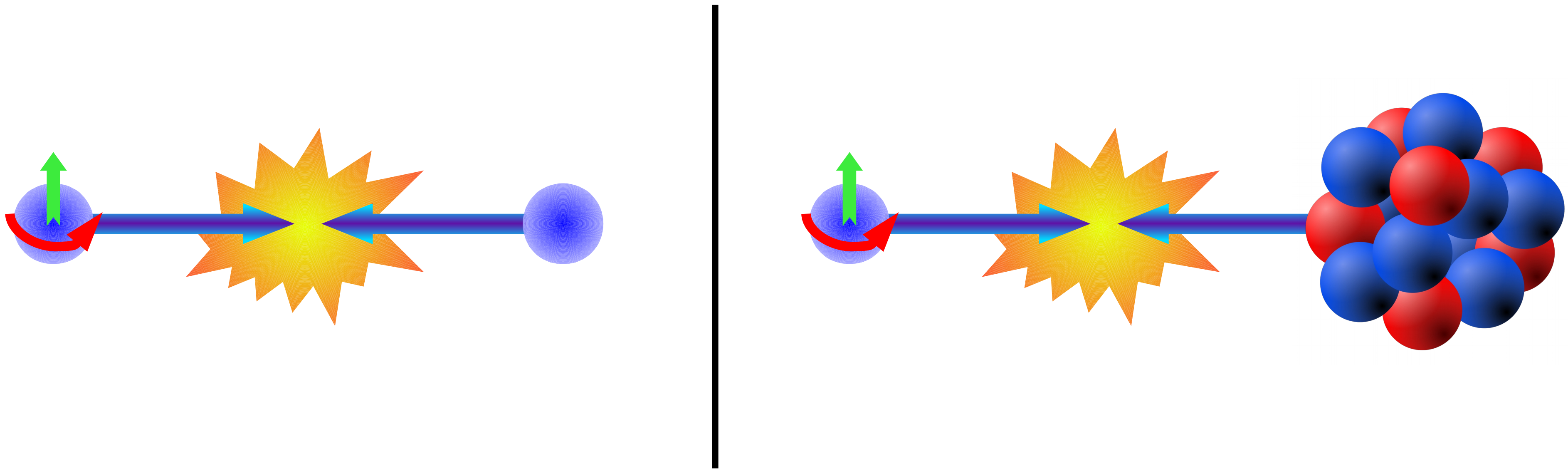
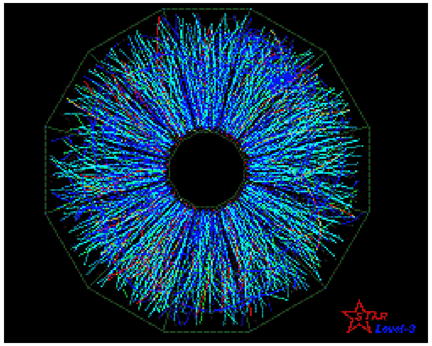
Transverse Single Spin Asymmetries in Forward π^0 Production from p+p and p+A Collisions at STAR



Christopher Dilks

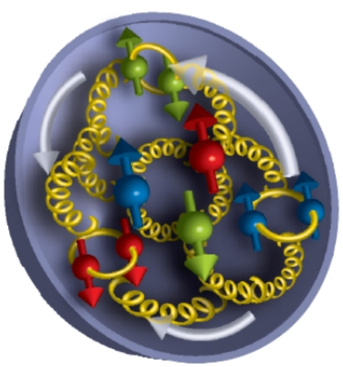
Emerging Spin and p_T Effects in pp and p+A Collisions

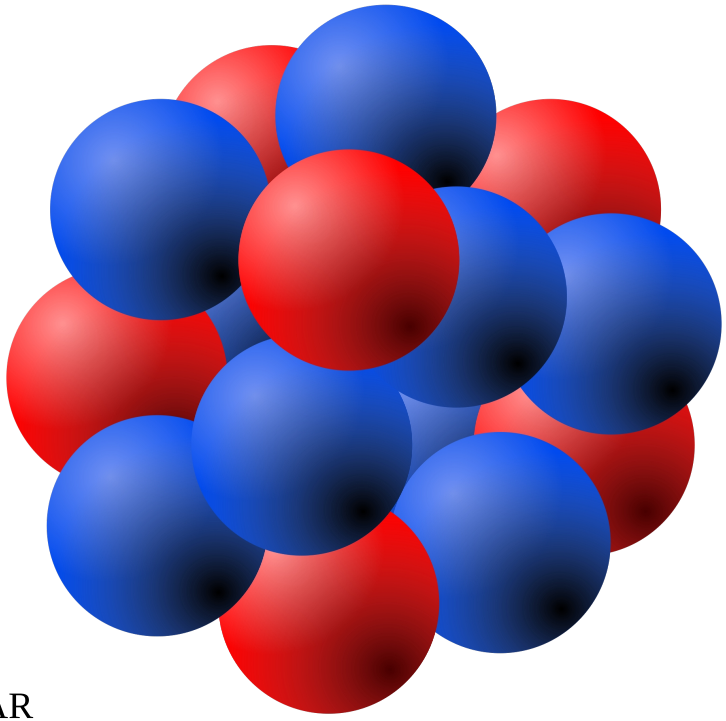
10 February 2016



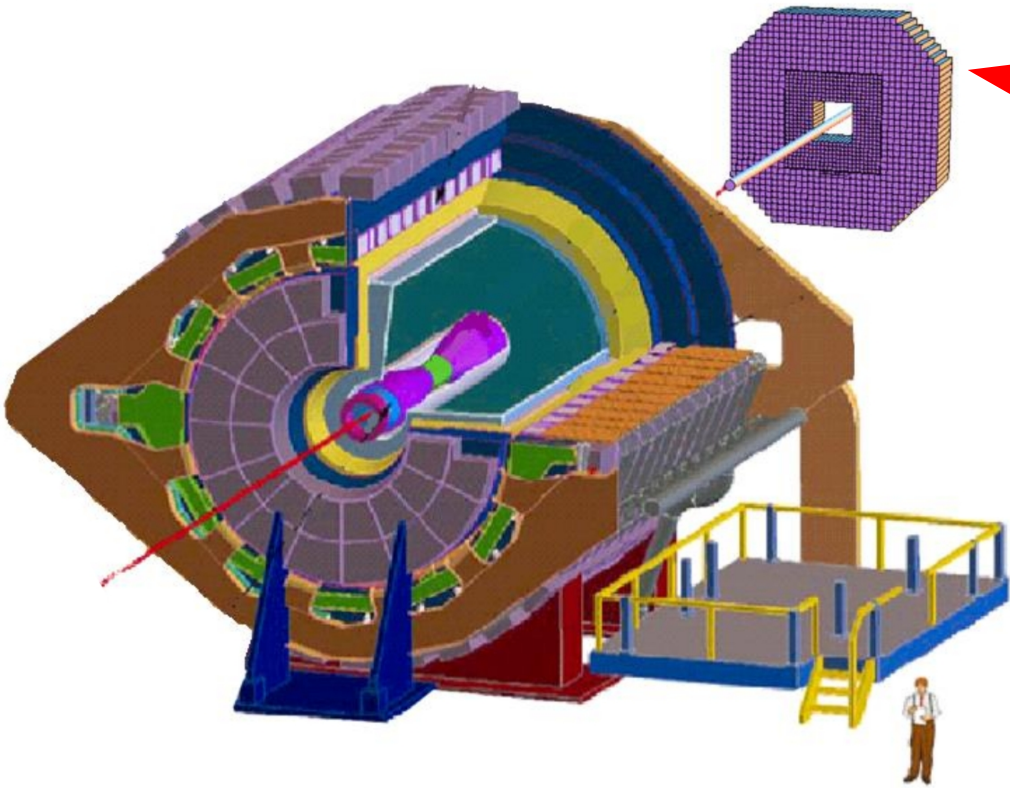
Outline

- **STAR and its detectors → Forward EM Calorimetry**
- Transverse Single Spin Asymmetry A_N
- Forward π^0 A_N in p+p – studies on topology and p_T-dependence
- Preliminary Results from forward π^0 A_N in p+Au





STAR Calorimetry

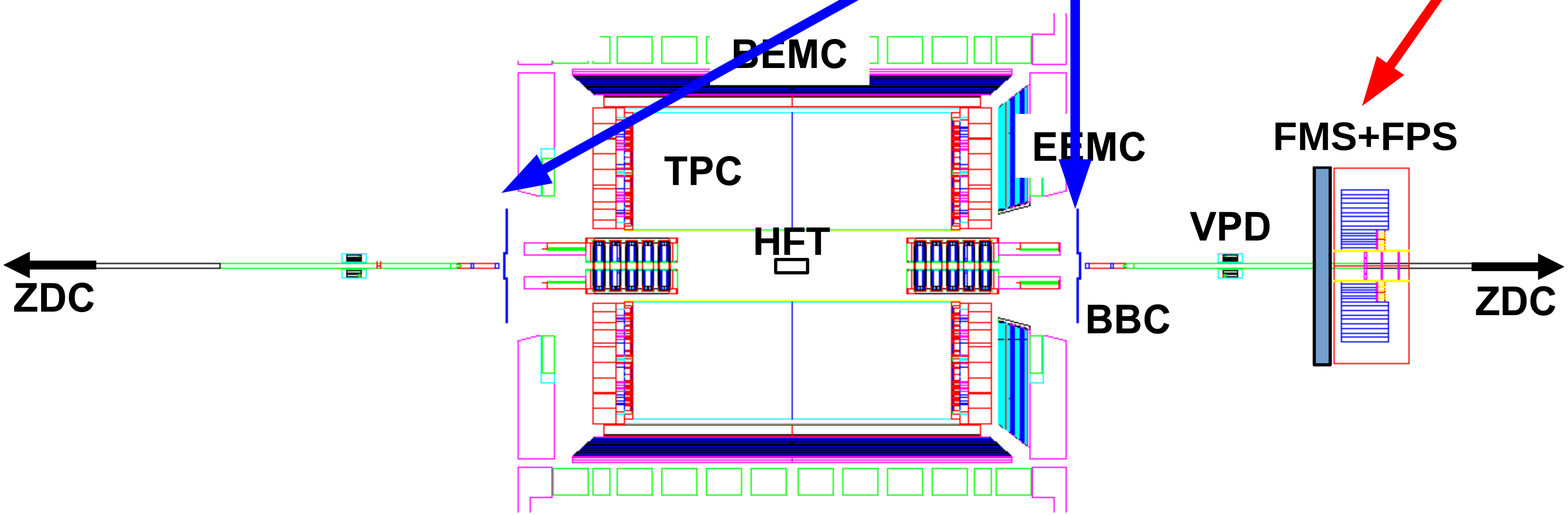


Forward Meson Spectrometer (FMS)

