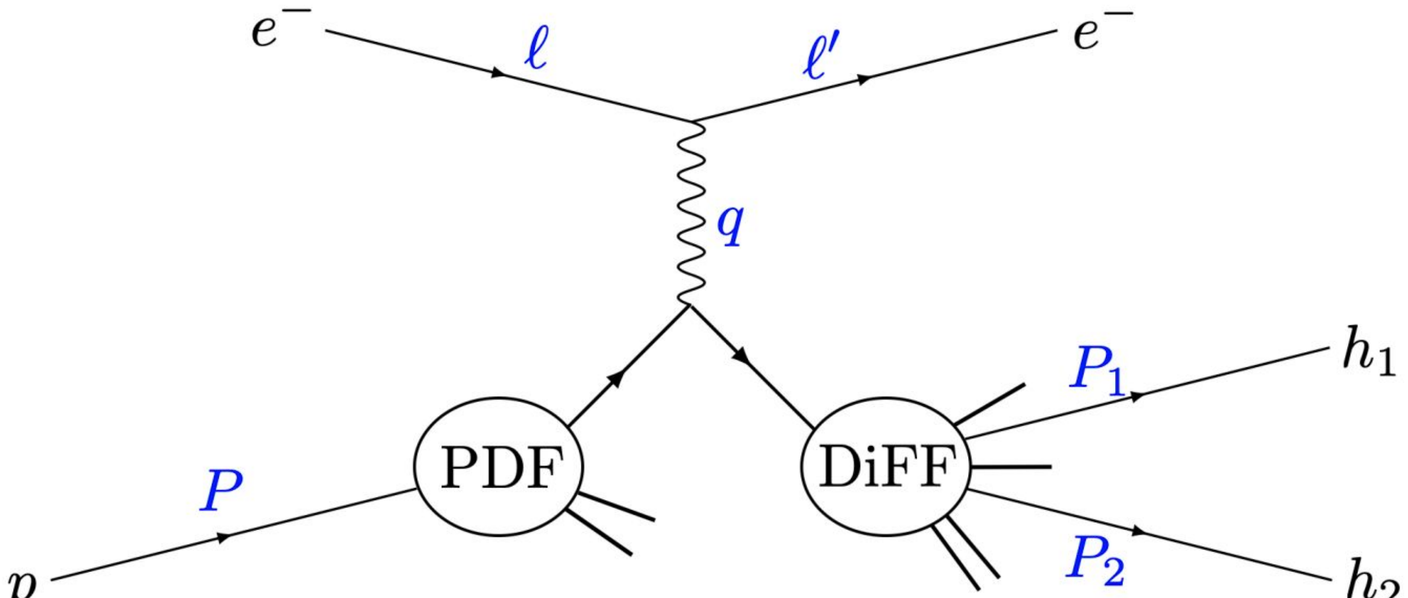
Partial Wave Decomposition of $\pi\pi$ Beam Spin Asymmetries

Gregory Matousek

Semi-Inclusive Dihadron Production

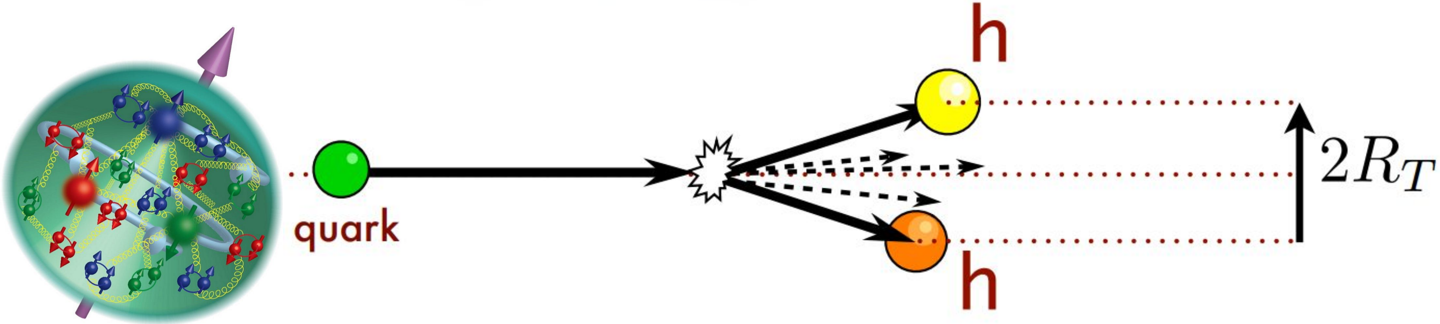
$$e(\ell) + p(P) \longrightarrow e(\ell') + h_1(P_1) + h_2(P_2) + X$$



Semi-Inclusive Dihadron Production

$$e(\ell) + p(P) \longrightarrow e(\ell') + h_1(P_1) + h_2(P_2) + X$$

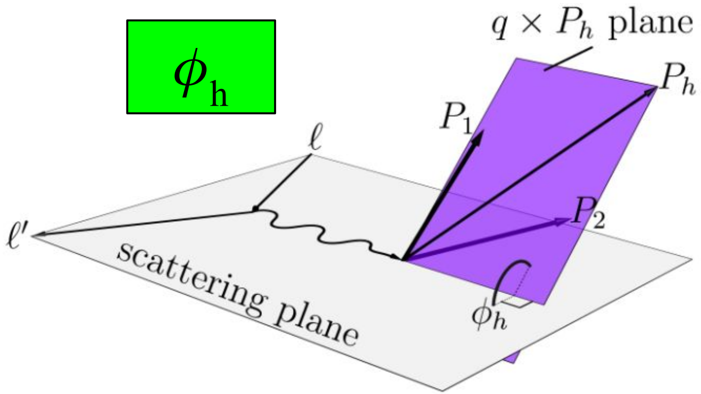
- Dihadron SIDIS production cross section: $\sigma = \hat{\sigma} \otimes \mathrm{PDF} \otimes \mathrm{DiFF}$
  - **Parton Distribution Function:** Probability to find a quark *q* with momentum fraction *x* in proton
  - **Dihadron Fragmentation Function:** Probability for a quark *q* to fragment into hadrons h_1 and h_2 with energy fraction z and invariant mass M_h

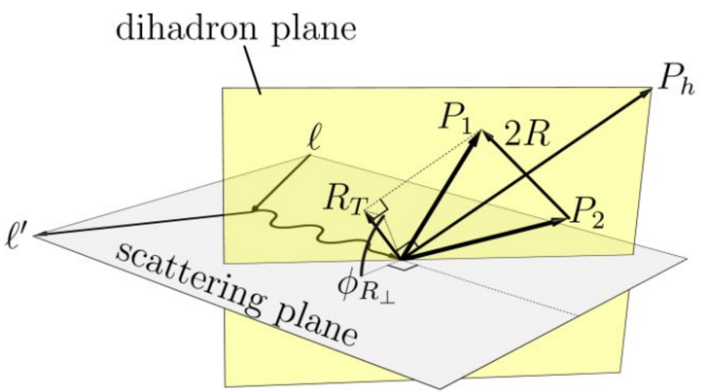


[1]

Dihadron Angular Variables

ϕ_h

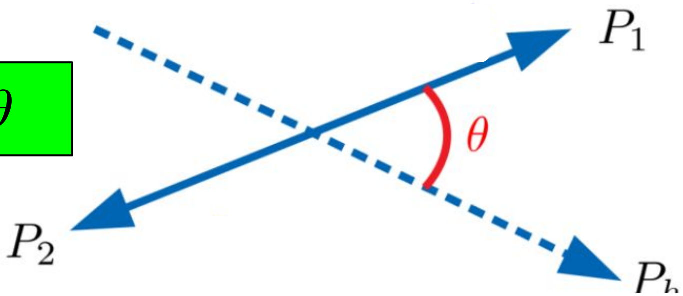




ϕ_R

Dihadron CoM frame

θ



★ *Our beam spin asymmetries are modulated by these 3 angles* ★

Dihadron Beam Spin Asymmetries

- Beam-spin dependent cross section contains twist-2 and twist-3 terms…

$$d\sigma_{LU} \propto \lambda_e \sum_{\ell=0}^{\ell_{\max}} \left\{ C(\epsilon, y) \sum_{m=1}^{\ell} 2\, P_{\ell,m}(\cos\theta)\, \sin[m(\phi_h - \phi_R)]\, F_{LU,\text{tw. }2}^{|\ell,m\rangle} + W(\epsilon, y) \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\theta)\, \sin[(1-m)\phi_h + m\phi_R]\, F_{LU,\text{tw. }3}^{|\ell,m\rangle} \right\}.$$

- Total of 12 independent modulations (7 when θ-integrated)

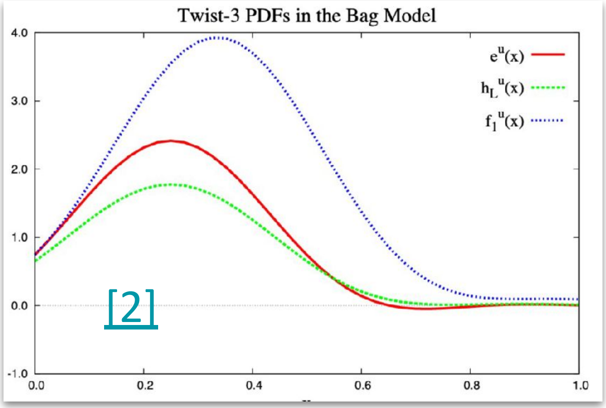
$$F_{LU,\text{tw.}2}^{|\ell,m\rangle} \to f_1 \otimes G_1^{\perp|\ell,m\rangle}$$

$$F_{LU,\text{tw.}3}^{|\ell,m\rangle} \to e \otimes H_1^{\perp|\ell,m\rangle}$$

The Twist-3 PDF *e(x)*

"Quark-gluon interactions help generate fundamental proton properties"

- Twist-2 PDFs $f_1(x)$, $g_1(x)$, and $h_1(x)$ describe **structure** $\longrightarrow$ probabilistic interpretation
- Twist-3 PDFs such as *e(x)* capture **dynamics** $\longrightarrow$ no number-density interpretation
  - Involves incoherent scattering off a ***quark-gluon*** pair in amplitude
  - Suppressed by 1/Q in the cross section $\longrightarrow$ JLab optimal!



"Why do we care about e(x)?"

- x^1 moment related to pion-nucleon sigma term $\longrightarrow \chi$-PT
- x^2 moment related to transverse force experienced by T-polarized quark in a T-polarized *N* [1]
- will not appear in deep-inelastic scattering if quark masses are ignored. In that we know of no practical way to measure $e(x)$ but we include it here for completeness and because its properties are interesting. Our discussion about

Jaffe, Ji 92

The Twist-3 PDF *e(x)*

★ **QUESTION:** *"Why study 2-hadron SIDIS?"* ★

★ **ANSWER:** In the dihadron BSA, *e(x)* appears without transverse momentum-dependence! ★

$$d^7\sigma_{LO} = \frac{\alpha^2}{2\pi Q^2 y}\lambda \sum_a e_a^2 W(y)\,\sin\phi_R \frac{|\vec{R}_T|}{Q}\left[\frac{M}{M_h} x\, e(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x)\,\tilde{G}^{\sphericalangle}(z,\zeta,M_h^2)\right]$$

★ This is not the case in 1-hadron SIDIS — e(x) extraction requires TMD modeling *and* appears in a structure function with 4 PDF⊗FF pairs ★

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right],$$

Dihadron Fragmentation Functions (DiFFs)

- The leading twist fragmentation quark-quark correlator (below) contains 4 **DiFFs** [1]

$$D_1 + i\, H_1^{\sphericalangle} \frac{\not{R}_T}{M_h} + i\, H_1^{\perp} \frac{\not{p}_T}{M_h} + G_1^{\perp} \frac{\varepsilon_T^{\mu\nu} R_{T\mu} p_{T\nu}}{M_h^2} \gamma_5$$

Projection along "good" light-cone component

- **$G_1^{\perp}$** = measures how much the hadron pair "swirls" clockwise or anti-clockwise about the jet axis (helicity-dependent) – *has no single hadron SIDIS counterpart!*

- **$H_1^{\perp}$** and **$H_1^{\sphericalangle}$** = measures how the hadron pair's **"R"** and **"h"** planes tilt left-or-right with respect to the quark's transverse spin — *chiral odd*

★ DiFFs are expanded into a basis of spherical harmonics with respect to θ. Each partial wave is assigned an |l,m> angular momentum eigenstate ★

Event Cuts (RG-A dataset)

SIDIS Channel

- $Q^2 > 1$ GeV^2
- $y < 0.8$
- $W > 2$ GeV
- $5 < \theta < 35$ [deg]
- Pass QA

Electron Cuts

- $-8 < v_z < 3$ [cm]
- $E_{PCAL} > 0.07$ [GeV]
- $E_{ECIN} > 0$, $E_{COUT} > 0$
- Pcal coords (9 < lu,lw < 400)
- SF cut
- DC fiducial cut
- Scattered e^- max energy with -3000 < status < -2000

Photon Cuts

- E > 0.2 [GeV]
- $0.9 < \beta < 1.1$
- $\alpha(e,\gamma) > 8$ [deg]
- $E_{PCAL} > 0$
- Pcal coords (14 < lv,lw < 400)
- **classifier output → p > 0.78 for M.L**

Pion Cuts

- $|v_z^e - v_z^\pi| < 20$ [cm]
- DC fiducial cut
- □$^2_{pid}$ cut
- **P(π±) > 1.25 [GeV] only for pass-1 analysis**
- Cannot be associated with CD !(4000<=status<5000)

Dihadron Cuts

- $M_X > 1.5$ GeV
- $x_F(\pi) > 0$
- $z < 0.95$

Inbending Datasets

$\pi^+\pi^+$, $\pi^+\pi^-$, $\pi^+\pi^0$

Outbending Datasets

$\pi^-\pi^-$, $\pi^-\pi^+$

RG-A Datasets

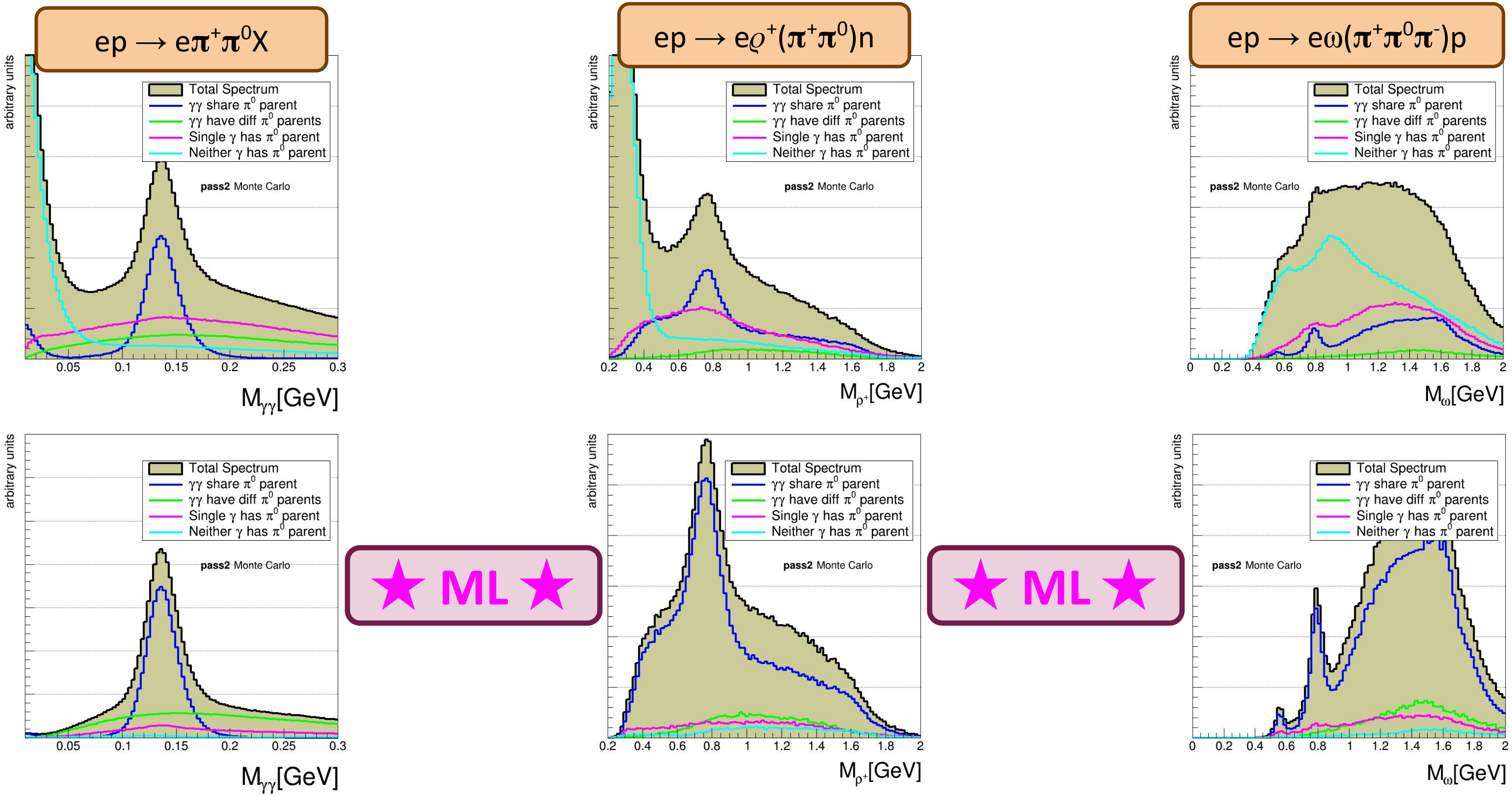
Dataset	Channel	Total	Legacy	ML
MC Inbending	$\pi^+\pi^+$	4.8 M	—	—
	$\pi^+\pi^-$	6.3 M	—	—
	$\pi^-\pi^-$	236 K	—	—
	$\pi^+\pi^0$	8.2 M	340 K	3.0 M
	$\pi^-\pi^0$	2.3 M	87 K	602 K
MC Outbending	$\pi^+\pi^+$	80 K	—	—
	$\pi^+\pi^-$	613 K	—	—
	$\pi^-\pi^-$	158 K	—	—
	$\pi^+\pi^0$	366 K	12 K	108 K
	$\pi^-\pi^0$	497 K	17 K	200 K
RG-A Inbending	$\pi^+\pi^+$	5.6 M	—	—
	$\pi^+\pi^-$	8.0 M	—	—
	$\pi^-\pi^-$	306 K	—	—
	$\pi^+\pi^0$	9.2 M	414 K	4.0 M
	$\pi^-\pi^0$	2.5 M	95 K	783 K
RG-A Outbending	$\pi^+\pi^+$	512 K	—	—
	$\pi^+\pi^-$	4.4 M	—	—
	$\pi^-\pi^-$	1.2 M	—	—
	$\pi^+\pi^0$	2.2 M	83 K	732 K
	$\pi^-\pi^0$	3.0 M	115 K	1.4 M

