Forward Spin Physics at STAR

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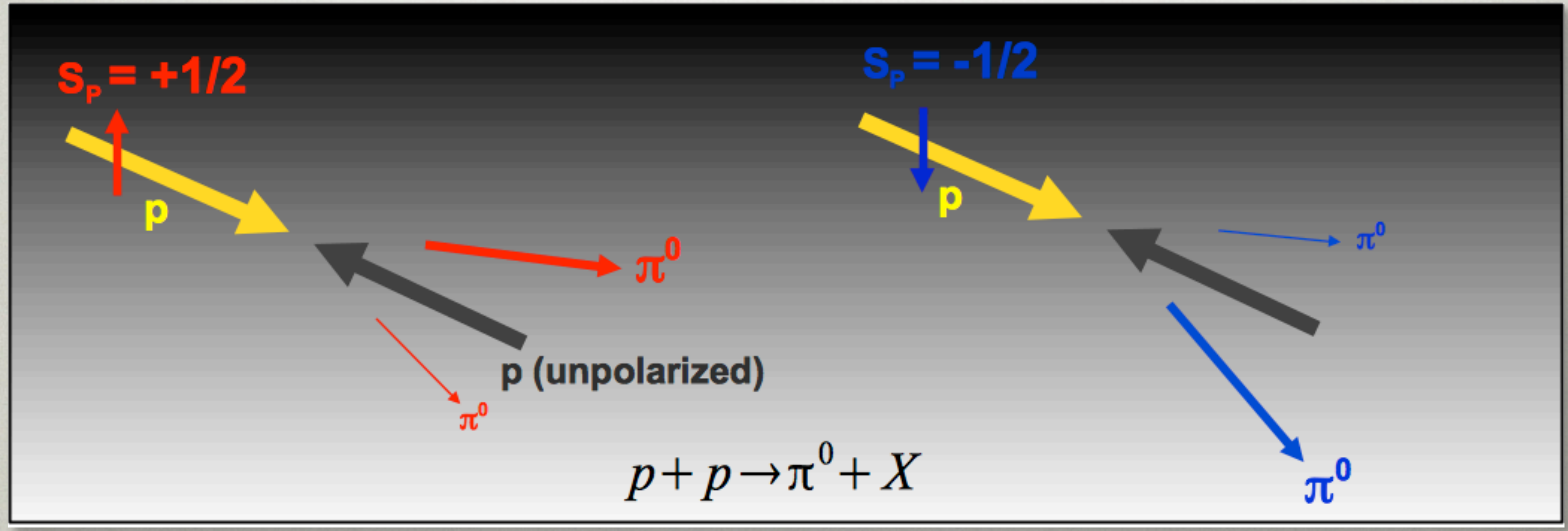
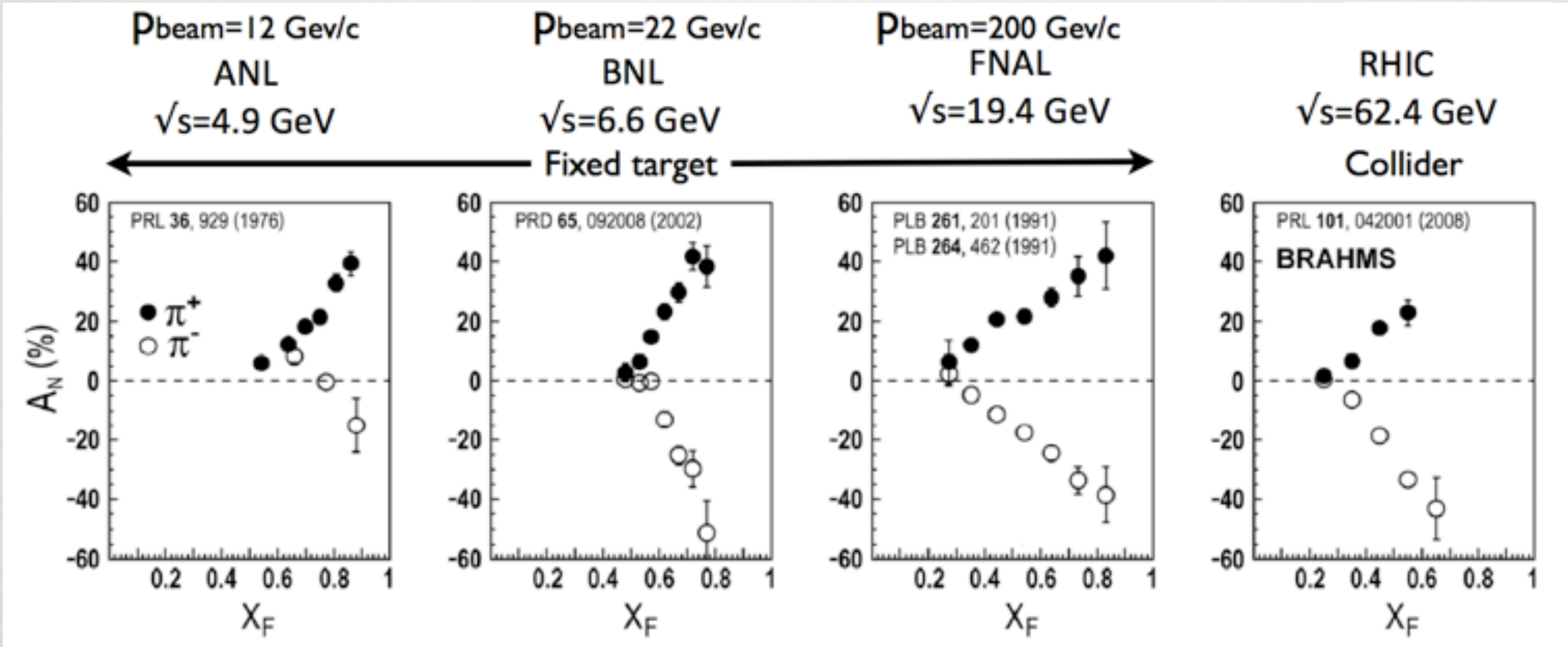
Transverse SSA (A_N)

Transverse Single Spin Asymmetry measures the **left-right asymmetry** in production cross-section in relation to the **transverse polarization of the incoming proton**. It is commonly measured by the **Analyzing Power, A_N**.

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



Large A_N in H-H Interaction

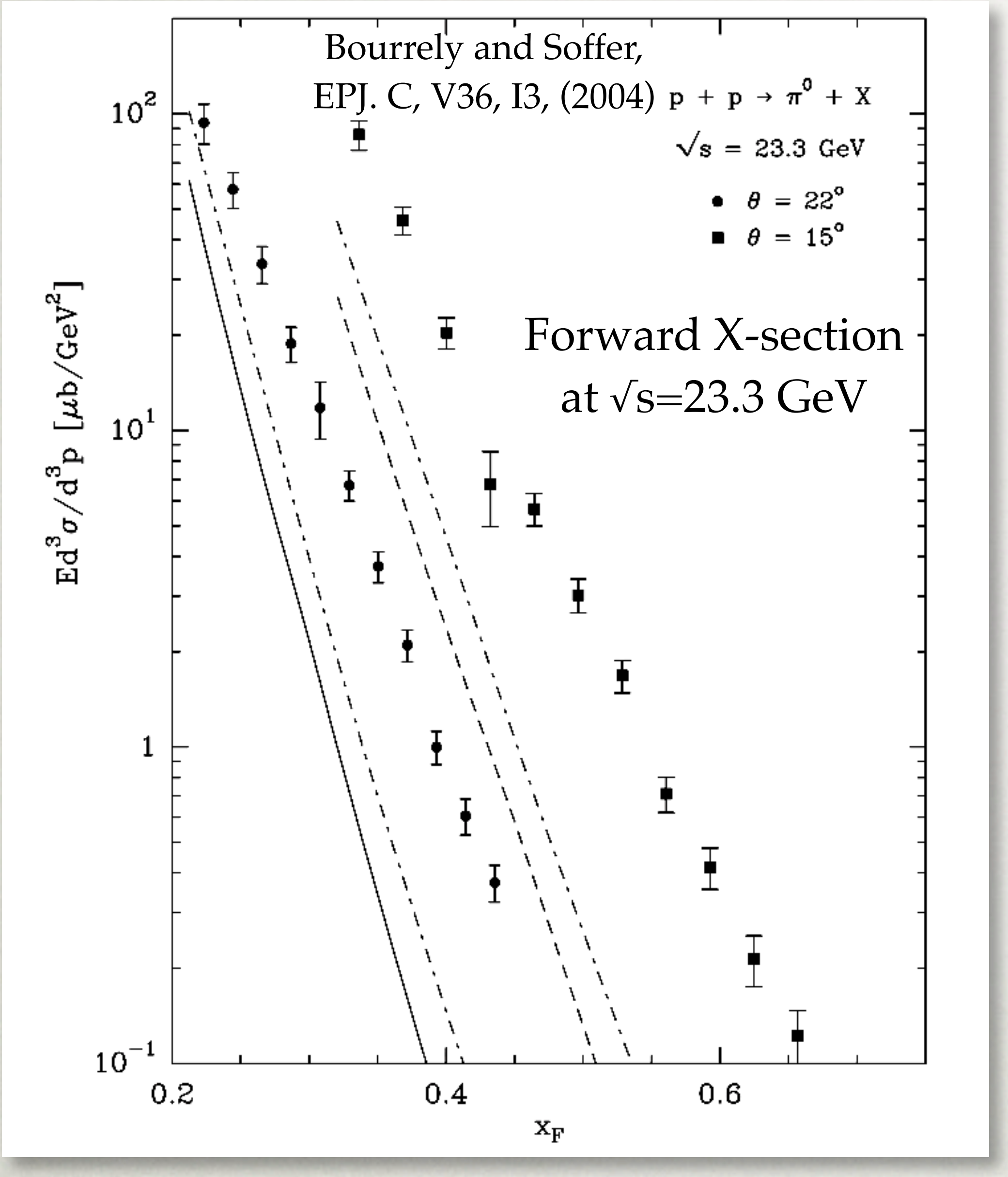


Large A_N in the forward region of "high energy" hadron-hadron interaction has a long experimental history, dating back to 1976.

Until the RHIC era, these measurements were performed in fixed target environments with polarized targets.

However, it was generally believed that these fixed target results could not be interpreted within the framework of pQCD.

Is Forward Physics pQCD?



The main issue is if very forward physics is in the domain of pQCD.

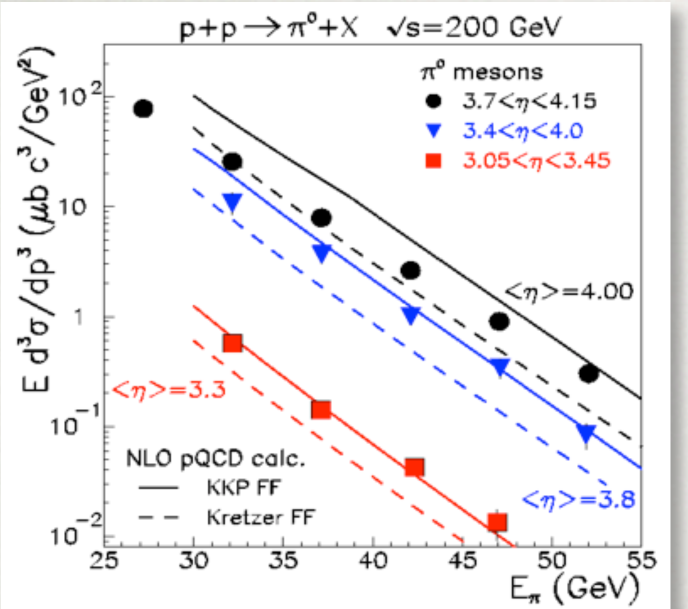
Small angle scattering means small transverse momentum transfer. **Even at RHIC energy, the average p_T in the forward region is relatively small (2~3GeV).**

Furthermore, the proximity to the beam line introduces the **beam remnant (underlying events) interaction** into the possible sources of observed high energy particles.

Not surprisingly, the unpolarized forward cross-sections at fixed target energy was found to be significantly larger than the pQCD prediction.

