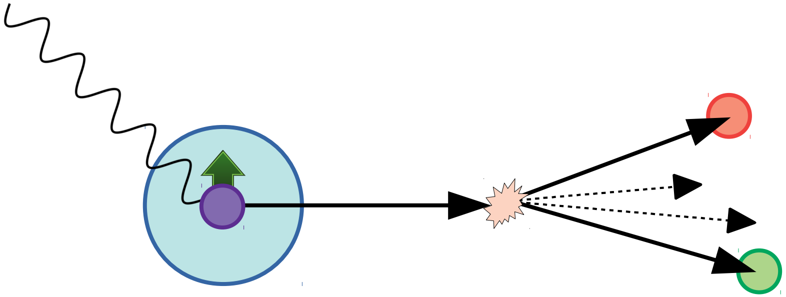
# Dihadrons at the EIC



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Yellow Report Workshop Pavia

May 2020

Duke UNIVERSITY

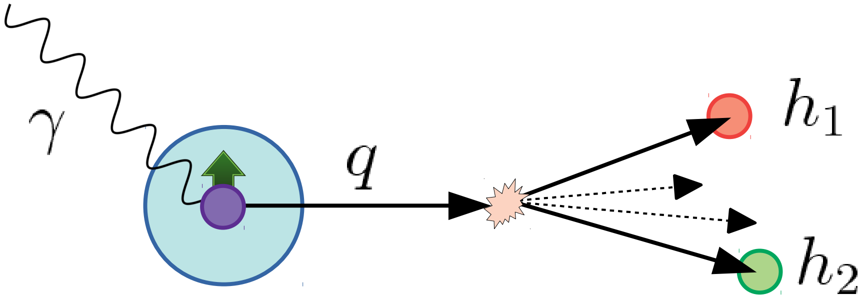
## Outline

- Introduction
- Event Selection and Monte Carlo Details
- $x, Q^2$ planes and binning
- Effects of y cuts
- Polar plots
- Effects of acceptance limits
- Dihadron kinematics
- PID performance

# Dihadrons: Probing Spin-Orbit Correlations in Hadronization

## Unpolarized SIDIS:

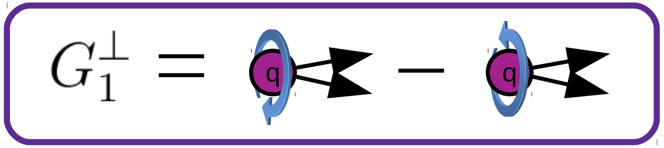
- **Cahn Effect**: quark transverse momentum leads to azimuthal modulations of SIDIS cross section
- **Boer-Mulders Effect:** Non-collinear quarks in an unpolarized proton can have transverse polarization, also contributing azimuthal modulations

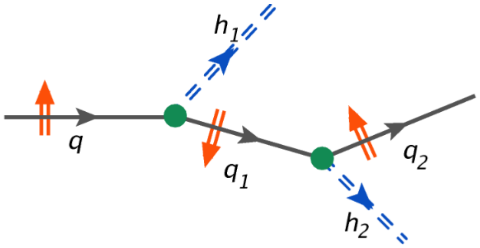



- **Boer-Mulders and Cahn effects are comparable in single hadron production**
  - HERMES and COMPASS data, e.g. Phys.Rev.D 81 (2010) 114026
- **Dihadrons can help decouple BM from Cahn**
  - Extra degree of freedom in dihadrons
    - Cahn effect impacts dihadron total momentum direction $P_h$
    - Utilize azimuthal angle about $P_h$, in addition to the azimuth about the virtual photon
- **Advantages from a broader and higher $Q^2$ range at an EIC**
  - Broader $Q^2$ range probes evolution effects
  - Higher $Q^2$ suppresses Cahn effect in single-hadron asymmetries (Cahn is twist-4)
  - Lower $Q^2$ for overlap with other SIDIS experiments

# Dihadrons: Probing Spin-Orbit Correlations in Hadronization

## Longitudinally polarized SIDIS:



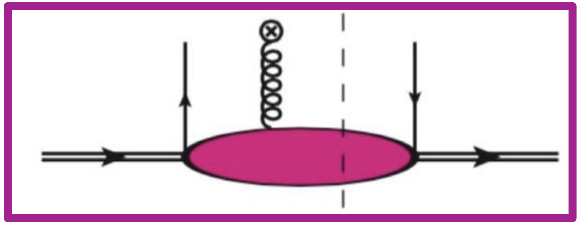




### Helicity DiFF $G_1^\perp$:

- **Not yet constrained by data!**
- **Spin-orbit correlations** in hadronization
- Fragmenting quark acquires transverse polarization via ‘wormgear’ splitting in the quark-jet hadronization model
- Preliminary CLAS12 data indicate **significant effect**, dependent on invariant mass

### Collinear Twist-3 PDFs e(x) and $h_L(x)$:

- **CLAS6 data provided the first e(x) extraction, consistent with models; CLAS12 data are in agreement**
- Physical Interpretation via moments of e(x):
  - **Transverse color-force** on a transversely polarized struck-quark, in an unpolarized proton
  - **πN sigma terms:**
    - Quark mass contribution to proton mass
    - Quark chromomagnetic dipole moment → CP-odd π-N coupling
- **No experimental constraints yet for $h_L(x)$**



# Dihadrons: Probing Spin-Orbit Correlations in Hadronization

## Transversely polarized SIDIS:

- Access to several additional **TMDs**:
  - **Transversity** → Tensor Charge

$$\delta q = \int_{-1}^{1} dx\, h(x) = \int_{0}^{1} dx \left[h(x) - \bar{h}(x)\right]$$

    - Quark EDM contribution to nucleon EDM → CP violation
    - Comparisons with lattice QCD calculation
  - **Sivers Function**
  - **Kotzinian-Mulders (wormgear) Function**
  - **Pretzelocity**
  - **Twist-3 TMDs**

$F_{UT}$: $f_{1T}^{\perp} \otimes D_1 + g_{1T} \otimes G_1$, $h_1 \otimes H_1$, $h_{1T}^{\perp} \otimes H_1$; $f_T \otimes D_1$, $f_T^{\perp} \otimes D_1$; $h_T \otimes H_1$, $h_T^{\perp} \otimes H_1$

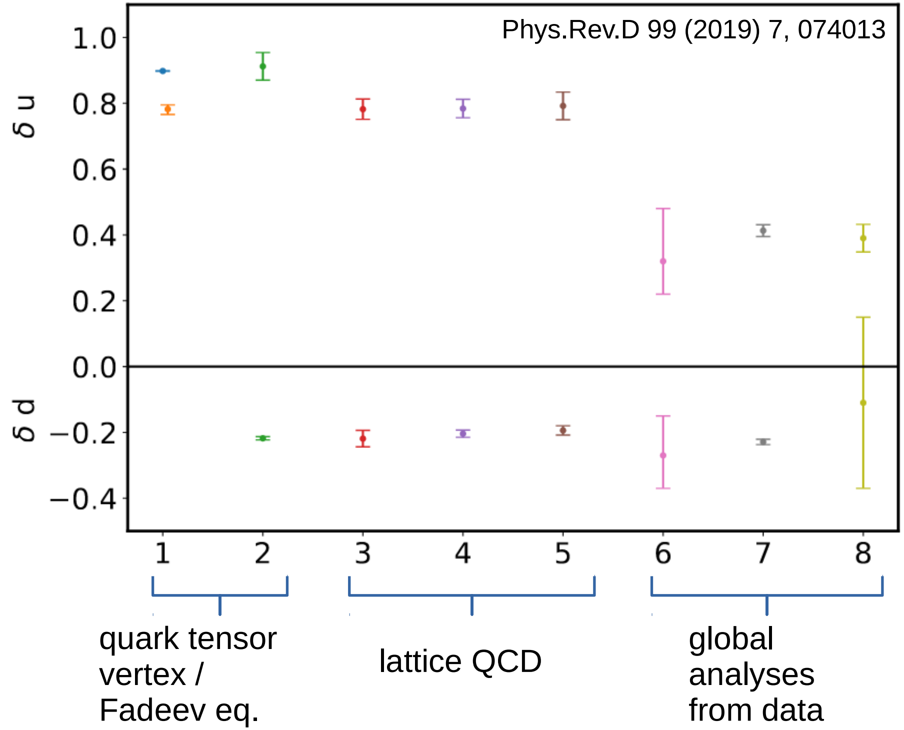
$F_{LT}$: $g_{1T} \otimes D_1 + f_{1T}^{\perp} \otimes G_1$; $g_T \otimes D_1$, $g_T^{\perp} \otimes D_1$; $e_T \otimes H_1$, $e_T^{\perp} \otimes H_1$

**Twist-2 TMDs**

| N/q | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^{\perp}$ |
| L | | $g_1$ | $h_{1L}^{\perp}$ |
| T | $f_{1T}^{\perp}$ | $g_{1T}$ | $h_{1T},\ h_{1T}^{\perp}$ |

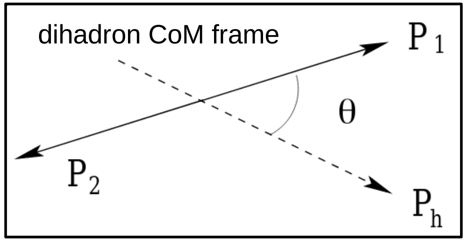
**Twist-3 TMDs**

| N/q | U | L | T |
|---|---|---|---|
| U | $f^{\perp}$ | $g^{\perp}$ | $h,\ e$ |
| L | $f_L^{\perp}$ | $g_L^{\perp}$ | $h_L,\ e_L$ |
| T | $f_T,\ f_T^{\perp}$ | $g_T,\ g_T^{\perp}$ | $h_T,\ e_T,\ h_T^{\perp},\ e_T^{\perp}$ |



# Dihadron Fragmentation and Partial Waves

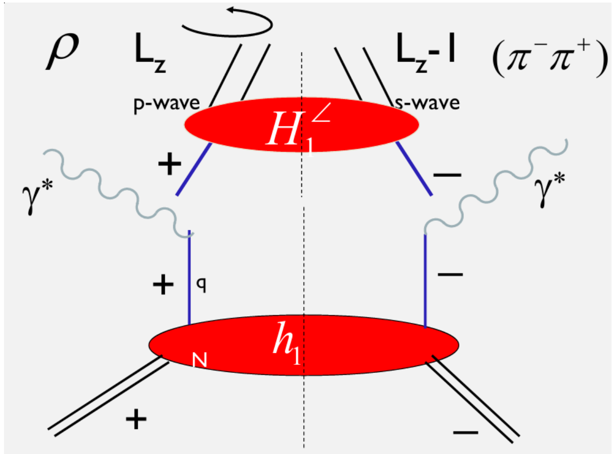
$$H_1^{\perp} = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\vartheta)\, e^{im(\phi_{R_\perp}-\phi_p)}\, H_1^{\perp|\ell,m\rangle}(z, M_h, |\boldsymbol{p}_T|)$$



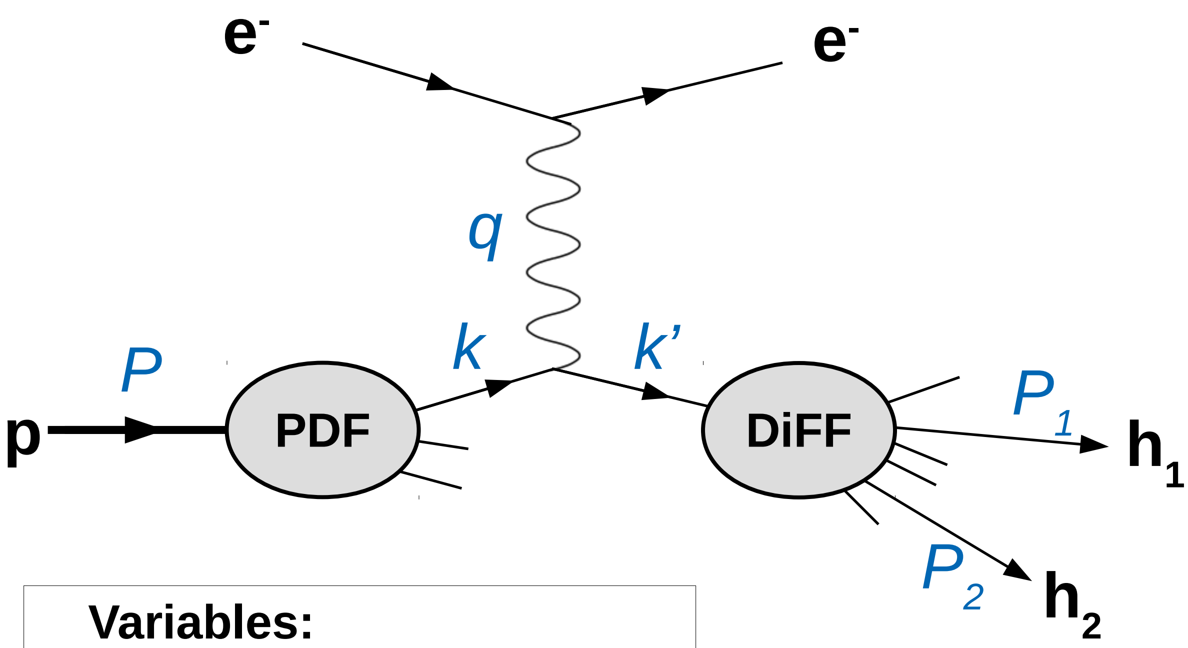

**Dihadron Fragmentation Functions (DiFFs)**

| $h_1h_2/q$ | **U** | **L** | **T** |
|---|---|---|---|
| **UU** | $D_{1,OO}$ | | $H_{1,OO}^{\perp}$ |
| **LU** | $D_{1,OL}$ | | $H_{1,OL}^{\perp}$ |
| **LL** | $D_{1,LL}$ | | $H_{1,LL}^{\perp}$ |
| **TU** | $D_{1,OT}$ | $G_{1,OT}^{\perp}$ | $\begin{cases} H_{1,OT}^{\perp} & \text{if } m<0 \\ H_{1,OT}^{\sphericalangle} & \text{if } m>0 \end{cases}$ |
| **TL** | $D_{1,LT}$ | $G_{1,LT}^{\perp}$ | $\begin{cases} H_{1,LT}^{\perp} & \text{if } m<0 \\ H_{1,LT}^{\sphericalangle} & \text{if } m>0 \end{cases}$ |
| **TT** | $D_{1,TT}$ | $G_{1,TT}^{\perp}$ | $\begin{cases} H_{1,TT}^{\perp} & \text{if } m<0 \\ H_{1,TT}^{\sphericalangle} & \text{if } m>0 \end{cases}$ |

