Back-to-back proton-pion asymmetries

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UCONN

Fracture Functions

- Information on the momentum distribution of quarks and gluons are encoded in TMDs that are measured in inclusive processes such as SIDIS.
- TMDs can be studied via azimuthal modulations of a final state hadron generated in the fragmentation of a struck quark (CFR).
- Final state hadrons can also form from the left-over target remnant (TFR) whose partonic structure is defined by “fracture functions”: the probability to form a certain hadron given a particular ejected quark.

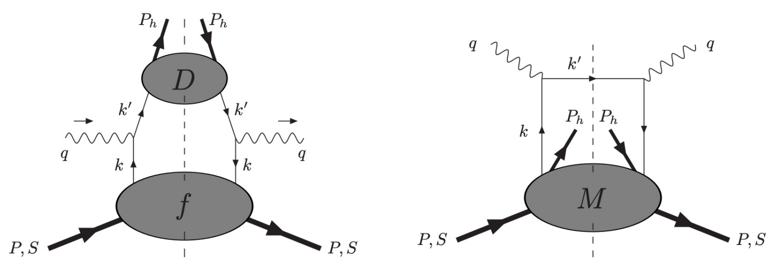


Figure 1: The handbag diagram for the SIDIS hadronic tensor in the current fragmentation region (left) and in the target fragmentation region (right).

	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

Phys. Lett. B. 699 (2011), 108-118, [hep-ph] 1102.4214

Back-to-back Formalism

$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2}\,\mathcal{C}\left[\boxed{w_5\,\hat{l}_1^{\perp h} D_1}\right],$$

$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\boxed{\sin\Delta\phi}$$

Phys. Lett. B. 713 (2012), 317-320, [hep-ph] 1112.2604

- When two hadrons are produced “back-to-back” with one in the CFR and one in the TFR the structure function contains a convolution of a fracture function and a fragmentation function.

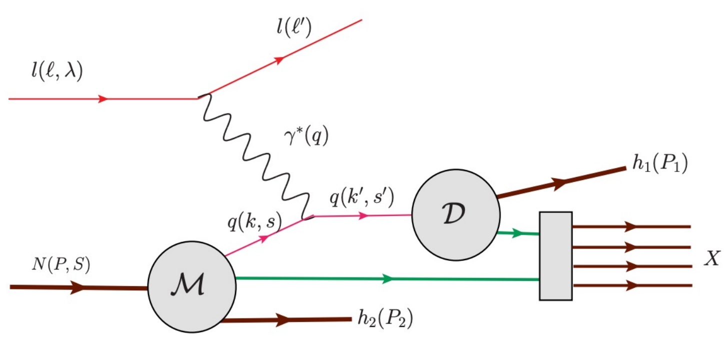


Figure 1: Lepto-production of two hadrons, one in the CFR and one in the TFR.

Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

Extra Modulations

$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}\boxed{\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}}\sin\Delta\phi$$
$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2}\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}$$
$$\times \frac{\mathcal{C}[w_5\,\hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}\sin\Delta\phi,$$

Structure functions can carry a dependence on $P_1^\perp P_2^\perp$ which introduces a dependence on $\cos\Delta\phi$

$$\hat{l}_1^{\perp h}(x_B,\zeta_2,\mathbf{k}_\perp^2,\mathbf{P}_{2\perp}^2,\mathbf{k}_\perp\cdot\mathbf{P}_{2\perp})$$
$$\simeq a(x_B,\zeta_2,\mathbf{k}_\perp^2,\mathbf{P}_{2\perp}^2)$$
$$+\,b(x_B,\zeta_2,\mathbf{k}_\perp^2,\mathbf{P}_{2\perp}^2)\boxed{\mathbf{k}_\perp\cdot\mathbf{P}_{2\perp}}.$$

If the correlations are assumed small, the fracture functions can be expanded in powers of $k^\perp \cdot P_2^\perp$

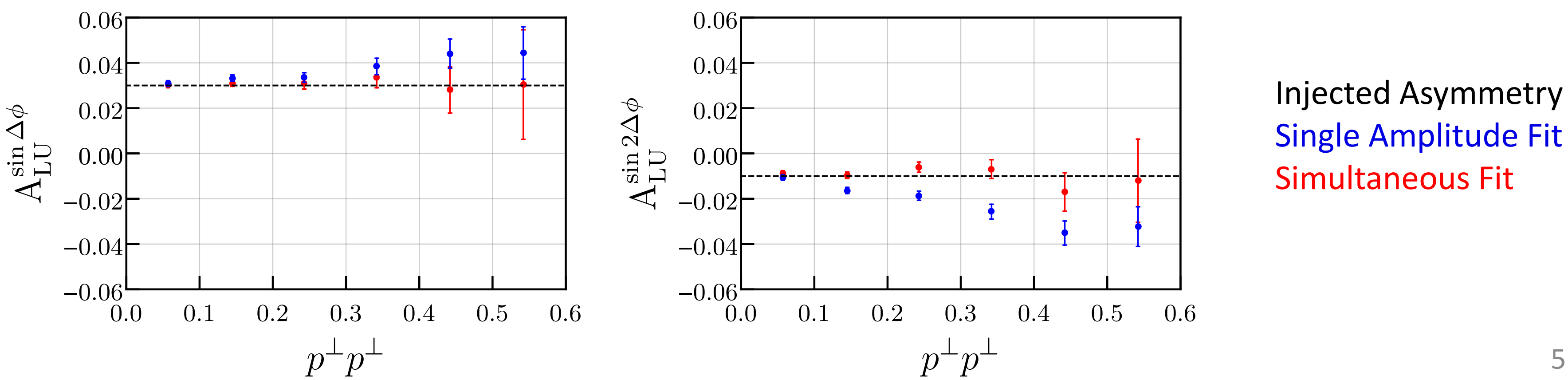
$$\mathcal{A}_{LU}(x_B,z_1,\zeta_2,\mathbf{P}_{1\perp}^2,\mathbf{P}_{2\perp}^2,\Delta\phi)$$
$$= A(x_B,z_1,\zeta_2,\mathbf{P}_{1\perp}^2,\mathbf{P}_{2\perp}^2)\,\sin\Delta\phi$$
$$+\,B(x_B,z_1,\zeta_2,\mathbf{P}_{1\perp}^2,\mathbf{P}_{2\perp}^2)\boxed{\sin(2\Delta\phi)}.$$

The term linear in $k^\perp \cdot P_2^\perp$ yields a $\cos\Delta\phi$ which when combined with the already existing $\sin\Delta\phi$ term results in a $\sin 2\Delta\phi$

