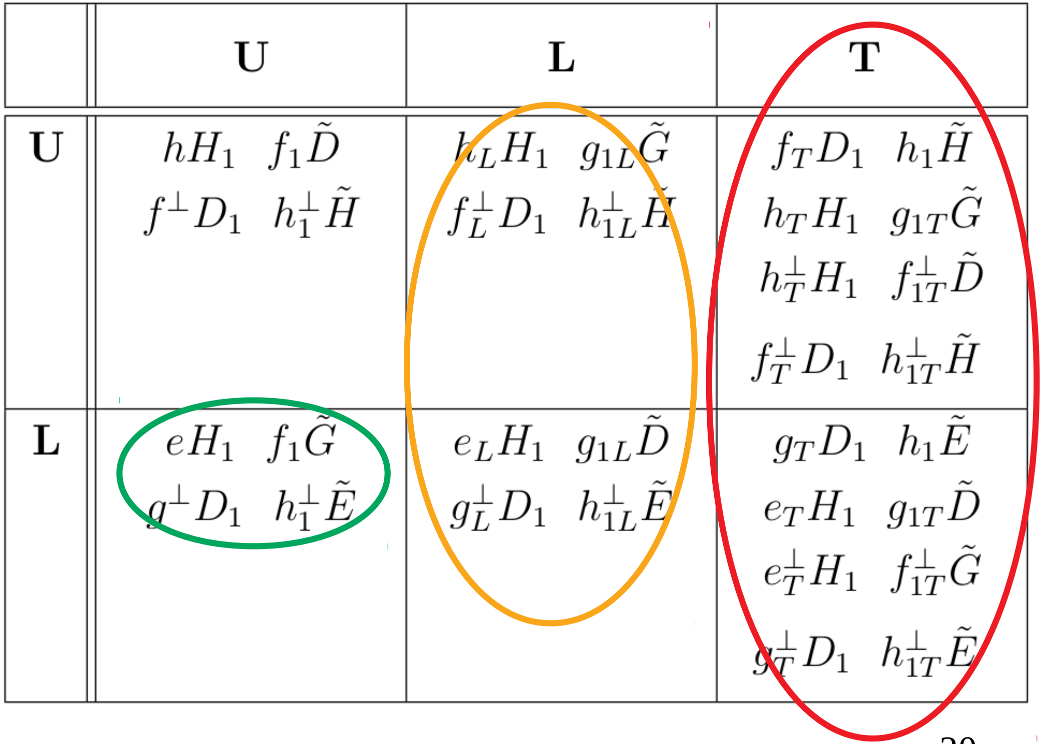
	U	L	T
U	f_1D_1 $h_1^\perp H_1$	$h_{1L}^\perp H_1$ $g_{1L}G_1$	$f_{1T}^\perp D_1$ $g_{1T}G_1$ h_1H_1 $h_{1T}^\perp H_1$
L	f_1G_1	$g_{1L}D_1$	$g_{1T}D_1$ $f_{1T}^\perp G_1$

- **2018-2020**
- **2022-2023**
- **Future (?)**

Twist 3

Target Polarization

Beam Polarization



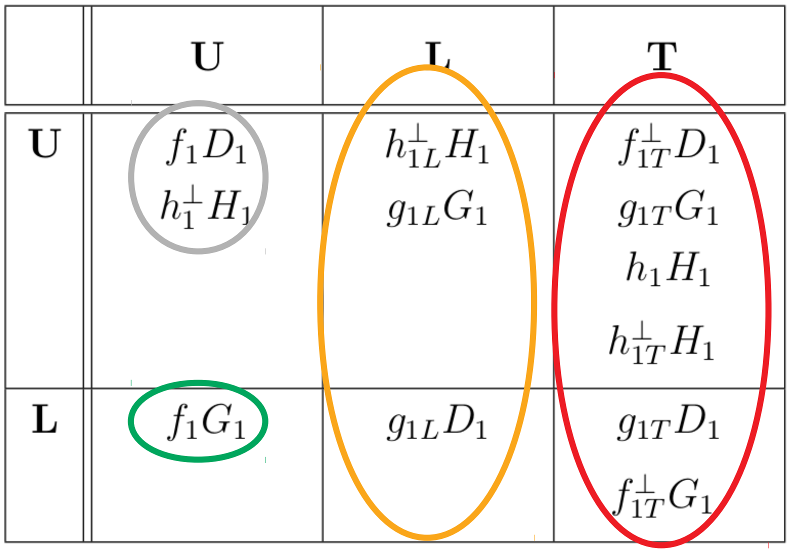
	U	L	T
U	hH_1 $f_1\tilde{D}$ $f^\perp D_1$ $h_1^\perp\tilde{H}$	h_LH_1 $g_{1L}\tilde{G}$ $f_L^\perp D_1$ $h_{1L}^\perp\tilde{H}$	f_TD_1 $h_1\tilde{H}$ h_TH_1 $g_{1T}\tilde{G}$ $h_T^\perp H_1$ $f_{1T}^\perp\tilde{D}$ $f_T^\perp D_1$ $h_{1T}^\perp\tilde{H}$
L	eH_1 $f_1\tilde{G}$ $g^\perp D_1$ $h_1^\perp\tilde{E}$	e_LH_1 $g_{1L}\tilde{D}$ $g_L^\perp D_1$ $h_{1L}^\perp\tilde{E}$	g_TD_1 $h_1\tilde{E}$ e_TH_1 $g_{1T}\tilde{D}$ $e_T^\perp H_1$ $f_{1T}^\perp\tilde{G}$ $g_T^\perp D_1$ $h_{1T}^\perp\tilde{E}$

Full Dihadron Cross Section

Twist 2

Target Polarization

Beam Polarization

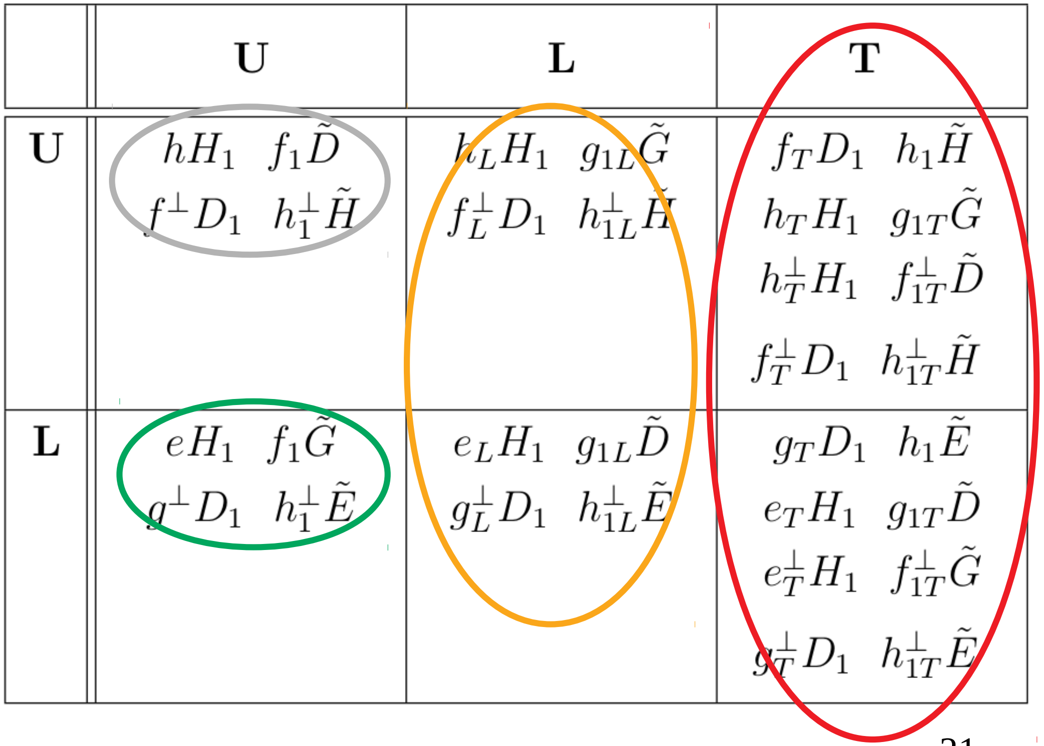


	U	L	T
U	$f_1 D_1$ $h_1^\perp H_1$	$h_{1L}^\perp H_1$ $g_{1L} G_1$	$f_{1T}^\perp D_1$ $g_{1T} G_1$ $h_1 H_1$ $h_{1T}^\perp H_1$
L	$f_1 G_1$	$g_{1L} D_1$	$g_{1T} D_1$ $f_{1T}^\perp G_1$

Twist 3

Target Polarization

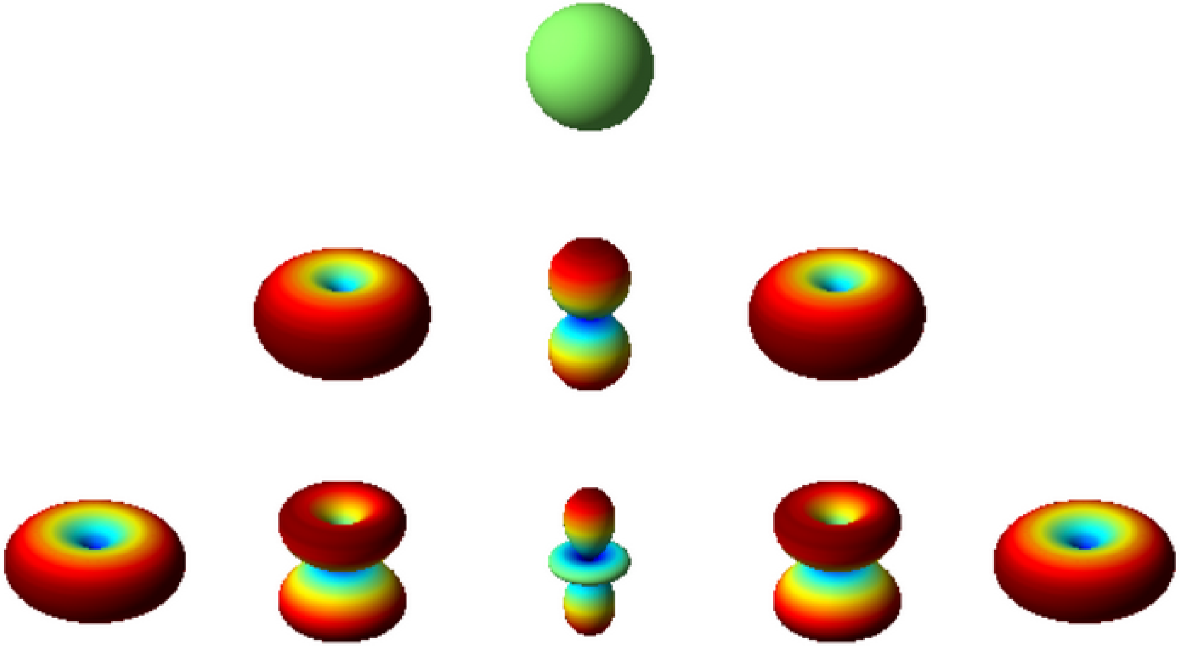
Beam Polarization



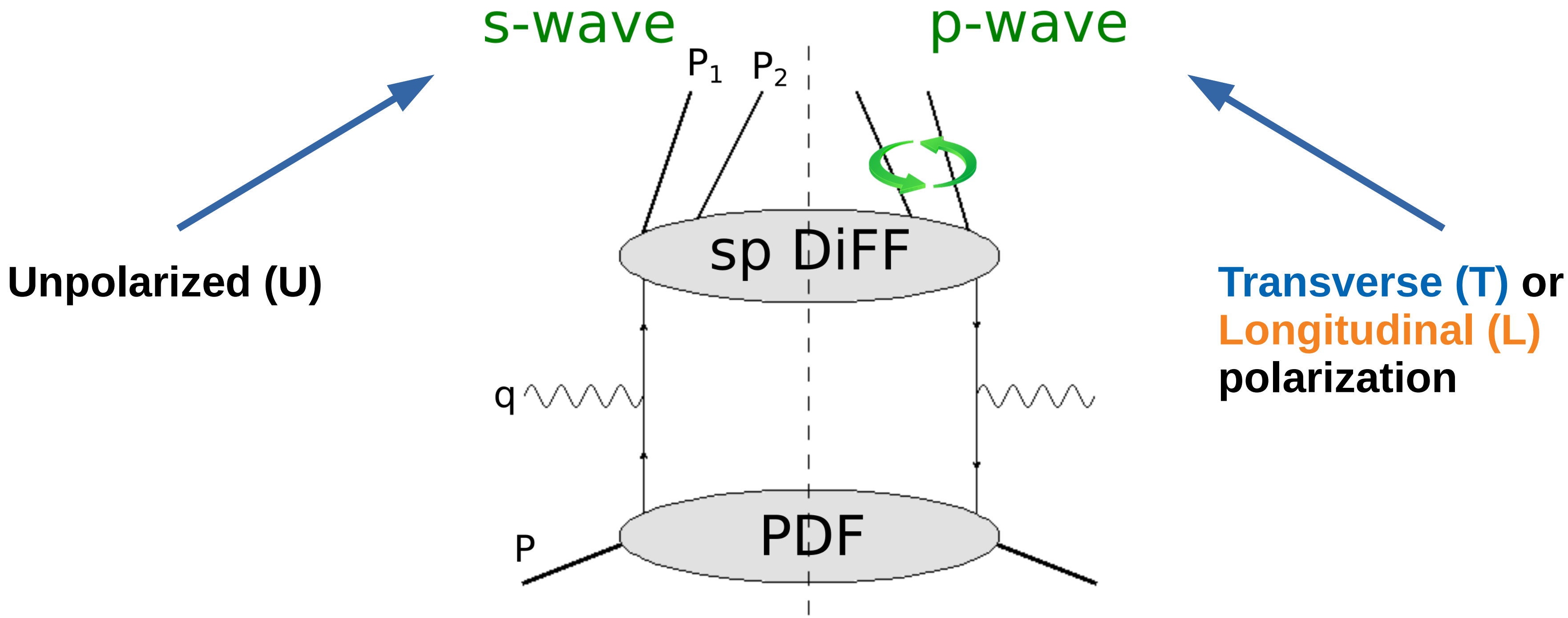
	U	L	T
U	$h H_1 \quad f_1 \tilde{D}$ $f^\perp D_1 \quad h_1^\perp \tilde{H}$	$h_L H_1 \quad g_{1L} \tilde{G}$ $f_L^\perp D_1 \quad h_{1L}^\perp \tilde{H}$	$f_T D_1 \quad h_1 \tilde{H}$ $h_T H_1 \quad g_{1T} \tilde{G}$ $h_T^\perp H_1 \quad f_{1T}^\perp \tilde{D}$ $f_T^\perp D_1 \quad h_{1T}^\perp \tilde{H}$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

- 2018-2020
- 2022-2023
- Future (?)
- (any time)

Partial Waves



Partial Wave Expansion



s-wave

p-wave

Unpolarized (U)

Transverse (T) or Longitudinal (L) polarization

- **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

ℓ = 0

ss

$|0,0\rangle$

U U

m = 0

Partial Waves

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

Partial Waves

	m = -2	*m = -1*	*m = 0*	*m = +1*	*m = +2*
ℓ = 0 *ss*			$\left|0,0\right\rangle$ **U U**		
ℓ = 1 *sp*		$\left|1,-1\right\rangle$ **U T**	$\left|1,0\right\rangle$ **U L**	$\left|1,1\right\rangle$ **U T**	
ℓ = 2 *pp*	$\left|2,-2\right\rangle$ **T T**	$\left|2,-1\right\rangle$ **L T**	$\left|2,0\right\rangle$ **L L**	$\left|2,1\right\rangle$ **L T**	$\left|2,2\right\rangle$ **T T**

