

# A Novel Target-Fragmentation Approach to Identifying Exclusive Vector Meson Production in SIDIS

**FATIHA BENMOKHTAR**

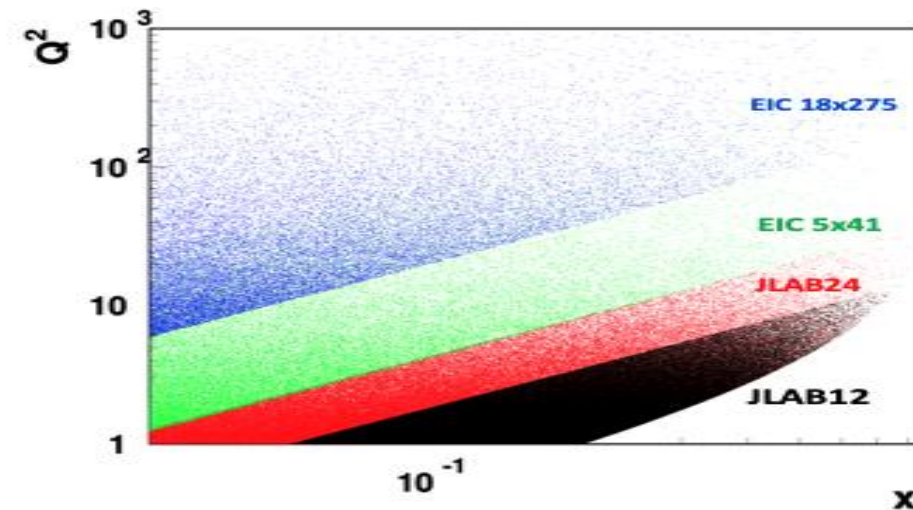
With: H. Avakian (Jefferson Lab),  
T. Hayward (UConn)

And many, many undergraduate students (>20)!

D. Terrero Cepeda, H. Valenty, N. Nicholson, N. Carpenter, B. Williams, etc...

# DIS kinematical coverage and observables

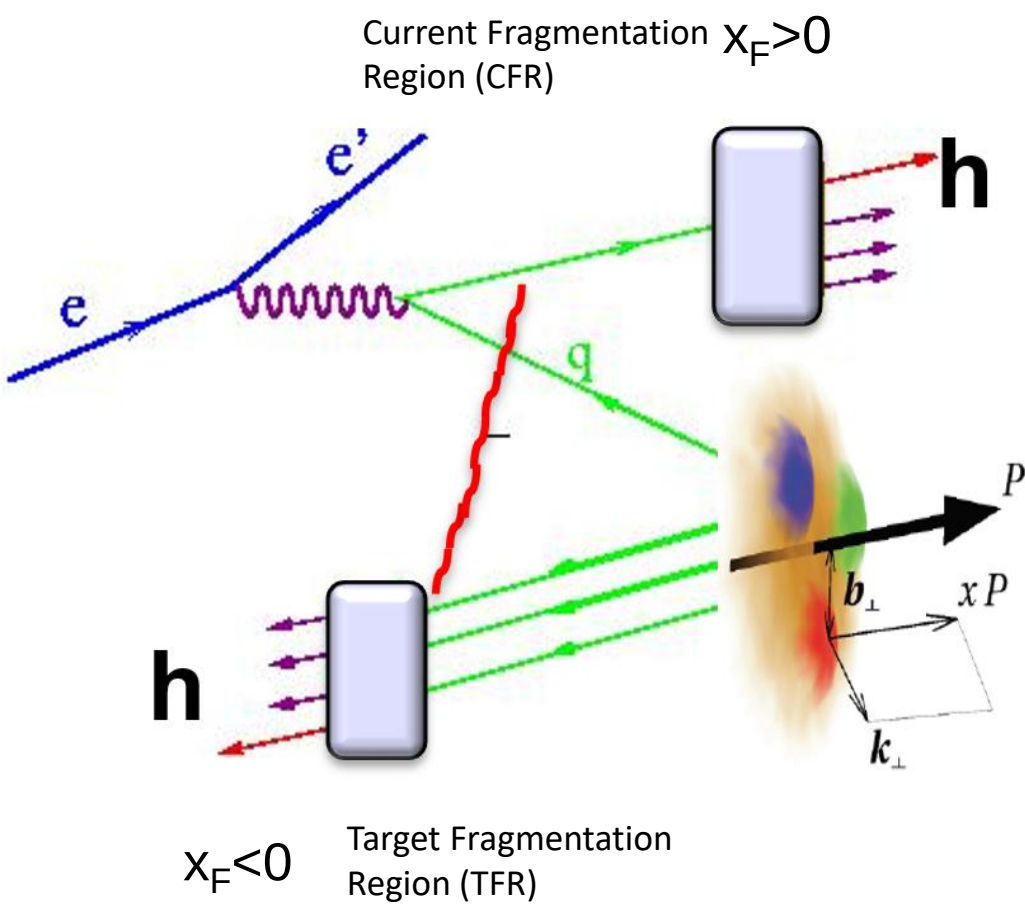
$$z = E_h / v$$



Azimuthal modulations provide access to QCD dynamics in general, and spin-orbit correlations, in particular

$$\begin{aligned} & \frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} \\ &= \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1-\varepsilon)} \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} \right. \\ &+ \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} + S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \\ &+ S_L \lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \\ &+ S_T \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} \right. \\ &+ \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} \\ &+ \left. \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] + S_T \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} \right. \\ &+ \left. \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \Big\} \end{aligned}$$

# 3D PDFs: Hadron production in electroproduction



## Study

|  |                                                                                                                                                                  |
|--|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | $x, Q^2, z, P_T, \phi, \phi_S \quad \sim 1/Q^4$<br><b>SIDIS</b> $\rightarrow$ Flavor and polarization dependence of transverse momentum distributions            |
|  | $x, Q^2, t, \phi, \phi_S + \phi, \theta \quad \sim 1/Q^6$<br><b>Exclusive</b> $\rightarrow$ Flavor and polarization dependence of transverse space distributions |
|  | <b>Back2Back</b> $\rightarrow$ correlations and entanglement of CFR and TFR, controlling CFR, allowing access to GPDs and GTMDs                                  |

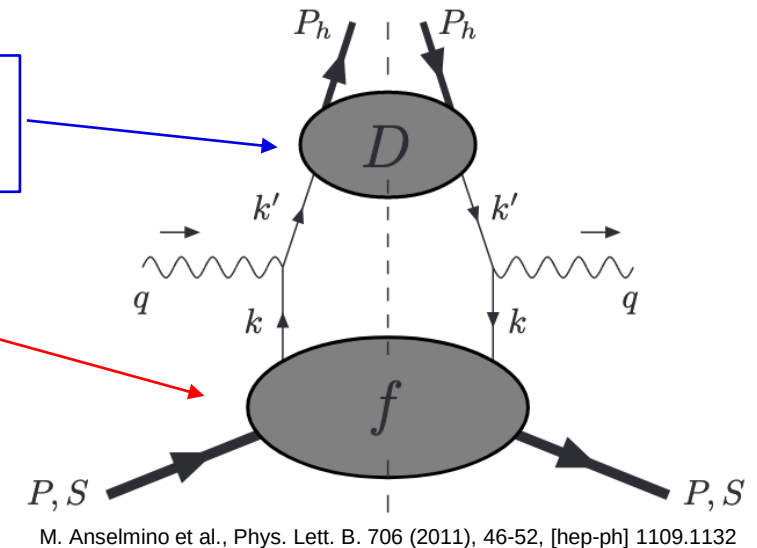
- Different non-perturbative objects may be involved with several independent variables involved
- Cross contributions make studies based on a given set of assumptions challenging

# Traditional SIDIS Measurements

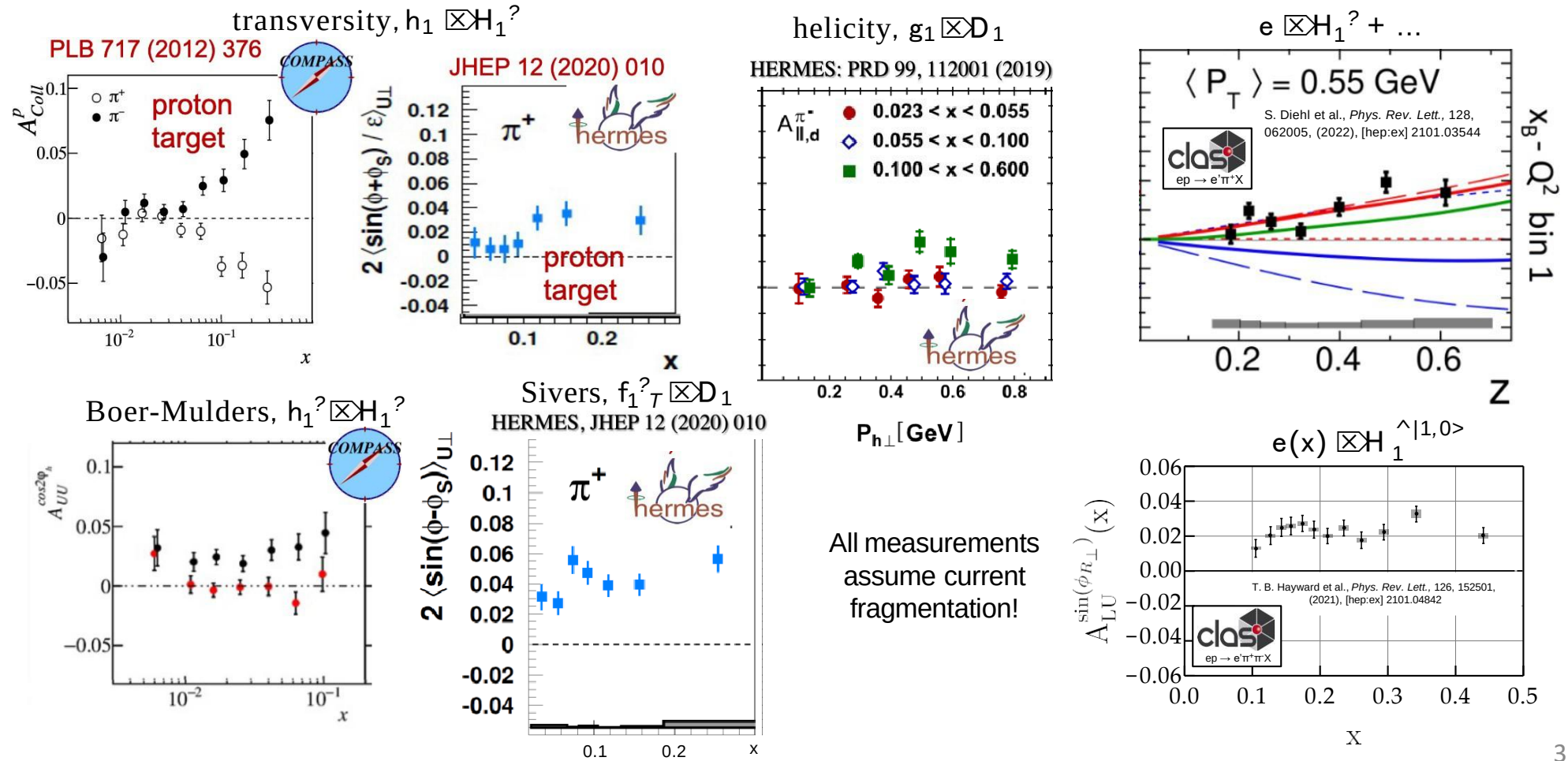
- Decades of study have led to detailed mappings of the momentum distribution of partons in the nucleon in terms of 1-D and 3-D transverse-momentum dependent parton distribution functions (TMDs).
- SIDIS measurements rely on the assumption that measured hadrons are produced in the CFR.
- Cross section factorized as a convolution of PDFs and Fragmentation Functions (FFs)<sup>1</sup>.

$$\frac{d\sigma^{\text{CFR}}}{dx_B dy dz_h} = \sum_a e_a^2 \boxed{f_a(x_B)} \frac{d\hat{\sigma}}{dy} \boxed{D_a(z_h)}$$

- **PDFs**
  - Confined motion of quarks and gluons inside the nucleus
  - Orbital motion of quarks, correlations between quarks and gluons
- **Fragmentation Functions**
  - Probability for a quark to form particular final state particles
  - Insight into transverse momenta and polarization



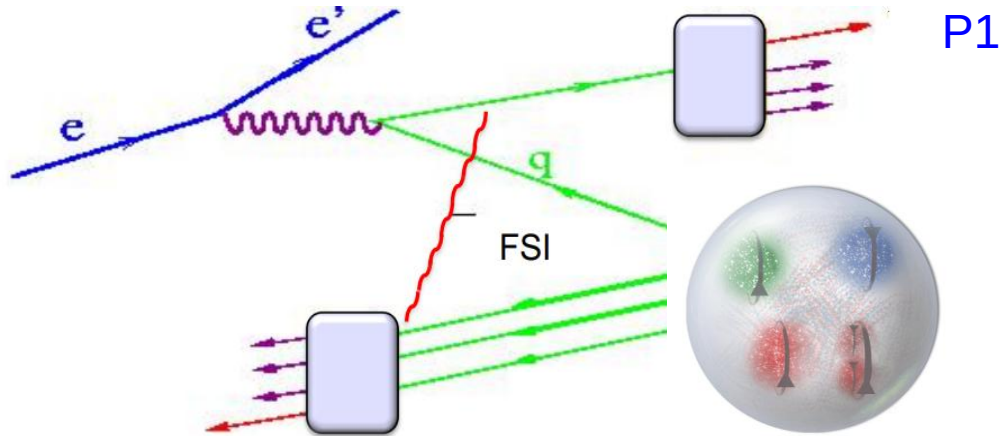
# Decades of Progress...



3

# The Neglected Hemisphere – Target Fragmentation

Current fragmentation,  $x_F > 0$

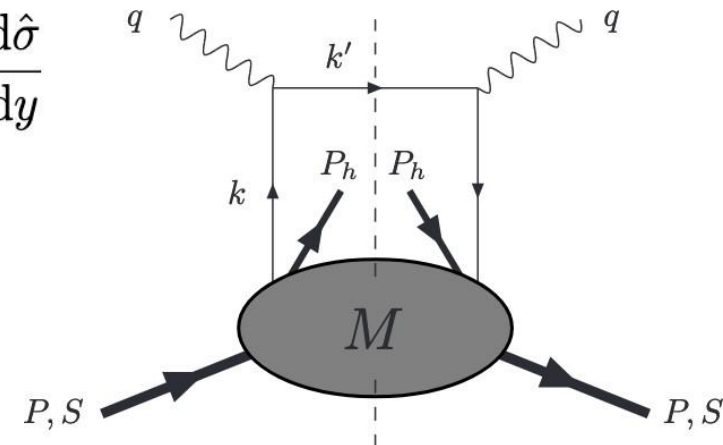


- TMDs and **Fragmentation Functions** have been extensively studied through azimuthal modulations of a final-state hadron (**P1**) generated in the fragmentation of a struck quark (**CFR**).

- Final-state hadrons can also form from the leftover target remnant (**TFR**), whose partonic structure is defined by “**Fracture Functions**”: the probability of forming a certain hadron (**P2**) given a particular ejected quark.

**P2**  
Target fragmentation,  $x_F < 0$

$$\frac{d\sigma^{\text{TFR}}}{dx_B dy dz} = \sum_a e_a^2 (1 - x_B) M_a(x_B, (1 - x_B)z) \frac{d\hat{\sigma}}{dy}$$



Karliner, Kharzeev, Ellis & Kotzinian, Strikman, Weiss & Schweitzer, Anselmino, Barone, Kotzinian

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

L. Trentadue and G. Veneziano, Phys. Lett. B323 (1994) 201,  
M. Anselmino et al., Phys. Lett. B. 699 (2011), 108-118, [hep-ph] 1102.4214  
TFR/CFR Fig. from EIC Yellow Report, (2021) [physics.ins-det] 2103.05419

# Analogs to PDFs (Thanks to T. Hayward)

- A direct relationship exists to the eight leading twist PDFs after the fracture functions are integrated over the fractional longitudinal nucleon momentum.

$$z(1-x) = \boxed{E_h/E = \zeta}$$

$$\sum_h \int d\zeta M_a(x_B)(x_B, k_\perp^2, \zeta) = (1-x_B) f_a(x_B, k_\perp^2)$$

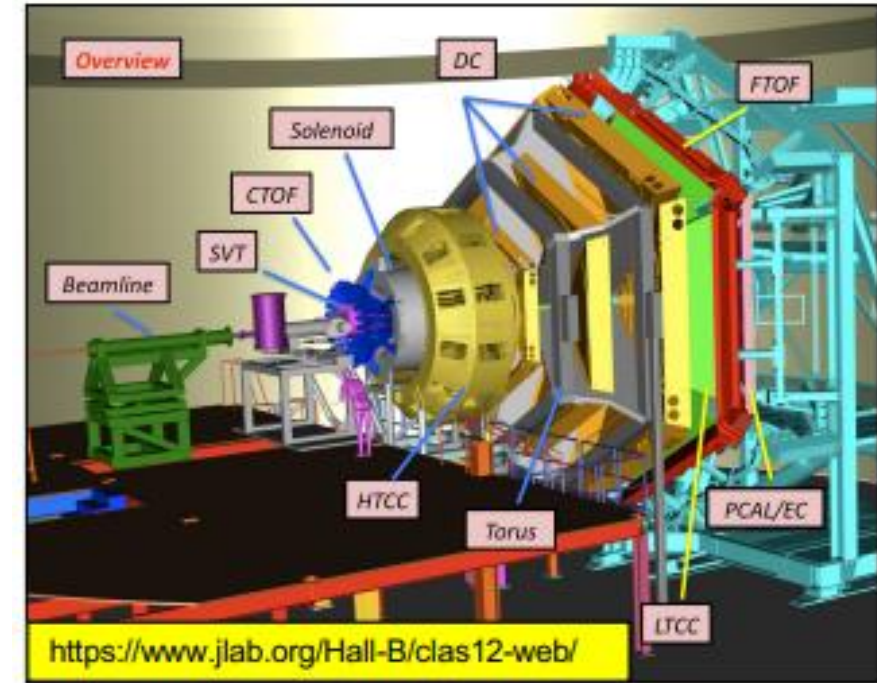
M. Anselmino et al., Phys. Lett. B. 699 (2011), 108, [hep-ph] 1102.4214

|                      |   | Quark polarization |          |                     |                        |  | Quark polarization |                                      |                                                                                                                                |
|----------------------|---|--------------------|----------|---------------------|------------------------|--|--------------------|--------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|
|                      |   | U                  | L        | T                   |                        |  | U                  | L                                    | T                                                                                                                              |
| Nucleon polarization | U | $f_1$              |          | $h_1^\perp$         | Unpolarized PDF analog |  | U                  | $\hat{u}_1$                          | $\hat{l}_1^\perp h$ , $\hat{t}_1^h, \hat{t}_1^\perp$                                                                           |
|                      | L |                    | $g_{1L}$ | $h_{1L}^\perp$      |                        |  | L                  | $\hat{u}_{1L}^\perp h$               | $\hat{l}_{1L}^h$ , $\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$                                                                        |
|                      | T | $f_{1T}^\perp$     | $g_{1T}$ | $h_1, h_{1T}^\perp$ | etc. etc.              |  | T                  | $\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$ | $\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$ , $\hat{t}_{1T}^h, \hat{t}_{1T}^\perp, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$ |
|                      |   |                    |          |                     |                        |  |                    |                                      |                                                                                                                                |

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

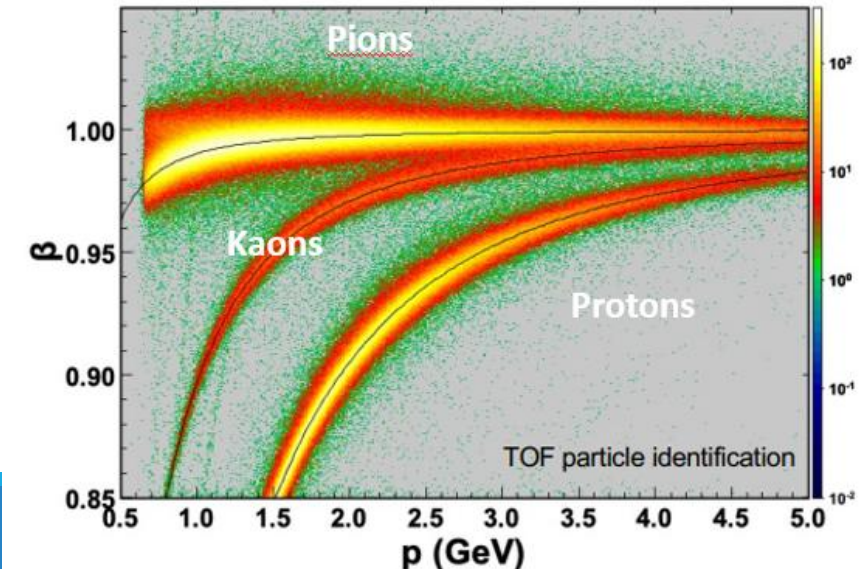
# Study possible at JLab!

