Run 11: P_T and Event Topology Dependence of A_N for π^0 Forward Production (FMS) (2011 Day 80-98)

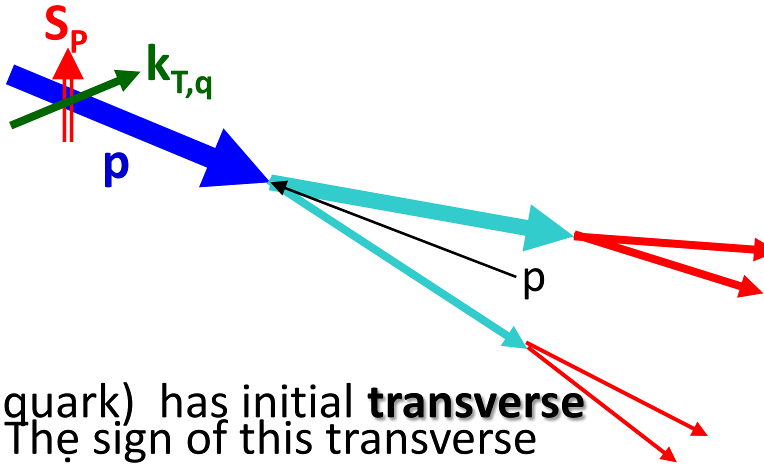
STAR Analysis Meeting

S. Heppelmann (PSU)

April 17 2012

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

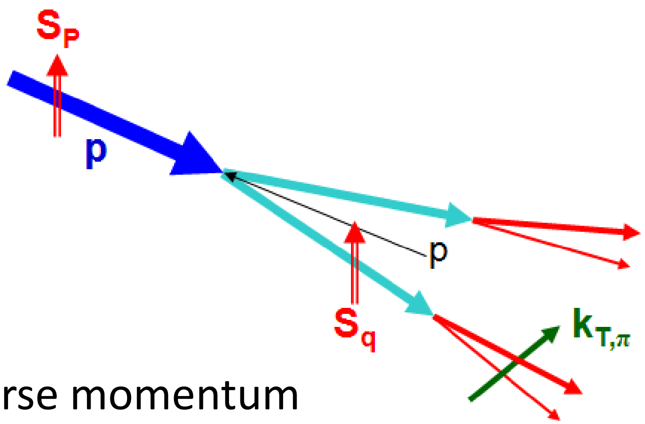
Sivers Model



- A fast quark in the polarized proton (probably a u quark) has initial **transverse motion relative to the incident proton direction**. The sign of this transverse momentum is connected to the proton transverse spin.
- The jet, **(apparently a u quark)** has a transverse direction that is biased relative to the nominal transverse momentum.
- The jet fragments with large z to produce a **meson that is moving in the direction of the jet**, with nearly p_T of the jet.
- Dependence of **initial state p_T** upon proton spin leads to Sivers A_N.
- Shape of **cross section similar for pi0 and eta**.
- This should be the **same whether** the jet fragments into a **pi0 or an eta**
- Observed (or unobserved secondary fragments are expected and should not reduce the asymmetry if observed).

Significant Dependence of A_N on the observation of additional near side jet fragments is not expected!

Collins Model



A_N vanishes as Z approaches 1

- Consider large eta A_N (perhaps of order unity)
  X_F~0.75 , Z~ .9 and **p_T~3.9 GeV/c**.
- Any associated jet fragments (n) will carry limited transverse momentum

$$k_T = \left| \sum_{\substack{n \\ additional \\ fragments}} \left(\vec{k}_T\right)_n \right|$$

$$|p_T| \to |p_T| + k_T \cos(\phi)$$

$$\phi = fragmentation\ \ azimuthal\ \ angle\ from\ spin\ direction$$

- If the cross section is given by

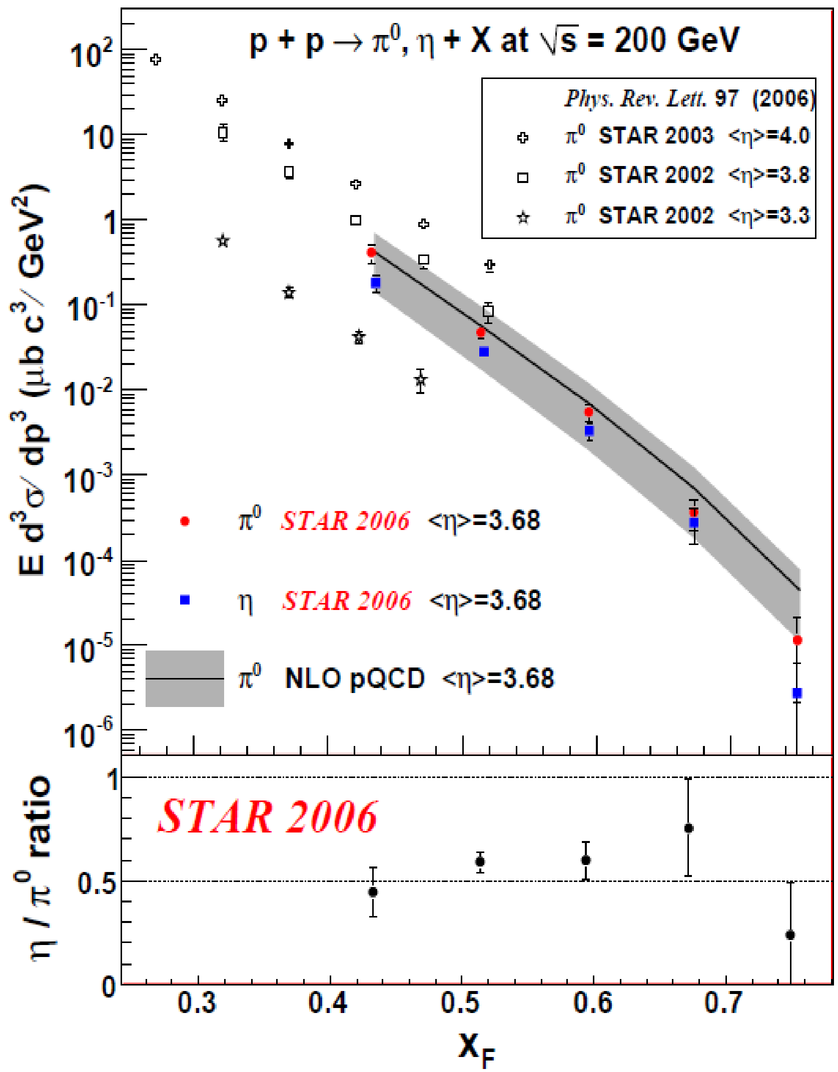
$$\sigma(p_T) \sim \frac{(1-x_F)^5}{p_T{}^6}$$

The Asymmetry would be for Collins or Sivers

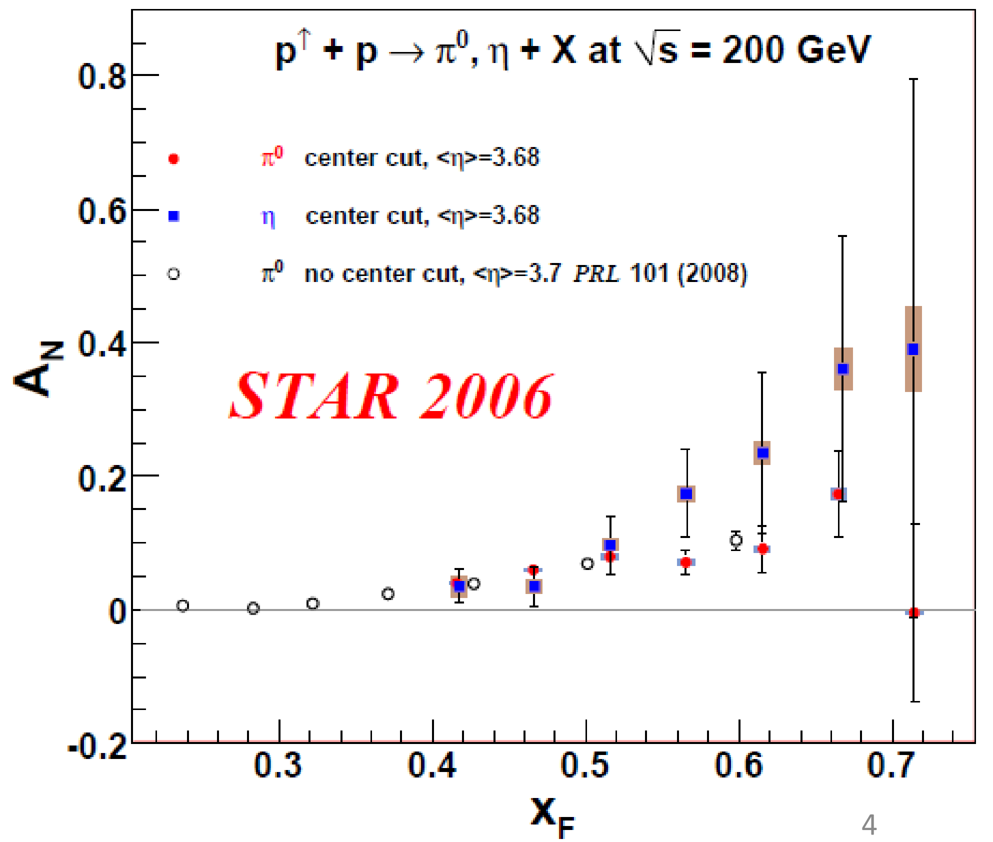
1. Expects that A_N will depend upon nature of jet fragment selection criterion.
2. A_N should fall as $1/p_T$. This is also the prediction from Sivers and “higher twist” PQCD.

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

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.
- $A_N(\eta) > A_N(\pi^0)$ for $X_F > 0.55$



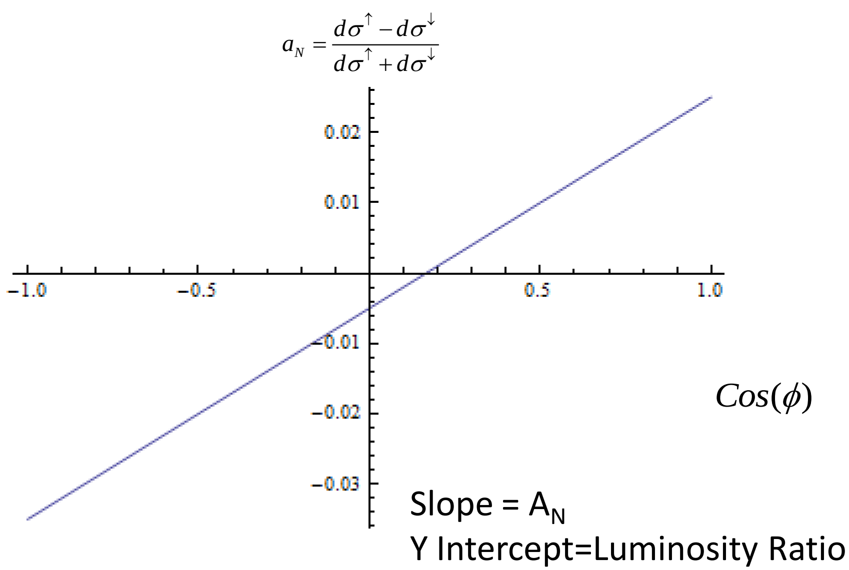
FMS History

- 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)
- Run 12
  - Pp (100x100 GeV) with transverse and longitudinal polarization (current run)

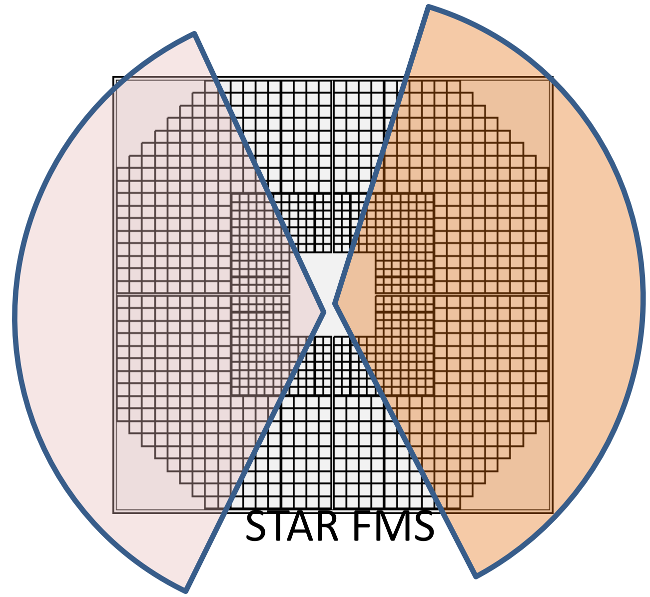
Cross Ratio Transverse Asymmetry
vs
A(ϕ) observation

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



Right(S): Cos(ϕ)>0.5

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

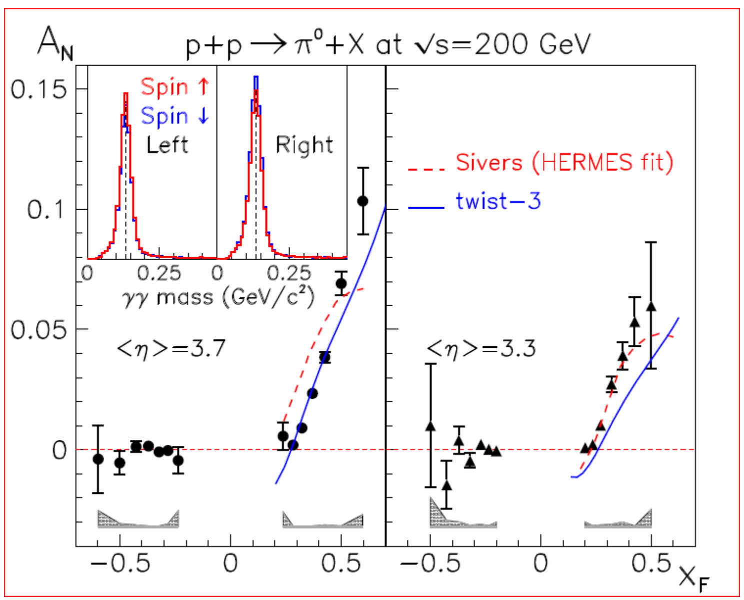
Method 2:

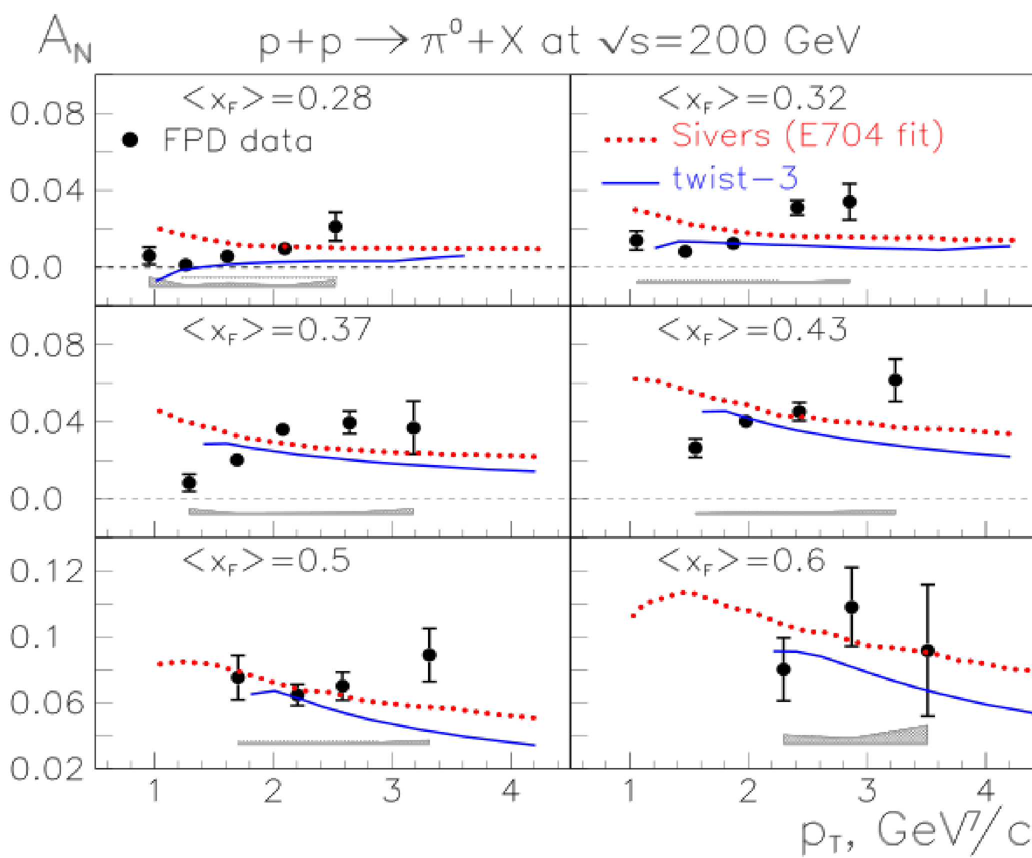
Fix a_0 for full data set for many small data subsets ….. One parameter fit for A_N

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

STAR Published Run 6 (FPD √s =200GeV)

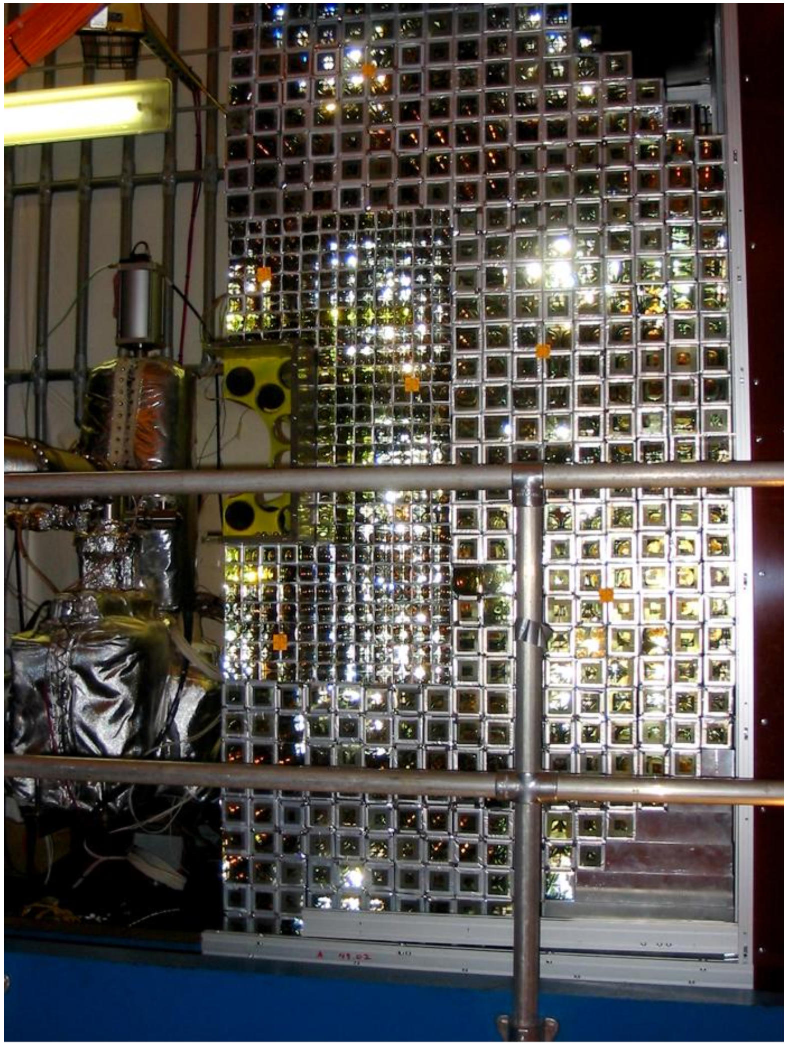
- Rising A_N with XF ($0<X_F<0.5$)   from 0% to 5-10%
- No evidence of fall in A_N with increasing P_T.