Partial Waves

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** $G_{1,TT}^{\perp}$ $H_{1,TT}^{\sphericalangle}$
	m = -2	***m = -1***	***m = 0***	***m = +1***	***m = +2***

Partial Waves

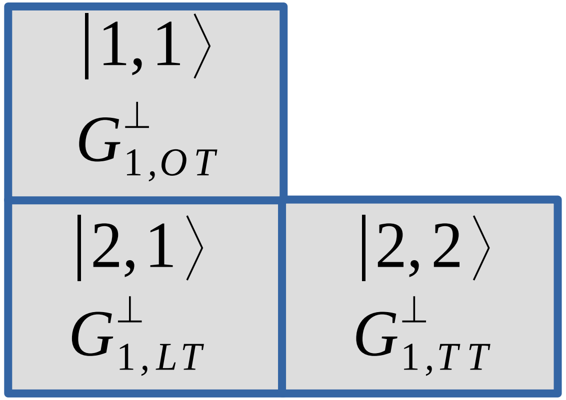
12 Parameter Simultaneous Fit

Twist 2

3 params

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

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



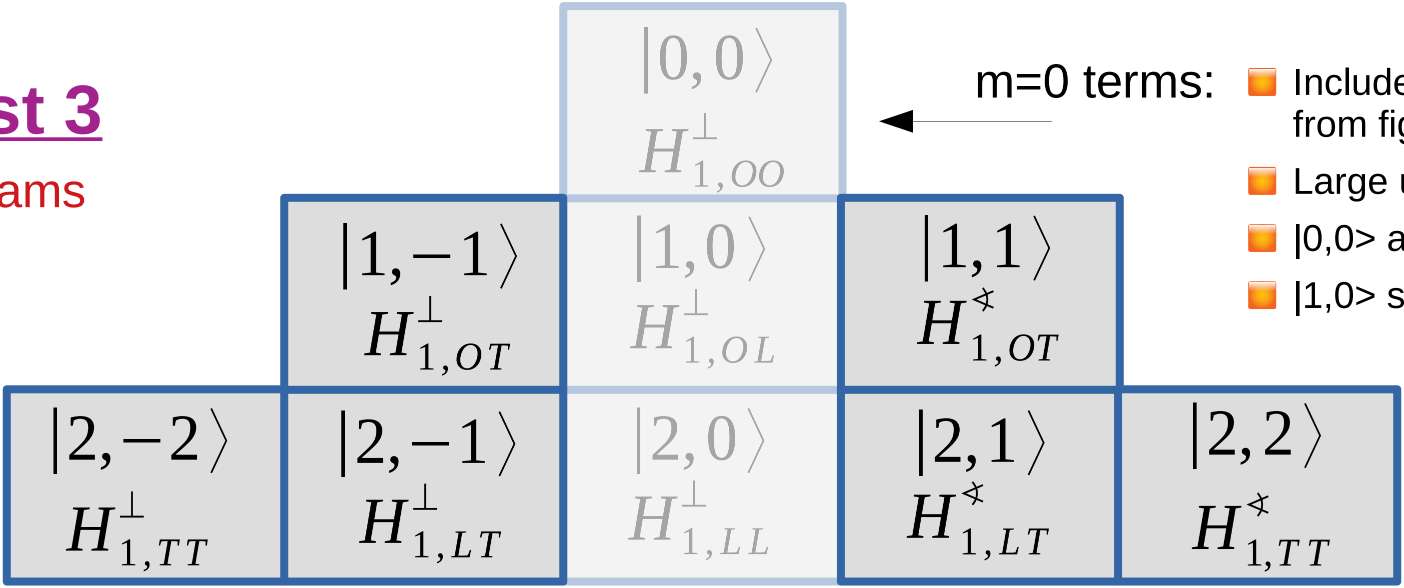
$|1,1\rangle$ $G_{1,OT}^{\perp}$

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

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

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

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

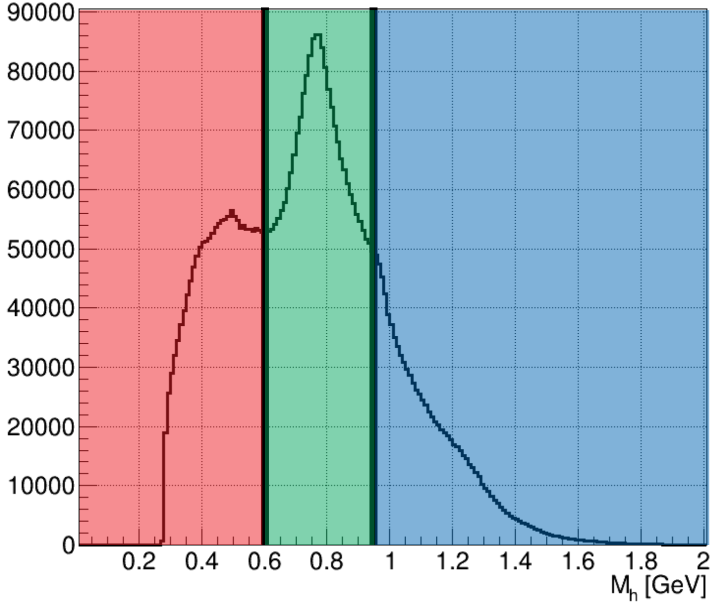
$$G_1^{\perp,|\ell,m\rangle}=G_1^{\perp,|\ell,-m\rangle}$$

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

Twist 3

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

Cuts and Distributions



Event Selection Criteria

General Cuts

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

Additional Cuts

- PID Refinement
- Vertex
- Fiducial volume

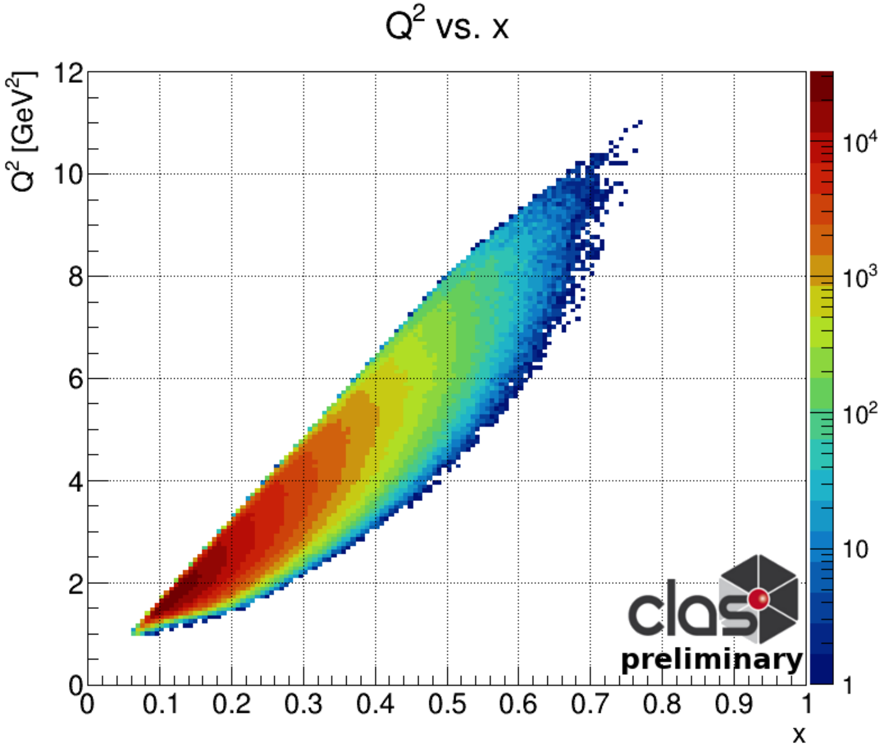
Pion and Dihadron Cuts

- $x_F(\pi^+), x_F(\pi^0) > 0$
- $p(\pi^+) > 1.25$ GeV
- $p(\pi^0)$ cut given by photon cuts (→)
- $z_{pair} < 0.95$