## CLAS12 at Jefferson Lab



T. Hayward, M.I.T

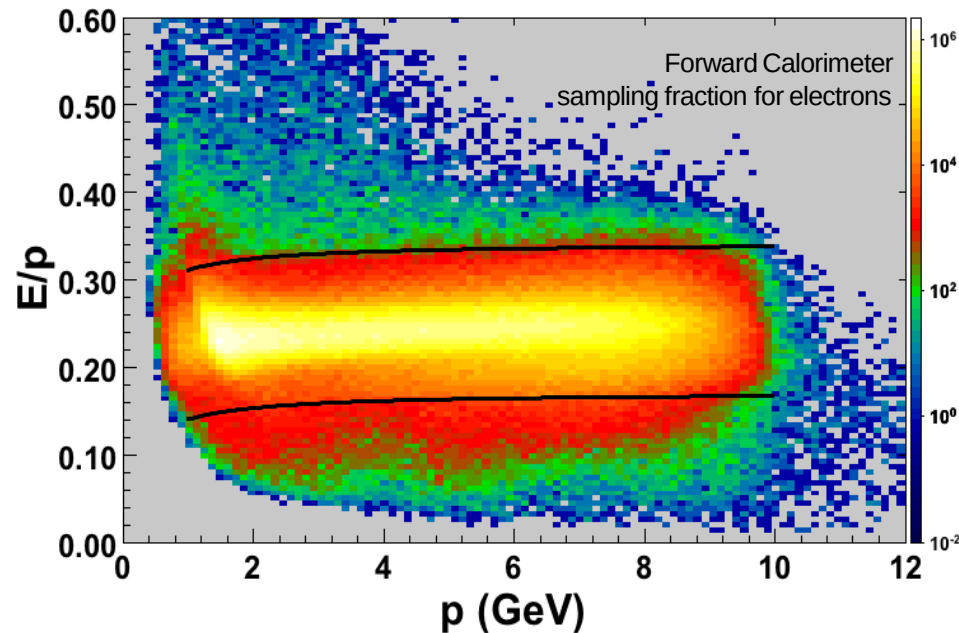
- RGA Data taken in fall 2018 and Spring 2019 with 10.6 and 10.2 GeV longitudinally polarized electron beam and **unpolarized LH2 target**. The full data set has been analyzed (e-pol ~86.5%)
- $ep \rightarrow e'p' + X$ , using only forward detector larger proton\_theta
- Fiducial cuts, channel selection vertex cut, Eloss, bin migration study, were performed. RGA PASS2



# Particle ID

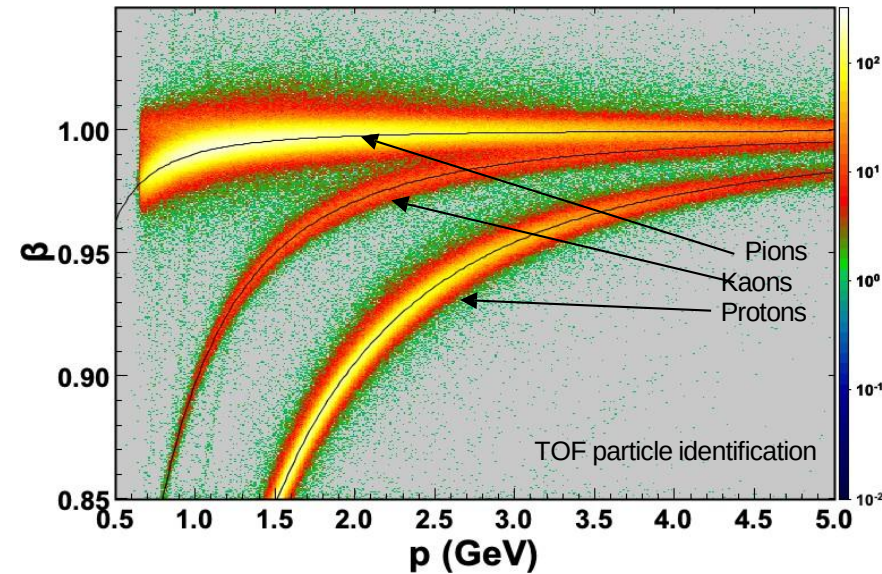
- **Electron**

- Electromagnetic calorimeter.
- Cherenkov detector.
- Vertex and fiducial cuts.



- **Hadron**

- $\beta$  vs  $p$  comparison between vertex timing and event start time.
- 100 ps TOF resolution.
- Vertex and fiducial cuts.



# SIDIS Observables at CLAS12 (T. Hayward)

## Run Group A (Unpolarized LH<sub>2</sub> target )

- ★ unpolarized SIDIS cross section off proton
- ★  $A_{LU}$  in Beam Spin Asymmetries

## Run Group B (Unpolarized LD<sub>2</sub> target )

- ★ Complementary to RG-A  
→ allow for *u/d* quark flavor separation

## Run Group C (longitudinally polarized NH<sub>3</sub> and ND<sub>3</sub> )

- ★  $F_{UL}$  and  $F_{LL}$

## Run Group K (Unpolarized LH<sub>2</sub> target)

- ★ 6.5, 7.5, 8.4 GeV e- beam
- ★  $F_{UU,L}$ ,  $F_{UU,T}$  Separation

## Run Group H (transversely polarized NH<sub>3</sub> )

- ★  $F_{UT}$  structure function

$$\frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right.$$

$$\left. + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} \right.$$

$$\left. + S_{\parallel} \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \right.$$

$$\left. + S_{\parallel} \lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \right.$$

$$\left. + |S_{\perp}| \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right. \right.$$

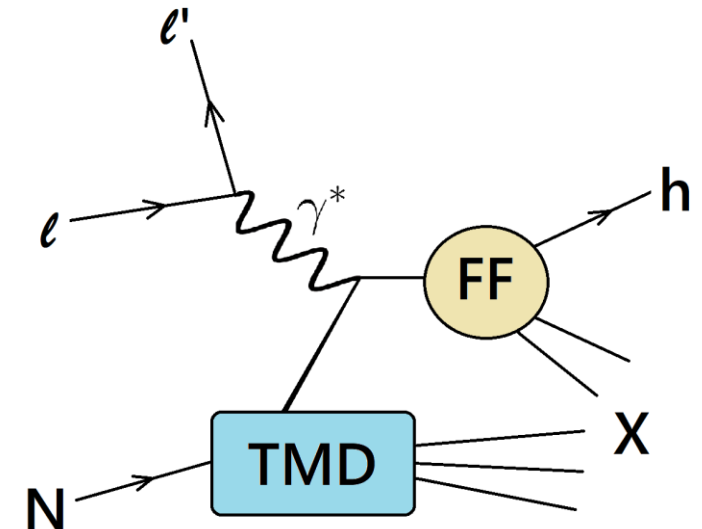
$$\left. + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \right.$$

$$\left. + \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right]$$

$$\left. + |S_{\perp}| \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \right. \right.$$

$$\left. + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \left. \right\}$$

The CLAS12 physics program will have access to the full SIDIS cross section including all observables in a variety of flavors.



# $\rho_0$ , the intruder in hadron detection in SIDIS

Example: Single  $\pi$  BSA. in the CFR, from S. Diehl,

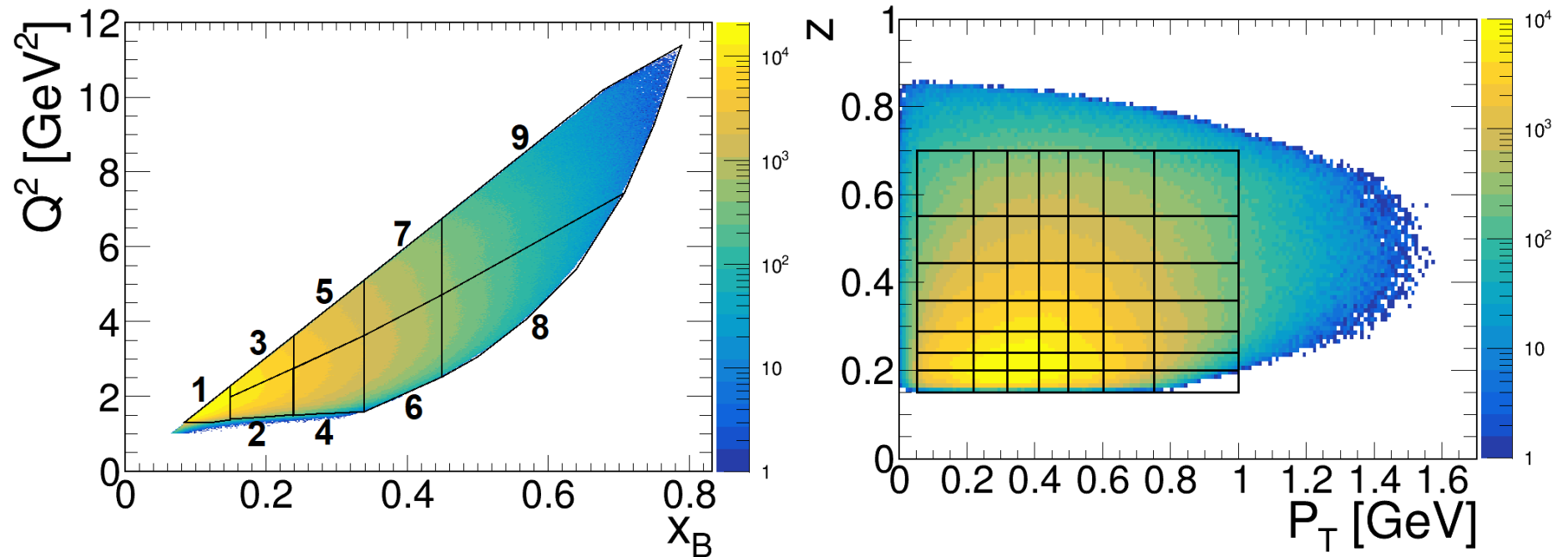
CLAS12: A multidimensional study in  $Q^2$ ,  $x_B$ ,  $z$  and  $P_T$  for  $\pi^\pm$ ,  $\pi^0$  and  $K^\pm$

$ep \rightarrow e\pi X$

$Q^2 > 1 \text{ GeV}^2$

$M_{e\pi X} > 1.5 \text{ GeV}$

$W > 2 \text{ GeV}$

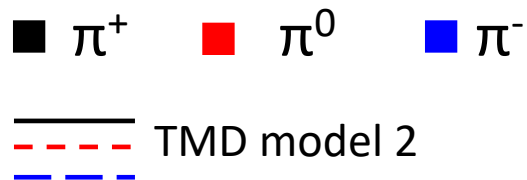
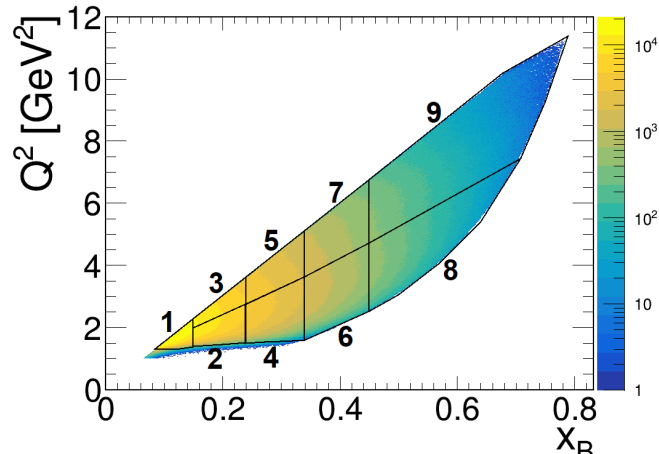


in total: 344 bins x 12 bins in  $\phi \rightarrow \sim 4130$  BSA bins

S. Diehl et al. (CLAS collab.) Phys. Rev. Lett. 128, 062005 (2022)

# Flavor Effects in Single Pion SIDIS

## $ep \rightarrow e\pi X$

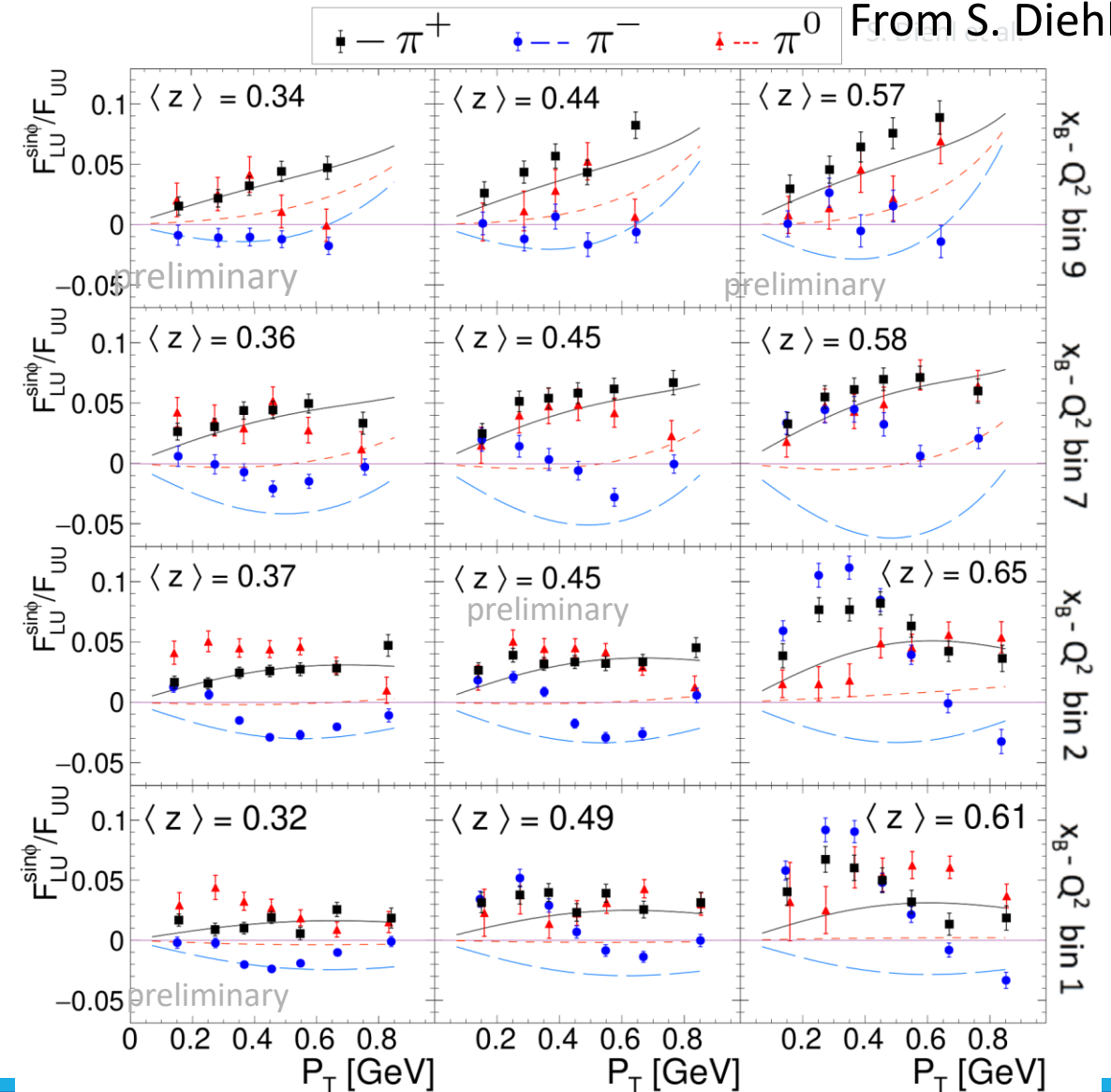


Significant differences in kinematics most affected by  $\rho$ os  $\rightarrow$  low  $P_T$  and large  $z$