- DiFFs expand in partial waves
- Access to interference between dihadrons with relative angular momenta
  - ss, sp, pp interference



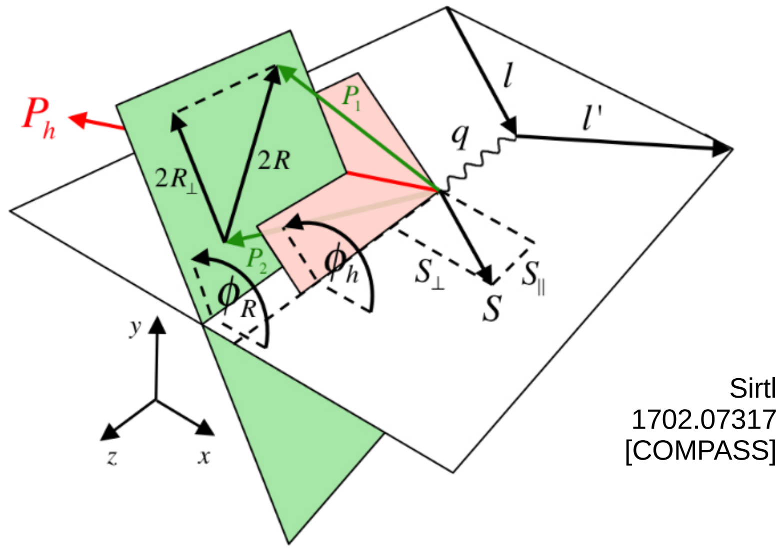
# Dihadron Kinematics




## Momenta and Angles

$$P_h = P_1 + P_2 \rightarrow \phi_h$$

$$R = \frac{1}{2}(P_1 - P_2) \rightarrow \phi_R$$

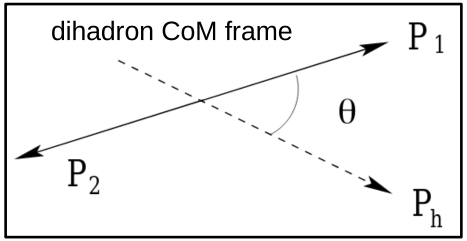



Sirtl
1702.07317
[COMPASS]

**Variables:**

- Scale: $Q^2$
- Bjorken-x: $x$
- Feynman-x: $x_F$
- Invariant Mass: $M_h$
- Fragmentation fraction: $z$
- Missing Mass: $M_X$

Dihadron CoM production angle:



# Monte Carlo

Energies:
- 5x41 $\sqrt{s}$ = 28.7 GeV
- 5x100 $\sqrt{s}$ = 44.7 GeV
- 10x100 $\sqrt{s}$ = 63.3 GeV
- 18x275 $\sqrt{s}$ = 140.7 GeV

## Event Generation
- Pythia6 (via pythiaeRHIC)
  - 1M events
  - Radiative corrections using RADGEN attempted, but was unsuccessful
  - Using steer file obtained from Elke
- Kinematic maps below focus on low and high CoM energy: 5x41 and 18x275

## Fast Simulation
- `eic_smear` with the `handbook` detector setting (via eJANA)
- Require the electron and hadron E and P to be smeared (in tracker+calorimeter)

## Analysis
- DIS kinematics reconstructed using highest-energy scattered electron
- Pions and Kaons are paired inclusively
- PID studies
- Architecture for asymmetry fits / projections is ready
  - Uses same code for a parallel analysis at CLAS
  - Projections for partial wave amplitudes is also possible

## Event Selection

$Q^2 > 1\ \text{GeV}^2$ cut for event generator

$W > 3\ \text{GeV}$ exclude elastic / resonance region

$0.01 < y < 0.95$ lower bound is to avoid region in which calculating x, Q2, etc. via the e' momentum may be insufficient

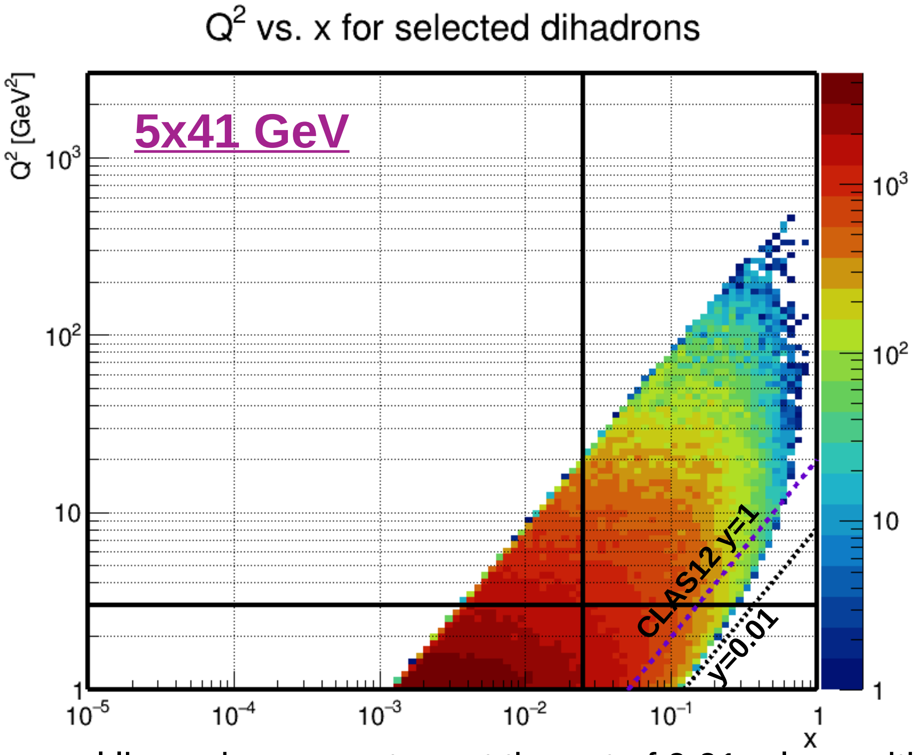
$x_{F_h} > 0$ help ensure hadrons are produced in the current fragmentation region

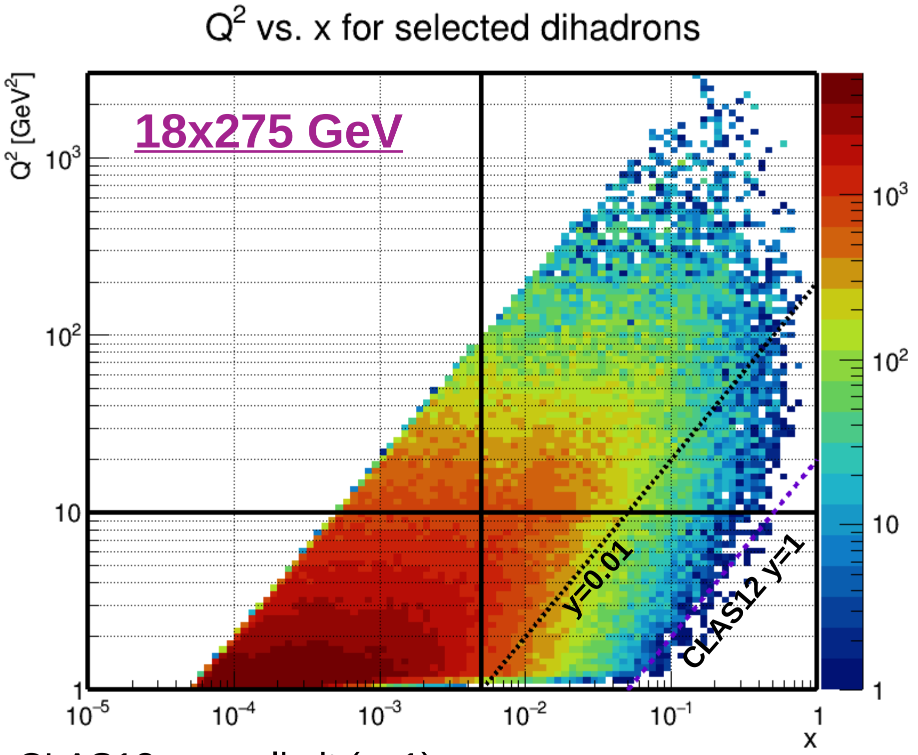
$z_h > 0.01$ cuts out long $M_h$ tail at z~0 peak (need to think about...)

$z_{h_1 h_2} < 0.95$ helps avoid exclusive region

**Focusing on $\pi^+\pi^-$ channel**

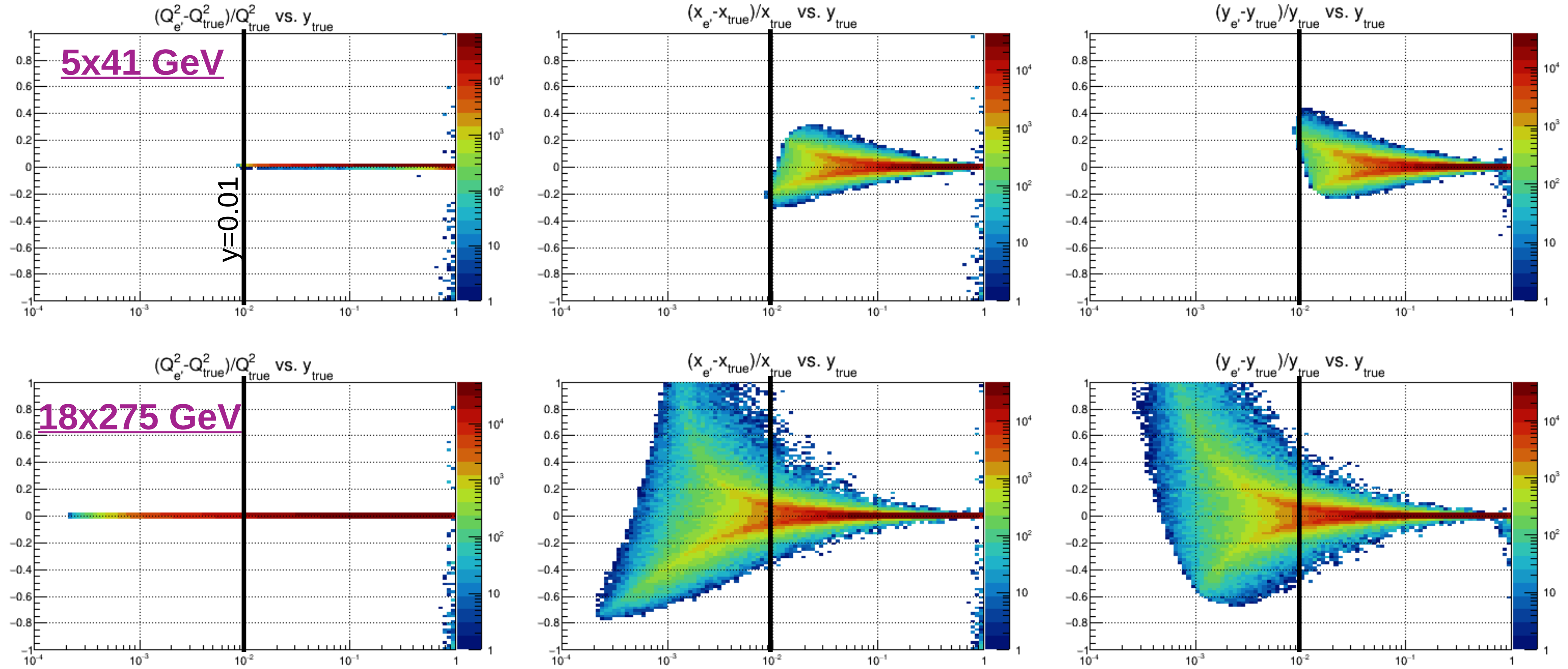
# (x,$Q^2$) Planes, with Binning




- Diagonal lines show y contour at the cut of 0.01, along with the CLAS12 upper limit (y=1)
  - 18x275 plot includes data with y<0.01
  - Kinematic reach of 5x41 with Q2>1 does not extend to y<0.01, but overlaps with CLAS12
- Vertical / horizontal lines demarcate (x,$Q^2$) bin boundaries, used in the following slides
- Next slides show matrices of plots corresponding to these bins

