Forward π^0 and η production in STAR at $\sqrt{s}$= 500 GeV with transversely polarized pp collisions

Transverse momentum Dependence of π^0 SSA in FMS Run 11 CIPANP

S. Heppelmann (PSU) for STAR collaboration

June 2 , 2012

- Background
  - Physics Questions
  - **Cross Ratio** method vs. $\mathbf{A(\phi)=A_N \cos(\phi)}$ fitting method
  - Previous FMS and STAR results
  - About P_T dependence of A_N
  - FMS Event Topology and Event Selection
- Present High Statistics A_N for STAR Run 11 $\sqrt{s}$=500 GeV
  - X_F dependence
  - P_T dependence for fixed X_F
  - Dependence on event topology

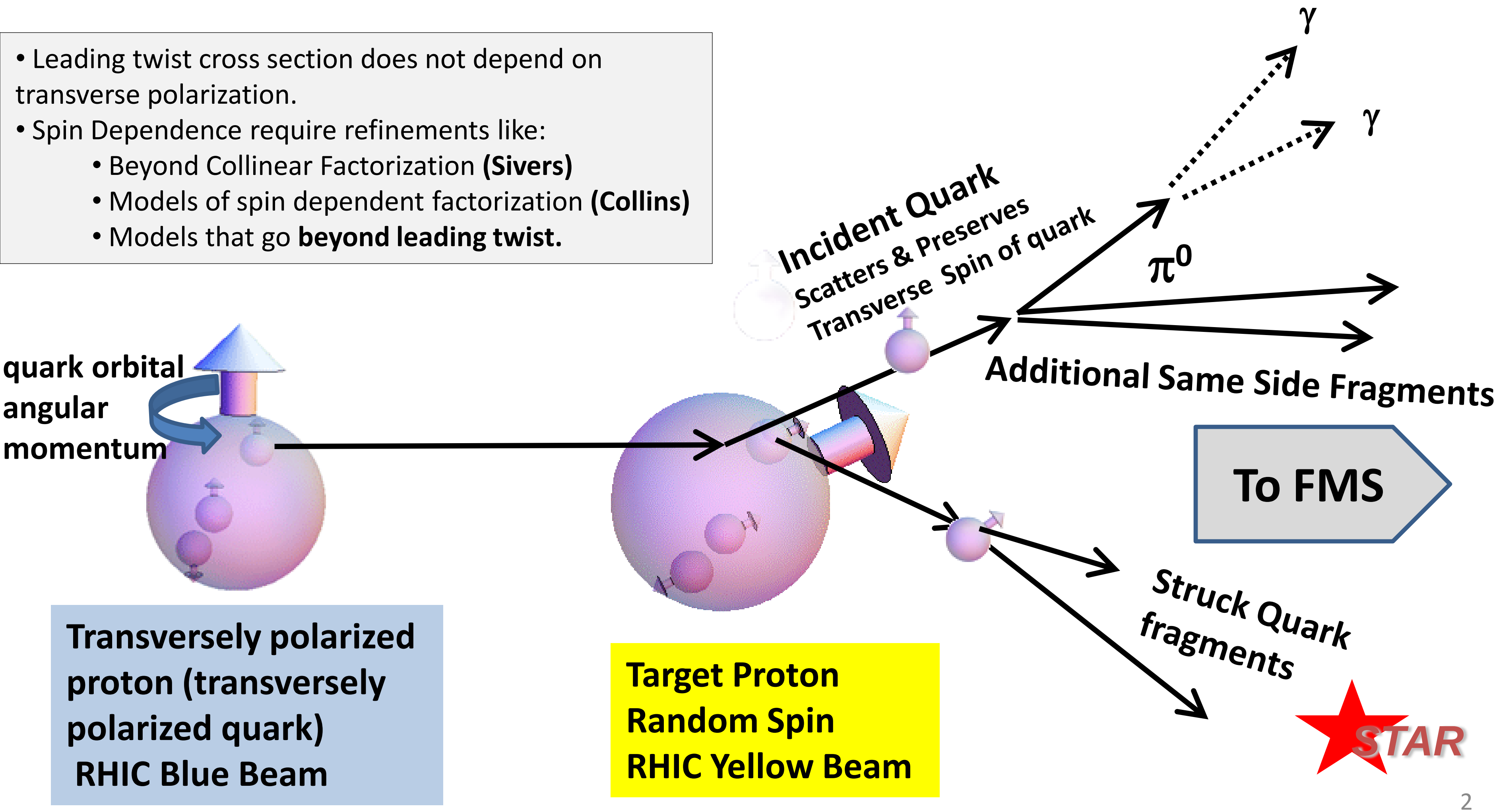
Proton Forward Scattering at High PT
QCD Perspective

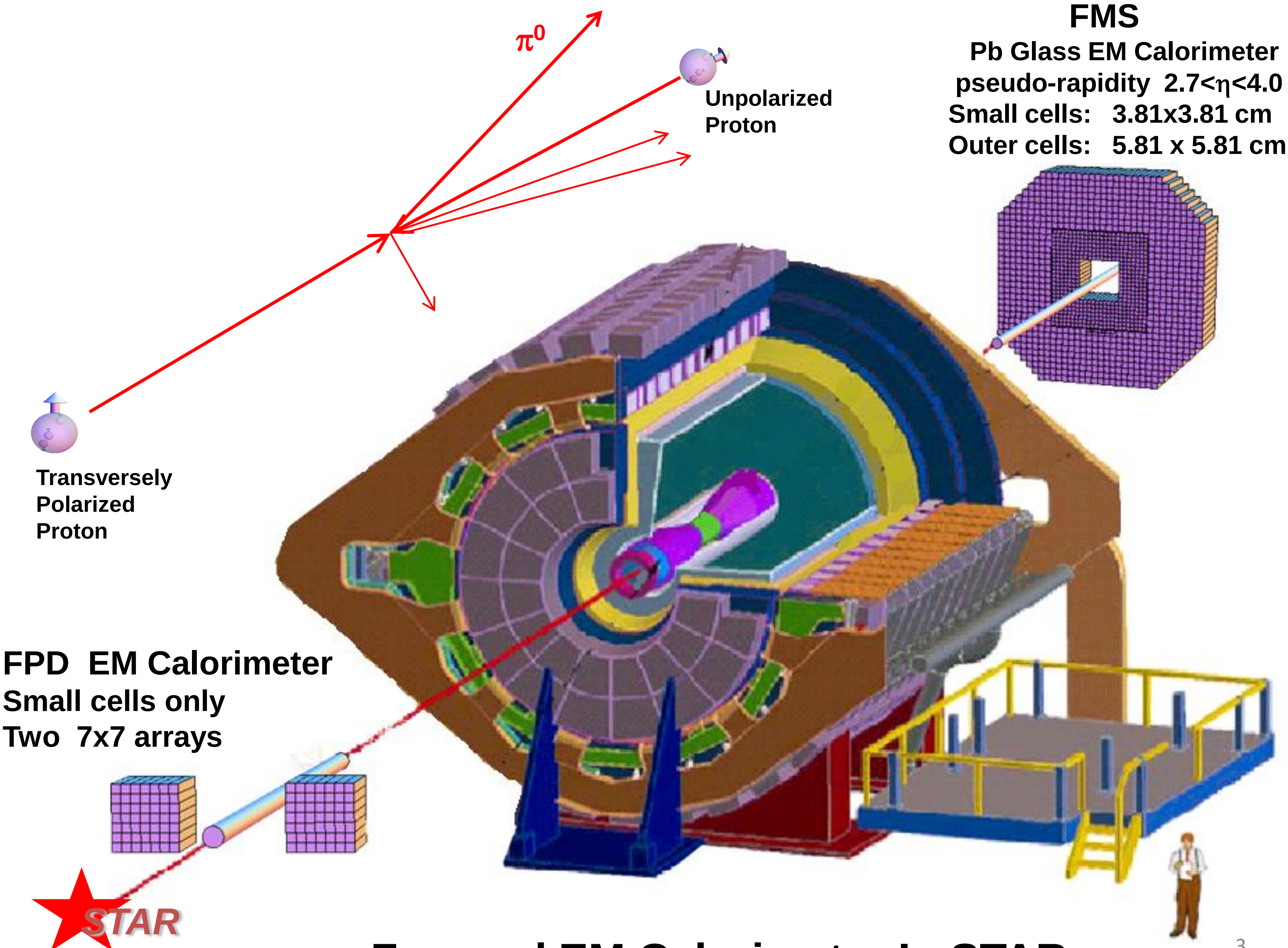
PQCD (Leading Twist):

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

- Does good job of predicting the spin averaged cross section.

- 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.**





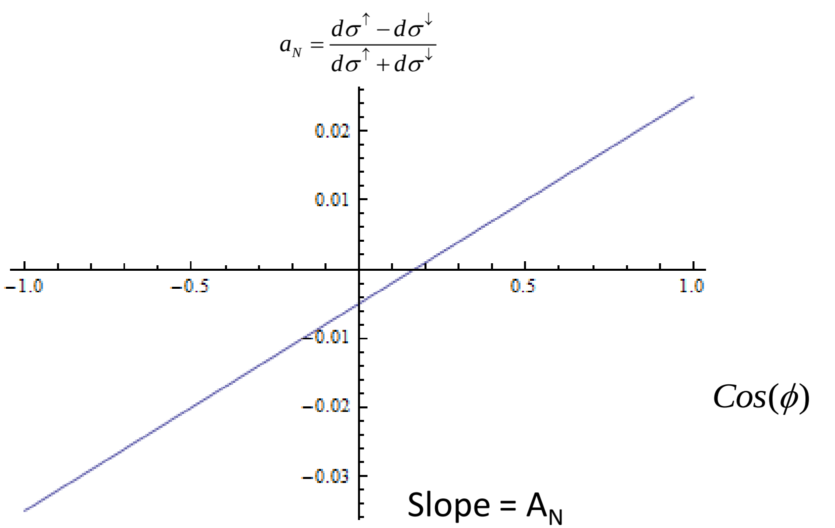
Forward EM Calorimetry In STAR.

1) Cross Ratio Transverse Asymmetry vs 2) A(ϕ) Fit

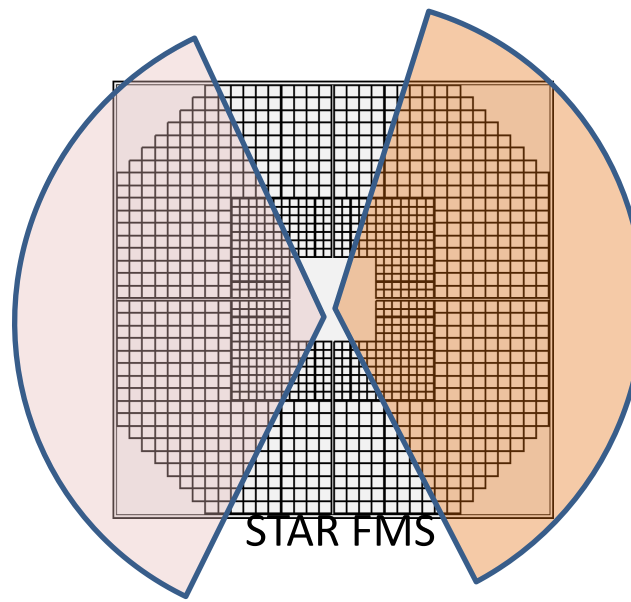
Method 1:
Cross Ratio:

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

Left(N): Cos(ϕ)<-0.5



Slope = A_N
Y Intercept=Luminosity Ratio



Right(S): Cos(ϕ)>0.5

Method 2: $$a_N(\phi) = a_0 + A_N \cos(\phi)$$

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.

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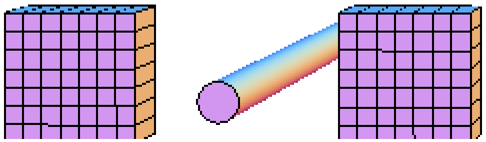
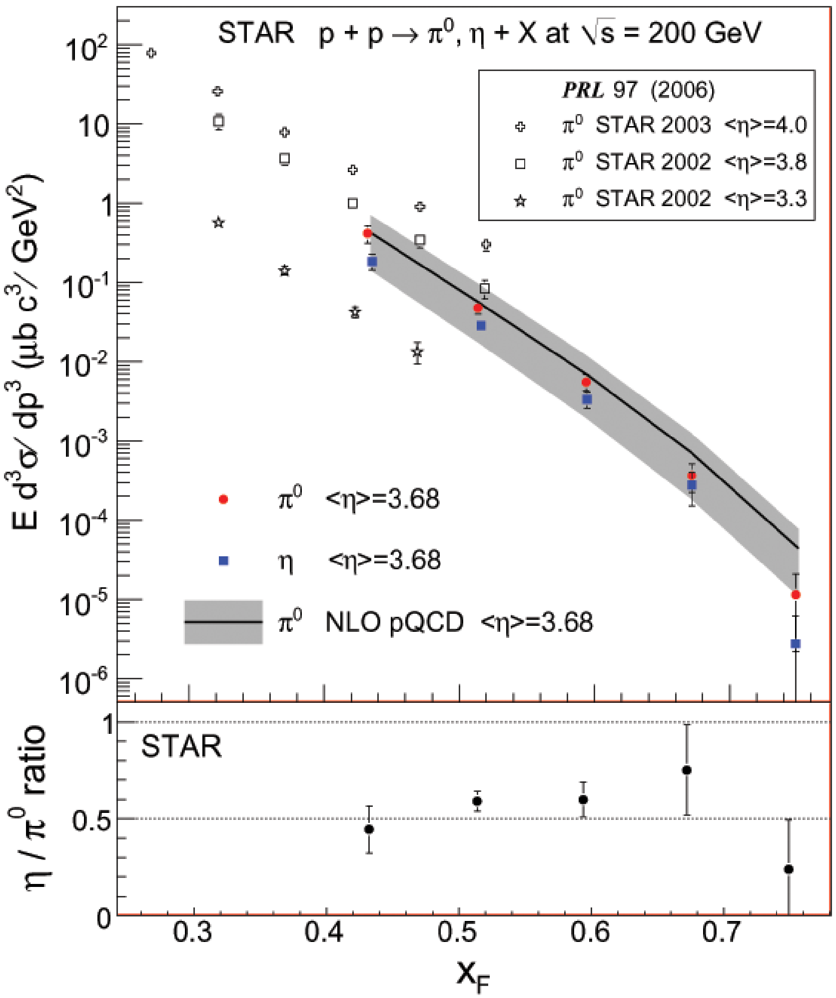
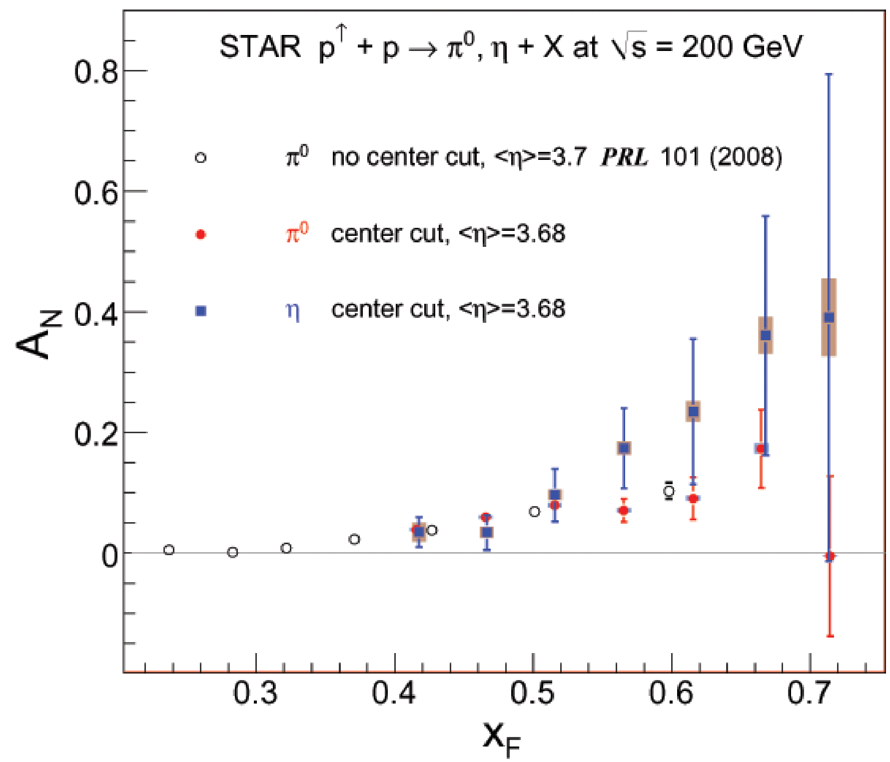
New paper on η/π^0 at $X_F>0.5$