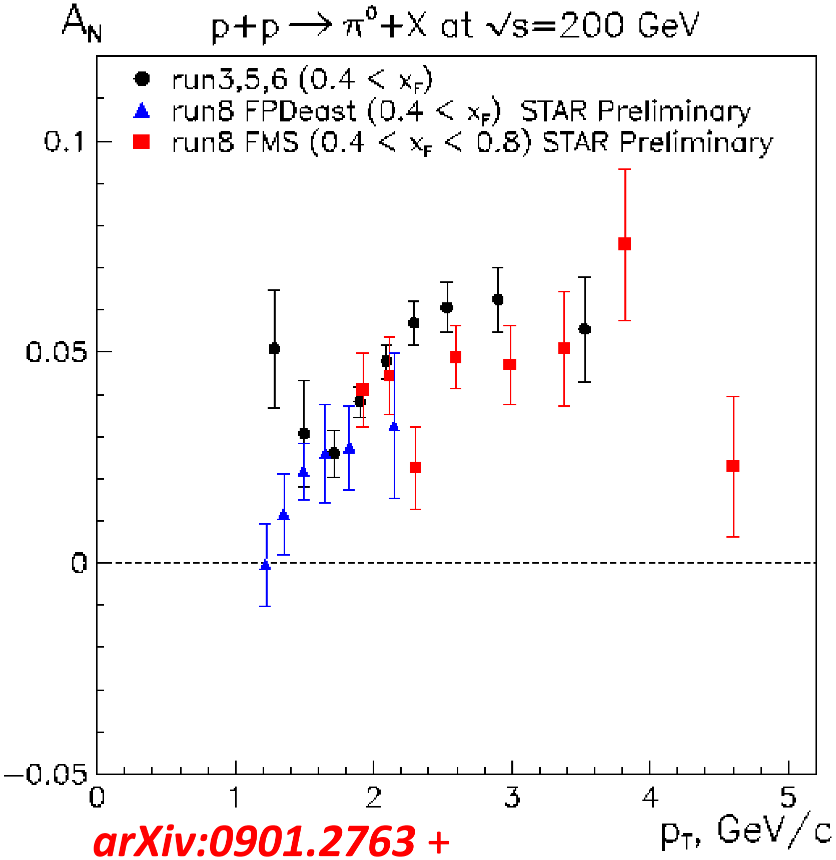




From FMS Run 8, STAR has Expanded Rapidity Coverage -1<Y<4.2

STAR Forward Meson Spectrometer
2.5 < Y < 4.0



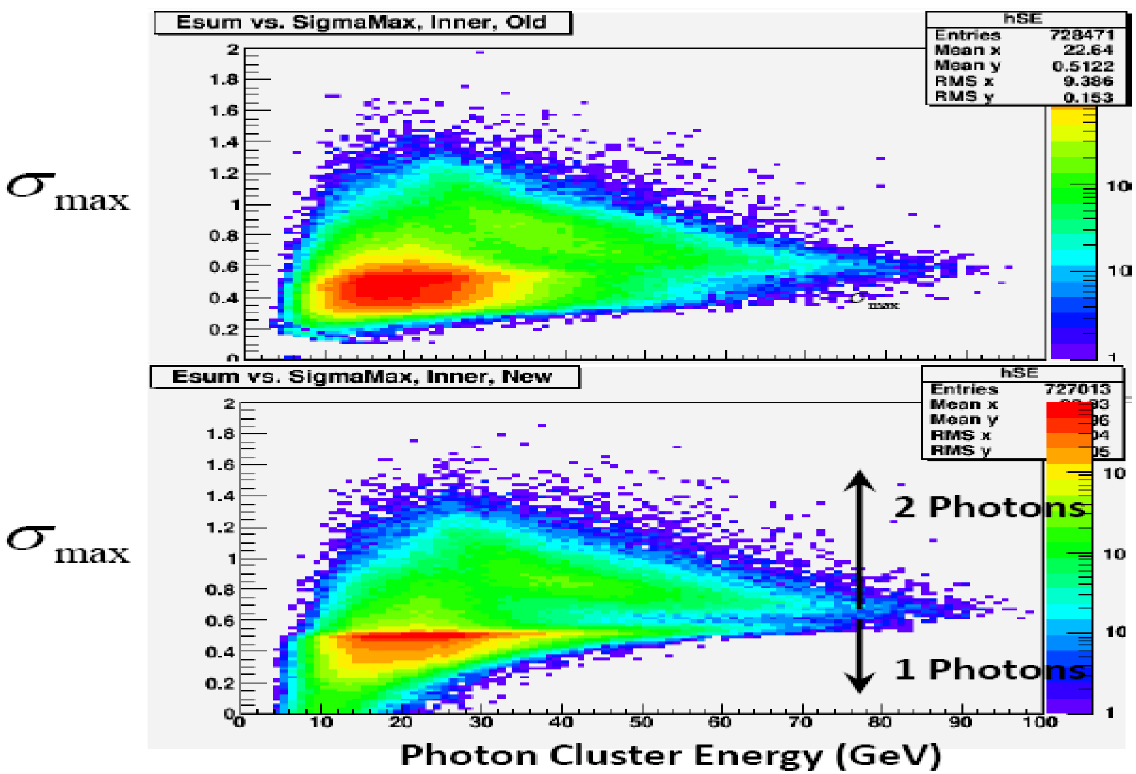


arXiv:0901.2763 +
A.Ogawa @CIPANP09

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

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

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



Old algorithm with
Energy weighted moments

Improved algorithm with
log energy weighted moments.

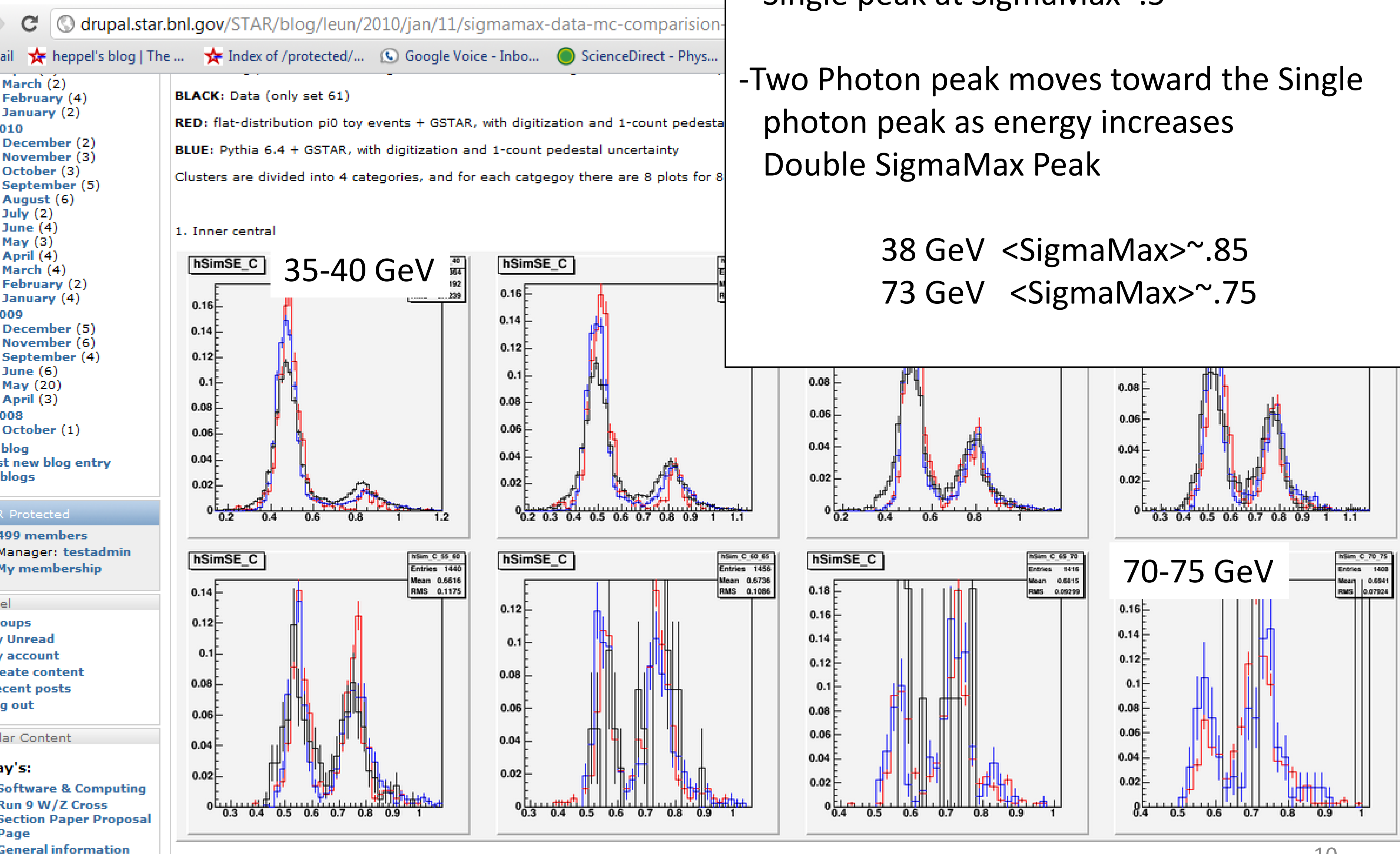
Provides clearer separation
Between π^0 and single photon.
Clusters up to ~80 GeV.

From Len's Analysis,

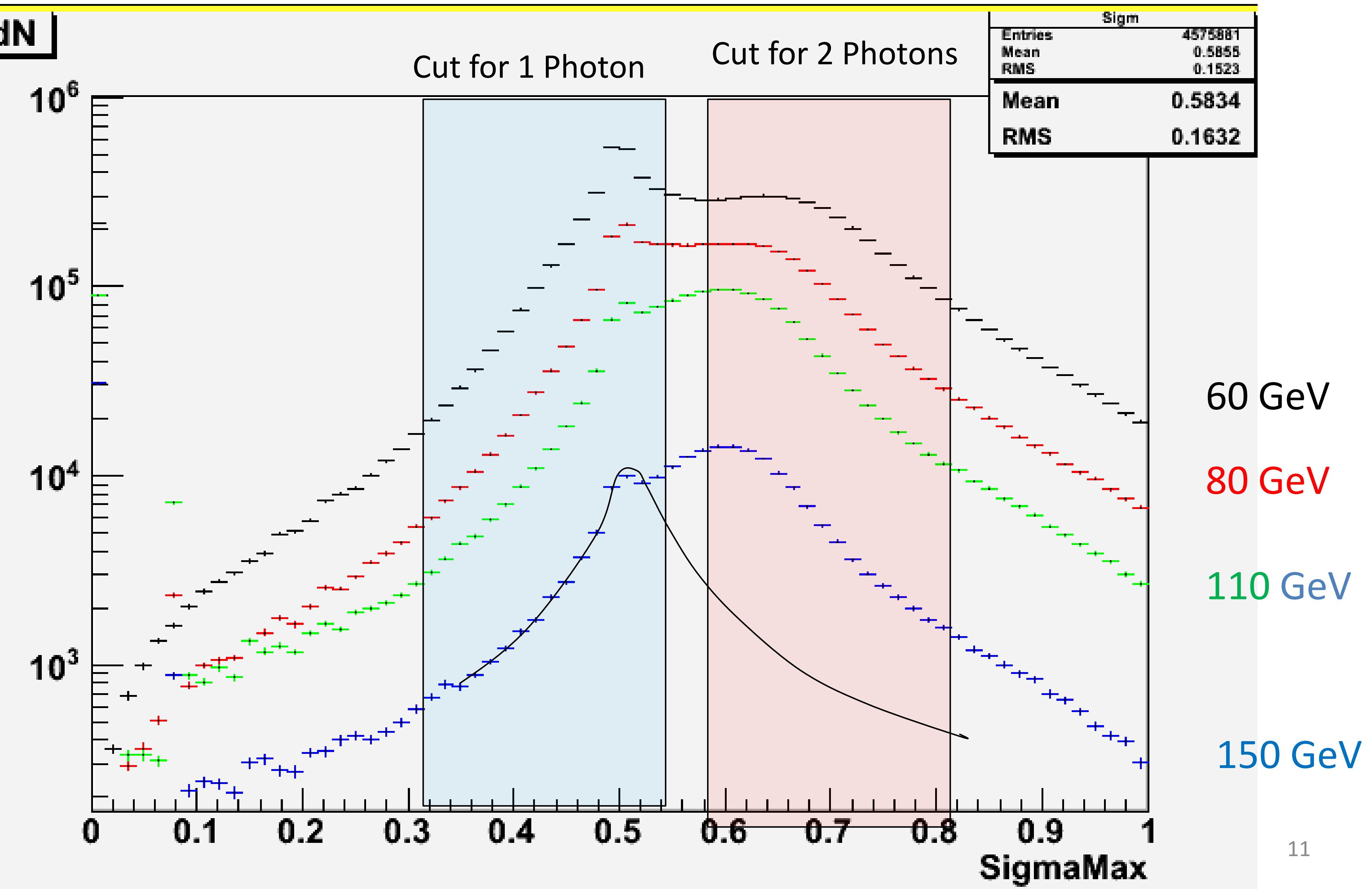
-Single Photon peak changes little with Energy
Single peak at SigmaMax~.5

-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.



Event Selection:

1. **Analyze FMS for all photon** candidates. (Showers that are fit successfully to photon hypothesis)
2. **Find Clusters of EM energy** 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.

   Cluster 4 Vector ->

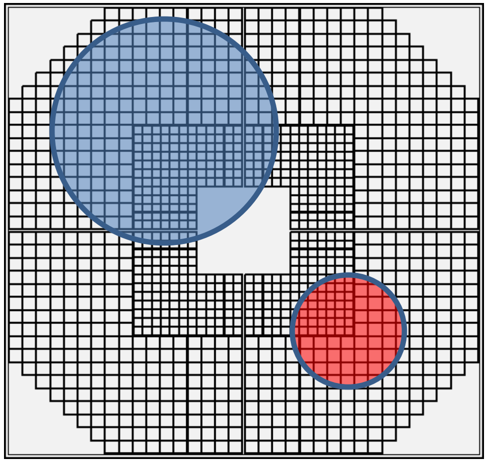
   $$(E_{cluster}, \theta_{cluster}, \phi_{cluster}, M_{cluster})$$

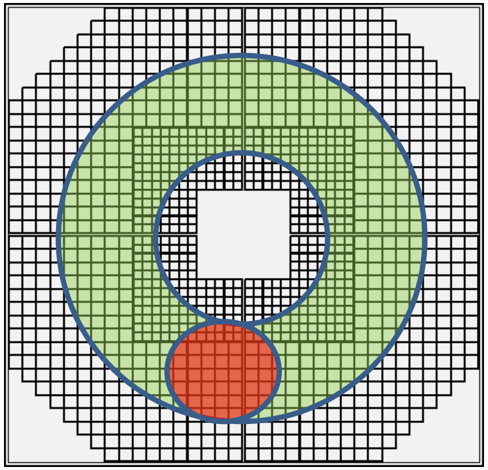
3. Find **the center of the rest of the FMS photon energy**, the complement of the Cluster.

   Away 4 Vector ->

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

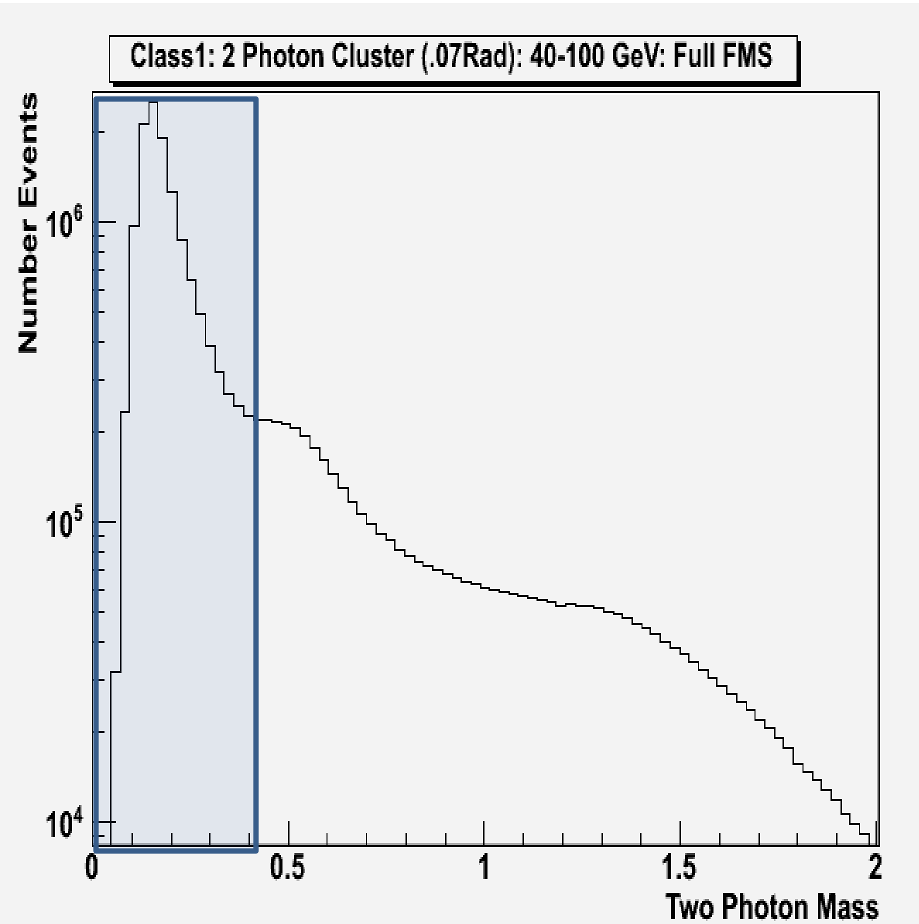
4. We consider 4 event classes {1,2,3,4}
   1. $\Delta\theta = 0.07$ 2 Photon clusters, Pi0 Mass (inclusive)?
   2. $\Delta\theta = 0.03$ 2 Photon clusters ,Pi0 Mass (inclusive)?
   3. $\Delta\theta = 0.03$ 2 Photon clusters ,Pi0 Mass, Y_{away} **inside Green**
   4. $\Delta\theta = 0.03$ 2 Photon clusters,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

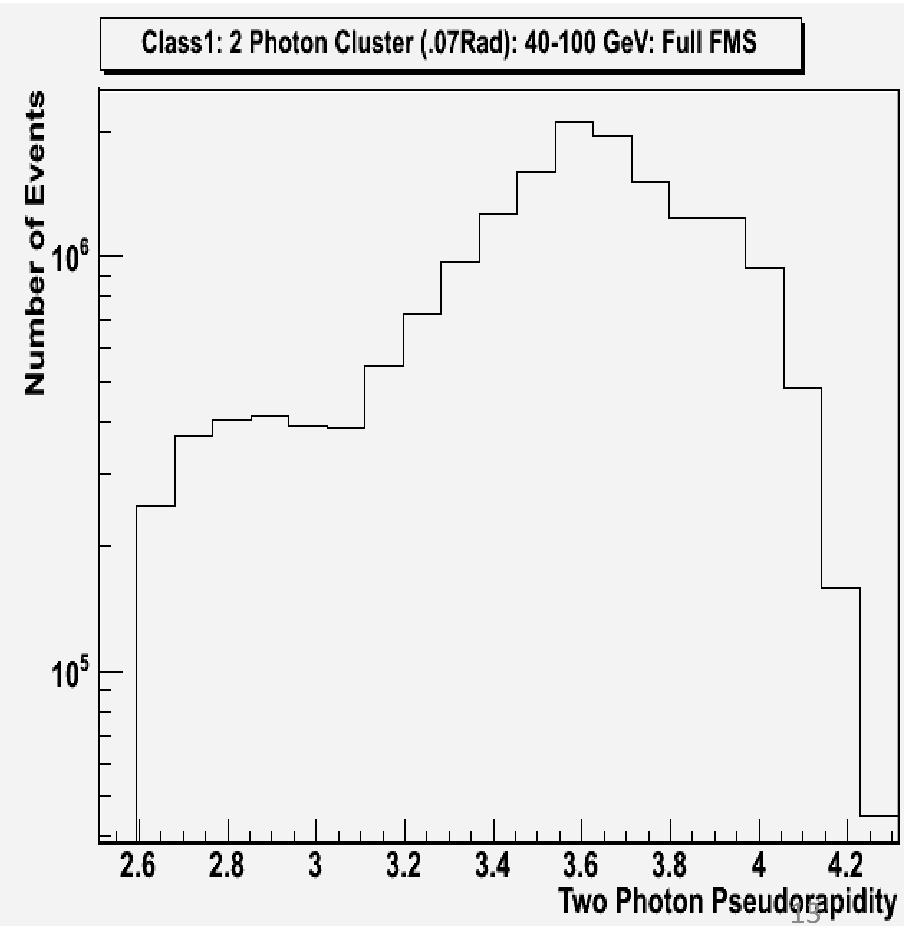




Class 1 Events: $\Delta\theta$ =0.07 2 Photon clusters, π^0 Mass (less inclusive)?