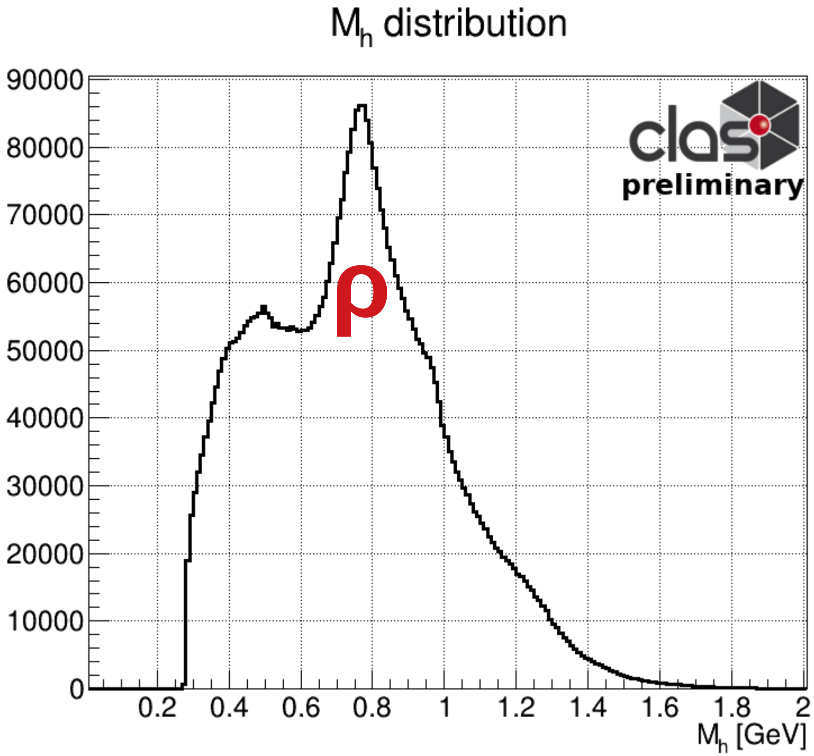
Photon Cuts

- $0.9 < \beta < 1.1$
- $E > 0.6$ GeV
- $\mathrm{Ang}(e^-,\gamma) > 8°$

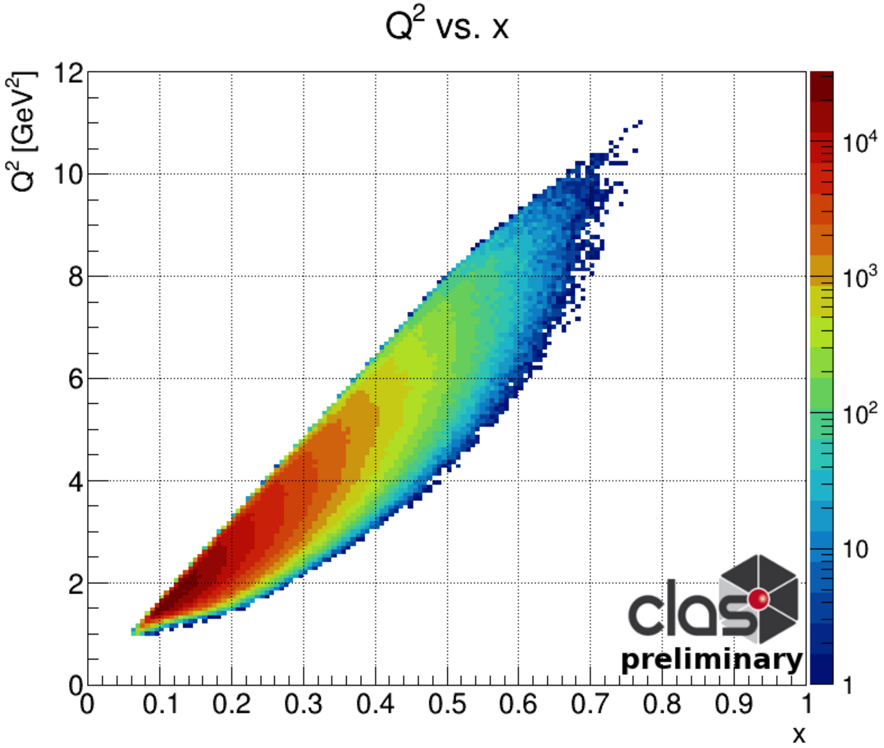
$\pi^+\pi^-$ Kinematics



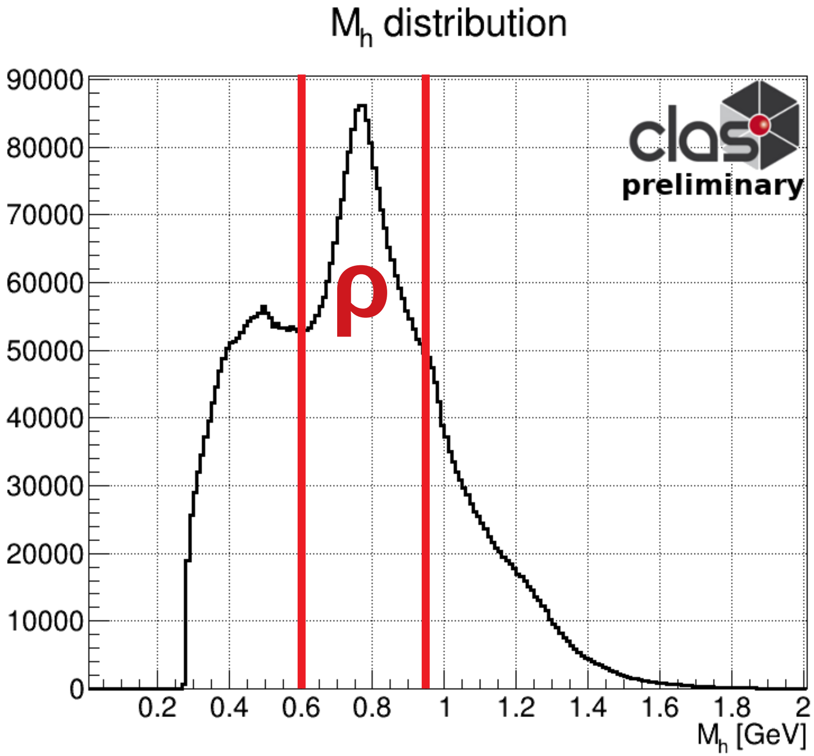
dihadron invariant mass



$\pi^+\pi^-$ Kinematics

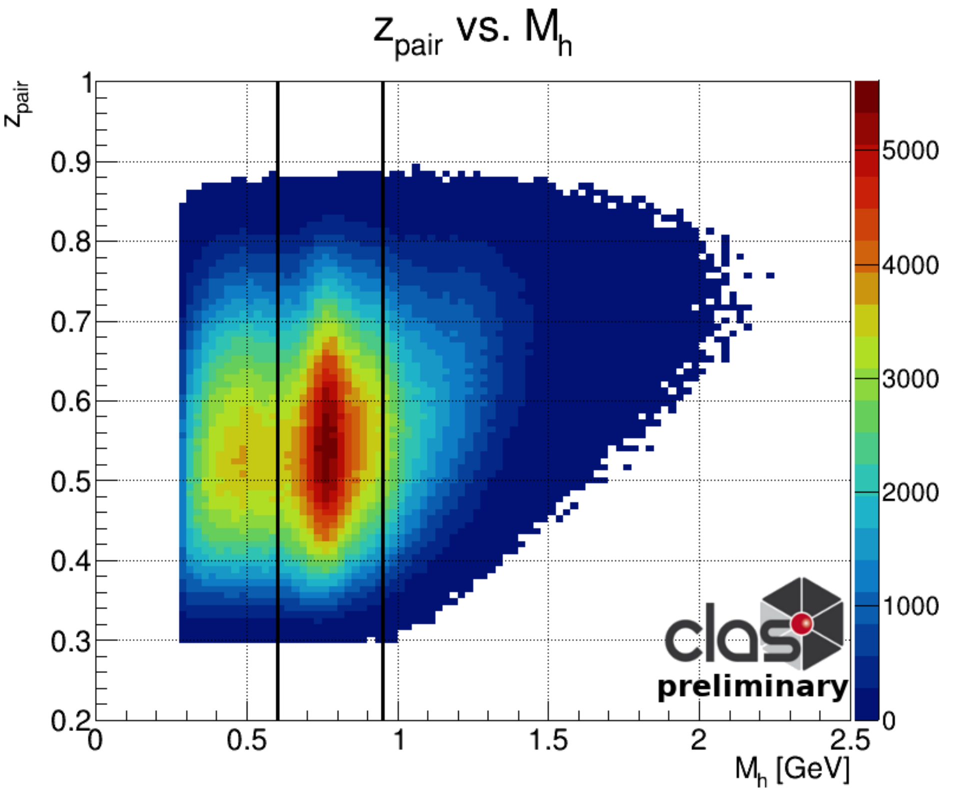


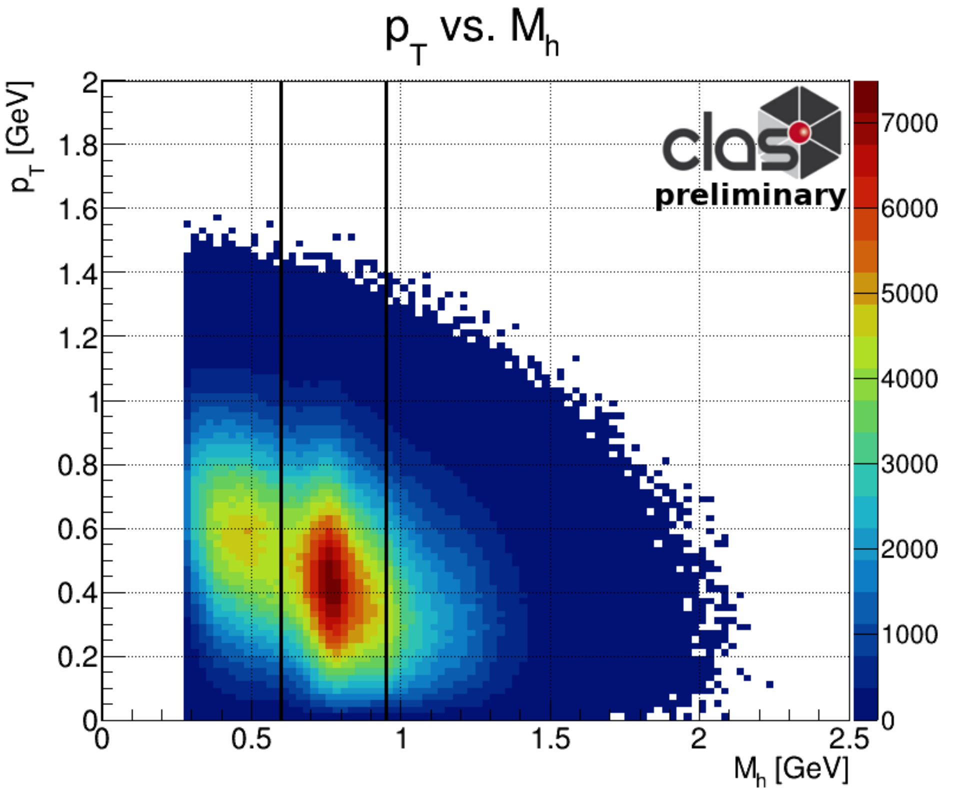
dihadron invariant mass



Multidimensional binning scheme in M_h

$\pi^+\pi^-$ Kinematics

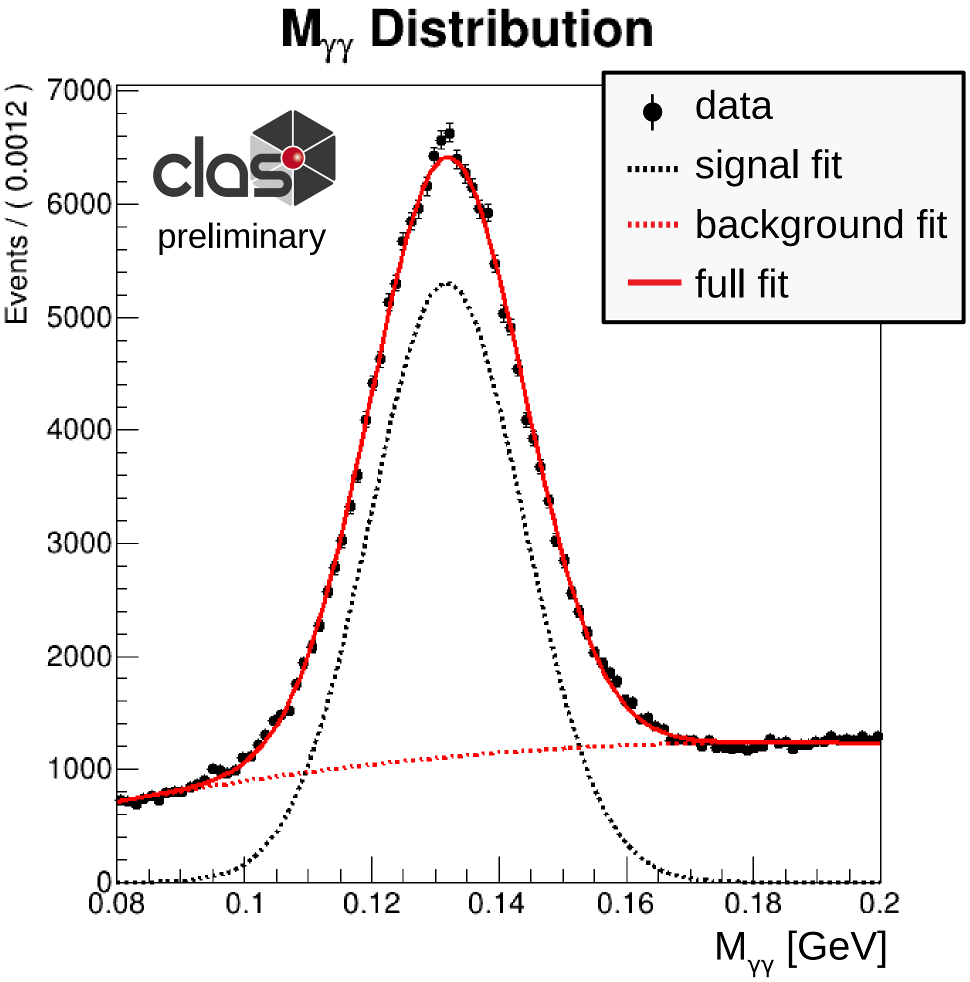




Diphoton Invariant Mass $M_{\gamma\gamma}$

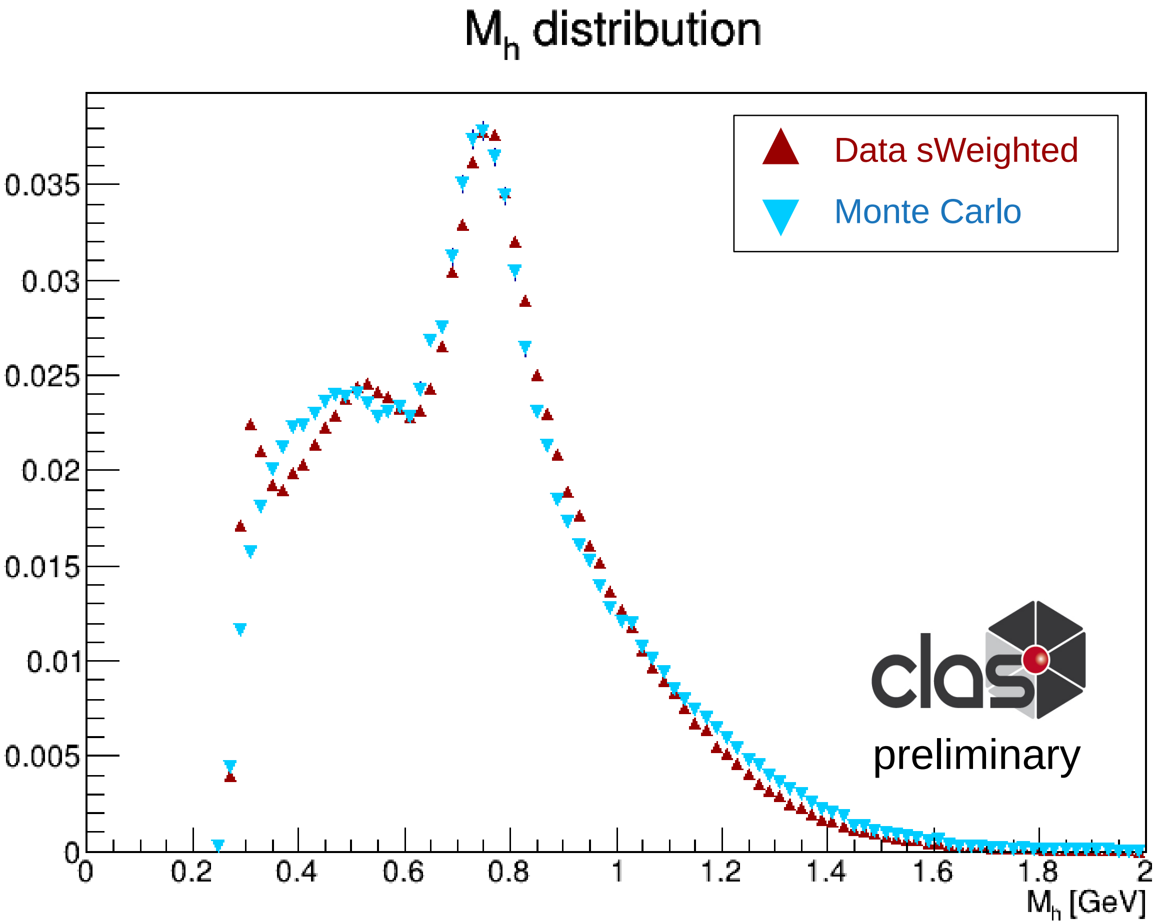
- Dihadrons with π^0s require photon pairing
- π^0 Mass Peak (→)
- Model: Gaussian + Chebyshev Quadratic
- 6 fit parameters
- One fit per A_{LU} bin
- Background Correction: sWeights

Nucl.Instrum.Meth.A 555 (2005) 356-369



C. Dilks

$\pi^+\pi^0$ Dihadron Invariant Mass



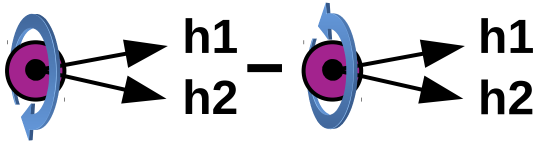
- Compare sWeighted data distributions with reconstructed MC from true $\pi^0 \rightarrow \gamma\gamma$ decays
- Data are normalized to sum of sWeights; MC data are normalized to number of dihadrons
- ρ^+(770) peak visible
- Some differences at low M_h, comparable to data/MC agreement in the $\pi^+\pi^-$ channel

Beam Spin Asymmetries

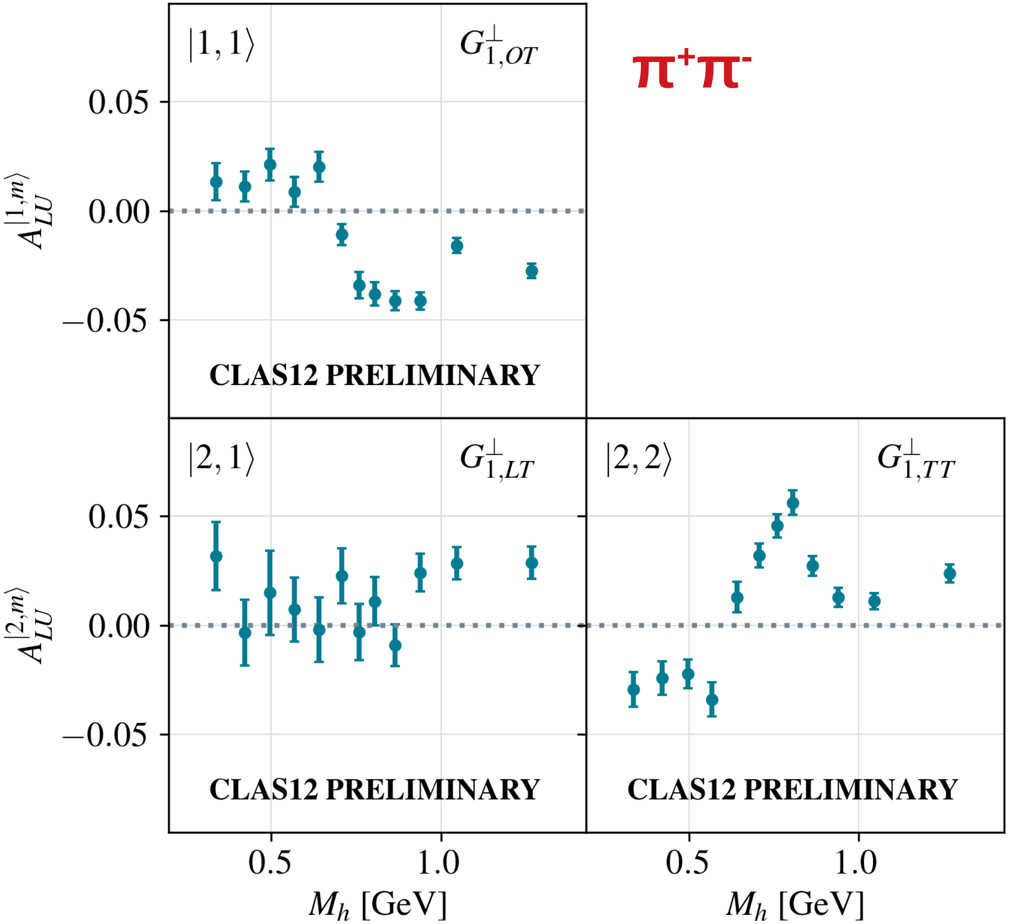
Twist 2

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

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



M_h Bins



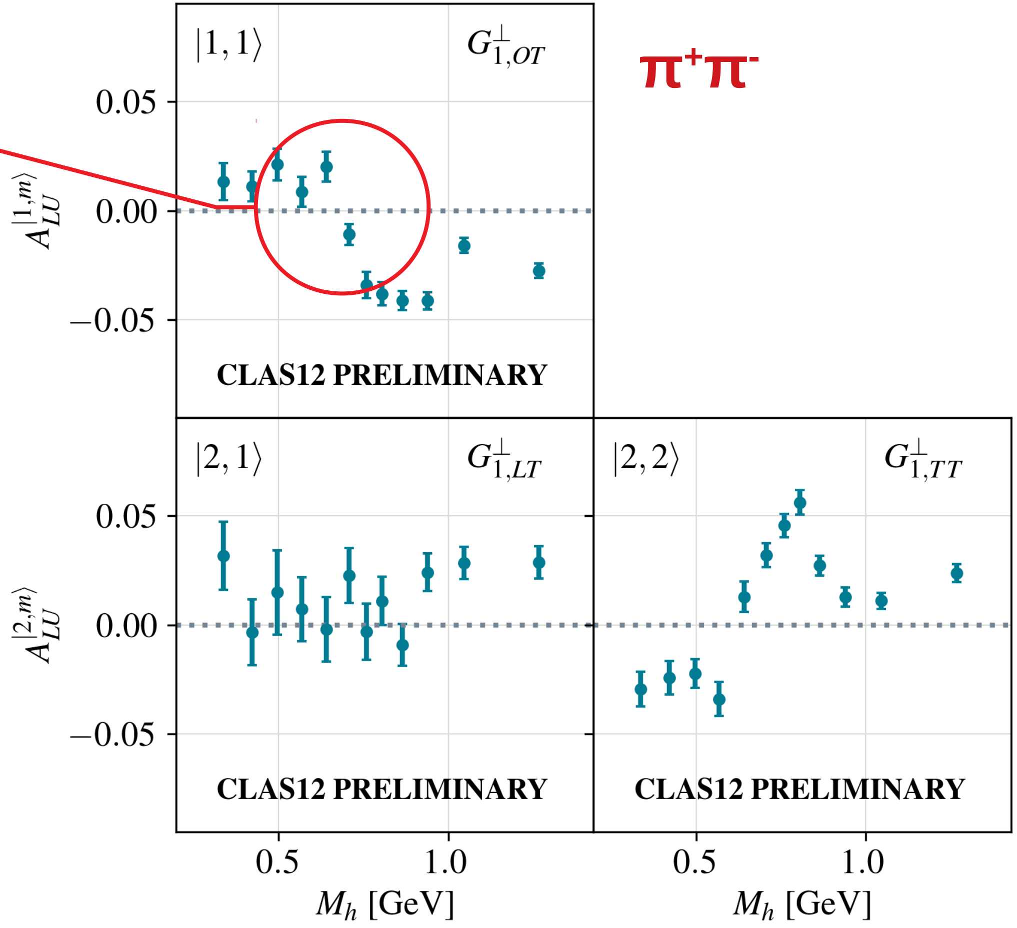
$\pi^+\pi^-$

e-Print: 2107.12965 [hep-ex]