Forward X-sec. at RHIC

STAR π⁰

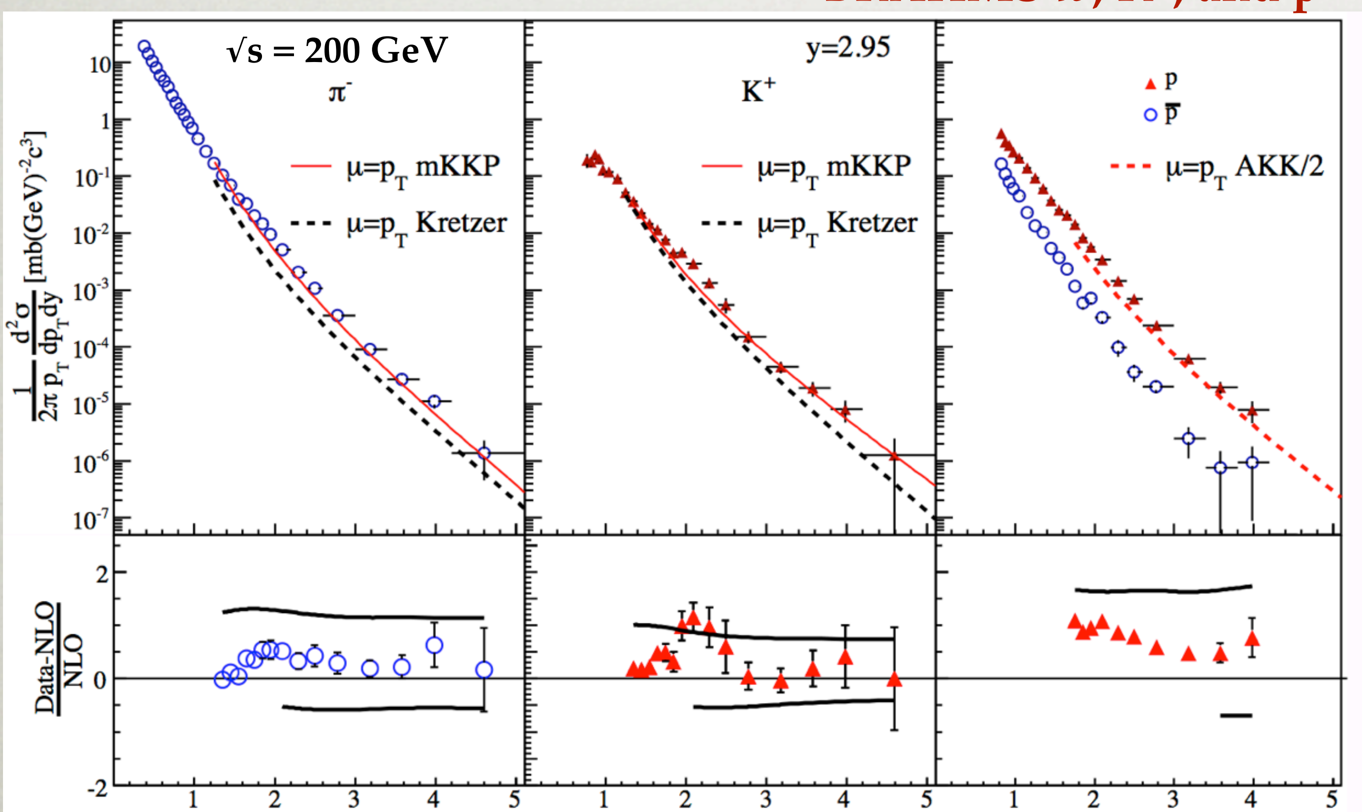


Phys. Rev. Lett. 97 (2006) 152302

In contrast, at RHIC (200GeV), there are good agreements between **forward hadron cross-sections** and **pQCD predictions**, with appropriate fragmentation functions.

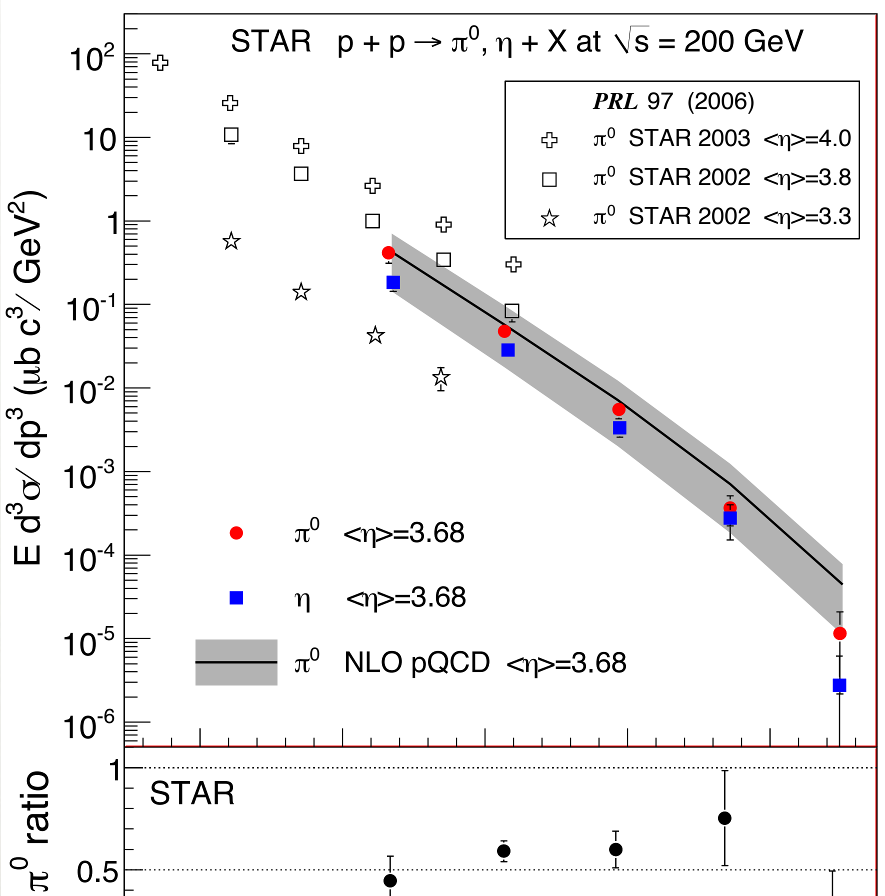
Consequently, many believe that the RHIC forward transverse spin results CAN be understood by pQCD.

BRAHMS π⁻, K⁺, and p



Phys. Rev. Lett. 98, 252001 (2007)

STAR π⁰ and η, high x_F

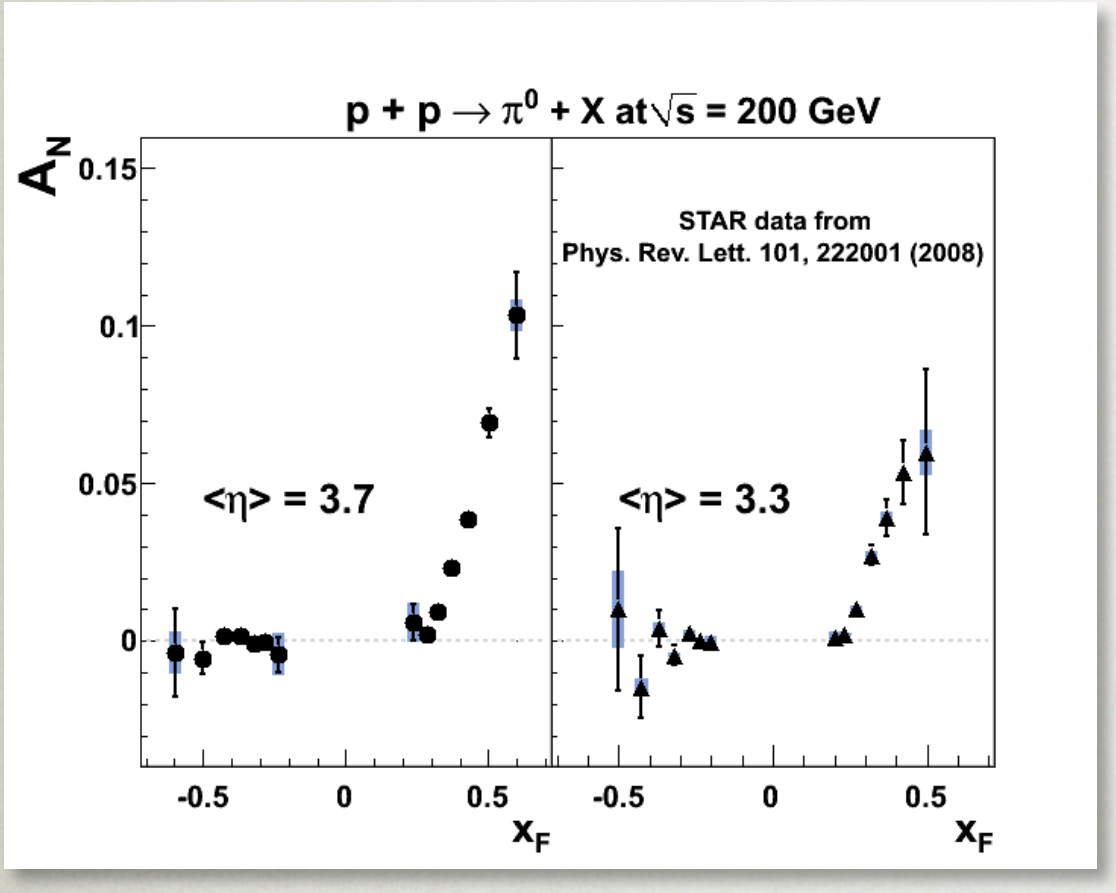


Phys. Rev. D 86, 051101(R) (2012)

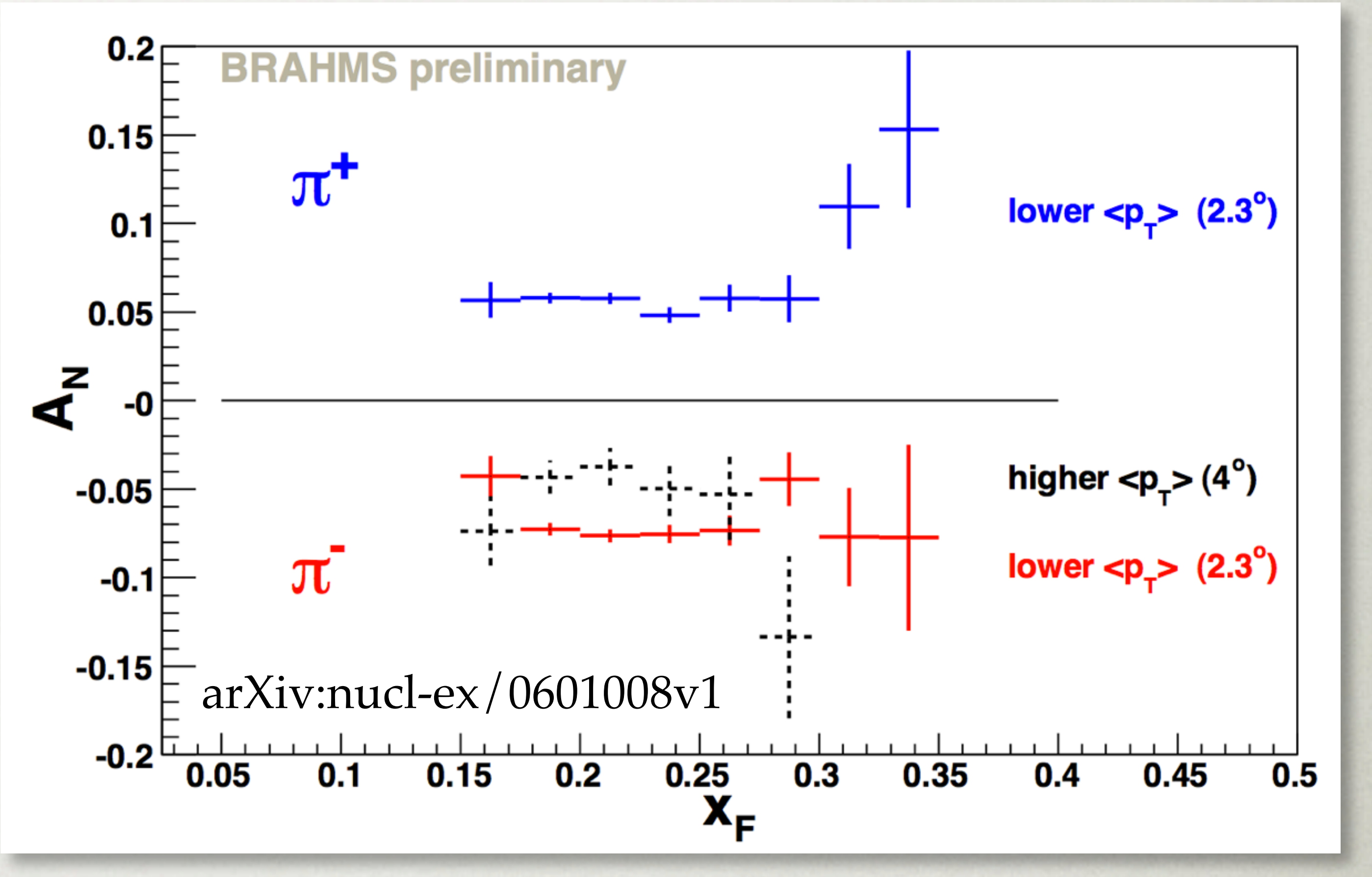
Forward A_N at RHIC

$\sqrt{s} = 200$ GeV

STAR π^0



BRAHMS π^+ and π^-



The large forward A_N persists at RHIC, as shown for all three species of pions.