Phys. Lett. B. 713 (2012), 317-320, [hep-ph] 1112.2604

Orthogonality of Modulations

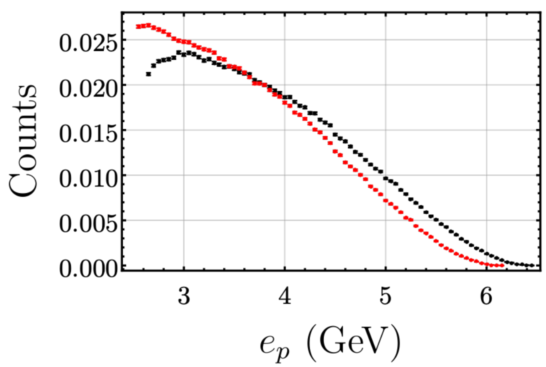
- In a perfect scenario each additional azimuthal modulation would be mutually orthogonal.
- Within the limited acceptance of CLAS12 this is not the case… the inner product between sin(Δφ) and sin(2Δφ) is approximately 0.3.
- Example from injected asymmetries:

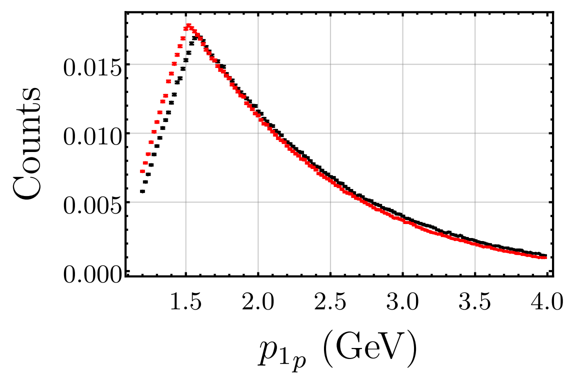


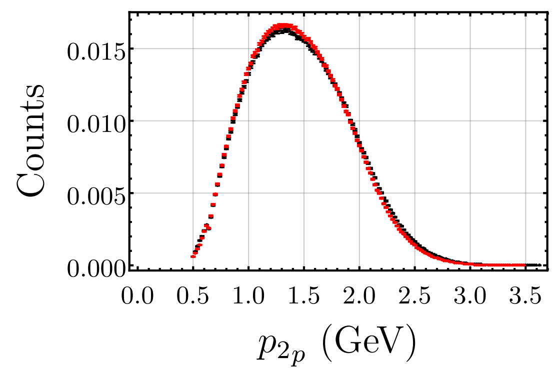
Data Sets

- Looking for final state: $e^{-} \pi^{+}$ P X
- Intend to use both RGA Fall2018 Inbending and Spring2019 Inbending pass1
  - "/cache/clas12/rg-a/production/recon/fall2018/torus-1/pass1/v0/dst/train/skim4/"
  - "/volatile/clas12/rg-a/production/recon/spring2019/torus-1/pass1/v1/dst/train/skim4/"
- Minor difference in beam energies: 10.6 vs 10.2 GeV respectively

Fall2018
Spring2019

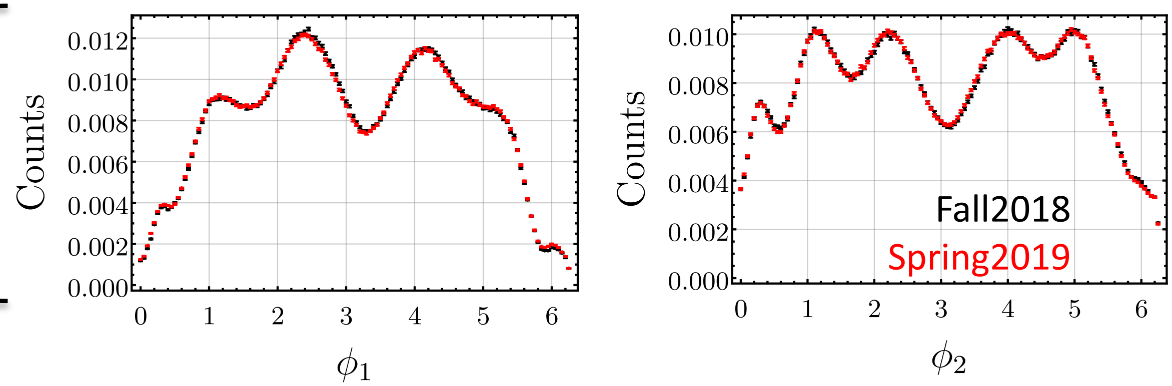


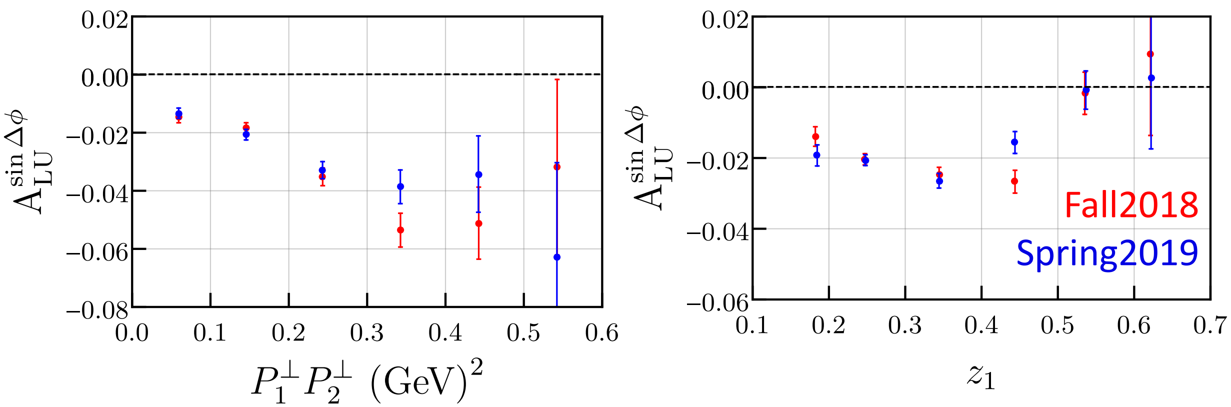




Comparing Run Periods

- Comparison of variables sensitive to the azimuthal modulations shows little difference.



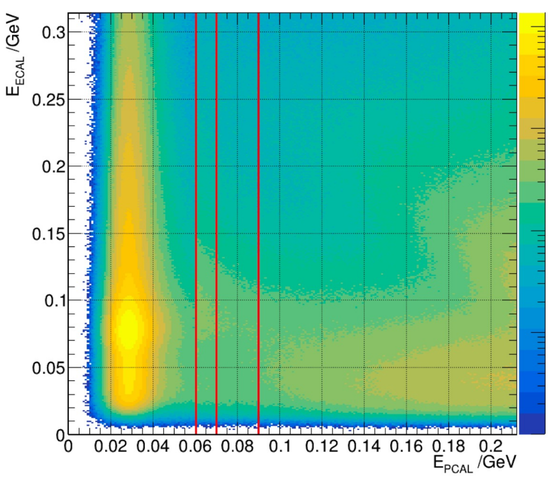


- Asymmetries are statistically consistent between run periods.

