Proton Fragmentation and Multi-Dimensional analysis of the ep→epX
RGA

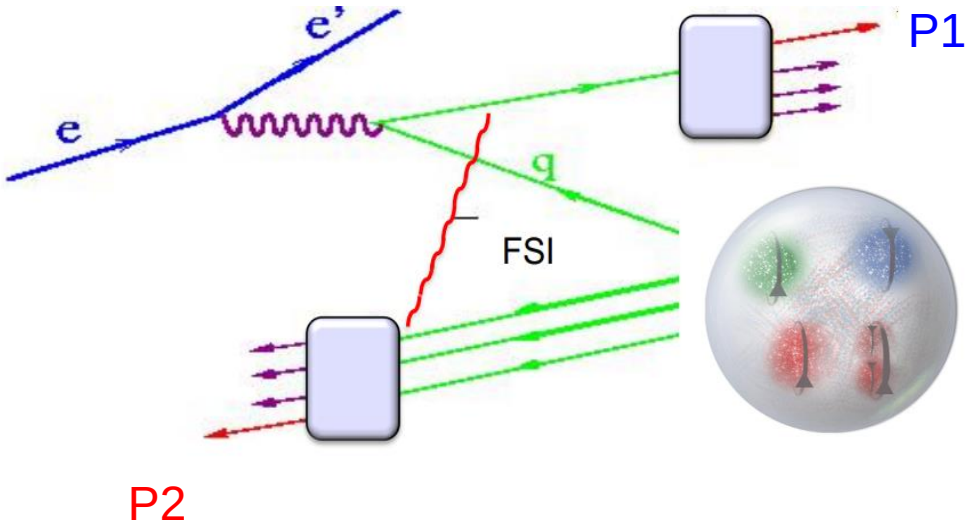
FATIHA BENMOKHTAR

With: H. Avakian (Jefferson Lab),
T. Hayward (UConn)
D. Terrero Cepeda , H. Valenty, N. Nicholson, N. Carpenter, M. Chitwood, A. Gadsby and A. Boyer (Duquesne)

Target/Current Fragmentations

X_F – frac. Momentum in the CM frame

Current fragmentation, $x_F>0$

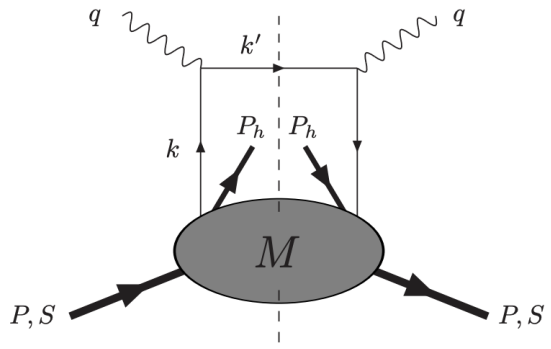


Target fragmentation, $x_F<0$

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

- **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 left-over target remnant (TFR) whose partonic structure is defined by "Fracture Functions": the probability to form a certain hadron (P2) given a particular ejected quark.**



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

N \ q	U	L	T
U	$\tilde{u}_2^{\perp h}$	$\tilde{l}_2^{\perp h}$	$\tilde{t}_2, \tilde{e}_2$
L	$\tilde{u}_{2L}^{\perp h}$	$\tilde{l}_{2L}^{\perp h}$	$\tilde{t}_{2L}, \tilde{e}_{2L}$
T	$\tilde{u}_{2T}^{\perp h}, \tilde{u}_{2T}^{\perp h}$	$\tilde{l}_T, \hat{l}_{2T}^{\perp h}$	$\tilde{t}_{2T}^h, \tilde{e}_{2T}^h, \tilde{t}_{2T}^{\perp h}, \tilde{e}_{2T}^{\perp h}$

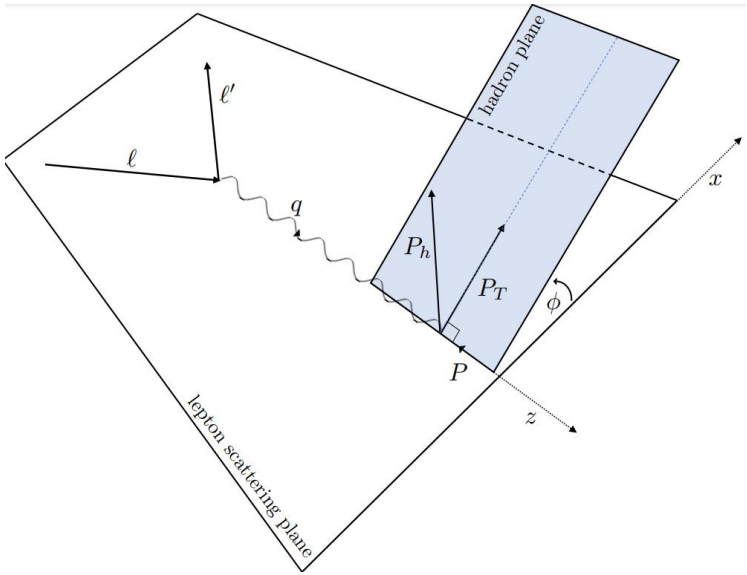
Twist-3 quark collinear FrFs.

Understanding of target fragmentation azimuthal distributions will help with interpretation of the azimuthal distributions in the current fragmentation region.

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

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

Fracture Function



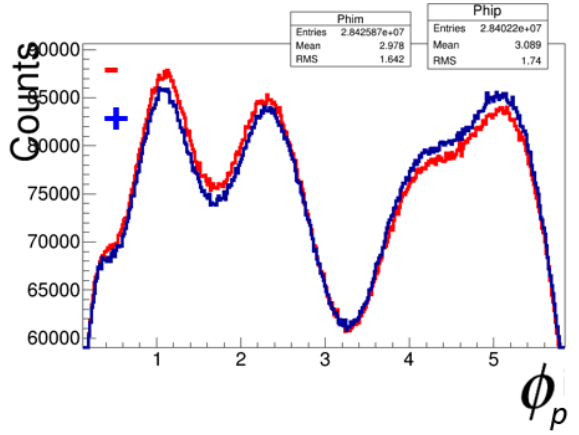
Method: Study Asymmetry modulations :

p0+p1 sin(ϕ) + p2 sin(2 ϕ) for different variables: P_T, Q^2, x, etc...

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

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

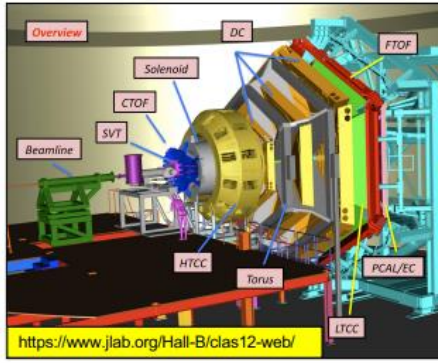
Depol. fac.



- RGA Data taken in fall 2018 and Spring 2019 with 10.6 and 10.2 GeV longitudinally polarized electron beam and **unpolarized LH_2 target**. The full data set has been analyzed (e-pol ~86.5%)
- **$ep \rightarrow e'p' + X$** , using only forward detector. Then checks with larger proton_theta
- Fiducial cuts, channel selection vertex cut, Eloss, bin migration study, were performed.

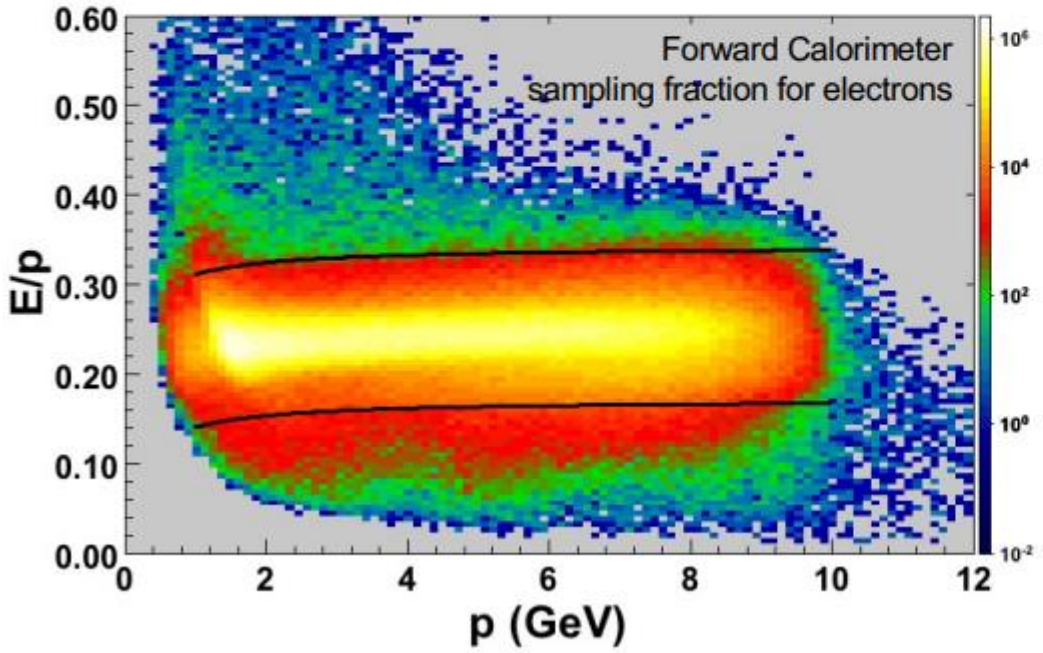
Particle Identification

ep → e'p' + X

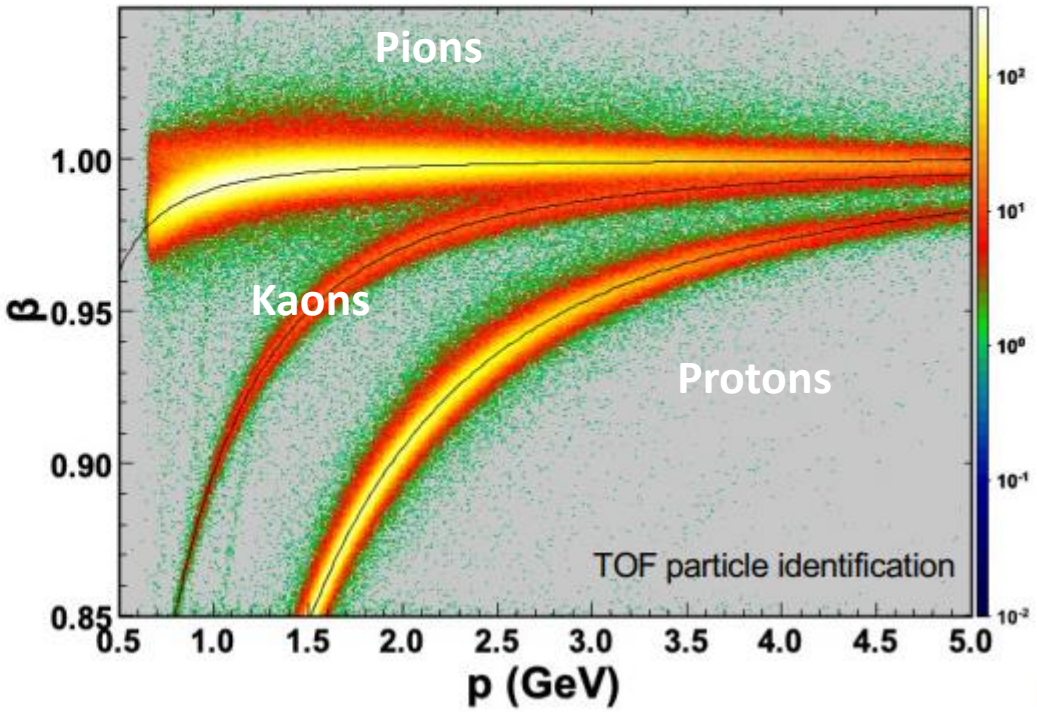


- Electron
  - Electromagnetic calorimeter.
  - Cherenkov detector.
  - Vertex and fiducial cuts.

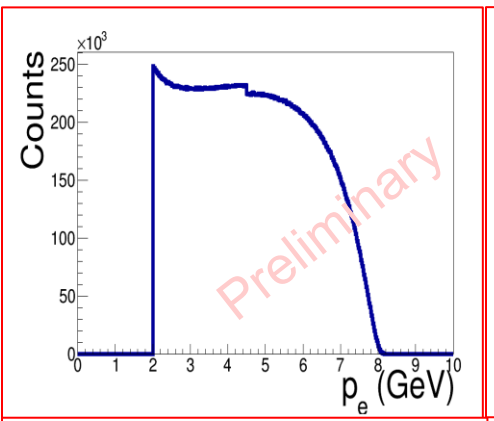
- Hadron
  - β vs p comparison between vertex timing and event start time.
  - Vertex and fiducial cuts.

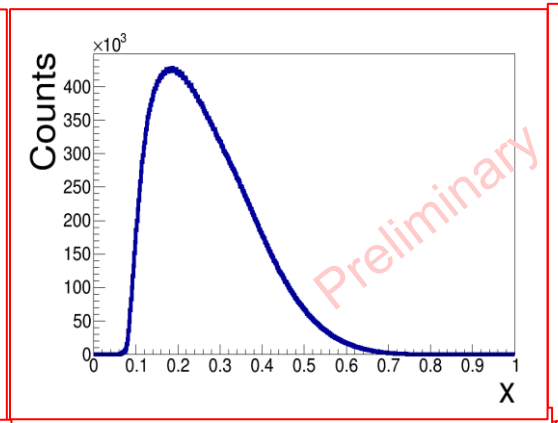


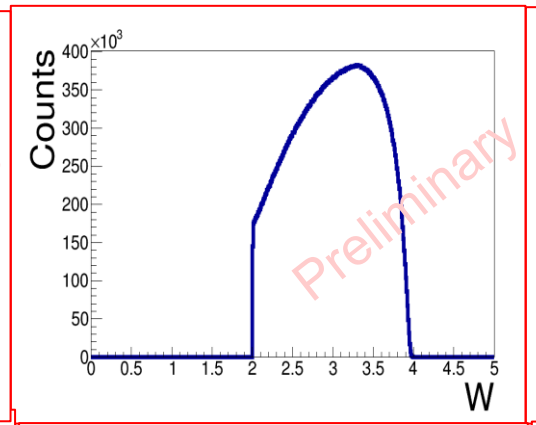
T. Hayward, M.I.T

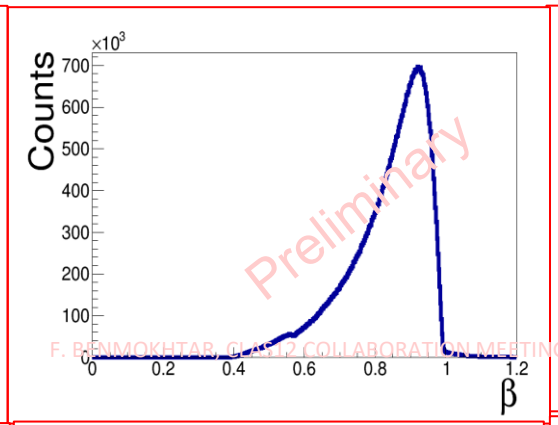


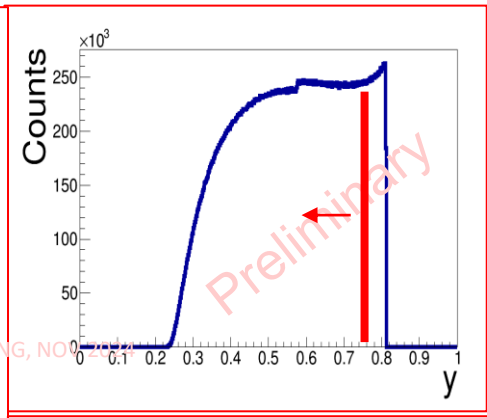
Variables of interest ($ep \rightarrow epX$)

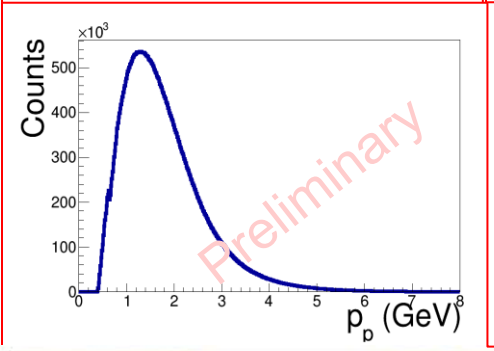


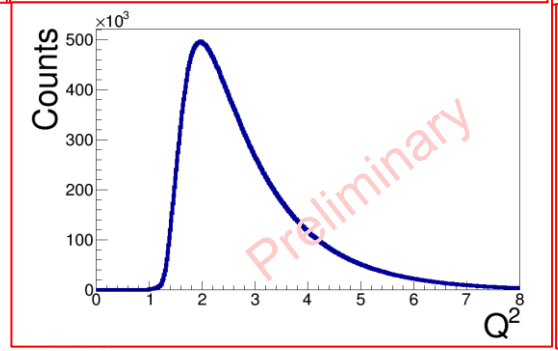


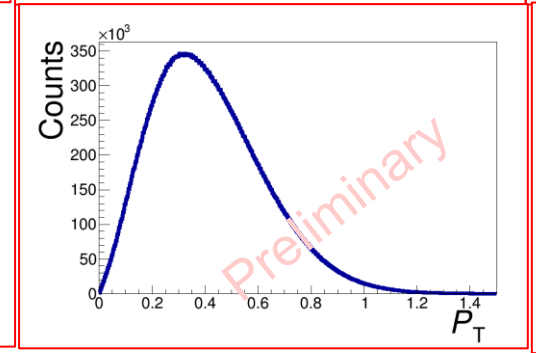


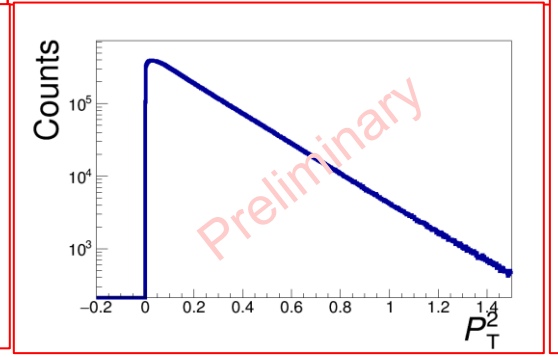


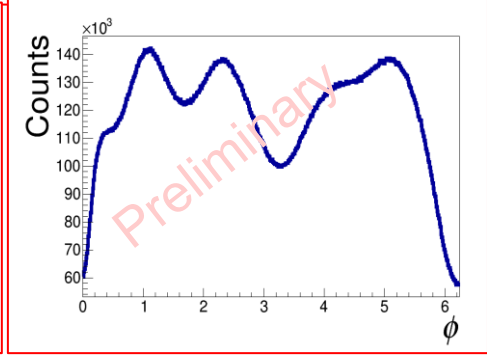


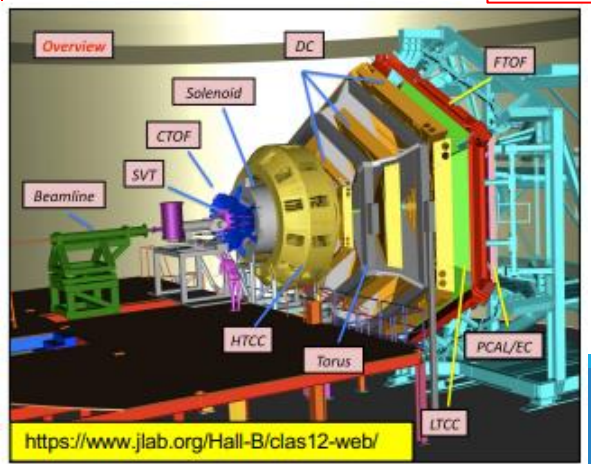


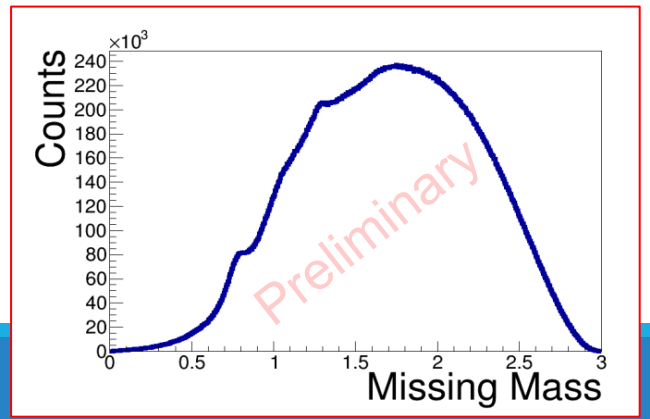


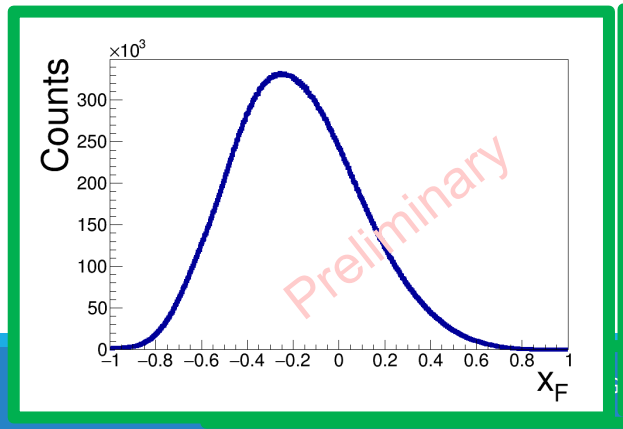


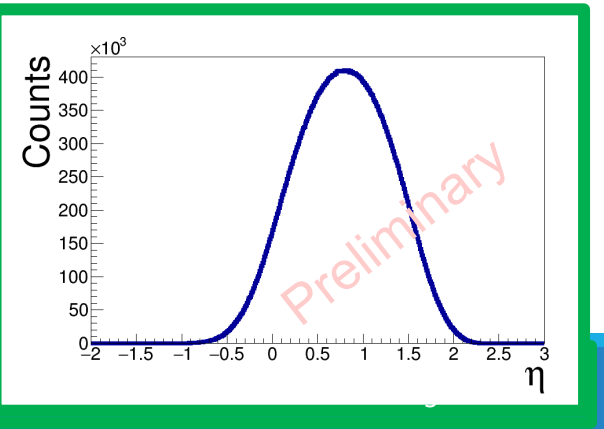




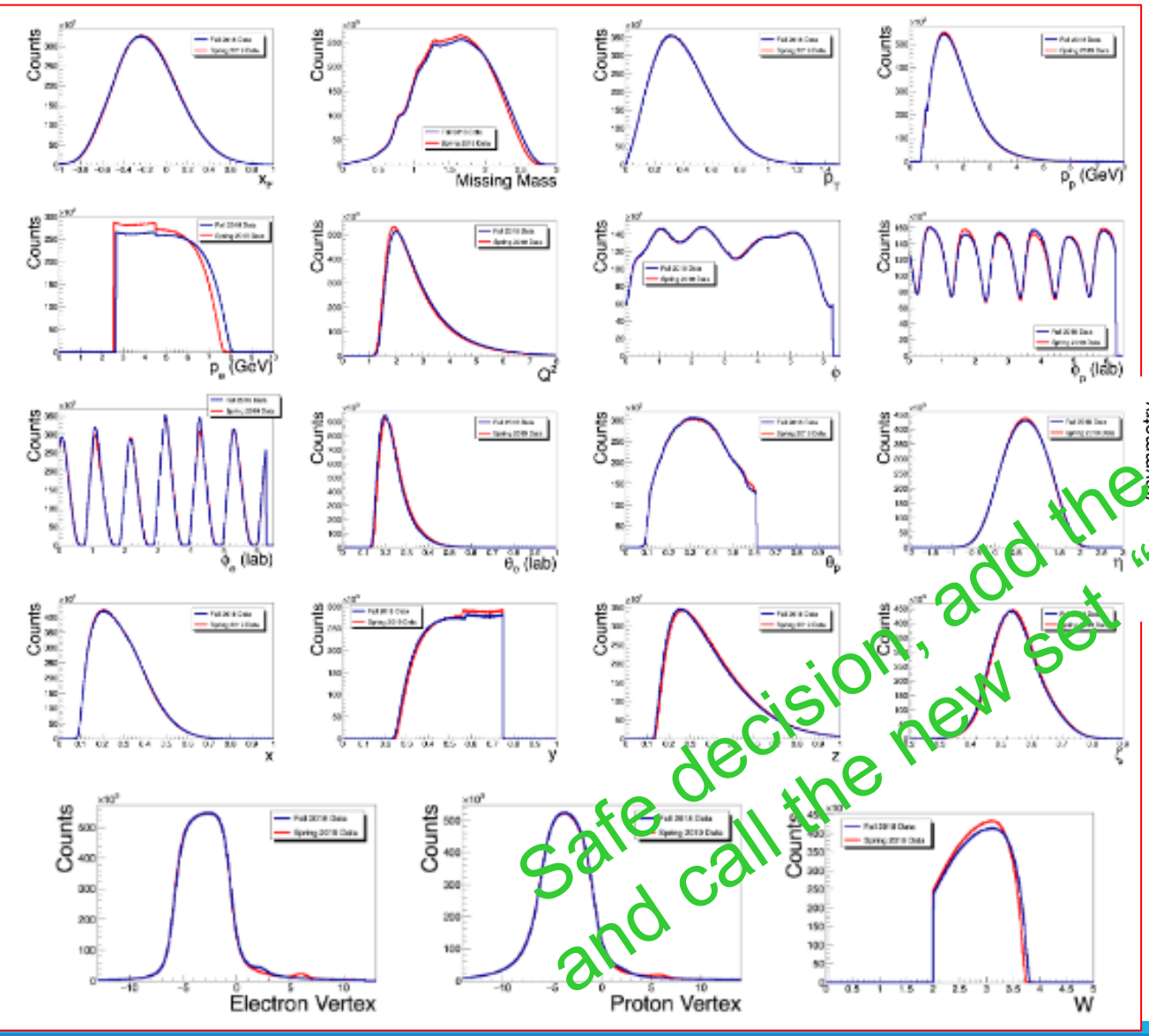


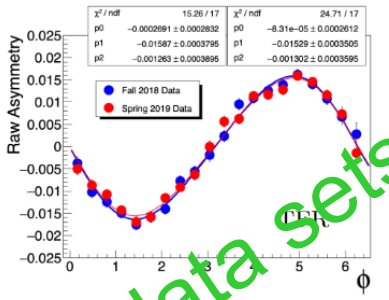


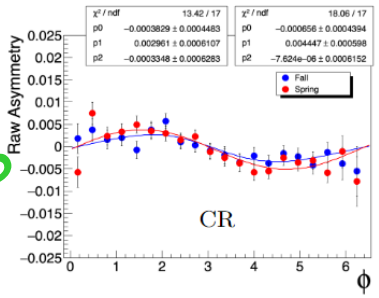


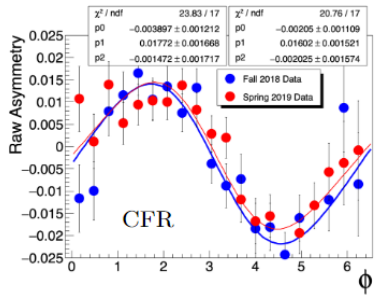


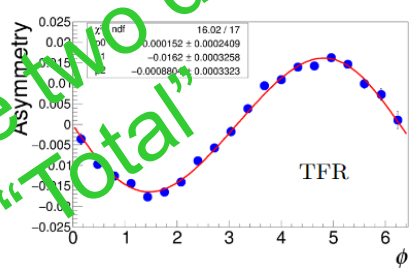
Comparison between Fall 2018 and Spring 2019