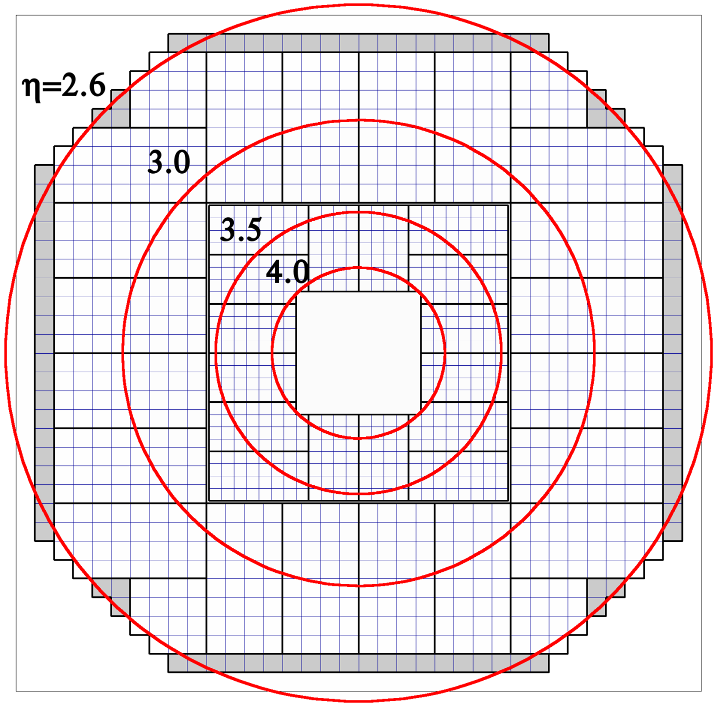
– EM calorimeter
– primarily detects *forward* π^0s

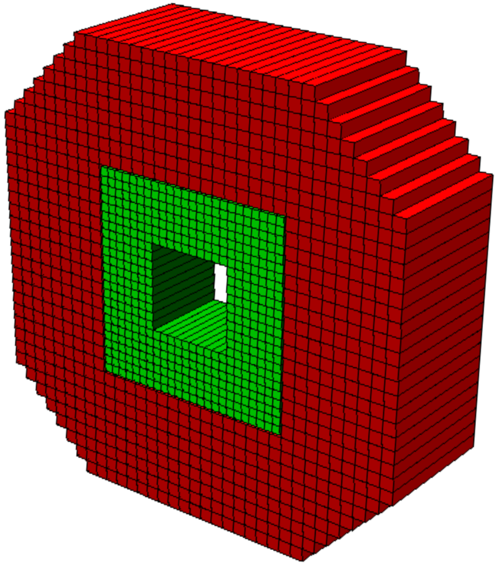
Beam Beam Counters (BBC)

– nuclear break-up in p+A
(discussed later)

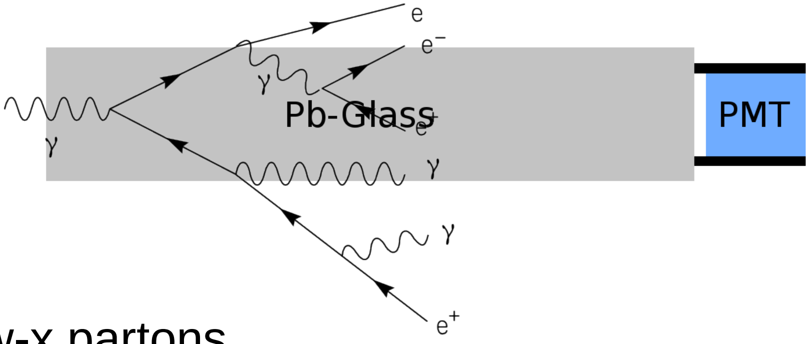


Forward Meson Spectrometer (FMS)



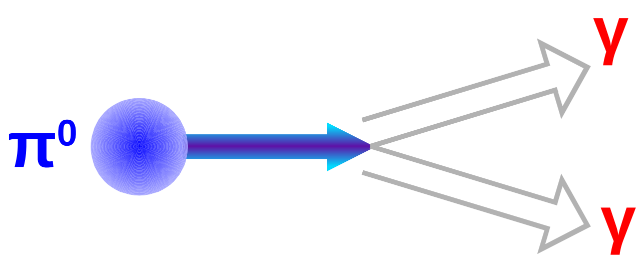


- Forward pseudorapdity: **2.5 < η < 4.2**
- 1,264 **Lead-glass cells** coupled to photomultiplier tubes
  - Large (5.8 x 5.8 cm) outer cells (red)
  - Small (3.8 x 3.8 cm) inner cells (green)
- Observes **π^0 → γ+γ** as 2 cluster events (M=135 MeV)
  - Can also observe η → **γ+γ**



  - Forward mid-to-high-x partons collide with a disk of low-x partons

Pion Reconstruction



$E_1 + E_2$

distance between detected photon pair

Invariant mass from 1 → 2 decay

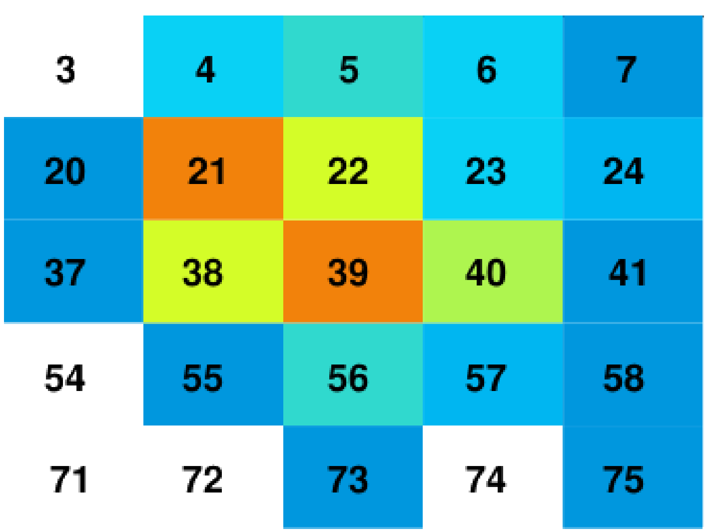
$$M_{\gamma\gamma} \approx E_{\gamma\gamma}\sqrt{1 - Z_{\gamma\gamma}^2} \cdot \frac{D_{xy}}{2D_z}$$

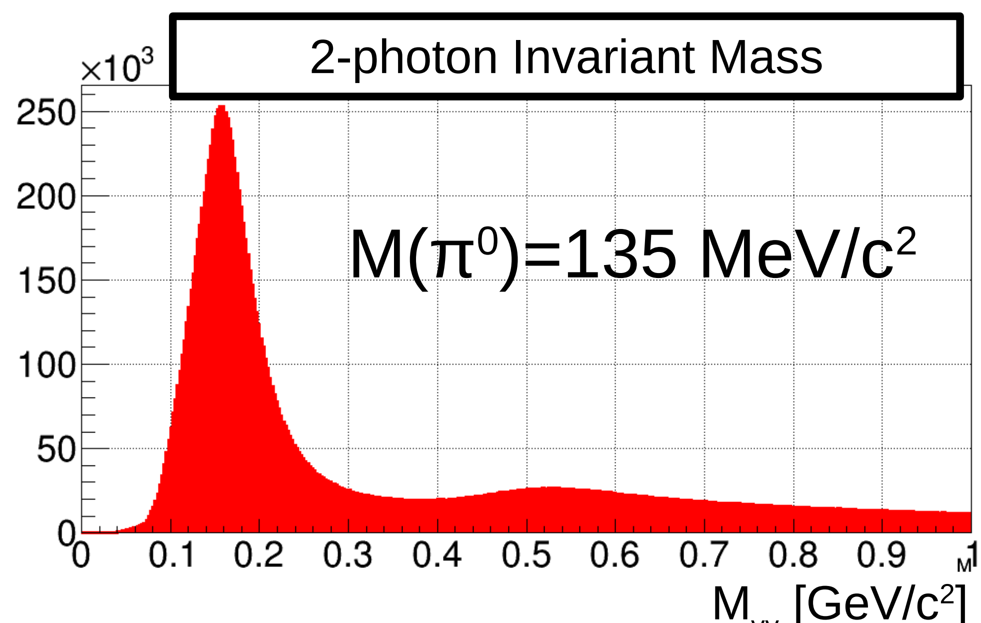
$$\frac{(E_1 - E_2)^2}{E_{\gamma\gamma}^2}$$

Distance to vertex ~7 m

FMS calibration is dependent on pion mass peak positions for each tower; gains are iteratively adjusted

Typical 2-photon Cluster

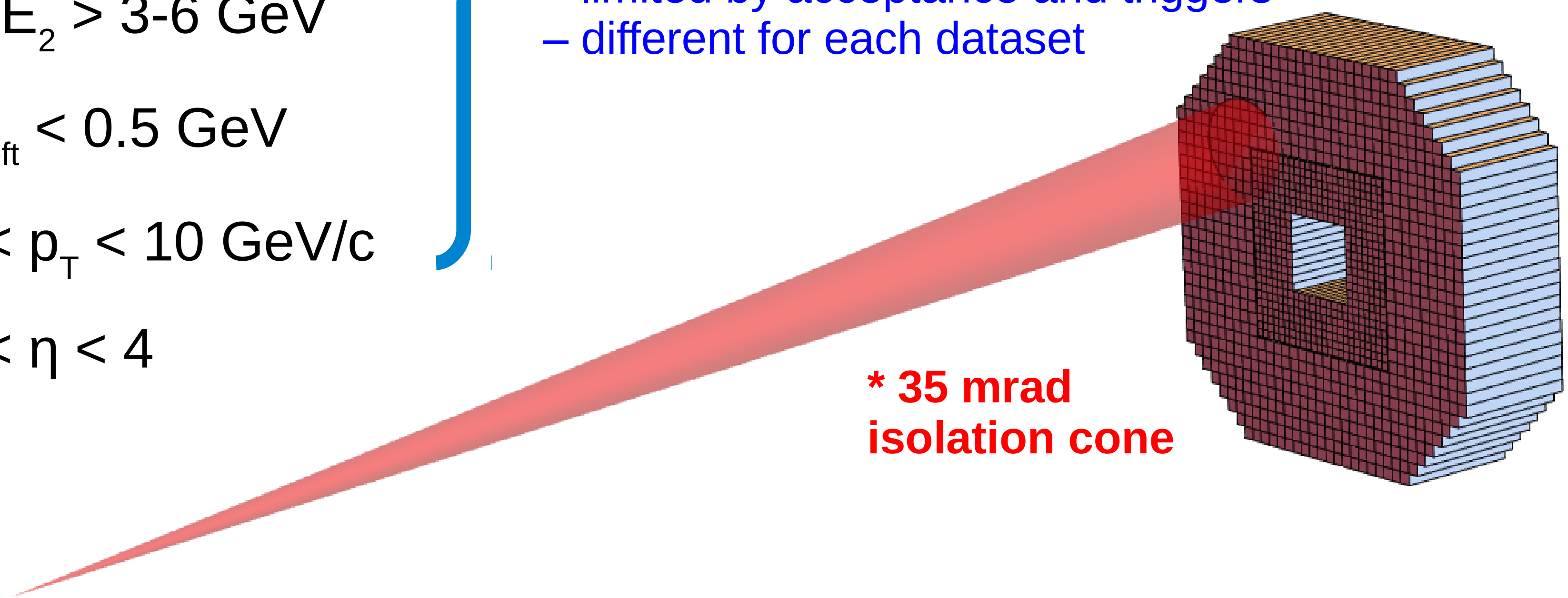




Typical Pion Event Selection

- Collect EM photon candidates into 35 mrad cone-clusters
- Select high-energy photon pair within cone
- $Z_{\gamma\gamma} < 0.7$
- $E_{\gamma\gamma}$-dependent $M_{\gamma\gamma}$ cut (to account for mass peak shift in higher E)
- $30 < E_{\gamma\gamma} < 100$ GeV
  - $E_1, E_2 > 3\text{-}6$ GeV
  - $E_{soft} < 0.5$ GeV
- $2.5 < p_T < 10$ GeV/c
- $2.6 < \eta < 4$

These cuts are only “typical”
– limited by acceptance and triggers
– different for each dataset



