Beam-Spin Asymmetry for back-to-back di-hadron electro-production with CLAS6 and CLAS12

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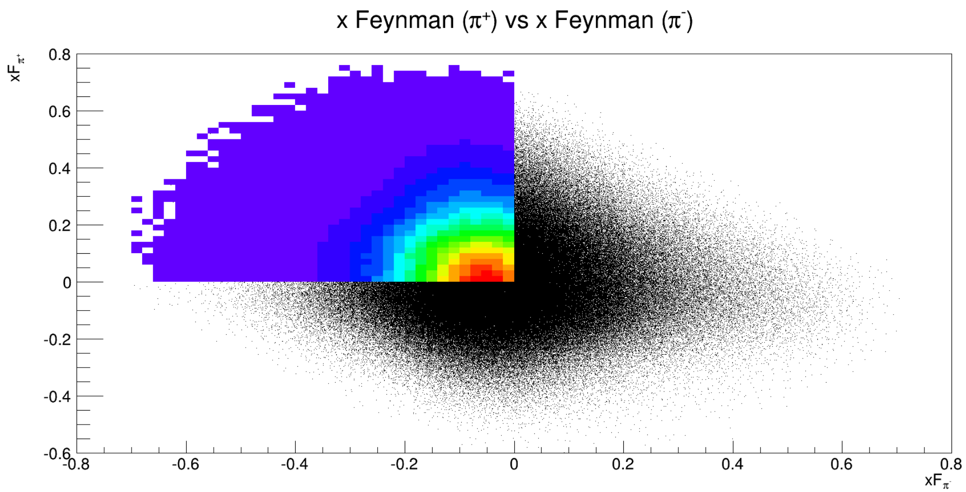
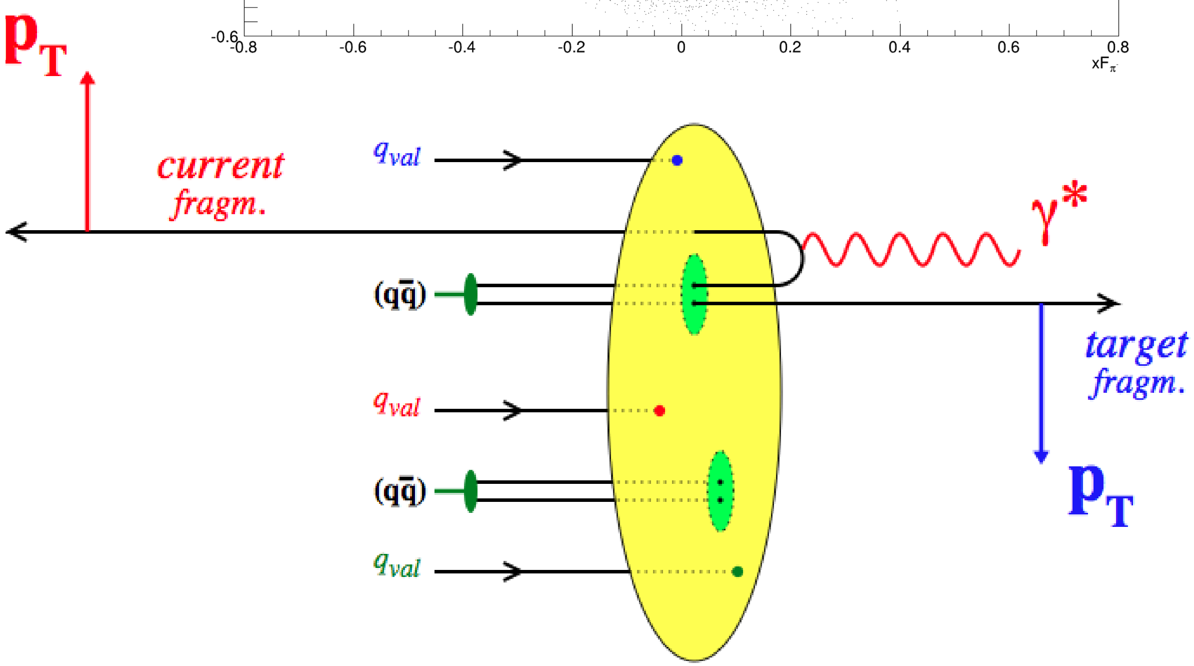
Di-hadron SIDIS: back2back configuration

- how the remnant system dresses itself up to become a full-fledged hadron?
- correlation with the spin of the target or/and the produced particles
- control the flavor content of the final state hadron in current fragmentation (detecting the target hadron)
- study correlations in target vs current and access factorization breaking effects (similar to pp case)
- access quark short-range correlations and χSB (*Schweitzer et al*)





back2back electro-production

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A novel beam–spin asymmetry in double-hadron inclusive lepto-production

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A B S T R A C T

We show that a new beam–spin asymmetry appears in deep inelastic inclusive lepto-production at low transverse momenta when a hadron in the target fragmentation region is observed in association with another hadron in the current fragmentation region. The beam leptons are longitudinally polarized while the target nucleons are unpolarized. This asymmetry is a leading-twist effect generated by the correlation between the transverse momentum of quarks and the transverse momentum of the hadron emitted by the target. Experimental signatures of this effect are discussed.

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b2b SIDIS cross section and structure functions

$$
\begin{aligned}
&\frac{\mathrm{d}\sigma^{l(\lambda_l)\,N\to l\,h_1 h_2\,X}}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}z_1\,\mathrm{d}\zeta_2\,\mathrm{d}\mathbf{P}_{1\perp}^2\,\mathrm{d}\mathbf{P}_{2\perp}^2\,\mathrm{d}\phi_1\,\mathrm{d}\phi_2} \\
&= \frac{\pi\alpha_{\mathrm{em}}^2}{x_B y Q^2}\left\{\left(1-y+\frac{y^2}{2}\right)\mathcal{F}_{UU}\right. \\
&+ (1-y)\,\mathcal{F}_{UU}^{\cos(\phi_1+\phi_2)}\cos(\phi_1+\phi_2) \\
&+ (1-y)\,\mathcal{F}_{UU}^{\cos(2\phi_1)}\cos(2\phi_1) \\
&+ (1-y)\,\mathcal{F}_{UU}^{\cos(2\phi_2)}\cos(2\phi_2) \\
&- \left.\boxed{\lambda_l}\,y\left(1-\frac{y}{2}\right)\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)}\sin\Delta\phi\right\} \\
&\equiv \sigma_{UU}+\lambda_l\,\sigma_{LU}\,,
\end{aligned}
$$

$$\mathcal{F}_{LU}, \mathcal{F}_{UU} \propto \mathcal{C}[\mathcal{M}\mathcal{D}]$$

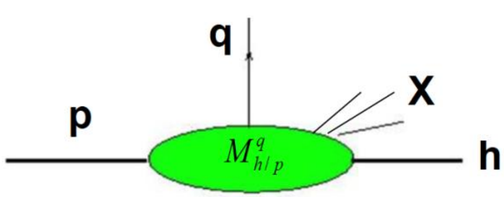
Fracture Functions:

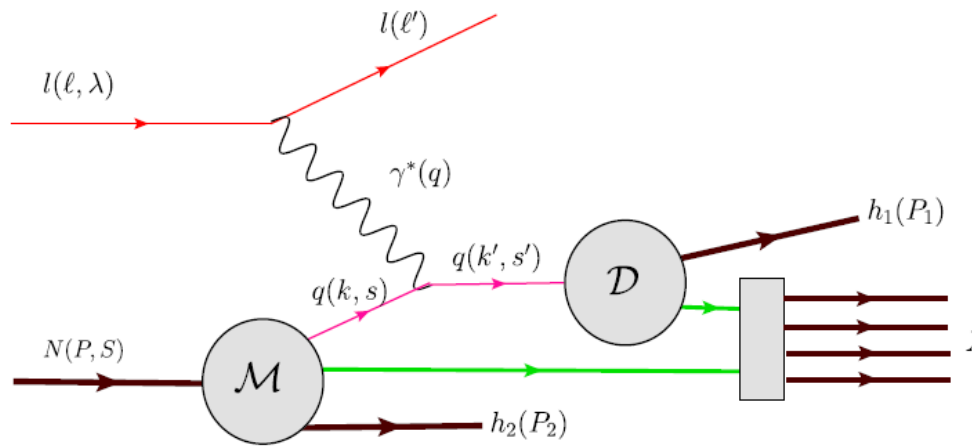
probability of finding a parton i with fractional momentum x_B and a hadron h with fractional momentum ζ

$$\mathcal{M}(x_B, \zeta, k_\perp, P_{\perp 2})$$

Fragmentation Functions:

$$\mathcal{D}(z_1, k_\perp)$$

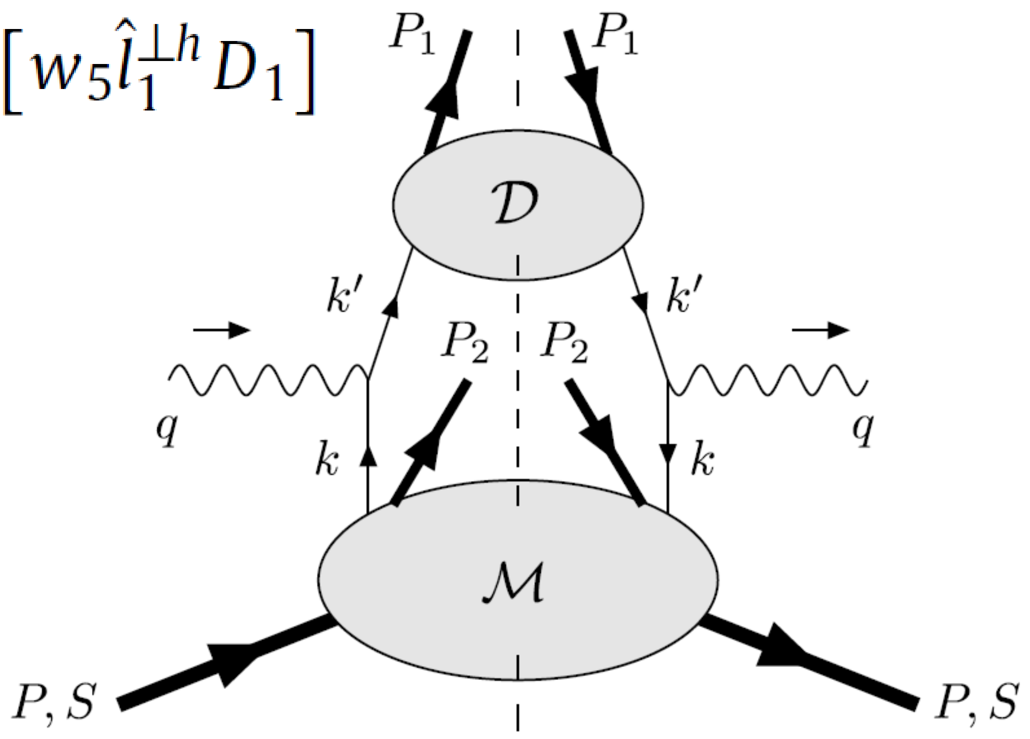




b2b Structure Functions

$$\mathcal{F}_{UU} = \mathcal{C}[\hat{u}_1 D_1]$$

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



$\mathcal{D}$ contains $D_1, H_1^{\perp}$ → 1 hadron unpolarized and Collins Fragmentation Functions

$\mathcal{M}$ contains Fracture Functions

b2b Beam-Spin Asymmetry: experimental signature

$$\mathcal{A}_{LU}\left(x_B, z_1, \zeta_2, \boldsymbol{P}_{1\perp}^2, \boldsymbol{P}_{2\perp}^2, \Delta\phi\right) = \frac{\int \mathrm{d}\phi_2\, \sigma_{LU}}{\int \mathrm{d}\phi_2\, \sigma_{UU}}$$

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

$$= -\frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2} \frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})} \frac{\mathcal{C}[w_5 \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi$$

Structure Functions

$\boldsymbol{\mathcal{F}}_{LU}, \boldsymbol{\mathcal{F}}_{UU} \propto P_{\perp 1} \cdot P_{\perp 2} = |P_1||P_2| \cos\Delta\varphi$

$\rightarrow \sin\Delta\varphi \cos\Delta\varphi$

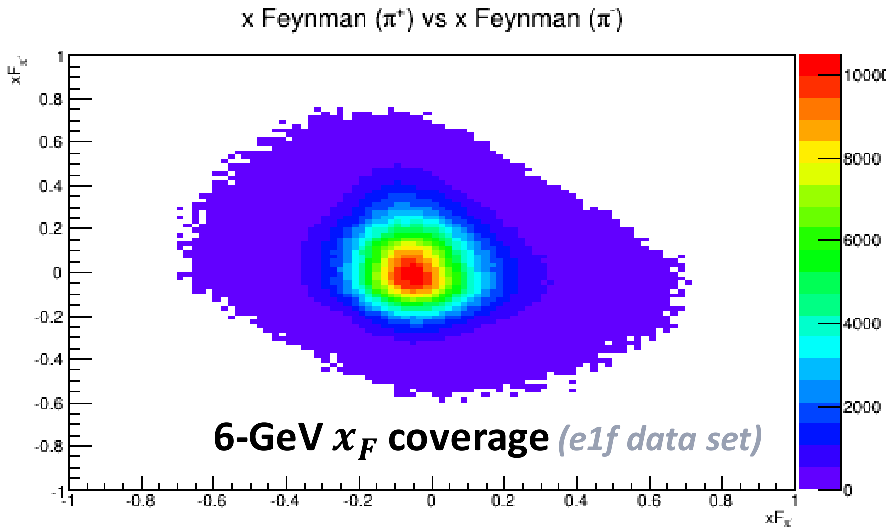
This series of $\sin(n\Delta\phi)$ terms, with $n = 1, 2, \ldots,$ in azimuthal modulations is typical of $\mathcal{A}_{LU}$ and would be a clear signature of its presence; such terms originate from a correlation between the quark transverse momentum $\boldsymbol{k}_\perp$ and the hadron transverse momentum $\boldsymbol{P}_{2\perp}$, resulting in a long range correlation between $\boldsymbol{P}_{1\perp}$, the momentum of the hadron in the CFR, and $\boldsymbol{P}_{2\perp}$, the momentum of the hadron in the TFR, which yields a specific and unambiguous dependence on $\phi_1 - \phi_2$. As the higher terms in n originate from higher powers of $\boldsymbol{P}_{1\perp} \cdot \boldsymbol{P}_{2\perp}$, we expect the first few terms in Eq. (20) to be the leading ones.