S. Diehl et al. (CLAS collab.) Phys. Rev. Lett. 128, 062005 (2022)



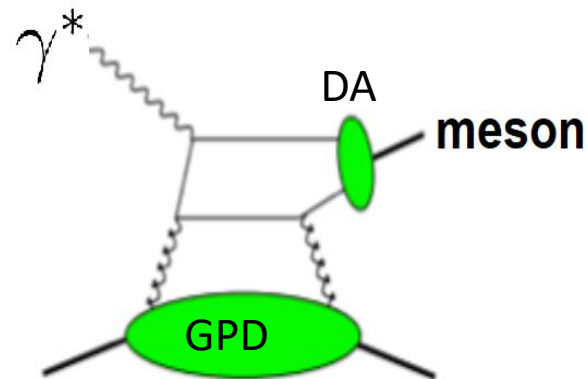
From S. Diehl



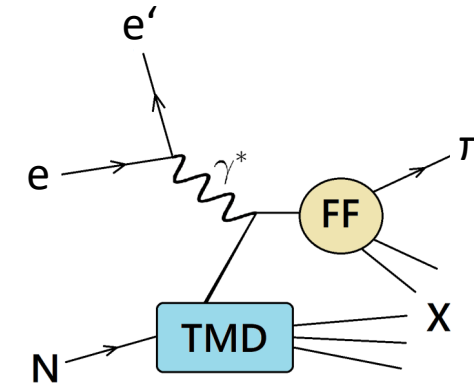
# Exclusive Contributions to the SIDIS Sample

- A TMD based description is only valid for pions from current fragmentation  
**BUT: The  $e\pi X$  sample contains also pions from exclusive processes**

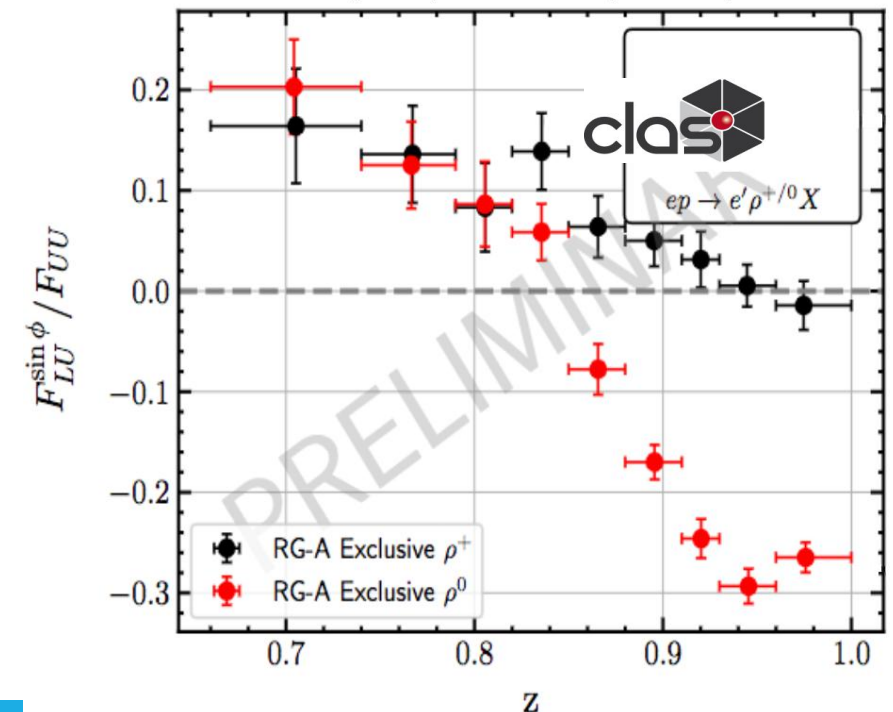
$$e p \rightarrow e' p \rho^0 \rightarrow e' p \pi^+ \pi^-$$



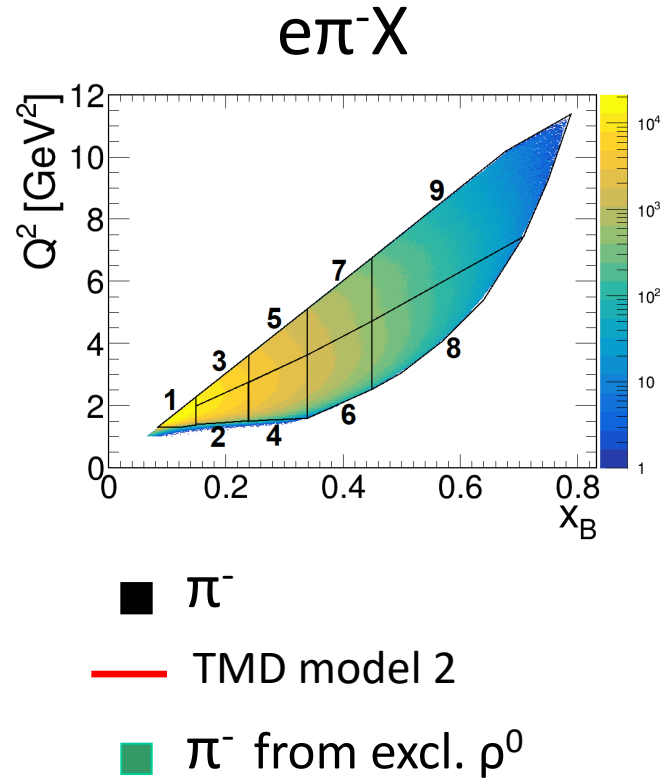
- Especially dominant at low  $-t$  / high  $z$
- Different mechanism in this region (gluon contributions to the GPDs)



G. Matousek (Duke) & N. Troppa (UCONN)

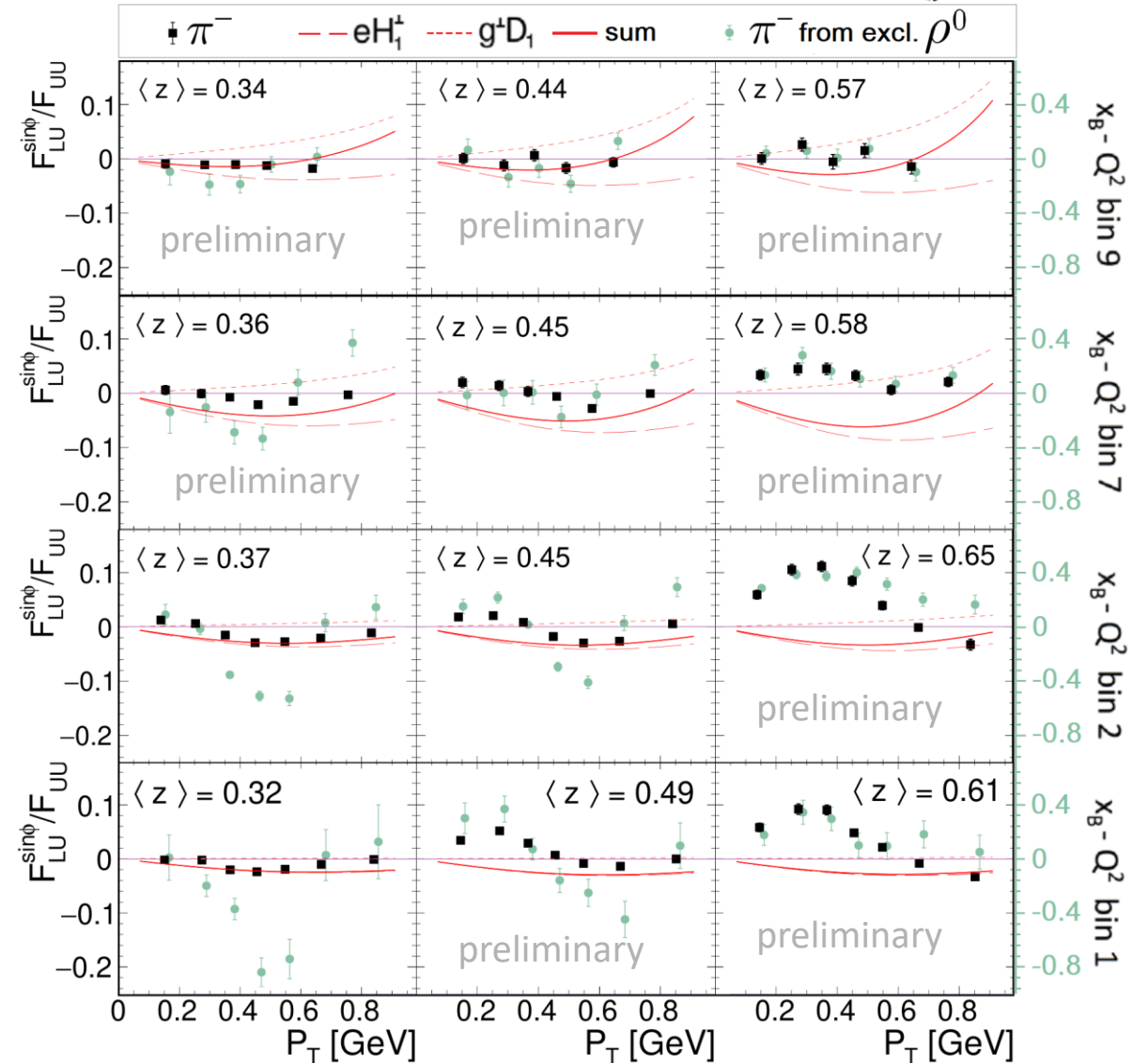


# Exclusive $\rho^0$ Effects in $\pi^-$ SIDIS



→  $\pi^-$  from excl.  $\rho^0$  show similar BSA as the whole SIDIS sample.

→ We are not measuring SIDIS pions properly in the CFR!!!



# A Novel Target-Fragmentation Approach to Identifying Exclusive Vector Meson Production in SIDIS

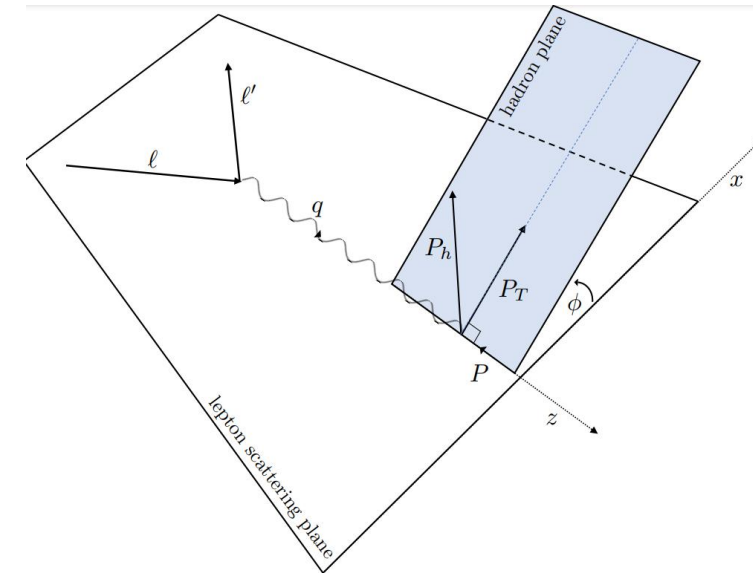
F. Benmokhtar & Students  
Harut Avakian & Timothy Hayward

- This approach opens new opportunities for studying exclusive vector meson production and for isolating its contribution to SIDIS. **In particular, proton detection in the TFR enables clean separation of vector-meson channels using the missing mass of the  $ep \rightarrow epX$  final state, providing an alternative pathway to quantify and remove vector-meson contamination from SIDIS measurements.** Such measurements will improve the understanding of longitudinal-photon contributions while simultaneously expanding the physics reach of **target-fragmentation** studies toward multidimensional probes of nucleon structure and hadronization dynamics.

# SSA Extraction for $\vec{e}p \rightarrow e'p' + X$

$$\frac{d\sigma}{dx dy d\zeta dP_T^2 d\phi_h} = \hat{\sigma}_U \left\{ F_{UU} + \sqrt{2\varepsilon(1+\varepsilon)} F_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda_\ell \sqrt{2\varepsilon(1-\varepsilon)} F_{LU}^{\sin\phi_h} \sin\phi_h \right\}$$

Fracture Function



**Method:** Study Asymmetry modulations :

$p_0 + p_1 \sin(\phi) + p_2 \sin(2\phi)$  for different variables:  $P_T$ ,  $Q^2$ ,  $x$ , etc...

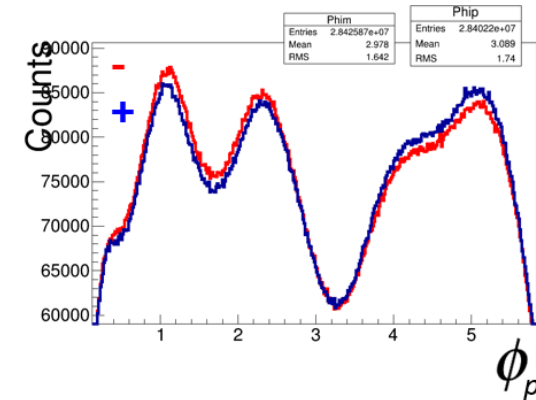
Extract

$$A(\phi)_{LU} = \frac{1}{p} \left( \frac{N^+ - N^-}{N^+ + N^-} \right)$$

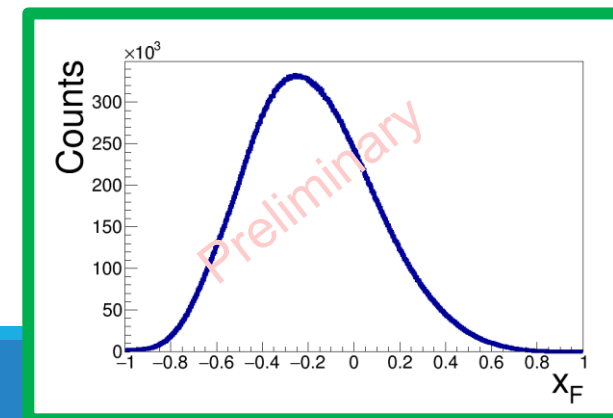
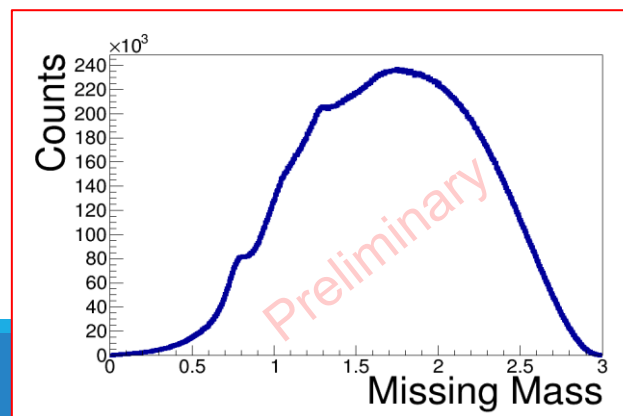
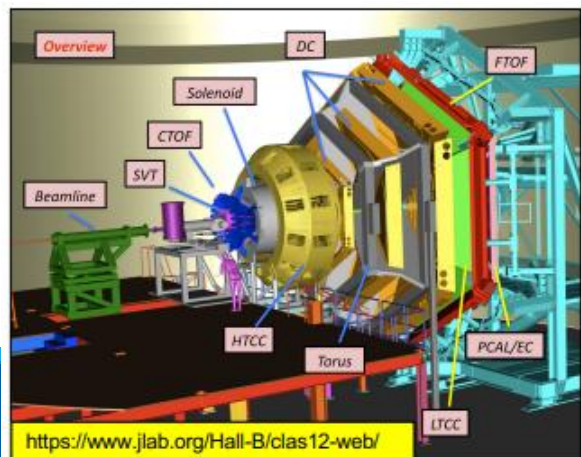
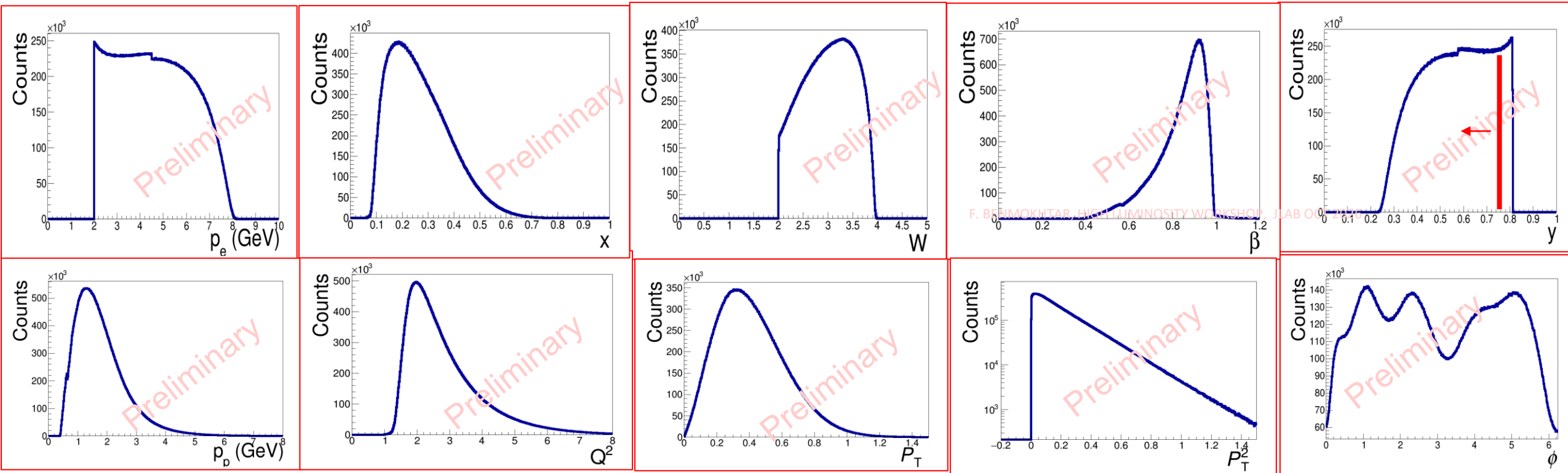
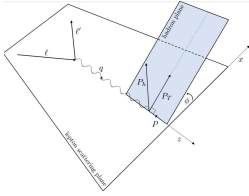
→

$$\frac{F_{LU}}{F_{UU}} = \frac{A_{LU}}{\sqrt{2\varepsilon(1-\varepsilon)}}$$

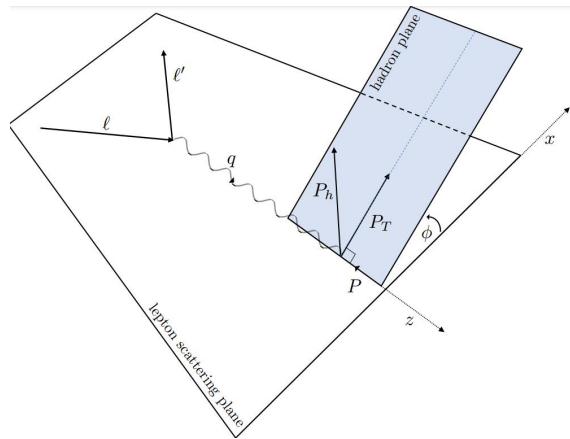
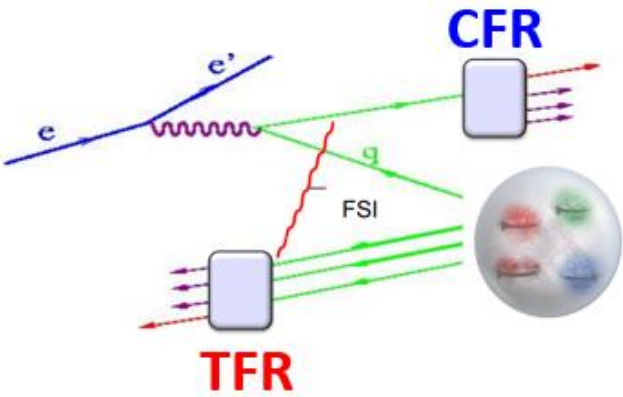
Depol. fac.