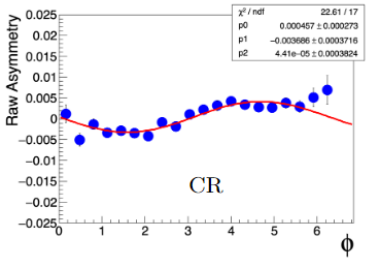


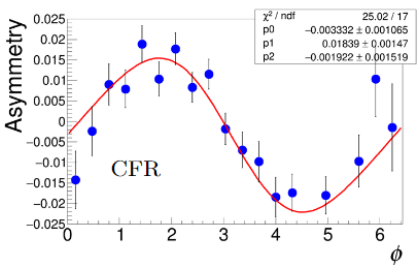




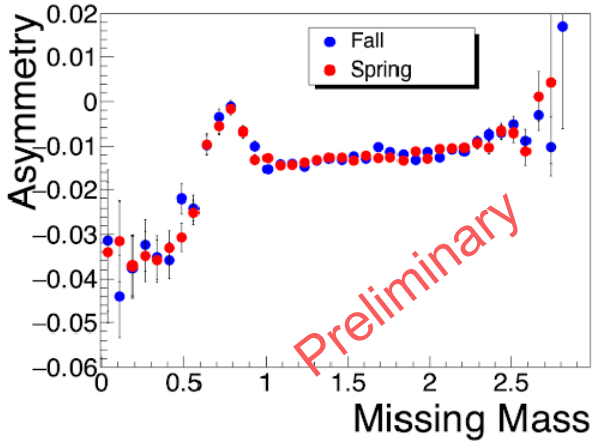








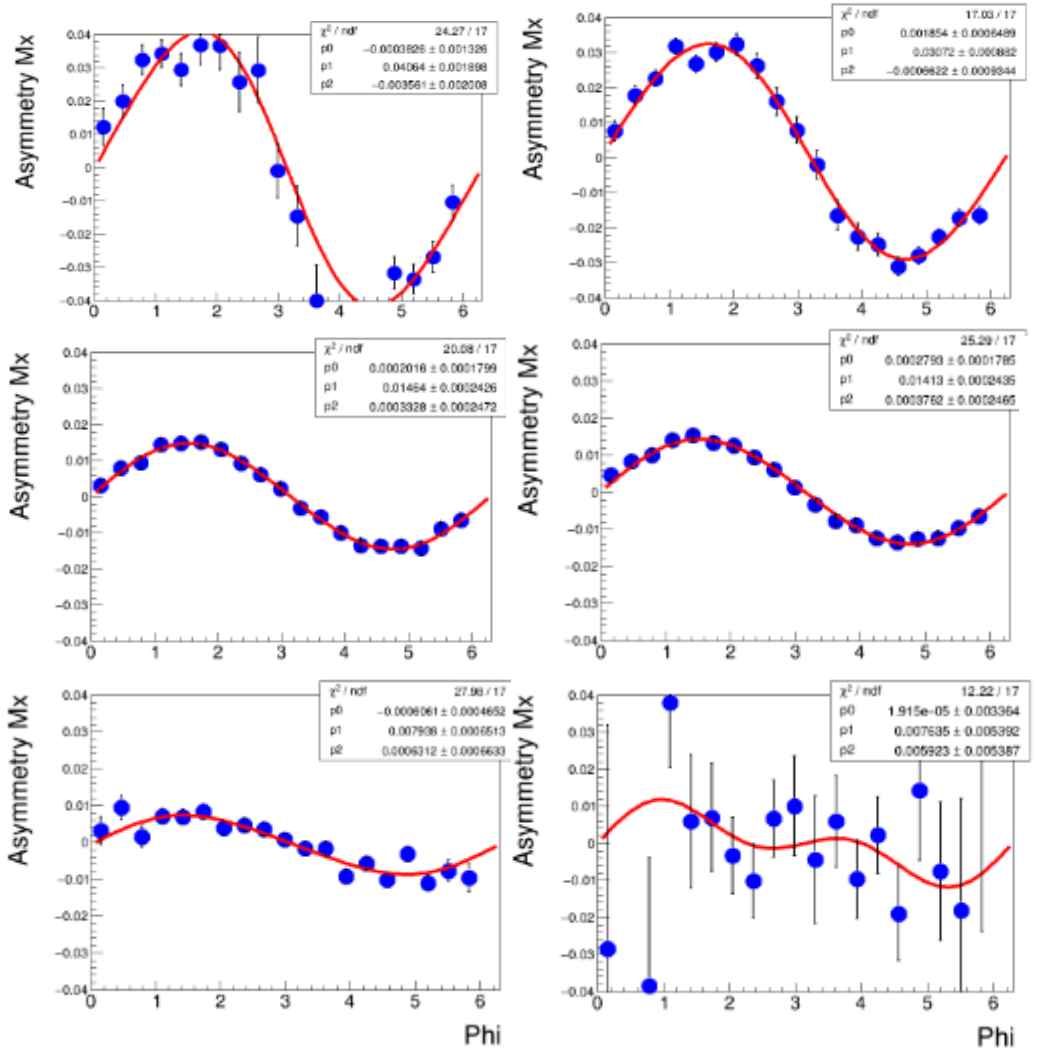
Safe decision, add the two data sets and call the new set "Total"

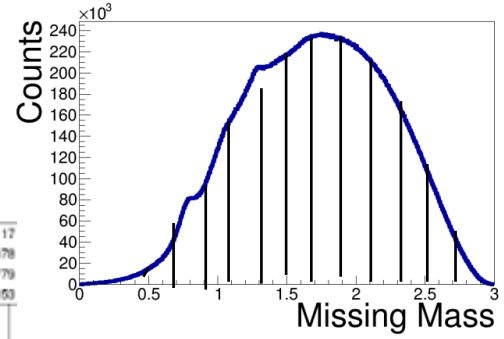


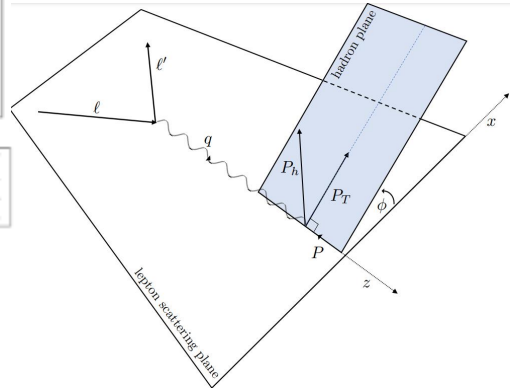
SSA Extraction method: expel: Sin(ϕ) modulation vs Missing Mass

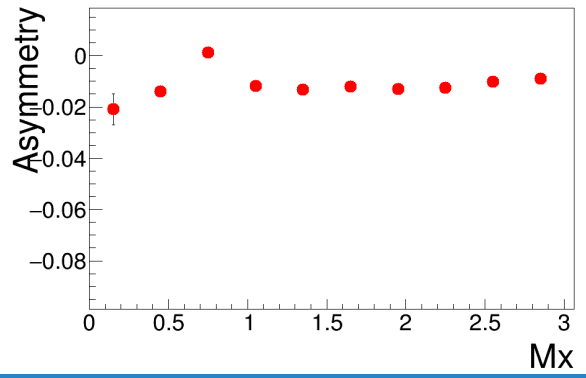
$$A(\phi)_{LU} = \frac{1}{p}\left(\frac{N^+ - N^-}{N^+ + N^-}\right)$$

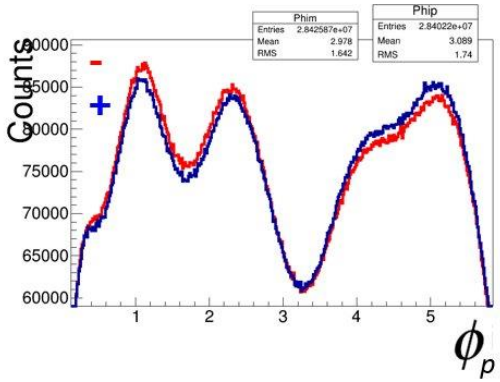
p0+p1 sin ϕ + p2 sin(2 ϕ)





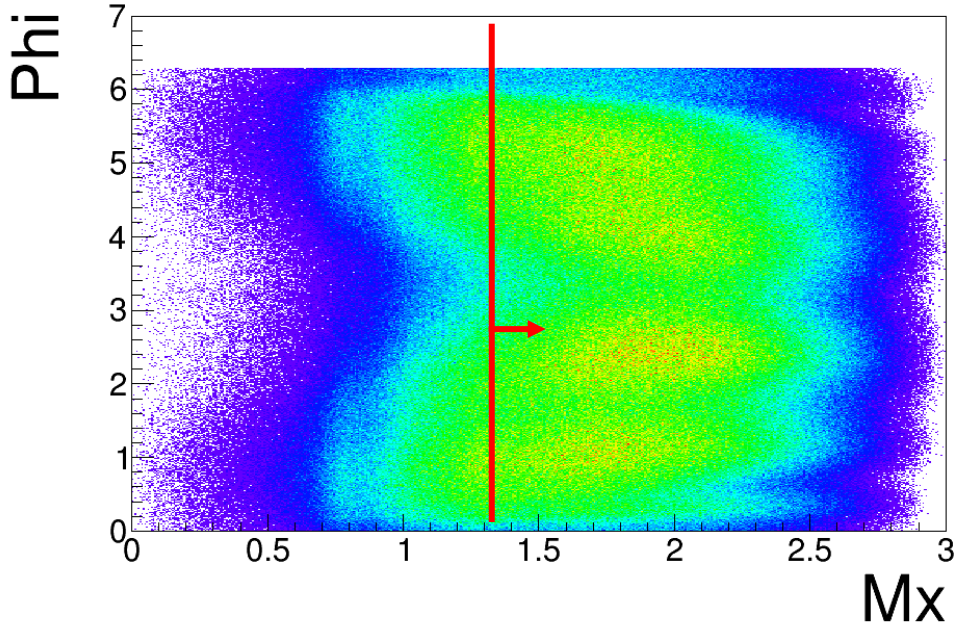




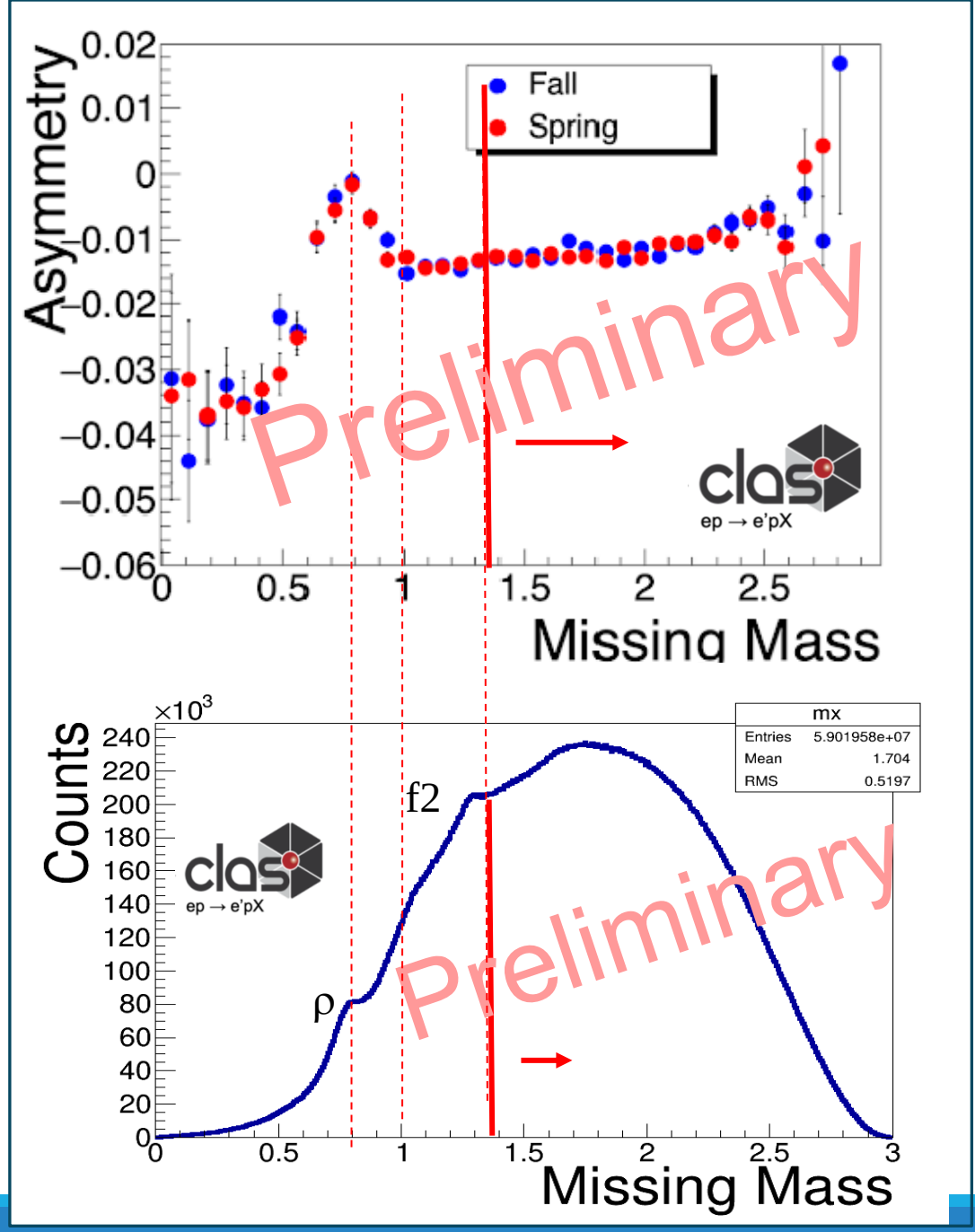


Preliminary Asymmetry vs Mx Results

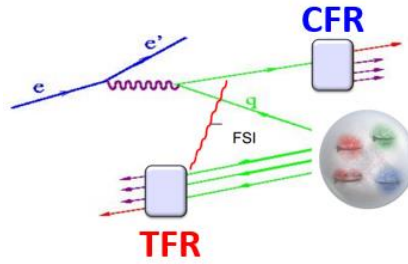
$$A(\phi)_{LU} = \frac{1}{p}\left(\frac{N^+ - N^-}{N^+ + N^-}\right)$$

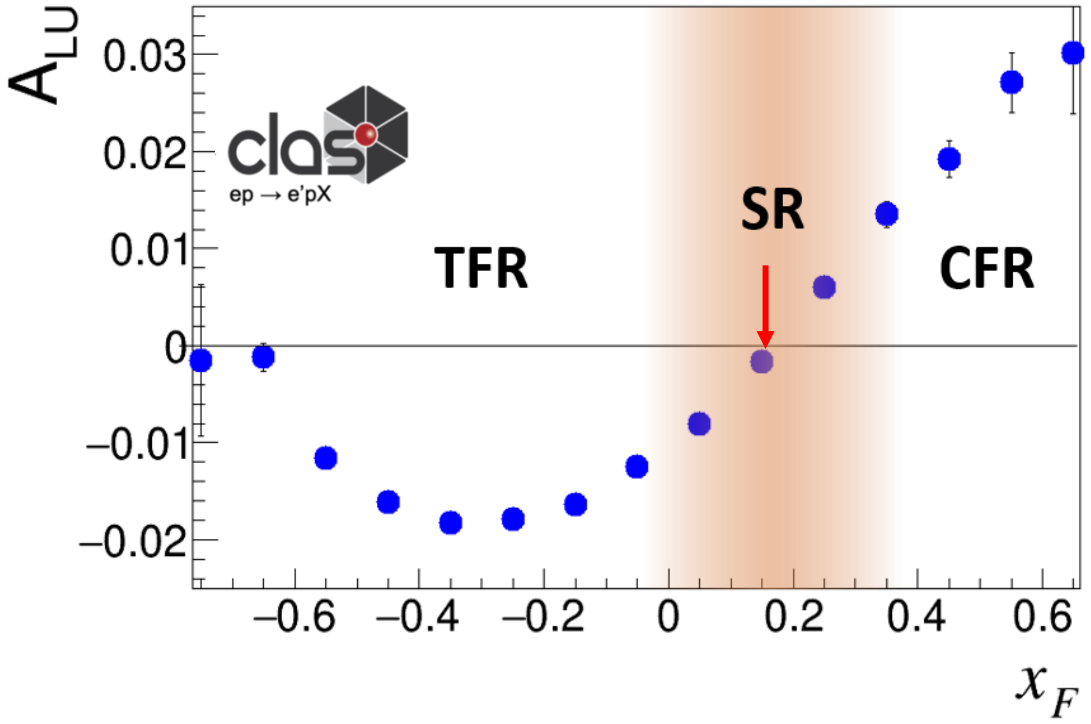


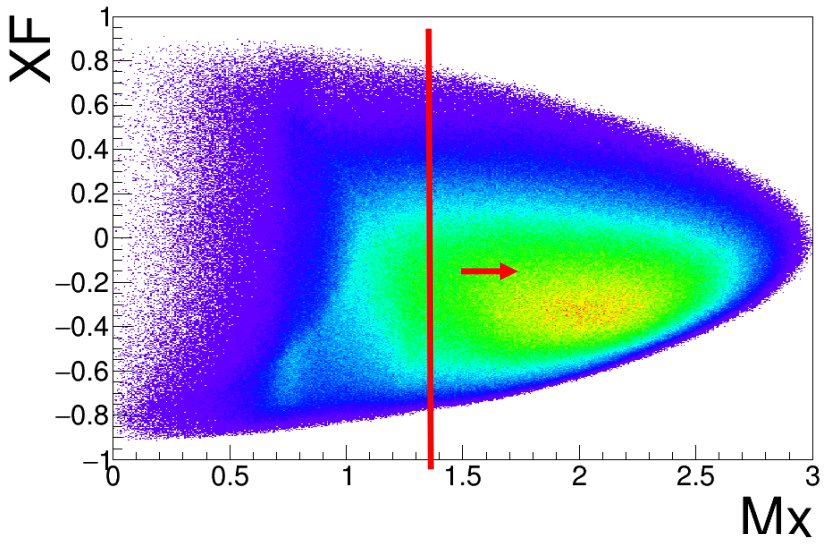
Decision: Take Mx>1.35

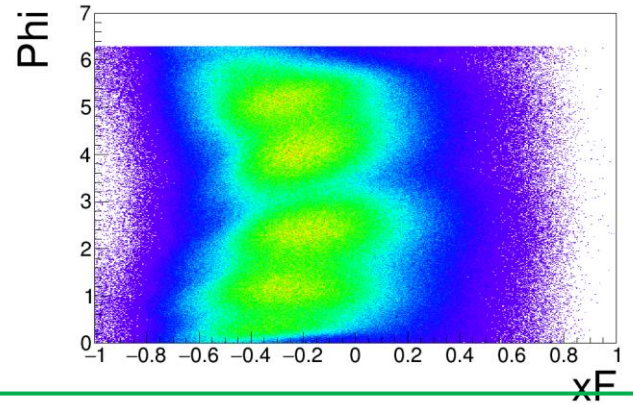


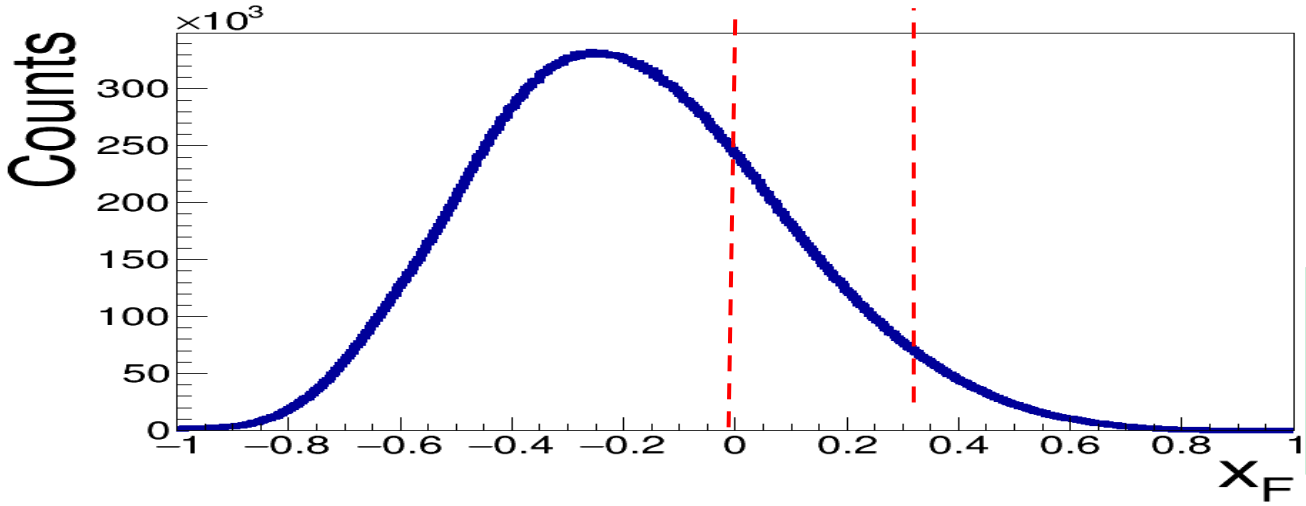
Asymmetry vs x_F Prel. Results, Mx > 1.35 (and appropriate cuts)