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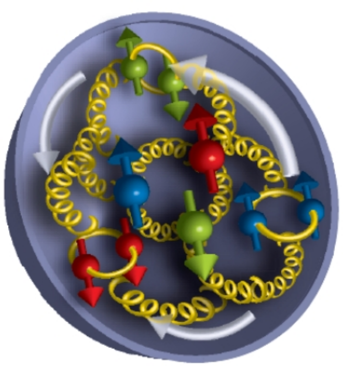
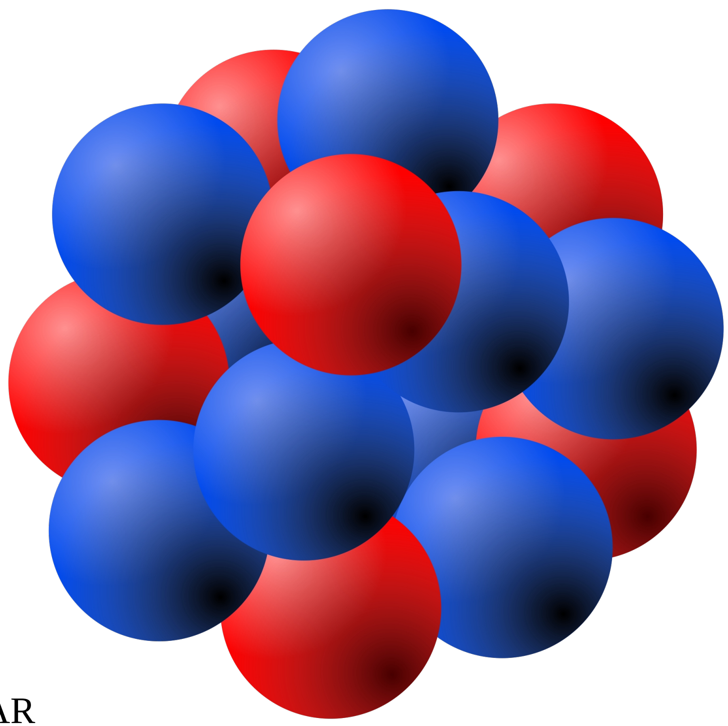




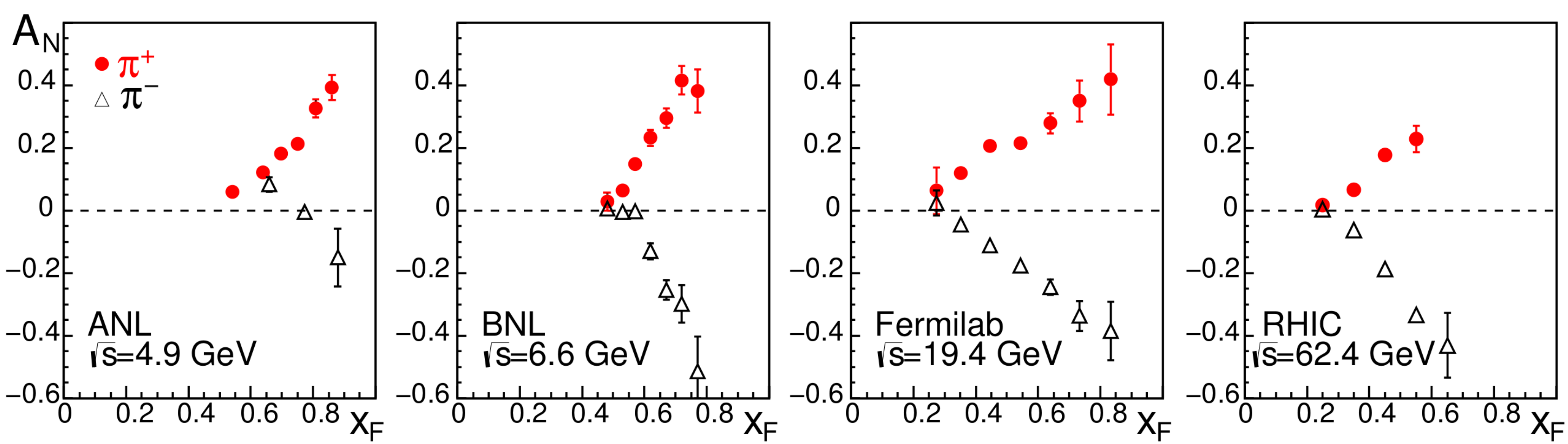
Transverse Single-Spin Asymmetry

integrate over polarization

Analyzing Power

$$\frac{1}{P}\frac{\sigma^{\uparrow}(\phi)-\sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi)+\sigma^{\downarrow}(\phi)} = B + \boxed{A_N}\cos(\phi)$$

Large pion A_N, independent of CoM energy and rising with $x_F=2p_L s^{-1/2}$, observed since 1976; collinear factorization (at leading twist*) predicts $A_N=0$



Klem et al (1976) | Allgower et al (2002) | Adams et al (1991) | Arsene et al (2008)

Aidala, Bass, Hasch, Mallot – arXiv:1209.2803

* twist ~ # external partons interacting with participant partons... twist-2 ~ O(log Q^2) twist-3 ~ O(Q^{-2})

Transverse Structure

Mechanisms for explaining large A_N

- Transverse parton motion
  - $k_{T,q}$-dependent distributions (TMDs)
  - Fragmentation dependencies
- Twist-3 $O(1/Q^2)$ terms → include a gluon interacting with struck parton

Leading-twist TMDs

	Unpol. parton	Long. parton	Tran. parton
Unpol. nucleon	PDF		Boer-Mulders
Long. nucleon		Polarized PDF	Wormgear 1
Tran. nucleon	Sivers	Wormgear 2	Transversity

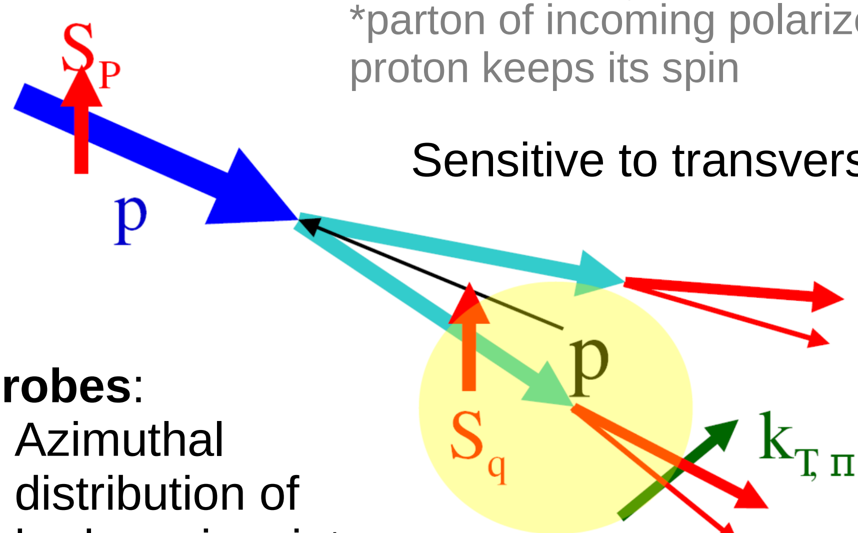
Collins Mechanism

Azimuthal dependence of hadrons in each jet

Correlation between struck parton* spin and fragmentation hadron $k_{T,\pi}$

*parton of incoming polarized proton keeps its spin

Sensitive to transversity



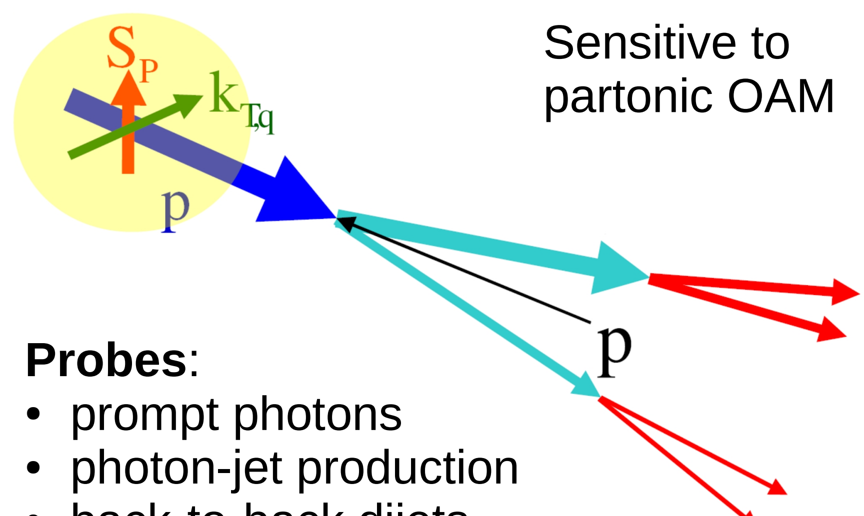
Probes:
- Azimuthal distribution of hadrons in a jet

Sivers Mechanism

Azimuthally dependent jet production

Correlation between initial parton $k_{T,q}$ and proton spin

Sensitive to partonic OAM



Probes:
- prompt photons
- photon-jet production
- back-to-back dijets

Implications from Polarized pA Collisions

- **Correlations of A_N with other observables, e.g.:**
  - Possible probe of nuclear saturation scale

    – Color glass condensate predicts p+A A_N decreases as A increases
  - Nuclear modification factor R_{pA}

    (production in pA / production in pp)
  - Fragmentation universality

    – e.g., A_N dependence on event topology / exclusiveness
  - Collision centrality

- **What about p_T and x_F dependences of A_N?**

  Do these characteristics persist in pA production, or are they “filtered” away by the nucleus?