- 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



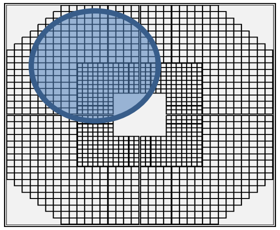


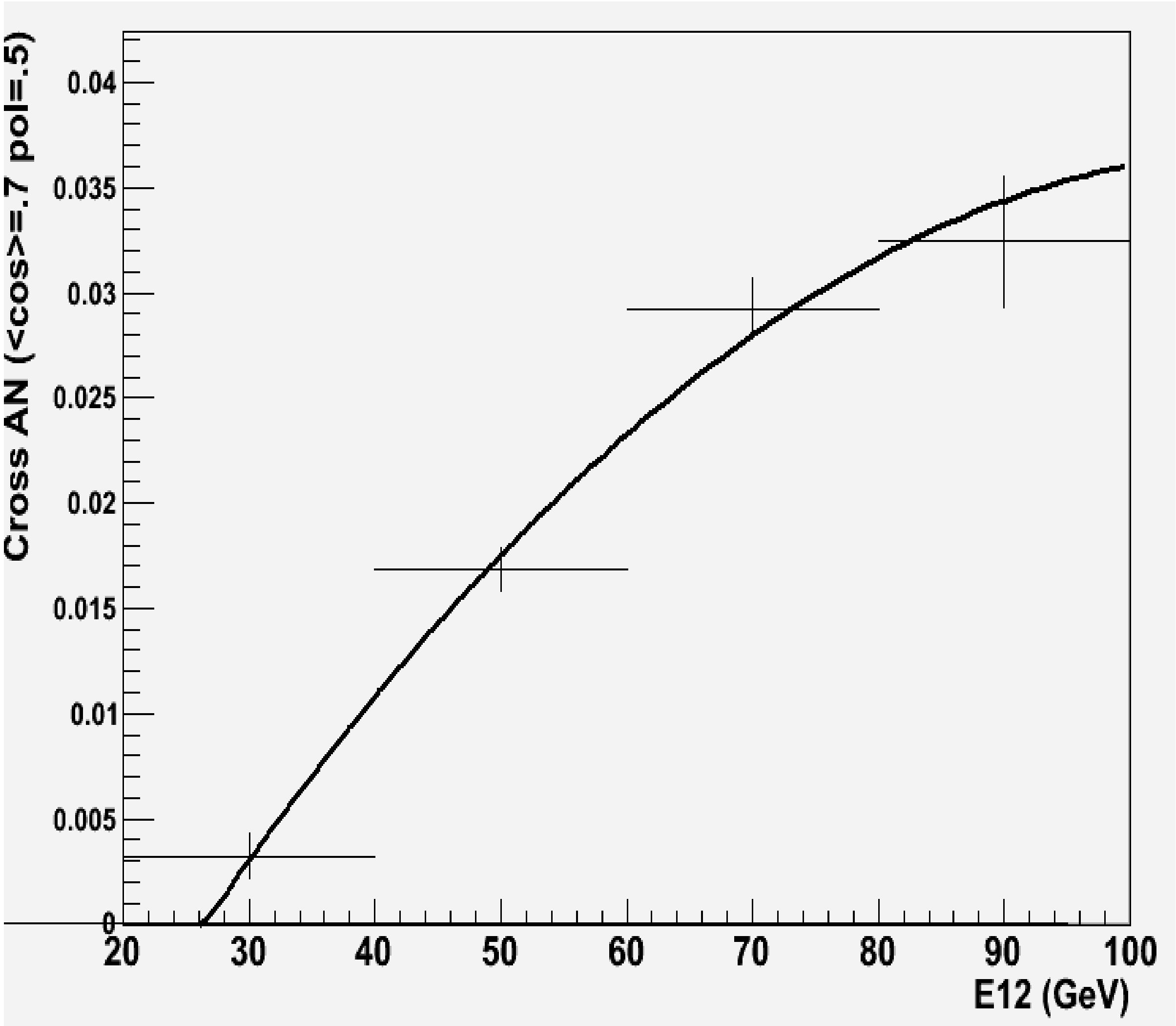
Cross Ratio Transverse Single Spin Asymmetry for Run 11

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

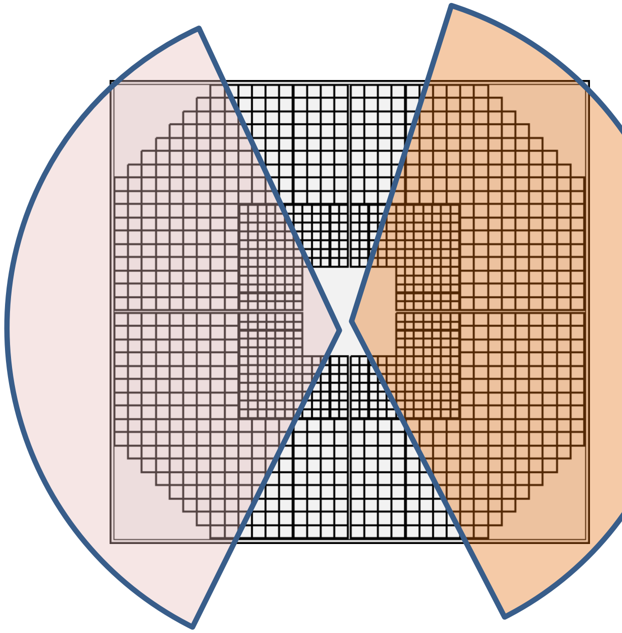
For Blue Beam (Forward)

Full FMS rapidity range.



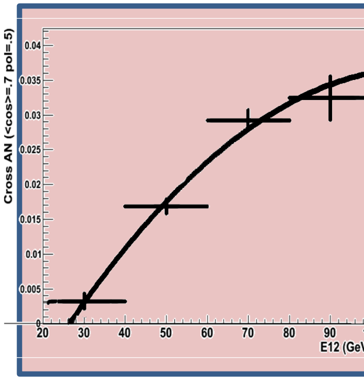


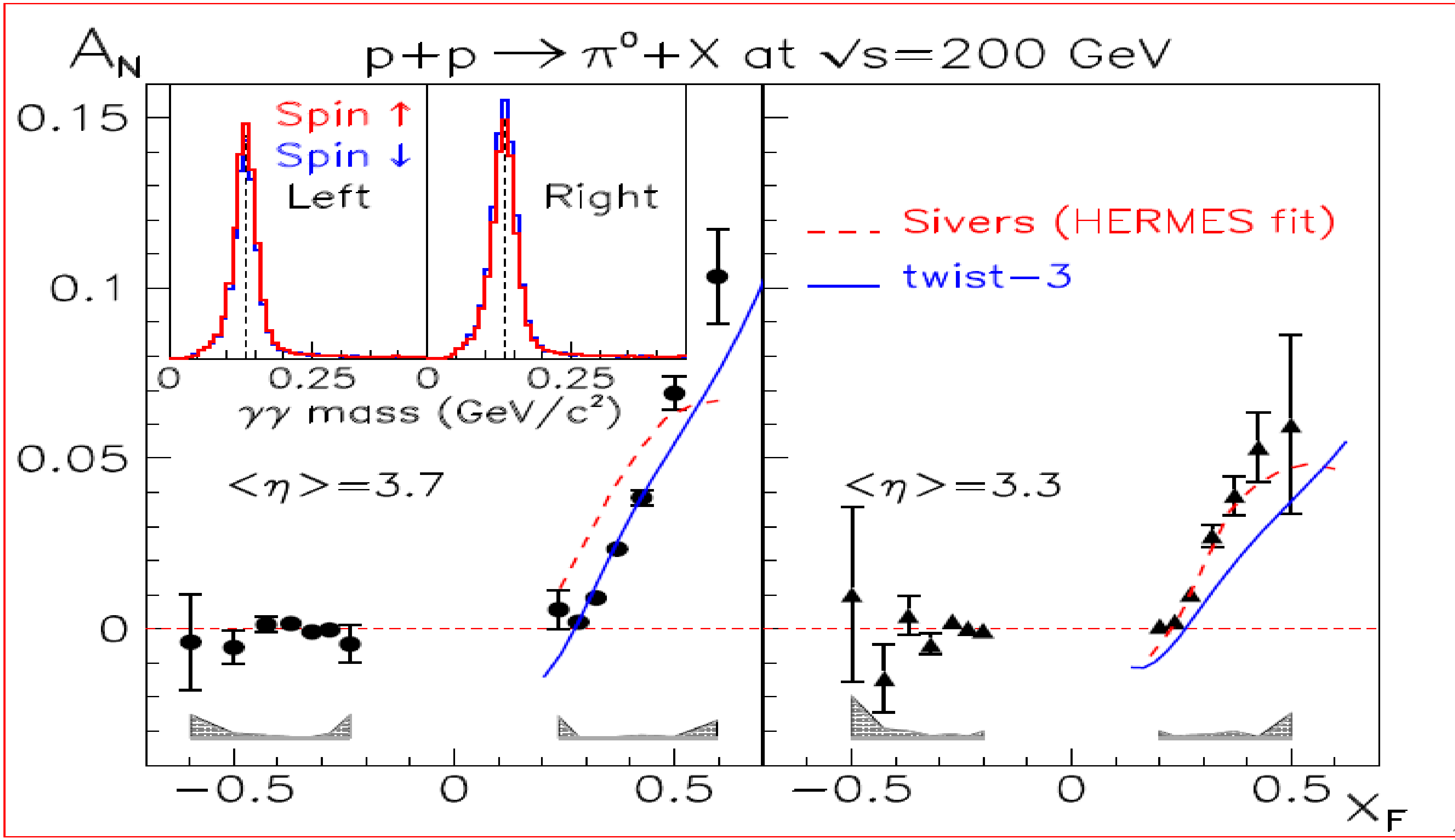
Left: $\cos(\phi)<-0.5$



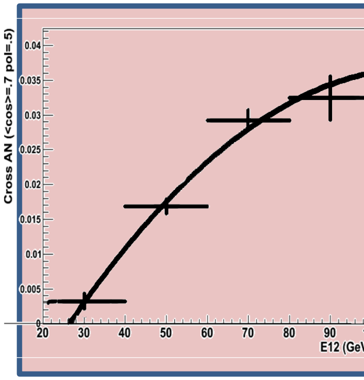
Left: $\cos(\phi)>0.5$

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

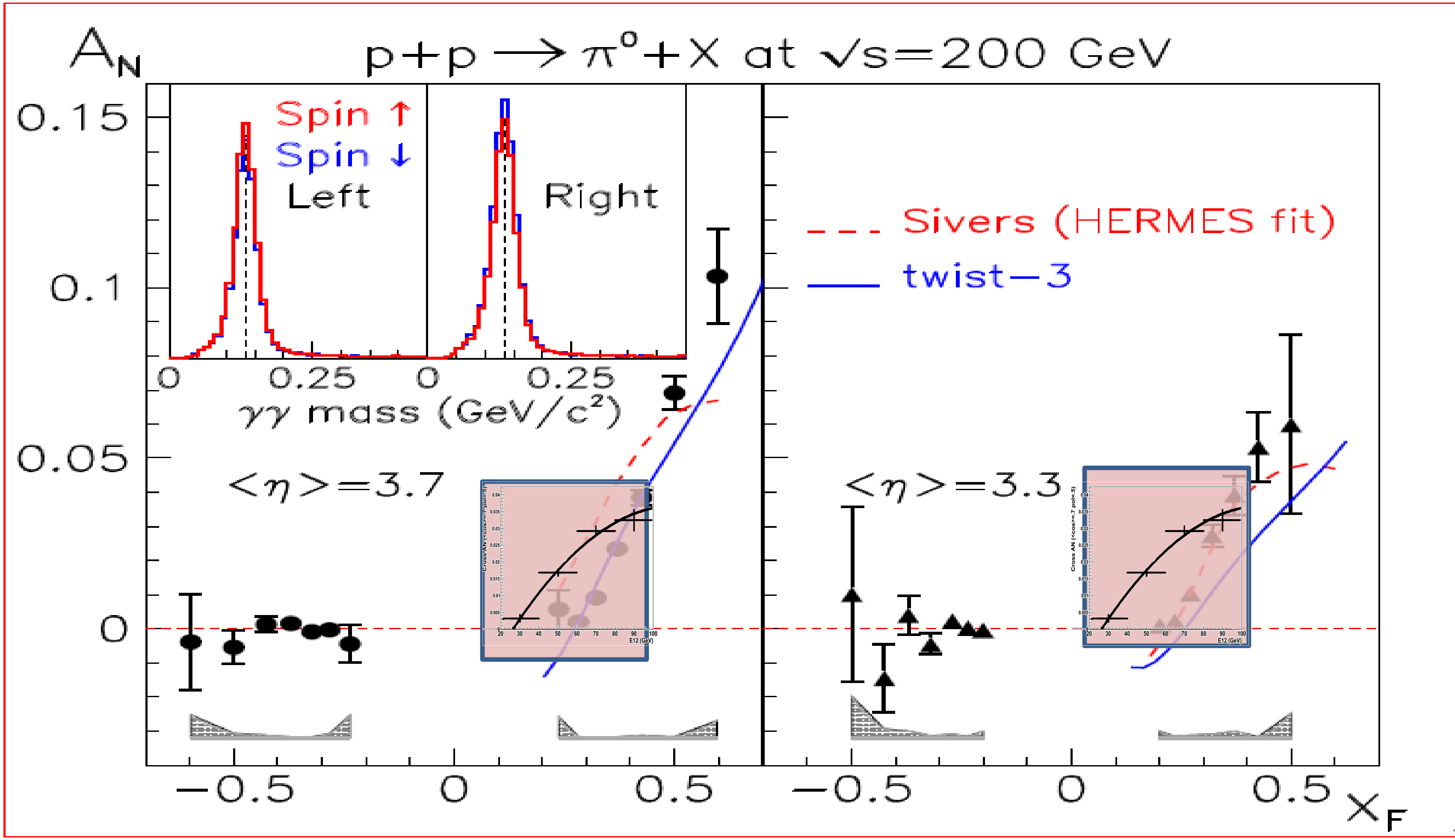


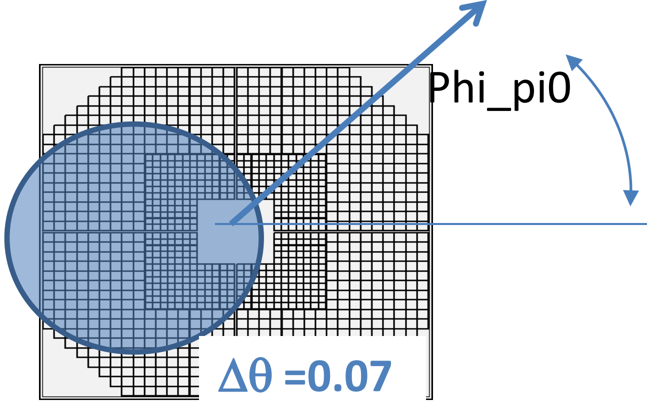


Compare **new √s=500 GeV Run 11** Full FMS Data on right with **Run 6 √s=200** published data below.

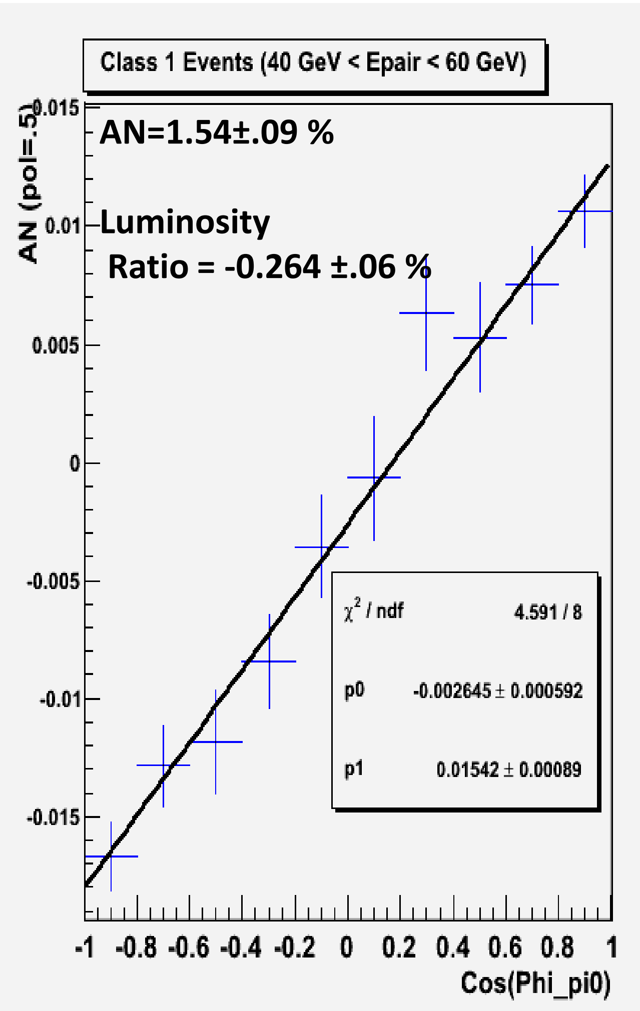


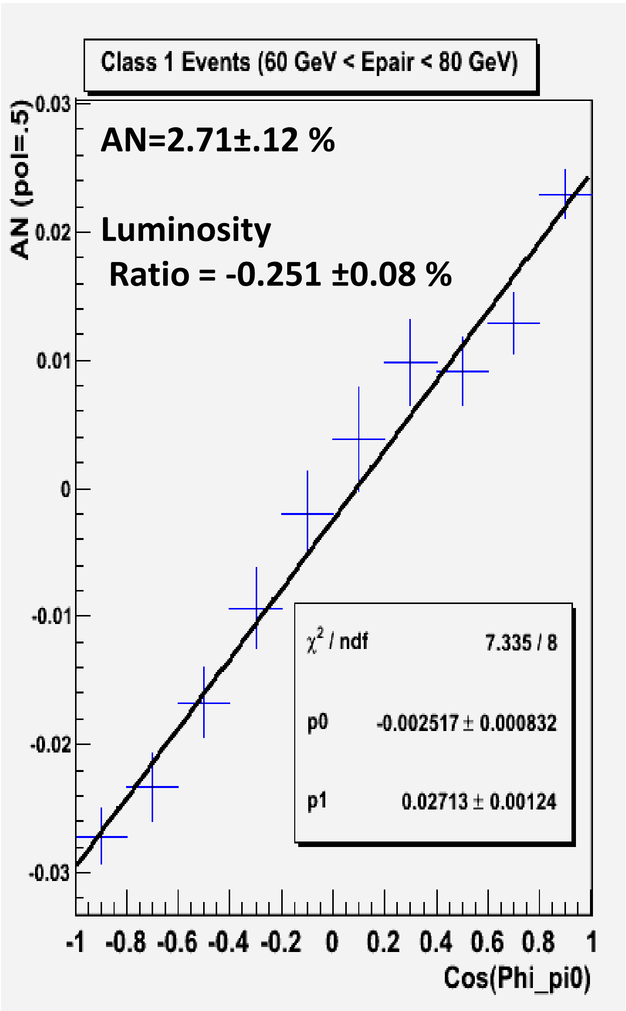
Scale of A_N similar but starts at lower X_F in Run 11 data.

