Transverse momentum and Event Topology Dependence of π^0 SSA in FMS Run 11
STAR Analysis Meeting

S. Heppelmann (PSU)

April 20 2012

- Background
  - Physics Questions
  - FMS History
- FMS Event Topology; Event Selection
- **Cross Ratio** method vs. $\mathbf{A(\phi)=A_N \cos(\phi)}$ method
- Explore high statistics A_N for Run 11
  - P_T dependence for fixed X_F
  - Dependence on event topology

FMS History

- Proposed (BNL, LBL Space Science, Texas AM, Penn State)
- Run 8: FMS Online dAu, pp (Transverse)
  - Calibration/Trigger problems.
- Conflicts over Management Of FMS
  - Little data in 2009
- Reorganized for Run 11; change of players (+UCLA, +new BNL)
  - ~25 pb-1 of pp (250 x 250 GeV) with transverse polarization (this presentation)

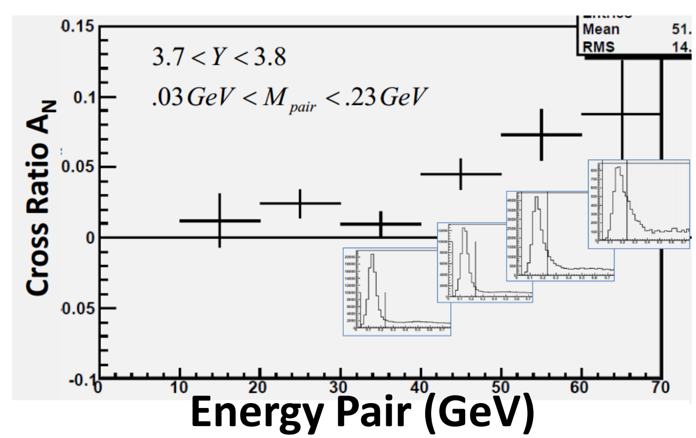
Current: Run 12

PP (100x100 GeV) with transverse and longitudinal polarization

FMS operated very successfully, thanks to huge effort from

Mriganka Mondal
Yu Xi Pan
Chris Dilks
and Stephen Trentelange and many others

Nearly Real Time Star Data analysis Run 12 (S. Heppelmann)
First look at about 20% of the runs taken between Friday Feb 17 and Tuesday Feb 21, 2012.
(Assume 60% polarization of Blue Beam)



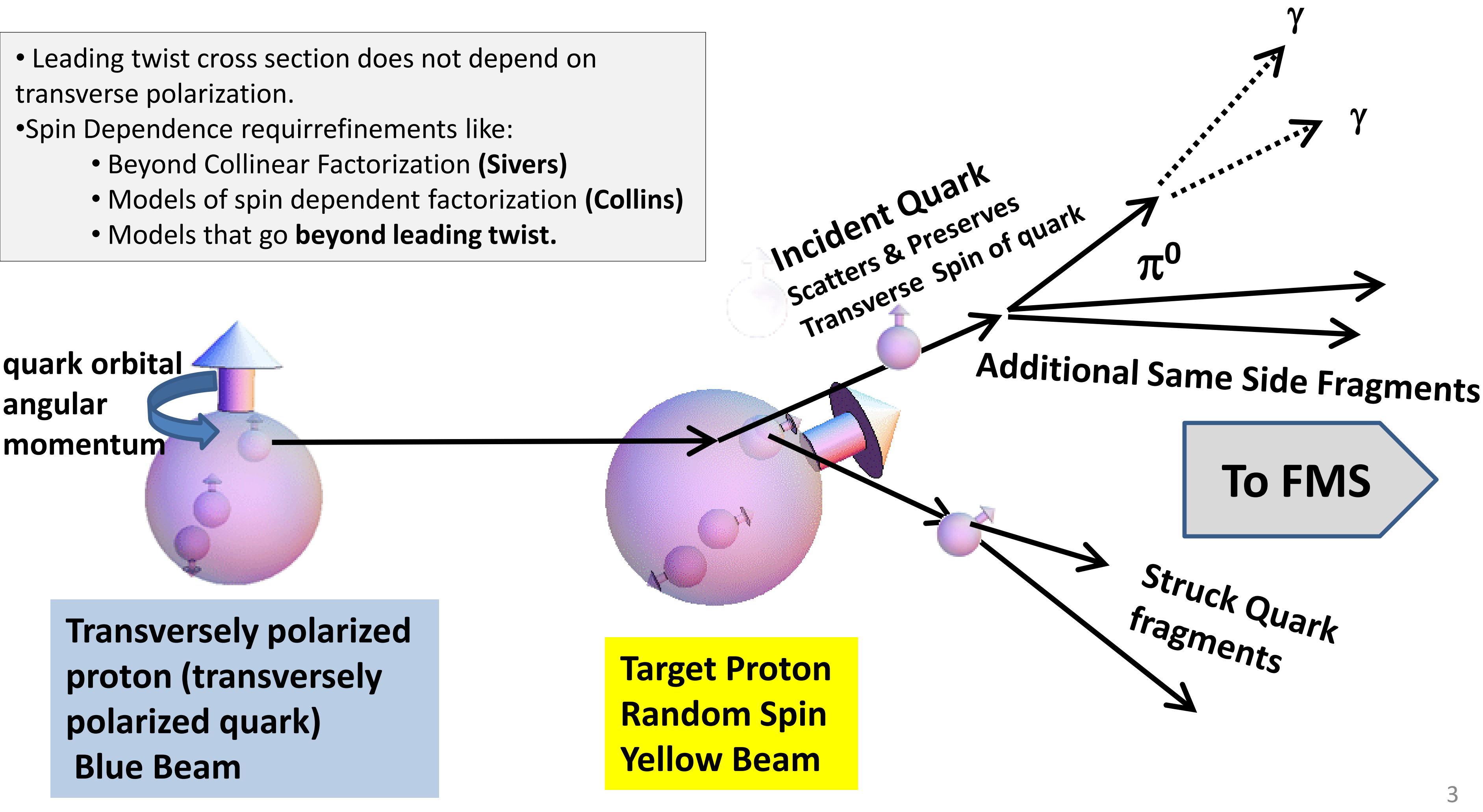
Proton Forward Scattering at High PT
QCD Perspective

PQCD (Leading Twist):

Factorized Cross Section= (initial state) x (quark scattering) x (fragmentation)

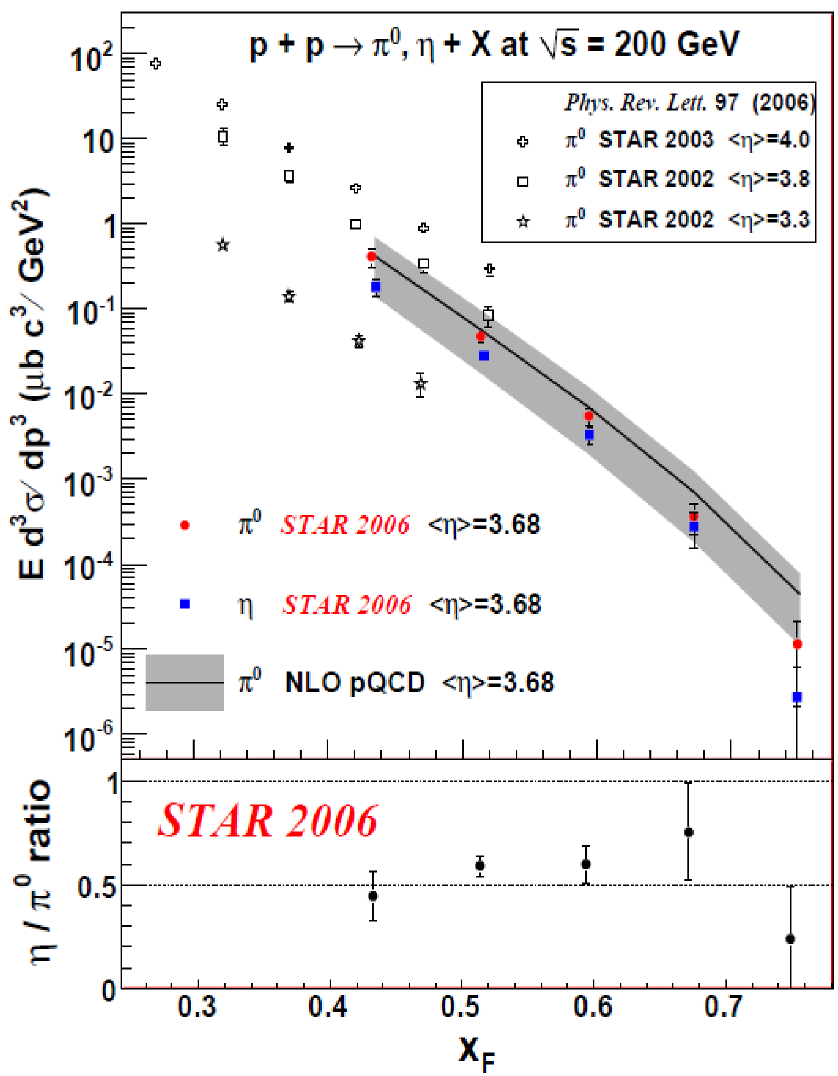
• Does good job of predicting the “> 90% “ of the cross section that does not depend on spin.

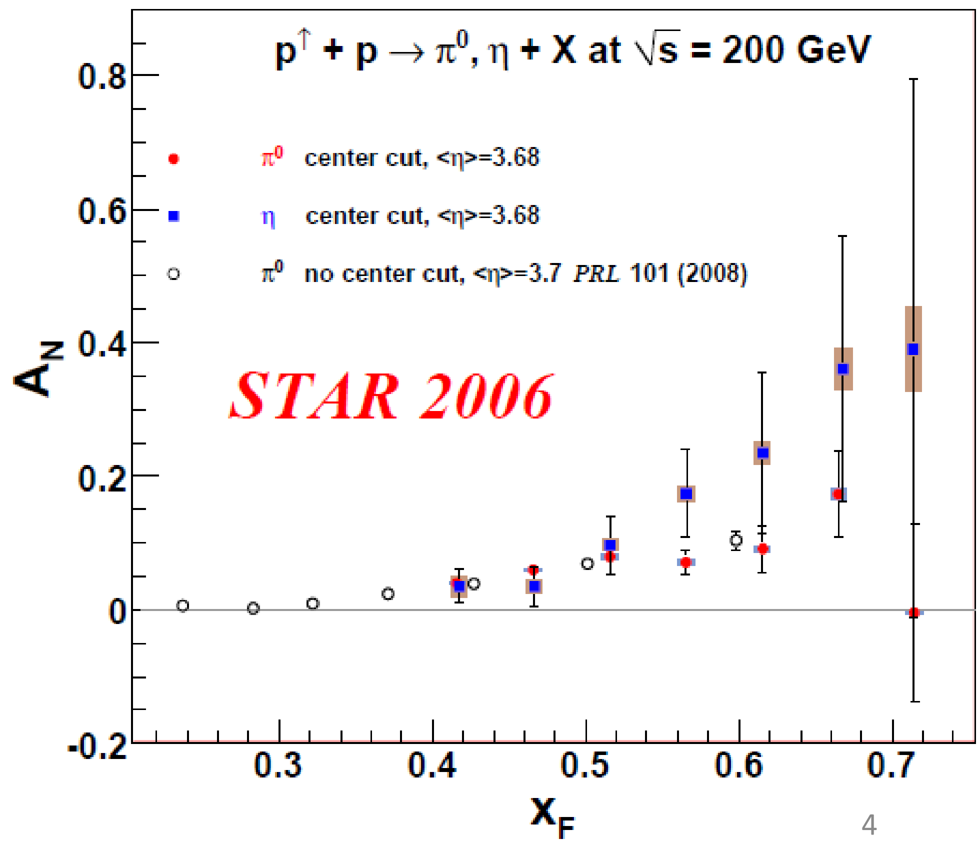
• Leading twist cross section does not depend on transverse polarization.
•Spin Dependence requirrefinements like:
  • Beyond Collinear Factorization **(Sivers)**
  • Models of spin dependent factorization **(Collins)**
  • Models that go **beyond leading twist.**



New paper on η/ π^0 at X_F>0.5

- π^0 cross section in **good agreement with PQCD calculation.**
- η/ π^0 cross section ratio similar to that observed where jet fragmentation is dominant.
- A_N (η) > A_N(π^0) for X_F > 0.55





- Leading twist cross section does not depend on transverse polarization.
- Spin Dependence require refinements like:
    - Beyond Collinear Factorization **(Sivers)**
    - Models of spin dependent factorization **(Collins)**
    - Models that go **beyond leading twist.**

Sivers Model: Initial quark picks up k_T from initial state wave function, proportional to orbital angular momentum.

Jet based Asymmetry, significant dependence of A_N on the details of near side jet fragments is not expected!

Collins Model: Final π^0 picks up k_T from fragmentation of polarized quark.

Vanishing jet asymmetry. Observed A_N will depend on the details of near side fragmentation!

Transverse momentum **increases/decreases** with transverse **spin up/down**

A toy model for proton Cross Section

$$\sigma(p_T) \sim \frac{(1-x_F)^5}{p_T{}^6}$$

$$A_N \sim \frac{\sigma(p_T+k_T)-\sigma(p_T-k_T)}{2\sigma(p_T)} \sim \frac{6k_T}{p_T} \sim \frac{1}{p_T}$$

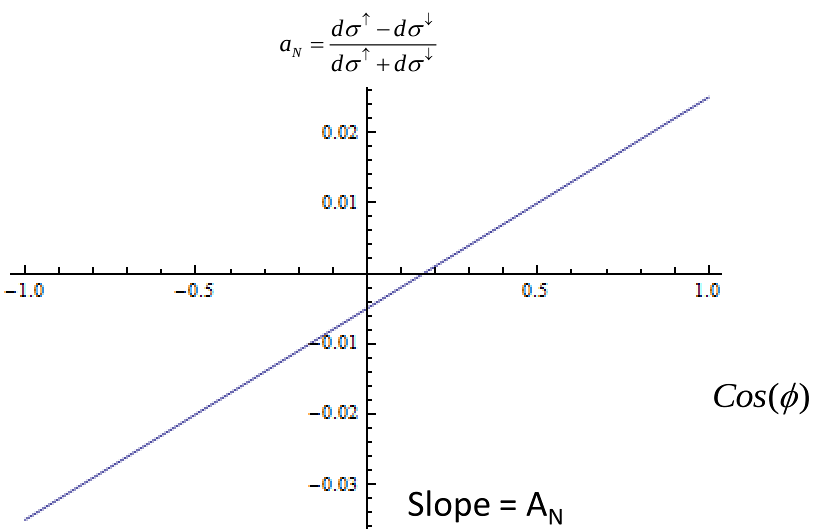
Similar transverse momentum dependence **for higher twist.**

Cross Ratio Transverse Asymmetry
vs
A(ϕ) observation

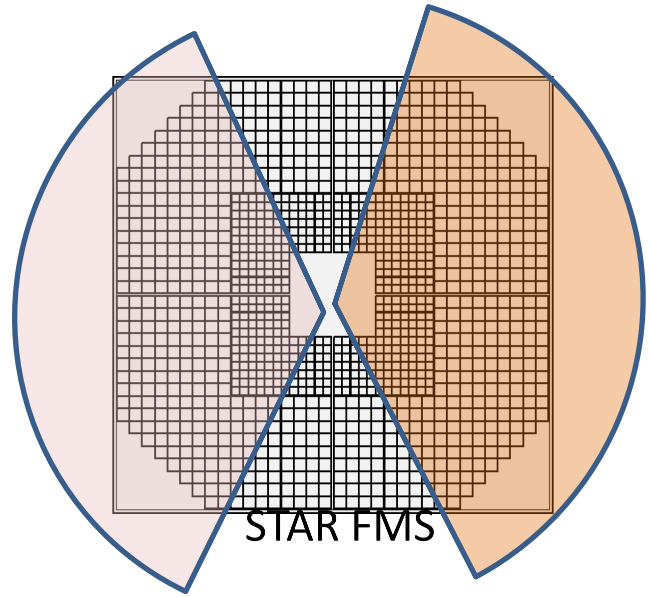
Method 1:
Cross Ratio:

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \cong \frac{1}{P}\frac{\sqrt{N^{\uparrow}S^{\downarrow}} - \sqrt{S^{\uparrow}N^{\downarrow}}}{\sqrt{N^{\uparrow}S^{\downarrow}} + \sqrt{S^{\uparrow}N^{\downarrow}}}$$

Left(N): Cos(ϕ)<-0.5



Slope = A_N
Y Intercept=Luminosity Ratio



Right(S): Cos(ϕ)>0.5

$$a_N(\phi) = a_0 + A_N \cos(\phi)$$

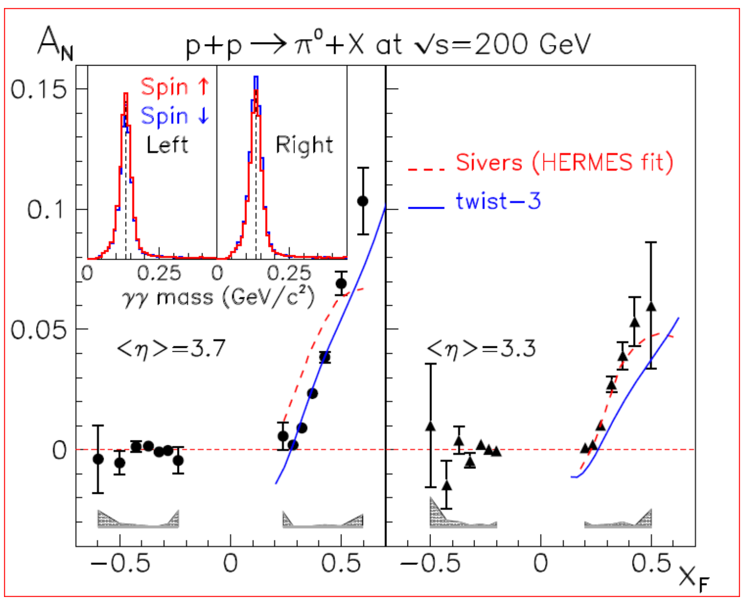
Method 2:

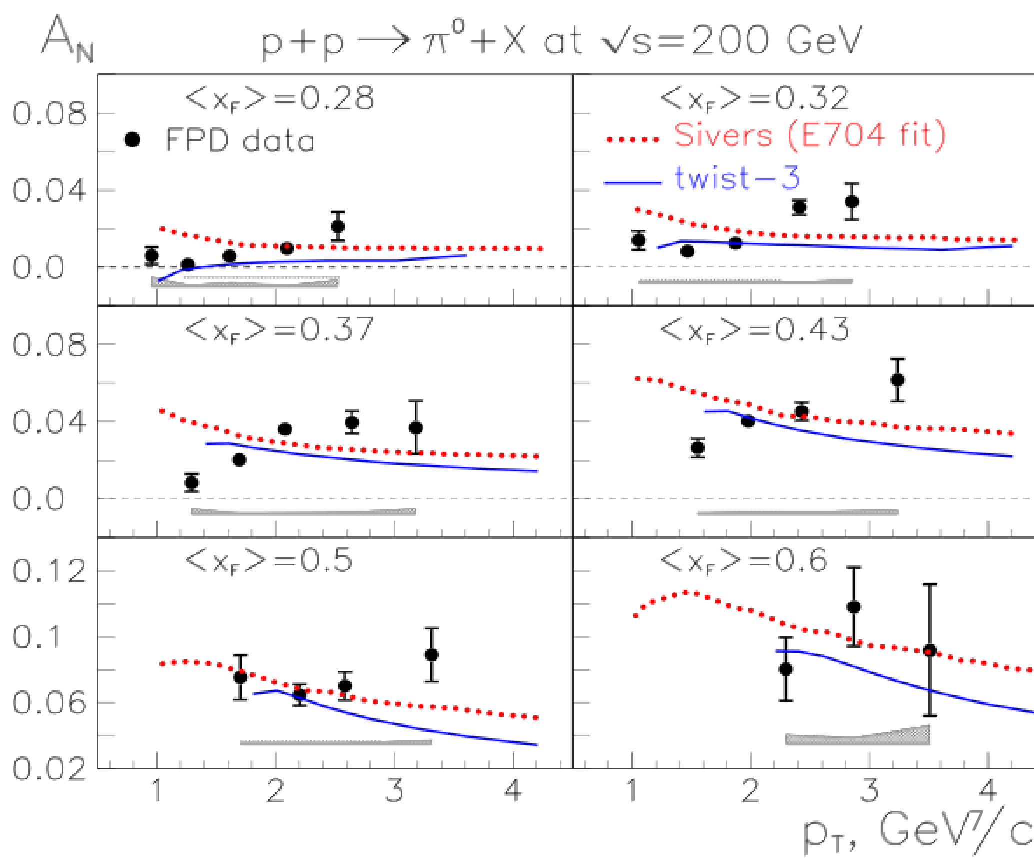
Fix a_0 for full data set for many small data subsets ….. One parameter fit for A_N

Advantage: Every fitted value of A_N comes with error and chi^2.