# Low-y Studies: effects of y cuts        Smearing Disabled

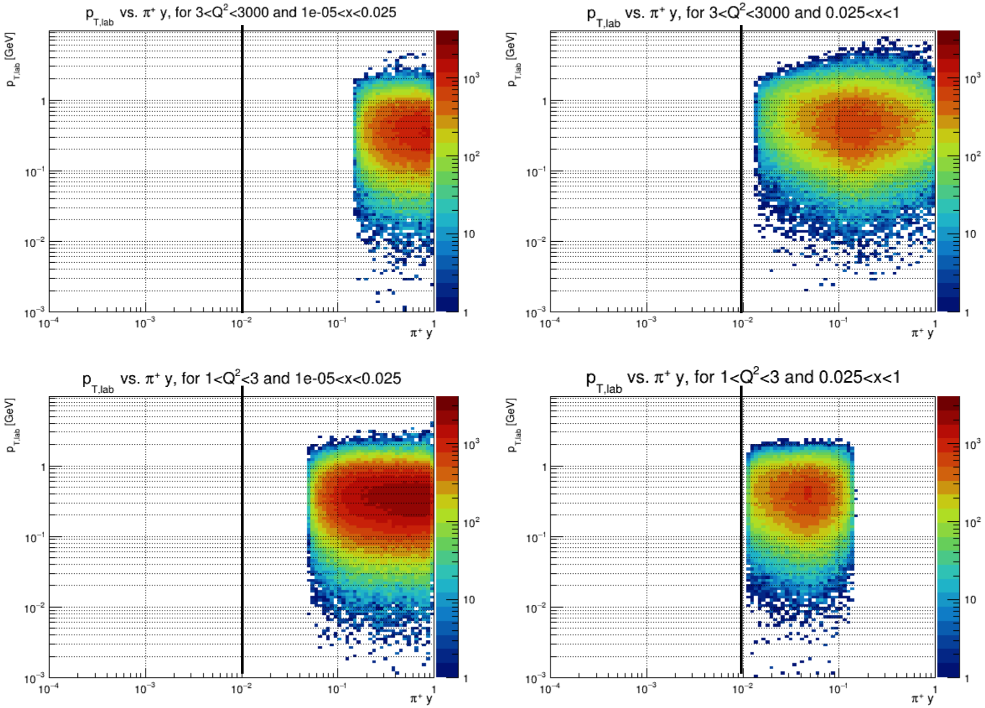



- DIS kinematics calculated using scattered electron are not reliable for y<0.01
- By y=0.1, there are already differences up to 15%
- (small fraction of high-y discrepancies not studied)

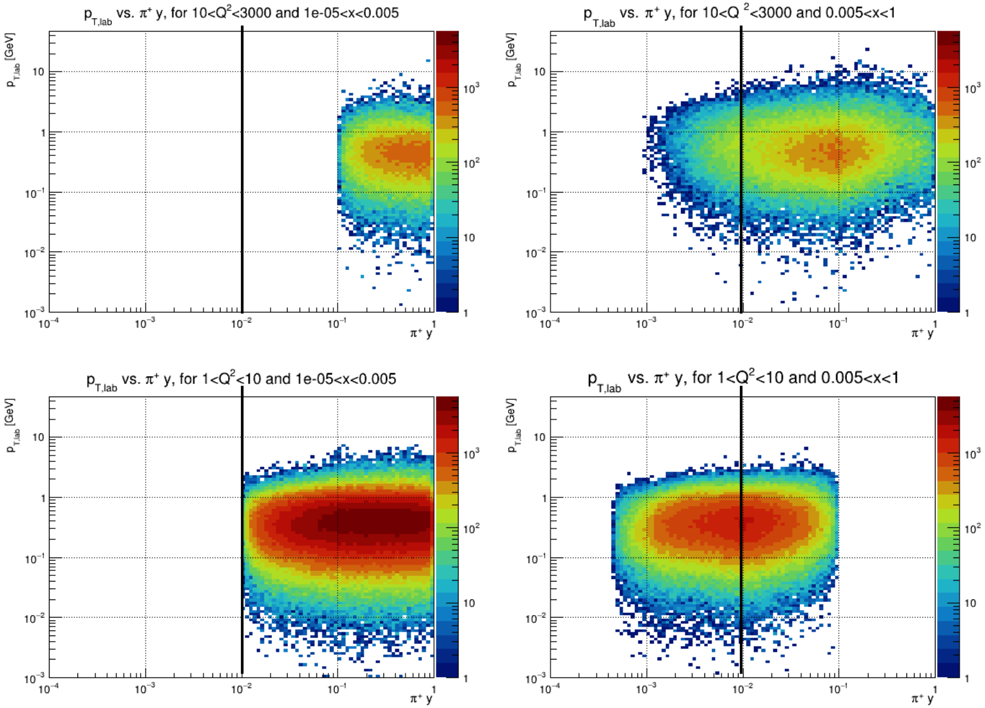
# Effects of y cut on $p_T$

Smearing Disabled

**5x41 GeV**




**18x275 GeV**

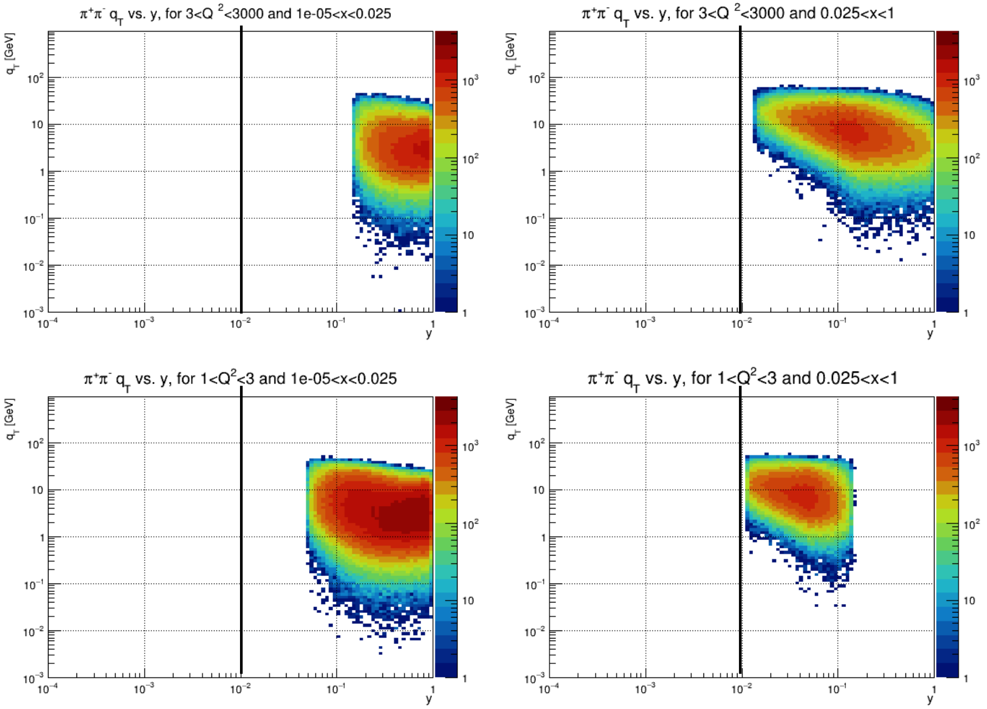



- This shows π+ $p_T$ versus y; black line indicates y=0.01
- 4 plot matrix corresponds to binning shown on $(x,Q^2)$ planes above
- The impact of y>0.01 cut is negligible
- Higher y cuts may start to shave away low $p_T$ at high-x and low $Q^2$

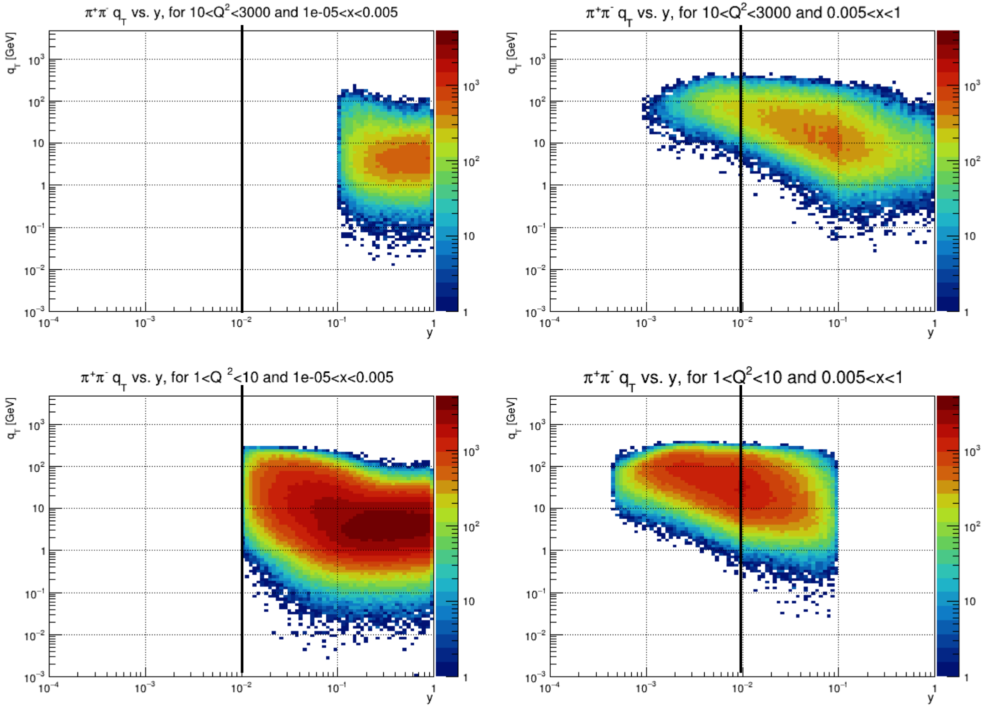
# Effects of y cut on $q_T$ ($=P_h^{\perp}/z_{pair}$)

Smearing Disabled

**5x41 GeV**



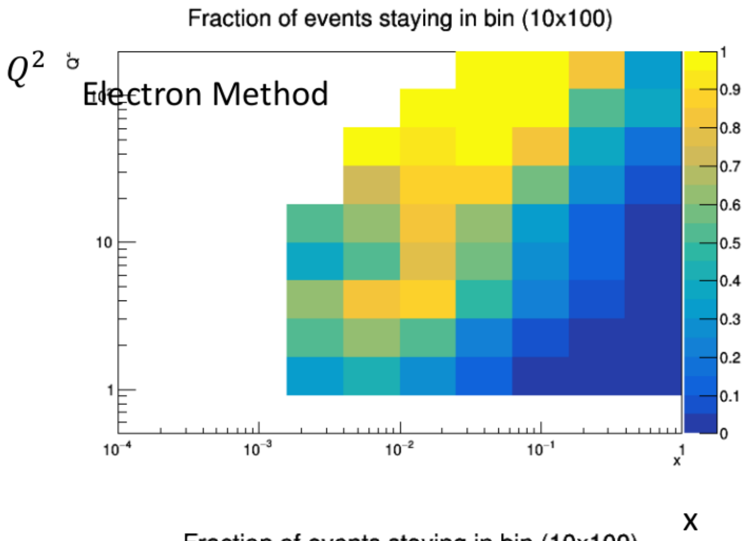

**18x275 GeV**

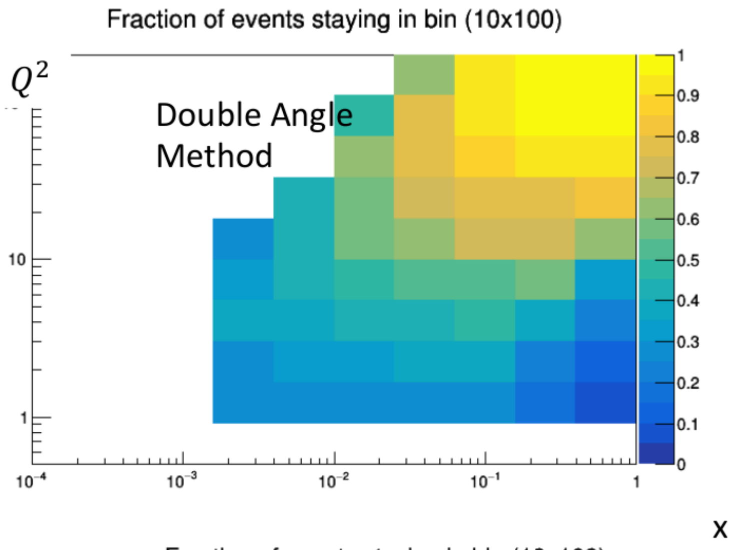


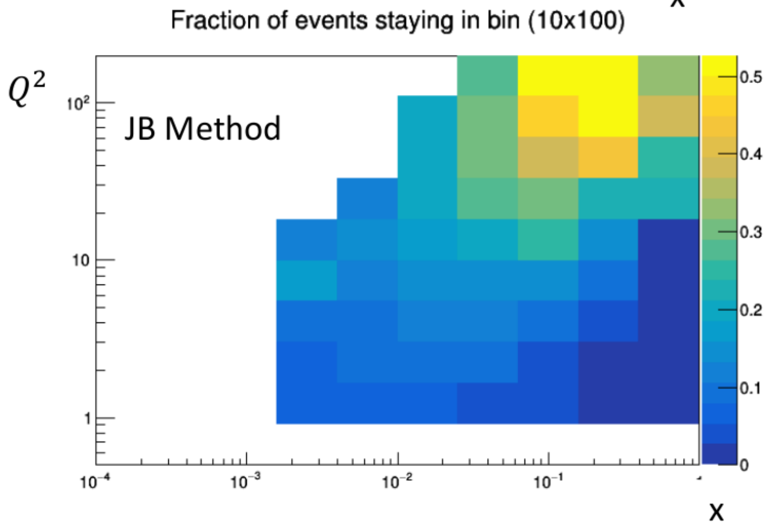

- Compare to $q_T$ versus y; black line indicates y=0.01
- Mean $q_T$ will decrease a bit as y cut is increased