$$\begin{aligned}\mathcal{A}_{LU}&\left(x_B, z_1, \zeta_2, \boldsymbol{P}_{1\perp}^2, \boldsymbol{P}_{2\perp}^2, \Delta\phi\right)\\ &\simeq A\left(x_B, z_1, \zeta_2, \boldsymbol{P}_{1\perp}^2, \boldsymbol{P}_{2\perp}^2\right)\sin\Delta\phi\\ &\quad + B\left(x_B, z_1, \zeta_2, \boldsymbol{P}_{1\perp}^2, \boldsymbol{P}_{2\perp}^2\right)\sin(2\Delta\phi)\\ &\quad + C\left(x_B, z_1, \zeta_2, \boldsymbol{P}_{1\perp}^2, \boldsymbol{P}_{2\perp}^2\right)\sin(3\Delta\phi)\end{aligned}$$

Preliminary extraction on e1f data: $ep \rightarrow e\pi^+\pi^- X$

1. at least one π^+ and one π^- (multi-pion case: all the possible two-pion combinations considered)
2. DIS cuts ($Q^2 > 1\ GeV^2$ & $W > 2\ GeV$) are applied
3. π^+ from the **Current Fragmentation Region,** π^- from the **Target Fragmentation Region**
4. exclusive events are removed through a cut on the missing mass

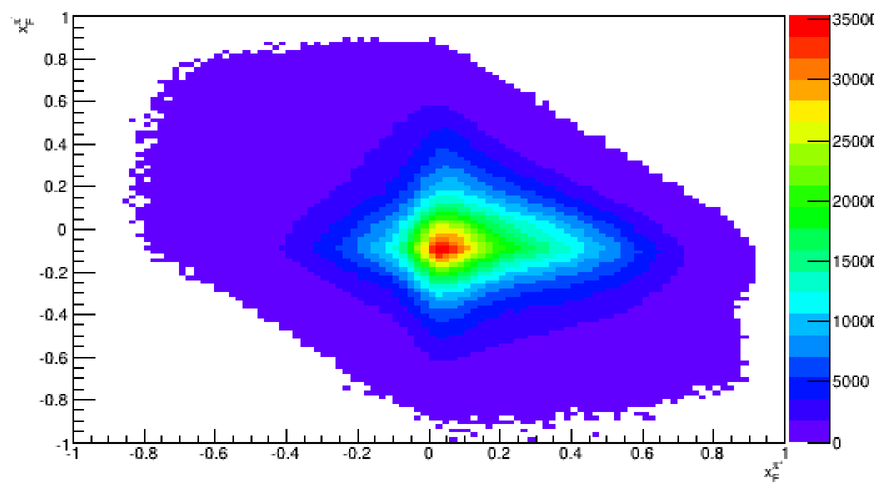
e1f data set
Liquid-hydrogen target H_2
Beam energy: 5.5 GeV
Luminosity: 21 fb^{-1}



6-GeV x_F coverage *(e1f data set)*

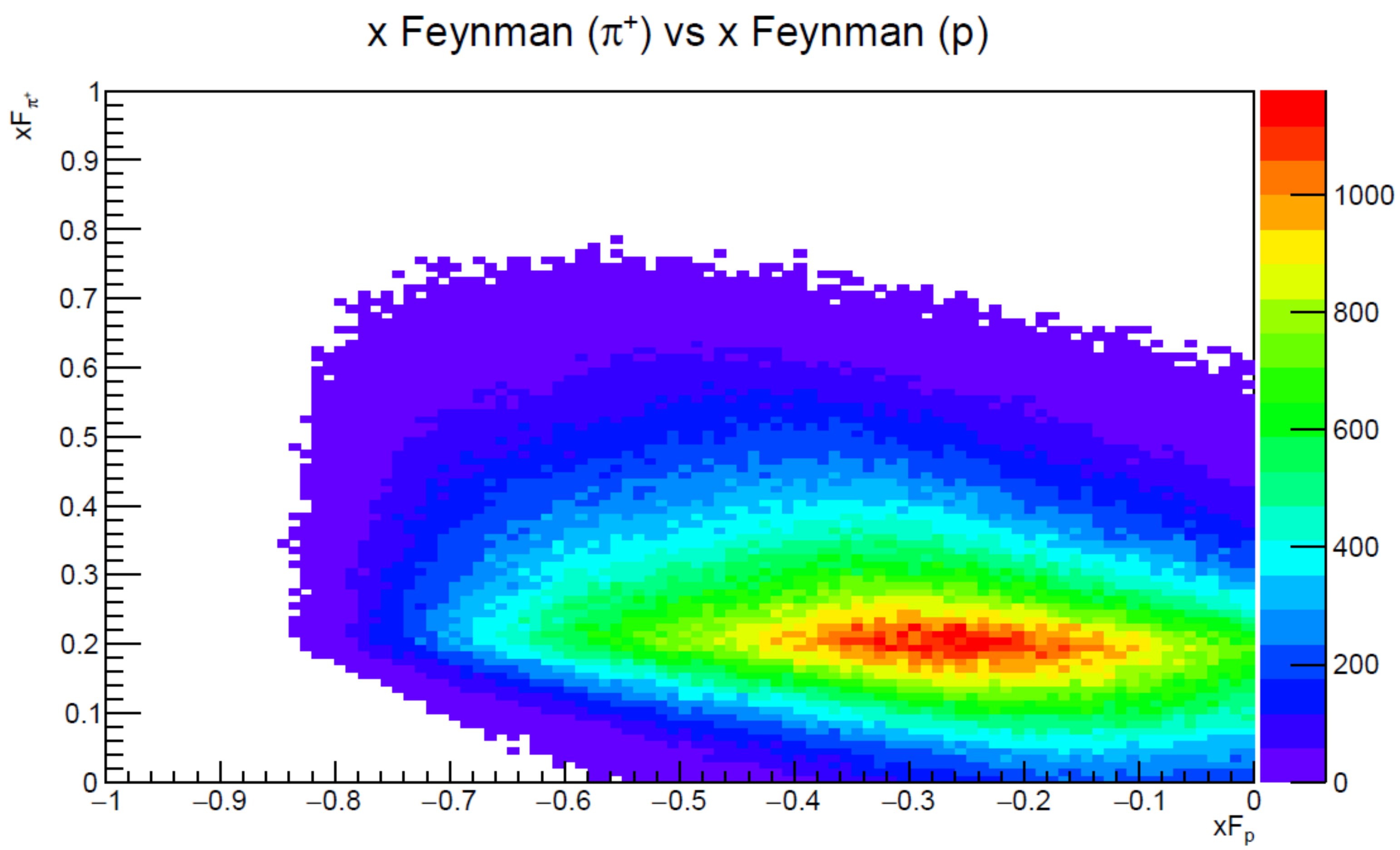
12-GeV x_F coverage

E12-06-112A/ E12-09-008B



Back-to-back pion and proton: $ep \rightarrow ep\pi^+X$

(In CLAS kinematics) proton is more likely to come from *target fragmentation*

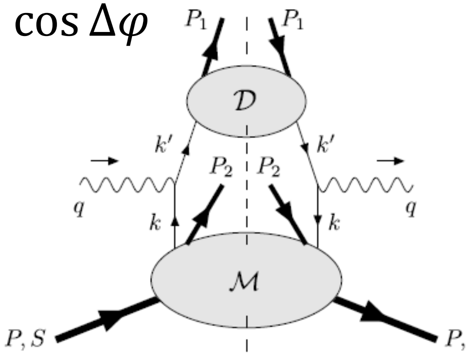


Binning

Variables of interest for a possible binning:

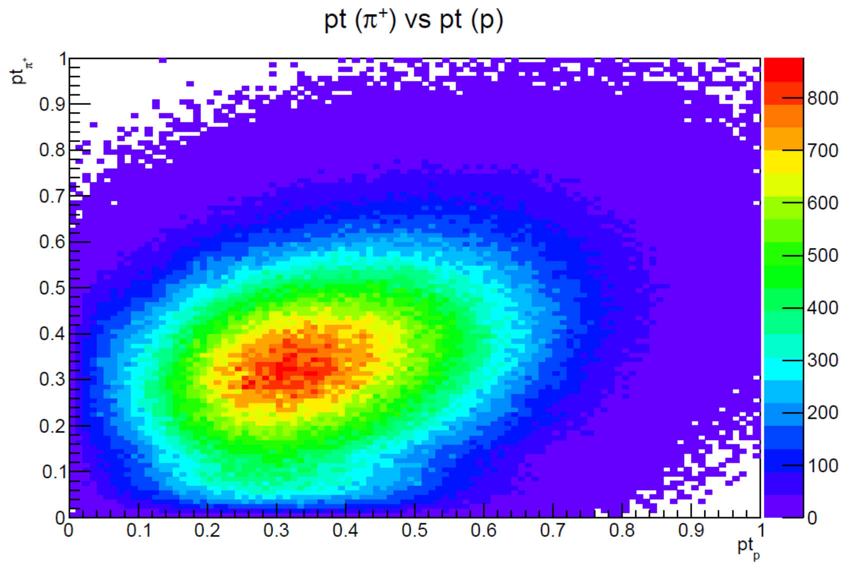
- z to explore the fragmentation function → comparison with single-pion measurements of D_1
- p_{T1}, p_{T2} → kinematical suppression of the asymmetry at low transverse momenta

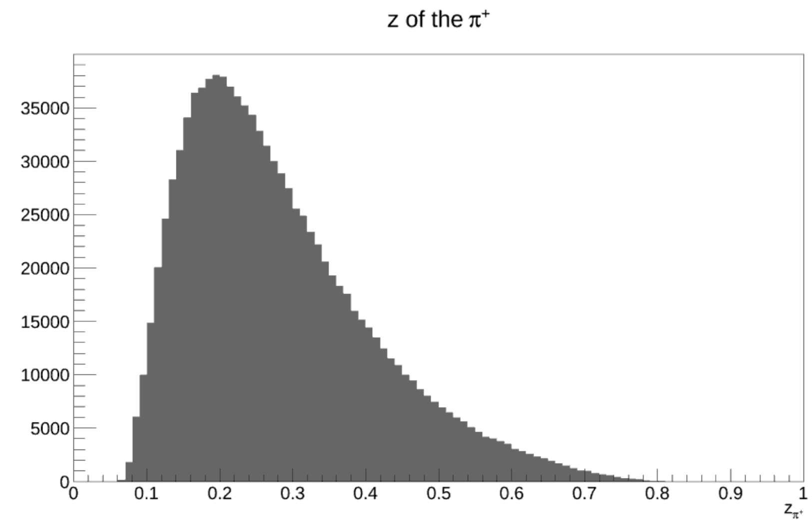
$$\mathcal{F}_{LU}, \mathcal{F}_{UU} \propto P_{\perp 1} \cdot P_{\perp 2} = |P_1||P_2| \cos \Delta\varphi$$



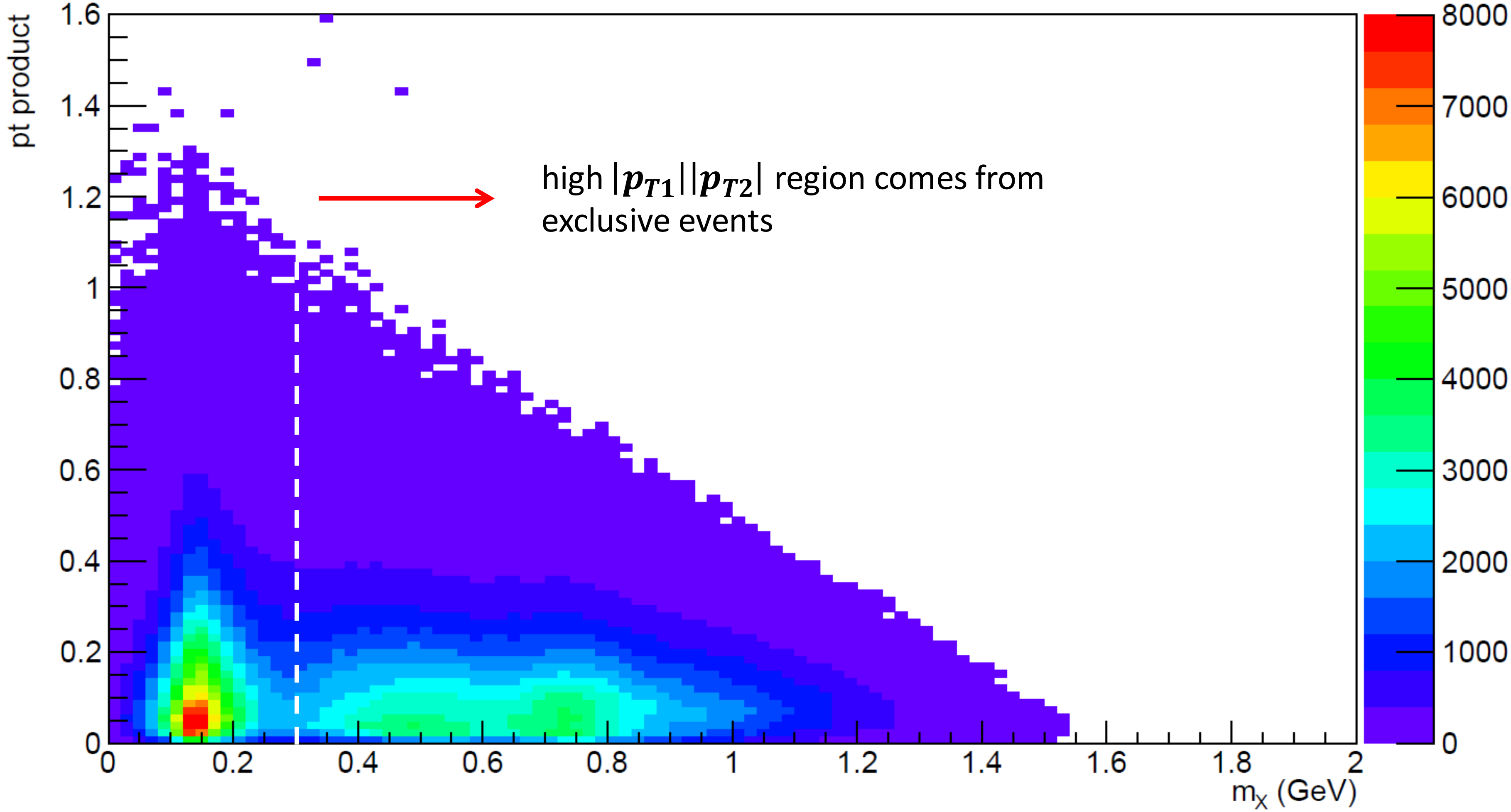
- x_B
- Q^2 → evolution?