M_h Bins

Twist-2 A_{LU} Amplitudes

Sign change near ρ mass



$\pi^+\pi^-$

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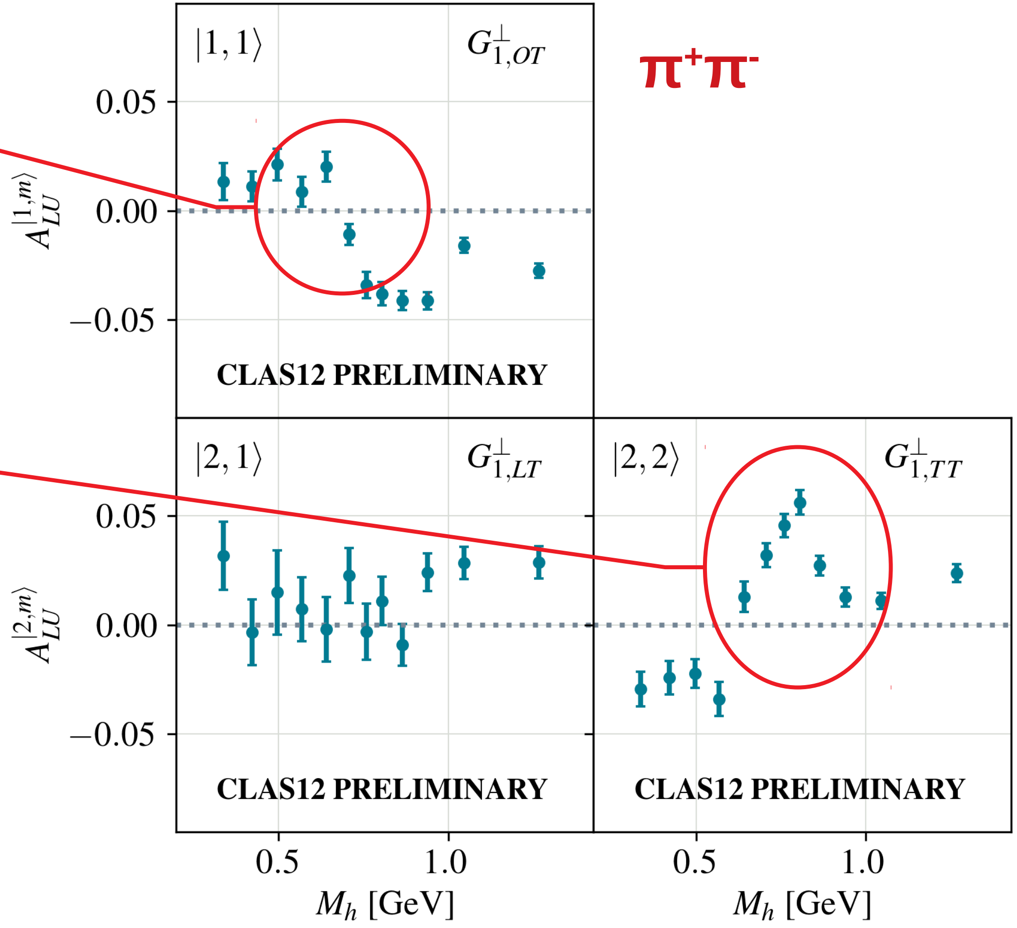
M_h Bins

Twist-2 A_{LU} Amplitudes



$\pi^+\pi^-$

Sign change near ρ mass

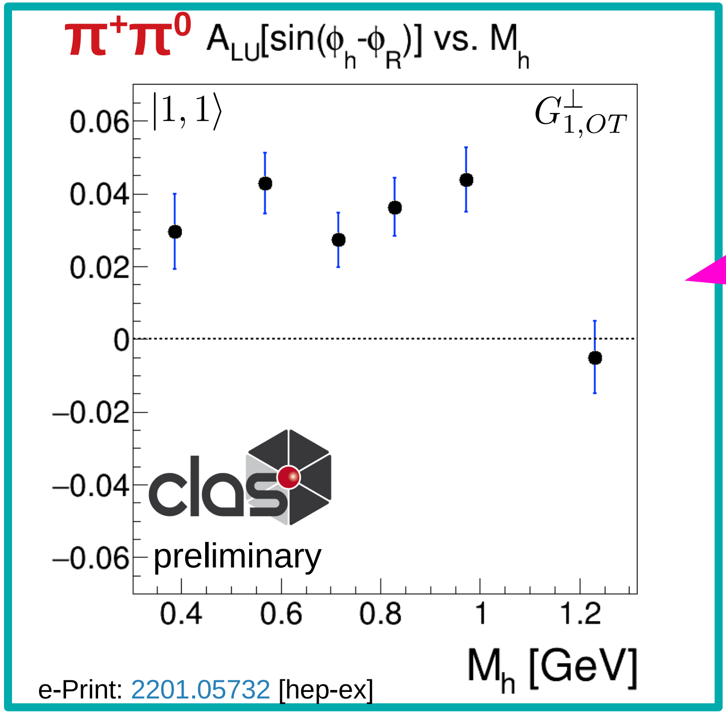
Enhancement at ρ mass (and a sign change)

ρ meson → p-wave $\pi^+\pi^-$

C. Dilks

e-Print: 2107.12965 [hep-ex]

M_h Bins



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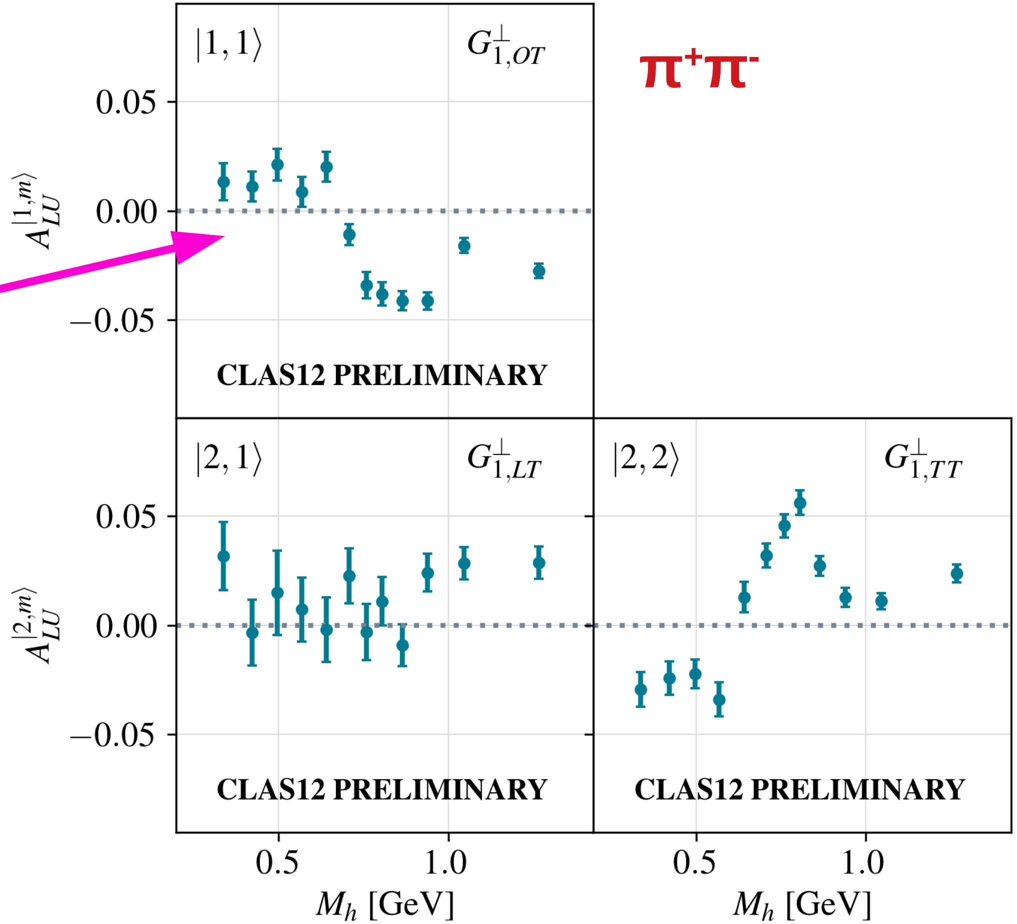


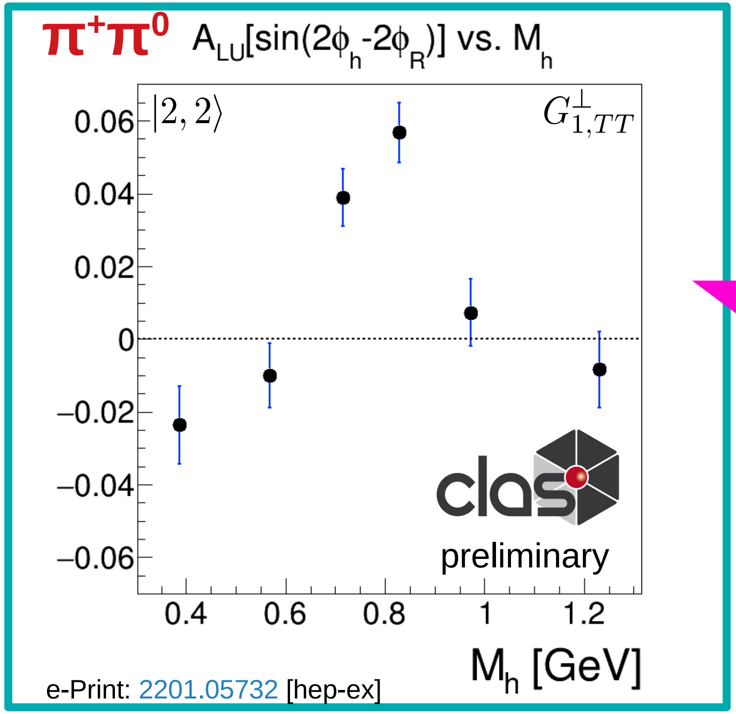
e-Print: 2107.12965 [hep-ex]

No sign change in $\pi^+\pi^0$

→ Flavor dependence of $G_1^{\perp}$

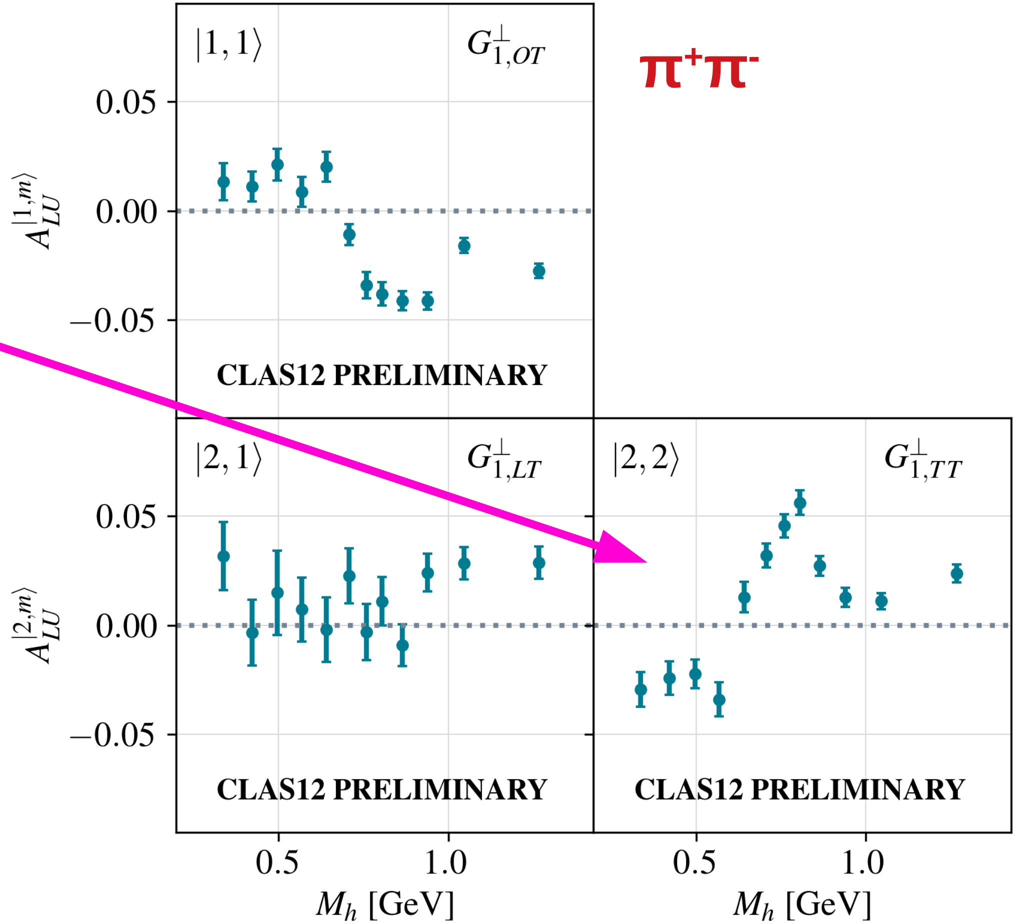
M_h Bins

Twist-2 A_{LU} Amplitudes


$\pi^+\pi^0$ $A_{LU}[\sin(2\phi_h-2\phi_R)]$ vs. M_h

e-Print: 2201.05732 [hep-ex]