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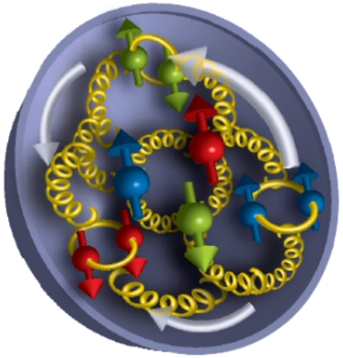
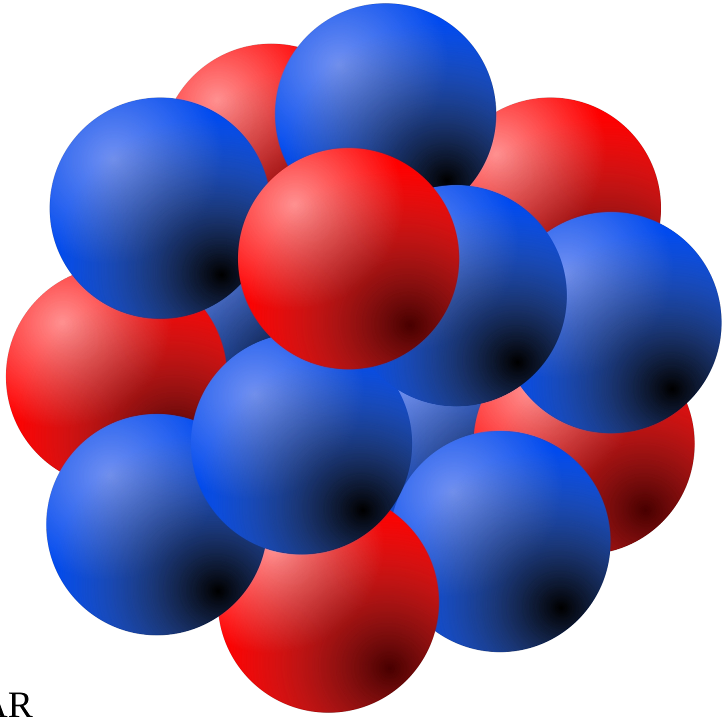
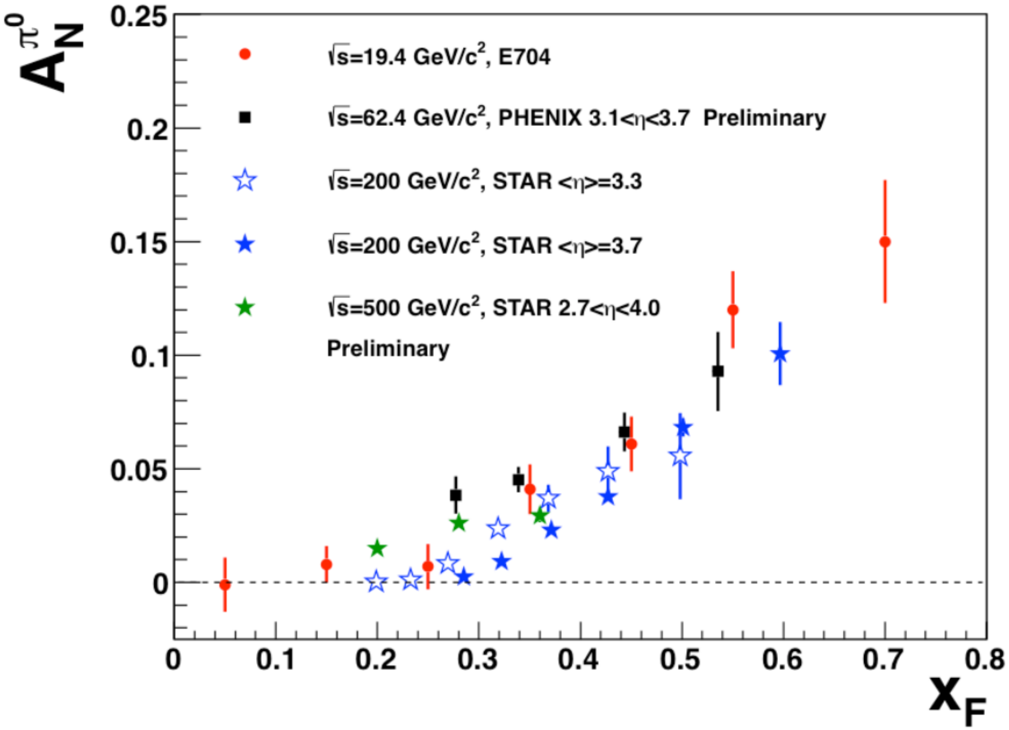
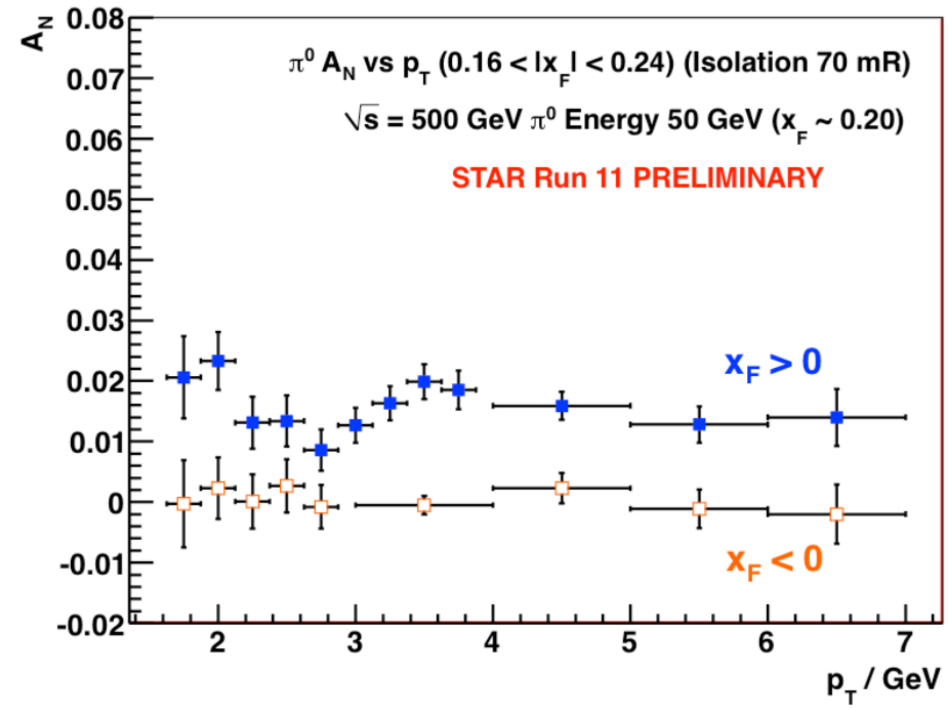




x_F and p_T-dependence of A_N



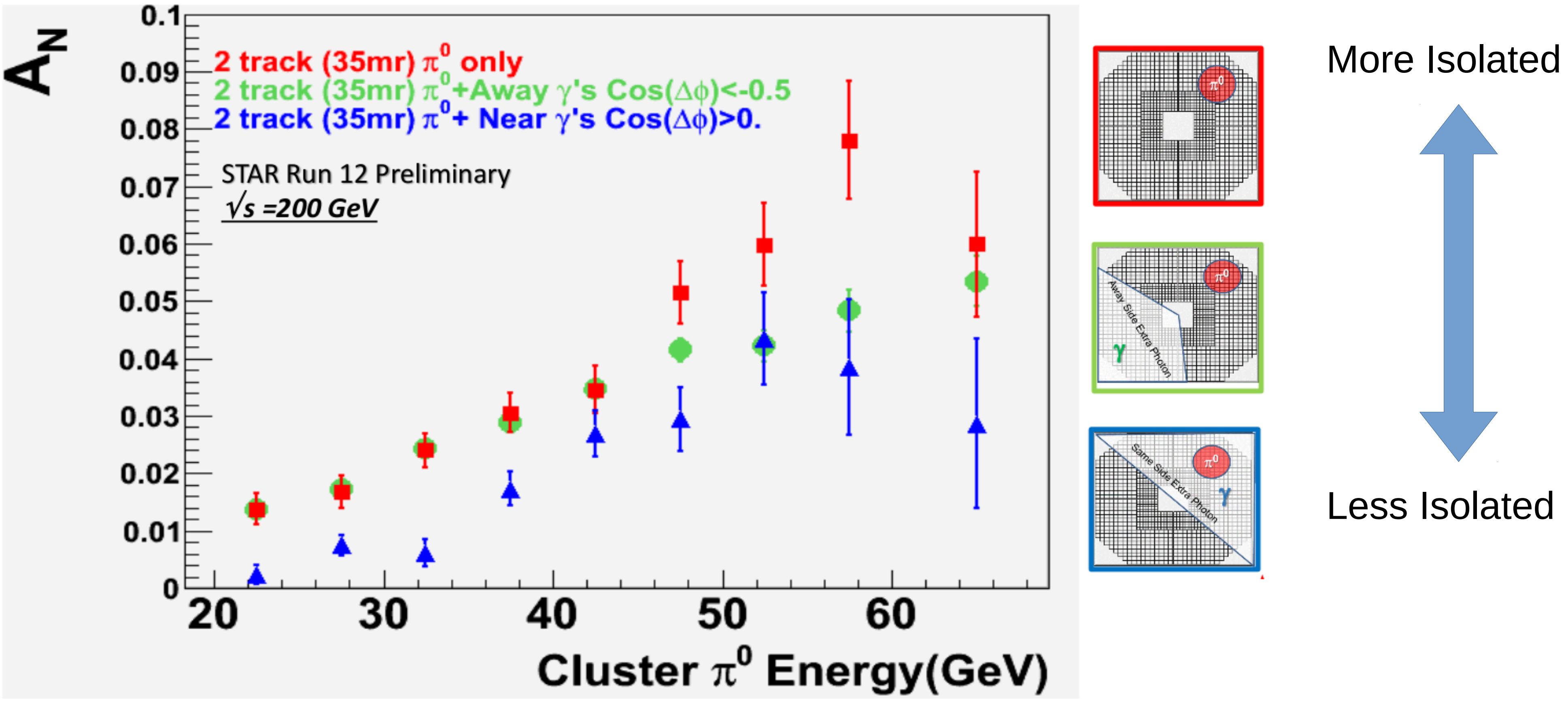


Steve Heppelmann – CIPANP 2012

$s^{1/2}$=200 GeV and 500 GeV show same rise of A_N vs. x_F as lower $s^{1/2}$ measurements

- Collins, Sivers, Twist-3 suggest A_N~$1/p_T$
- Flat P_T-dependence observed and raises the question as to what causes it

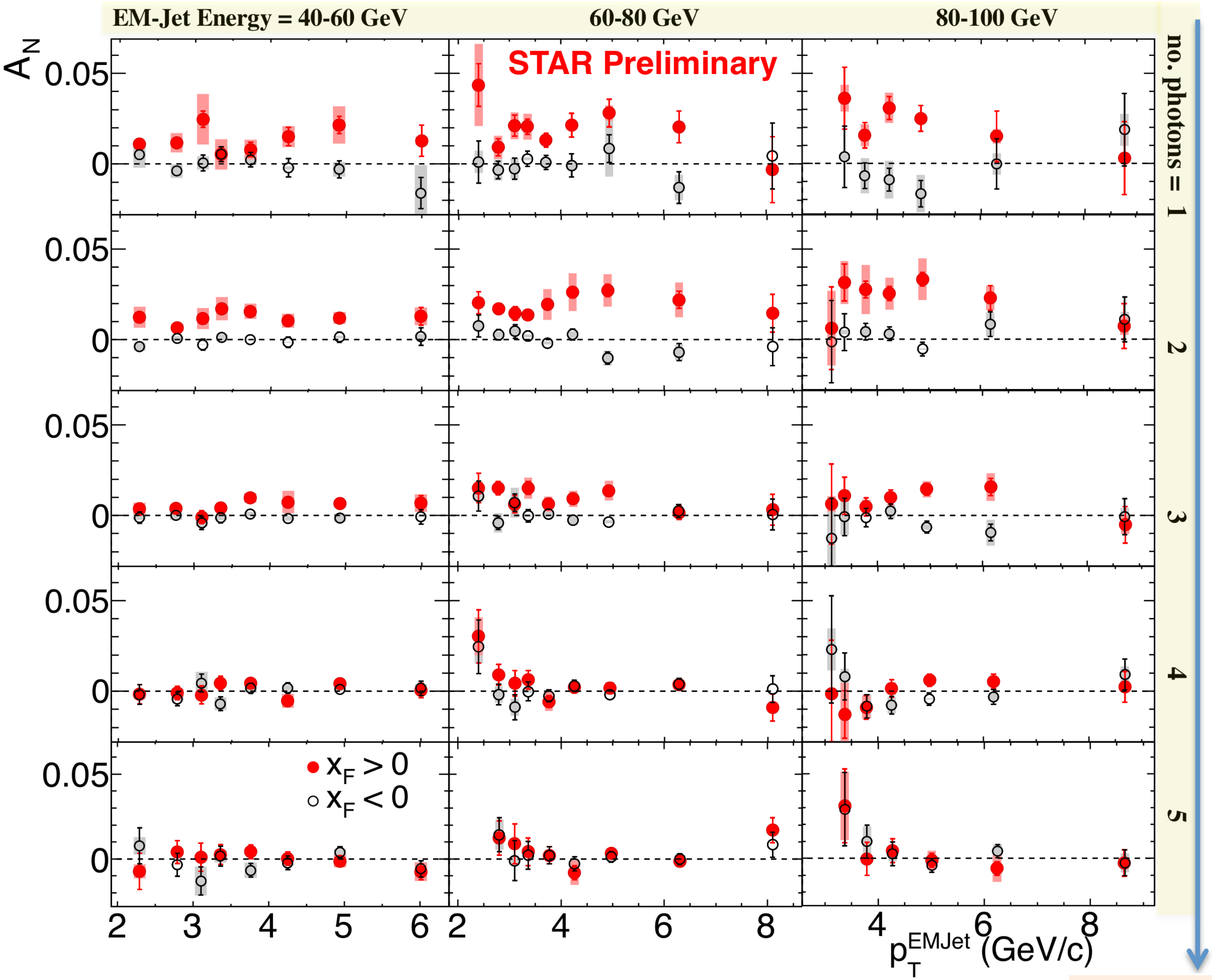
Dependence on π^0 Isolation



Steve Heppelmann – DIS 2013

- More isolated pions have greater A_N than those with nearby energy deposits (presence of E>6 GeV photon(s) outside 35mrad cone)
- Pion A_N is therefore event topology-dependent