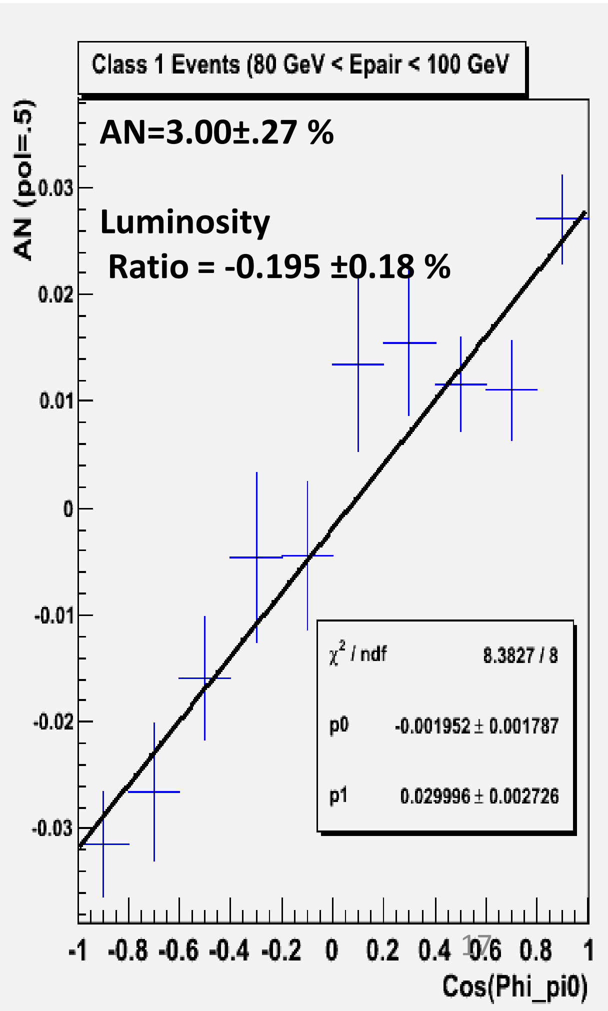




Blue Beam AN
As and alternative to Cross Ratio, the raw asymmetry
Can be plotted as a function of Cos(Phi)
(with polarization axis at Phi=pi/2)
Slope =AN
Intercept = Luminosity Ratio for data set
Luminosity ratio for all **~- 0.25 ±.05 %**







Yellow Beam (backward scattered)

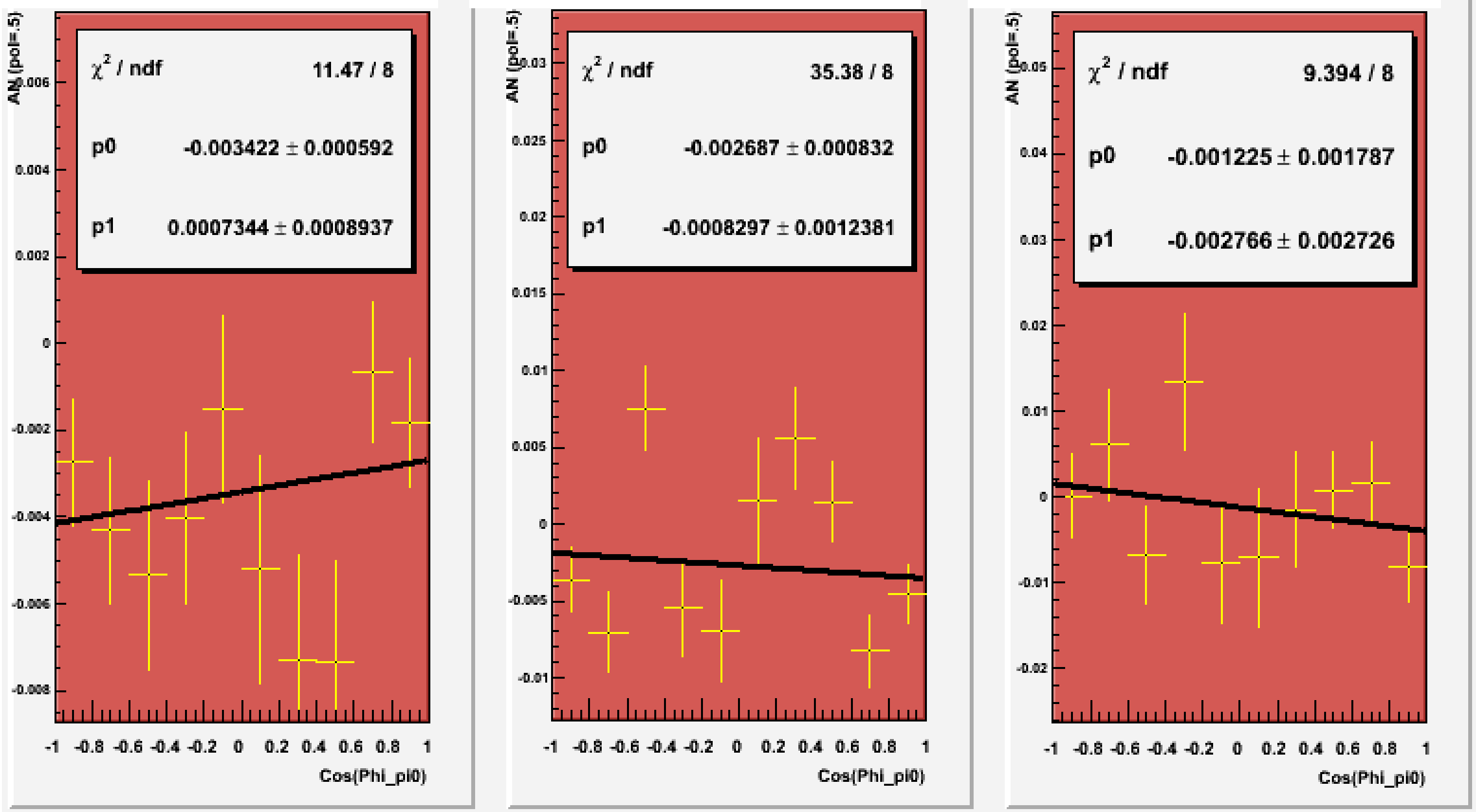
No significant A_N seen.

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 %

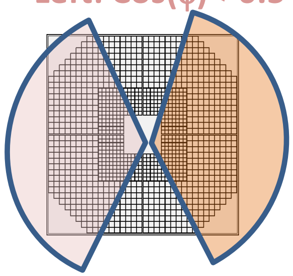
60 GeV < Epair < 80 GeV
AN=-0.08±0.12 %

80 GeV < Epair < 100 GeV
AN=-0.28±0.2 %



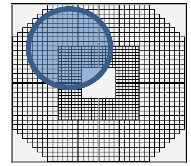
Cross Ratio Analysis of Transverse Single Spin Asymmetry As a function of P_T.

Left: Cos(ϕ)<-0.5

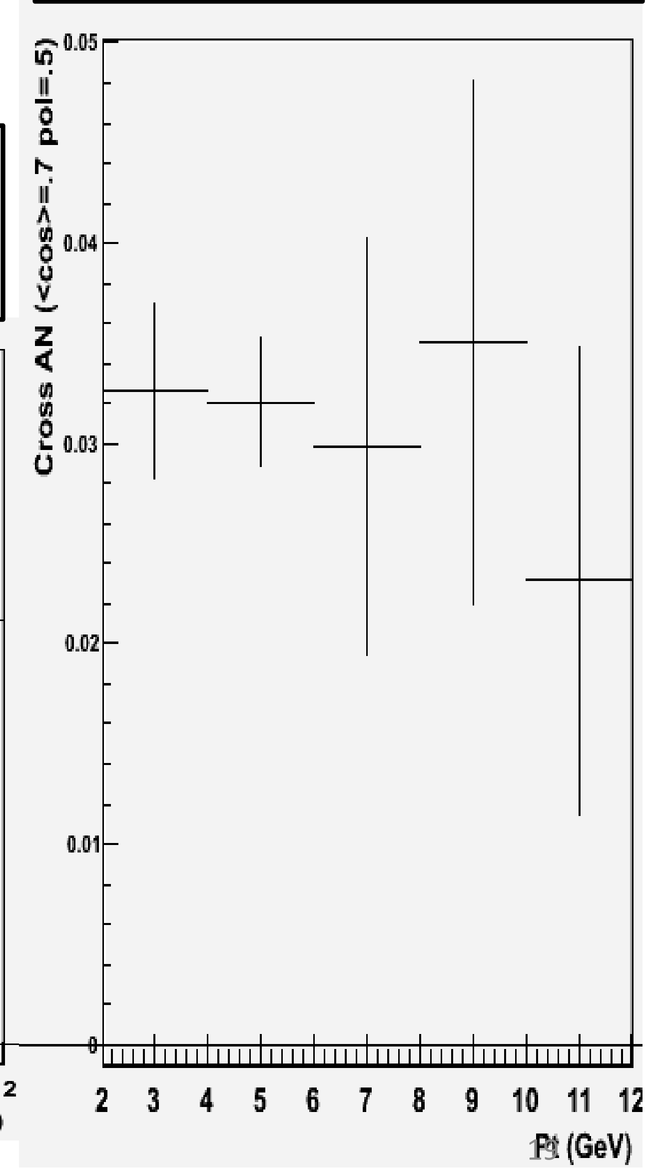


Right: Cos(ϕ)>0.5

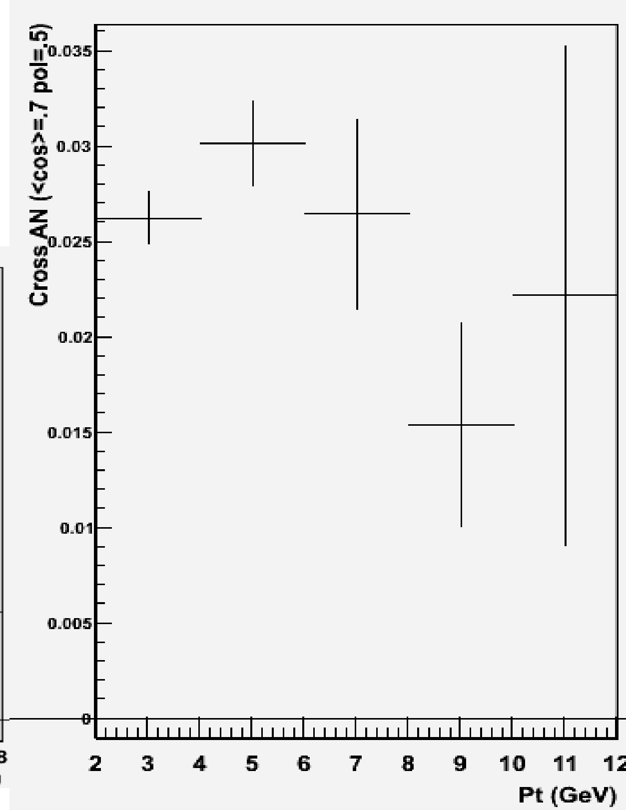
$\Delta\theta$ =0.07 Large 2 Photon clusters



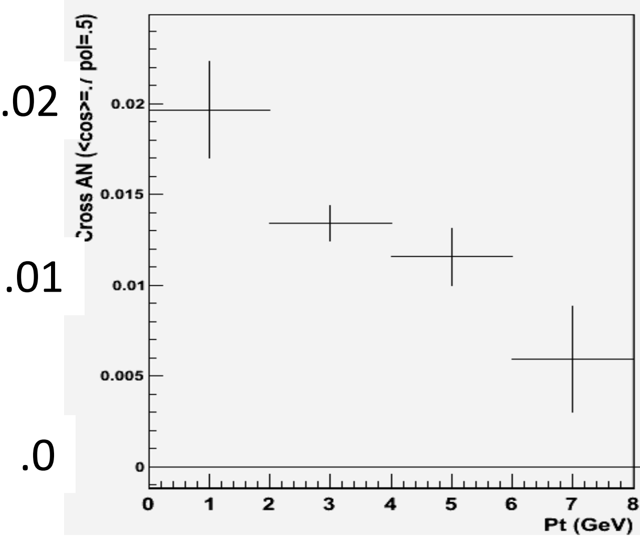
80 GeV < E_pair < 100 GeV
0.32 < X_F < 0.40



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



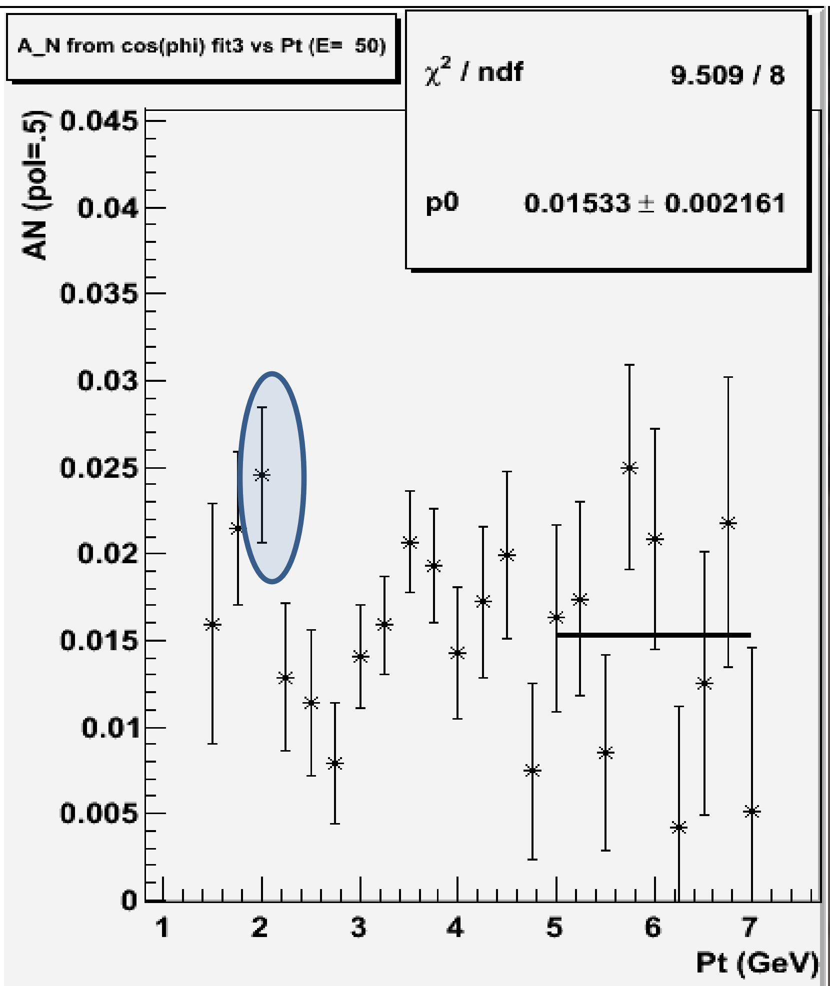
40 GeV < E_pair < 60 GeV
0.16 < X_F < 0.24

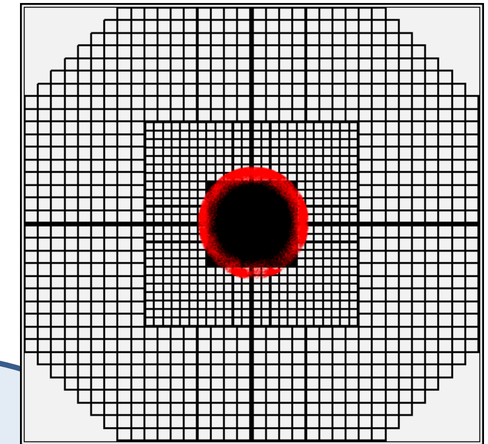


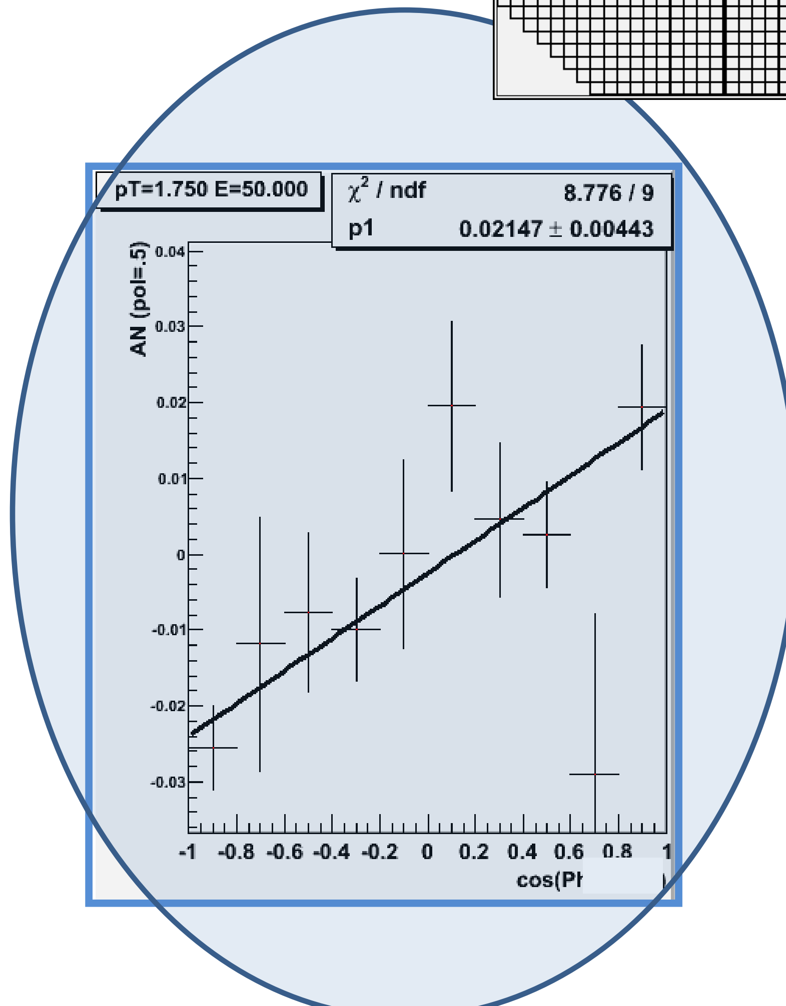
Cut data into small data sets and analyze the ϕ dependence of up/down asymmetry

