Transverse Spin Physics at STAR

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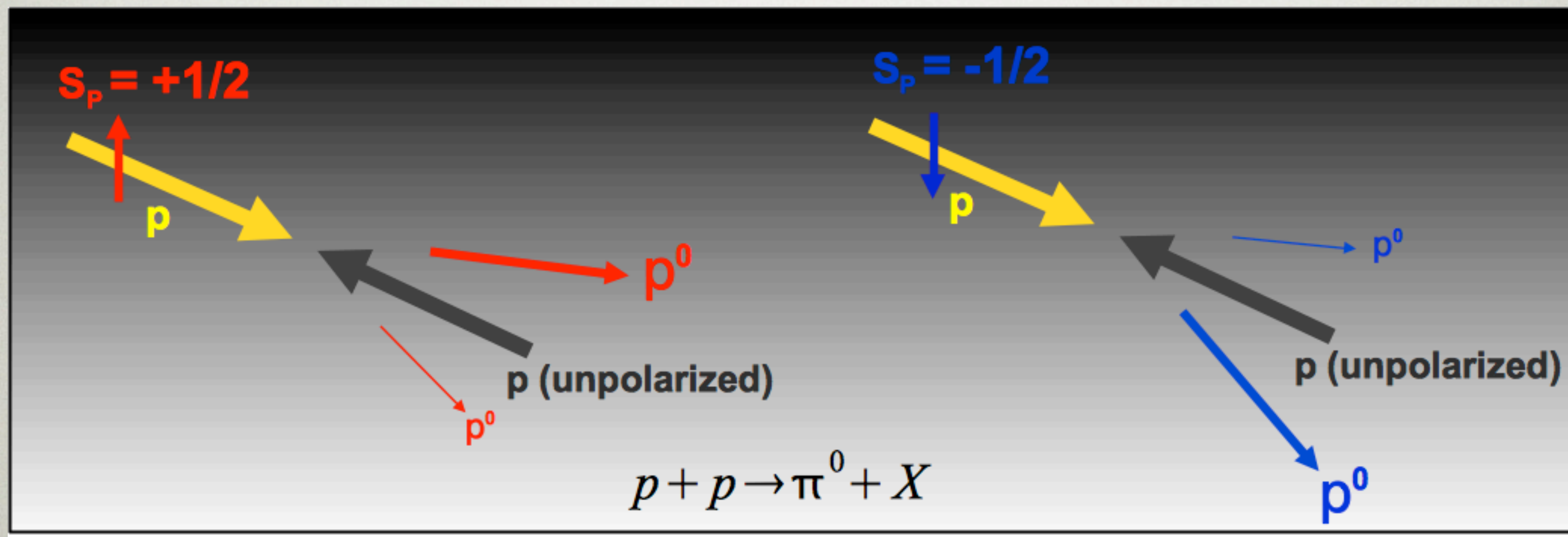
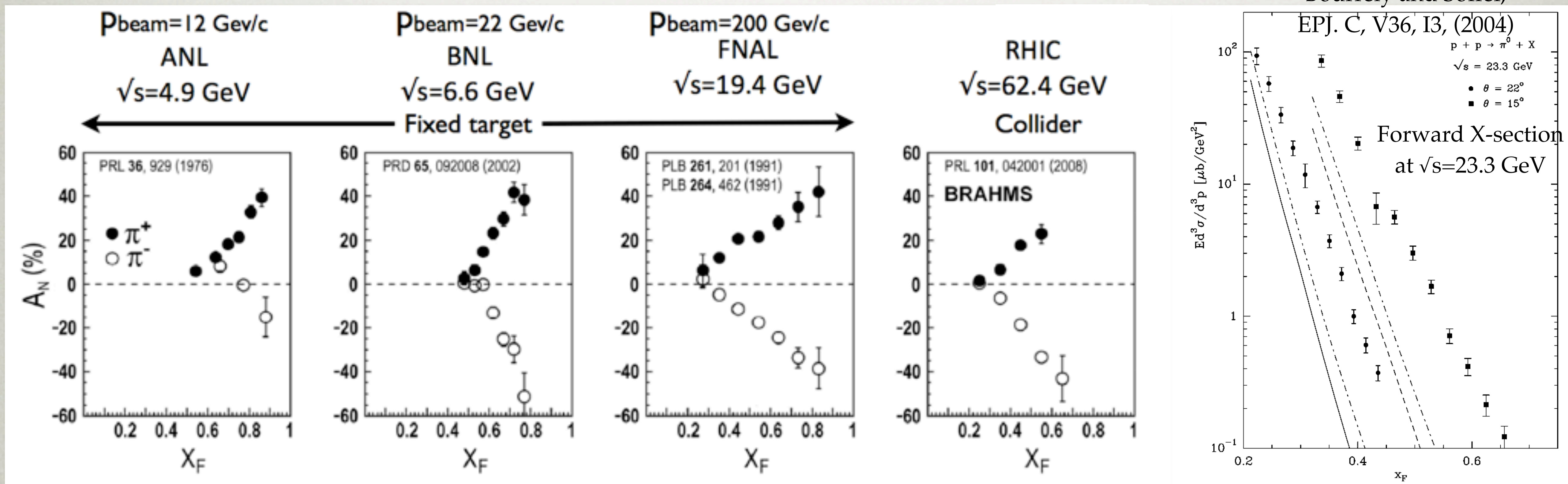
Transverse SSA (A_N)