pass-1

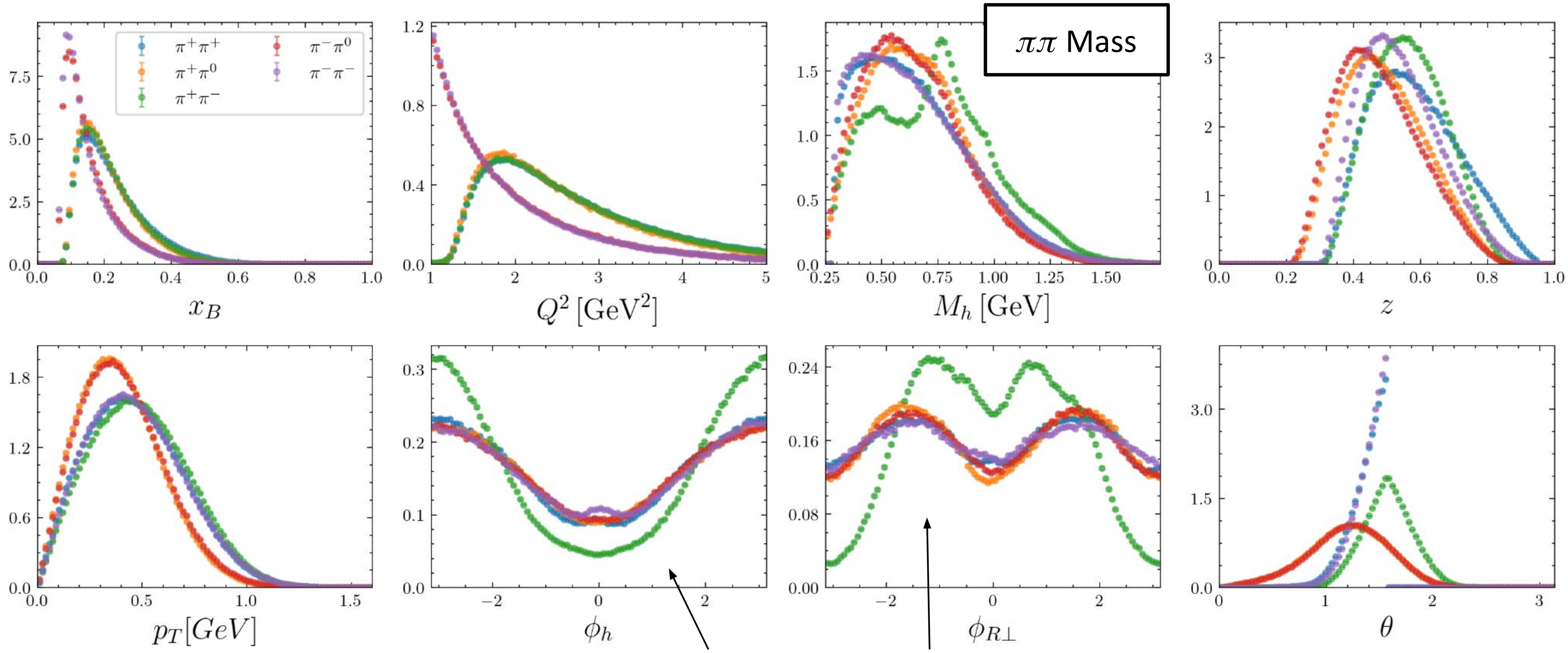
Dataset	Channel	Total	Legacy	ML
MC Inbending	$\pi^+\pi^+$	3.4 M	—	—
	$\pi^+\pi^-$	4.6 M	—	—
	$\pi^-\pi^-$	177 K	—	—
	$\pi^+\pi^0$	5.2 M	248 K	1.1 M
	$\pi^-\pi^0$	1.5 M	63 K	252 K
MC Outbending	$\pi^+\pi^+$	998 K	—	—
	$\pi^+\pi^-$	7.4 M	—	—
	$\pi^-\pi^-$	2.0 M	—	—
	$\pi^+\pi^0$	3.9 M	149 K	801 K
	$\pi^-\pi^0$	5.4 M	218 K	1.1 M
RG-A Inbending	$\pi^+\pi^+$	41.6 M	—	—
	$\pi^+\pi^-$	59.2 M	—	—
	$\pi^-\pi^-$	2.3 M	—	—
	$\pi^+\pi^0$	61.0 M	3.0 M	15.8 M
	$\pi^-\pi^0$	16.3 M	695 K	3.6 M
RG-A Outbending	$\pi^+\pi^+$	6.2 M	—	—
	$\pi^+\pi^-$	52.9 M	—	—
	$\pi^-\pi^-$	14.4 M	—	—
	$\pi^+\pi^0$	24.3 M	1.0 M	5.6 M
	$\pi^-\pi^0$	34.0 M	1.5 M	8.1 M

pass-2

CLAS12 Photon AI … SIDIS $\pi^+\pi^0$… Exclusive ϱ^+, ω



Kinematic Distributions



$\pi^+\pi^-$ differences tied to sharp ρ peak

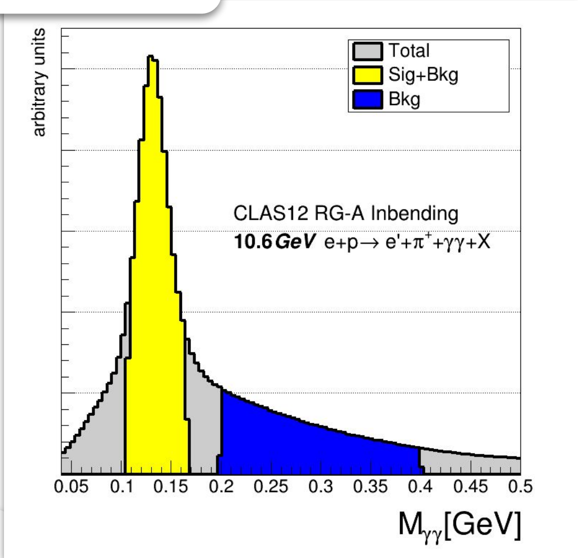
Asymmetry Extraction

- An unbinned maximum log-likelihood fit motivated by the dihadron cross section is used to extract the A_{LU}'s.
  - 12 w/o θ-integration
  - 7 with θ-integration

$$P \propto 1+\lambda_e P_b\left[A_{LU}^{\Psi_1(\phi_h,\phi_R,\theta)}\Psi_1(\phi_h,\phi_R,\theta)+\ldots\right]$$

- For π^0-having dihadrons, **signal+background** & **background** regions are defined where separate asymmetries are extracted.

★ Correlations of the π^0 purity "u" with ϕ_h, ϕ_R require us to bin the purity…
  - Without this, asymmetries from one modulation can "pull at" the asymmetry in other modulations
  - Verified with MC injection studies (extra slides)



$$\mathcal{P}_{\pm}(\phi_h,\phi_R;A_\ell)=\frac{L_\pm}{L}\left(1\pm P_b\sum_\ell \psi_\ell(\phi_h,\phi_R)\left[u(\phi_h,\phi_R)A_{LU,\ell}^{\rm sig}+(1-u(\phi_h,\phi_R))A_{LU,\ell}^{\rm bkg}\right]\right).$$

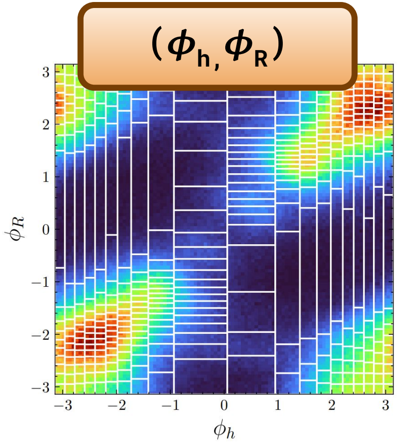
Calculating Event-By-Event Purity

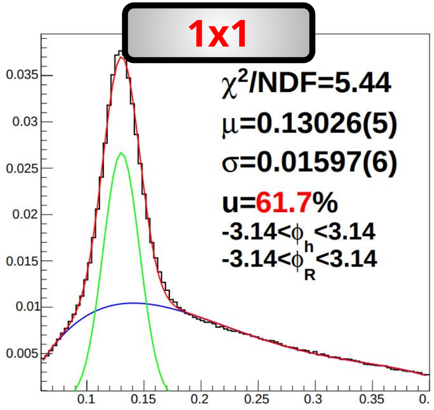
$u(\phi_h, \phi_R)$ Procedure:

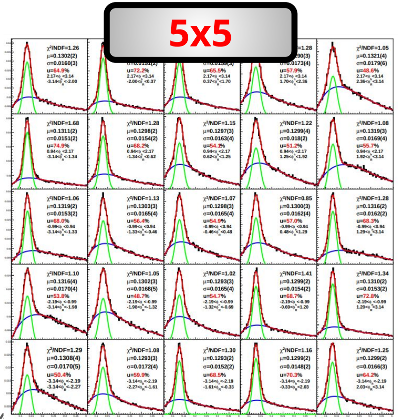
1. For each kinematic bin (x, z, etc.) subdivide the (ϕ_h, ϕ_R) space into NxM asymmetric bins such that each bin contains *roughly* the same # events

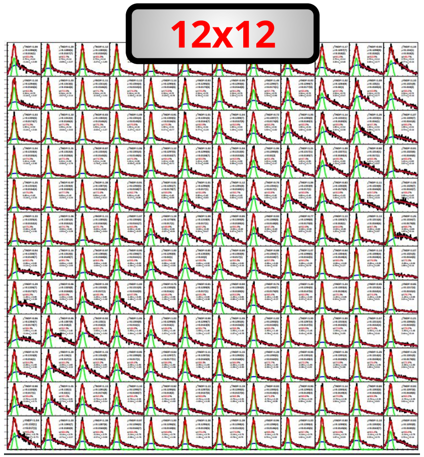
2. $f(M_{\gamma\gamma})$ = gaus + pol4 in each sub-bin to calculate its purity (signal integral between $0.106 < M_{\gamma\gamma} < 0.166$

3. For the **MLM** in the sig+bkg region, estimate the event-by-event purity as the purity bin for which the event's (ϕ_h, ϕ_R) is inside





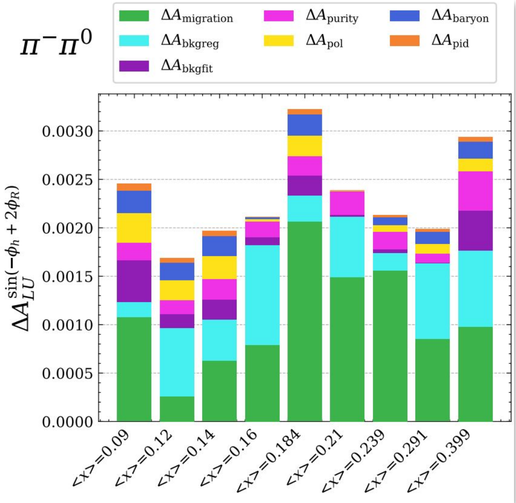


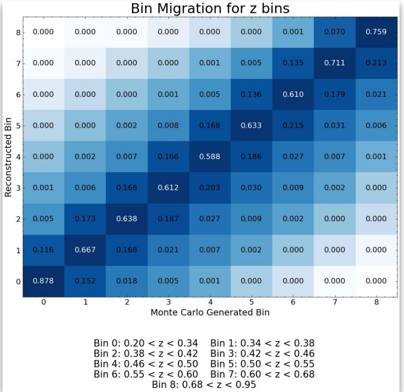


Systematic Uncertainties

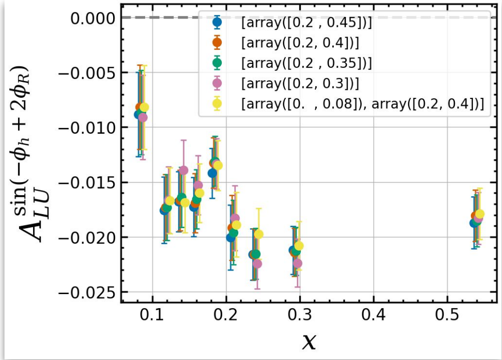
- ➢ One source of normalization error (beam polarization)
- ➢ Six sources of point-to-point errors explored
  - Bin Migration
  - Density of the purity-binning scheme
  - Baryonic decay contamination (ex: $\Lambda \rightarrow p\pi^-$)
  - Particle misidentification
  - Background polynomial fit degree (π^0 purity)
  - Sideband region definition (π^0 background asymmetry)

★ Ex: $\pi^-\pi^0$ systematic error breakdown for A_{LU} twist-3 |2,2> . ★





← Bin migration systematic



← π^0 sideband-region systematic

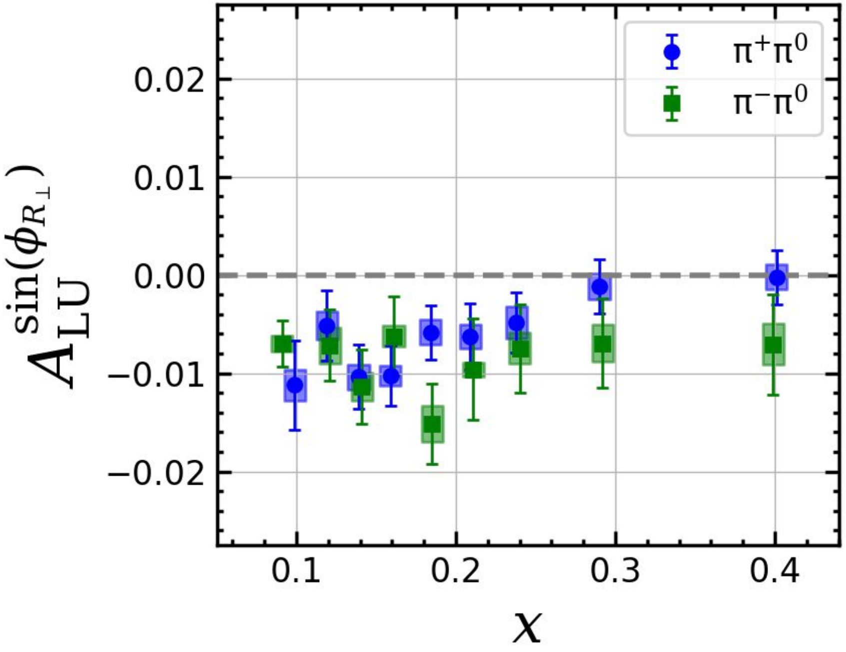
PRL Plots: $\pi^{\pm}\pi^{0}$ Twist-3

Non-zero result measured for both channels

Second, independent avenue for extracting *e(x)* !

$A_{LU} < 0$ as opposed to large positive signal found for the $\pi^{+}\pi^{-}$ at CLAS12 [1] (due to sign of H_1?)

Twist-3 DiFF $\tilde{G}^{\sphericalangle}$ believed to be negligible due to Wandzura Wilcek approximation (to be measured with complementary RG-C dihadron studies)



$$d^7\sigma_{LO} = \frac{\alpha^2}{2\pi Q^2 y}\lambda\sum_a e_a^2 W(y)\sin\phi_R \frac{|\vec{R}_T|}{Q}\left[\frac{M}{M_h}x\,e(x)\,H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z}f_1(x)\,\tilde{G}^{\sphericalangle}(z,\zeta,M_h^2)\right]$$

$\zeta \equiv \zeta(\theta)$

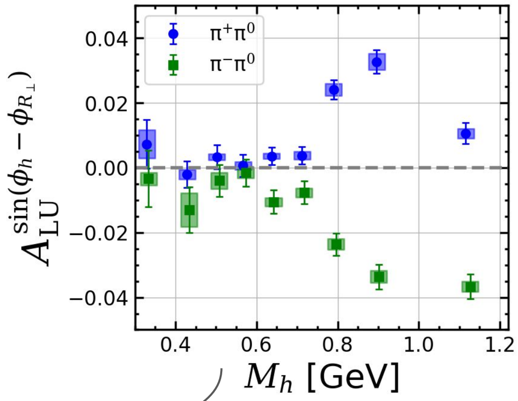
PRL Plots: $\pi^{\pm}\pi^{0}$ Twist-2

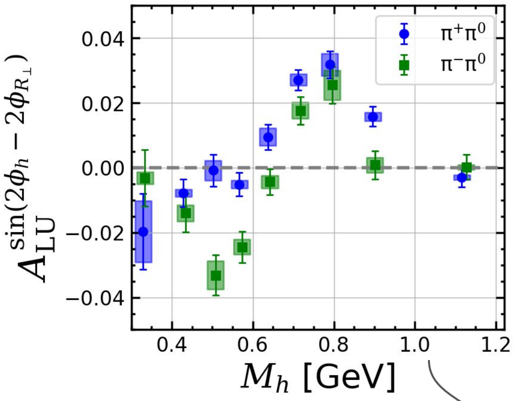
Clear resonant behavior near ϱ-mass, indicative of s- and p- wave dihadron interference

First evidence of isospin-dependence in $G_1^{\perp}$, depends on the partial wave!

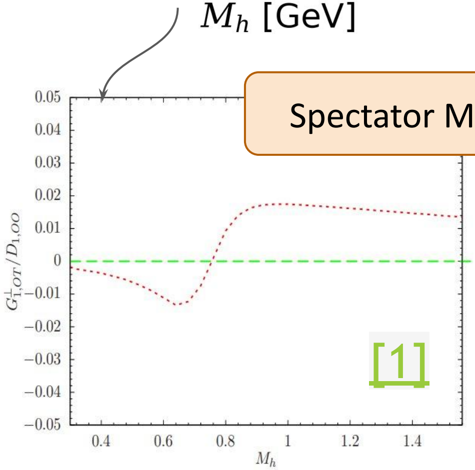
Very limited model predictions for non-$\pi^+\pi^-$, future phenomenology?