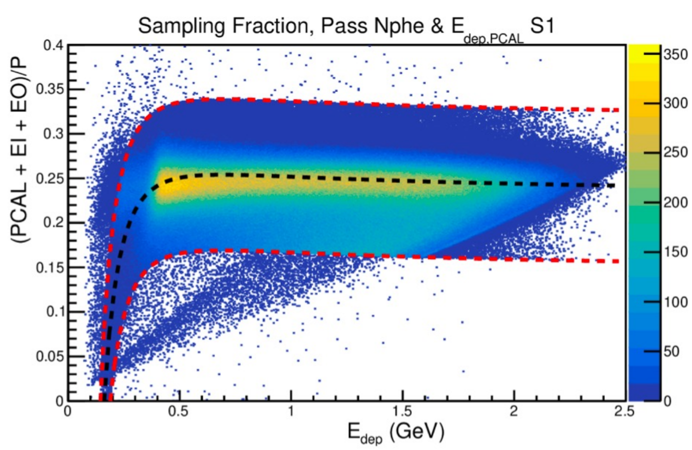
Data Analysis

- Same PID and fiducial cuts as dihadron PRL: eventBuilder plus “enhanced PID”.

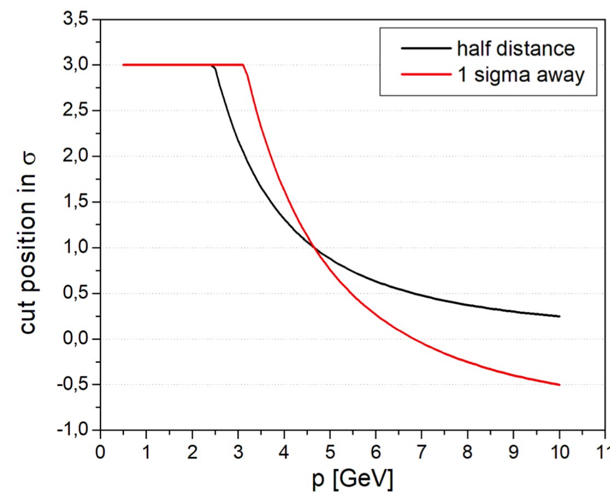
Increased cut on energy deposition in calorimeter.



Sector dependent sampling fraction cut.



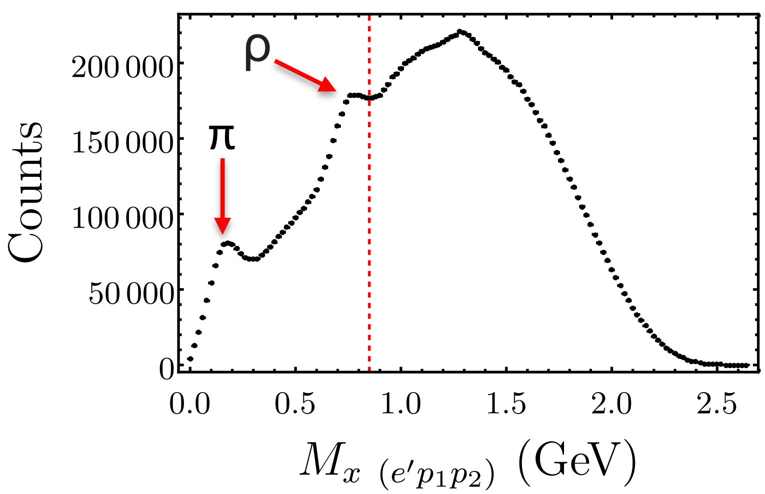
Momentum dependent chi2pid cut on hadrons.

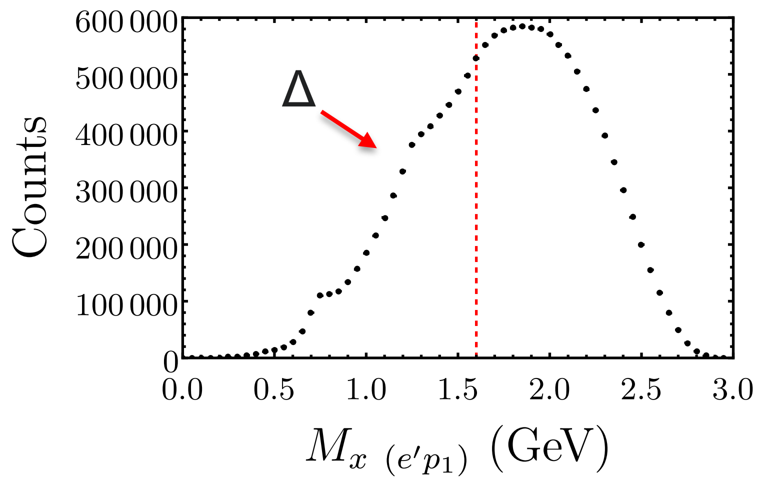


Kinematic Cuts: Exclusivity

- Remove exclusive events with cuts on the missing mass of multiple final states.
- $M_x(ep_1p_2) > 0.85$ GeV
- $M_x(ep_1) > 1.6$ GeV

p_1 = pion
p_2 = proton



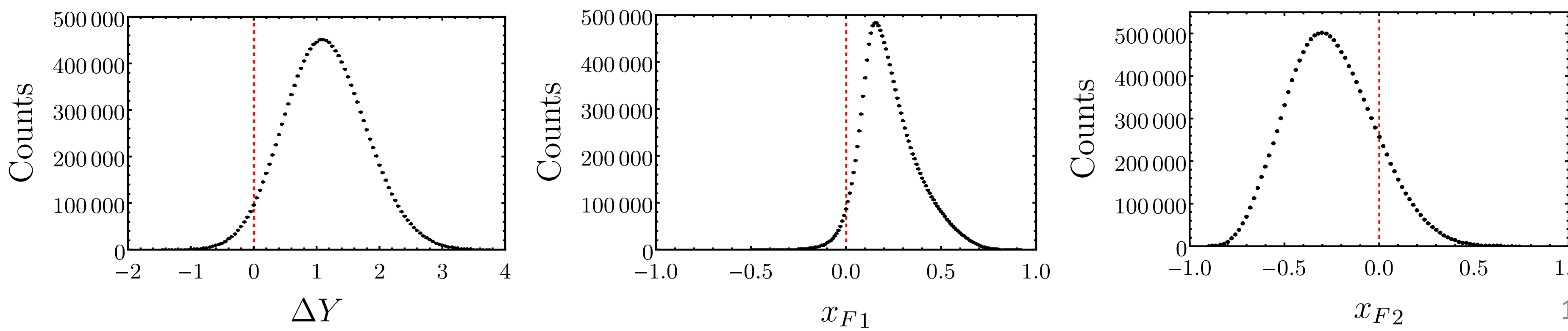


Kinematic Cuts: CFR/TFR

- Looking for a TFR proton and a CFR pion.
- Cuts on rapidity and Feynman-x. Consistent with dihadron PRL.
- $x_{F1} > 0$, $x_{F2} < 0$.
- $\Delta Y > 0$.