STAR Published Run 6 (FPD $\sqrt{s}$ =200GeV)

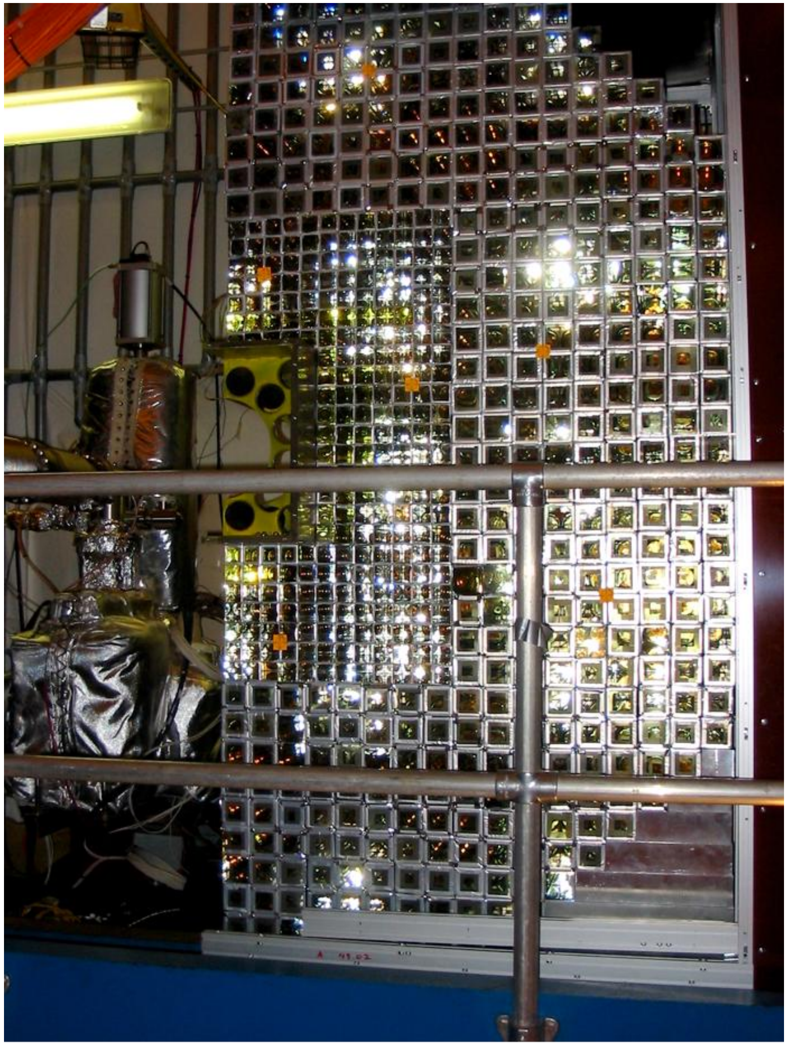
- Rising A_N with XF ($0<X_F<0.5$) from 0% to 5-10%
- No evidence of fall in A_N with increasing P_T.

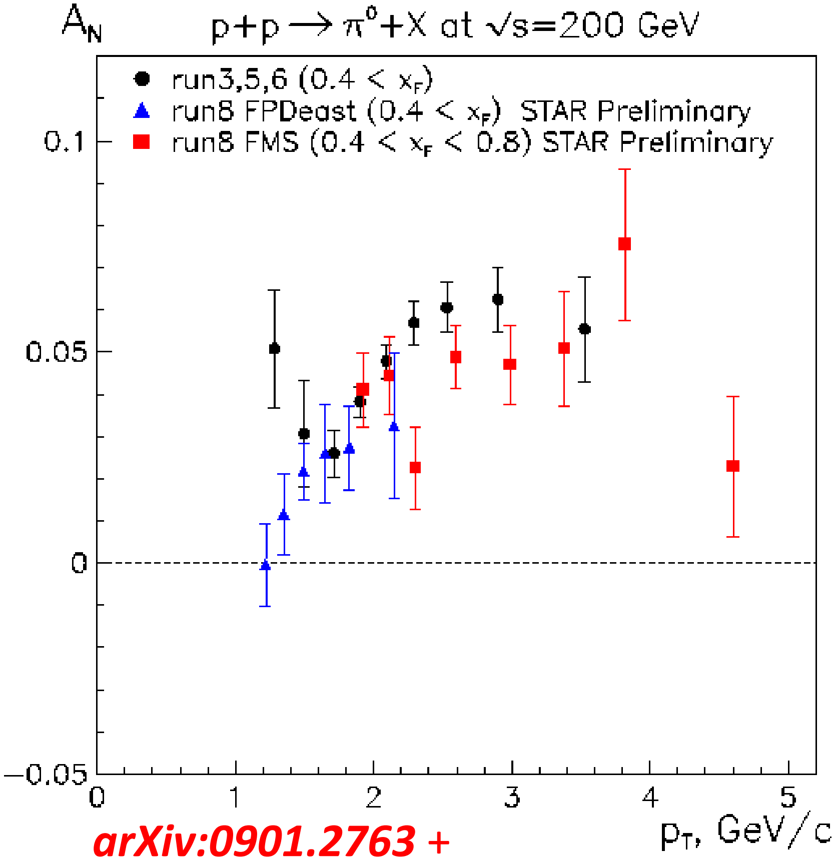




From FMS Run 8, STAR has Expanded Rapidity Coverage -1<Y<4.2

STAR Forward Meson Spectrometer
2.5 < Y < 4.0





arXiv:0901.2763 + A.Ogawa @CIPANP09

Event Selection:

1. **<u>Analyze FMS for all photon</u>** candidates. (Showers that are fit successfully to photon hypothesis)
2. **<u>Find Clusters of EM energy</u>** grouping photon candidates that are within opening angle cone $\Delta\theta$ (relative to energy weighted center)

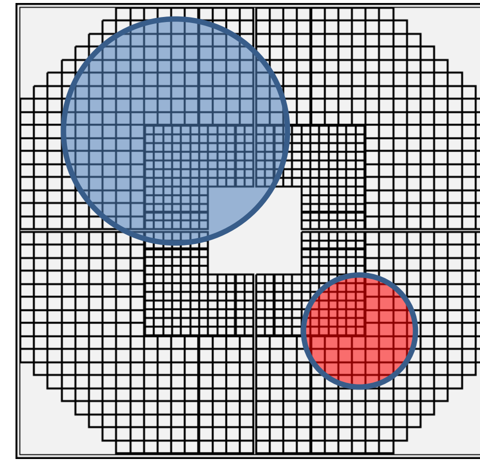
   - A) data analyzed with $\Delta\theta$ **=0.07** radians.
   - B) data analyzed with $\Delta\theta$ **=0.03** radians.
     - For the case of $\Delta\theta$ **=0.03** clustering, we define a band of PseudoRapidity ΔY lc $(E_{cluster}, \theta_{cluster}, \phi_{cluster}, M_{cluster})$ e cluster.

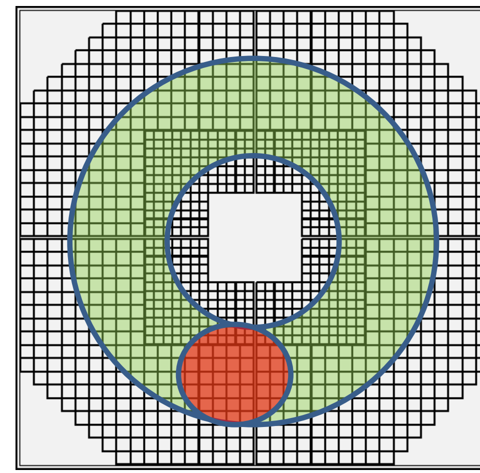
     <u>Cluster 4 Vector</u> ->

$$(E_{away}, \theta_{away}, \phi_{away}, M_{away})$$

3. Find **<u>the center of the rest of the FMS photon energy</u>**, the complement of the Cluster.

   <u>Away 4 Vector</u> ->

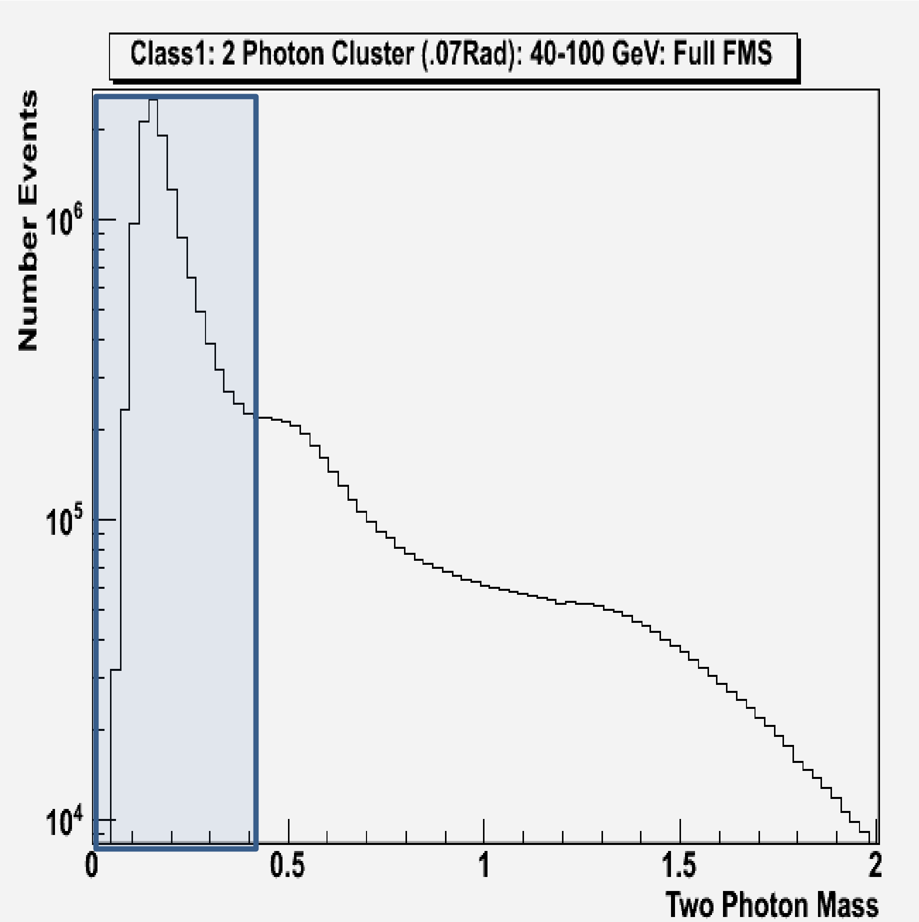


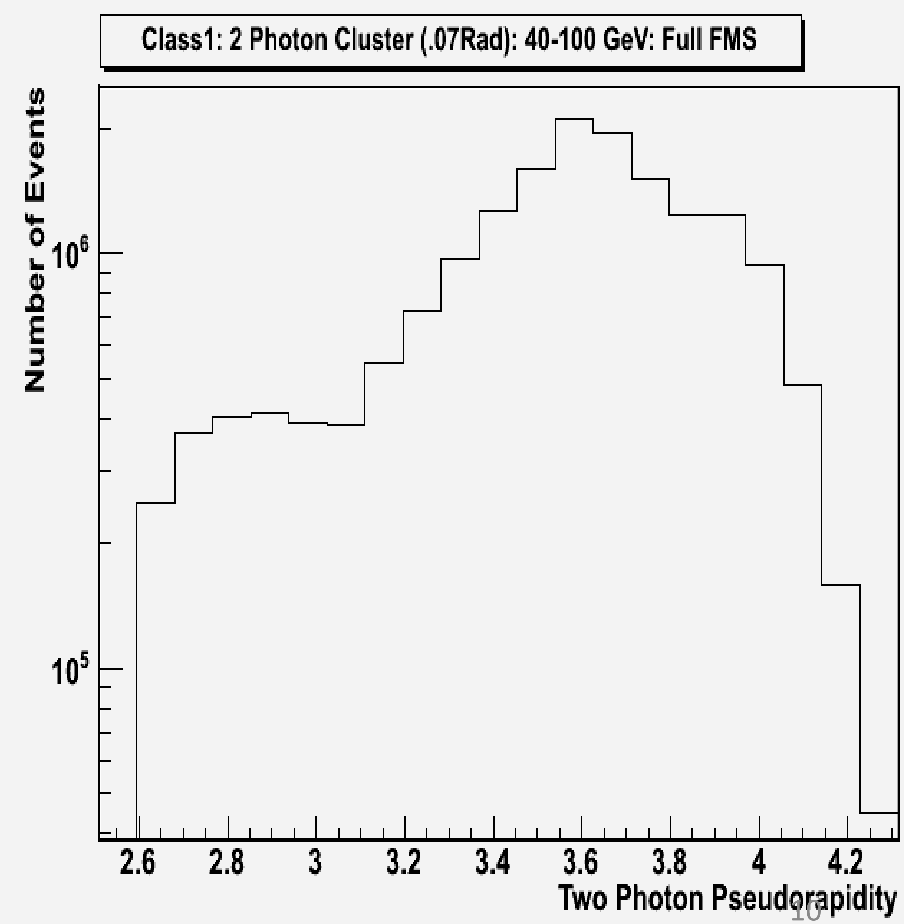


4. We consider 4 event classes {1,2,3,4}
   1. $\Delta\theta$ **=0.07** 2 Photon clusters, Pi0 Mass (inclusive)?
   2. $\Delta\theta$ **=0.03** 2 Photon clusters ,Pi0 Mass (inclusive)?
   3. $\Delta\theta$ **=0.03** 2 Photon clusters ,Pi0 Mass, Y_{away} **inside Green**
   4. $\Delta\theta$ **=0.03** 2 Photon clusters, Pi0 Mass, Y_{away} **outside Green**

Class 1 Events: $\Delta\theta$ =0.07 2 Photon clusters, π^0 Mass (less inclusive)?

- 40 GeV < Epair <100 GeV
- Z=|(E1-E2)/(E1+E2)| <.7
- 2.6 < Y < 4.1 (Full FMS Pseudo-rapidity)
- Selection of π^0 Peak



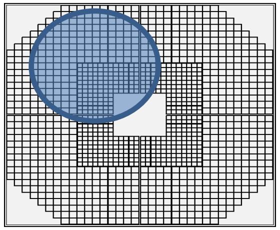


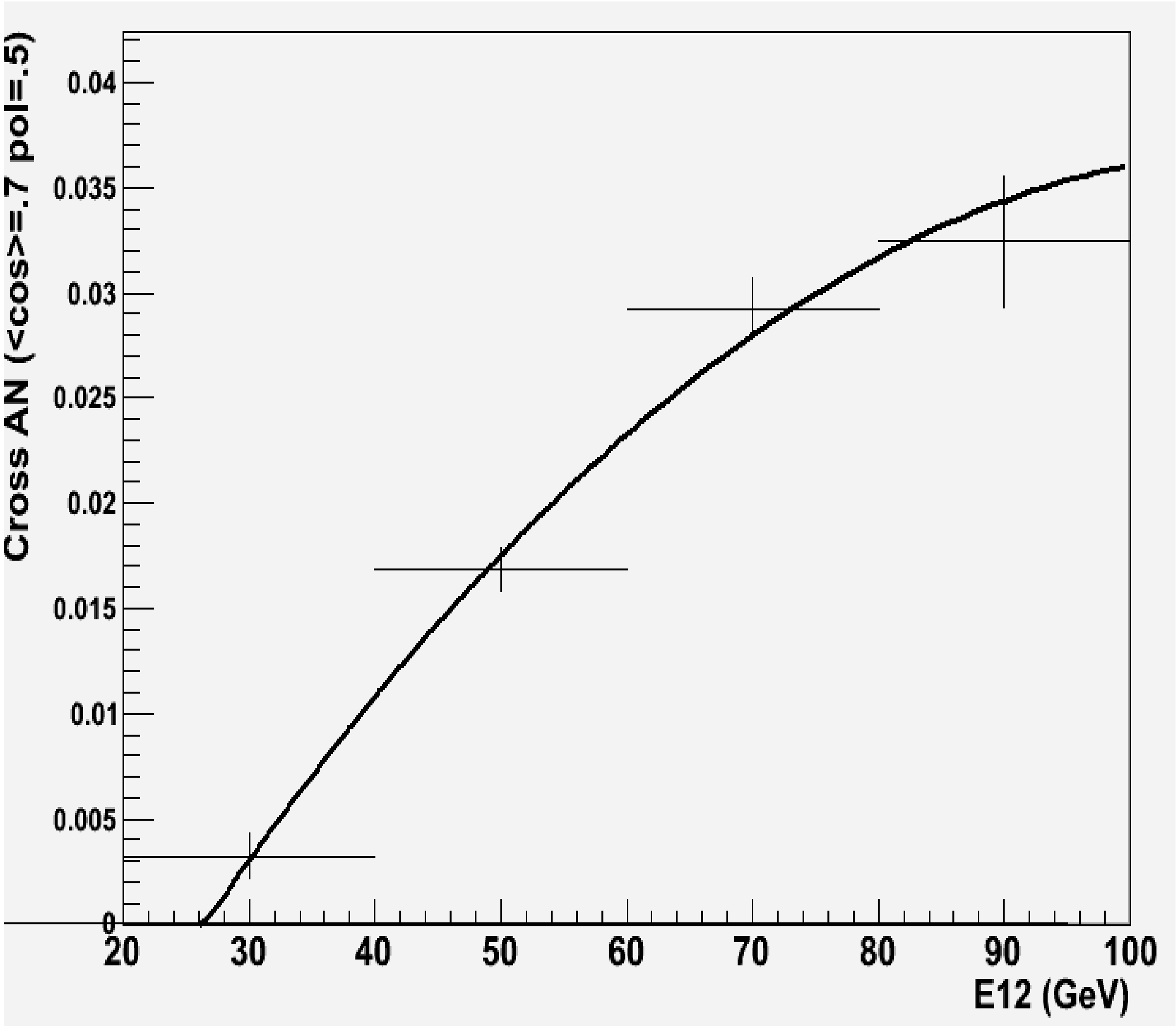
Cross Ratio Transverse Single Spin Asymmetry for Run 11

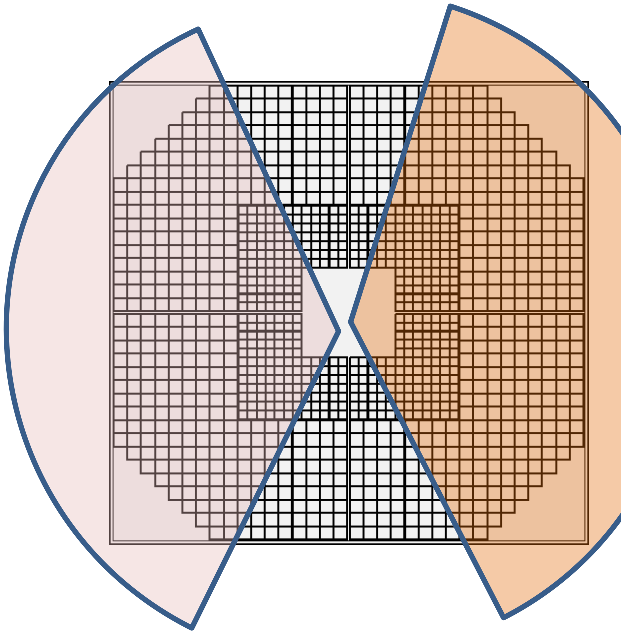
π^0 (2 Photon Cluster) Cluster size = 0.07 Rad

For Blue Beam (Forward)

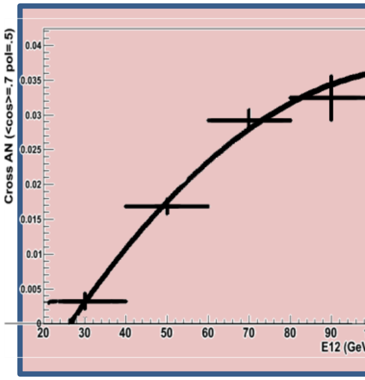
Full FMS rapidity range.