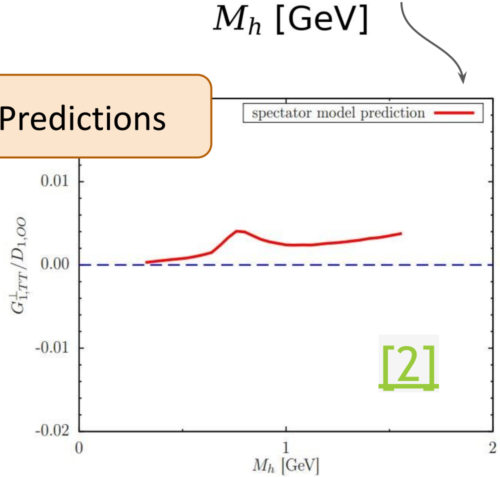
$$F_{LU,\text{tw.2}}^{|\ell,m\rangle} \rightarrow f_1 \otimes G_1^{\perp|\ell,m\rangle}$$





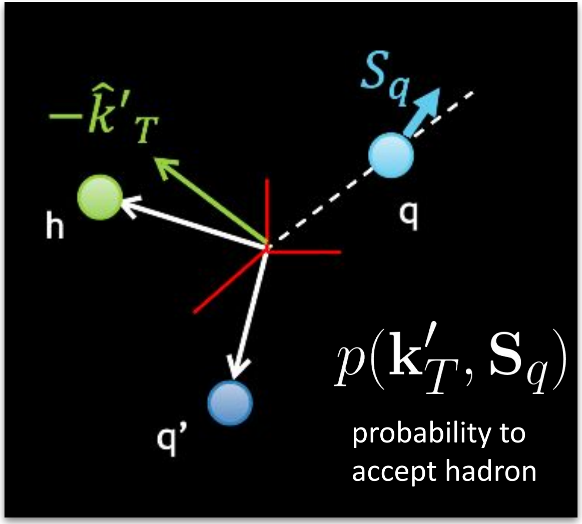
Spectator Model Predictions



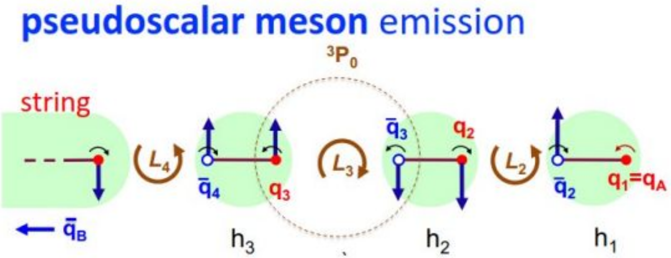


Spin-dependent fragmentation in PYTHIA8

- **StringSpinner** is a plugin for the introduction of the spin effects in the hadronization part of PYTHIA8 [1], [2]
  - Replicates COMPASS π, K Collins asymmetries – Replicates BELLE b2b hadron asymmetries [3]
- Quark-spin propagated in hadronization using the String+3P0 fragmentation model [4]
  - Initialize struck quark with longitudinal polarization
  - Generate q-qbar with **L**=**S**=1, **J**=0 (vacuum quantum #'s)
  - Bias hadrons with $\mathbf{k_T}$ relative to fragmenting quark $\mathbf{S_q}$
  - Propagate spin to next quark **q'** and (if produced) vector mesons



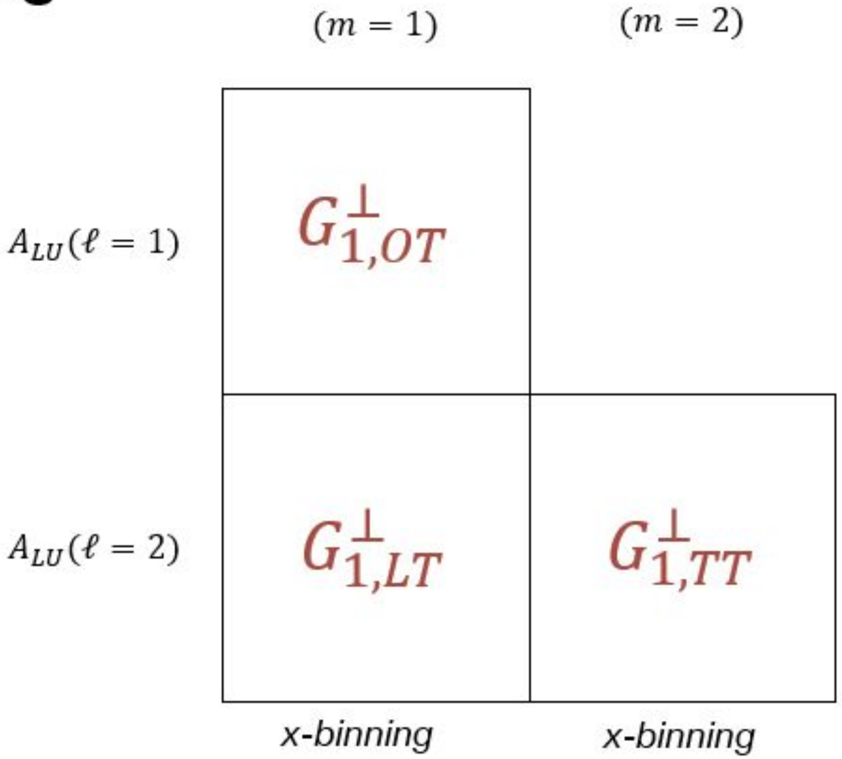
★ Can **StringSpinner** MC reproduce **CLAS12** partial waves? ★

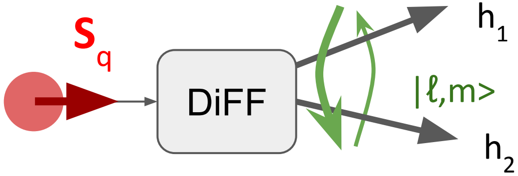


Plot Formatting (Twist-2)

$\vert\ell,m\rangle$	Twist-2 Amplitude	Twist-3 Amplitude
$\vert0,0\rangle$	—	$P_{0,0}\sin(\phi_h)$
$\vert1,1\rangle$	$P_{1,1}\sin(\phi_h-\phi_R)$	$P_{1,1}\sin(\phi_R)$
$\vert1,0\rangle$	—	$P_{1,0}\sin(\phi_h)$
$\vert1,-1\rangle$	—	$P_{1,-1}\sin(2\phi_h-\phi_R)$
$\vert2,2\rangle$	$P_{2,2}\sin(2(\phi_h-\phi_R))$	$P_{2,2}\sin(-\phi_h+2\phi_R)$
$\vert2,1\rangle$	$P_{2,1}\sin(\phi_h-\phi_R)$	$P_{2,1}\sin(\phi_R)$
$\vert2,0\rangle$	—	$P_{2,0}\sin(\phi_h)$
$\vert2,-1\rangle$	—	$P_{2,-1}\sin(2\phi_h-\phi_R)$
$\vert2,-2\rangle$	—	$P_{2,-2}\sin(3\phi_h-2\phi_R)$

$$A_{LU}^{tw2} \propto f_1 \otimes G_1^{\perp}$$



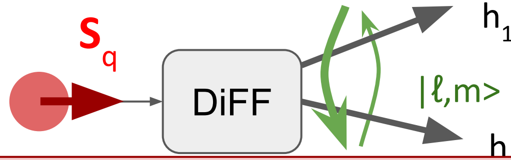


Plot Formatting (Twist-2)

	$(m=1)$	$(m=2)$
$A_{LU}(\ell=1)$	$G_{1,OT}^{\perp}$	
$A_{LU}(\ell=2)$	$G_{1,LT}^{\perp}$	$G_{1,TT}^{\perp}$

$\vert\ell,m\rangle$	Twist-2 Amplitude	Twist-3 Amplitude
$\vert 0,0\rangle$	—	$P_{0,0}\sin(\phi_h)$
$\vert 1,1\rangle$	$P_{1,1}\sin(\phi_h-\phi_R)$	$P_{1,1}\sin(\phi_R)$
$\vert 1,0\rangle$	—	$P_{1,0}\sin(\phi_h)$
$\vert 1,-1\rangle$	—	$P_{1,-1}\sin(2\phi_h-\phi_R)$
$\vert 2,2\rangle$	$P_{2,2}\sin(2(\phi_h-\phi_R))$	$P_{2,2}\sin(-\phi_h+2\phi_R)$
$\vert 2,1\rangle$	$P_{2,1}\sin(\phi_h-\phi_R)$	$P_{2,1}\sin(\phi_R)$
$\vert 2,0\rangle$	—	$P_{2,0}\sin(\phi_h)$
$\vert 2,-1\rangle$	—	$P_{2,-1}\sin(2\phi_h-\phi_R)$
$\vert 2,-2\rangle$	—	$P_{2,-2}\sin(3\phi_h-2\phi_R)$

$$A_{LU}^{tw2} \propto f_1 \otimes G_1^{\perp}$$

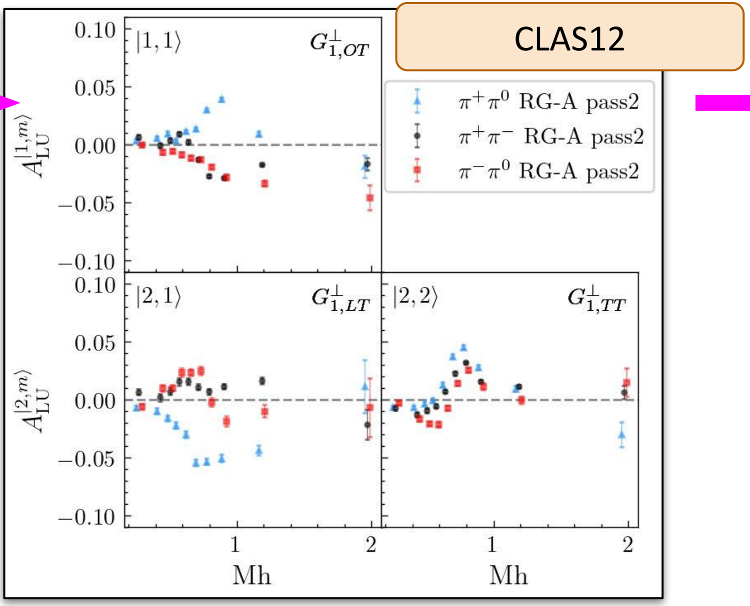


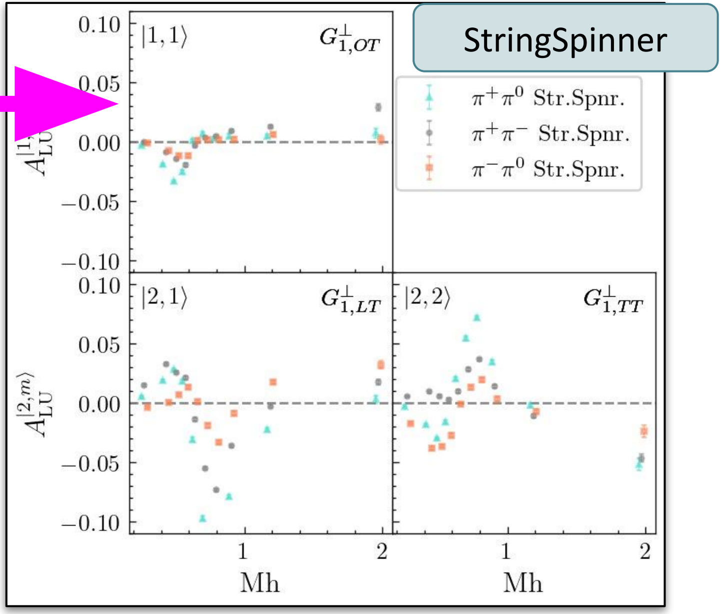
$$d\sigma_{LU} = \lambda_e\left(\ldots + A_{LU,\mathrm{tw.2}}^{|2,1\rangle} \sin 2\theta \sin\left[\phi_h - \phi_R\right] + \ldots\right)$$

Twist-2 Partial Waves ($\pi^+\pi^-, \pi^+\pi^0, \pi^-\pi^0$)

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

- Sign change only in **CLAS12** $\pi^+\pi^-$ (predicted in Spectator Model [1])
- ω→$\pi\pi$X decay creates negative **StringSpinner** signal. Why CLAS12 $\pi^+\pi^0$ so positive?

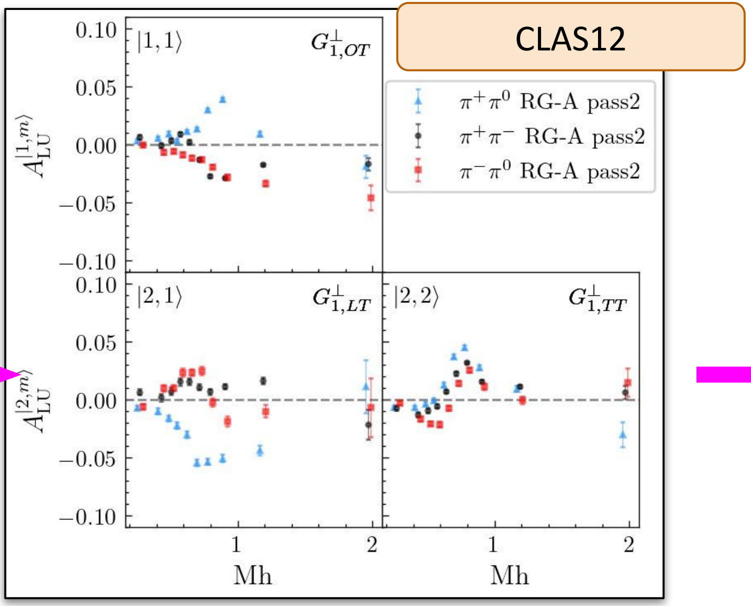


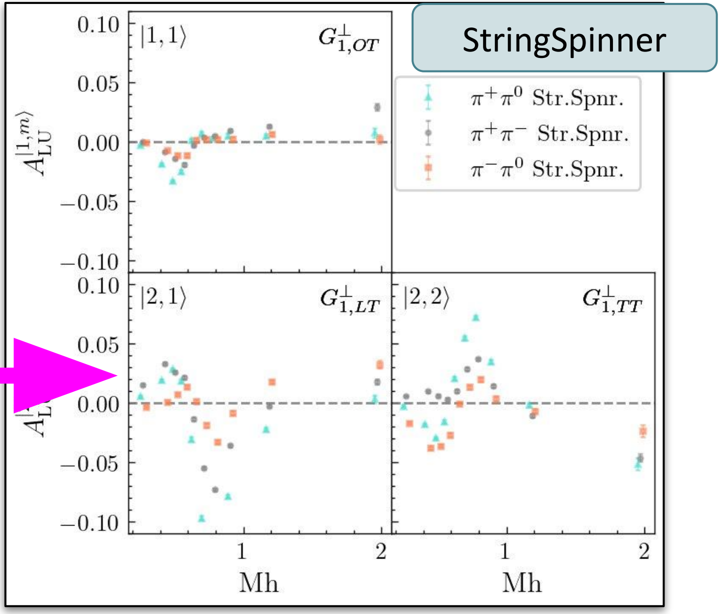


Twist-2 Partial Waves $(\pi^+\pi^-, \pi^+\pi^0, \pi^-\pi^0)$

$G_{1,LT}^{\perp}$

- ➢ Unexplored in literature → large **CLAS12** asymmetries observed!
- ➢ Interference of **L** and **T** polarized VM's create effect in **StringSpinner**
  - ○ Mechanism for $\pi+\pi-$ staying positive still unknown…

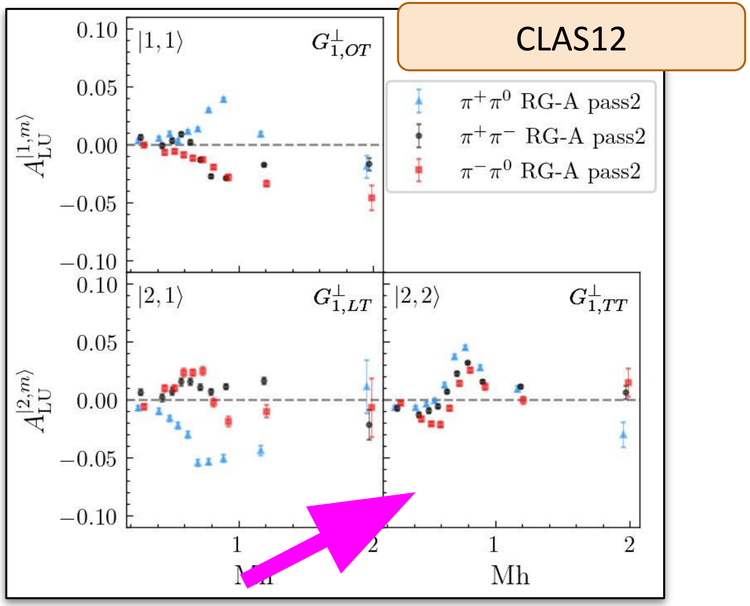


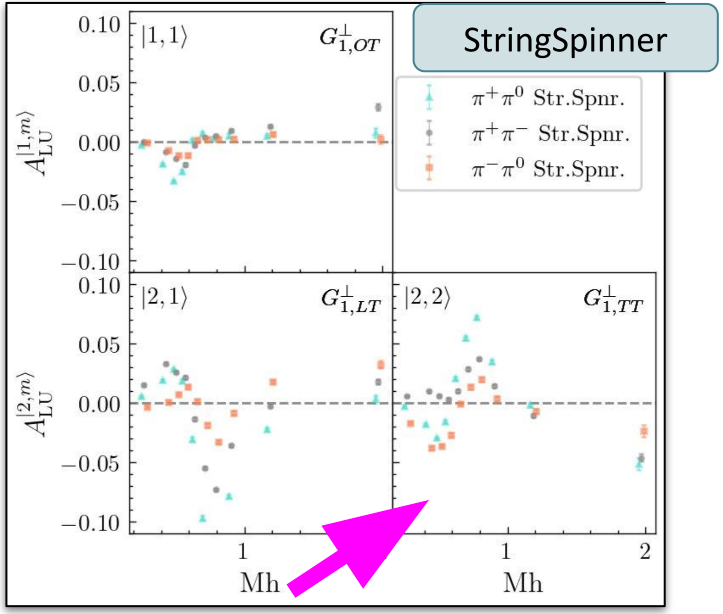


Twist-2 Partial Waves ($\pi^+\pi^-, \pi^+\pi^0, \pi^-\pi^0$)

$G_{1,TT}^{\perp}$

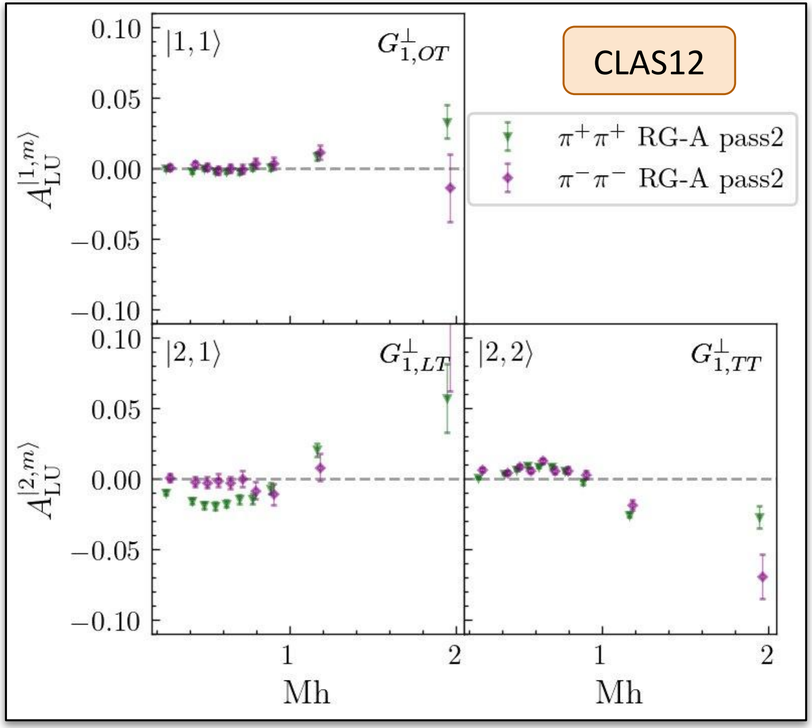
- Excellent agreement between **CLAS12** and **StringSpinner**
- Asymmetry generated by interference of polarized ϱ's → captures relative size!