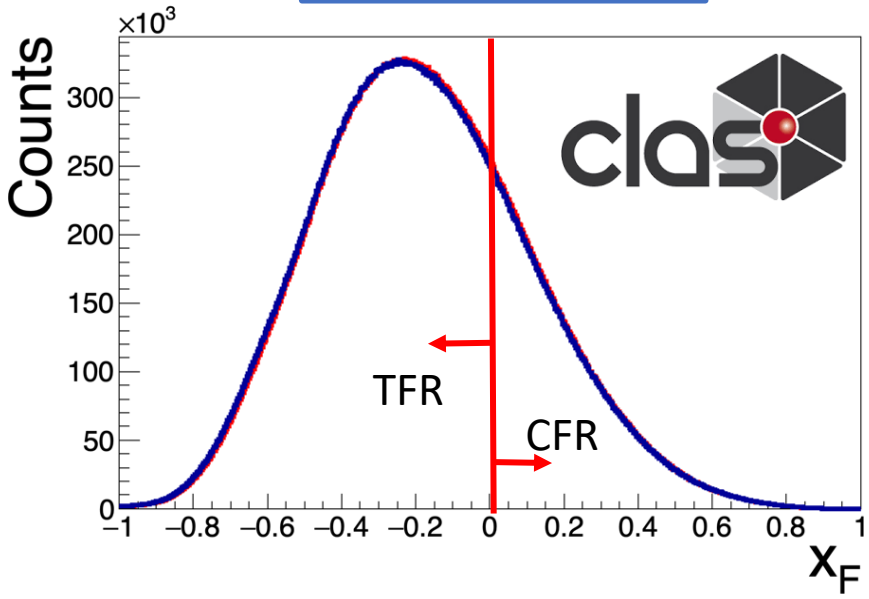


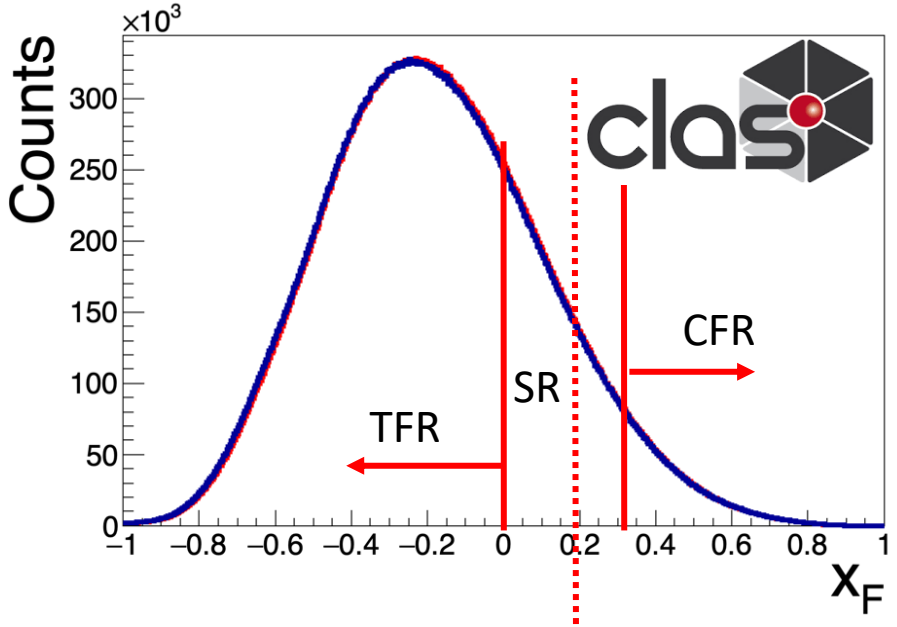


Note***: "*New tool for kinematic regime estimation in semi-inclusive deep-inelastic scattering*: Target, central and current regions": M. Boglione *et al.*, *High Energ. Phys.* **2022,** 84 (2022). https://doi.org/10.1007/JHEP04(2022)084

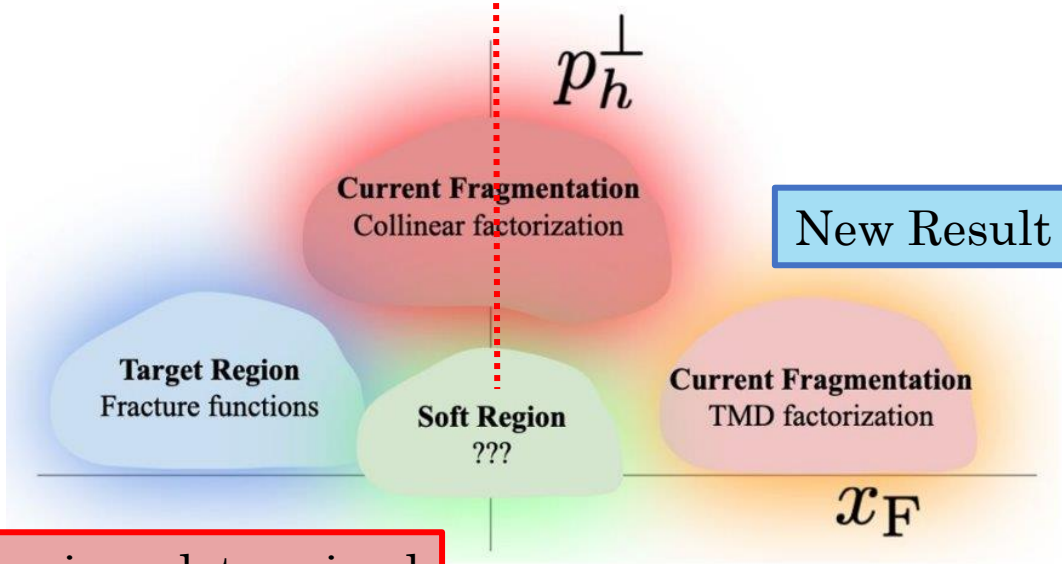
Fragmentation Regions

Previous Belief





New Result



New cuts available for analysis

- **TFR:** xF < 0
- **SR:** 0 < xF < 0.3
- **CFR:** 0.3 < xF

Fragmentation regions determined to be separated by soft region

Proton Energy Loss Corrections

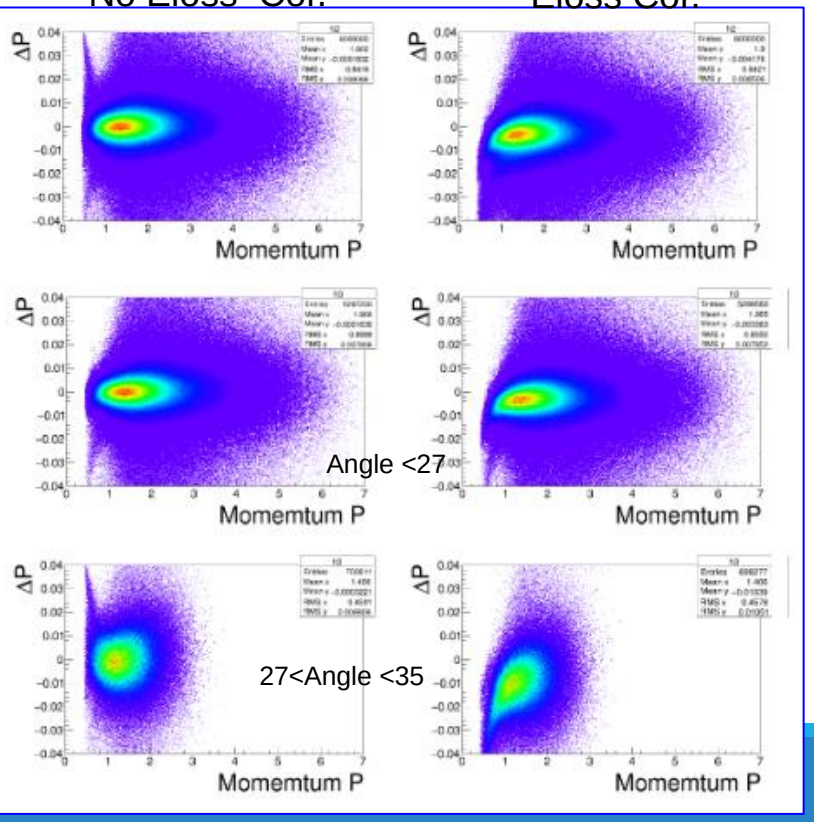
. Momentum corrections analysis have been described in great detail in the exclusive π0 electro-production analysis note of Andrey Kim , https://clas12-docdb.jlab.org/DocDB/0009/000948/260001/AKim_pi0_note.pdf

Same method was applied to our analysis.

$$\Delta P = P_{gen} - P_{rec}$$

$$\Delta P = e^{p0+p1P} + p2$$

No Eloss Cor. Eloss Cor.



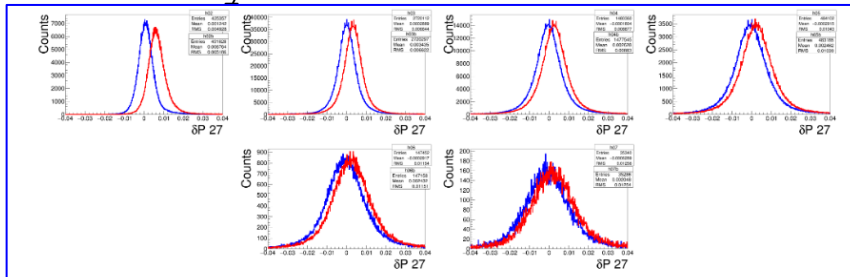


Figure 22: δP with and without energy loss sliced on proton momentum bins for angles less than 27 deg.

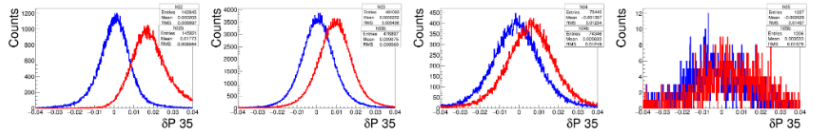
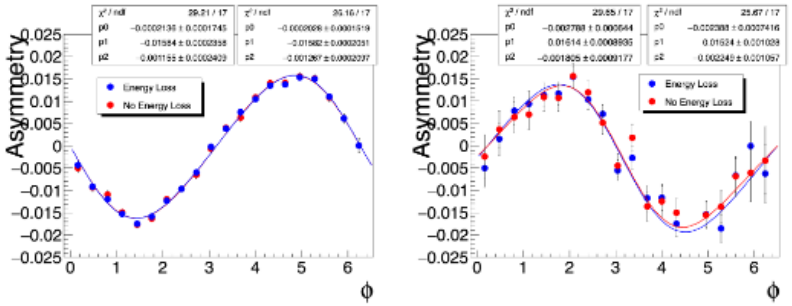
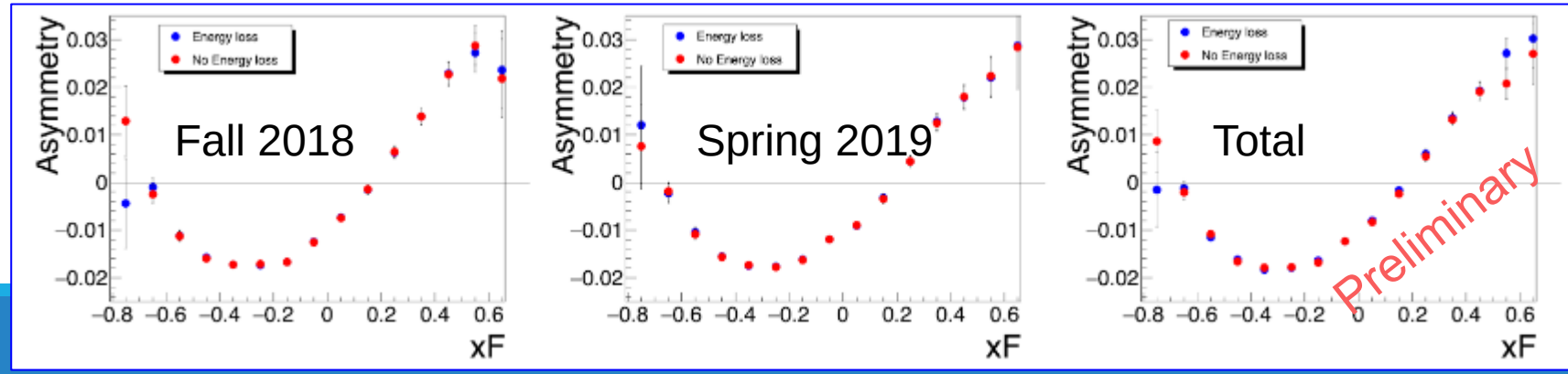


Figure 23: Proton momentum with and without Eloss corrections, for angle between 17 and 35 deg

. Energy loss corrections were applied to the data from now on.



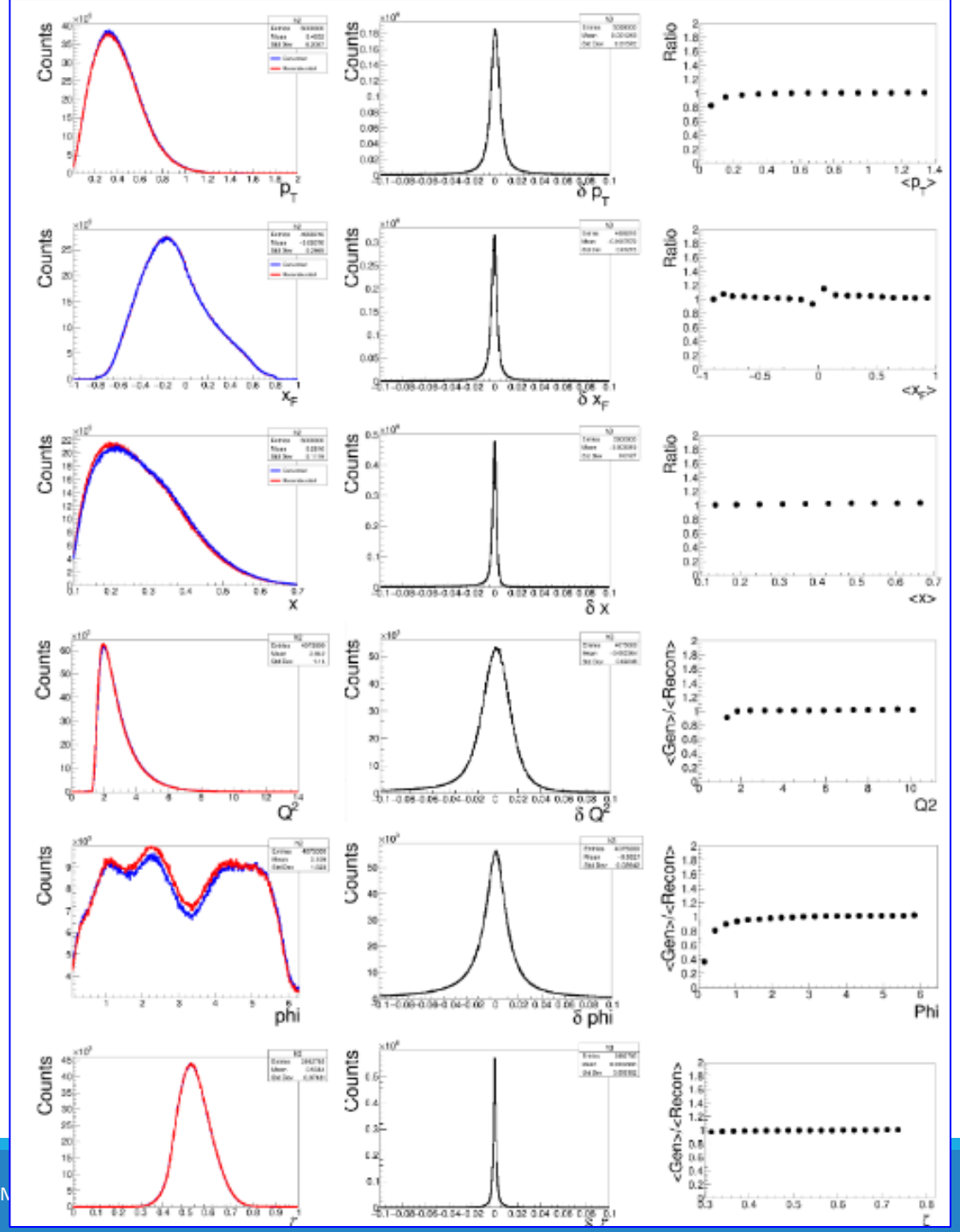


Studies of Bin Migration

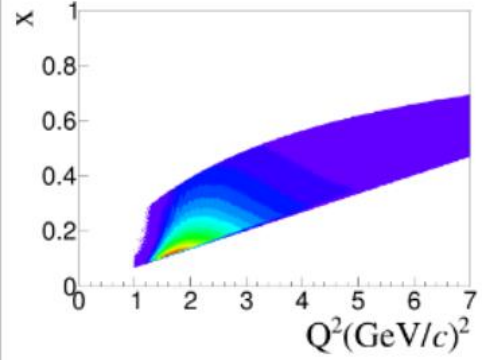
. It is possible to encounter event migration across bins. This phenomena is due to the finite resolution of the kinematic variables used to analyze the single-spin asymmetries.

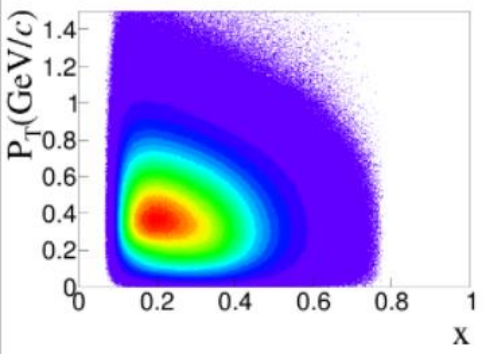
. Perform Reconstructed − Generated

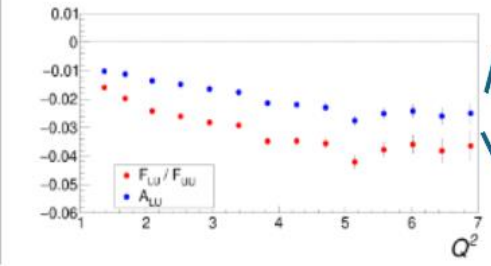
Bin Migration effects are small

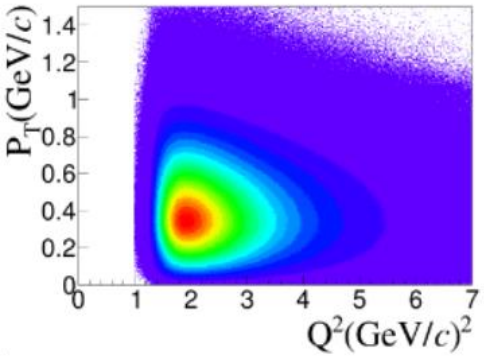


Multi-Dim Results

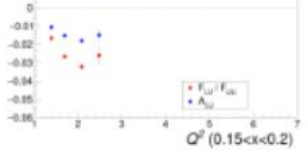

x
Q^2(GeV/c)^2

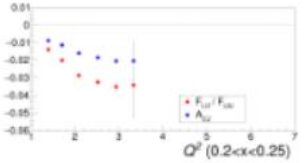

P_T(GeV/c)
x

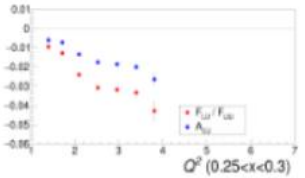

F_{LU} / F_{UU}
A_{LU}
Q^2

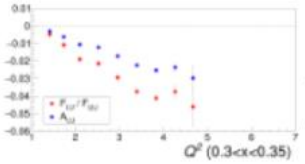

P_T(GeV/c)
Q^2(GeV/c)^2

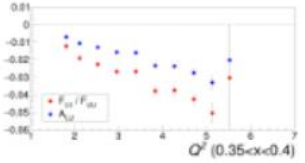
Q^2 (x, P_T, z)

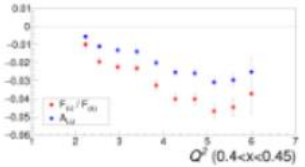

Q^2 (0.15<x<0.2)

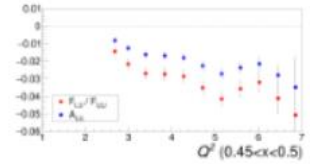

Q^2 (0.2<x<0.25)

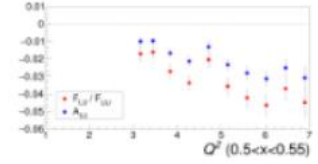

Q^2 (0.25<x<0.3)

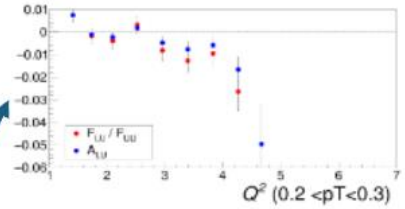

Q^2 (0.3<x<0.35)

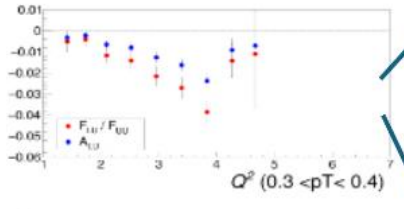

Q^2 (0.35<x<0.4)

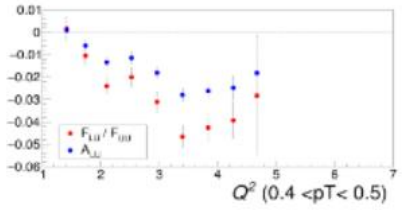

Q^2 (0.4<x<0.45)

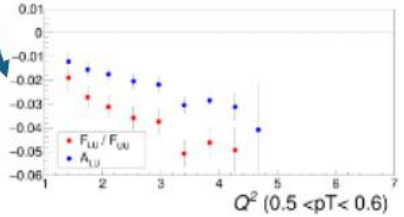

Q^2 (0.45<x<0.5)

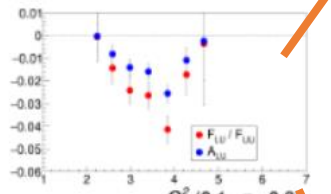

Q^2 (0.5<x<0.55)

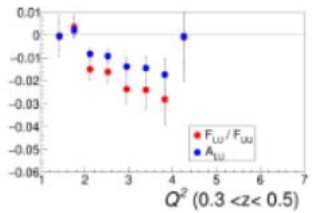

Q^2 (0.2 <pT<0.3)

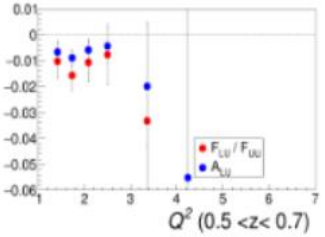

Q^2 (0.3 <pT< 0.4)

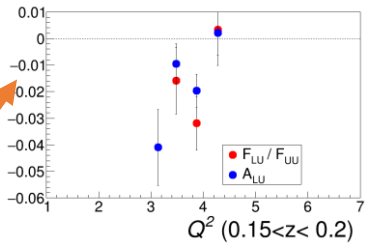

Q^2 (0.4 <pT< 0.5)

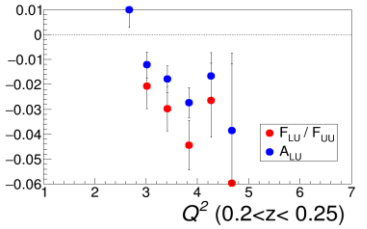

Q^2 (0.5 <pT< 0.6)

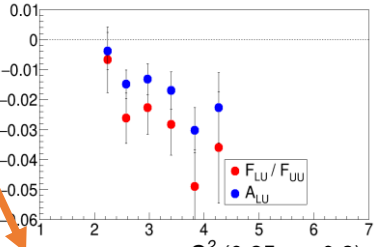

Q^2 (0.1 <z< 0.3)

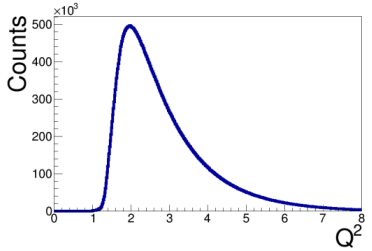

Q^2 (0.3 <z< 0.5)

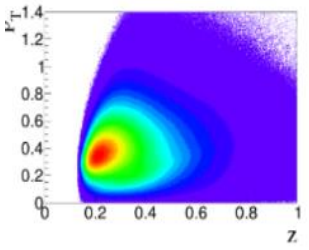

Q^2 (0.5 <z< 0.7)

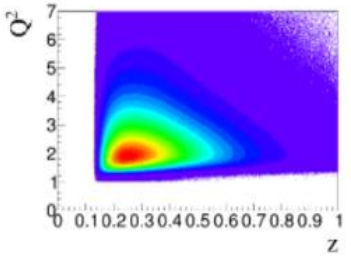

Q^2 (0.15<z< 0.2)