Extra page 29 is a possible substitute for this slide



- 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 $X_F > 0.55$





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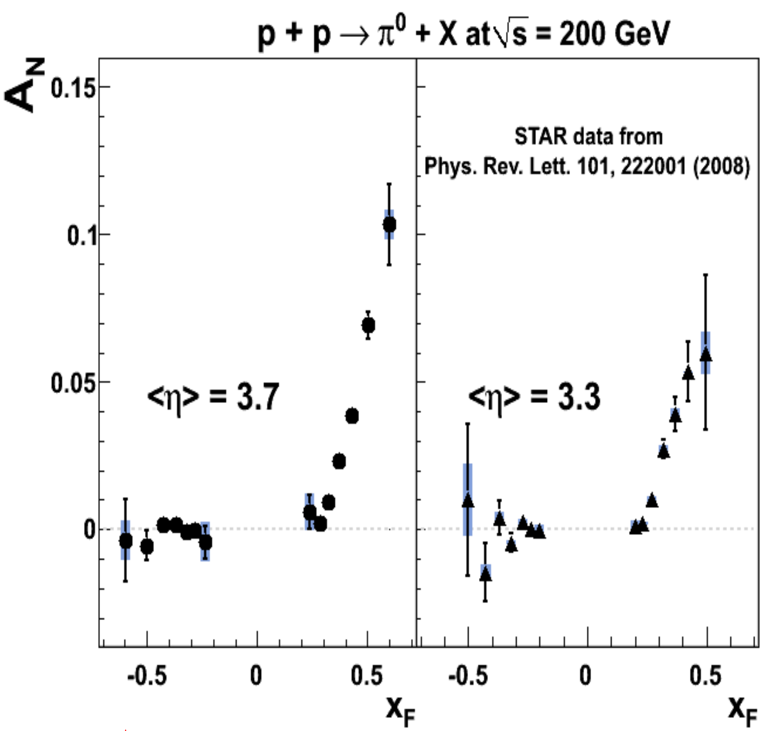
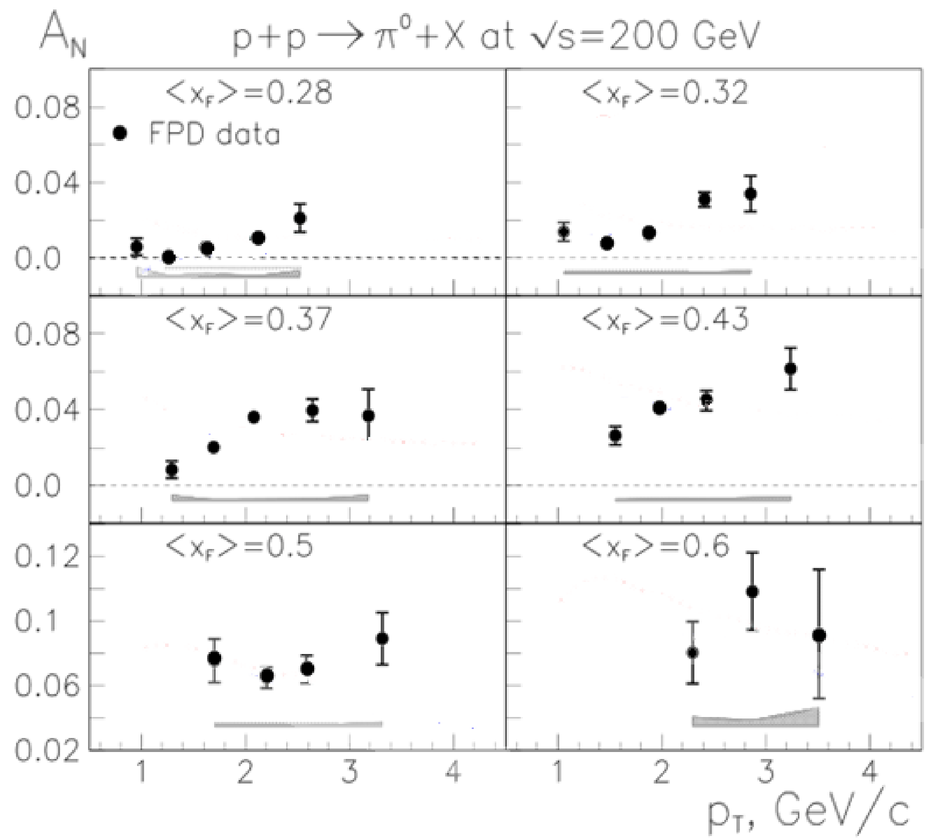
STAR Published Run 6 (FPD $\sqrt{s}$ =200GeV)

PRL 101, 222001 (2006)

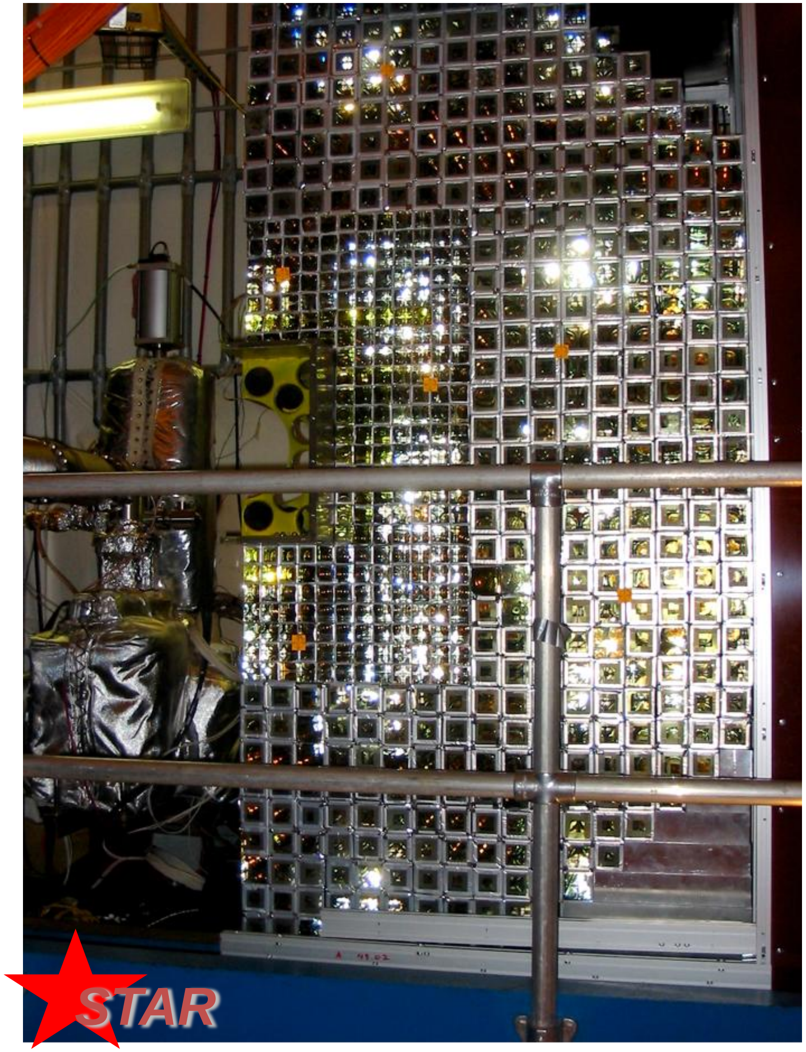
- Rising A_N with X_F ($0<X_F<0.5$) from 0% to 5-10%
- No evidence of fall in A_N with increasing P_T up to P_T ~ 3 GeV/c

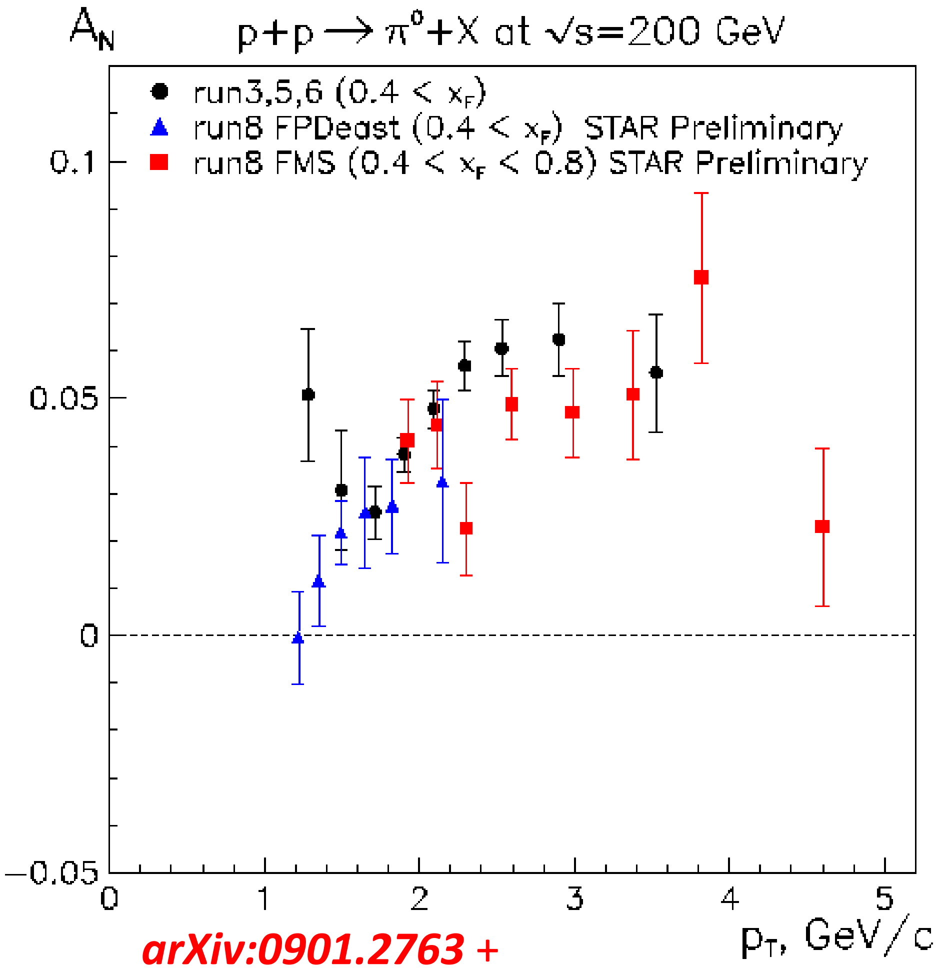




From FMS Run 8, STAR has Expanded Rapidity Coverage -1<Y<4.2

STAR Forward Meson Spectrometer
2.5 < Y < 4.0





arXiv:0901.2763 +
A.Ogawa @CIPANP09

- 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.**

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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!

A toy model for proton Cross Section at large x.

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

Suppose initial state structure or final state fragmentation modifies the hard scattering $\mathbf{p_T}$.
If the spin dependent initial/final state momentum is $\mathbf{k_T}$.

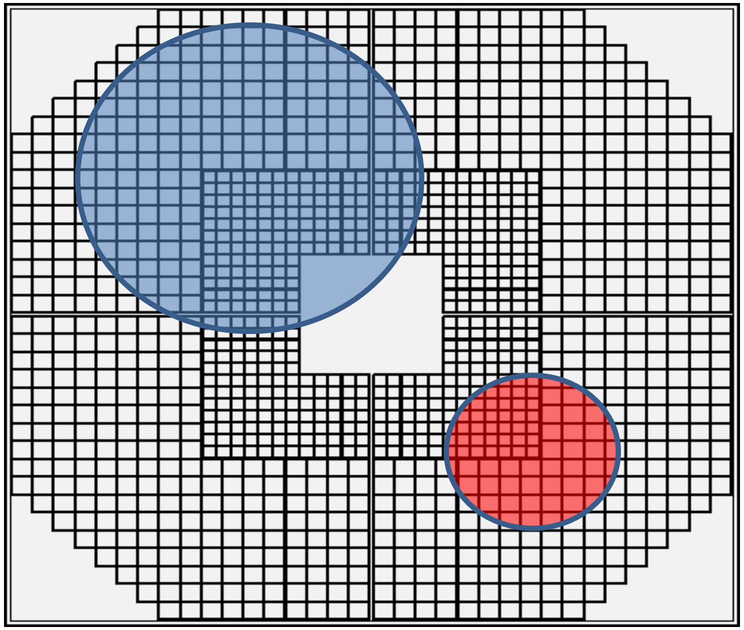
For spin proton spin up: $\langle p_T \rangle \Longrightarrow \langle p_T \rangle - k_T$

For spin proton spin dn: $\langle p_T \rangle \Longrightarrow \langle p_T \rangle + k_T$

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

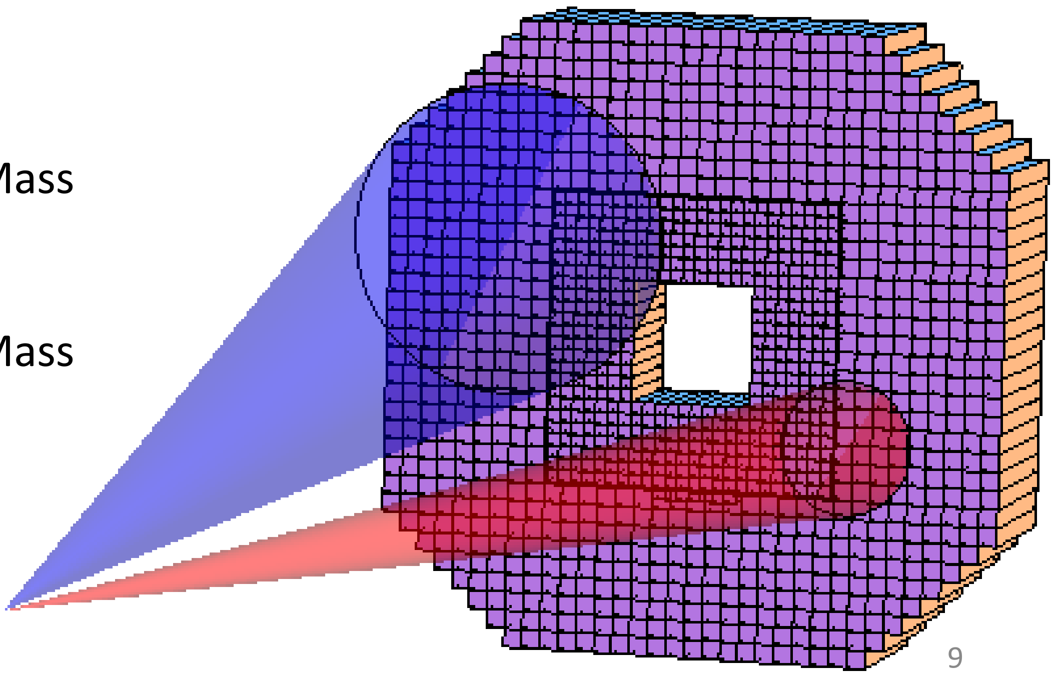
Similar for **for higher twist:** $A_N(p_T) \propto \dfrac{1}{p_T}$

Isolation of π^0 's



Event Selection:

1. **Analyze FMS for all photon** candidates. (Showers that are fit successfully to photon hypothesis)
   A photon candidates must have a minimum of 6 GeV in the small inner detector or 4 GeV in the outer cells.
2. **Find Clusters of EM energy** grouping photon candidates that are within opening angle cone $\Delta\theta$ (relative to energy weighted center)
3. We consider 2 event classes {1 and 2}
   1. $\Delta\theta = 0.07$ 2 Photon clusters, Pi0 Mass (**isolation radius of .07 radians**).
   2. $\Delta\theta = 0.03$ 2 Photon clusters ,Pi0 Mass (**isolation radius of .03 radians**).