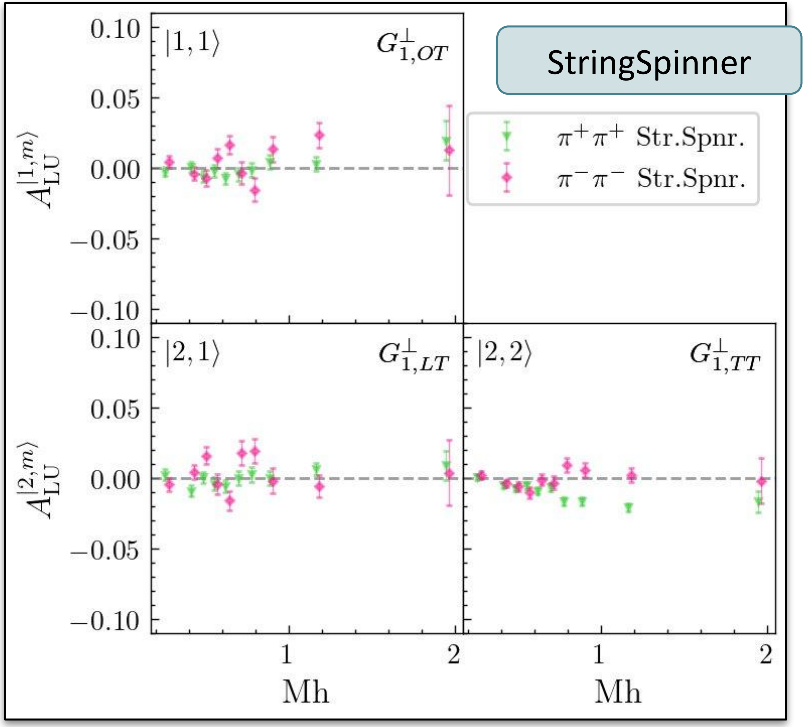




Twist-2 Partial Waves ($\pi^+\pi^+, \pi^-\pi^-$)

- High M_h asymmetry in like-pion pairs *mysterious* – high angular momentum states?

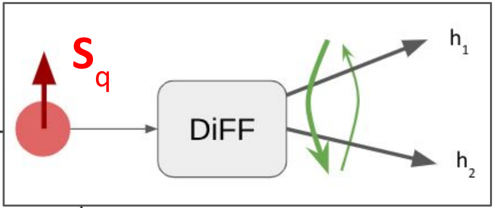




Plot Formatting (Twist-3)

$\lvert \ell, m \rangle$	Twist-2 Amplitude	Twist-3 Amplitude
$\lvert 0,0 \rangle$	—	$P_{0,0}\sin(\phi_h)$
$\lvert 1,1 \rangle$	$P_{1,1}\sin(\phi_h - \phi_R)$	$P_{1,1}\sin(\phi_R)$
$\lvert 1,0 \rangle$	—	$P_{1,0}\sin(\phi_h)$
$\lvert 1,-1 \rangle$	—	$P_{1,-1}\sin(2\phi_h - \phi_R)$
$\lvert 2,2 \rangle$	$P_{2,2}\sin(2(\phi_h - \phi_R))$	$P_{2,2}\sin(-\phi_h + 2\phi_R)$
$\lvert 2,1 \rangle$	$P_{2,1}\sin(\phi_h - \phi_R)$	$P_{2,1}\sin(\phi_R)$
$\lvert 2,0 \rangle$	—	$P_{2,0}\sin(\phi_h)$
$\lvert 2,-1 \rangle$	—	$P_{2,-1}\sin(2\phi_h - \phi_R)$
$\lvert 2,-2 \rangle$	—	$P_{2,-2}\sin(3\phi_h - 2\phi_R)$

$$A_{LU}^{tw3} \propto e \otimes H_1^{\perp,\sphericalangle}$$



	$(m=-2)$	$(m=-1)$	$(m=1)$	$(m=2)$
$A_{LU}(\ell=1)$		$H_{1,OT}^{\perp}$	$H_{1,OT}^{\sphericalangle}$	
$A_{LU}(\ell=2)$	$H_{1,TT}^{\perp}$	$H_{1,LT}^{\perp}$	$H_{1,LT}^{\sphericalangle}$	$H_{1,TT}^{\sphericalangle}$
	x-binning	x-binning	x-binning	x-binning

Omitting m=0 to save some space. Also, twist-3 |2,0> and |0,0> correlate with one another

$$P_{0,0} = 1 \leftrightarrow P_{2,0} = \frac{1}{2}(3\cos^2\theta - 1)$$

Plot Formatting (Twist-3)

$\vert \ell, m\rangle$	Twist-2 Amplitude	Twist-3 Amplitude
$\vert 0,0\rangle$	—	$P_{0,0}\sin(\phi_h)$
$\vert 1,1\rangle$	$P_{1,1}\sin(\phi_h - \phi_R)$	$P_{1,1}\sin(\phi_R)$
$\vert 1,0\rangle$	—	$P_{1,0}\sin(\phi_h)$
$\vert 1,-1\rangle$	—	$P_{1,-1}\sin(2\phi_h - \phi_R)$
$\vert 2,2\rangle$	$P_{2,2}\sin(2(\phi_h - \phi_R))$	$P_{2,2}\sin(-\phi_h + 2\phi_R)$
$\vert 2,1\rangle$	$P_{2,1}\sin(\phi_h - \phi_R)$	$P_{2,1}\sin(\phi_R)$
$\vert 2,0\rangle$	—	$P_{2,0}\sin(\phi_h)$
$\vert 2,-1\rangle$	—	$P_{2,-1}\sin(2\phi_h - \phi_R)$
$\vert 2,-2\rangle$	—	$P_{2,-2}\sin(3\phi_h - 2\phi_R)$

$$A_{LU}^{tw3} \propto e \otimes H_1^{\perp,\measuredangle}$$

$money plot$

	$(m=-2)$	$(m=-1)$	$(m$	$m=2)$
$A_{LU}(\ell = 1)$		$H_{1,OT}^{\perp}$	\$\$\$\$\$\$\$\$\$ $H_{1,OT}^{\measuredangle}$ \$\$\$\$\$\$\$\$\$	
$A_{LU}(\ell = 2)$	$H_{1,TT}^{\perp}$	$H_{1,LT}^{\perp}$	$H_{1,LT}^{\measuredangle}$	$H_{1,TT}^{\measuredangle}$
	x-binning	x-binning	x-binning	x-binning

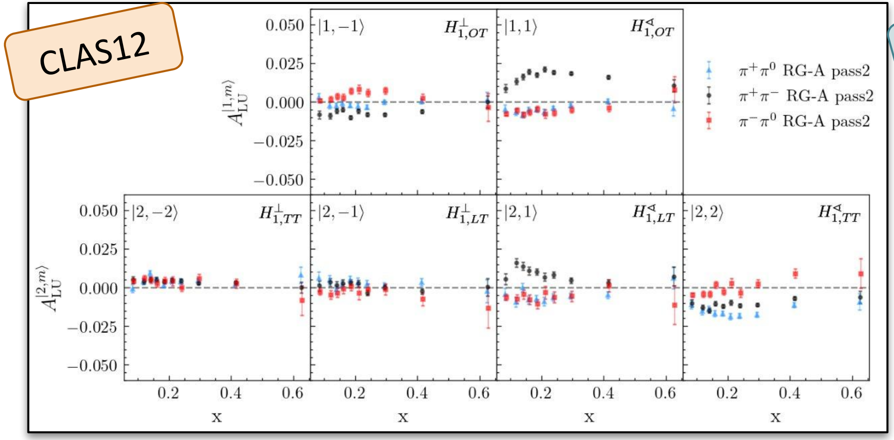
Direct access to collinear *e(x)* without TMD-modeling

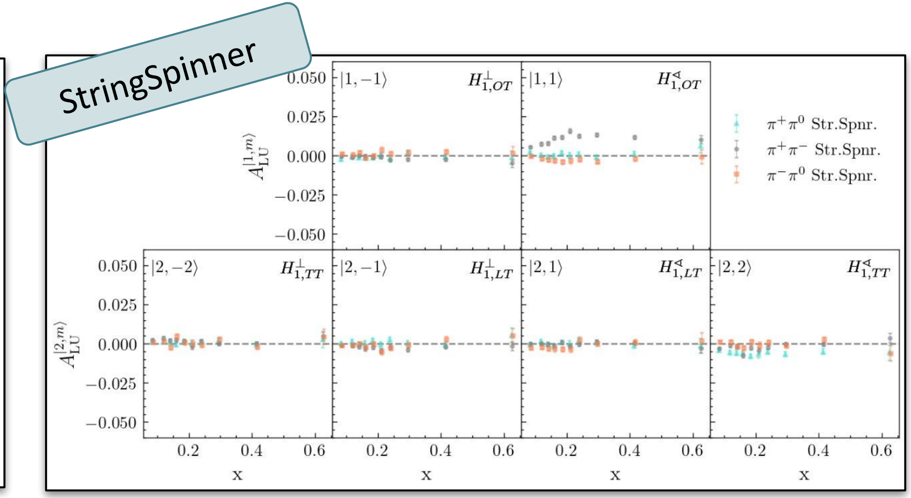
Omitting m=0 to save some space. Also, twist-3 |2,0> and |0,0> correlate with one another

$$P_{0,0} = 1 \leftrightarrow P_{2,0} = \frac{1}{2}(3\cos^2\theta - 1)$$

Twist-3 Partial Waves ($\pi^+\pi^-, \pi^+\pi^0, \pi^-\pi^0$)

- ➢ The **CLAS12** e(x) $money plot$ |1,1> asymmetry replicated by **StringSpinner**
  - ○ Negative asymmetry seen in **CLAS12** $\pi\pm\pi 0$ – pion-pair dependence of $\mathbf{H_1}$? [1]
  - ○ Two new avenues of accessing e(x) – limited knowledge of $\mathbf{H_1}$ for $\pi\pm\pi 0$ however
  - ○ We still don't understand how **StringSpinner** recreates this asymmetry, has no **e(x)** parameterization!
- ➢ Large effects in other tw.3 partial waves seen at **CLAS12**
  - ○ Relatively muted in **StringSpinner**

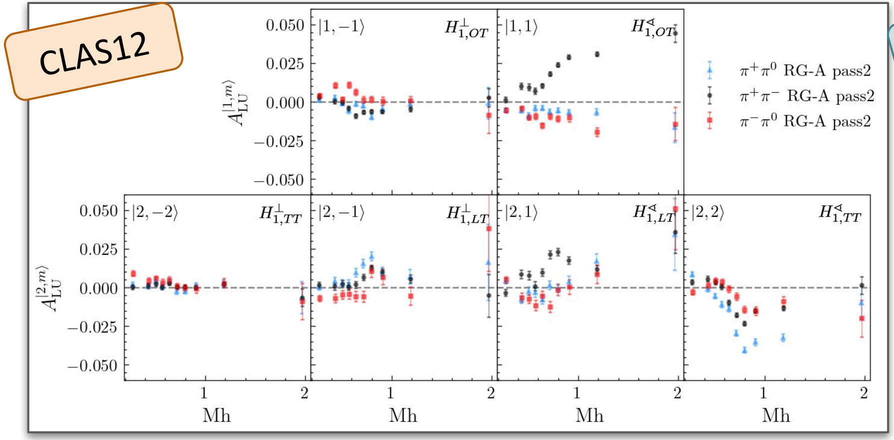


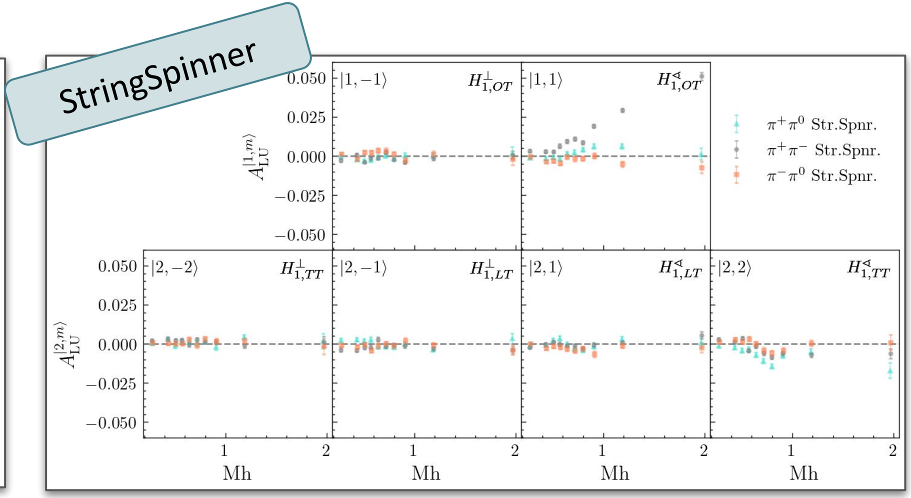


Twist-3 Partial Waves ($\pi^+\pi^-, \pi^+\pi^0, \pi^-\pi^0$)

- ➢ Never-before seen ϱ-induced resonances in H_1 visible
  - ○ Both **CLAS12** and **StringSpinner** match for |2,2> partial wave (similar to tw.2 result)
- ➢ For **CLAS12** the |1,1> M_h dependence in $\pi^+\pi^-$ is far stronger than $\pi\pm\pi 0$

★ *It is abundantly clear that VM's play a significant role towards interpreting our asymmetries* ★





Outlook and Conclusion

- Analysis Note for $\pi^+\pi^0$ and $\pi^-\pi^0$ BSA's APPROVED (*May 2025*)
  - Pass-1 RG-A data
  - θ-integrated results = 7 modulations
  - **PRL** paper first draft written (waiting for CLAS committee to form)

- Partial Wave Decomposition of five $\pi\pi$ channels (excluding $\pi^0\pi^0$) *in progress*
  - Pass-2 RG-A data
  - Full θ-dependence captured = 12 modulations/partial waves
  - Collaborating with Chris Dilks $\longrightarrow$ in development of $\pi^+\pi^-$ PW analysis note
  - Meeting with theorists to interpret results $\longrightarrow$ comparing with theoretical models

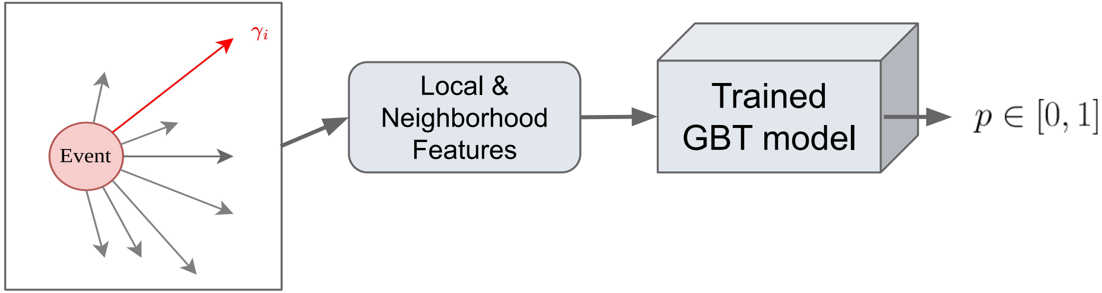
★ *These analyses will provide the most comprehensive catalog of dihadron fragmentation to date.* ★

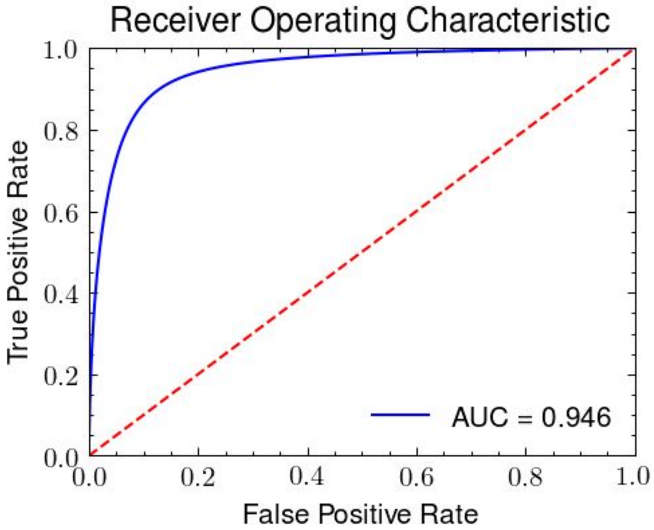
Extra Slides

Photon GBT Classifier

Train on intrinsic (E_{dep}, θ , calo-shape, etc.) and nearest neighbor (angular separation with N-nearest charged hadron, neutral particle, etc.) features (total = 16 feat.)

photon of interest (POI)