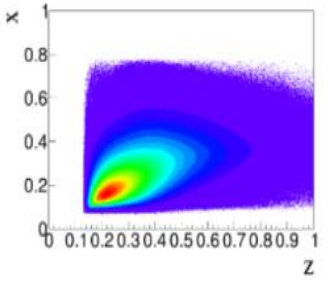

Q^2 (0.2<z< 0.25)


Q^2 (0.25<z< 0.3)

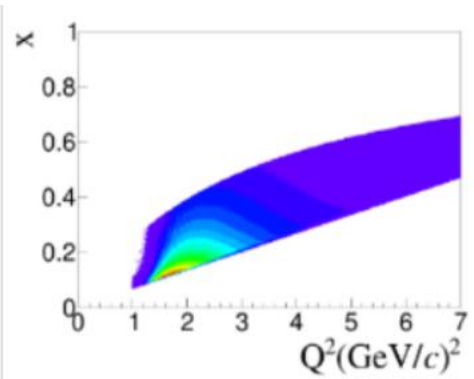

Counts
Q^2

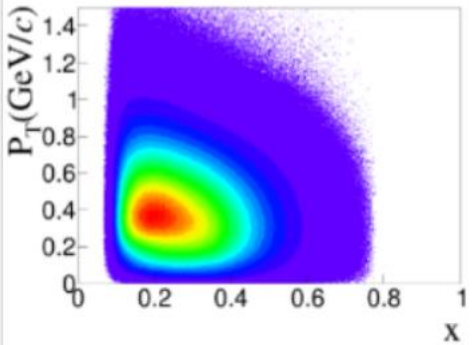

P_T
z

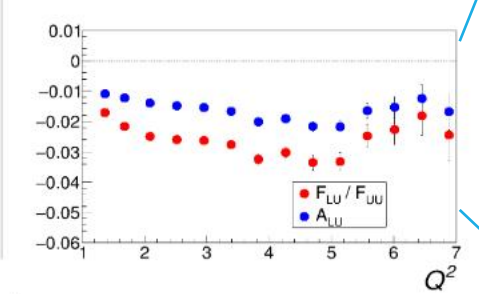

Q^2
z

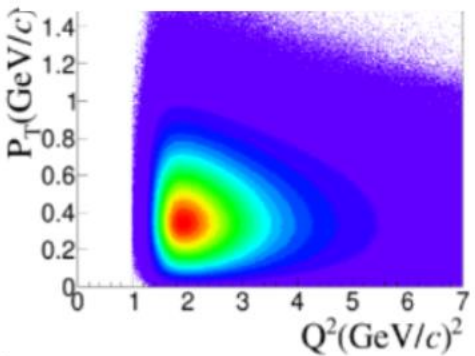

x
z

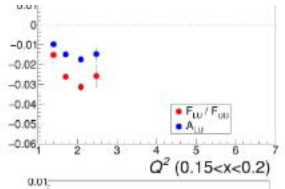
$Q^2(x, P_T, z, M_x)$

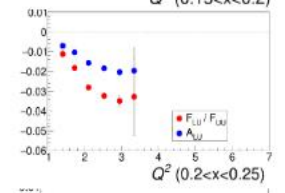

x
Q²(GeV/c)²

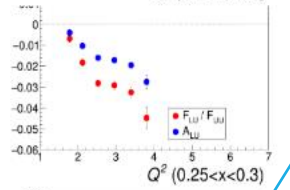

P_T(GeV/c)
x

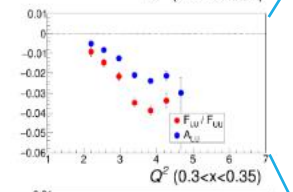

F_LU / F_UU
A_LU
Q²

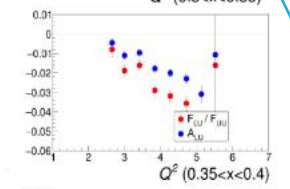

P_T(GeV/c)
Q²(GeV/c)²

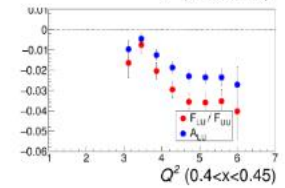

Q² (0.15<x<0.2)

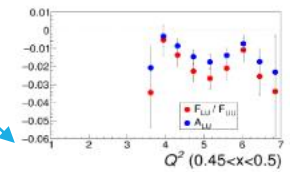

Q² (0.2<x<0.25)

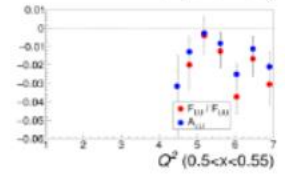

Q² (0.25<x<0.3)

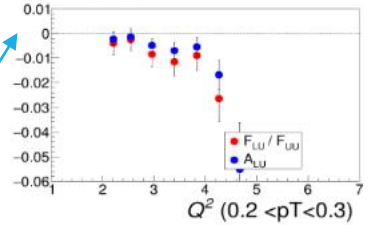

Q² (0.3<x<0.35)

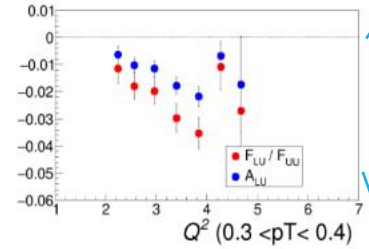

Q² (0.35<x<0.4)

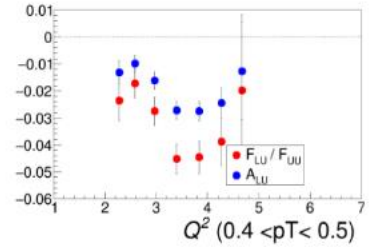

Q² (0.4<x<0.45)

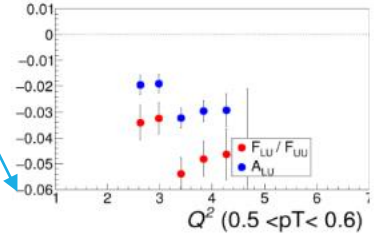

Q² (0.45<x<0.5)

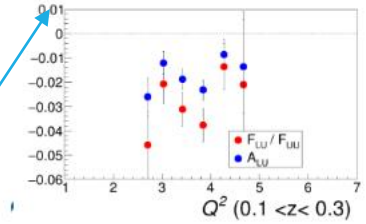

Q² (0.5<x<0.55)

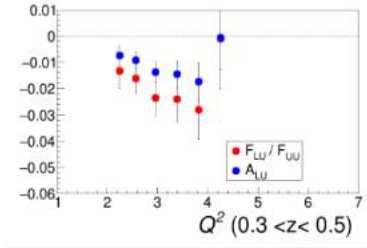

Q² (0.2 <pT<0.3)

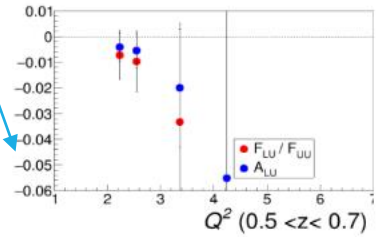

Q² (0.3 <pT< 0.4)

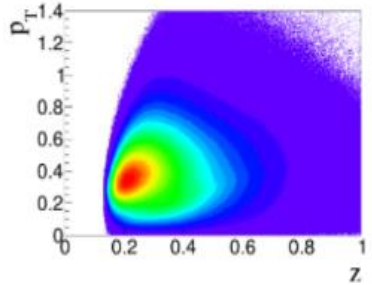

Q² (0.4 <pT< 0.5)

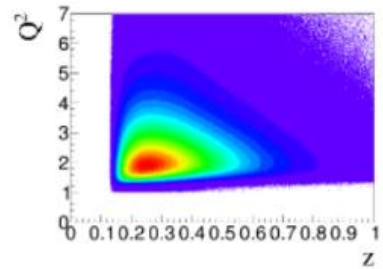

Q² (0.5 <pT< 0.6)

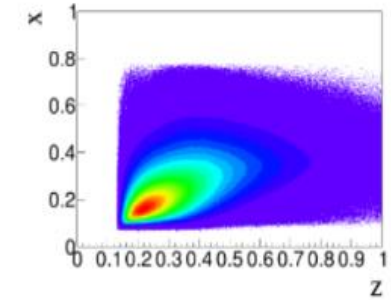

Q² (0.1 <z< 0.3)

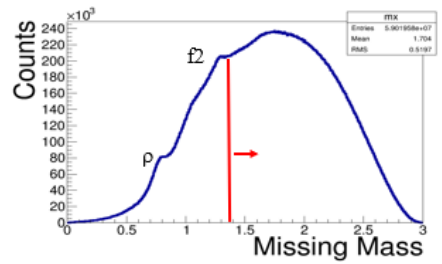

Q² (0.3 <z< 0.5)

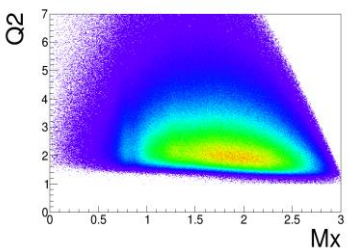

Q² (0.5 <z< 0.7)


P_T
z

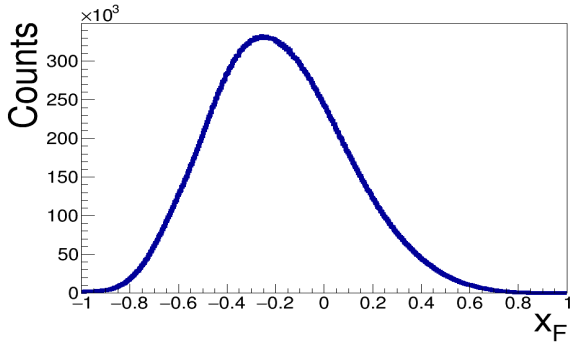

Q²
z

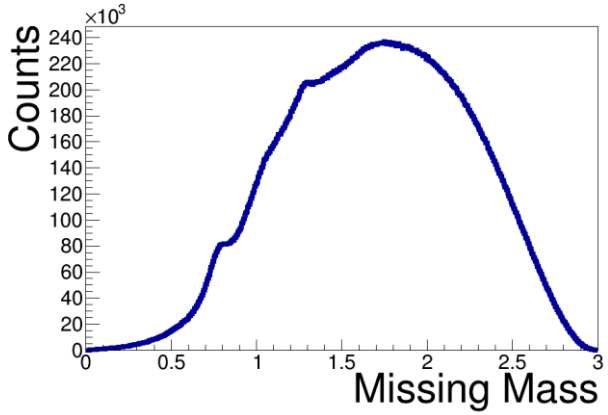

x
z

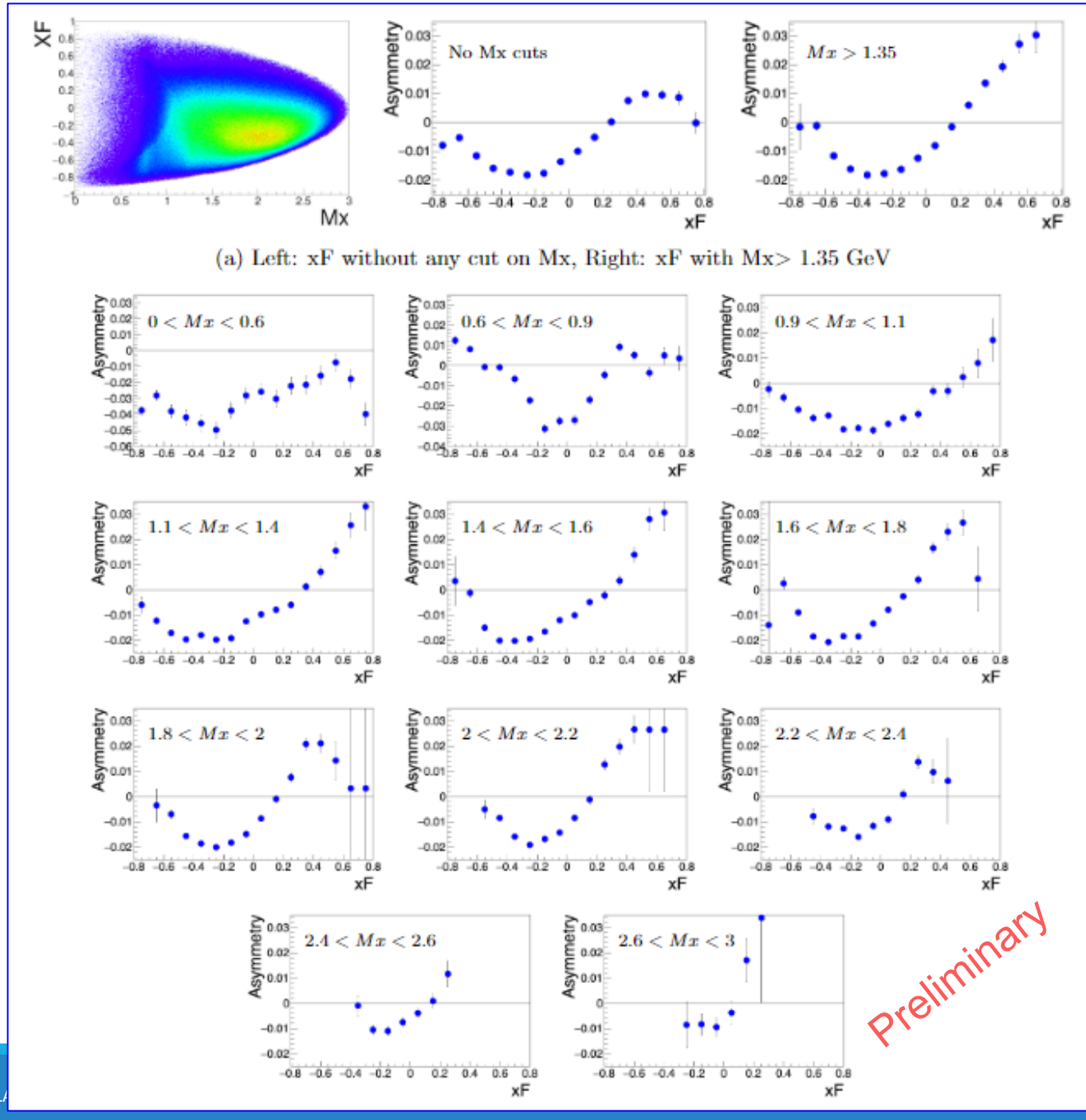

Counts
f2
ρ
Missing Mass


Q2
Mx

$x_F\,(M_X)$







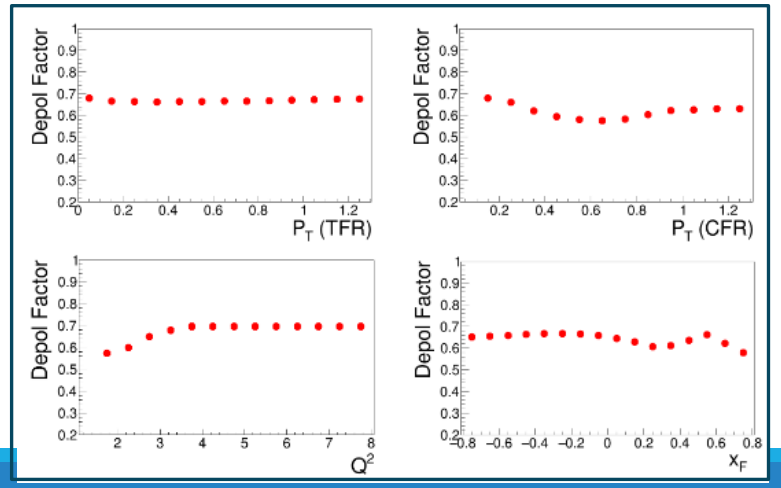
(a) Left: xF without any cut on Mx, Right: xF with Mx> 1.35 GeV

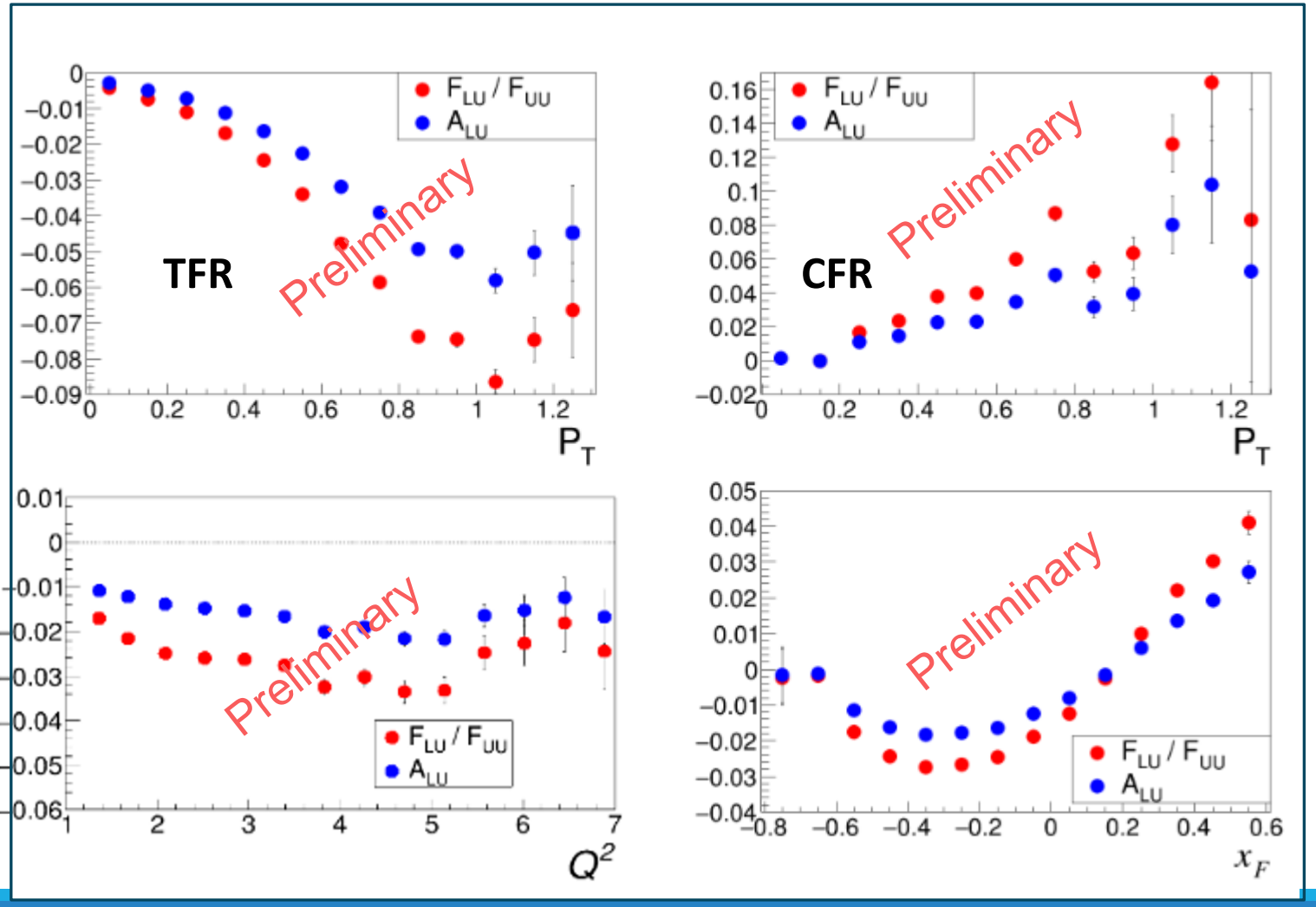
Preliminary

Ratio of FF Results

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

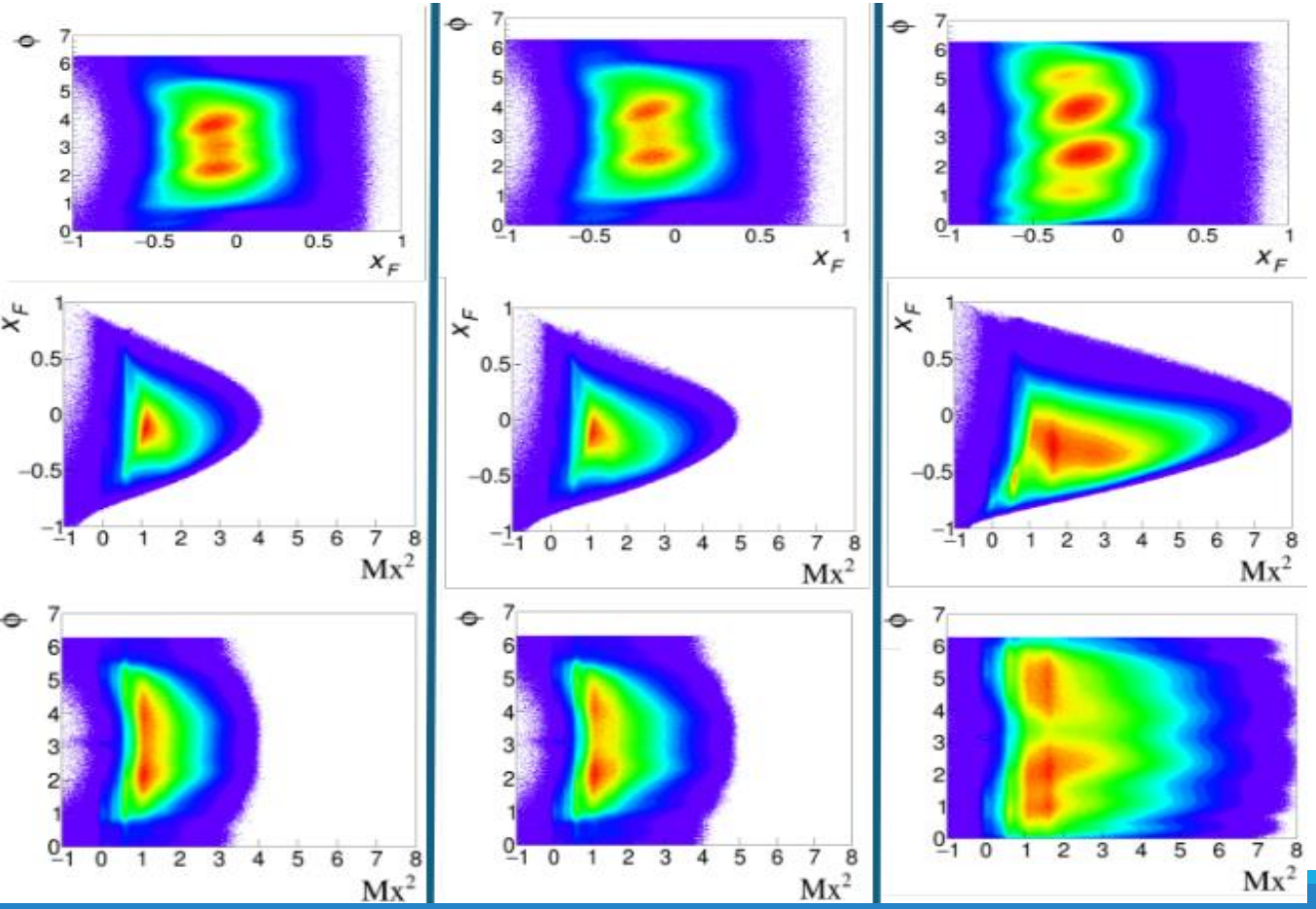
$$\frac{F_{LU}}{F_{UU}} = \frac{A_{LU}}{\sqrt{2\epsilon(1-\epsilon)}}$$