EM-jet A_N



- $s^{1/2}$=500 GeV
- EM-jet A_N decreases as number of photons increase
- 1-photon events have pion contamination, so A_N is similar to that of 2-photon events, which are mostly pions
- Pion A_N is also reduced when there are correlated central EM-jets (see backup)
- Sivers-type asymmetry in the jets is too small to explain high pion A_N

Mriganka Mondal
DIS 2014

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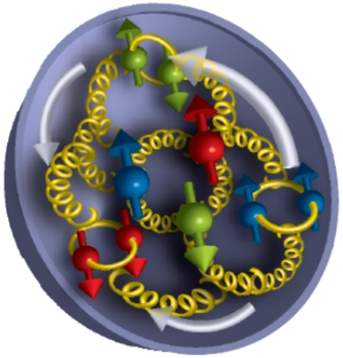
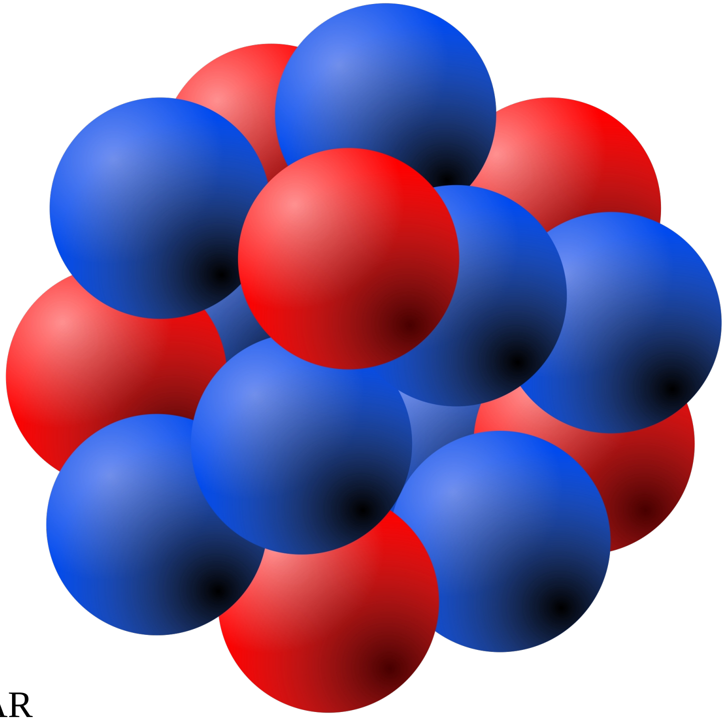




Analysis of 2015 p+p and p+Au Dataset

- In 2015, RHIC collided polarized p+Au and p+Al (along with transversely polarized p+p) at $s^{1/2}$=200 GeV

– A(Au)=197
– A(Al)=27

- This analysis is of the p+Au data set, compared p+p

Event Selection for 2015 Analysis (inclusive: π^0 + X)

1) Collect photons within 35 mR cones.
2) π^0 mass |M-.135| < 0.12 GeV
3) Organize into P_T and E Bins
4) For photon pair, Z < 0.7
5) Beam Beam Counter (BBC) cuts
   (gold or away side proton breakup cut)
6) Require P_T above trigger threshold.

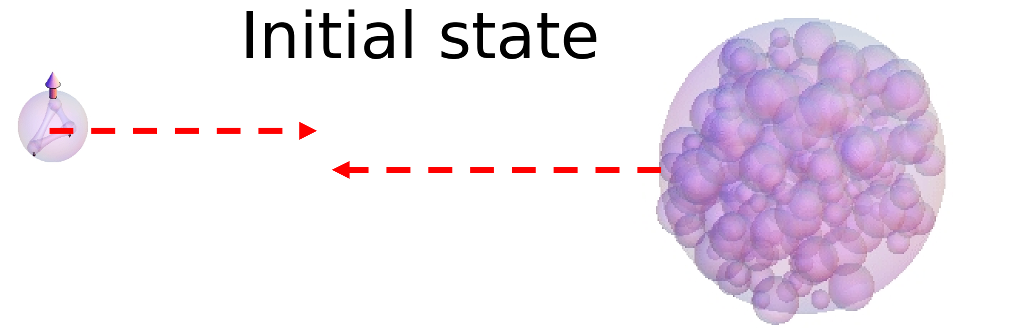
A_N depenence on pAu Break-up Multiplicity

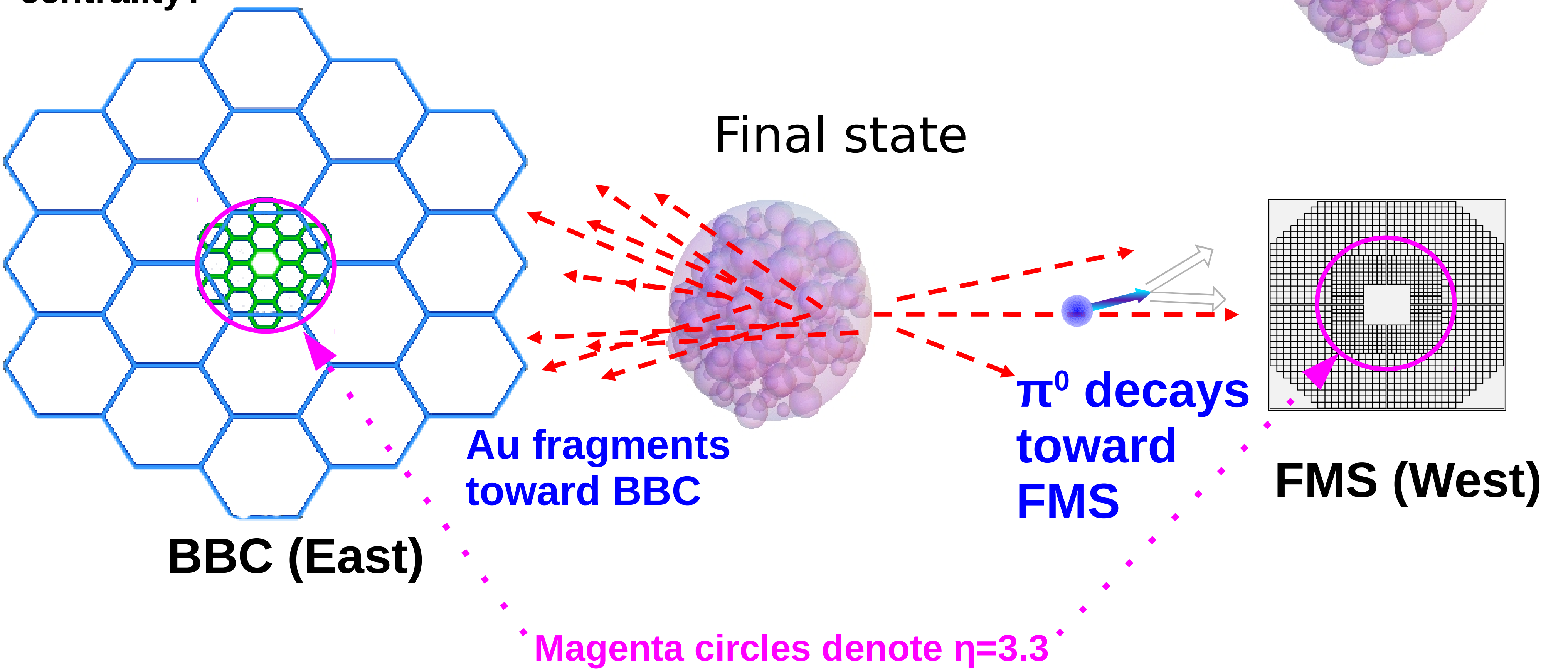
(possibly related to centrality)

BBC – composed of scintillator panels

Consider BBC multiplicity and summed PMT signals

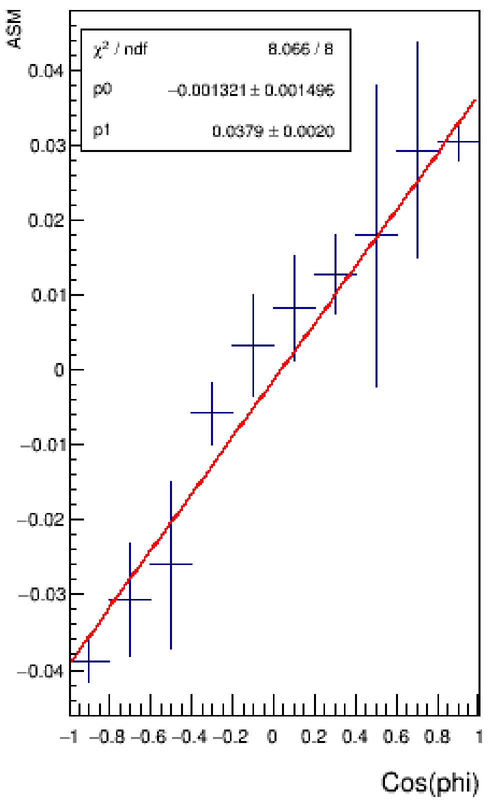
Could A_N depend on nuclear breakup / centrality?