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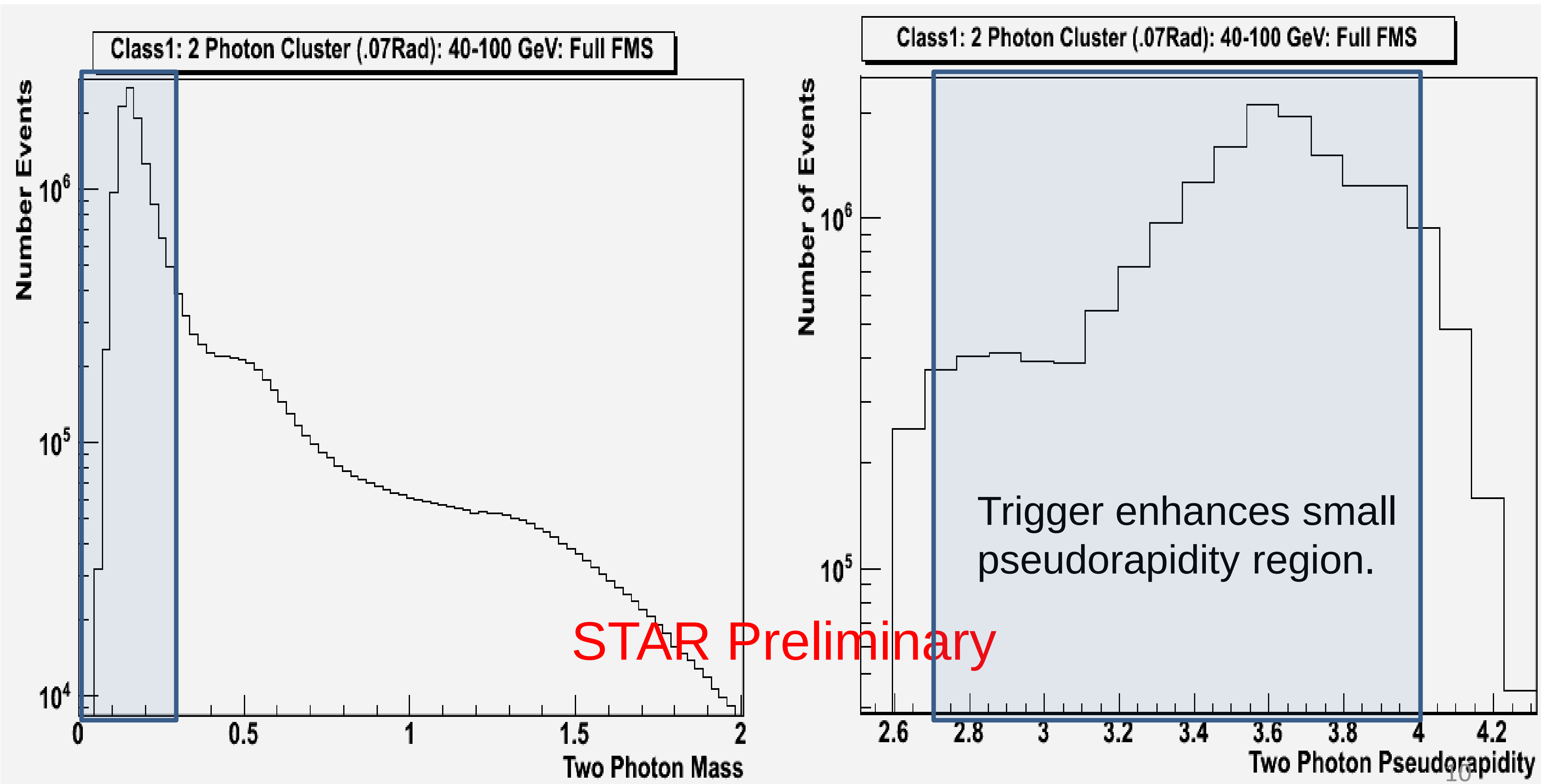
Class 1 Events: $\Delta\theta = 0.07$ 2 Photon clusters, π^0 Mass (less inclusive)?

- 40 GeV < Epair <100 GeV
- Z=|(E1-E2)/(E1+E2)| <.7
- 2.7 < Y < 4.0 (Full FMS Pseudo-rapidity)
- Selection of π^0 Peak (0.02 <Mass<.3)
- Average polarization: 48% ±5% (RHIC Spin CNI Group http://www.phy.bnl.gov/cnipol/)
- Integrated Luminosity: 22 pb^{-1}

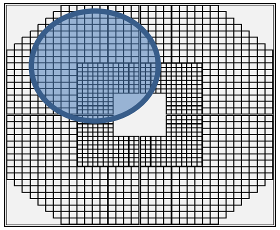


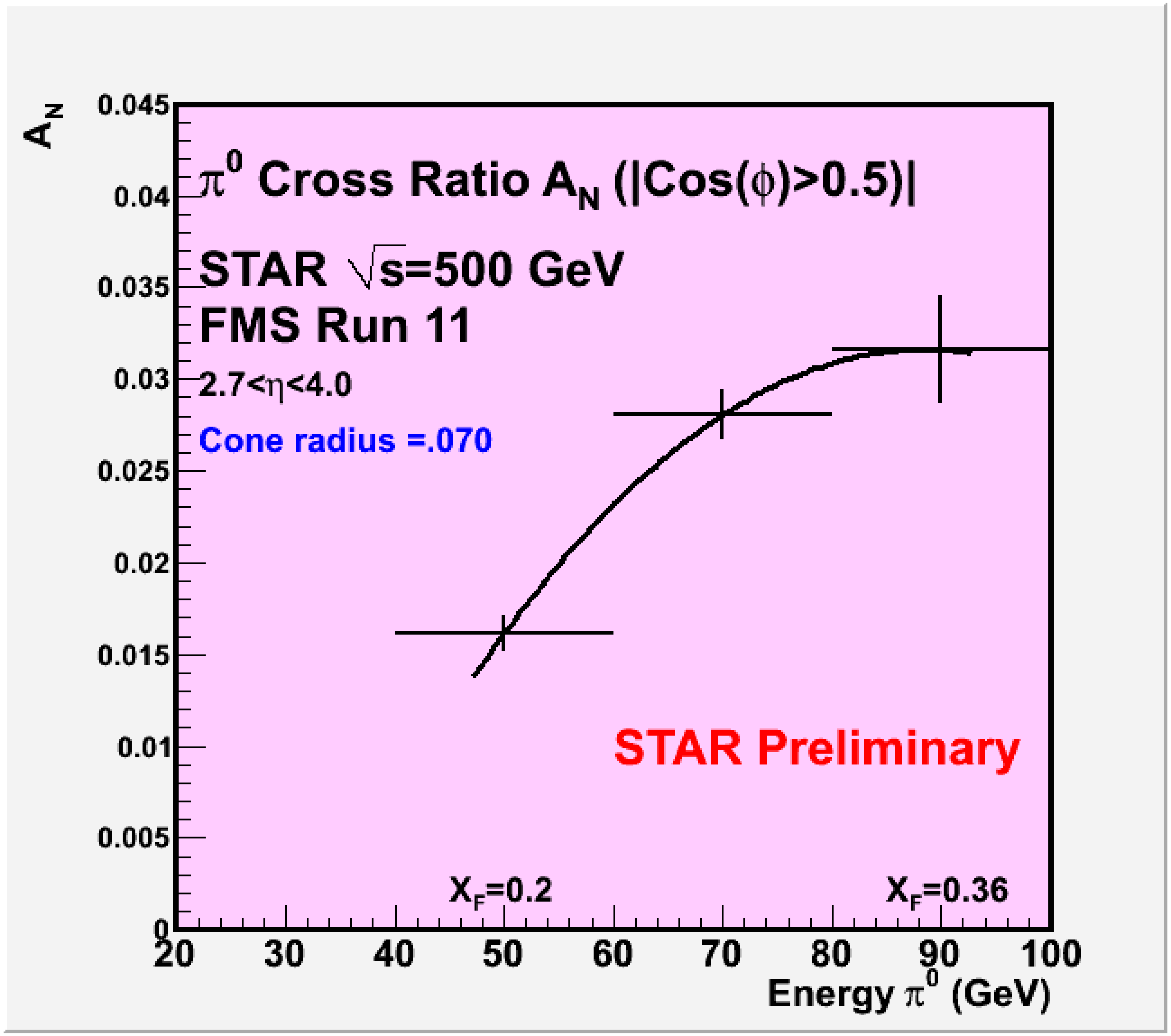
Cross Ratio Transverse Single Spin Asymmetry for Run 11

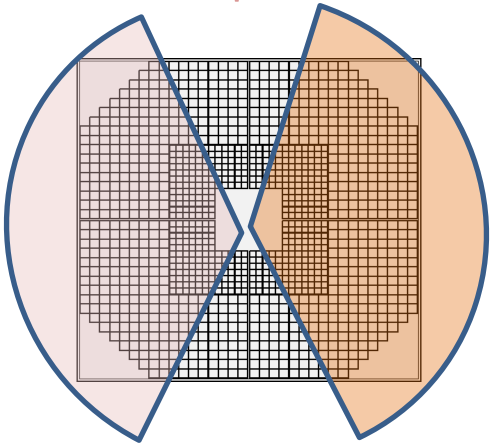
π^0 (2 Photon Cluster) Cluster size = 0.07 Rad

For Blue Beam (Forward)

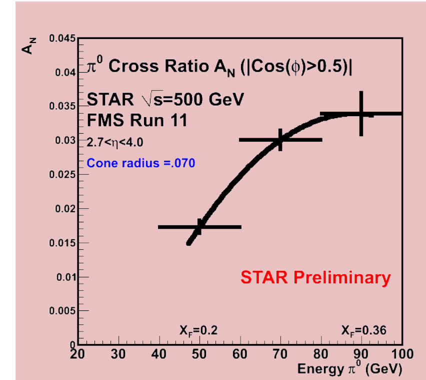
Full FMS rapidity range (2.6<Y<4.1)

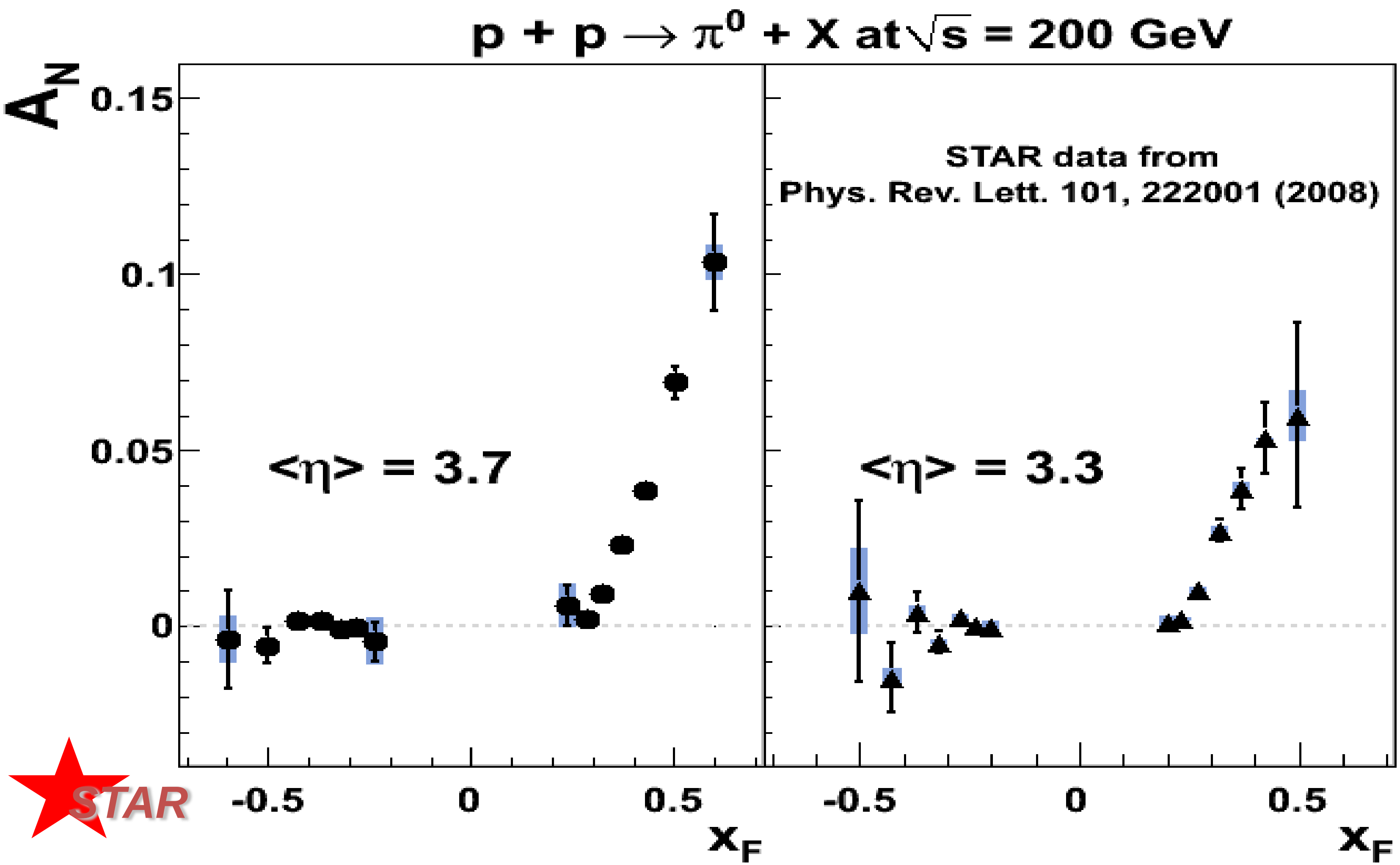






Compare **new √s=500 GeV Run 11** Full FMS Data on right with **Run 6 √s=200** published data below.





