Beam Spin Asymmetries of $\pi^+\pi^0$ dihadrons from SIDIS at CLAS12

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for the CLAS Collaboration

SPIN 2021

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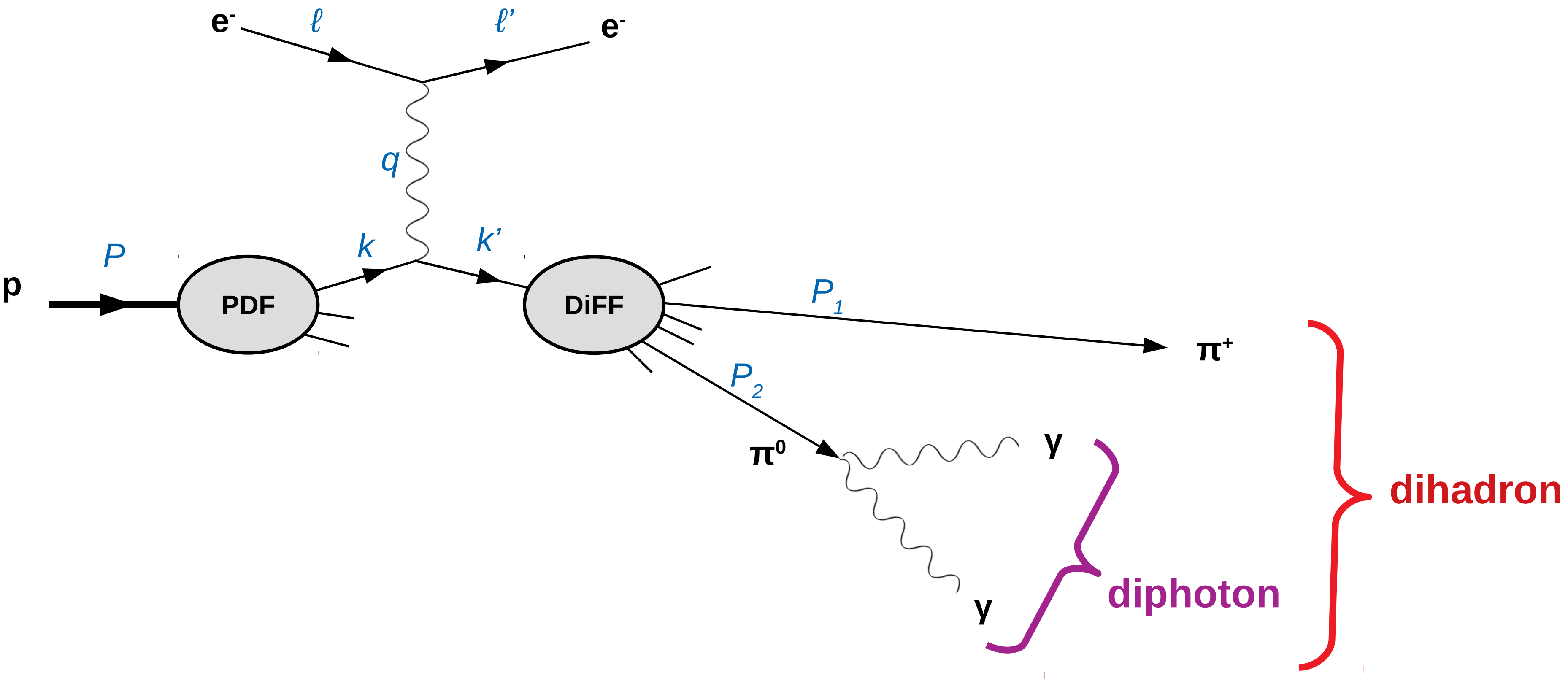
Duke UNIVERSITY

ep → e $\pi^+\pi^0$ X → e $\pi^+\gamma\gamma$ X

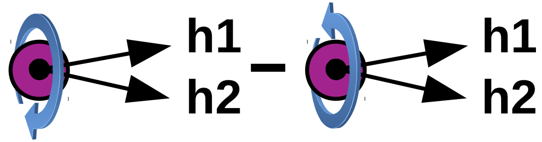


Beam Spin Asymmetries

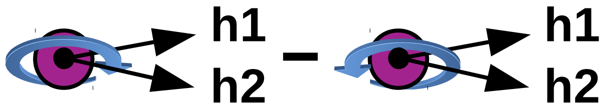
$$A_{LU} = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-}$$

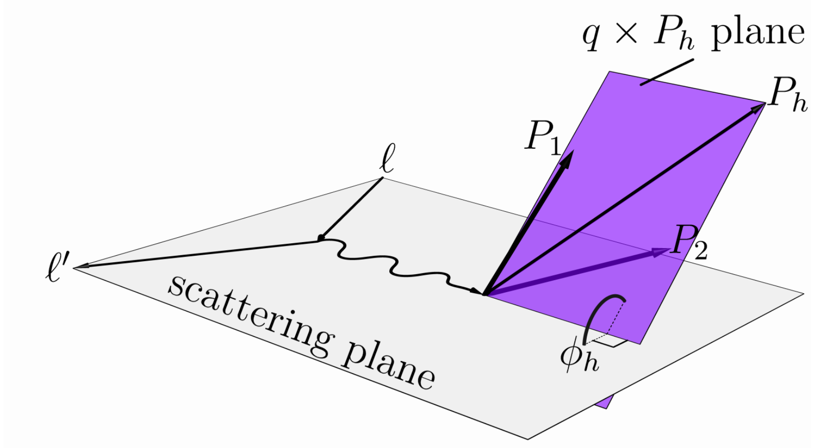
Sensitive to: $\mathrm{PDF} \otimes \mathrm{DiFF}$

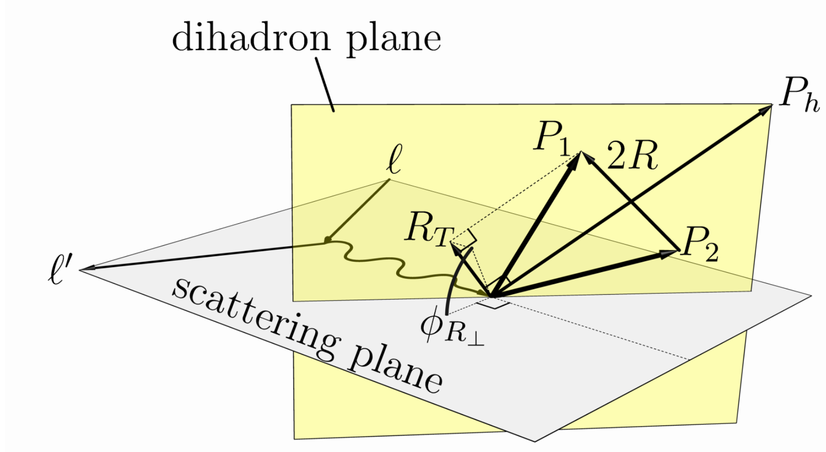
Twist 2 $\quad A_{LU} \sim f_1 G_1^{\perp|\ell,m\rangle}$

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

Twist 3 $\quad A_{LU} \sim e\, H_1^{\sphericalangle|\ell,m\rangle}$

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





Insights from $\pi^{\pm}\pi^{0}$ Dihadrons

$\pi^{+}\pi^{-}$ DiFFs:

$$D^{u/\pi^+\pi^-} \quad D^{d/\pi^-\pi^+}$$
$$D^{\bar{d}/\pi^+\pi^-} \quad D^{\bar{u}/\pi^-\pi^+}$$

