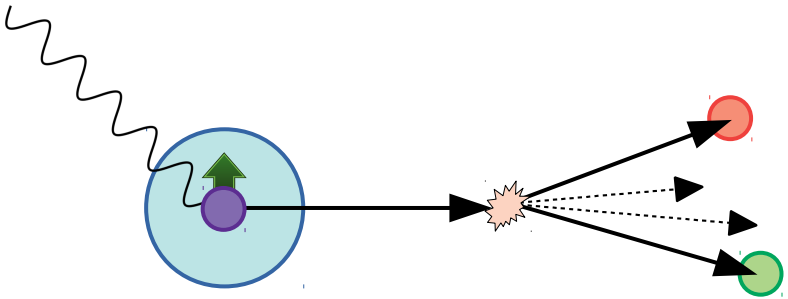
Dihadron Partial Waves and PID at high Q^2



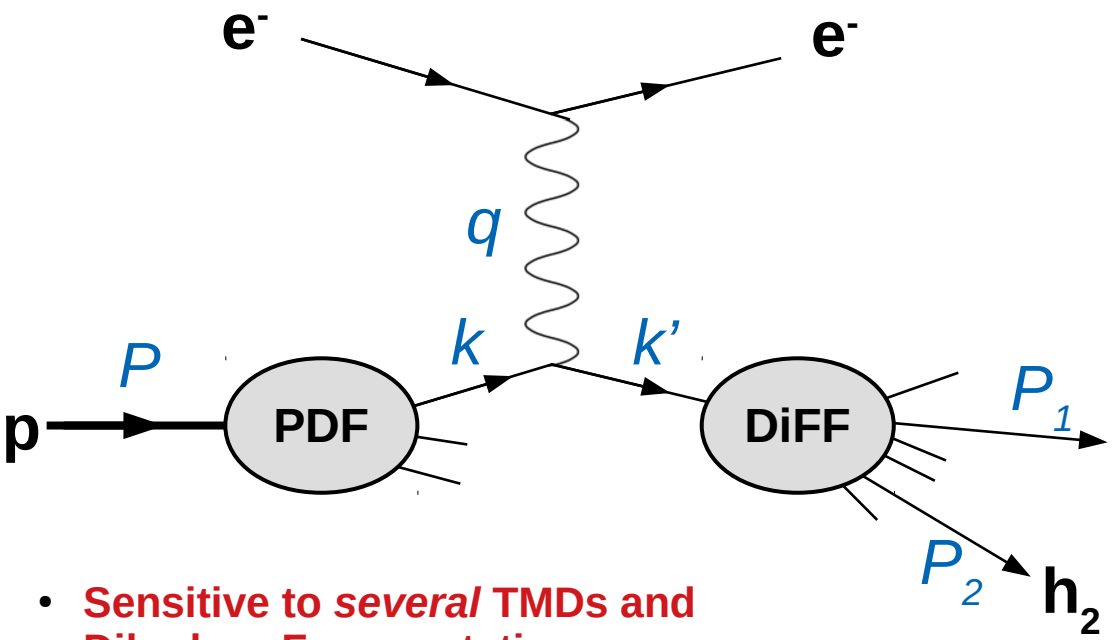
Christopher Dilks

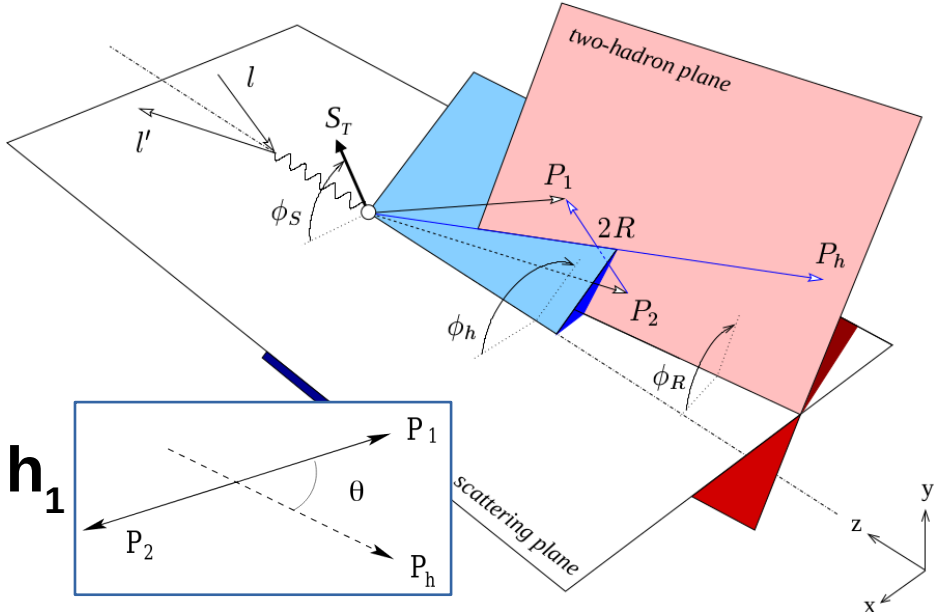
EIC Yellow Report – SIDIS Meeting

17 August 2020

Duke UNIVERSITY

SIDIS Dihadrons





- **Sensitive to *several* TMDs and Dihadron Fragmentation Functions (DiFFs)**
- **Spin-momentum correlations in hadronization**
- **Complement single-hadron SIDIS, with the advantage of another degree of freedom**

Momenta and Angles

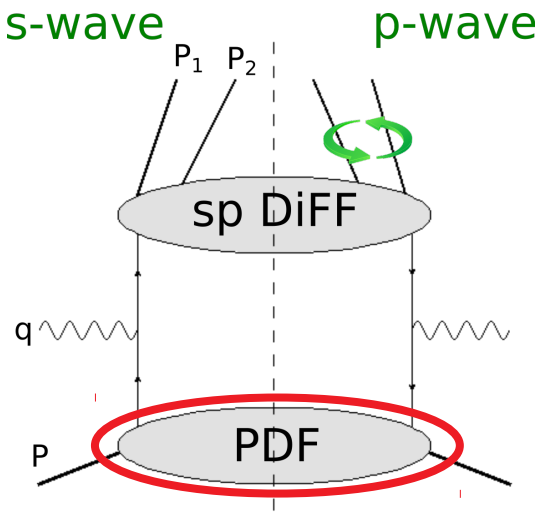
$P_h = P_1 + P_2$ → ϕ_h

$R = \frac{1}{2}(P_1 - P_2)$ → ϕ_R

Kinematic Variables:

- DIS: Q^2, x, W, y
- Momenta, e.g. P_1, P_2, $P_h^{\perp}$
- Invariant Mass: M_h
- Fragmentation fraction: z
- Missing Mass: M_X
- Dihadron CoM Decay Angle: θ

TMD PDFs



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

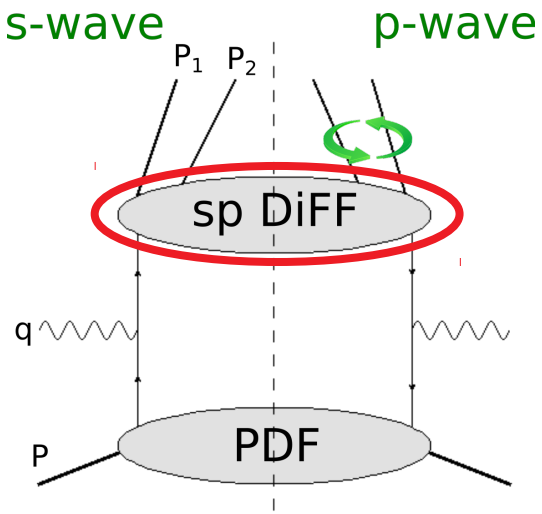
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h,\ e$
L	$f_L^\perp$	$g_L^\perp$	$h_L,\ e_L$
T	$f_T,\ f_T^\perp$	$g_T,\ g_T^\perp$	$h_T,\ e_T,\ h_T^\perp,\ e_T^\perp$

- 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**

Partial Wave Expansion



Dihadron Fragmentation Functions (DiFFs)

L	|M|	$h_1 h_2/q$	U	L	T
0	0	UU	$D_{1,OO}$		$H^{\perp}_{1,OO}$
1	0	LU	$D_{1,OL}$		$H^{\perp}_{1,OL}$
2	0	LL	$D_{1,LL}$		$H^{\perp}_{1,LL}$
1	1	TU	$D_{1,OT}$	$G^{\perp}_{1,OT}$	$\begin{cases} H^{\perp}_{1,OT} & \text{if } m<0 \\ H^{\sphericalangle}_{1,OT} & \text{if } m>0 \end{cases}$
2	1	TL	$D_{1,LT}$	$G^{\perp}_{1,LT}$	$\begin{cases} H^{\perp}_{1,LT} & \text{if } m<0 \\ H^{\sphericalangle}_{1,LT} & \text{if } m>0 \end{cases}$
2	2	TT	$D_{1,TT}$	$G^{\perp}_{1,TT}$	$\begin{cases} H^{\perp}_{1,TT} & \text{if } m<0 \\ H^{\sphericalangle}_{1,TT} & \text{if } m>0 \end{cases}$

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

Partial Wave Expansion

- Expand cross section on the basis of spherical harmonics
- Dihadron fragmentation functions expand in partial waves
- Basis is total PW angular momentum |L,M>
- A_{UT} contains several modulations of 4 angles

