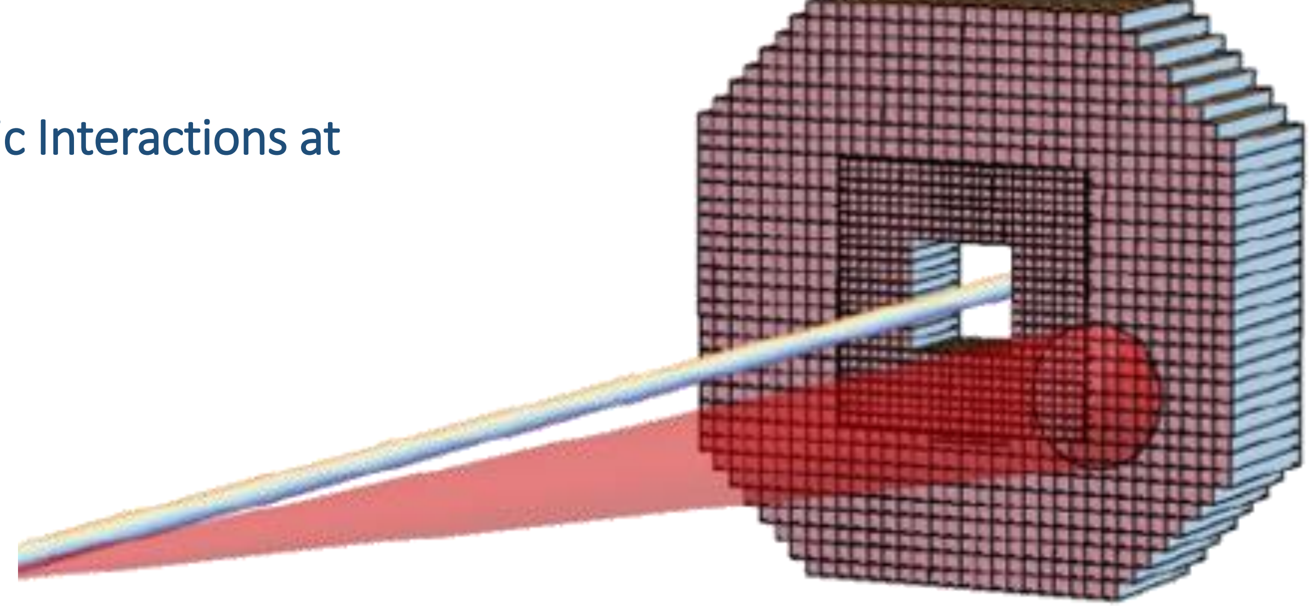
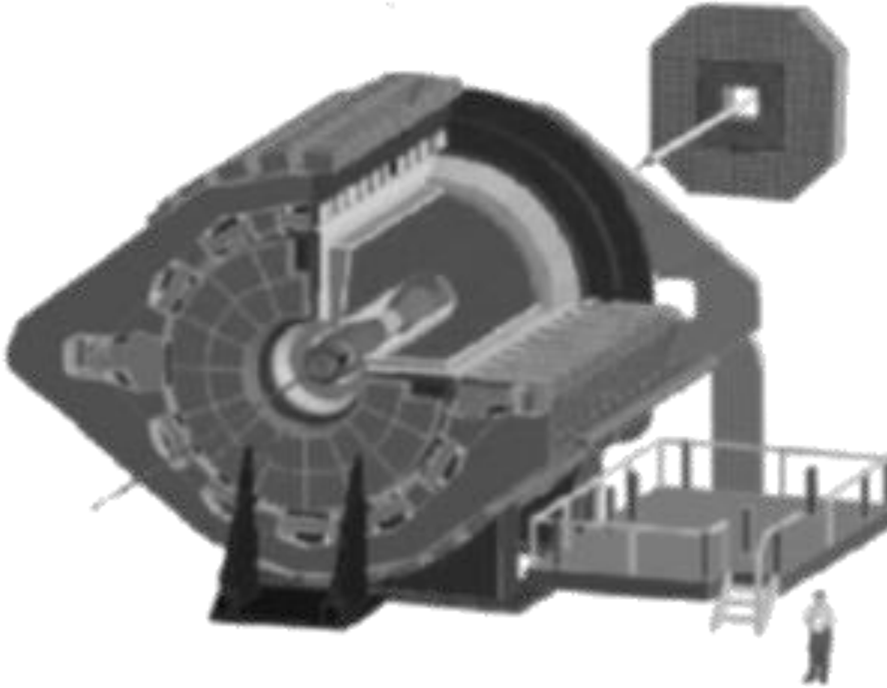
The Abdus Salam International Centre for Theoretical Physics op on Multiple Partonic Interactions at the LHC .



Preview from RHIC Run 15 p-p and p-Au Forward Neutral Pion Production from Transversely Polarized Protons

Steve Heppelmann Penn State University (STAR)*



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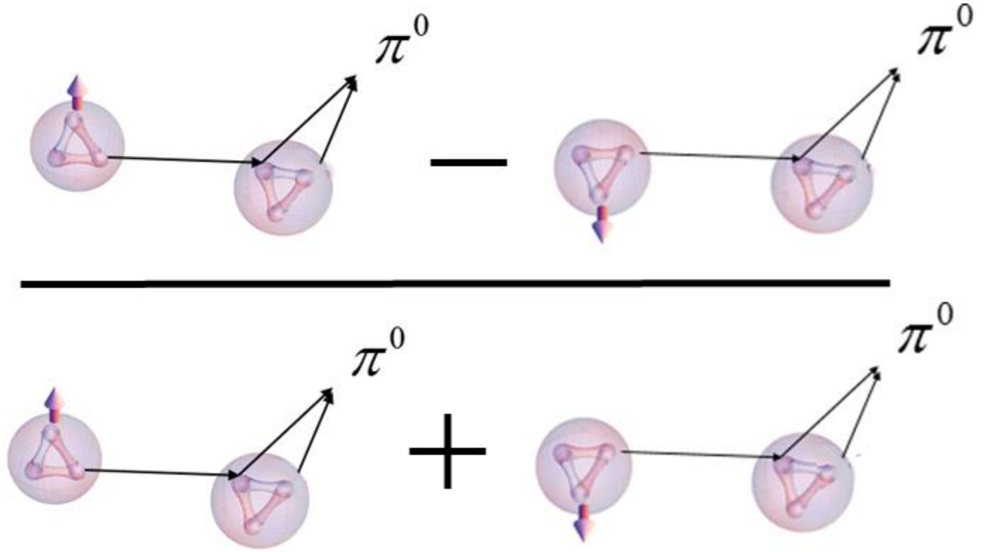
* *Supported by NSF*

Transverse Single Spin Asymmetries (TSSA)

A_N

$$A_N \equiv \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} =$$



Scattering Process <u>Factorizes</u> into 3 parts

1) **Parton distribution**: Select a quark from the incident proton and a parton from the target proton
2) **Hard scattering:** Scatter the quark from a parton in the target proton does not depend on transverse spin.
3) **Universal Jet Fragmentation**: Color neutralize the scattered quark , pulling partons from one of the protons

Possible sources of non-zero A_N :

1) "Sivers Effect" with Transverse Spin Dependent initial parton momentum components..
2) "Collins Effect" with Transverse Spin Dependent Fragmentation.

RHIC Collisions at STAR, between Polarized Protons and Polarized Protons or Nuclei

- The hard parton cross sections **do depend** on the longitudinal spins of colliding partons.
- The hard parton cross sections **do not depend** on the transverse components of parton spin for two reasons.

  1. Dependence of scattering amplitude on transverse spin implies helicity flip amplitudes.

  2. Dependence of the cross section on transverse spin implies interference between amplitudes of different phases. Leading twist amplitudes do not provide the required phases changes.

- Dependence of hard cross sections on transverse spin does not come from the hard parton cross section but is expected to involve initial and final state or “higher twist” effects.

PHYSICAL REVIEW D VOLUME 41, NUMBER 1 1 JANUARY 1990

Single-spin production asymmetries from the hard scattering of pointlike constituents

Dennis Sivers
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 28 April 1989)

* Parton Momentum Direction
  ≠ Proton Momentum Direction
* Transverse Momentum Dependent Parton Distributions (TMD)
- Parton Angular Momentum
- Wilson Line for phase change

$$\left(P^{\uparrow/\downarrow}{}_{parton}\right)_T \rightarrow \pm\Delta P_T$$

$$A_N = \frac{\Delta\sigma}{2\sigma} \propto \frac{\Delta P_T}{P_T}$$

Sivers 1990

Collins 1993

Higher Twist 1991

ELSEVIER Nuclear Physics B 420 (1994) 565–582

Measuring transversity densities in singly polarized hadron–hadron and lepton–hadron collisions

John C. Collins [a], Steve F. Heppelmann [a], Glenn A. Ladinsky [b]
[a] *Physics Department, Pennsylvania State University, University Park, PA 16802, USA*
[b] *Department of Physics and Astronomy, Michigan State University, East Lansing MI 48824, USA*

Received 21 April 1993; revised manuscript received 26 January 1994; accepted 26 January 1994

Spin Dependent Fragmentation

$$P_T \xrightarrow{q^{\uparrow/\downarrow}\rightarrow\pi^0} P_T \pm \Delta P_T$$

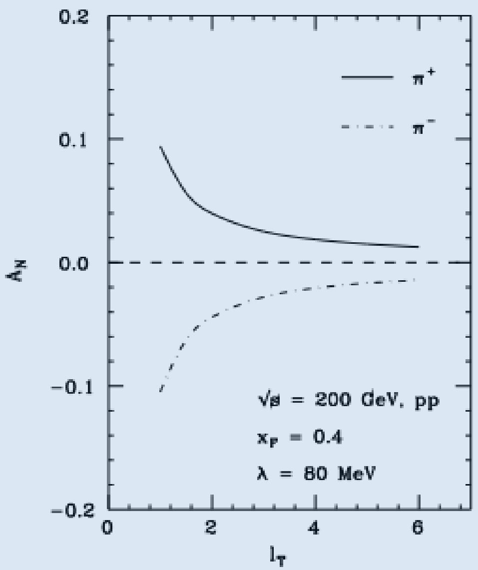
$$A_N = \frac{\Delta\sigma}{2\sigma} \propto \frac{\Delta P_T}{P_T}$$

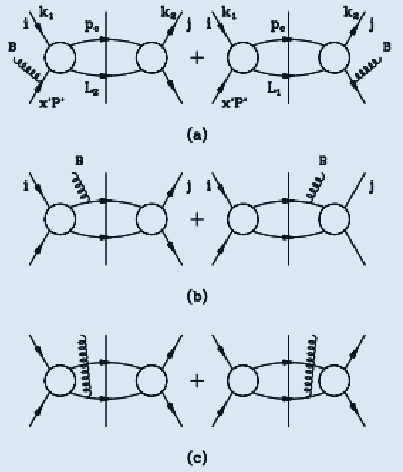
$$A_N = \frac{\Delta\sigma}{2\sigma} \propto \frac{1}{P_T}$$

VOLUME 67, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER

Single Transverse Spin Asymmetries

Jianwei Qiu [(1),(2)] and George Sterman [(1)]
[(1)] *Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794-3840*
[(2)] *Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011*
(Received 22 July 1991)





$$p_{\uparrow} + p \Rightarrow \pi + X$$

π^0 – E704, PLB261 (1991) 201.