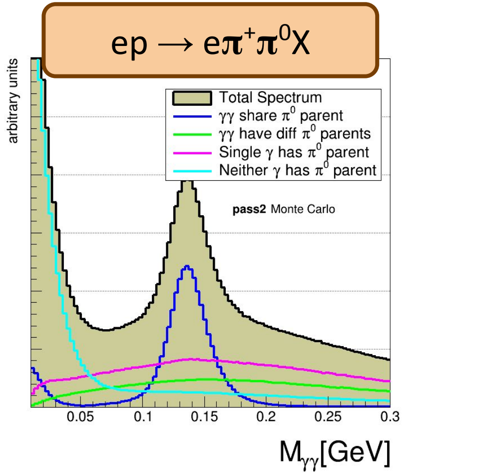


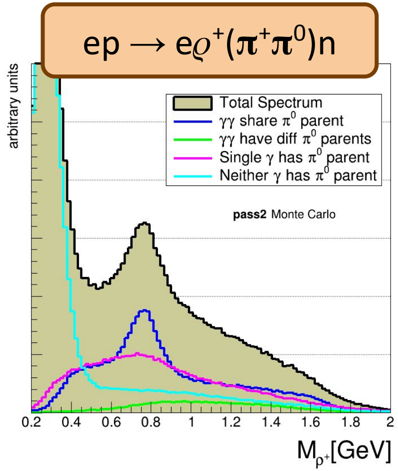

```
p ≈ 0 → Photon does not have a MC match (background)
p ≈ 1 → Photon likely has MC match (signal)
```

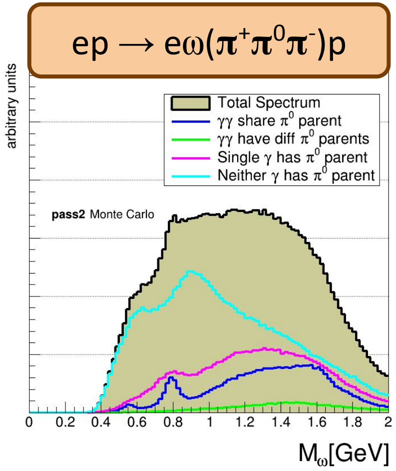
- LogLoss Evaluation Metric
- 75/25 split with 0.1 LR
- Symmetric Growth policy (10 depth)
- 50 generations early stopping

★ **Avoids learning resonant structure**

Impact on … SIDIS $\pi^+\pi^0$… Exclusive ρ^+, ω





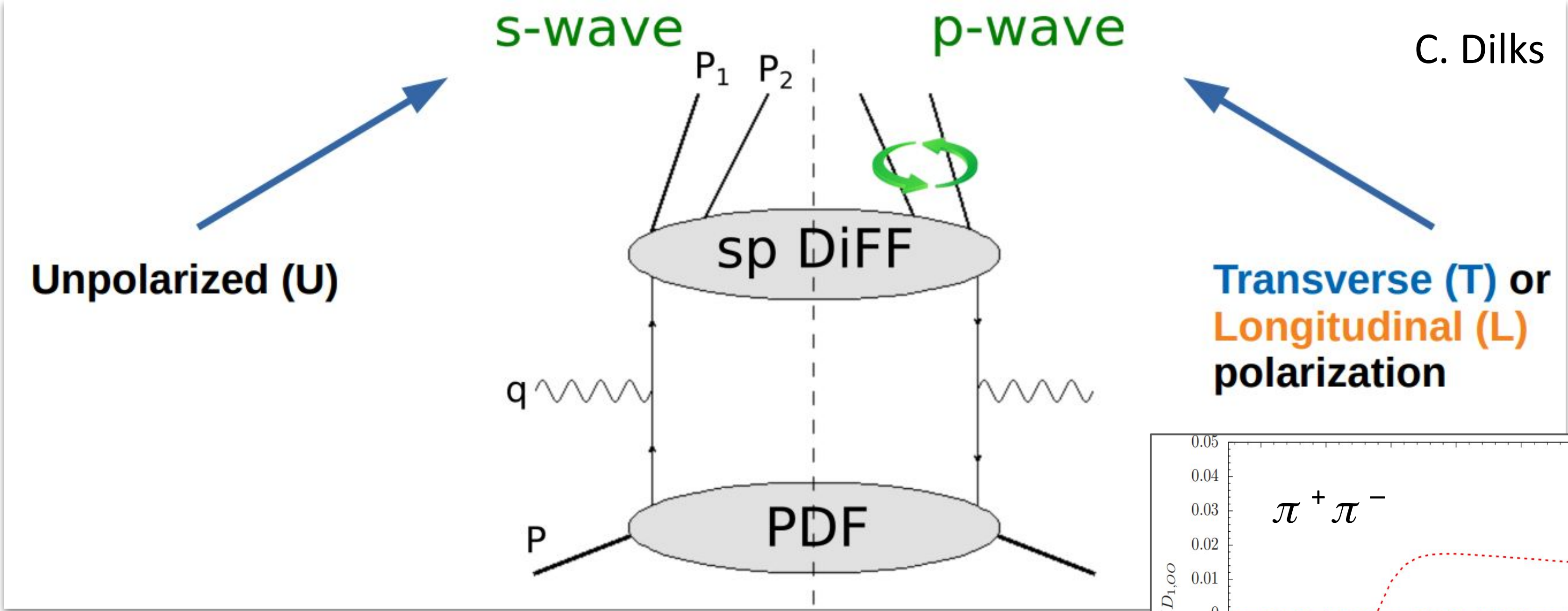


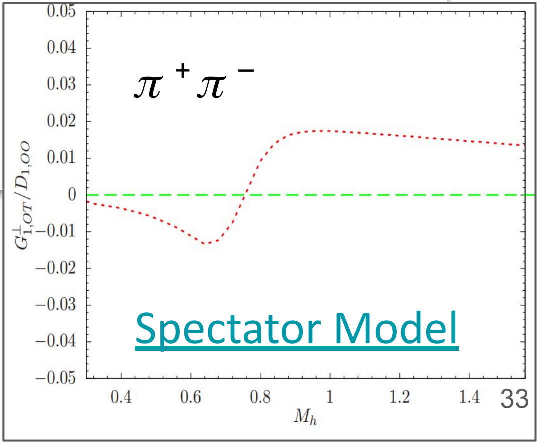
$\pi^0 \rightarrow \gamma\gamma$ background is a mix of true combinatoric (**LIME GREEN**) and false combinatoric (**MAGENTA and TEAL**)

Exclusive ρ^+ (M_{miss} < 1.2 GeV) region is *dominated* by false combinatoric backgrounds (**MAGENTA and TEAL**)

Exclusive ω (M_{miss} < 1.2 GeV) region is *dominated* by false combinatoric backgrounds (**MAGENTA and TEAL**)

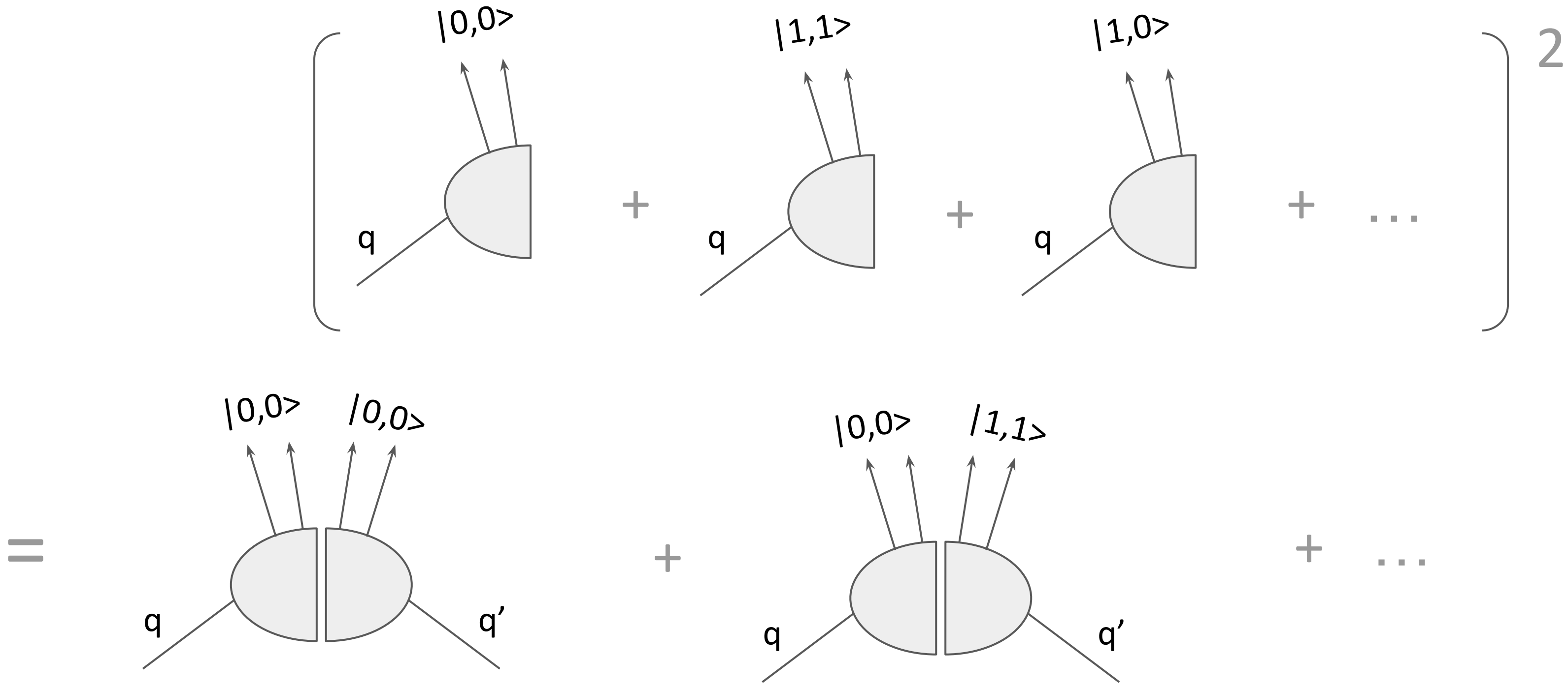
Partial Wave Decomposition





★ *Ex:* $\mathbf{G^{\perp}_{1,OT}}$ is an |1,1> DiFF partial wave — interference between an unpolarized pair and a transversely polarized pair ★

Dihadron Fragmentation Functions (DiFFs)



|L=0, M=0>

|L=1, M=1>

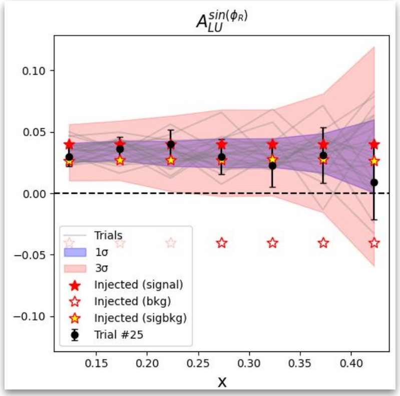
False Asymmetry Injection Studies

- ★ By default, Monte Carlo has **`helicity = 0`**
- ★ By defining false A^{sig} and A^{bkg} we can probabilistically assign **`helicity = ±1`** event-by-event

$$f(\phi_h, \phi_R; A^{\text{sig}}_{\text{inj}}, A^{\text{bkg}}_{\text{inj}}) = \begin{cases} \frac{1}{2}\left(1 + \sum_\ell A^{\text{sig}}_{\text{inj},\ell} \times \psi_\ell(\phi_h^{\text{true}}, \phi_R^{\text{true}})\right) & \text{if event e's } \gamma\gamma \text{ came from a } \pi^0 \\ \frac{1}{2}\left(1 + \sum_\ell A^{\text{bkg}}_{\text{inj},\ell} \times \psi_\ell(\phi_h^{\text{true}}, \phi_R^{\text{true}})\right) & \text{otherwise .} \end{cases}$$

Allows us to test the accuracy of our asymmetry extraction

- ★ We study the pulls of with only one injection **(Case A)**



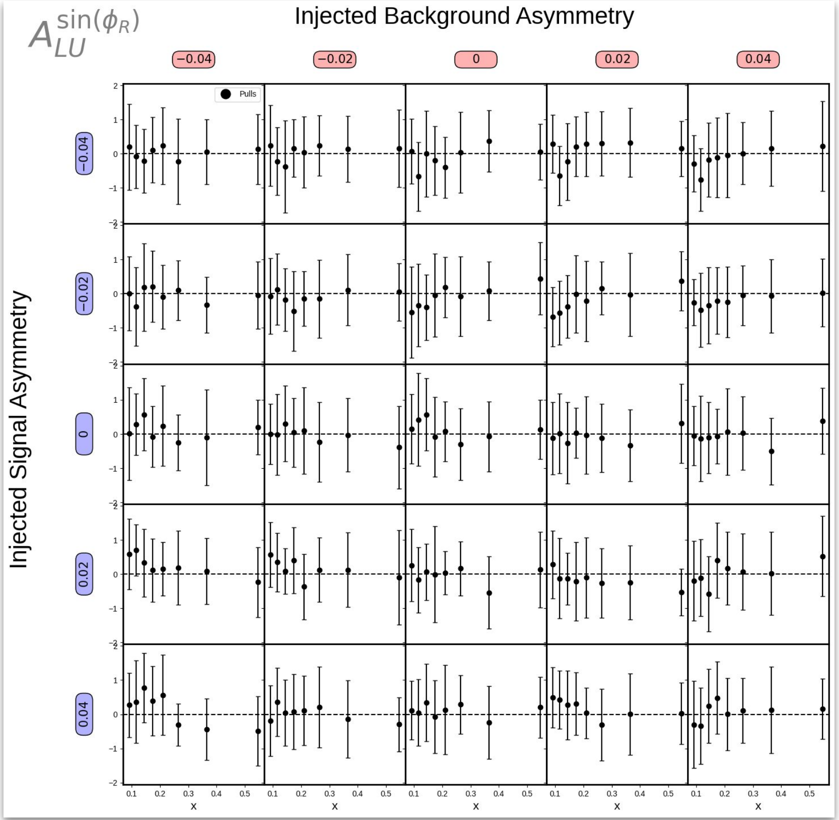
$$A^{\text{sig,bkg}}_{\sin(\phi_R)} \in [-0.04, -0.02, 0, 0.02, 0.04]$$

$$A^{\text{sig,bkg}}_{\text{other}} = 0$$

Only one injected mod

→ Only need one purity

(no correlations)



1x1 purity binning

False Asymmetry Injection Studies

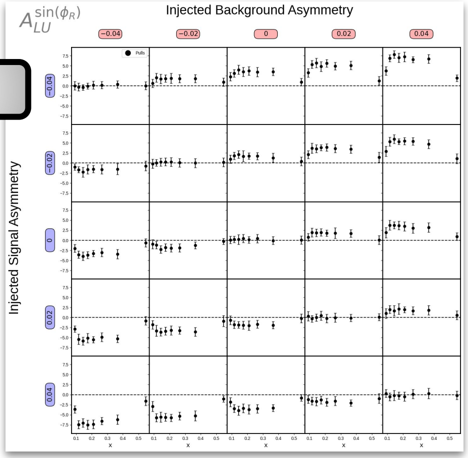
- ★ In the extreme case, simultaneously inject all mods. **(Case B)**

$$A_{\text{all}}^{\text{sig,bkg}} \in [-0.04, -0.02, 0, 0.02, 0.04]$$

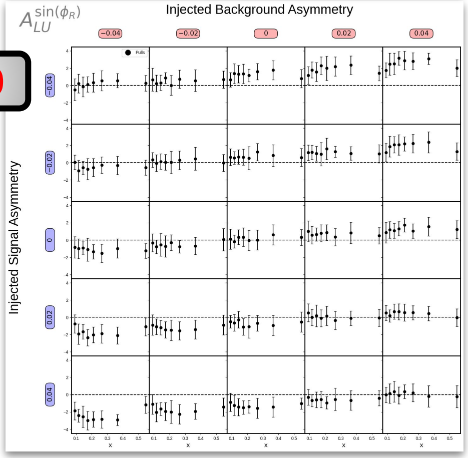
- ★ In the **1x1** purity binning case, the average pull across many trials climbs to ~ **5-8**
- ★ In the **10x10** purity binning case, the average pull across many trials climbs to ~ **2-3**
- ★ We find that purity binning is *more important* when the **signal** and **background** asymmetries are farther apart
  - ○ In the analysis note, **signal** and **background** asymmetries are compared. They at most have ~ **0.02** separation which purity binning cleans up

We assign a systematic error based on the choice of the purity binning scheme later

1x1



10x10



Monte Carlo Injection Analysis Slides **(Analysis Note Review)**

Injection Analysis — *Addressing GBT vs. Legacy*

- **Observation**: Monte Carlo studies with *Legacy cuts* show that simultaneous asymmetry injections do not cause significant pulls in the extracted asym.
  - Why does this happen with the GBT analysis?
- **Solution**: As argued in the analysis note, if the "purity X modulation$_i$" $u(\phi_H, \phi_R)\Psi_i$ correlates with "purity X modulation$_j$" $u(\phi_H, \phi_R)\Psi_j$ then they affect one another when simultaneously injected

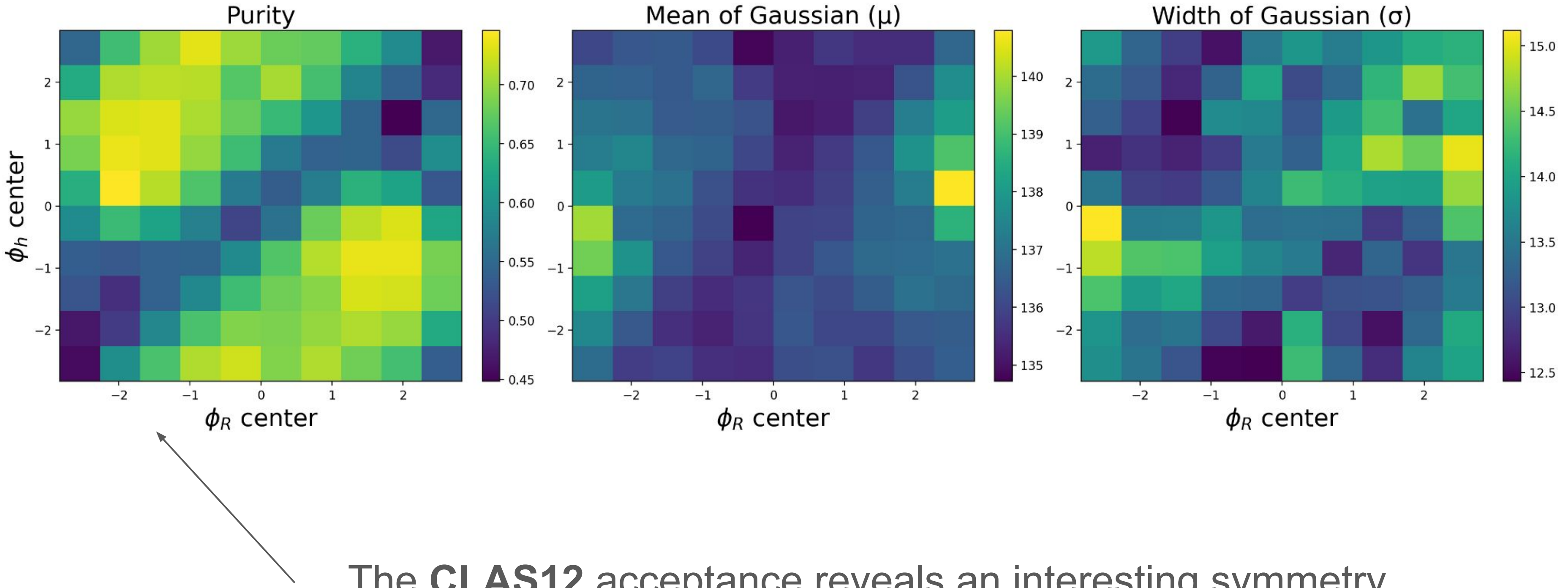
→ Interestingly, the legacy purity $u(\phi_H, \phi_R)$ is far less symmetric than the GBT purity $u(\phi_H, \phi_R)$. There are *still* false photons in the legacy analyses, so the ϕ_H, ϕ_R distribution is more "smeared" and "uncorrelated". Without a clear correlation, the pulls shouldn't affect one another, as observed.