DiFFs: $D \in \{D_1, G_1^{\perp}, H_1^{\perp}, H_1^{\sphericalangle}\}$

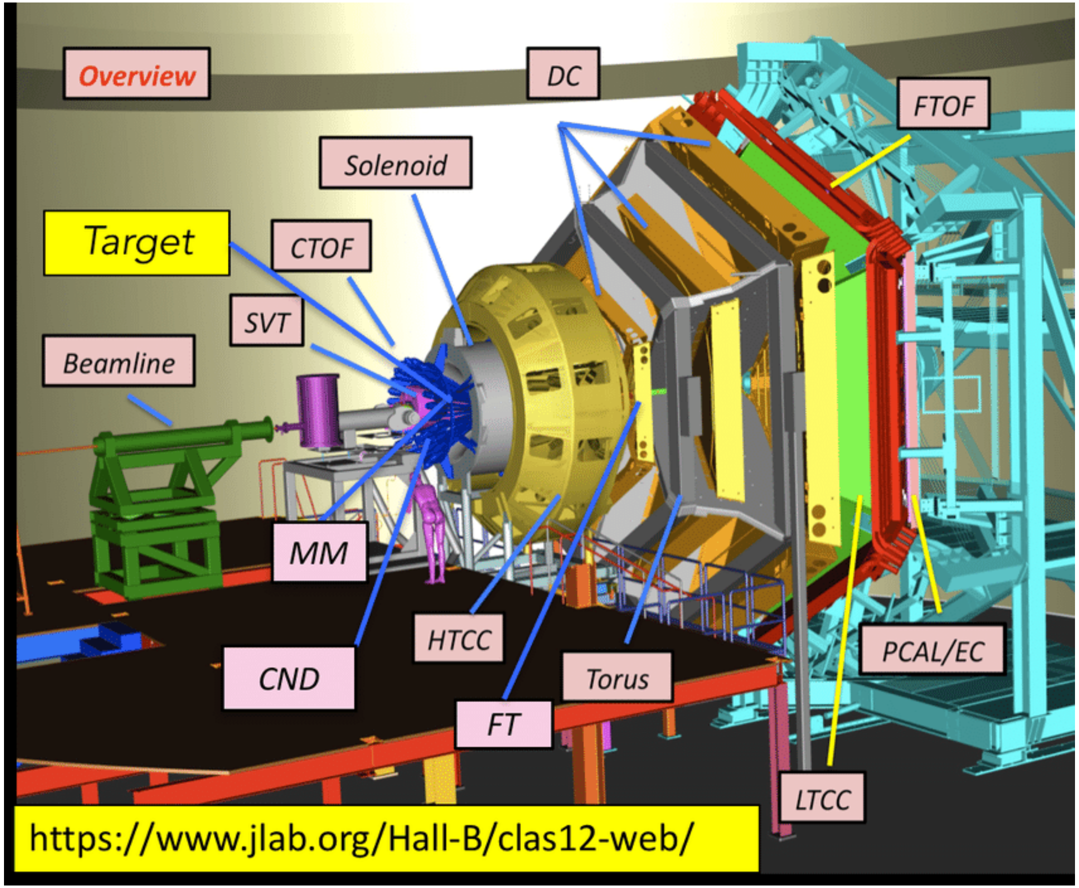
CLAS12 $\pi^{+}\pi^{-}$ A_{LU}: Phys. Rev. Lett. 126, 152501 (2021)

$\pi^{\pm}\pi^{0}$ DiFFs:

$$D^{u/\pi^+\pi^0} \quad D^{d/\pi^-\pi^0} \quad D^{u/\pi^-\pi^0} \quad D^{d/\pi^+\pi^0}$$
$$D^{\bar{d}/\pi^+\pi^0} \quad D^{\bar{u}/\pi^-\pi^0} \quad D^{\bar{d}/\pi^-\pi^0} \quad D^{\bar{u}/\pi^+\pi^0}$$

- $\pi^{+}\pi^{0}$ and $\pi^{-}\pi^{0}$ measurements are complementary to $\pi^{+}\pi^{-}$ measurements, broadening insight to DiFF flavor dependence
- No evidence of exclusive dominance at low missing mass M_X, but should be studied in more detail with Monte Carlo (MC) comparisons
- The presented measurement focuses on $\pi^{+}\pi^{0}$

CLAS 12



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

Forward Detector

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

Longitudinally Polarized Electron Beam
- E = 10.2-10.6 GeV
- P = 86–89%

Unpolarized Liquid H_2 Fixed Target

Data Set:
- Fall 2018 (10.6 GeV) + Spring 2019 (10.2 GeV)
- Torus magnet → electrons inbending
- ~800k $\pi^+\pi^0$ dihadrons

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 ($\rightarrow$)
- $z_{pair} < 0.95$

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

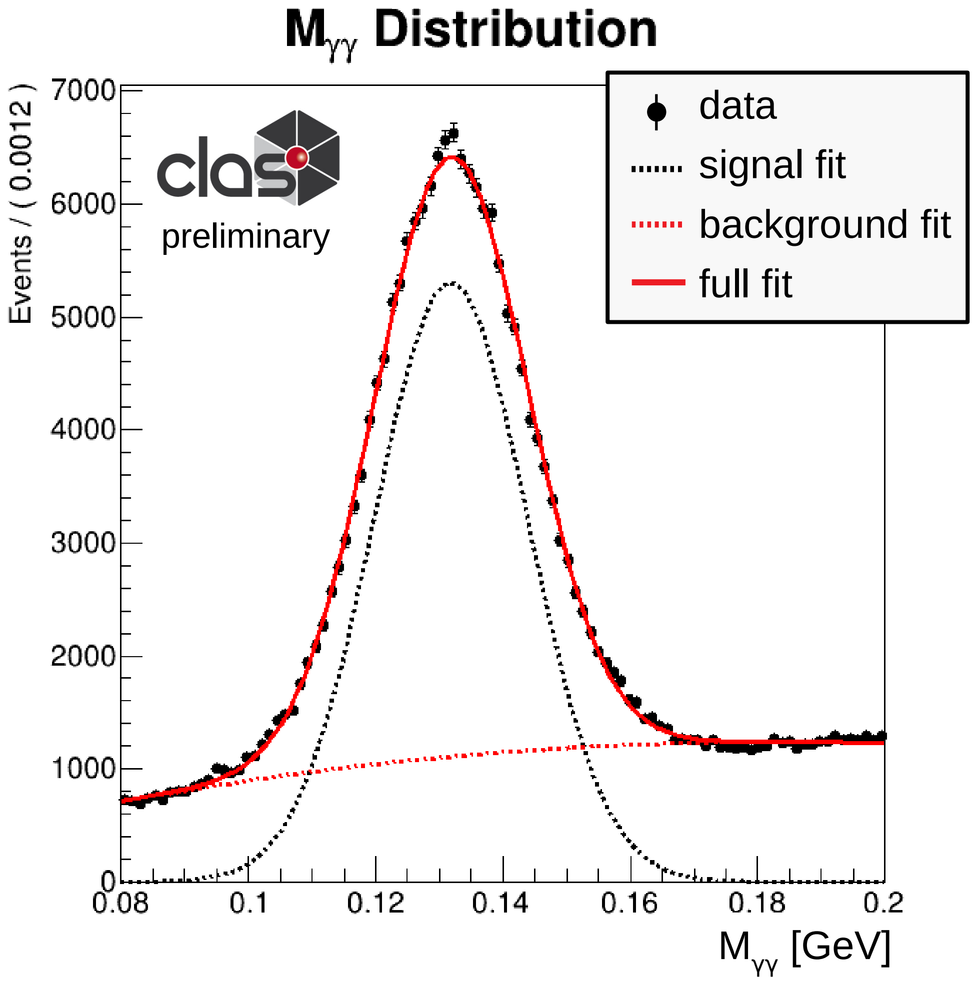
Diphoton Invariant Mass $M_{\gamma\gamma}$

- Model: Gaussian + Chebyshev Quadratic

$$f(M_{\gamma\gamma}) = N_s f_s\left(M_{\gamma\gamma}\right) + N_b f_b\left(M_{\gamma\gamma}\right)$$

  - $f_s(M_{\gamma\gamma}) = \mathrm{Gauss}\left(M_{\gamma\gamma}, \mu, \sigma\right)$
  - $f_b(M_{\gamma\gamma}) = b_1 M_{\gamma\gamma} + b_2\left(2M_{\gamma\gamma}^2 - 1\right)$

- 6 fit parameters
- One fit per A_{LU} bin



Background Corrections: sWeighted Likelihood Fit

Calculate sWeights W_s for each $\pi^+\gamma\gamma$ event with $80 < M_{\gamma\gamma} < 200$ MeV

covariance

$$W_s\left(M_{\gamma\gamma}\right) = \frac{V_{ss} f_s\left(M_{\gamma\gamma}\right) + V_{sb} f_b\left(M_{\gamma\gamma}\right)}{f\left(M_{\gamma\gamma}\right)}$$

π^0 fit model: $$f\left(M_{\gamma\gamma}\right) = \underbrace{N_s f_s\left(M_{\gamma\gamma}\right)}_{\text{signal}} + \underbrace{N_b f_b\left(M_{\gamma\gamma}\right)}_{\text{background}}$$

- Weighting a data distribution D(x) with $W_s(M_{\gamma\gamma})$ reproduces, on average, the true signal distribution
- **Requires $M_{\gamma\gamma}$ to not be correlated with x**