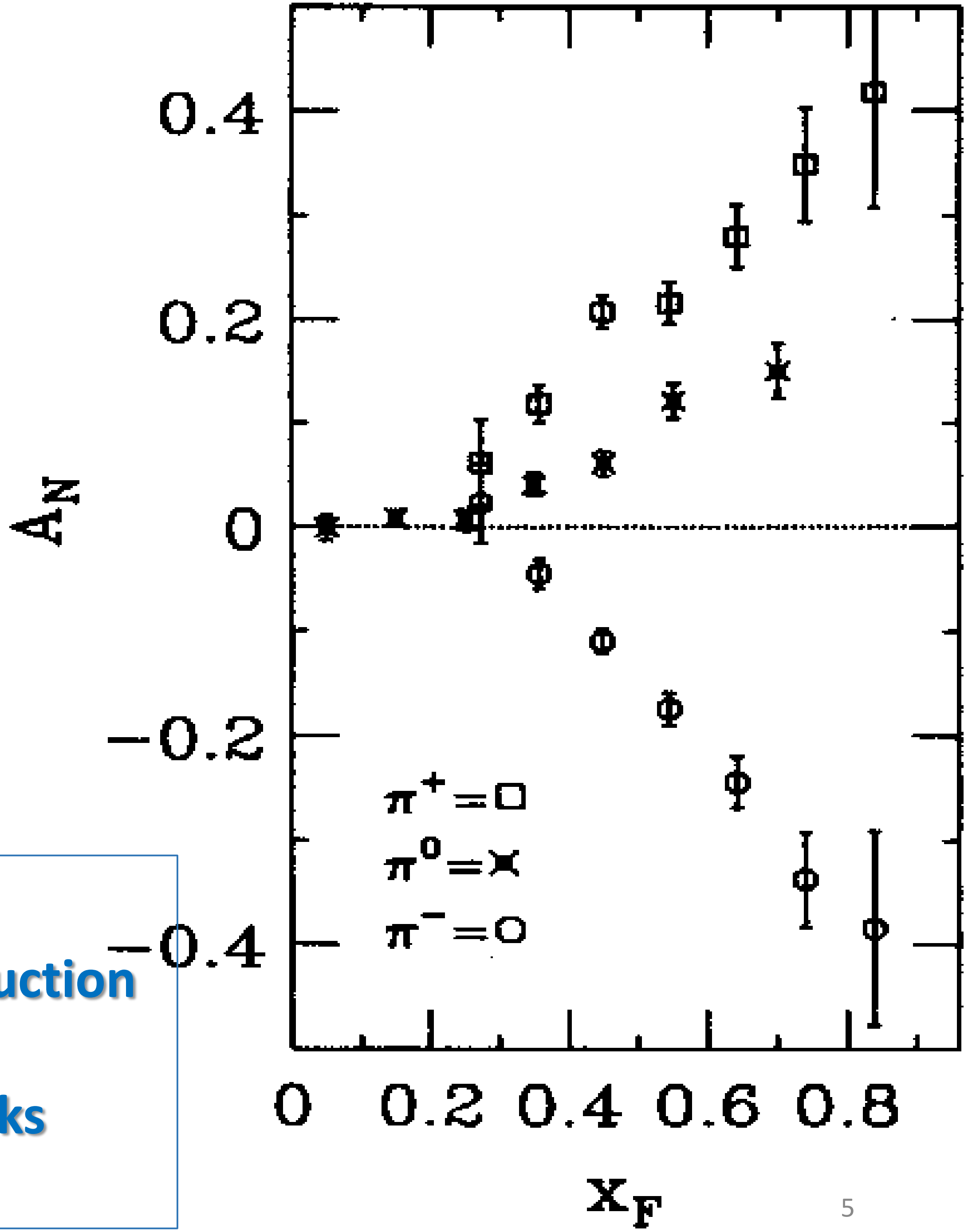
$\pi^{+/-}$ - E704, PLB264 (1991) 462.

√s=20 GeV,

p_T=0.5-2.0 GeV/c:

π^+, π^0 $(Large\ X_F\ up\ quark\ scattering)$

π^- $(Large\ X_F\ down\ quark\ scattering)$

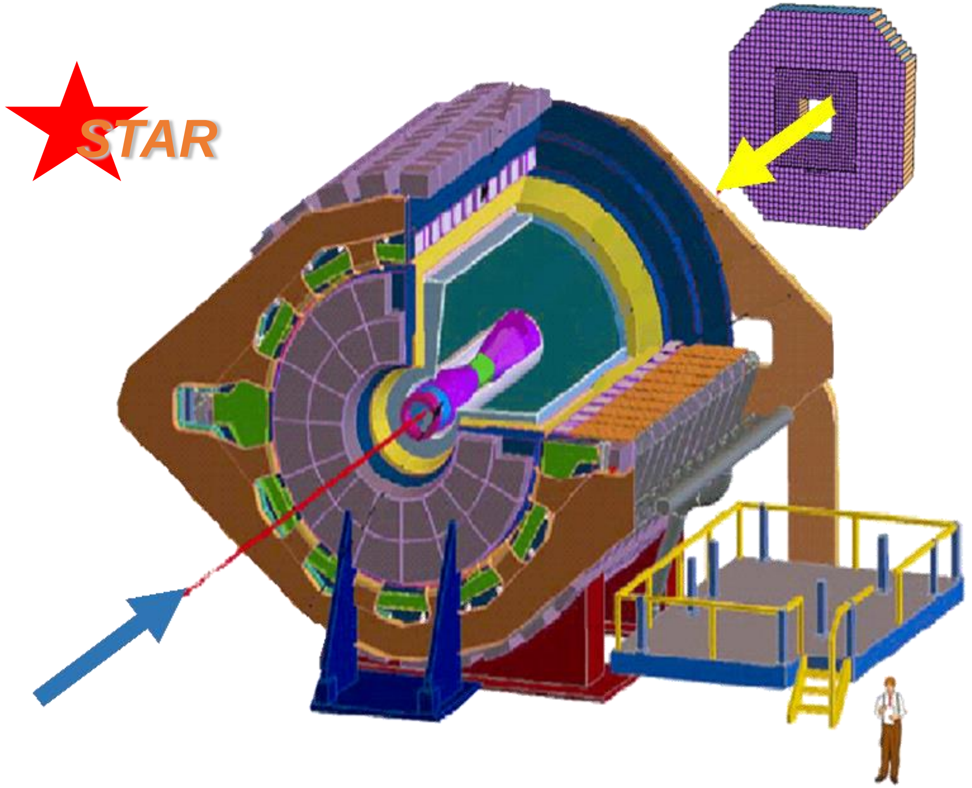


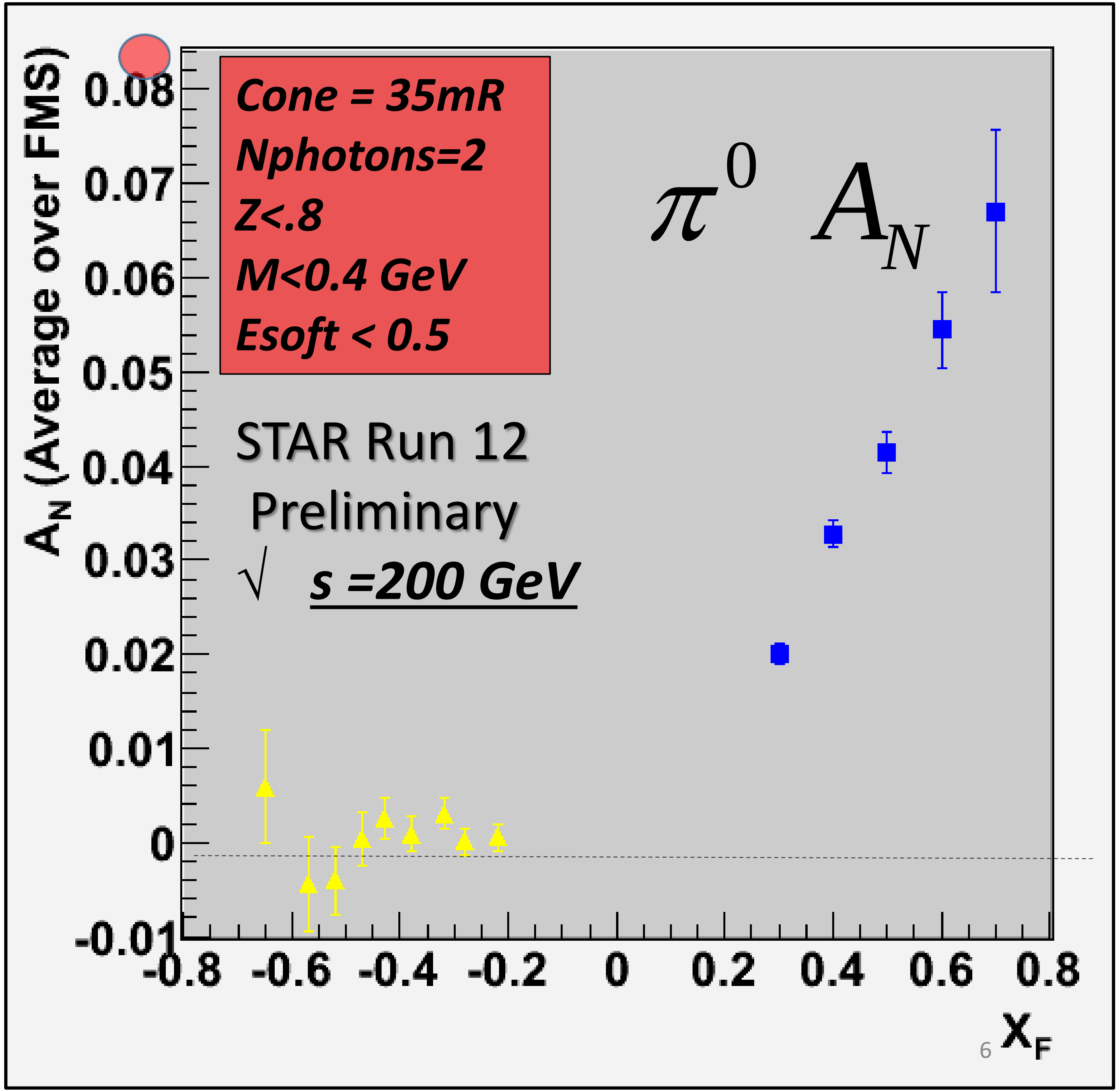
Fermi Lab Fixed Target Energies

Strong historical evidence that forward pion production transverse polarized pion production reflects the interactions of large momentum "u" and "d" quarks correlated with the transverse spin of the proton.

The FMS is illuminated by forward scattering From the RHIC blue beam

and backward scattering from the yellow beam. No significant backward asymmetry is seen.





RHIC Run 12 2012
STAR FMS @ √s=200 GeV

Selection:

$$N_{photons} = 2(in\ cone)$$

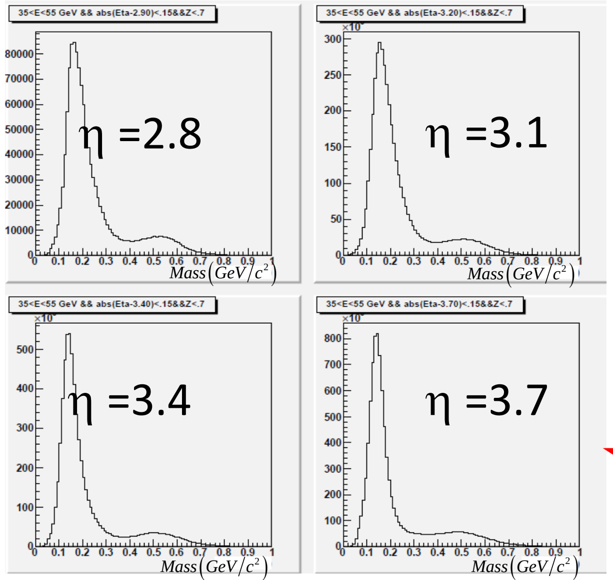
$$E_1 > 6\ GeV\ \ \&\ \mathrm{E}_2 > 6\,GeV$$

$$Z = \left|\frac{E_2 - E_1}{E_2 + E_1}\right| < 0.7$$

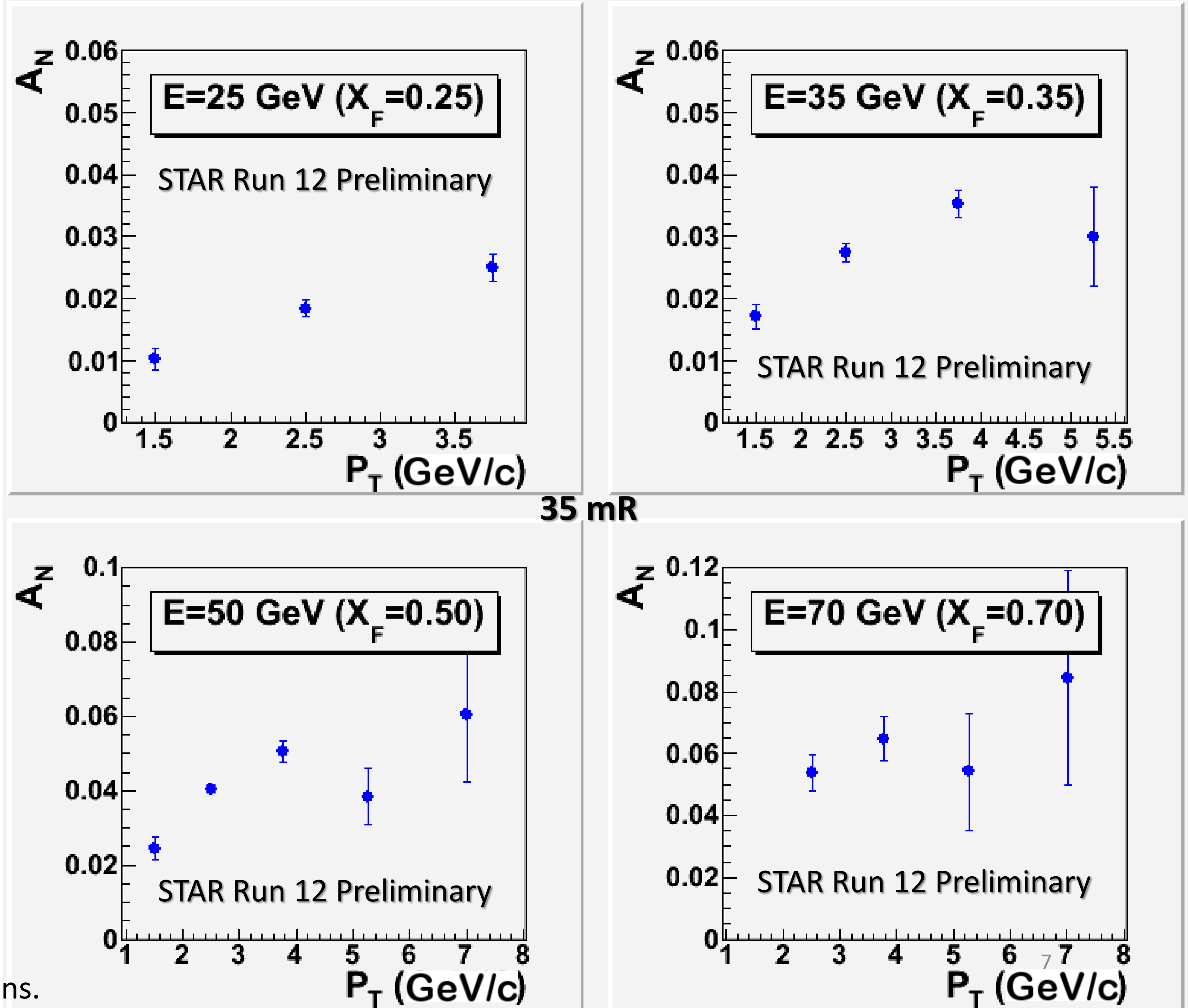
$$M_{1,2} < 0.4\,GeV/c^2$$

$$E_{soft} < 0.5\,GeV$$

$$Cone: 35mR$$

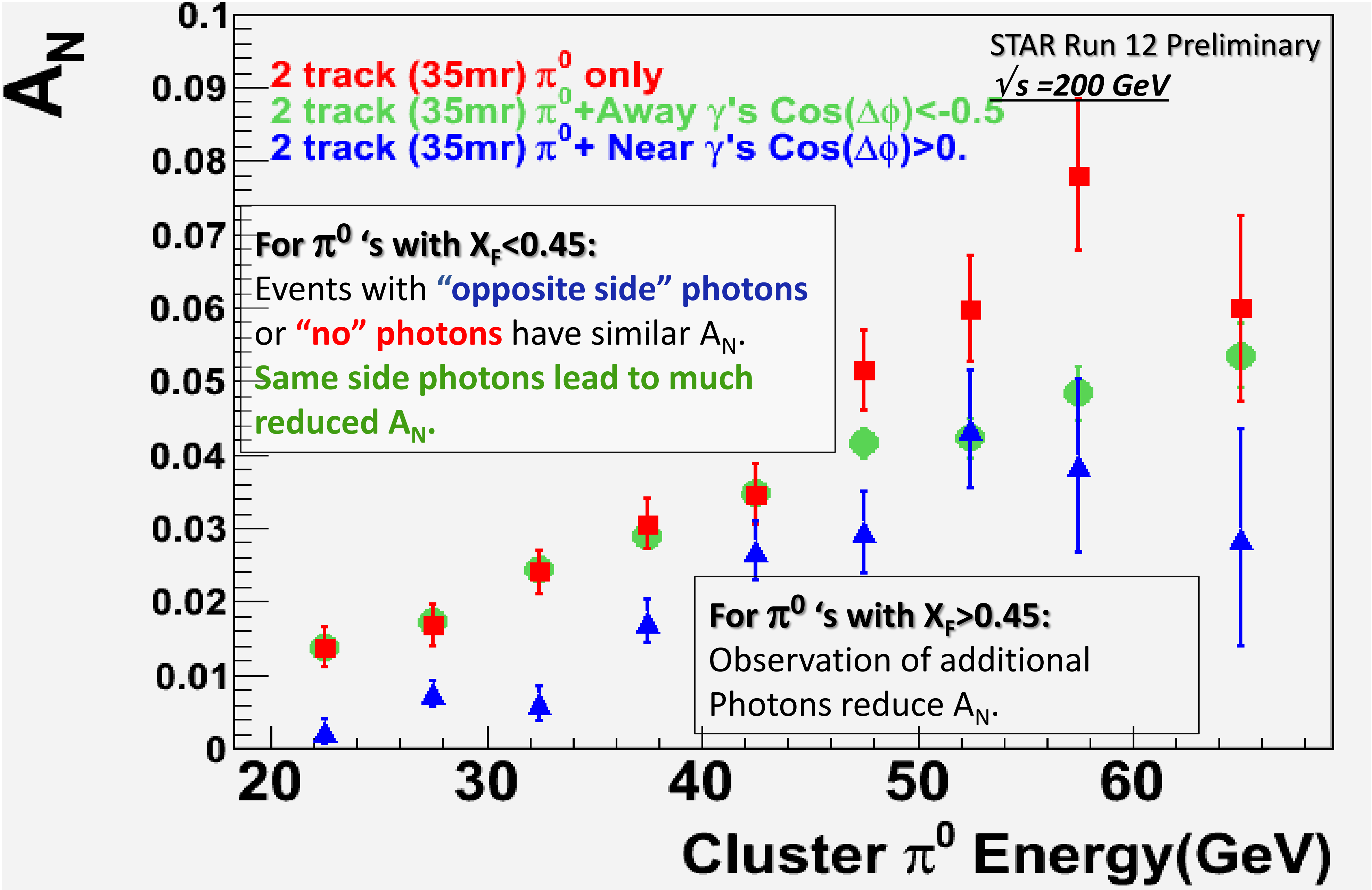


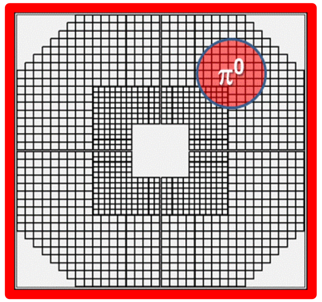
Examples of Run 12 Mass Distributions:
35<E<55GeV, four pseudo-rapidity (η) regions.