Procedure

1. Using Monte Carlo simulated data calculate purity ***u(ϕ***$_H$ ***, ϕ***$_R$***)*** in NxN bins
2. Create toy $\pi^+\pi^0$ data
    a. Randomly generated phi variables
    b. Inject a +0.04 signal asymmetry and -0.04 background asymmetry for all 7 modulations
    c. Using the Monte Carlo purity table, generate a ϕH , ϕR dependent $M_{\gamma\gamma}$ spectrum
3. Use the *same* maximum-likelihood analysis method to extract the injected asymmetries (no variable smearing). Only use **1** purity bin when extracting

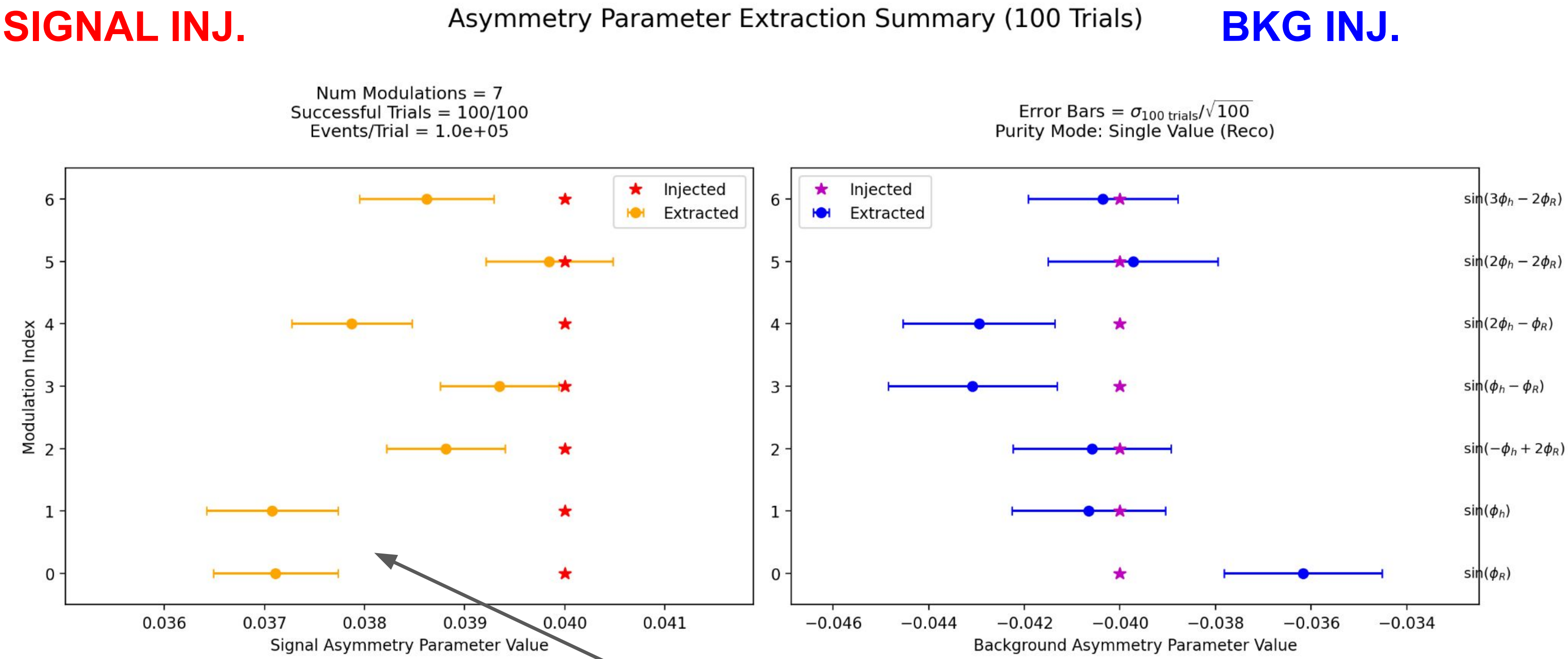
Hypothesis: Since the toy model extraction results for **legacy purity** and **GBT purity** will *only* be dependent on their ***u(ϕ***$_H$ ***, ϕ***$_R$***)*** binning, a systematic difference in the extraction performance ***must*** be connected to it.

purity binning gbt cuts



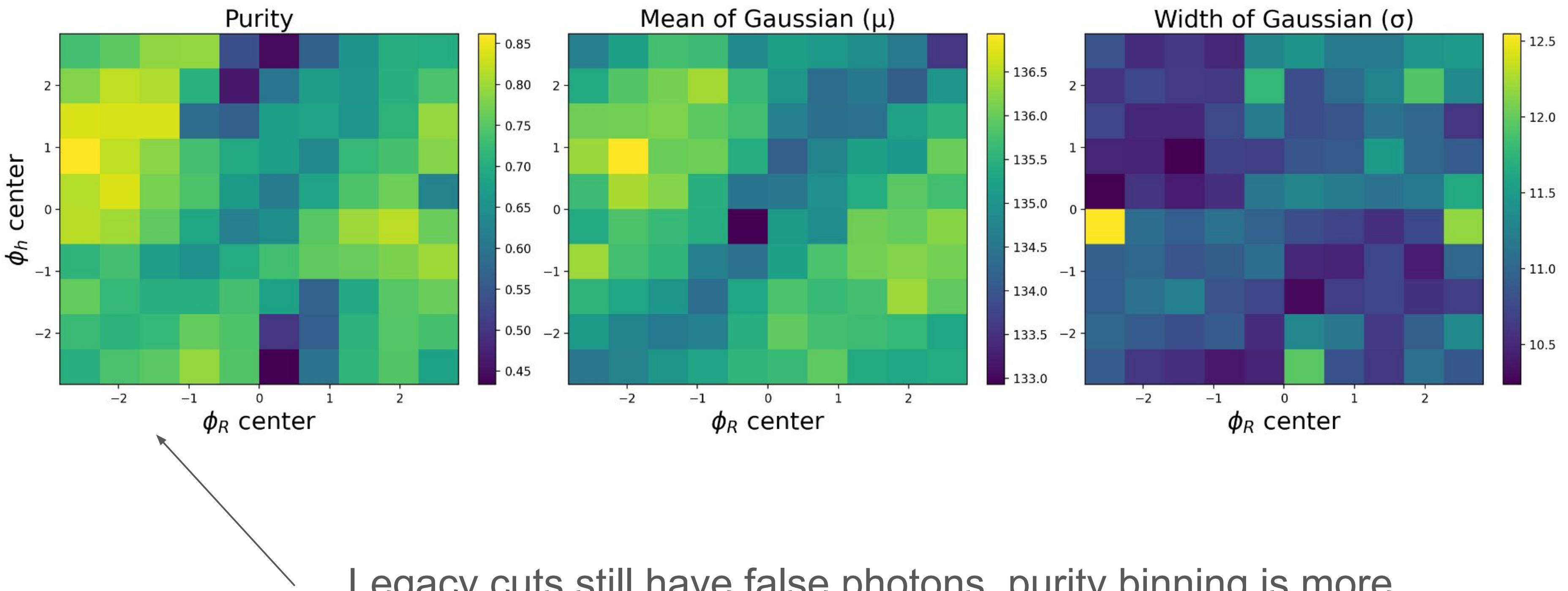
The **CLAS12** acceptance reveals an interesting symmetry along phiH=phiR for the $M\gamma\gamma$ distribution.

Results of using the gbt purity binning



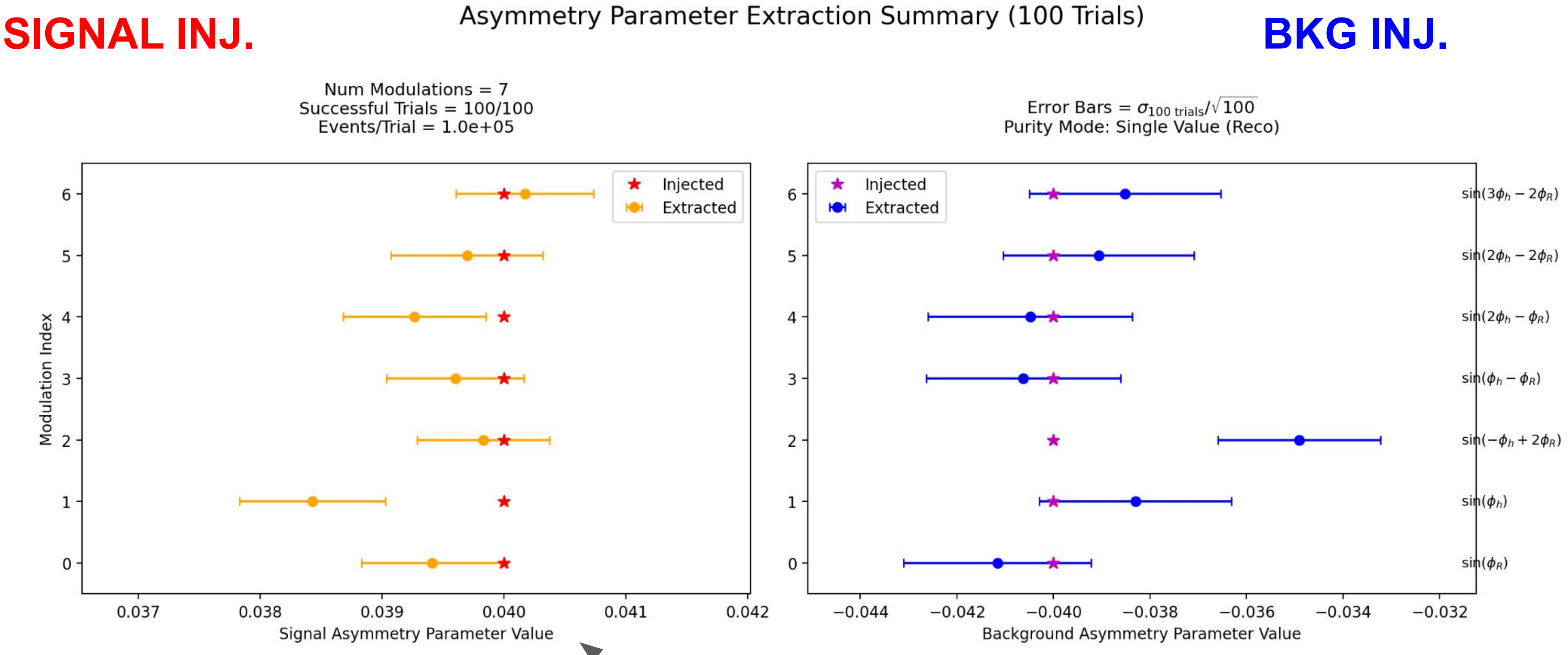
Huge pulls seen in, ex: sin(phi) asymmetries

purity binning legacy cuts



Legacy cuts still have false photons, purity binning is more smeared (less physical), but *some* correlation still.

Results of using the legacy purity binning



Pulls are much more in line with +/- 1 StD Dev

Conclusion

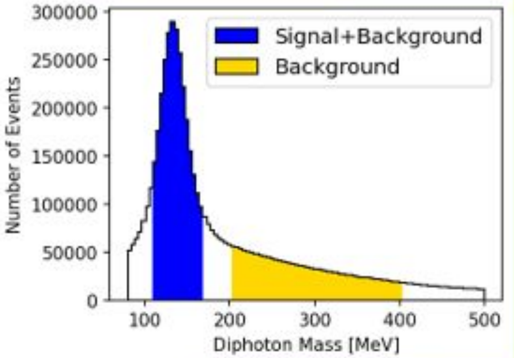
- With CLAS12 acceptance, the true phi-dependent purity **u(ϕH , ϕR)** contains sharp symmetries which affect the pulls of simultaneously injected asymmetries

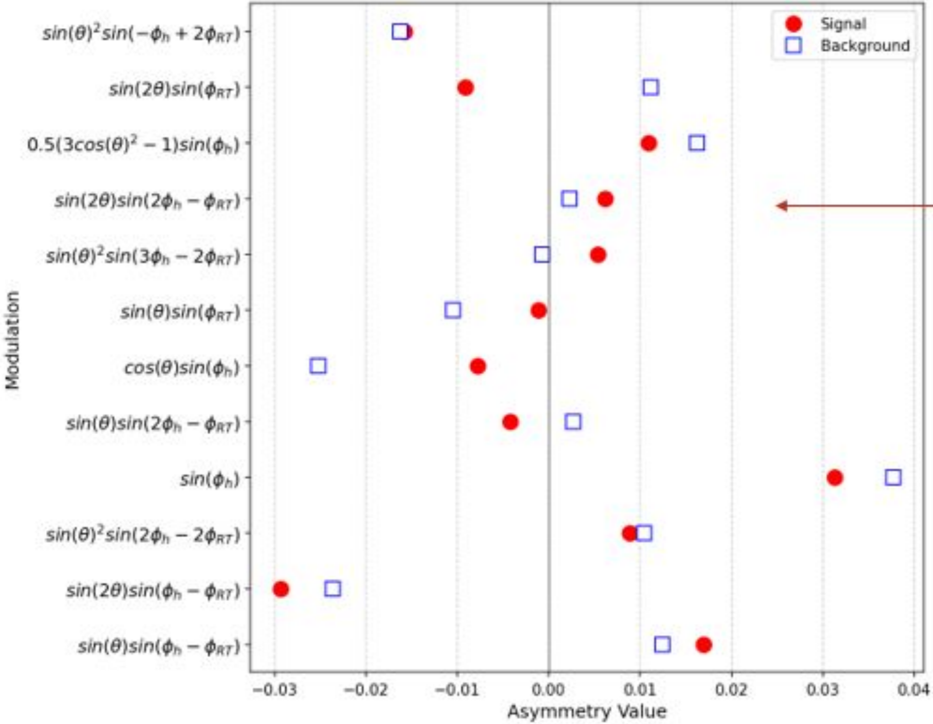
- The legacy purity **u(ϕH , ϕR)** does not have nearly as sharp a symmetry as the GBT purity, which we expect to better represent the actual SIDIS events

An asymmetry extraction toy model was put together with the purity binning as the **only independent** variable, validating our hypothesis.

π^0 sideband subtraction

- Combinatorial background asymmetry (sideband) is close to signal asymmetry for most modulations (shown below for $\pi^+\pi^0$)





Fully-integrated results

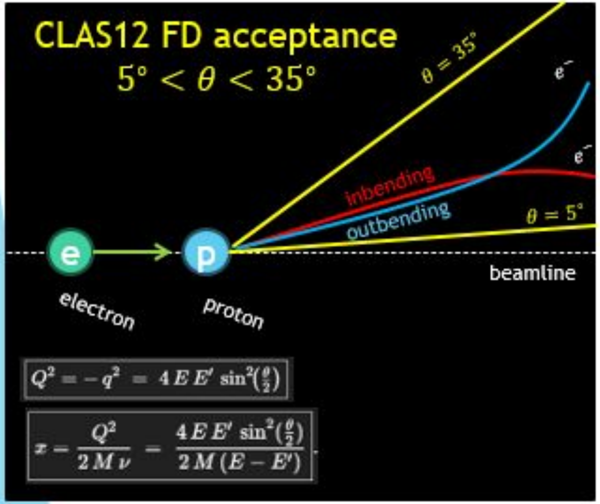
(no x, Mh, z binning)

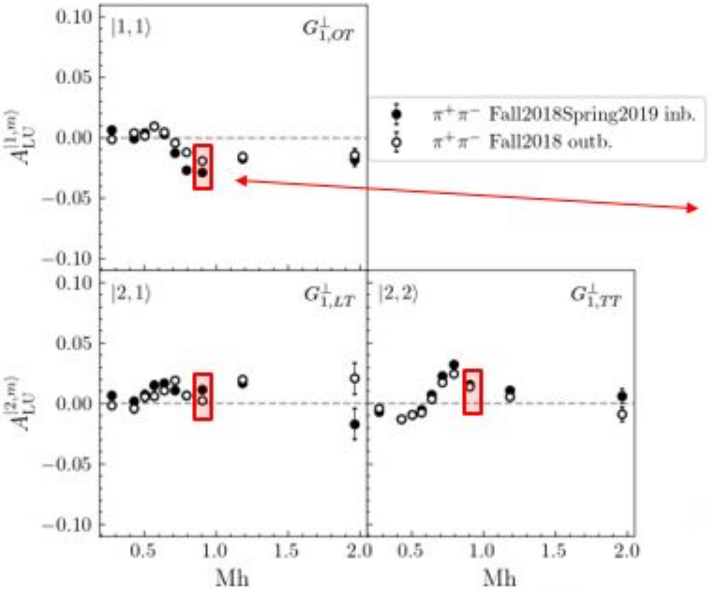
How can we explain why some modulations have a vastly different background asymmetry, while some are nearly identical?