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.

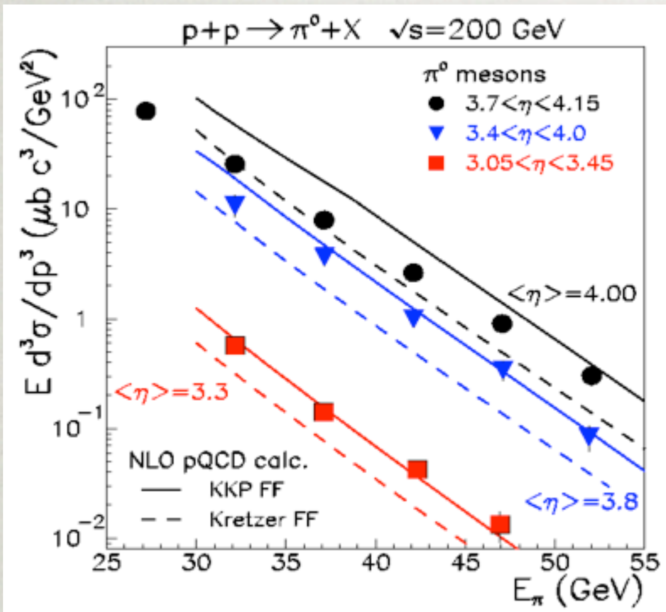
However, it was generally believed that these fixed target results could not be interpreted within the framework of pQCD.