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

Background Corrections: sWeighted Likelihood Fit

PDF for A_{LU} fit:

$$\mathcal{P}(x;A) = 1 + hP_b \left[d_3 \cdot A_{LU}^{\sin(\phi_R)} \cdot \sin(\phi_R) \ + \ d_2 \cdot A_{LU}^{\sin(\phi_h - \phi_R)} \cdot \sin(\phi_h - \phi_R) \ + \ \ldots \right]$$

helicity {-1,+1}

beam polarization

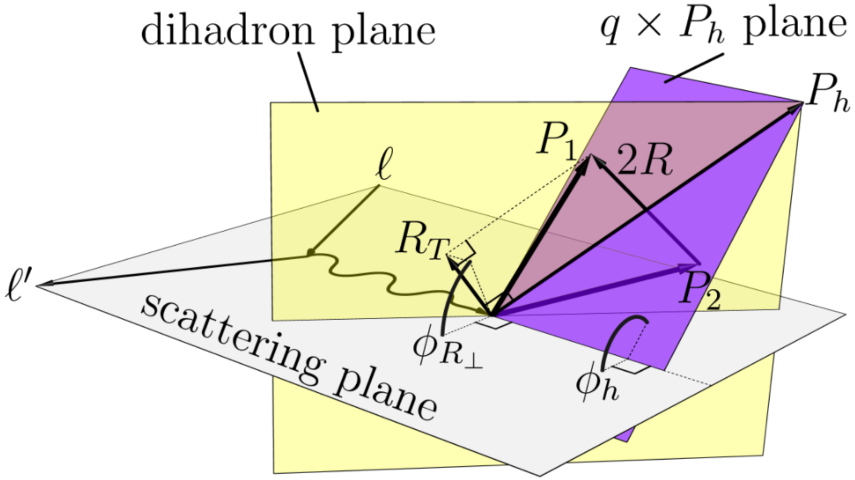
depolarization

A_{LU} amplitude (fit param.)

modulation

other modulations

$$A_{LU} = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-}$$



Background Corrections: sWeighted Likelihood Fit

PDF for A_{LU} fit:

$$\mathcal{P}(x;A) = 1 + hP_b \left[d_3 \cdot A_{LU}^{\sin(\phi_R)} \cdot \sin(\phi_R) \; + \; d_2 \cdot A_{LU}^{\sin(\phi_h-\phi_R)} \cdot \sin(\phi_h - \phi_R) \; + \; \ldots \right]$$

sWeighted Likelihood:

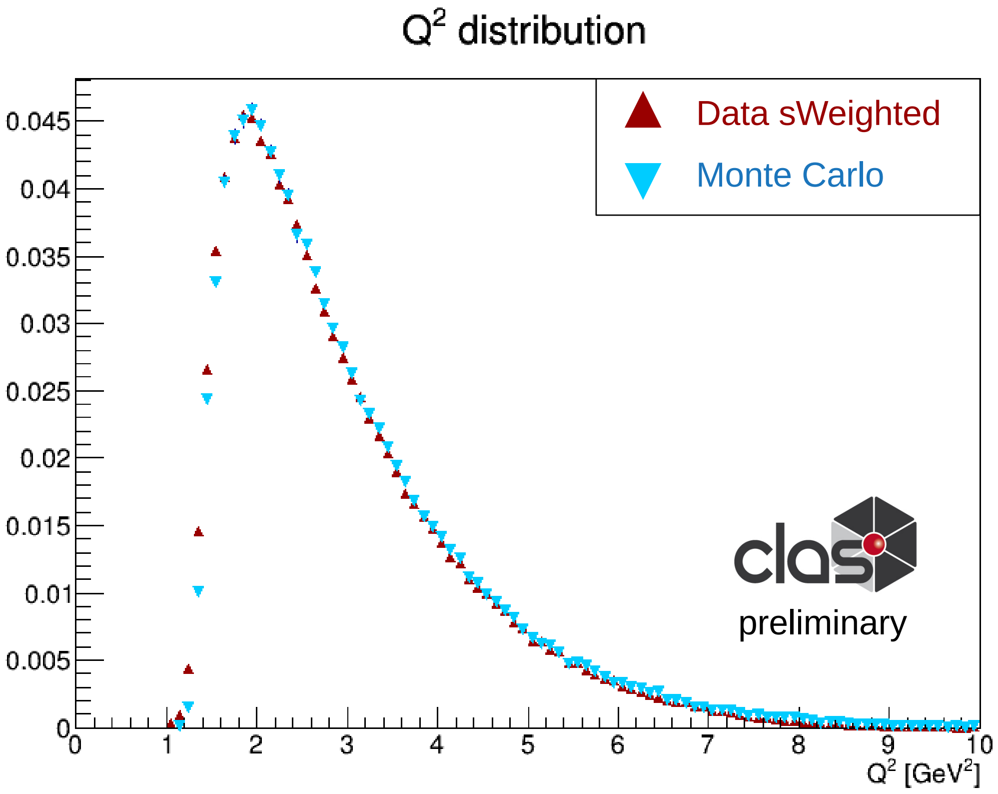
$$\mathcal{L}(A) = \prod_{e\in E} \mathcal{P}\left(x^{(e)};A\right)^{W_s\left(M_{\gamma\gamma}^{(e)}\right)}$$

product over
each event "e"

sWeights

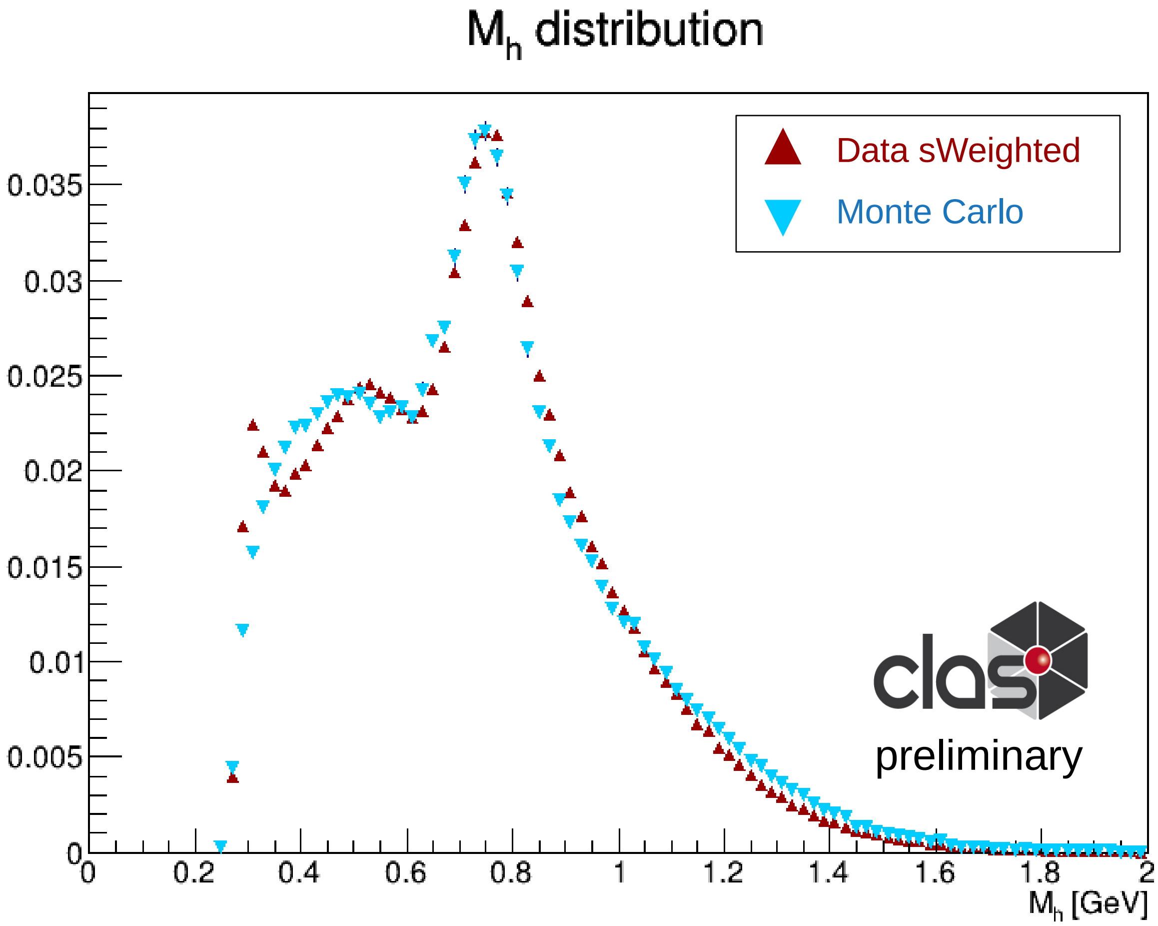
- BG-corrected fit performed by weighting likelihood with W_s(m)
- Advantage over "sideband subtraction" correction methods by minimizing the amount of sideband data needed, which could have different physics and acceptance effects