L=0: ss
L=1: sp
L=2: pp
M = –L,…,L

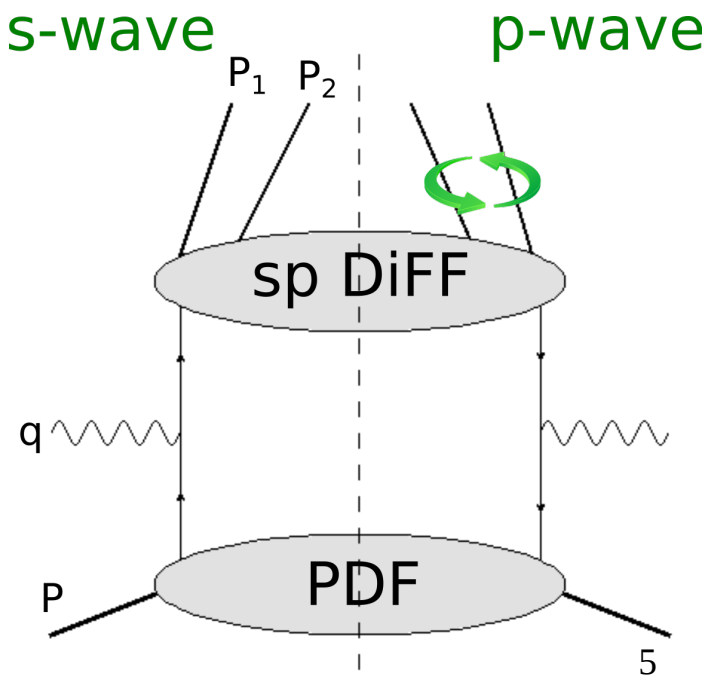
General Modulation form:

$$P_{\ell,m}(\cos\theta) \cdot f_m(\phi_h, \phi_R, \phi_S)$$

Associated Legendre Polynomials

ϕ modulations (Fourier functions)

- Gliske, Bacchetta, Radici, Phys.Rev.D 90 (2014) 11, 114027, Phys.Rev.D 91 (2015) 1, 019902 (erratum)



θ Modulations

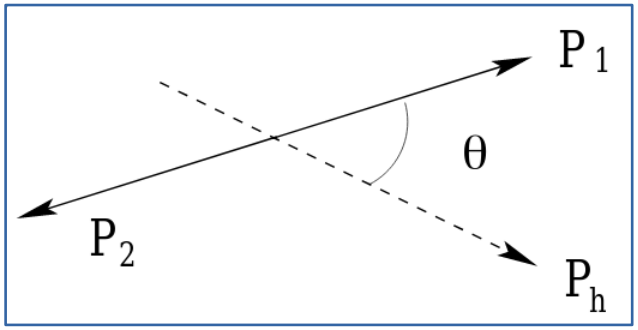
$$\boxed{P_{\ell,m}(\cos\theta)} \cdot f_m(\phi_h, \phi_R, \phi_S)$$

Associated Legendre Polynomials

$$P_{0,0} = 1 \,, \qquad P_{2,0} = \frac{1}{2}\left(3\cos^2\vartheta - 1\right)$$

$$P_{1,0} = \cos\vartheta \,, \qquad P_{2,1} = \sin 2\vartheta \,,$$

$$P_{1,1} = \sin\vartheta \,, \qquad P_{2,2} = \sin^2\vartheta \ldots$$



ϕ Modulations of F_{UT}

$$P_{\ell,m}(\cos\theta)\cdot \boxed{f_m(\phi_h,\phi_R,\phi_S)}$$

twist	ϕ modulation	PDF⊗FF
2	$\sin[(1+m)\phi_h - m\phi_R - \phi_S]$	$f_{1T}^{\perp}\otimes D_1^{[\ell,m\rangle},\ \ g_{1T}\otimes G_1^{[\ell,m\rangle}$
2	$\sin[(1-m)\phi_h + m\phi_R + \phi_S]$	$h_1\otimes H_1^{[\ell,m\rangle}$
2	$\sin[(3-m)\phi_h + m\phi_R - \phi_S]$	$h_{1T}^{\perp}\otimes H_1^{[\ell,m\rangle}$
3	$\sin[-m\phi_h + m\phi_R + \phi_S]$	$f_T\otimes D_1^{[\ell,m\rangle},\ \ h_T\otimes H_1^{[\ell,m\rangle},\ \ h_T^{\perp}\otimes H_1^{[\ell,m\rangle}$
3	$\sin[(2-m)\phi_h + m\phi_R - \phi_S]$	$f_T^{\perp}\otimes D_1^{[\ell,m\rangle},\ \ h_T\otimes H_1^{[\ell,m\rangle},\ \ h_T^{\perp}\otimes H_1^{[\ell,m\rangle}$

Sensitive to transversity:

- $\sin(\phi_R+\phi_S) \rightarrow h_1\otimes\sum_\ell H_1^{|\ell,1\rangle}$
- $\sin(\phi_h+\phi_S) \rightarrow h_1\otimes\sum_\ell H_1^{|\ell,0\rangle}$

Include θ dependence to select a partial wave |L,M> of the IFF H_1

ϕ Modulations of F_{UT}

5 azimuthal modulations x 9 partial waves (L<=2) = 45 A_{UT} amplitudes

3 Tests to Focus on sensitivity to transversity

1. **PWs of modulation with h(x)**
2. **All |L,0> modulations**
3. **All |L,1> modulations**

*** note: no θ-dep in tests 2 & 3**

$f_m(\phi_h, \phi_R, \phi_S)$ \ $P_{\ell,m}(\cos\theta)$	$\lvert 0,0\rangle$	$\lvert 1,1\rangle$	$\lvert 1,0\rangle$	$\lvert 1,-1\rangle$	$\ldots$
$\sin[(1+m)\phi_h - m\phi_R - \phi_S]$					
$\sin[(1-m)\phi_h + m\phi_R + \phi_S]$				1	
$\sin[(3-m)\phi_h + m\phi_R - \phi_S]$					
$\sin[-m\phi_h + m\phi_R + \phi_S]$					
$\sin[(2-m)\phi_h + m\phi_R - \phi_S]$	2	3	2		

Monte Carlo

- **Event Generation**
  - Pythia6 (via pythiaeRHIC)
    - 1M events
    - Radiative corrections using RADGEN attempted, but was unsuccessful
- **Fast Simulation**
  - EICsmear 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

Event Selection

$$Q^2 > 1\ \mathrm{GeV}^2$$
$$W > 3\ \mathrm{GeV}$$
$$0.01 < y < 0.95$$

$$x_{F_h} > 0$$
$$0.2 < z_{pair} < 0.95$$

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

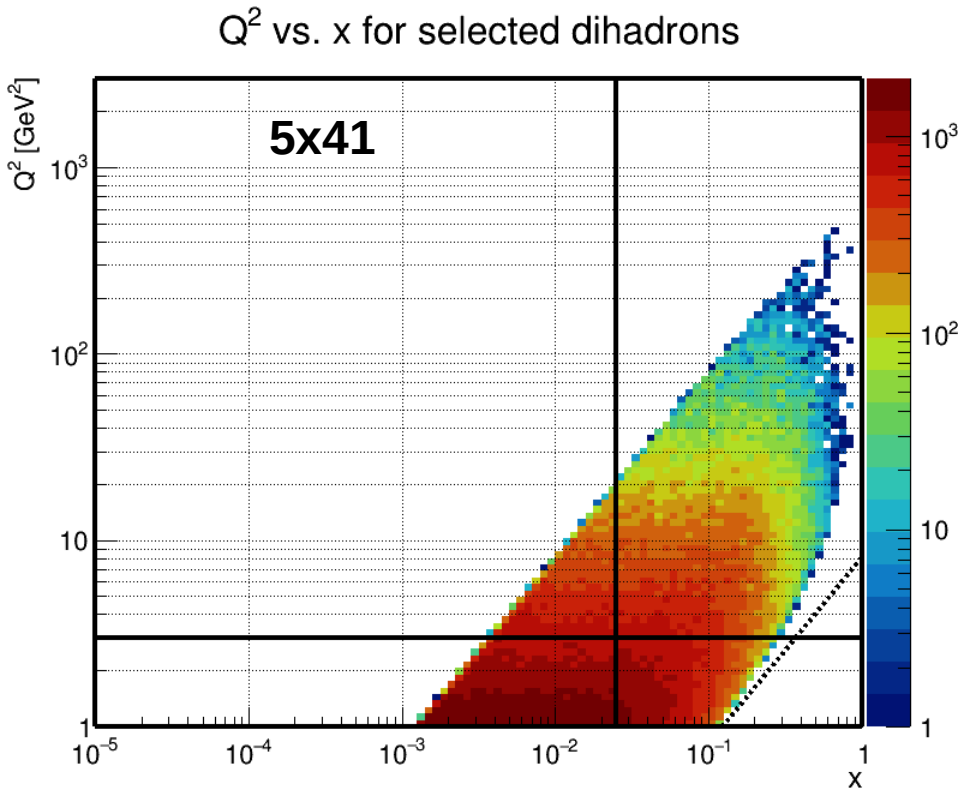
In addition, test 3 lab-frame pion p_T cuts

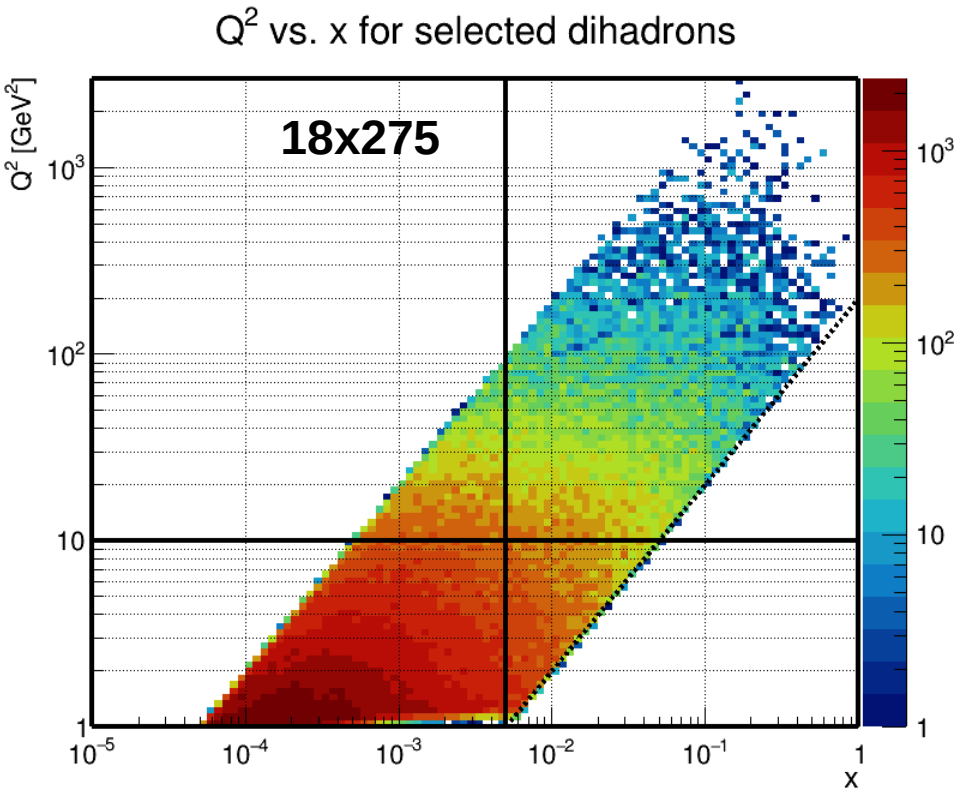
- **$p_T > 0$ (control test)**
- **$p_T > 100$ MeV**
- **$p_T > 300$ MeV**