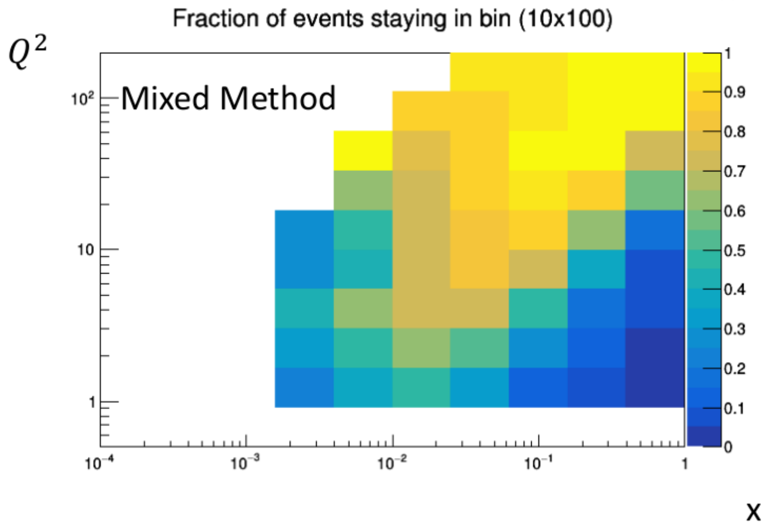
# Aside: Alternative methods for calculating $(x,Q^2)$

Study from Anselm



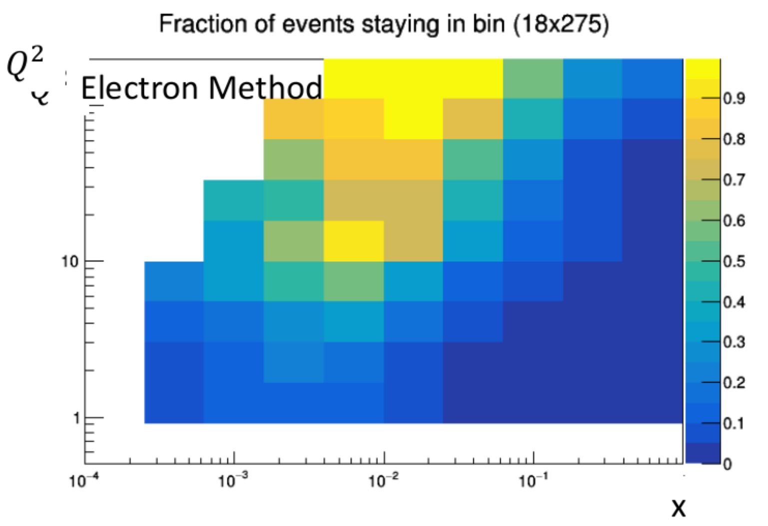



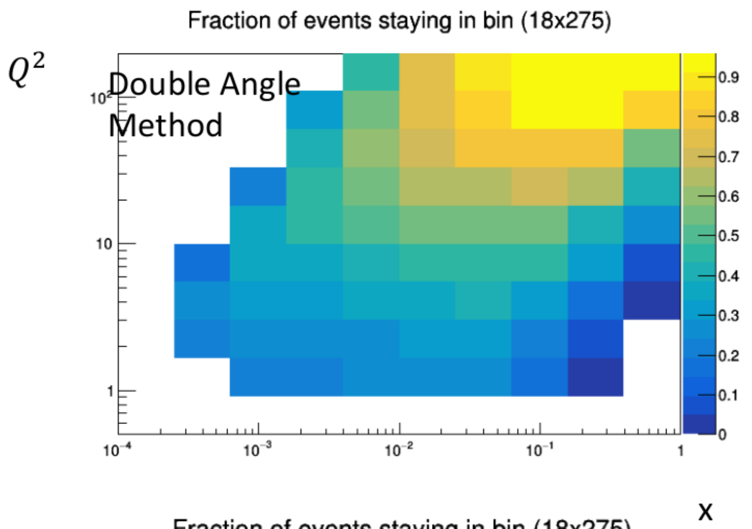



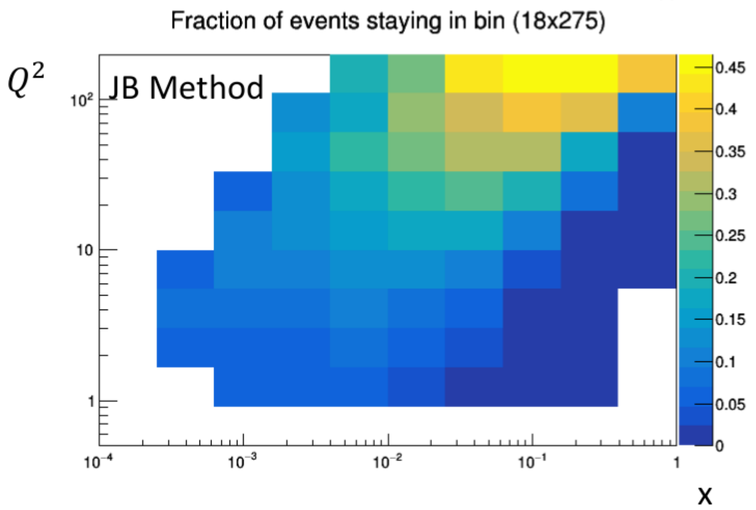



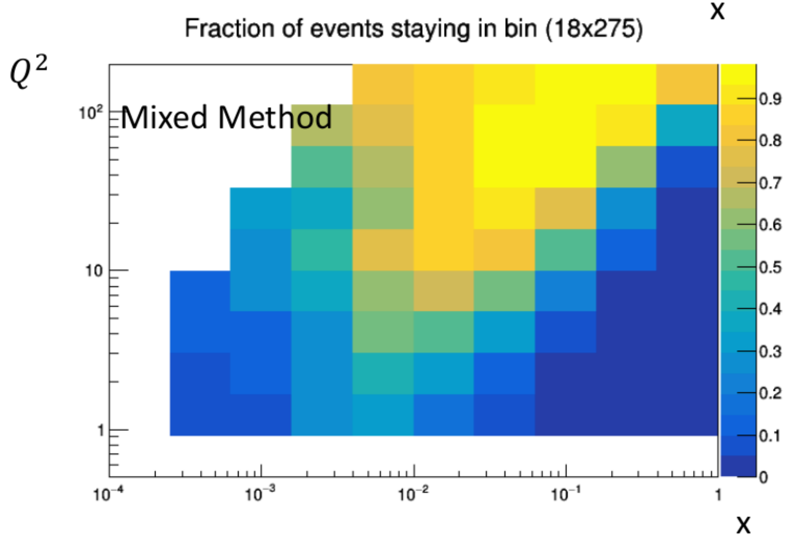
# Aside: Alternative methods for calculating (x,Q²)

Study from Anselm



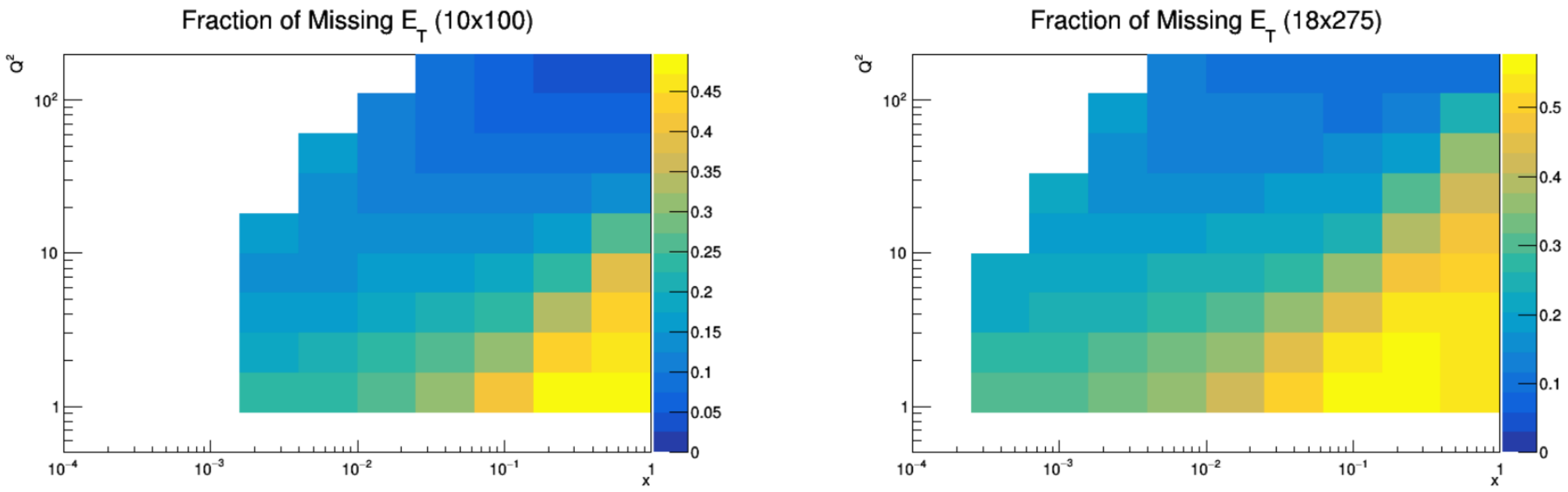



# Aside: Alternative methods for calculating $(x,Q^2)$

Study from Anselm

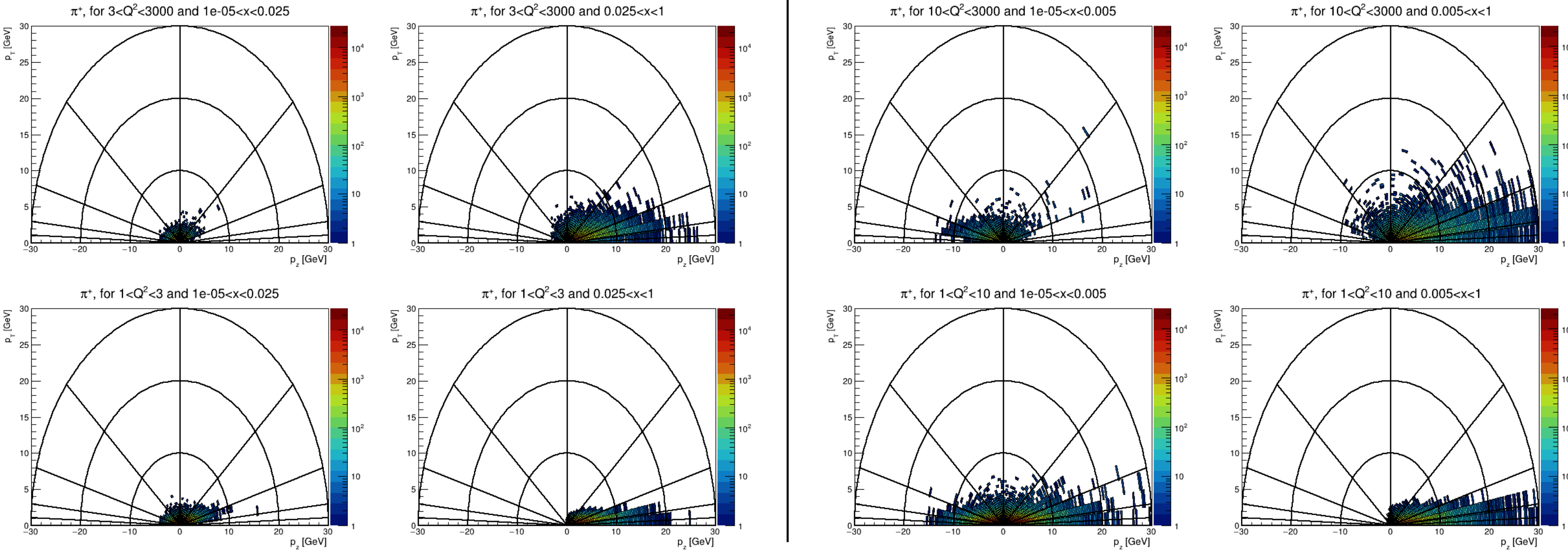
Fraction of missing energy, from acceptance limits