Extracting asymmetries in p+Au – Example

This Example with π^0 within ($0.55<X_F<0.65$) and ($2.55\text{GeV} <p_T[\text{GeV/c}]<3.05$)



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

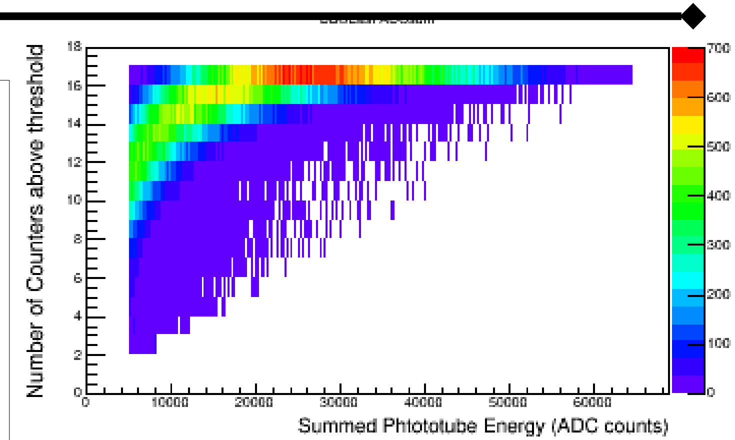
$$Raw\,A(\phi) = P_0 + P_1\,\mathrm{Cos}(\phi)$$

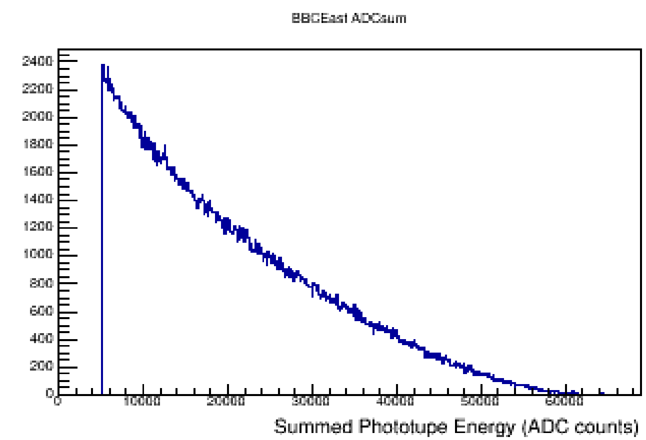
$$A_N = \frac{P_1}{Beam\ \ Polarization}$$

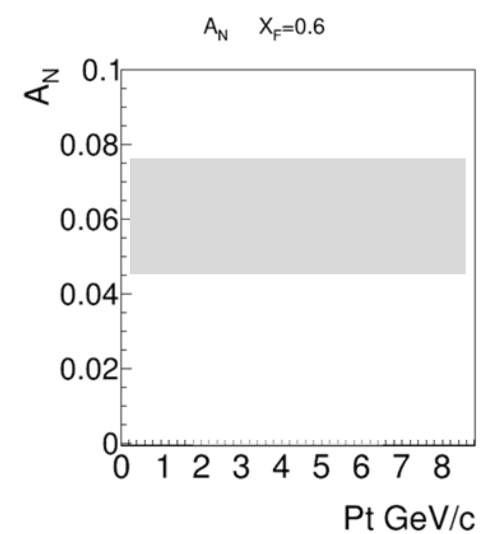
The p+Au Asymmetry depends upon BBC charged particle distribution from gold breakup in the East BBC (and to lesser extent similar away side proton breakup in pp collisions)

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.







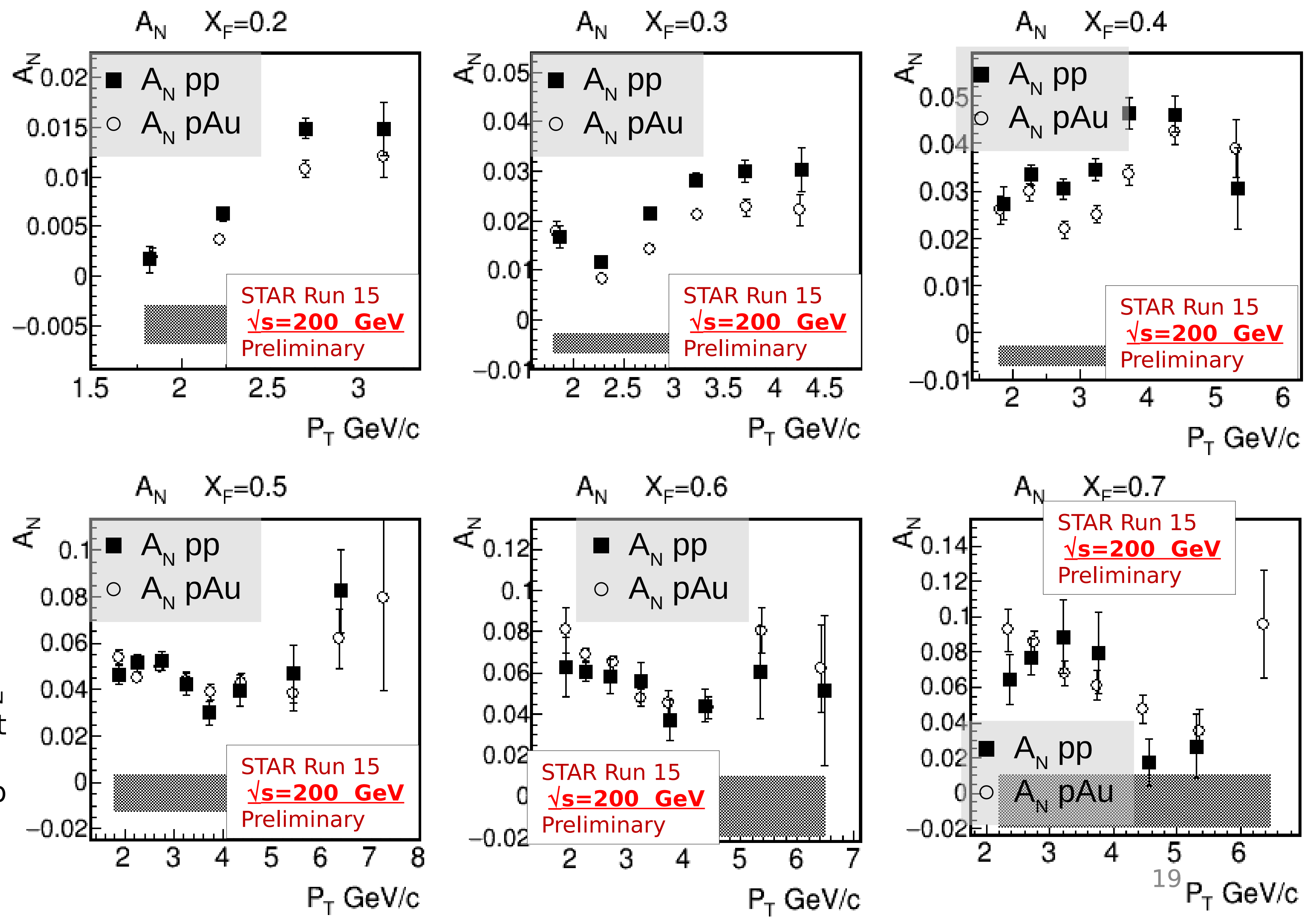
$s^{1/2}$=200 GeV π^0 A_N for pp vs. pAu

Error bars represent statistical errors only.

Luminosity:
pAu=204.6 nb^{-1}
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)

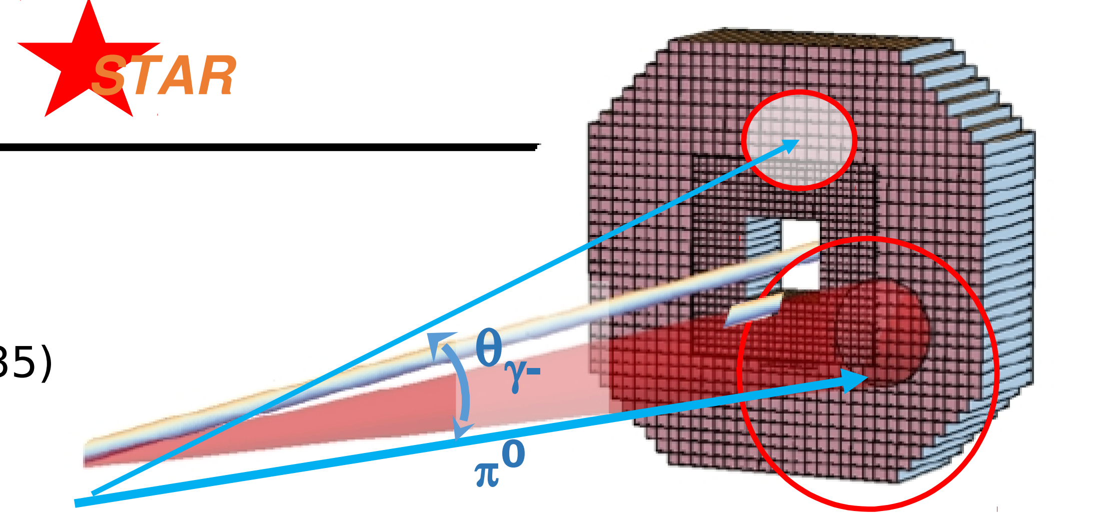


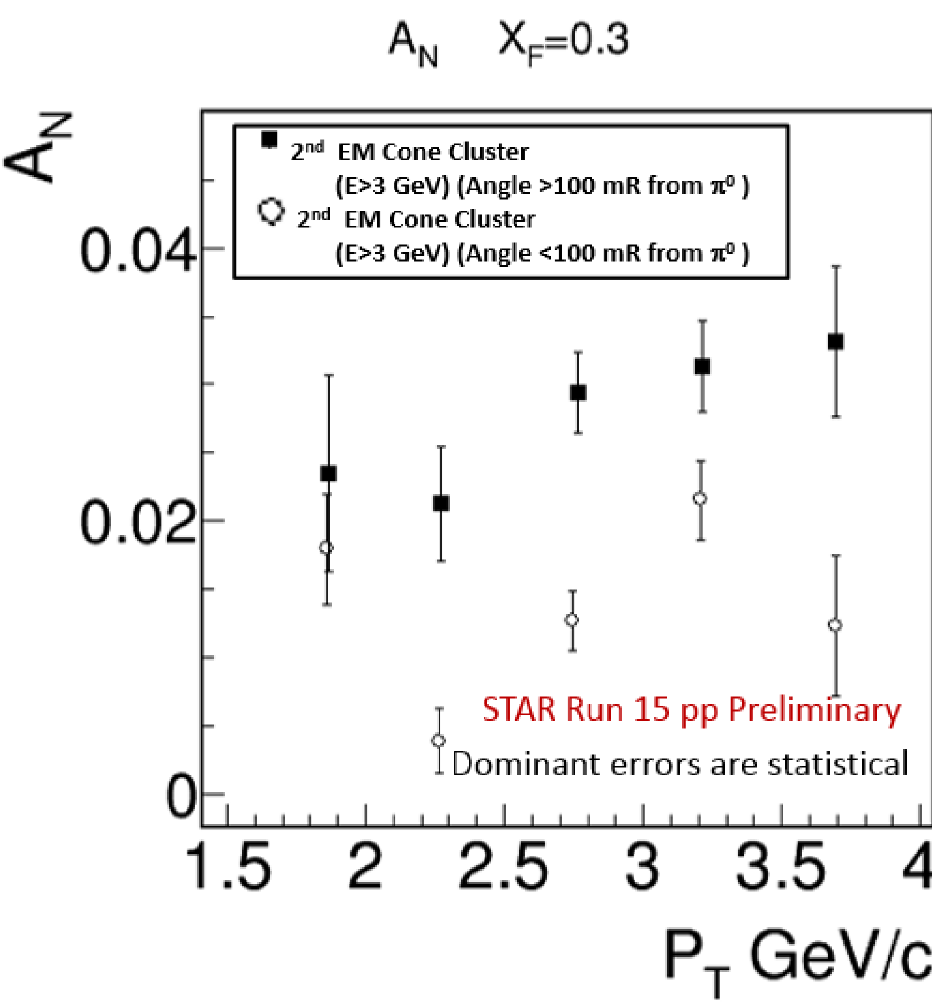
Topology Dependence

Run 15 2015 pp √s=200 GeV Data

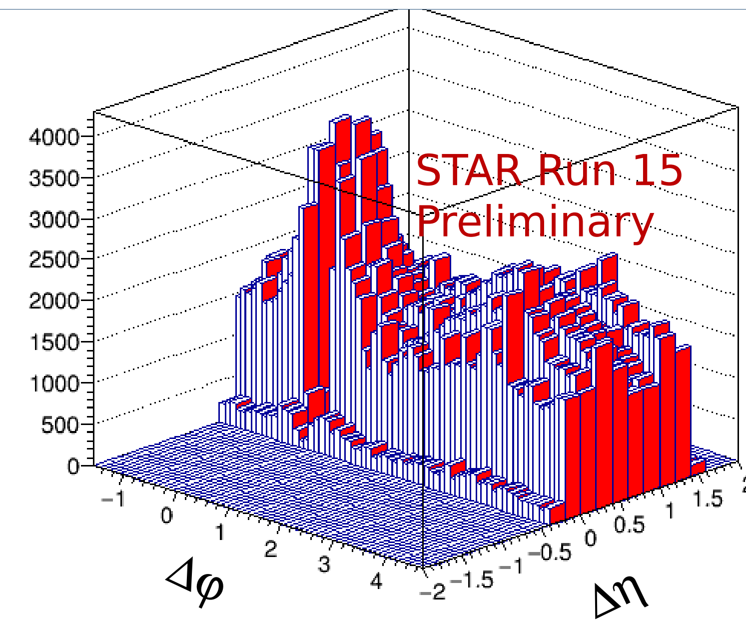
Example showing suppression of π^0 A_N for jet–like events. This shows **2 photon cluster FMS events**, with a π^0 ($0.25<X_F<0.35$)