Further question: **non-collinear factorization?**





Back-to-back pion and proton: $|p_{T1}||p_{T2}|$ vs. $m_{ep\pi^+X}$

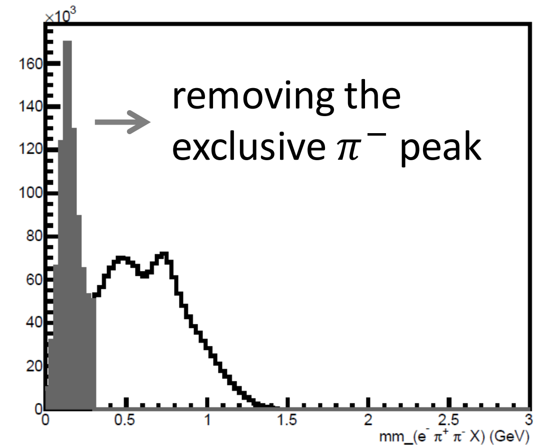


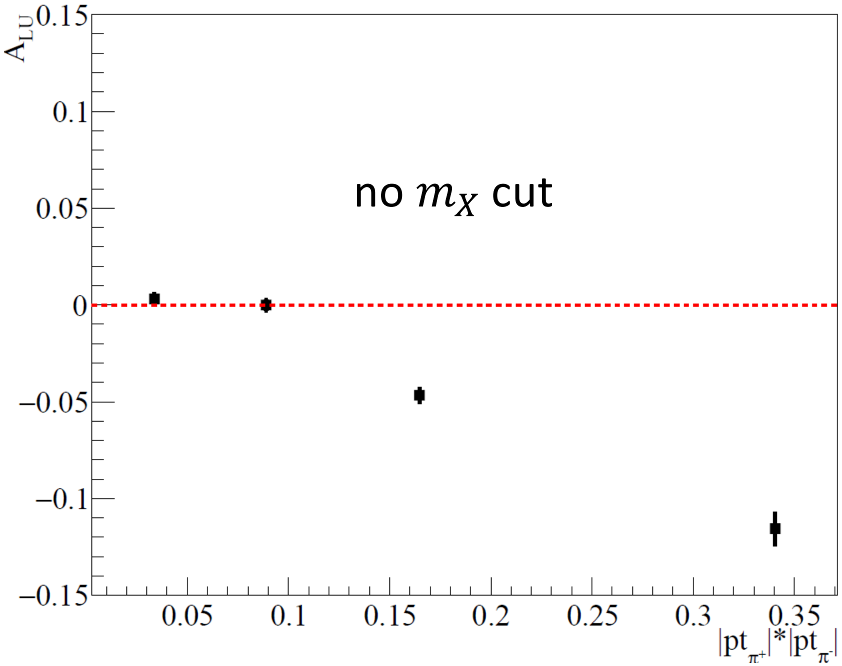
high $|p_{T1}||p_{T2}|$ region comes from exclusive events

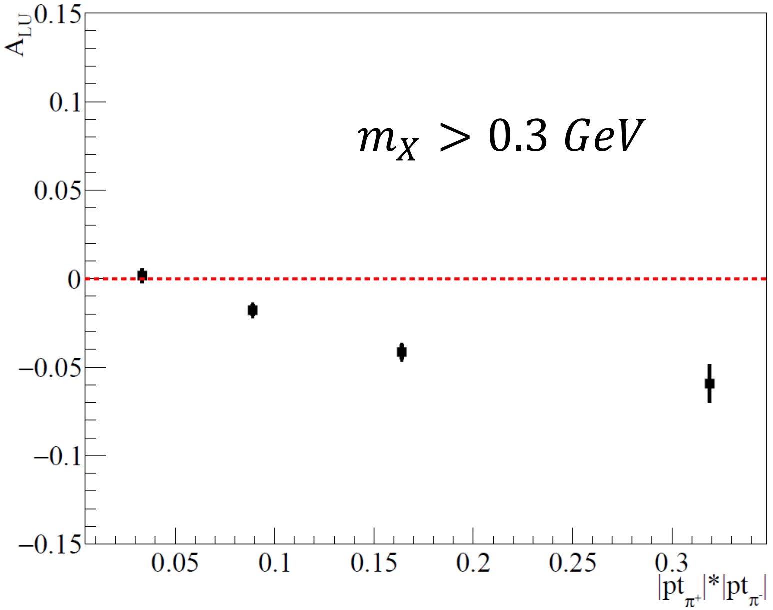
Back-to-back pion and proton: $|p_{T1}||p_{T2}|$ vs. $m_{ep\pi^+X}$ cut

removing the exclusive region removes the highest $|\boldsymbol{p_{T1}}||\boldsymbol{p_{T2}}|$ region, without affecting significantly the form of the dependence

→ a more linear behaviour is recovered



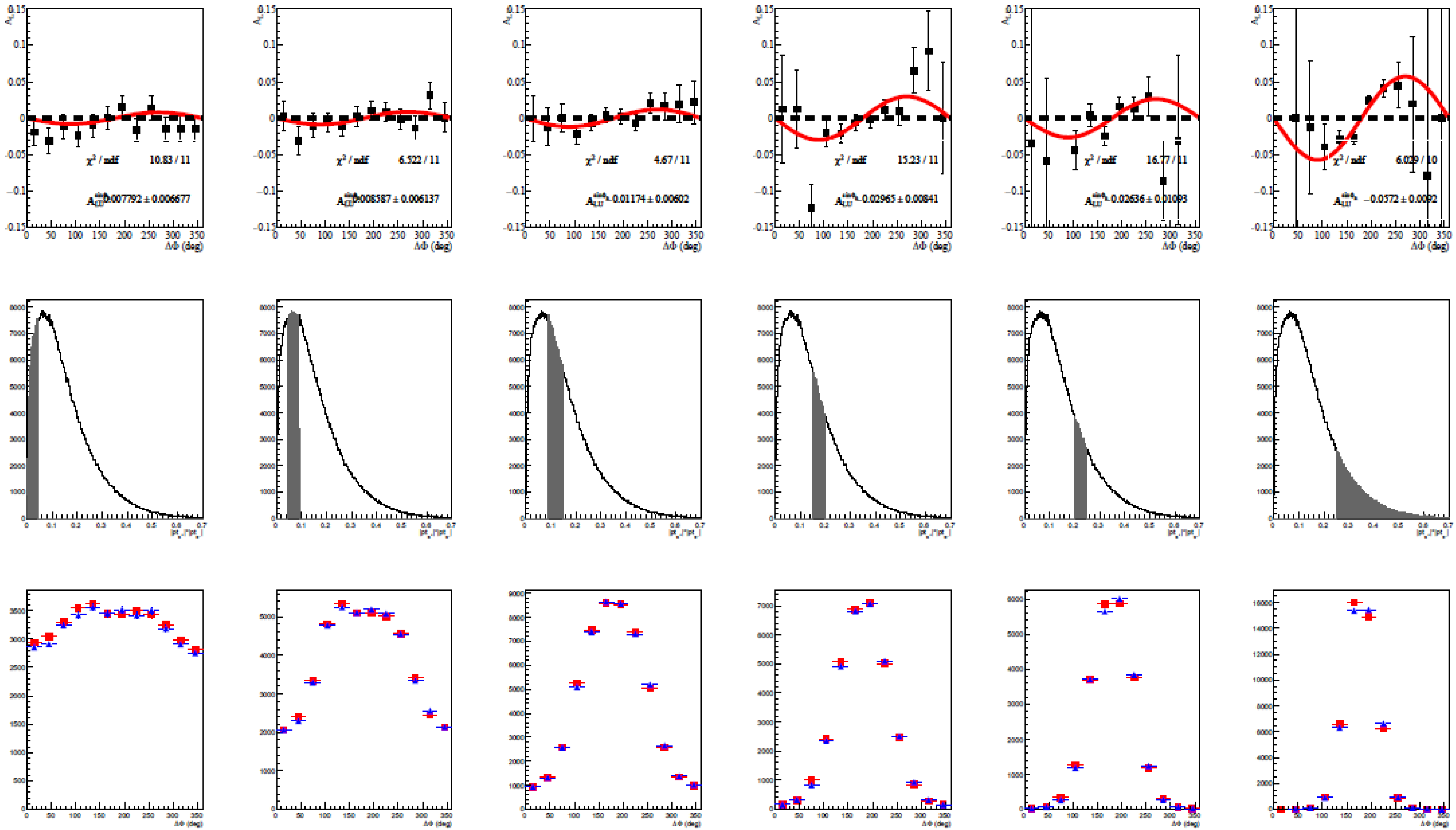




Latest progresses

- Binning optimized to access the most relevant dependences
- comparison among the two parallel analyses on e1f and e1-6
- test different proton-pion channels $(p\pi^-, p\pi^0)$
- evaluating possible extension to polarized-target data-sets (**eg1-dvcs**) or data set with forward calorimeter (**e1-dvcs**)
- work on simulations for CLAS12 – plan to submit a proposal

Back-to-back pion and proton: $|p_{T1}||p_{T2}|$distribution

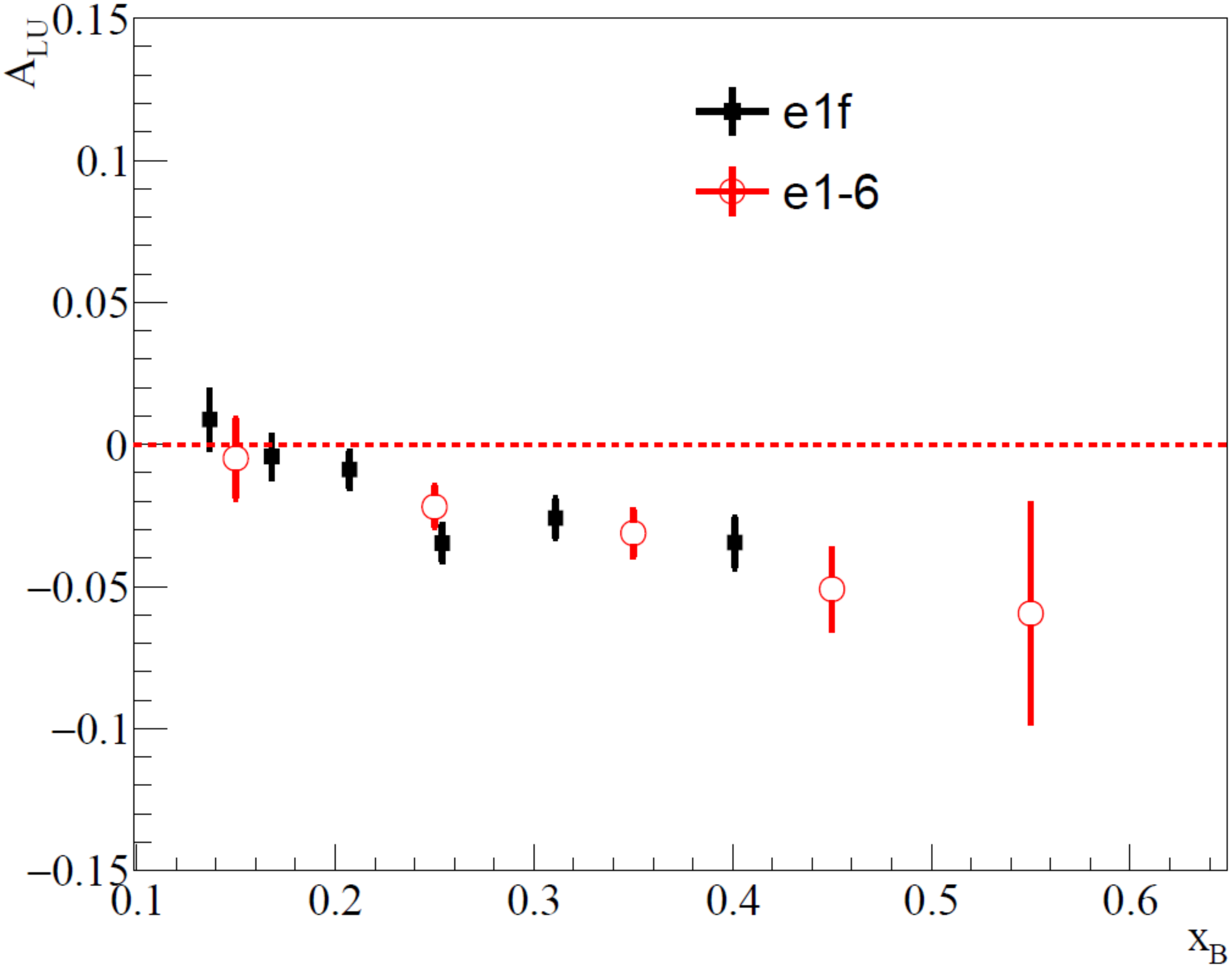


Back-to-back $ep \rightarrow ep\pi^+X$: x_B on e16 and e1f

Parallel analysis by Harut Avakian on ***e16 data set***:

- different target position with respect to e1f (- 4 cm instead of -25 cm)
- different torus
- coverage extended to high Q^2

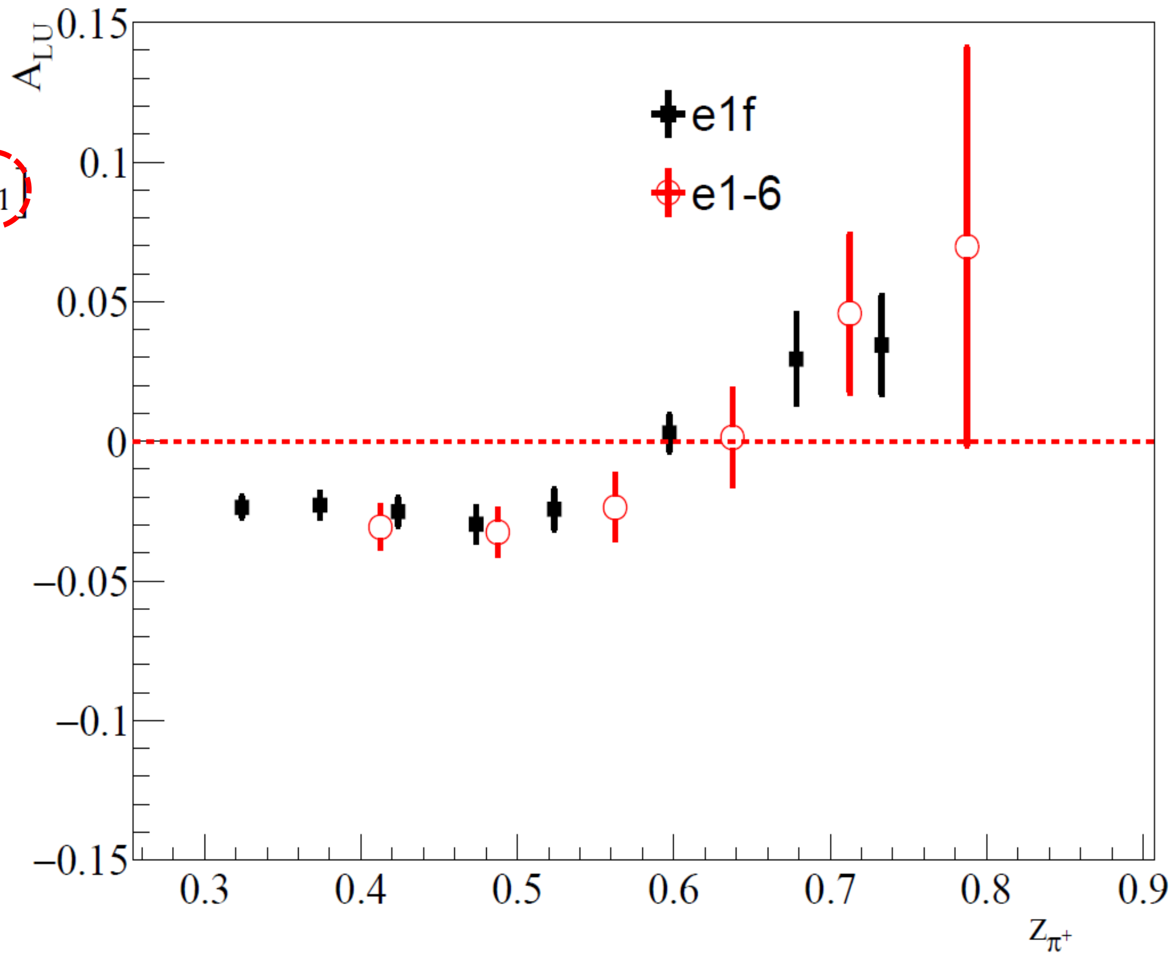
The measurements on the two hydrogen data sets can be combined