Kinematics Distributions Comparisons



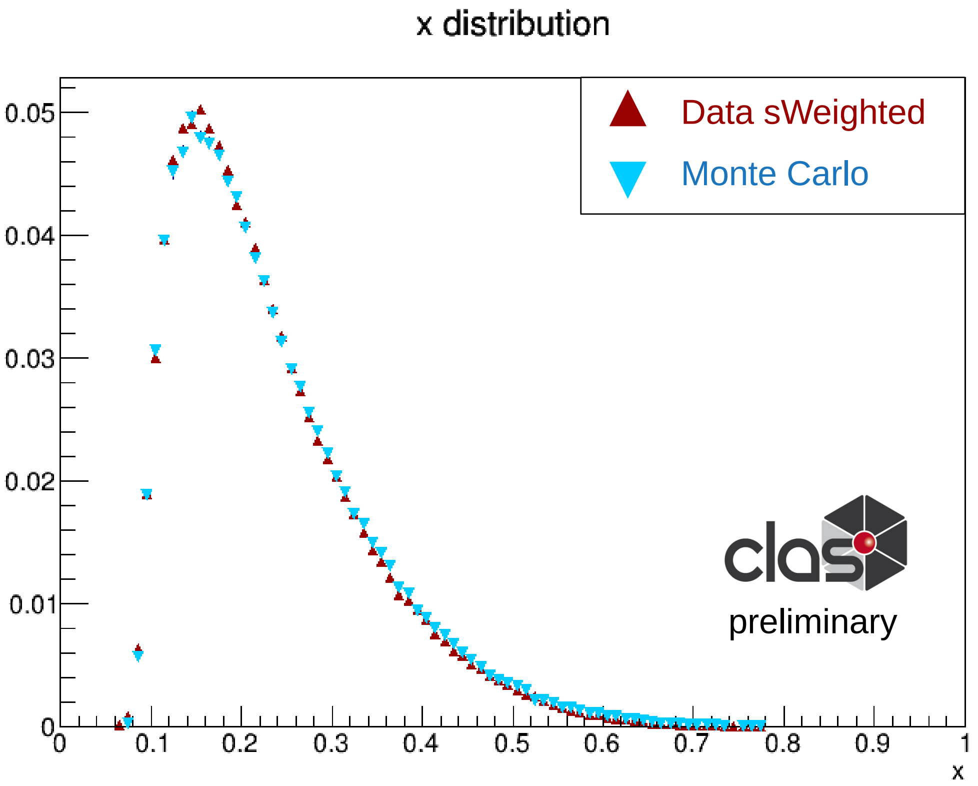
- Compare sWeighted data distributions with reconstructed MC
- Reconstructed MC diphotons are matched to generated true $\pi^0 \rightarrow \gamma\gamma$ decays
- Data are normalized to sum of sWeights
- MC are normalized to number of dihadrons
- Q^2 shapes are in very good agreement

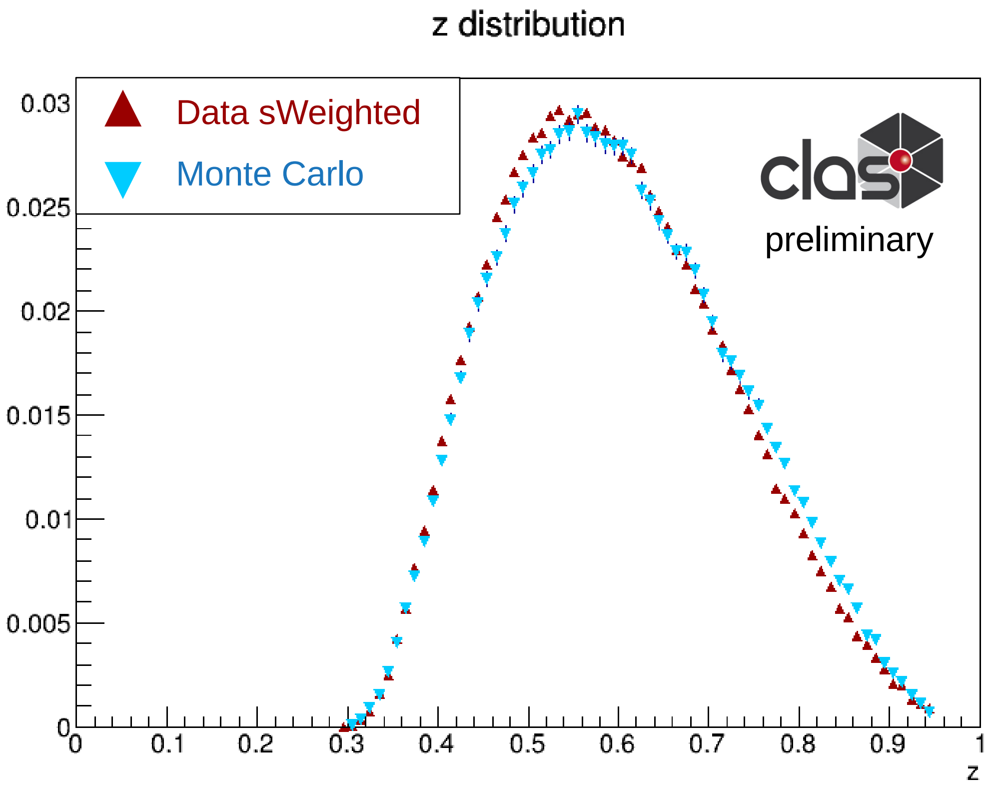
$\pi^+\pi^0$ Dihadron Invariant Mass



- $\rho^+(770)$ peak visible
- Some differences at low M_h, comparable to data/MC agreement in the $\pi^+\pi^-$ channel
- M_h correlates with $\gamma\gamma$-background around M_h<0.5 GeV, possibly impacting sWeighting efficacy in this region
- Agreement better for M_h>0.5 GeV, where correlated $\gamma\gamma$-background is at $M_{\gamma\gamma}>>M_{\pi0}$