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



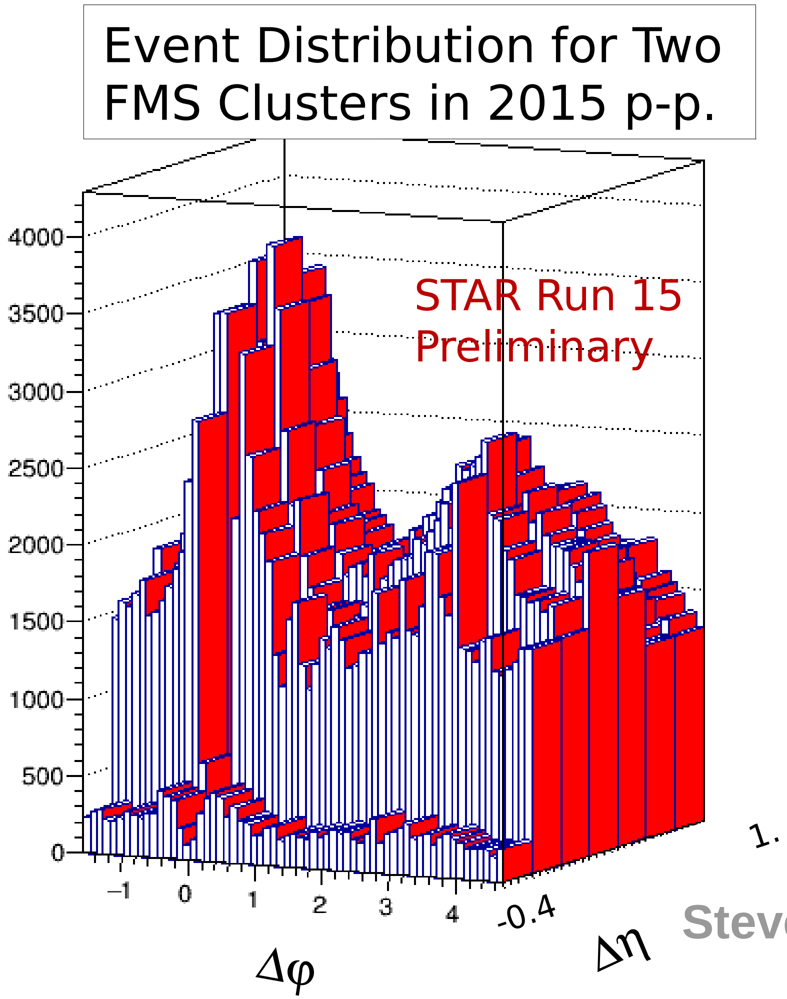


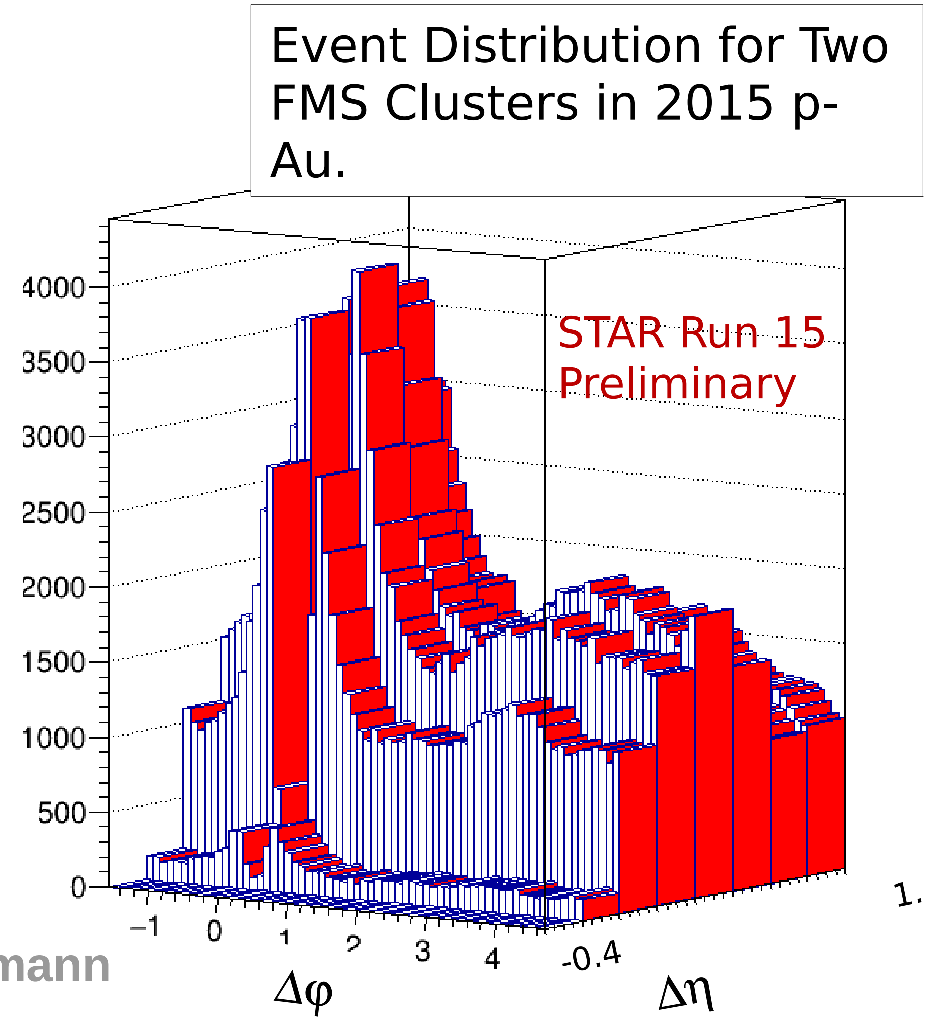
FMS π^0 + 1 EM Cluster (Cluster Energy>3 GeV)
2nd EM Cluster Distribution in $\Delta\eta$ (pseudo-rapidity) vs. $\Delta\varphi$ (azimuthal angle) Relative to π^0 Direction



Steve Heppelmann
MPI 2015

2-Cluster Distributions in pp vs. pA





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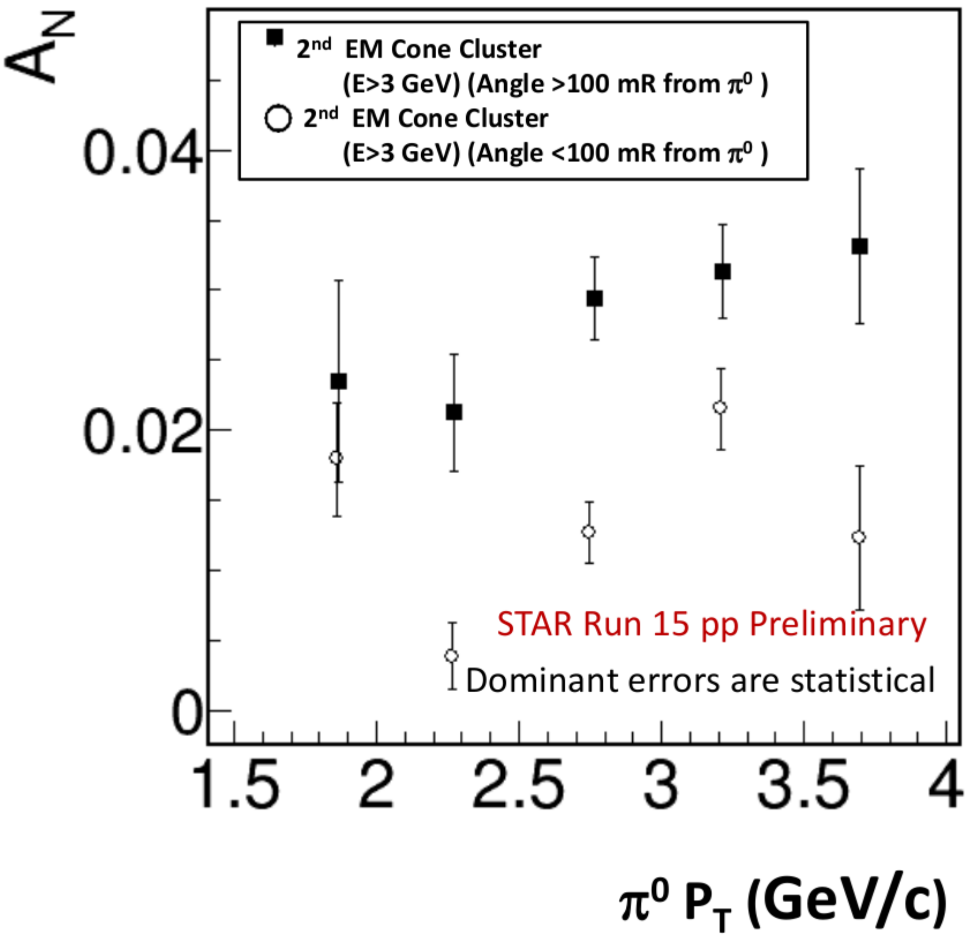
First cluster contains π^0

$0.25 < x_F(\pi^0) < 0.35$
$3.55 < p_T(\pi^0) < 4.05$ GeV/c

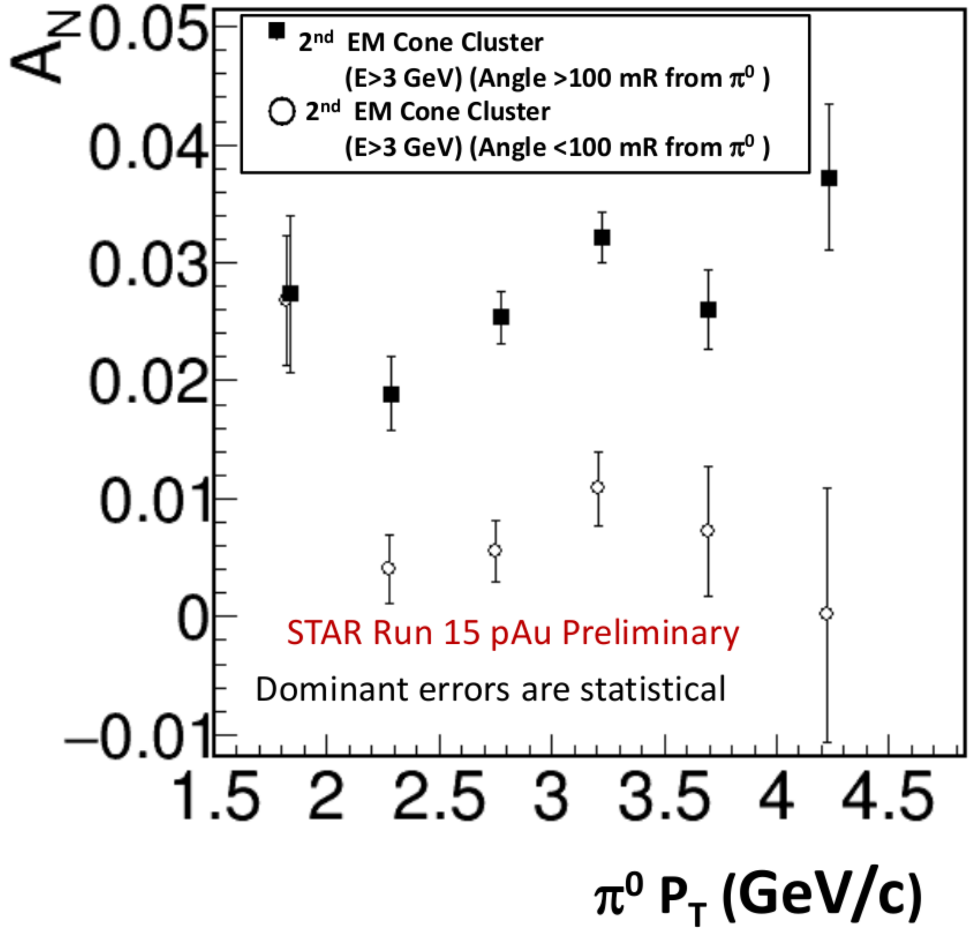
E>3 GeV for 2nd cluster in momentum direction relative to π^0 direction