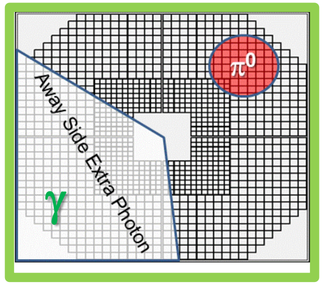


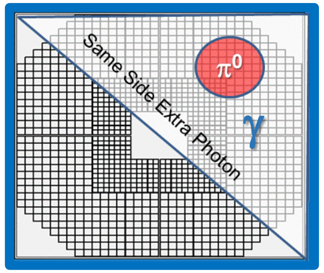
A_N vs. Energy, averaged over pseudo-rapidity.

Compare 3 selection criteria based on presence of 2nd photon energy (>6 GeV) outside the cone (35mR cone)









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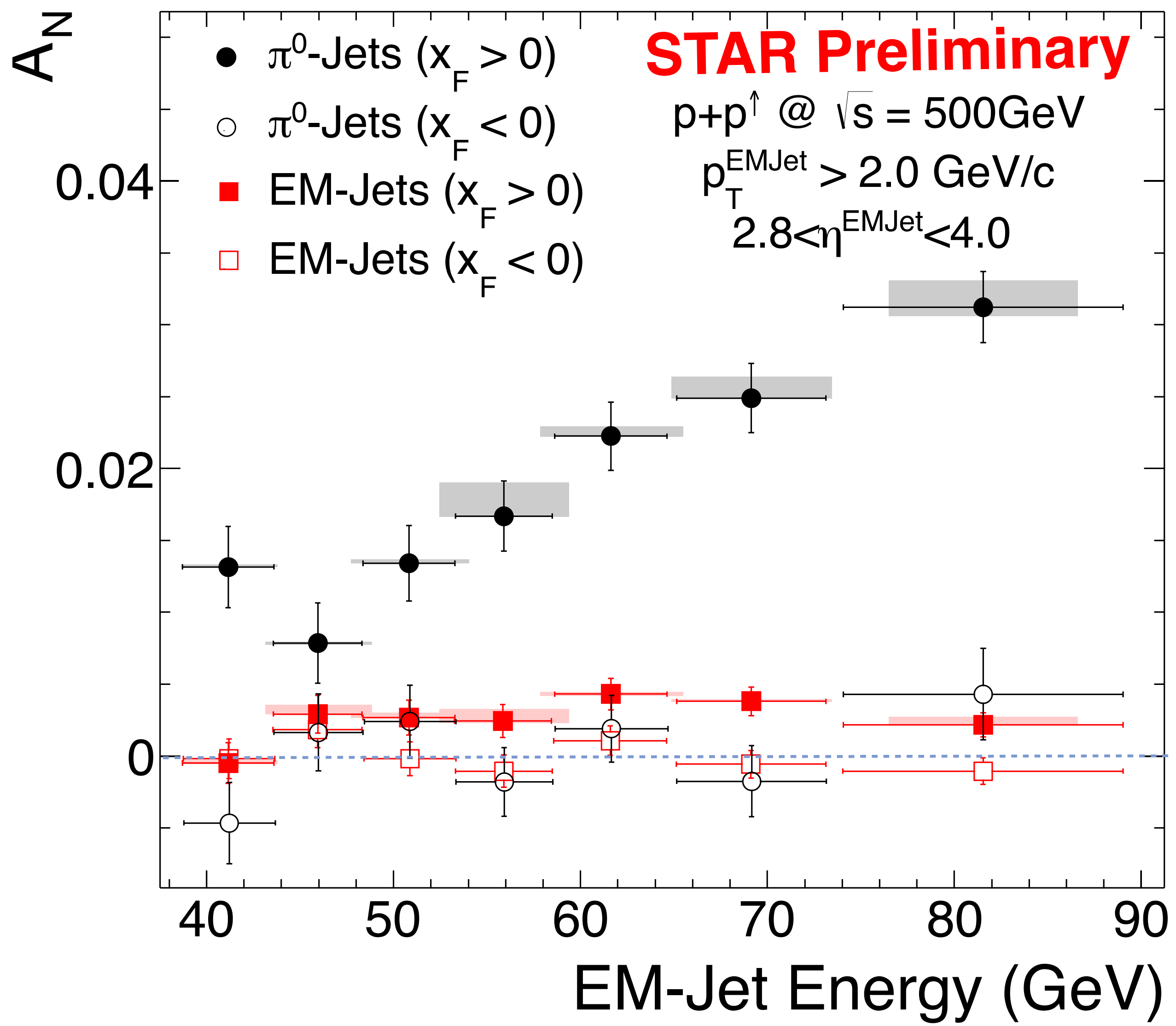
STAR FMS Run   Run 11 (2011) 500 GeV transverse polarized pp.

A_N vs. EM-Jet Energy for **π^0s and jet-like multiple photon events.**



π^0-Jets – 2 photon-EM-Jets with
$M_{\gamma\gamma}$ <0.3 $Z_{\gamma\gamma}$ <0.8

EM-Jets –   with no. photons >2

Newest STAR FMS Data Transversely polarized p-p and p-Au ($\sqrt{s}$=200 GeV) Run 15 (2015)

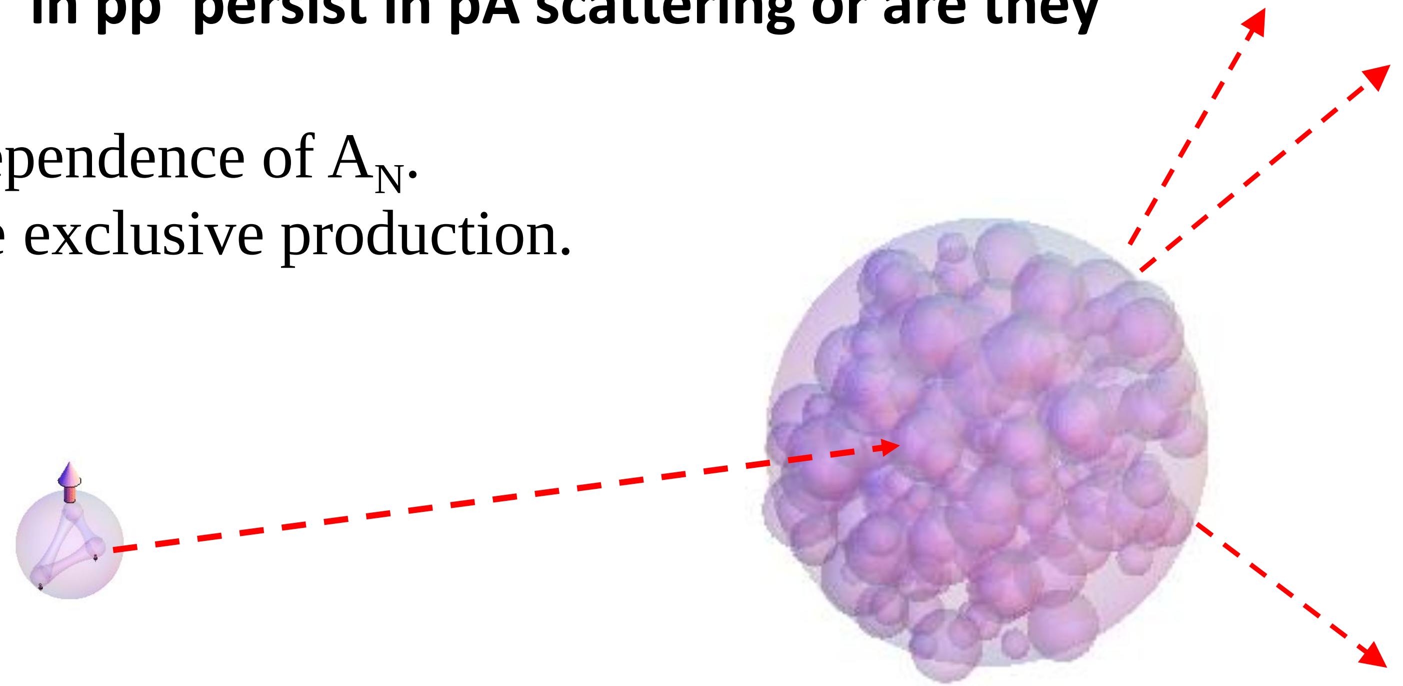
Event Selection (inclusive: $\pi^0 + X$)

1) Collect photons within 35 mR cones.
2) π^0 mass $|M-.135|< 0.12$ GeV
3) P_T (transverse momentum) and E (energy) Bins
4) For photon pair, Z<.7 $(Z=|E_{photon1}-E_{photon2})/(E_{photon1}+E_{photon2})|)$
2) Beam Beam Counter (BBCE) cuts (gold or away side proton breakup cut)
3) Require P_T above trigger threshold.