Back-to-back $ep \rightarrow ep\pi^{+}X$: z on e16 and e1f

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

$\mathcal{D}(z)$

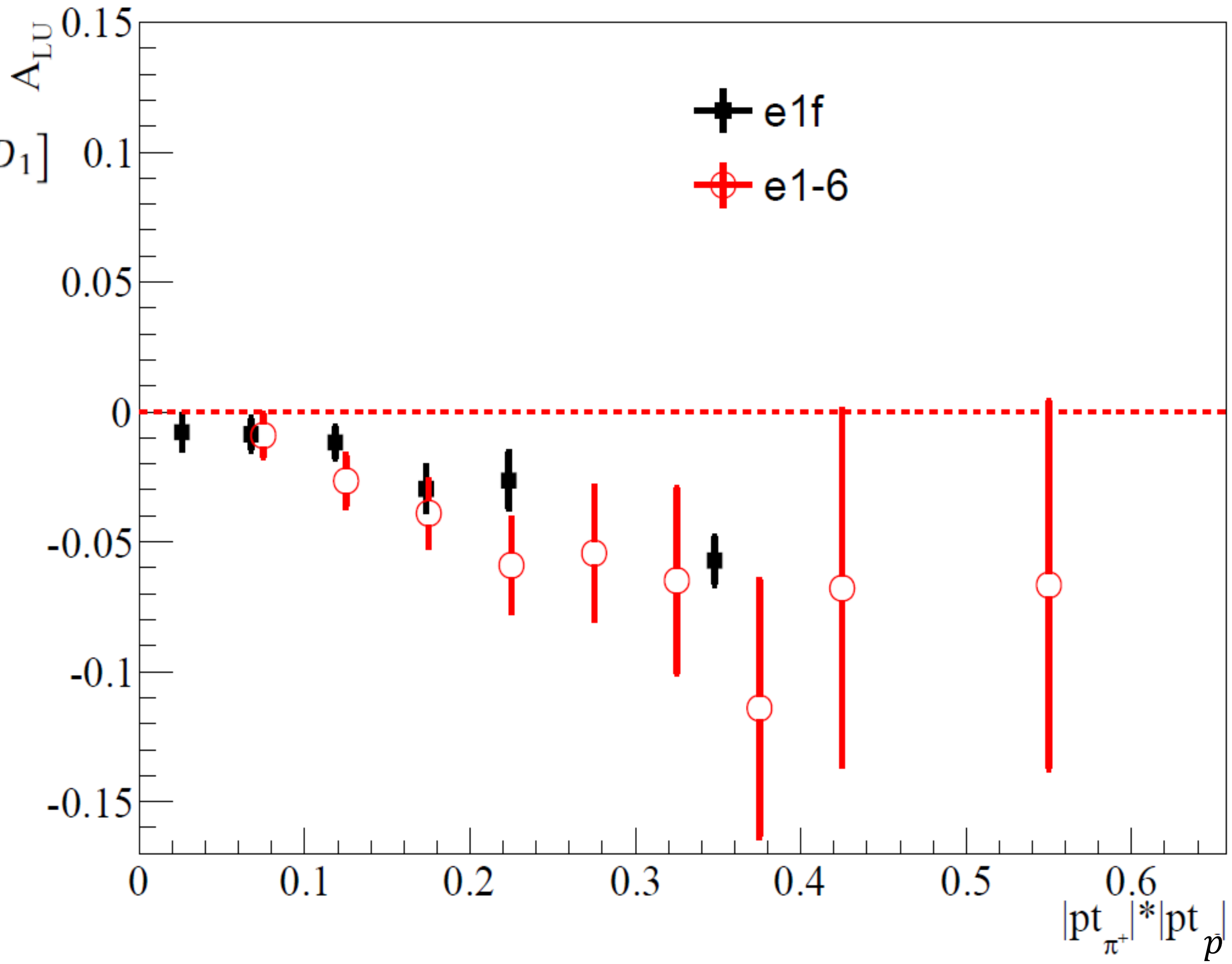


z dependence common to single-hadron SIDIS → dictated by single-hadron Fragmentation Functions

excellent agreement among the two data sets

Back-to-back $ep \to ep\pi^+X$: $|p_{T1}||p_{T2}|$ on e16 and e1f

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



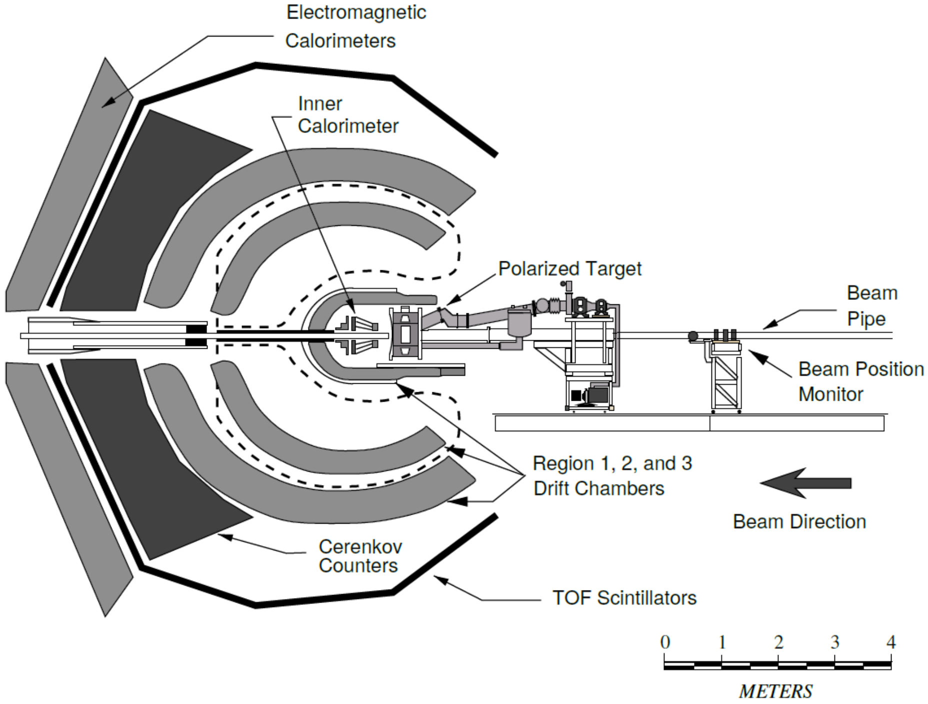
linear dependence foreseen by theory observed on data

excellent agreement among the two data sets

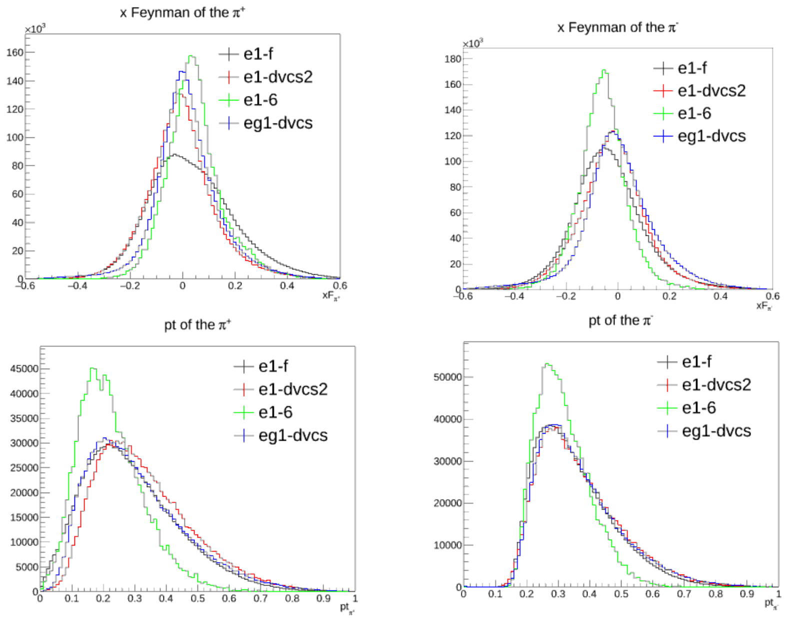
Back2back SIDIS in other CLAS 6-GeV data sets

Different 6-GeV data sets potentially interesting in dh analysis with

- different target positions
- different magnetic fields
- the presence of the Inner Calorimeter



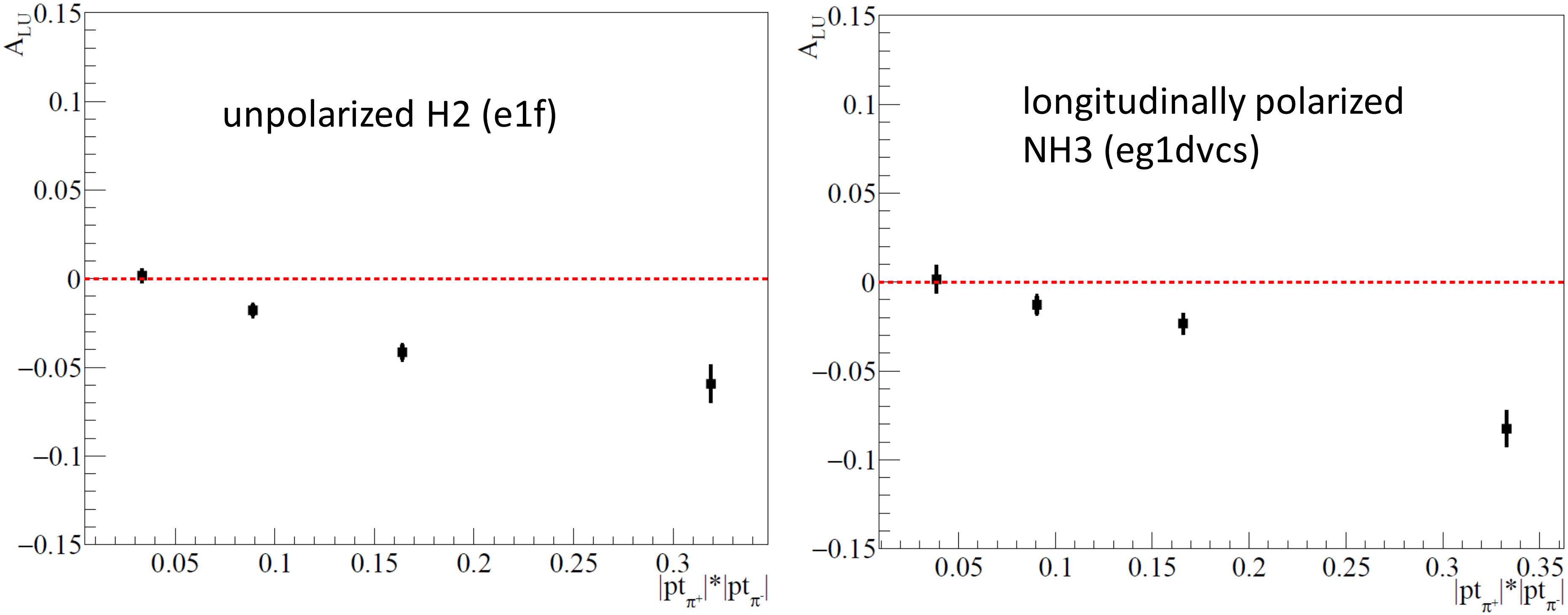
- e1-f: unpolarized hydrogen target @-25 cm
- e1-6: unpolarized hydrogen target @-4 cm
- e1-dvcs: unpolarized hydrogen target @-57 cm
- eg1-dvcs: longitudinally polarized $^{14}NH_3$target @-67(-57) cm



Longitudinal observables - A_{UL} with the NH3 target

- Other observables can be accessed on polarized NH3 data, as A_{UL}, A_{LL} → extraction of different combinations of Fracture Functions and Fragmentation Functions