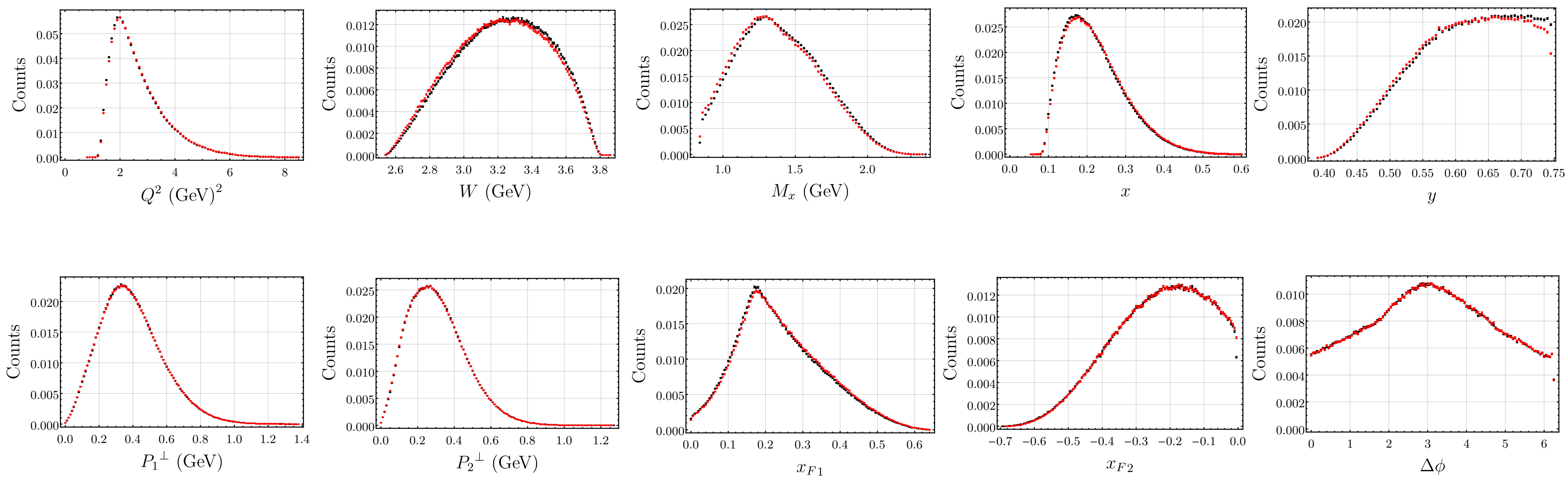
$$x_F = \frac{2p \cdot q}{|q|W}$$

$$Y = \frac{1}{2} \log \left[\frac{E_h + p_z}{E_h - p_z} \right]$$



Monte Carlo

- OSG mass produced clasdis for SIDIS analysis. Same as dihadron PRL.
- Excellent agreement between data and MC.



Data Monte Carlo

Maximum Likelihood Method

- A probability density function is created of the form

$$p_{\pm}(\Delta\phi; A_{LU}^{\Psi_i}) = 1 \pm P A_{LU}(\Delta\phi; A_{LU}^{\Psi_i})$$

where $A_{LU}^{\Psi_i}$ is the amplitude of the *i*th modulation of the asymmetries (Δφ, 2Δφ). A likelihood function is then built from the joint probabilities of each event:

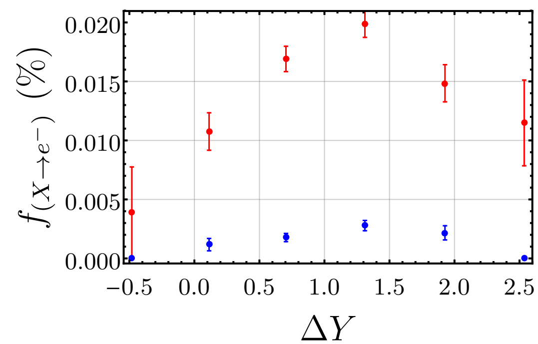
$$\mathcal{L} = \prod_{j=1}^{N_+} p_+(\Delta\phi; A_{LU}^{\Psi_i}) \prod_{j=1}^{N_-} p_-(\Delta\phi; A_{LU}^{\Psi_i})$$

It's computationally easier to minimize the negative log-likelihood:

$$-\ln\mathcal{L} = -\sum_{j=1}^{N^+} \ln\left[1 + P A_{LU}(\Delta\phi; A_{LU}^{\Psi_i})\right] - \sum_{j=1}^{N^-} \ln\left[1 - P A_{LU}(\Delta\phi; A_{LU}^{\Psi_i})\right]$$

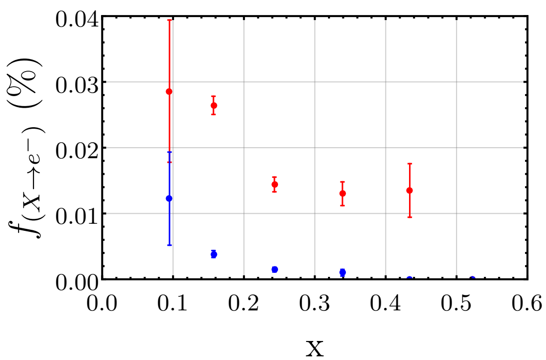
Systematic: Electron PID

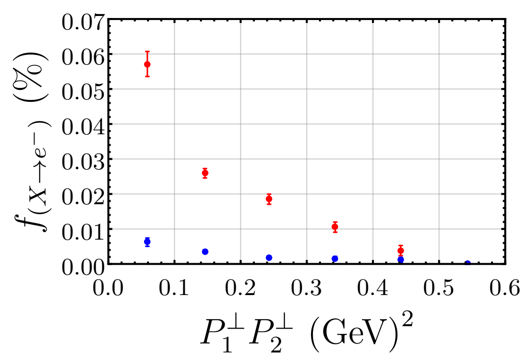
- Monte Carlo used to match reconstructed electrons with generated particles.
- Rate of contamination from pions and kaons appears negligible.