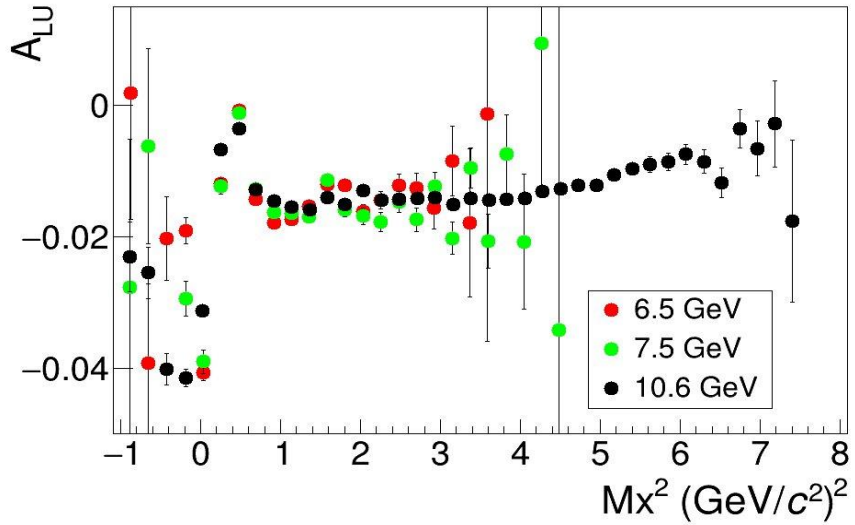


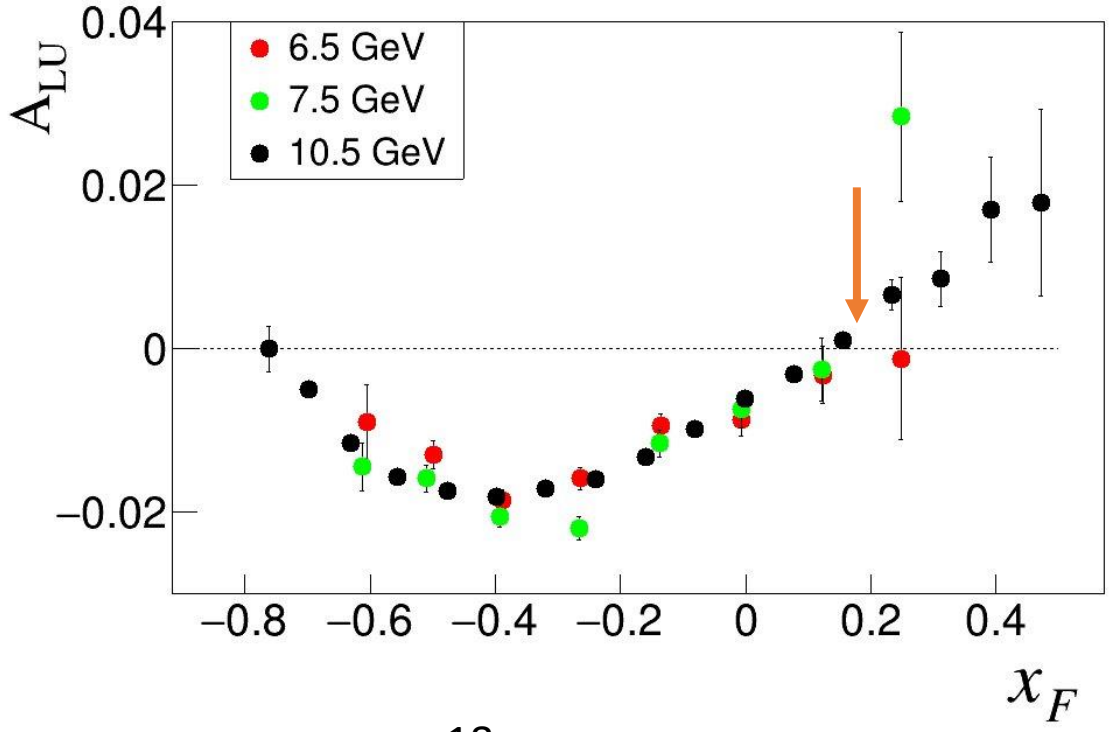


Beam Energy scans

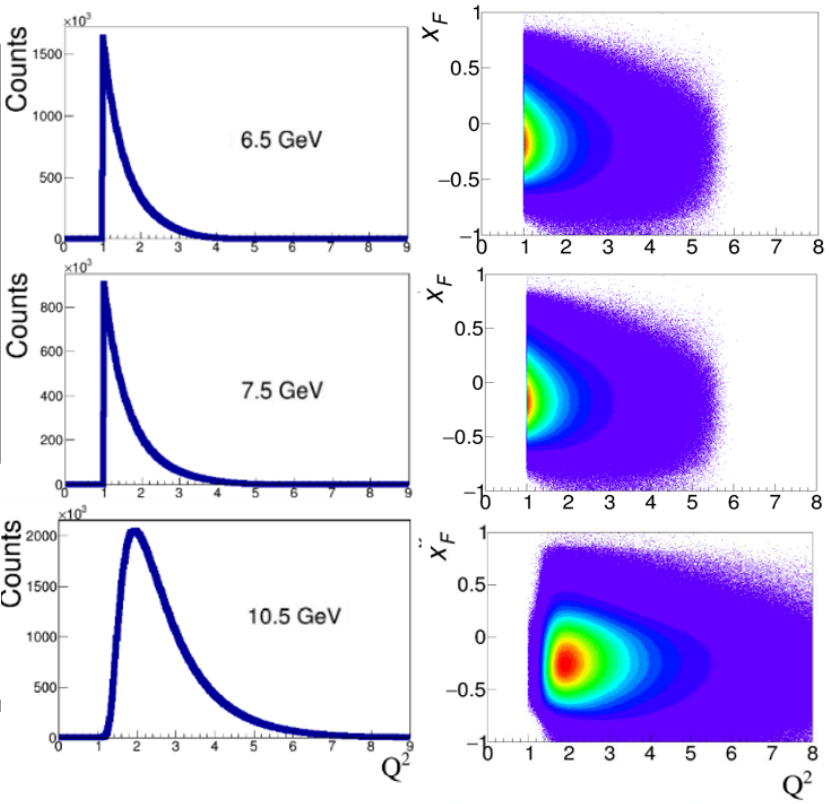
6.5 GeV **7.5 GeV** **10.6 GeV**

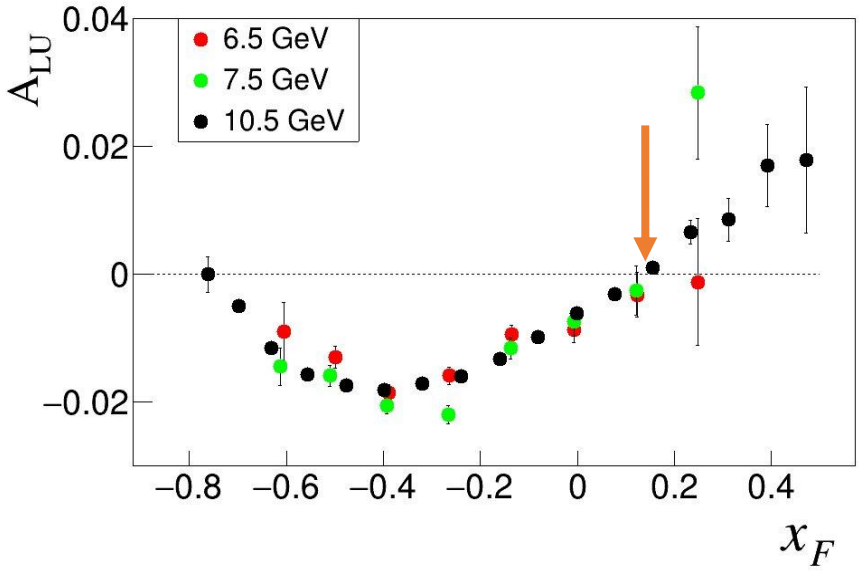


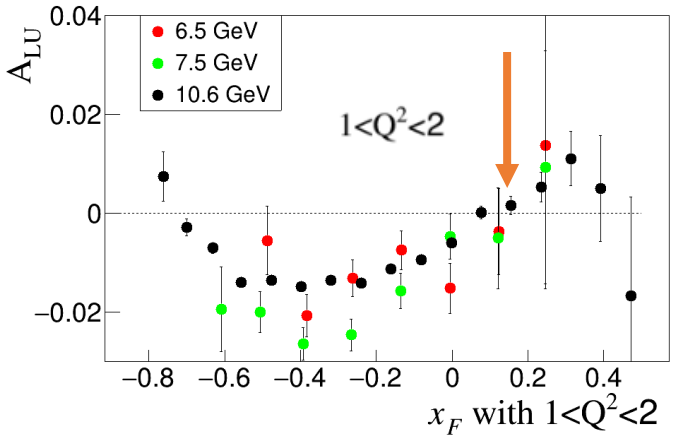


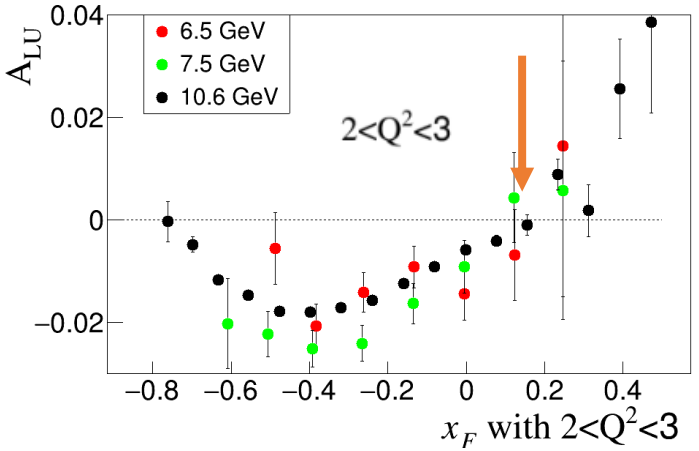


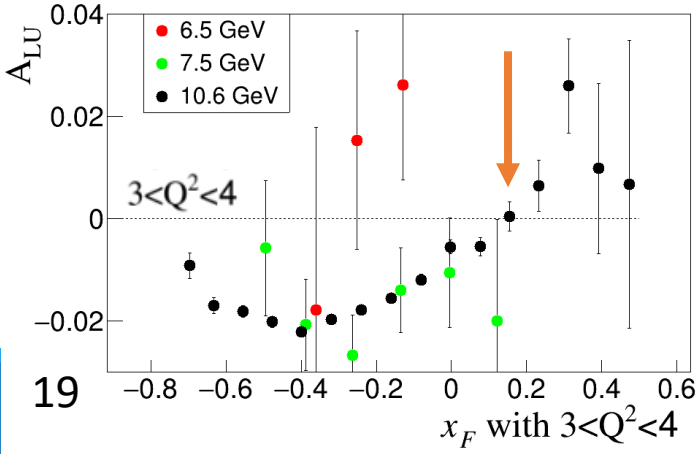
$X_F(Q^2)$ dependence



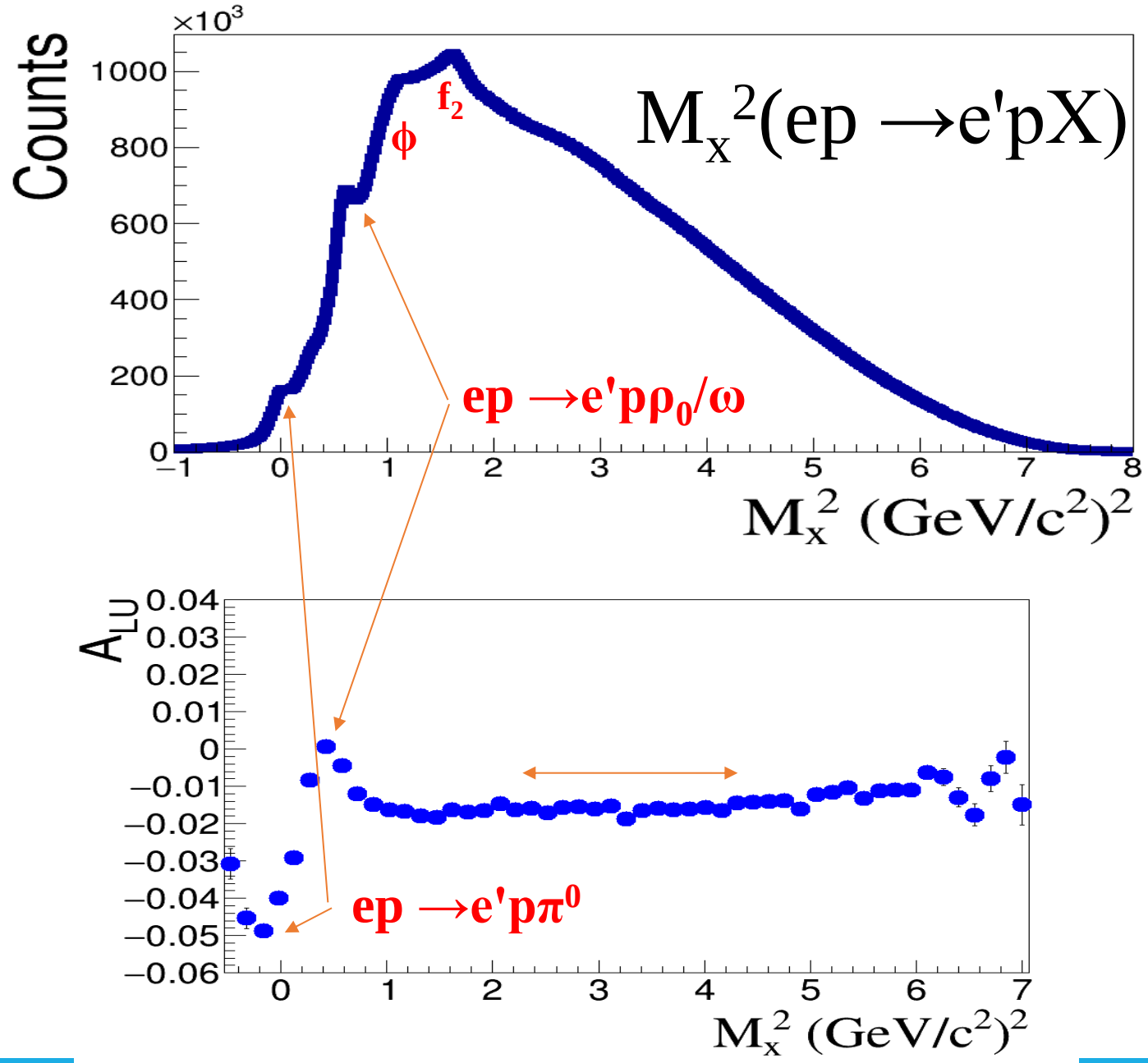






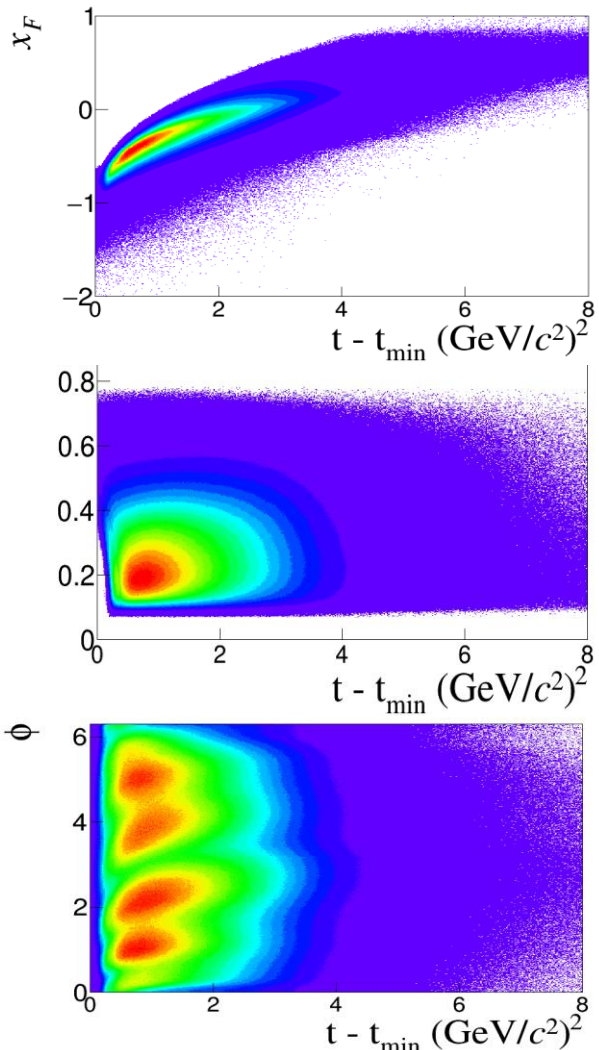


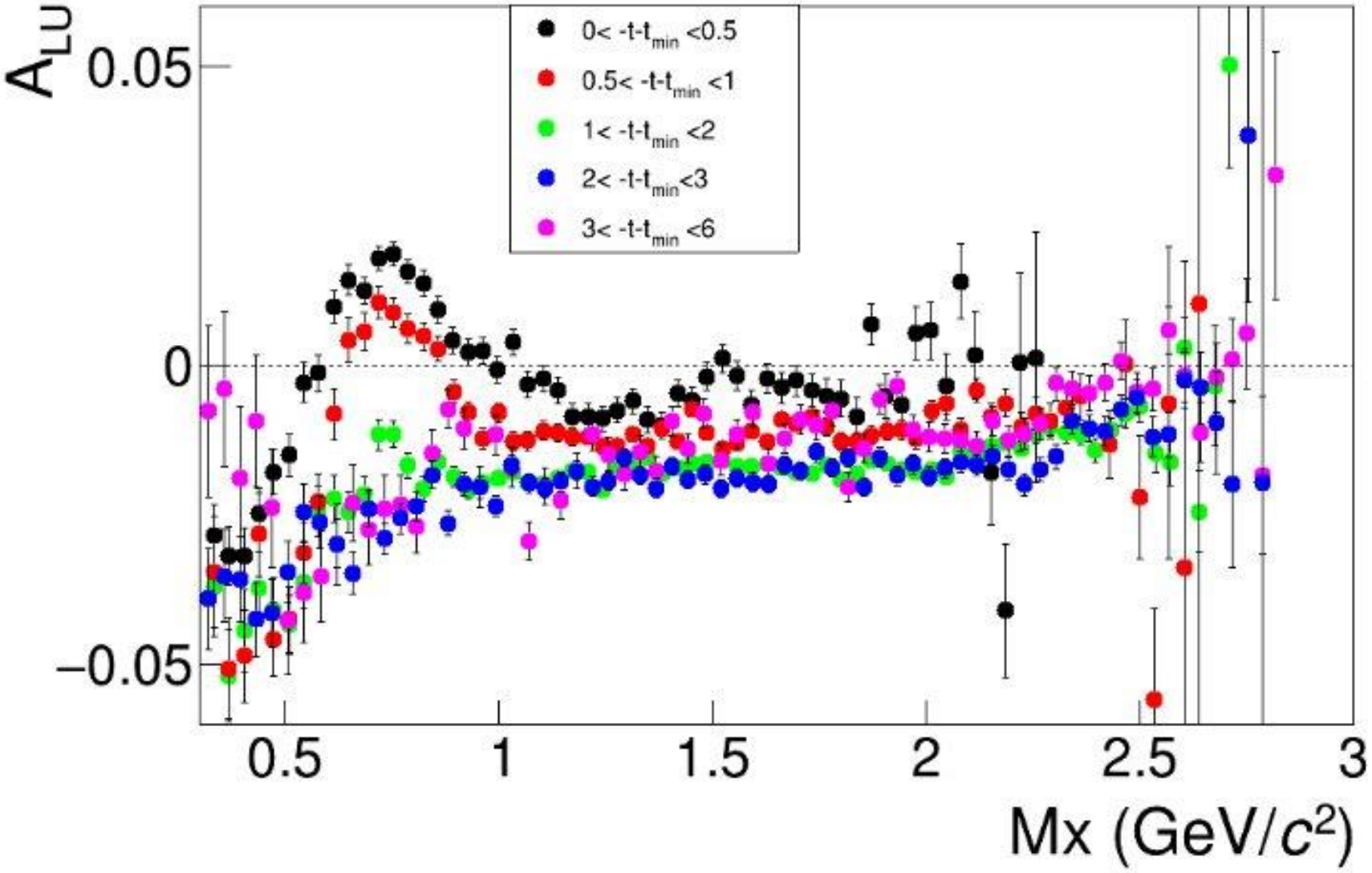
Taking care of Exlusive Channels Contributions



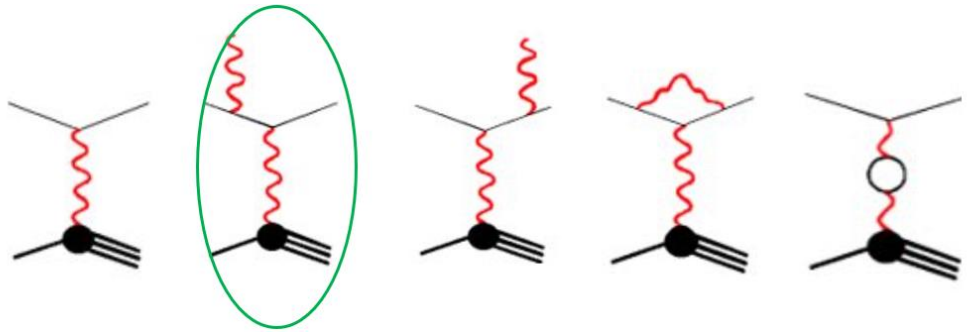
t dependance study

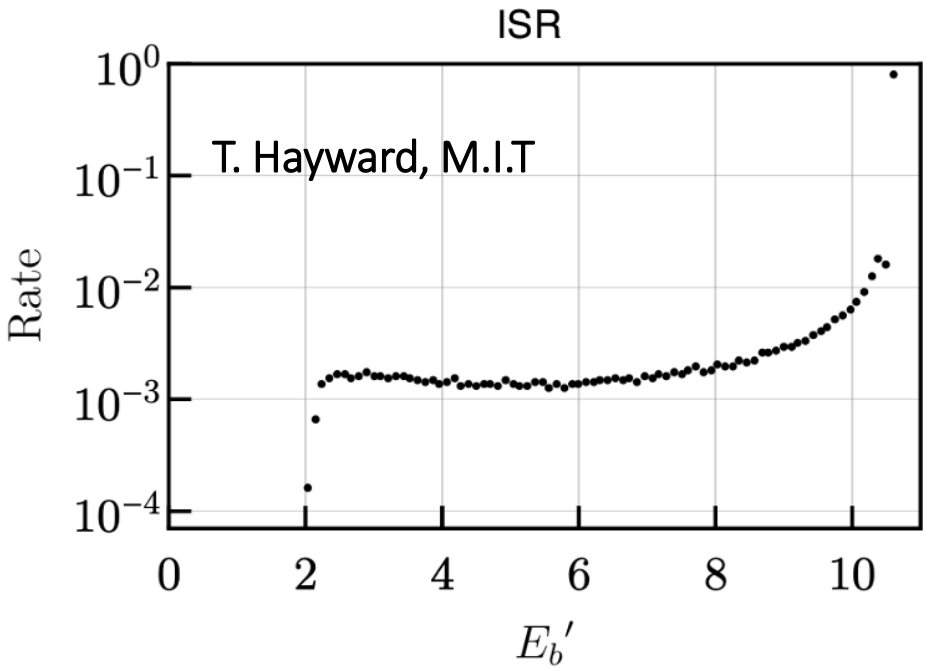
10.6 GeV



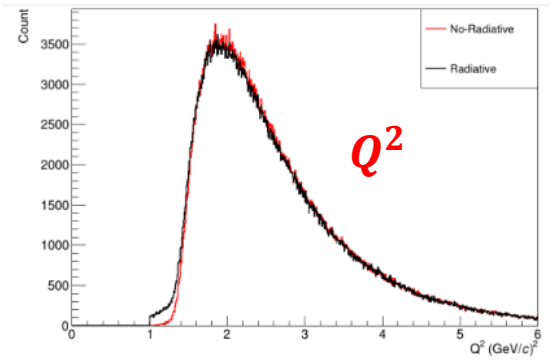


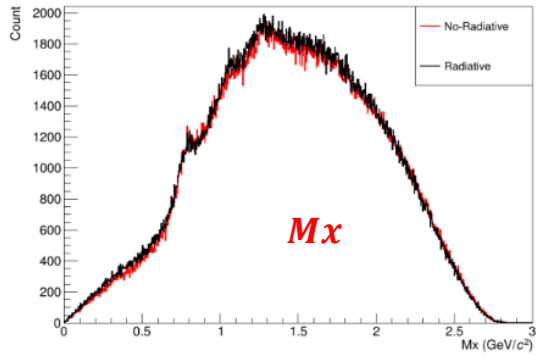
Electron Initial State Radiation studies

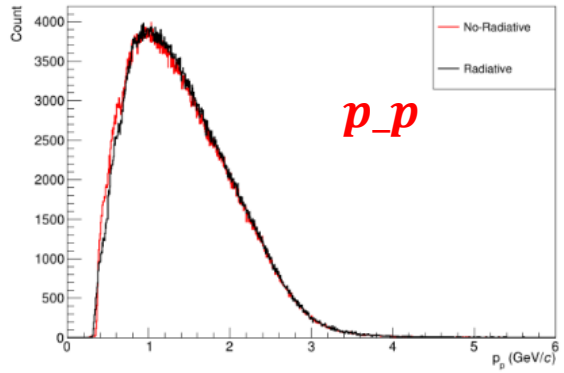


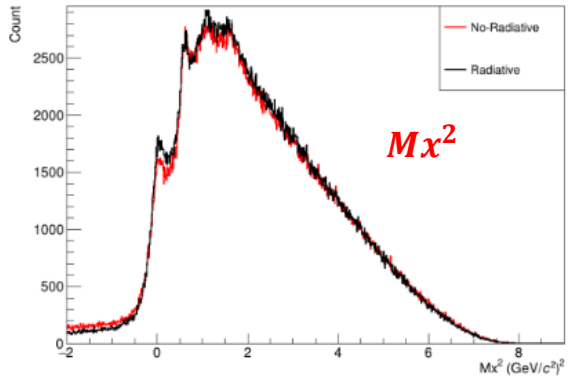


Use RADGEN to simulate rate of photons emitted from 10.6 GeV e.