Forward X-sec. at RHIC

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

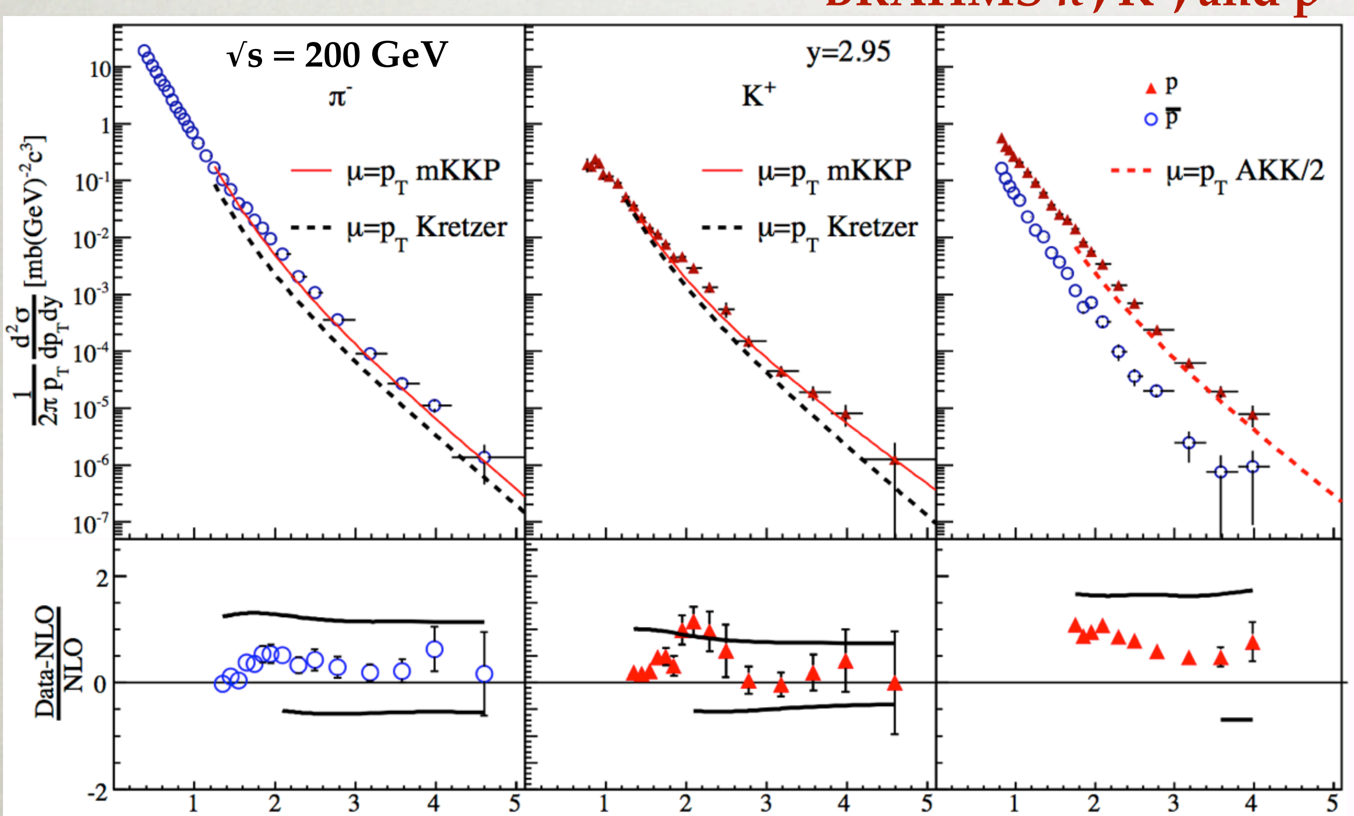
Consequently, many believe that the RHIC forward transverse spin results CAN be understood by pQCD.