The sign of the asymmetries are the same as before, and the magnitudes are comparable.

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A_N in pQCD

The initial prediction (1978) based on **collinear, leading twist** pQCD was **A_N ~ 0.**

VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

G. L. Kane
Physics Department, University of Michigan, Ann Arbor, Michigan 48109

and

J. Pumplin and W. Repko
Physics Department, Michigan State University, East Lansing, Michigan 48823

(Received 5 July 1978)

We point out that the polarization P of a scattered or produced quark is calculable perturbatively in quantum chromodynamics for $e^+e^- \to q\bar{q}$, large-p_T hadron reactions, and large-Q^2 leptoproduction, and is infrared finite. The quantum-chromodynamics prediction is that $P=0$ in the scaling limit. Experimental tests are or will soon be possible in $pp \to \Lambda X$ [where presently $P(\Lambda) \simeq 25\%$ for $p_T > 2$ GeV/c] and in $e^+e^- \to$ quark jets.

"The result is zero for m_q=0 and is numerically small if we calculate $m_q/\sqrt{s}$ corrections for light quarks."

$$A_N \sim \alpha_s \frac{m_q}{P_T} \to 0$$

Since the 90's, new approaches have been developed to explain the observed large A_N.

Beyond collinear factorization: **Transverse Momentum Dependent (TMD) factorization**

Sivers effect (*D. W. Sivers, Phys. Rev. D 41, 83 (1990)*)

Collins effect (*J. C. Collins, Nucl. Phys. B 396, 161 (1993)*)

Beyond leading twist: **Twist-3 (next-to-leading-twist) approach**

(*J.-W. Qiu and G. F. Sterman, Phys. Rev. Lett. 67, 2264 (1991)*)

(*C. Kouvaris, J.-W. Qiu, W. Vogelsang, and F. Yuan, Phys. Rev. D 74, 114013 (2006)*)

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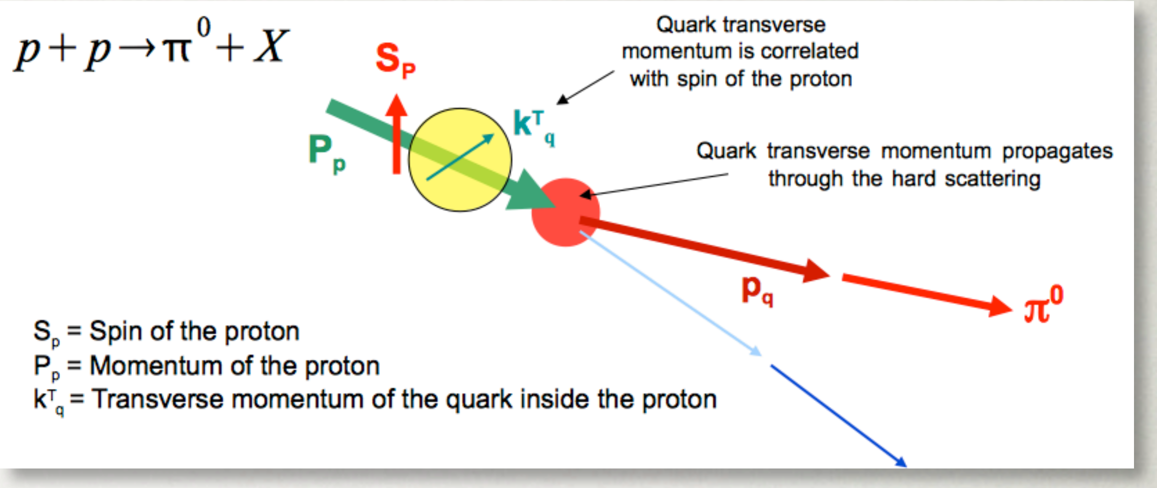
A_N IN PQCD

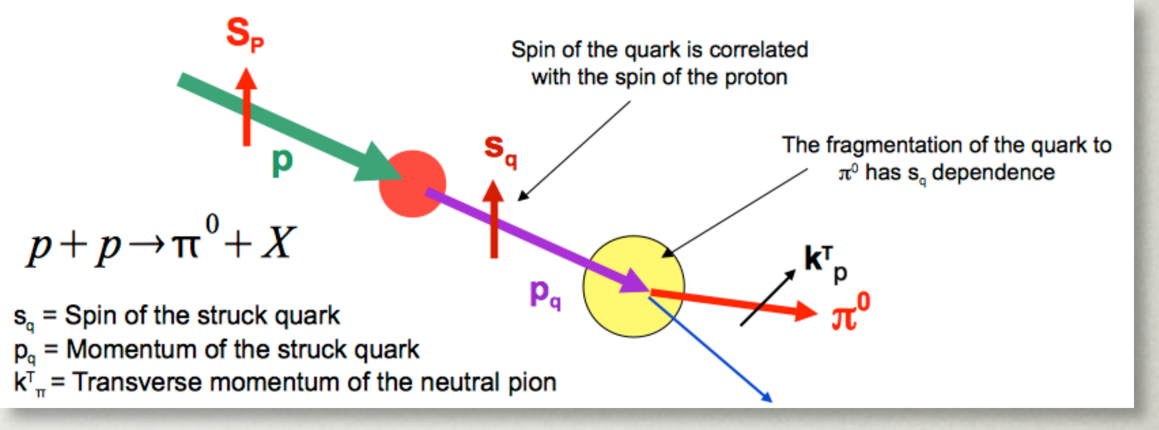
Sivers effect (TMD)

The orbital angular motion of the struck parton, correlated with the spin of the proton, generates the asymmetry.



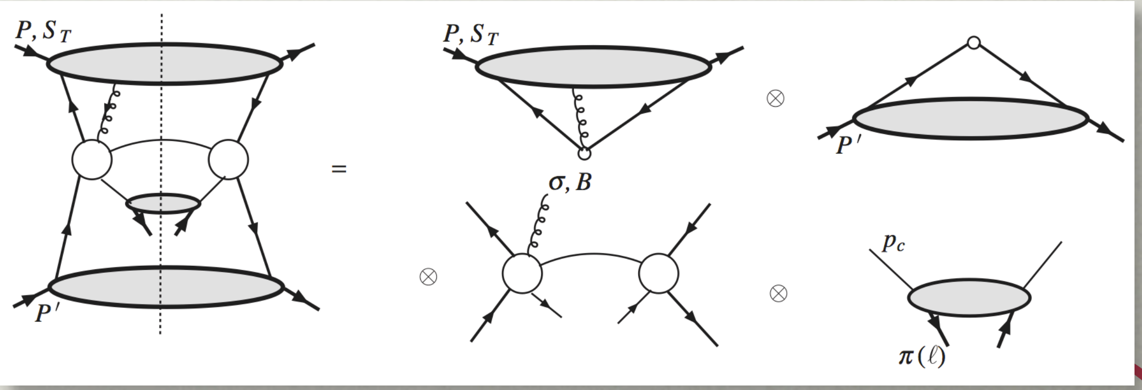
Collins effect (TMD)

Asymmetry arises from the fragmentation process that depends on the **quark transversity**.



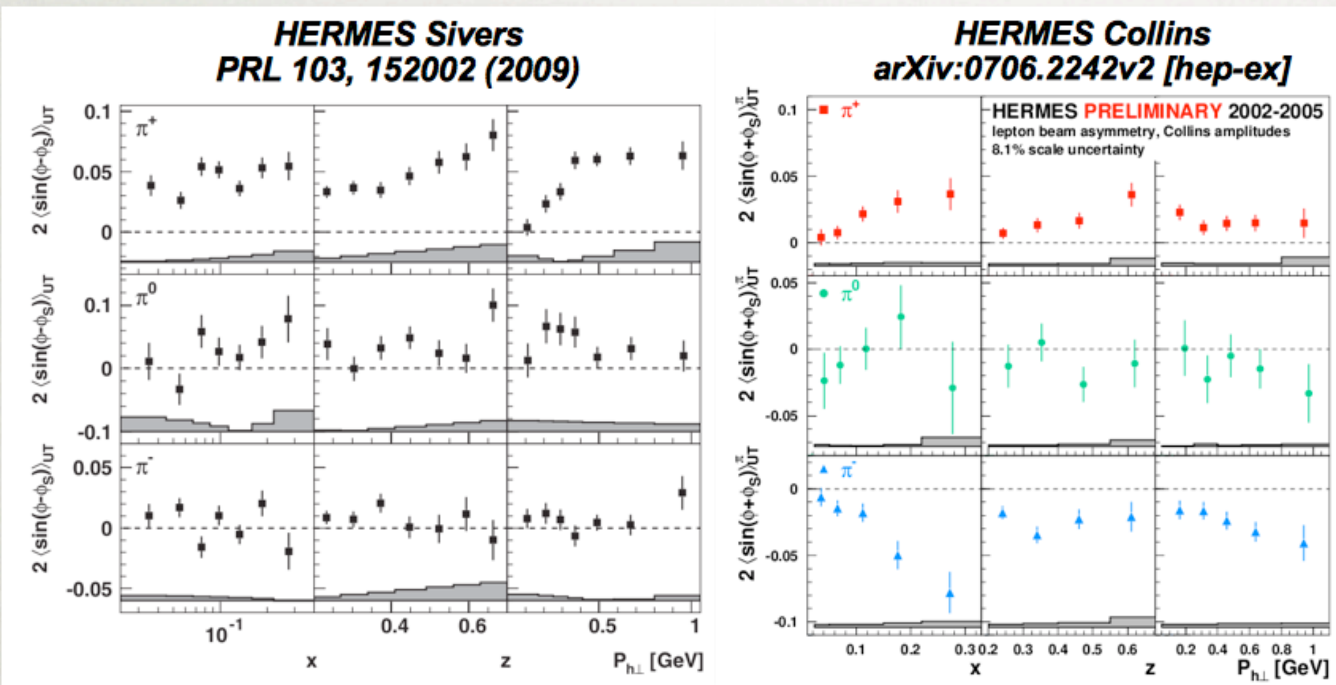
Twist-3 (Collinear)

Twist-3, **three-parton correlation/ fragmentation functions** can generate the asymmetry within collinear factorization.