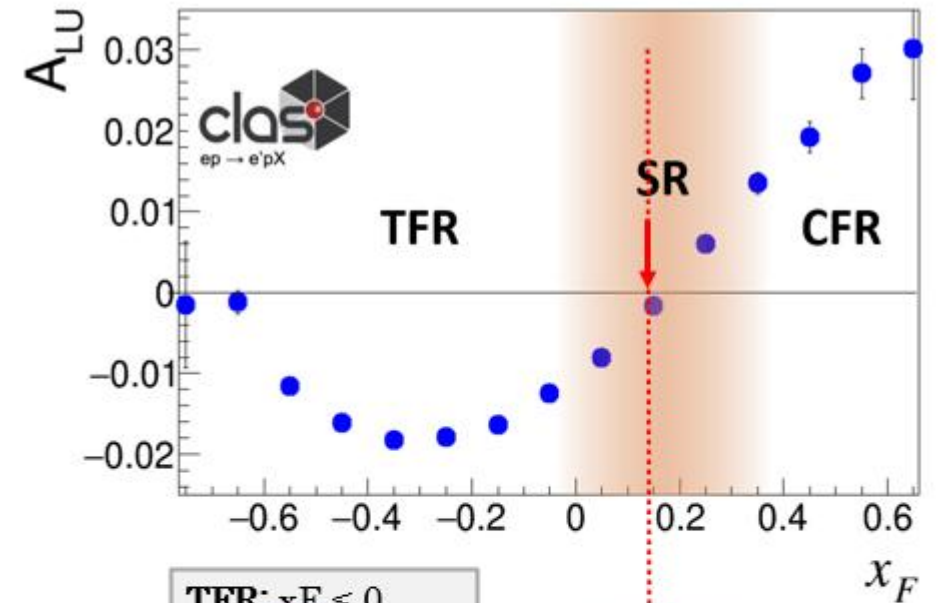
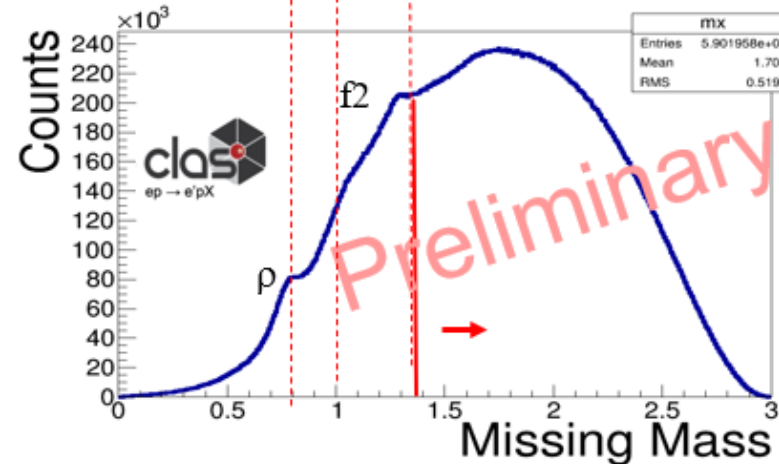
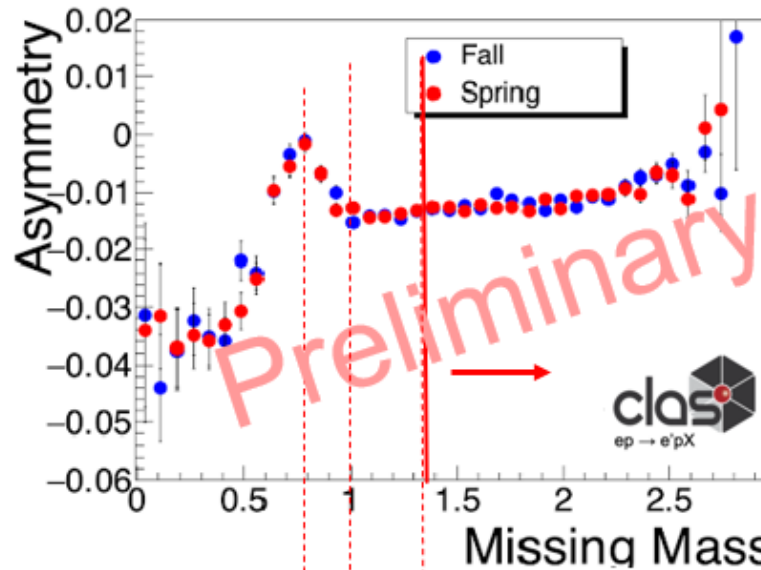
# Variables of interest ( $ep \rightarrow epX$ )



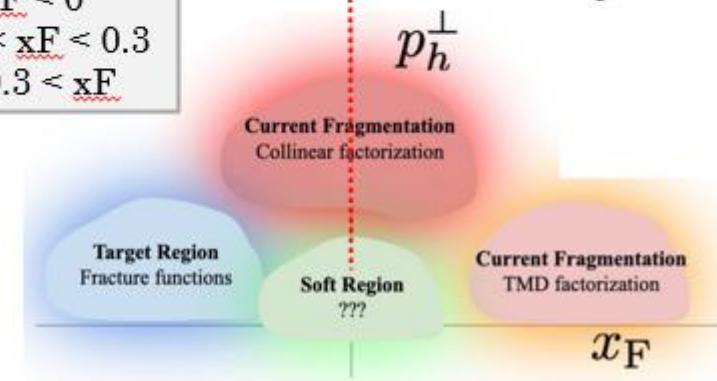
# Selection of Target Fragmentation Region events: epX



$$A(\phi)_{LU} = \frac{1}{p} \left( \frac{N^+ - N^-}{N^+ + N^-} \right)$$



TFR:  $x_F < 0$   
 SR:  $0 < x_F < 0.3$   
 CFR:  $0.3 < x_F$



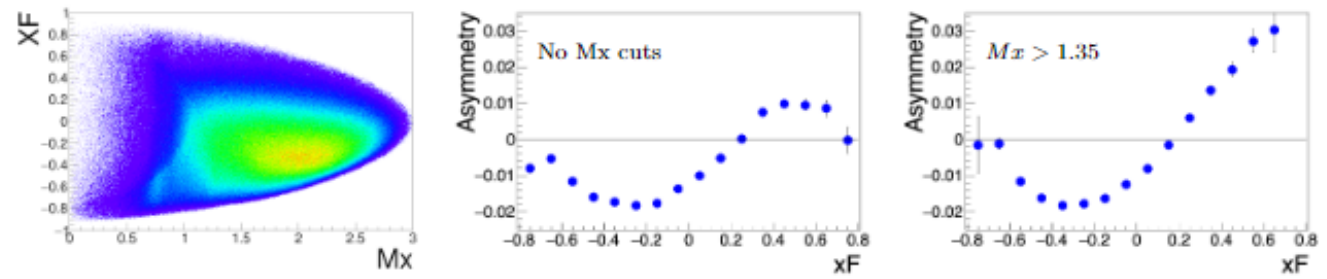
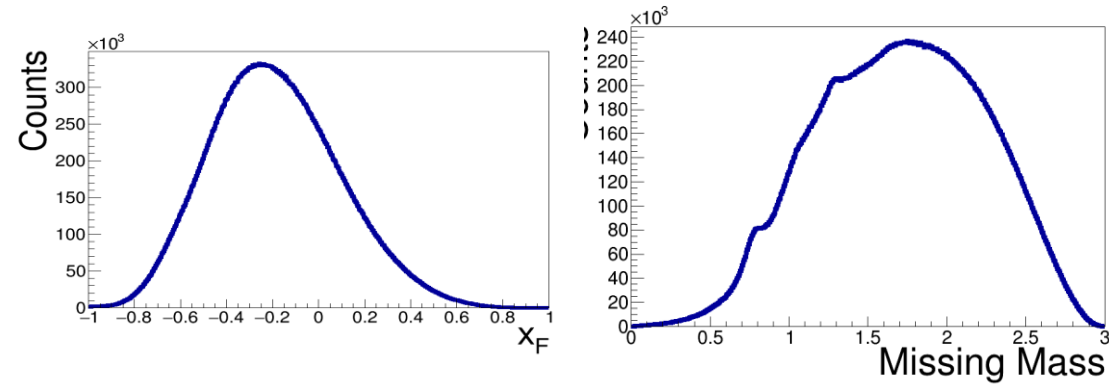
# $x_F$ ( $M_x$ dependance)

Feynman variable

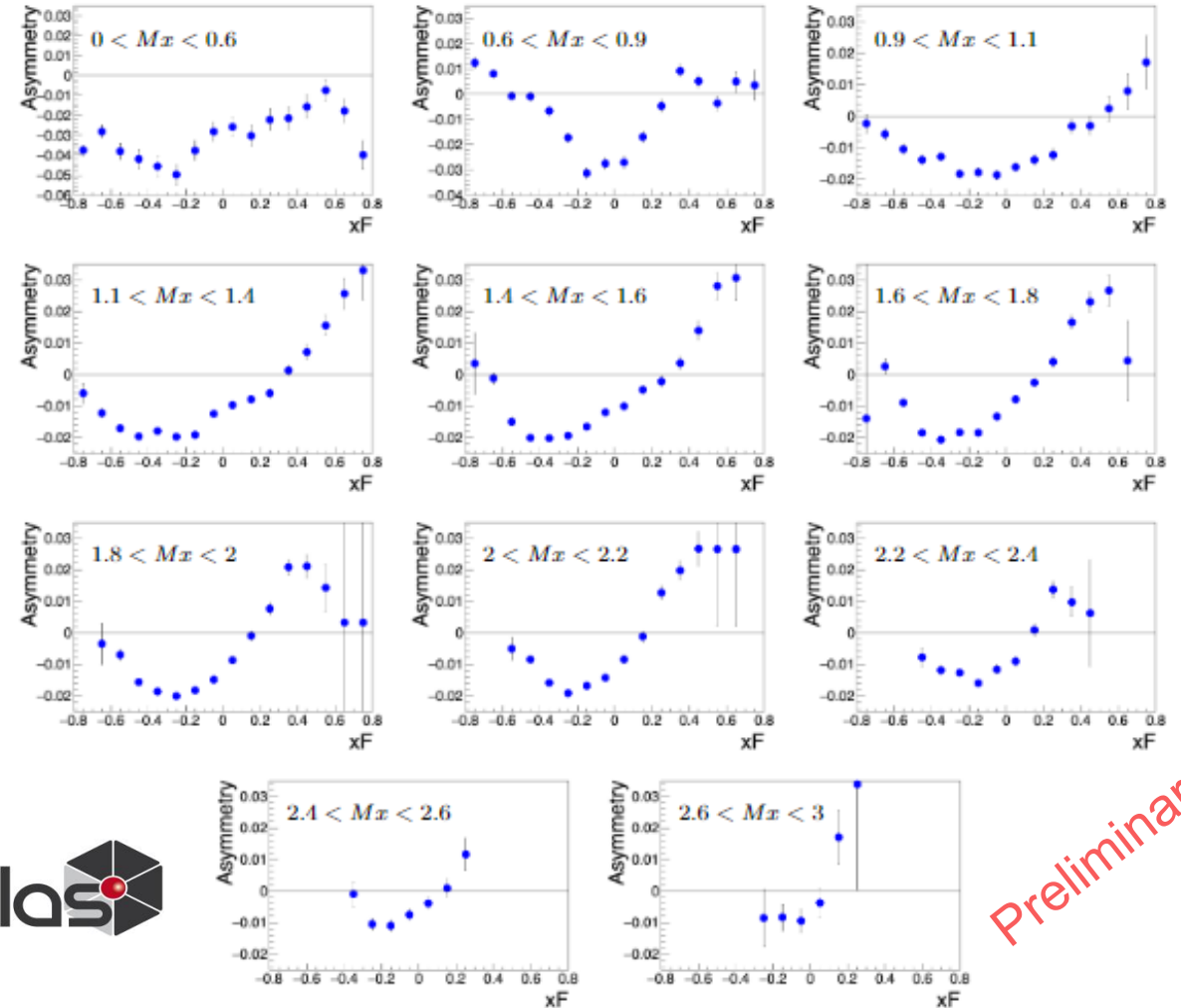
$$x_F = \frac{p_h^z}{p_h^z(\text{max})} \quad \text{in CM frame } \mathbf{p} = -\mathbf{q}, \quad -1 < x_F < 1$$

Rapidity

$$y = \frac{1}{2} \log \frac{p_h^+}{p_h^-} = \frac{1}{2} \log \frac{E_h + p_h^z}{E_h - p_h^z}$$



(a) Left:  $x_F$  without any cut on  $M_x$ , Right:  $x_F$  with  $M_x > 1.35$  GeV

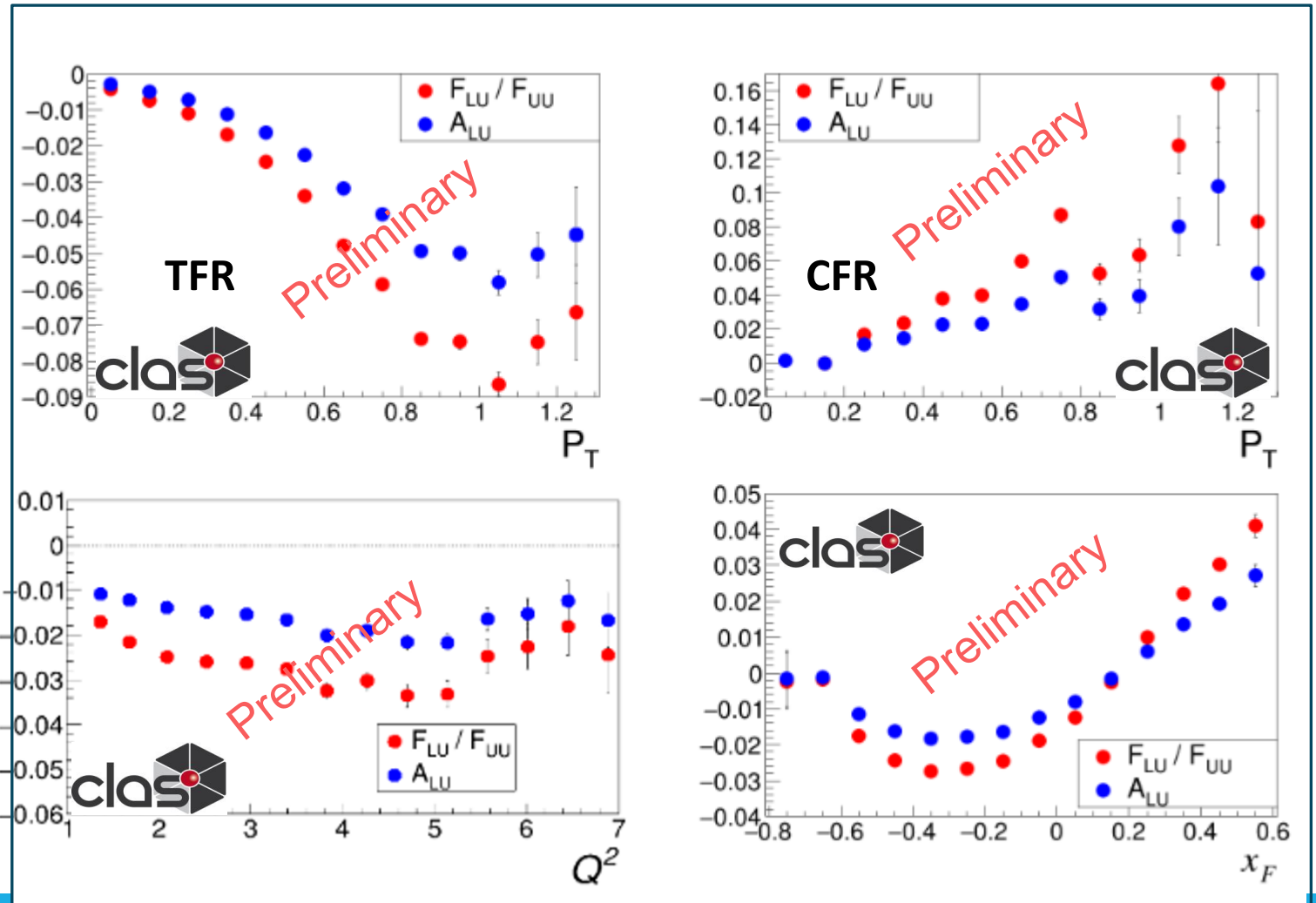
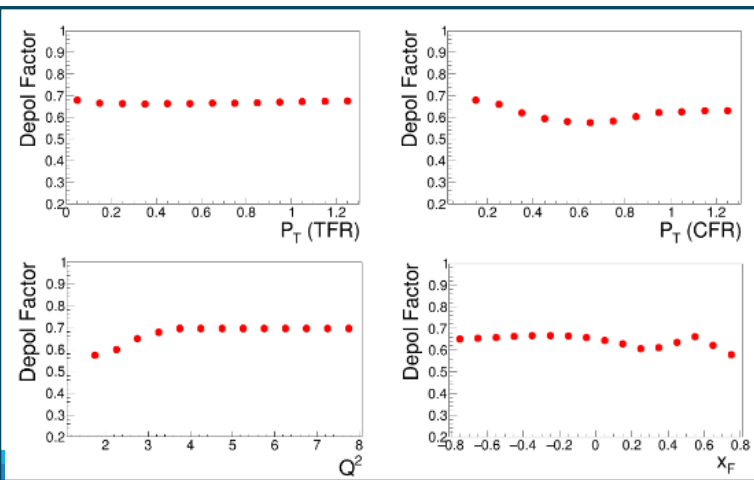