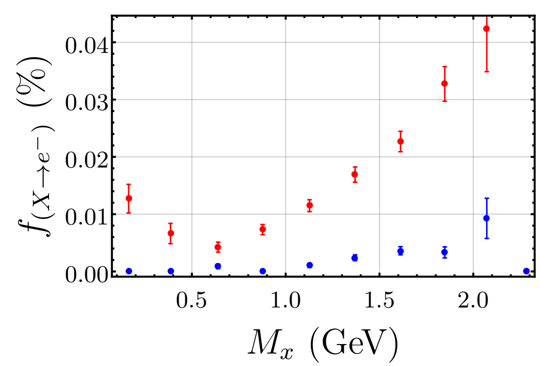


$\pi^- \rightarrow e^-$

$k^- \rightarrow e^-$

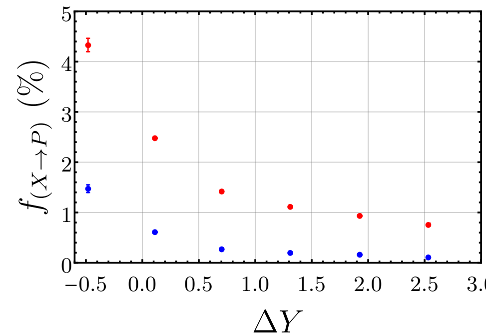






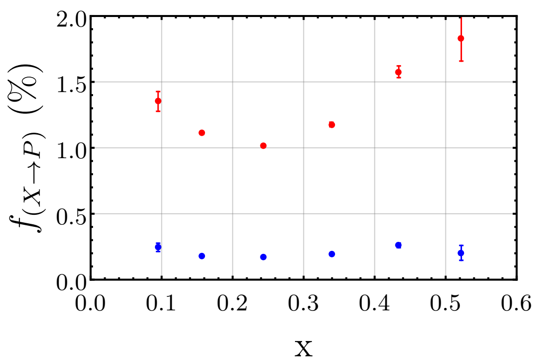
Systematic: Proton PID

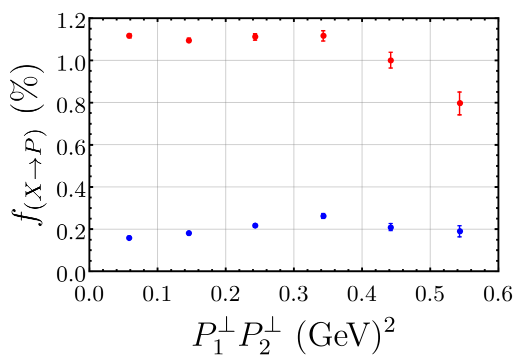
- Monte Carlo used to match reconstructed protons with generated particles.
- About 1% of protons appear to be misidentified pions.

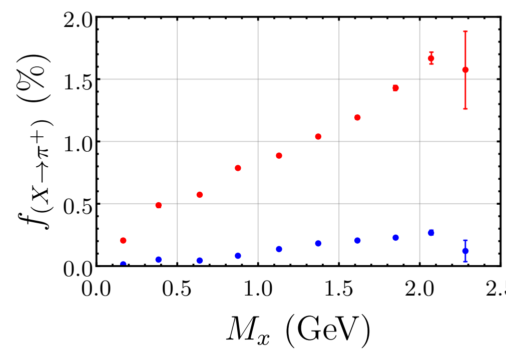


$\pi^+ \to$ P

$k^+ \to$ P

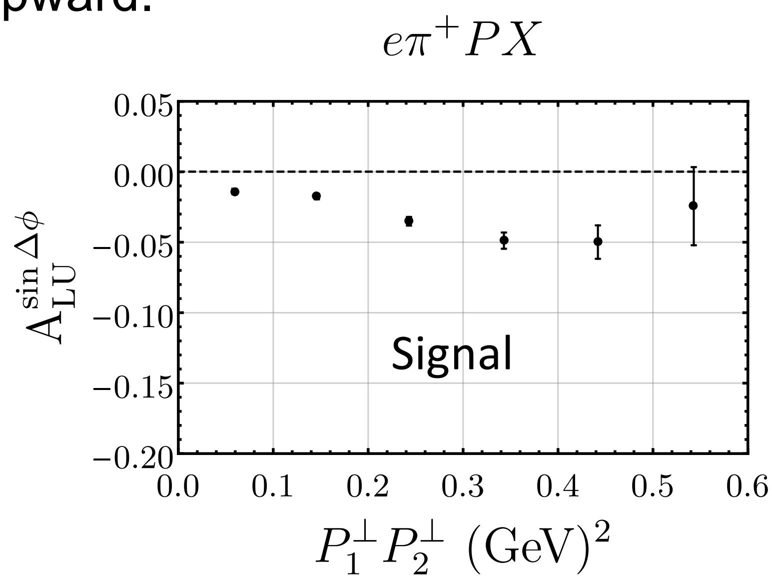


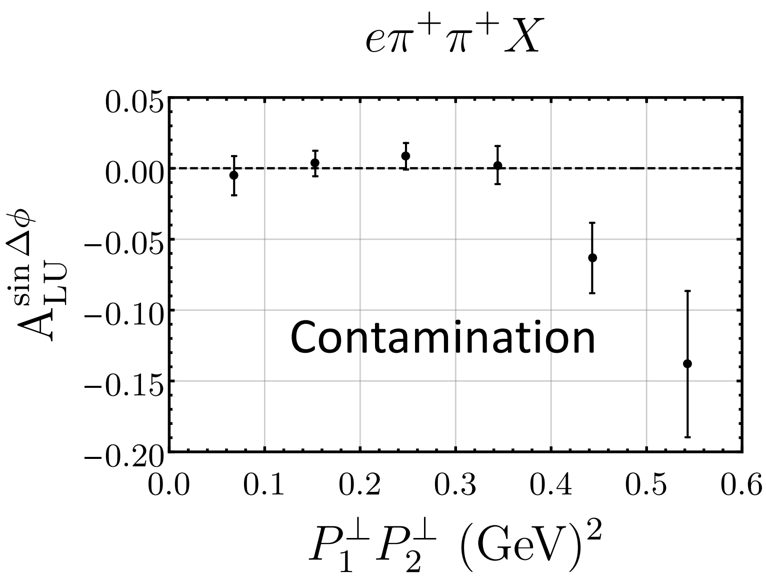




Use $eP \to e\pi^+\pi^+X$

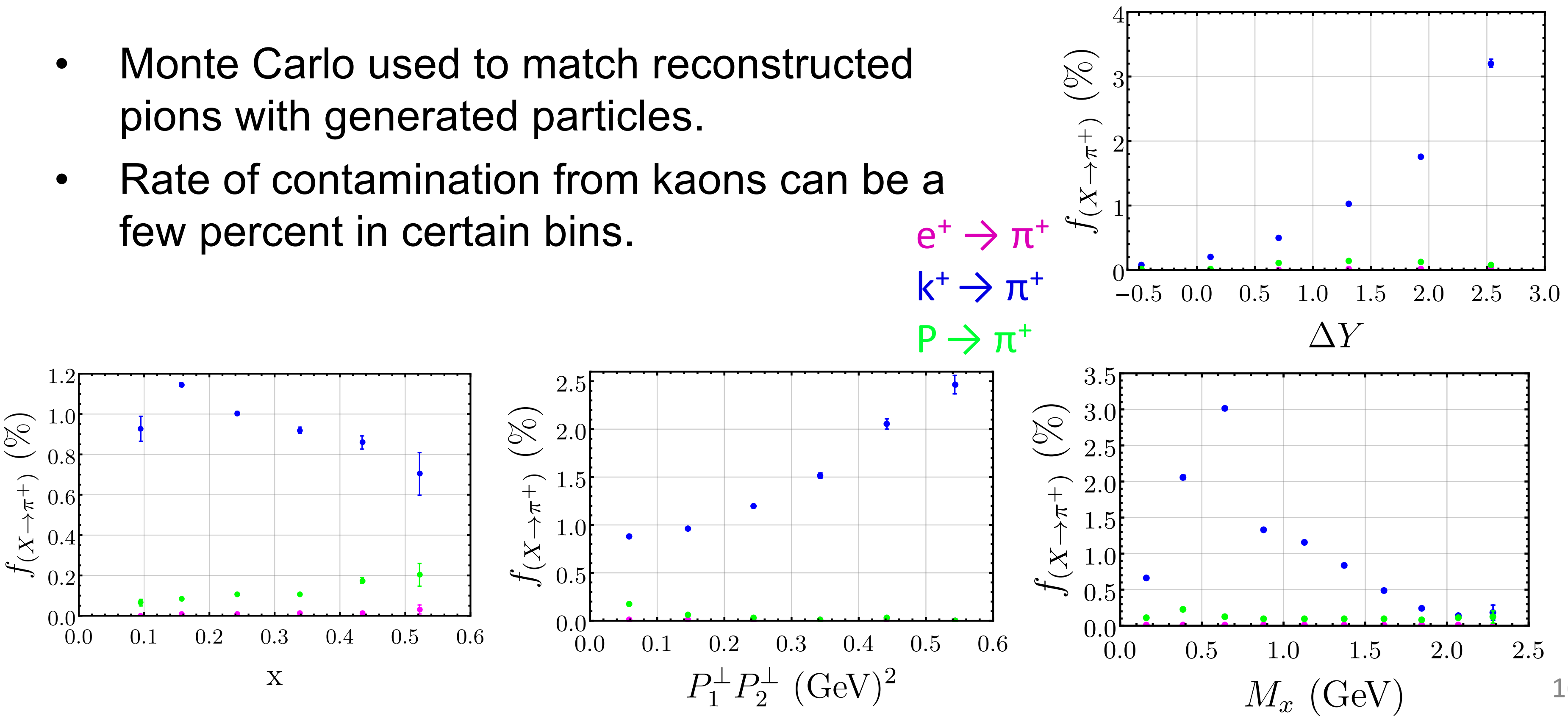
- Repeat entire analysis chain except for final state with two positive pions (to simulate a proton misidentified as a pion).
- The ~1% of events with misidentified protons are shifting asymmetries upward.