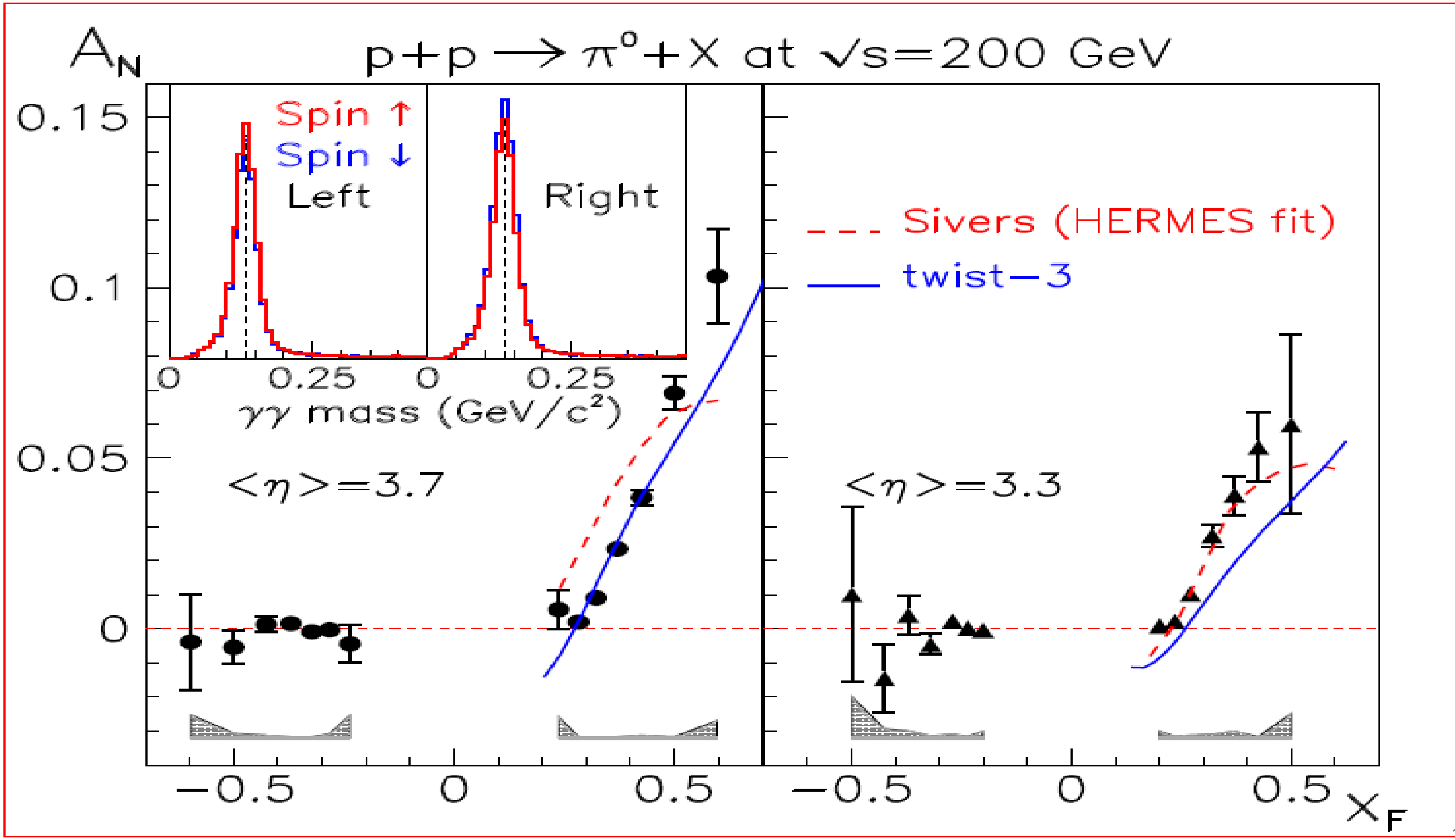






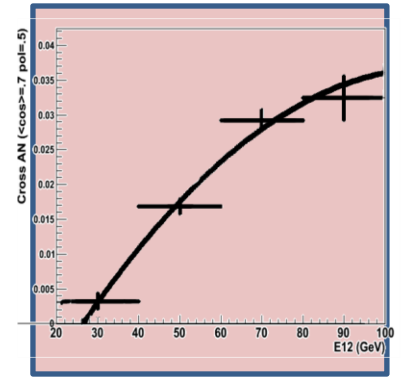
Compare New √s=500 GeV Run 11 Full FMS Data on right with **Run 6 published data below.**

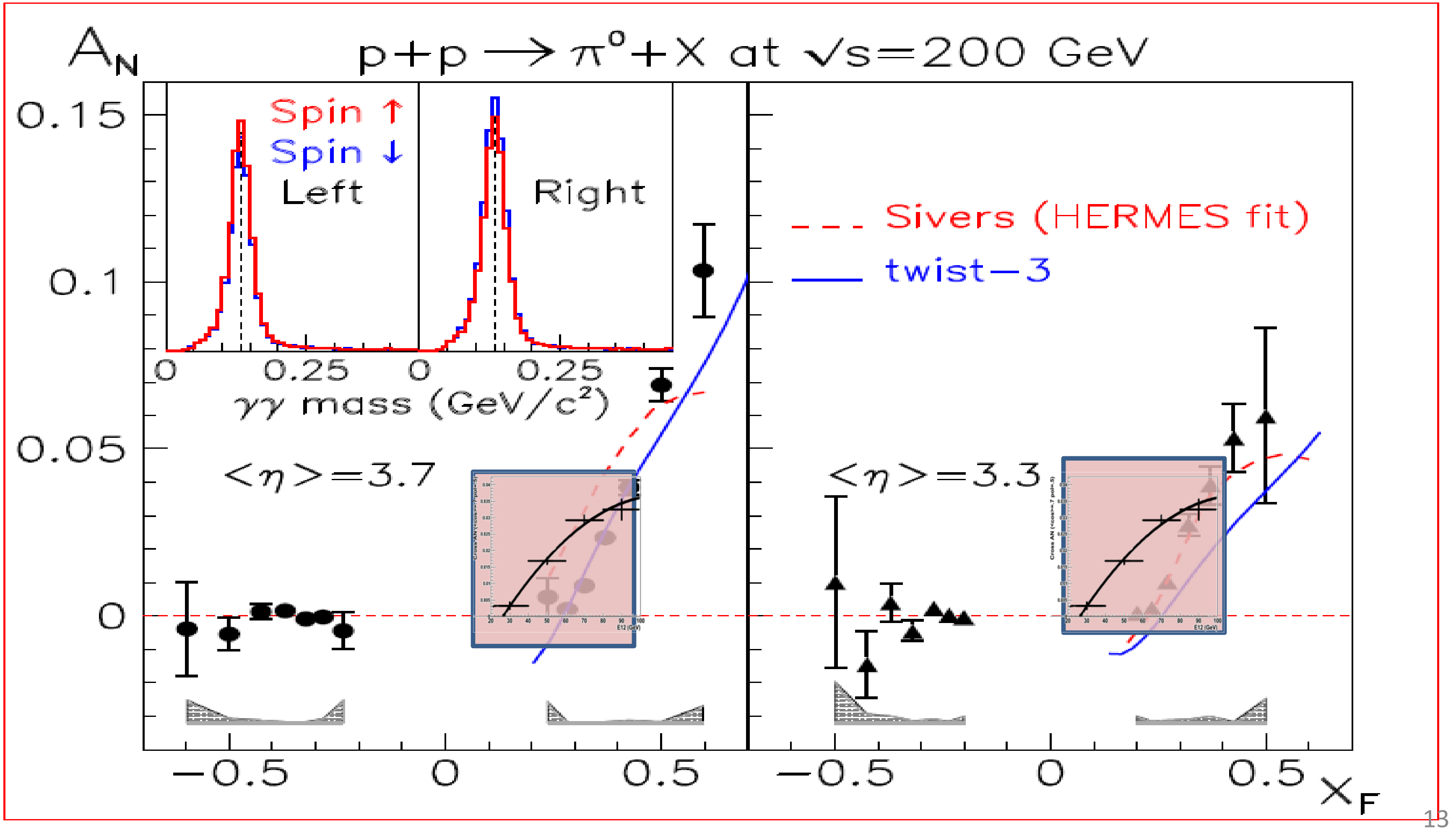


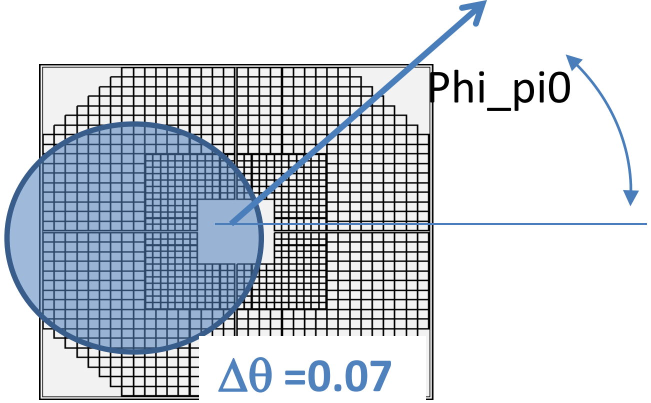


Compare **new √s=500 GeV Run 11** Full FMS Data on right with **Run 6 √s=200** published data below.

Scale of A_N similar but starts at lower X_F in Run 11 data.



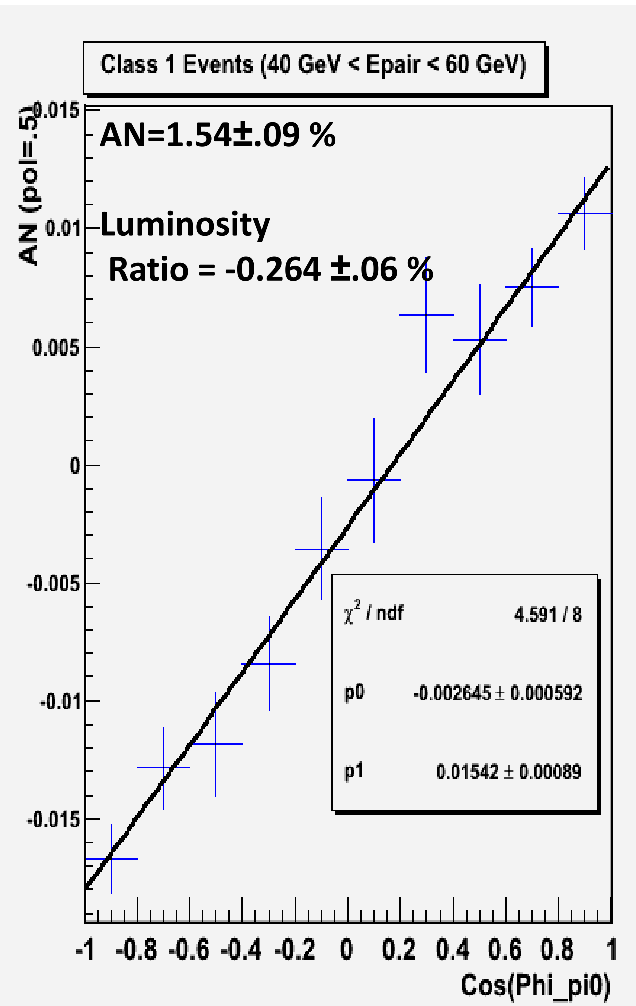


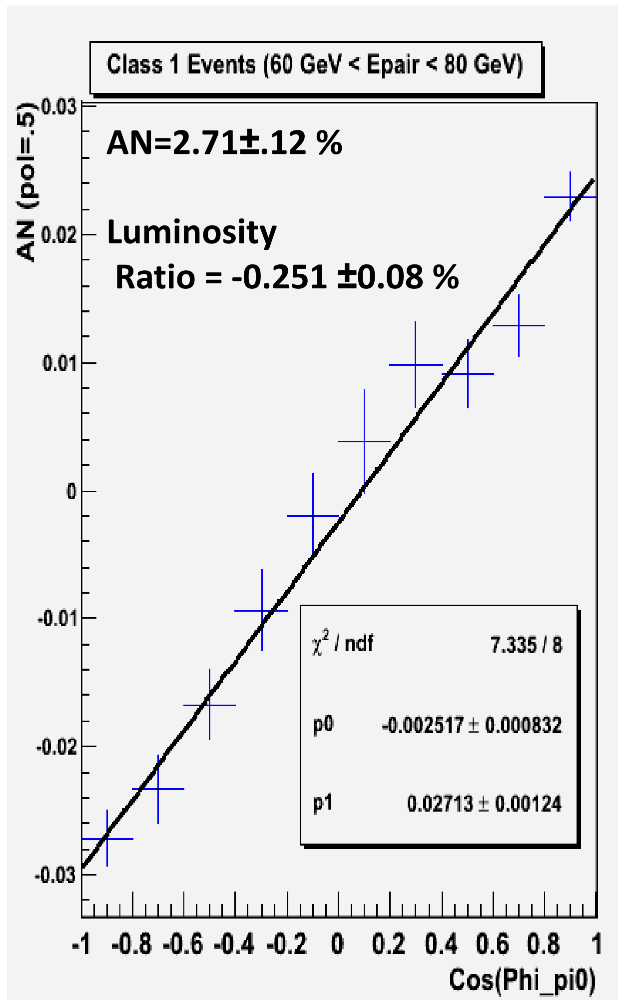


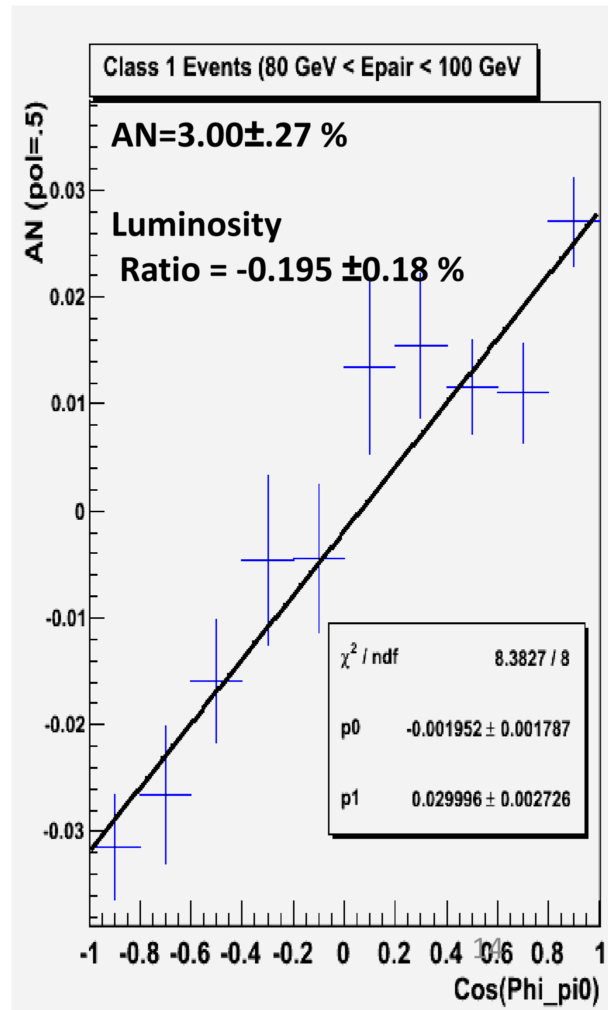
Blue Beam AN

As and alternative to Cross Ratio, the raw asymmetry
Can be plotted as a function of Cos(Phi)
(with polarization axis at Phi=pi/2)
Slope =AN
Intercept = Luminosity Ratio for data set

Luminosity ratio for all ~- 0.25 ±.05 %







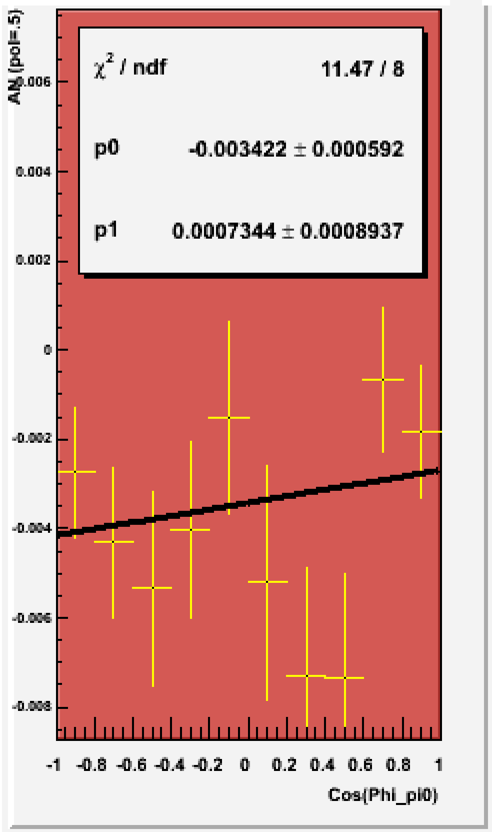
Yellow Beam (backward scattered)

No significant A_N seen.

Note: bad Chi2/DOF for 60-80 GeV region may be pointing to some physics effect.

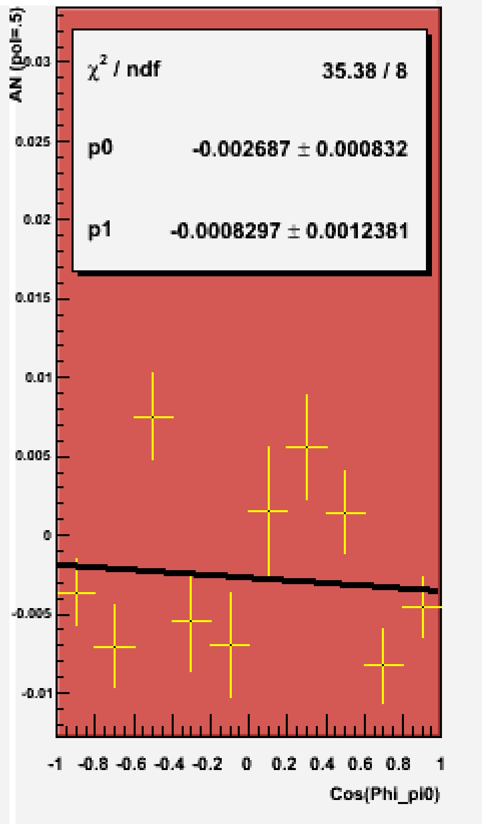
40 GeV < Epair < 60 GeV

AN=0.07±0.09 %



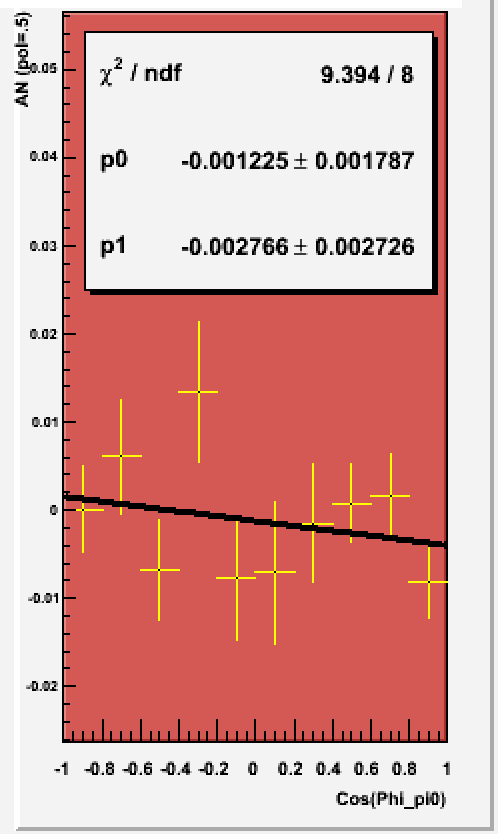
60 GeV < Epair < 80 GeV

AN=-0.08±0.12 %



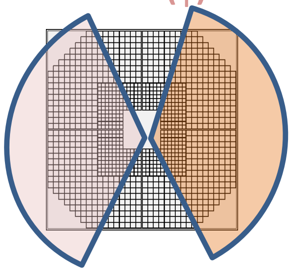
80 GeV < Epair < 100 GeV

AN=-0.28±0.2 %



Cross Ratio Analysis of Transverse Single Spin Asymmetry As a function of P_T.