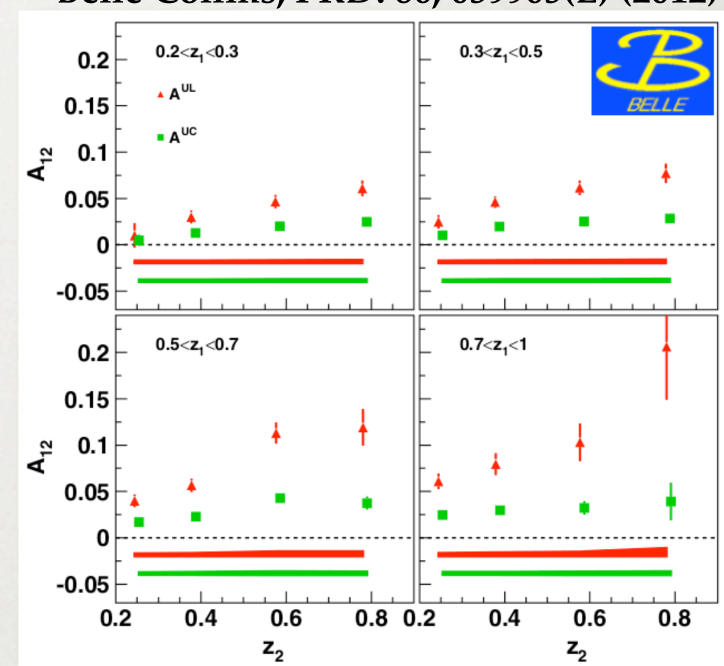


Sivers and Collins

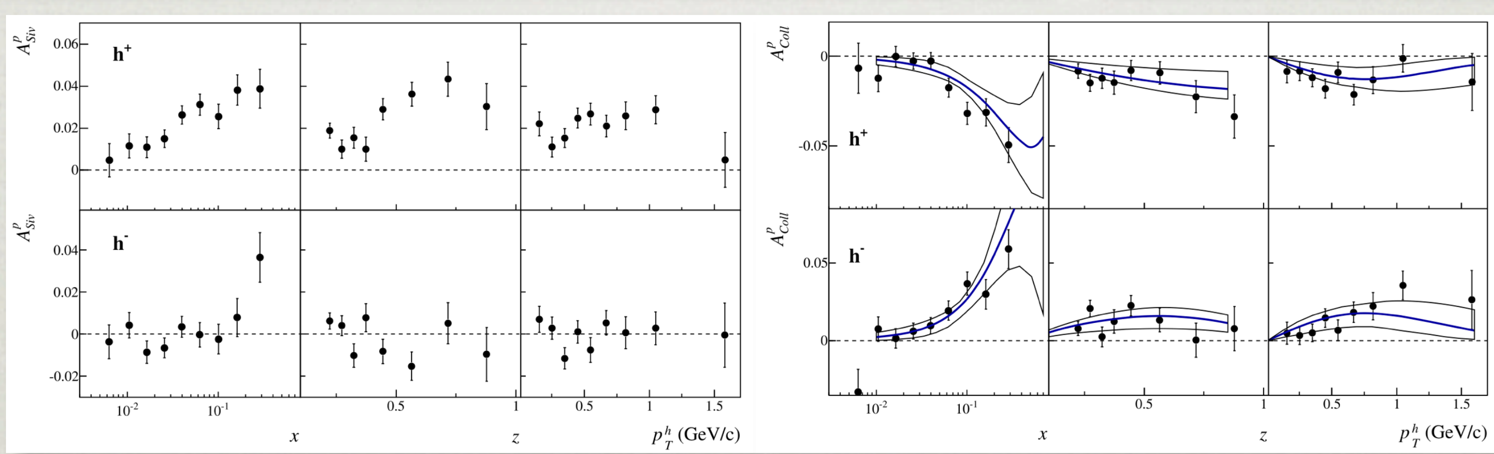
The TMD functions (Collins and Sivers) have been measured in various SIDIS experiments (HERMES, COMPASS, JLab) and e^+e^- (Belle), and shown to be non-zero.



Belle Collins, PRD. 86, 039905(E) (2012)



COMPASS Sivers
PLB 717 (2012) 383-389



COMPASS Collins
PLB 717 (2012) 376-382

Furthermore, **the twist-3 correlations have been shown to be related to the TMD functions**. (*D. Boer, P. J. Mulders, and F. Pijlman, Nucl. Phys. B667, 201 (2003)*)

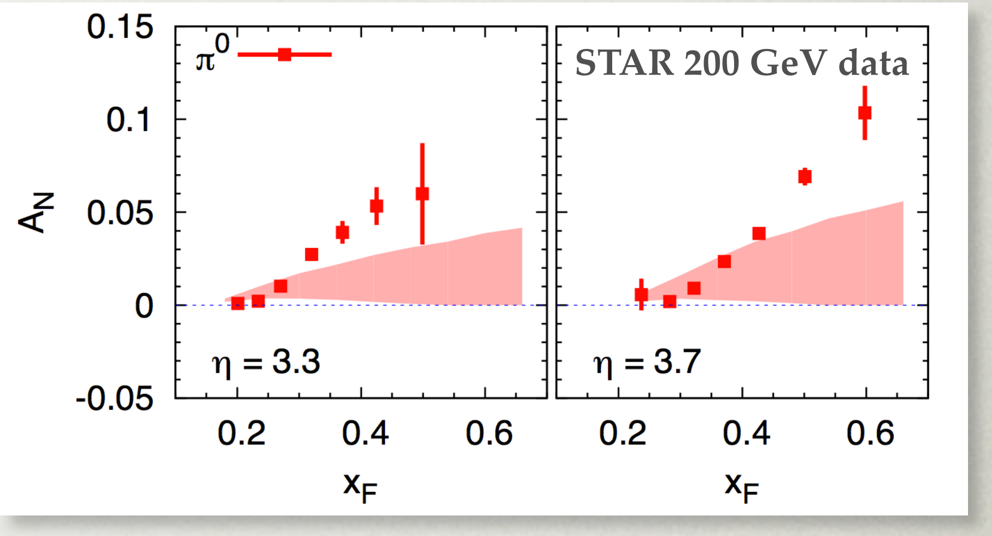
THE ORIGIN OF A_N IN P+P

Unlike in SIDIS, it is much more difficult to untangle the dynamic origin of the observed large A_N in p+p collisions.

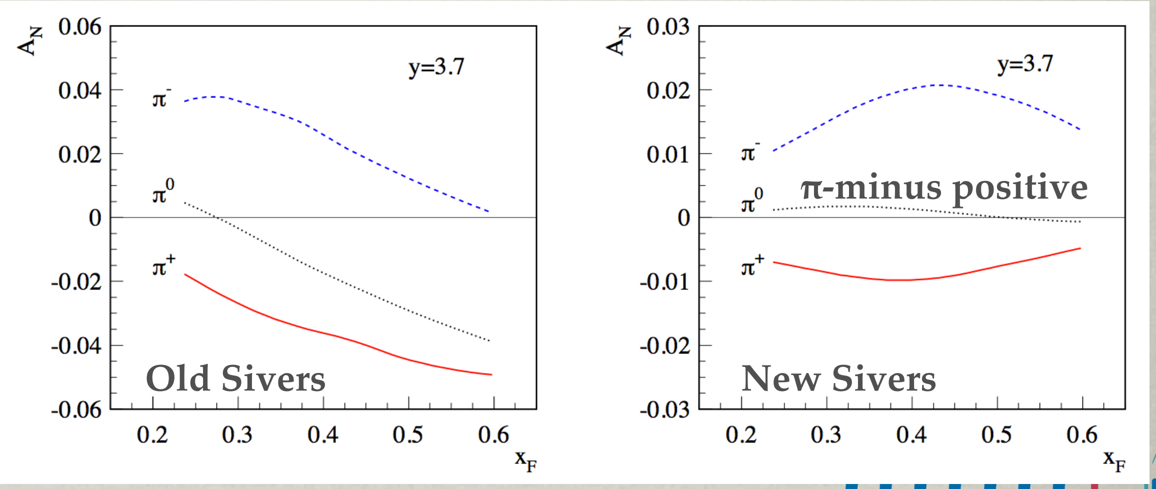
While the Sivers and Collins effects (or their twist-3 relatives) likely contribute, the SIDIS results do not provide quantitative understanding of A_N in p+p .

The current estimate of Collins contribution based on SIDIS and e^+e^- is **"not sufficient for the medium-large x_F range of STAR data, x_F >~ 0.3"**

Anselmino *et al*. arXiv: 1207.4529 [hep-ph]



It is unclear if the Sivers function from SIDIS can be applied directly to p+p due to **universality breaking**, (*Phys. Rev. D 81, 094006 (2010)*) and when "translated" to the twist-3 formalism, **it produces the opposite sign**.



Kang, Qiu, Vogelsang, and Yuan, Phys. Rev. D83, 094001 (2011)

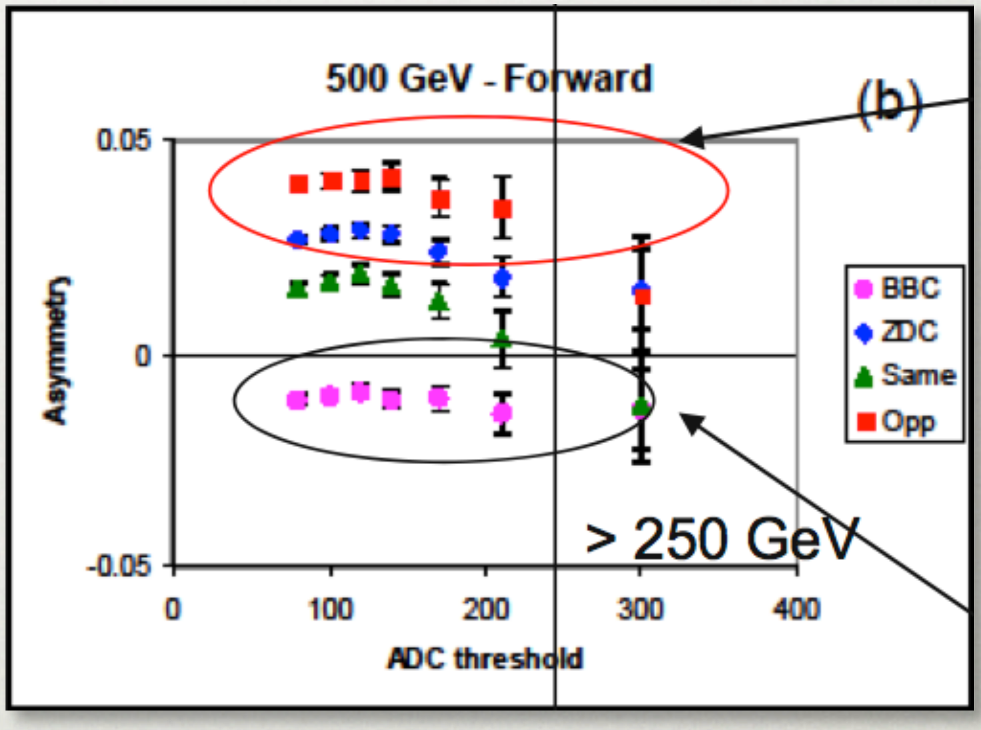
The Origin of A_N in P+P

Furthermore, it is not certain that the TMD and Twist-3 models are sufficient to explain the full scope of forward A_N in hadronic interactions.

If the collider A_N is pQCD, then **what was the A_N observed in fixed target experiments**? Are they simply two different processes that look similar?

At STAR, we see sizable asymmetries in the BBC and the ZDC, both of which are more forward than our calorimeters, likely from diffractive physics.

Can similar (or other soft) process contributes to our π^0 and η A_N?