Larger fraction at low-y → correlates to inaccuracy of $(x,Q^2)$



# Pion Momentum

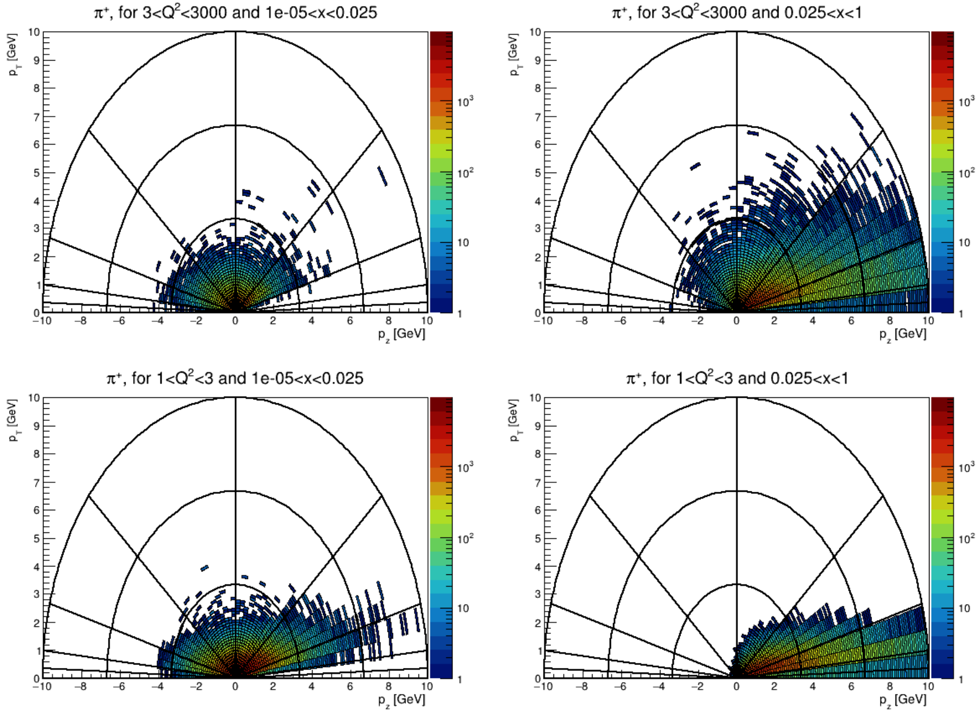
**5x41 GeV** | **18x275 GeV**



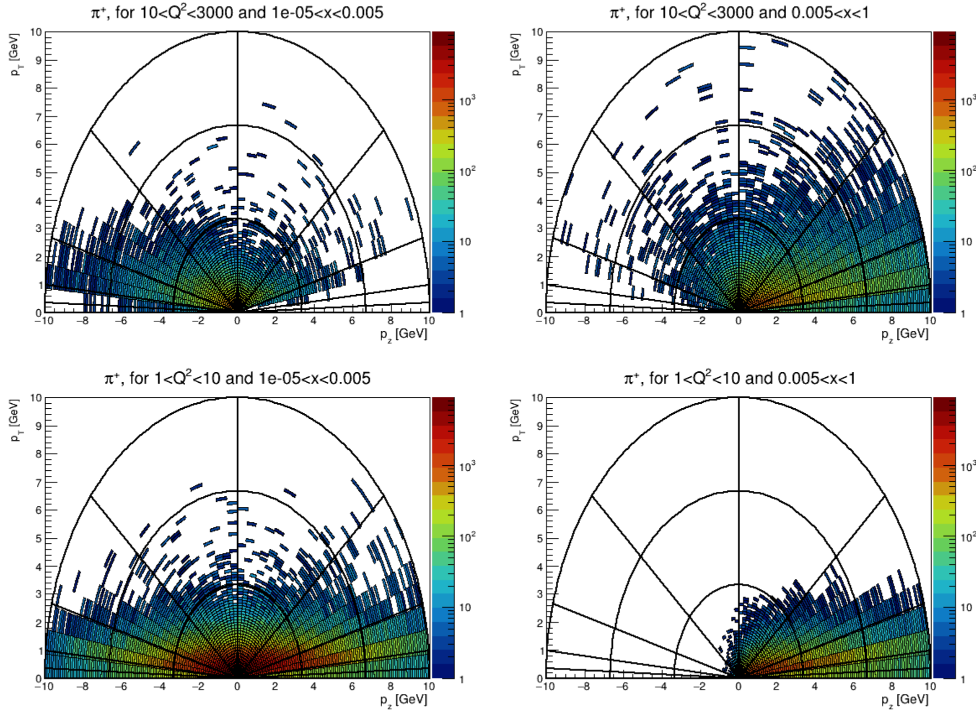

- Radius set at 30 GeV; compare to next slide's zoomed plot
- Smearing with eic-smear enabled → acceptance cuts at |η|=3.5
- This is for π+ of π+π- dihadrons, but the π- looks the same

# Pion Momentum

**5x41 GeV**




**18x275 GeV**

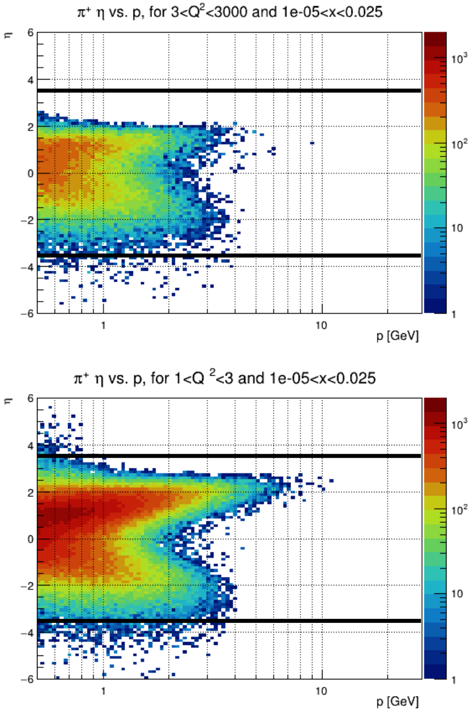



- Radius set at 10 GeV
- Smearing with eic-smear enabled → acceptance cuts at $|\eta|=3.5$
- This is for π+ of π+π- dihadrons, but the π- looks the same
- Some backward production at low x

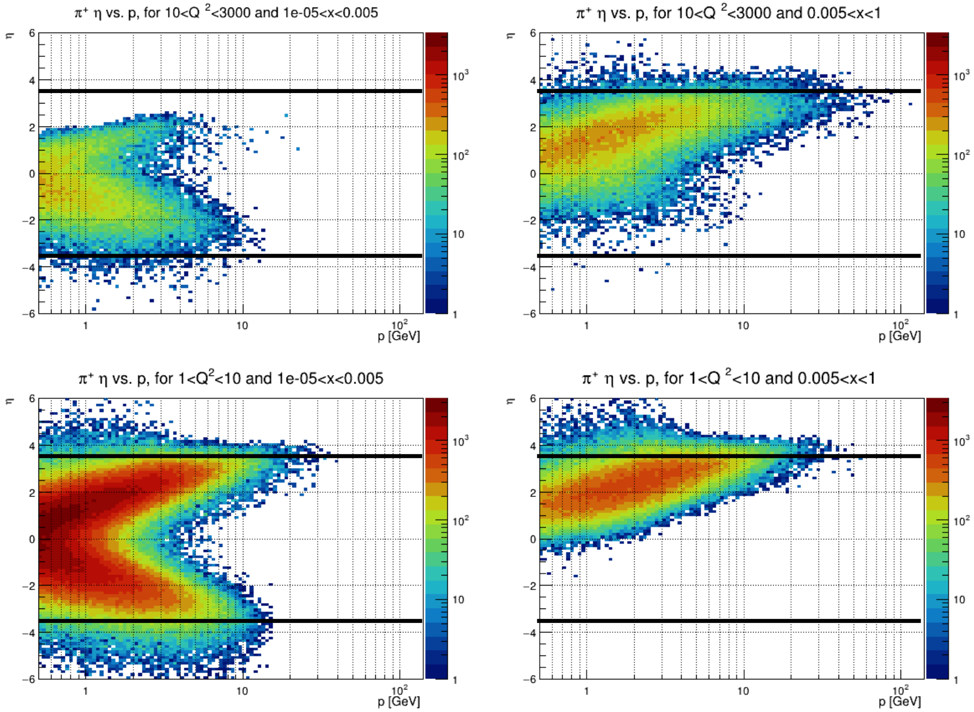
# Pion Momentum vs. Pseudorapidity

Smearing Disabled

**5x41 GeV**




**18x275 GeV**

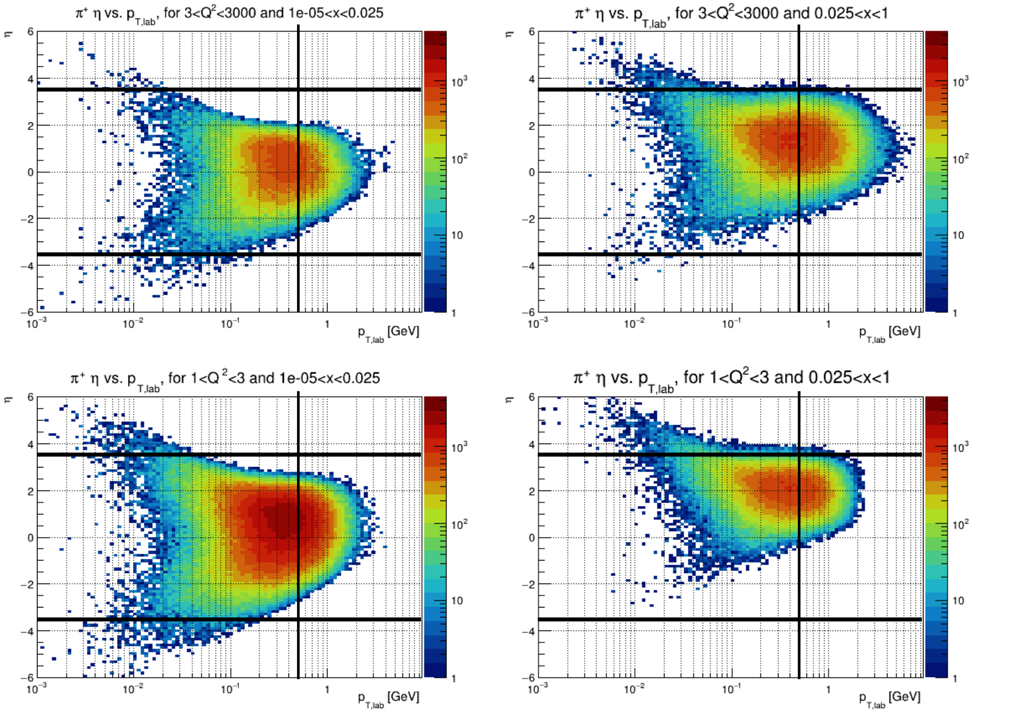



- Smearing disabled, to show activity beyond acceptance cuts
  - Enabling smearing does not alter the shape of the distributions much
- Lines for $|\eta|=3.5$ are shown
- Acceptance cuts only effect $p < \sim 4$ GeV
- π/K/p separation up to p~8 GeV is sufficient

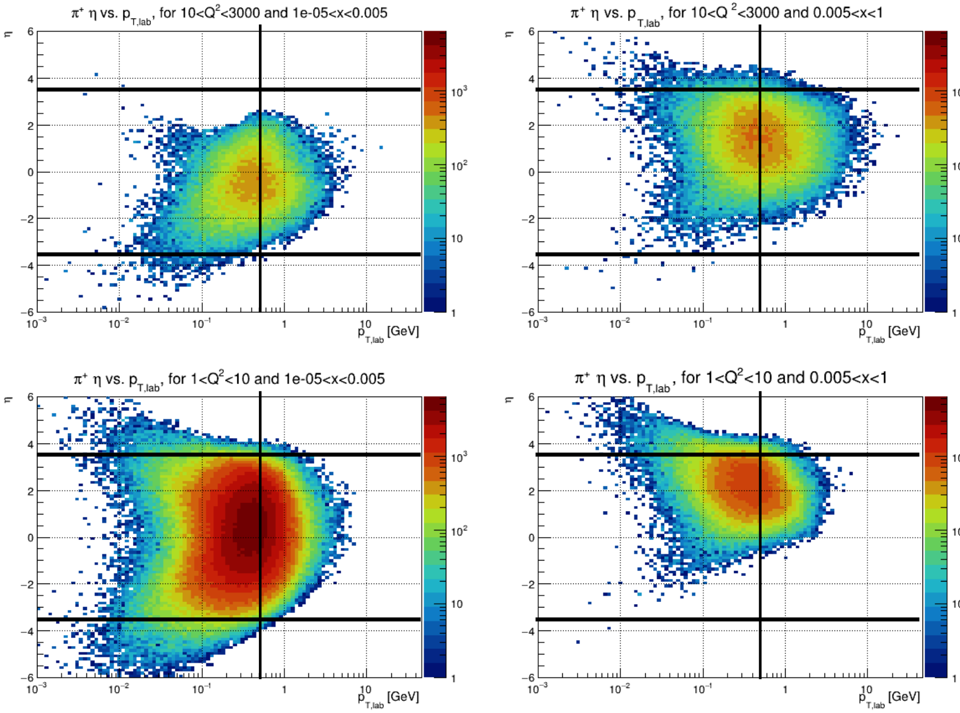
# Pion Transverse Momentum vs. Pseudorapidity