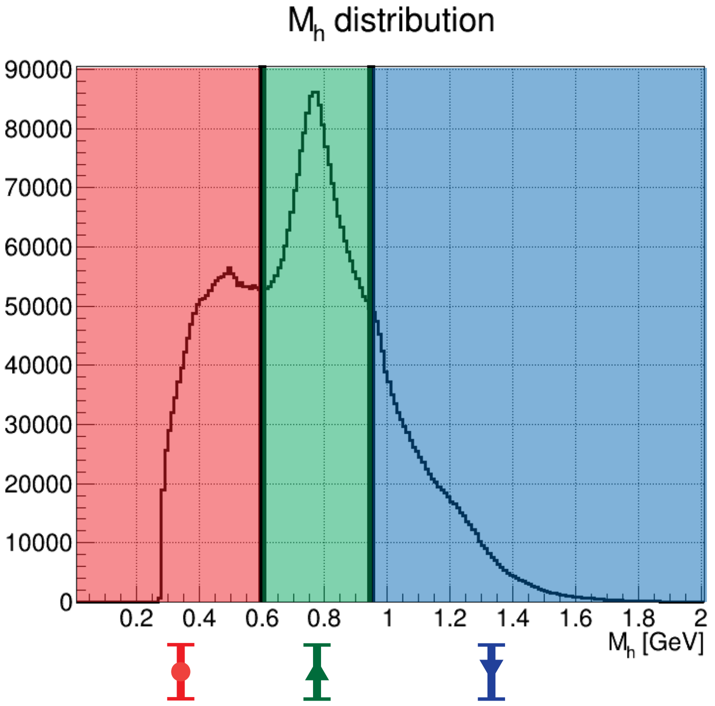
$\pi^+\pi^-$



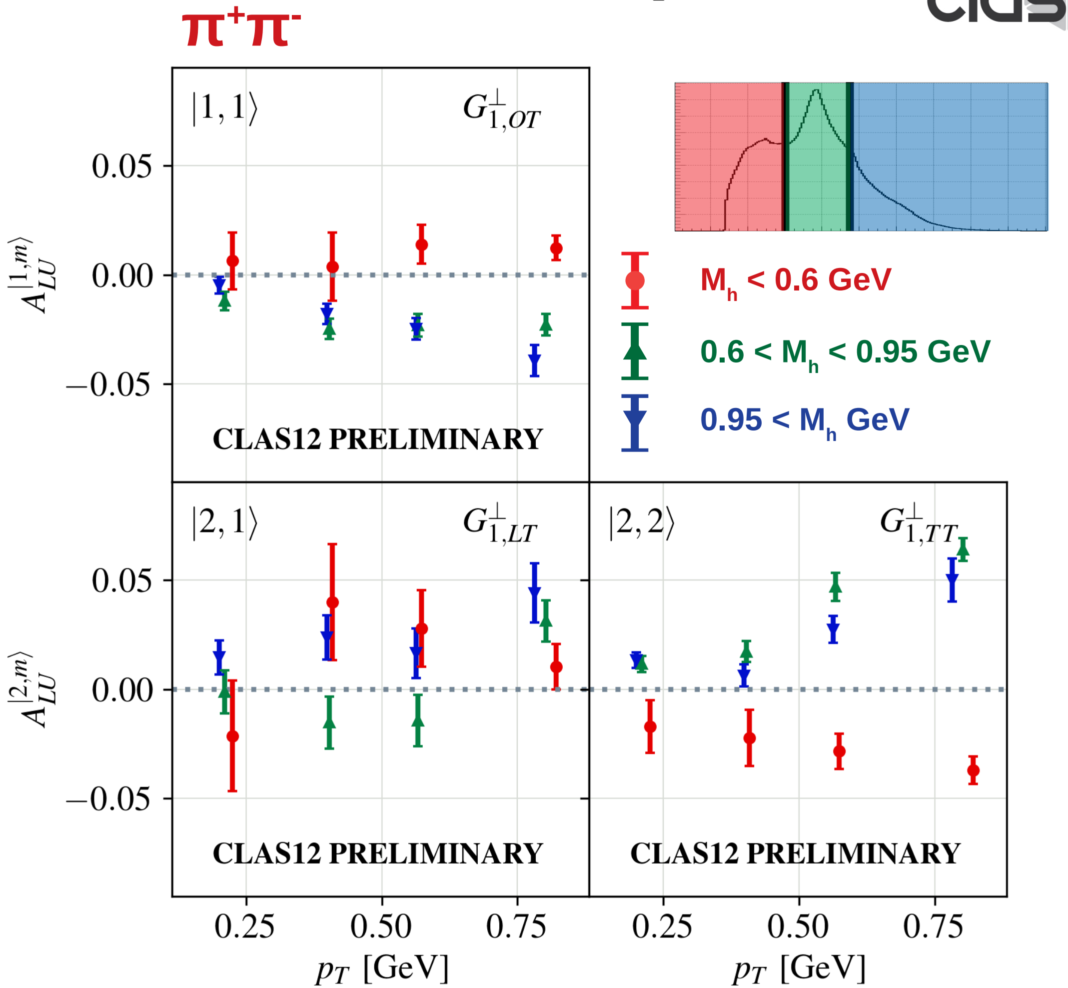
e-Print: 2107.12965 [hep-ex]

Similar ρ enhancement in $\pi^+\pi^0$

p_T Bins in 3 M_h Regions

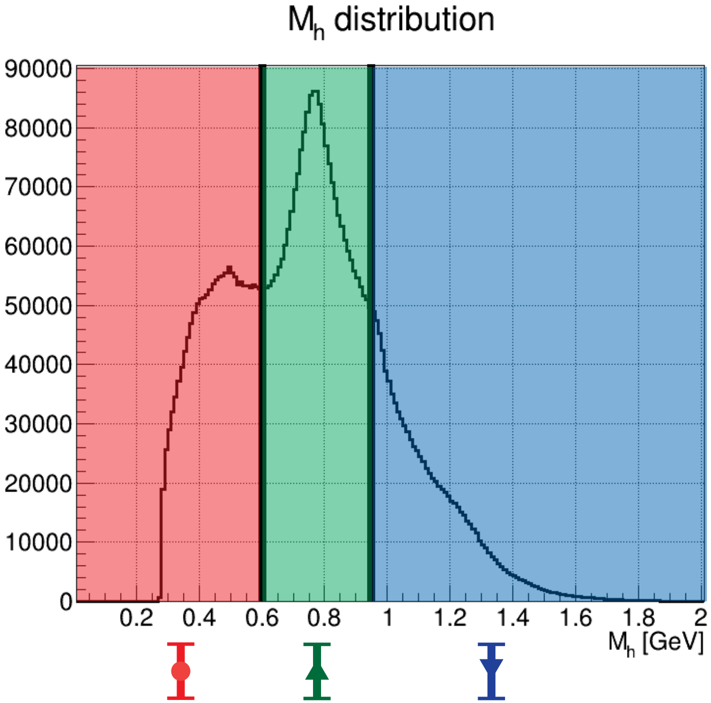


Twist-2 A_{LU} Amplitudes

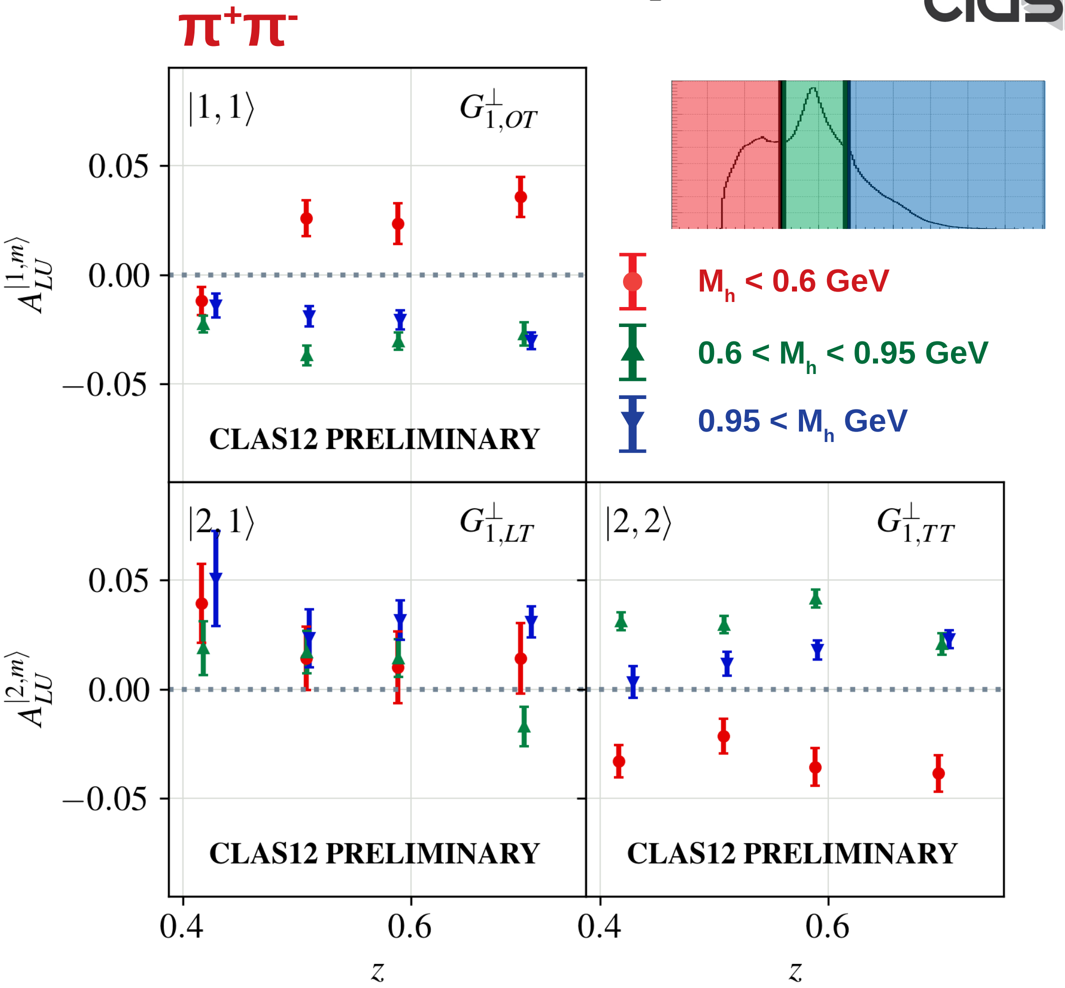


e-Print: 2107.12965 [hep-ex]

z Bins in 3 M_h Regions



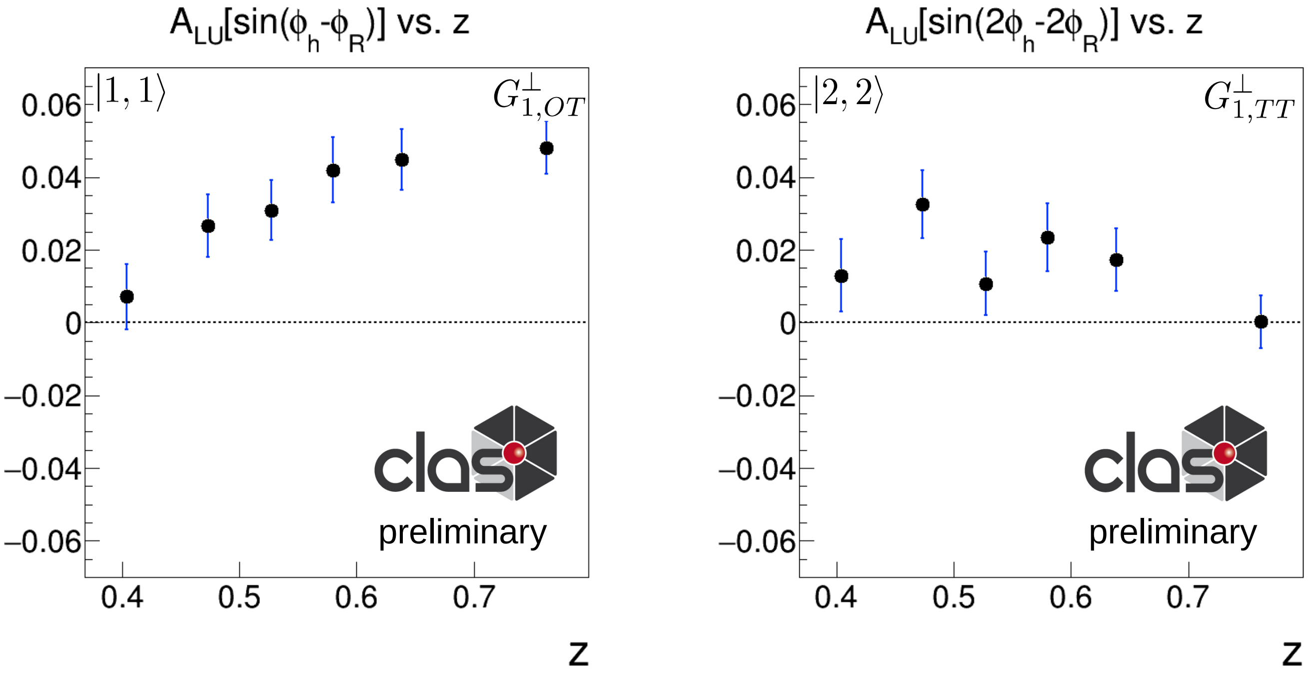
Twist-2 A_{LU} Amplitudes



e-Print: 2107.12965 [hep-ex]

CLAS12 $\pi^+\pi^0$ A_{LU} Preliminary Measurement

$\pi^+\pi^0$



e-Print: 2201.05732 [hep-ex]

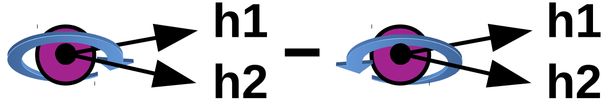
- z dependence of $\sin(\phi_h - \phi_R)$ amplitude has a slow rise
- $\sin(2\phi_h - 2\phi_R)$ may be relatively constant / decreasing

Beam Spin Asymmetries

Twist 3

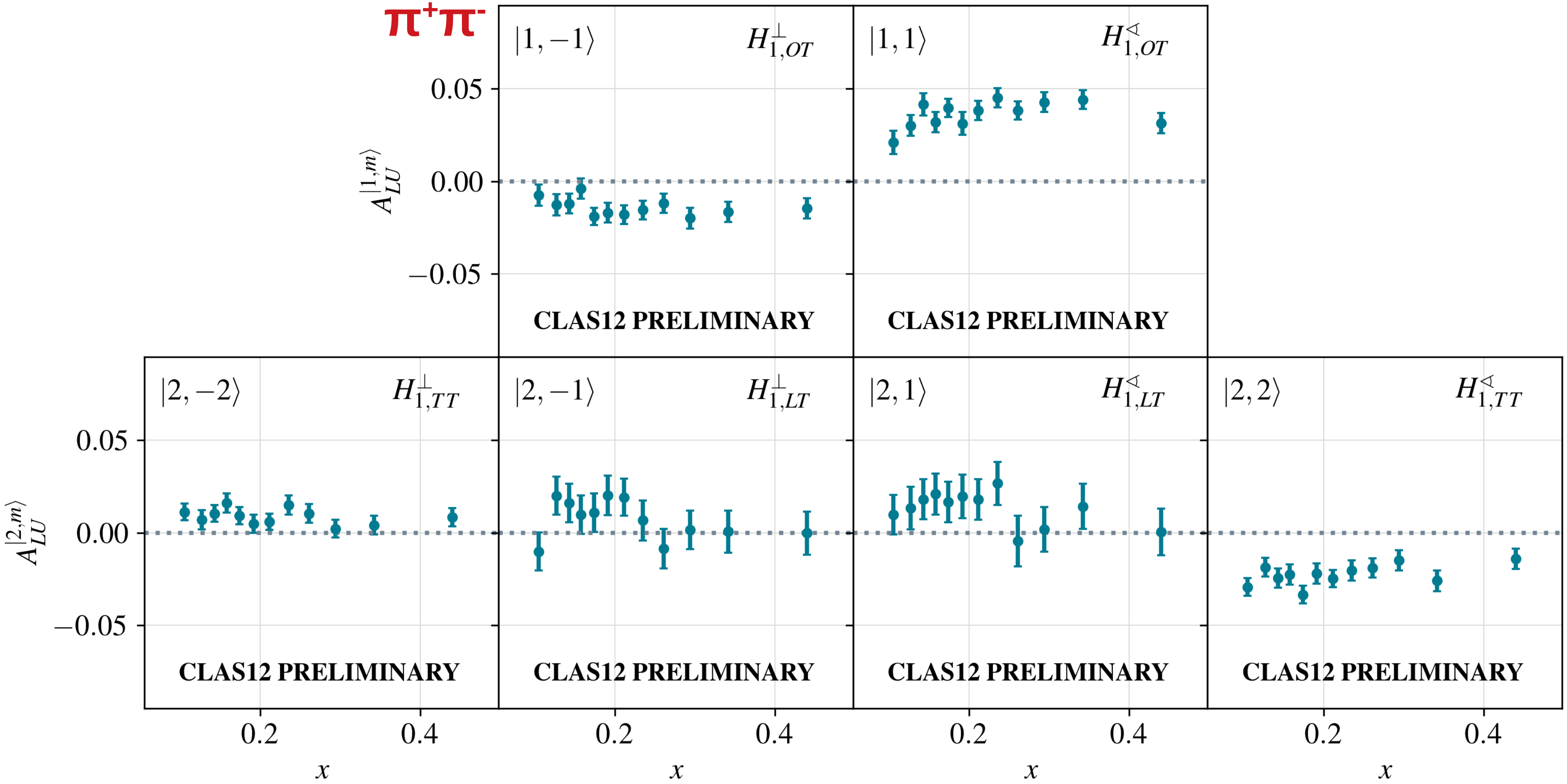
$$F_{LU} \sim e \otimes H_1^{\perp|\ell,m\rangle}$$