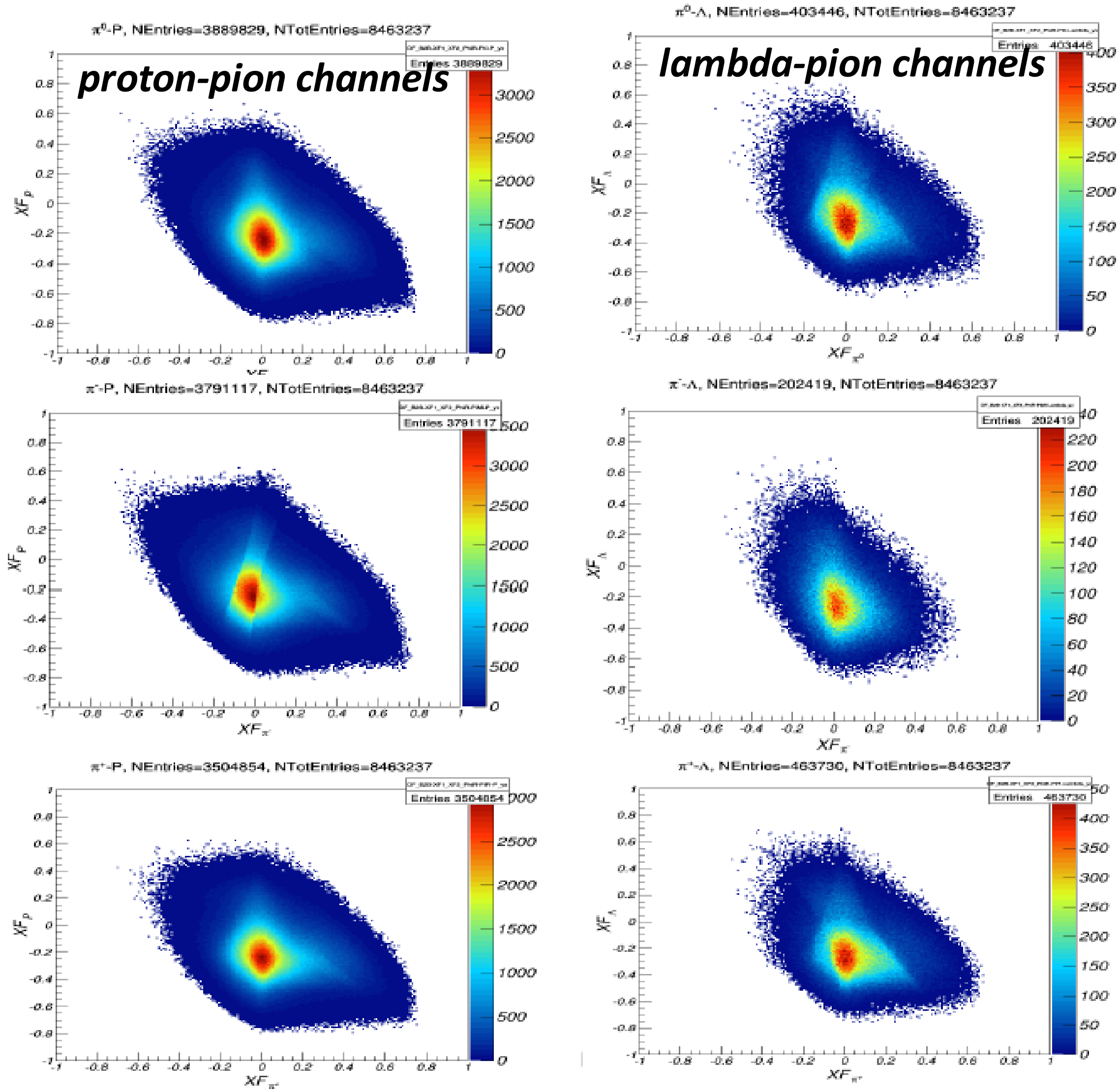
- Good agreement of A_{LU} dependences between data on hydrogen and on a nuclear target



Back2back SIDIS@CLAS12

- CLAS12 will provide an excellent environment to measure b2b A_{LU}
- **controlling the flavor content with target-current correlations**
- reasonable azimuthal coverage to extract relevant modulations
- improvements in statistics and coverage

Large acceptance of CLAS12 provides a unique possibility to detect simultaneously hadrons in the forward and backward regions



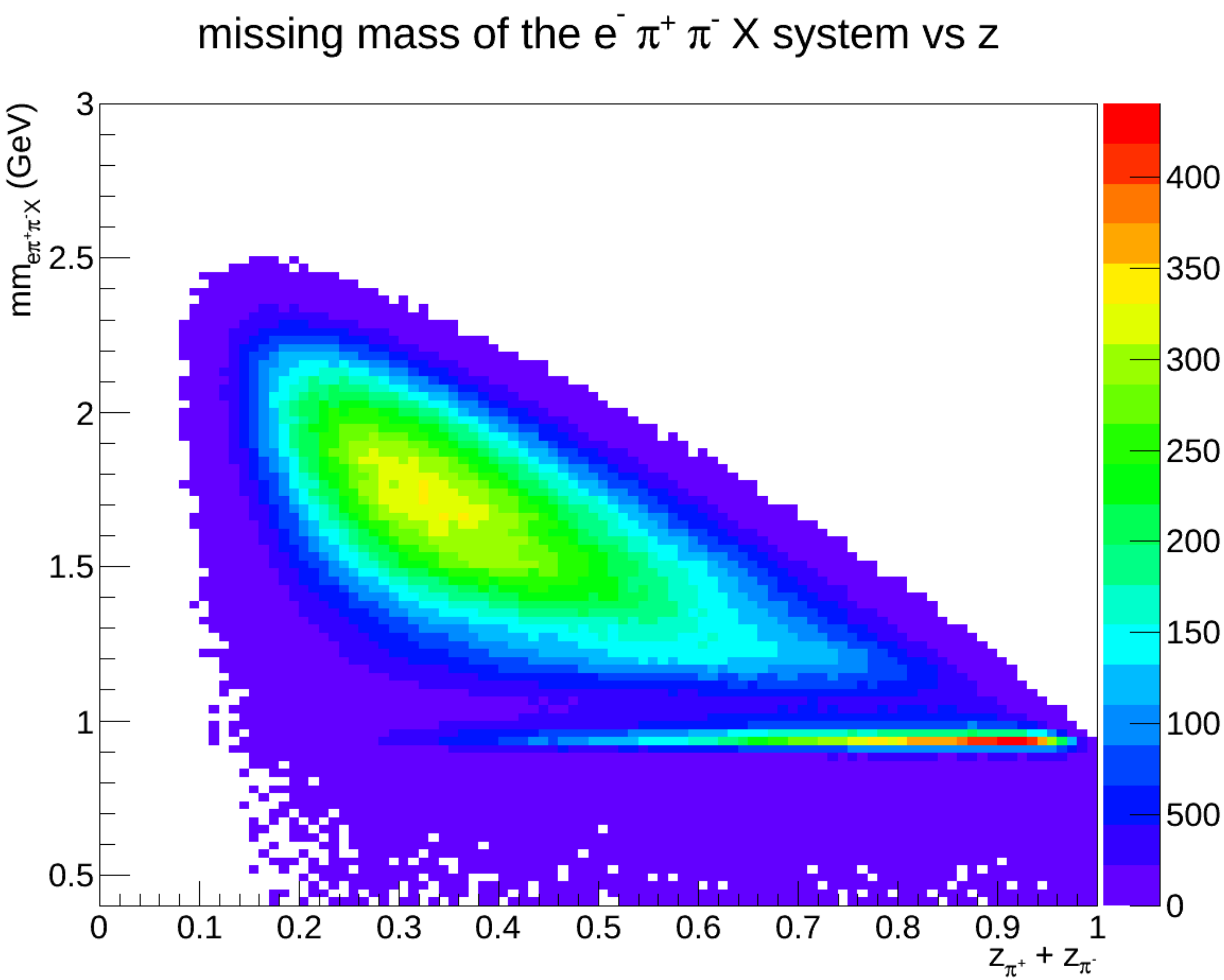
Conclusions

- Novel beam-spin asymmetry in back2back di-hadrons SIDIS
- ***Correlations between target and current***: **correlated $(\mathbf{q\bar{q}})$ pair present in the nucleon**
- CLAS 6-GeV experiments have a good coverage in x_F → back2back di-hadron configuration can be accessed
- preliminary analyses on e1f and e1-6 data show sensitivity to this phenomenon → non-zero $\mathrm{A_{LU}}$ observed
- parallel analyses on e1f and e1-6 provide access in complementary kinematics. Excellent agreement on the overlapping region
- CLAS 6 statistics can provide a pioneering exploration of the $\mathrm{A_{LU}}$ dependence on the kinematical variables of interest (mainly $p_{T1}, p_{T2}, \mathrm{z}, x_B$). ***However, 2D mapping is essential to disentangle the different effects***
- write-up of the analysis note in progress → expected to be ready in few weeks
- **CLAS12 high statistics will provide a full, multi-dimensional mapping of these dependences**

Thanks to Aram Kotzinian and Christian Weiss for all the useful discussions

backup

Selection of semi-inclusive events



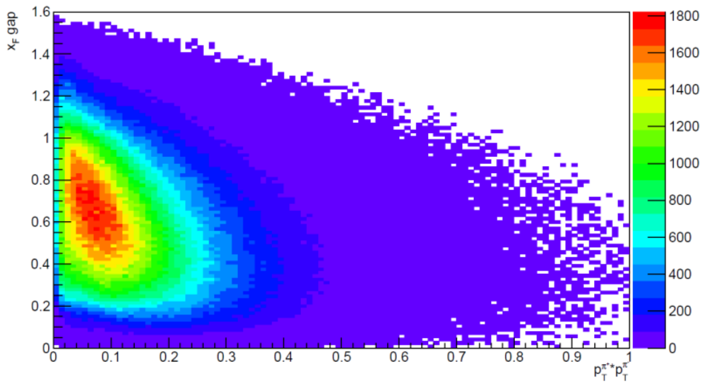
- Exclusive events lie in the high-z region
- They are cut through the condition

$mm_{e\pi^+\pi^- X} > 1.05$ GeV

- z coverage important to understand the fragmentation

Back-to-back pion and proton: x_F −gap dependence

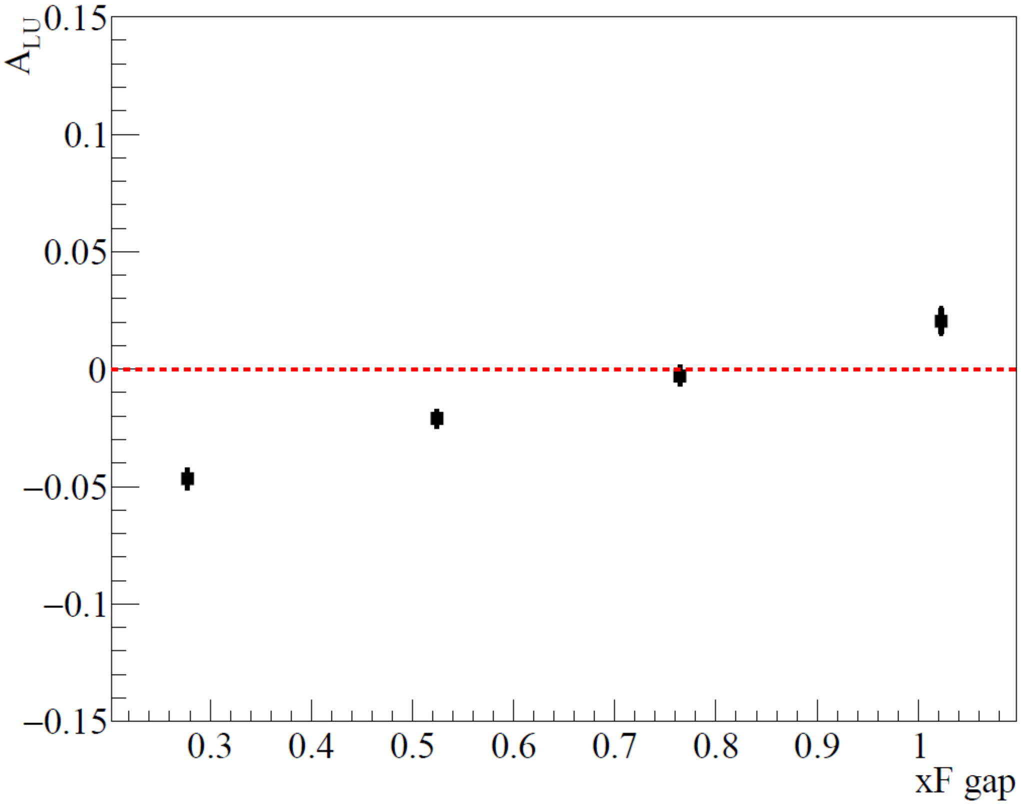
- strong dependence on the product of p_T of the gap → high gap region corresponds to low p_T product, and so the asymmetry moment is low



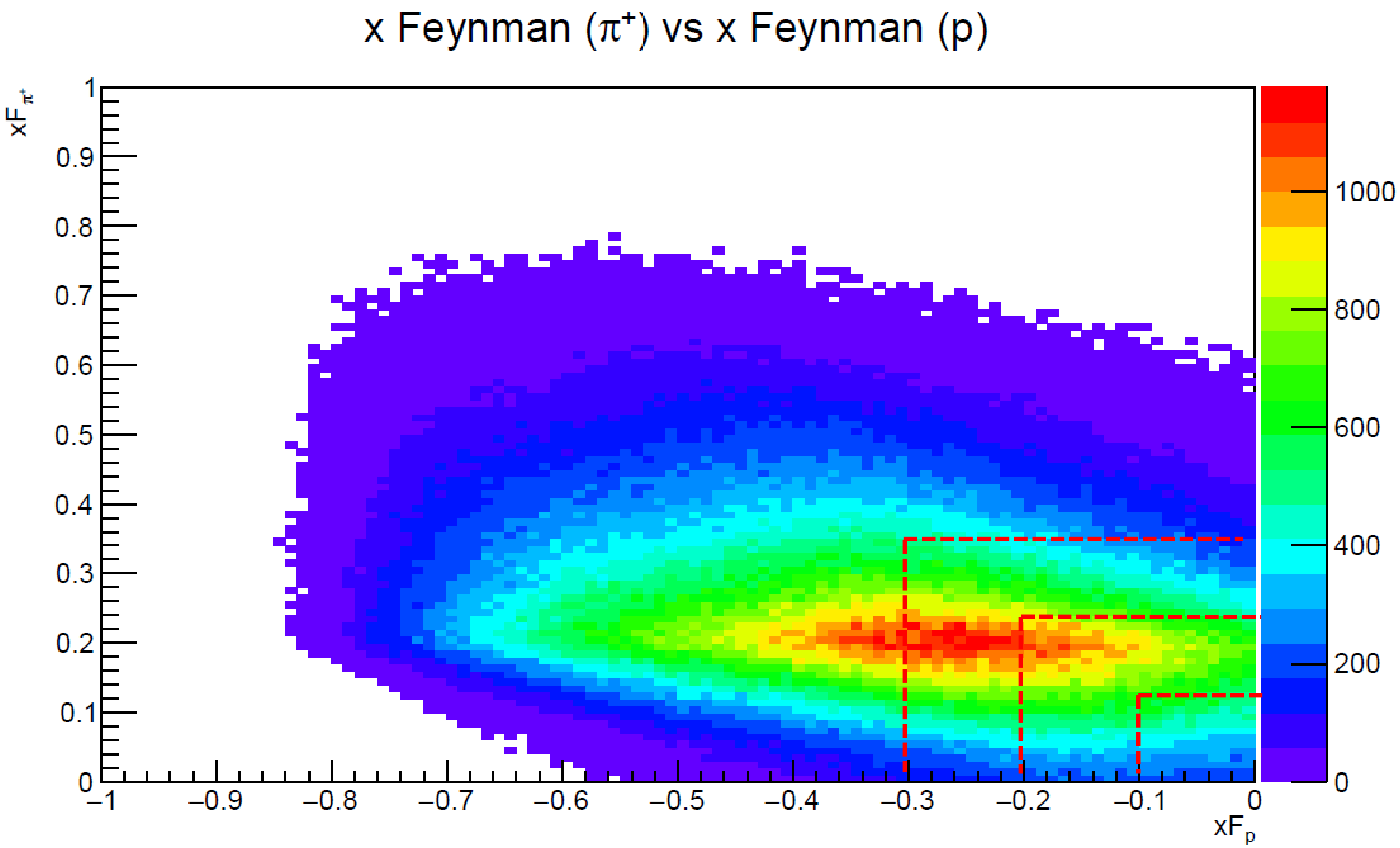
- a change of sign is observed when the distance among the particles on x_F goes beyond 0.8