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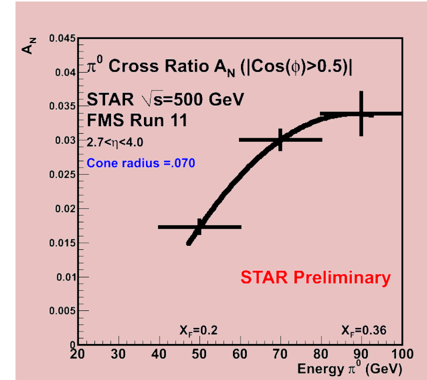
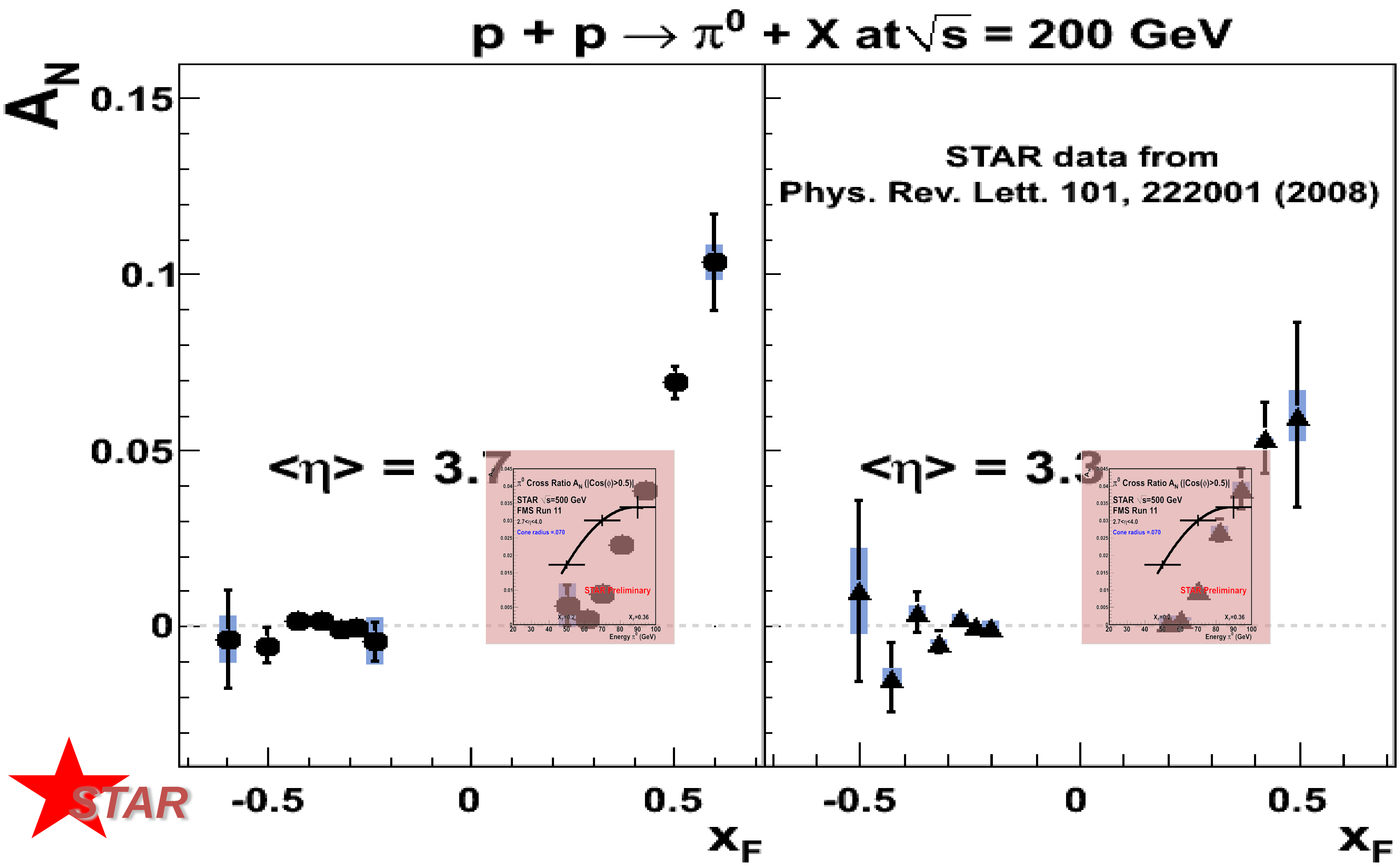
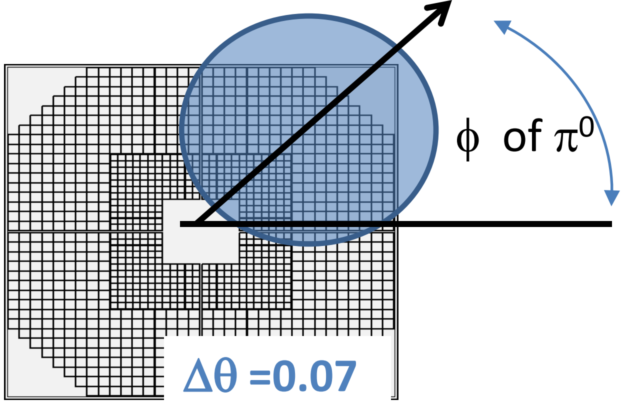


Scale of A_N similar but starts at lower X_F in Run 11 data.





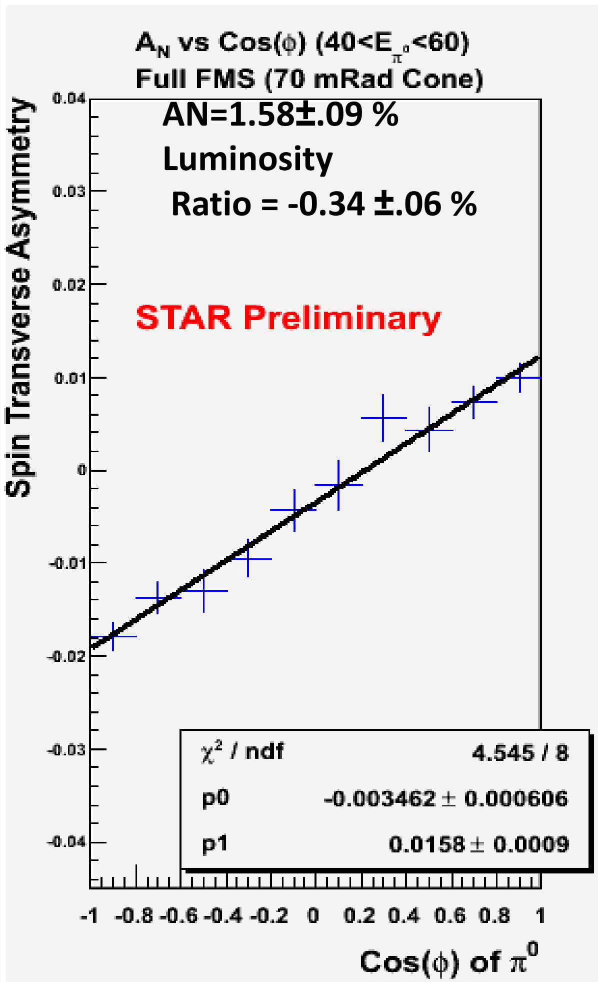
Blue Beam A_N

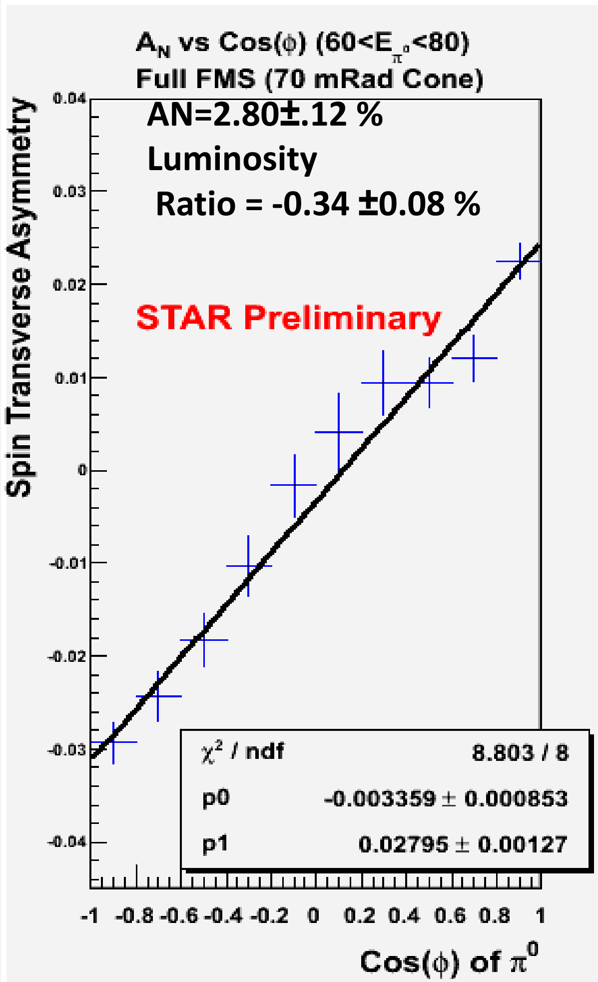
As and alternative to Cross Ratio, the raw asymmetry can be plotted as a function of Cos(ϕ)
(with polarization axis at Phi=π/2)

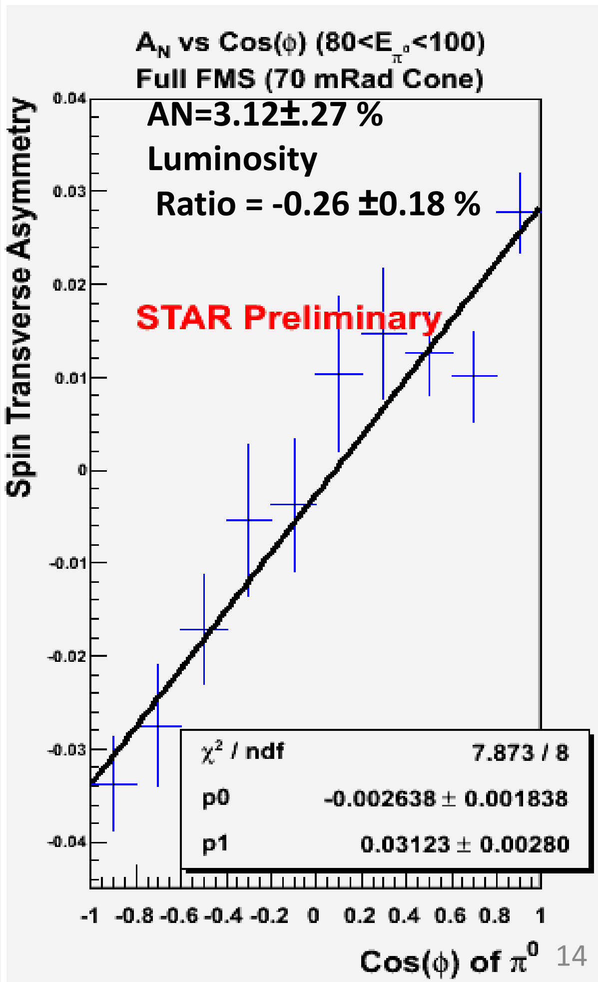
Slope =A_N

Intercept = Luminosity Ratio for data set

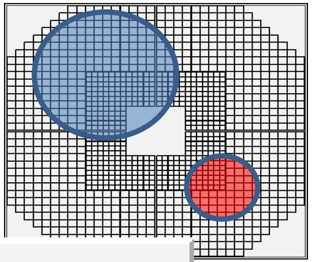
Luminosity ratio for all **~ - 0.33 ±.05 %**

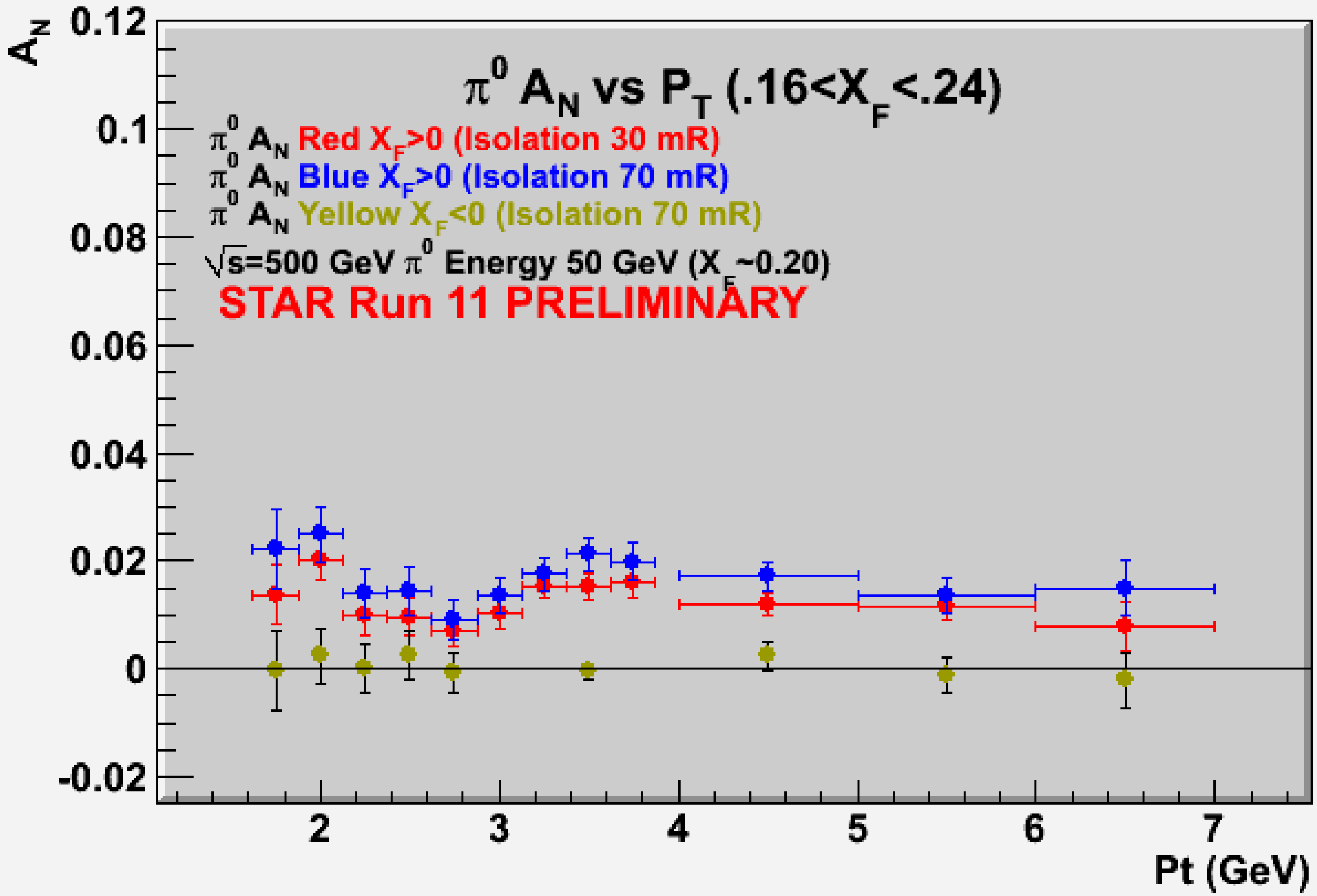






Transverse Single Spin π^0 Asymmetry vs P_T for small and large π^0 isolation cones. (Errors shown are statistical)





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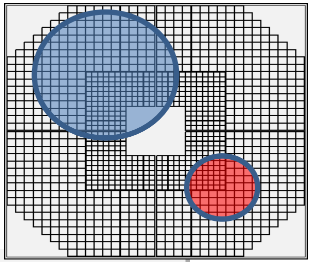