What we need to learn from new p-Au RHIC Run 15 (2015)

1. **Correlating TSSA A_N with other observables like**
   - R_{pA}
   - Fragmentation universality.
   - Collision centrality.

2. **Do the surprising aspects of A_N seen in pp persist in pA scattering or are they "Filtered" away.**
   - Surprising transverse momentum dependence of A_N.
   - Surprising increase in A_N with more exclusive production.

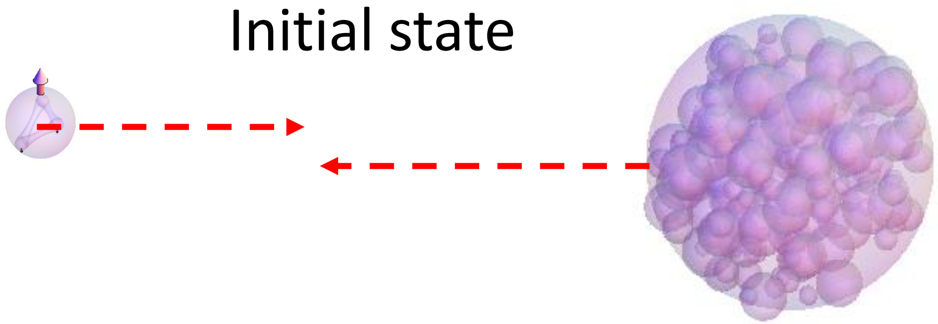


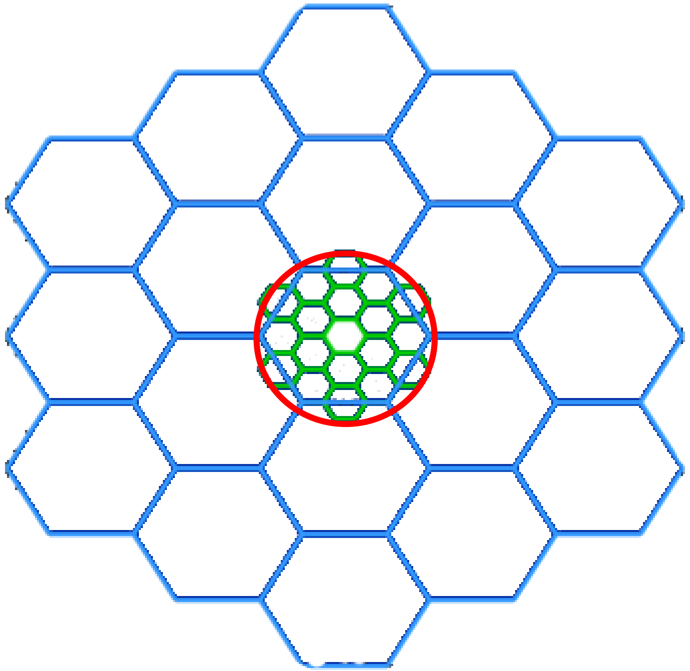
TSSA A_N: Dependence on p-Au Gold Breakup Multiplicity

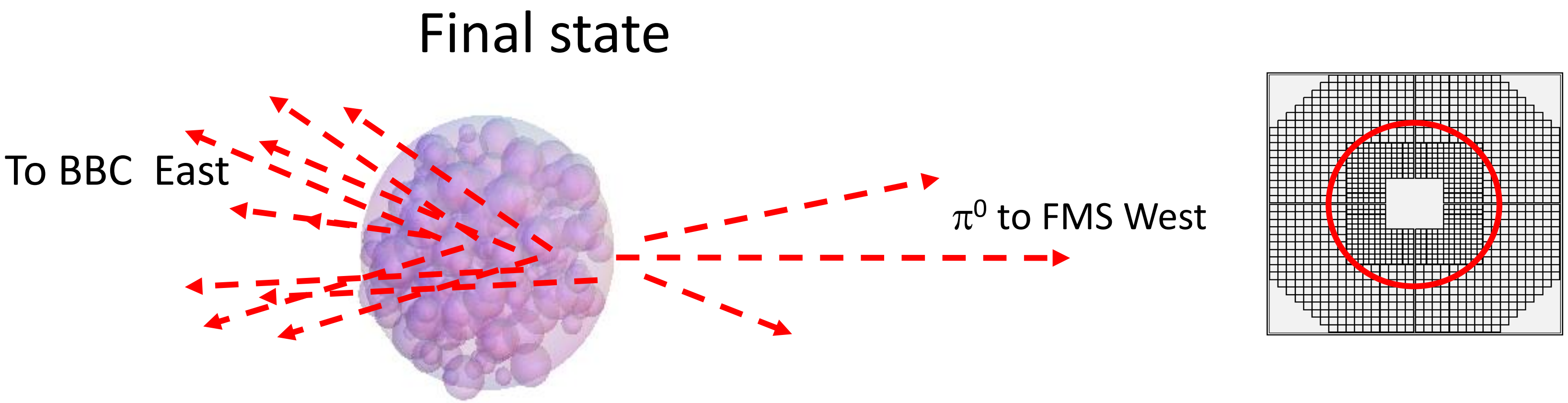
(perhaps related to centrality)

East (Au direction) multiplicity and summed photo-multiplier signals in Beam-Beam Counter (BBC)

Consider the dependence on the distribution of summed photo-tube light from 16 small cells of BBC







Red circles on both the FMS and the BBC scintillator tiles shown the loation of pseudo-rapidy η= 3.3.

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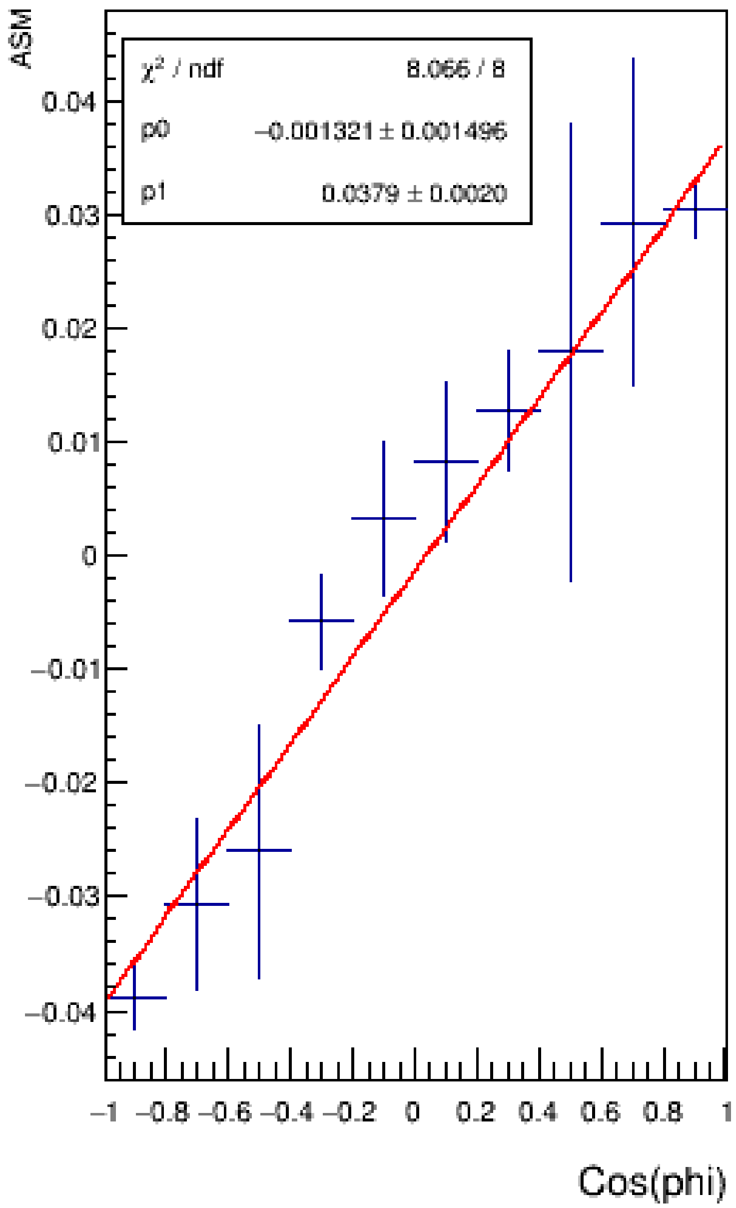
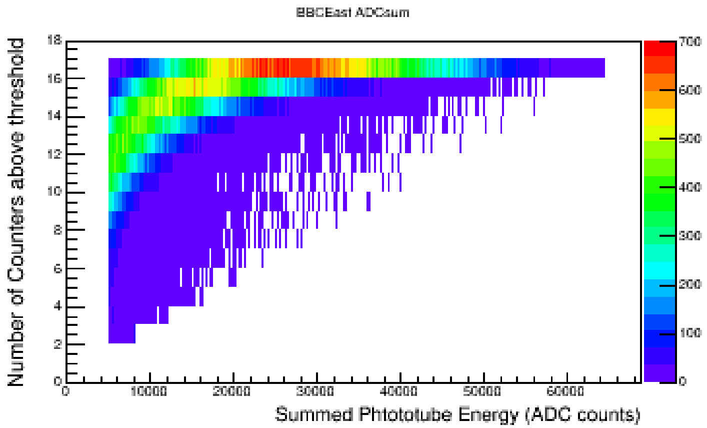
The TSSA A_N is obtained from selected π^0 events in p-Au collisions.
This Example with π^0 within ($0.55<X_F<0.65$) and ($2.55GeV < p_T[GeV/c] < 3.05$)