p_T limits arise from tracking limitations at low p_T

Goal: Assess impact of p_T limits on A_{UT} projections

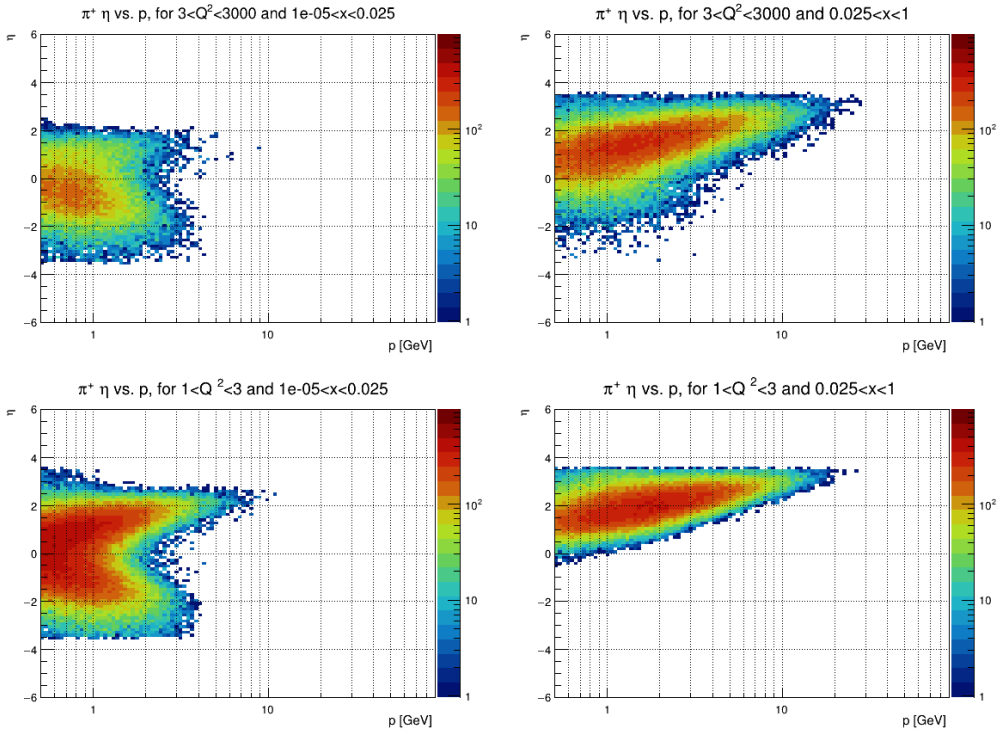
Kinematics pion $p_T > 0$



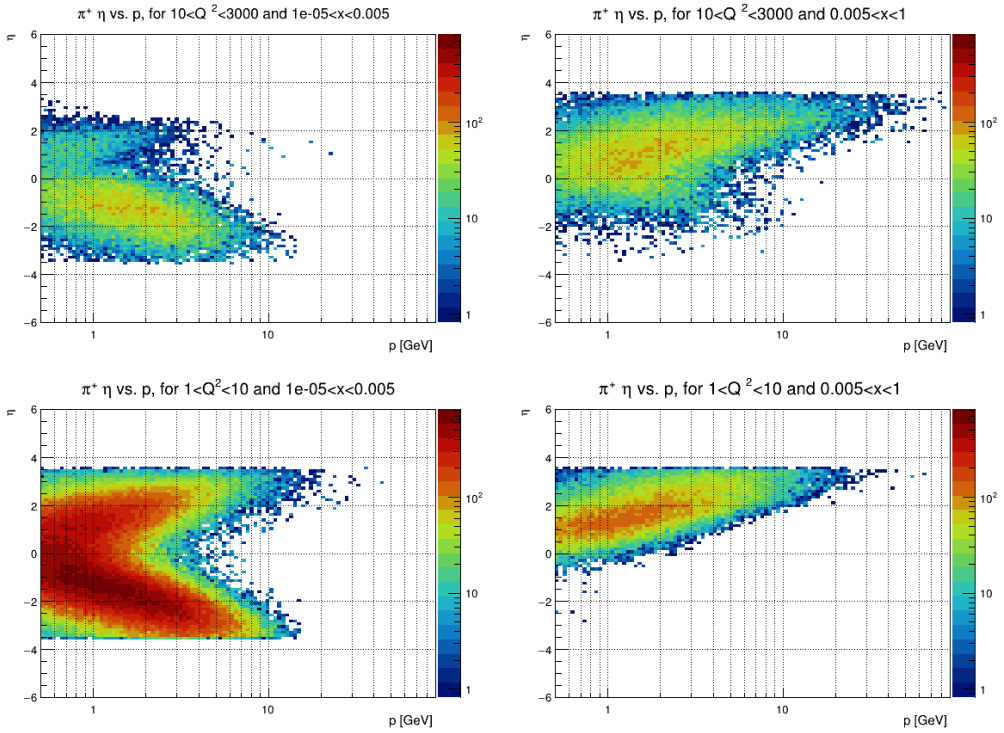


Kinematics pion $p_T > 0$

5x41

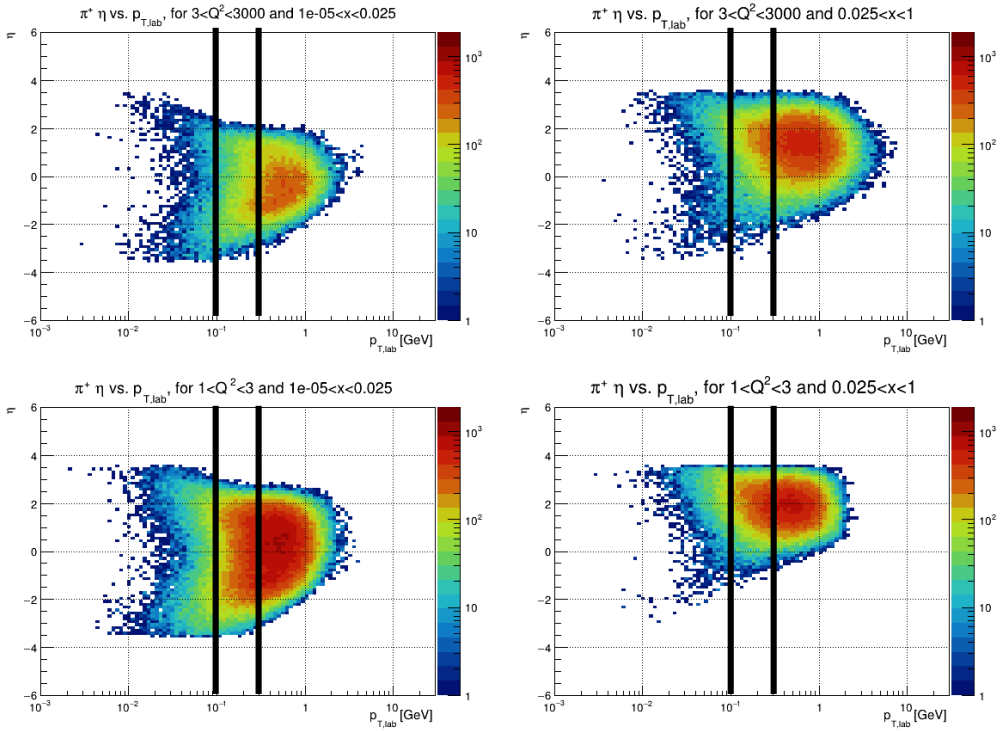


18x275



Kinematics pion $p_T > 0$

5x41



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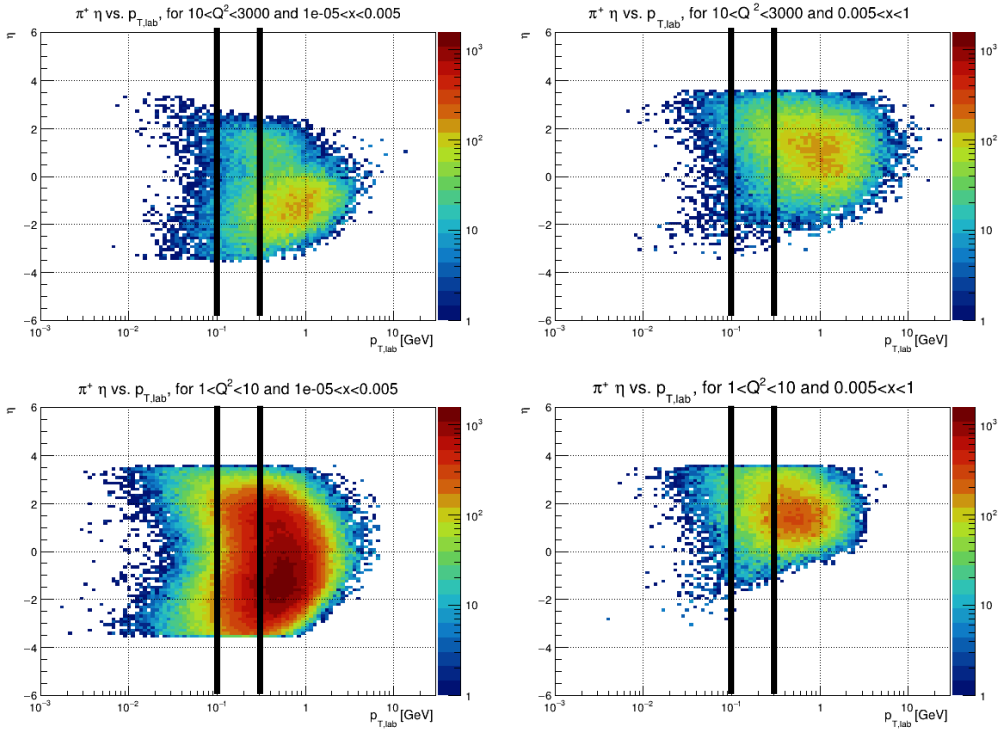