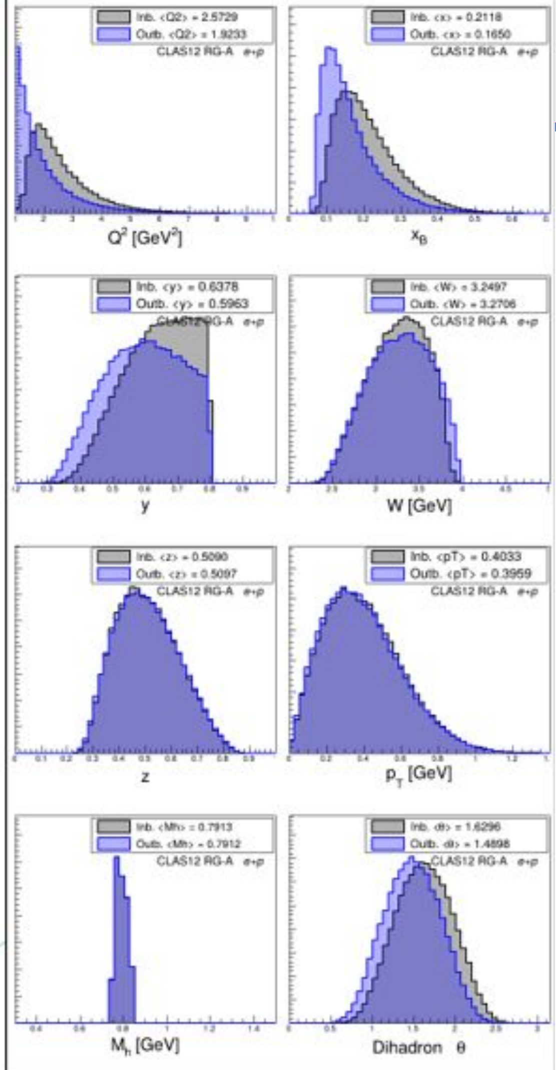
CLAS12 Inbending vs. Outbending

- CLAS12's toroidal magnet polarization effects charged particle acceptance
  - *Inbending → Negatively charged particles bent towards beamline*
- Mainly effects electron acceptance (x, Q^2, y) → different $PDF(x), D(y)$
  - Also seems to effect θ for some bins, could explain differences in some PW's?

Inbending Field ●
Outbending Field ○







$\pi^+\pi^-$ Twist-3

CLAS12 Run Group A vs. B

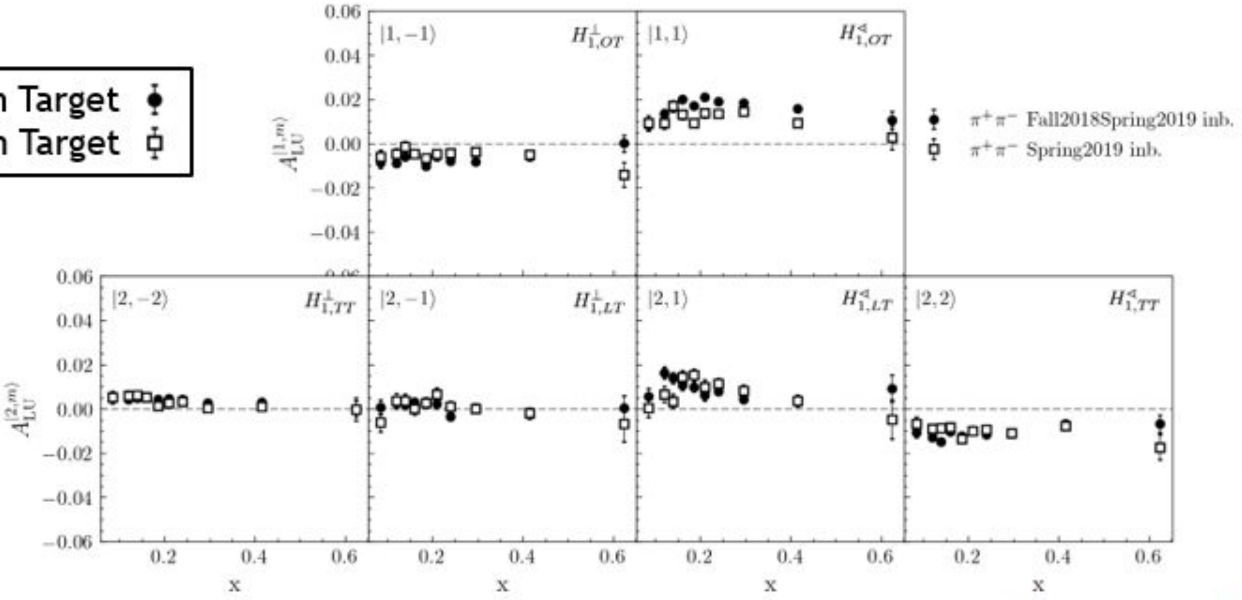
- Existing data at CLAS12 may be enough to disentangle flavor composition of $e(x)$
  - We observe a slightly smaller signal in twist-3 |1,1> BSA

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

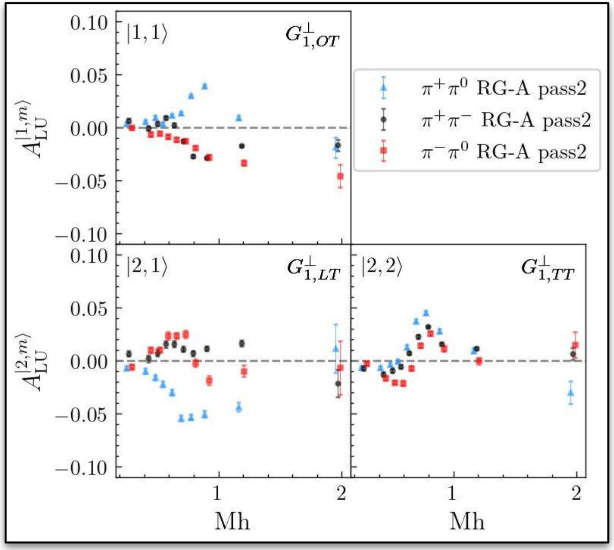
$$A_{LU,\mathbf{d}}^{\text{twist }3} \propto xe^{u_V}(x) + xe^{d_V}(x)$$

$e \otimes H_1^{\perp}$

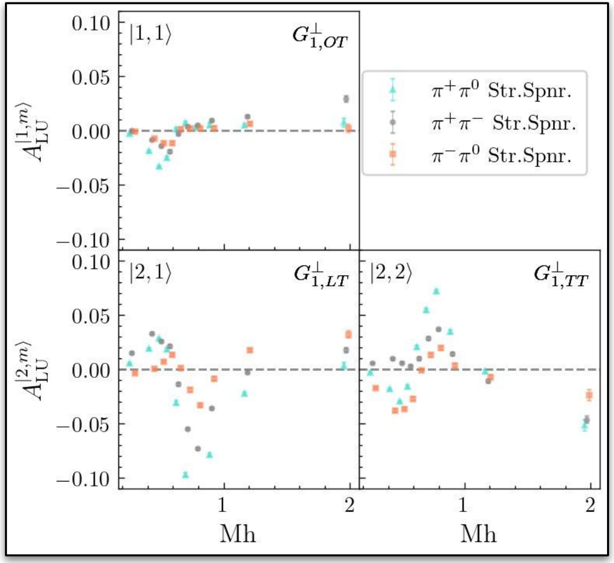
Proton Target ●
Deuteron Target □



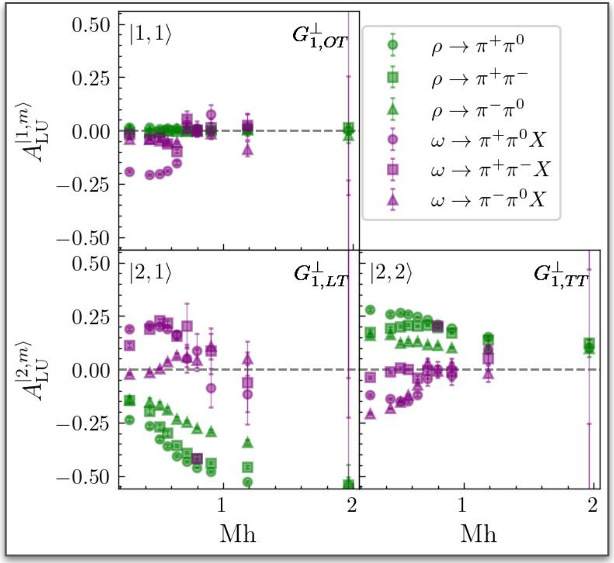
Contributions of VM's to Partial Waves



CLAS12



StringSpinner

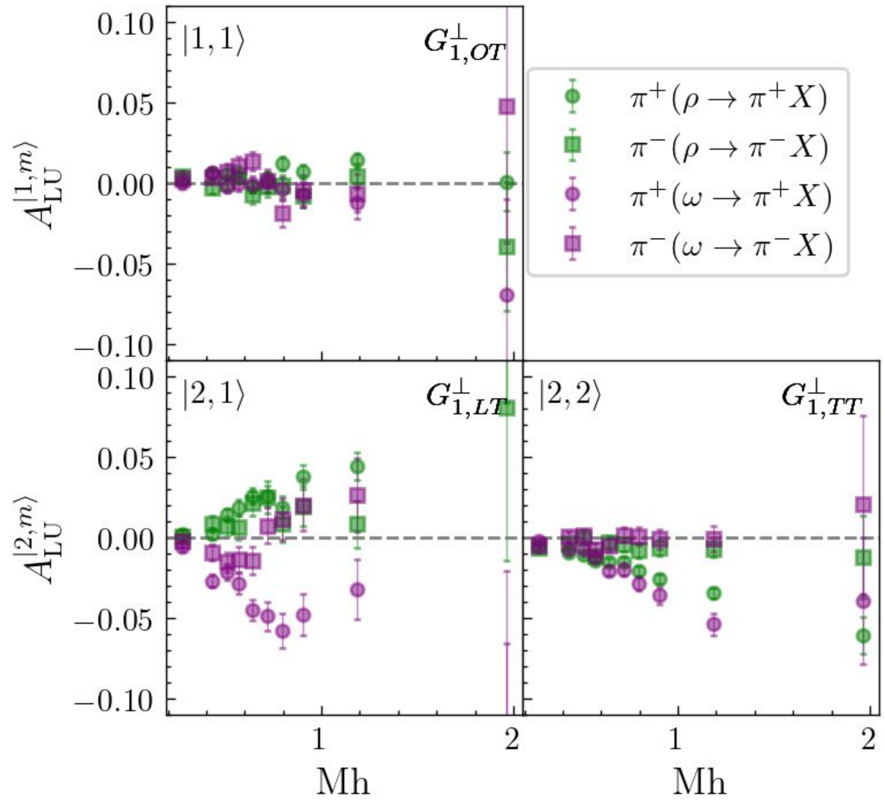


StringSpinner VM's

VM Origin's of Like-Pion Partial Waves

Premise: VM decays only one of the pions (other *can* come from a VM, but not the same)

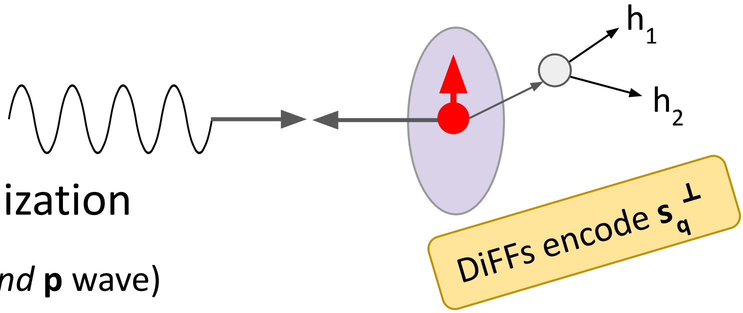
Looks as if coincidenting on the ω can generate asymmetries in like-pion pairs



Dihadron Production

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

- Dihadron SIDIS production cross section: $\sigma = \hat{\sigma} \otimes \mathrm{PDF} \otimes \mathrm{DiFF}$
- **(PDFs)** Probe quark-gluon dynamics in proton
  - Twist-3 PDF e(x) directly accessible without p_T convolutions
  - e(x) related to forces between quarks and gluons and $\sigma_{\pi N}$



- **(DiFFs)** Probe more complex correlations in hadronization
  - Interference Fragmentation Functions (h_1h_2 produced in **s** *and* **p** wave)
  - Impact of quark polarization on hadronization
  - Comparing different pion channels (ex: $\pi^+\pi^-$ and $\pi^+\pi^0$) → compare with theory
  - Separate Resonant production (ρ^0 , $\rho^{+/-}$) vs. Non-Resonant fragmentation

Systematic Error (1/6) Beam Polarization

★ Uncertainty does not depend on the kinematic bin or the modulation studied

$$\frac{\sigma_{A_{\text{true}}}}{A_{\text{true}}} = \frac{\sigma_P}{P}$$

★ 2% systematic error in the reported polarization assumed

★ For $\pi^+\pi^0$ we use the Total Inbending, for $\pi^+\pi^0$ we use the Fall2018 Outbending

Run Period	Beam Polarization	Number of Triggers	$\Delta A_{LU}/A_{LU}$
Fall 2018 Inbending	$85.92\% \pm 1.29\% \pm 2\%$	$1.04e^{10}$	2.8%
Fall 2018 Outbending	$89.22\% \pm 2.509\% \pm 2\%$	$1.346e^{10}$	3.6%
Spring 2019 Inbending	$84.53\% \pm 1.474\% \pm 2\%$	$1.262e^{10}$	2.9%
Total RG-A Inbending	$85.16\% \pm 1.7\% \pm 2\%$	$2.302e^{10}$	3.1%

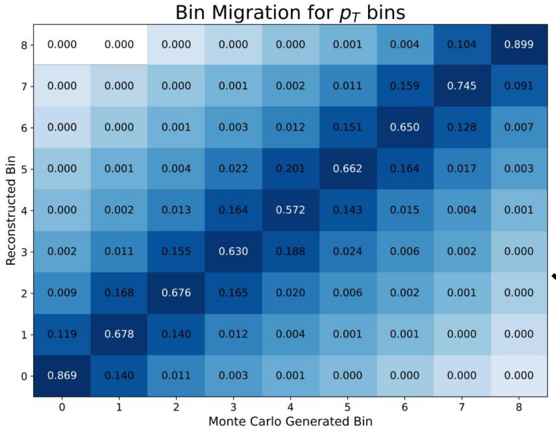
TABLE 18: Collection of beam polarizations for the RG-A experiment and their impact on the extracted BSA uncertainties.

Systematic Error (2/6) Bin Migration

★ Relative uncertainty depends on the kinematic bin studied and modulation #

$$\Delta A_i = \sum_{k=1}^{K} \left(f_{i+k,i} A_{i+k} + f_{i-k,i} A_{i-k} - f_{i+k,i} A_i - f_{i-k,i} A_i \right)$$

Error in bin "i" Asymmetries leaking into bin "i" Asymmetry leaking out of bin "i"



Bin 0: $0.00 < p_T < 0.18$ Bin 1: $0.18 < p_T < 0.25$
Bin 2: $0.25 < p_T < 0.32$ Bin 3: $0.32 < p_T < 0.38$
Bin 4: $0.38 < p_T < 0.43$ Bin 5: $0.43 < p_T < 0.50$
Bin 6: $0.50 < p_T < 0.57$ Bin 7: $0.57 < p_T < 0.68$
Bin 8: $0.68 < p_T < 1.82$

★ $f_{i,j}$ → fraction of reconstructed events in bin "i" that were generated in bin "j"

Modulation	p_{T0}	p_{T1}	p_{T2}	p_{T3}	p_{T4}	p_{T5}	p_{T6}	p_{T7}	p_{T8}
$\sin(\phi_R)$	0.0032	0.041	0.021	0.029	0.018	0.06	0.15	0.0062	0.015
$\sin(\phi_h)$	0.089	0.0088	0.027	0.012	0.1	0.064	0.022	0.043	0.034
$\sin(-\phi_h + 2\phi_R)$	0.11	0.015	0.013	0.017	0.07	0.07	0.0071	0.063	0.057
$\sin(\phi_h - \phi_R)$	0.46	0.057	0.12	0.049	0.1	0.036	0.075	0.033	0.029
$\sin(2\phi_h - \phi_R)$	0.19	0.098	0.53	0.097	0.47	0.14	0.14	0.055	0.034
$\sin(2\phi_h - 2\phi_R)$	0.0094	0.26	0.05	0.038	0.049	0.078	0.048	0.02	0.055
$\sin(3\phi_h - 2\phi_R)$	0.016	0.036	0.012	0.017	0.51	0.25	0.041	0.0066	0.026

$\Delta A/A$ for $\pi^+\pi^0$ binned in p_T

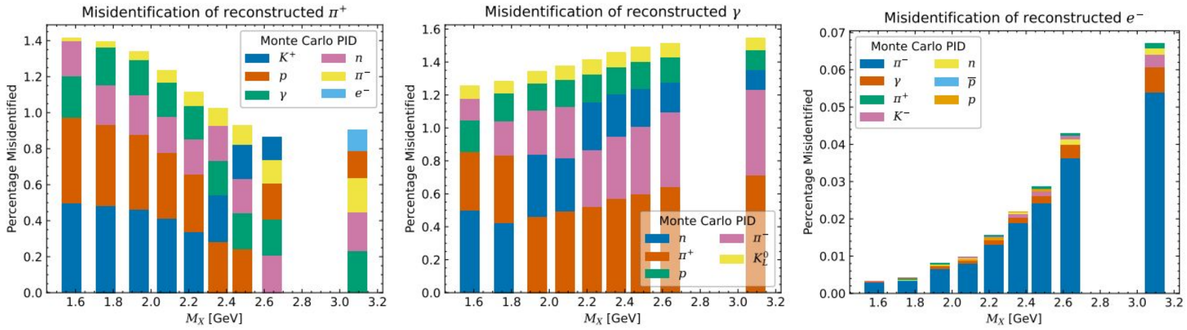
CLAS Co

Systematic Error (3/6) Particle Misidentification

- ★ Relative uncertainty depends on the kinematic bin studied
- ★ Assumes that the fractional asymmetry from misidentified events is much less than that of correctly identified events

$$\frac{\Delta A}{A} = \frac{f_m}{1 - f_m}$$

- ★ f_m → fraction of events with a misidentified e, γ, or π



(a) False π^+'s (b) False γ's (c) False e^-'s

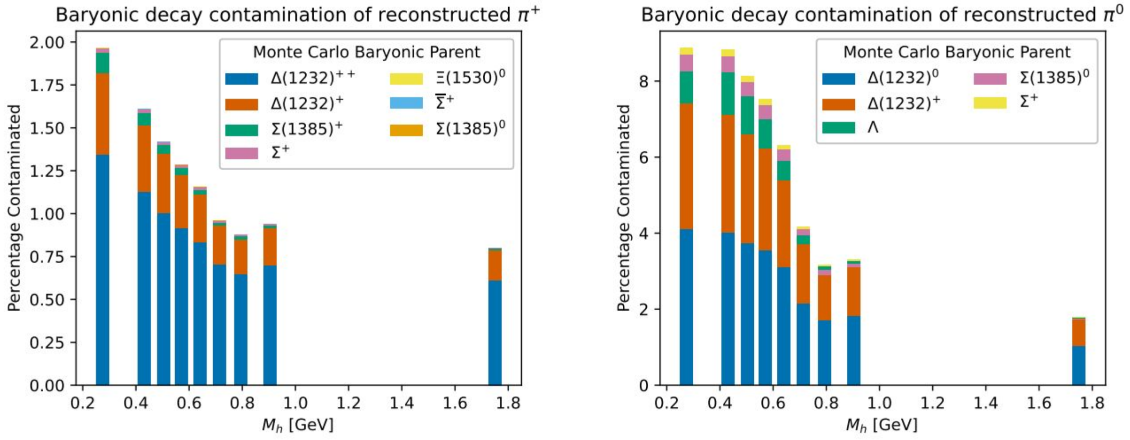
FIG. 138: Particle misidentification percentages for $\pi^+\pi^0$ dihadrons, binned in M_X.