Systematic: Pion PID

- Monte Carlo used to match reconstructed pions with generated particles.
- Rate of contamination from kaons can be a few percent in certain bins.



Systematic: Baryon Resonances

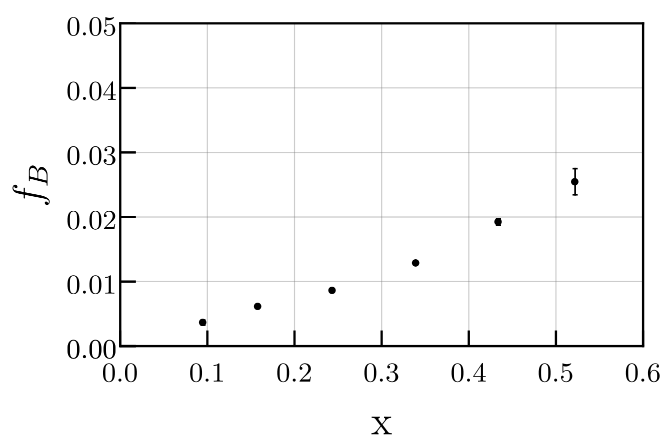
- Pions coming from the decay of baryonic resonances are not truly part of the CFR.

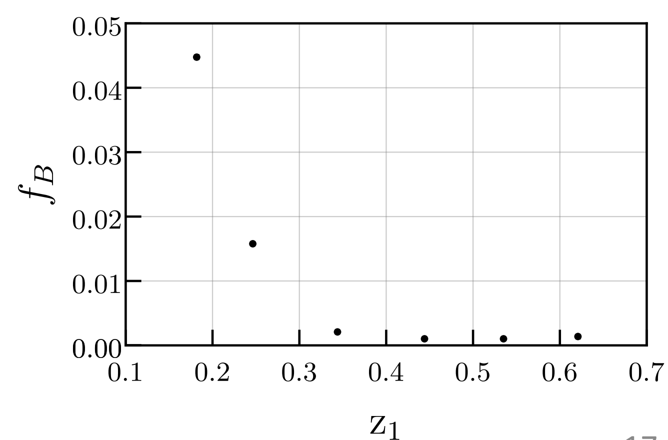
$$\frac{\Delta A}{A} = \frac{f_B}{1 - f_B}.$$

1. $\Delta^{++} \rightarrow \pi^+ p$

2. $\Delta^{+} \rightarrow \pi^+ n$

3. $\Sigma^{+} \rightarrow \pi^+ n$

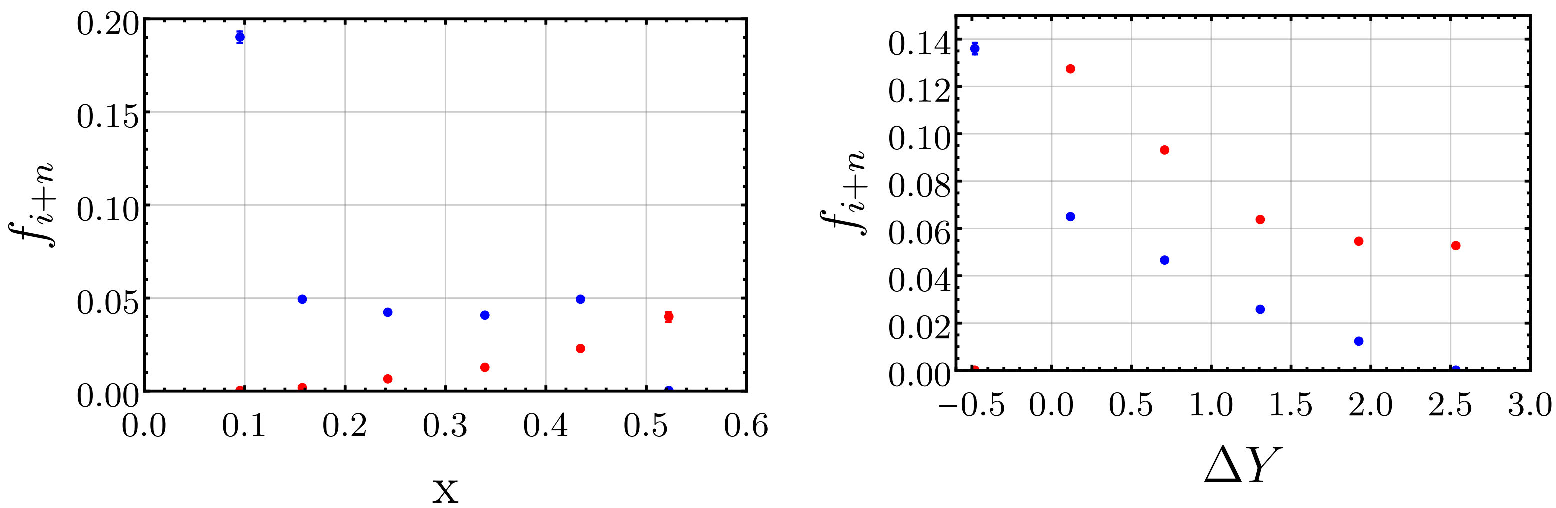




Systematic: Bin Migration

- Finite bin widths can cause events to be reconstructed in different bins than they originated.

$$\frac{\Delta A}{A} \approx \frac{|(f_{i-1}+f_{i+1})A_i - f_{i-1}A_{i-1} - f_{i+1}A_{i+1}|}{(1-f_{i-1}-f_{i+1})\,A_i}.$$