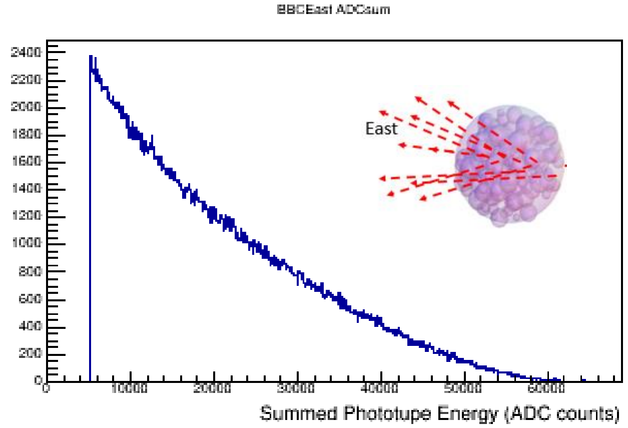


$$Raw\ A = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \quad in\ 10\ \mathrm{Cos}(\phi)\ bins$$

$$Raw\ A(\phi) = P_0 + P_1 \mathrm{Cos}(\phi)$$

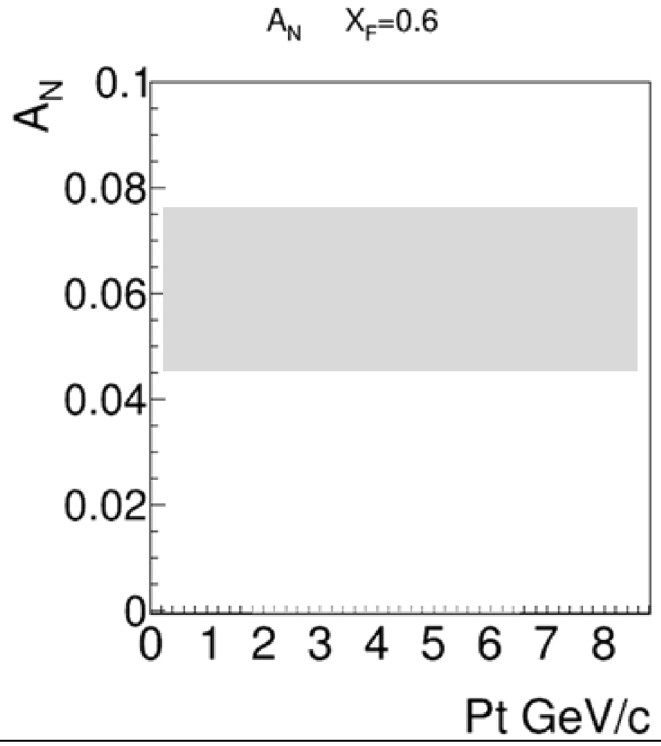
$$A_N = \frac{P_1}{Beam\ Polarization}$$





The p-Au Asymmetry depends upon BBC charged particle distribution from gold breakup in the East BBC (and to lesser extent similar away side proton breakup in pp collisions)

For now, that will be included as a systematic uncertainty in the measured A_N and is the dominant systematic uncertainty. This dependence will be fully characterized in the future.



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STAR RHIC Run 15: (2015)

$\sqrt{s}$=200 GeV

$$p^{\uparrow} p \rightarrow \pi^0 X$$

$$p^{\uparrow} Au \rightarrow \pi^0 X$$

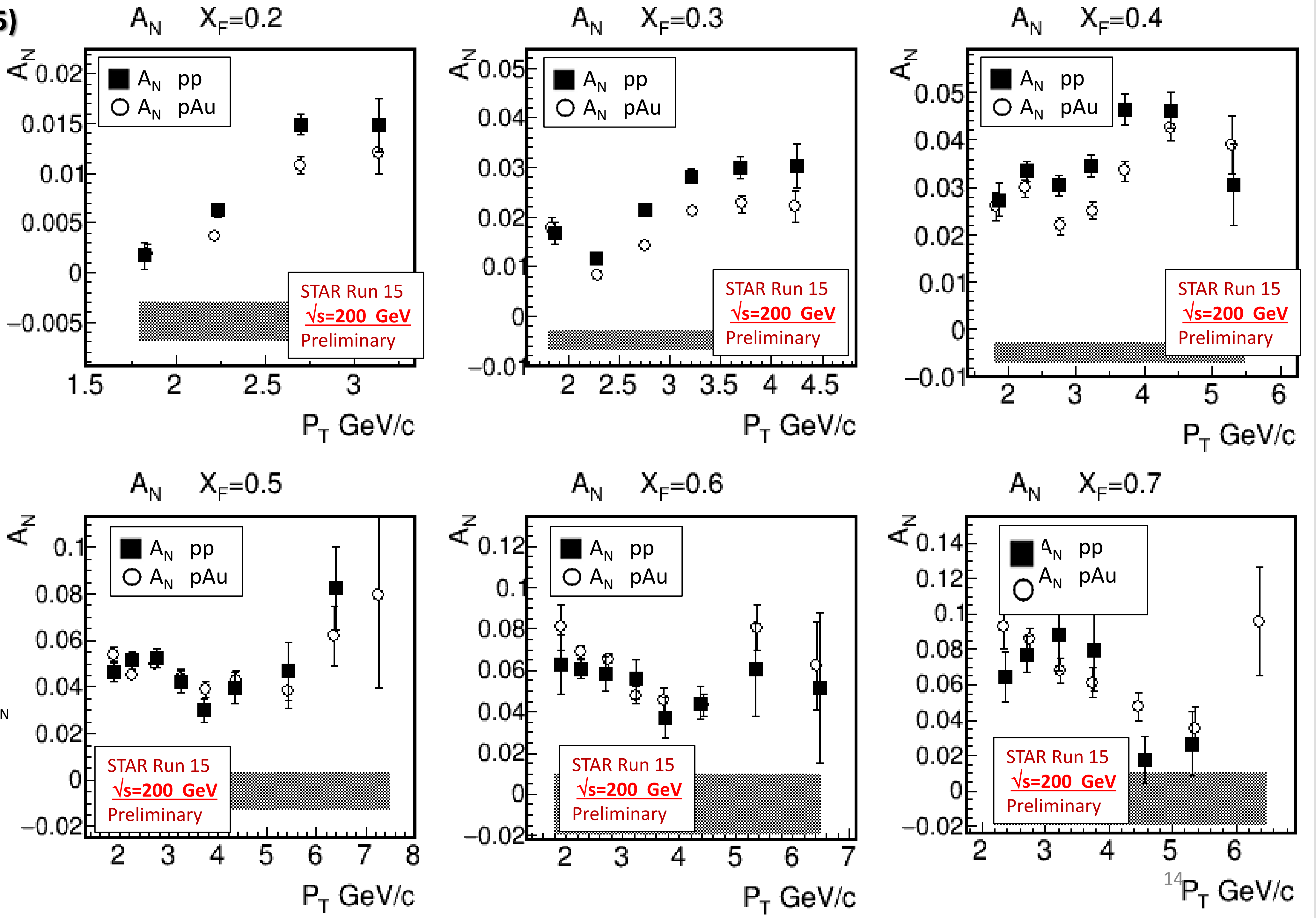
TSSA A_N

Inclusive π^0 event selection described above

Error bars represent statistical errors only.

Luminosity pAu=204.6 nb^{-1}
Luminosity pp=34.8 pb^{-1}
Average Polarization:
pp 55.6±. 2 %
pAu 60.4 ± 2%

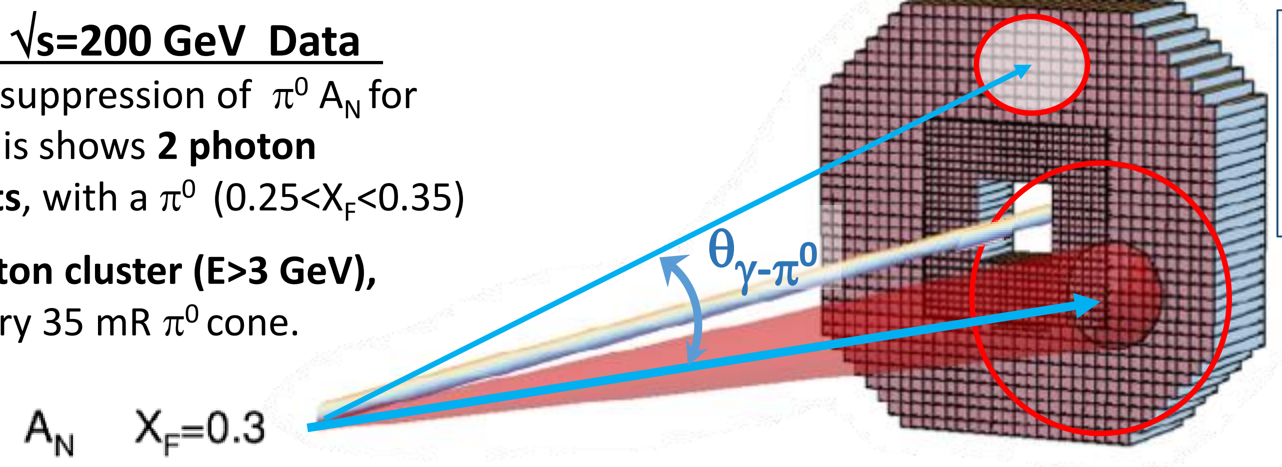
Shaded bands represent systematic uncertainty, dominated by dependence of A_N on observed East BBC energy (gold or proton breakup charge multiplicity)