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

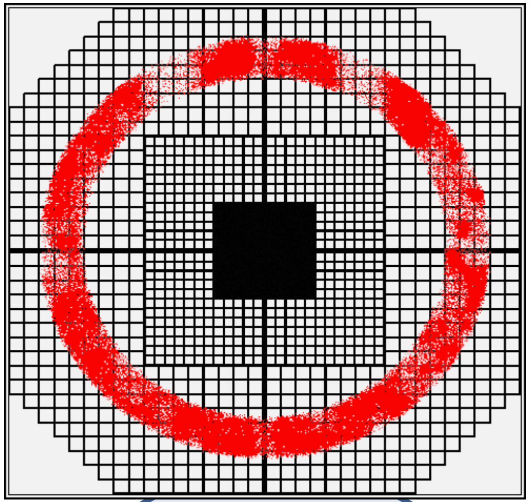


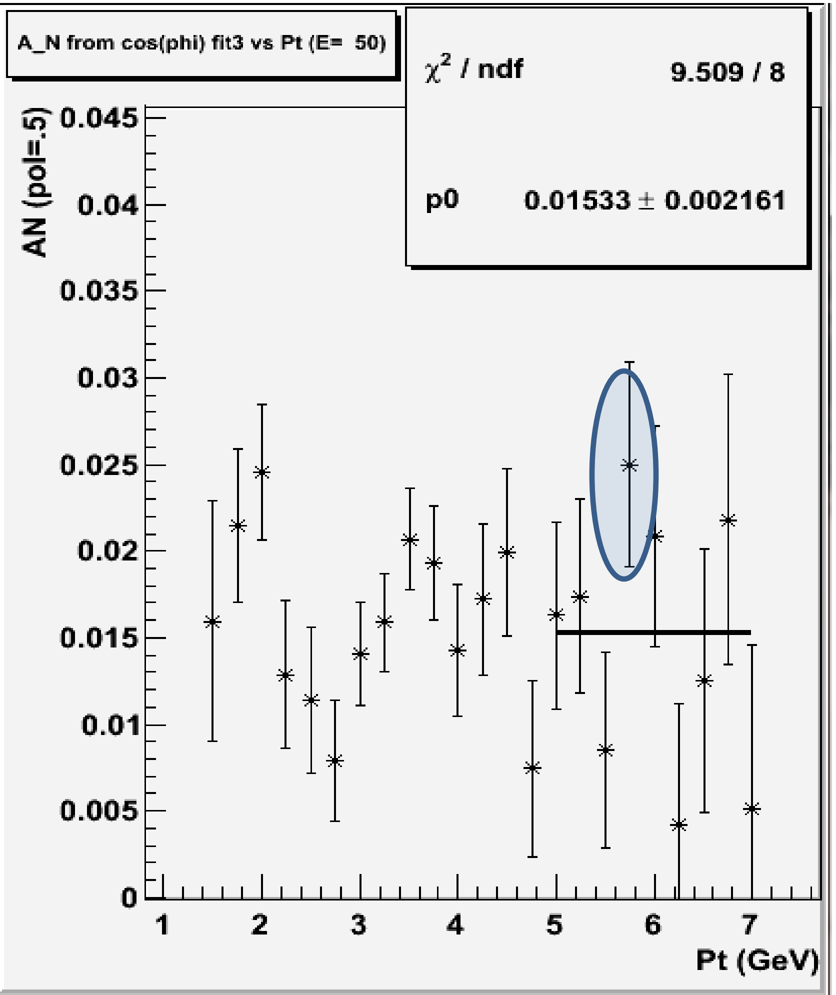


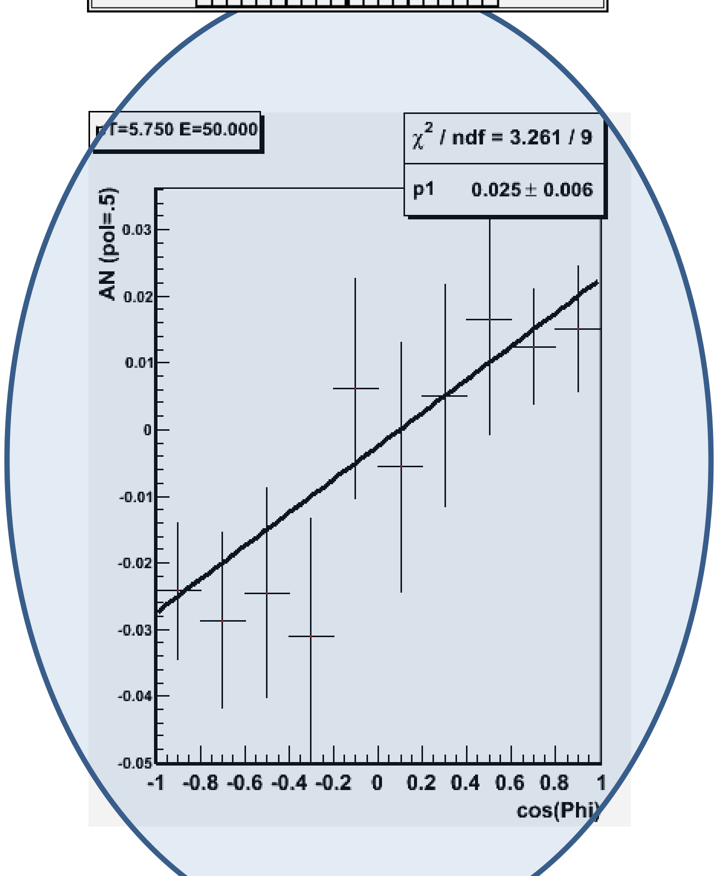


40 GeV < E_pair < 60 GeV

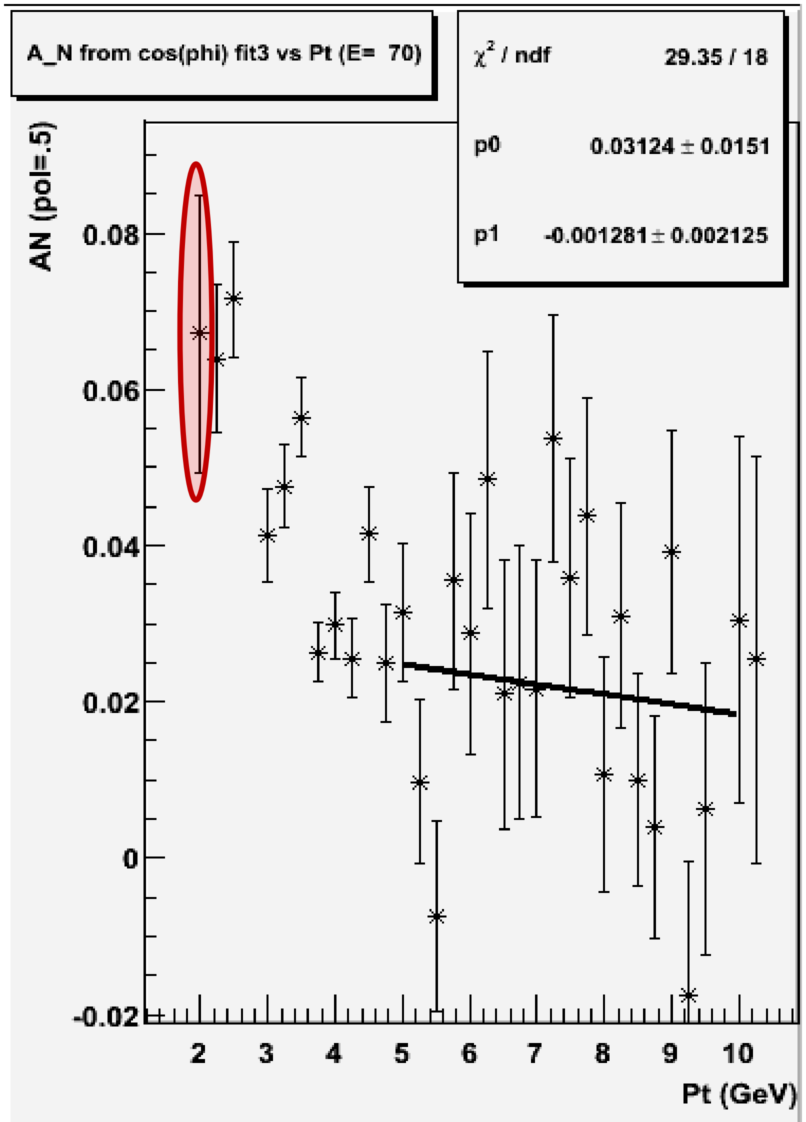
5.625 GeV <Pt< 5.875 GeV

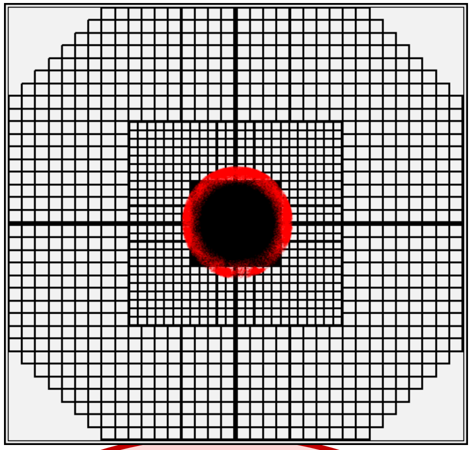


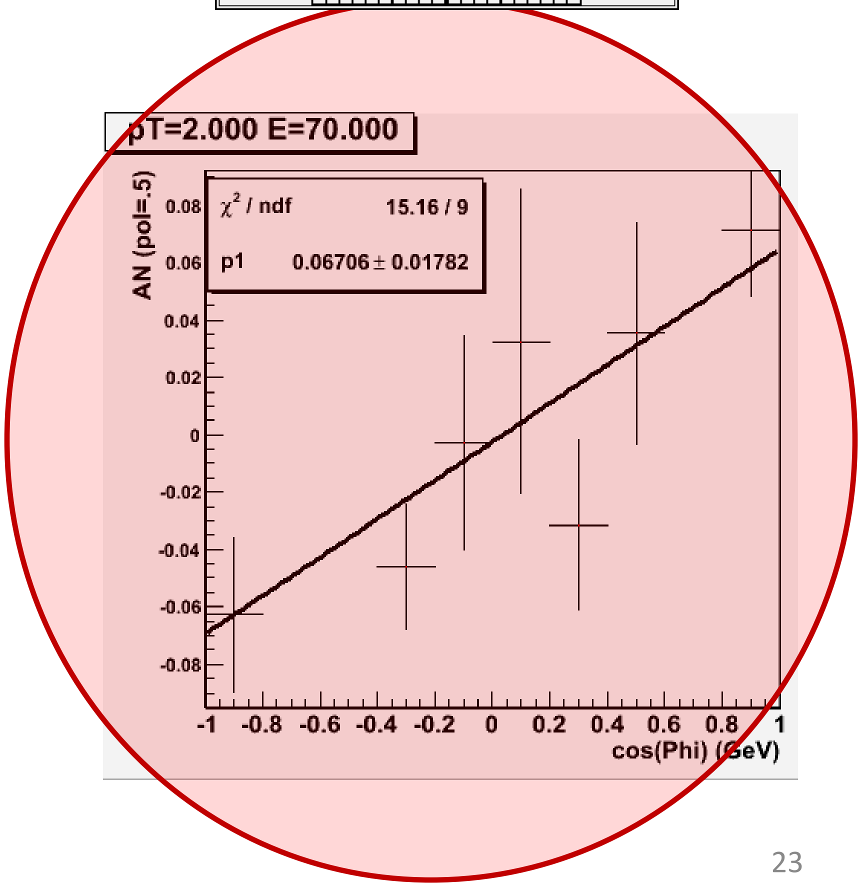




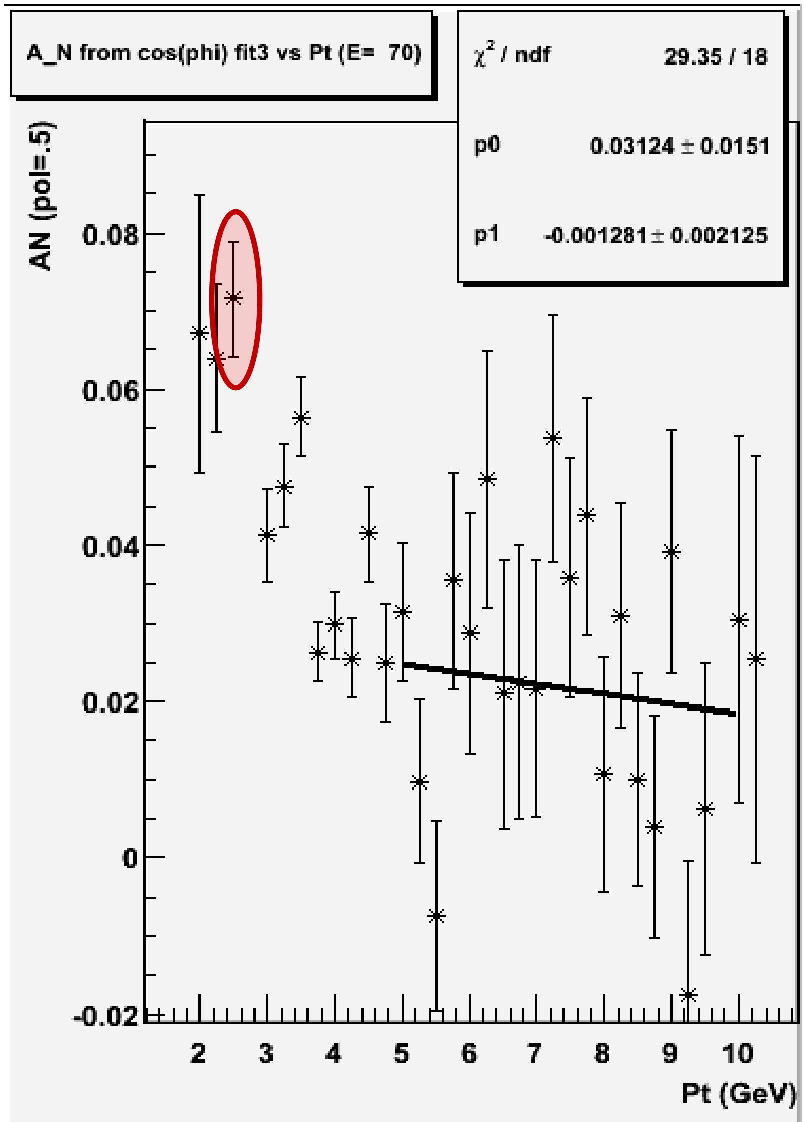
60 GeV < E_pair < 80 GeV

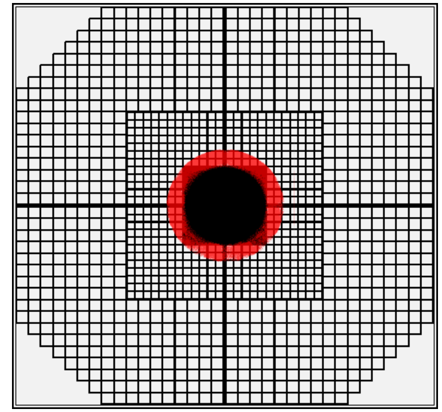


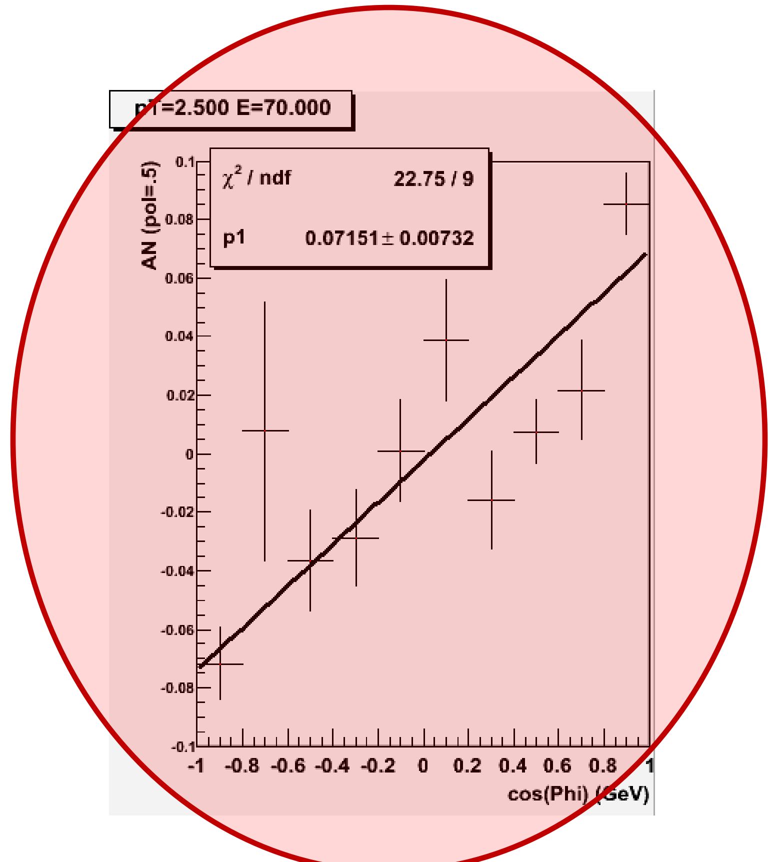




60 GeV < E_pair < 80 GeV





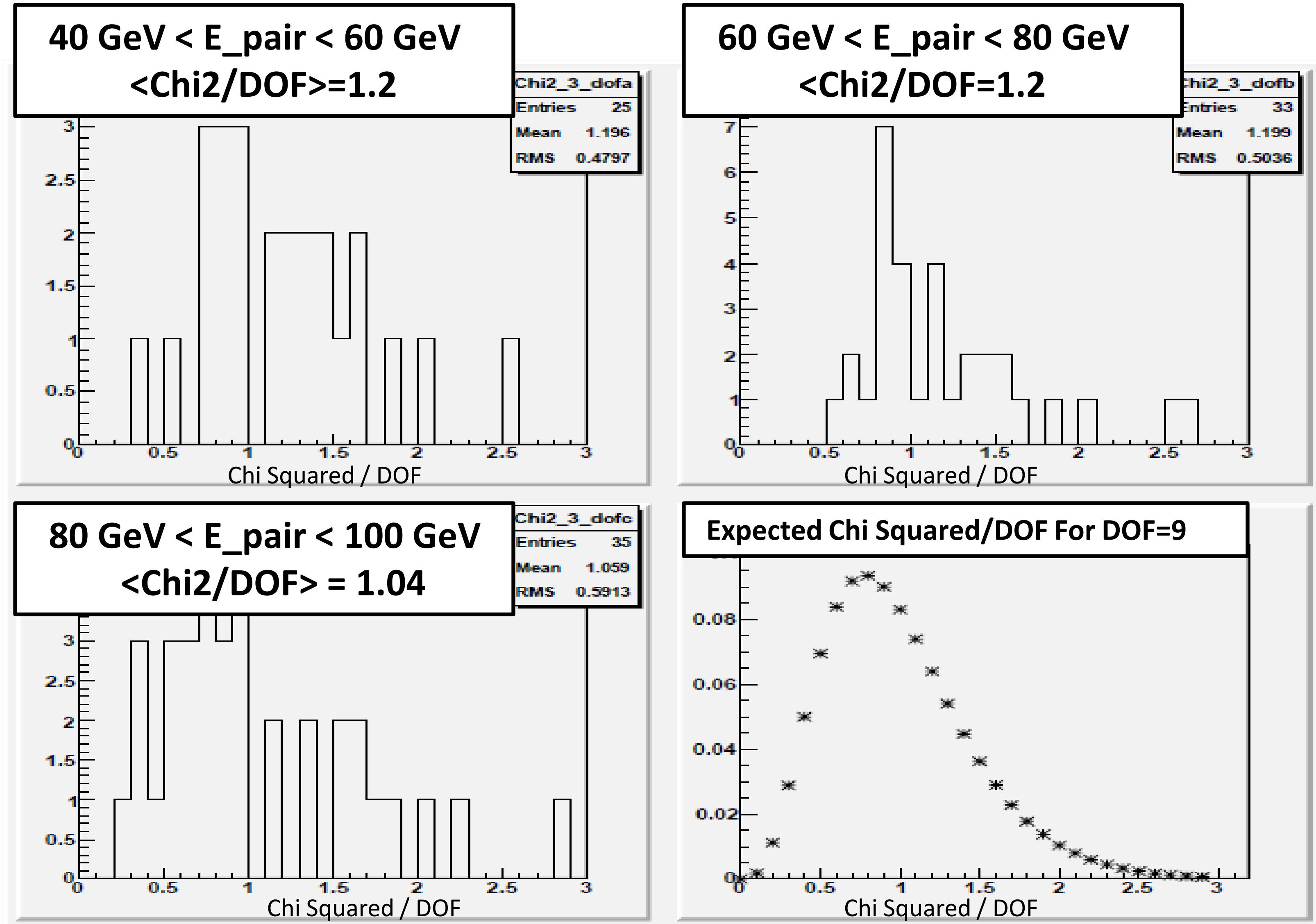


Chi Squared / DOF Distribution for Assumpted Form

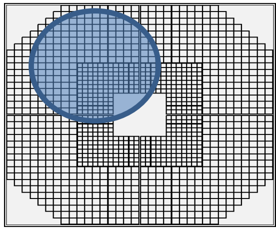
SSA ~ A_N Cos() -0.0025

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)