Smearing Disabled

5x41 GeV




18x275 GeV

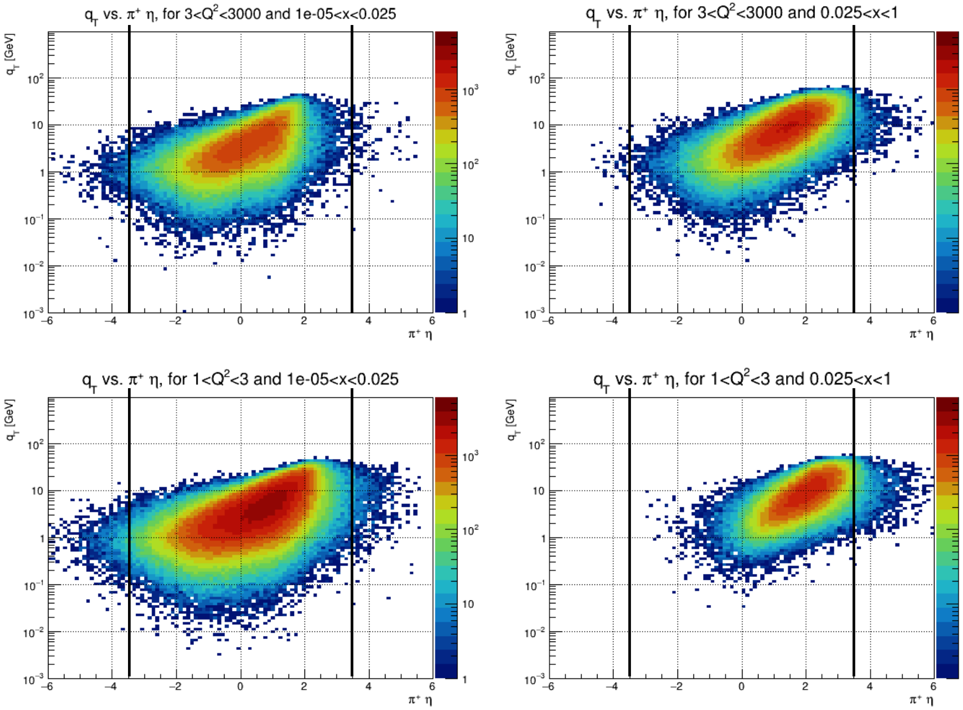



- Smearing disabled, to show activity beyond acceptance cuts
  - Enabling smearing does not alter the shape of the distributions much
- Horizontal lines for $|\eta|=3.5$
- Impact of acceptance cuts is primarily on low $p_T$, well below the 500 MeV threshold (vertical lines)

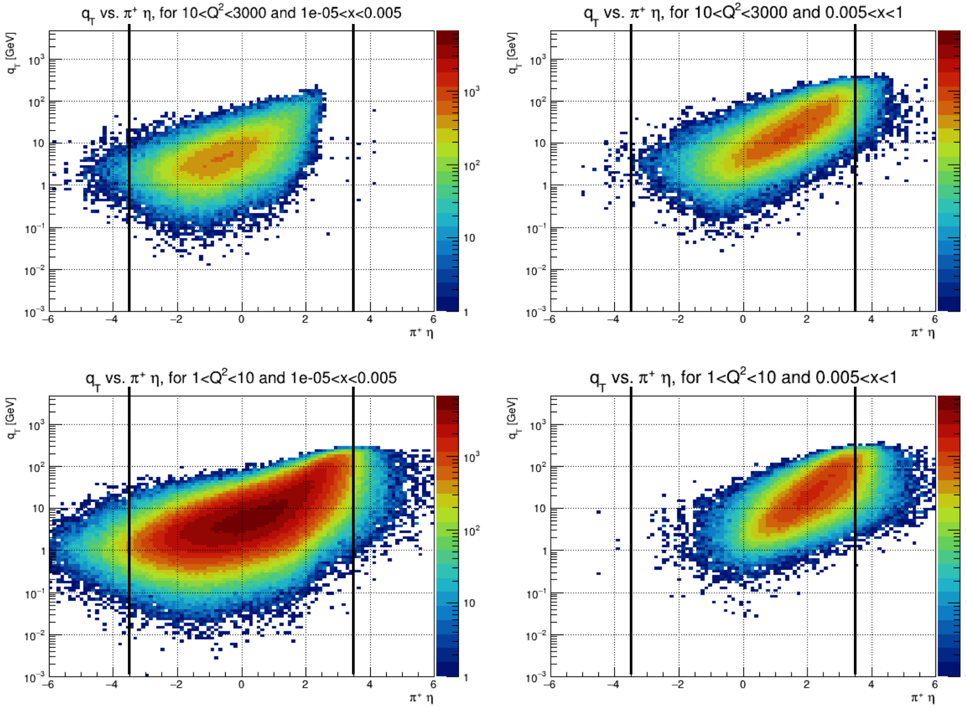
# Effects of η cuts on $q_T$

Smearing Disabled

## 5x41 GeV




## 18x275 GeV

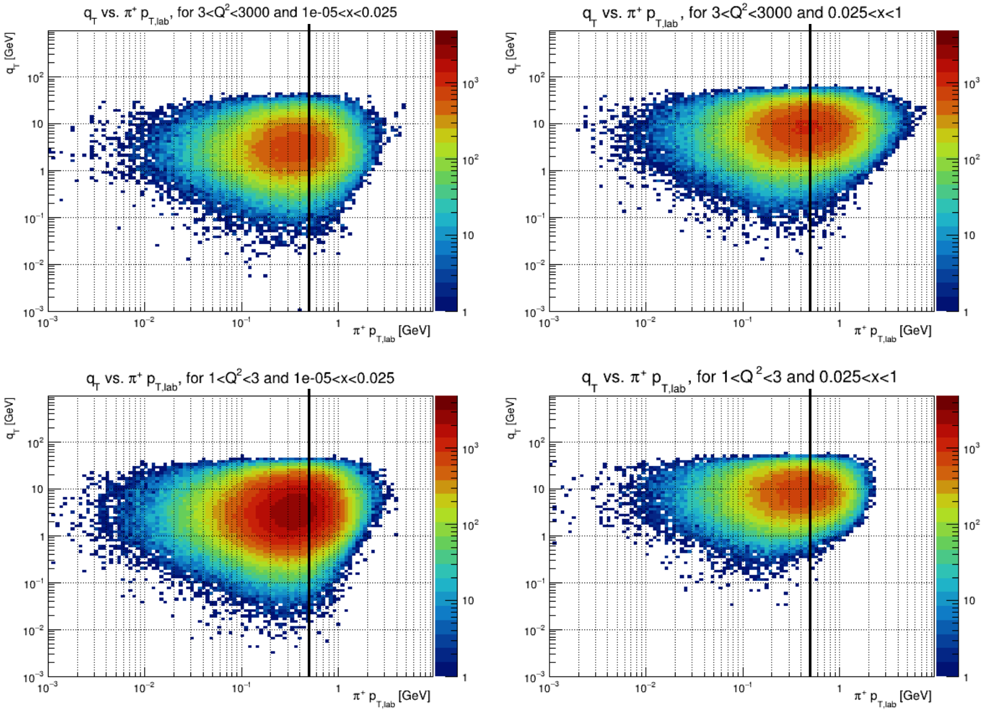



- Plots show $q_T = P_h^{\perp}/z_{pair}$ vs. η of π+
- Smearing disabled, to show activity beyond acceptance cuts
- Vertical lines for |η|=3.5
- Little impact of acceptance cuts on $q_T$

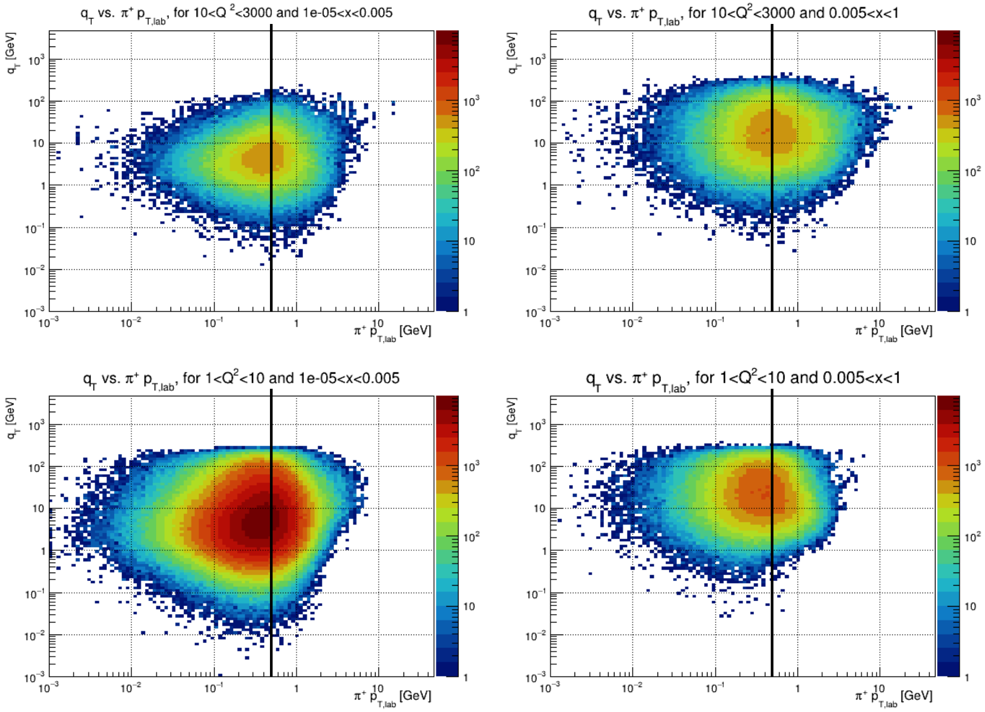
# Effects of $p_T$ cuts on $q_T$

Smearing Disabled

**5x41 GeV**



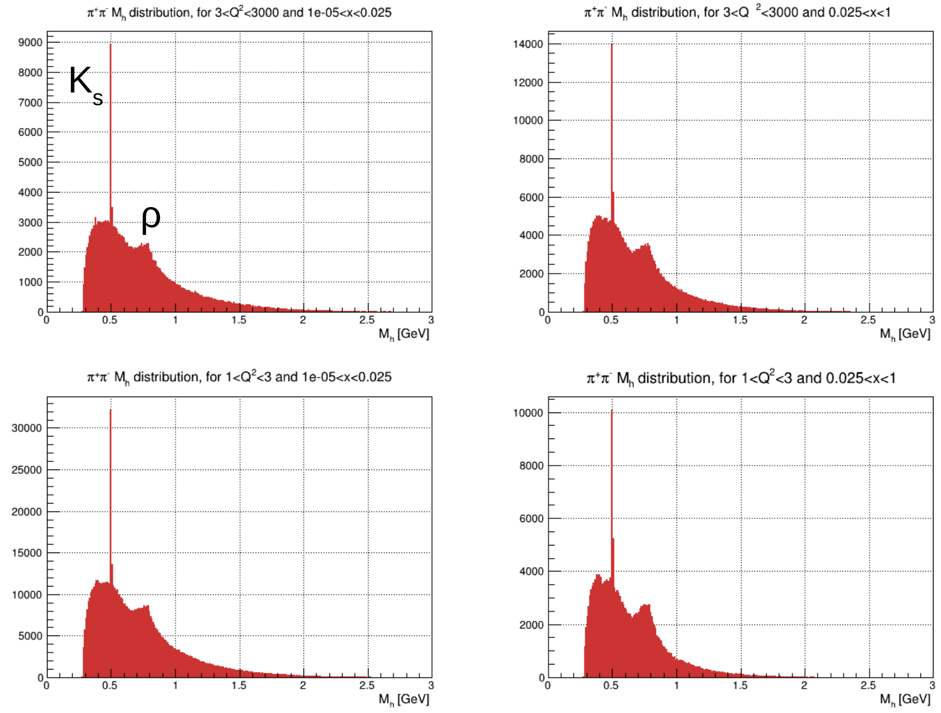

**18x275 GeV**



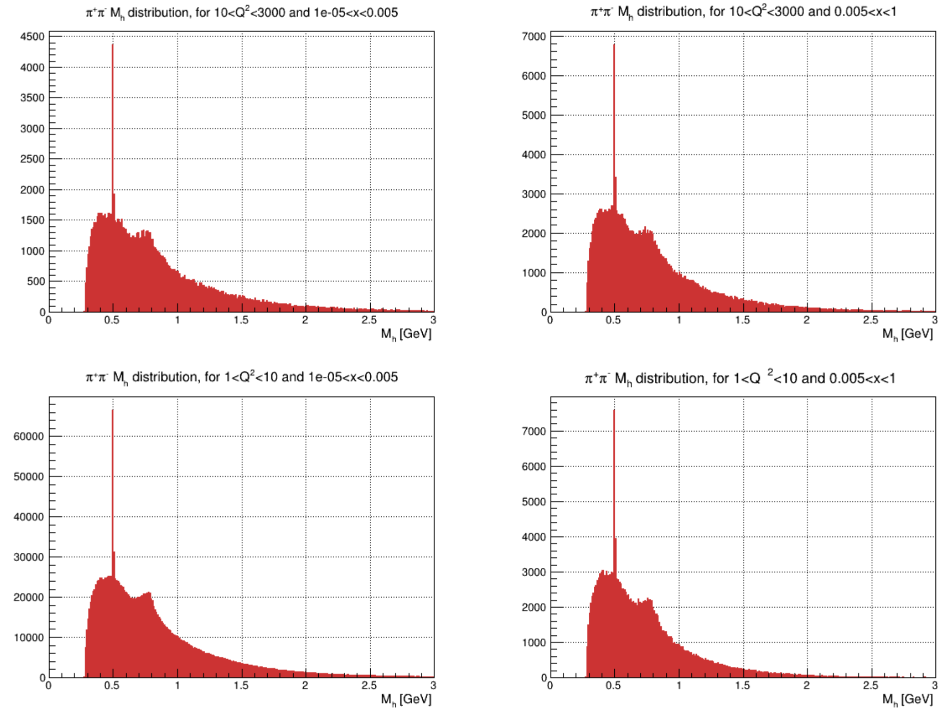

- Plots show $q_T$ vs. $p_T$ of $\pi$+
- Smearing disabled, to show activity beyond acceptance cuts
- Vertical lines $p_T$ = 500 MeV
- Higher $p_T$ cuts may have mild impact at low $q_T$