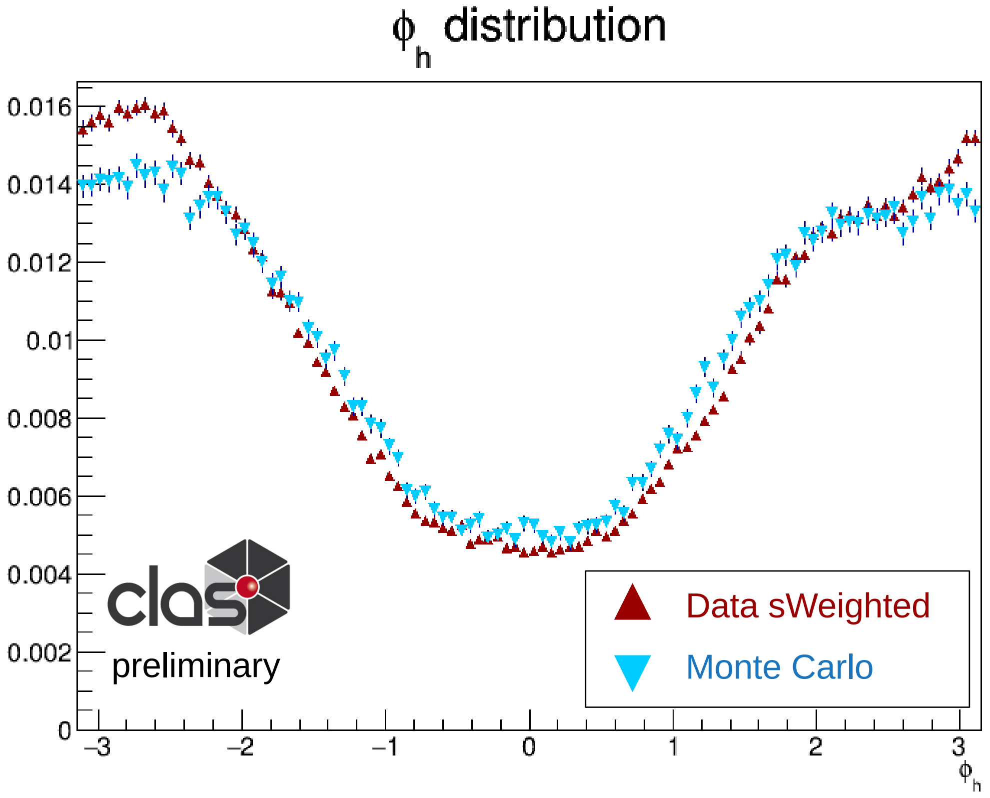
$\pi^+\pi^0$ Kinematics Distributions

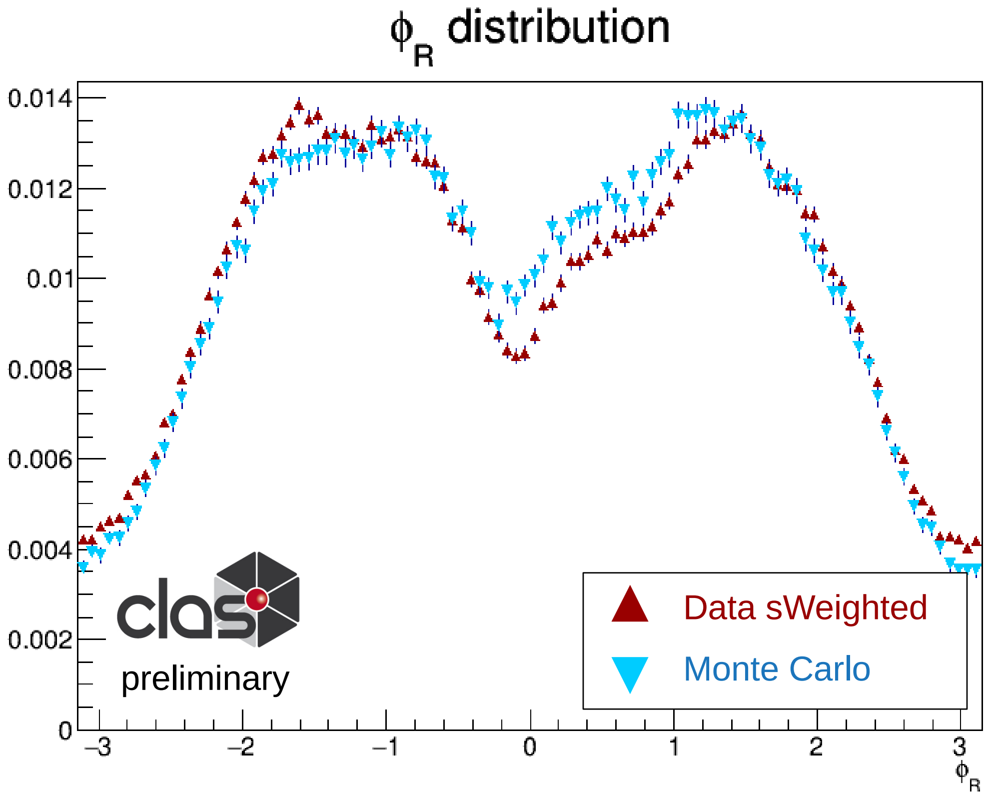




- x distributions agree very well
- z distributions differ slightly, but cover the same range

$\pi^+\pi^0$ Kinematics Distributions





- Similar differences of ϕ_h near $\pm\pi$ are also seen in Data/MC comparisons for $\pi^+\pi^-$ dihadrons
- Some differences in $0<\phi_R<\pi$, possibly attributable to mild correlated $\gamma\gamma$ background in that region

Beam Spin Asymmetry A_{LU} Fit

7 amplitude simultaneous fit

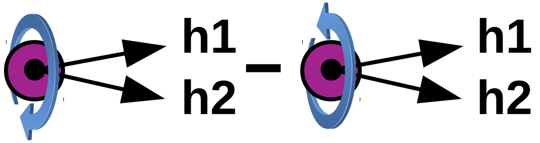
Not including θ-modulations (partial waves)

Presented asymmetries focus on $G_1^{\perp}$, and $\sin(\phi_R)$ for $eH_1^{\sphericalangle}$

Twist 2

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

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

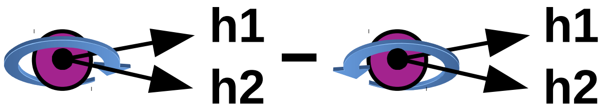


$\sin(2\phi_h - 2\phi_{R_\perp})$
$\sin(\phi_h - \phi_{R_\perp})$

Twist 3

$$A_{LU} \sim e H_1^{\sphericalangle|\ell,m\rangle}$$

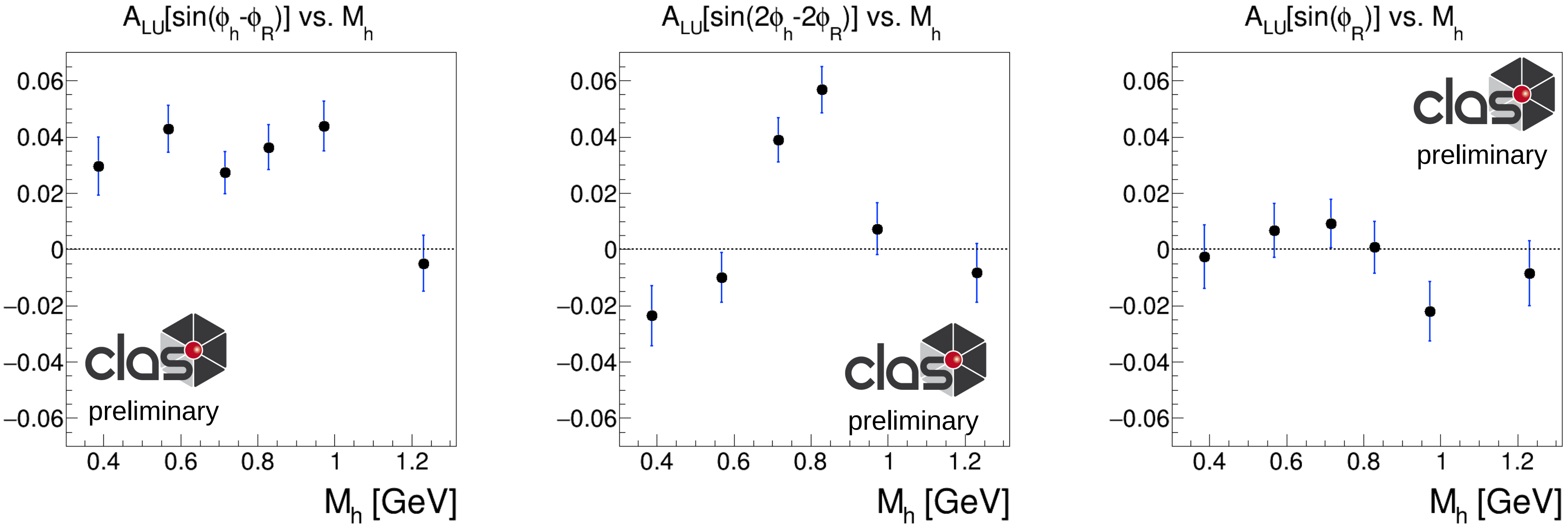
$$H_1^{\sphericalangle|\ell,m\rangle} =$$



$\sin(-\phi_h + 2\phi_{R_\perp})$
$\sin(\phi_{R_\perp})$
$\sin(\phi_h)$

$\sin(2\phi_h - \phi_{R_\perp})$
$\sin(3\phi_h - 2\phi_{R_\perp})$

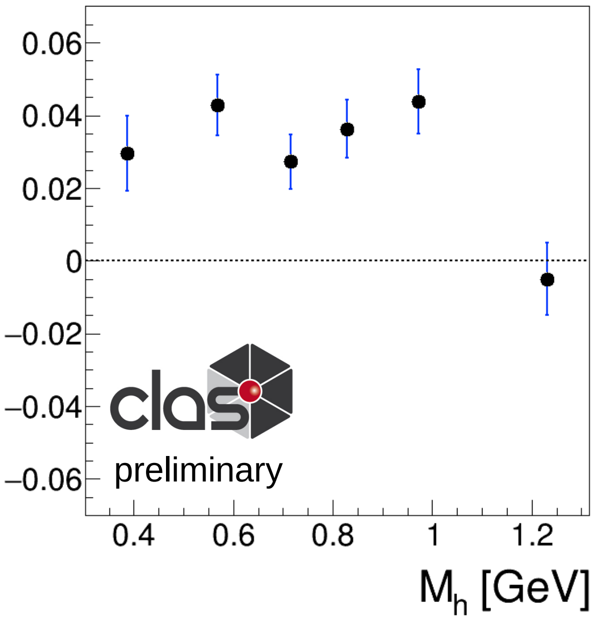
CLAS12 $\pi^+\pi^0$ A_{LU} Preliminary Measurement