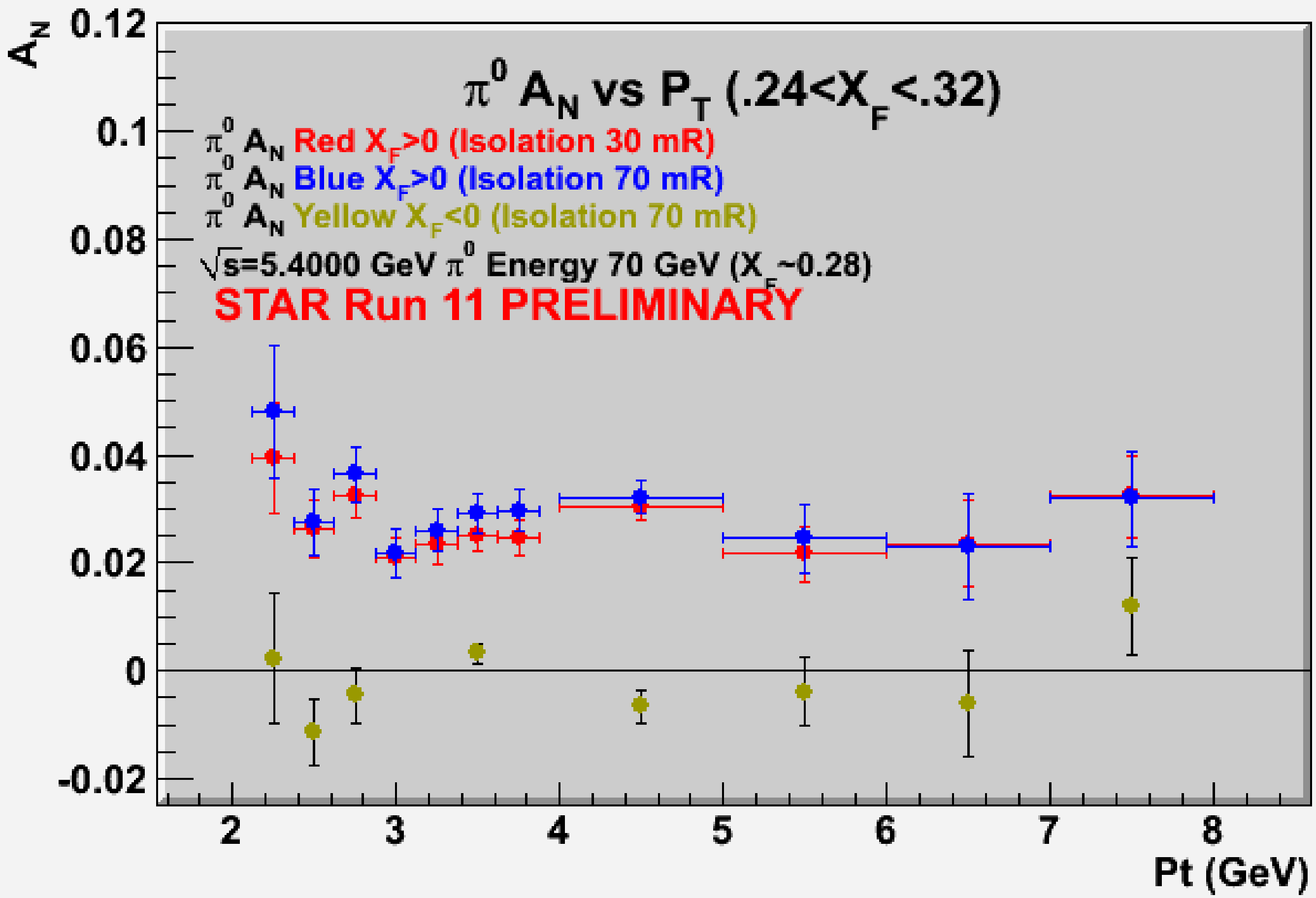

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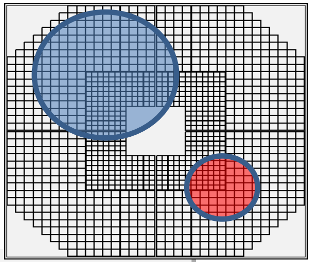

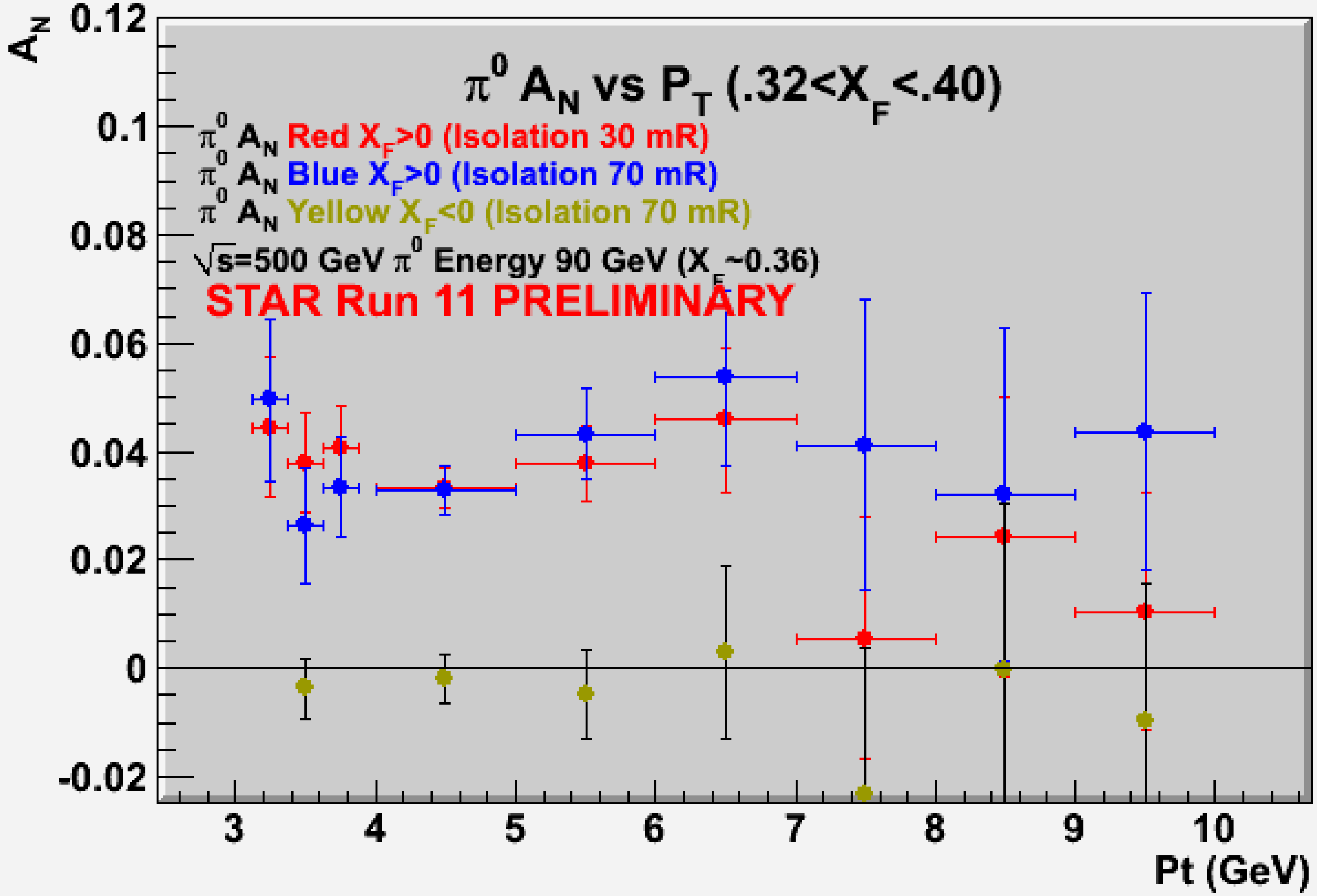

Higher Twist or other pQCD related models imply

A_N should fall at large P_T with at least 1 power of P_T.

The following plots fit the A_N vs P_T data to a power of P_T.

Fits are shown for both the **70 mRad** and **30 mRad** isolation cones.

Characterize P_T dependence with
a two Parameter Fit:

$$A_N(P_T) = [p_0] \times \left(P_T\right)^{[p_1]}$$

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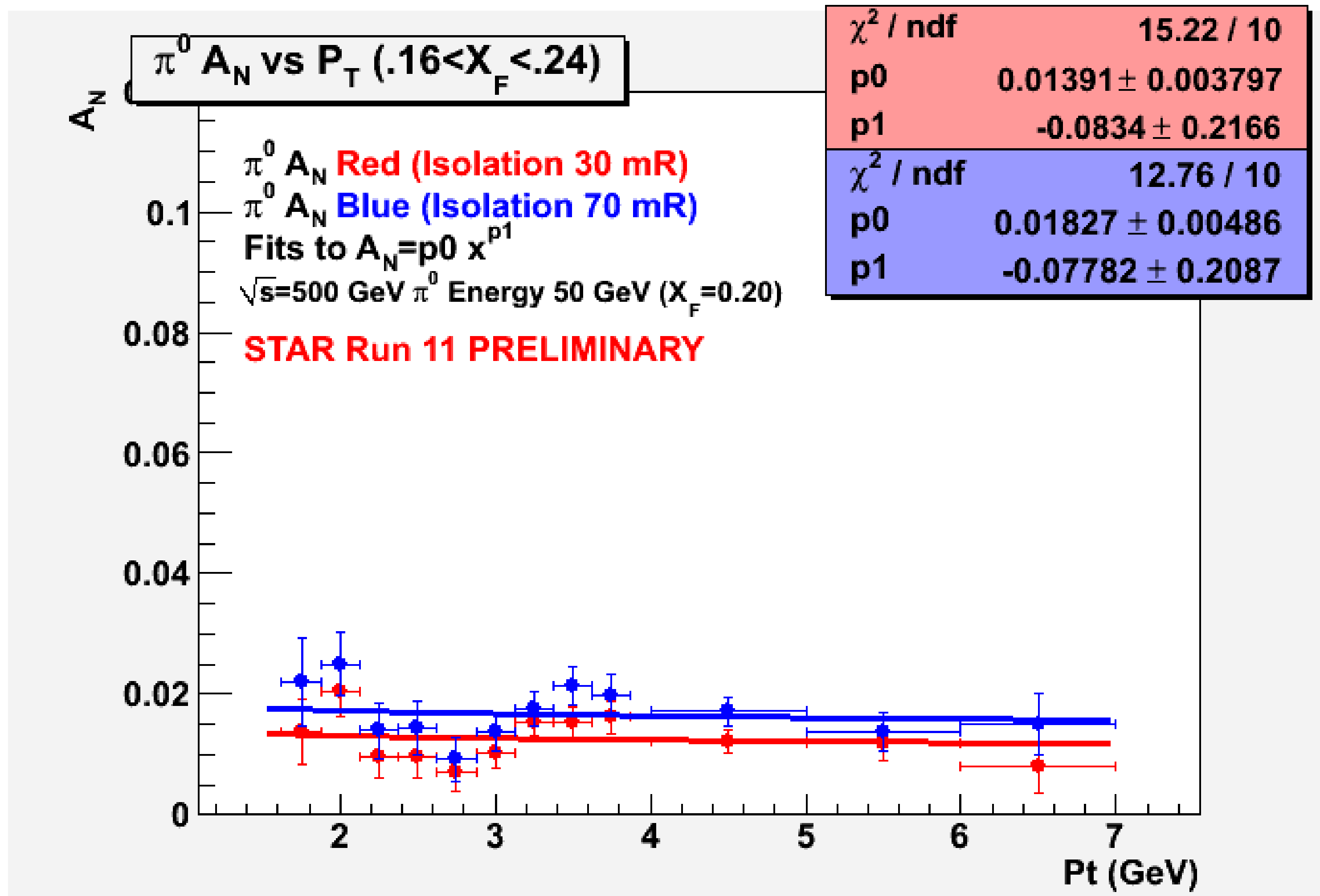
Transverse Single Spin π^0 Asymmetry vs P_T for small and large π^0 isolation cones. Fits to power of P_T. (Errors shown are statistical)



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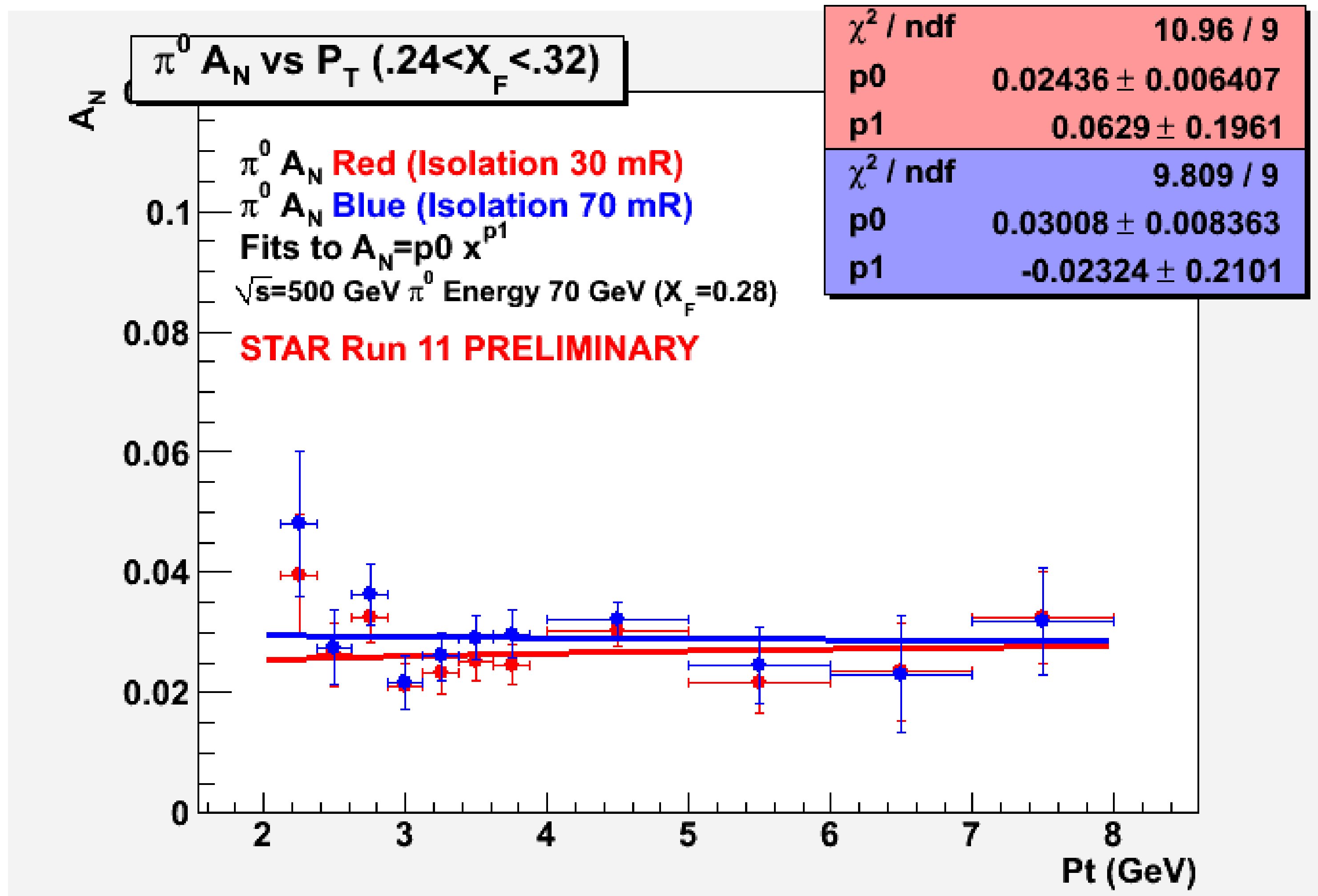
Transverse Single Spin π^0 Asymmetry vs P_T for small and large π^0 isolation cones. Fits to power of P_T. (Errors shown are statistical)