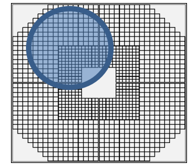
Left: Cos(ϕ)<-0.5



Right: Cos(ϕ)>0.5

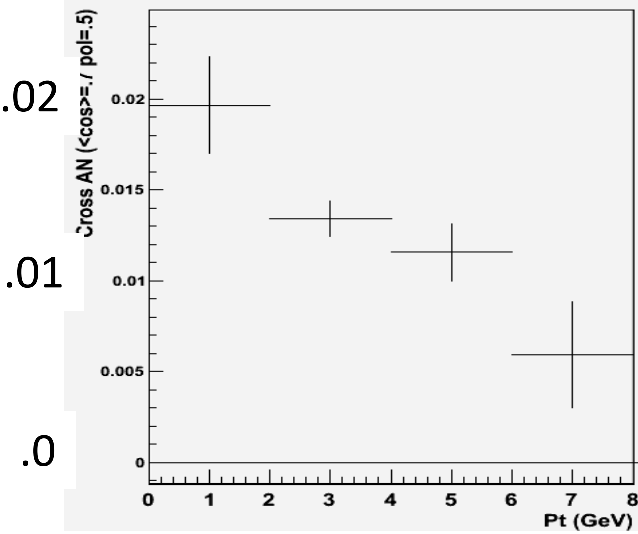
$\Delta\theta$ =0.07 Large

2 Photon clusters



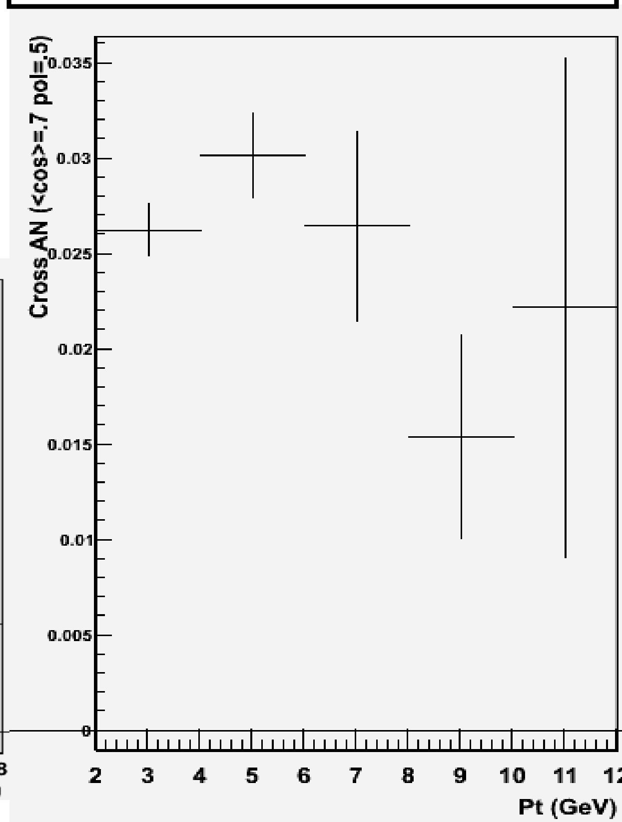
40 GeV < E_pair < 60 GeV

$0.16 < X_F < 0.24$



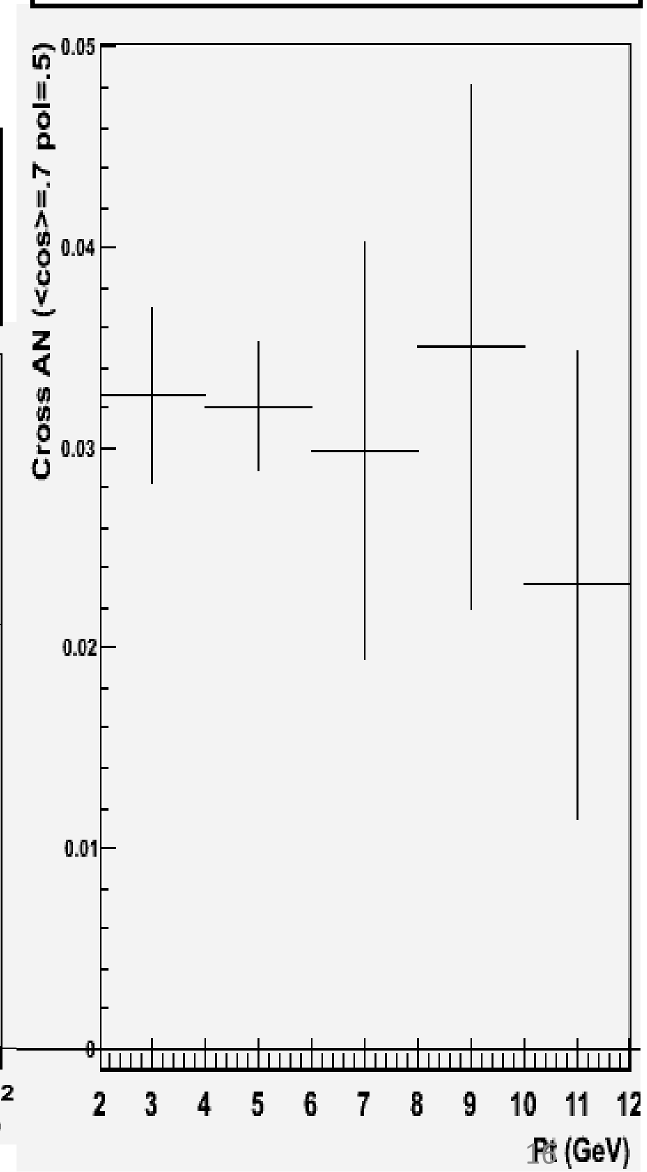
60 GeV < E_pair < 80 GeV

$0.24 < X_F < 0.32$



80 GeV < E_pair < 100 GeV

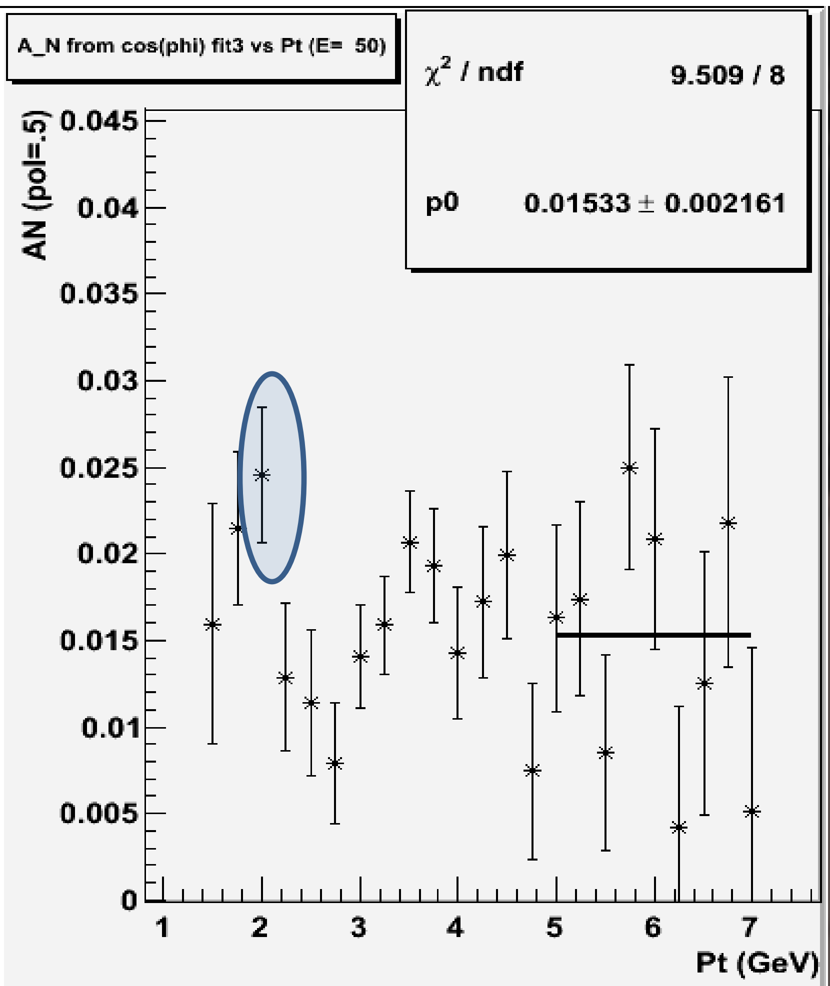
$0.32 < X_F < 0.40$

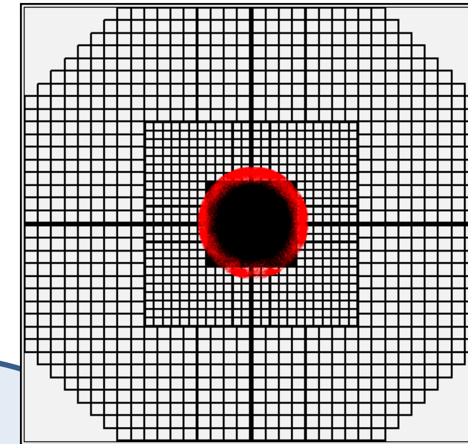


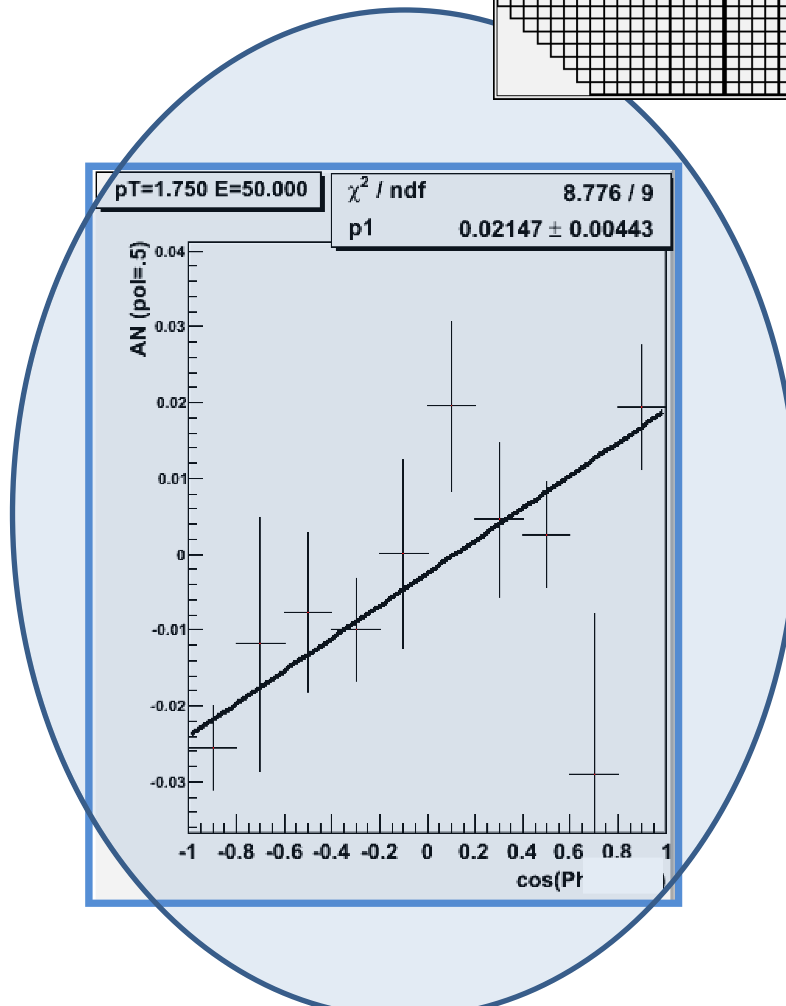
Cut data into small data sets and analyze the ϕ dependence of up/down asymmetry

Generate Asymmetries and Errors for selected data based on fits to A vs Cos(Phi)