# Dihadron Kinematics: Invariant Mass

## 5x41 GeV



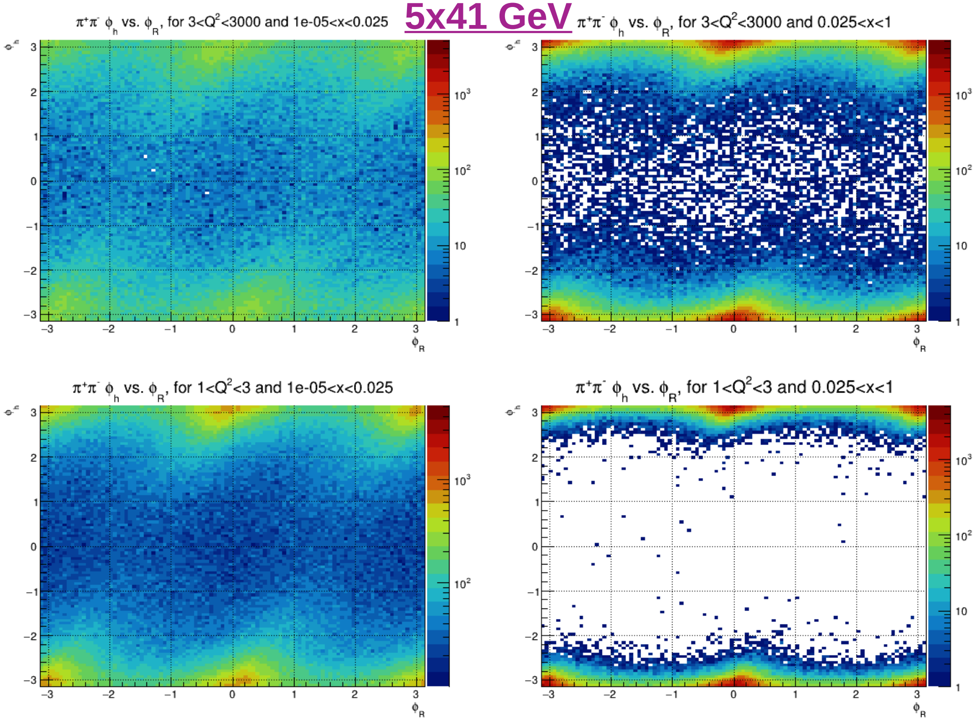

## 18x275 GeV



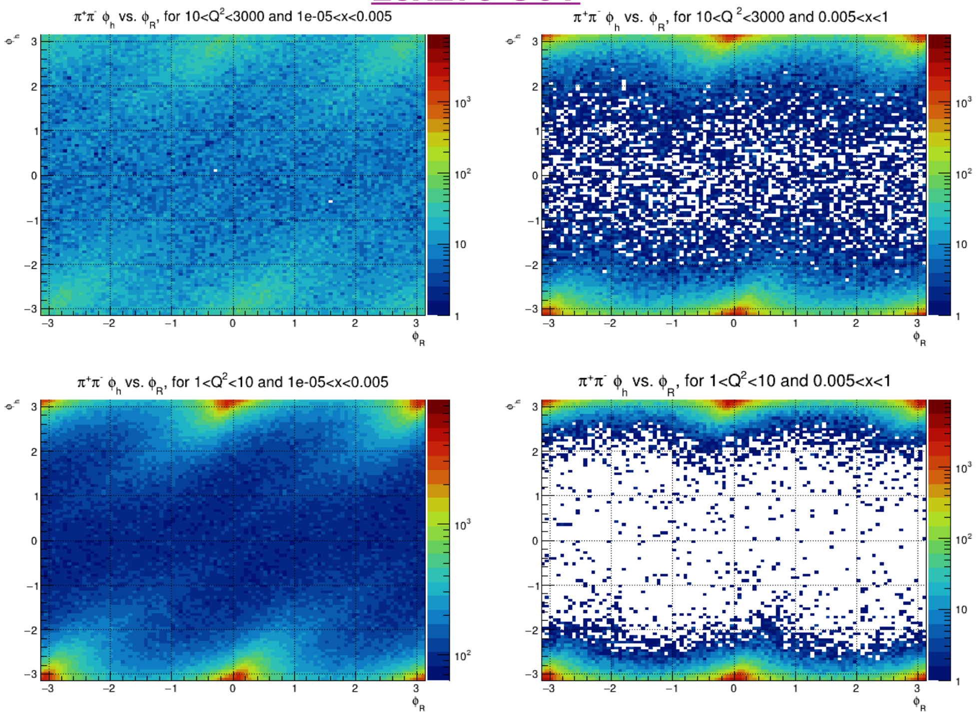

- Strong $K_s$ peak seen, not smeared very much
- ρ peak also visible
- Not much dependence on x, $Q^2$, or $\sqrt{s}$

# Dihadron Kinematics: Azimuthal correlations $\phi_h$ vs. $\phi_R$

5x41 GeV



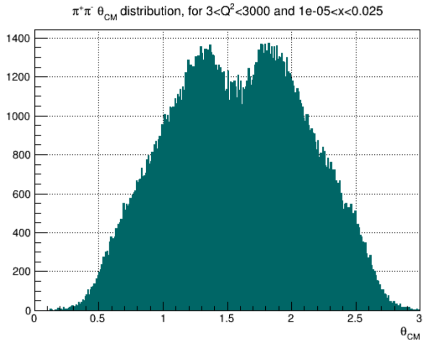

18x275 GeV

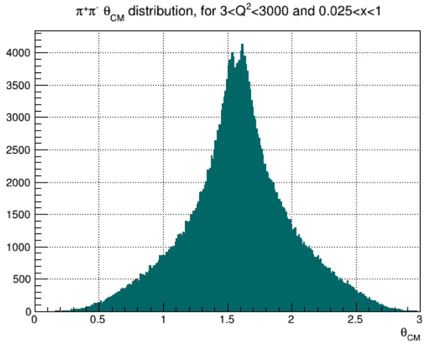


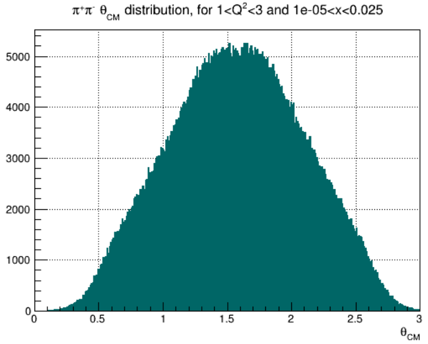

- $\phi_h$ peaks at ±π indicate a strong tendency of dihadron momentum sum $P_h$ to be in lepton scattering plane, with $P_h^{\perp}$ opposite of $p_e^{\perp}$, where “⊥” denotes the plane transverse to q
  - Similar shape seen in $\phi_h$ of single hadrons
- $\phi_R$ peaks at ±π and 0 indicate the hadrons also tend to be within the lepton scattering plane
- These shapes are also present in the generated (not smeared) sample

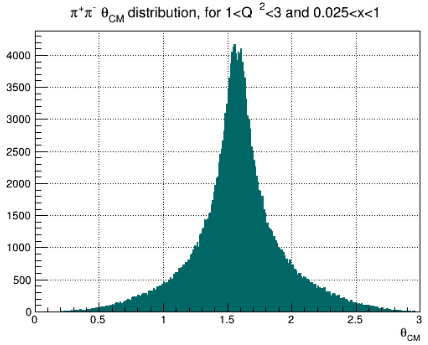
# Dihadron Kinematics: CoM Frame Production Angle

**5x41 GeV**

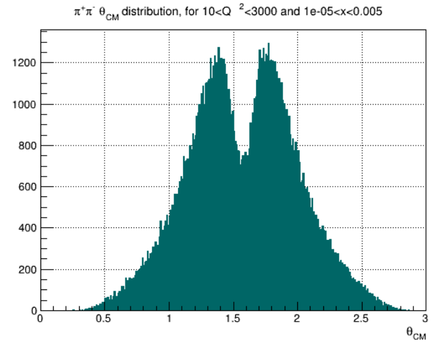


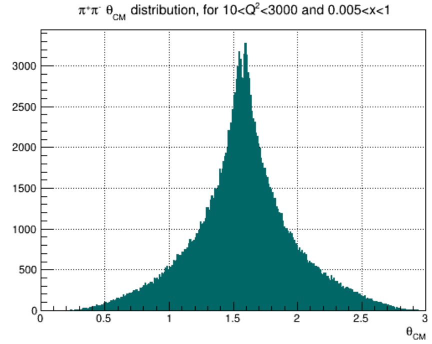



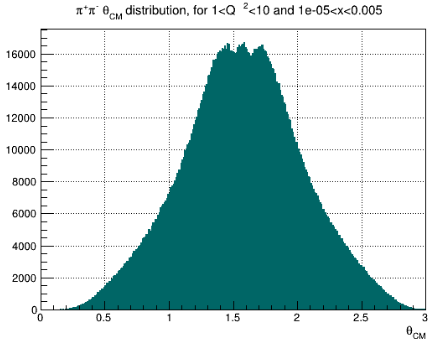



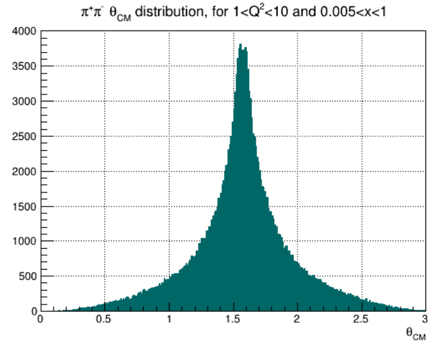




**18x275 GeV**

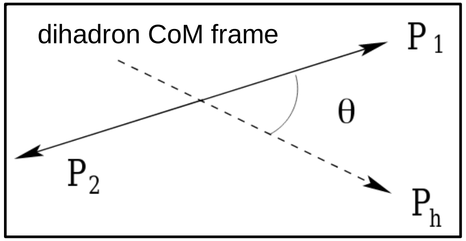


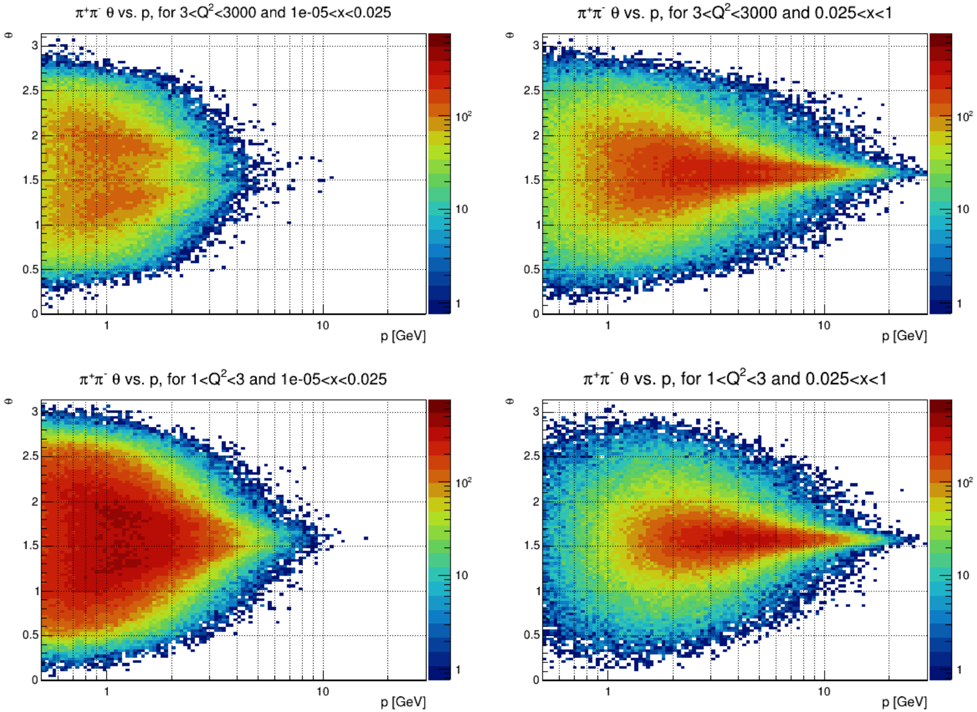




- θ represents the "decay" angle of the hadron pair, in the rest frame of the dihadron
- Dihadron Fragmentation Functions are expanded in partial waves, parameterized by θ
  - Sensitivity to ss, sp, pp interference of dihadroproduction
- Ideal distribution follows a sinθ shape
- Double peaking visible at low-x and high $Q^2$