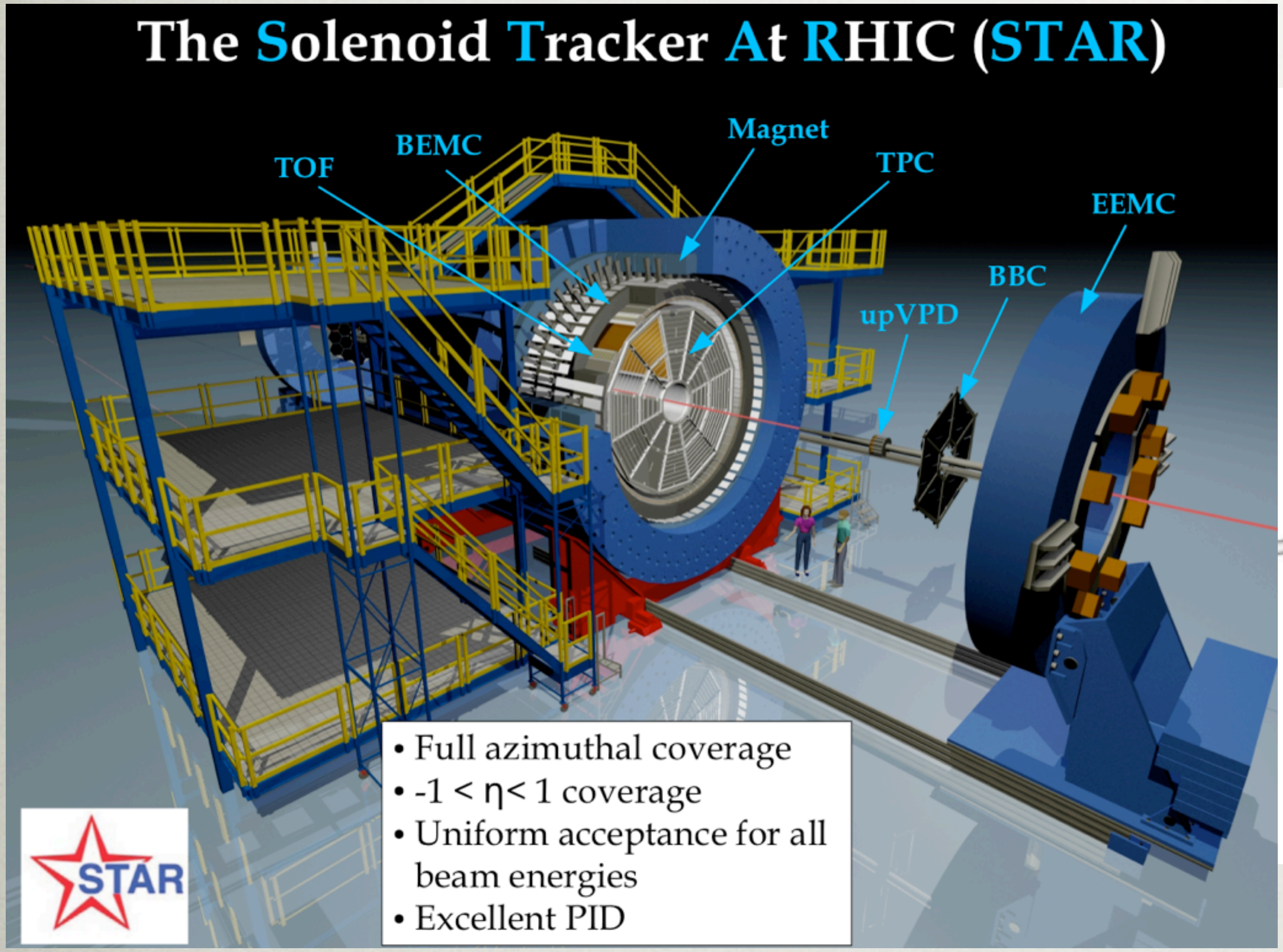


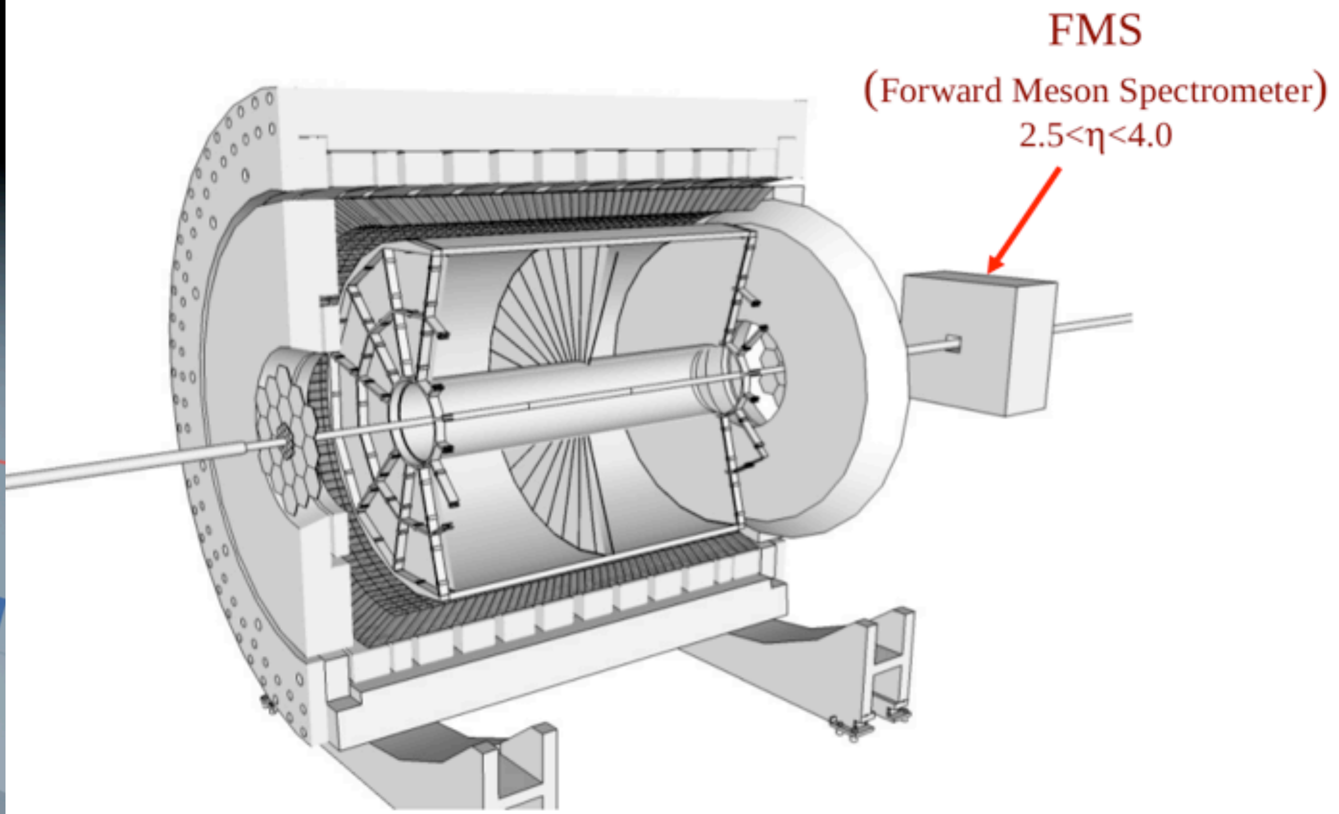
ZDC L(R) - BBC R(L) anti-correlation increases the asymmetry!

BBC with ZDC charge requirement

Answering these questions requires going beyond inclusive pion A_N vs. x_F.
→ **Characterize A_N as functions of x_F, p_T, η, and for diverse final states.**

STAR Detector





Full jet capability (tracking, dE/dx, EM cal) for $\mathbf{-1.0 < \eta < 1.4}$
EM coverage for $\mathbf{-1.0 < \eta < 2.0}$, and $\mathbf{2.5 < \eta < 4.0}$
Full **2π acceptance** for all of the above.

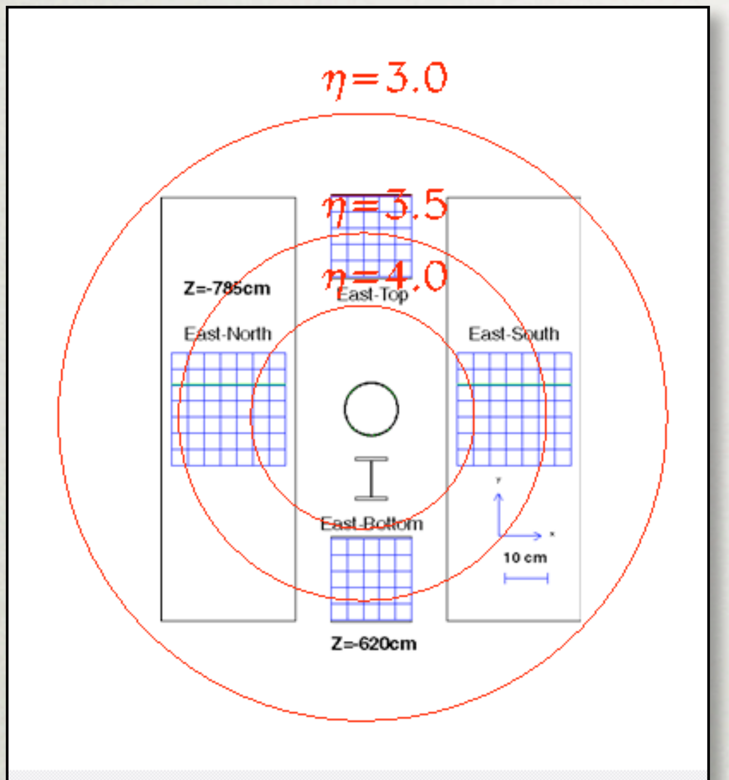
Forward Calorimeters

STAR forward calorimetry consists of Pb glass detectors located ~8m from IR.

Forward Pion Detector (FPD)

East: Run3 ~ Current

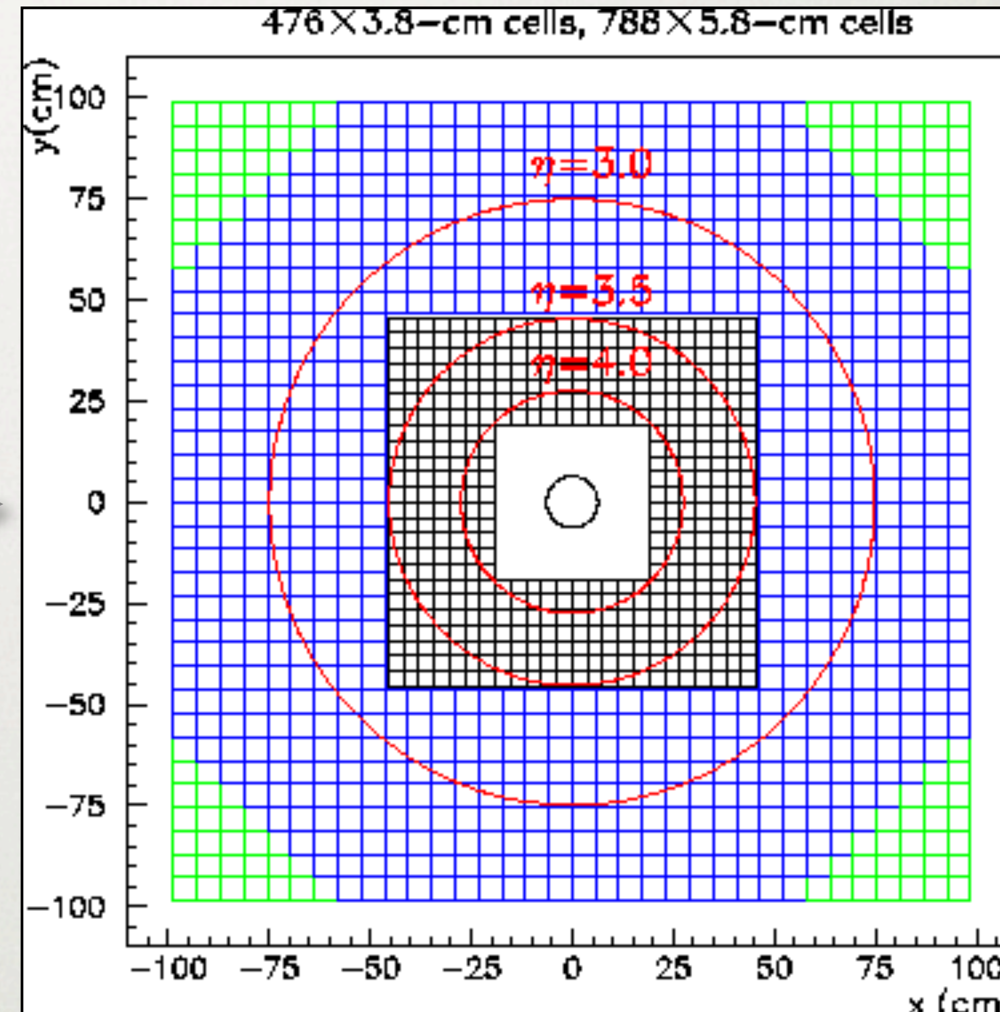
West: Run3 ~ Run5

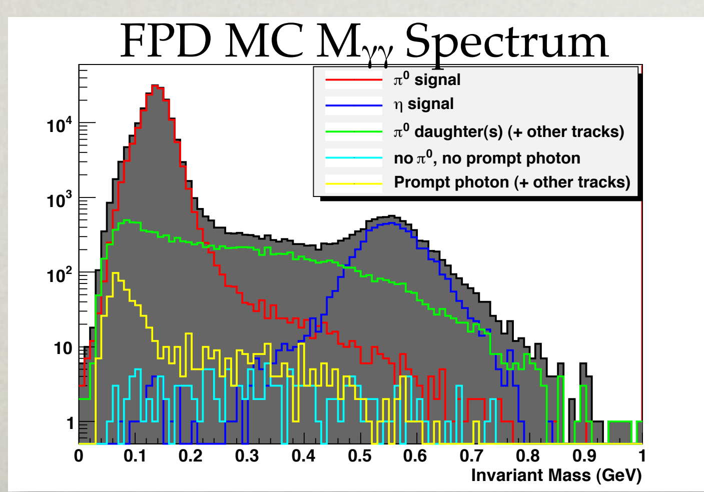


Run 2008

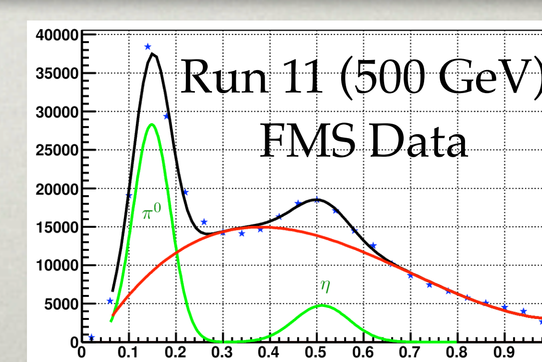
Forward Meson Spectrometer (FMS)