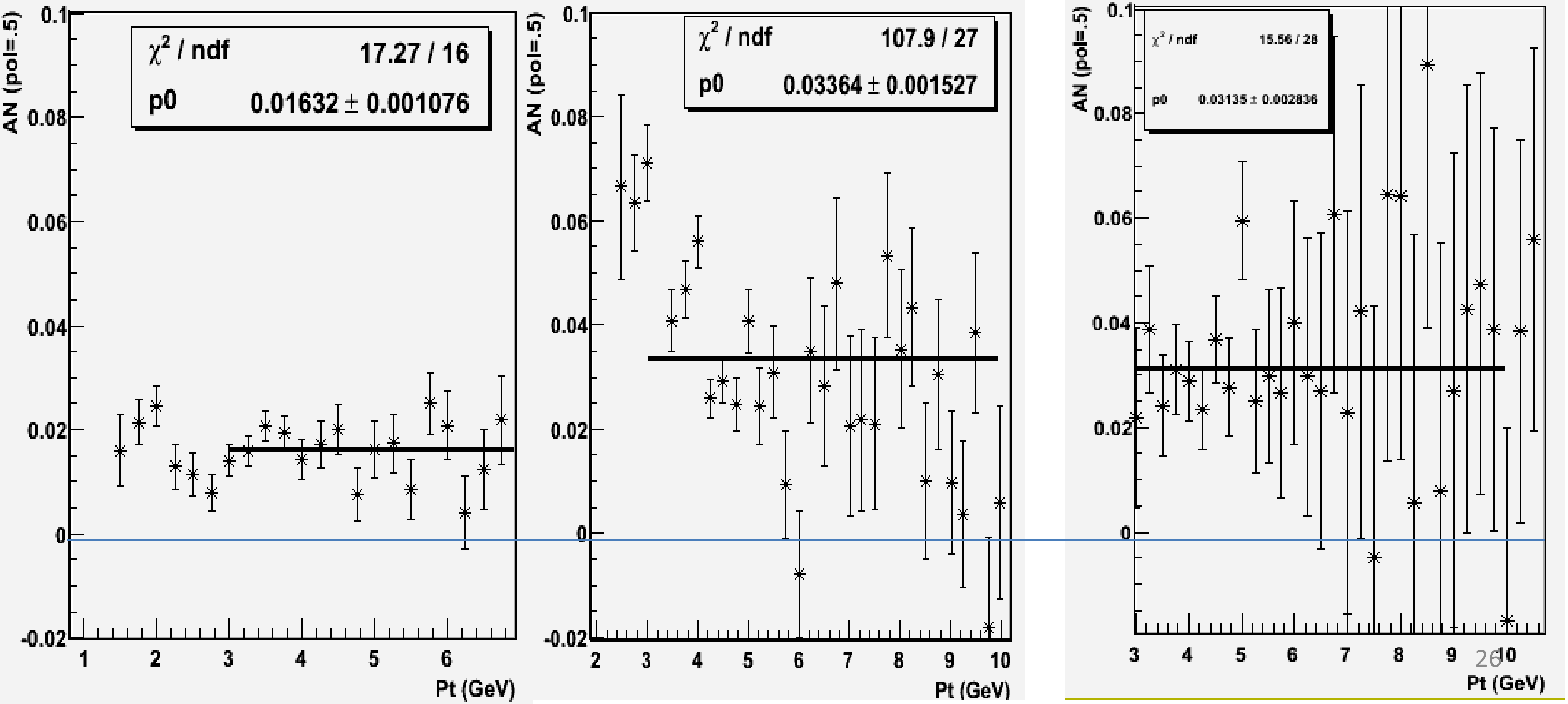
$\Delta\theta$ =0.07 Large
2 Photon clusters



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

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



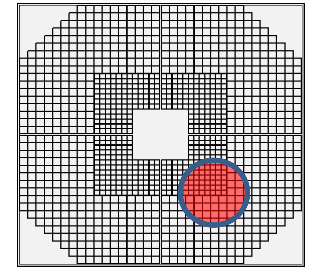
Transverse Single Spin Asymmetry for π^0 Production

Blue Beam (Forward Scattering)

STAR pp (250 GeV x 250 GeV)

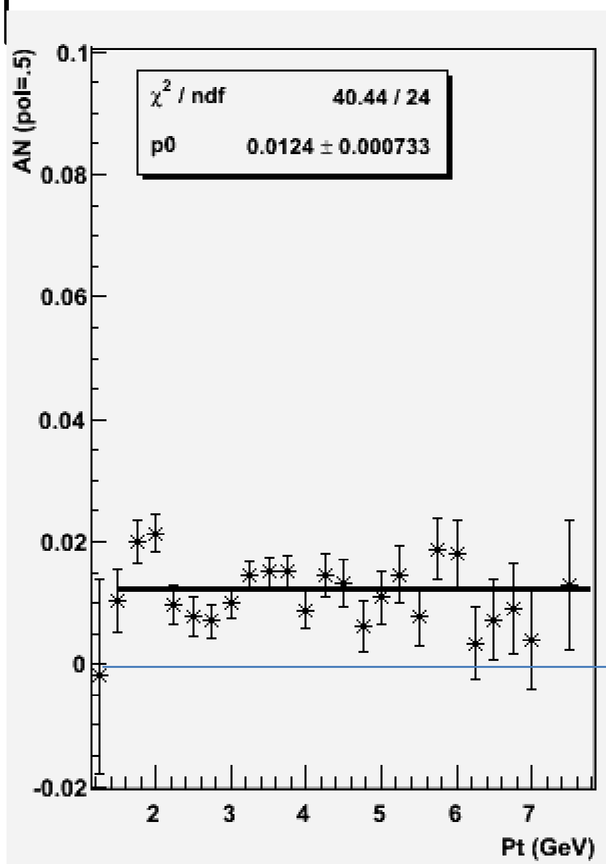
Run 11 ~ 20 pb^{-1} 2.65 < Y < 4.1

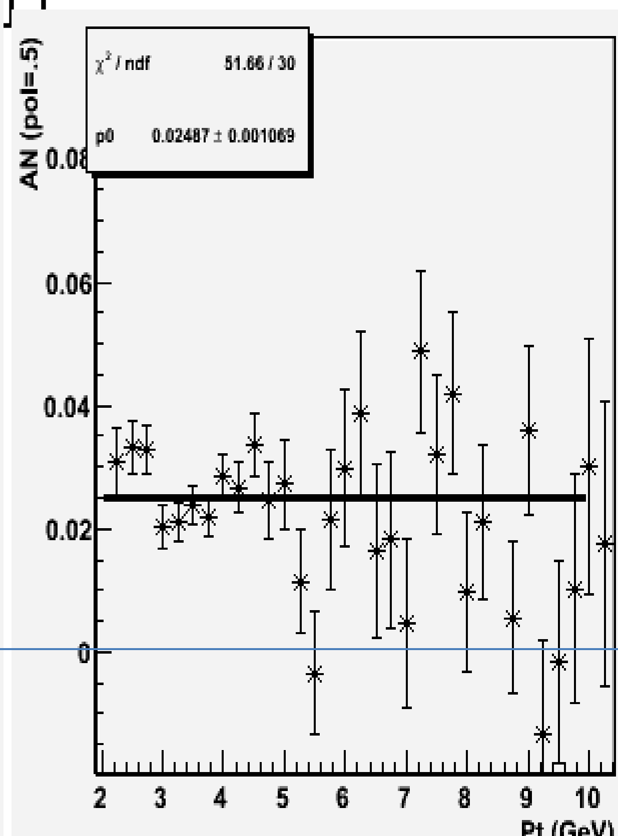
Δθ =0.03 small 2 Photon clusters

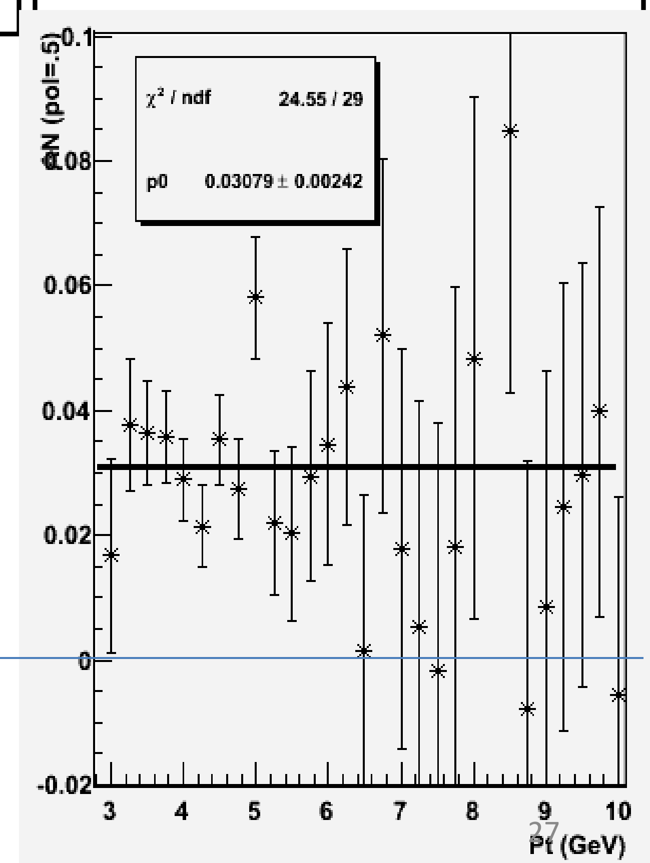


Δθ =0.03 small

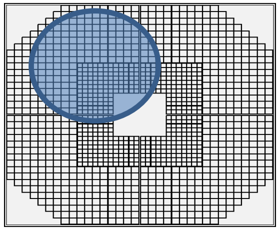
40 GeV < E_pair < 60 GeV $0.16 < X_F < 0.24$	60 GeV < E_pair < 80 GeV $0.24 < X_F < 0.32$	80 GeV < E_pair < 100 GeV $0.32 < X_F < 0.40$





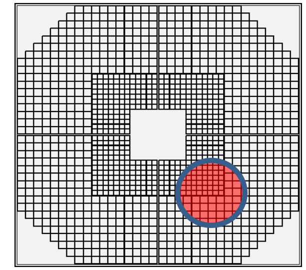


Large 2 Photon clusters



$\Delta\theta$ =0.07 small

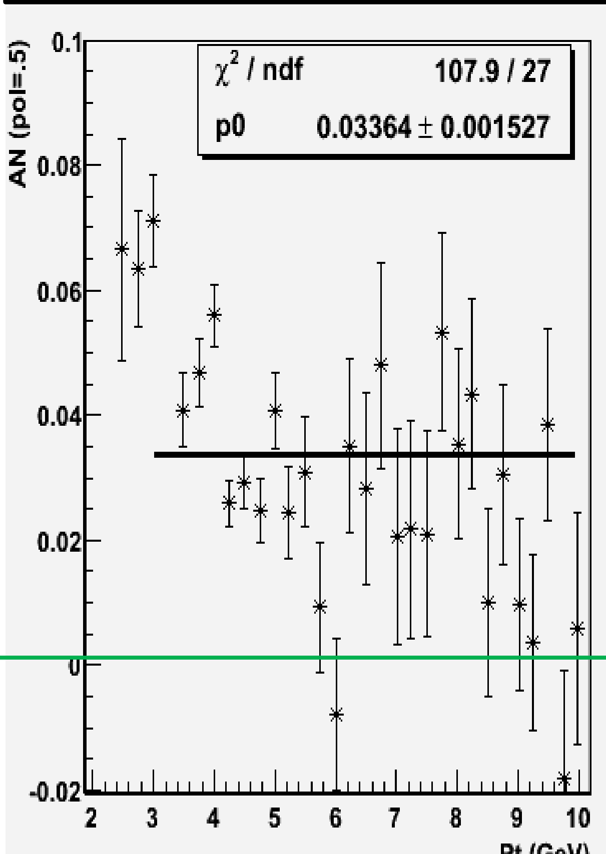
There is significant differences in the Transverse momentum Dependence of A_N for different cluster cone sizes.



$\Delta\theta$ =0.03 small

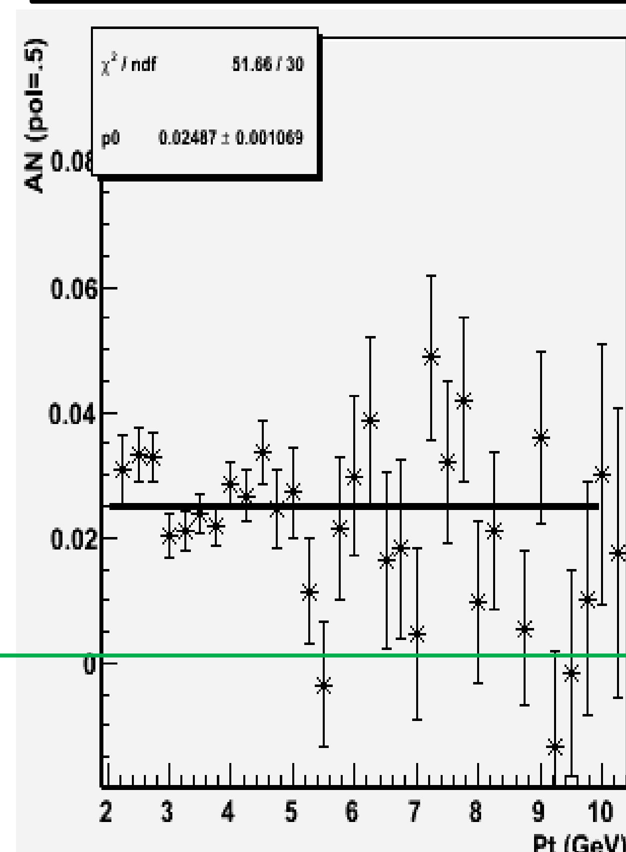
60 GeV < E_pair < 80 GeV
$0.24 < X_F < 0.32$

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

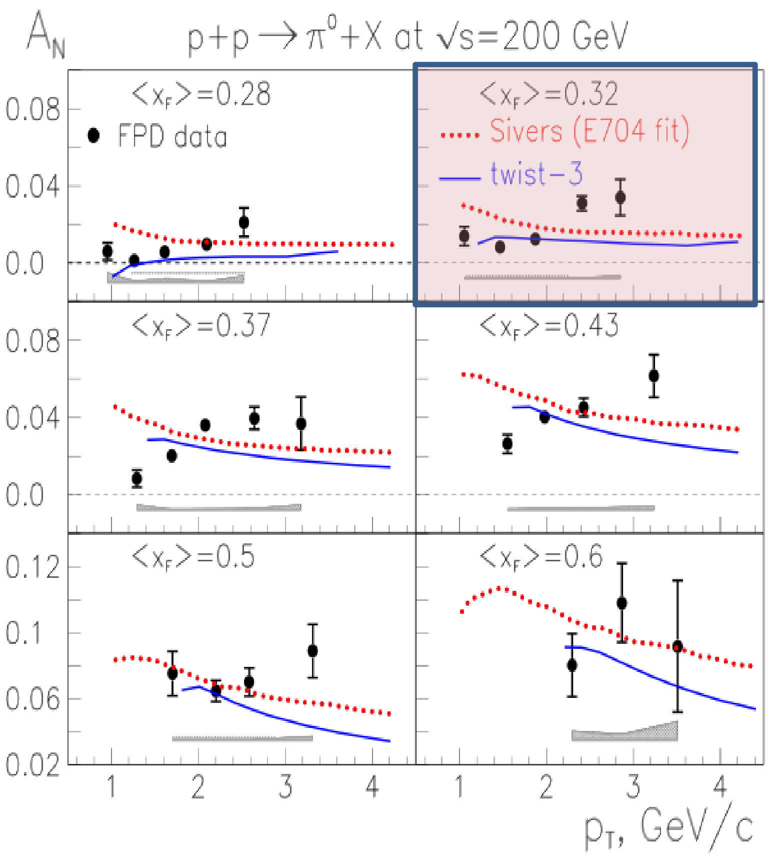


More inclusive π^0 →

More isolated π^0 ←

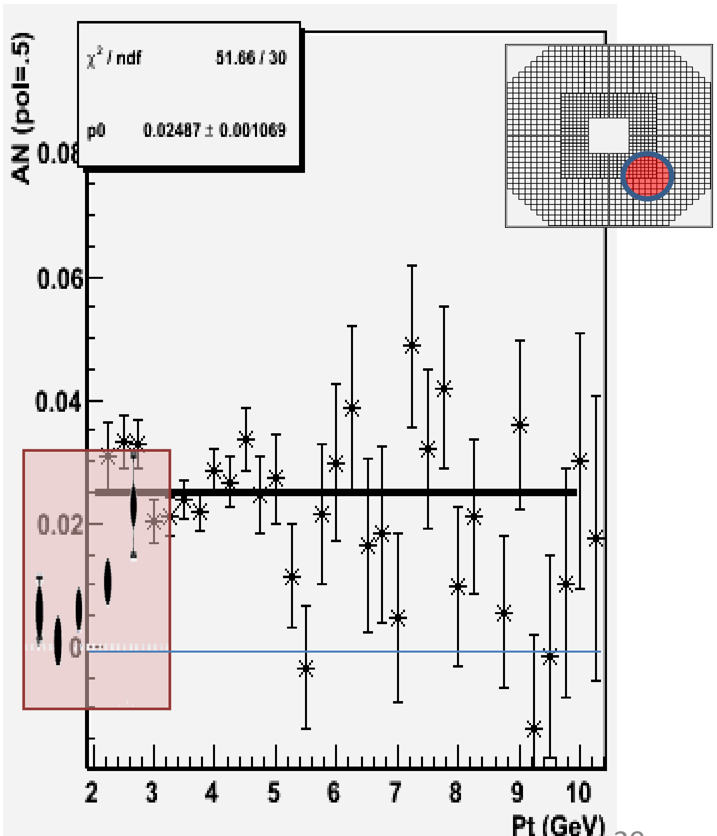


Run 6 ($\sqrt{s}$=200GeV FPD) published P_T Dependence of A_N

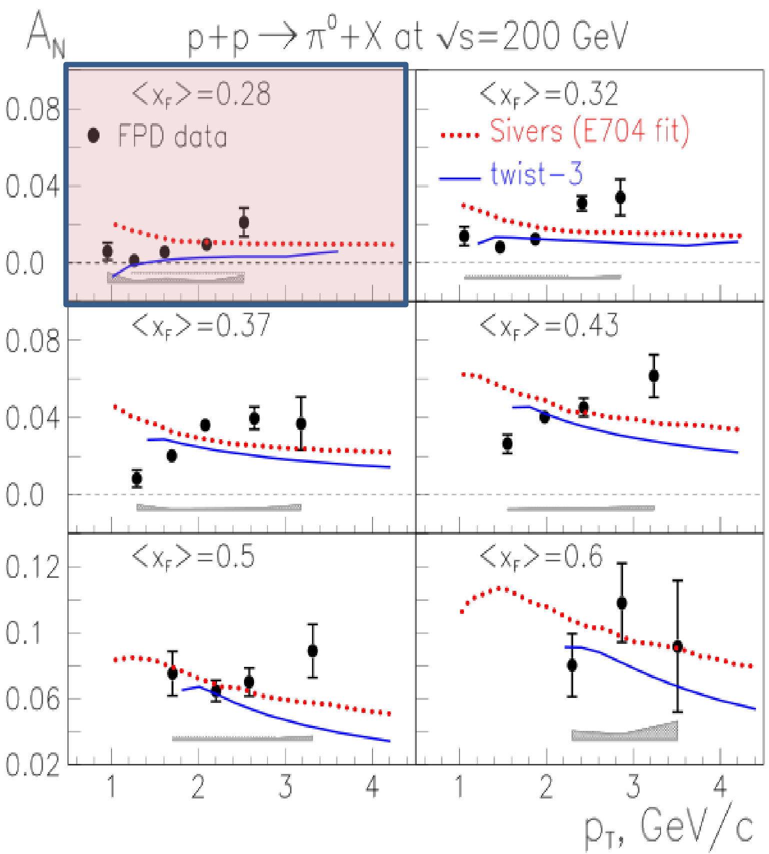


Run 11 ($\sqrt{s}$=500GeV FMS) published P_T Dependence of A_N at $0.24<X_F<0.32$ ($\Delta\theta$ =0.03 small clusters)