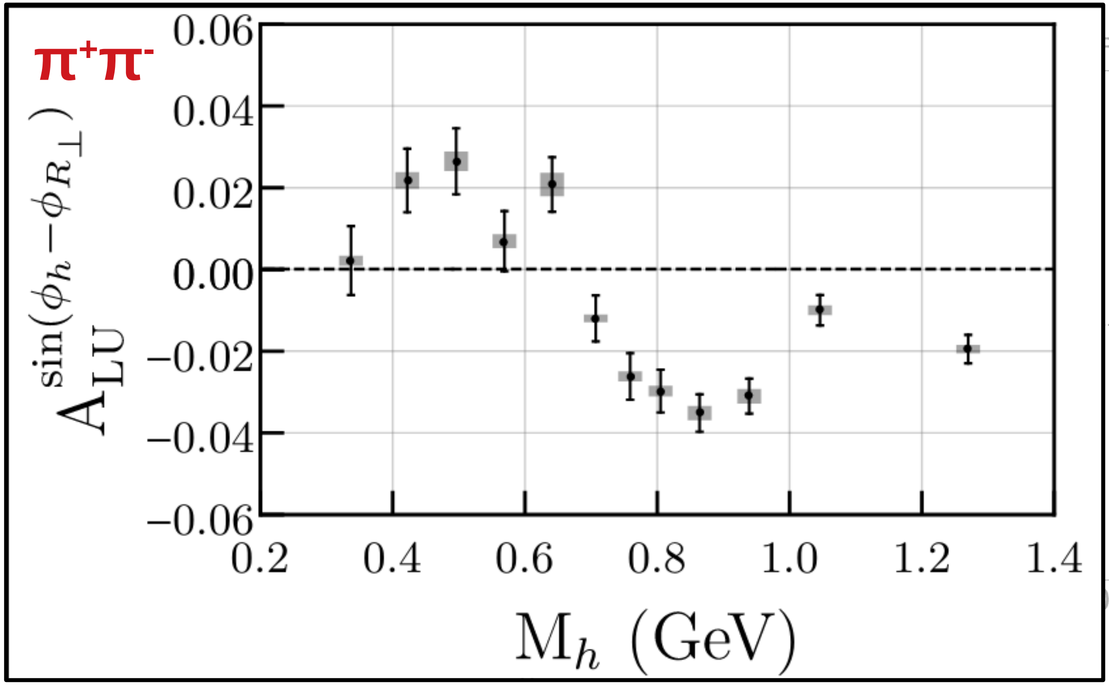


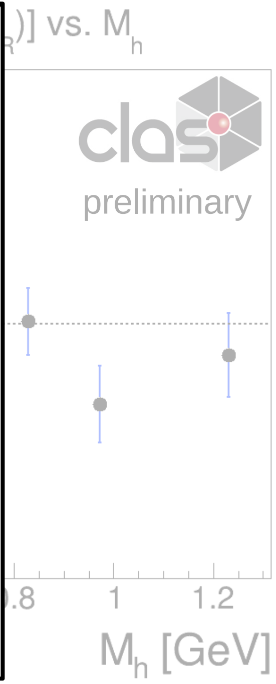
- A_{LU} $\sin(\phi_h - \phi_R)$ amplitude is positive for most of M_h range
- Peak near $\rho^+(770)$ in $\sin(2\phi_h - 2\phi_R)$ amplitude (interference of *p*-state dihadrons)
- A_{LU} $\sin(\phi_R)$ amplitude seems much smaller

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

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





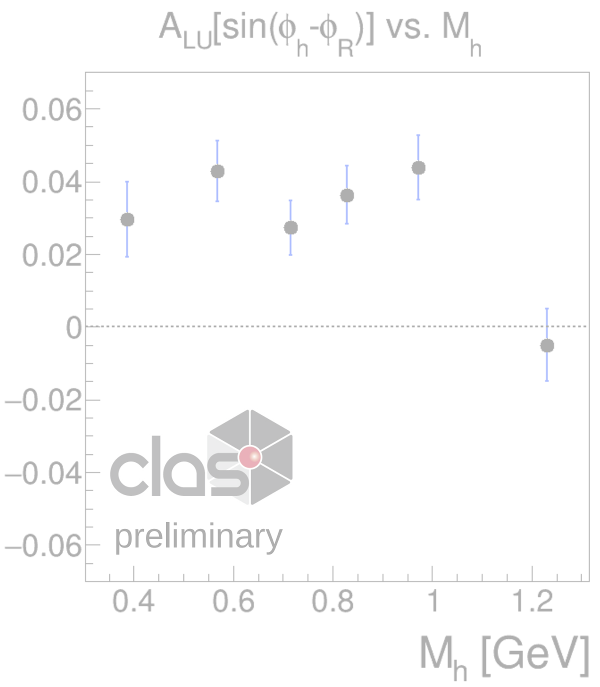


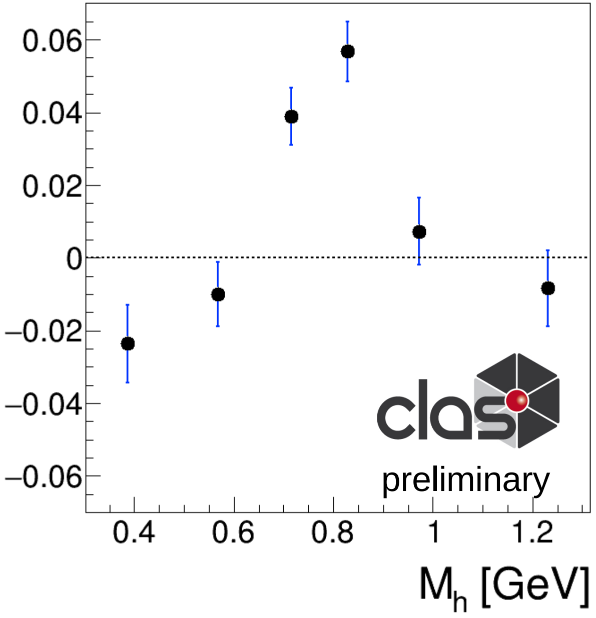
CLAS12 $\pi^+\pi^-$ A_{LU}: Phys. Rev. Lett. 126, 152501 (2021)

- Compare A_{LU} $\sin(\phi_h - \phi_R)$ amplitude for $\pi^+\pi^0$ (left) to $\pi^+\pi^-$ (right)
- Sign change seen in $\pi^+\pi^-$ around the ρ mass (0.77 GeV) not observed in $\pi^+\pi^0$

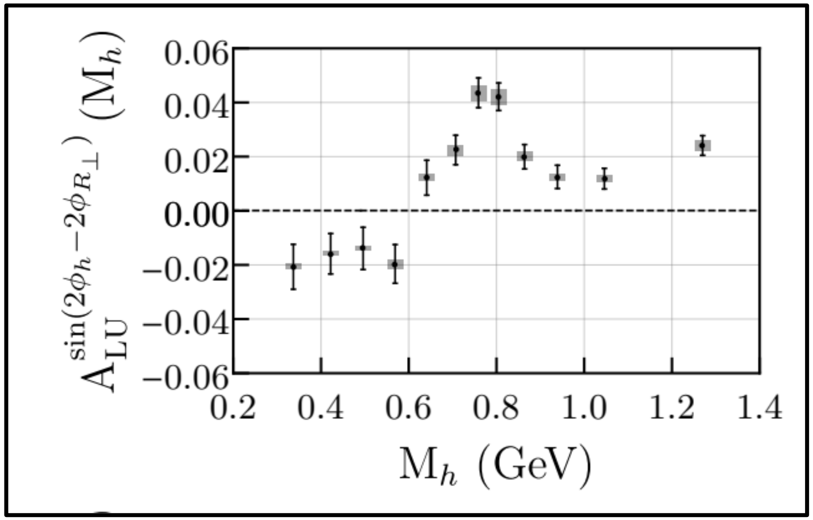
CLAS12 $\pi^+\pi^0$ A_{LU} Preliminary Measurement

$\pi^+\pi^0$





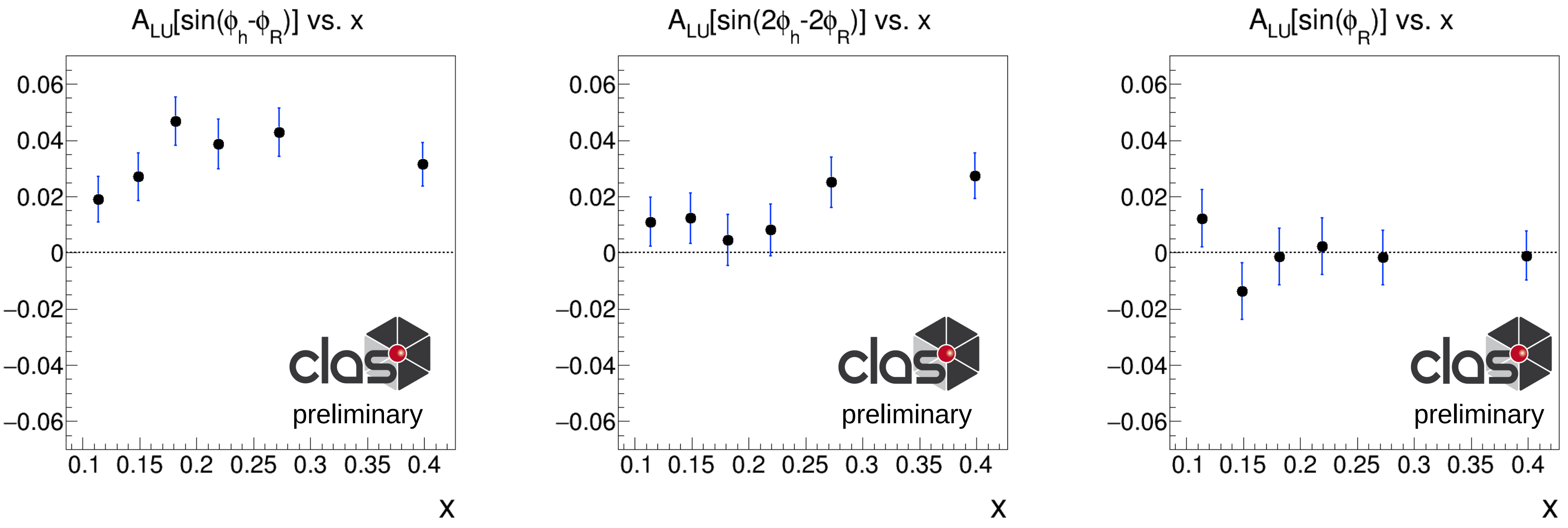
$\pi^+\pi^-$



CLAS12 $\pi^+\pi^-$ A_{LU}: Phys. Rev. Lett. 126, 152501 (2021) [appendix]