- need theoretical understanding

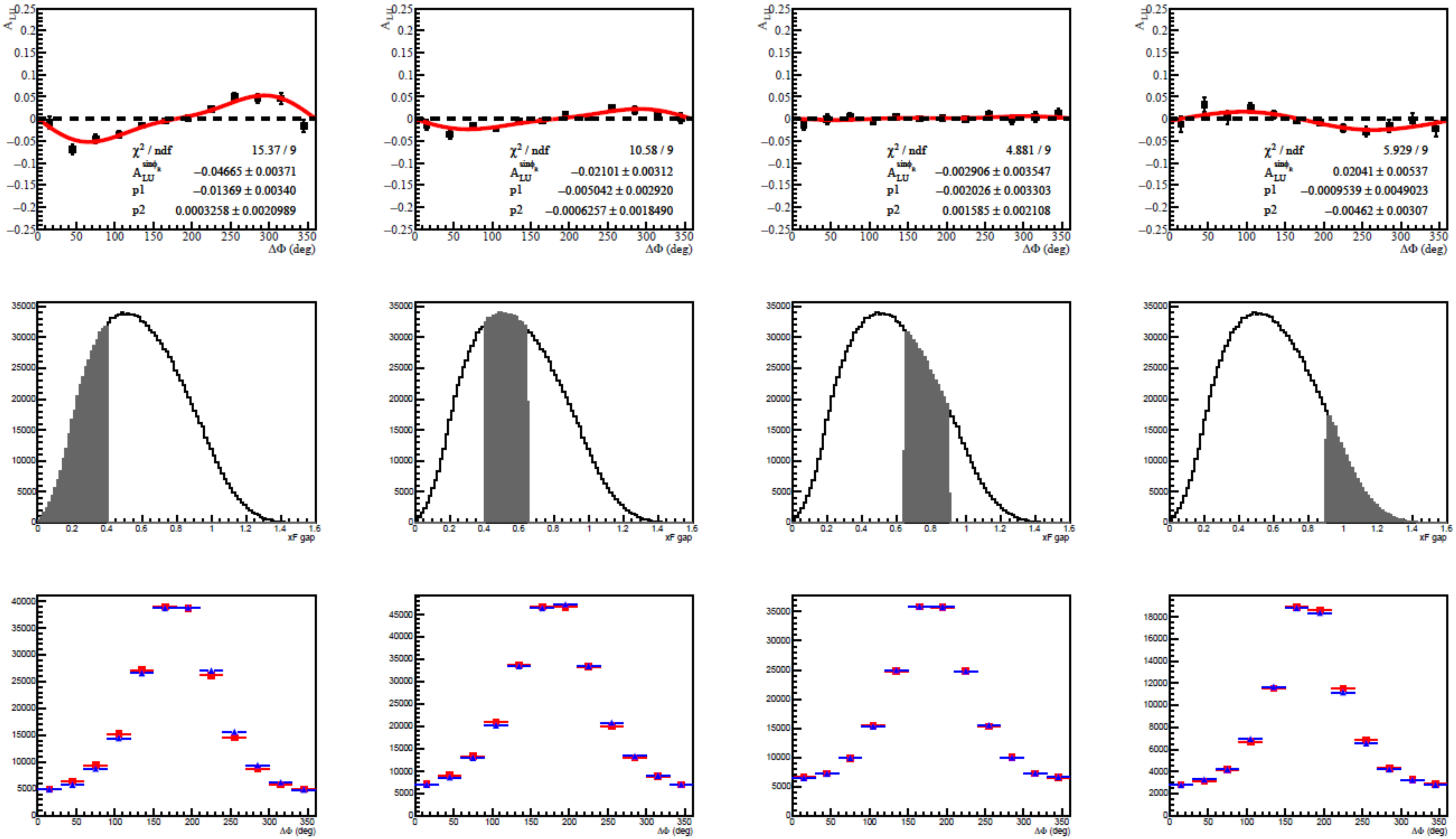
- a symmetric cut on x_F is being explored



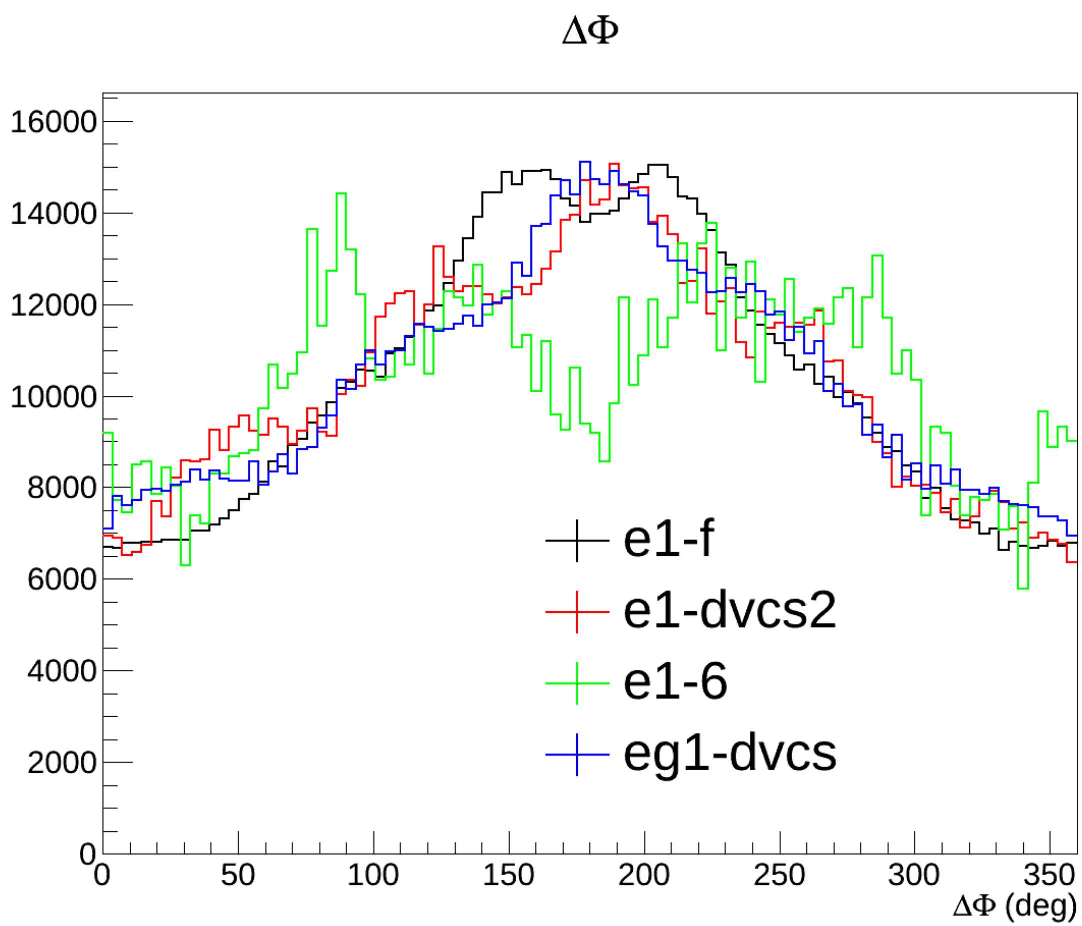
Dependence on a symmetric x_F gap



Back-to-back pion and proton: x_F-gap = $x_F(\pi^+) - x_F(p)$



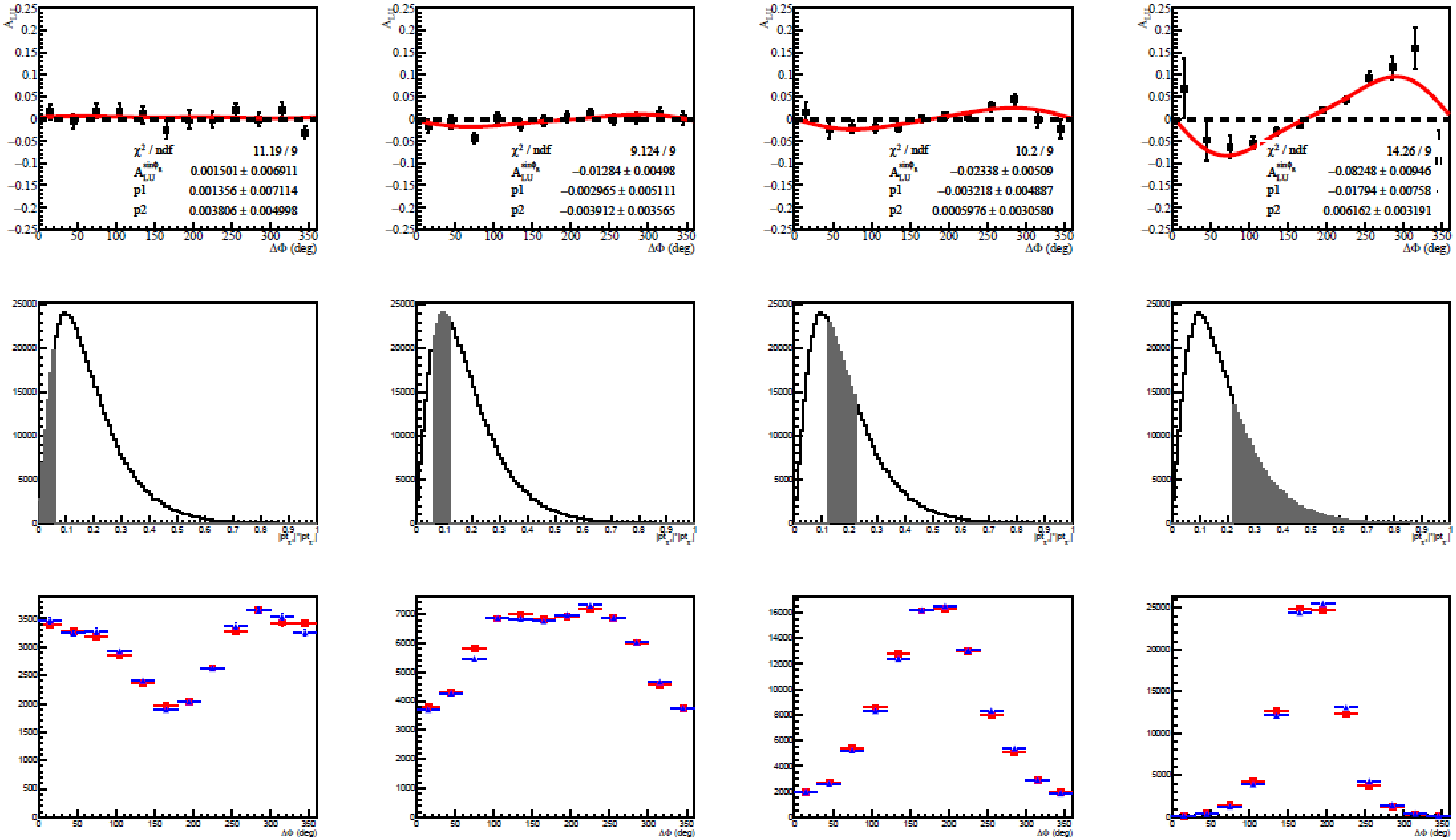
Δφ coverage



- e1-f: unpolarized hydrogen target @-25 cm
- e1-6: unpolarized hydrogen target @-4 cm
- e1-dvcs: unpolarized hydrogen target @-57 cm
- eg1-dvcs: longitudinally polarized $^{14}NH_3$target @-67(-57) cm

1. Good Δφ coverage in all the data sets
2. Different observables accessible by combining the available beam/target polarization configurations
3. Hydrogen *vs.* nuclear target

Back-to-back $ep \to ep\pi^+X$: $|p_{T1}||p_{T2}|$ on NH3 (eg1dvcs)



Target Fragmentation Functions

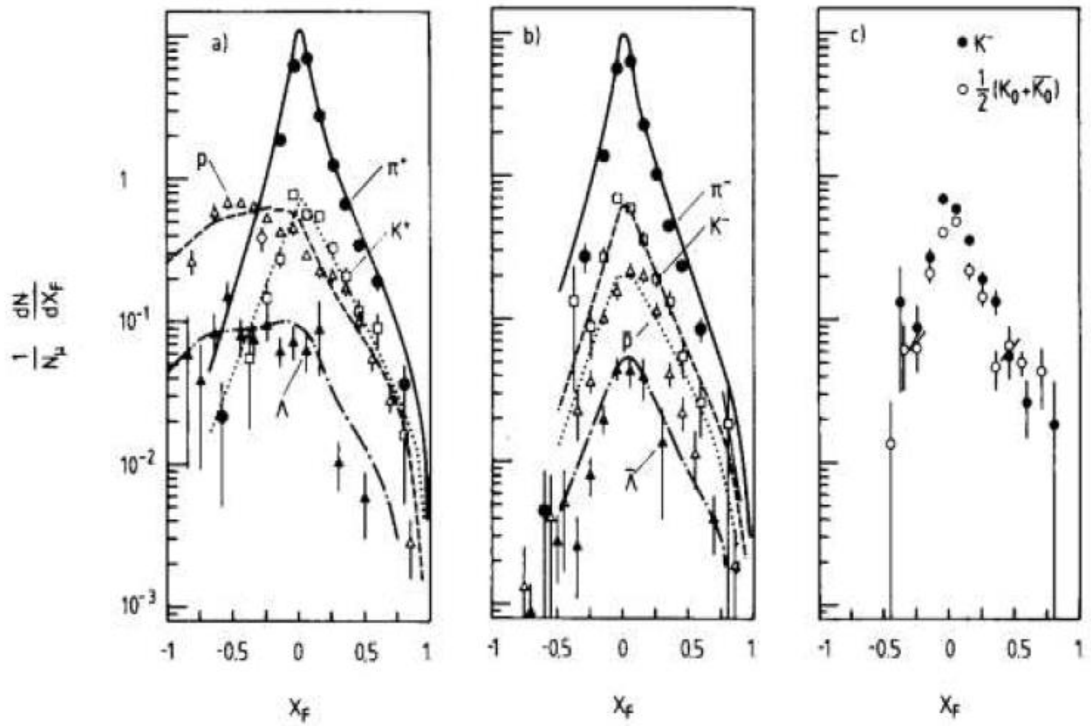


Figure 3: *Feynman x distributions normalized to the number of scattered muons measured by EMC [19] for positive and negative hadrons. (a)* π^+, K^+, *p and* Λ, *(b)* π^-, K^-, $\bar{p}$ *and* $\bar{\Lambda}$, *(c)* K^- *and* $(K^0+\bar{K}^0)/2$. *The curves represent the predictions of the Lund model.*