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

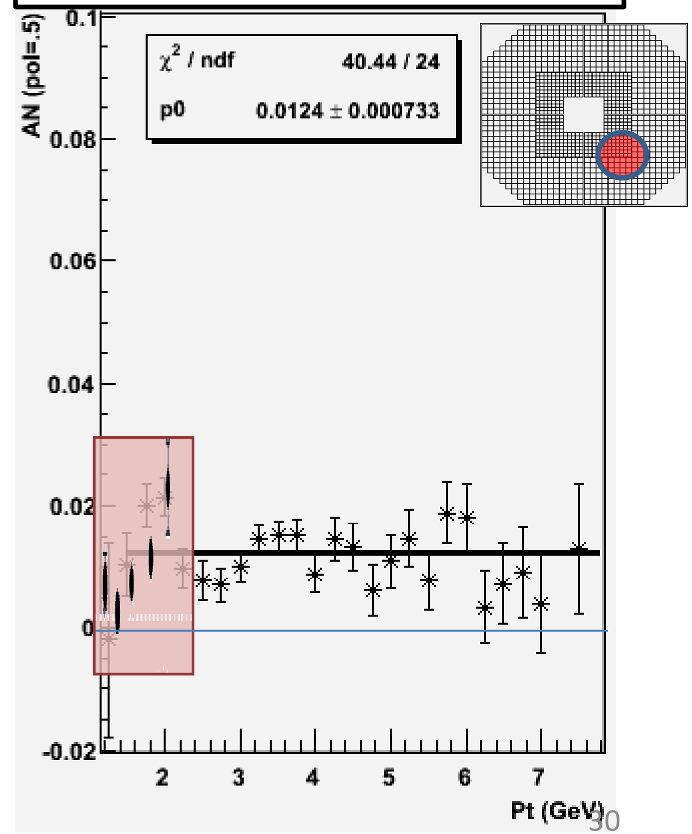


Run 6 ($\sqrt{s}$=200GeV FPD) published P_T Dependence of A_N



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

2. Δθ =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

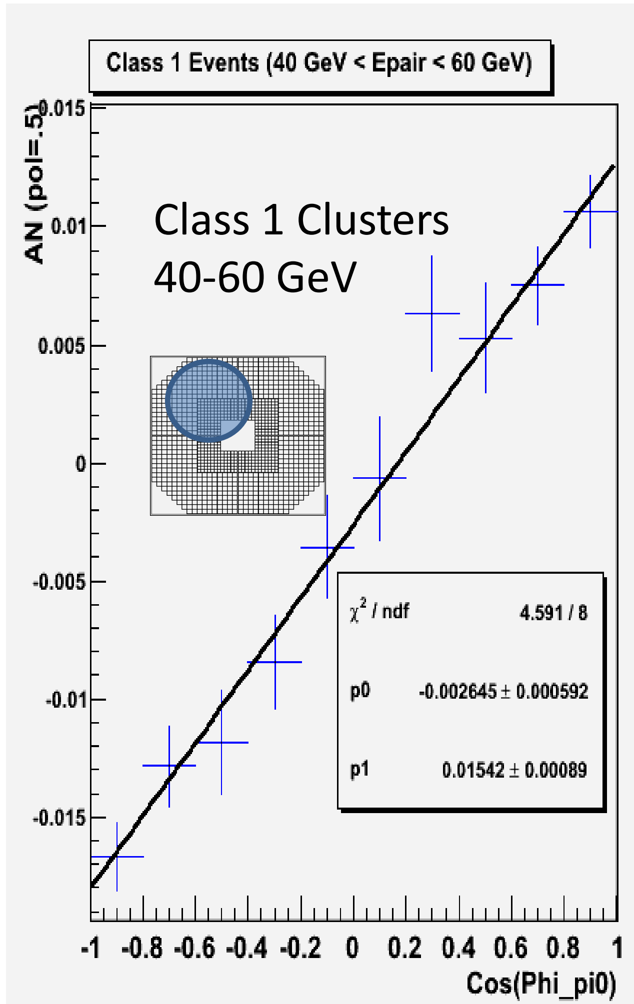
Class 1: <AN> (slope) = 2.71 ±.12 %

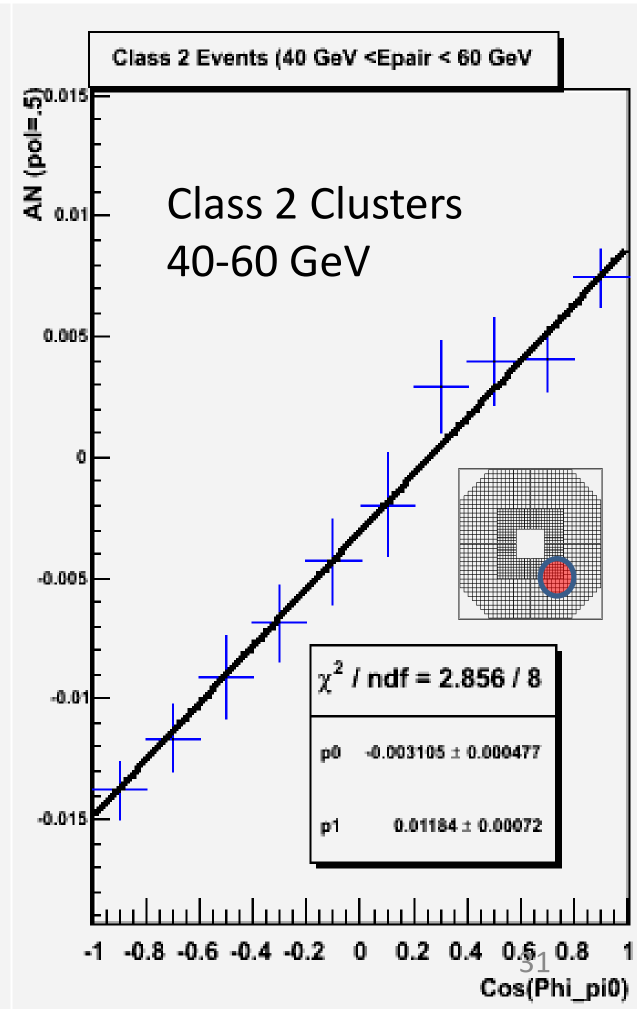
Class 2: <AN> (slope) = 2.45±.1 %

80-100 GeV Bin

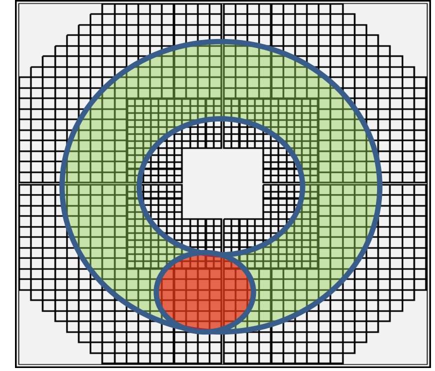
Class 1: <AN> (slope) = 3.0 ±.27 %

Class 2: <AN> (slope) = 2.93±.23 %

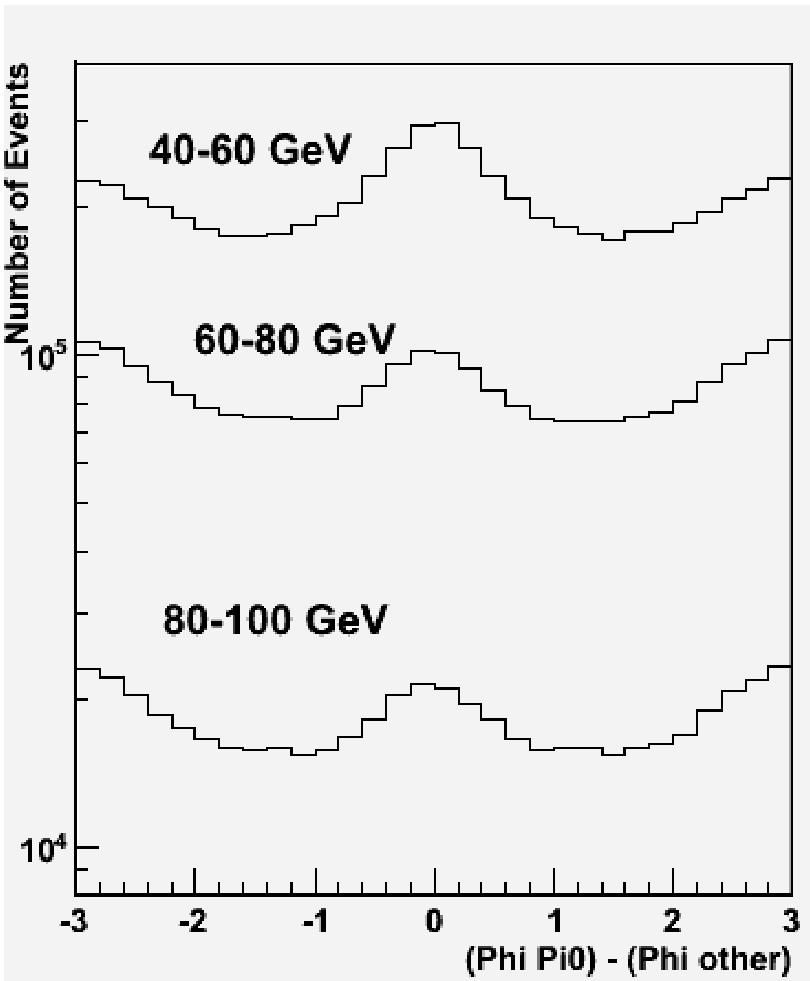


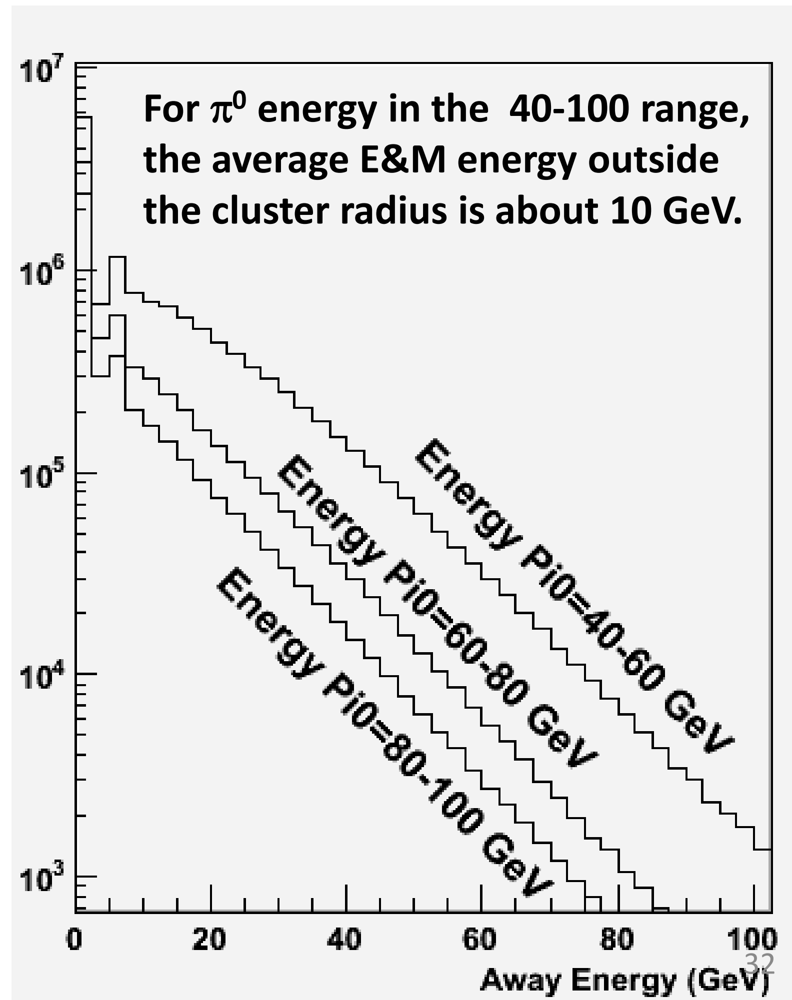


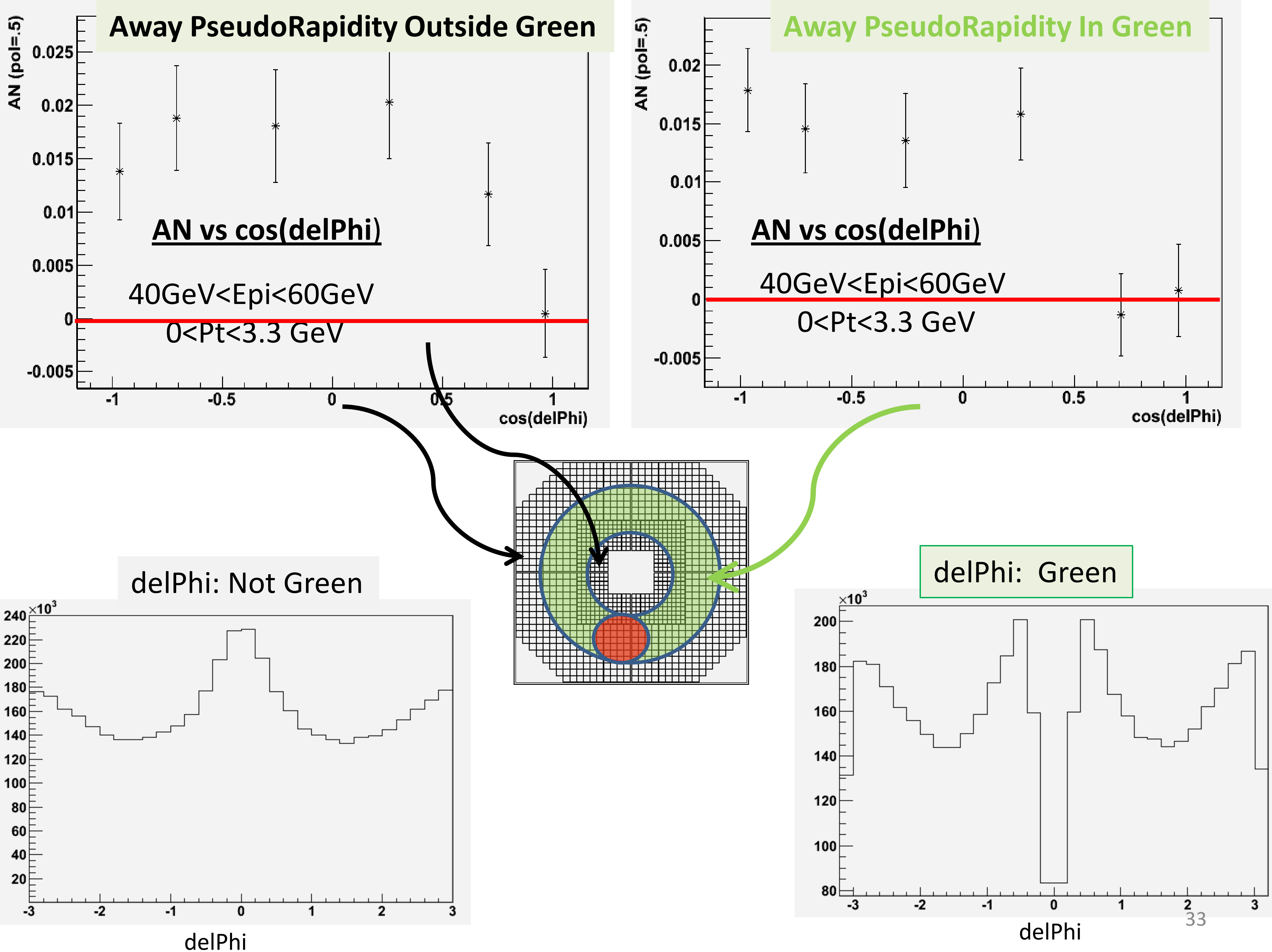
Left: **Azimuthal angle (ange bewteen π^0 and Away energy).**
Right: **Away Energy Distribution for 3 π^0 Energies.**