West: Run8 ~ Current



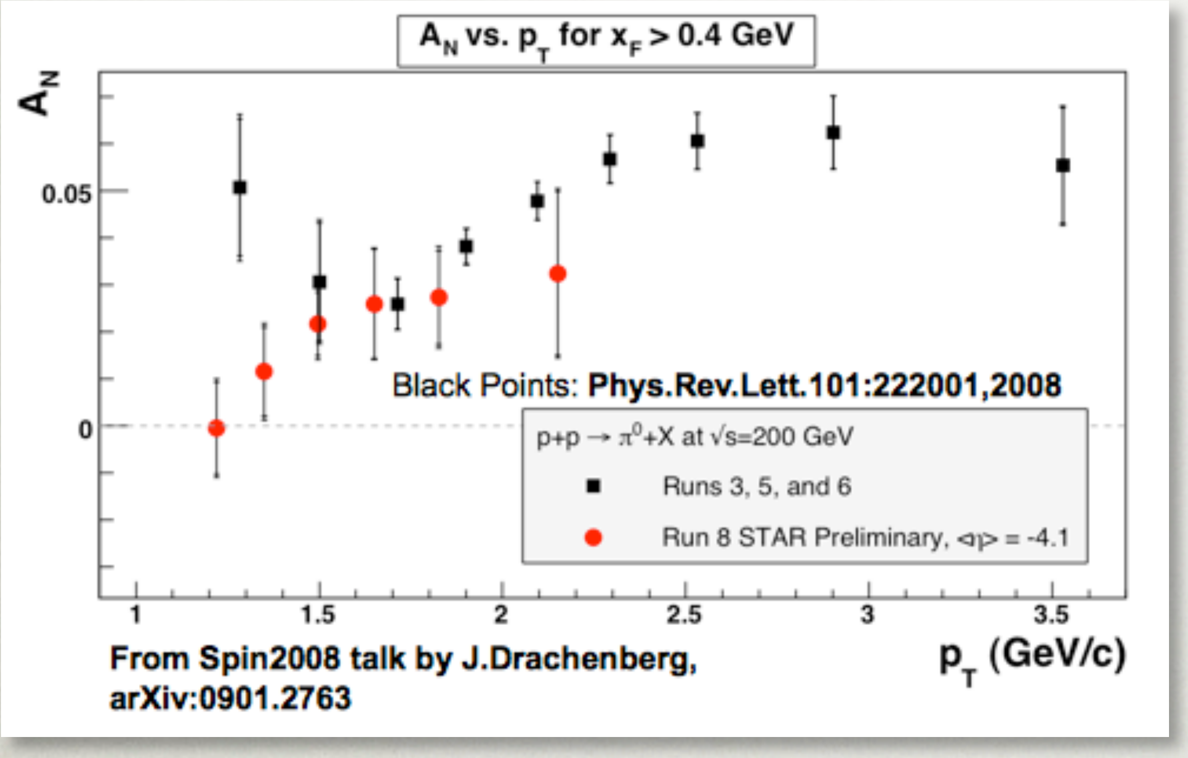


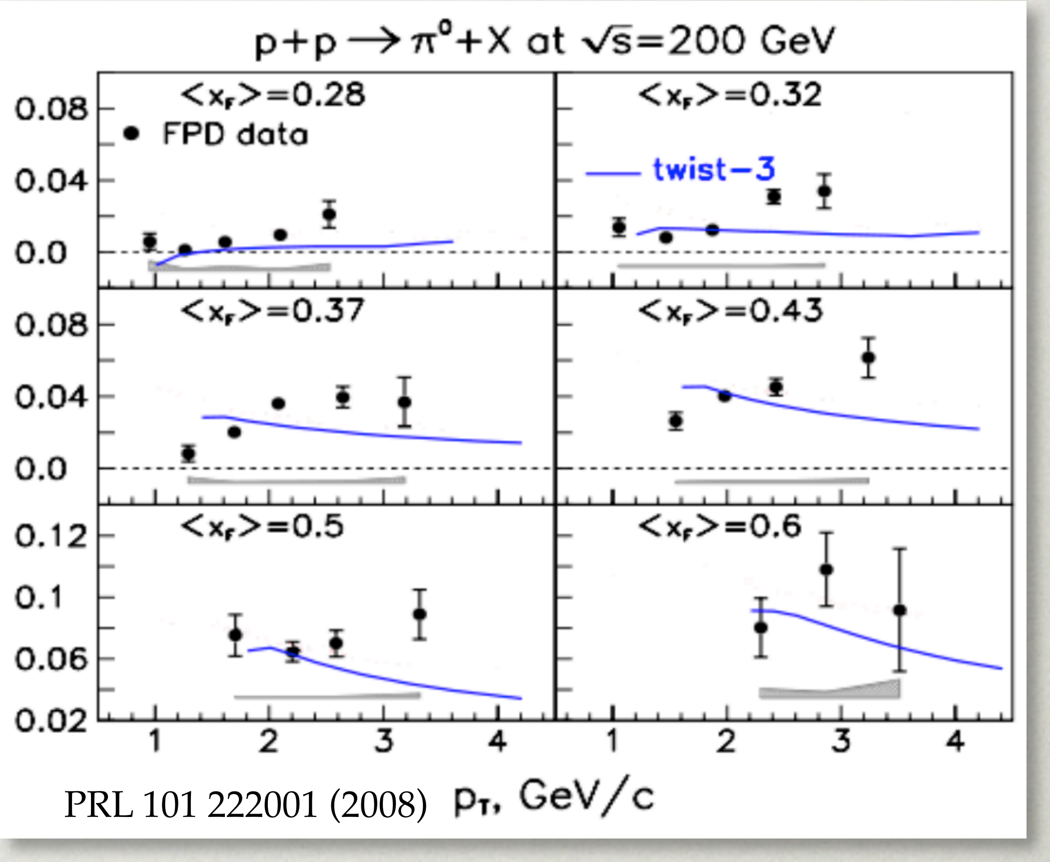
Both detectors are capable of π^0 - γ separation up to 80 GeV or higher, with ~8% energy resolution.



π^0 A_N vs. p_T at 200 GeV

Naively, one might expect the A_N **to fall roughly as $1/p_T$.**
For TMD effects, the power law behavior of the large-x cross-section combined with the k_T kick suggests $1/p_T$. One might also expect the twist-3 effect to fall as $1/p_T$, due to the p_T suppression of higher twist diagrams.



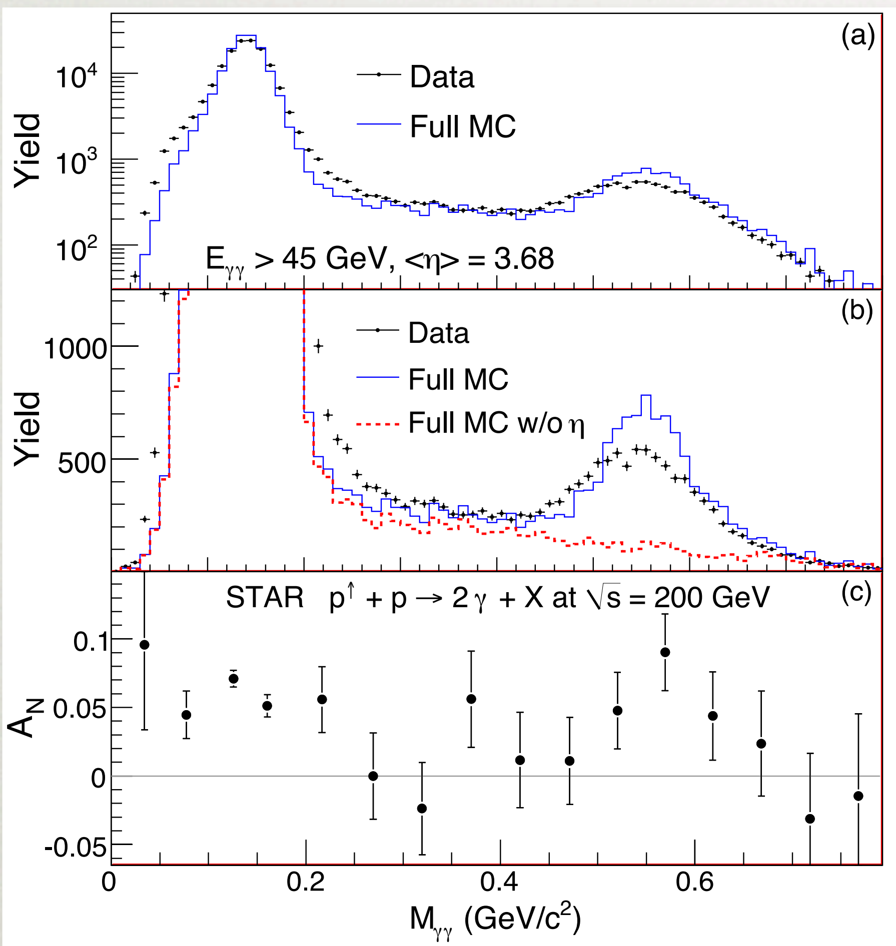


PRL 101 222001 (2008)

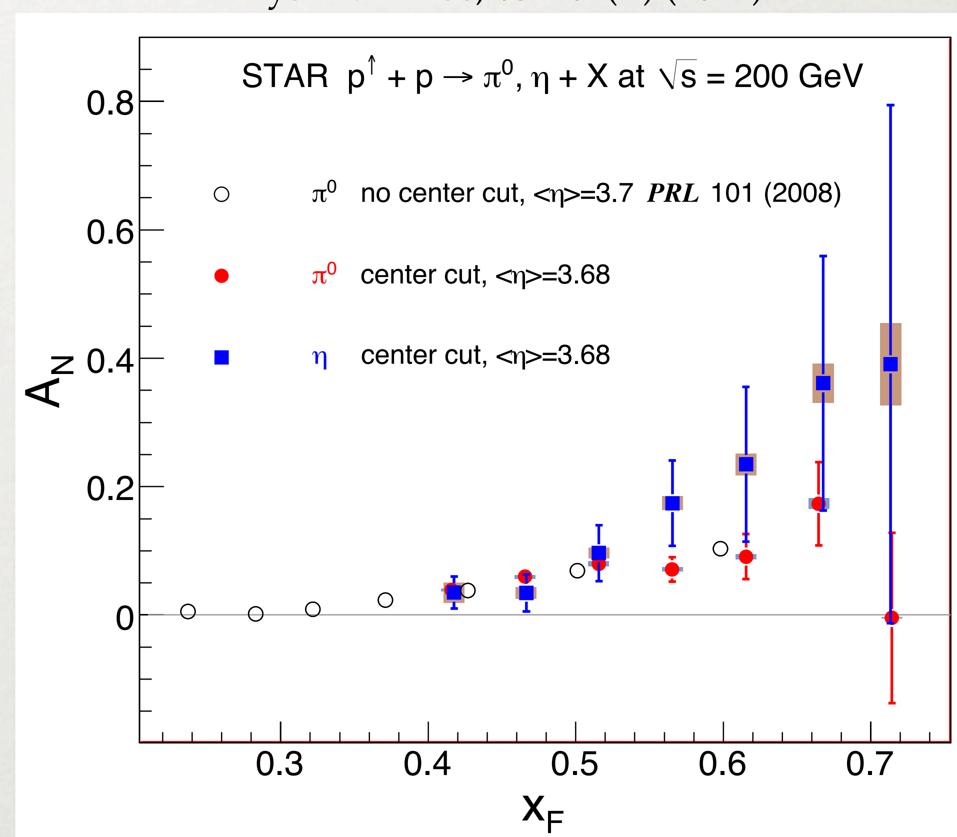
However, based on the FPD data, STAR previously reported the p_T dependence of forward π^0 A_N at $\sqrt{s}$=200 GeV that shows **no sign of falling out to ~3.5 GeV/c.**

Forward η A_N at 200 GeV

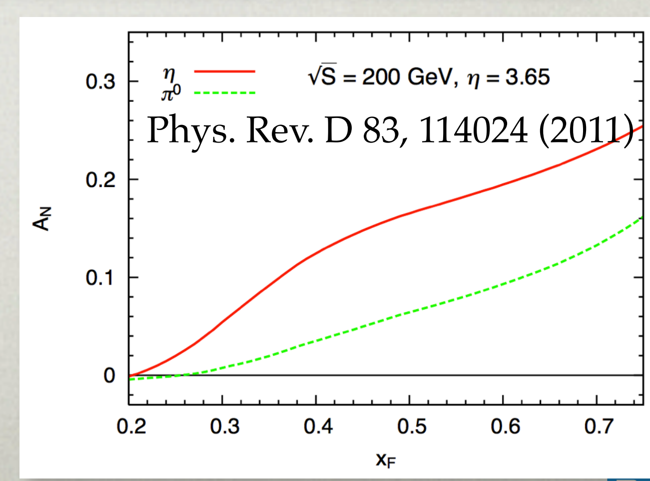
In addition to the π^0's, we measured the **forward cross-section (slide 4) and A_N for the η mesons** using the FPD. At high x_F ($x_F > 0.55$), the A_N for the η is very large, and may not be consistent (~3%) with that of the π^0.