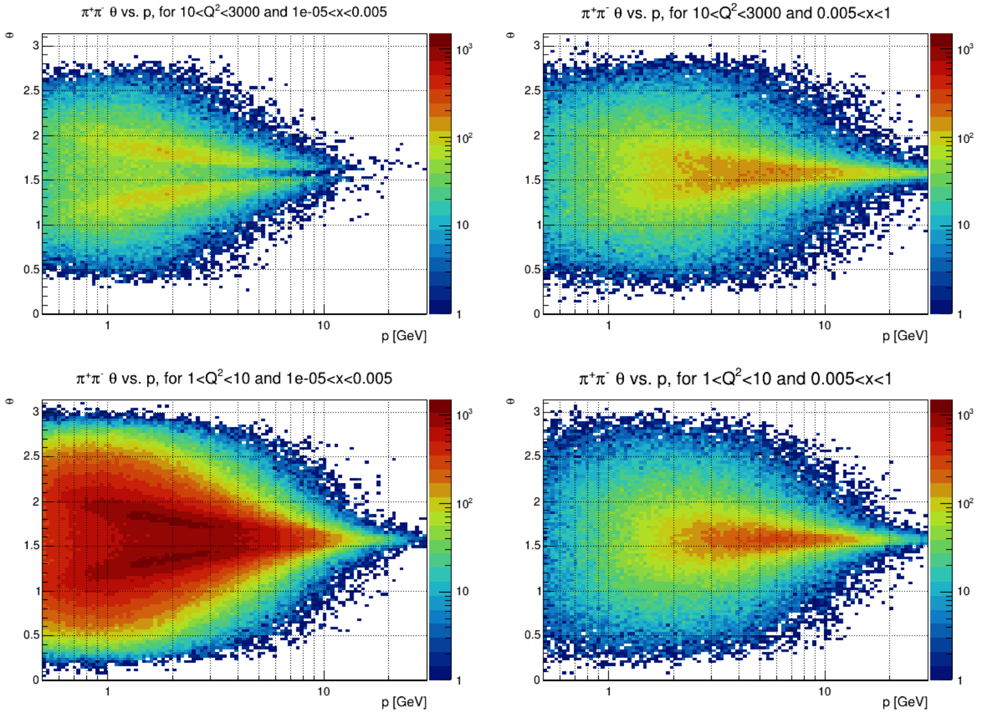


# Dihadron Kinematics: θ vs. $P_h$

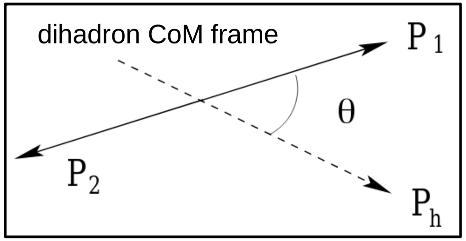
## 5x41 GeV




## 18x275 GeV




- Plots show correlation between θ and the hadron momentum sum $P_h$
- Double peak separation correlates with $P_h$

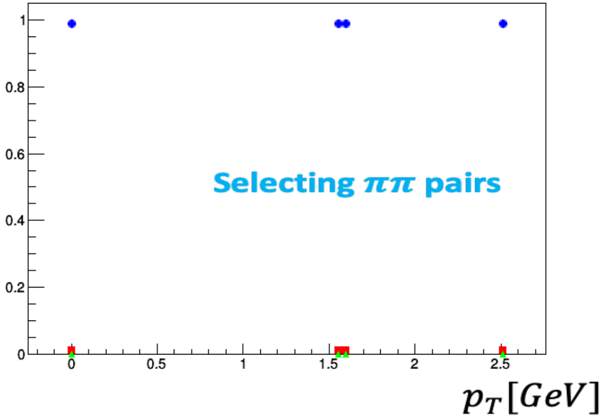


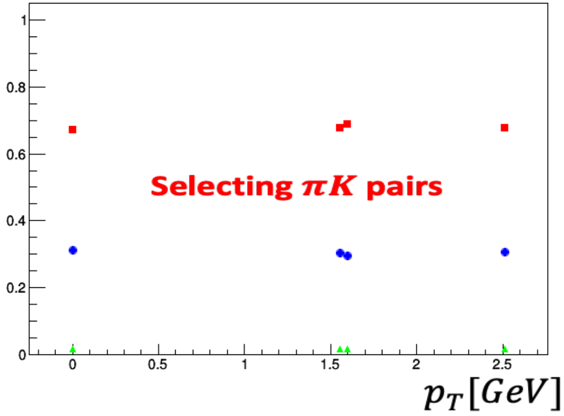
# PID Performance

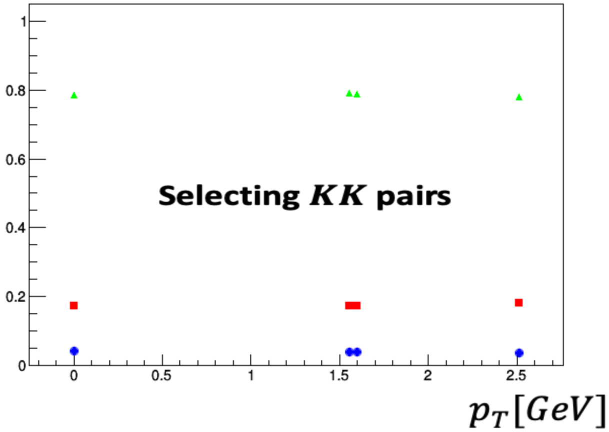
- Fraction of reconstructed $\pi\pi$ pairs
- Fraction of reconstructed $\pi K$ pairs
- Fraction of reconstructed KK pairs

Study from Anselm

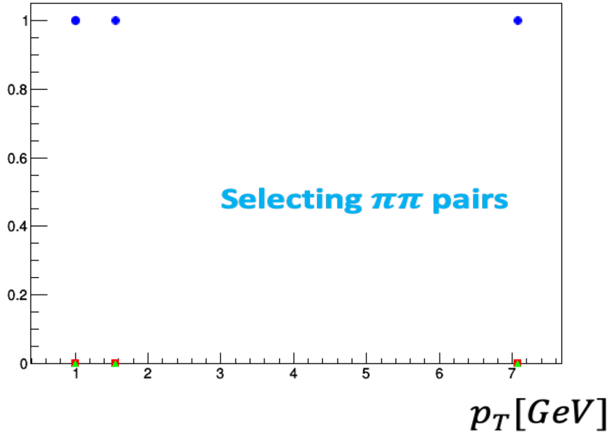
## Using 2σ separation:

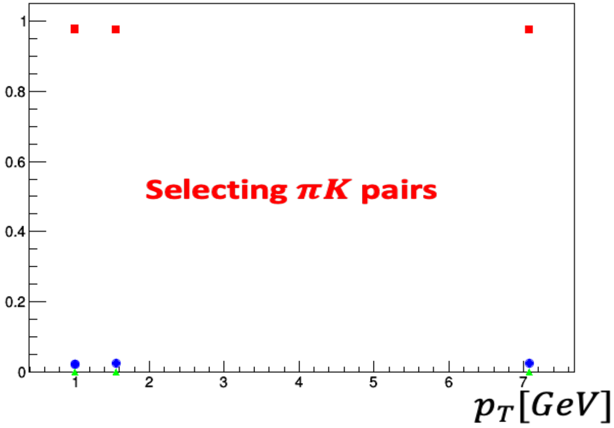


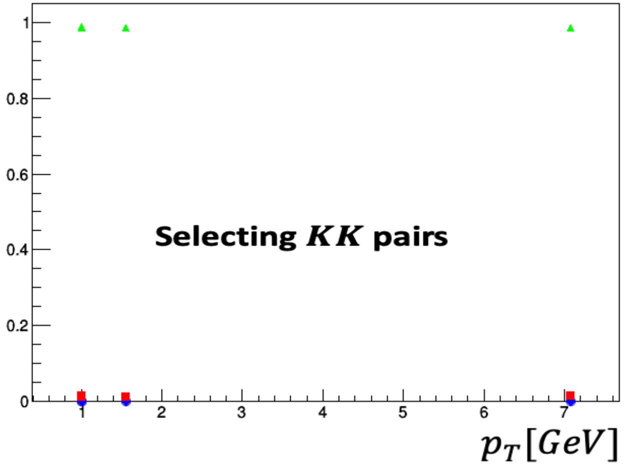




## Using 3σ separation:



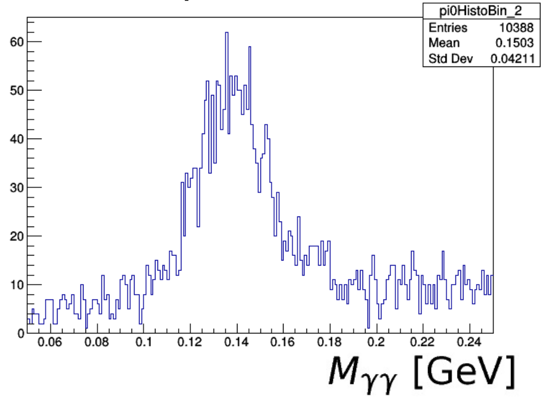



# PID Performance

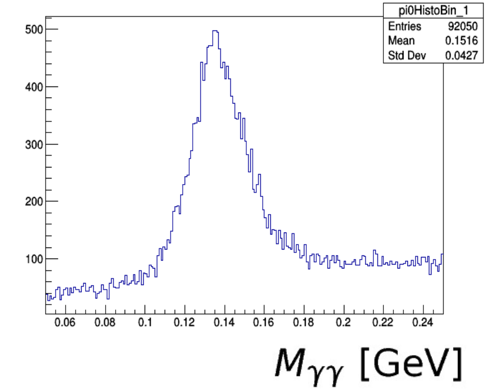
Study from Anselm

## $\pi^0$ Reconstruction with $E_\gamma$>200 MeV

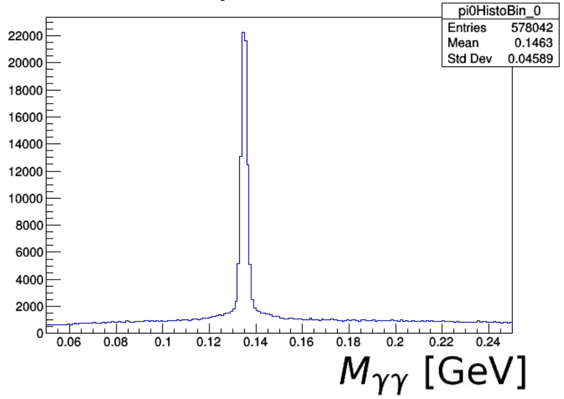
-4.5 < η < -0.5




-0.5 < η < 1.5

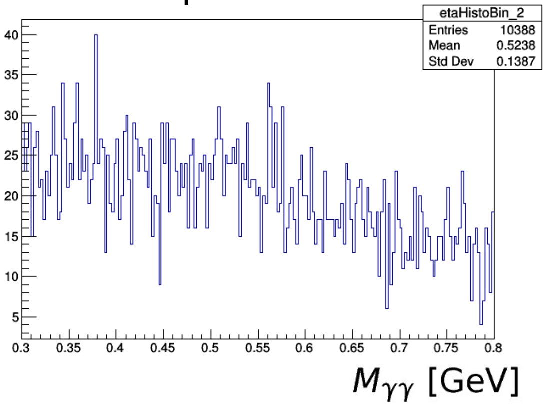



1.5 < η < 4.5

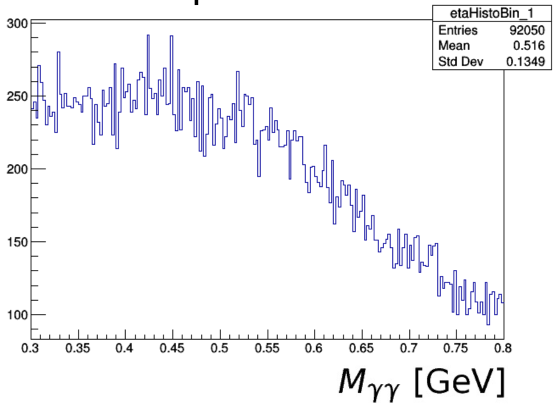



## η Reconstruction with $E_\gamma$>200 MeV

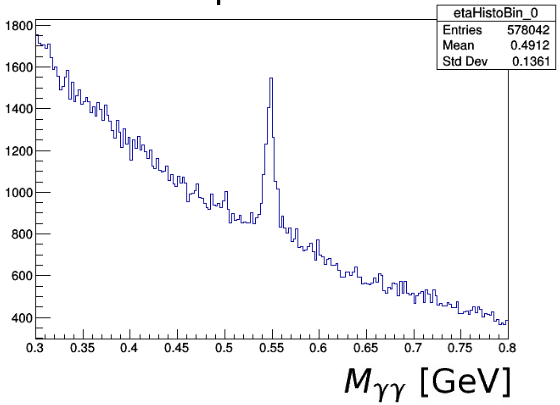
-4.5 < η < -0.5




-0.5 < η < 1.5




1.5 < η < 4.5



## Summary and Outlook

- Dihadrons access several aspects of the nucleon:
  - Spin-momentum correlations in hadronsization
  - Transverse-momentum dependent PDFs
  - Twist-3 TMD PDFs
- EIC simulation studies are well underway
- Next Steps:
  - Asymmetry projections, including partial wave sensitivity
  - Study other dihadron channels, including kaons