Lines drawn at test pion p_T cuts

- $p_T > 100$ MeV
- $p_T > 300$ MeV

Scaling projections to 10 fb^{-1}

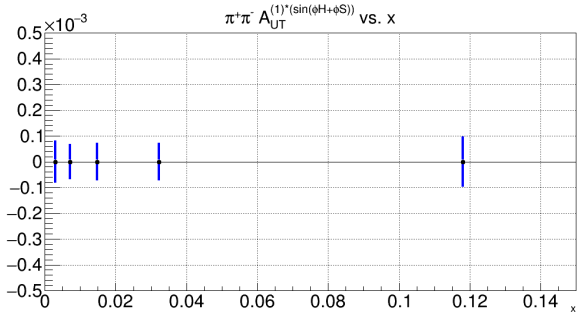
Beam Energies 5x41

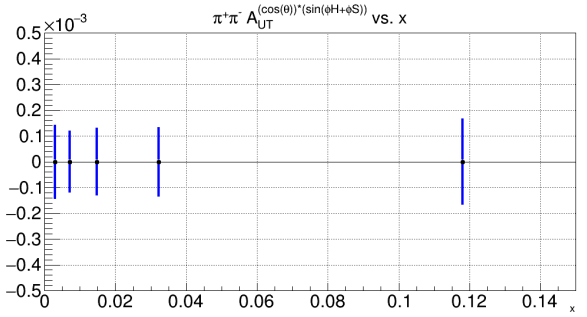
- number of generated events: 1,000,000
- cross section: 362.418 nb
- generated luminosity: 0.002759 fb^-1
- scale factor to 10 fb^-1: 3624.18
- scale uncertainty by: 0.016611

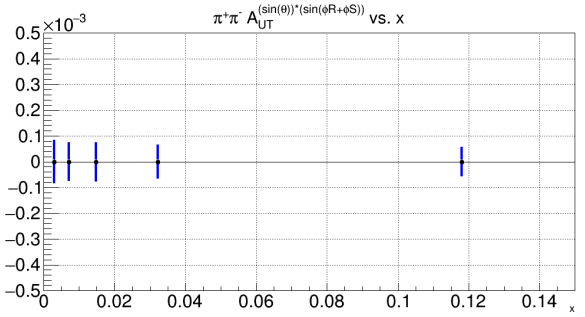
Test 1

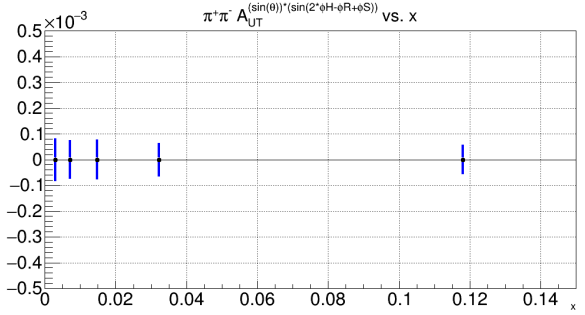
1. PWs of modulation with h(x)

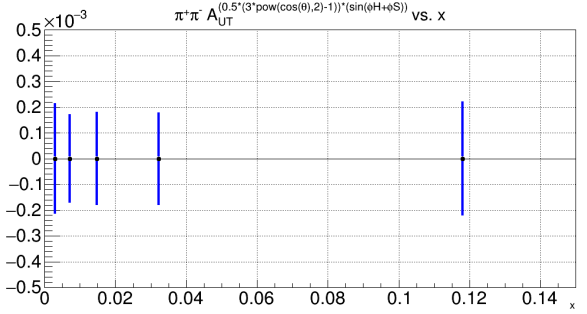
p_T > 0 MeV (control)

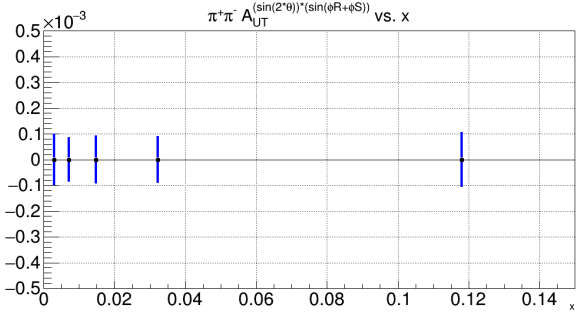


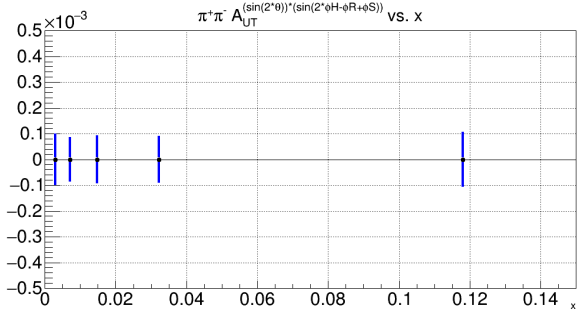


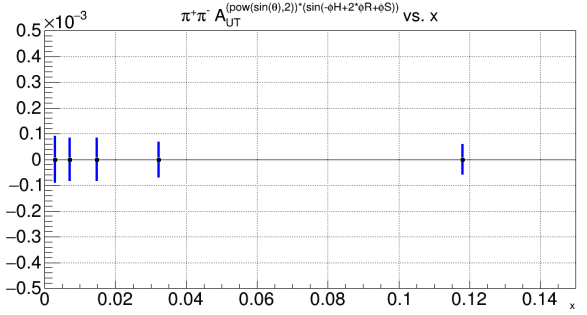


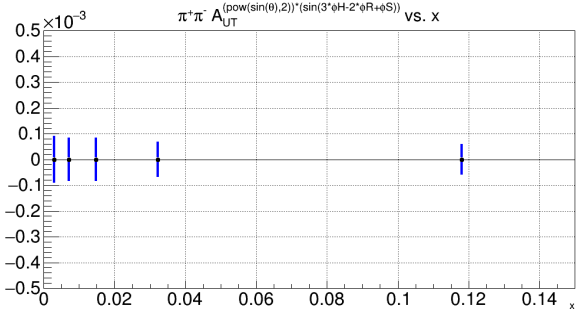








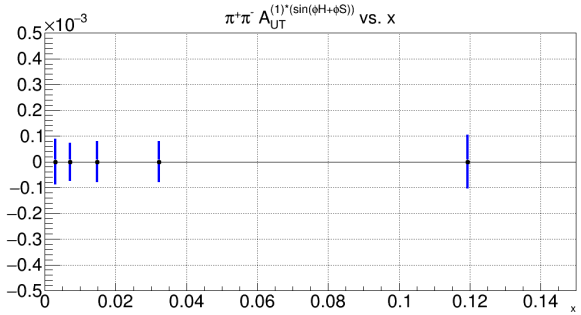


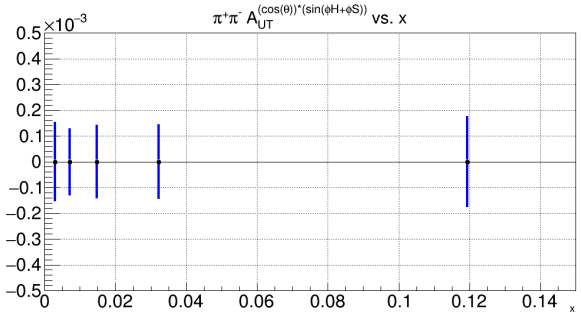


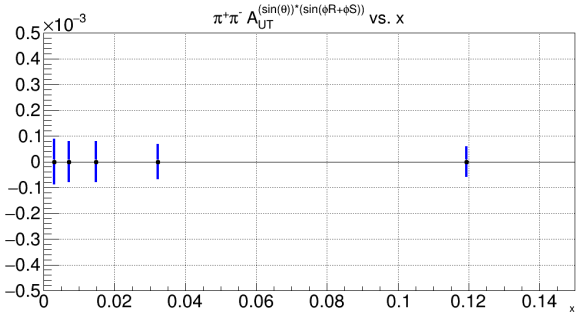
Test 1

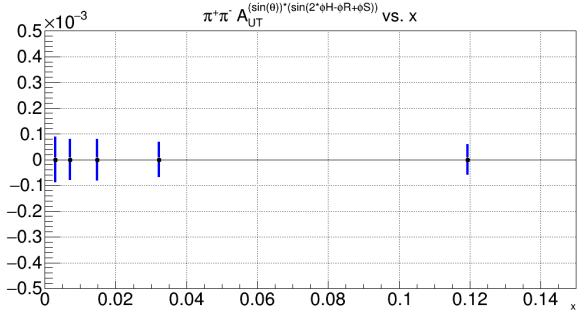
1. PWs of modulation with h(x)