Phys. Rev. D 86, 051101(R) (2012)



Kanazawa & Koike calculates larger A_N for η than π^0, from the strangeness contribution. However, the x_F dependence deviates from the data.



Phys. Rev. D 83, 114024 (2011)

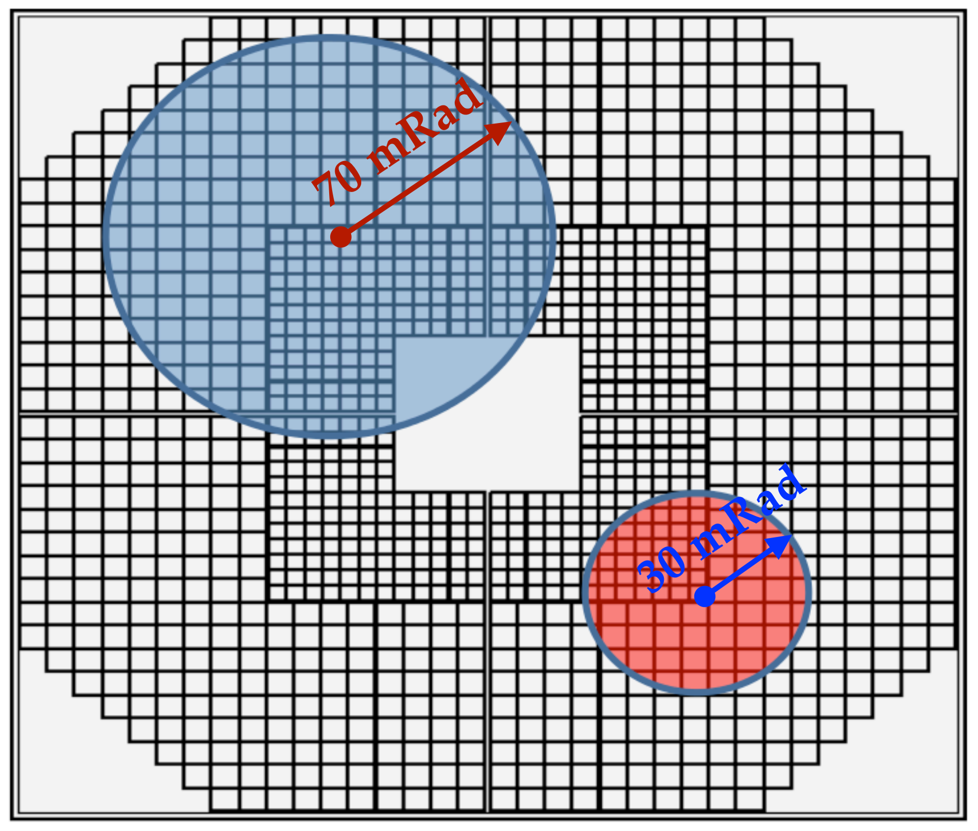
Forward π^0 A_N at 500 GeV

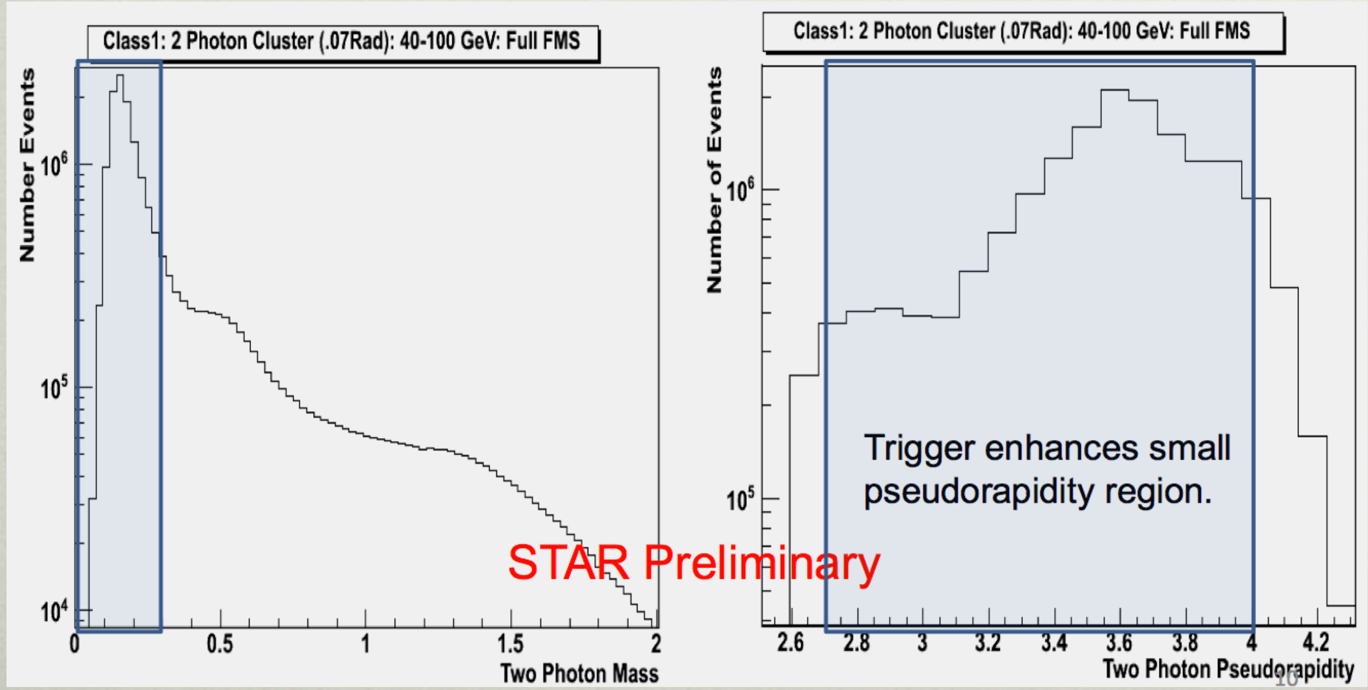
STAR FMS ($2.7 < \eta < 4.0$) has measured **π^0 A_N at $\sqrt{s}$ = 500GeV**, based on 2011 data. (22.4 pb^{-1}, 48% polarization)

The π^0 reconstruction is effective up to ~100 GeV ($x_F < 0.4$).

Two different isolation cones for the photon pairs are used. Two and only two photons ($E_\gamma > E_{min}$) are found within the cone.

Isolation cut = 30 & 70 mRad



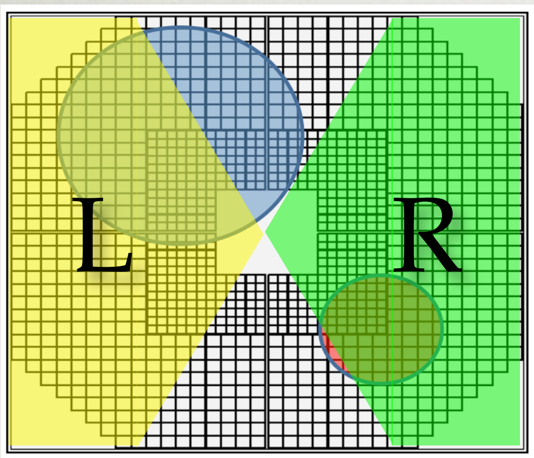


$40\ GeV < E_{\gamma\gamma} < 100\ GeV$
$Z_{\gamma\gamma} = |E1-E2|/E_{\gamma\gamma} < 0.7$
$0.02\ GeV < M_{\gamma\gamma} < 0.3\ GeV$

$E_\gamma > 6$ GeV for small cells
$E_\gamma > 4$ GeV for large cells

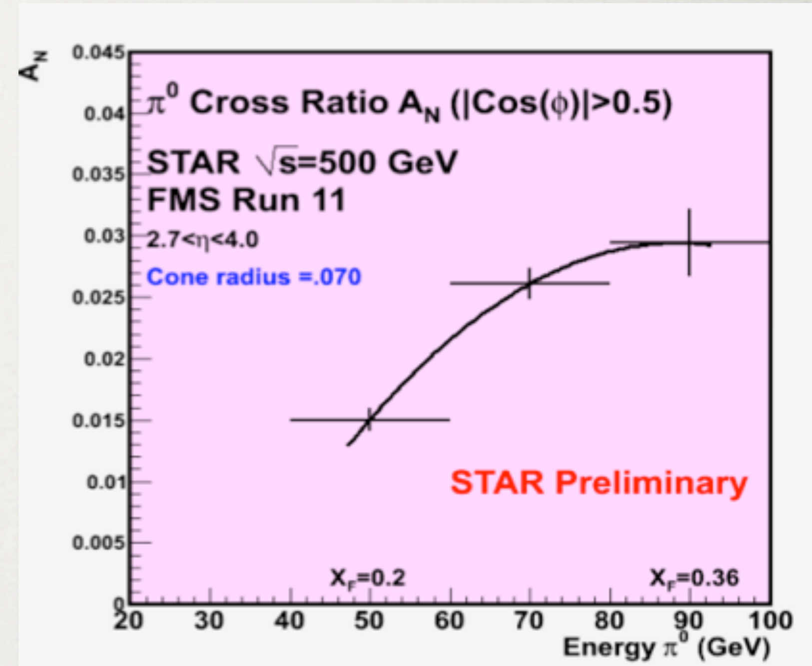
π^0 A_N vs. x_F at 500 GeV

L: cos(Φ) > 0.5, R: cos(Φ) < 0.5



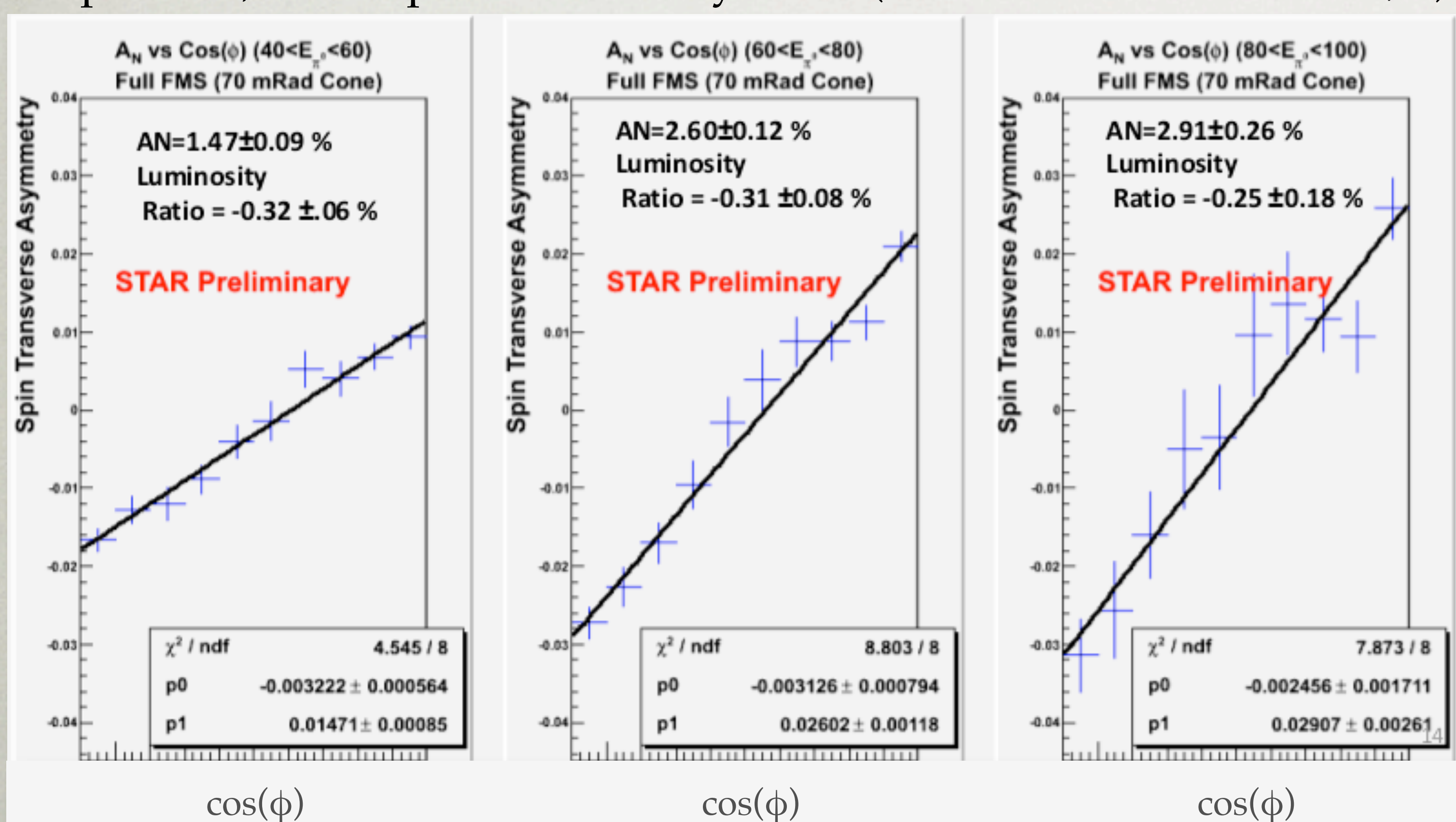
The cross-ratio method shows that the **onset of positive A_N is lower in x_F** compared to 200 GeV.