STAR π^0



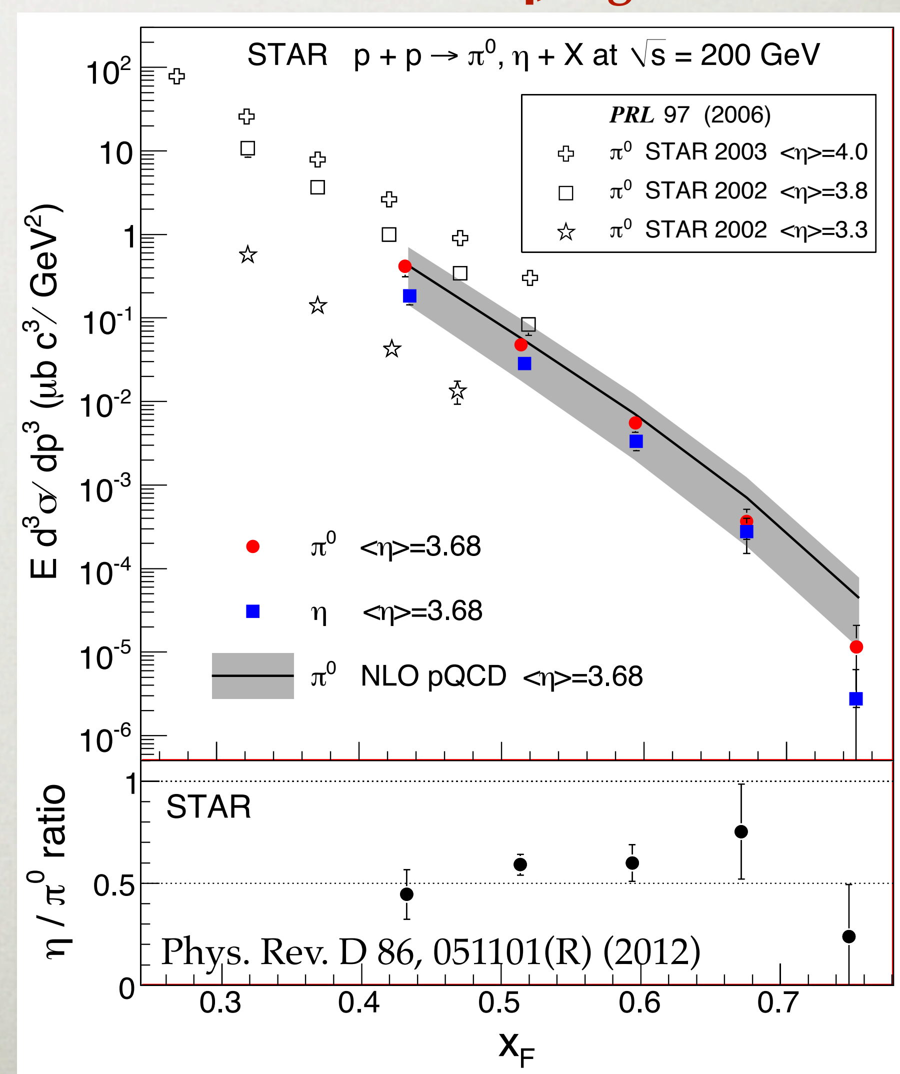
Phys. Rev. Lett. 97 (2006) 152302

BRAHMS π^-, K^+, and p



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

STAR π^0 and η, high x_F

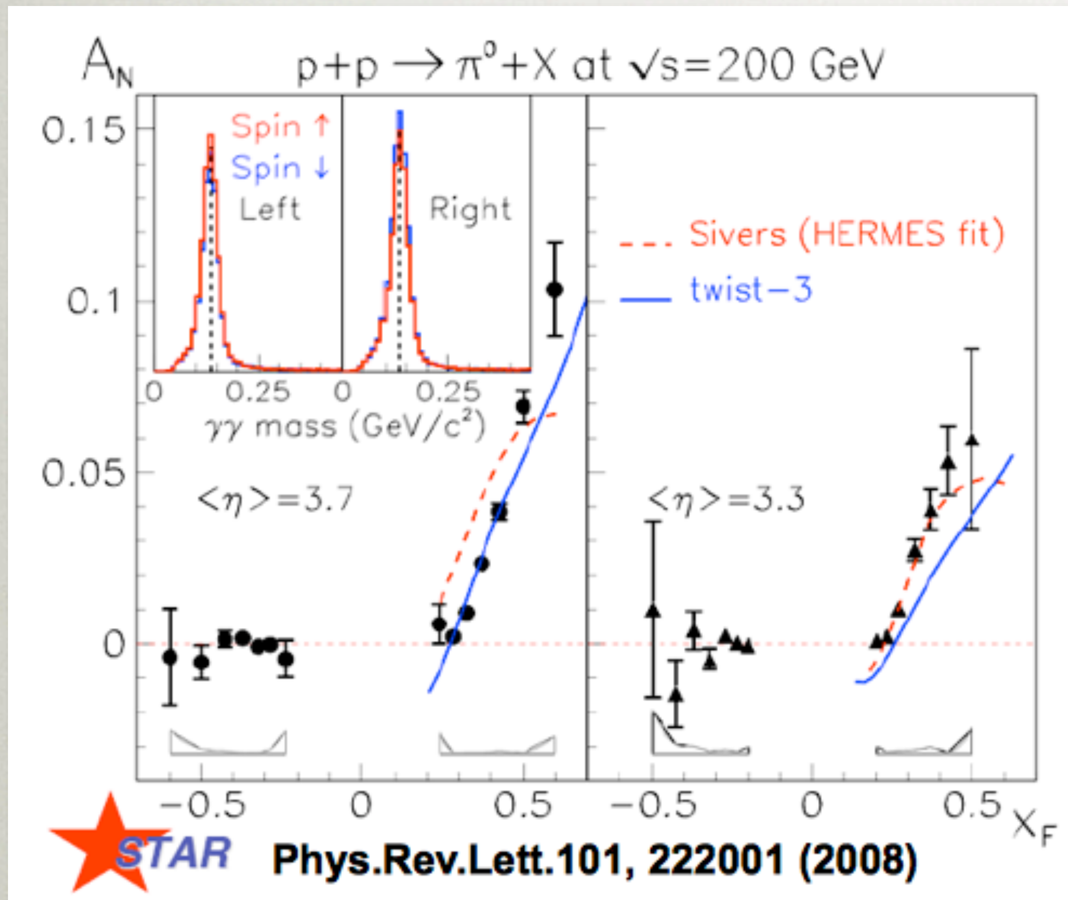


Phys. Rev. D 86, 051101(R) (2012)