40 GeV < E_pair < 60 GeV
1.875 GeV < Pt < 2.135 GeV

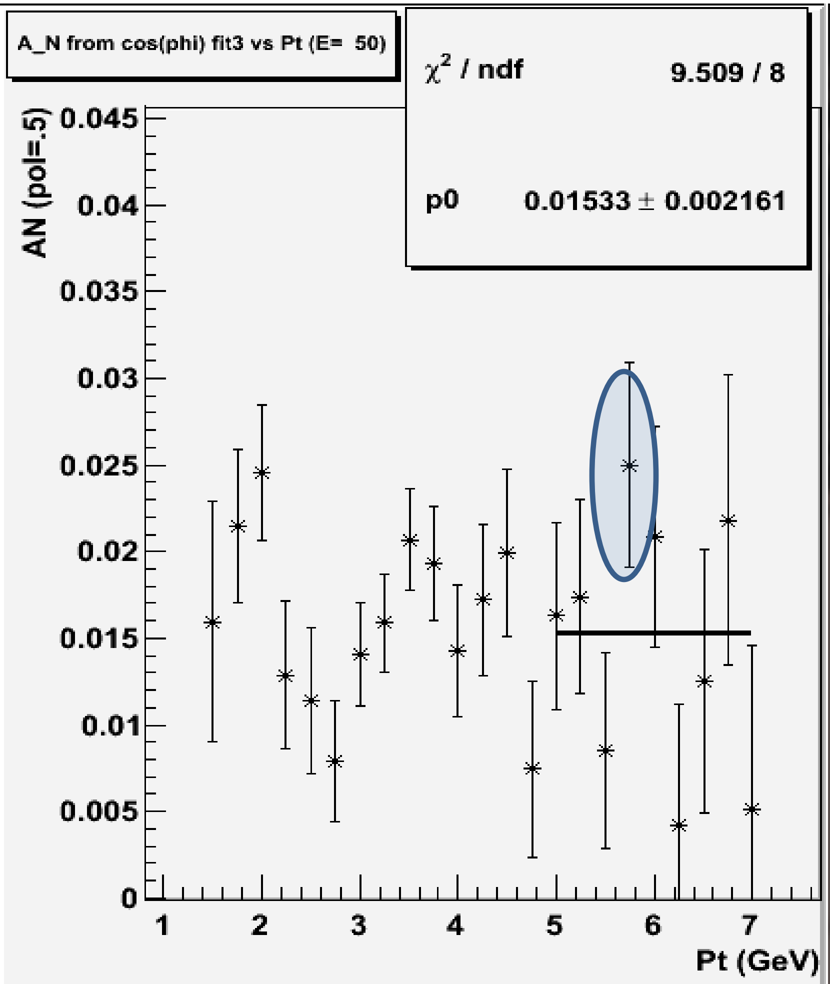


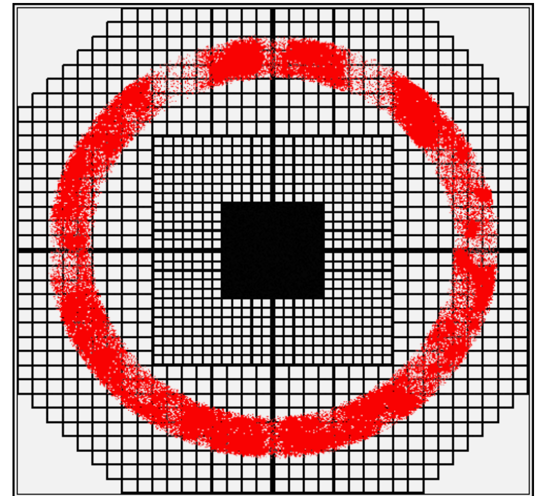


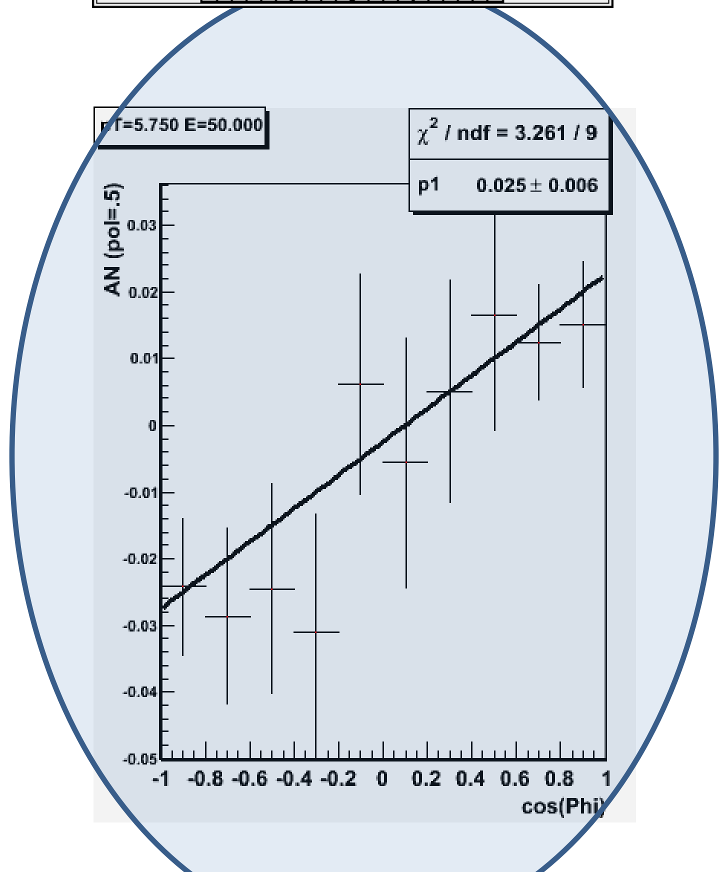


40 GeV < E_pair < 60 GeV

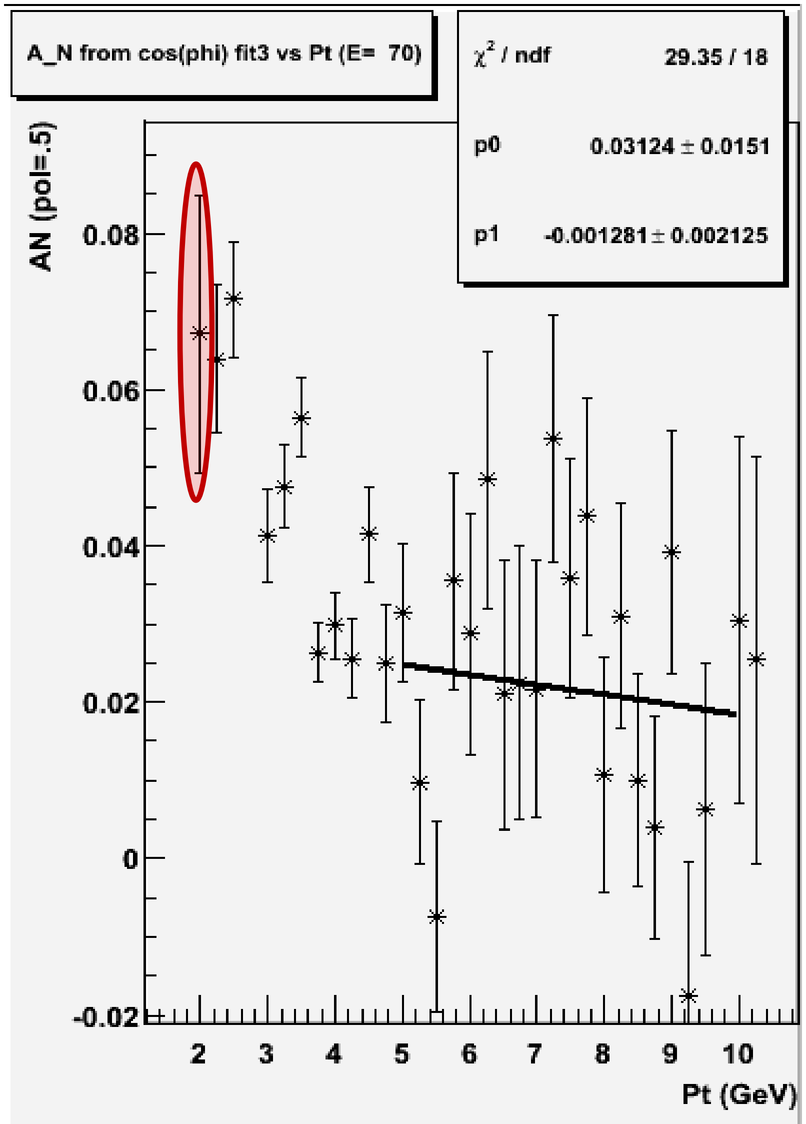
5.625 GeV <Pt< 5.875 GeV

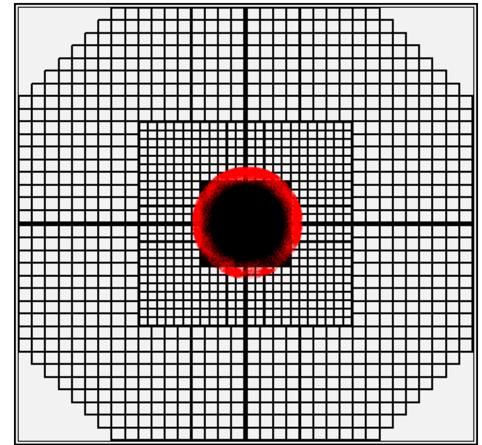


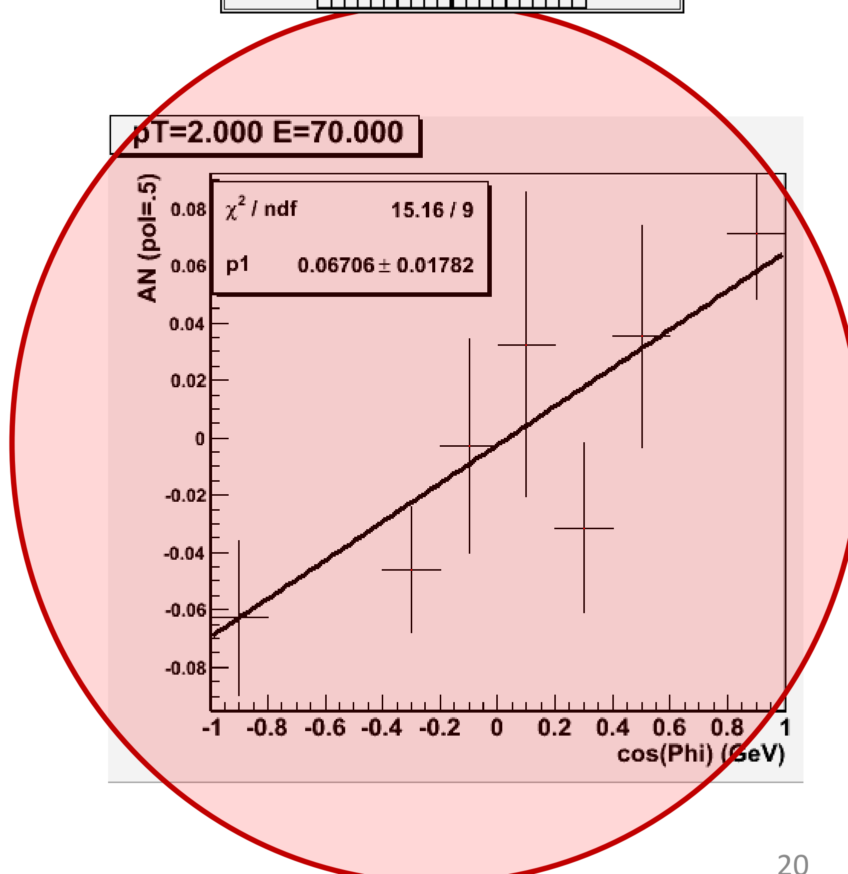




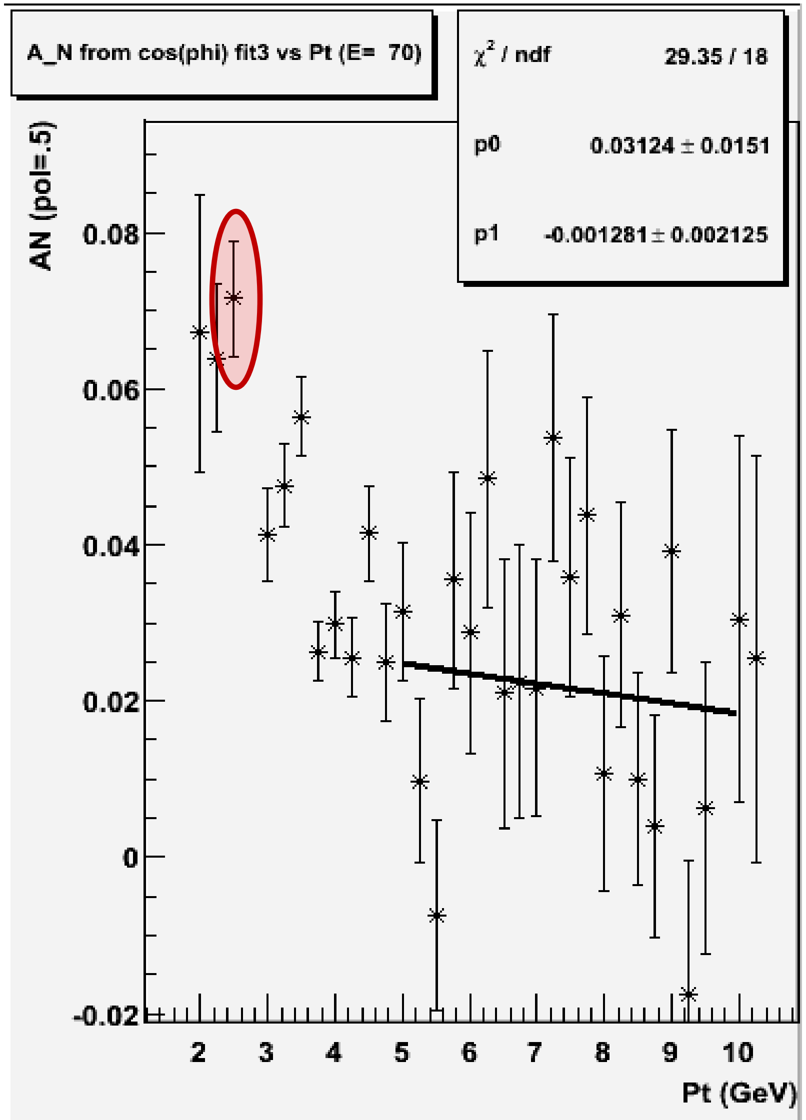
60 GeV < E_pair < 80 GeV

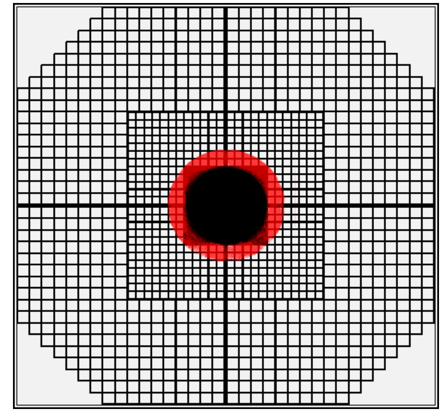


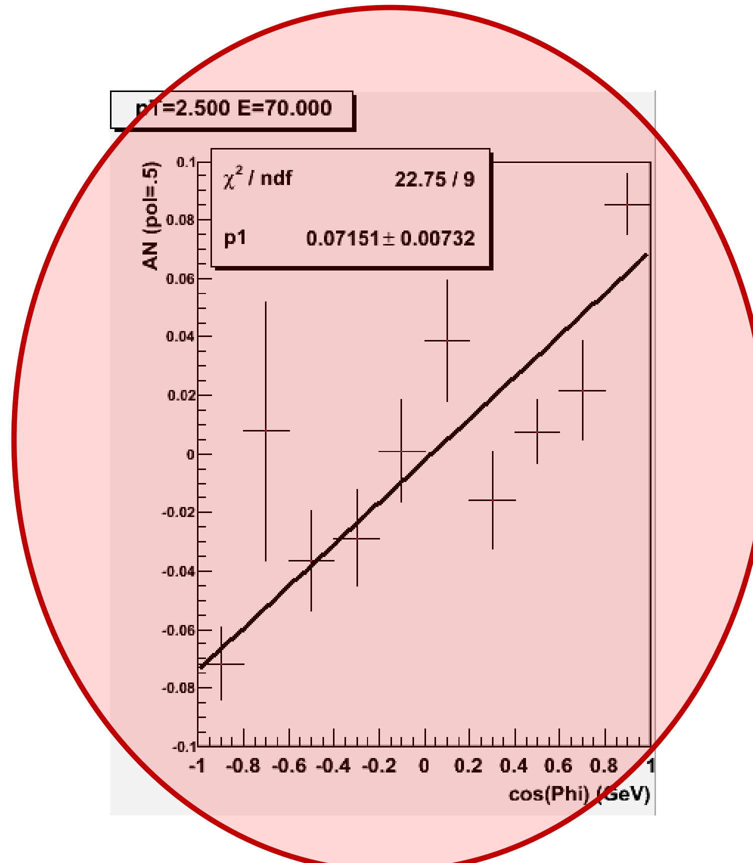




60 GeV < E_pair < 80 GeV





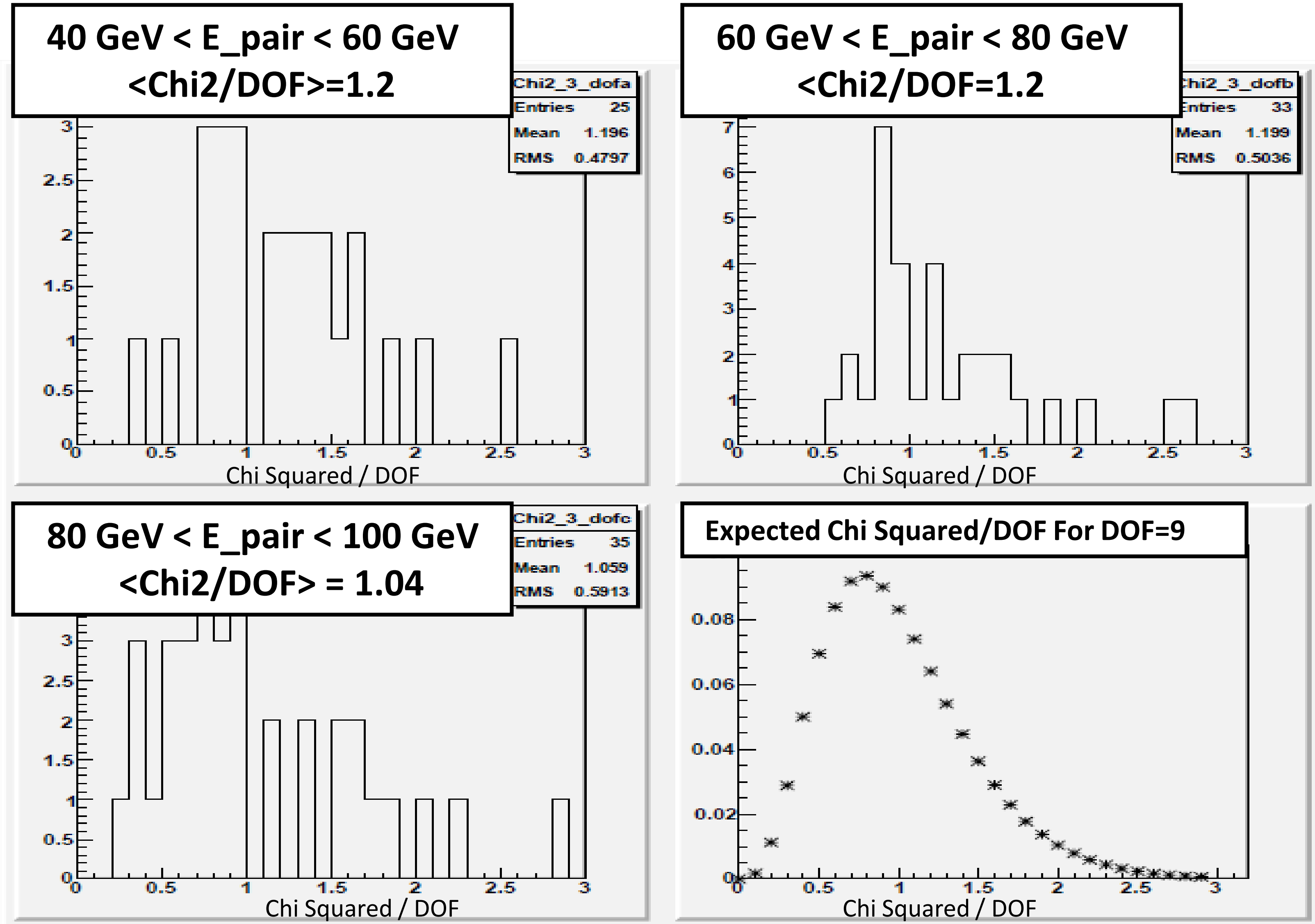


Chi Squared / DOF Distribution for Assumpted Form

SSA ~ A_N Cos() -0.0025

data in fixed Pt and Energy bins.

E~50 GeV (25 Pt points) E~70 GeV (33 Pt points) E~90 GeV (35 Pt points)



Transverse Single Spin Asymmetry for π^0 Production

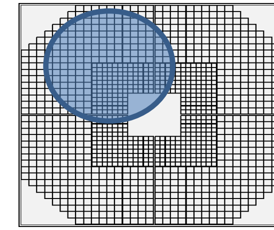
Single Pi0 in Large Size Cluster

Blue Beam (Forward Scattering)

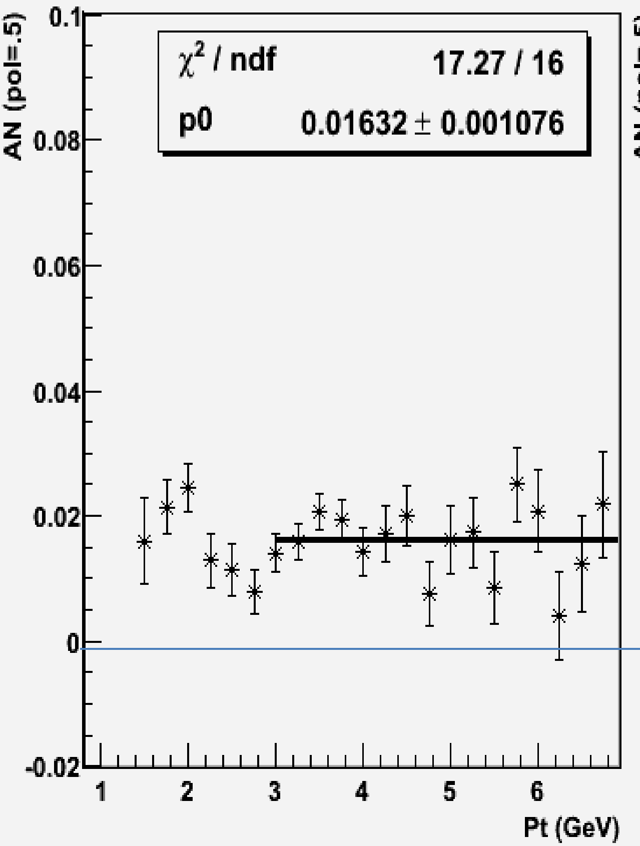
STAR pp (250 GeV x 250 GeV)

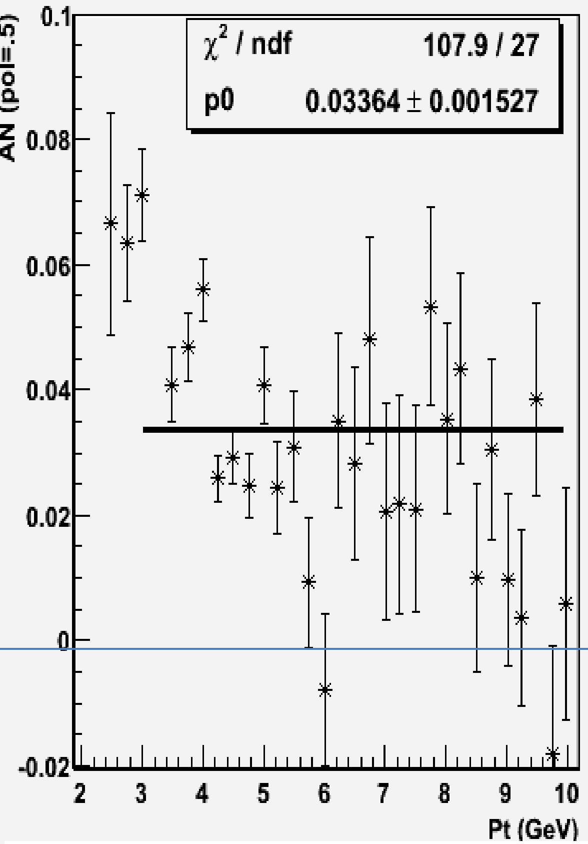
Run 11 ~ 20 pb^{-1} 2.65 < Y < 4.1

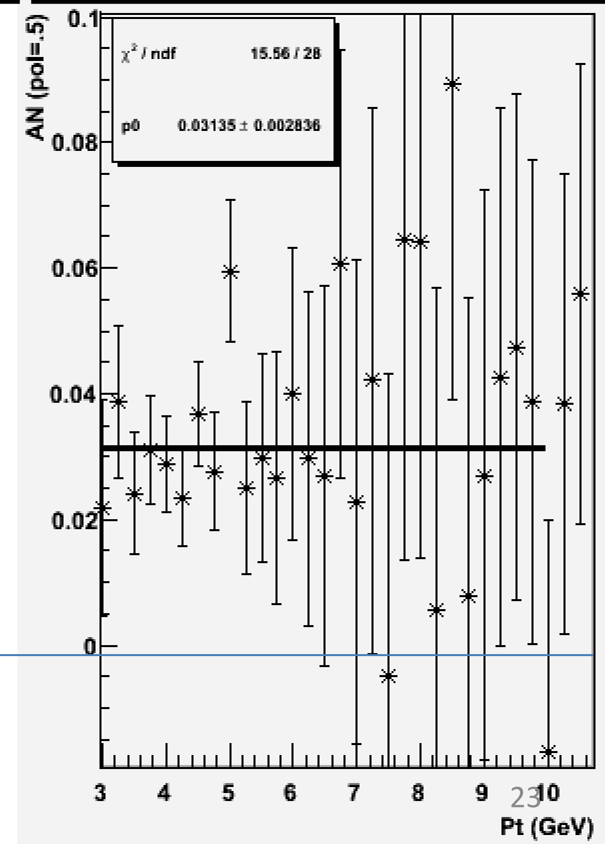
$\Delta\theta$ =0.07 Large 2 Photon clusters



40 GeV < E_pair < 60 GeV	60 GeV < E_pair < 80 GeV	80 GeV < E_pair < 100 GeV
$0.16 < X_F < 0.24$	$0.24 < X_F < 0.32$	$0.32 < X_F < 0.40$







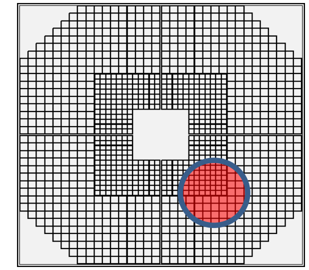
Transverse Single Spin Asymmetry for π^0 Production

Blue Beam (Forward Scattering)

STAR pp (250 GeV x 250 GeV)

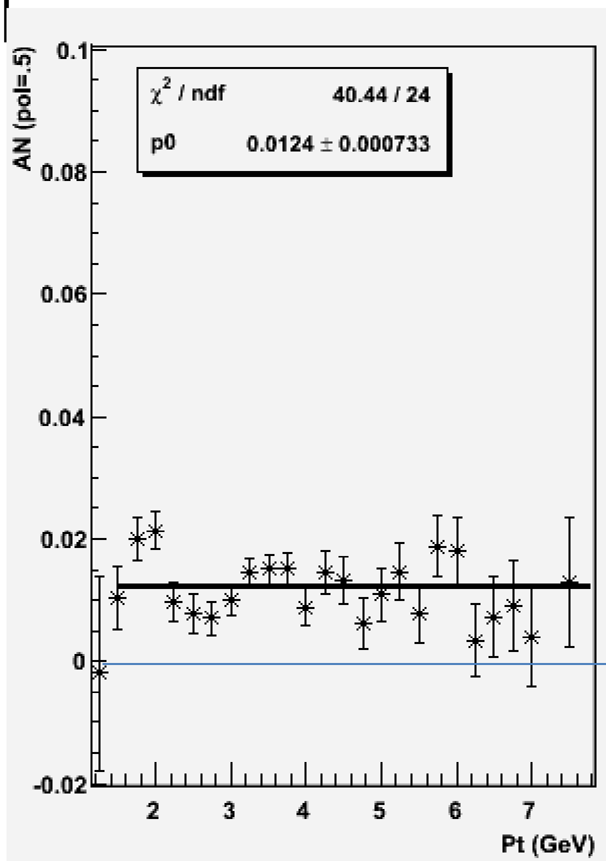
Run 11 ~ 20 pb^{-1} $2.65 < Y < 4.1$

$\Delta\theta$ =0.03 small 2 Photon clusters

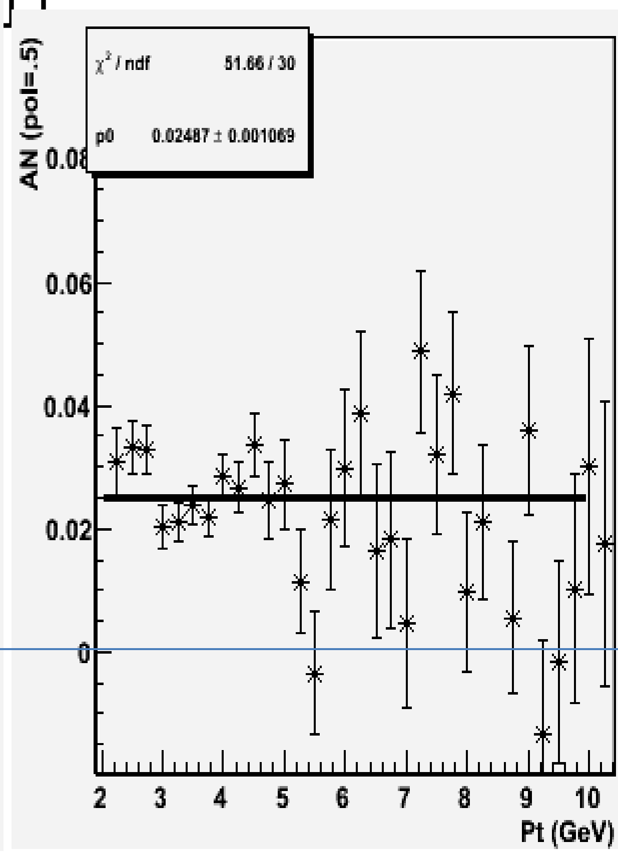


$\Delta\theta$ =0.03 small

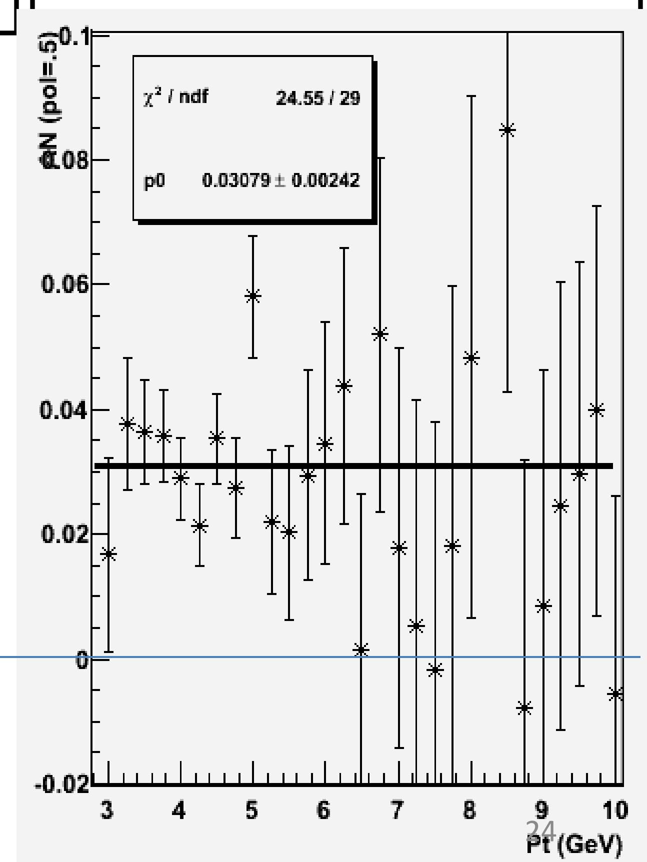
40 GeV < E_pair < 60 GeV
$0.16 < X_F < 0.24$



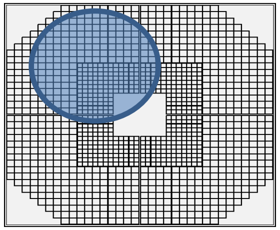
60 GeV < E_pair < 80 GeV
$0.24 < X_F < 0.32$



80 GeV < E_pair < 100 GeV
$0.32 < X_F < 0.40$

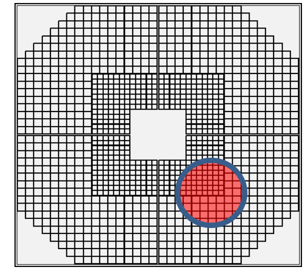


Large 2 Photon clusters



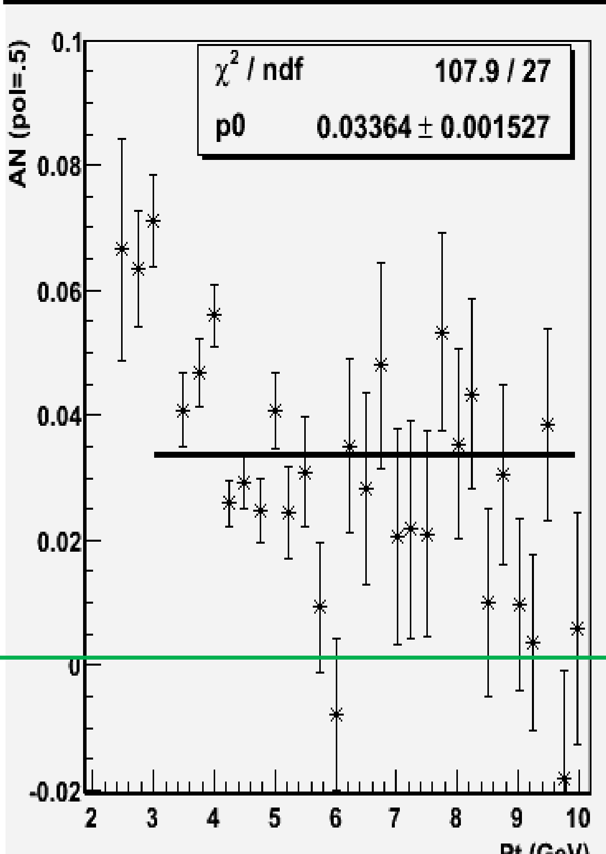
$\Delta\theta$ =0.07 small

There is significant differences in the Transverse momentum Dependence of A_N for different cluster cone sizes.