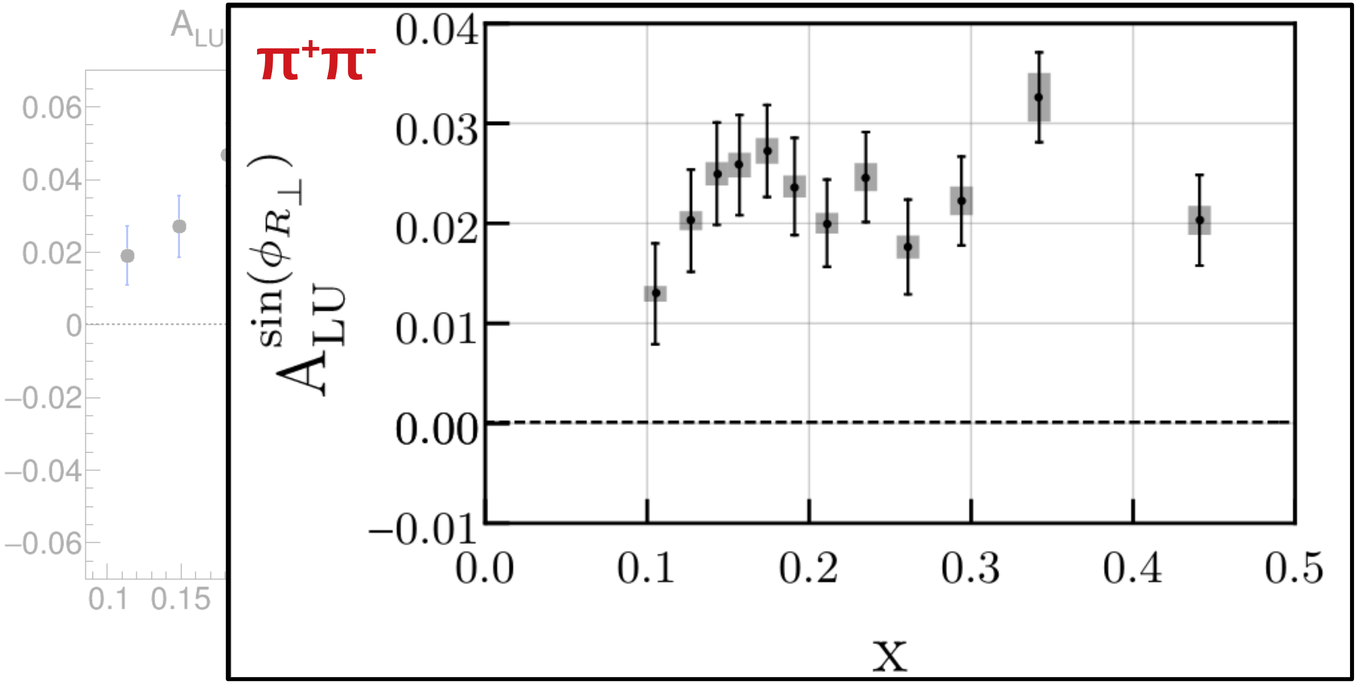
- Compare A_{LU} $\sin(2\phi_h - 2\phi_R)$ amplitudes
- This amplitude requires *pp*-interference, and ρ mesons being spin 1 prefer to decay to p-state ππ
- Similar enhancement at the ρ mass is observed for both channels

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

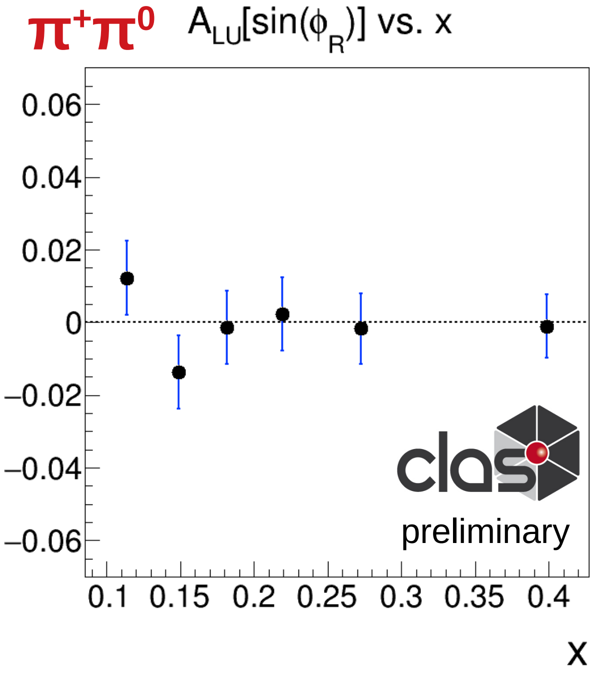


- A_{LU} can be a function of *x* via the PDF: $f_1(x)$ for twist-2 (left,middle) and $e(x)$ for twist-3 (right)
- Twist-3 amplitude of $\sin(\phi_R)$ is consistent with zero; this is sensitive to $e(x)\ H_1^{<}$

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

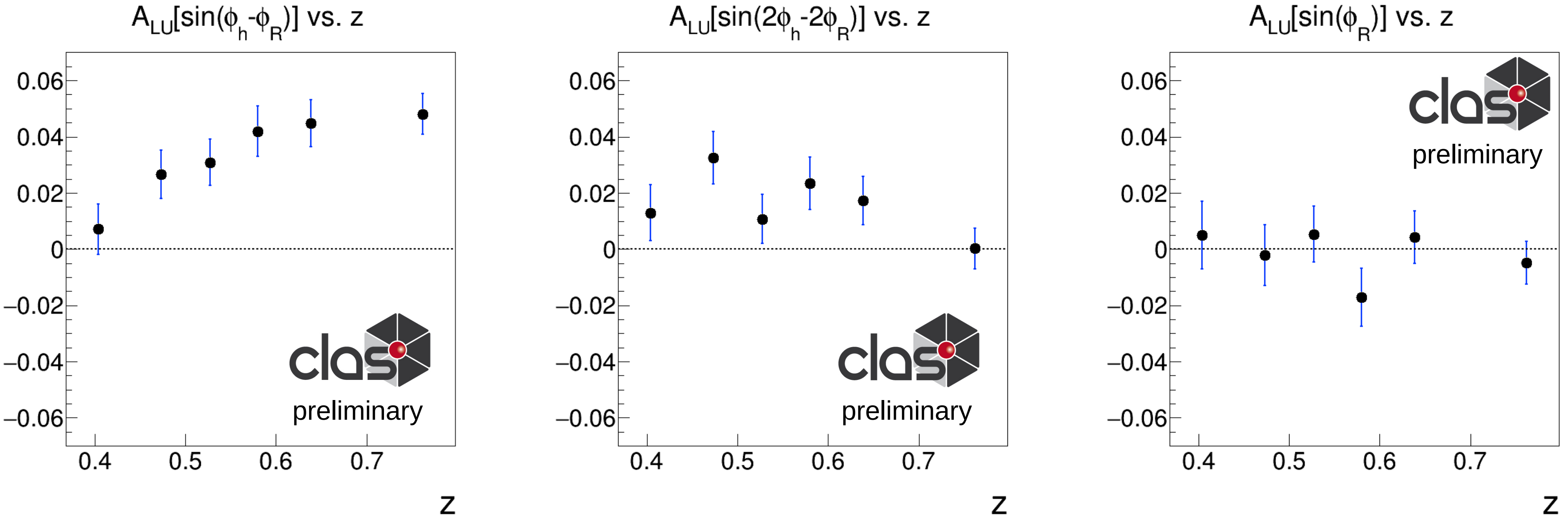


CLAS12 $\pi^+\pi^-$ A_{LU}: Phys. Rev. Lett. 126, 152501 (2021)