Topology-dependent A_N in pp vs. pA

<u>STAR Run 15 p- $x_F = 0.3$. $\sqrt{s}$=200 GeV</u>
Dependence of π^0 A_N on the location of second forward EM particle in pp collisions at $x_F = 0.3$.



<u>STAR Run 15 p-Au $x_F = 0.3$. $\sqrt{s}$=200 GeV</u>
Dependence of π^0 A_N on the location of second forward EM particle



Steve Heppelmann
MPI 2015

Summary

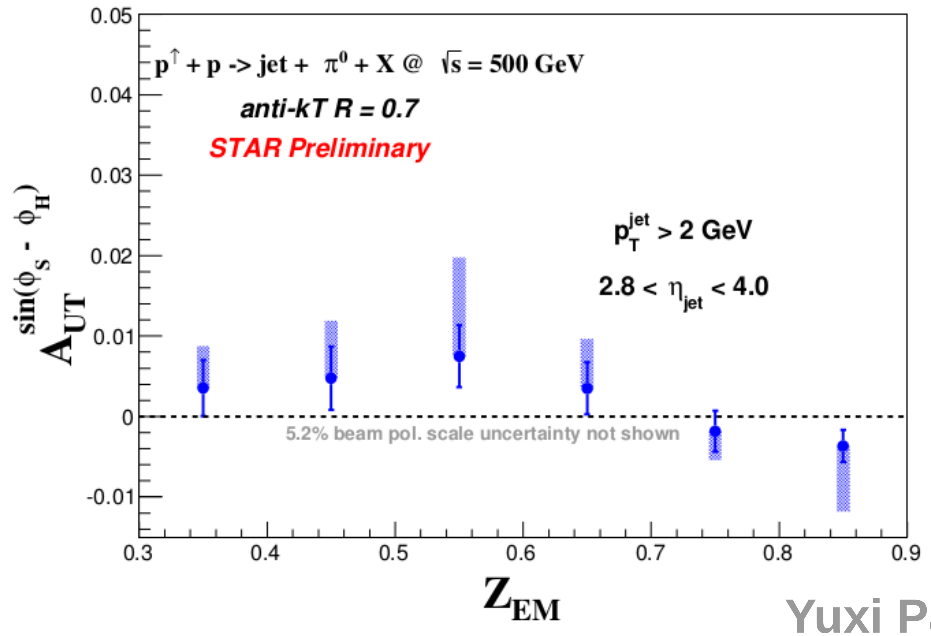
- Large A_N has been observed since 1976
  - Rising with x_F
  - A_N tends to increase w.r.t p_T
  - Dependent on event topology for π^0s
    - – Isolated π^0s have higher asymmetries
    - – Asymmetries suppressed in multi-photon EM jets

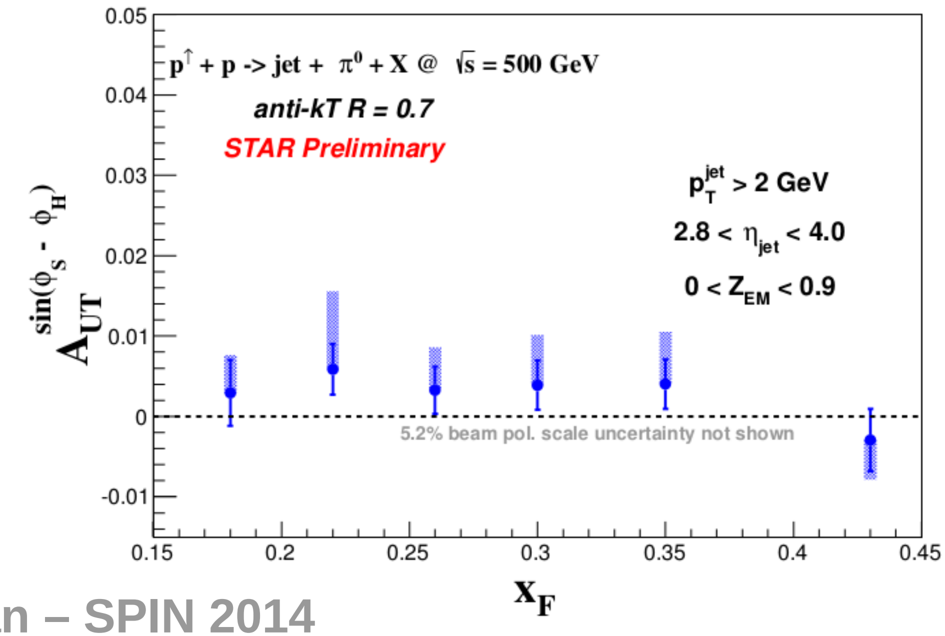
- 2015 – first data recorded for polarized p+A collisions
  - How does A_N in p+A production compare to A_N in p+p?
  - Similar dependence on topology, though A_N for non-isolated π^0s in p+A seems to be slightly smaller than that in p+p
  - Dependence on centrality – to be characterized
  - Can also look at nuclear modification factors

- Roman Pots were installed in 2015
  - Possible to tag outgoing proton(s) as a signature for diffractive events
  - Do the asymmetries depend on diffraction?

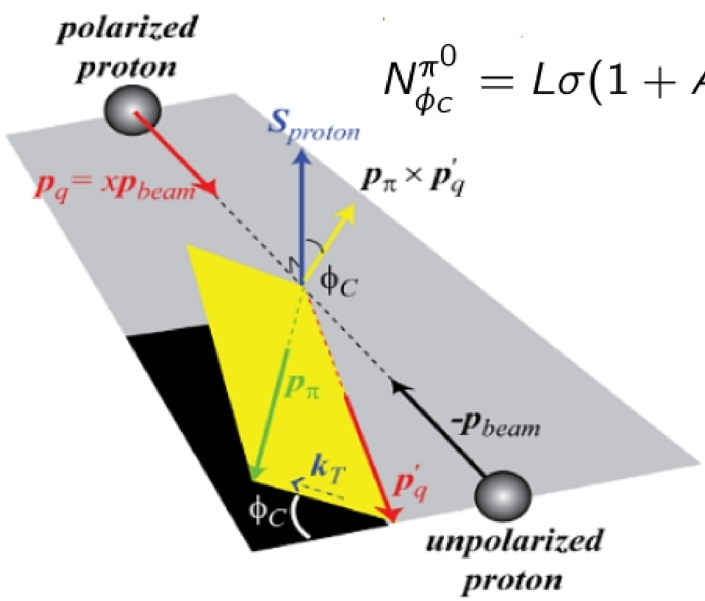
backup

Collins Asymmetry (“A_N within a Jet”)





Yuxi Pan – SPIN 2014



$$N_{\phi_C}^{\pi^0} = L\sigma(1 + A_{UT}\sin(\phi_s - \phi_h))$$

Φ_s = angle btwn proton spin & reaction plane

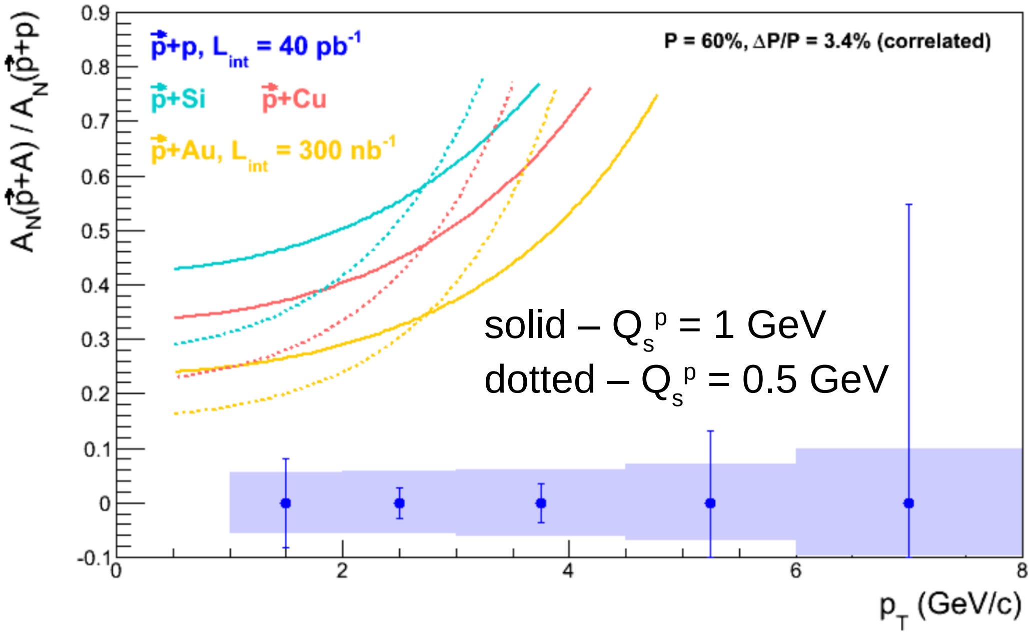
Φ_h = angle btwn pion jet-transverse momentum and reaction plane

- The Collins asymmetry A_{UT} is an asymmetry of a hadron within a jet
- Z_{EM} = longitudinal momentum fraction of pion in EM-jet
- Hints of possible non-zero π^0 A_{UT}

A_N for pp vs. pA Predictions

STAR

A_N^{pA} / A_N^{pp} vs. p_T for FMS π^0s



- Color glass condensate model predicts pA A_N decreases as A increases
- pQCD & factorization predicts same A_N for any size of nuclear target

A_N in pA vs. in pp as a possible probe to nuclear saturation scale Q_s^A

In 2015, RHIC collided $p^{\uparrow}$+Au and $p^{\uparrow}$+Al
- A(Au)=197
- A(Al)=27

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 \ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2 \delta^2}{Q_{sp}^4}}$$

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 \gg Q_s^2} \approx 1$$

$$Q_s^A \propto A^{1/3} Q_s^p$$

Kang and Yuan arXiv:1106.1375

Roman Pots

RPs are vessels which house Silicon trackers within beam-pipe vacuum, and are moved close to the beam during optimal running conditions

They are designed to track protons which were only slightly deflected after a collision