Preliminary

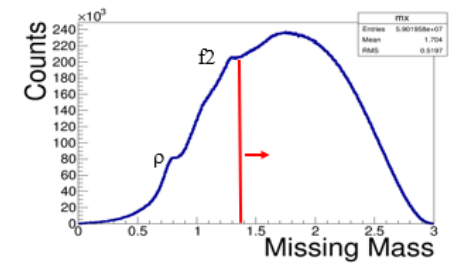
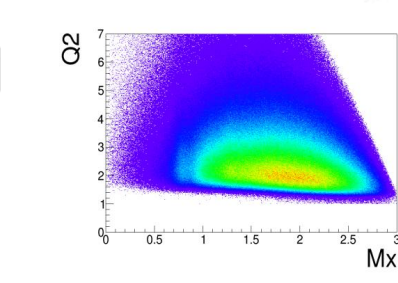
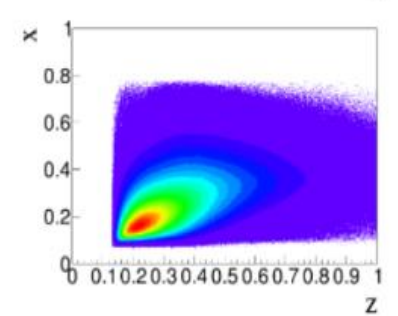
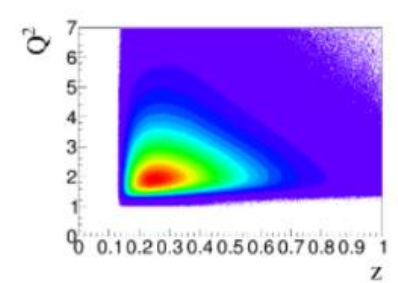
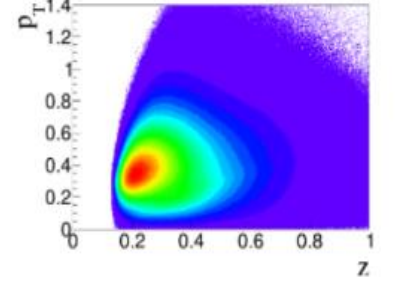
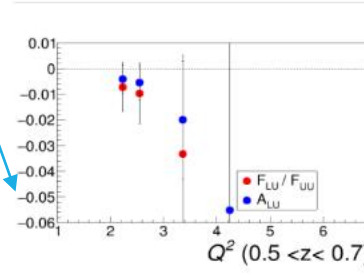
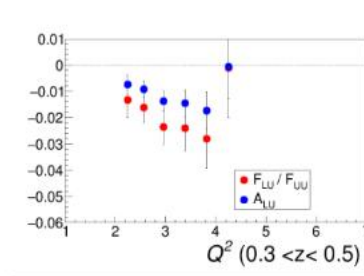
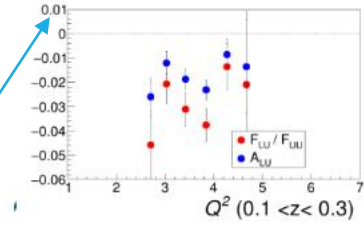
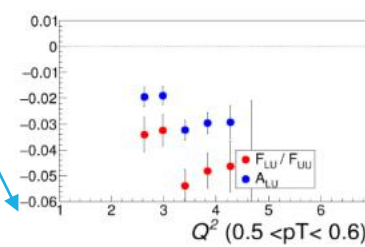
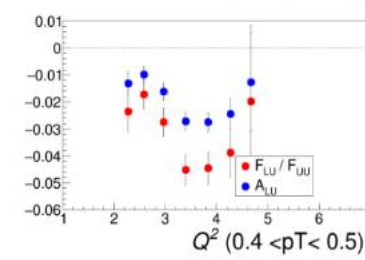
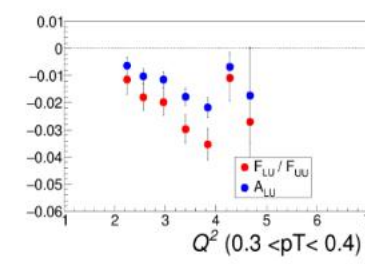
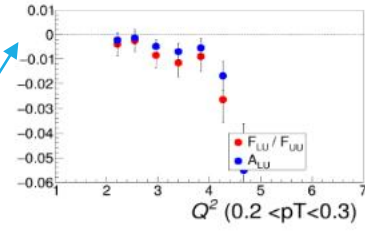
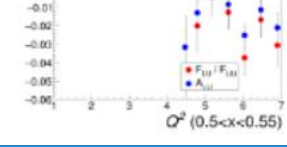
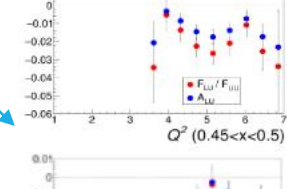
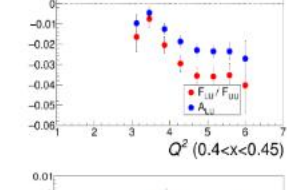
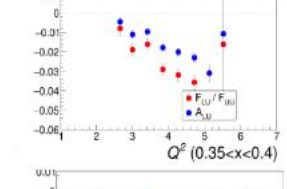
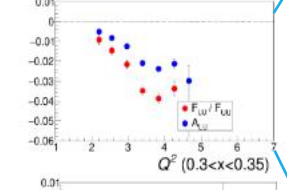
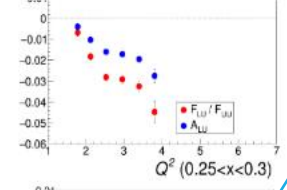
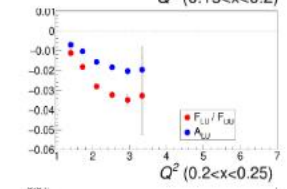
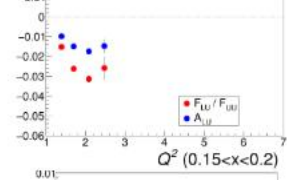
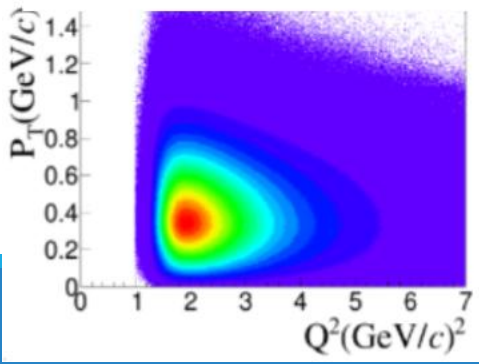
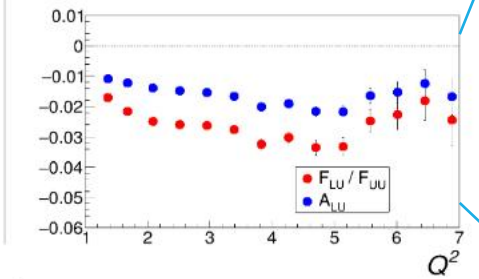
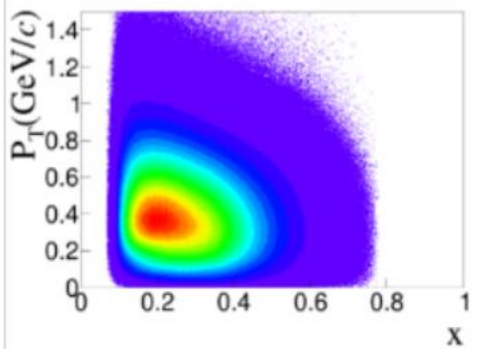
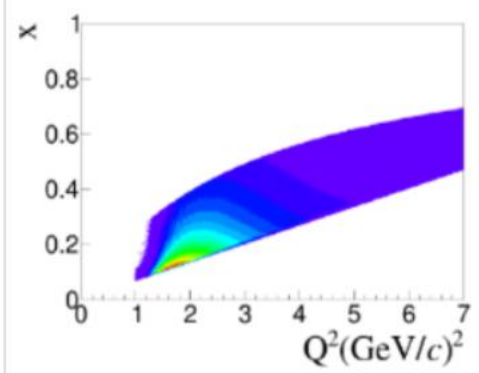
# Ratio of FF Results

$$A(\phi)_{LU} = \frac{1}{p} \left( \frac{N^+ - N^-}{N^+ + N^-} \right)$$

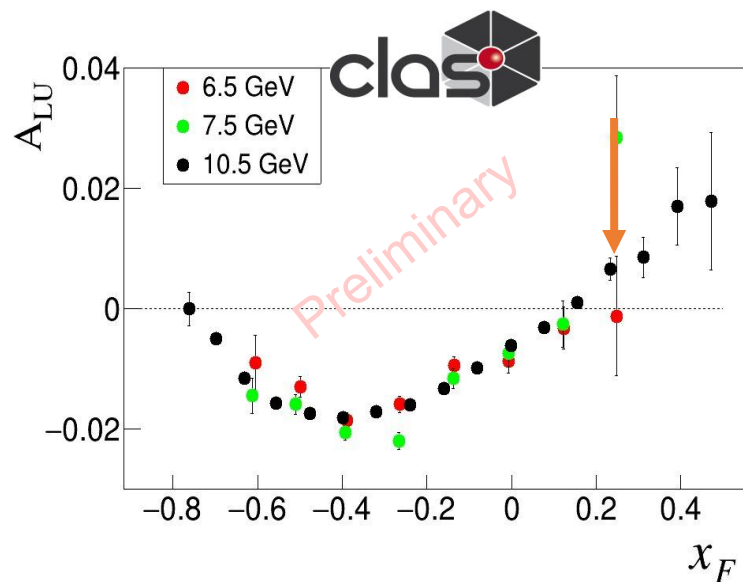
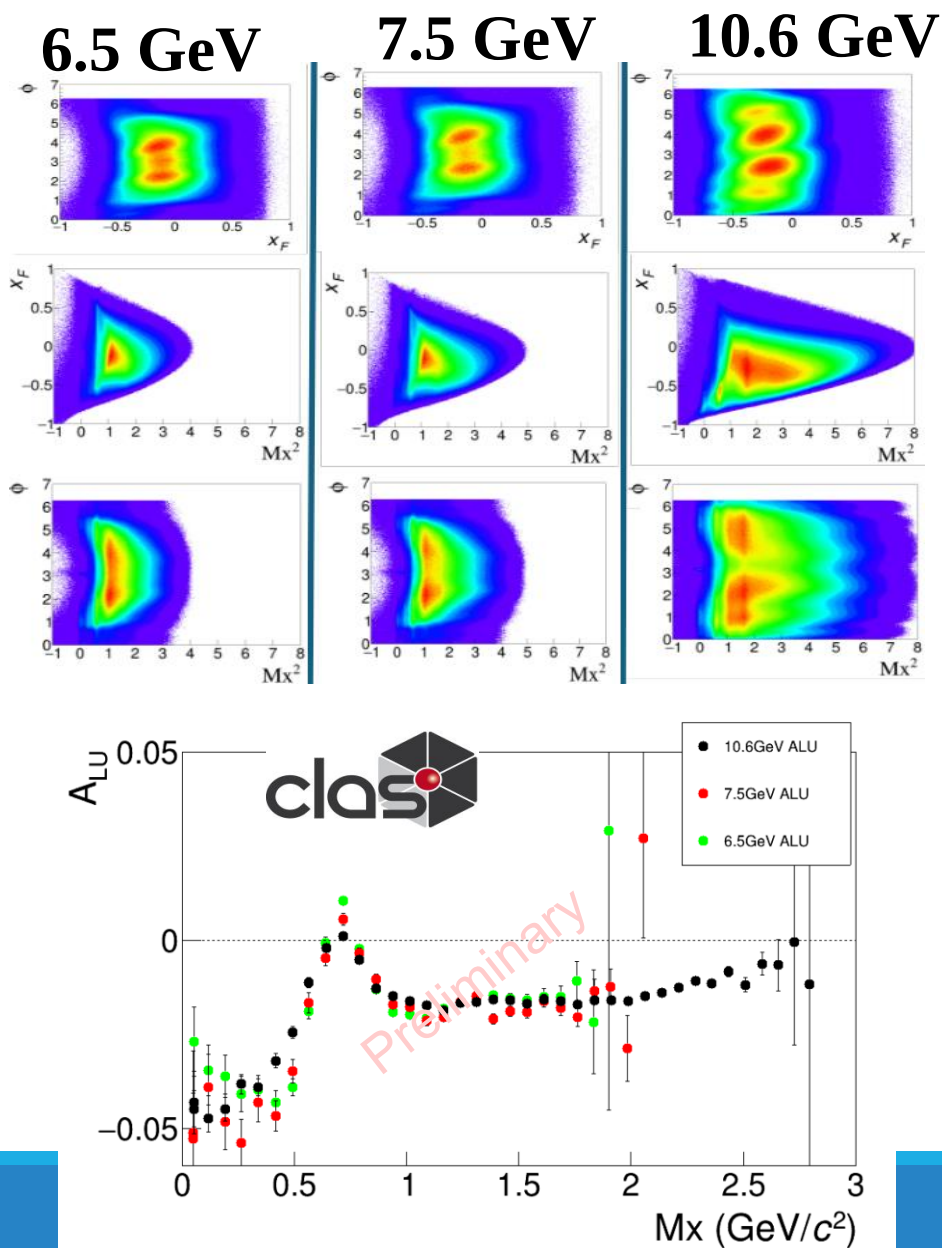
$$\frac{F_{LU}}{F_{UU}} = \frac{A_{LU}}{\sqrt{2\epsilon(1-\epsilon)}}$$



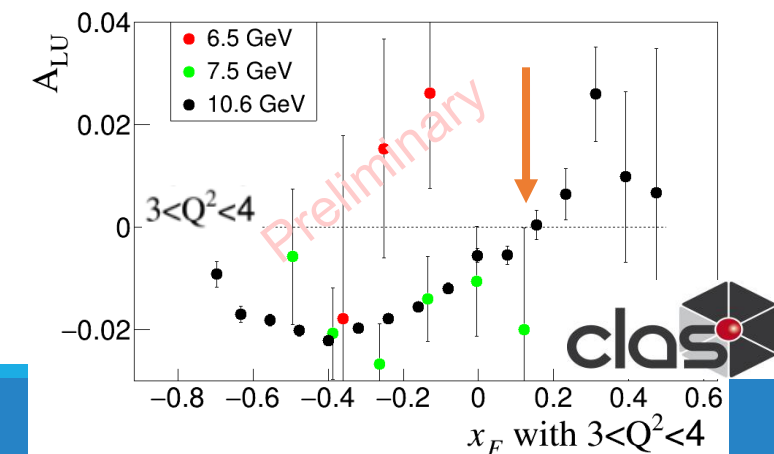
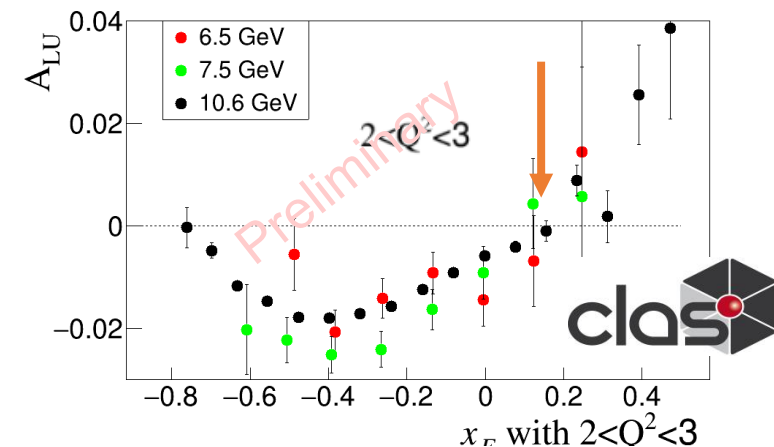
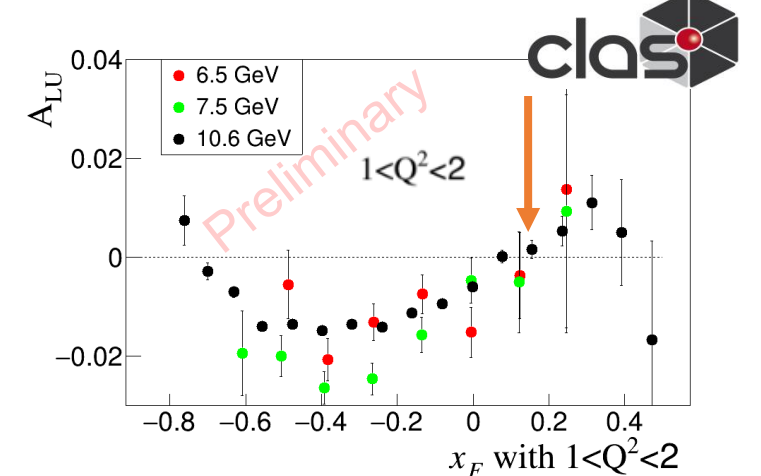
$$Q^2(x, P_T, z, M_x)$$



# Evolution with Beam Energy



No big change in SSA, hint that Rad Corr are small.