$\Delta\theta$ =0.03 small

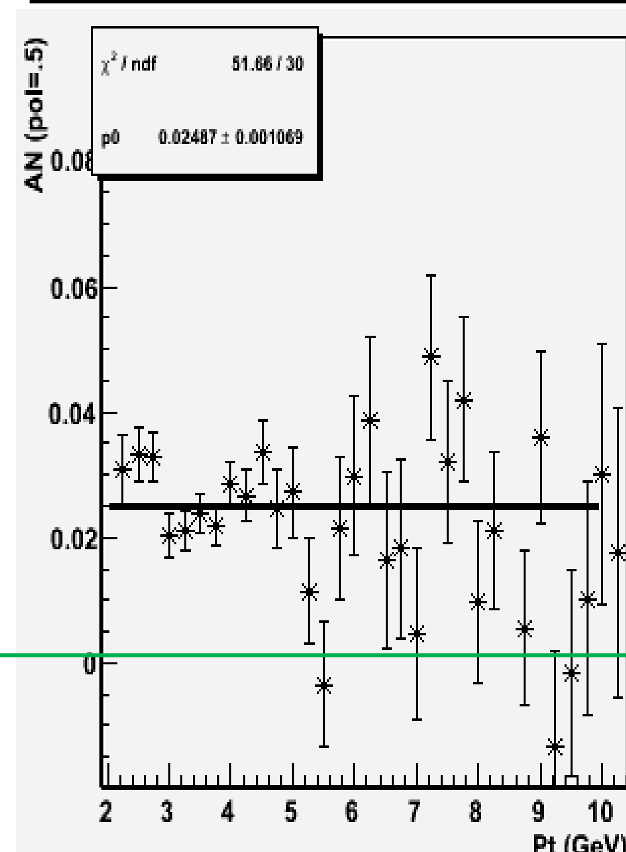
60 GeV < E_pair < 80 GeV
$0.24 < X_F < 0.32$



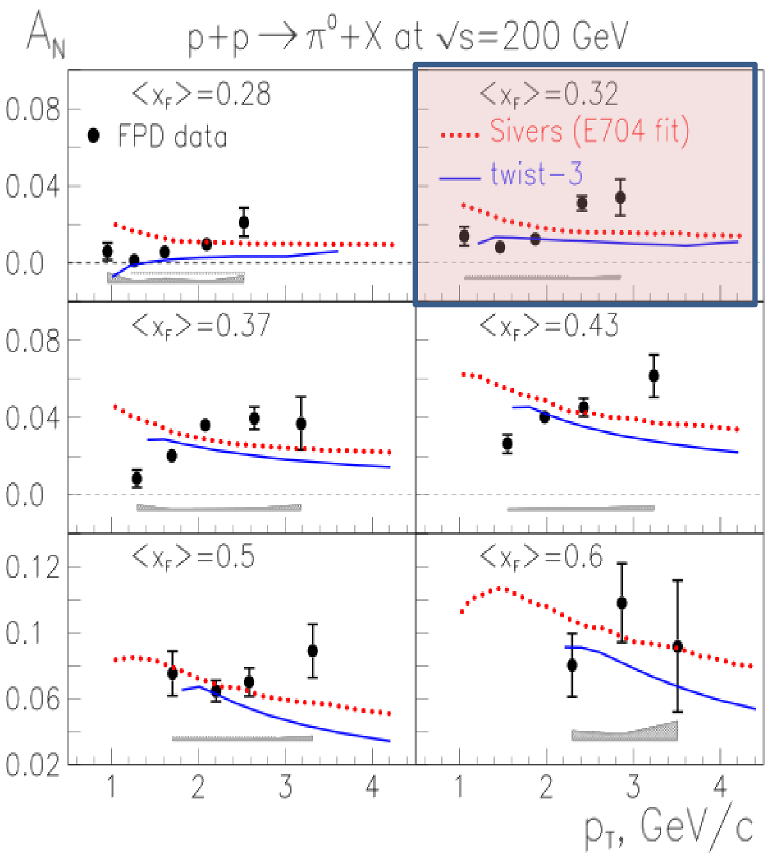
More inclusive π^0 →

← **More isolated π^0**

60 GeV < E_pair < 80 GeV
$0.24 < X_F < 0.32$

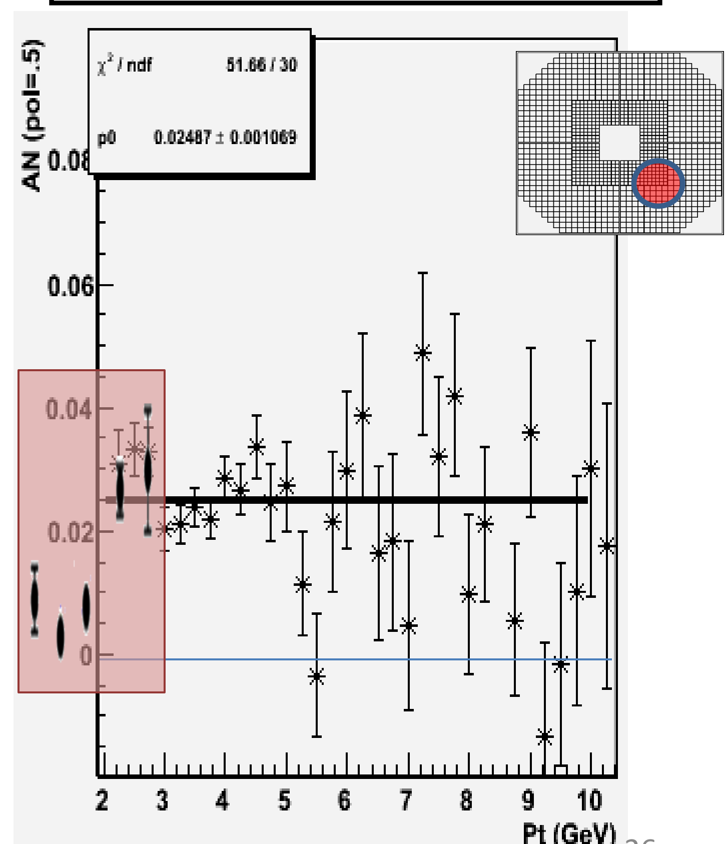


Run 6 ($\sqrt{s}$=200GeV FPD) published P_T Dependence of A_N

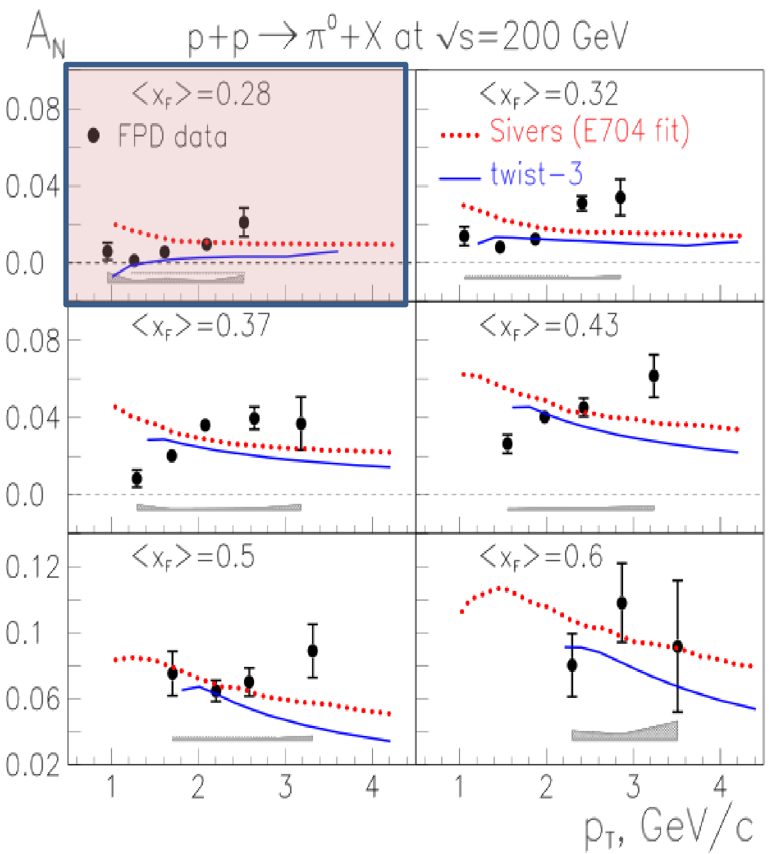


Run 11 ($\sqrt{s}$=500GeV FMS) published P_T Dependence of A_N at $0.24<X_F<0.32$ ($\Delta\theta$ =0.03 small clusters)

60 GeV < E_pair < 80 GeV
$0.24 < X_F < 0.32$

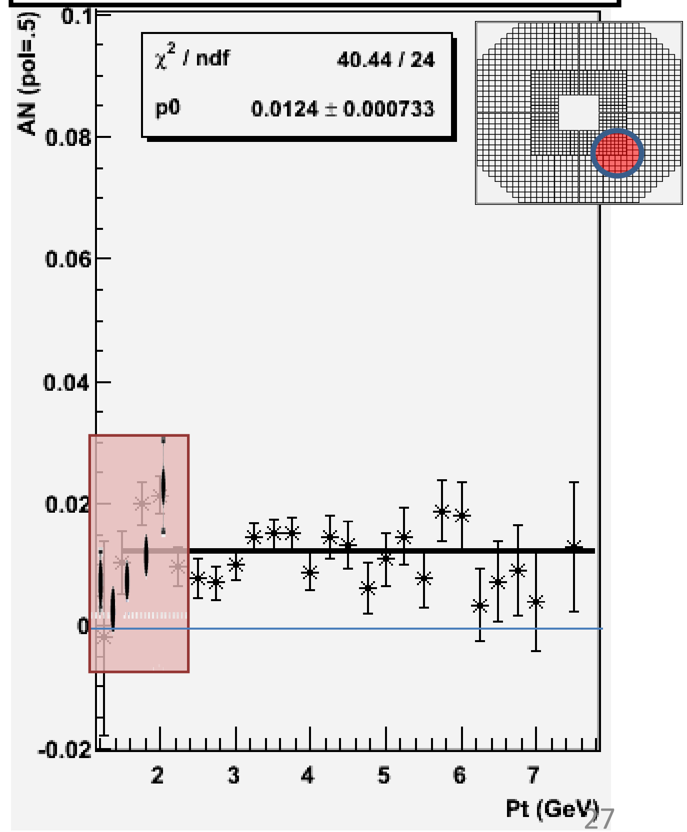


Run 6 ($\sqrt{s}$=200GeV FPD) published P_T Dependence of A_N



Run 11 ($\sqrt{s}$=500GeV FMS) published P_T Dependence of A_N at 0.16<X_F<0.24 ($\Delta\theta$ =0.03 small clusters)

40 GeV < E_pair < 60 GeV
0.16 < X_F < 0.24



Compare A_N for Full FMS (40 GeV < E pair<60 GeV)

1. $\Delta\theta$ =0.07 2 Photon clusters, Pi0 Mass (inclusive)? **(Class 1)**
   <AN> (slope) = 1.54 ±.09 %

2. $\Delta\theta$ =0.03 2 Photon clusters ,Pi0 Mass (inclusive)? **(Class 2)**
   <AN> (slope) = 1.18±.07 %

The Asymmetry is reduced as the cone size of N=2 cluster is reduced.

Conclusion:

Asymmetry greater for more isolated π^0's .

60-80 GeV Bin

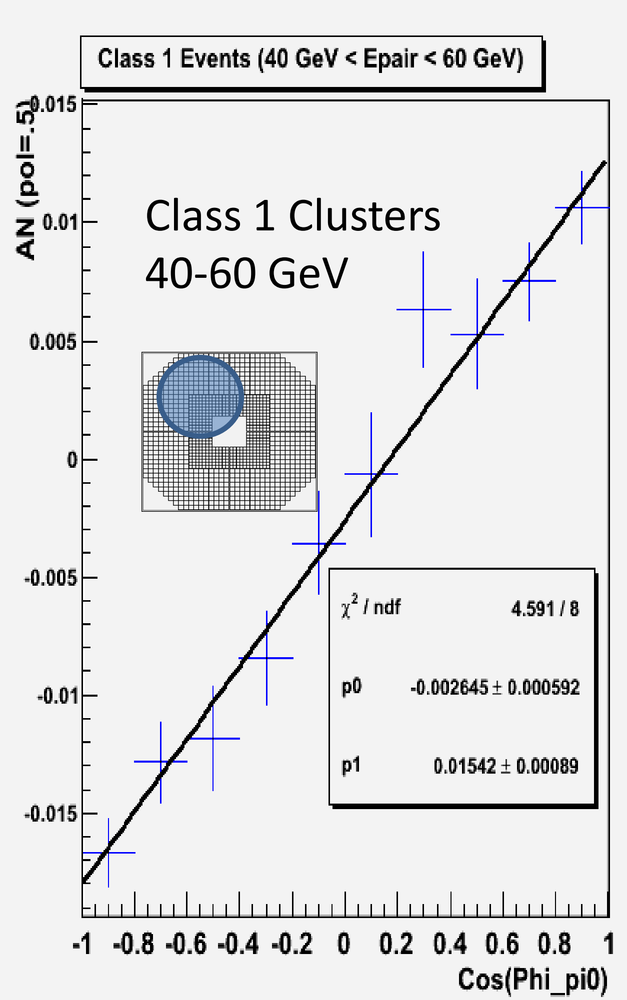
Class 1: <AN> (slope) = 2.71 ±.12 %

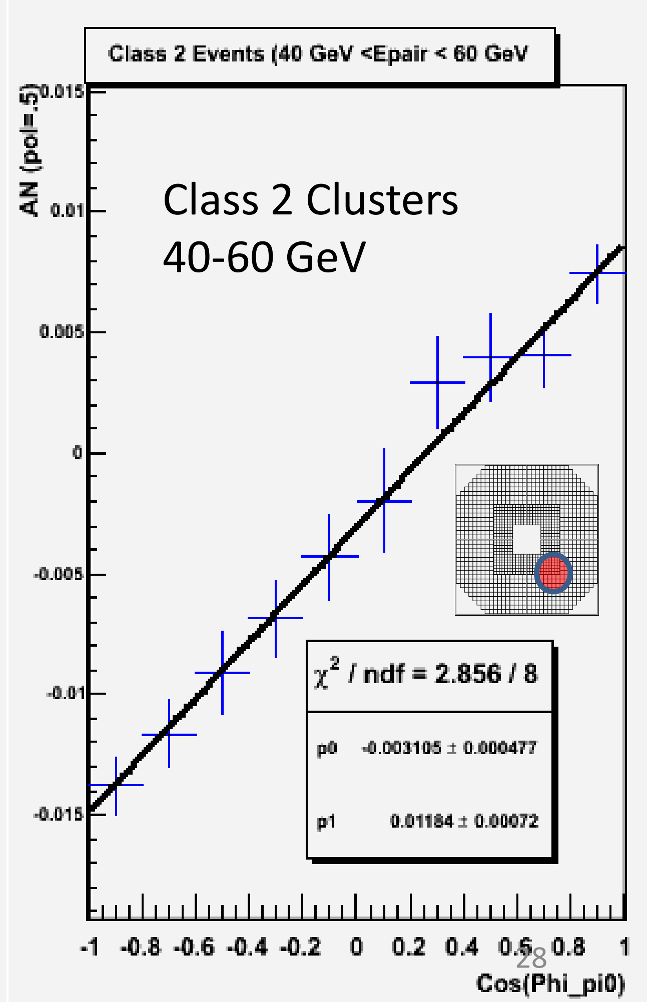
Class 2: <AN> (slope) = 2.45±.1 %

80-100 GeV Bin

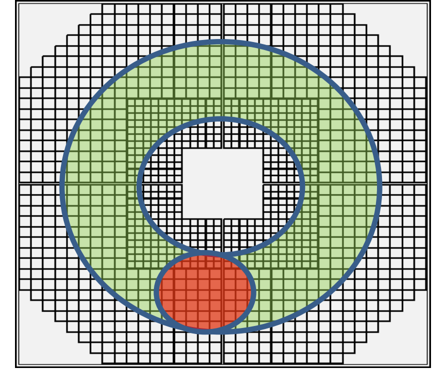
Class 1: <AN> (slope) = 3.0 ±.27 %

Class 2: <AN> (slope) = 2.93±.23 %



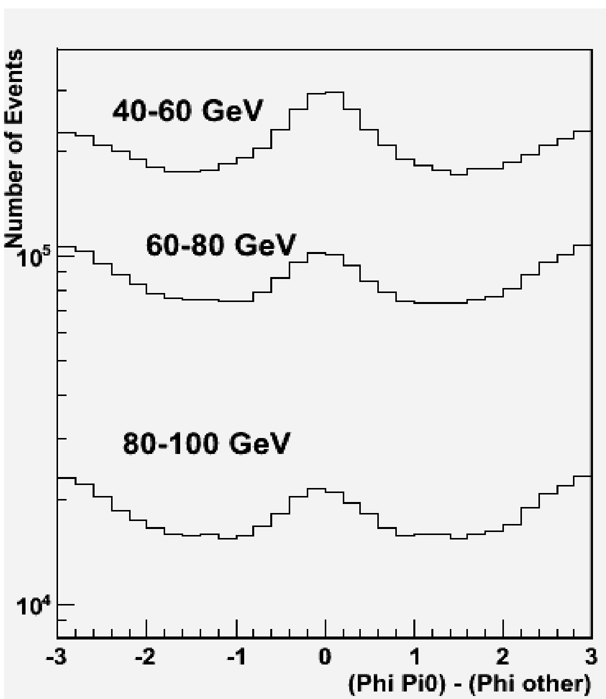


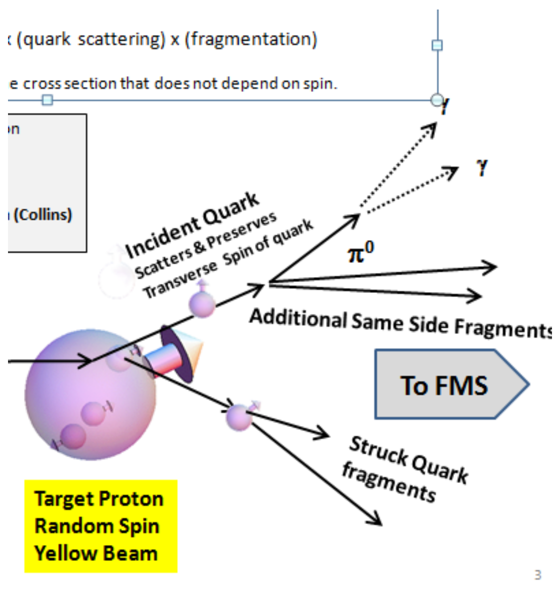
Left: **Azimuthal angle (ange bewteen π^0 and Away energy).**
Right: **Away Energy Distribution for 3 π^0 Energies.**