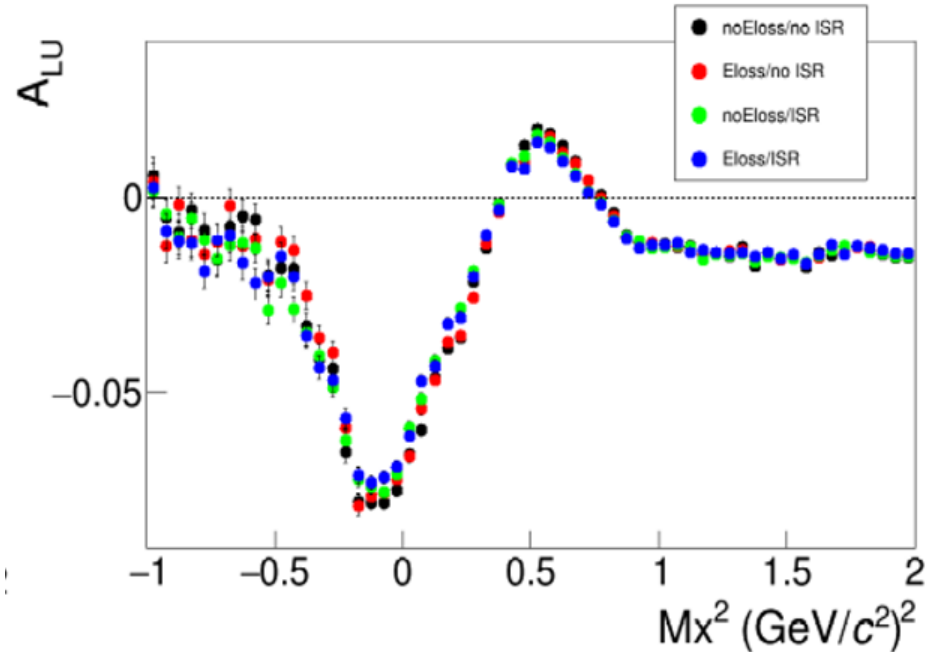




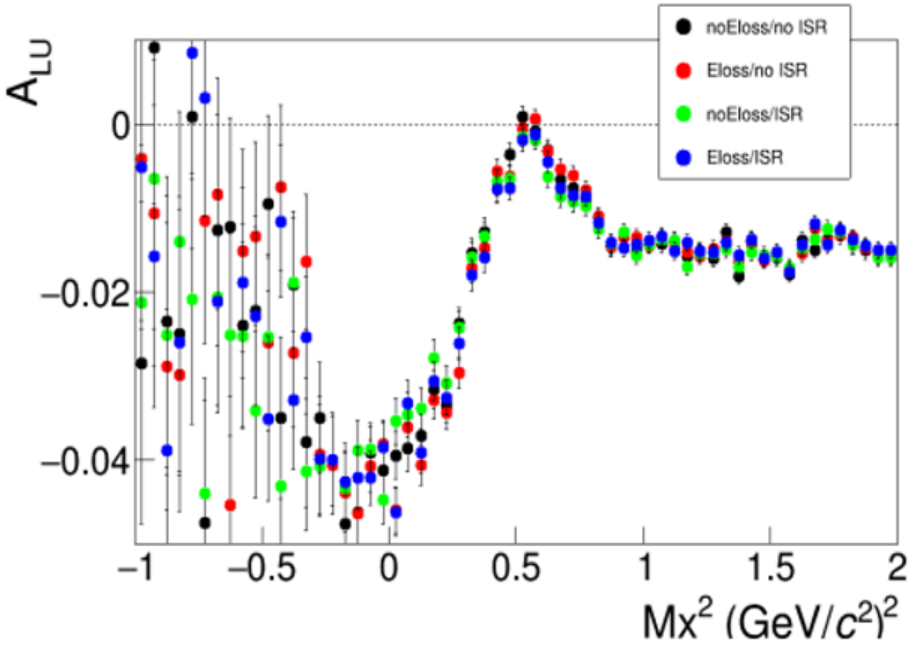




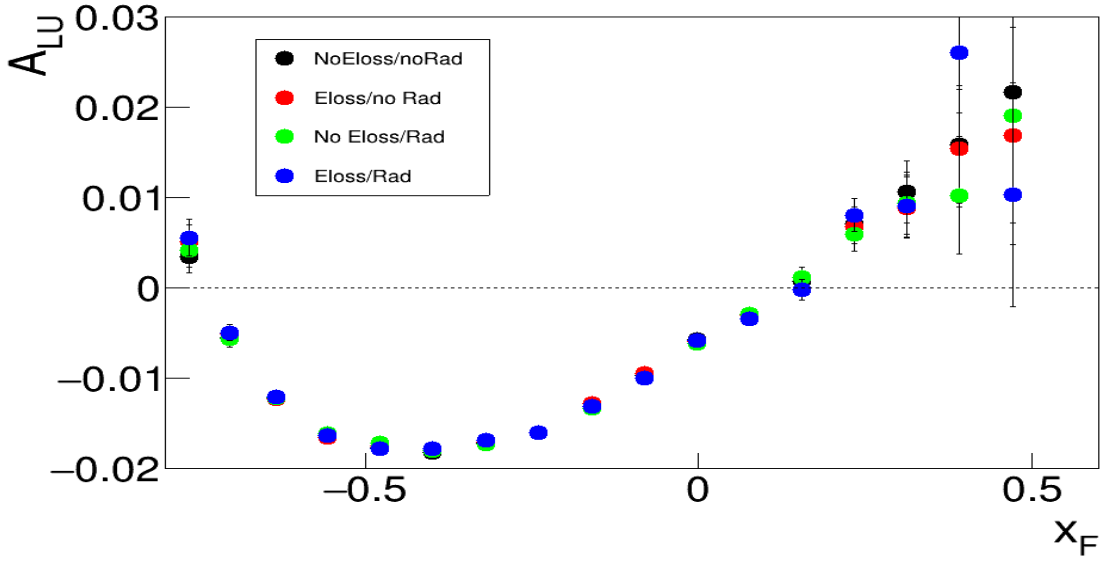
Full proton_theta coverage

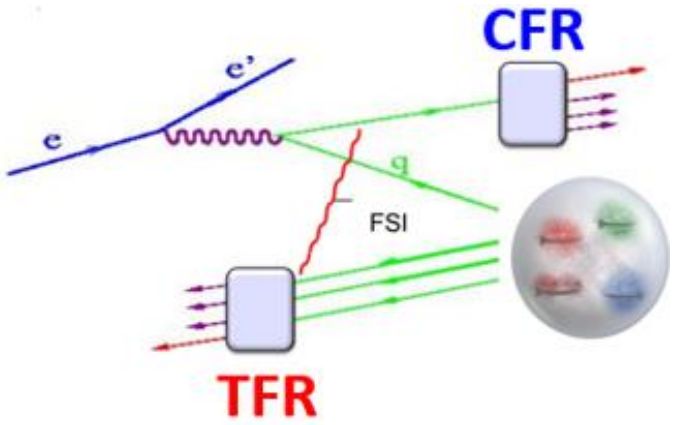


Proton_theta <0.65 rad

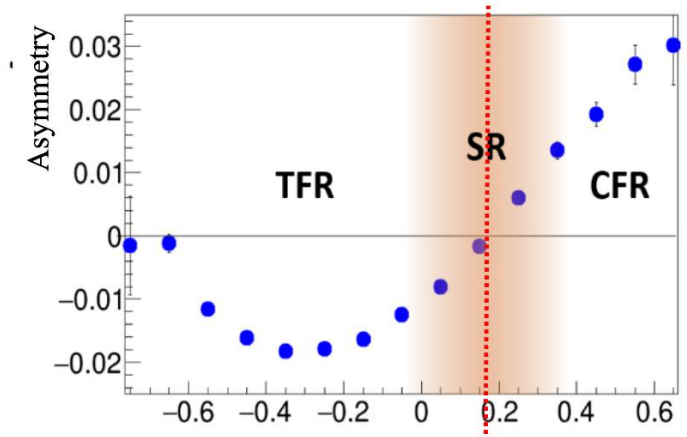


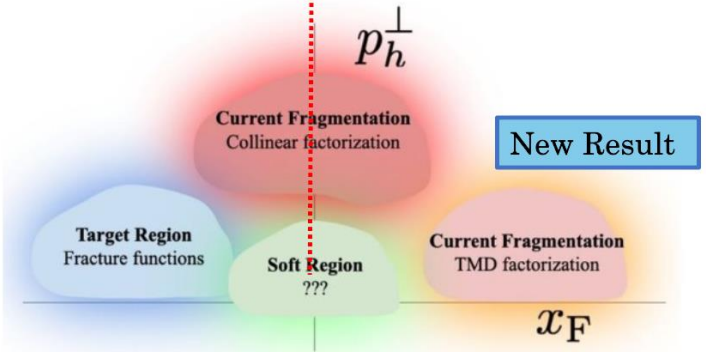
Small effect on xf
And in all variables in general.



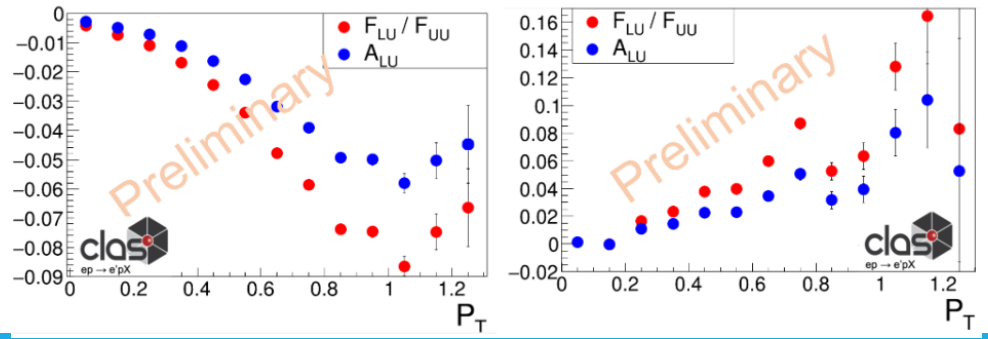


Summary



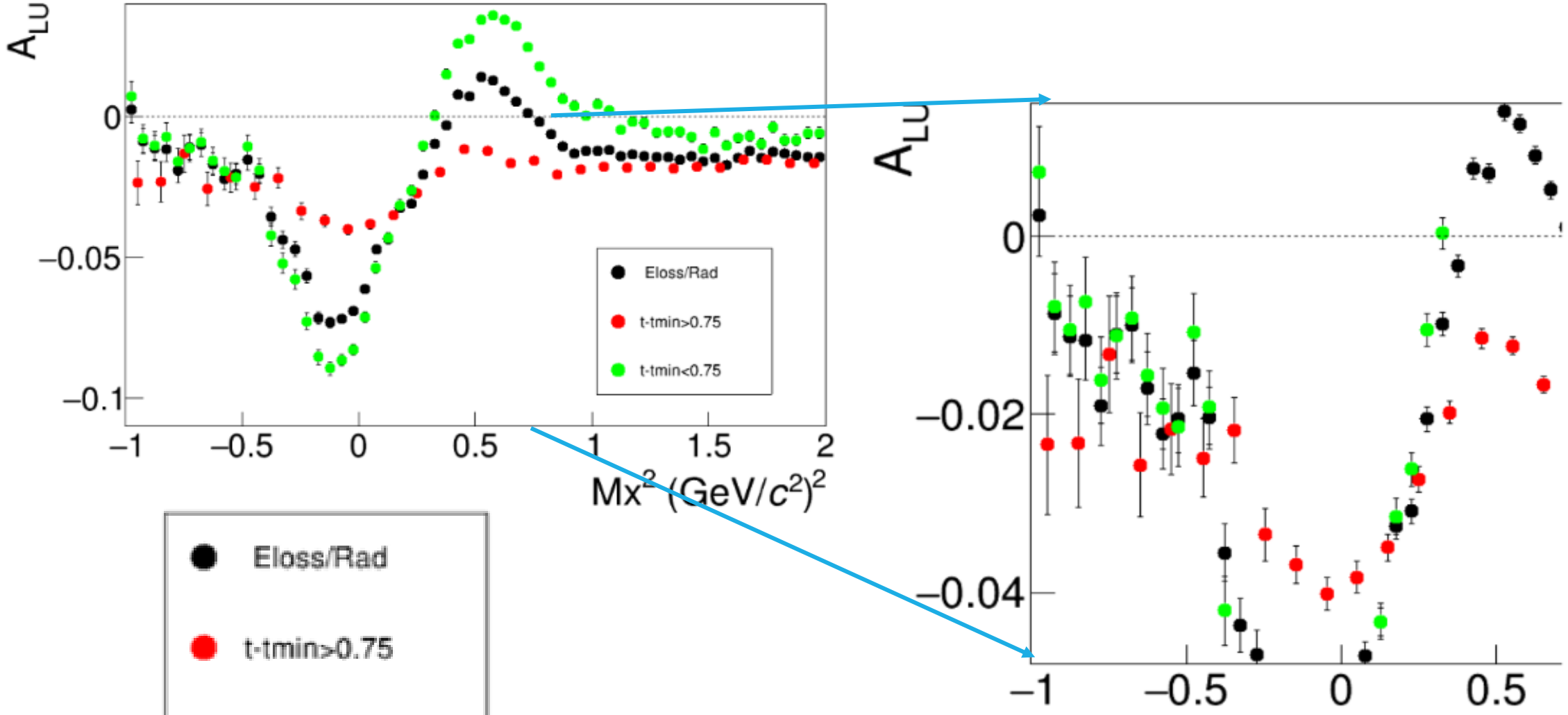


- For the first time at Jlab, we've captured the transition between TFR and CFR in the ep->epX.
  - There are significant beam SSAs for baryons in TFR, with opposite sign to what we observe in CFR.
  - **Proton Energy Loss corrections were performed**
  - **Electron Initial State Radiations under study**
  - **Bin Migration effects are small**
  - **Analysis note and publication in progress, will submit for review by January.**

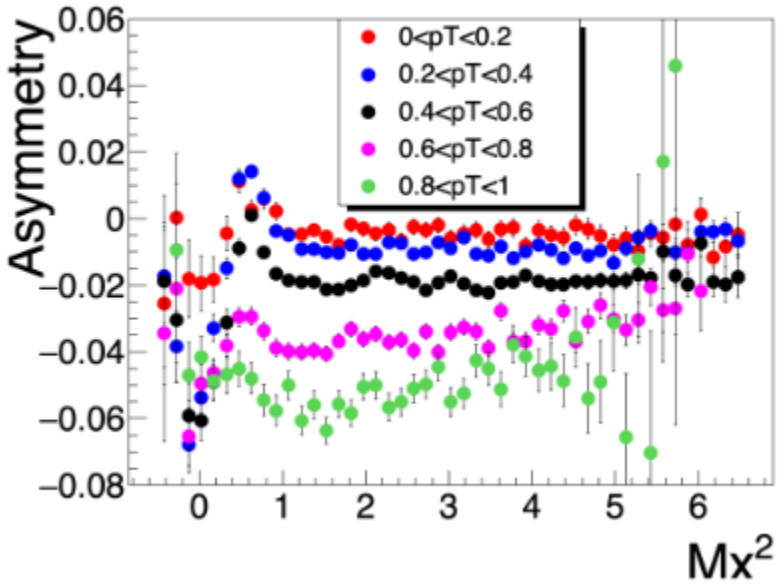


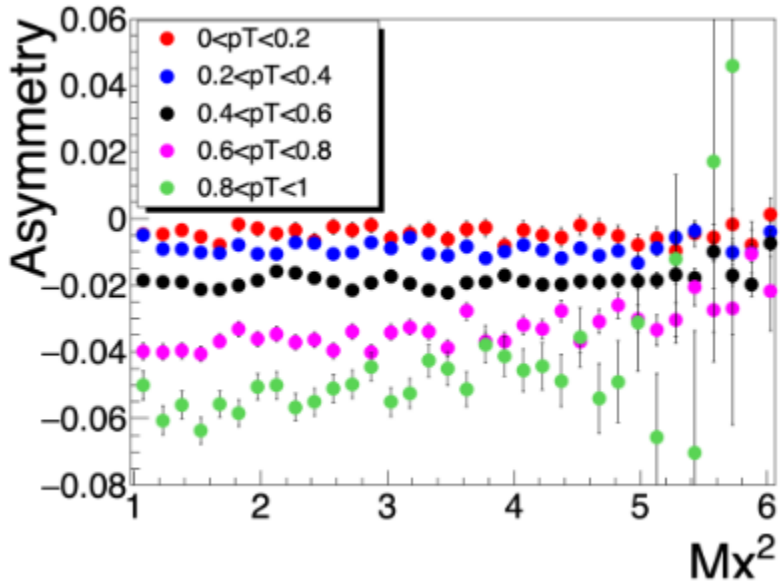
Thank you!!!