Structure Functions

$$\mathcal{F}_{UU} = \mathcal{C}[\hat{u}_1 D_1],$$

$$\mathcal{F}_{UU}^{\cos(\phi_1+\phi_2)} = \frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_1 m_2}\mathcal{C}[w_1 \hat{t}_1^h H_1^\perp],$$

$$\mathcal{F}_{UU}^{\cos(2\phi_1)} = \frac{\boldsymbol{P}_{1\perp}^2}{m_1 m_N}\mathcal{C}[w_2 \hat{t}_1^\perp H_1^\perp],$$

$$\mathcal{F}_{UU}^{\cos(2\phi_2)} = \frac{\boldsymbol{P}_{2\perp}^2}{m_1 m_2}\mathcal{C}[w_3 \hat{t}_1^h H_1^\perp] + \frac{\boldsymbol{P}_{2\perp}^2}{m_1 m_N}\mathcal{C}[w_4 \hat{t}_1^\perp H_1^\perp],$$

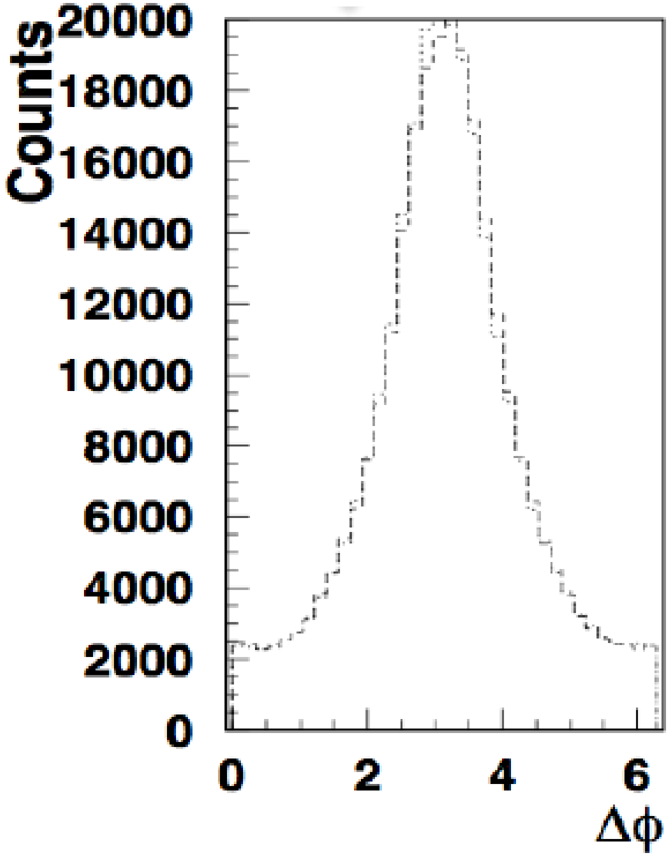
$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\mathcal{C}[w_5 \hat{l}_1^{\perp h} D_1],$$

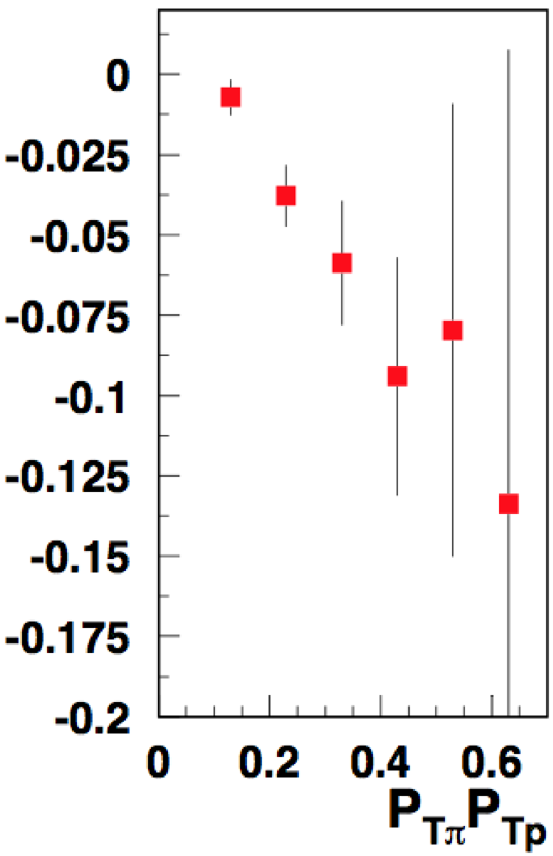
Back-to-back $ep \rightarrow ep\pi^+X$: $|p_{T1}||p_{T2}|$ on H2 (e16)

Parallel analysis by Harut on e16 data set:

- different target position with respect to e1f (- 4 cm instead of -25 cm)
- different torus
- coverage extended to high Q^2

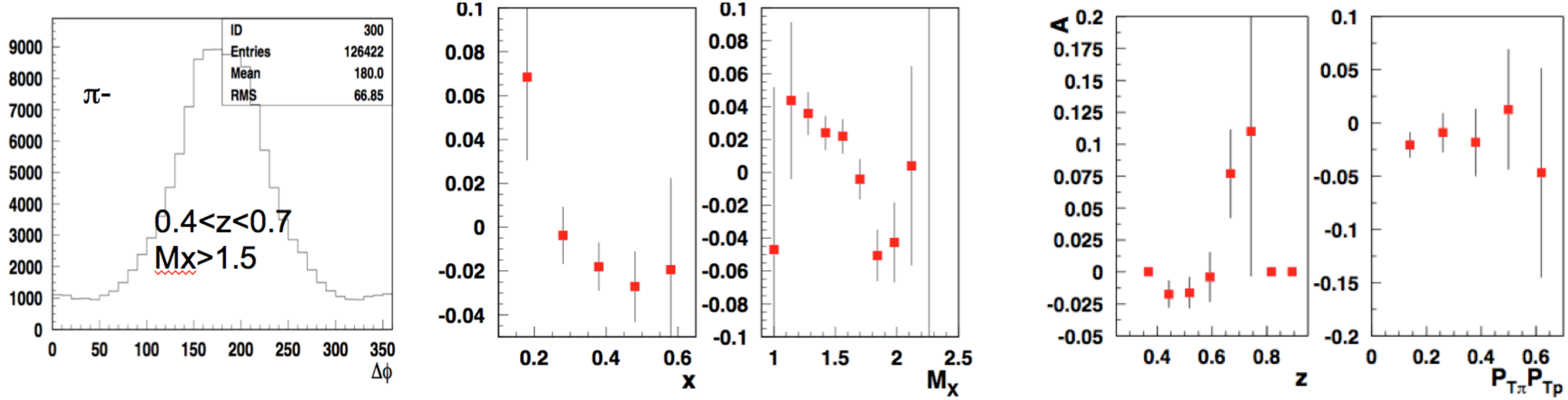
The measurements on the two hydrogen data sets can be combined

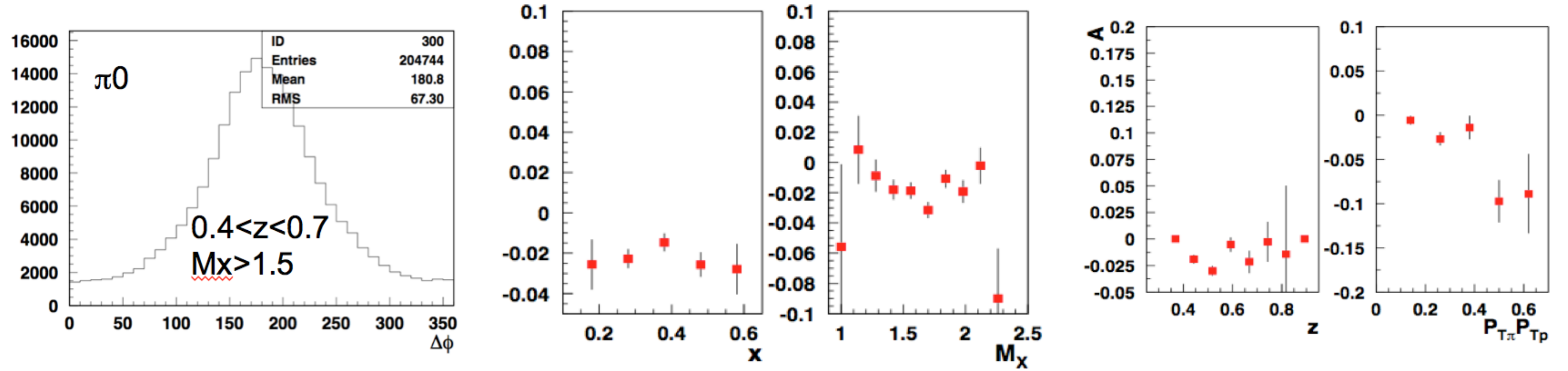




Analysis by Harut Avakian

Back-to-back $ep \to ep\pi^{-/0}X$ on H2 (e16)





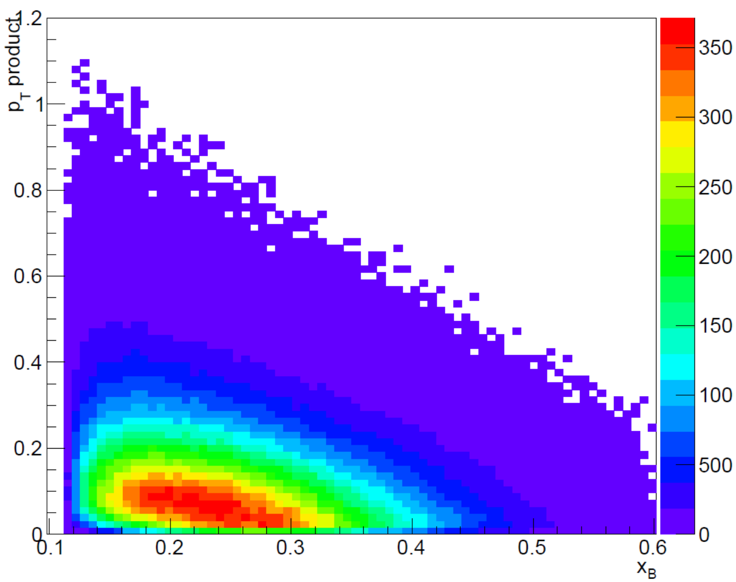
m_X is the missing mass of the $(e\pi)$ system

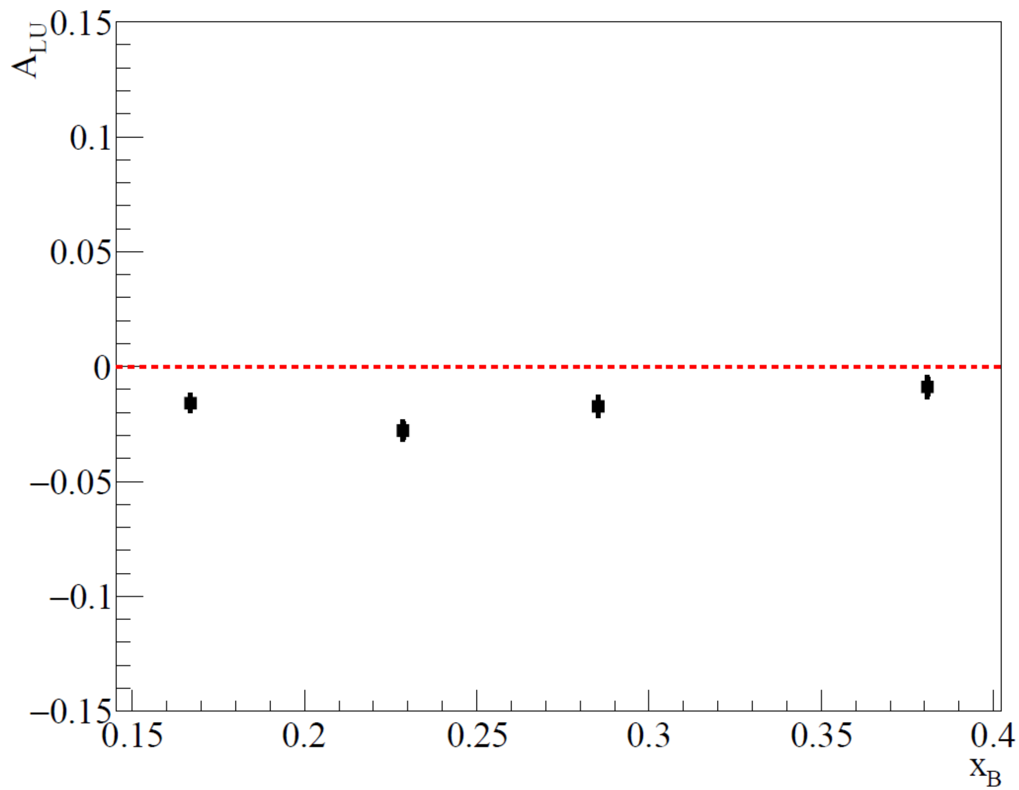
Analysis by Harut Avakian

Back-to-back pion and proton: x_B dependence

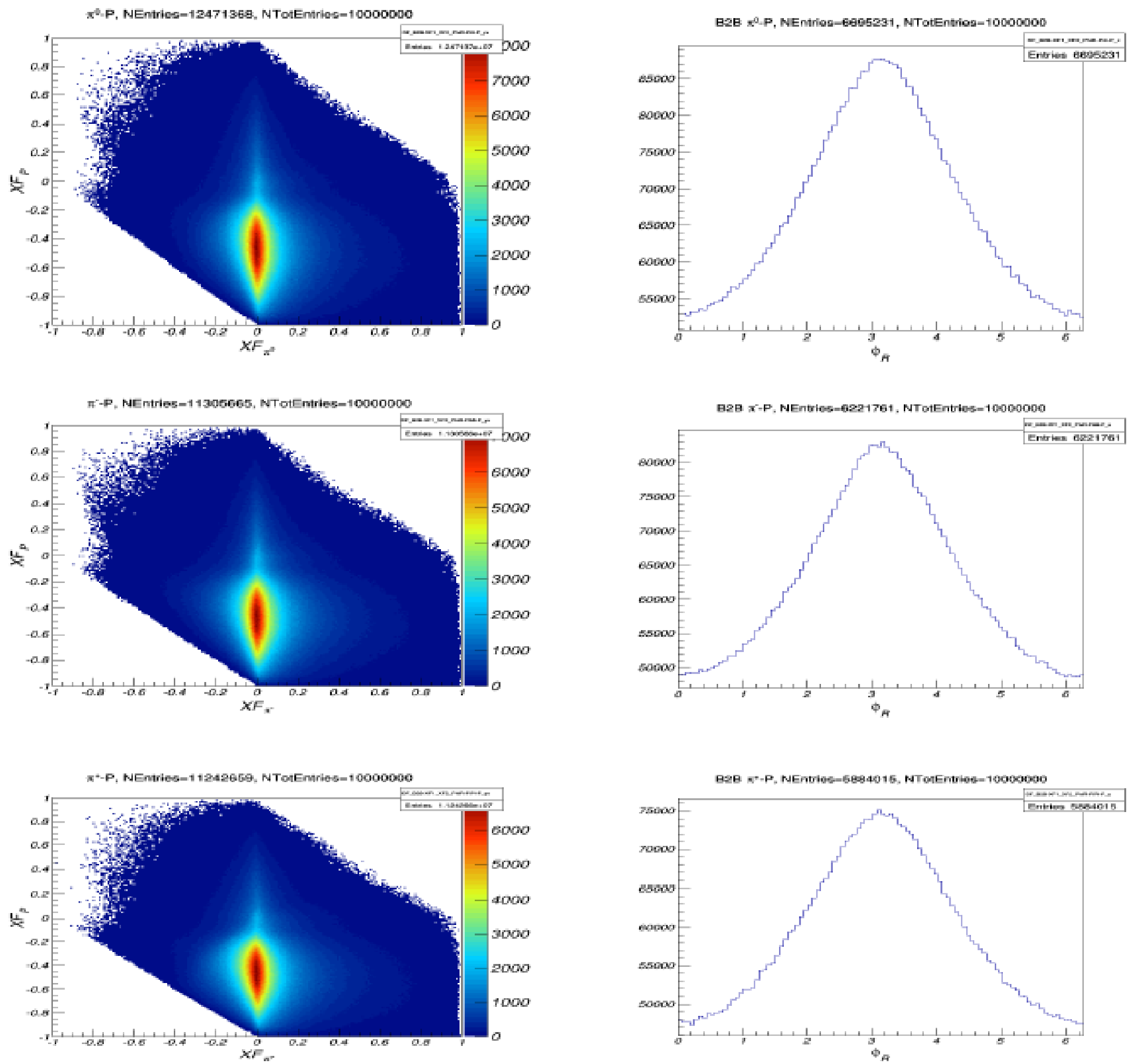
1D binning on x_B doesn't show any strong dependence since it integrates over a wide p_T product range