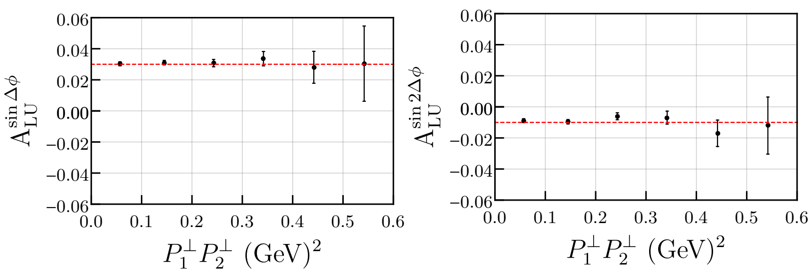


Injected Asymmetries

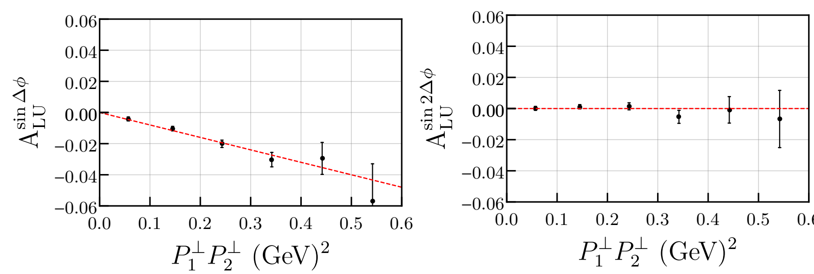
- Effects related to PID, kinematic smearing, acceptance, efficiency, etc. studied by comparing reconstructed to injected asymmetries.
- Asymmetry injected by assigning a helicity based on a random number

$$r < \frac{1}{2}(1 + P_e A_i)$$

Injected: $0.03\sin(\Delta\varphi) - 0.01\sin(2\Delta\varphi)$

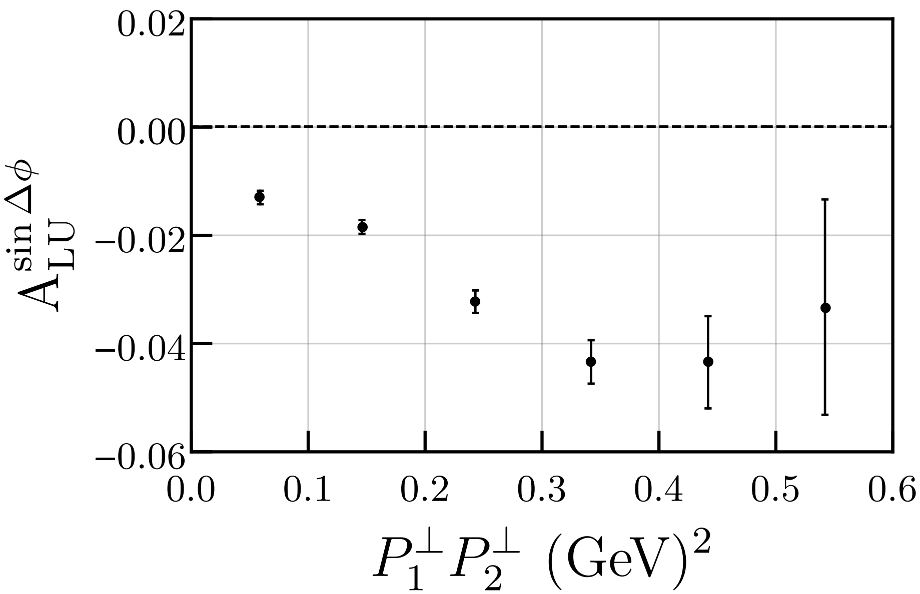


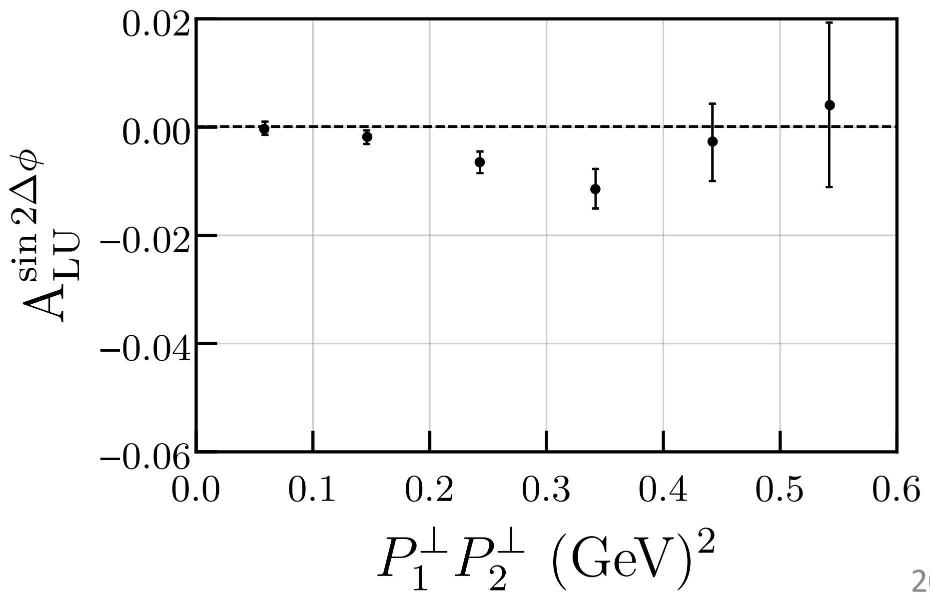
Injected: $-0.08P^{\perp}P^{\perp}\sin(\Delta\varphi) + 0.00\sin(2\Delta\varphi)$



Results

- Product of transverse momenta appears as a kinematic factor in front of asymmetries. $\sin 2\Delta\phi$ appears because of this product.