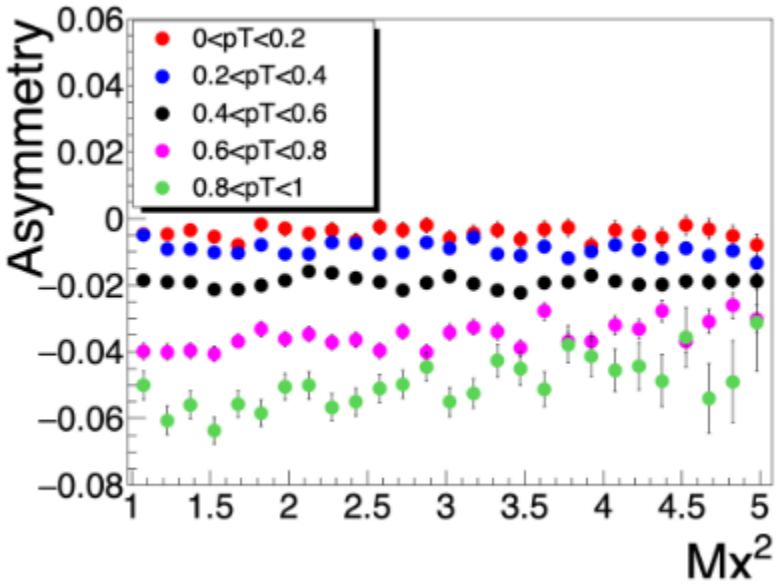
The issue with the -0.2 shift



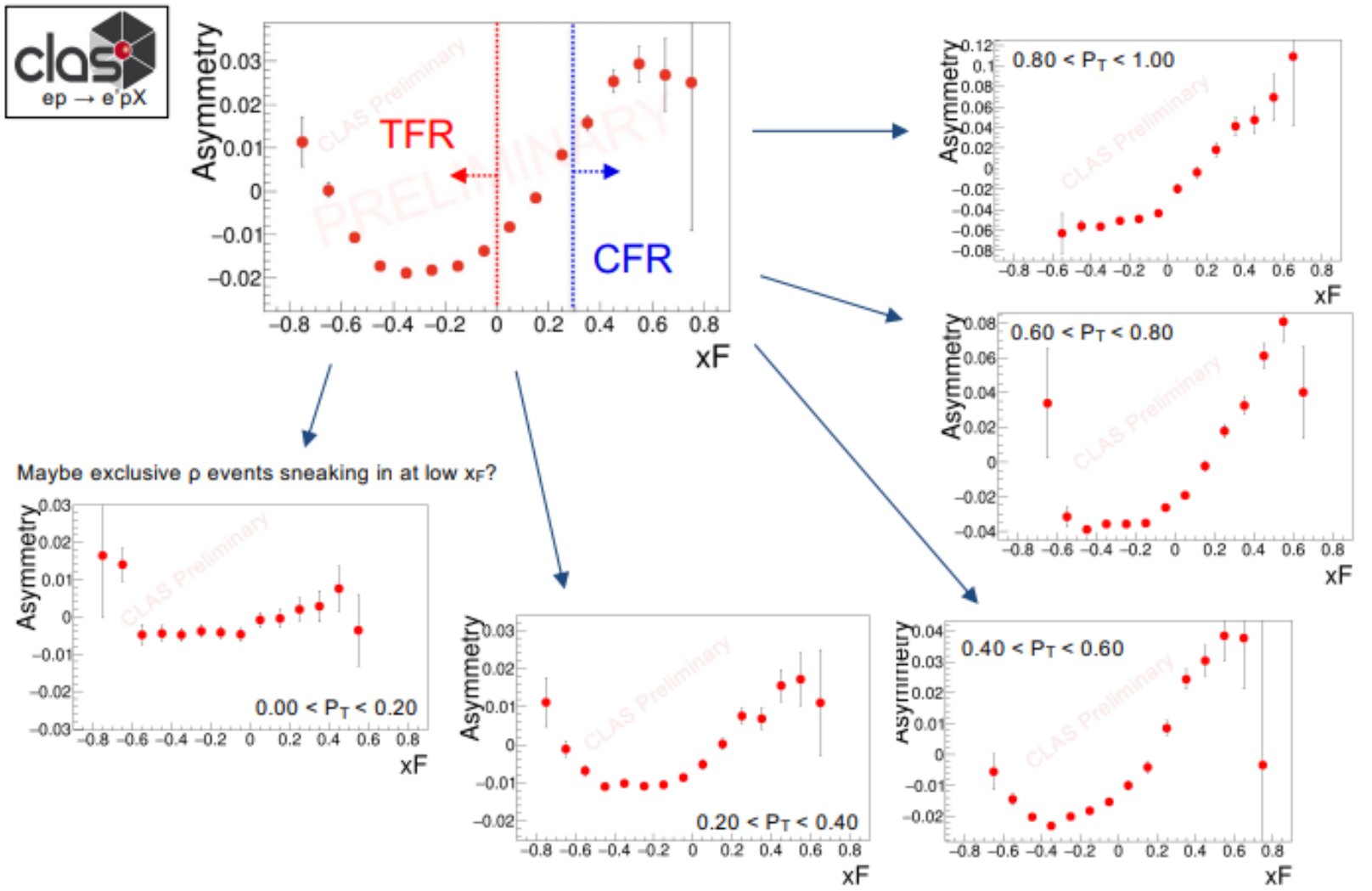
PT dependence

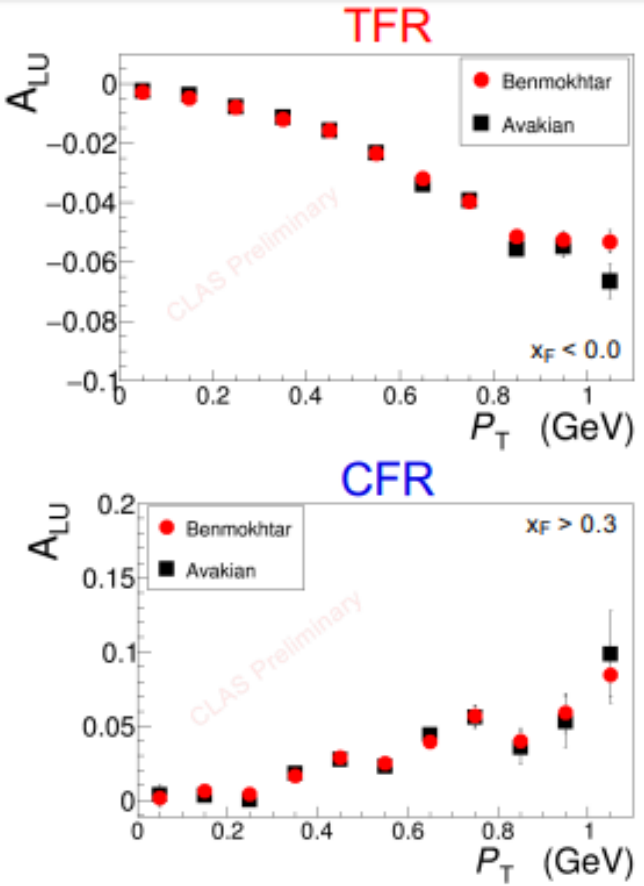






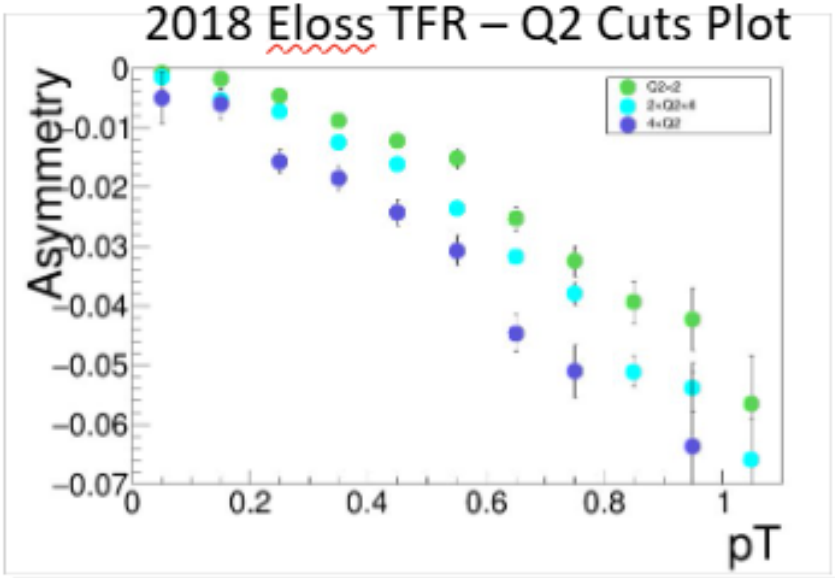
Transverse Momentum Effects

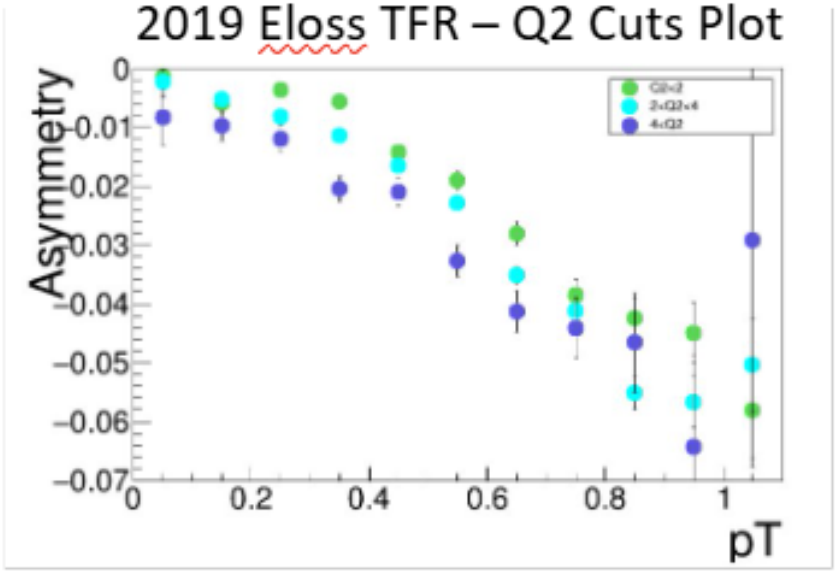


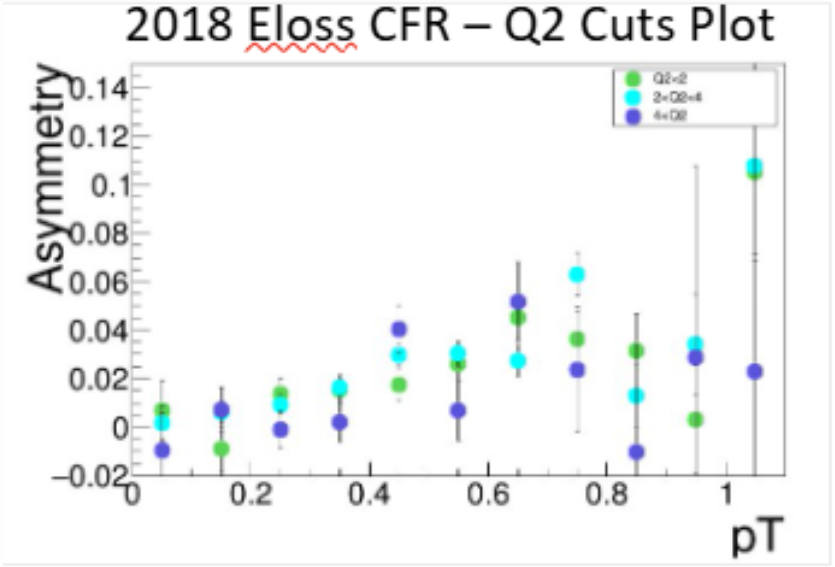


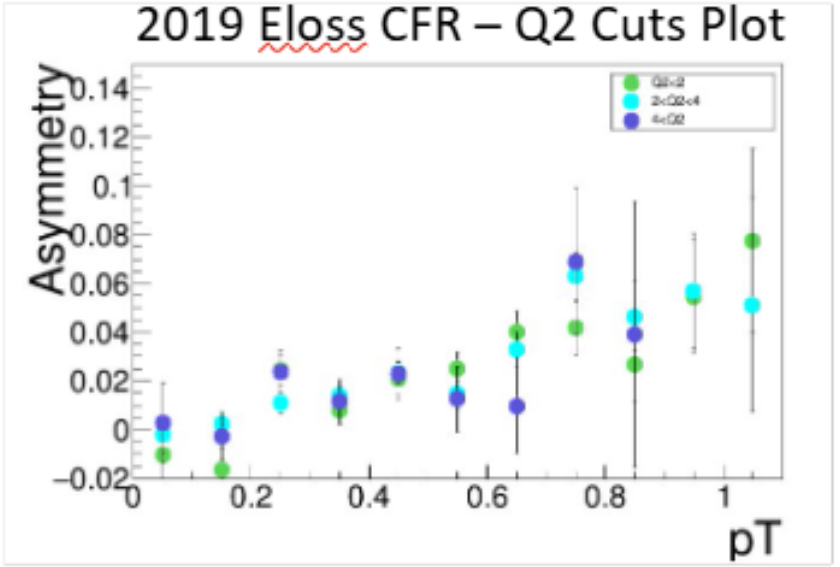
Strong linear dependence on P_T.

Q2 Cut Comparisons

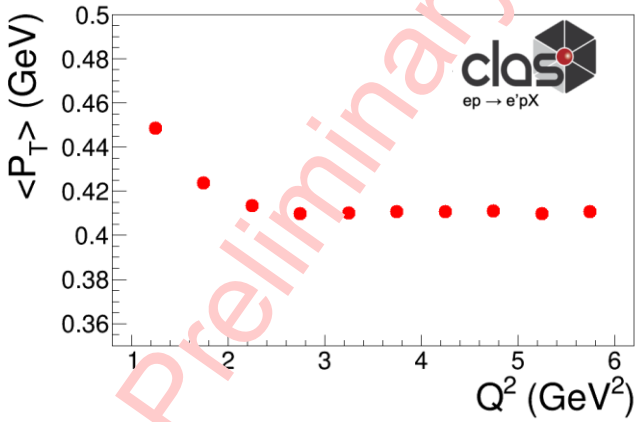


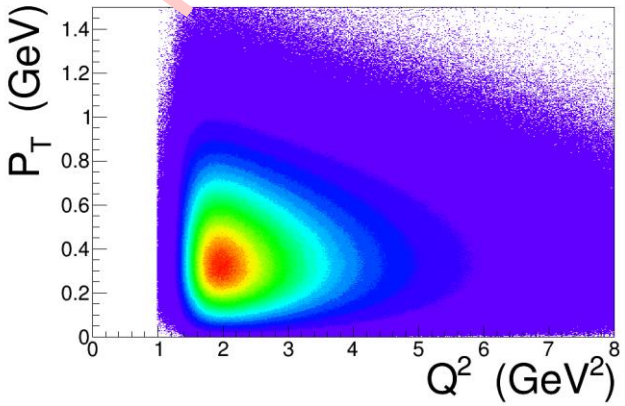


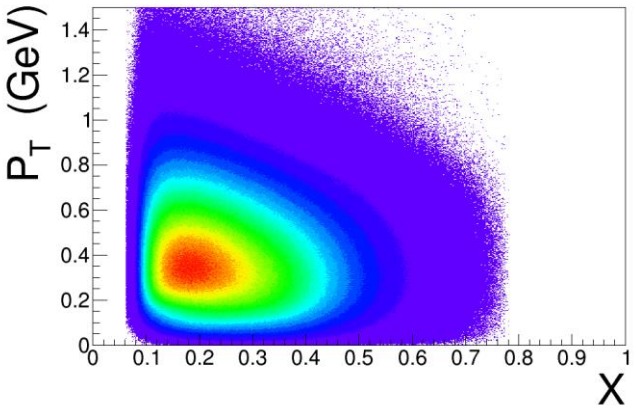




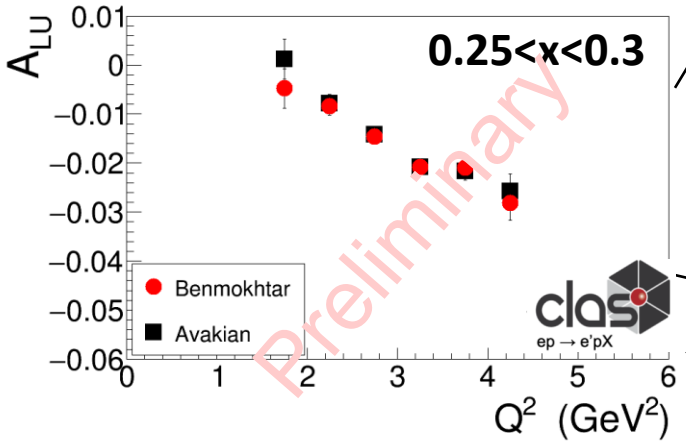
More Q^2 Dependence Studies

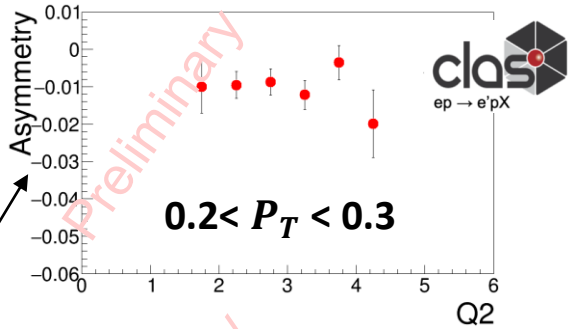


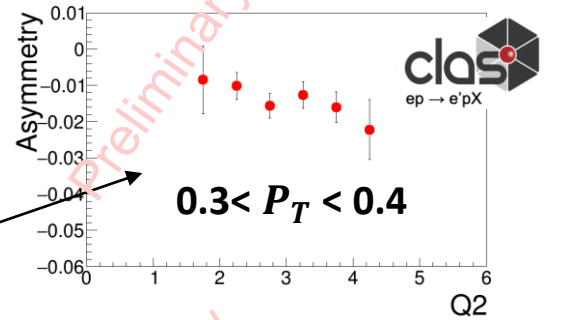


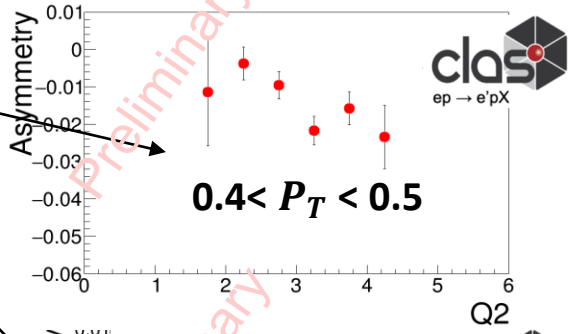


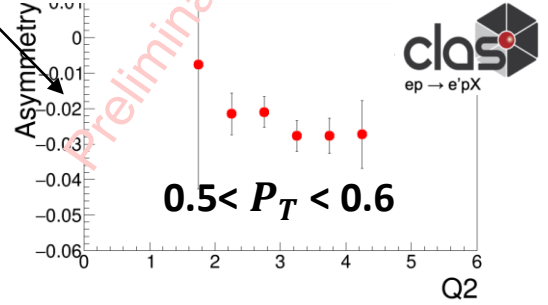
Fall 2018 Data







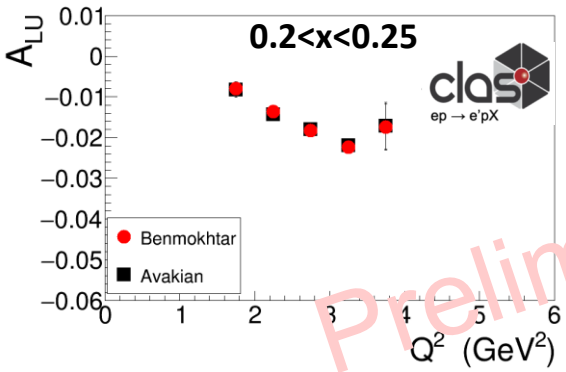


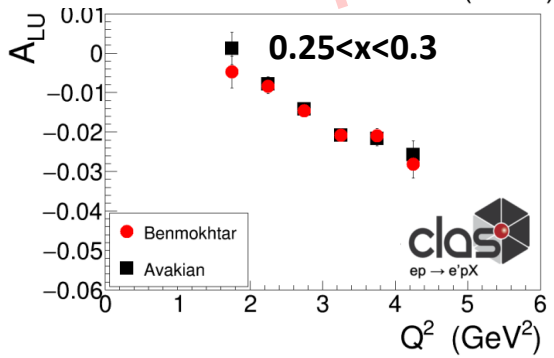


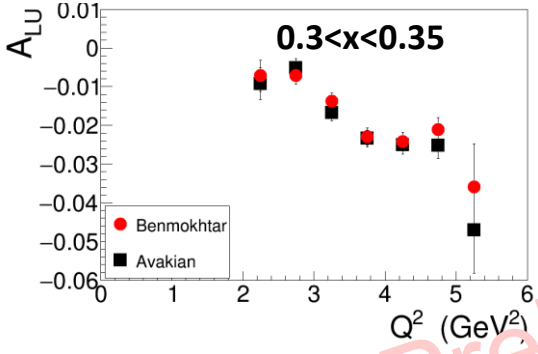
Note: ***With the full data set we are able to involve more dimensions.***

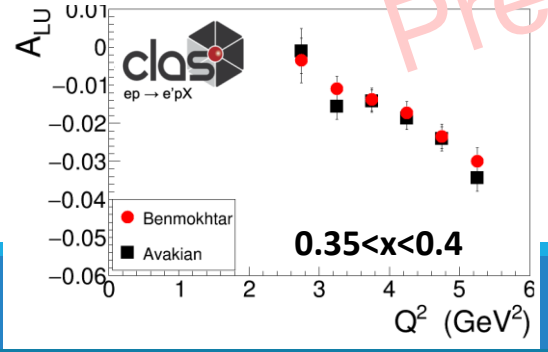
Q^2 Dependence Prel. Res.

Target Fragmentation Single Spin Asymmetries

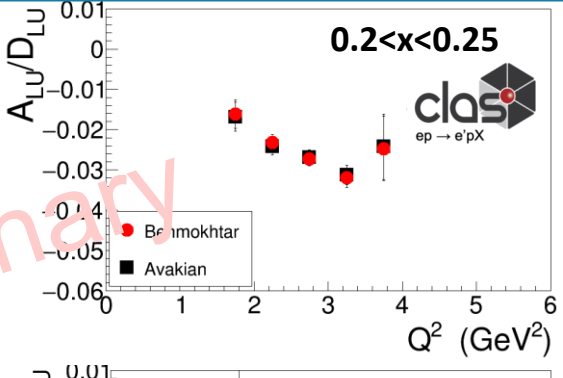


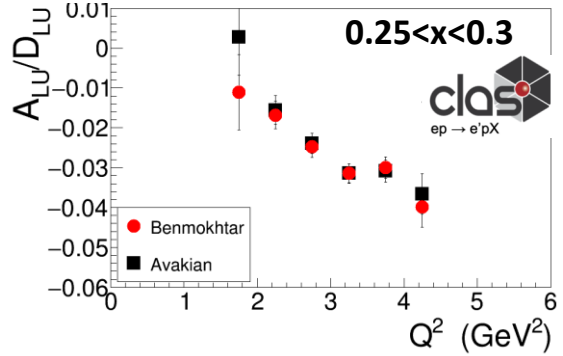


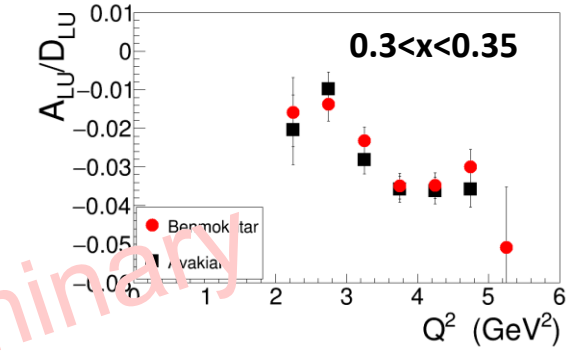


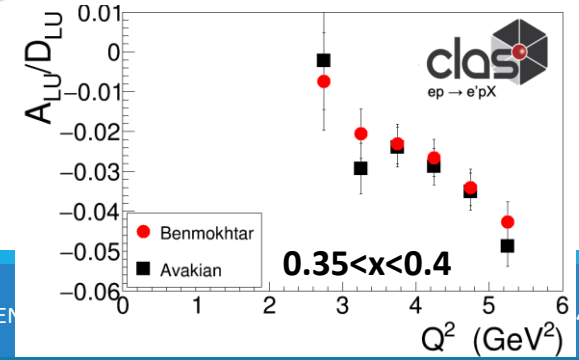


Target Fragmentation Fracture Functions





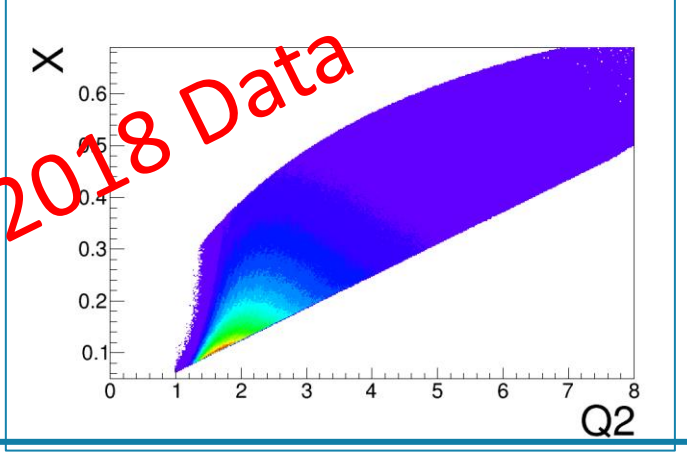




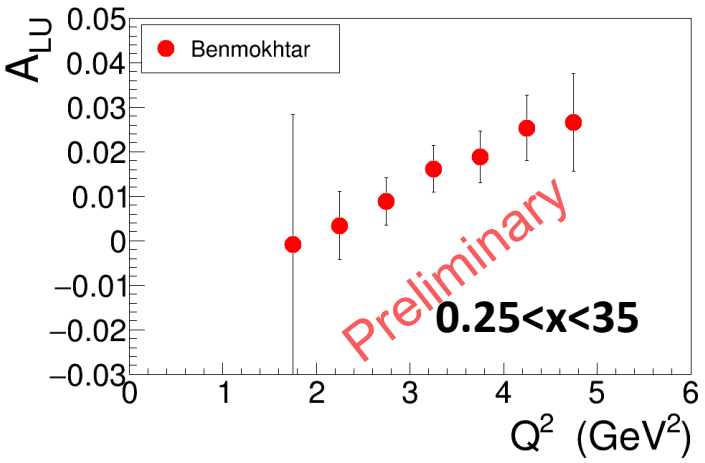
Preliminary

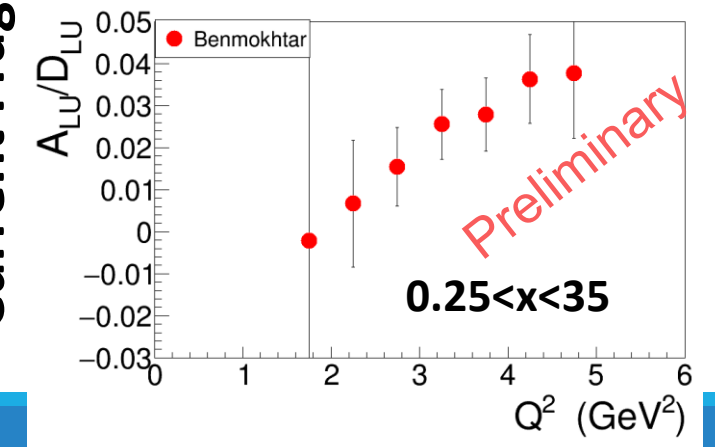
Preliminary

Fall 2018 Data

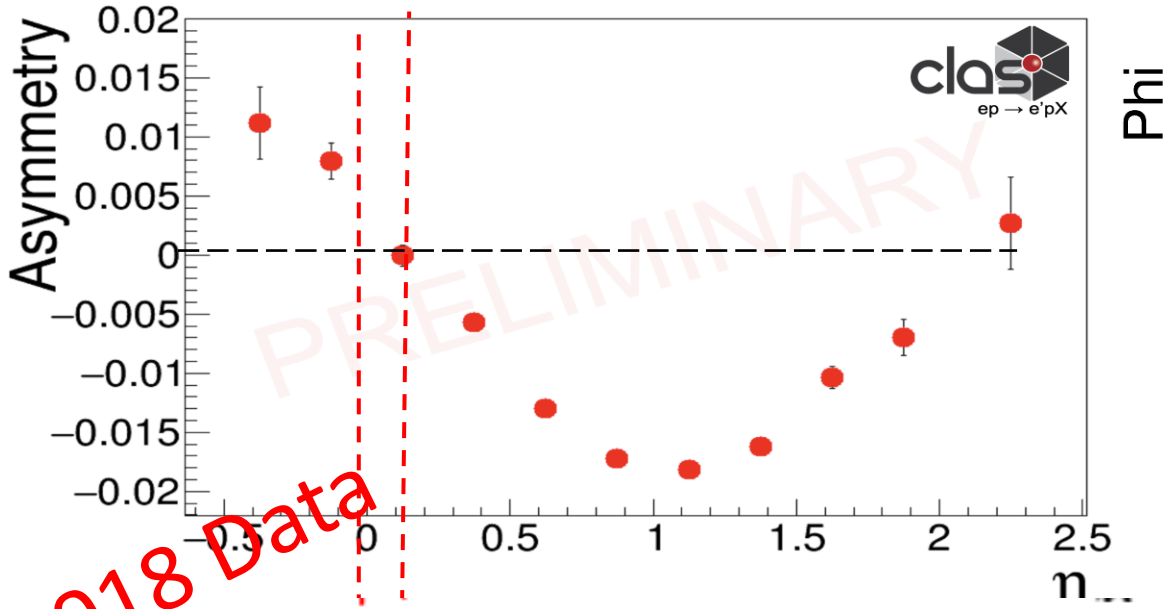


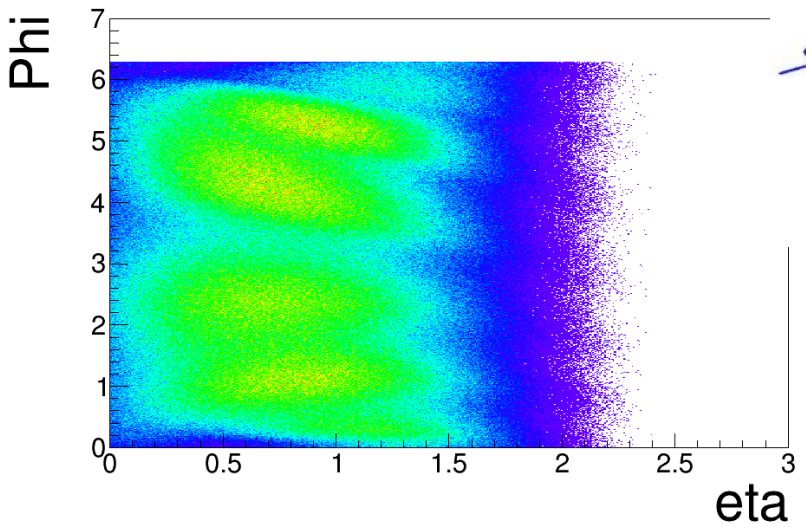
Current Fragmentation

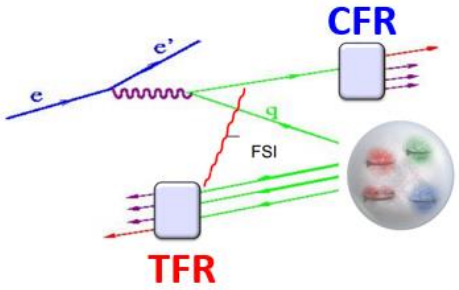


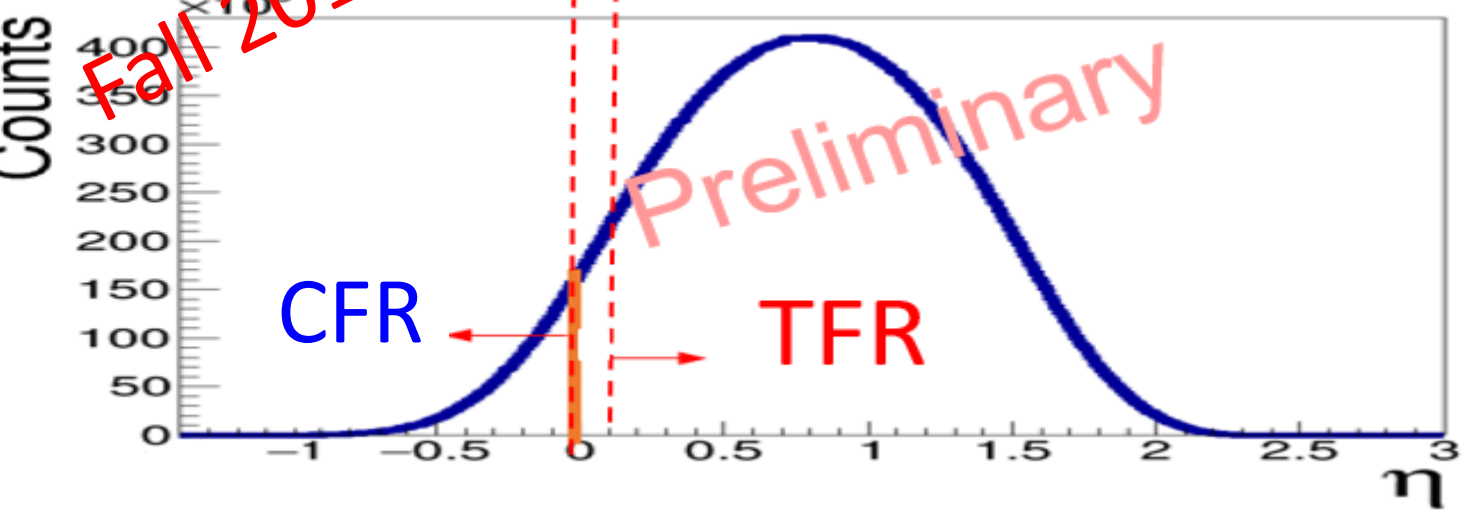


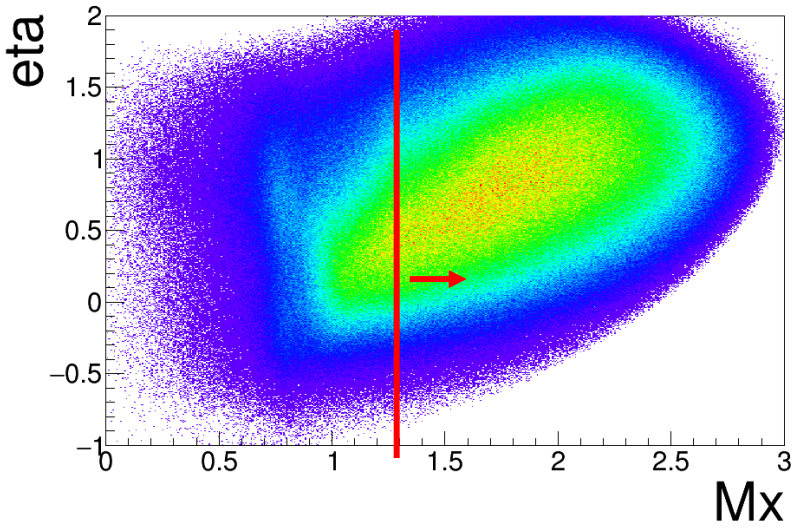
Asymmetry vs η Prel. Results, Mx > 1.35 (and appropriate cuts)