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



x Bins

Twist-3 A_{LU} Amplitudes



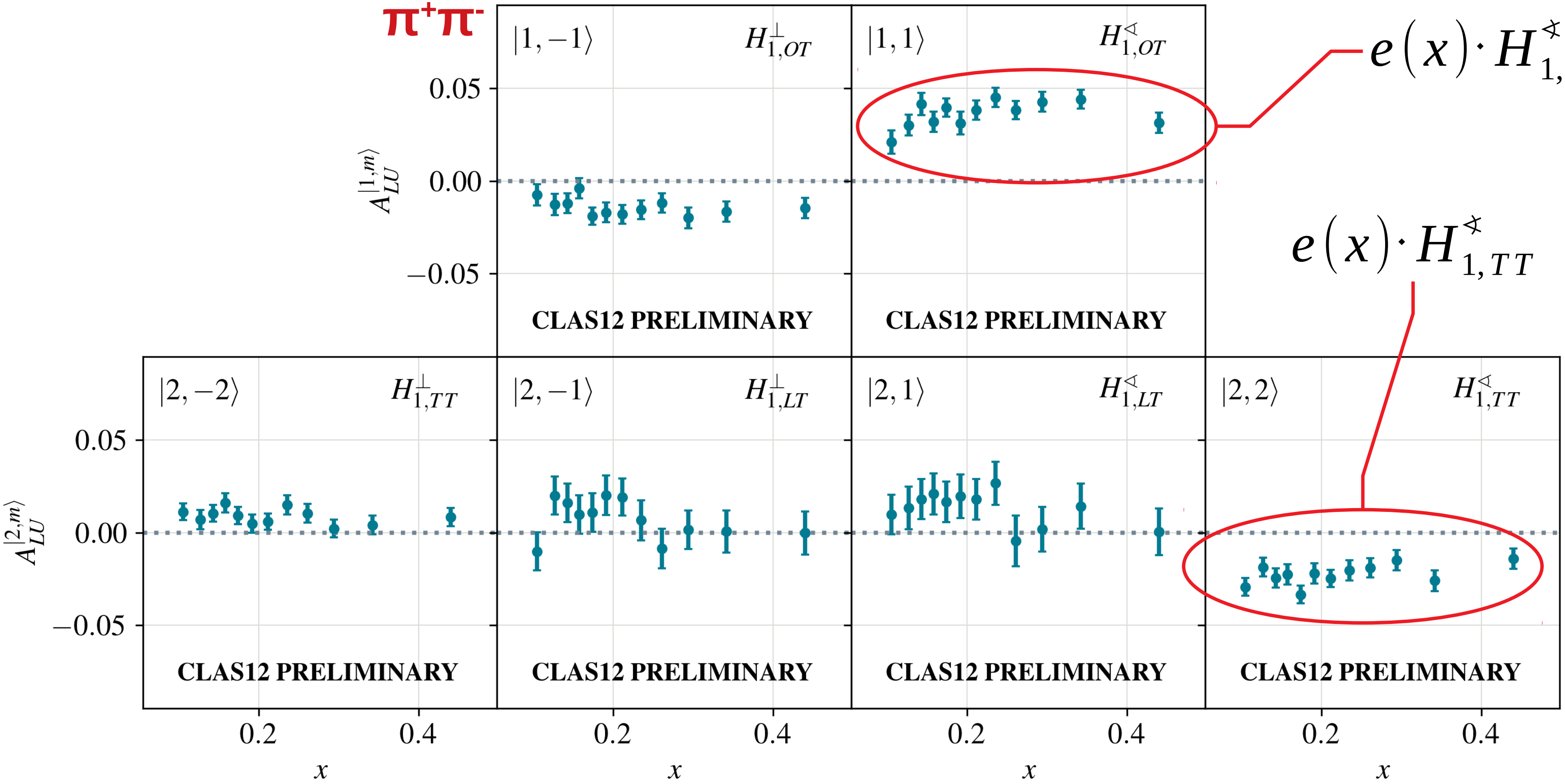
C. Dilks

e-Print: 2107.12965 [hep-ex]

x Bins

Twist-3 A_{LU} Amplitudes

$\pi^+\pi^-$



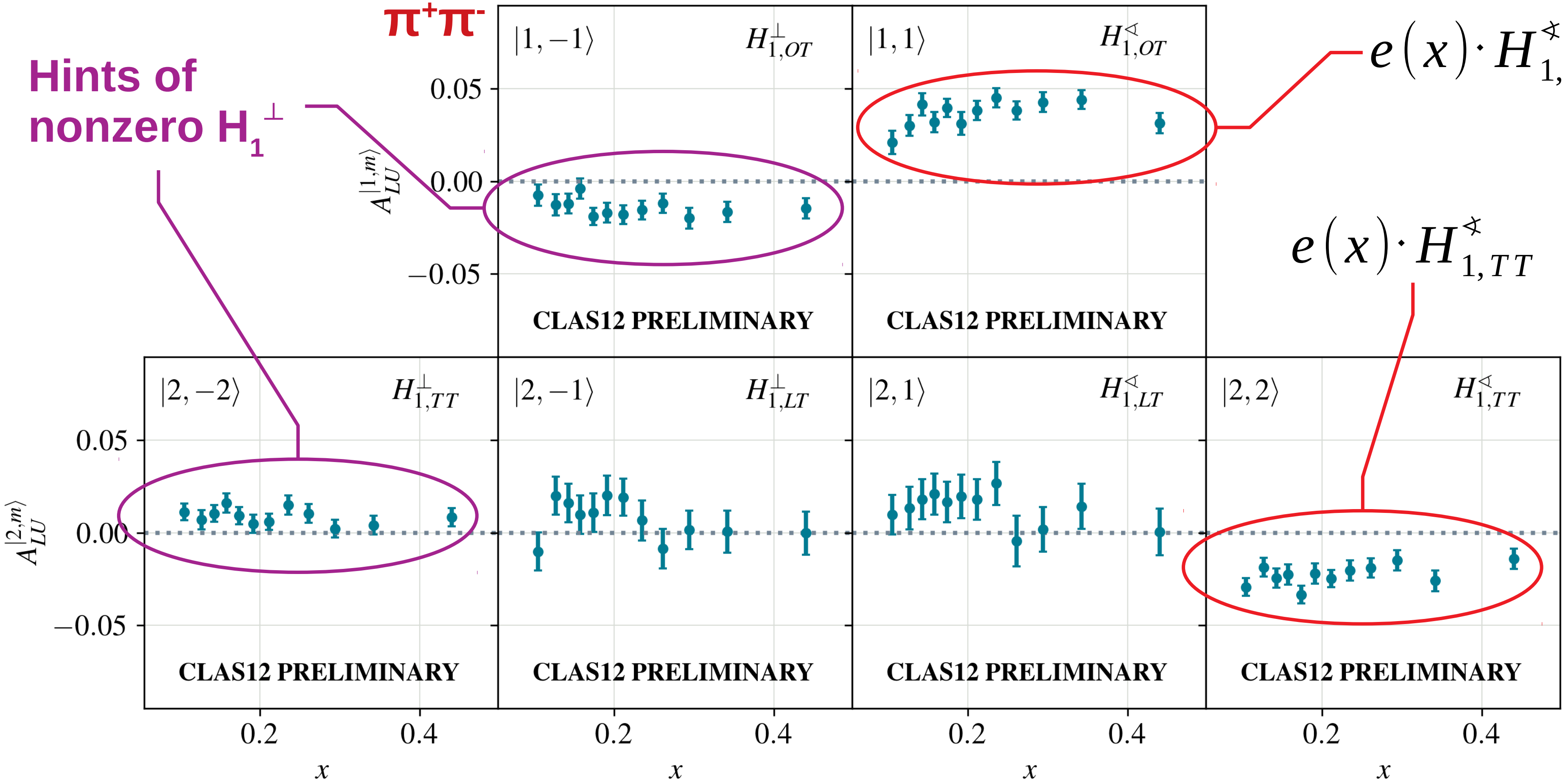
$e(x)\cdot H_{1,OT}^{\sphericalangle}$

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

e-Print: 2107.12965 [hep-ex]

x Bins

Twist-3 A_{LU} Amplitudes



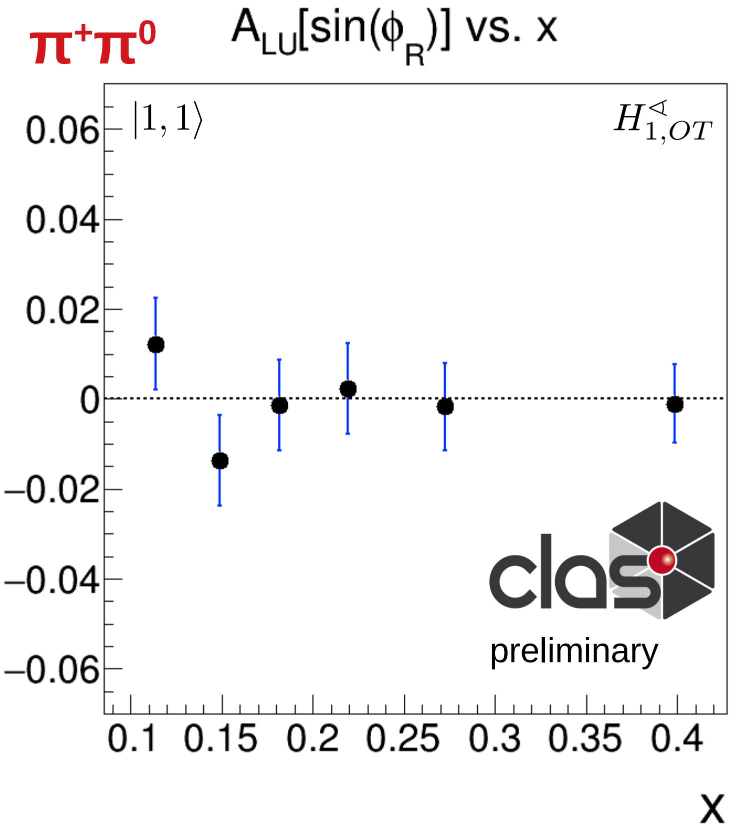
Hints of nonzero $H_1^{\perp}$

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

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

e-Print: 2107.12965 [hep-ex]

CLAS12 $\pi^+\pi^0$ A_{LU} Preliminary Measurement

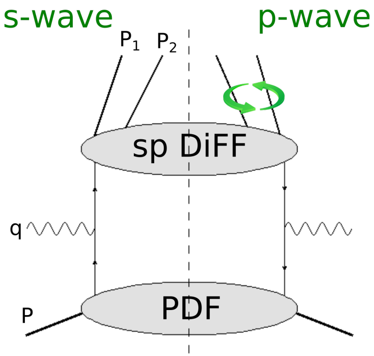


e-Print: 2201.05732 [hep-ex]

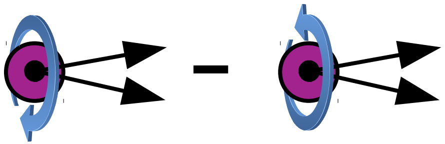
- Twist-3 amplitude of $\sin(\phi_R)$ is consistent with zero for $\pi^+\pi^0$
- cf. $\pi^+\pi^-$ |1,1>, which is about +4% → Flavor (channel) dependence of H_1

Summary

- **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 $h_L(x)$
  - 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 $H_1^{\perp}$