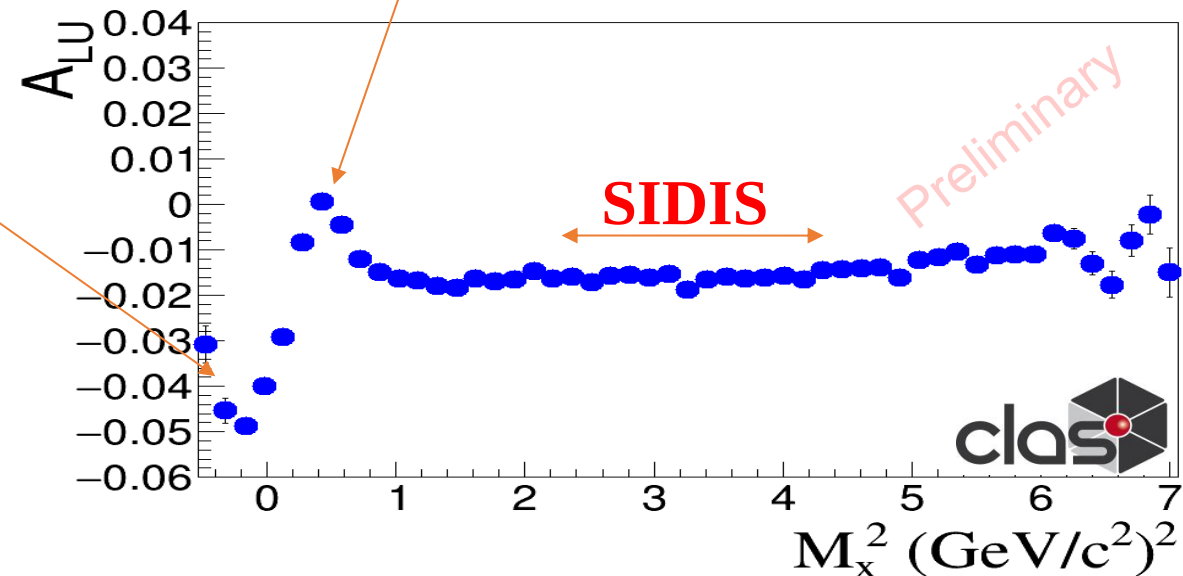
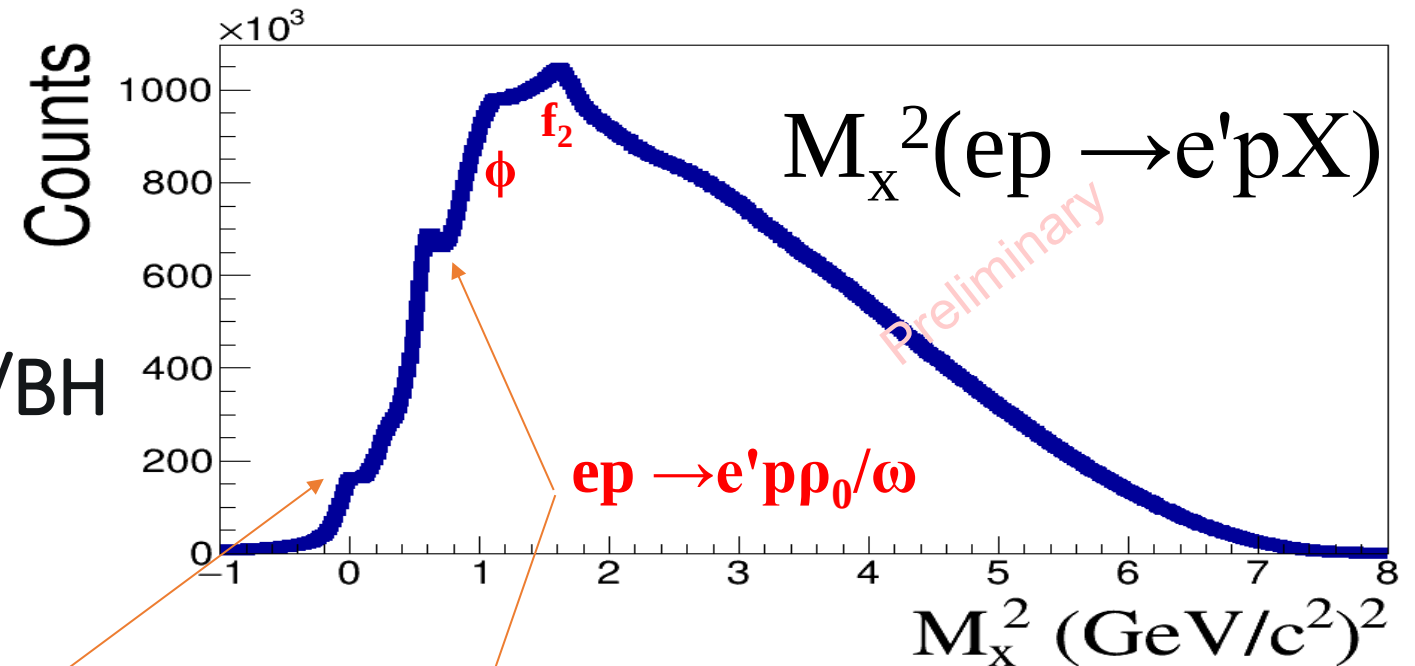


# rho-less analysis

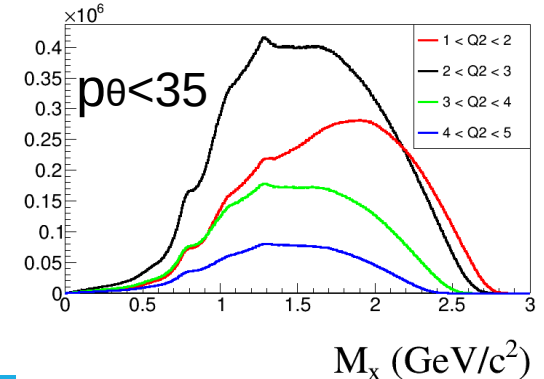
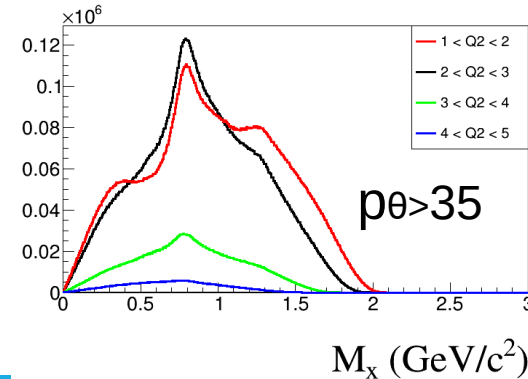
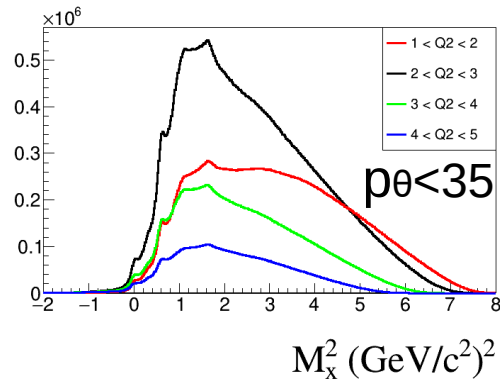
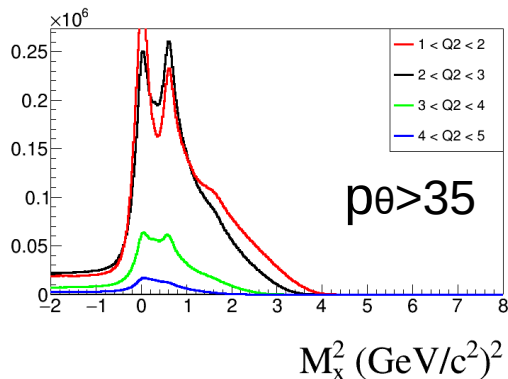
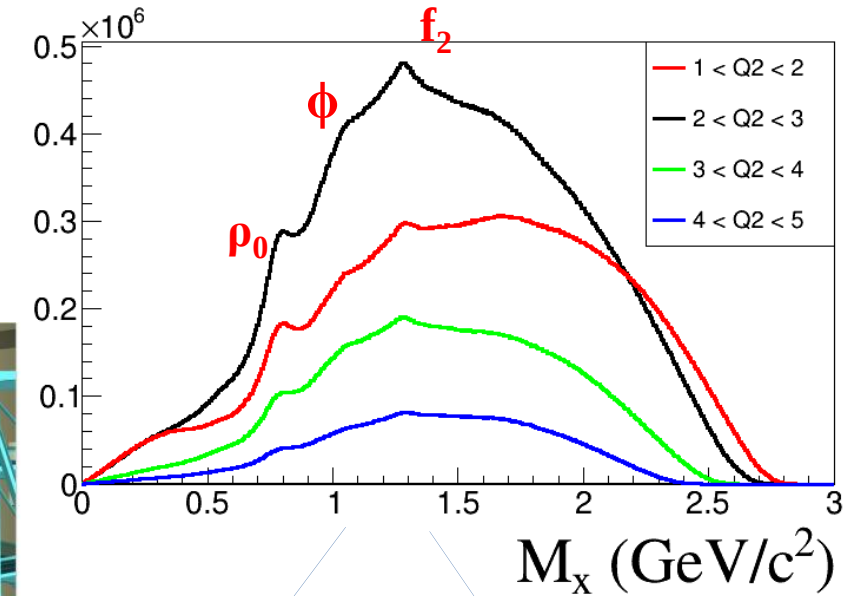
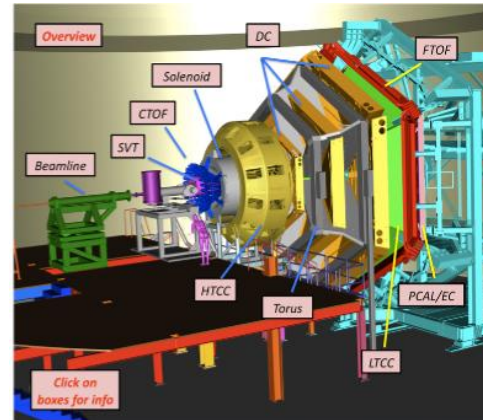
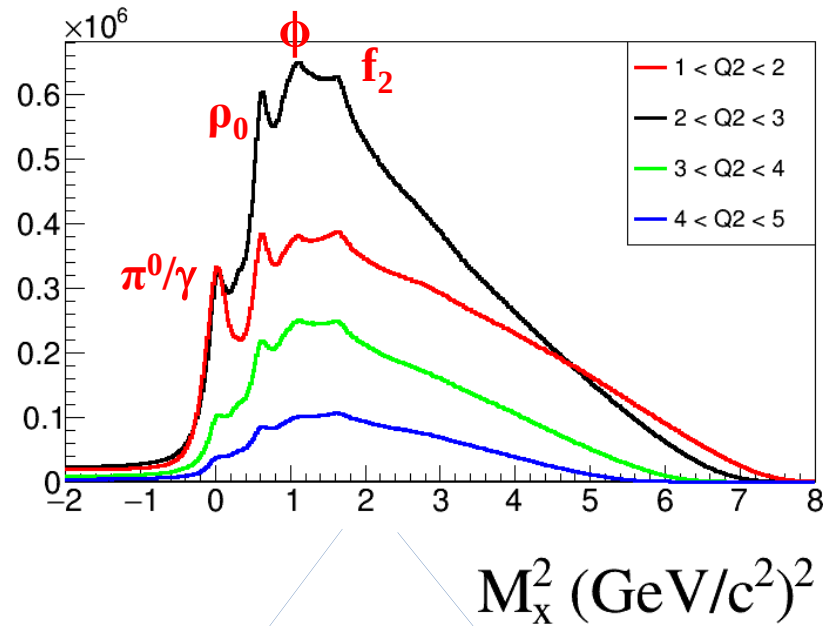
How do we handle  
Radiative cont. from exclusive /BH  
channels?

$ep \rightarrow e'p\pi^0 / e'p\gamma$

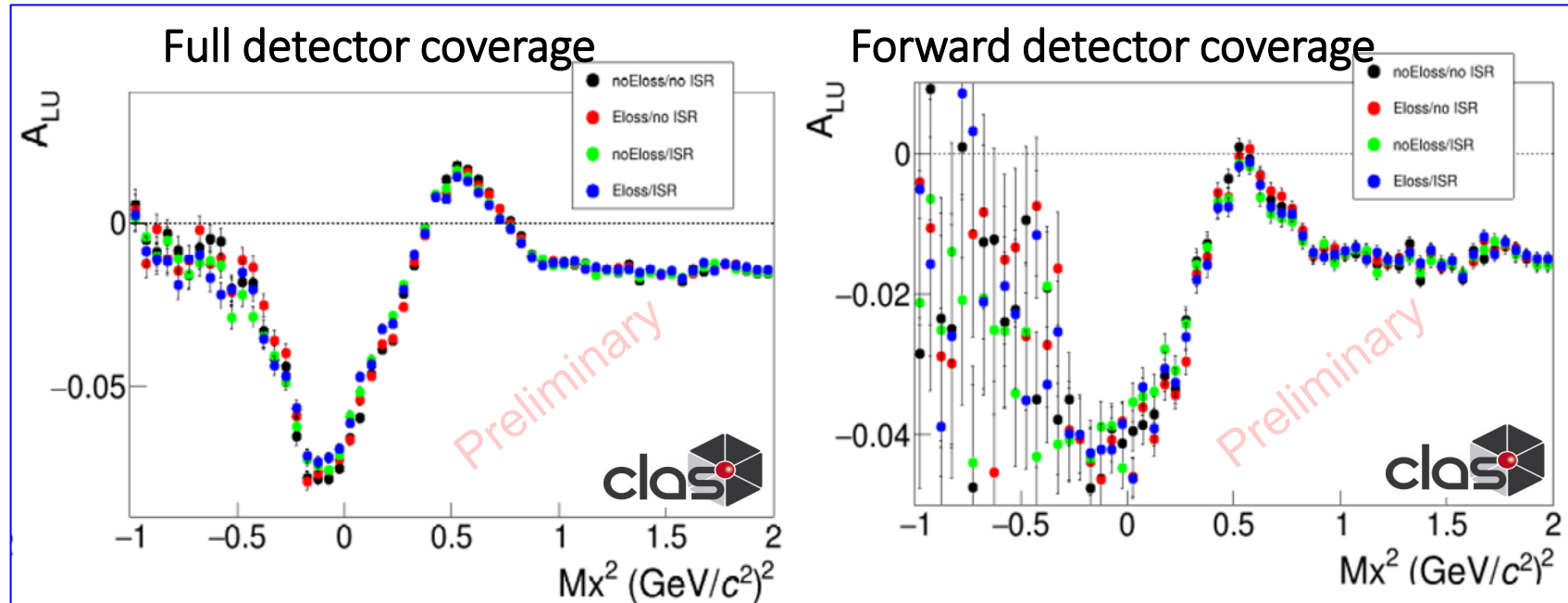
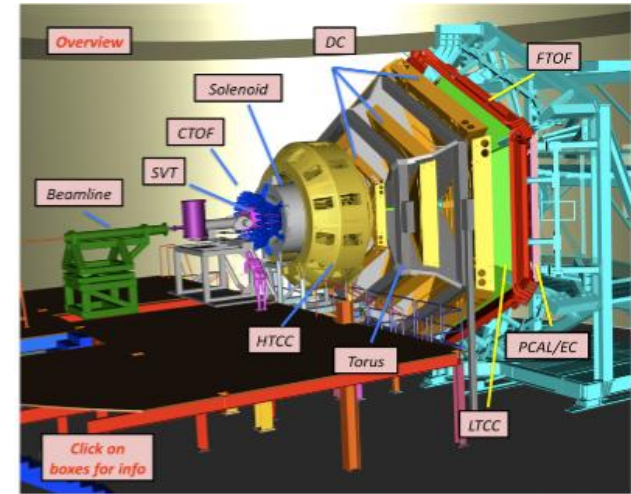
$ep \rightarrow e'p\gamma$  "Bethe-Heitler photons" refer to photons produced through the Bethe-Heitler process, which interferes with the DVCS signal when studying the structure of the nucleon using high-energy electron scattering;



# Origins of the resonances (goal rho-less analysis)

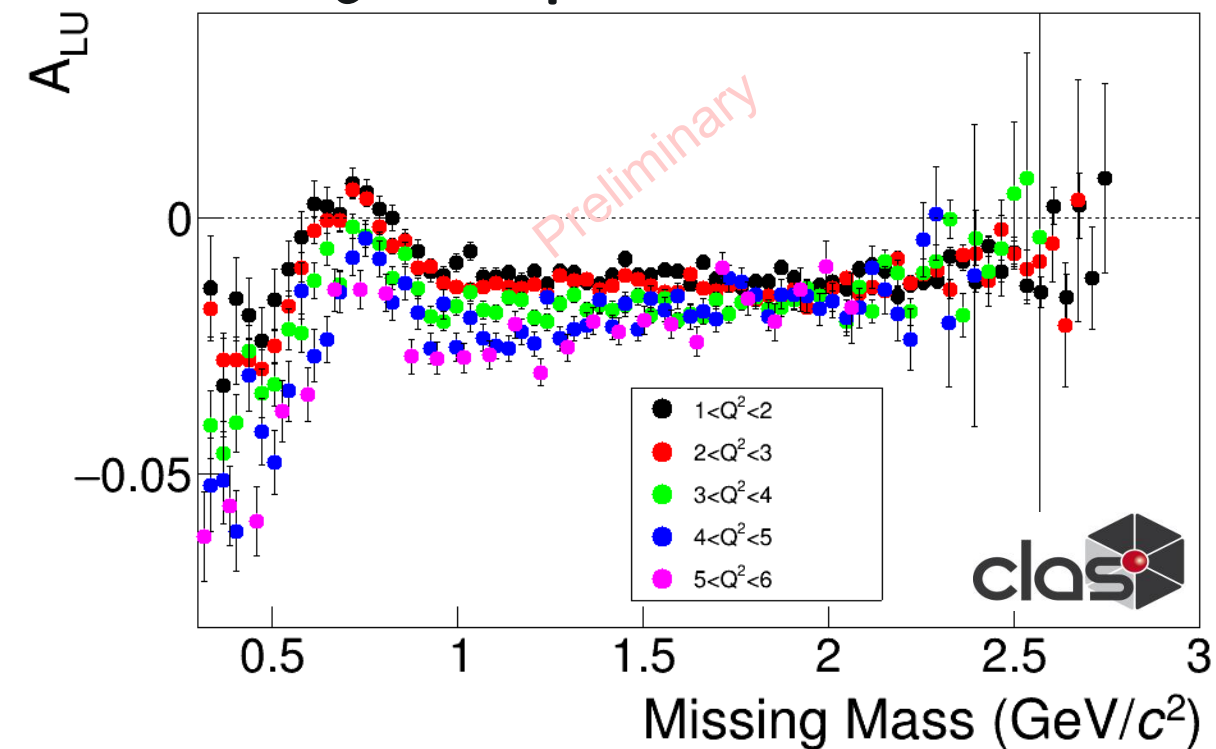


# Origins of the resonances (goal rho-less analysis)



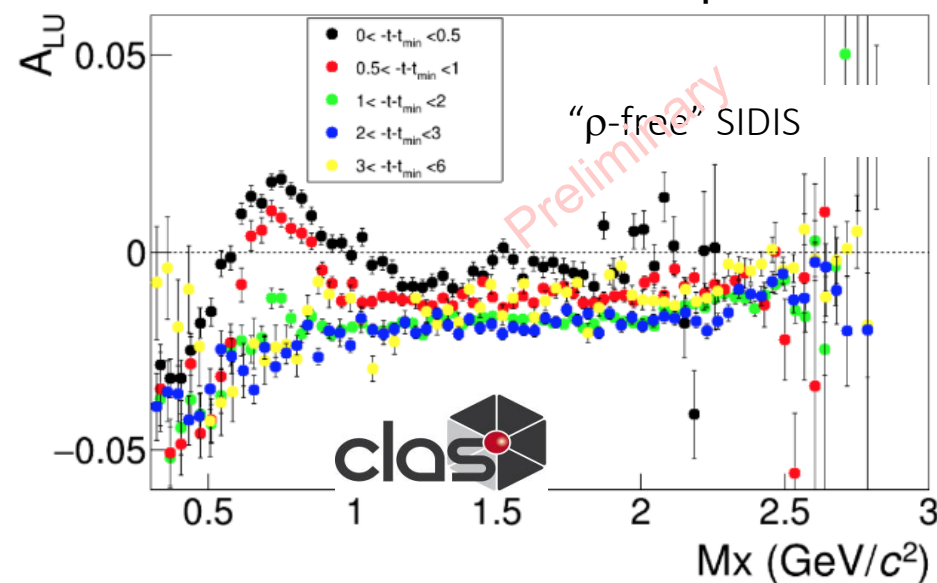
# SSA distributions ( $x_F < 0$ )

## $Q^2$ dependence

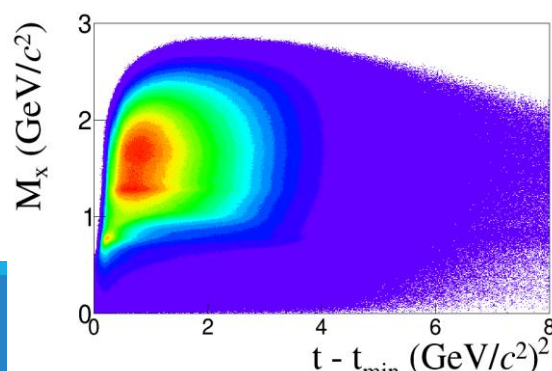
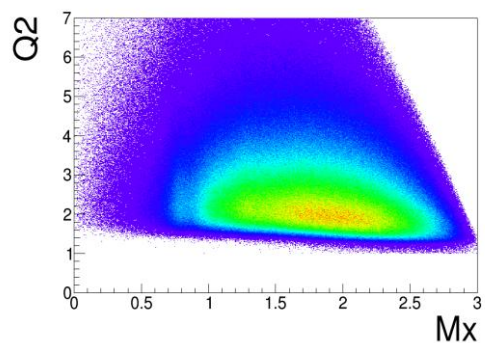


## $t$ dependence

F. Benmokhtar & Duquesne U.



Major difference only for protons at small  $t$ !