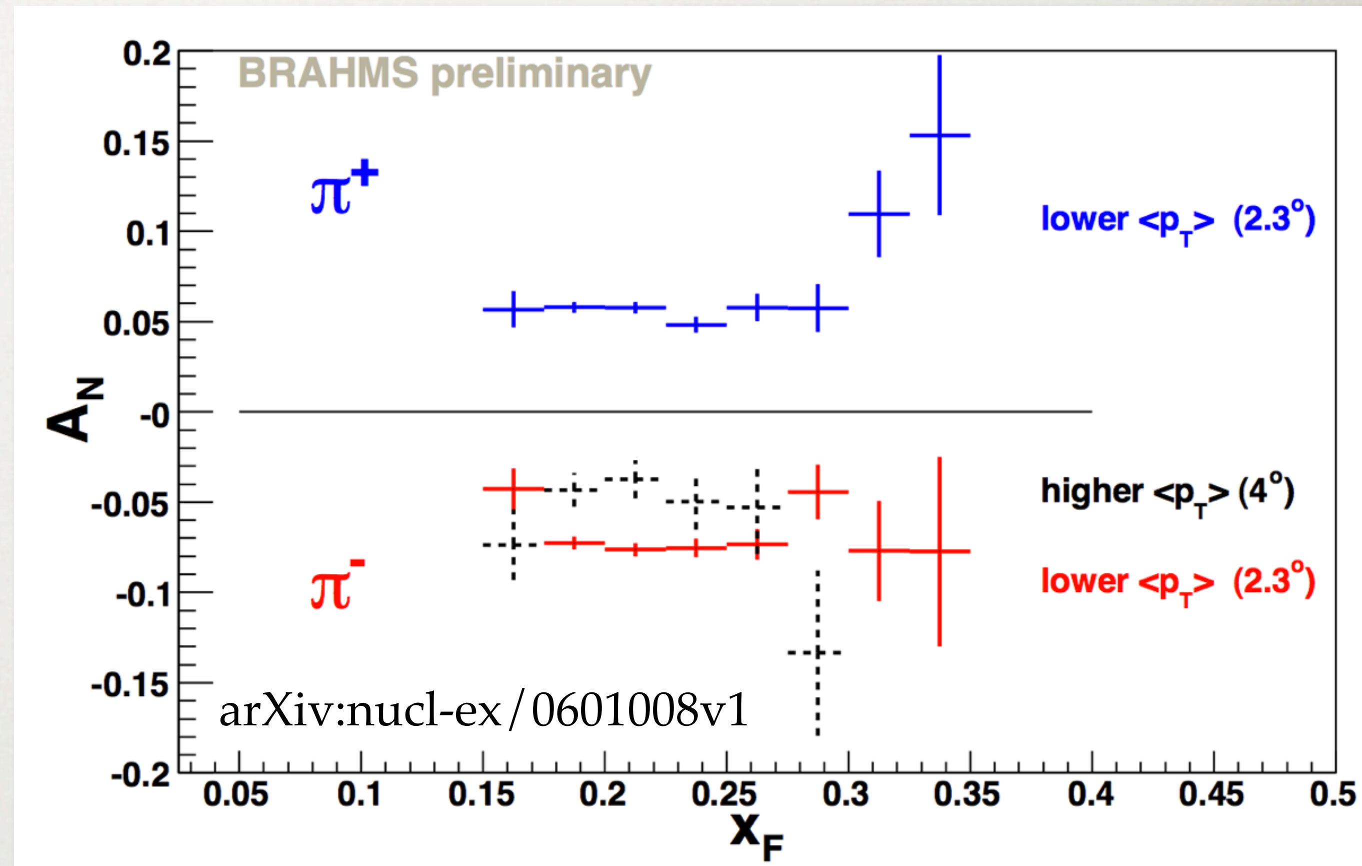
Forward A_N at RHIC

$\sqrt{s} = 200$ 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.