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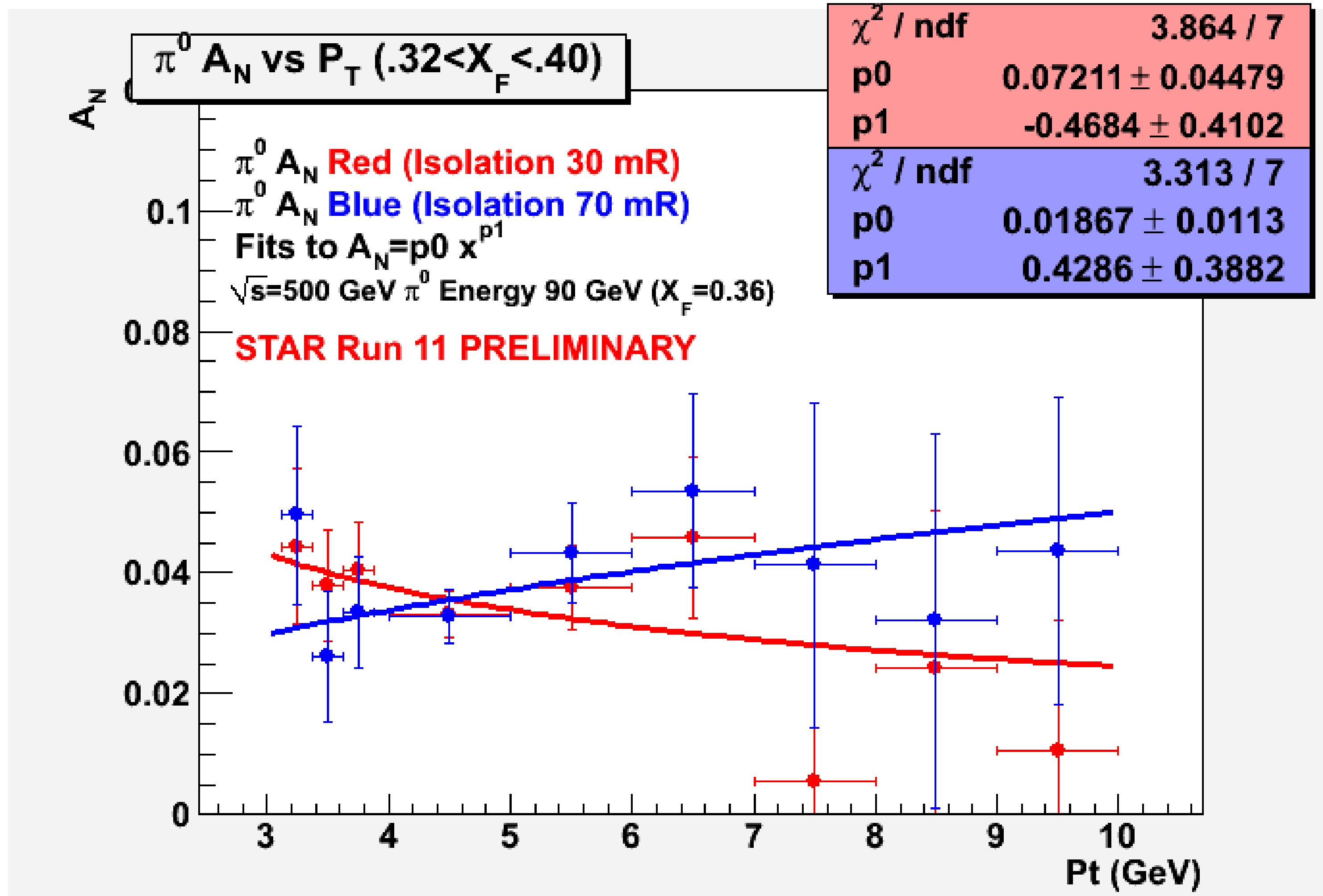
Transverse Single Spin π^0 Asymmetry vs P_T for small and large π^0 isolation cones. Fits to power of P_T. (Errors shown are statistical)



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Systematic Errors

- Run 11 blue beam polarization 48% ± 5%

$$\frac{\Delta A_N}{A_N} < 10\%$$

- Non π^0 signal <10%
- Similar asymmetries for Background:

$$\frac{\Delta P_T}{P_T} < 12\%$$

$$\frac{\Delta A_N}{A_N} < 5\%$$

$$\frac{\Delta A_N}{A_N} < 5\%$$

- P_T uncertainty
  - Energy 10%
  - Angle 6%

$$\frac{\Delta P_T}{P_T} < 12\%$$

$$\frac{\Delta A_N}{A_N} < 5\%$$

Total Systematic Asymmetry Error
Common to all data points. $\frac{\Delta A_N}{A_N} < 15\%$

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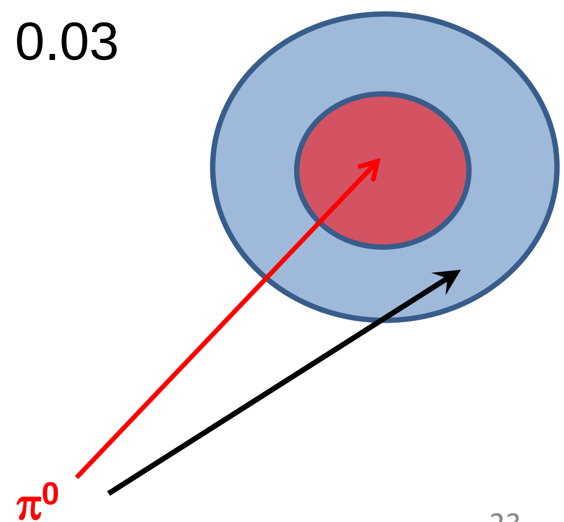
Conclusion

STAR π^0 A_N at $\sqrt{s}$=500 GeV

- A_N increases with X_F (as seen at lower energies).
- A_N less dependent on P_T that models predict to P_T~ 10 GeV/c. Data may be consistent with flat dependence on P_T.

- A_N larger for isolated π^0s.

- π^0 events with additional E&M signals in the same general direction as the π^0 (>~5 GeV between 0.03 and 0.07 radians from the π^0) contribute little to the observed Transverse Single Spin Asymmetry.



- **New Data Coming RHIC RUN 12**
  - **~20 pb^{-1} of $\sqrt{s}$=200 GeV pp**
  - **~Transversely Polarized FMS data**
  - **~ Similar measurement up to P_T >6 GeV/c**

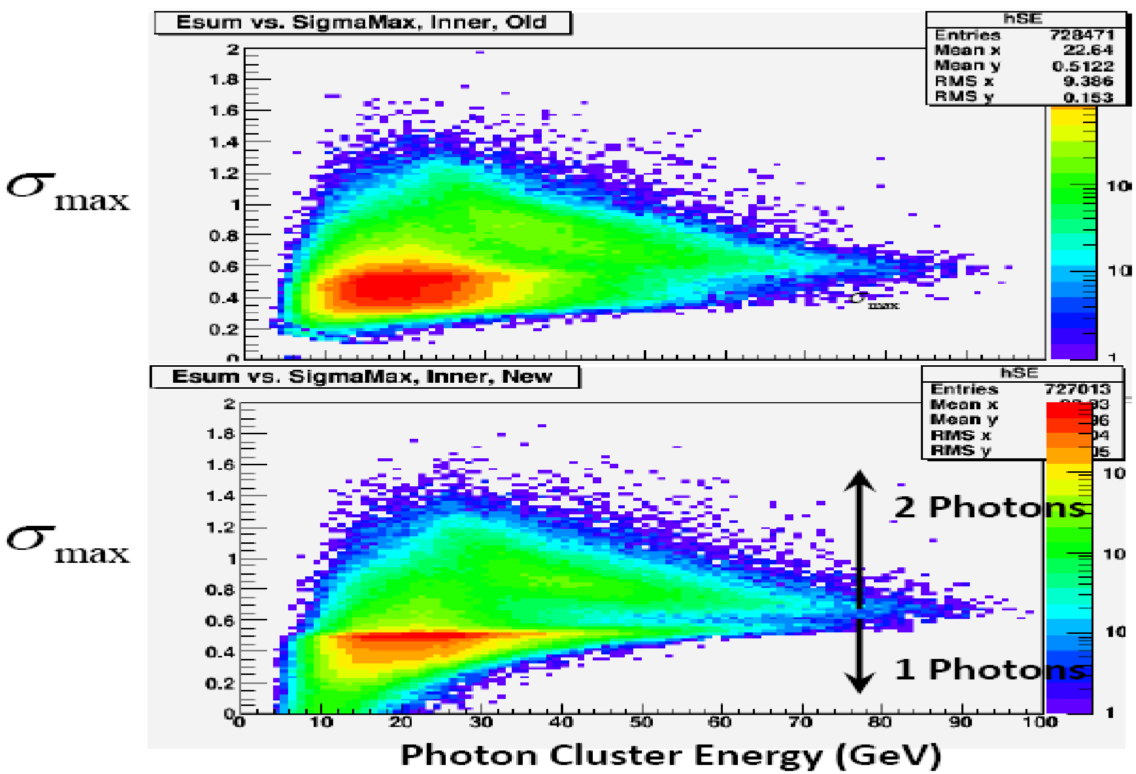
Extra

$$\Delta\sigma_x{}^2 = \frac{\sum\limits_{i\,(e_i>e_0)} (x_i - x_0)^2 \ln(e_i / e_0)}{\sum\limits_{i\,(e_i>e_0)} \ln(e_i / e_0)}$$

$$\Delta\sigma_x \Delta\sigma_y = \frac{\sum\limits_{i\,(e_i>e_0)} (x_i - x_0)(y_i - y_0) \ln(e_i / e_0)}{\sum\limits_{i\,(e_i>e_0)} \ln(e_i / e_0)}$$

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.

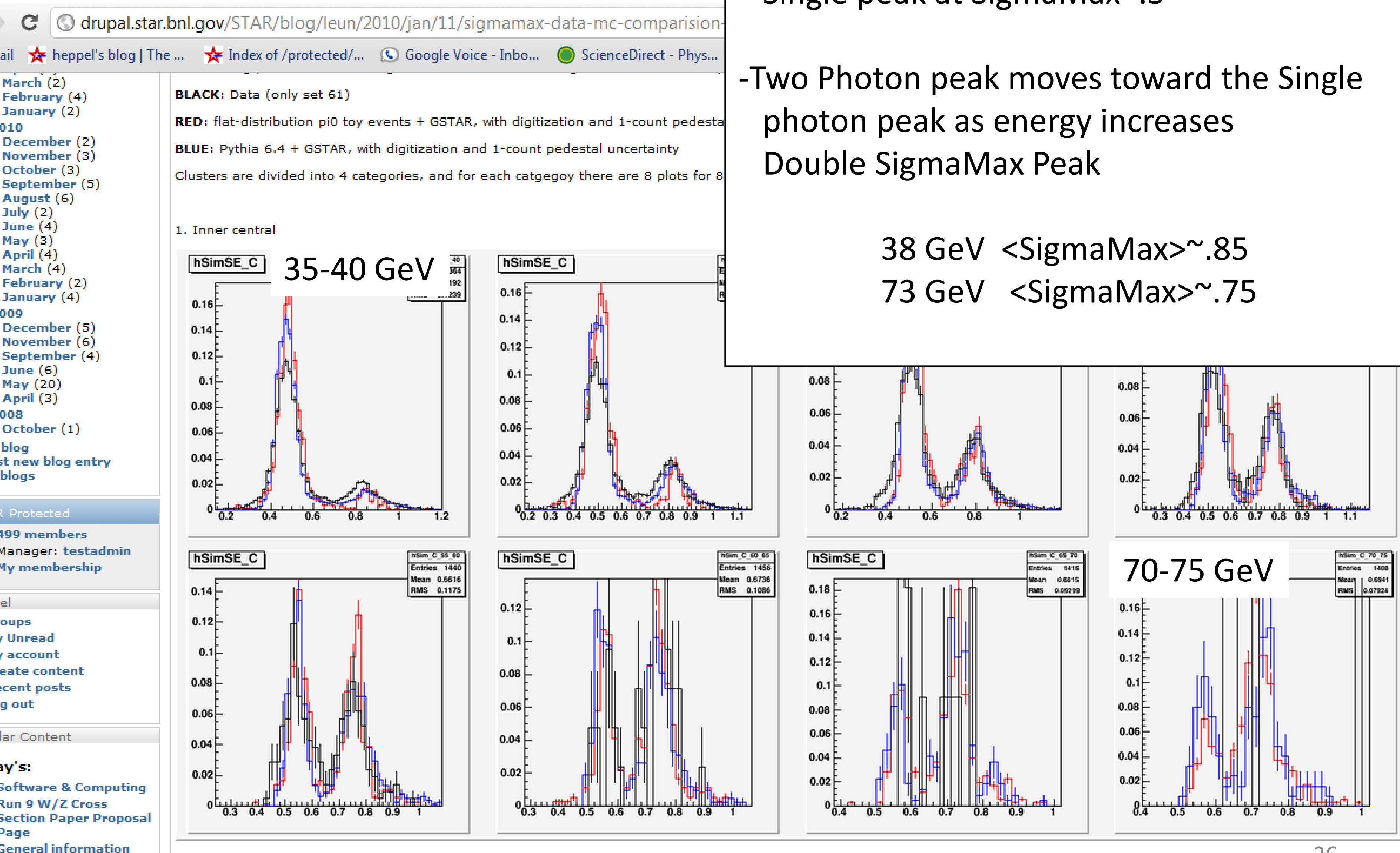
Provides clearer separation
Between π^0 and single photon.
Clusters up to ~80 GeV.

From Len's Analysis,

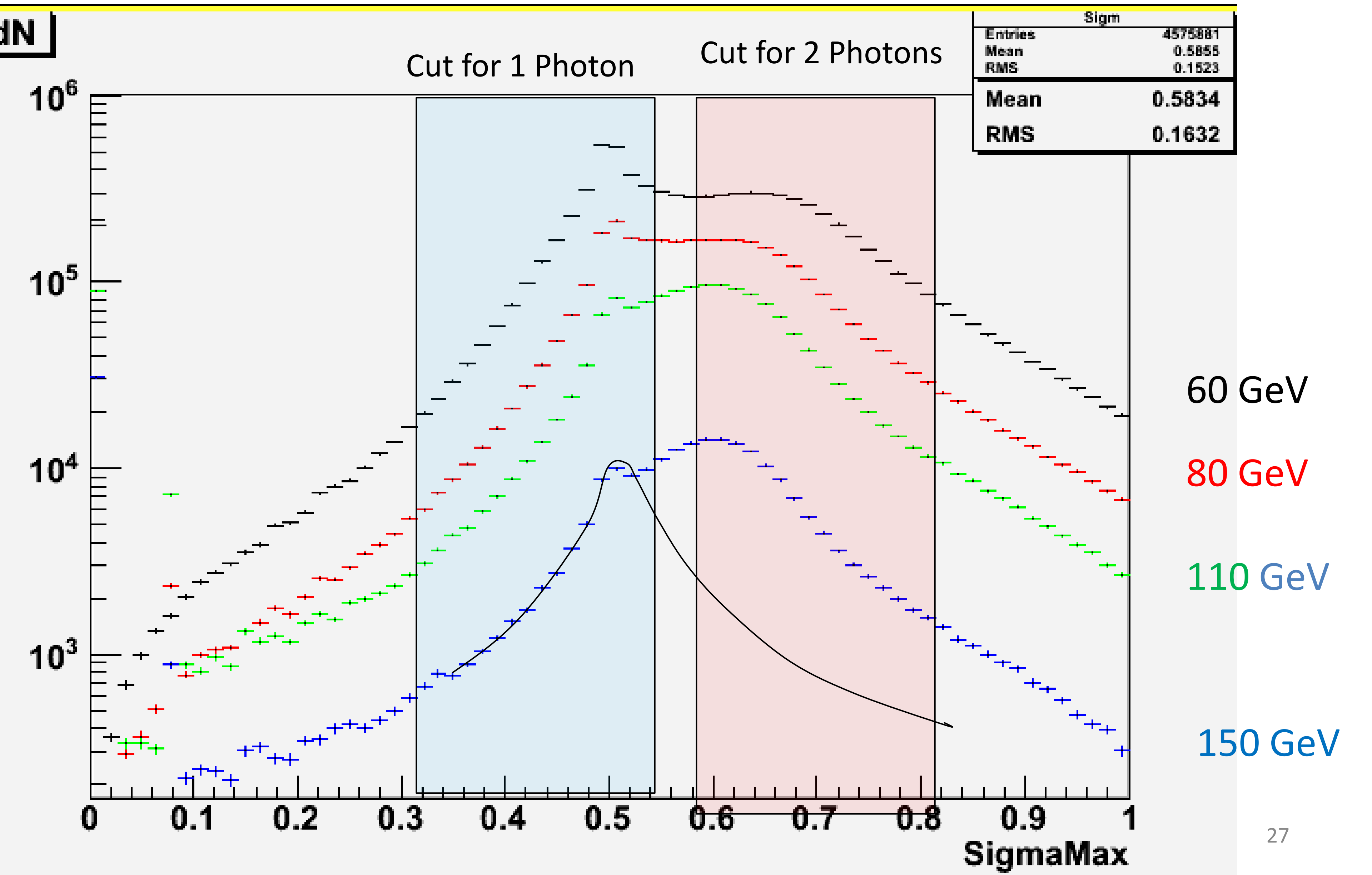
-Single Photon peak changes little with Energy
Single peak at SigmaMax~.5