With beams in polarized SIDIS typically always polarized, beam SSA can serve as a tool to separate

- 1) kinematical regions (CFR/TFR)
- 2) dynamical contributions
- 3) cut on  $M_x$  eliminate exclusive VMs

# Next steps, clear separation of the rho0

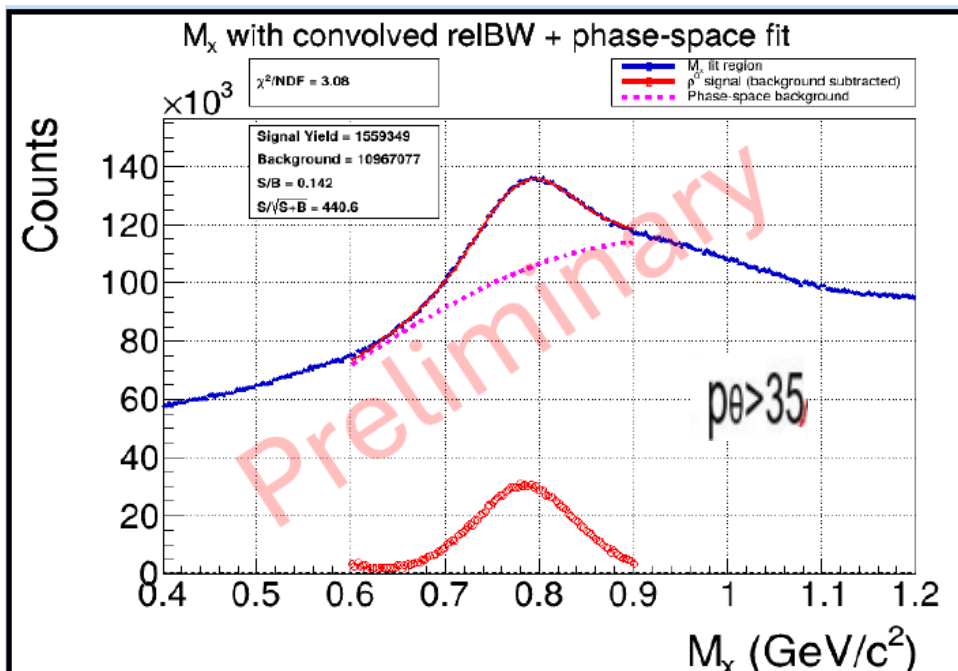


Fig. 8: Revised  $\rho^0$  extraction model

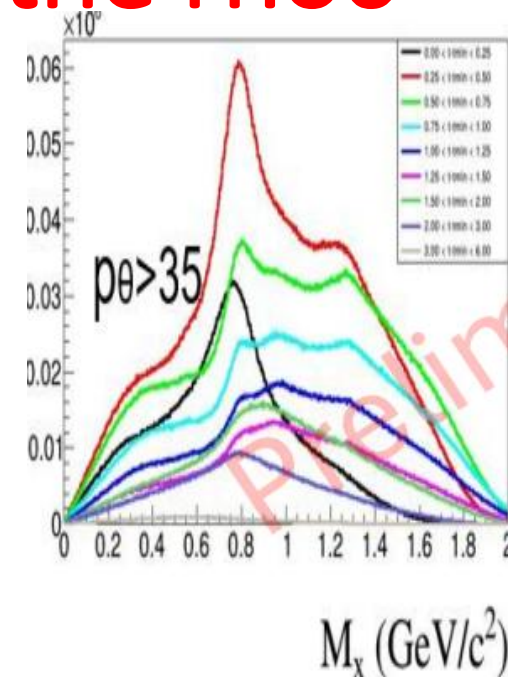


Fig. 9:  $\rho^0$  for  $t-t_{\min}=0-0.25$

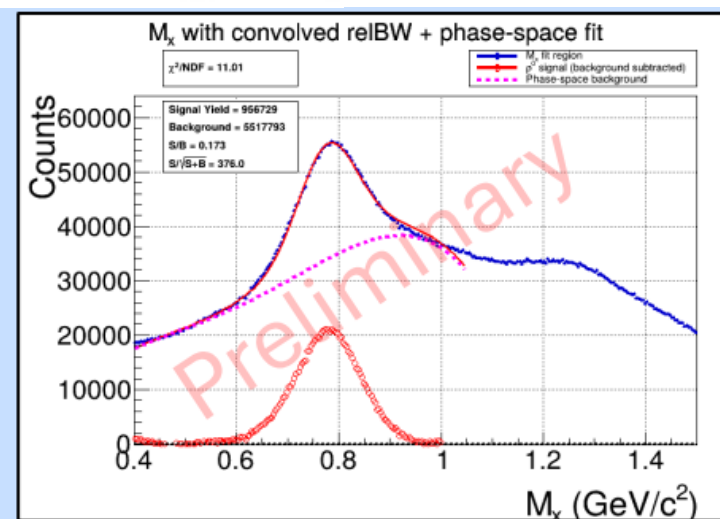
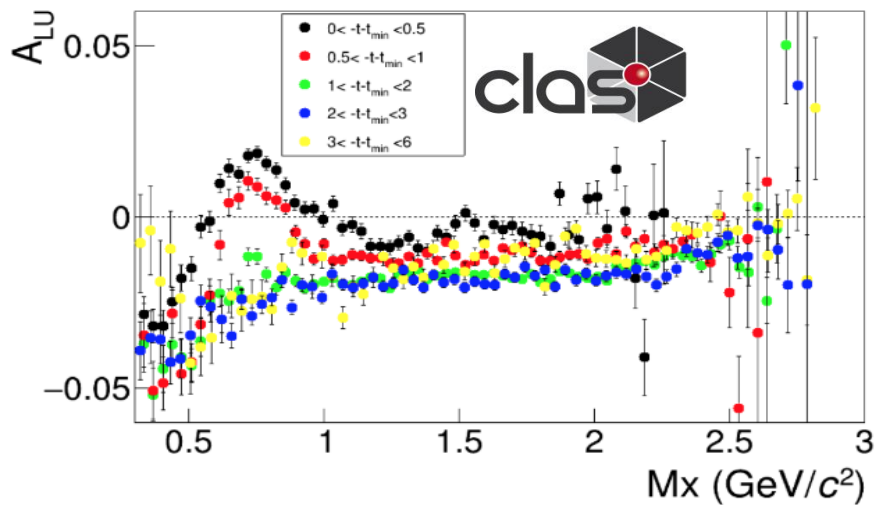
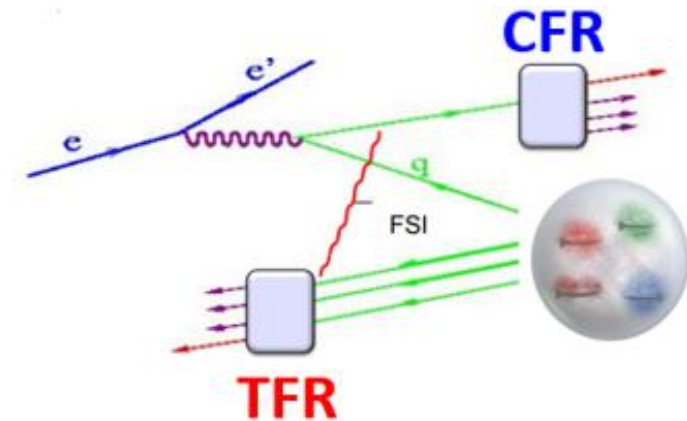


Fig. 10:  $\rho^0$  for  $t-t_{\min}=0.25-0.5$



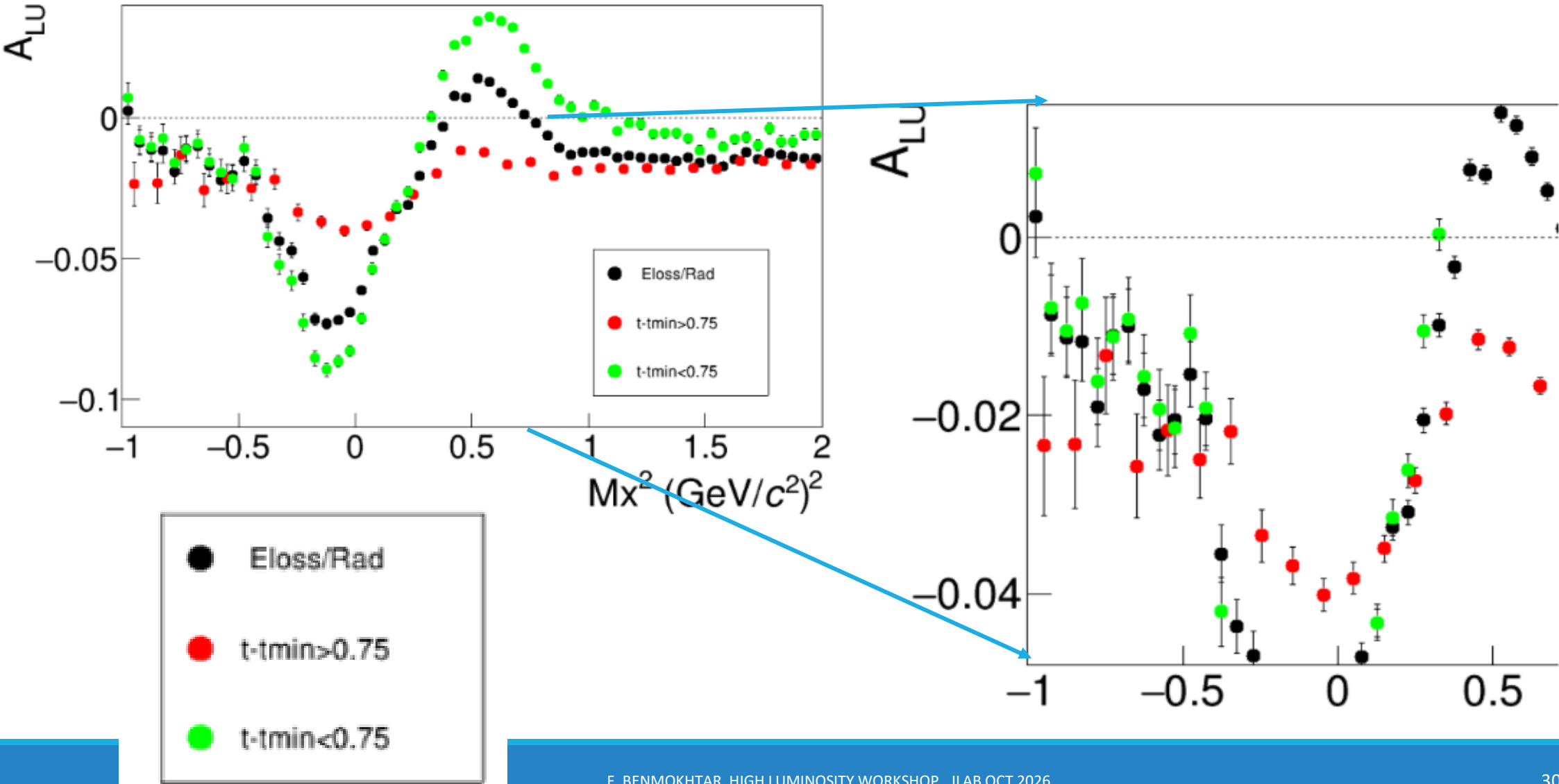
# Conclusions



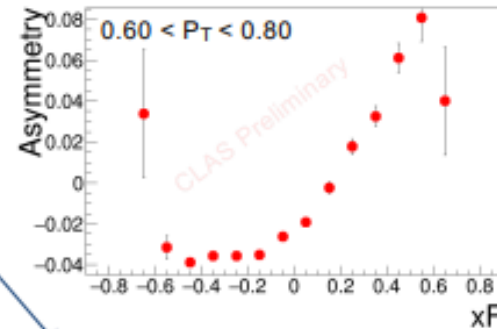
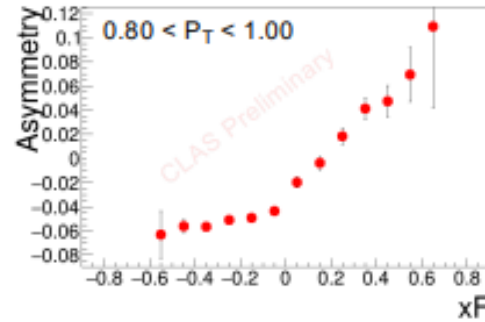
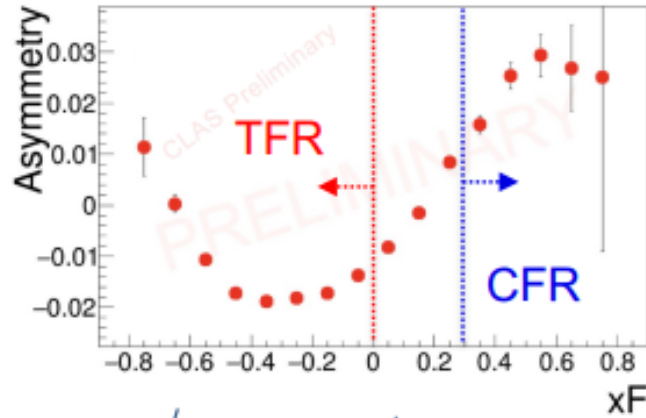
- For the first time at JLab, we've captured the transition between **TFR** and **CFR** in inclusive proton production. Baryons show significant beam SSAs in TFR, with the opposite sign to what we observe in CFR.
- Studies in the TFR allow clean separation of exclusive channels.
- Going to **high luminosity** will help apply this rho-less analysis through the missing mass technique to different hadron species.

# Thank you!

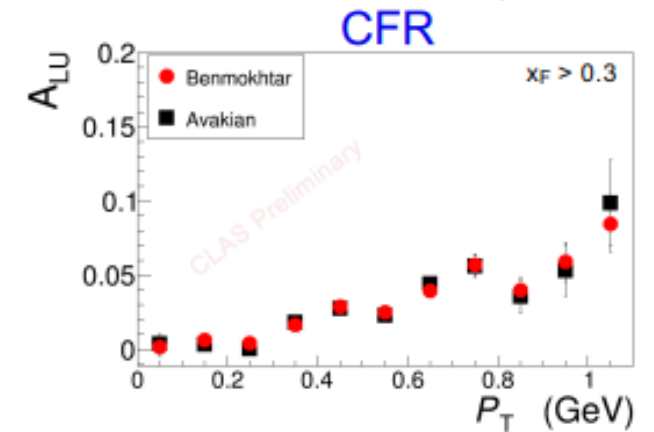
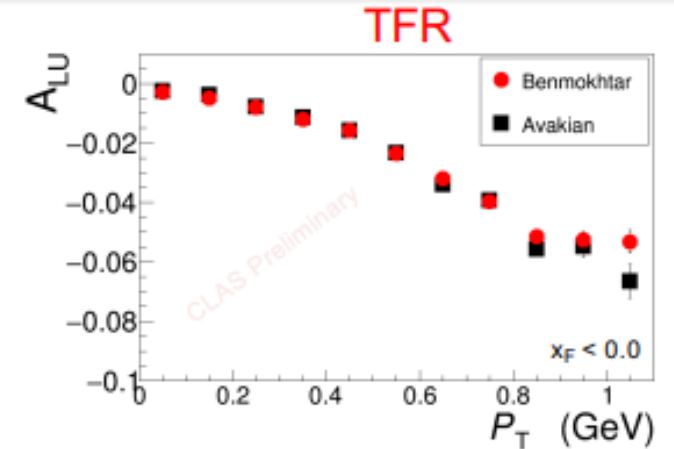
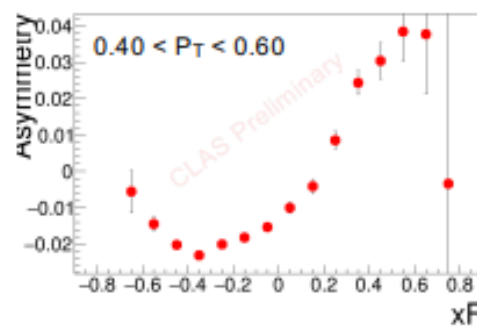
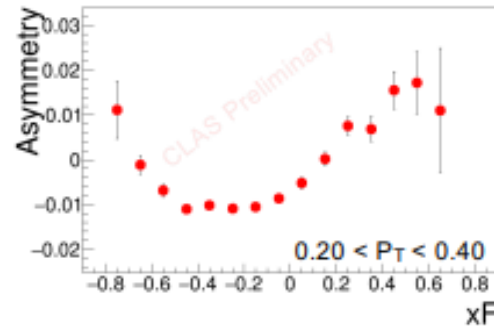
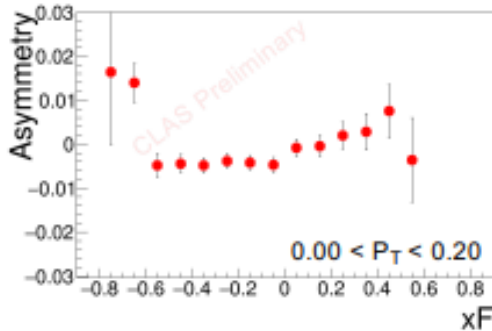
The issue with the -0.2 shift