Systematic Error (4/6) Baryon Decays

- ★ Relative uncertainty depends on the kinematic bin studied
- ★ $ep \to e\pi^{\pm}\pi^{0}X$ where either π originates from a baryon's decay is background
- ★ Assumes that the fractional asymmetry from baryonic decays is much less than that from traditional fragmentation

$$\frac{\Delta A}{A} = \frac{f_b}{1 - f_b}$$

- ★ f_b → fraction of events where one or more of the pions originated from a baryon's decay

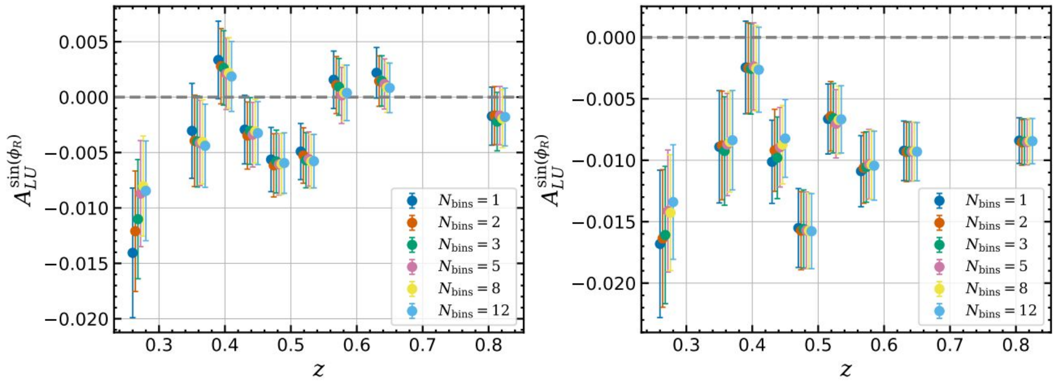


(a) Parents of π^+'s (b) Parents of π^0's

FIG. 144: Percentanges of baryonic parents for $\pi^+\pi^0$ dihadrons, binned in M_h.

Systematic Error (5/6) Purity Binning

- ★ Relative uncertainty depends on the kinematic bin studied and modulation
- ★ The choice of how many bins to subdivide (ϕ_h, ϕ_R) can have a slight impact on the asymmetry extracted
- ★ Estimate the systematic by taking half the range across multiple options



(a) $\pi^+\pi^0$ dihadron pairs

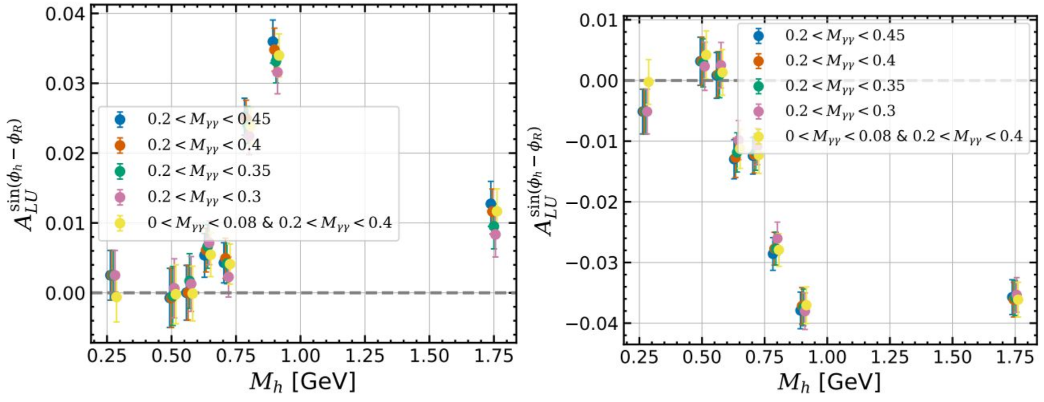
(b) $\pi^-\pi^0$ dihadron pairs

FIG. 208: $A_{LU}^{\sin(\phi_R)}$ results for changing the number of rows and columns in the u(ϕ_h,ϕ_R) purity binning scheme, binned in z.

In this hand-picked example, the purity binning has a notable impact at low **z**, with nearly an error bar of separation between a **1x1** and **8x8** grid

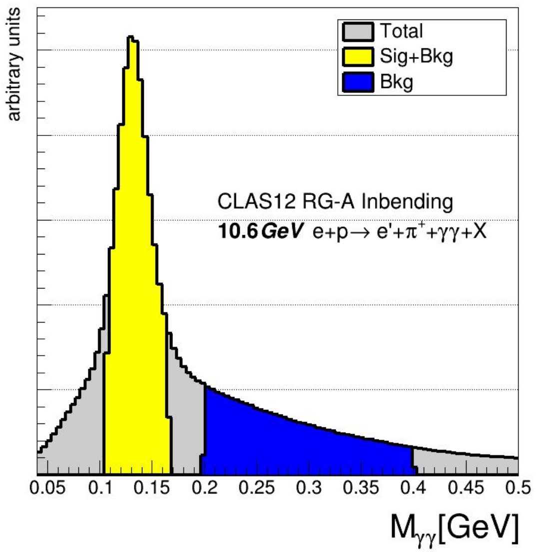
Systematic Error (6/6) Sideband Region

- ★ Relative uncertainty depends on the kinematic bin studied and modulation
- ★ The choice of where to define the "**background**" (a.k.a sideband) region may have a non-negligible impact on the $\mathbf{A^{bkg}}$ and therefore $\mathbf{A^{sig}}$ extracted
- ★ Estimate the systematic by taking half the range across multiple options



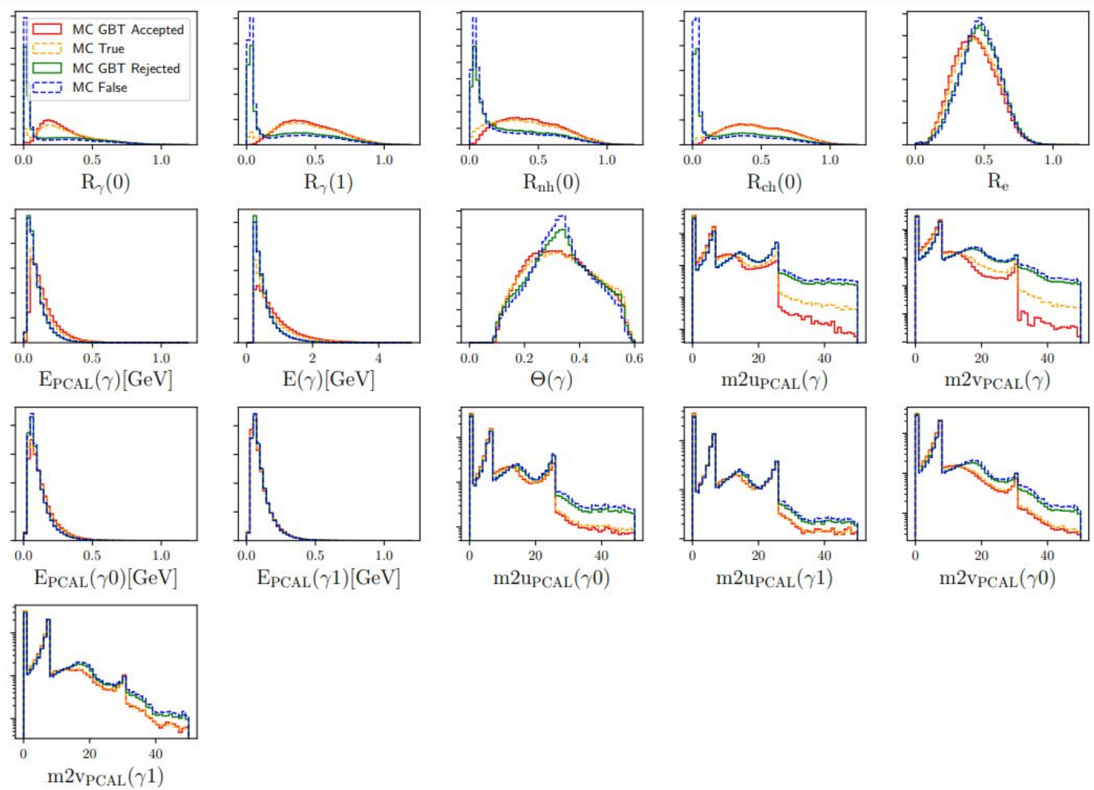
(a) $\pi^+\pi^0$ dihadron pairs (b) $\pi^-\pi^0$ dihadron pairs

FIG. 260: $A_{LU}^{\sin(\phi_h-\phi_R)}$ results for changing the definition of the $M_{\gamma\gamma}$ sideband region(s) for the background asymmetries, binned in M_h.



Input Features (Monte Carlo Inbending)

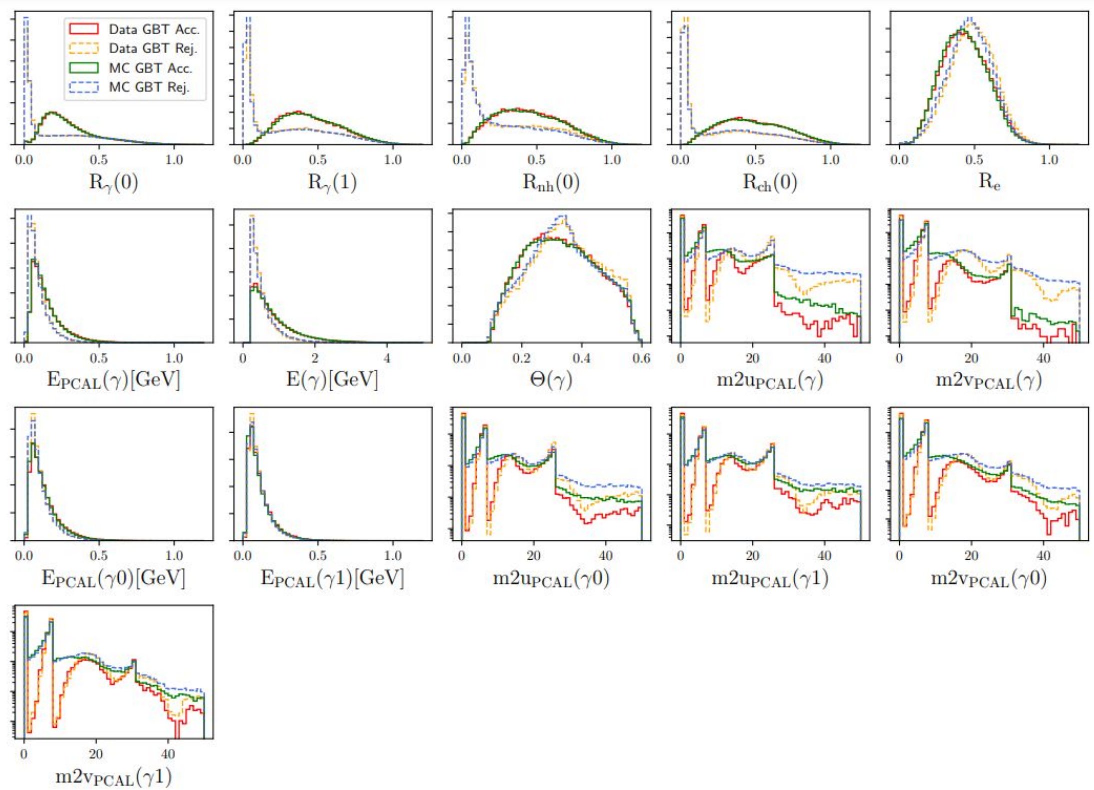
R_n(#) → Angle between nearest "#" neighbor and photon of interest



...

Input Features (Monte Carlo vs Data)

R_n(#) → Angle between nearest "#" neighbor and photon of interest



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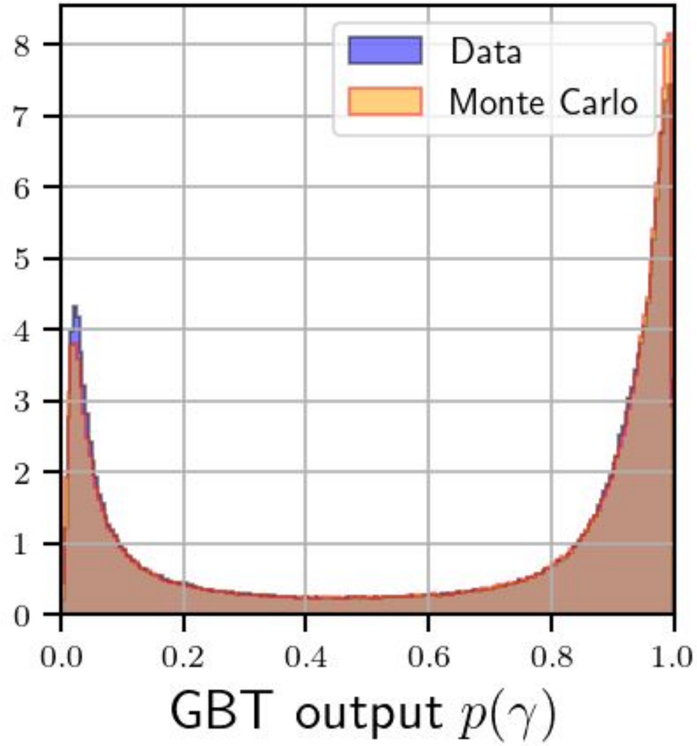
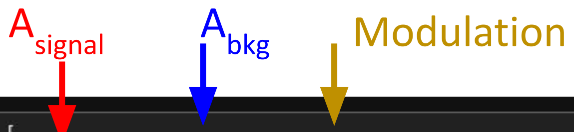
GBT Output



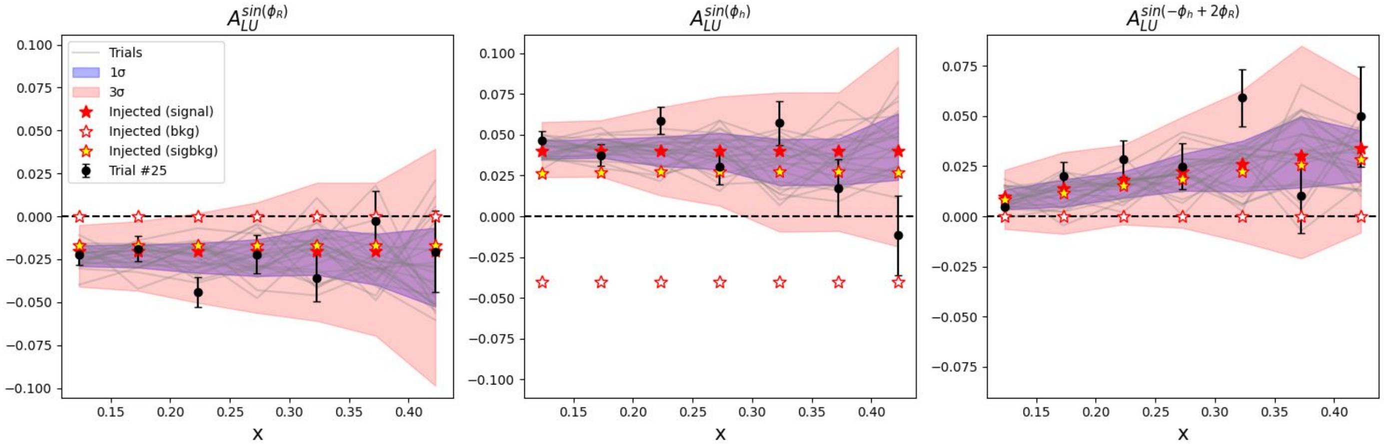
- ★ For each photon in **data** and **Monte Carlo** we histogram the GBT output value
  - We see that the aggregate outputs are *very similar* → indicates that the feature spaces are very similar
- ★ Results speaks to our confidence that the predictions made on data <u>can be trusted</u>

Example Injection (3 modulations)



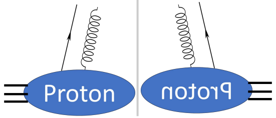

```
injector.load_weight_funcs( [
                           ["-0.02"    , "-0.00", "sin(:phi_R0:)"] ,
                           ["0.04"     , "-0.04", "sin(:phi_h:)"],
                           ["0.08*:x:",  "0.00", "sin(-:phi_h:+2*:phi_R0:)"],
                          ])
```

```
injector.addSideband("signal+bkg",0.115,0.15)
injector.addSideband("bkg",0.24,0.4)
```



The Twist-3 PDF *e(x)*

- ➢ Quark-gluon interactions play a significant role in describing the proton
  - Encoded in higher twist PDFs such as *e(x)*
  - Interference of coherent scattering of *qg* pair
  - We rely on quark-gluon interactions to manifest proton spin and mass



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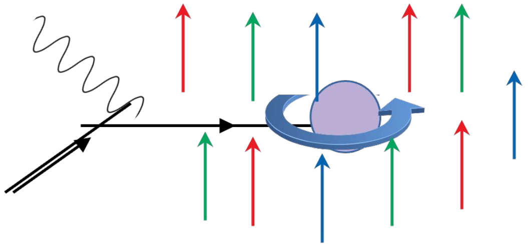

- ➢ *e(x)* is better understood through its moments
  - x^2 moment sensitive to transverse force experienced by transversely polarized quark in a transversely polarized *N* [1]

★ **QUESTION:** *"Why study 2-hadron SIDIS?"* ★

★ **ANSWER:** In the dihadron BSA, *e(x)* appears without transverse momentum-dependence! ★

$$d^7\sigma_{LO} = \frac{\alpha^2}{2\pi Q^2 y}\lambda \sum_a e_a^2 W(y) \sin\phi_R \frac{|\vec{R}_T|}{Q}\left[\frac{M}{M_h} x\, e(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x)\, \widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)\right]$$

★ This is not the case in 1-hadron SIDIS — e(x) extraction requires TMD modeling *and* appears in a structure function with 4 PDF⊗FF pairs ★