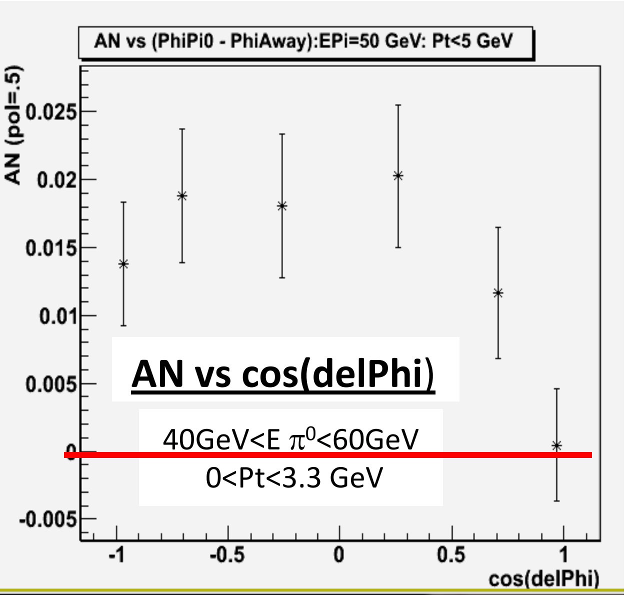


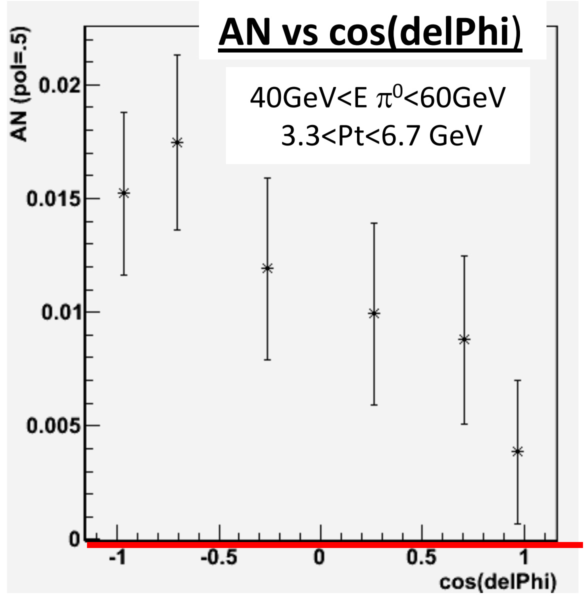
Class 4 Clusters: **$\Delta\theta$ =0.03** 2 Photon clusters
Pi0 Mass, **Y_{away} outside Green region.**

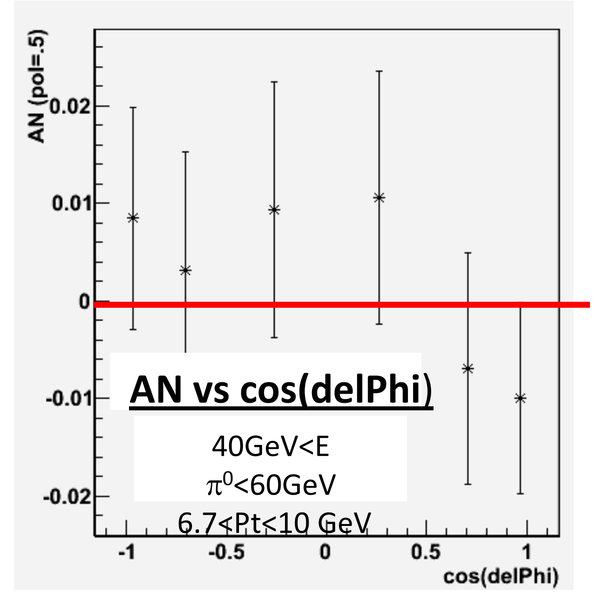


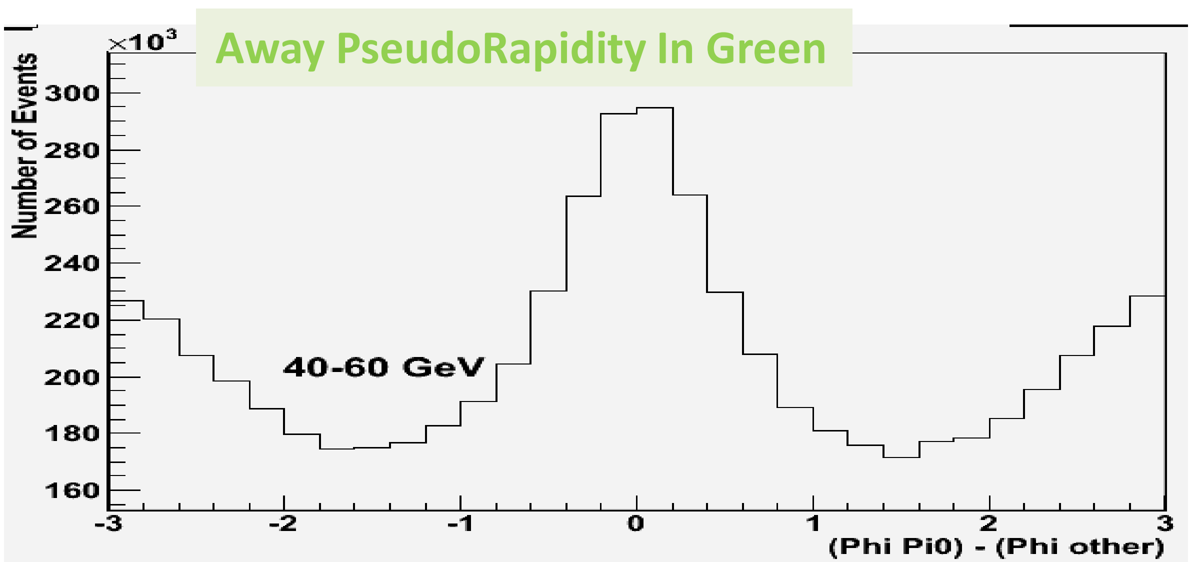


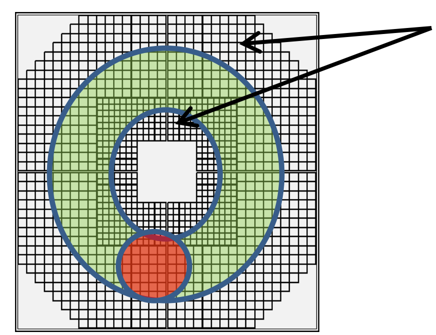

Away PseudoRapidity Outside Green
AN (pol=.5)
AN vs cos(delPhi)
40GeV<Epi<60GeV
0<Pt<3.3 GeV
cos(delPhi)
Away PseudoRapidity In Green
AN (pol=.5)
AN vs cos(delPhi)
40GeV<Epi<60GeV
0<Pt<3.3 GeV
cos(delPhi)
delPhi: Not Green
delPhi
delPhi: Green
delPhi

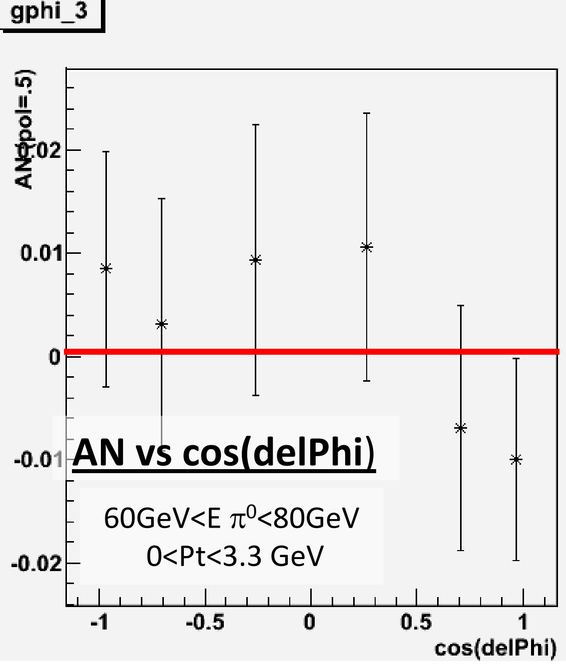

AN vs (PhiPi0 - PhiAway):EPi=50 GeV: Pt<5 GeV
AN (pol=.5)
cos(delPhi)
AN vs cos(delPhi)
40GeV<E π^0<60GeV
0<Pt<3.3 GeV

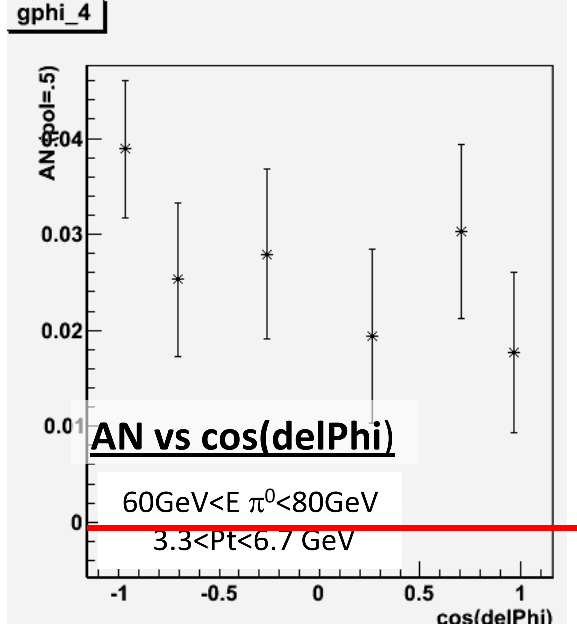

AN vs cos(delPhi)
40GeV<E π^0<60GeV
3.3<Pt<6.7 GeV
AN (pol=.5)
cos(delPhi)

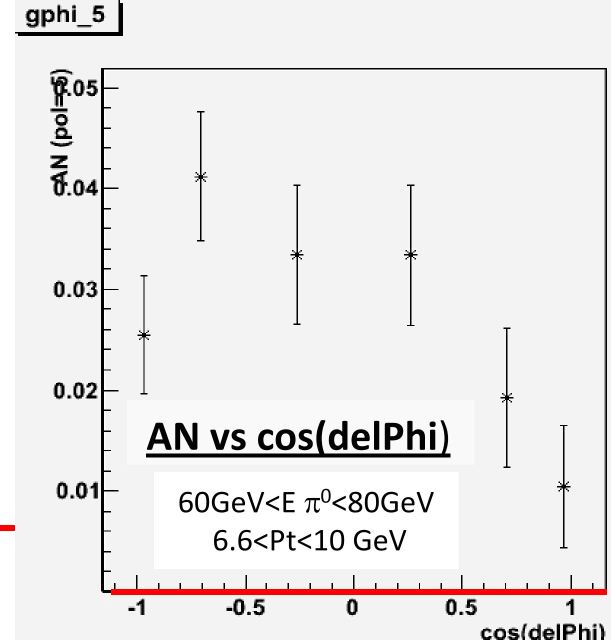

AN (pol=.5)
AN vs cos(delPhi)
40GeV<E
π^0<60GeV
6.7<Pt<10 GeV
cos(delPhi)

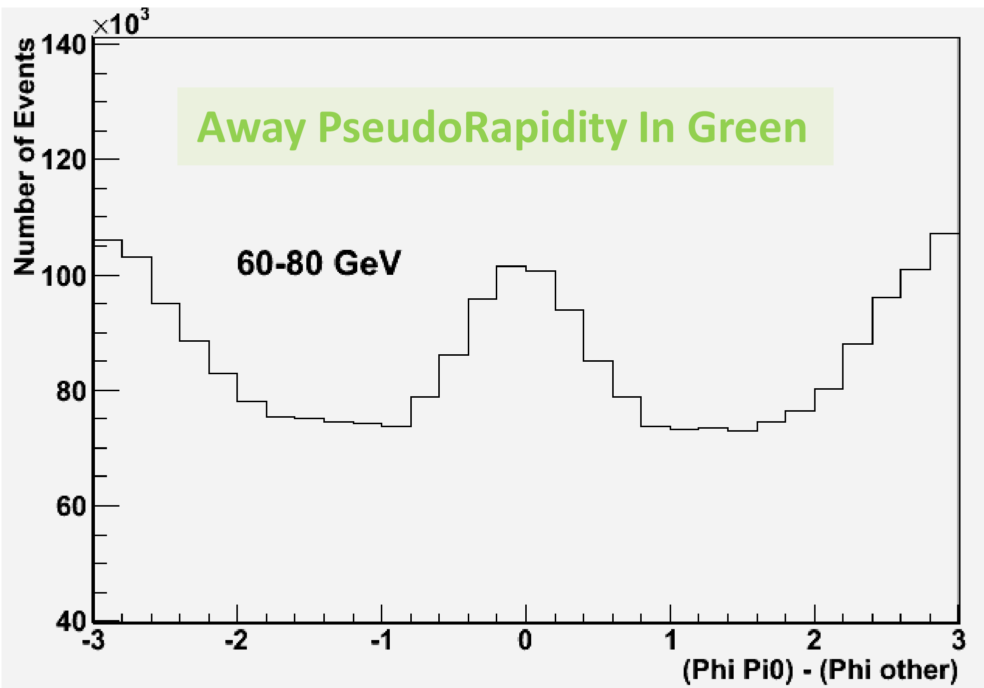

Away PseudoRapidity In Green
Number of Events
$\times 10^3$
40-60 GeV
(Phi Pi0) - (Phi other)

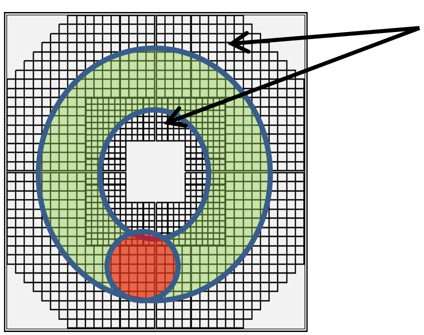


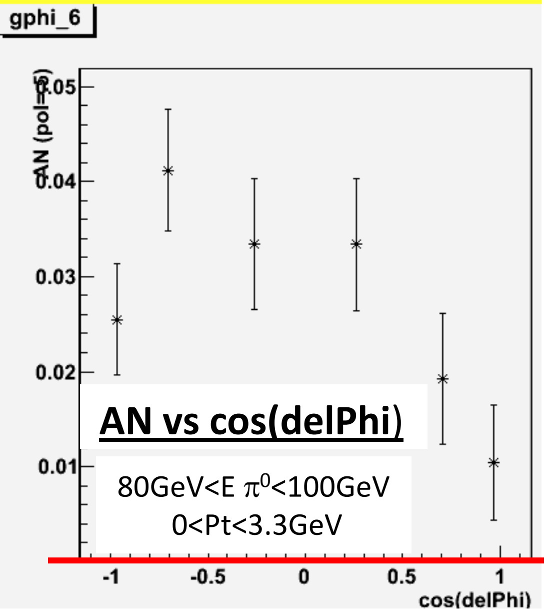

gphi_3
AN vs cos(delPhi)
60GeV<E π⁰<80GeV
0<Pt<3.3 GeV
AN (pol=.5)
cos(delPhi)

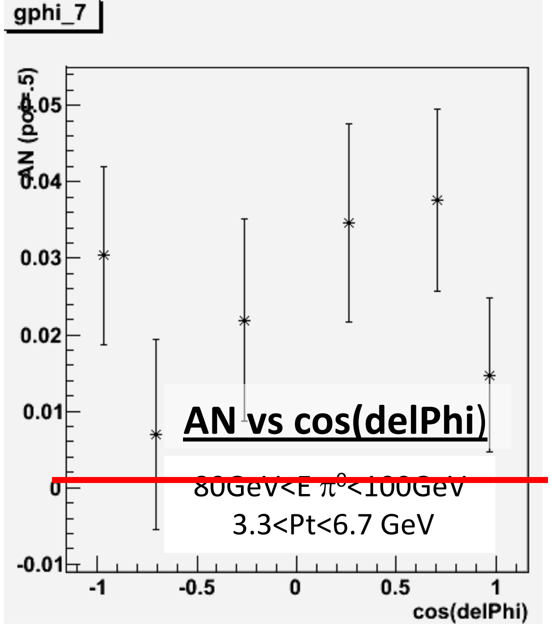

gphi_4
AN vs cos(delPhi)
60GeV<E π⁰<80GeV
3.3<Pt<6.7 GeV
AN (pol=.5)
cos(delPhi)

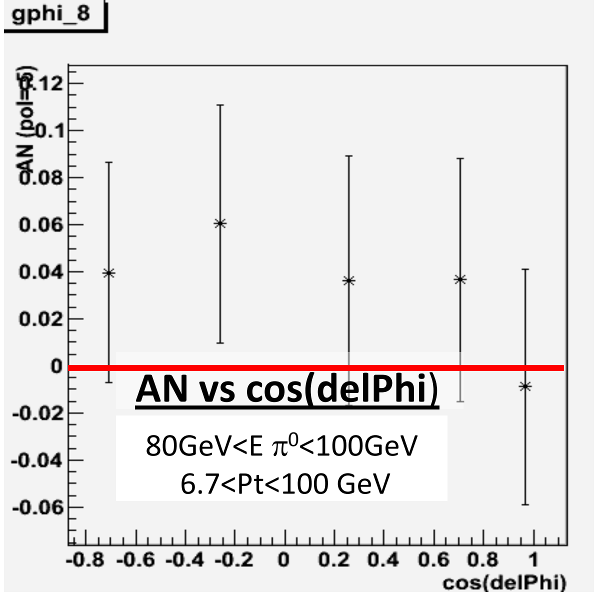

gphi_5
AN vs cos(delPhi)
60GeV<E π⁰<80GeV
6.6<Pt<10 GeV
AN (pol=.5)
cos(delPhi)

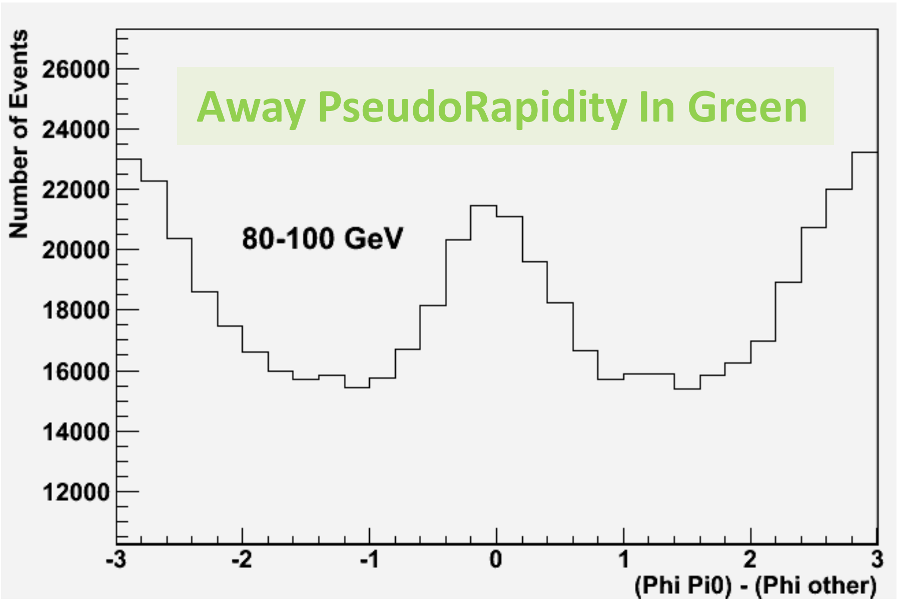

Away PseudoRapidity In Green
60-80 GeV
Number of Events
×10³
(Phi Pi0) - (Phi other)

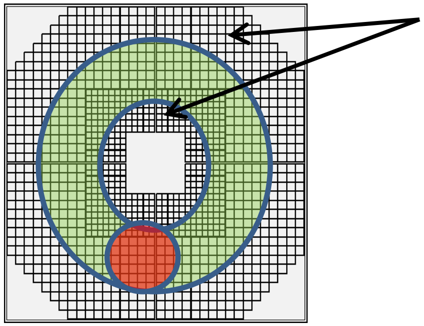



gphi_6
AN (pol=.5)
AN vs cos(delPhi)
80GeV<E π0<100GeV
0<Pt<3.3GeV
cos(delPhi)


gphi_7
AN (pol=.5)
AN vs cos(delPhi)
80GeV<E π0<100GeV
3.3<Pt<6.7 GeV
cos(delPhi)


gphi_8
AN (pol=.5)
AN vs cos(delPhi)
80GeV<E π0<100GeV
6.7<Pt<100 GeV
cos(delPhi)


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



Summary

- **<u>A high statistic measurement is presented for A_N in forward π^0 production</u>** 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, **<u>gives an asymmetry which, which is nearly constant in transverse momentum out to ~ 10 GeV/c.</u>**
- 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 .
- **<u>We report that observation of additional jet particles reduces reduced the observed values of A_N.</u>**
- 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