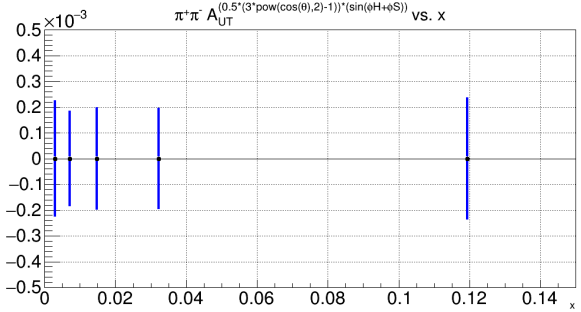
p_T > 100 MeV

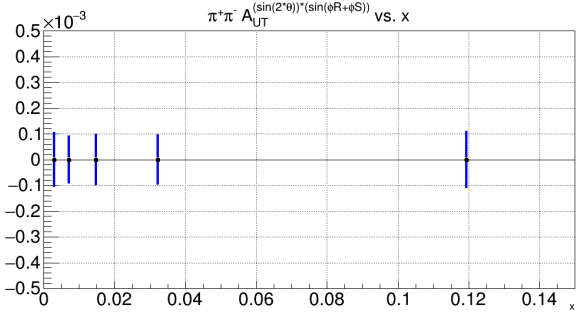


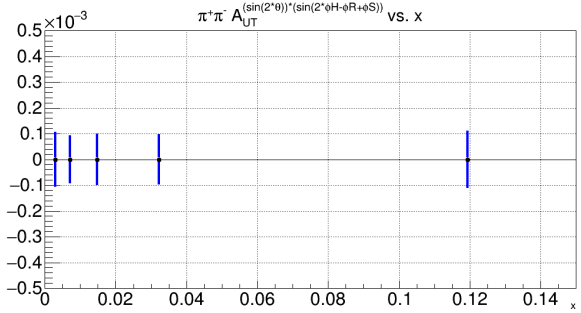


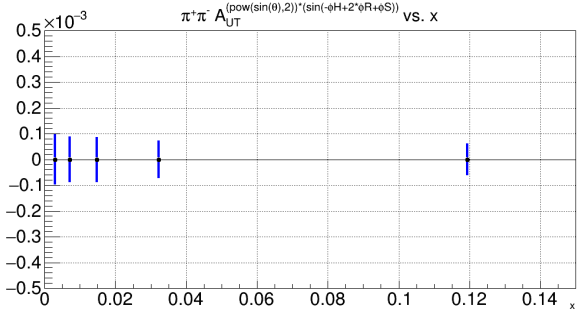


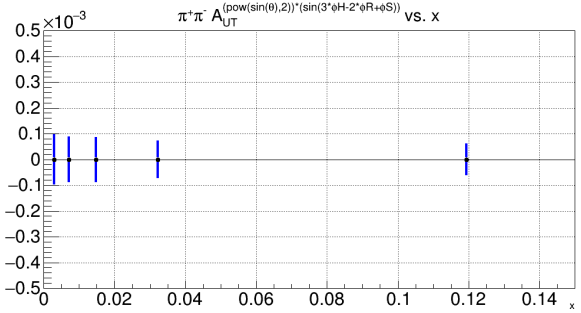








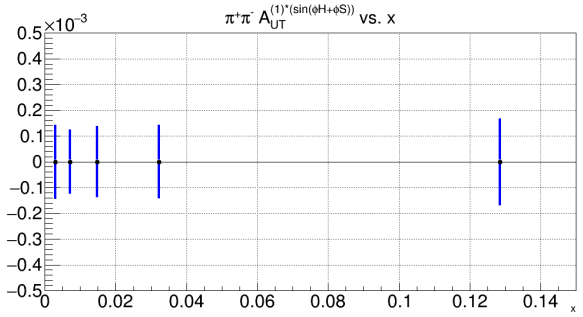


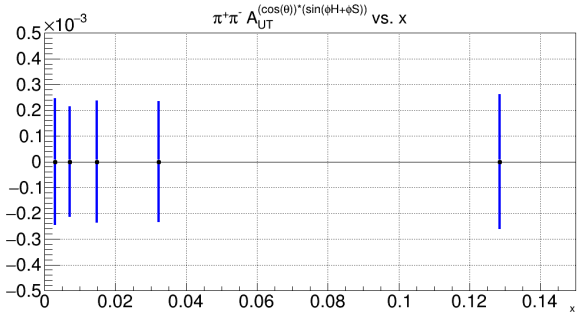


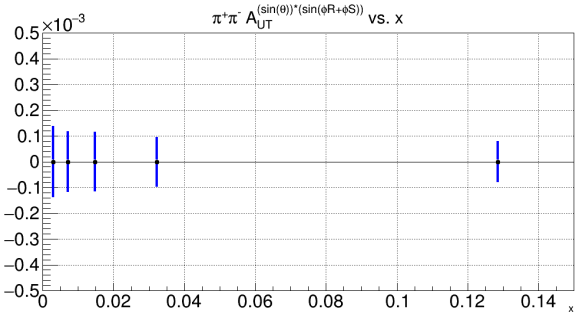
Test 1

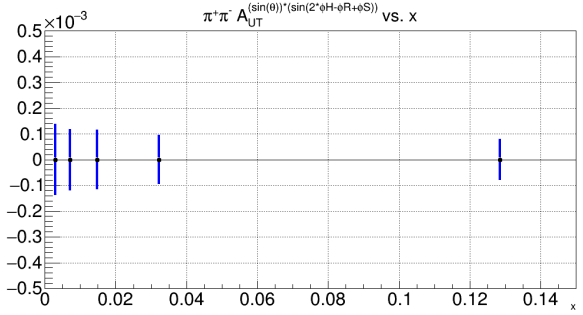
1. PWs of modulation with h(x)

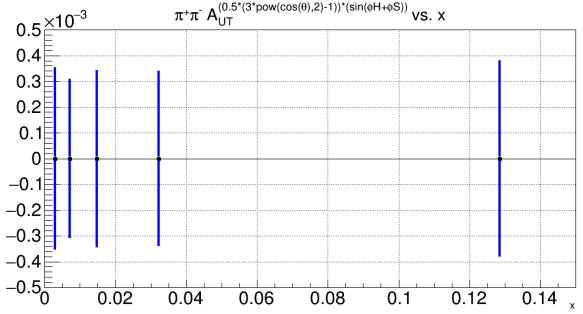
p_T > 300 MeV

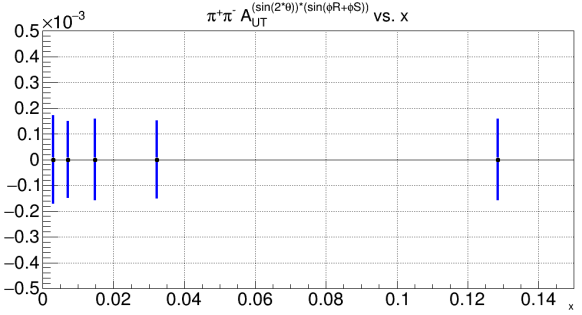


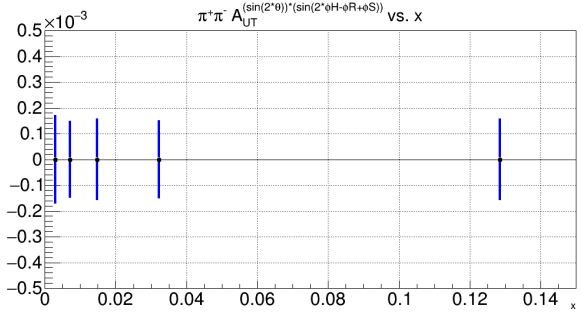


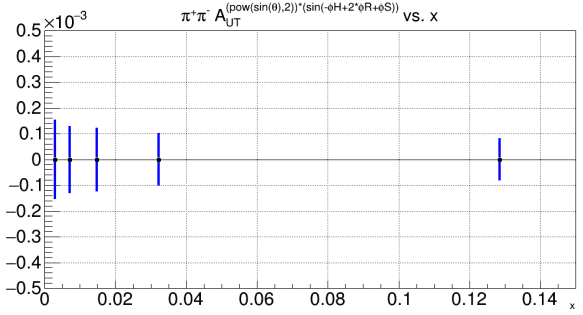


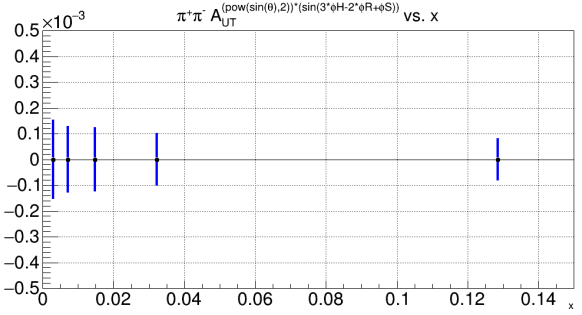










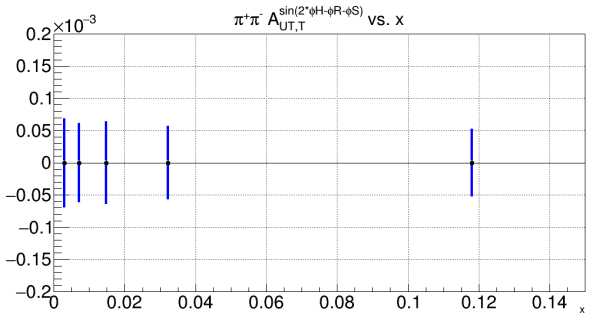


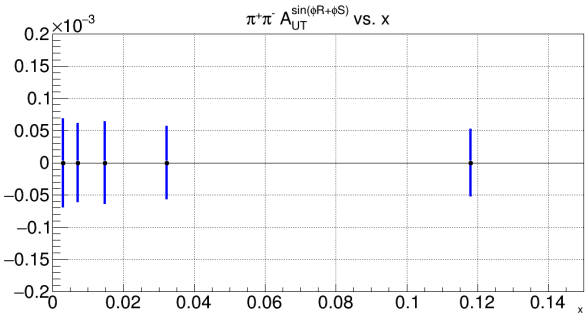
Test 3

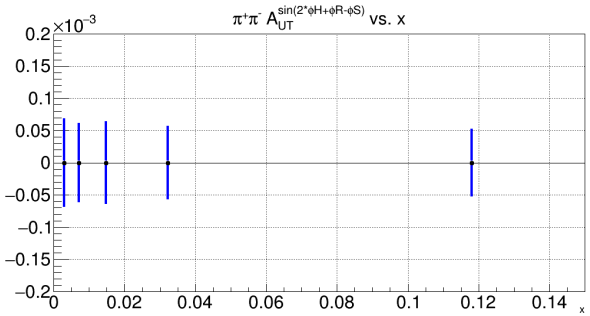
3. All |L,1> modulations

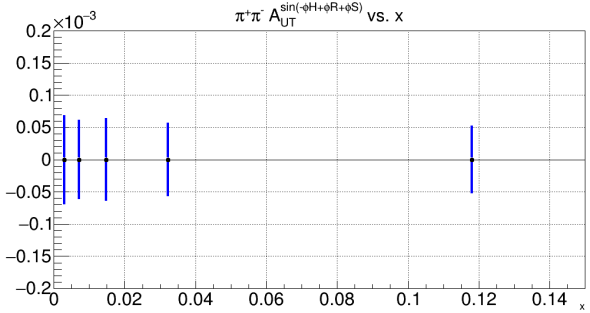
p_T > 0 MeV (control)