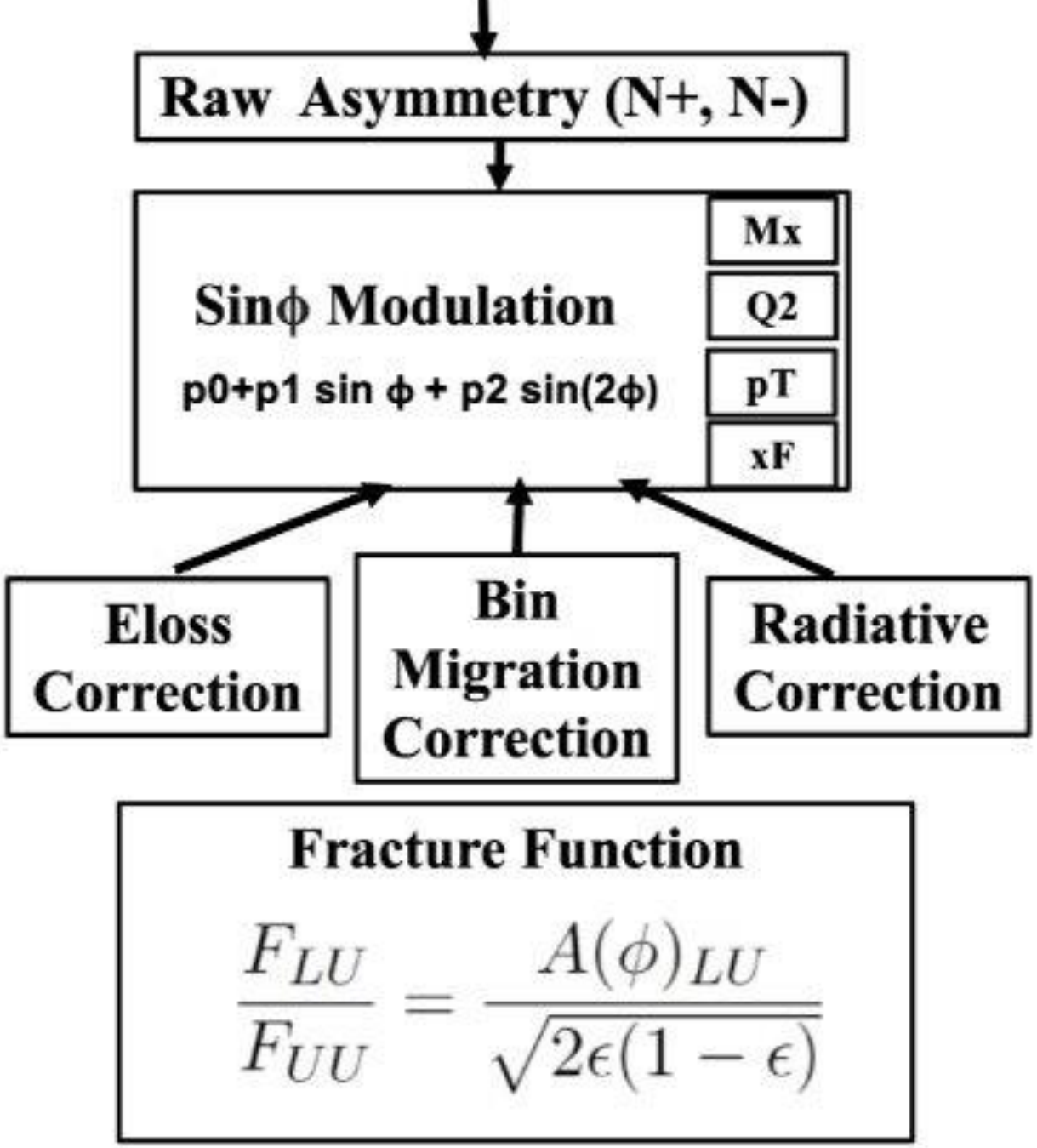






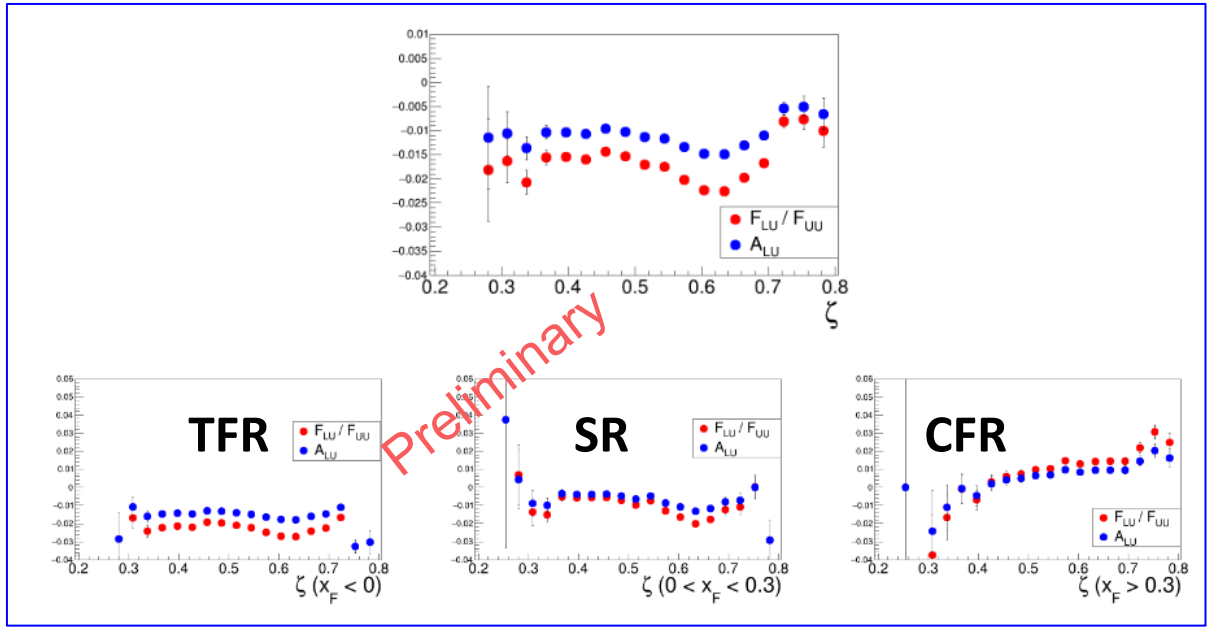


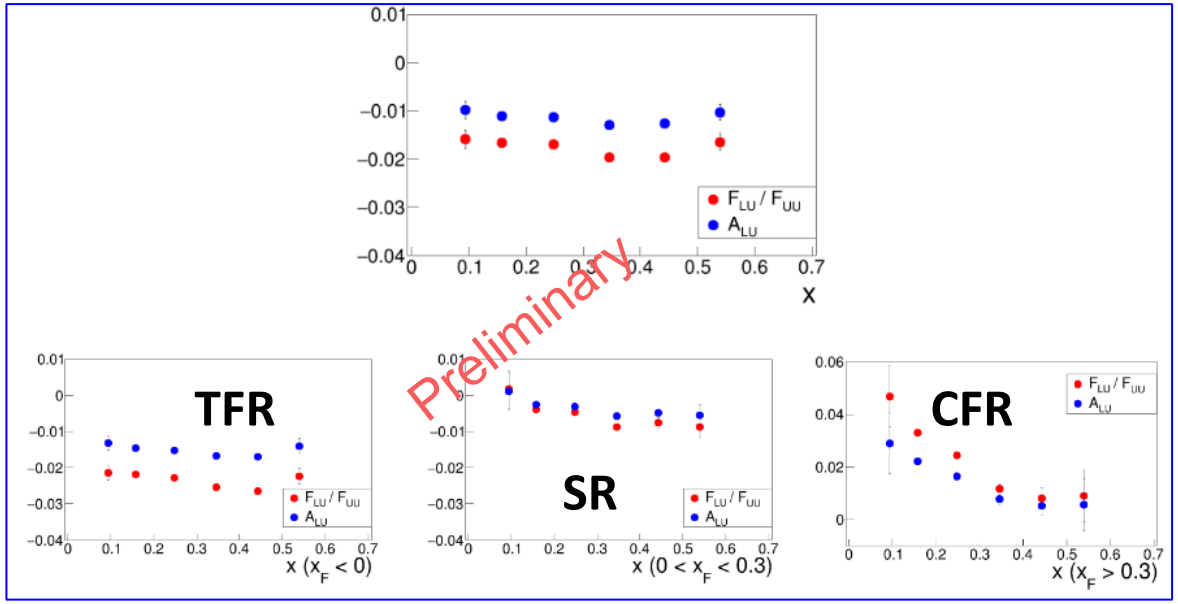



Raw Asymmetry (N+, N-)
Sinϕ Modulation
p0+p1 sin ϕ + p2 sin(2ϕ)
Mx
Q2
pT
xF
Eloss Correction
Bin Migration Correction
Radiative Correction
Fracture Function
$\frac{F_{LU}}{F_{UU}} = \frac{A(\phi)_{LU}}{\sqrt{2\epsilon(1-\epsilon)}}$

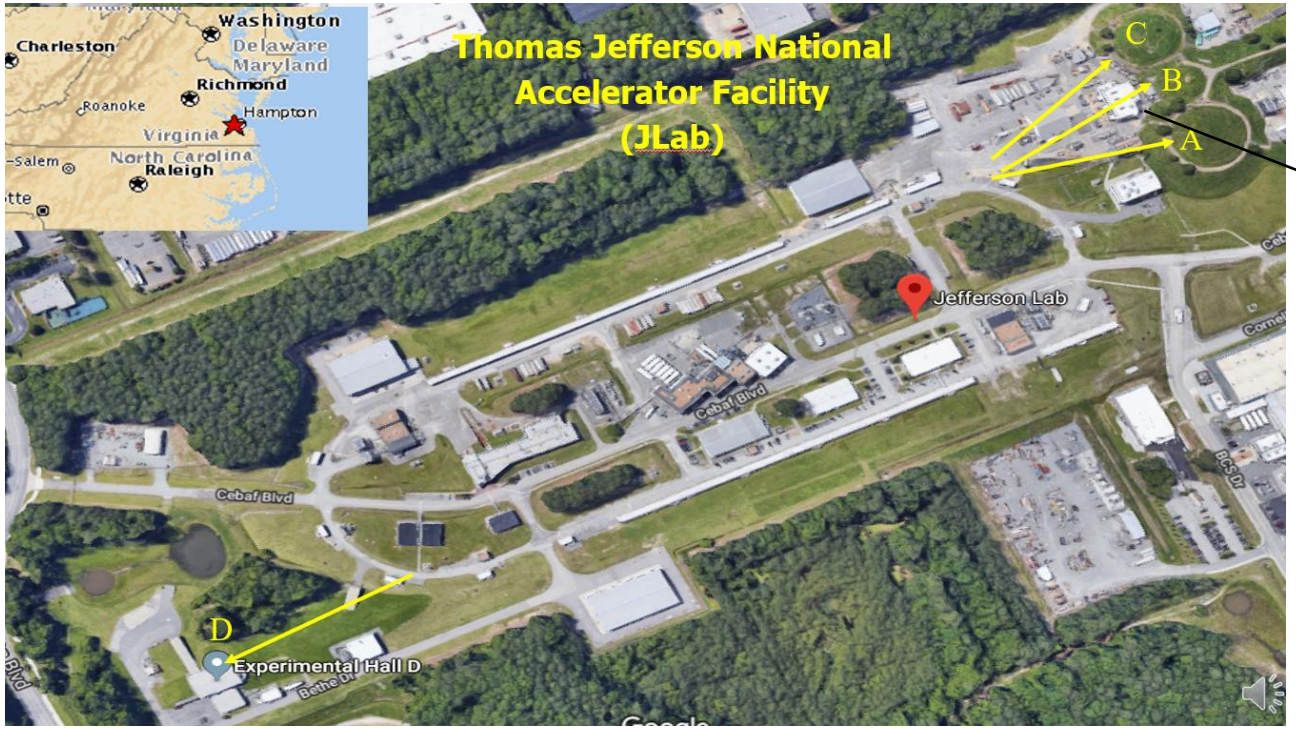
Ratio of FF

Zeta and *x*

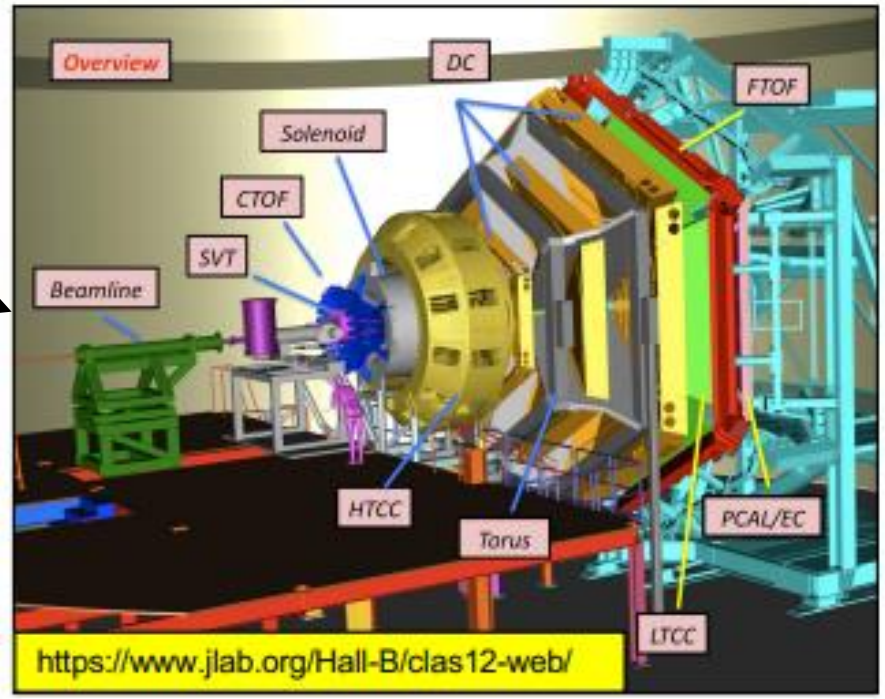




The Experiment



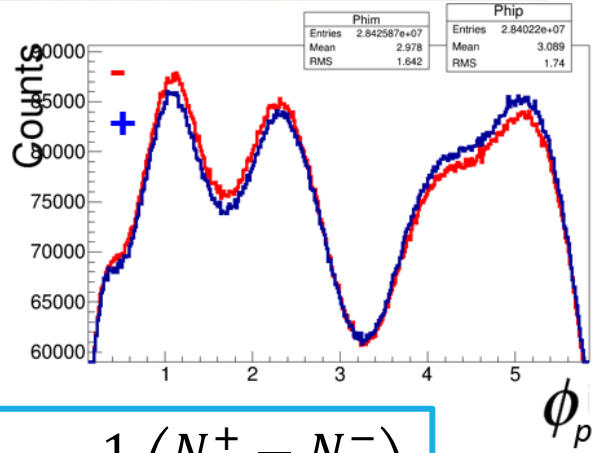
CLAS12 at Jefferson Lab



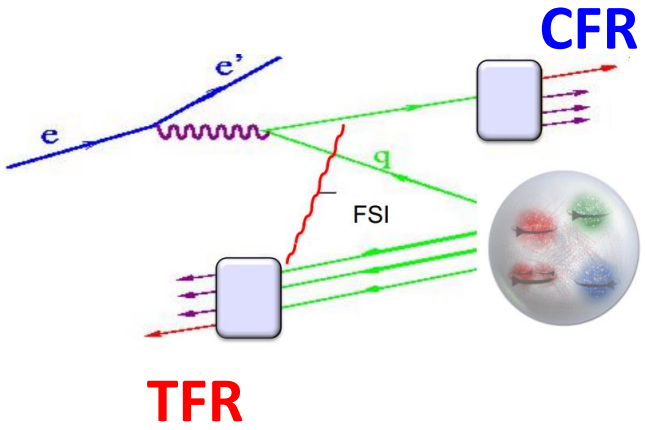
- RGA Data taken in fall 2018 and Spring 2019 with 10.6 and 10.2 GeV longitudinally polarized electron beam and **unpolarized LH_2 target**.

- The full data set has been analyzed (e-pol ~86.5%)
- **$ep \rightarrow e'p' + X$** , using only forward detector.

- Fiducial cuts, channel selection vertex cut, Eloss, bin migration study, were performed.



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



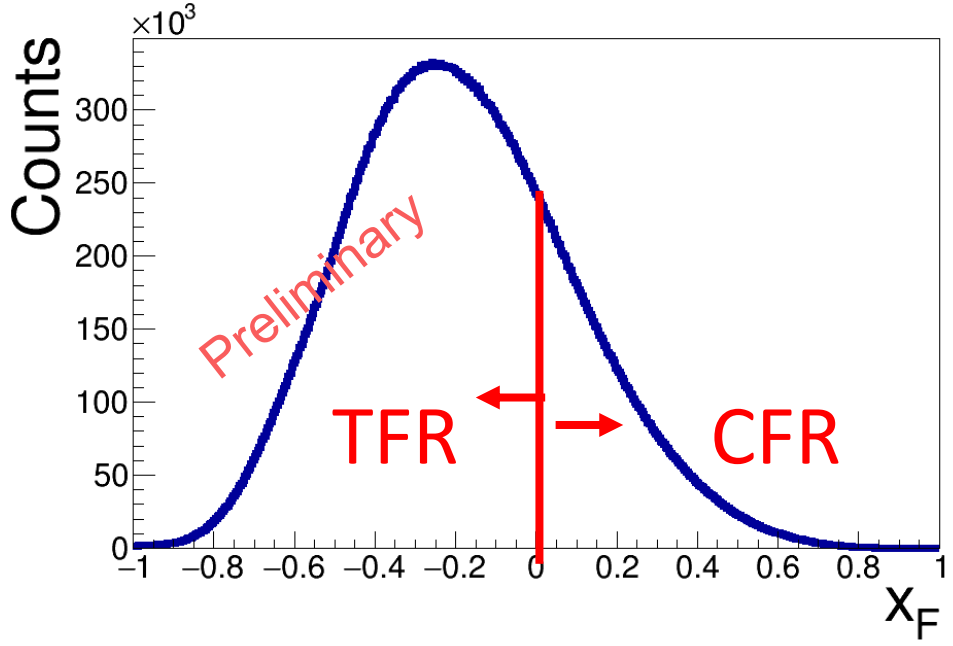
The old belief…

X_F and η

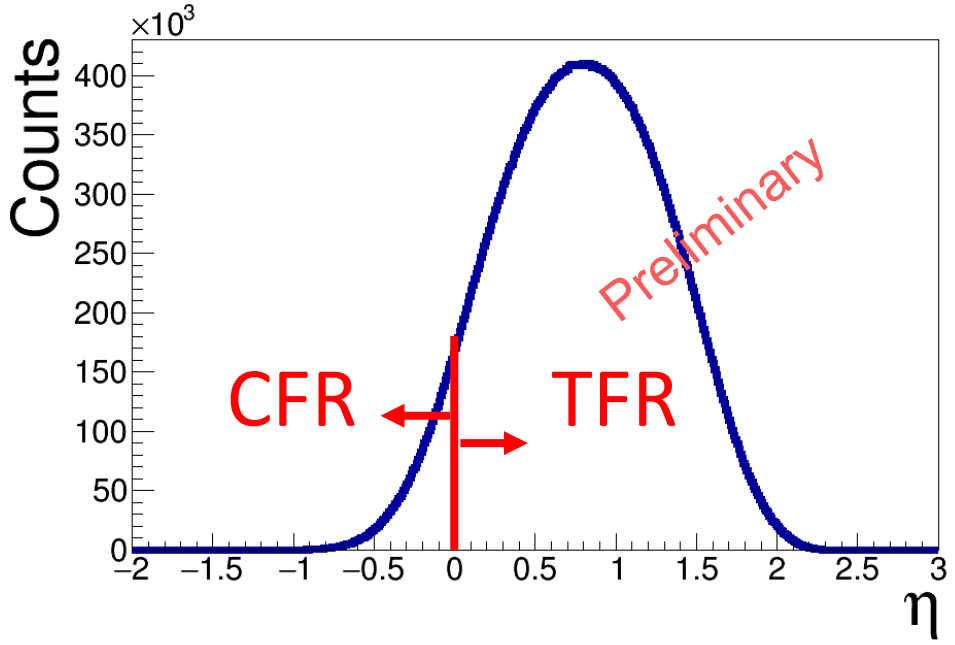
$$x_F = \frac{2P_h \cdot q}{|q|W},$$

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

$$\eta = -\ln\sqrt{\frac{x_n^2 M^2 + x_n Q^2}{(1-x_n)Q^2}} - Y,$$



Fraction of longitudinal momentum carried by the hadron in the CM frame



Rapidity in the Breit frame.

Sine Fit Equation

$$p0+p1 \sin \varphi + p2 \sin(2 \varphi)$$

FLU $\propto$ **P (perp.)^2**

With taylor expansion: (1 + cosx)

Existing sin multiplied: sinx(1 + cosx)

Asinx + Bsin2x + C