The **magnitude of A_N is comparable to the 200 GeV result up to x_F=0.4.**



70 mRad Cone

Slope =A_N , Intercept = Luminosity Ratio (for all data ~ - 0.31 ± .05 %)

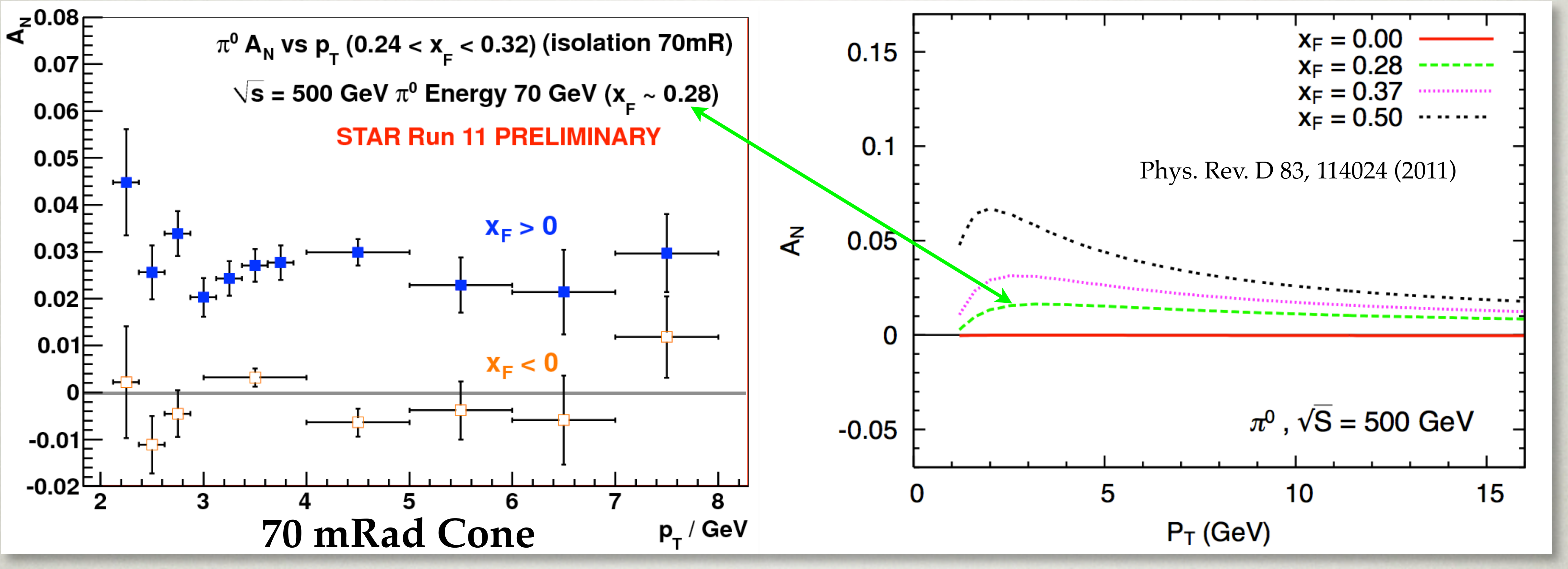


As an alternative to cross-ratio, the raw asymmetry can be plotted as a function of cos(Φ). (with polarization axis at Φ=π/2)

The slope fits are consistent with the cross-ratio result, and the luminosity ratio is small.

π^0 A_N vs. p_T at 500 GeV

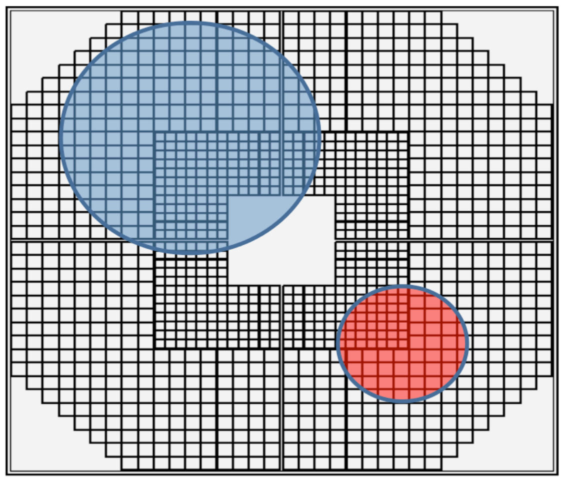
Continuing the previous FPD measurement, the FMS reported the **p_T dependence of forward π^0 A_N at $\sqrt{s}$=500 GeV, up to ~10 GeV.**

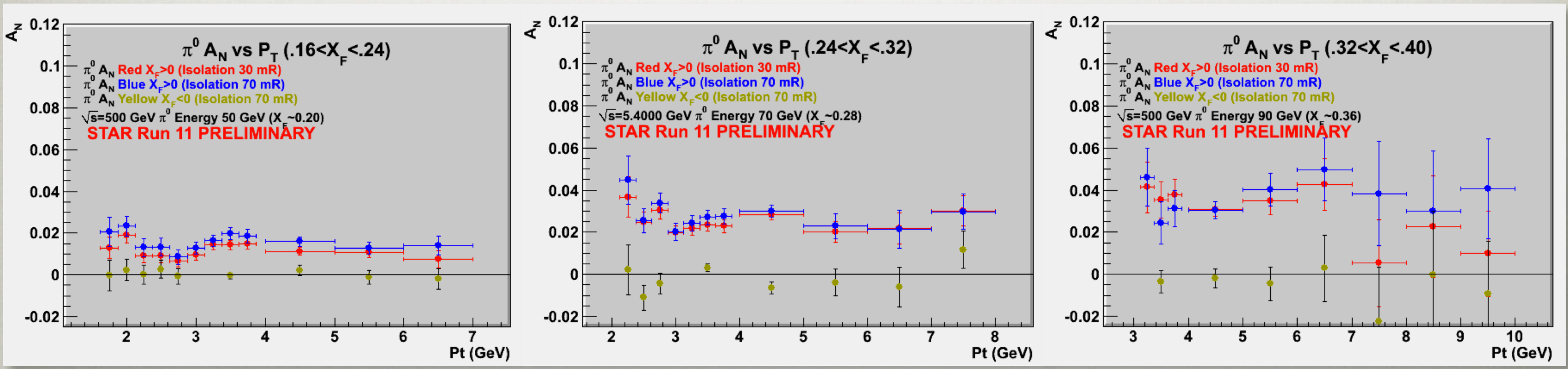


Even at 7~10 GeV, we see no sign of $1/p_T$ like fall.
While this is counter-intuitive, **Kanazawa & Koike obtain an almost flat p_T dependence** based on twist-3 formalism combined with DSS fragmentation function, which has a large gluon component.

30 vs. 70 mRad Isolation

When we compare A_N vs. p_T for the two isolation cones at **30** and **70 mRad**, we find that **the larger isolation cone produces consistently larger asymmetries** than the smaller one.

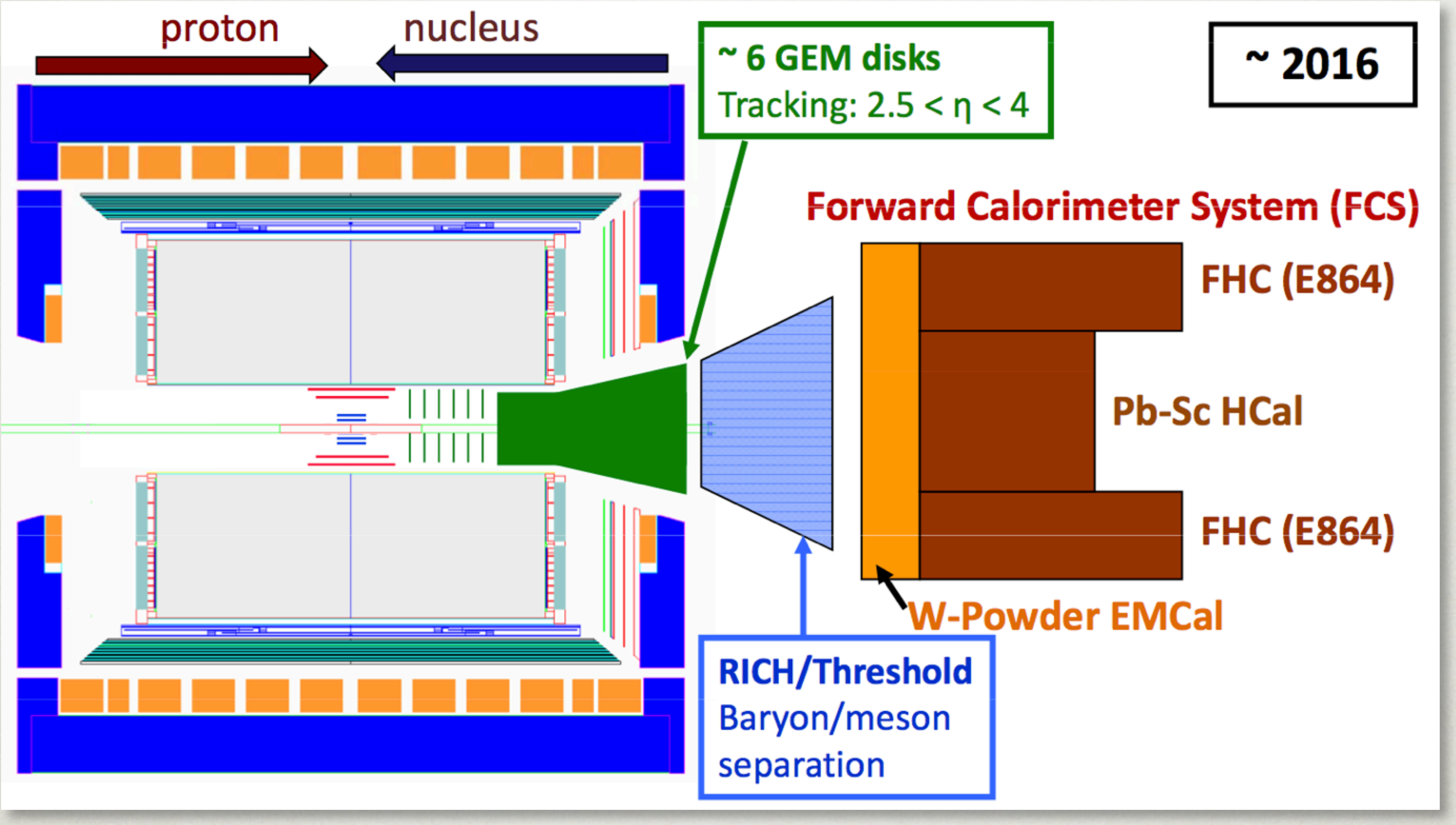




This result shows that events that contain additional EM clusters (E > 4 or 6 GeV) in the region between 30~70 mRad from the π^0s have significantly lower asymmetry than π^0s that are fully isolated up to 70 mRad.

→ **Similar analysis is on-going with the new run 12, 200 GeV transverse data.**

Forward Upgrades



Forward instrumentation upgrade optimized for p+A and transverse spin physics.

The prototype for FCS (e/h and γ/π^0 discriminations) is planned.
Forward charged-particle tracking will likely be based on GEM technology.
Threshold detector currently under consideration for baryon/meson separation.

Summary

The large transverse single spin asymmetry in the forward region of hadron collisions has persisted through a wide range of collision energies.

Number of pQCD based models have been proposed to explain these large asymmetries, many of which have been validated in SIDIS and $e^+ e^-$ experiments. However, this has not yet led to a quantitative understanding of forward A_N in hadron collisions.

STAR is continuing its effort to map out the kinematic dependence of A_N in the forward region, and to expand the measurements beyond inclusive pions. We believe these measurements are crucial in bringing the theoretical understanding of the large forward A_N in p+p to the quantitative level.

The near future upgrade plan at the STAR forward region focuses on p+A and transverse spin physics. It is aimed at measuring jets, direct photons, identified hadrons, and DY.