# Transverse Momentum Effects



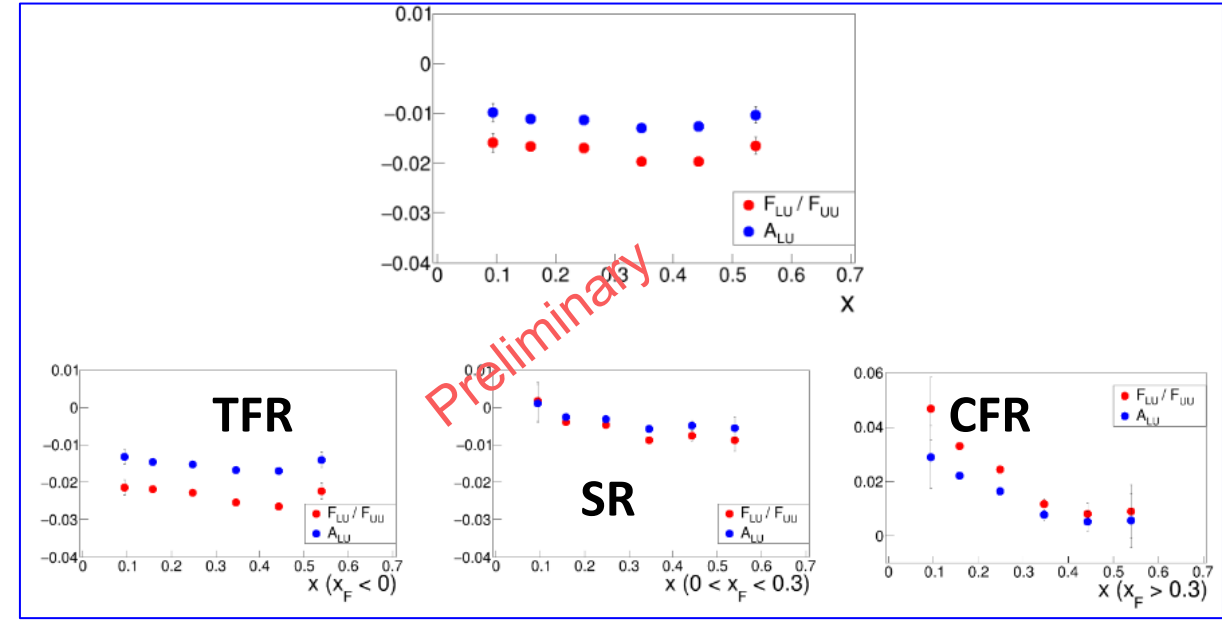
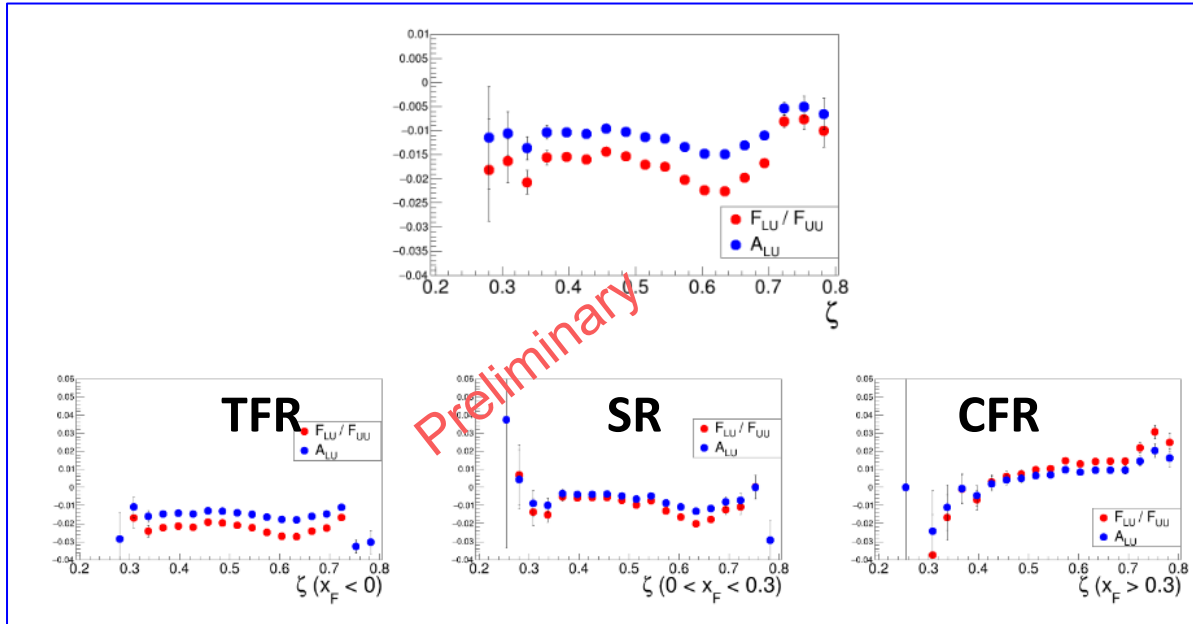
Maybe exclusive p events sneaking in at low  $x_F$ ?



Strong linear dependence on  $P_T$ .

# Ratio of FF

*Zeta and x*



# Sine Fit Equation

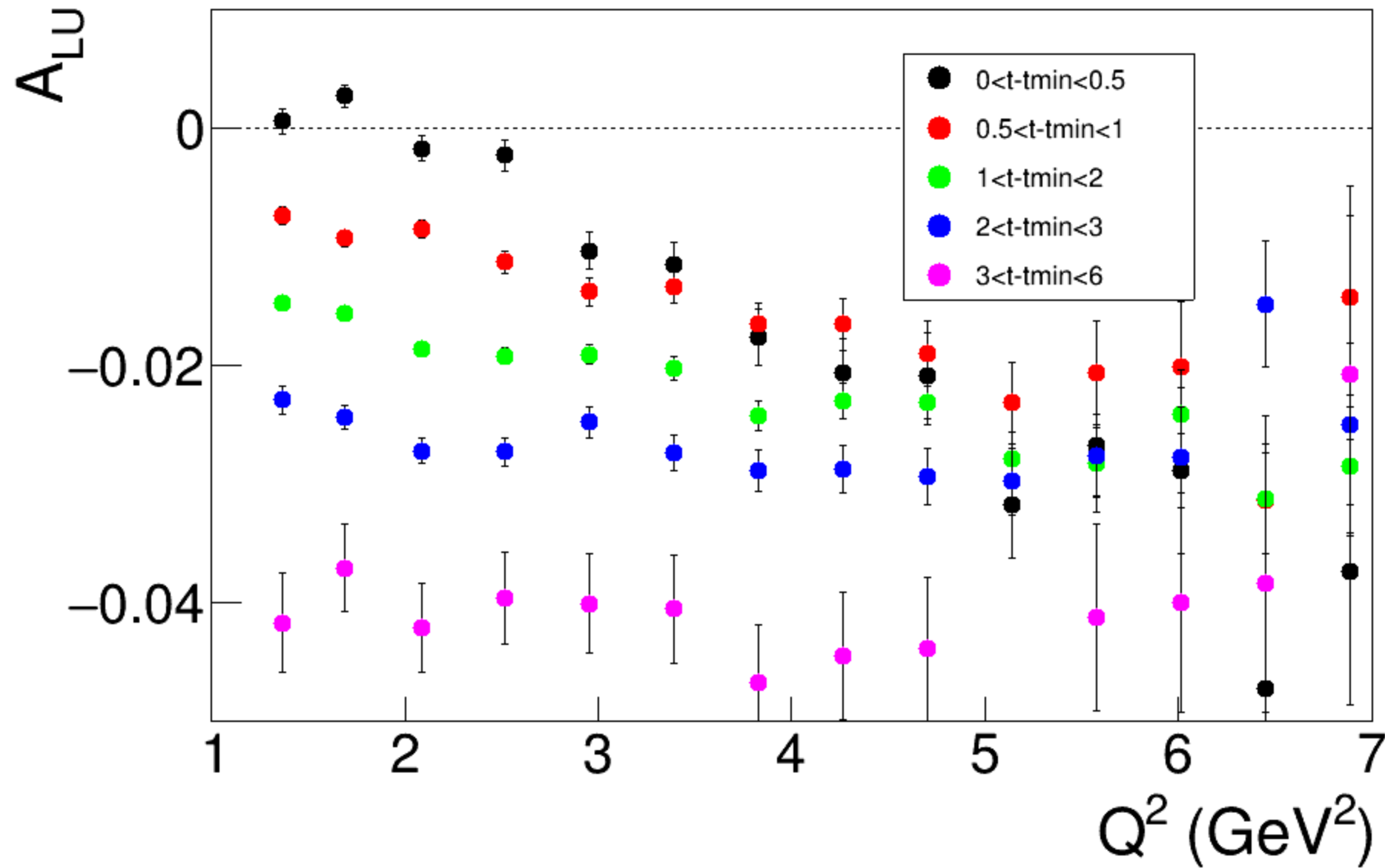
$$p_0 + p_1 \sin \varphi + p_2 \sin(2 \varphi)$$

$$\text{FLU} \propto P (\text{perp.})^2$$

With Taylor expansion:  $(1 + \cos x)$

Existing sin multiplied:  $\sin x (1 + \cos x)$

$$A \sin x + B \sin 2x + C$$



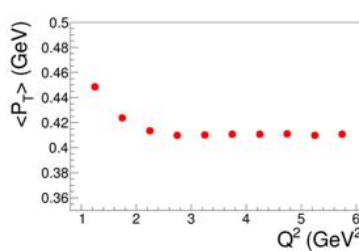
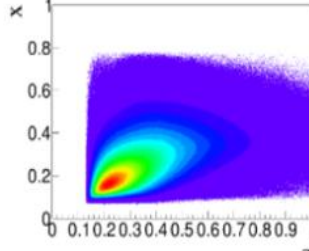
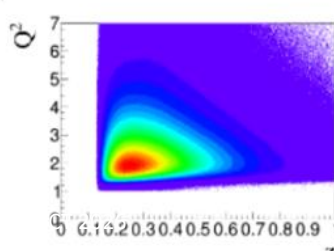
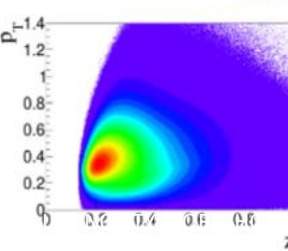
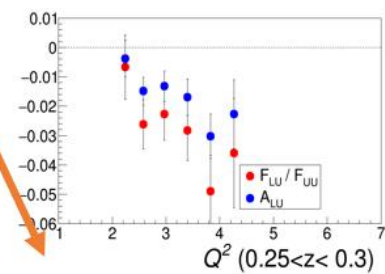
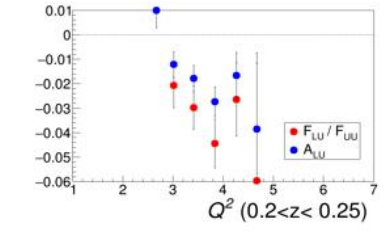
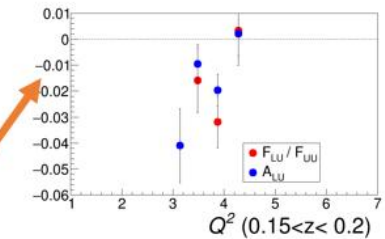
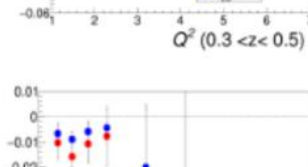
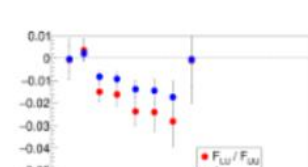
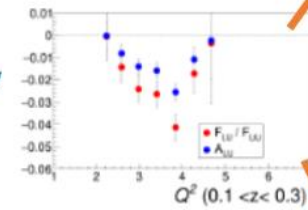
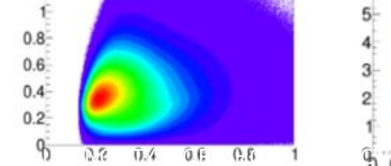
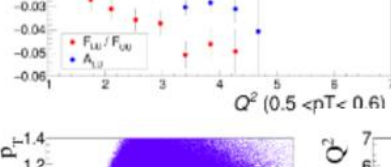
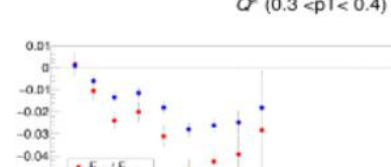
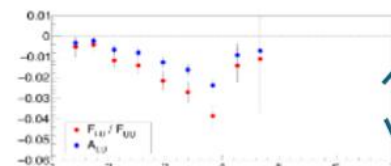
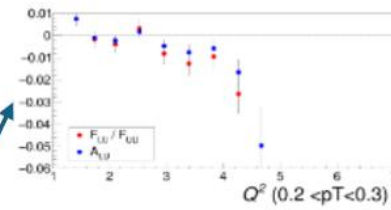
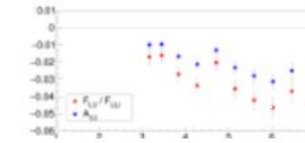
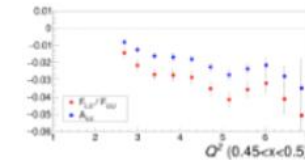
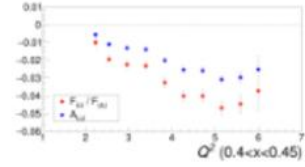
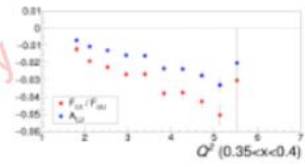
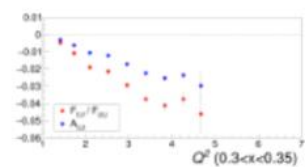
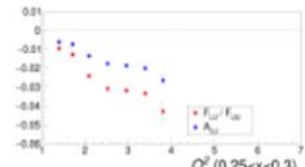
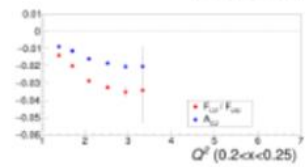
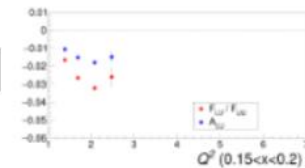
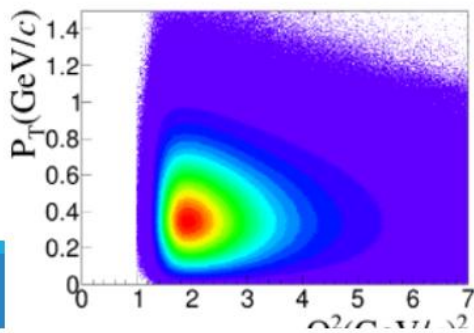
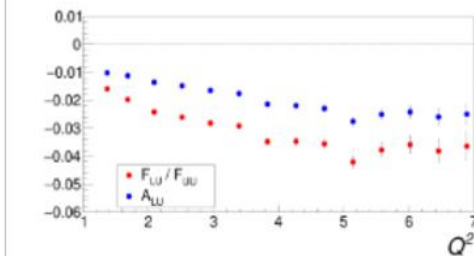
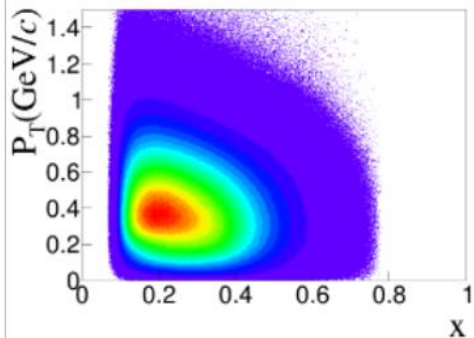
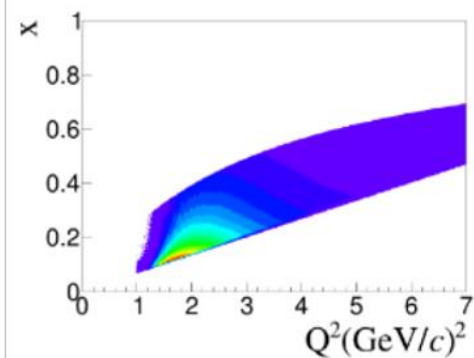
# Why fracture functions?

Sometimes possible to kinematically separate CFR and TFR (some jets, high energy DY, etc) ... but not always clear (fixed target experiments).

- Without an understanding of the signals we expect from target fragmentation we may misinterpret results that we expect are from the current.
- Studying the TFR tests our complete understanding of the SIDIS production mechanism while also providing access to information not available in the CFR.
- Access to more familiar TMD/PDFs through momentum sum rules, but with different systematics (different gluon radiation, different acceptance, etc.)



# $Q^2 (x, P_T, z)$



Preliminary

Preliminary

# Categorizing Fracture Functions

- At leading twist fracture functions exist that can be organized into tables of quark and nucleon polarizations just like the more familiar PDFs.
- Access to *both*  $k_T$  and  $p_T$  effects gives  $2 \times 8 = 16$  FrFs.

|                      |   | Quark polarization |                |          |                     |     | <th colspan="3">Quark polarization</th> |   | Quark polarization                   |                                      |                                                                                            |
|----------------------|---|--------------------|----------------|----------|---------------------|-----|-----------------------------------------|---|--------------------------------------|--------------------------------------|--------------------------------------------------------------------------------------------|
|                      |   |                    | U              | L        | T                   |     |                                         |   | U                                    | L                                    | T                                                                                          |
| Nucleon polarization | U |                    | $f_1$          |          | $h_1^\perp$         | CFR | TFR                                     | U | $\hat{u}_1$                          | $\hat{l}_1^{\perp h}$                | $\hat{t}_1^h, \hat{t}_1^\perp$                                                             |
|                      | L |                    |                | $g_{1L}$ | $h_{1L}^\perp$      |     |                                         | L | $\hat{u}_{1L}^{\perp h}$             | $\hat{l}_{1L}$                       | $\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$                                                       |
|                      | T |                    | $f_{1T}^\perp$ | $g_{1T}$ | $h_1, h_{1T}^\perp$ |     |                                         | T | $\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$ | $\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$ | $\hat{t}_{1T}^h, \hat{t}_{1T}^{hh}$<br>$\hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$ |

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