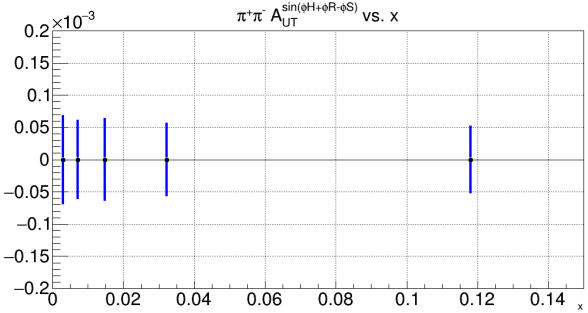
Results identical to Test 2, all |L,0> modulations









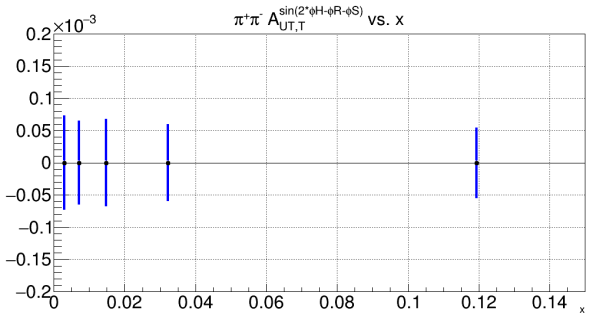


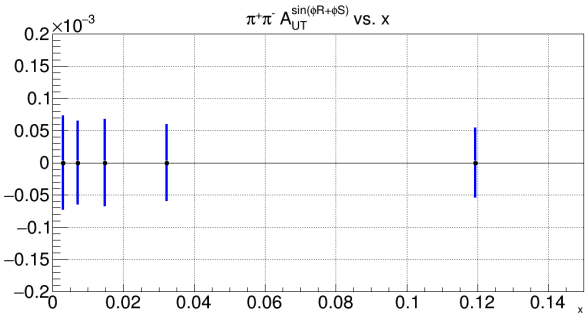
Test 3

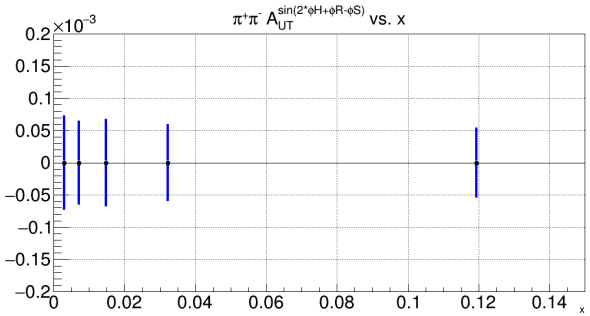
3. All |L,1> modulations

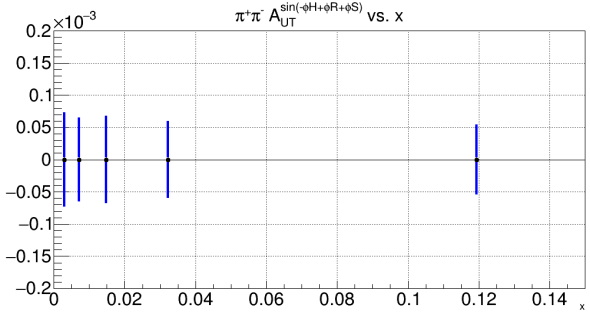
p_T > 100 MeV

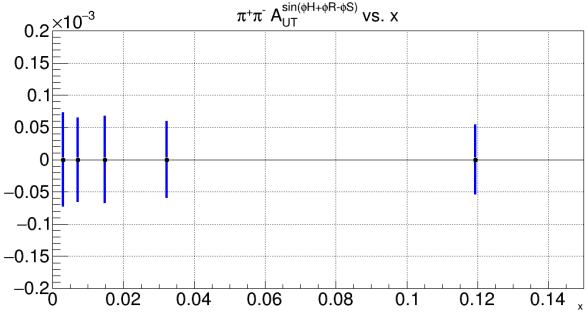
Results identical to Test 2, all |L,0> modulations









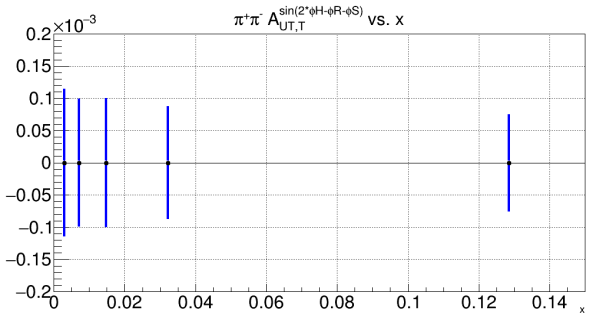


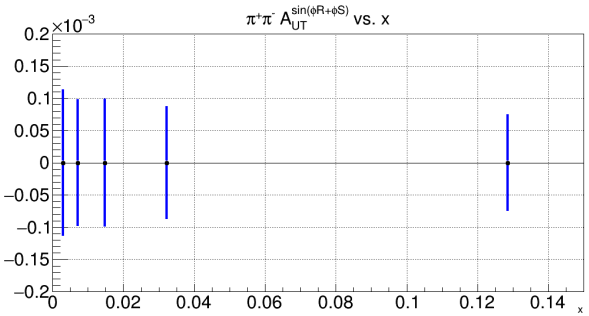
Test 3

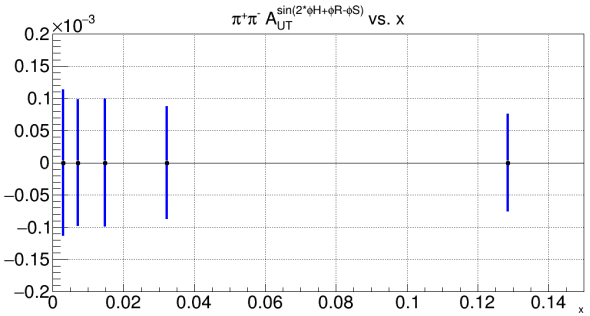
3. All |L,1> modulations

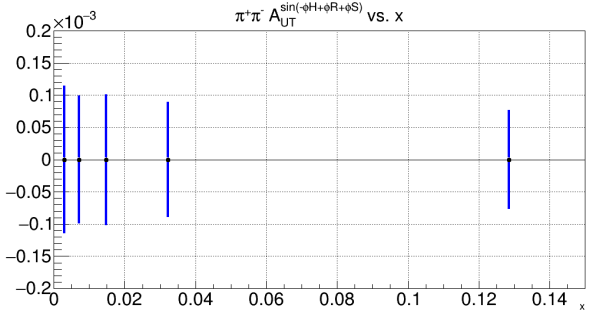
p_T > 300 MeV

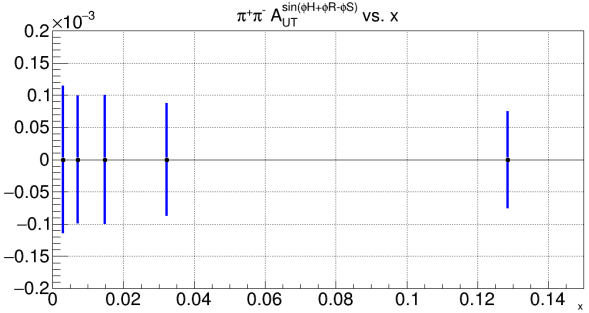
Results identical to Test 2, all |L,0> modulations









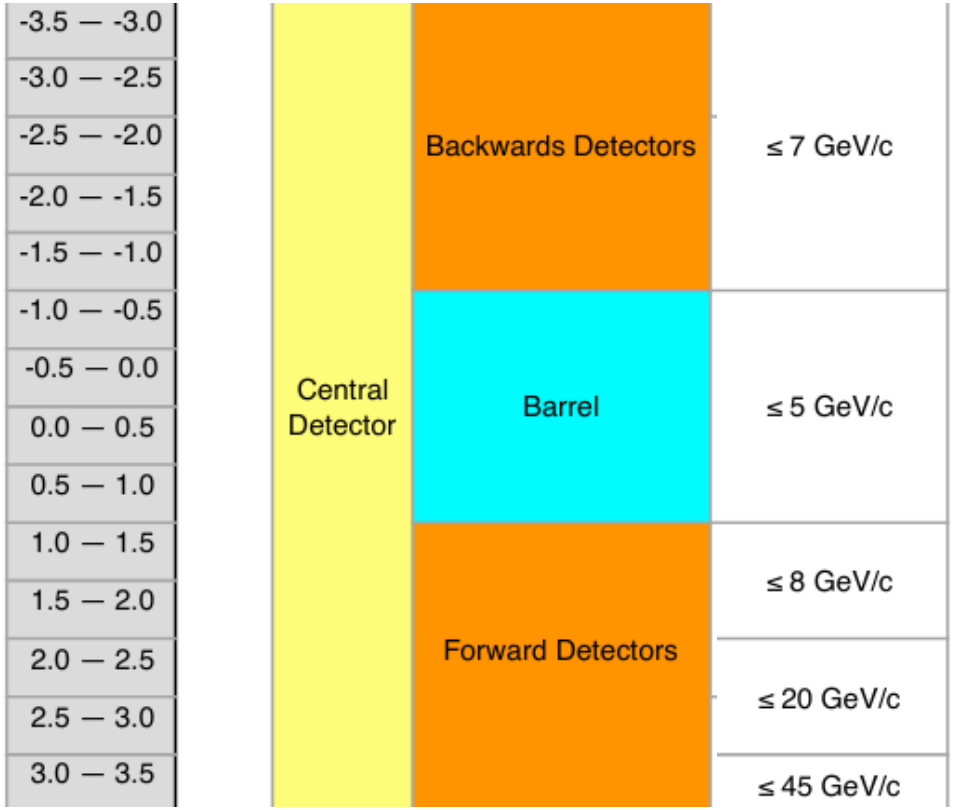


General Conclusions:

- Very little difference between 100 MeV limit and control test
- Between 100 MeV and 300 MeV limits, statistical uncertainties increase by ~50%

Handbook PID Limits

π/K/p PID momentum limits for >3σ separation



For the following plots, pion p_T>100 MeV cut is used

Beam energies 18x275

Goal: assess losses at high (x,Q^2) from regions where PID separation is less than 3σ

Test event generation cut levels:

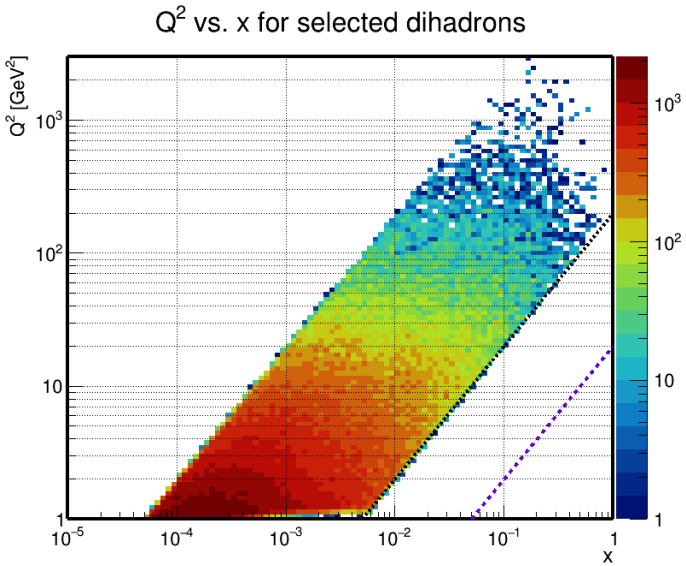
- **Q^2 > 1 GeV^2**
- **Q^2 > 100 GeV^2**
- **Q^2 > 1000 GeV^2**

For 10 fb^{-1} of data with Q^2>1 GeV^2, we get:

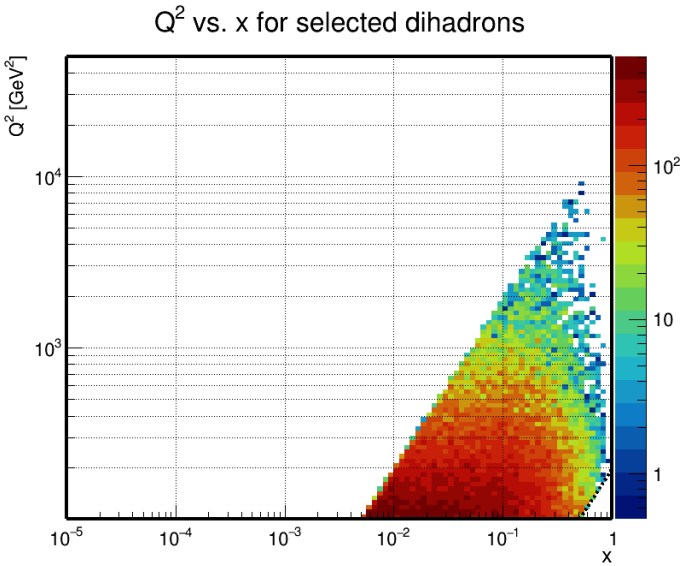
- 0.08 fb^{-1} with Q^2>100 GeV^2
- 0.0016 fb^{-1} with Q^2>1000 GeV^2

(x,Q2) Planes

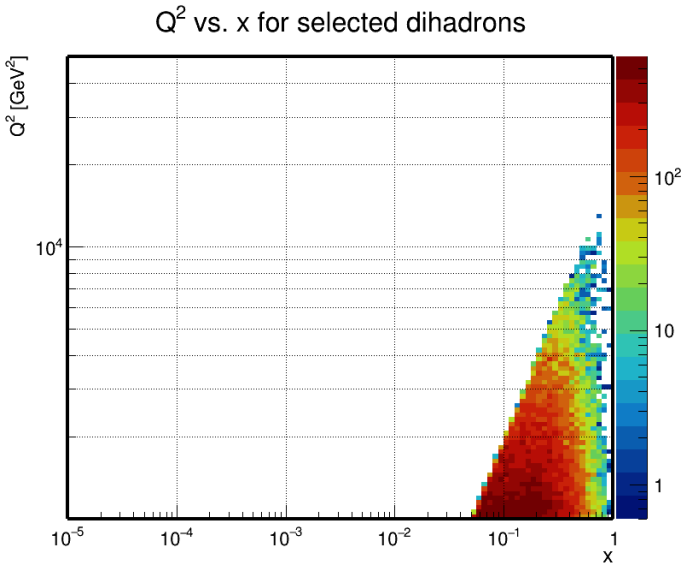
$Q^2 > 1\ GeV^2$



$Q^2 > 100\ GeV^2$



$Q^2 > 1000\ GeV^2$



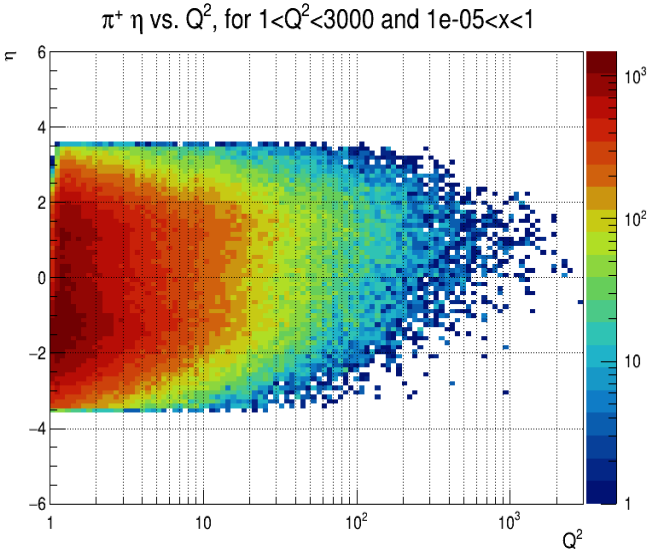
NOTE: Q^2 cuts are applied on Pythia, separately for each case, and different numbers of events were generated for each case (limited by available computation time);

The generated luminosities are:

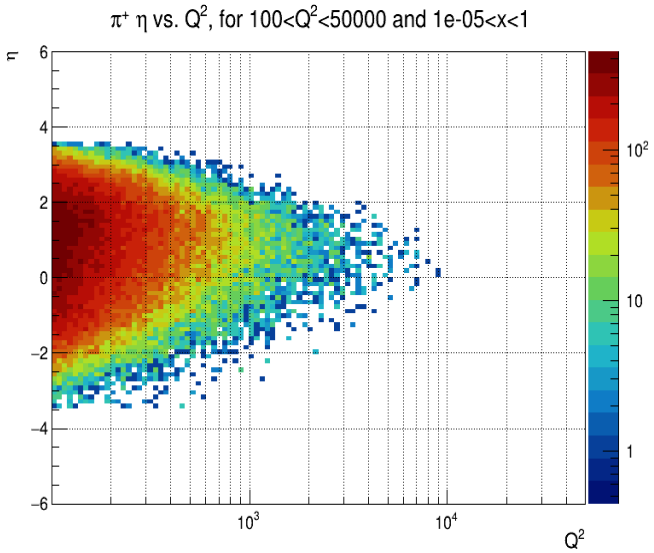
1.1e-3 fb^{-1}	1.0e-4 fb^{-1}	6.8e-5 fb^{-1}
1,000,000 events	~90,000 events	~60,000 events

π^+ η vs. Q^2 distributions (from $\pi^+\pi^-$ dihadrons)