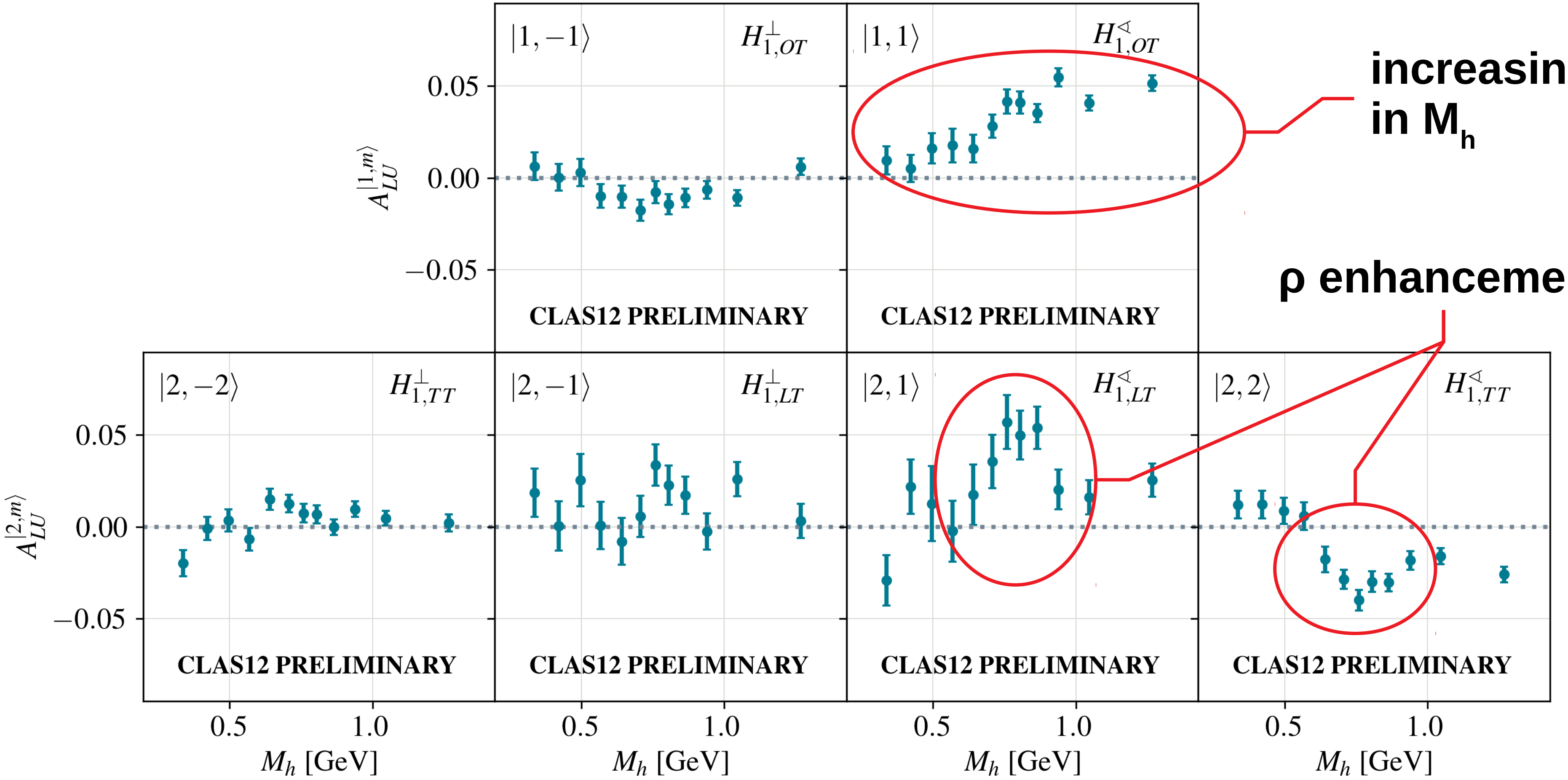


- **Stay tuned for data with a longitudinally polarized target!**

backup

M_h Bins

Twist-3 A_{LU} Amplitudes



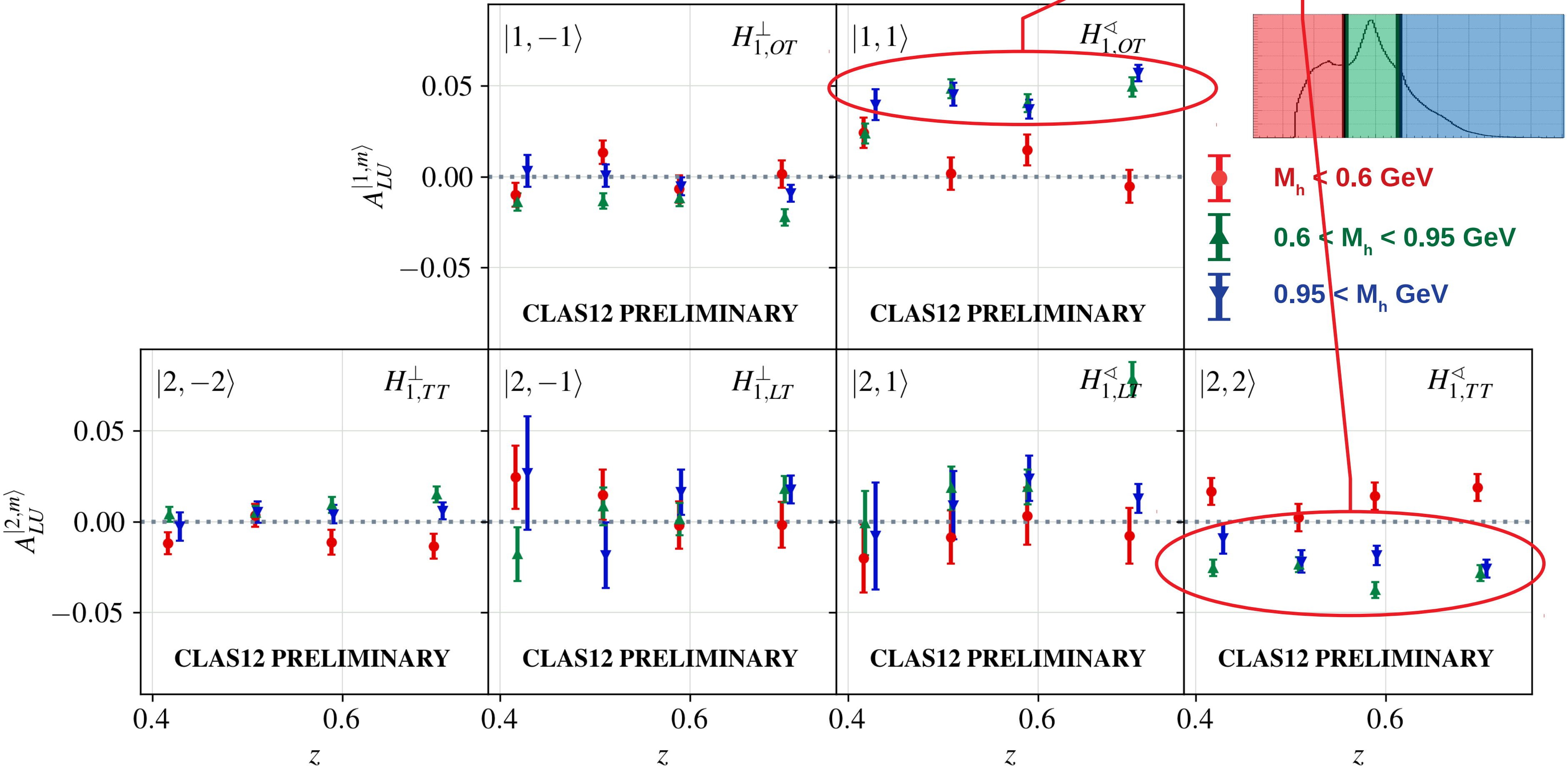
increasing in M_h

ρ enhancement

C. Dilks

z Bins in 3 M_h Regions

Twist-3 A_{LU} Amplitudes

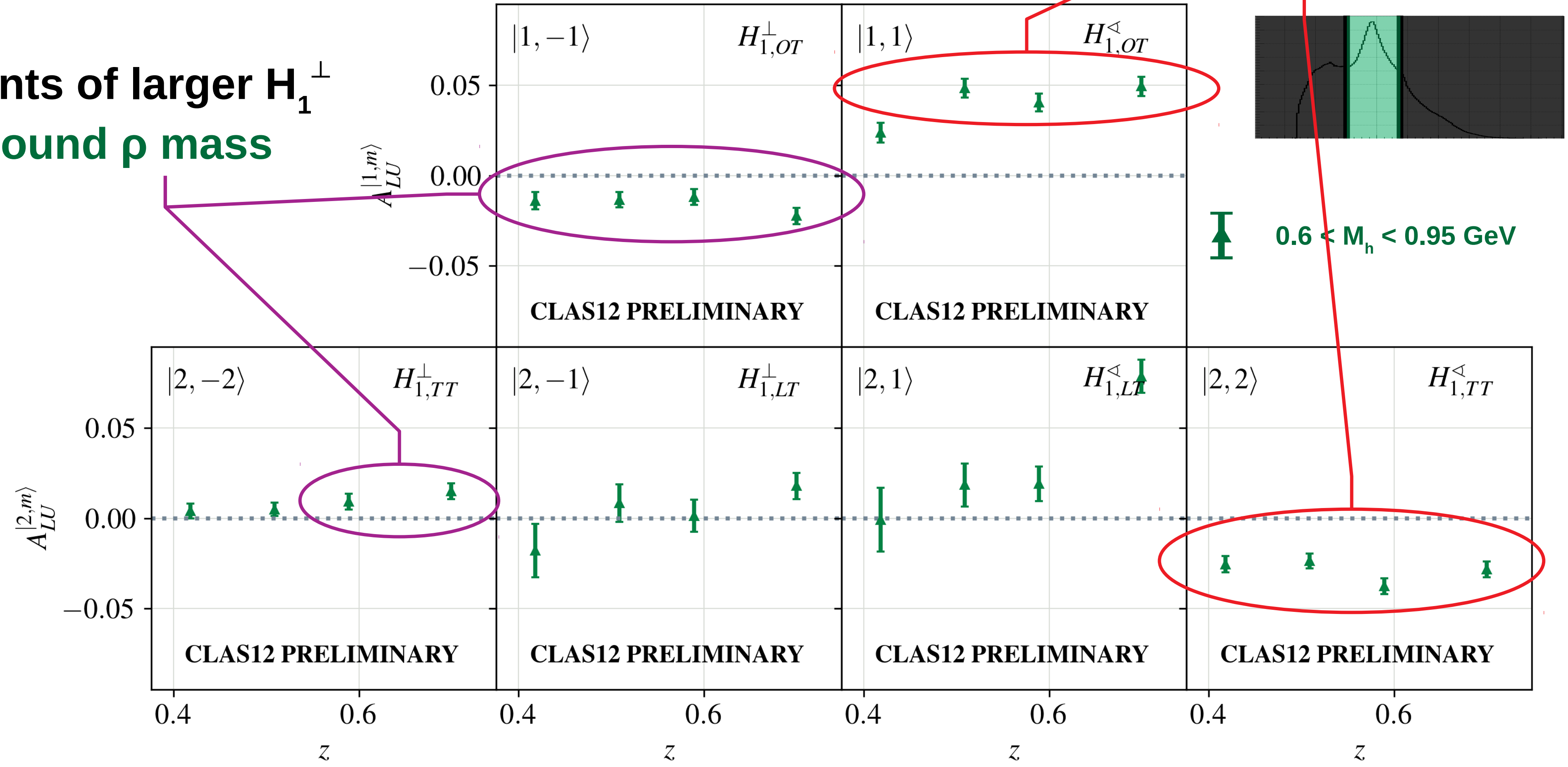


flat in z

z Bins, $M_h \sim M_\rho$

Twist-3 A_{LU} Amplitudes

flat in z

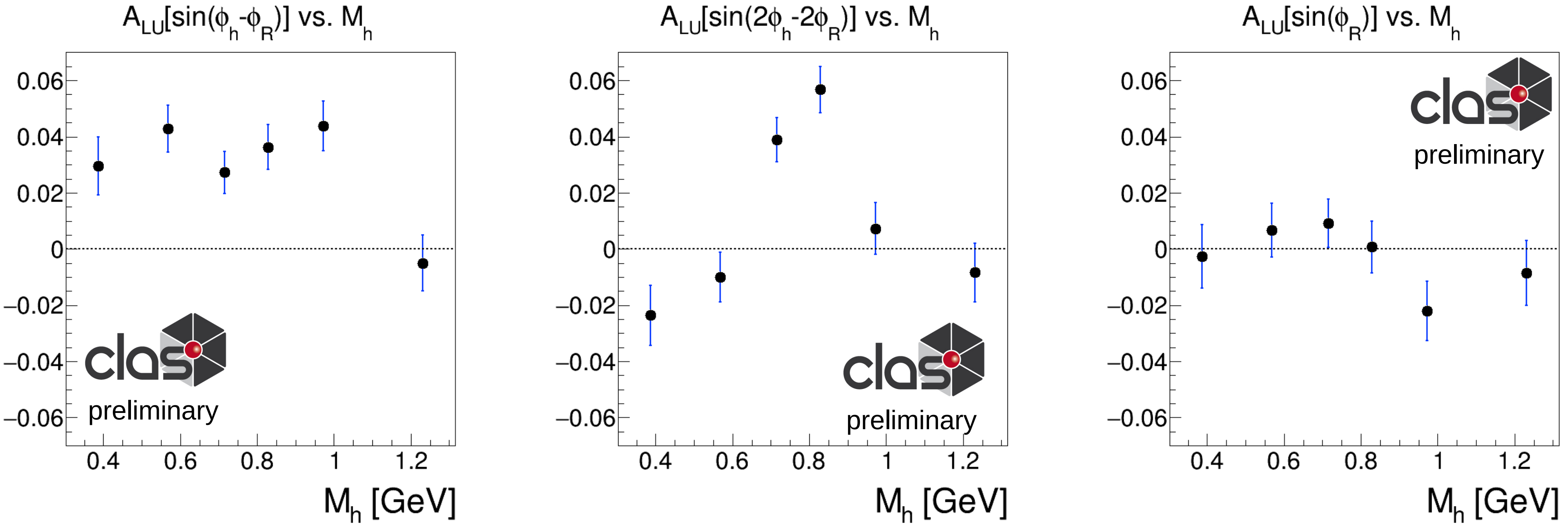


hints of larger $H_1^\perp$

around ρ mass

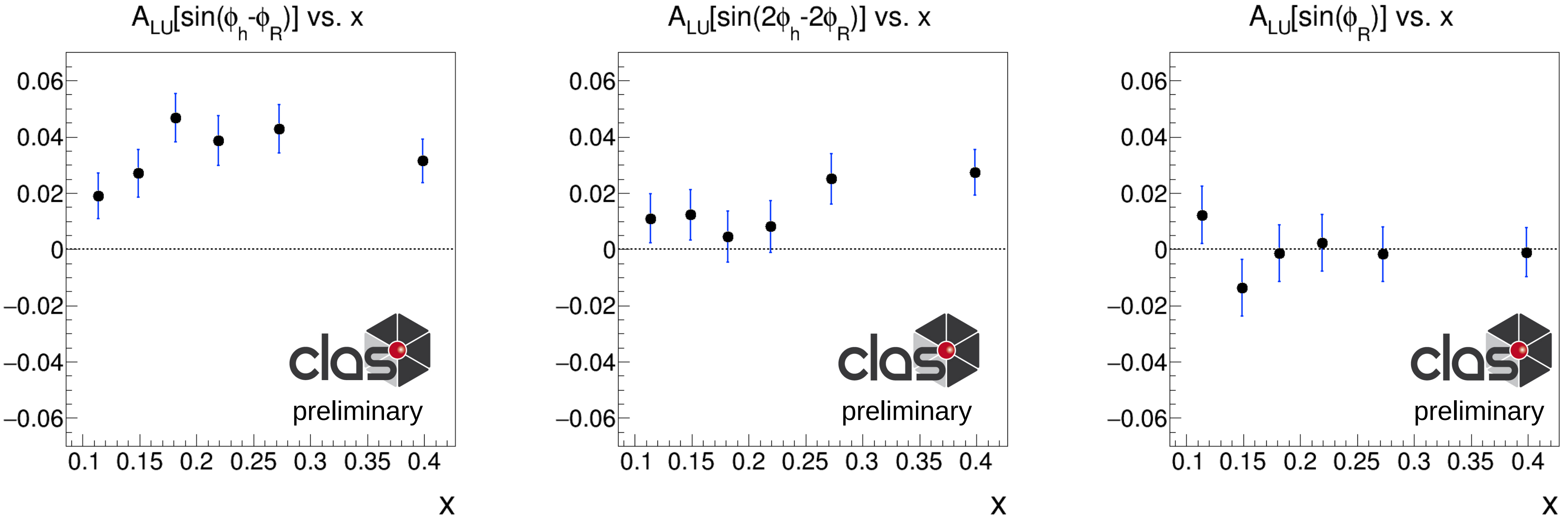
C. Dilks

CLAS12 $\pi^+\pi^0$ A_{LU} Preliminary Measurement



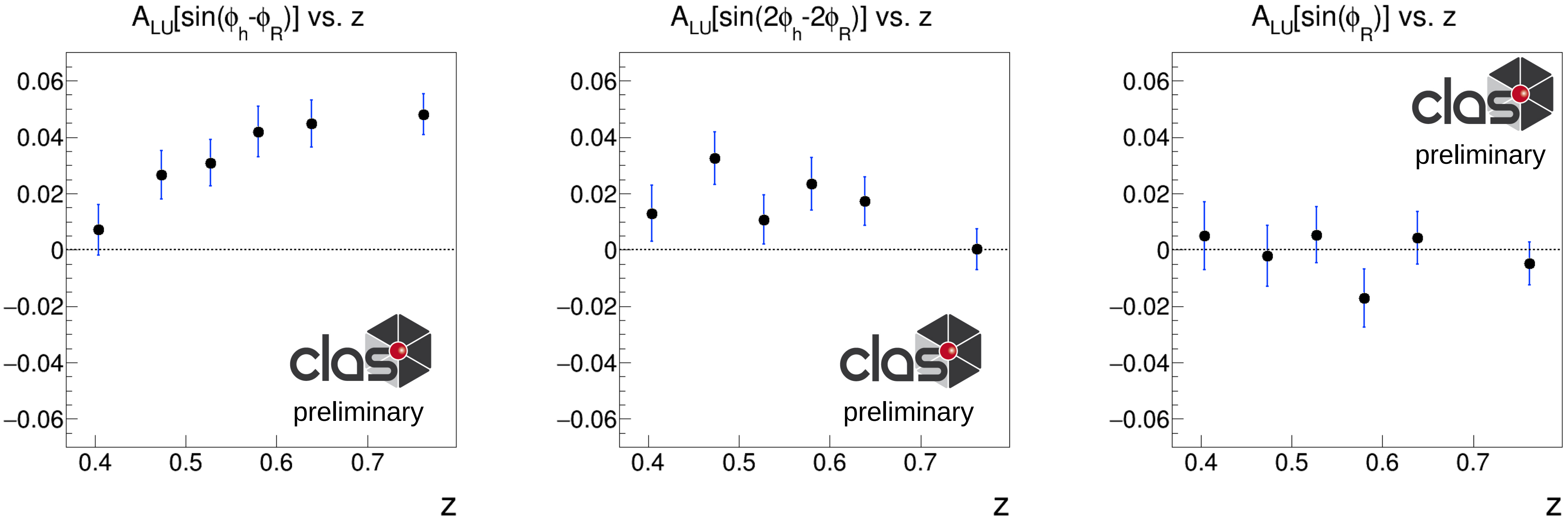
- A_{LU} $\sin(\phi_h-\phi_R)$ amplitude is positive for most of M_h range
- Peak near $\rho^+(770)$ in $\sin(2\phi_h-2\phi_R)$ amplitude (interference of *p*-state dihadrons)
- A_{LU} $\sin(\phi_R)$ amplitude seems much smaller