→ test of a 2D dependence





Back2back SIDIS@EIC

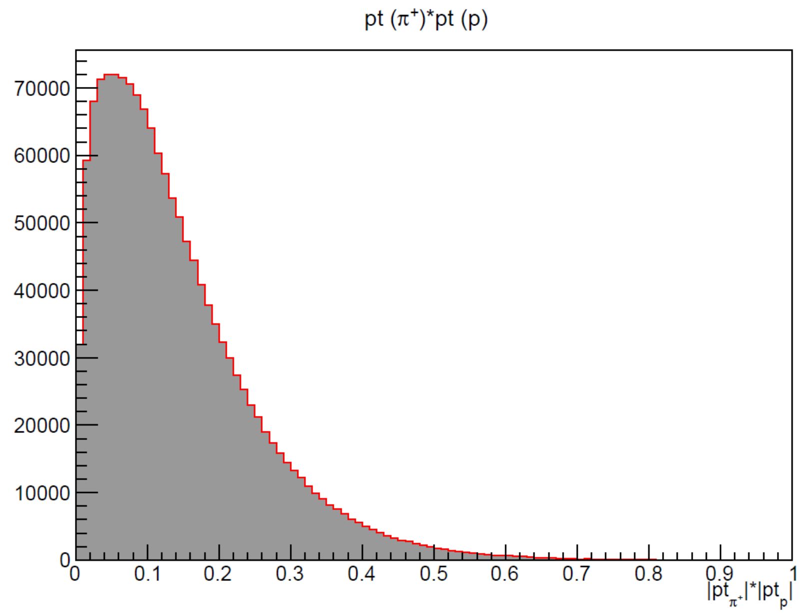


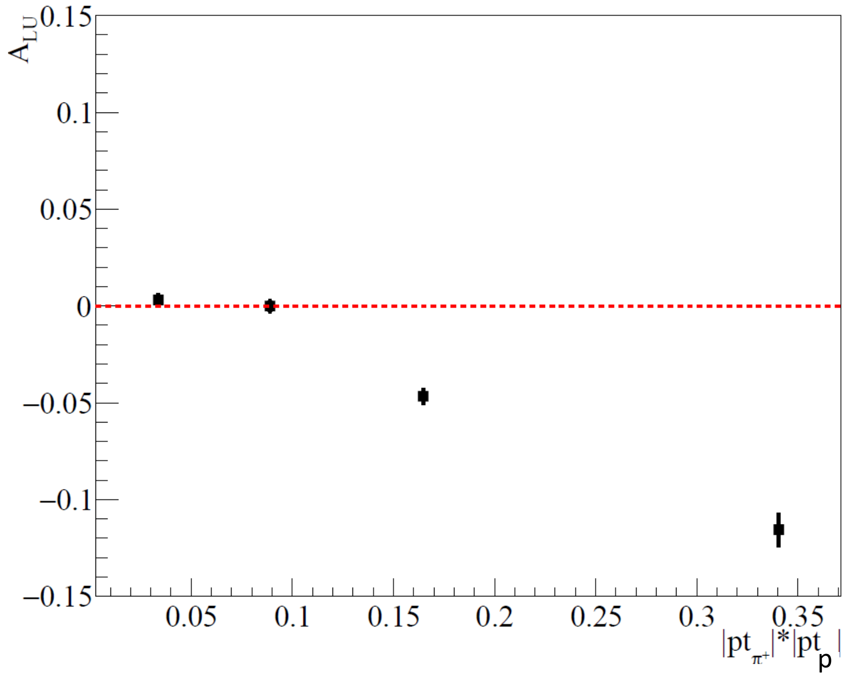
Back-to-back pion and proton: $|p_{T1}||p_{T2}|$ dependence

Expected dependence of the $\sin\Delta\varphi$ moment on $|p_{T1}||p_{T2}|$ observed on data:

- kinematical suppression at low $|p_{T1}||p_{T2}|$
- almost linear dependence
- 2D binning ($|p_{T1}||p_{T2}|, z$) → z-dependence of D_1

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

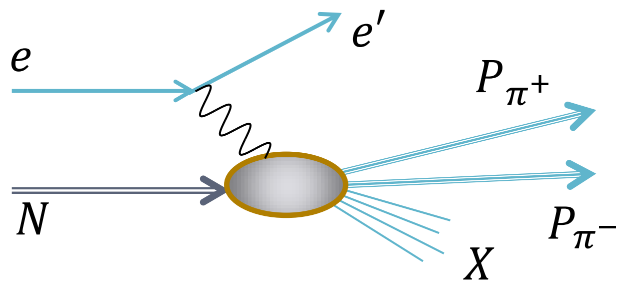




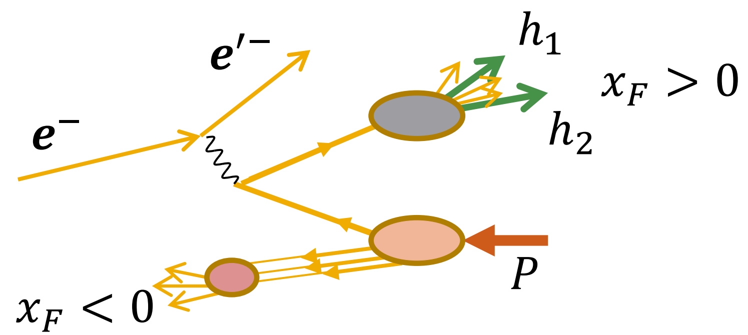
Semi-Inclusive electroproduction of two hadrons

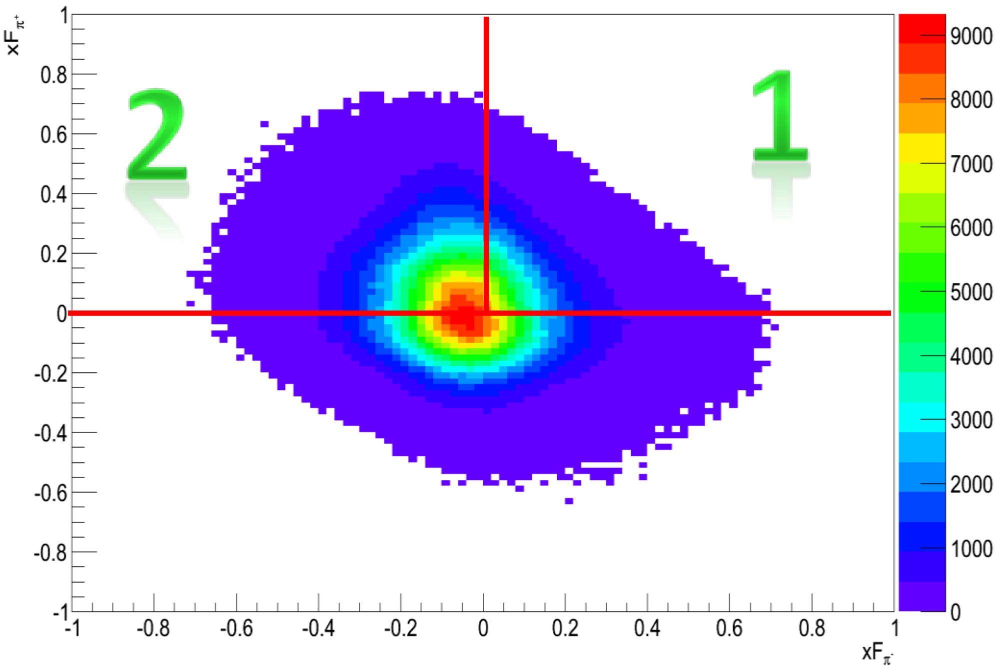
$e\,p \rightarrow e\,\pi^+\pi^- X$

→ x-Feynman «controls» the hadron origin



$$x_F = \frac{2p_\parallel}{W}$$

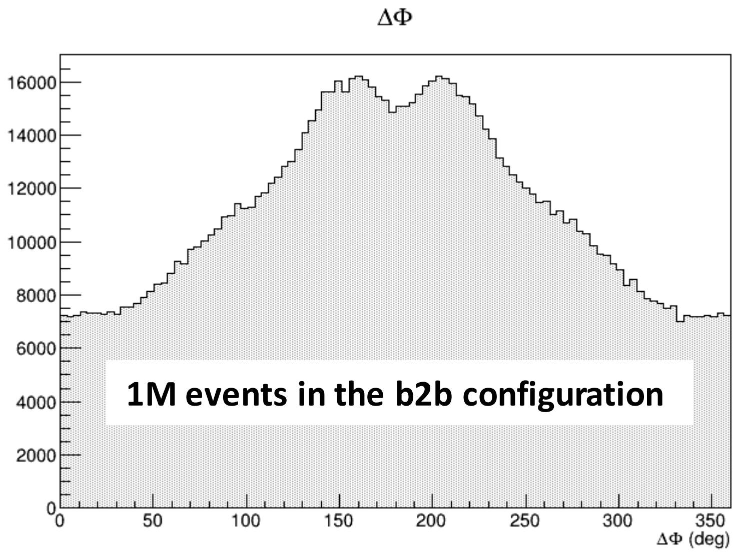


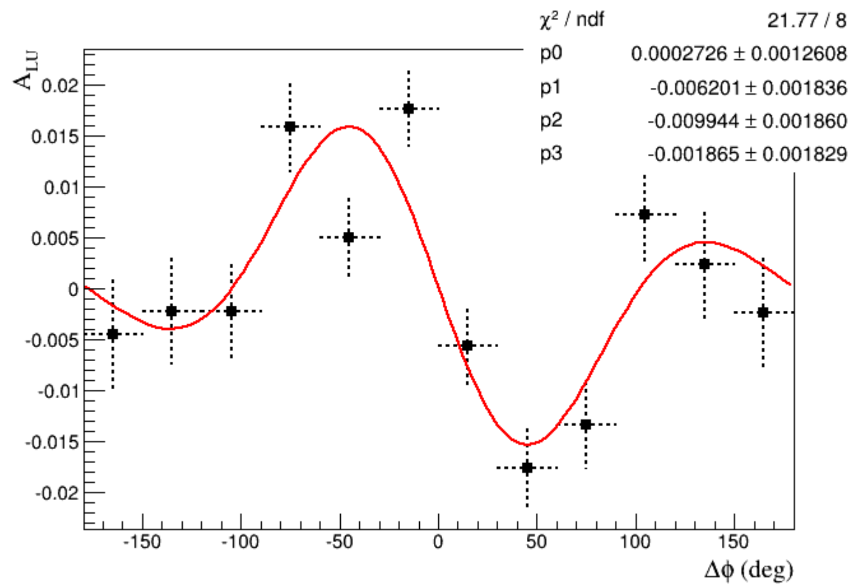


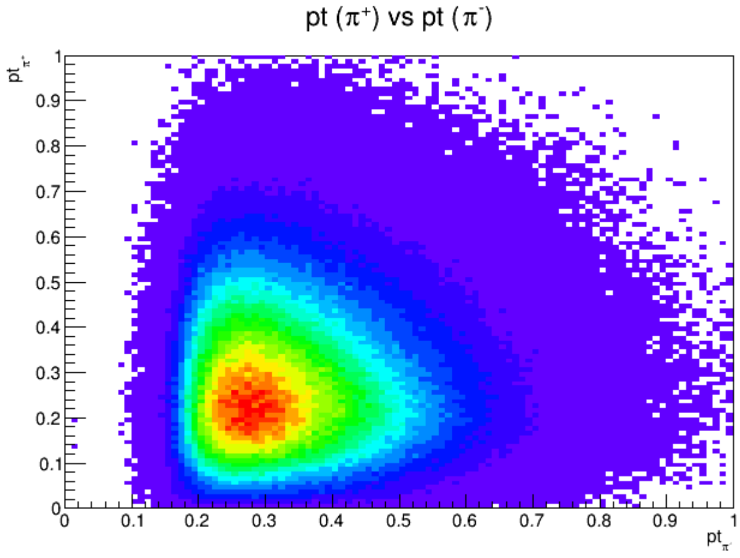
1. $x_{F1} > 0, x_{F2} > 0$: fragmentation of one single quark in the two final hadrons ,dedicated (*Interference*) Fragmentation Functions. → ***See A. Courtoy talk***

2. $x_{F1} > 0, x_{F2} < 0$: the two final hadrons come from two different (but correlated?) quarks

Beam-Spin Asymmetry: first observation







$$p_0 + p_1 \sin\Delta\varphi + p_2 \sin 2\Delta\varphi + p_3 \sin 3\Delta\varphi$$

1. Modulations observed as the theory predicts → $\sin\Delta\varphi$, $\sin 2\Delta\varphi$ dominant terms
2. Present statistics should allow to explore A_{LU} dependence on p_{T1}, p_{T2} → effect should vanish as they tend to zero