- CLAS12 $\pi^+\pi^-$ A_{LU} measurement can be used for point-by-point extraction of e(x), given knowledge of $H_1^<$ from Belle measurements [Phys.Rev.D 85 (2012) 114023]
- $\pi^+\pi^0$ could give some insight onto flavor dependence of $H_1^<$

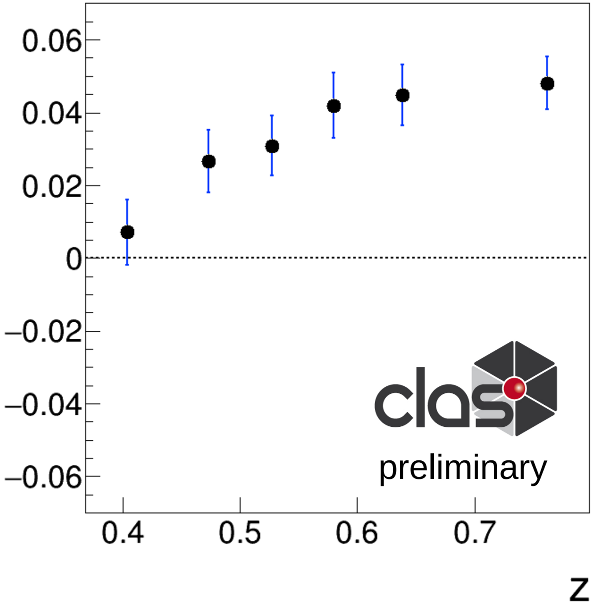
CLAS12 $\pi^+\pi^0$ A_{LU} Preliminary Measurement

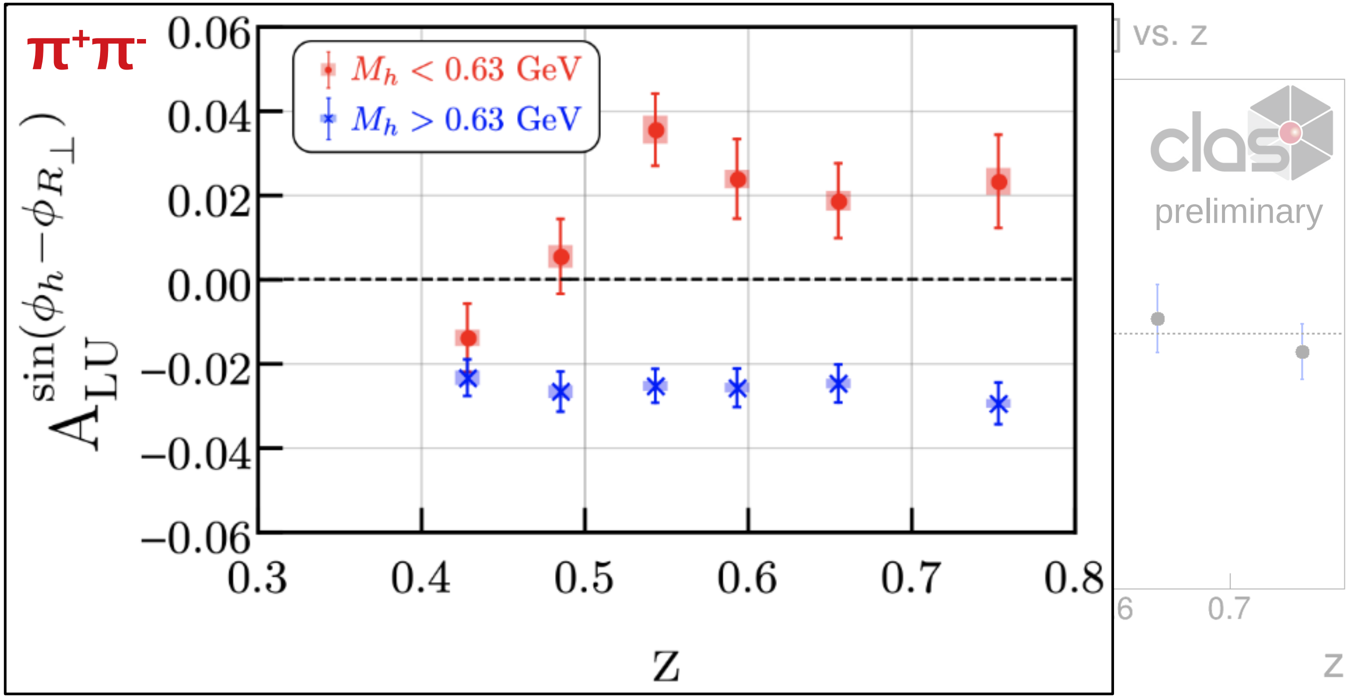


- z dependence of $\sin(\phi_h - \phi_R)$ amplitude has a slow rise
- $\sin(2\phi_h - 2\phi_R)$ may be relatively constant / decreasing

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

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





CLAS12 $\pi^+\pi^-$ A_{LU}: Phys. Rev. Lett. 126, 152501 (2021)

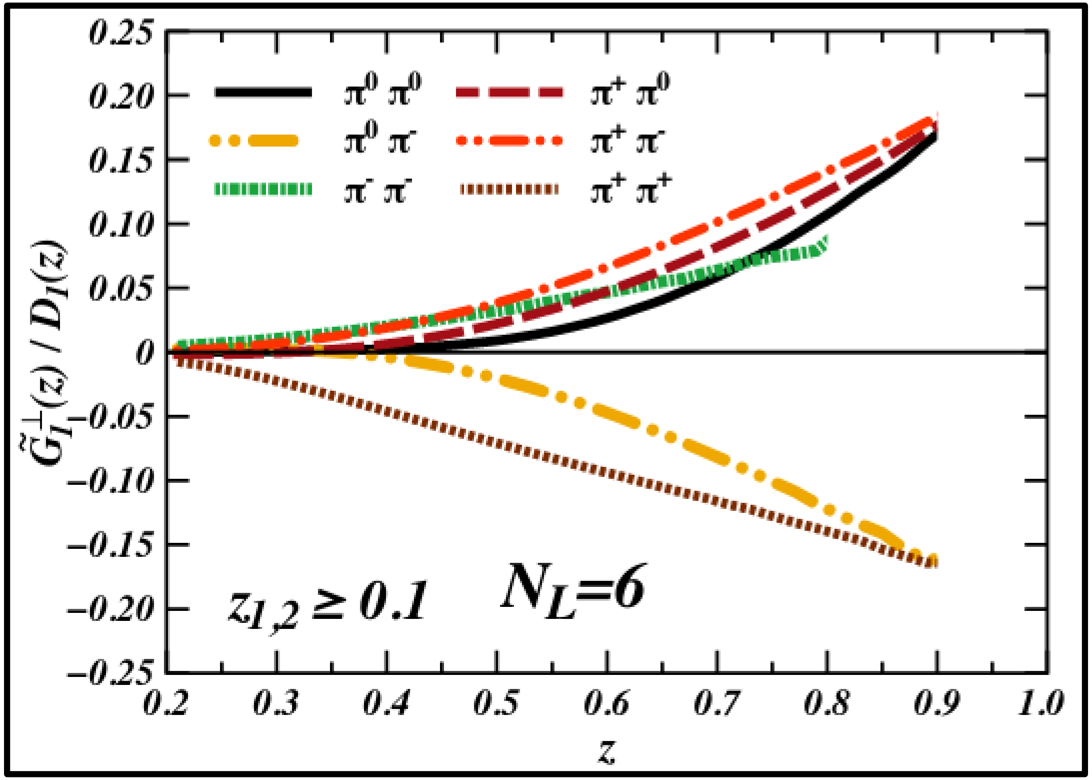
- Compare to $\pi^+\pi^-$ measurement, which was divided into two M_h bins
- Slow rise with respect to *z* also seen in $\pi^+\pi^-$ for $M_h<M_\rho$

Summary

- **$\pi^{+/-}\pi^0$ Asymmetries:**
  - Access different sets of flavor-dependent DiFFs
  - Exclusive production suppressed
  - Requires γγ-background corrections – implemented with sWeighted likelihood fit
- **Preliminary Measurement Observations:**
  - Significant twist-2 asymmetries, sensitive to $G_1^{\perp}$, no sign change at ρ (unlike $\pi^+\pi^-$)
  - Twist-3 asymmetry $\sin\phi_R$ amplitude consistent with zero
- **Outlook and Plans**
  - Systematic uncertainties
  - $\pi^-\pi^0$ channel
  - Investigate nonzero background asymmetries
  - Improve photon selection and matching
  - Partial wave fits with Markov Chain Monte Carlo (MCMC)

- **backup**

Quark-jet model comparison



H. Matevosyan, et al.,
Phys.Rev.D 96 (2017) 7, 074010