CLAS12 $\pi^+\pi^0$ A_{LU} Preliminary Measurement



- A_{LU} can be a function of *x* via the PDF: $f_1(x)$ for twist-2 (left,middle) and e(x) for twist-3 (right)
- Twist-3 amplitude of $\sin(\phi_R)$ is consistent with zero; this is sensitive to e(x) $H_1^{<}$

CLAS12 $\pi^+\pi^0$ A_{LU} Preliminary Measurement



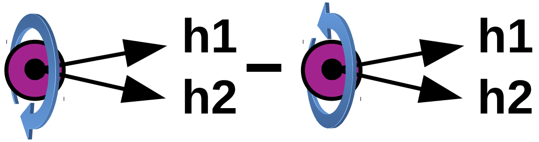
- z dependence of $\sin(\phi_h - \phi_R)$ amplitude has a slow rise
- $\sin(2\phi_h - 2\phi_R)$ may be relatively constant / decreasing

CLAS12 Beam Spin Asymmetry Measurements

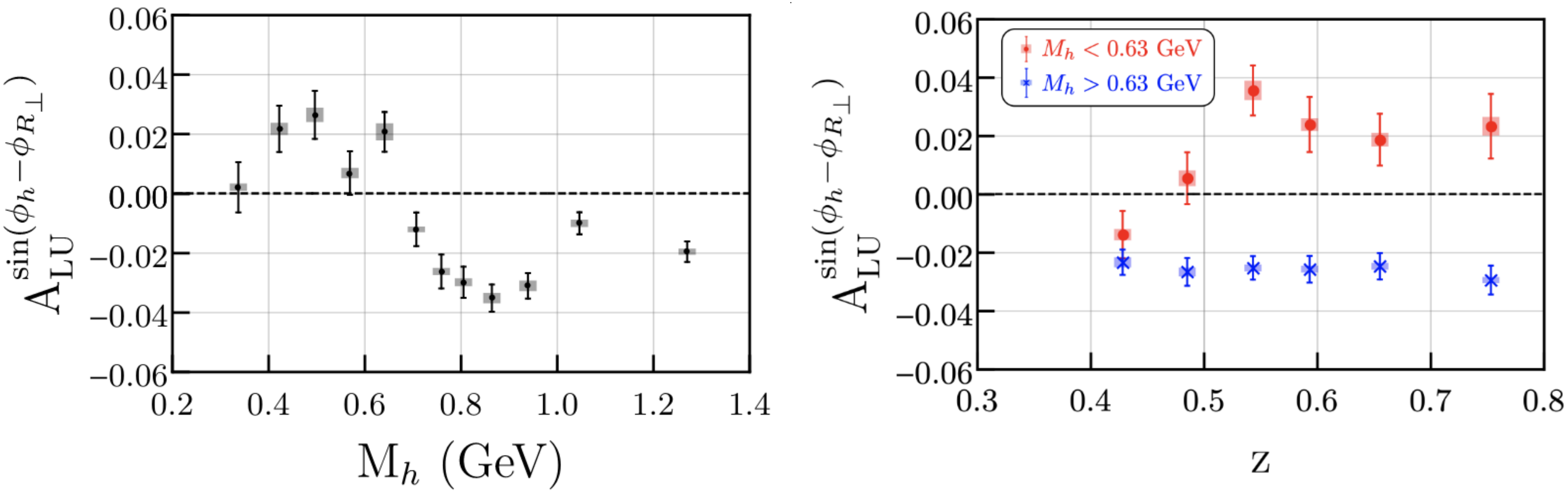
Twist 2

$$A_{LU} \sim f_1 G_1^{\perp|\ell,m\rangle}$$

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



- Matevosyan, Kotzinian, Thomas, Phys.Rev.Lett. 120 (2018) 25, 252001
- Gliske, Bacchetta, Radici, Phys.Rev.D 90 (2014) 11, 114027, Phys.Rev.D 91 (2015) 1, 019902 (erratum)



Hayward, CD, Vossen, Avakian, et al.,
Phys.Rev.Lett. 126 (2021) 15, 152501

CLAS12 Beam Spin Asymmetry Measurements

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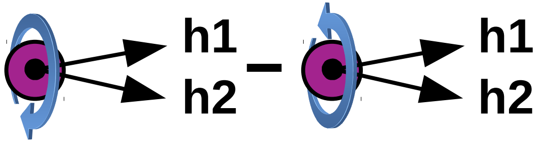

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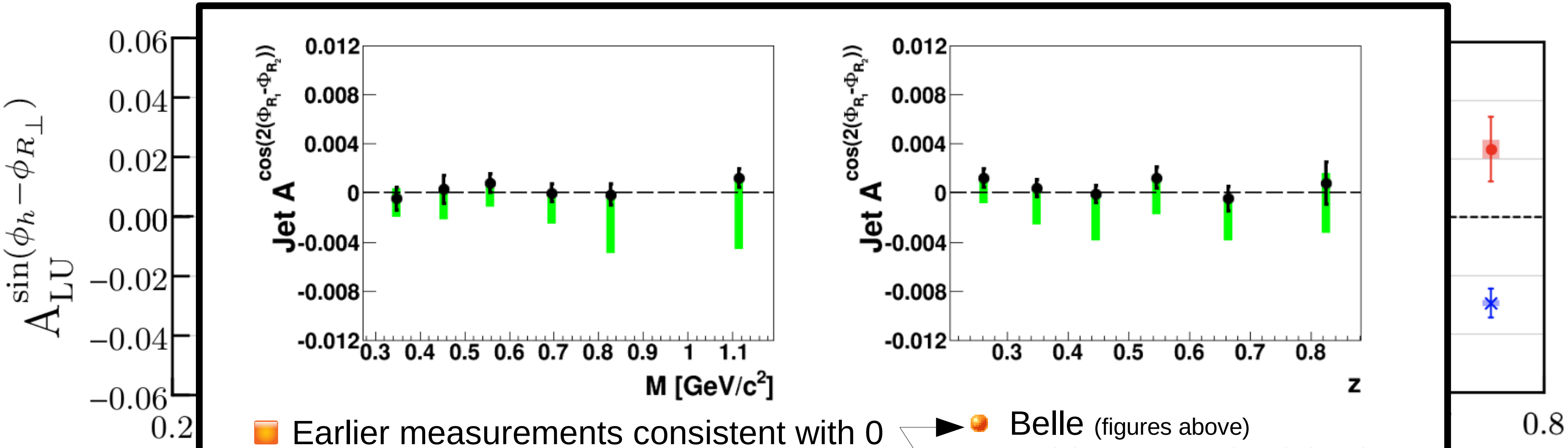


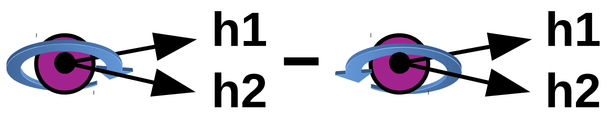
- Earlier measurements consistent with 0
  - Belle (figures above)
    - Abdesselam, et al. (Belle), (2015), arXiv:1505.08020 [hep-ex]
    - Vossen, PoS DIS2015, 216 (2015)
  - COMPASS
    - Sirtl, SPIN2016, (2017)
- e+e-: Error in cross section expression → wrong modulation

  Matevosyan, Kotzinian, Thomas Phys.Rev.Lett. 120 (2018) 25, 252001

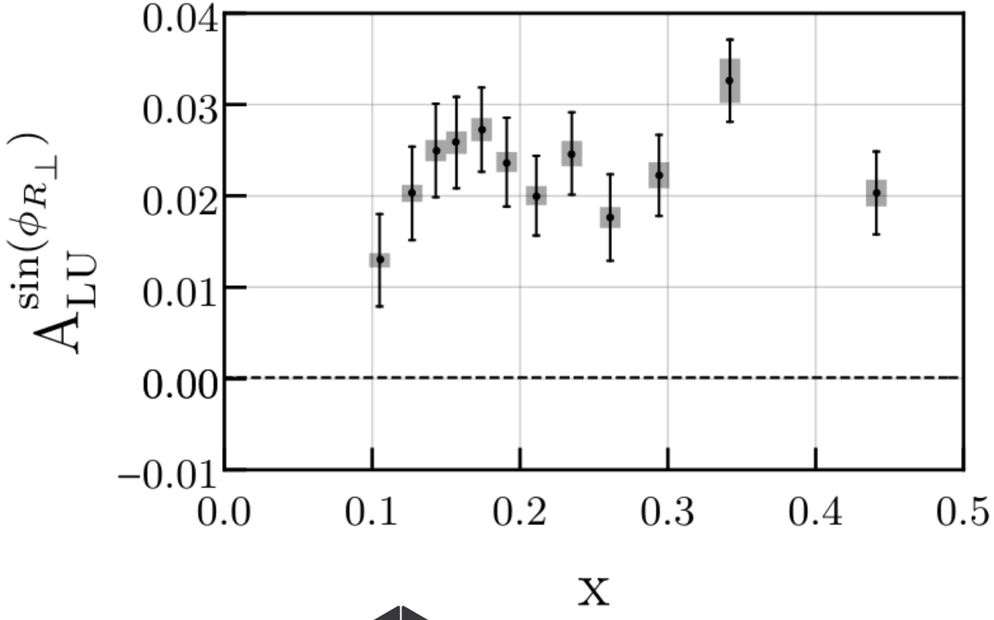
CLAS12 Beam Spin Asymmetry Measurements

Twist 3

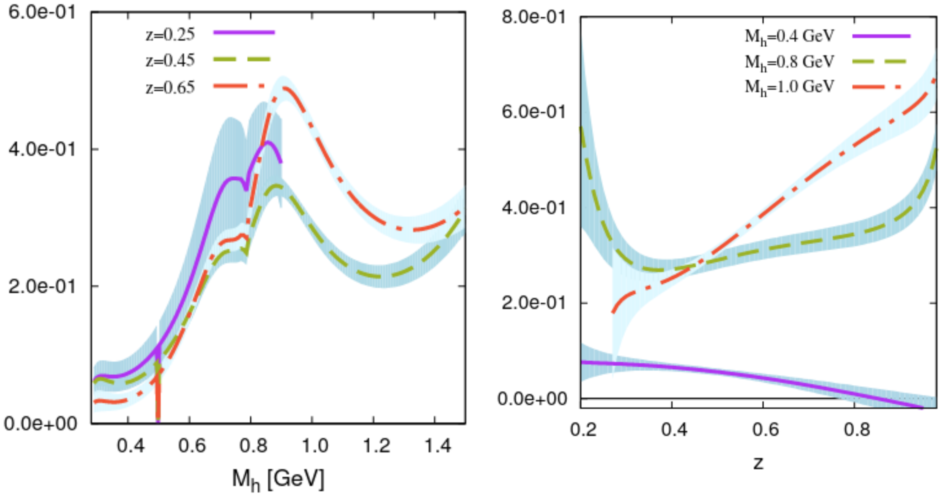
$$A_{LU} \sim e\, H_1^{\perp|\ell,m\rangle} \qquad H_1^{\perp|\ell,m\rangle} =$$



- Bacchetta, Radici, Phys.Rev.D 69 (2004) 074026
- Gliske, Bacchetta, Radici, Phys.Rev.D 90 (2014) 11, 114027, Phys.Rev.D 91 (2015) 1, 019902 (erratum)



$$R(z, M_h) = \frac{|\boldsymbol{R}|}{M_h} \frac{H_{1,sp}^{\sphericalangle u}}{D_1^u}$$



$H_1^<$ Extractions from Belle Data

Courtoy, Bacchetta, Radici, Bianconi
Phys.Rev.D 85 (2012) 114023

Hayward, CD, Vossen, Avakian, et al.,
Phys.Rev.Lett. 126 (2021) 15, 152501

CLAS12 Beam Spin Asymmetry Measurements

Twist 3

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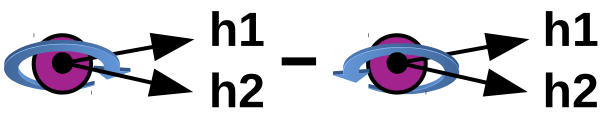

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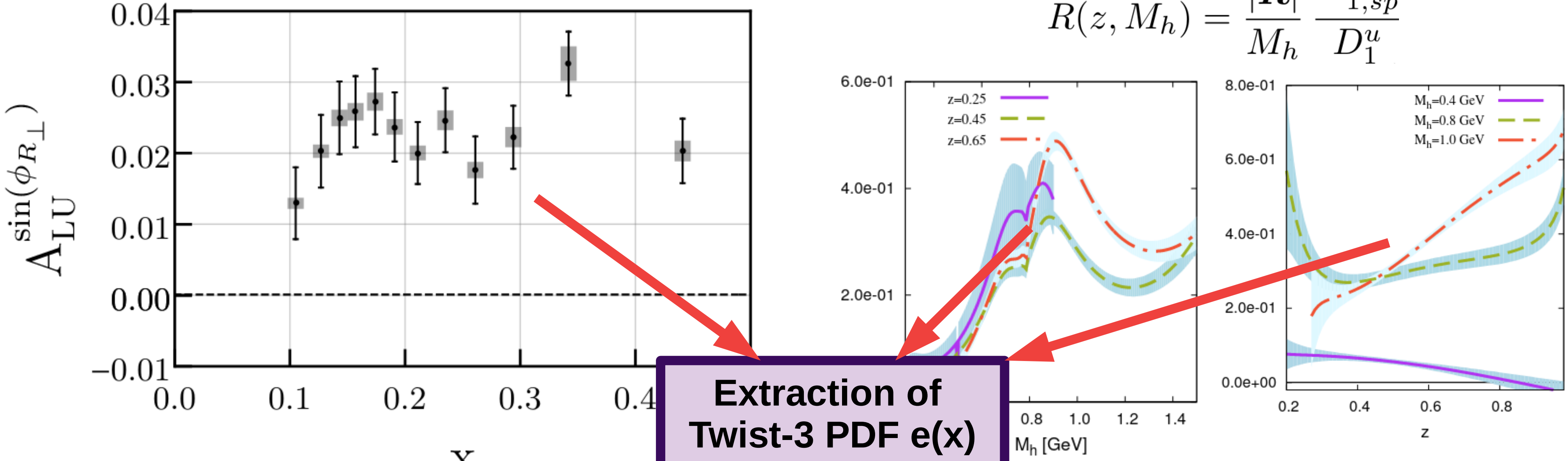

Extraction of Twist-3 PDF e(x)

$H_1^{\sphericalangle}$ Extractions from Belle Data

Courtoy, Bacchetta, Radici, Bianconi Phys.Rev.D 85 (2012) 114023

Hayward, CD, Vossen, Avakian, et al., Phys.Rev.Lett. 126 (2021) 15, 152501