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

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

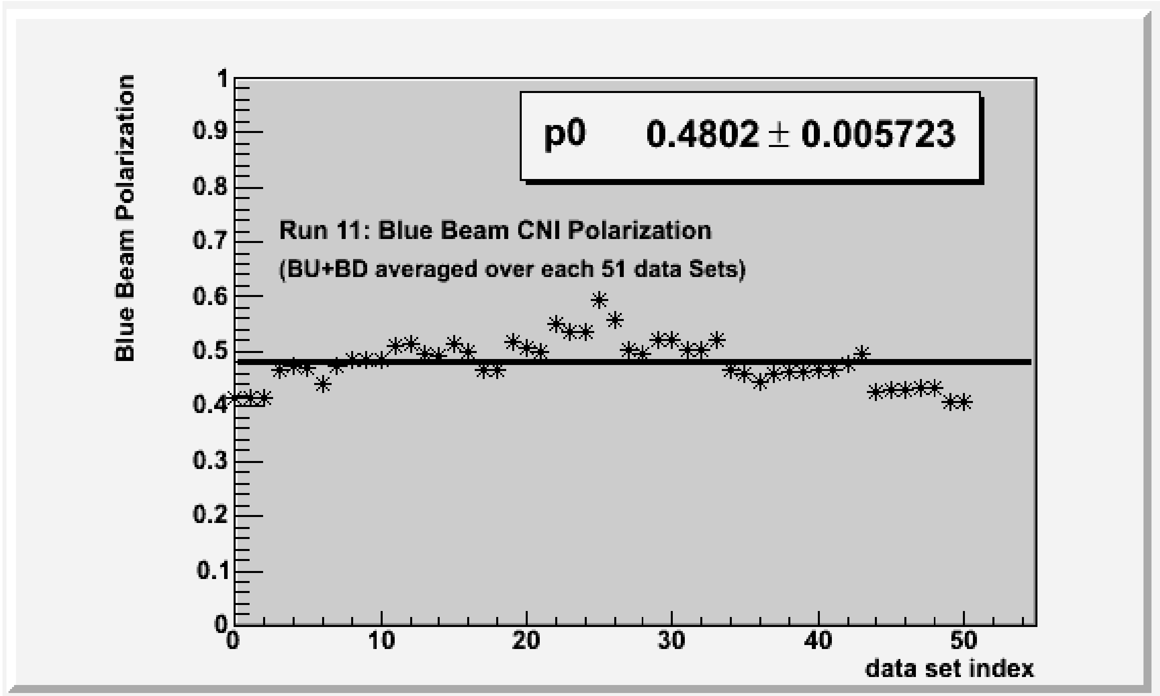


Run 11 distributions of SigmaMax as a indicator of single photon vs π^0 only slowly degrades with higher energy.



Blue Beam Polarization Measurements

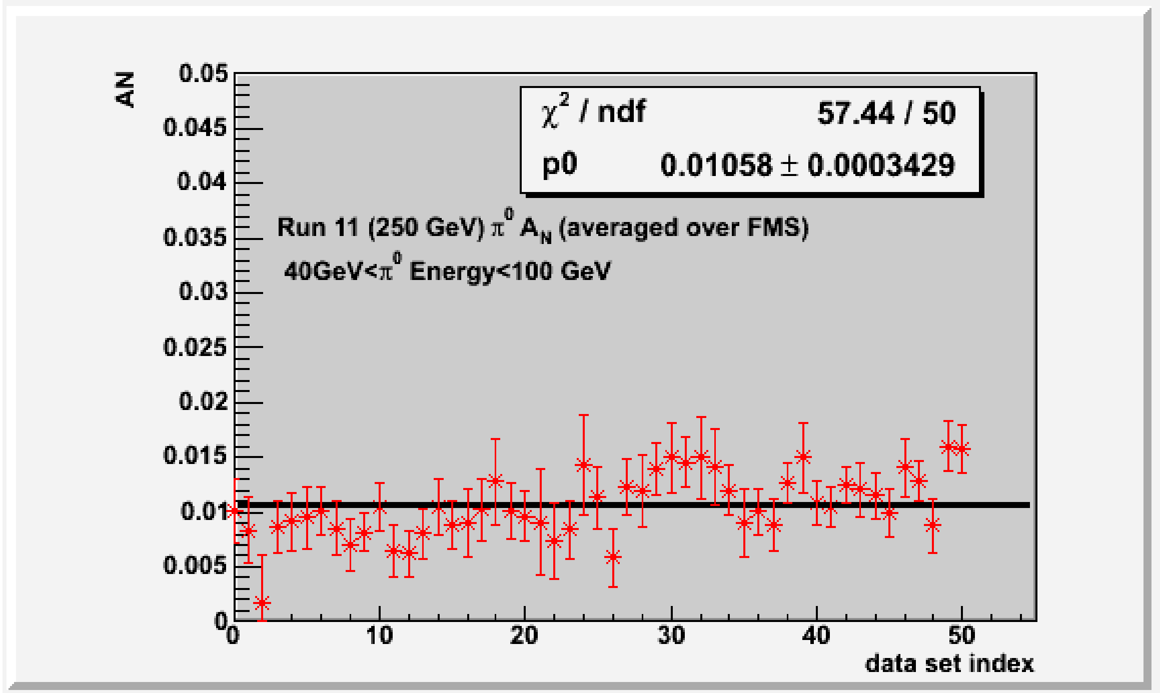
- CNI polarimeter data
- Average polarization for 51 consecutive time periods each data set represents ~ ½ day of running.



As from previous slide:

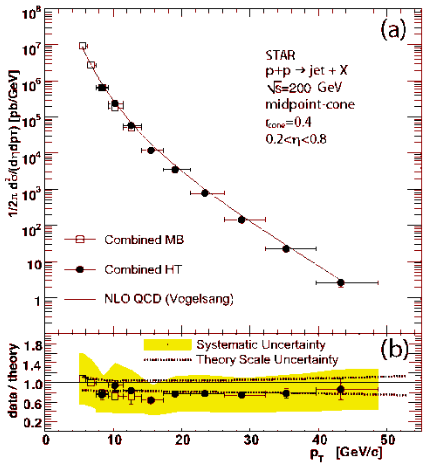
For the **"A_N vs cos(ϕ)"** fits to all FMS data divided into the 51 consecutive time periods.

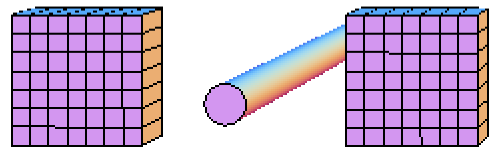
- 22.4 pb^{-1}
- 2.6< pseudorapidity<4.1
- 40 GeV < Energy π^0< 100 GeV
- Average polarization 48%
- Corrected each of of 51 sets (each set ~ ½ day of data)



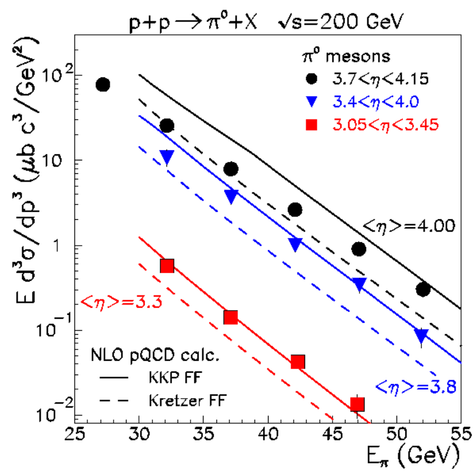
Unpolarized Cross Sections agree with Collinear Factorization PQCD

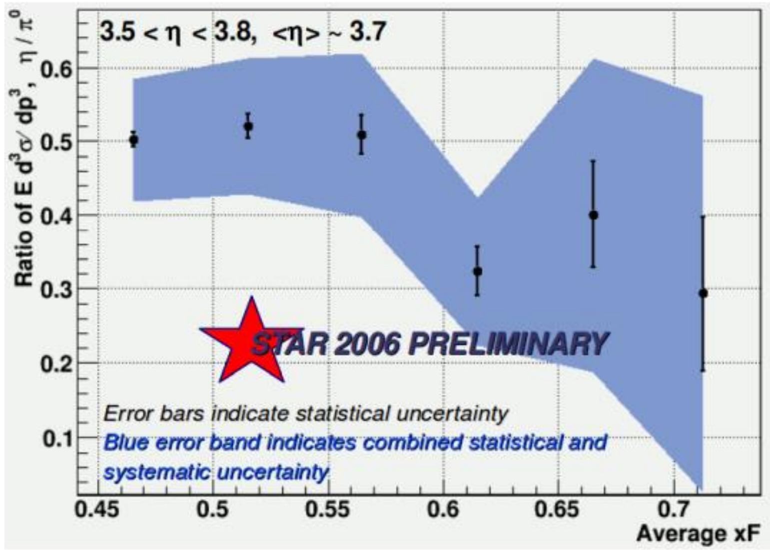
PRL 97, 252001





PRL 97, 152302





- Jet Mid-rapidity (Left) and Pi0 Forward Rapidity (right)
- Cross section for π^0 nominally consistent with NLO pQCD.
- Cross section for η (with nominal fragmentation) may also be consistent.

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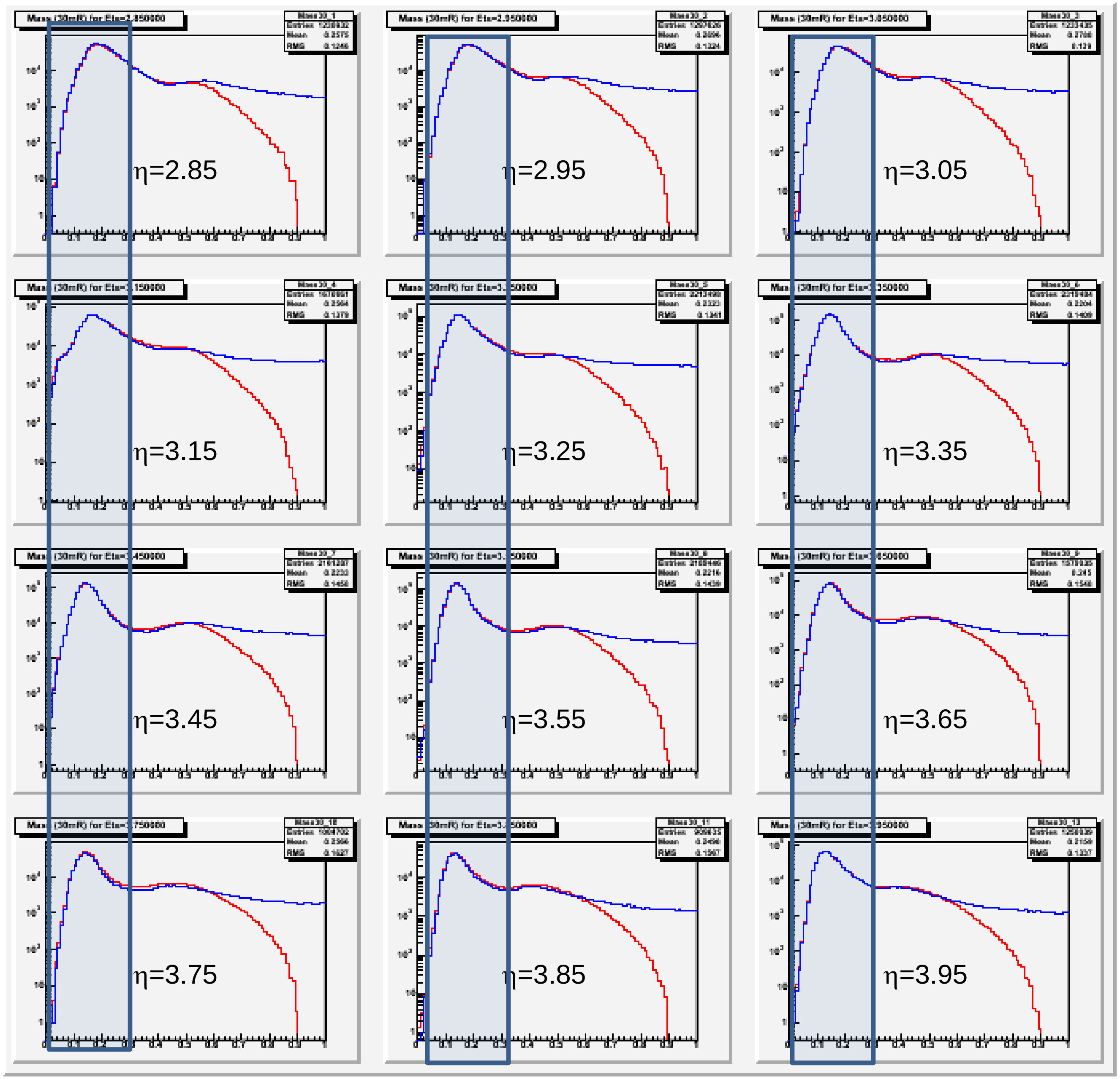
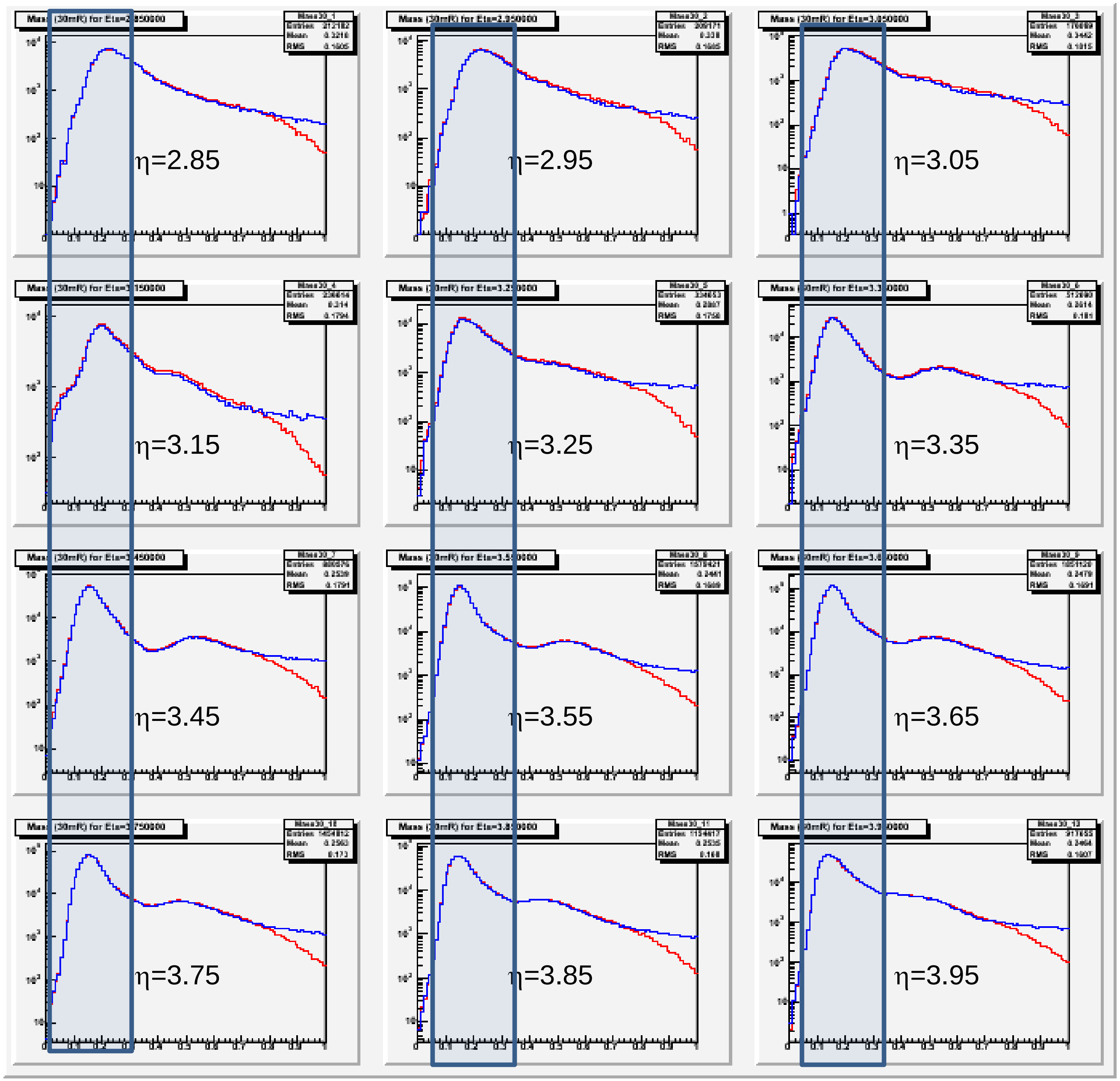
Mass Distribution in η bins (40<E<60 GeV)   r=1.53