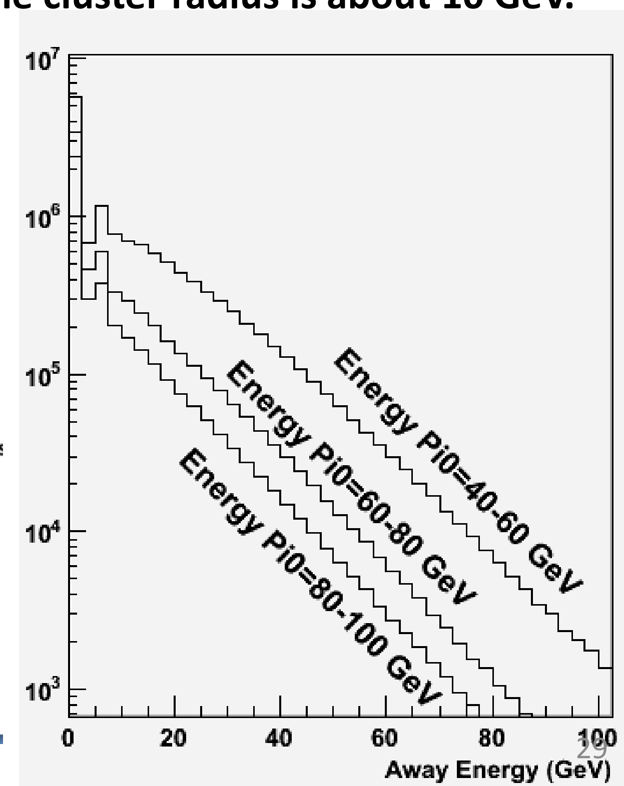


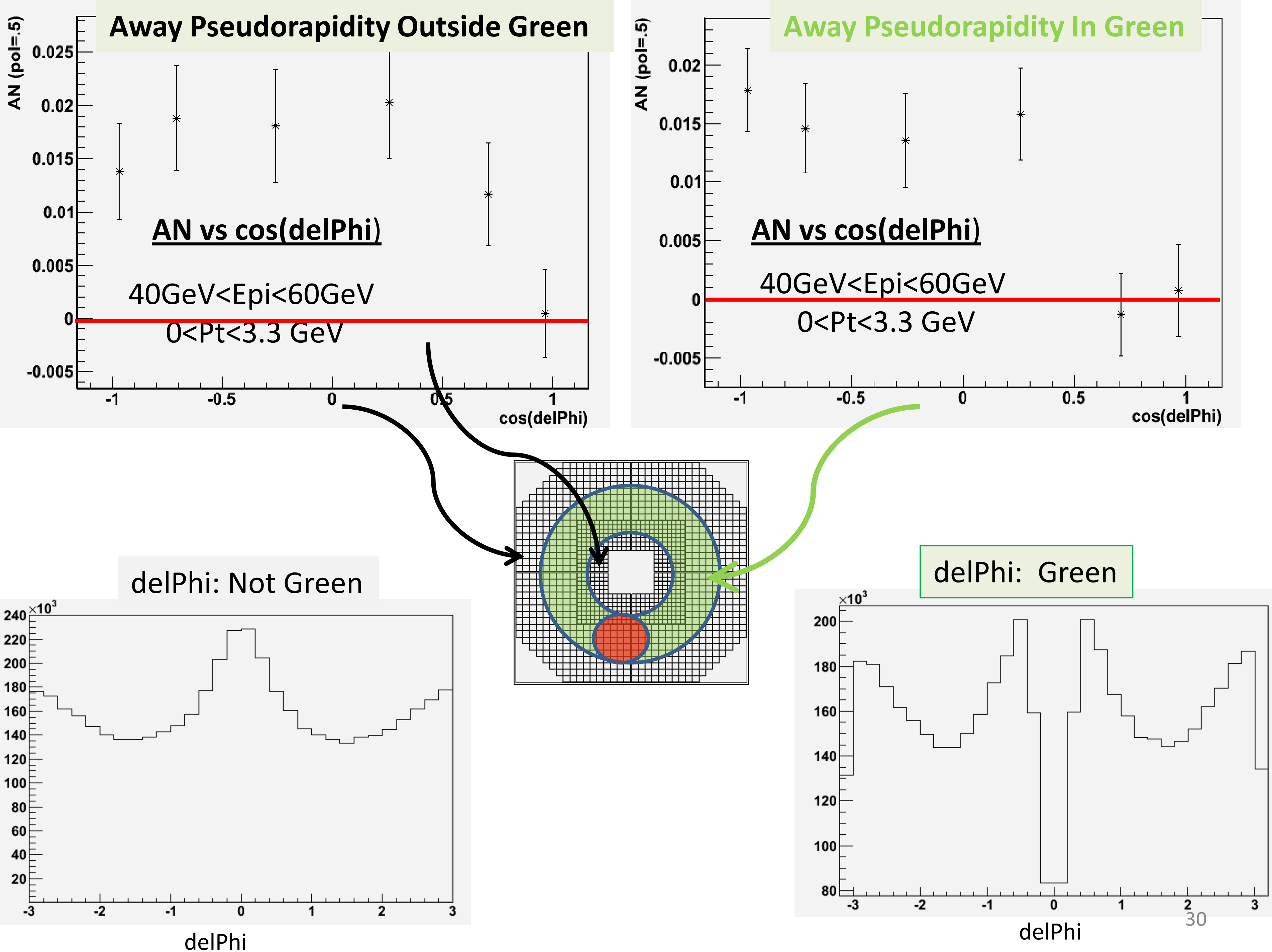
Class 4 Clusters: **$\Delta\theta$ =0.03** 2 Photon clusters
Pi0 Mass, **Y_{away} outside Green region.**

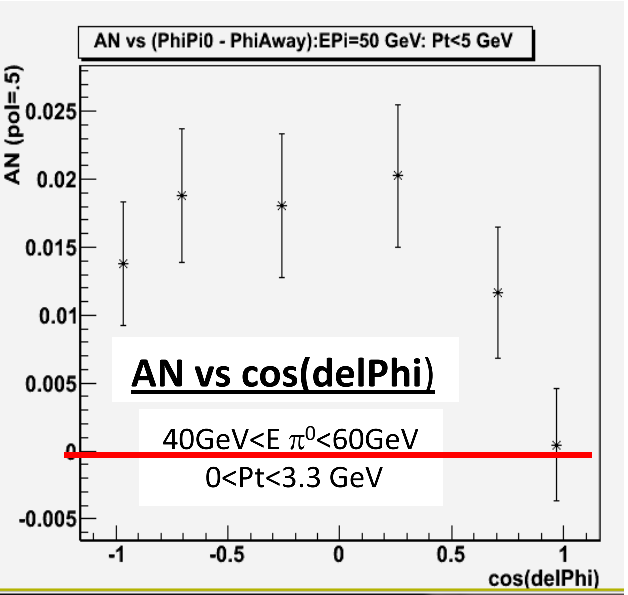
For π^0 energy in the 40-100 range, the average E&M energy outside the cluster radius is about 10 GeV.

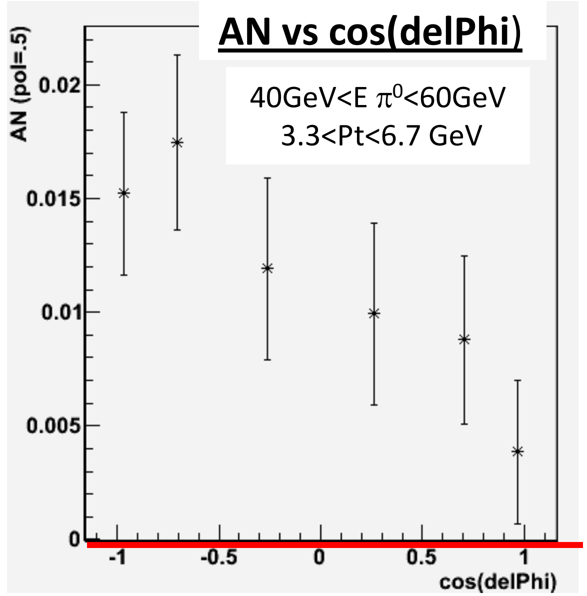


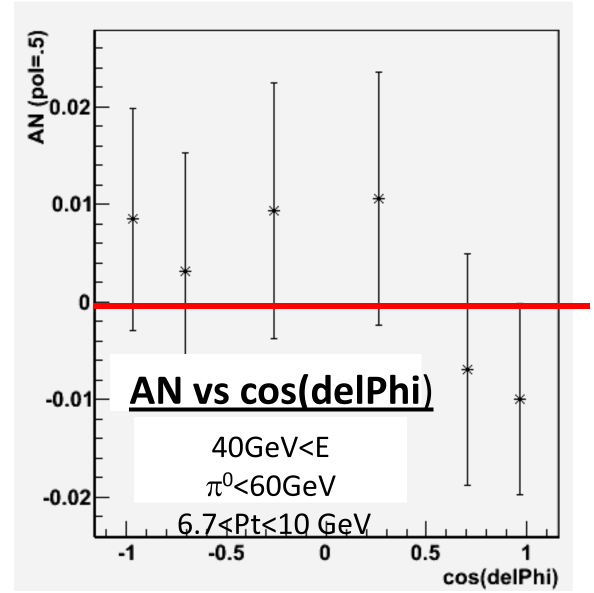


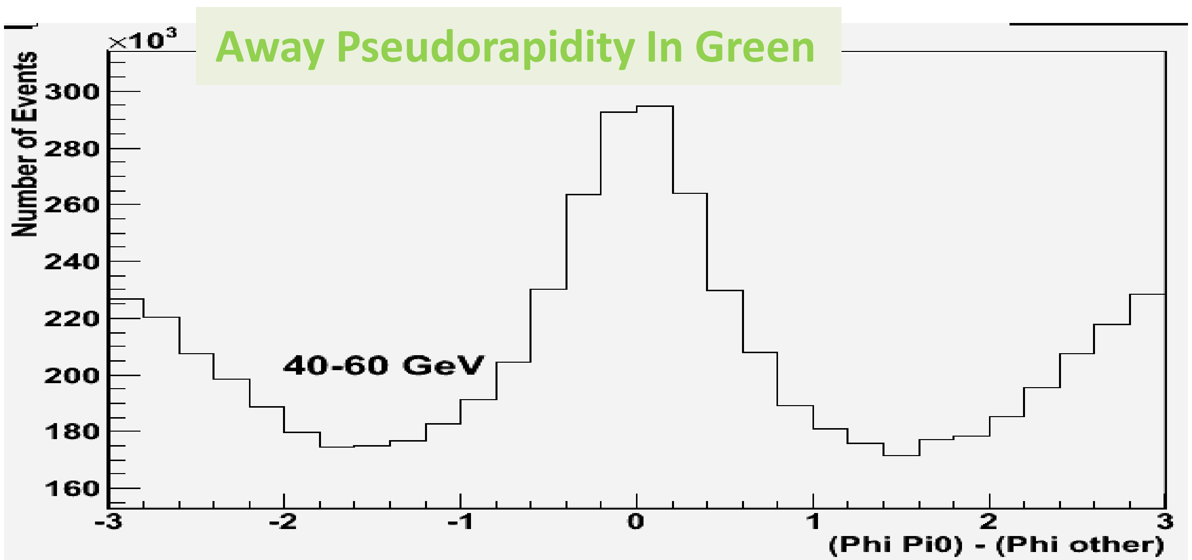


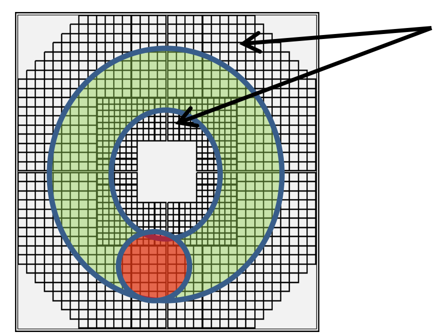

Away Pseudorapidity Outside Green
AN vs cos(delPhi)
40GeV<Epi<60GeV
0<Pt<3.3 GeV
AN (pol=.5)
cos(delPhi)
Away Pseudorapidity In Green
AN vs cos(delPhi)
40GeV<Epi<60GeV
0<Pt<3.3 GeV
AN (pol=.5)
cos(delPhi)
delPhi: Not Green
delPhi
delPhi: Green
delPhi

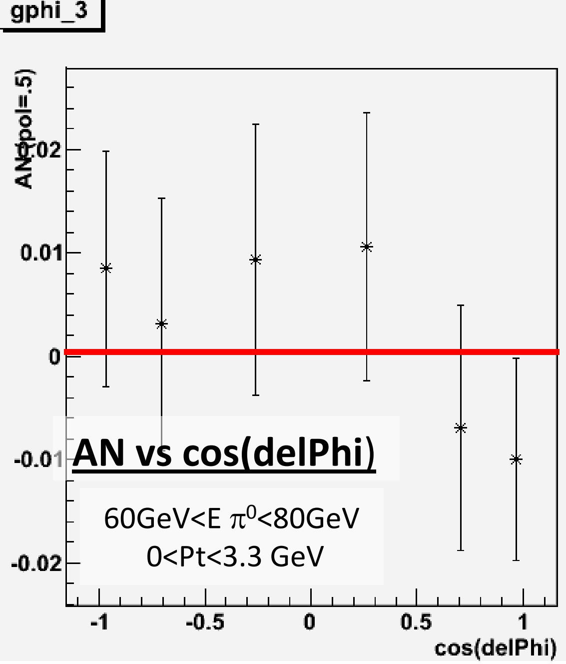

AN vs (PhiPi0 - PhiAway):EPi=50 GeV: Pt<5 GeV
AN (pol=.5)
cos(delPhi)
AN vs cos(delPhi)
40GeV<E π0<60GeV
0<Pt<3.3 GeV

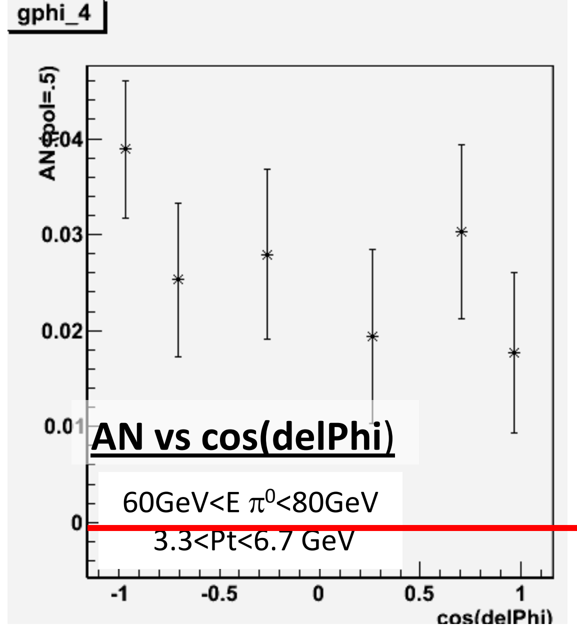

AN vs cos(delPhi)
40GeV<E π0<60GeV
3.3<Pt<6.7 GeV
AN (pol=.5)
cos(delPhi)

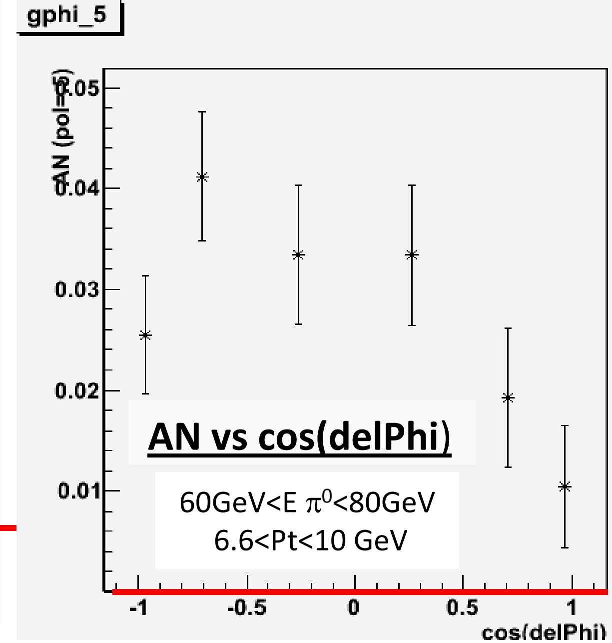

AN (pol=.5)
AN vs cos(delPhi)
40GeV<E
π0<60GeV
6.7<Pt<10 GeV
cos(delPhi)

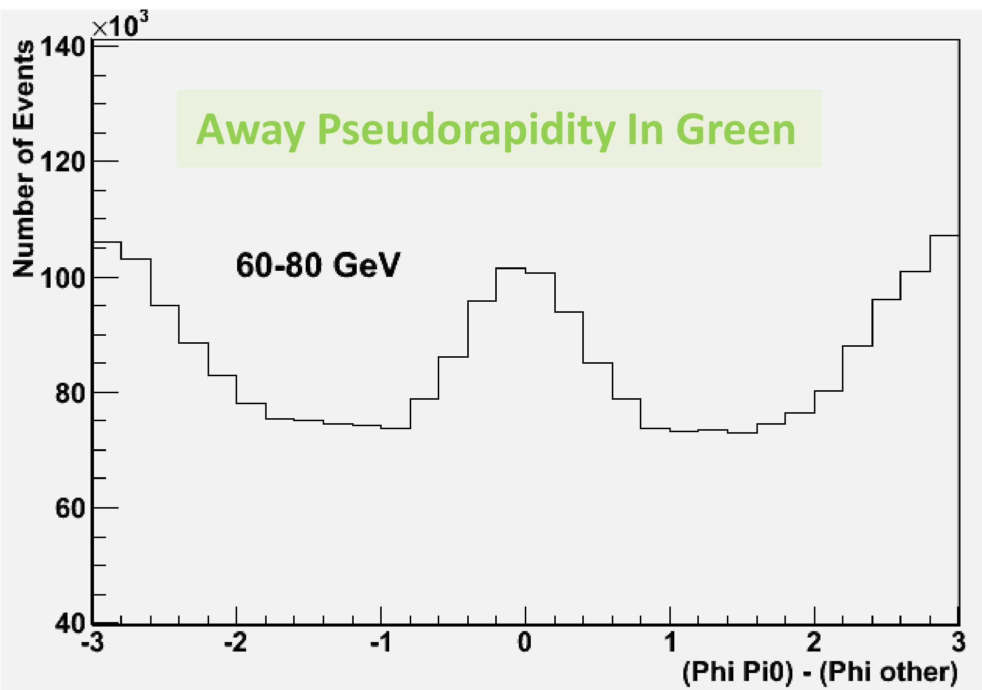

Away Pseudorapidity In Green
×10³
Number of Events
40-60 GeV
(Phi Pi0) - (Phi other)

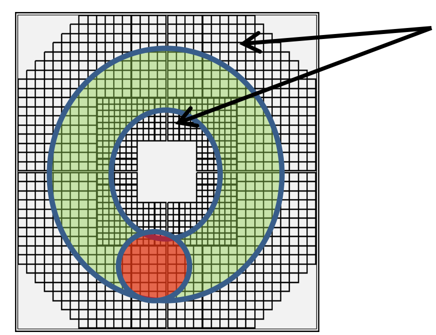


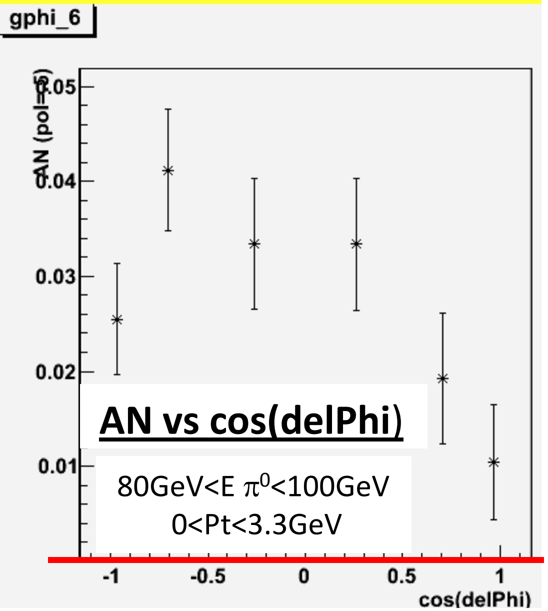

gphi_3
AN (pol=.5)
AN vs cos(delPhi)
60GeV<E π^0<80GeV
0<Pt<3.3 GeV
cos(delPhi)

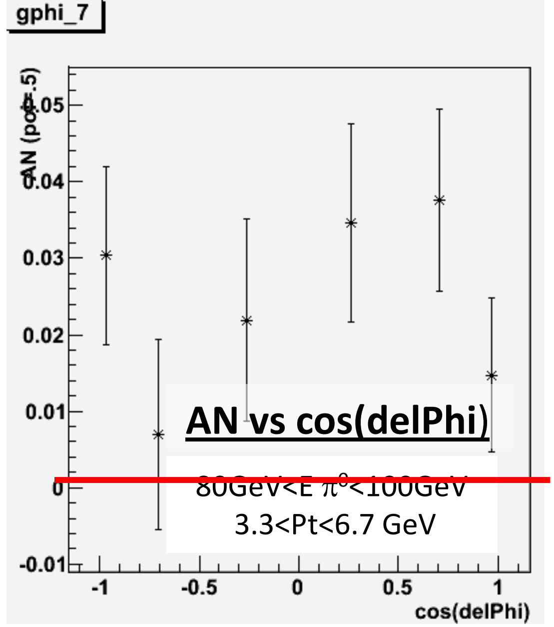

gphi_4
AN (pol=.5)
AN vs cos(delPhi)
60GeV<E π^0<80GeV
3.3<Pt<6.7 GeV
cos(delPhi)

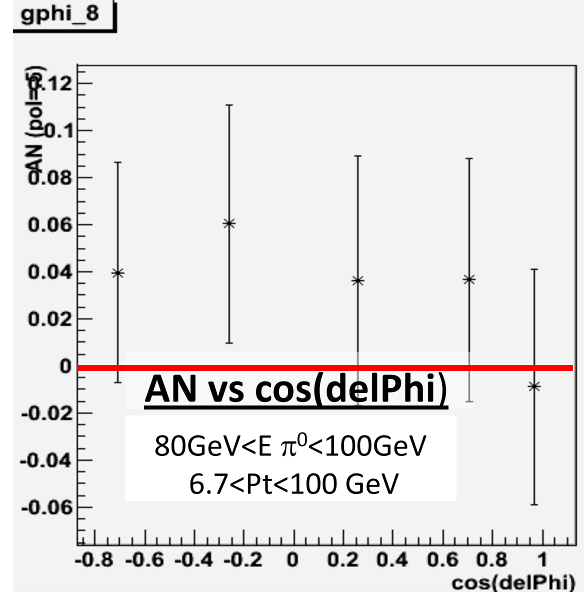

gphi_5
AN (pol=.5)
AN vs cos(delPhi)
60GeV<E π^0<80GeV
6.6<Pt<10 GeV
cos(delPhi)

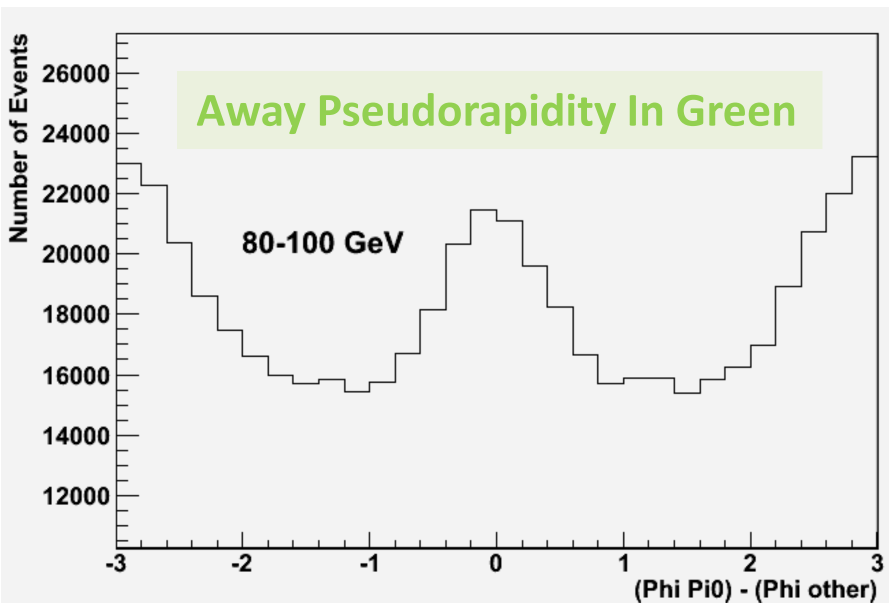

Away Pseudorapidity In Green
60-80 GeV
Number of Events
$\times 10^3$
(Phi Pi0) - (Phi other)