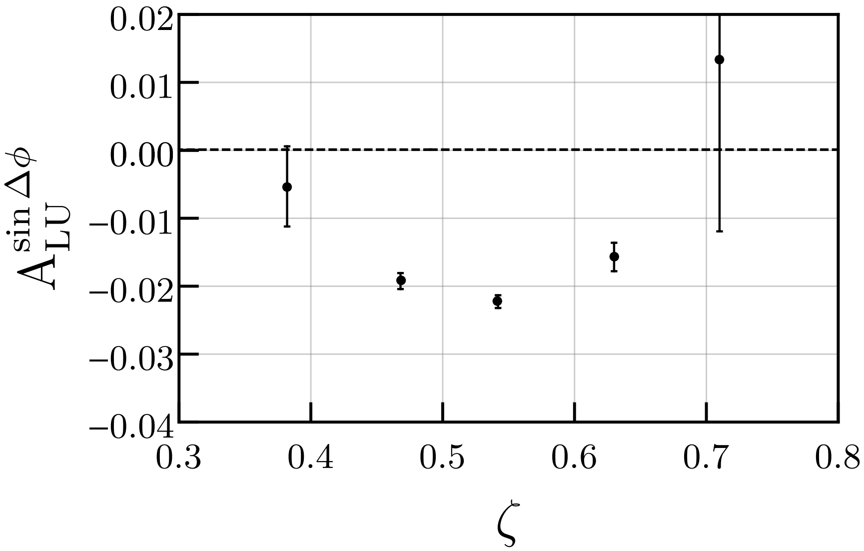


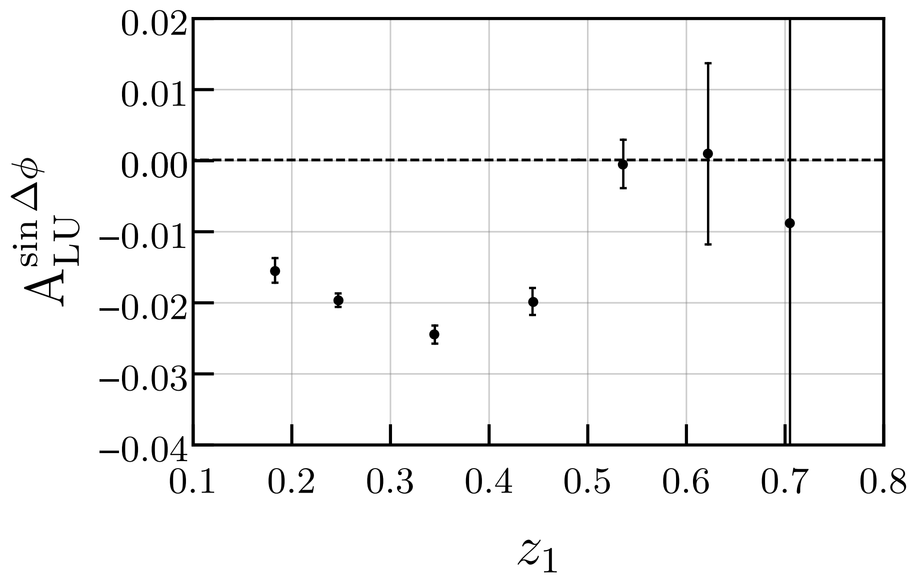
Results

- Fracture function $\hat{\ell}_1^{\perp h}$ depends on ζ .
- Fragmentation function D_1 depends on z_1.

$$\zeta = E_h/E$$

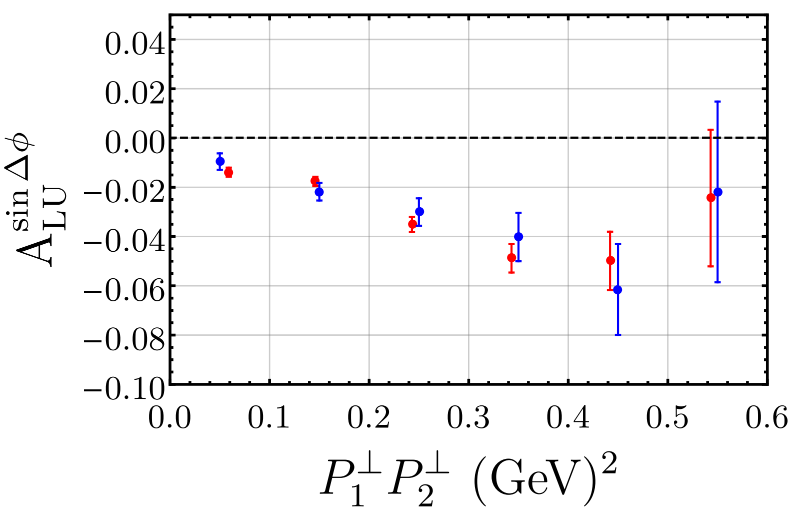
$$z_1 = \frac{E_1}{\nu}$$

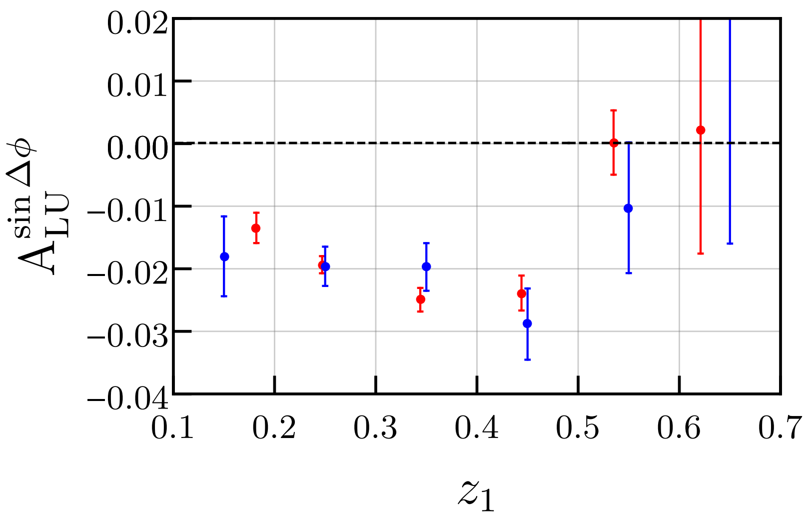




Cross Check

- Finalizing cross check between Timothy and Harut. Few minor differences left attributable to difference in fit procedure and few cuts.





Conclusions

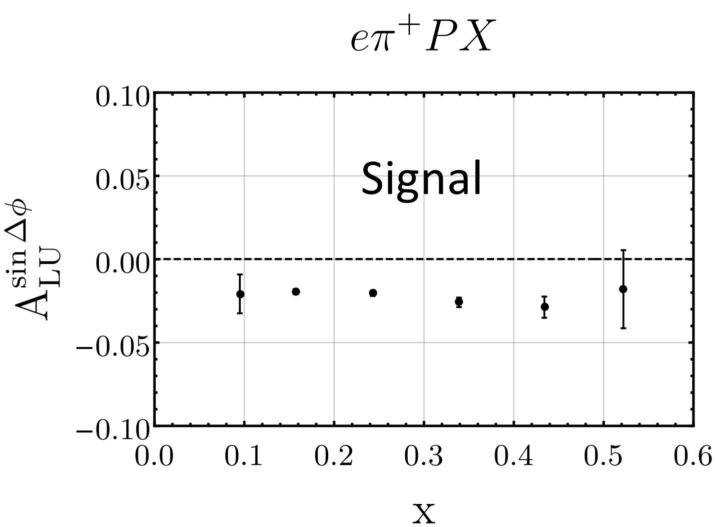
- Significant single-spin asymmetries have been observed in back-to-back proton-pion electroproduction.
- Amplitudes indicate that spin-orbit correlations exist between hadrons produced simultaneously in the target and current fragmentation regions.
- Analysis note at >80% completion. Paper draft in progress. Ready to submit for analysis review in the coming weeks.

- Submit to PRL … first measurement of its kind.

Supplementary Slides

Use $eP \to ek^+PX$

- Repeat process for kaon asymmetries. Is the kaon PID good enough to use rough estimate of asymmetry?
- No published back-to-back kaon-proton asymmetries…



Kaon analysis in progress.