Red=(cone 30 mR)   Blue=**1.53** (cone 70 mR)



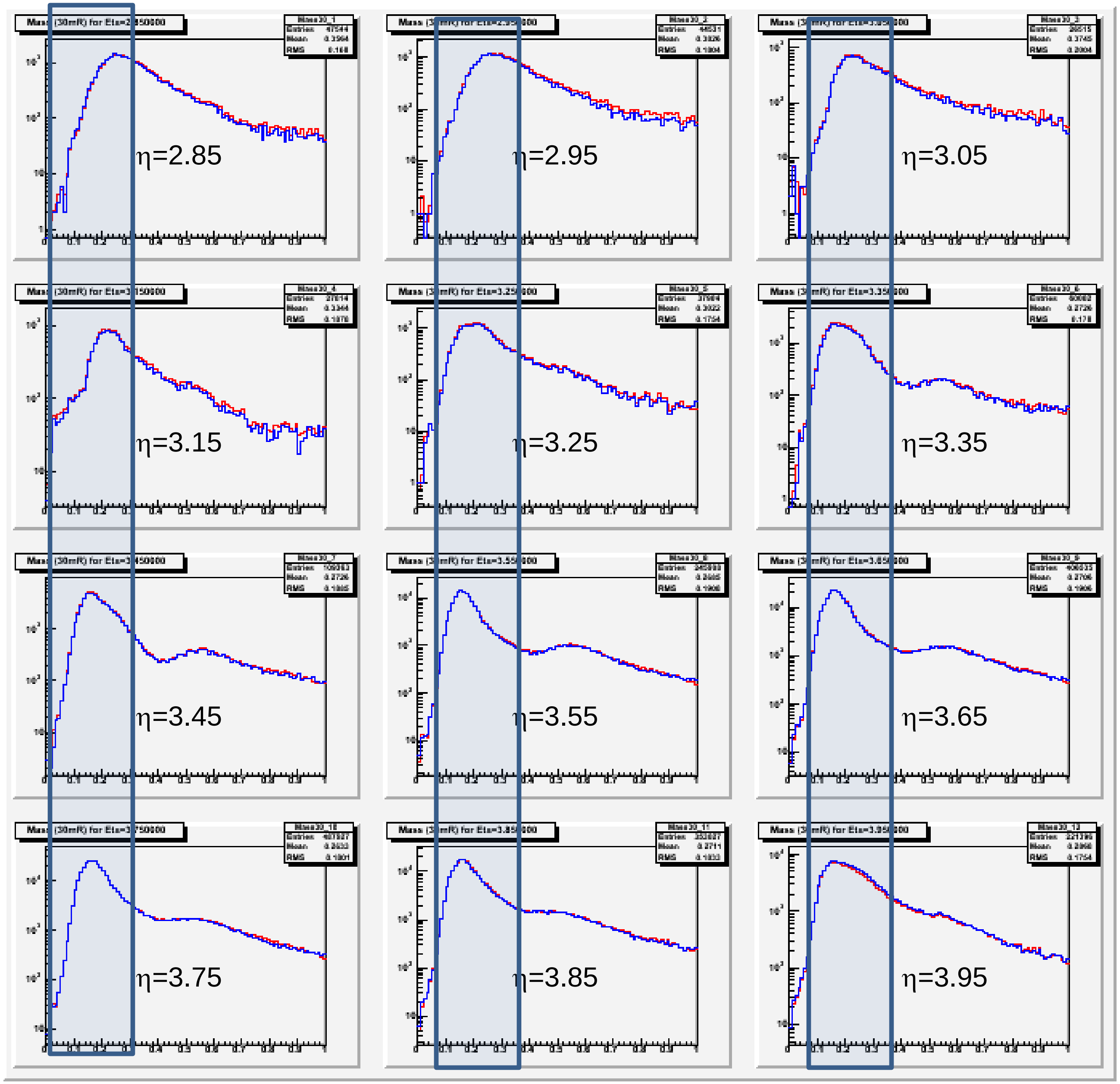
Mass Distribution in η bins (60<E<80 GeV) r=1.41

Red=(cone 30 mR) Blue=**1.41**(cone 70 mR)



Mass Distribution in η bins (80<E<100 GeV) r=1.37

Red=(cone 30 mR) Blue=**1.37**(cone 70 mR)



Calculate the **asymmetry** and **error** associated with the "Extra Events" that are included in the 30 mR cone but not the 70 mR Cone

Let A_{N30} be the Asymmetry for the 30mR cone

Let A_{N70} be the Asymmetry for the 70mR cone

Let ΔA_{N30} and ΔA_{N70} be the Errors.

Let N_{30} and N_{70} be the numbers of events.

$$A_{N30} = \frac{N_{u30} - N_{d30}}{N_{u30} + N_{d30}} = \frac{N_{u30} - N_{d30}}{N_{30}}$$

$$A_{N70} = \frac{N_{u70} - N_{d70}}{N_{70}}$$

$$\Delta A_{N30} \sim \frac{1}{\sqrt{N_{30}}}$$

$$\Delta A_{N70} \sim \frac{1}{\sqrt{N_{70}}}$$

Assume

E=50 GeV: r=1.51

E=70 GeV: r=1.41

E=90 GeV: r=1.31

$$\frac{N_{30}}{N_{70}} = r$$

$$\frac{N_{30}}{N_{30} - N_{70}} = \frac{r}{r-1}$$

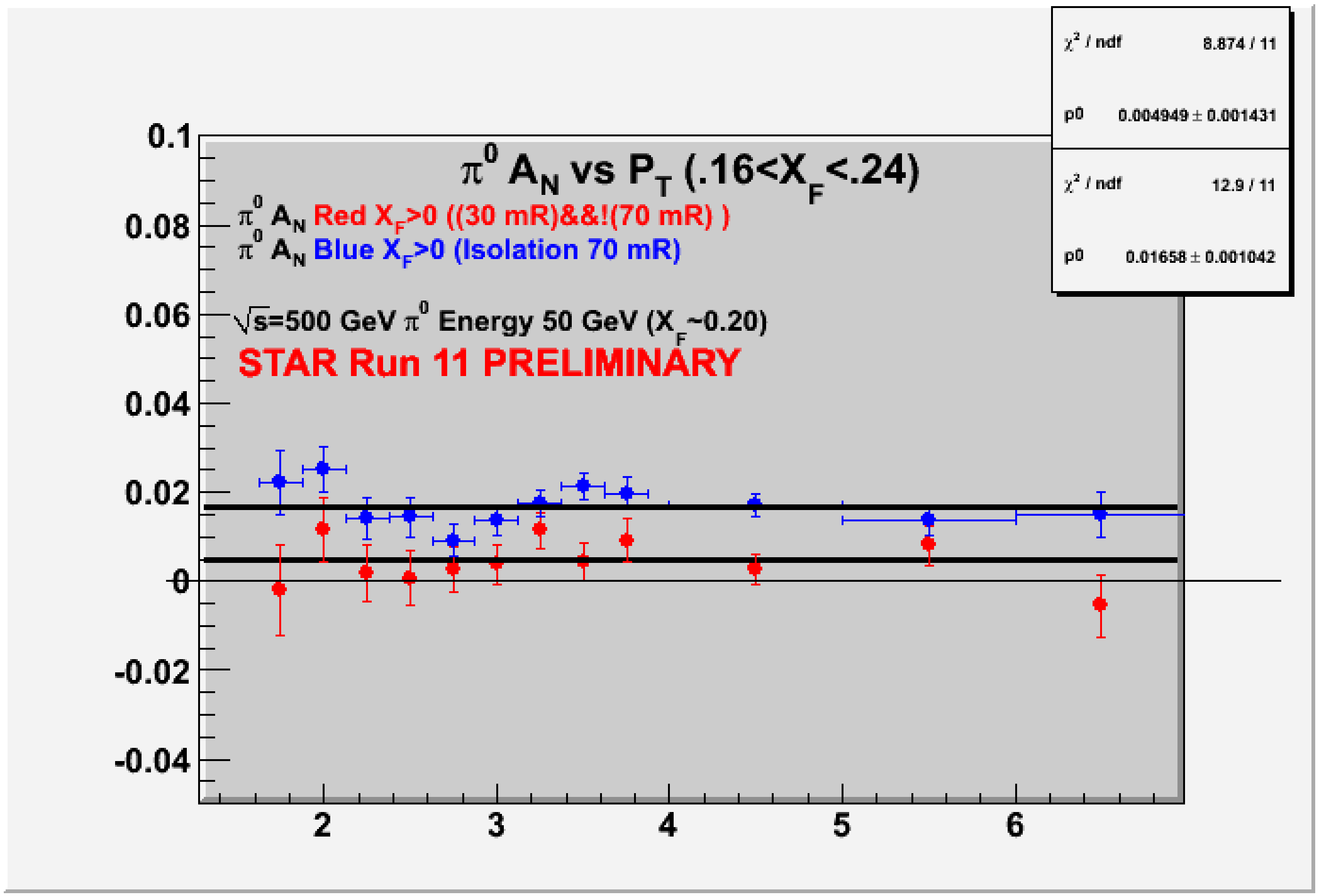
$$\frac{N_{70}}{N_{30} - N_{70}} = \frac{1}{r-1}$$

$$A_{ring} = \frac{r}{r-1} A_{N30} - \frac{1}{r-1} A_{N70}$$

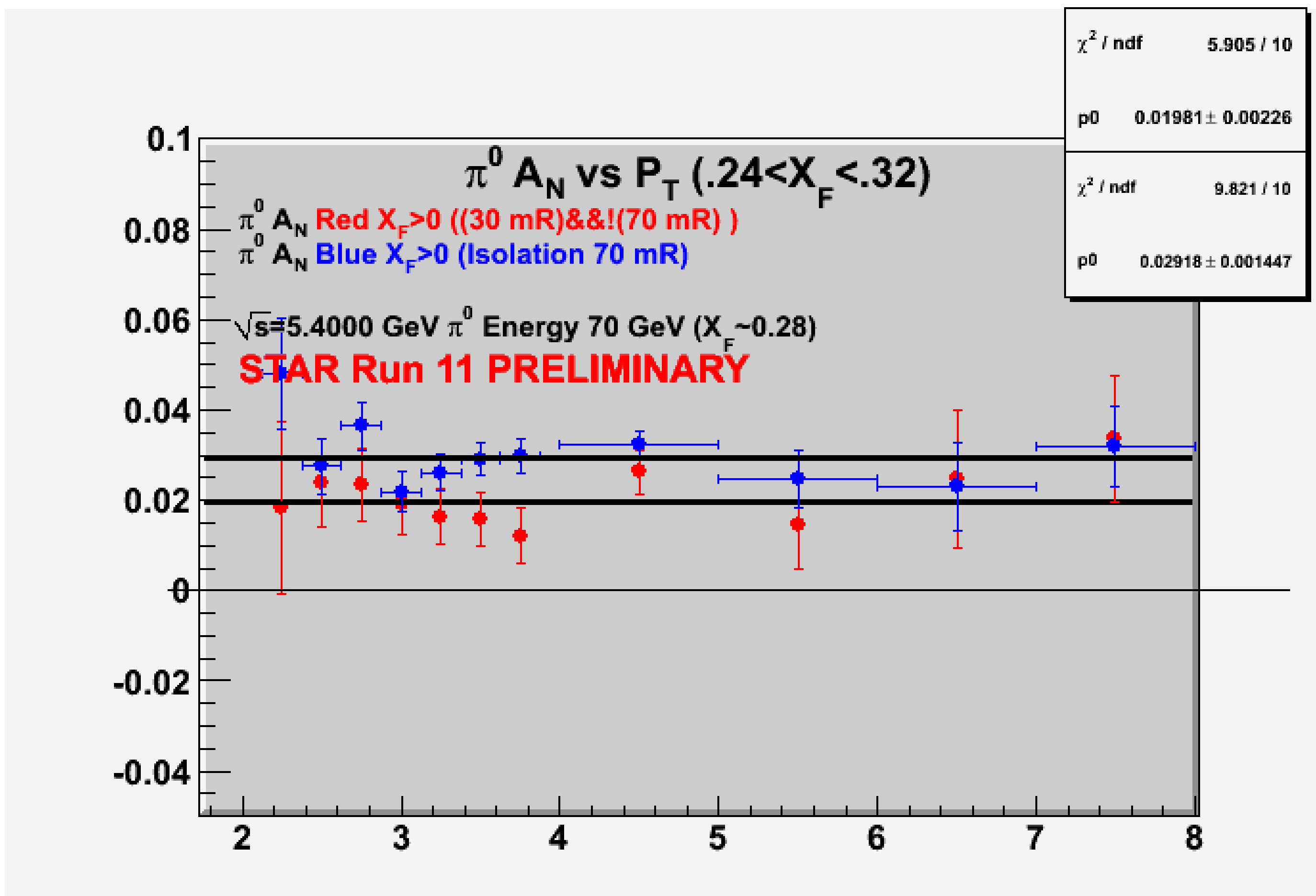
$$\Delta A_{ring} = \frac{1}{\sqrt{N_{ring}}} = \frac{1}{\sqrt{N_{30} - N_{70}}}$$

$$= \frac{1}{\sqrt{N_{70}}} \frac{1}{\sqrt{r-1}} = \Delta A_{70} \frac{1}{\sqrt{r-1}}$$

Compare Fits to constant A_N
Red= 30mR cone but not 70 mR cont
Blue=70mR cone
Difference : (1.66% - .49%)=1.17%   (8 sigma difference)



Compare Fits to constant A_N
Red= 30mR cone but not 70 mR cont
Blue=70mR cone
Difference 2.92% - 1.98%=0.94% (4 sigma difference)



Compare Fits to constant A_N
Red= 30mR cone but not 70 mR cont
Blue=70mR cone
Difference 3.57% - 3.44% = 0.13% (0.4 sigma difference)