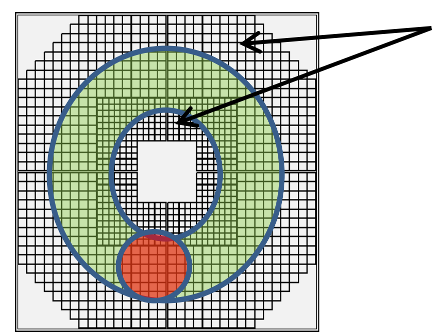



gphi_6
AN (pol=.5)
AN vs cos(delPhi)
80GeV<E π^0<100GeV
0<Pt<3.3GeV
cos(delPhi)


gphi_7
AN (pol=.5)
AN vs cos(delPhi)
80GeV<E π^0<100GeV
3.3<Pt<6.7 GeV
cos(delPhi)


gphi_8
AN (pol=.5)
AN vs cos(delPhi)
80GeV<E π^0<100GeV
6.7<Pt<100 GeV
cos(delPhi)


Number of Events
Away Pseudorapidity In Green
80-100 GeV
(Phi Pi0) - (Phi other)

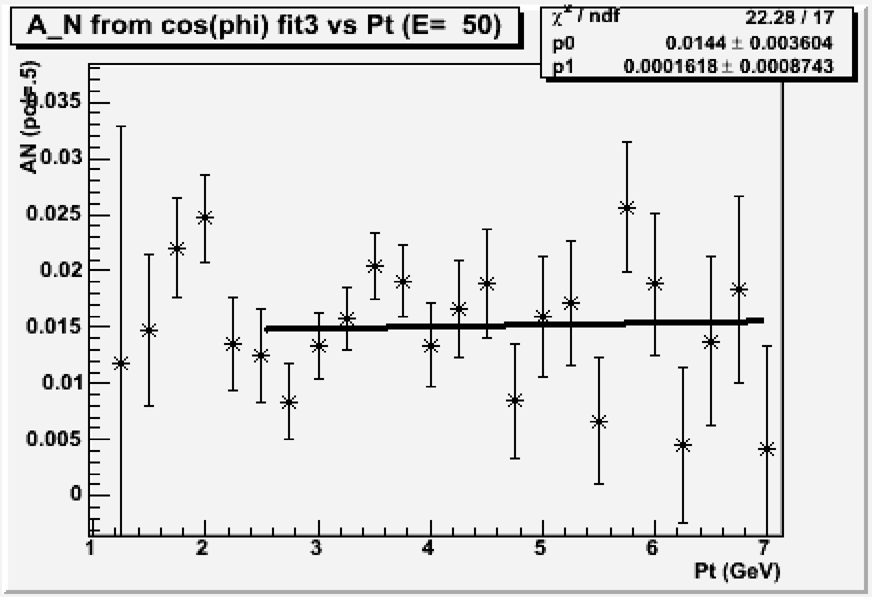


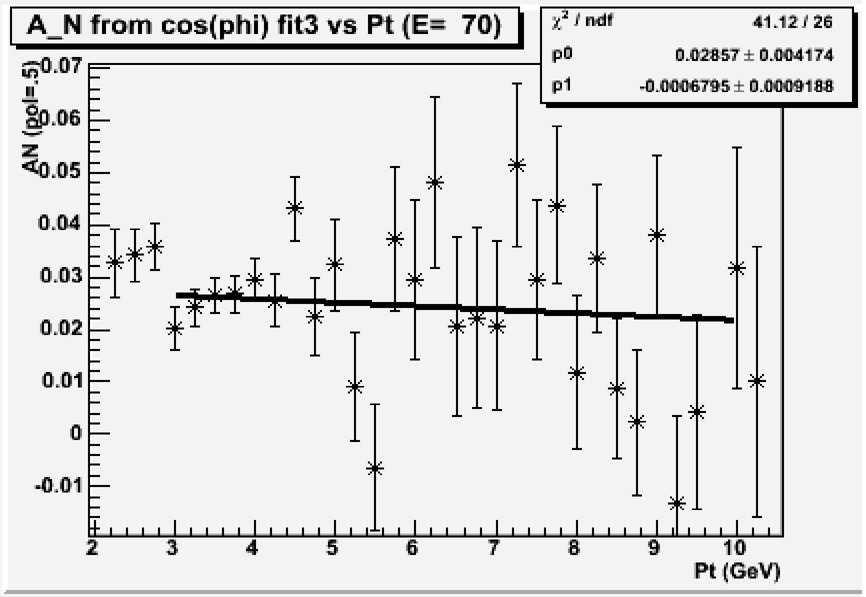
Summary

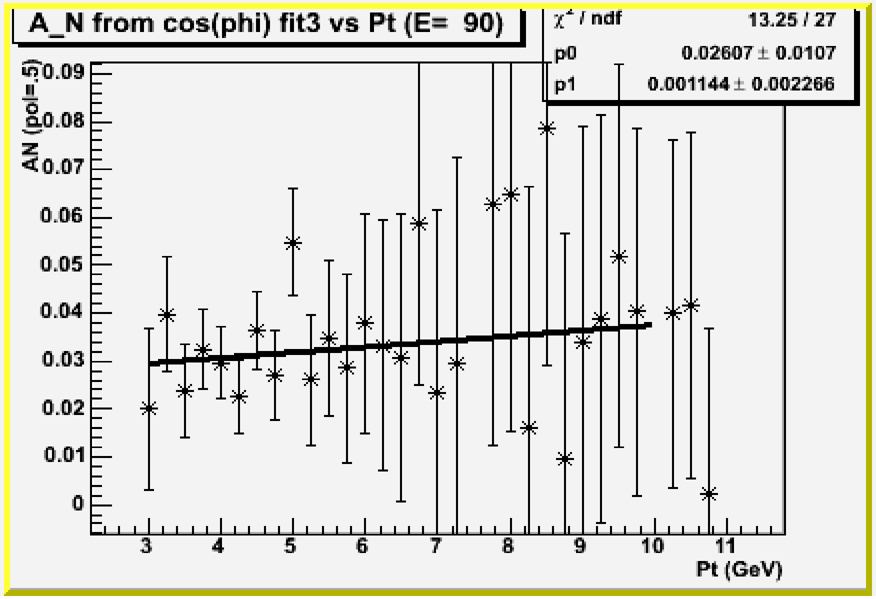
- **A high statistic measurement is presented for A_N in forward π^0 production** in transversely polarized pp collisions ($\sqrt{s}$ =500 GeV) at STAR from Run 11 in the 0.16<XF<0.4. Where they overlap in Pt, the scale of new values of A_N are similar to that previously measured at $\sqrt{s}$ =200 GeV).
- Asymmetry is measured as a function of transverse momentum for different methods of π^0 event selection. The methods that use **a larger cluster size (implying more isolated π^0 s) gives significantly larger values of A_N** at lower transverse momentum.
- The transverse momentum distribution for smaller cluster sizes, a measurement more approximating an inclusive measurement, **gives an asymmetry which, which is nearly constant in transverse momentum out to ~ 10 GeV/c.**
- The energy and angular distribution of the rest of the electromagnet energy in the event is studied. The asymmetry A_N is suppressed when the additional energy is on the same side as the principle π^0 .
- **We report that observation of additional jet particles reduces reduced the observed values of A_N.**
- Both Collins and Sivers effect models involve at jet that fragments to produce a π^0 to produce single spin transverse asymmetries.
  - (?) In "Collins Effect", the ovserved A_N require fragmentation to several fragment. The structure of the jet is what gives us asymmetry.
  - (X) In Sivers effect, that jet itself produces the asymmetry and the π^0 asymmetry is a somewhat diluted version of that associated with a jet observation.
  - Theoretical Analysis needed

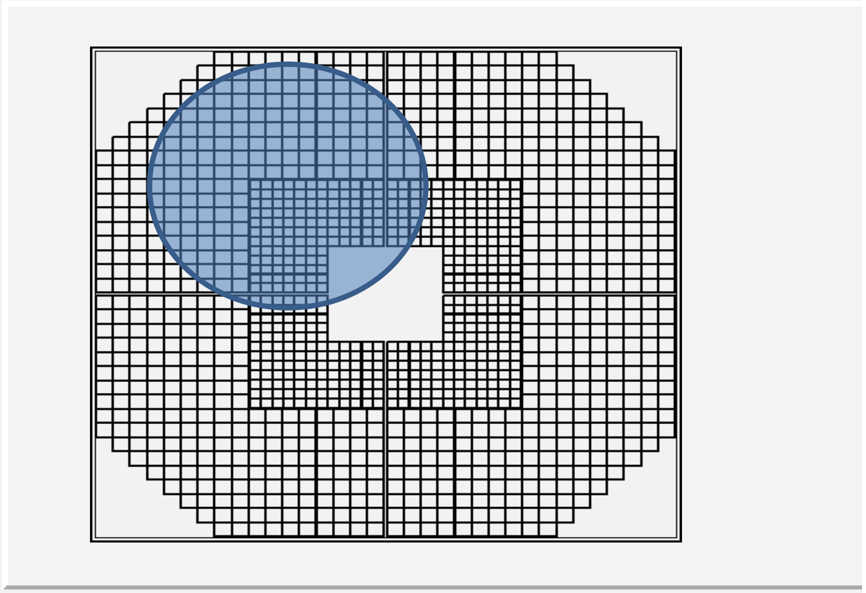
Extra Slides

Fitted Pt Slopes: (70mR cone)

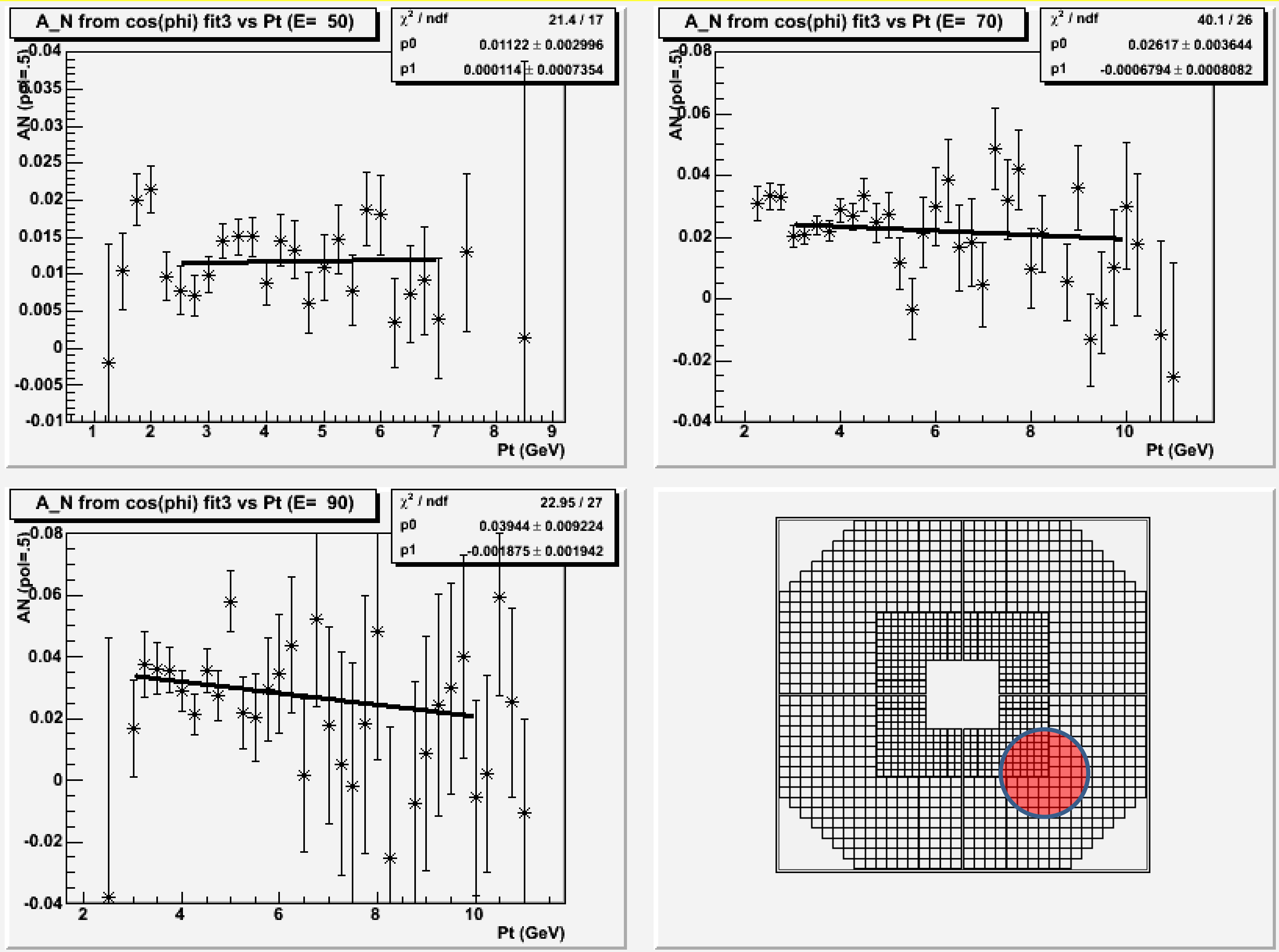








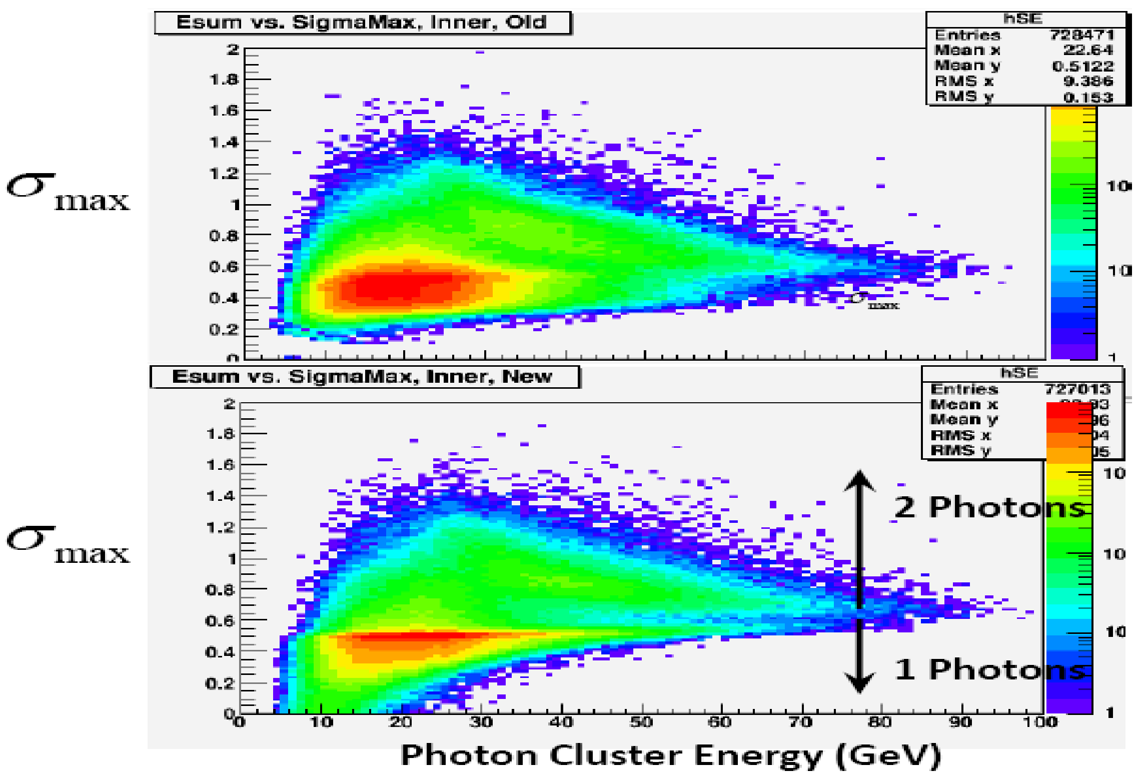
Fitted Pt Slopes: (30mR cone)



$$\Delta\sigma_x{}^2 = \frac{\sum_{i\,(e_i>e_0)} (x_i - x_0)^2 \ln(e_i / e_0)}{\sum_{i\,(e_i>e_0)} \ln(e_i / e_0)} \qquad \Delta\sigma_x \Delta\sigma_y = \frac{\sum_{i\,(e_i>e_0)} (x_i - x_0)(y_i - y_0) \ln(e_i / e_0)}{\sum_{i\,(e_i>e_0)} \ln(e_i / e_0)}$$

Separation of single photon cluster from two photon cluster based upon distribution of shower energy along a preferred axis.

$$\sigma_{\max} \equiv Max\ Eigenvalue\ of \begin{bmatrix} \Delta\sigma_x{}^2 & \Delta\sigma_x\Delta\sigma_y \\ \Delta\sigma_y\Delta\sigma_x & \Delta\sigma_y{}^2 \end{bmatrix}$$



Old algorithm with Energy weighted moments

Improved algorithm with log energy weighted moments.

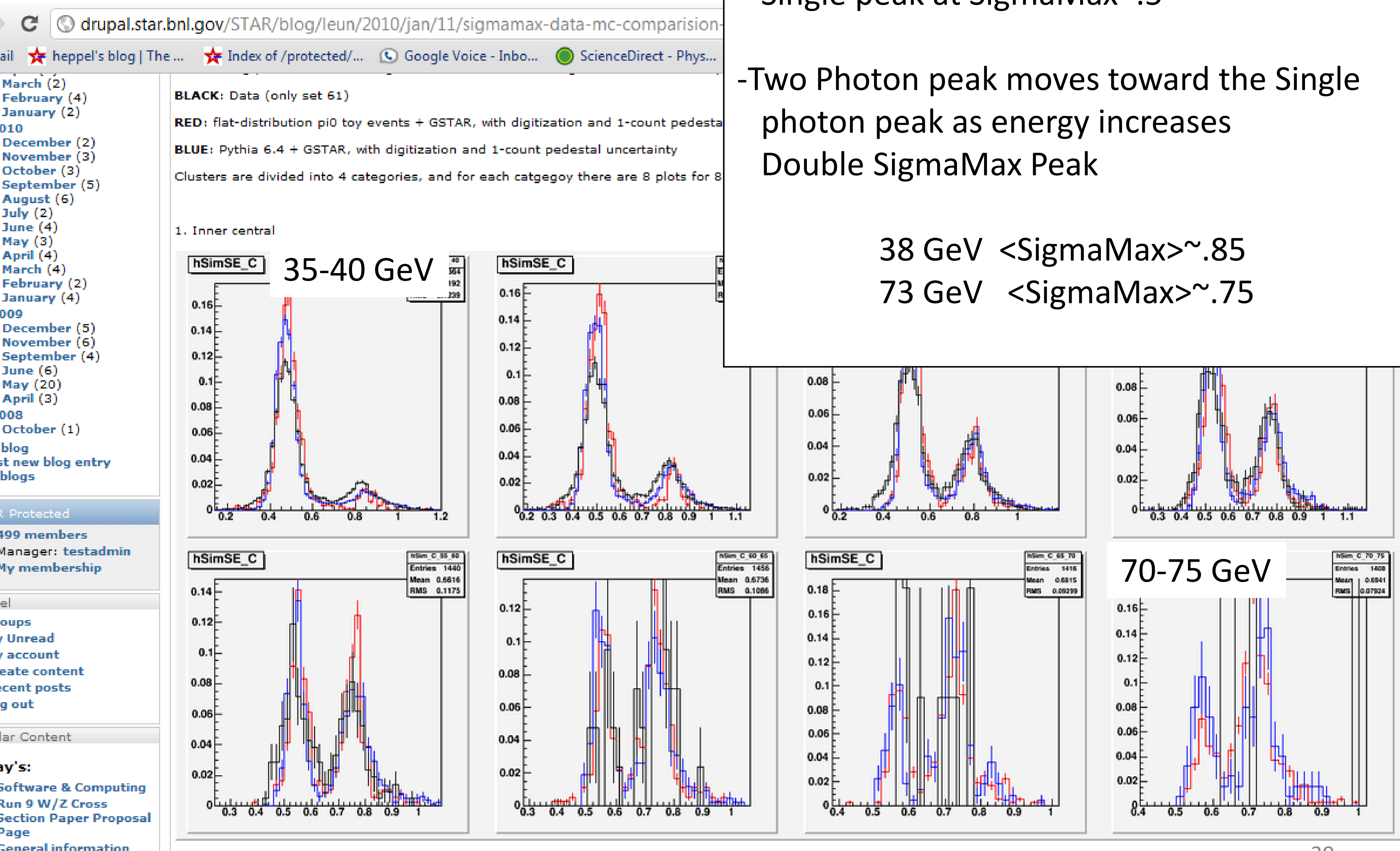
Provides clearer separation Between π^0 and single photon. Clusters up to ~80 GeV.

From Len's Analysis,

-Single Photon peak changes little with Energy
Single peak at SigmaMax~.5

-Two Photon peak moves toward the Single photon peak as energy increases
Double SigmaMax Peak

38 GeV <SigmaMax>~.85
73 GeV <SigmaMax>~.75



Run 11 distributions of SigmaMax as a indicator of single photon vs π^0 only slowly degrades with higher energy.