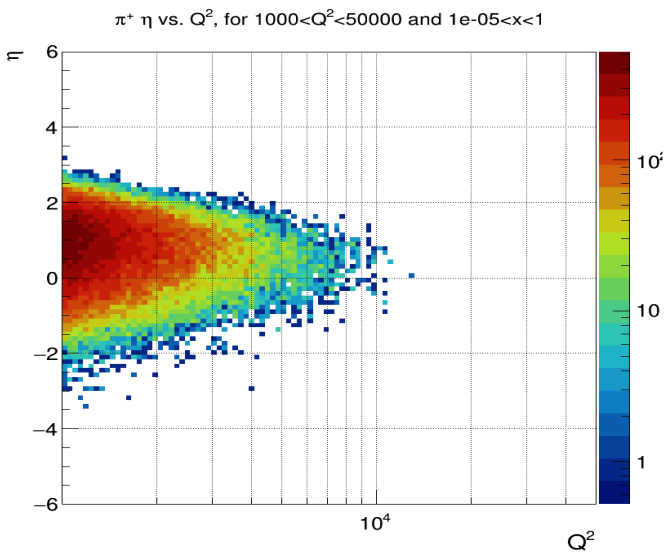
$Q^2 > 1$ GeV^2



$Q^2 > 100$ GeV^2



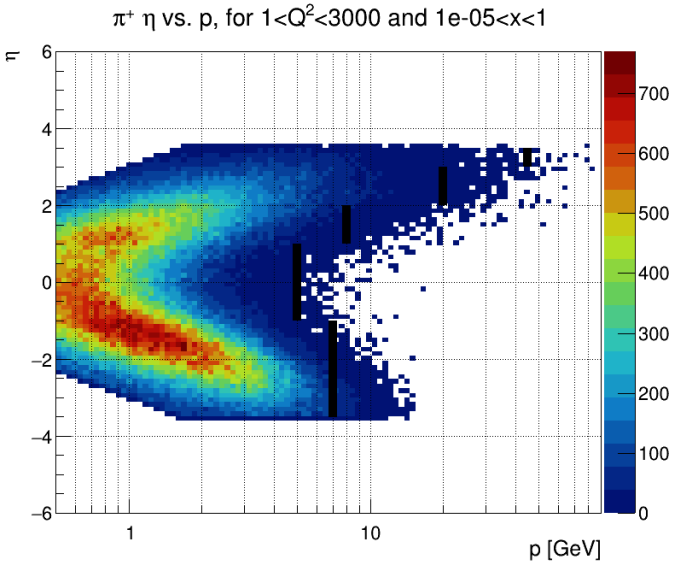
$Q^2 > 1000$ GeV^2



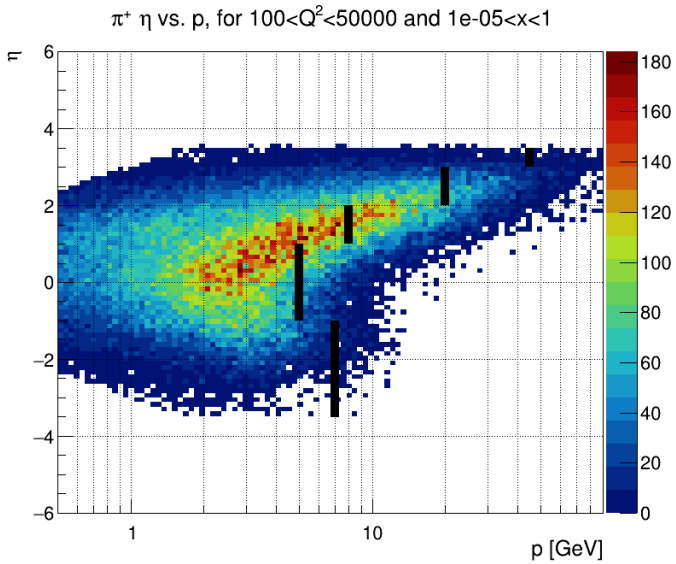
- Tendency toward central production at high Q^2, where PID limits are tightest

π^+ η vs. p distributions (from $\pi^+\pi^-$ dihadrons)

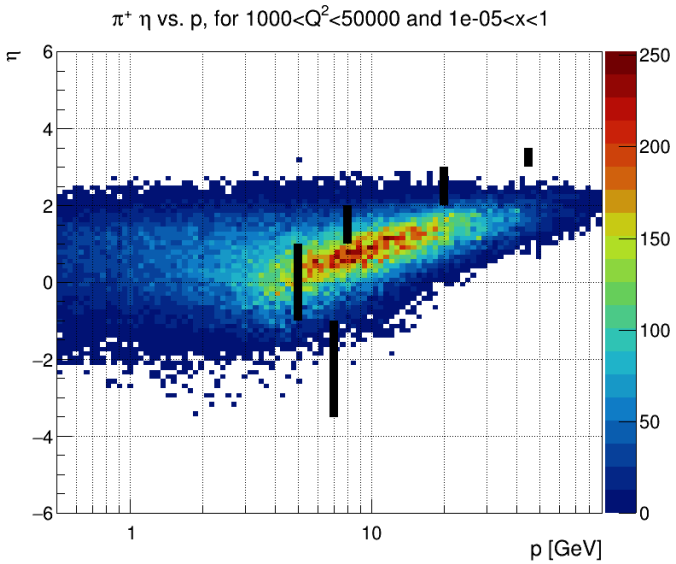
$Q^2 > 1$ GeV^2



$Q^2 > 100$ GeV^2



$Q^2 > 1000$ GeV^2



- Vertical lines denote PID p limits
- Majority of Q^2>1000 GeV^2 data will have less than 3σ PID separation

Takeaway Messages

- Asymmetry Projections and Partial Waves
  - Very little difference between p_T>100 MeV limit and control test with no p_T cut
  - Between 100 MeV and 300 MeV p_T limits, statistical uncertainties increase by ~50%
- PID studies at high Q^2
  - Majority of Q^2>1000 GeV^2 data will have less than 3σ PID separation

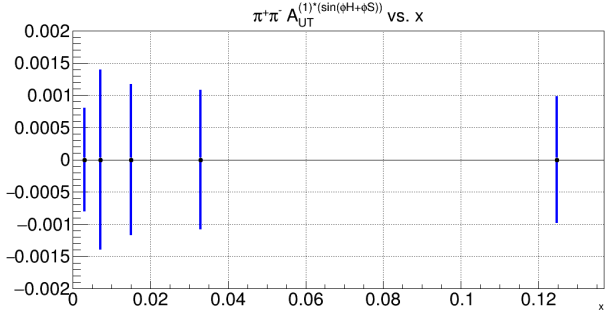
backup

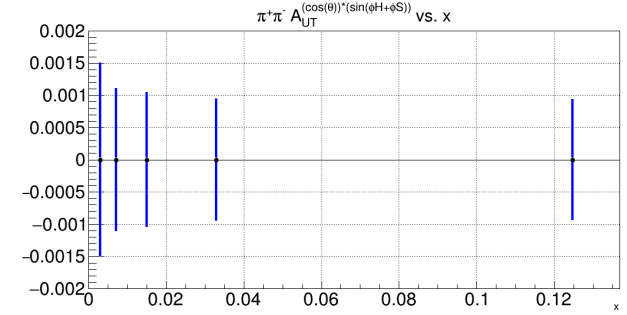
Test 1

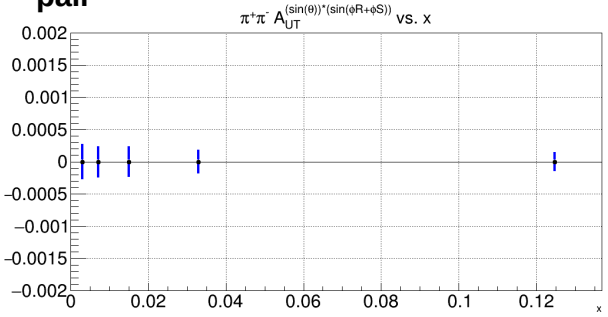
1. PWs of modulation with h(x)

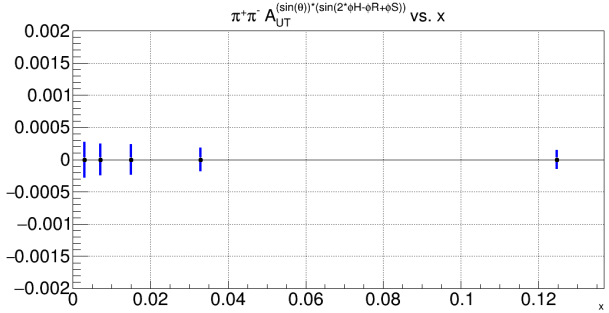
p_T > 100 MeV

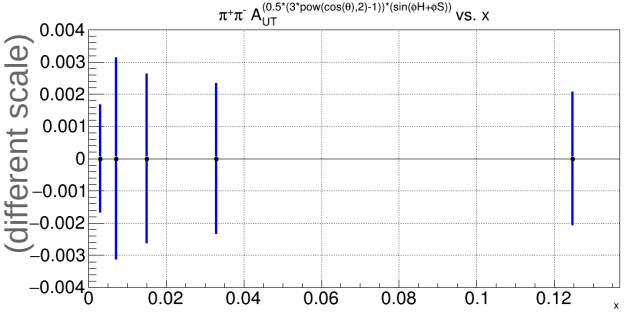
With z_{pion}>0.2 instead of z_{pair}>0.2

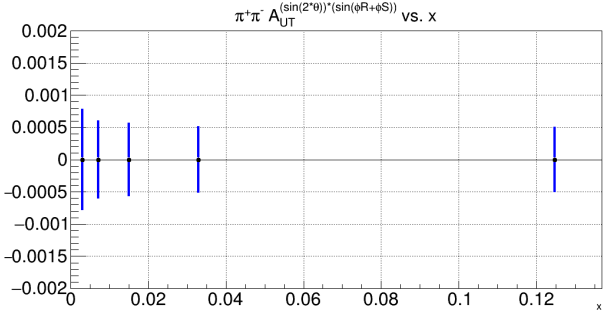


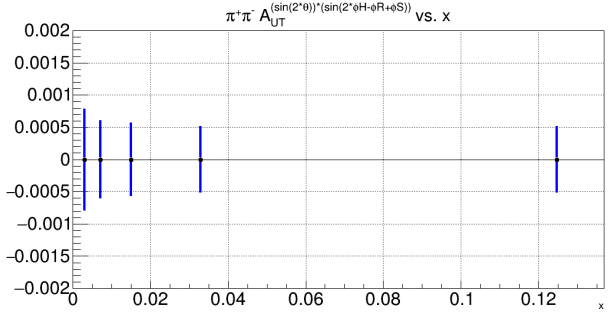


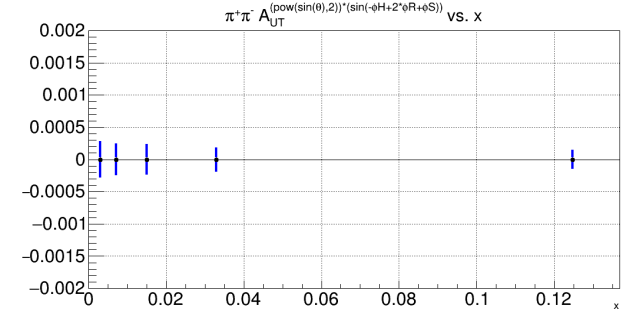


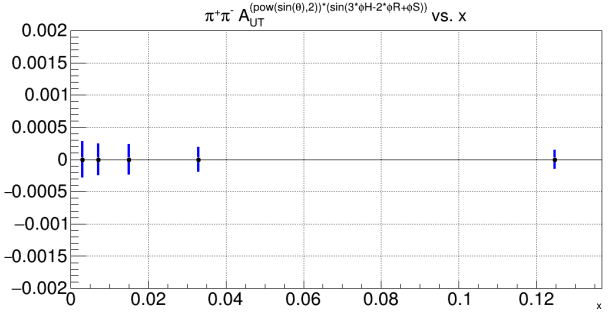












Test 1

1. PWs of modulation with h(x)

p_T > 300 MeV

With z_{pion}>0.2 instead of z_{pair}>0.2