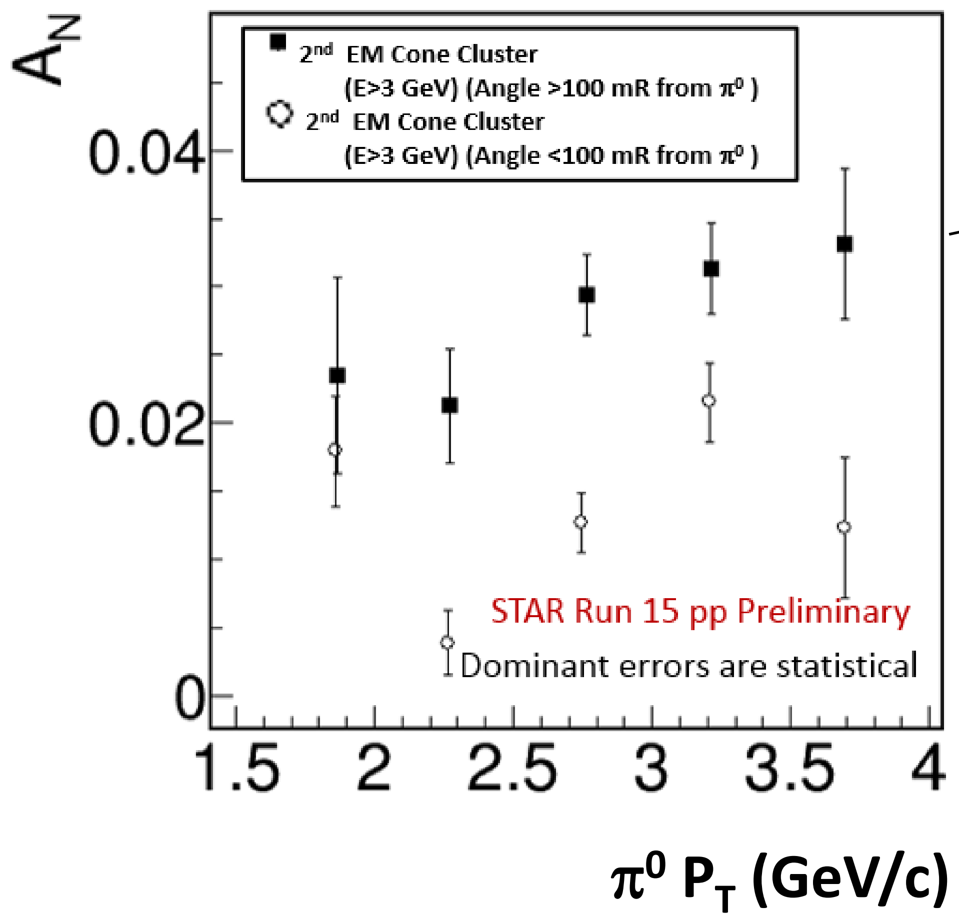


Run 15 2015 pp $\sqrt{s}$=200 GeV Data

Example showing suppression of π^0 A_N for jet–like events. This shows **2 photon cluster FMS events**, with a π^0 ($0.25<X_F<0.35$)

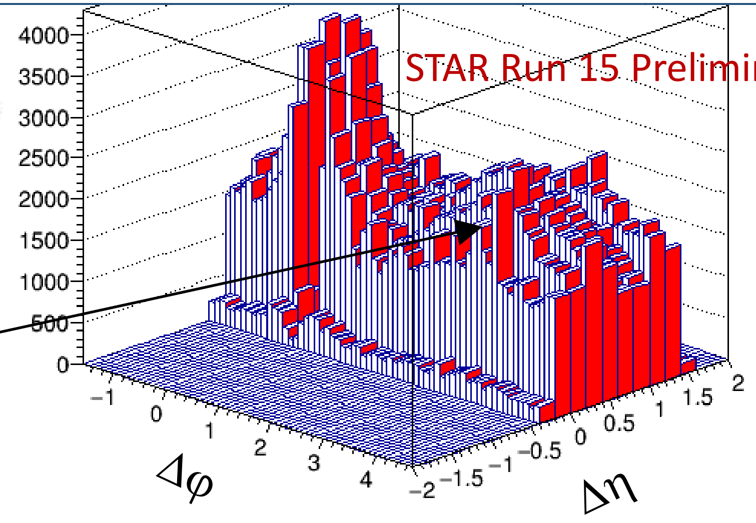
Second E&M photon cluster (E>3 GeV), outside the primary 35 mR π^0 cone.





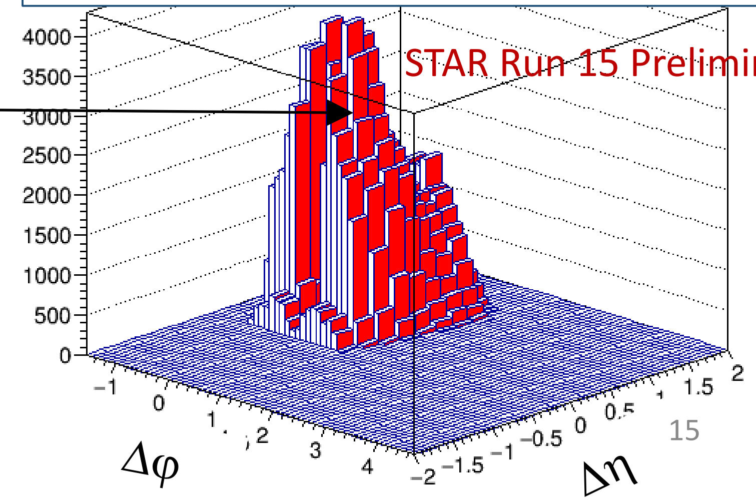
FMS π^0 + 1 EM Cluster (Cluster Energy>3 GeV)

2nd EM Cluster Distribution in $\Delta\eta$ (pseudo-rapidity) vs. $\Delta\varphi$ (azimuthal angle) Relative to π^0 Direction



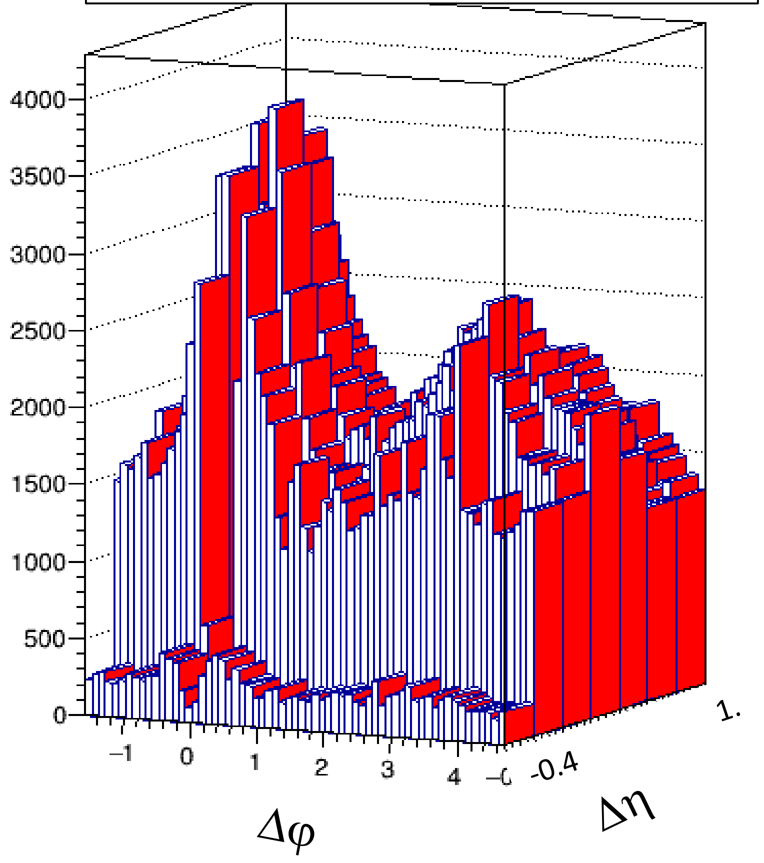
2nd EM Photon Cone Cluster Distribution

$\theta_{\gamma\text{-}\pi^0}$ < 100 mRad



Distribution of Event with 2 EM Energy Cone Clusters
Cone radius=35mR

Event Distribution for Two FMS Clusters in 2015 p-p.



STAR Run 15 Preliminary

First cluster contains π^0

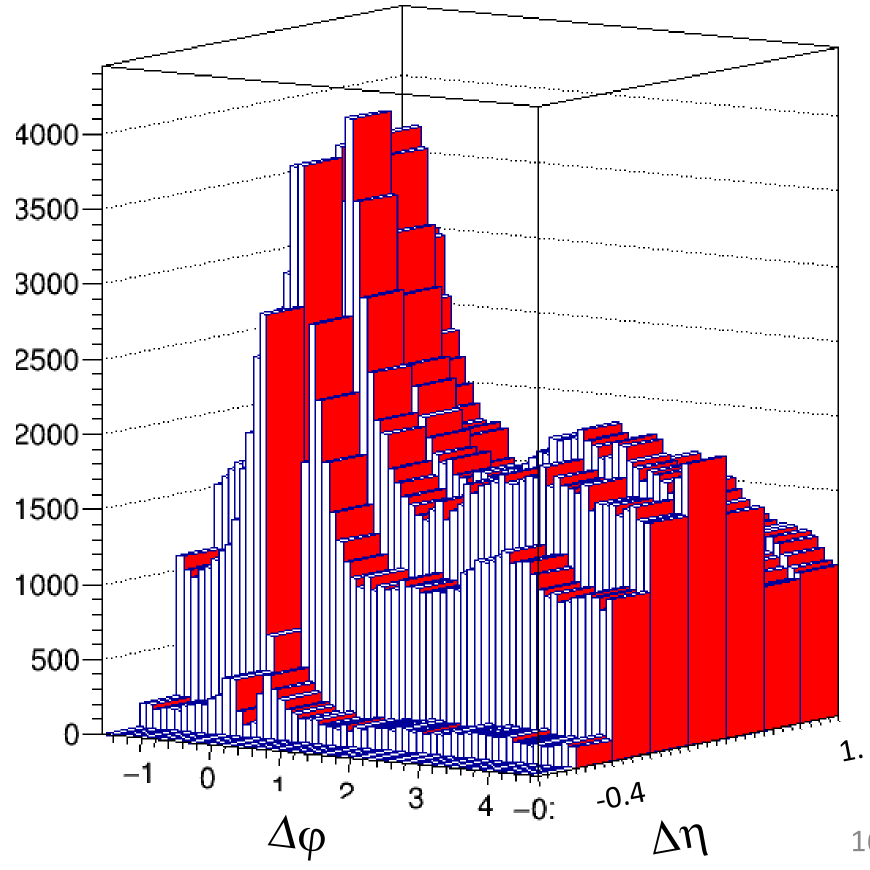
$$0.25 < X_{F(\pi^0)} < 0.35$$

$$3.55\ GeV/c < p_{T(\pi^0)} < 4.05\ GeV/c$$

for 2nd cluster momentum
Direction relative to π^0 direction

Δη (pseudo-rapidity)
vs.
Δφ (azimuthal angle)

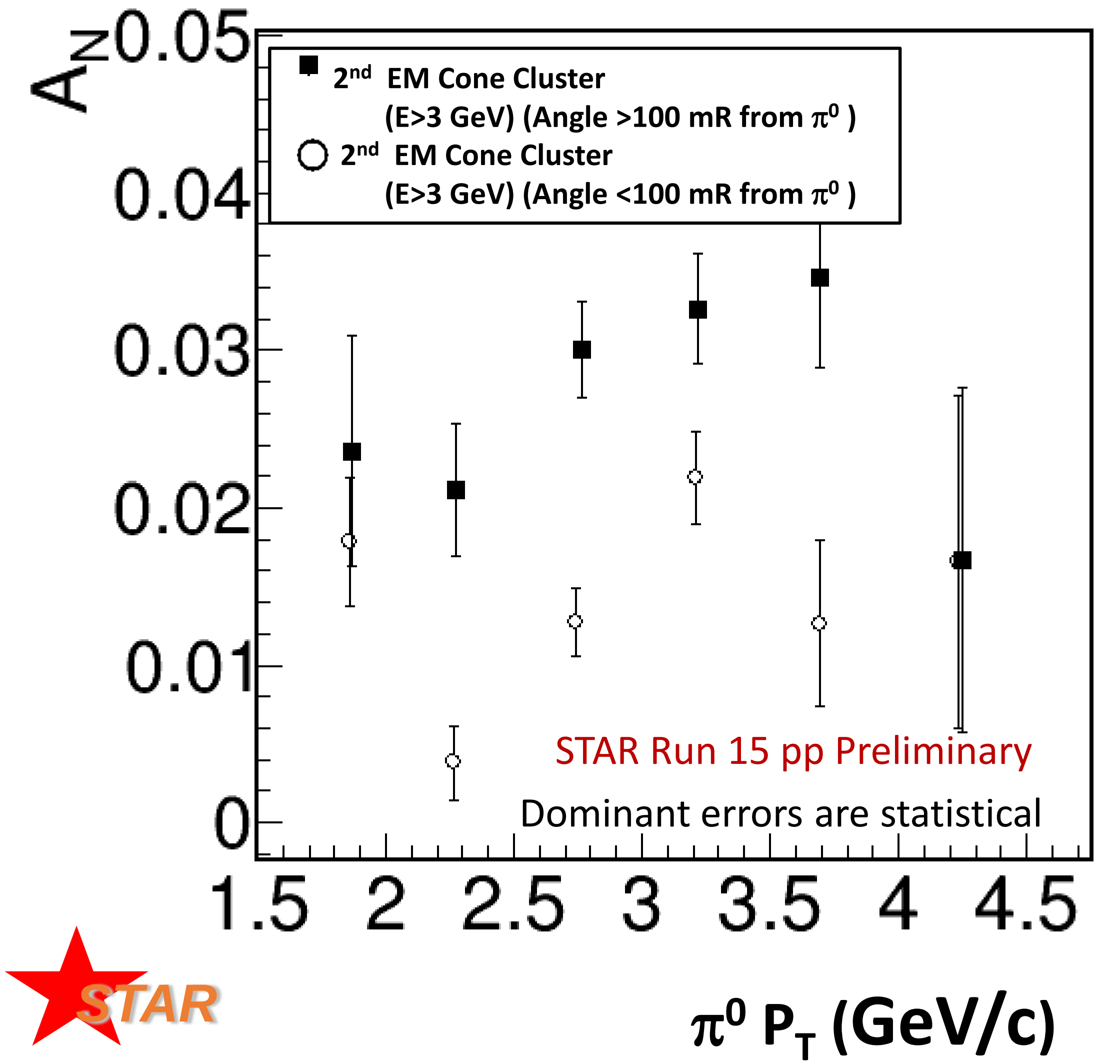
Event Distribution for Two FMS Clusters in 2015 p-Au.



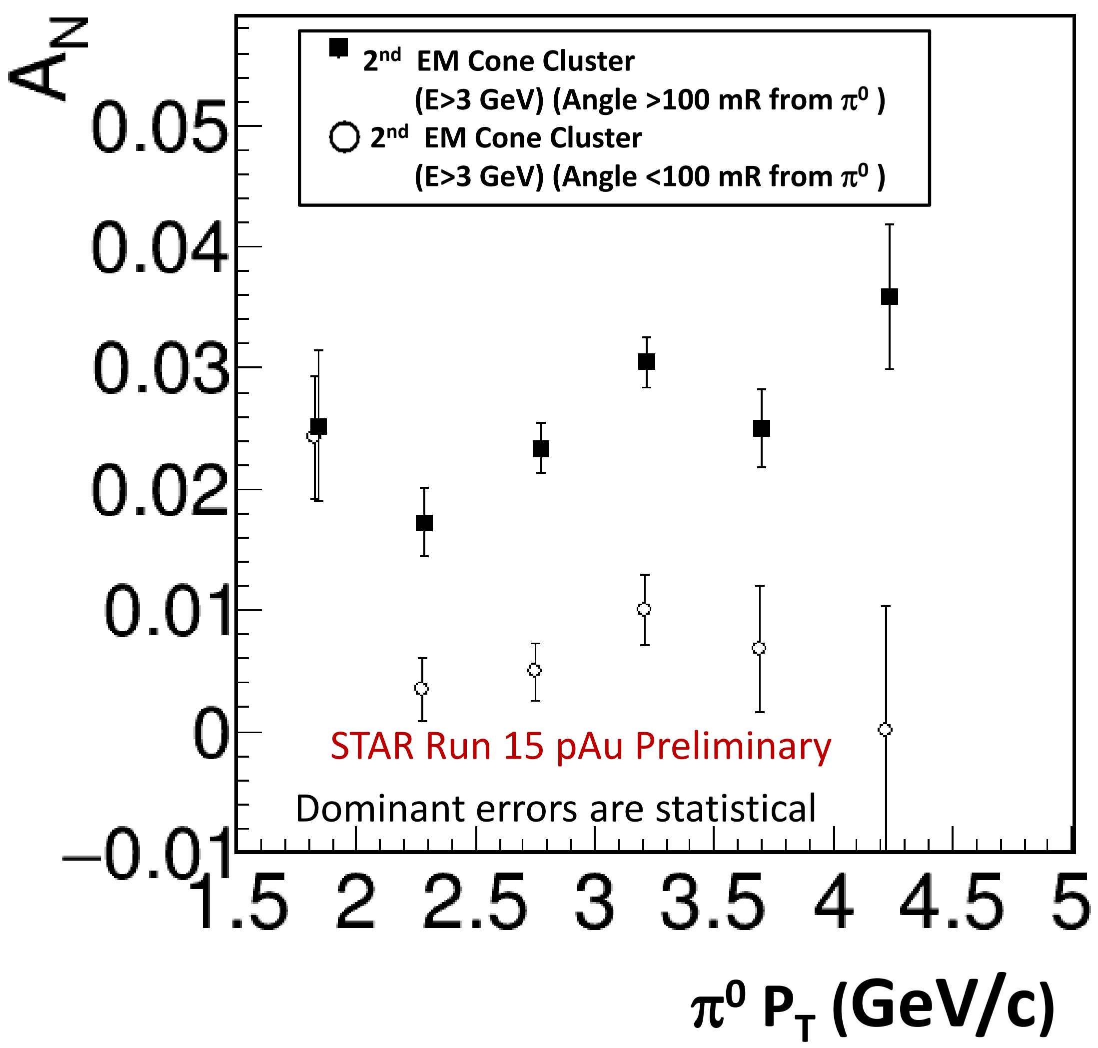
STAR Run 15 Preliminary

Comparison of π^0 A_N for second Cone of energy "Near" or "Far" from π^0

STAR Run 15 p-p x_F = 0.3. √s=200 GeV
Dependence of π^0 A_N on the location of second forward EM particle in FMS.



STAR Run 15 p-Au x_F = 0.3. √s=200 GeV
Dependence of π^0 A_N on the location of second forward EM particle in FMS.



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Conclusions

- Forward π^0 production at large p_T is expected to be dominated by scattering of an energetic parton (an up quark at large X_F) on a soft parton in the target nucleon.
- A_N complements spin averaged hard scattering because it is only sensitive to initial and final state effects. Measurement of A_N in various kinematic regions gives information about the dependence of such initial and final state processes on kinematic observables.
- In conventional factorizable PQCD models, we expect A_N to fall with p_T above nominal strong interaction scale. **This is not what we observe.**
- Asymmetries A_N are largest for more isolated π^0 events and smaller for jet-like events. This may provide insight into the role of factorization or fragmentation in this kinematic region.
- **We show first STAR FMS results from RHIC run 15, for the comparison of A_N for p-p and p-Au collisions. The inclusive asymmetries with unexpected enhanced asymmetry for isolated π^0s is now also seen in p-Au collisions as well as in pp collisions.**

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Both Sivers (initial state) and Collins (final state) interactions are expected to be higher twist, amplitudes involving more than a minimal number of participating partons.
This generally means that **these effects should fall with transverse momentum p_T by powers of p_T** relative to the leading twist hard scattering amplitude!

Sivers

- A Spin Dependent proton **T**ransverse **M**omentum **D**istribution (**TMD**) for large X_F partons, so the initial state p_T of the scattering parton is correlated with the initial state transverse proton spin. (**helicity conserved**).

- Does the p_T bias in the initial state violate "T" invariance? "NO".

- **Phase** from a Wilson line integral as struck quark passes through the gluon field.

Collins

- In the initial state, the spin of the parton is correlated with the transverse proton spin, and is sensitive to proton the transversity distribution. (**helicity is conserved**).

- In standard PQCD, we assume that fragmentation functions are universal. Collins correlation functions can be measured in one fragmentation process and applied to another process.

- If final state particles do not fragment there is no Collins effect. (direct photon, Drell-Yan)

Run 12 (2012) 200 GeV Polarized pp STAR FMS Data

1) Does TSSA A_N fall with transverse momentum as expected for higher twist (no!)

2) Collins $\rightarrow$ A_N derives from quark transverse spin dependence of fragmentation. Is large A_N correlated with the presence of fragments. (no!)

3) Sivers $\rightarrow$ A_N derives from bias in parton p_T distribution, seen in overall jets …. not enhanced (nor reduced) by looking at events with jet fragments. (no!)