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)*)

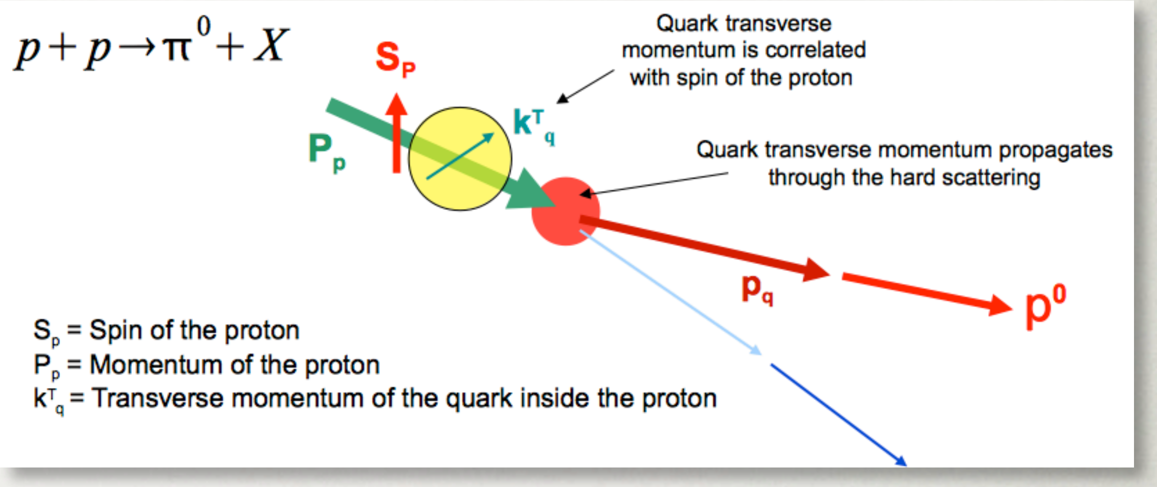
Beyond leading twist: **Twist-3 (next-to-leading-twist) approach**

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

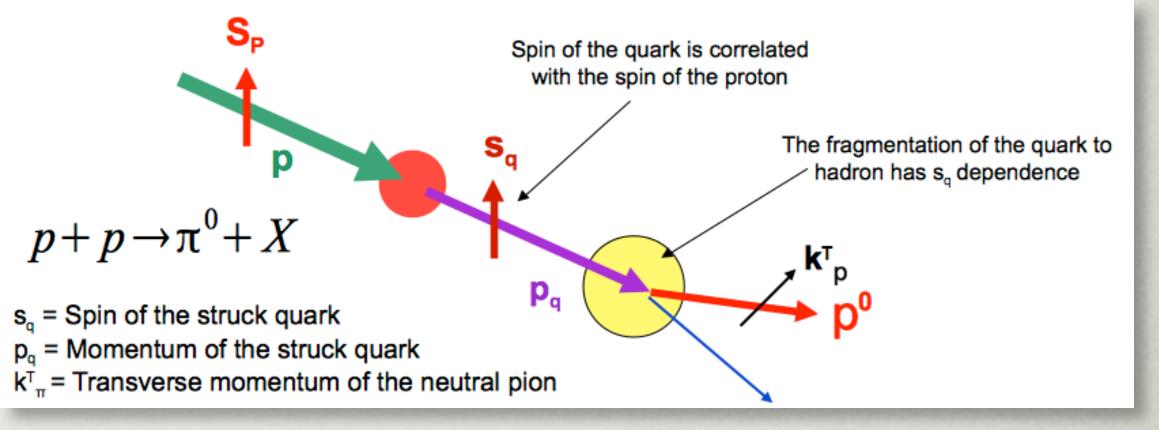
(*C. Kouvaris, J.-W. Qiu, W. Vogelsang, and F. Yuan, Phys. Rev. D 74, 114013 (2006)*)

A_N in pQCD

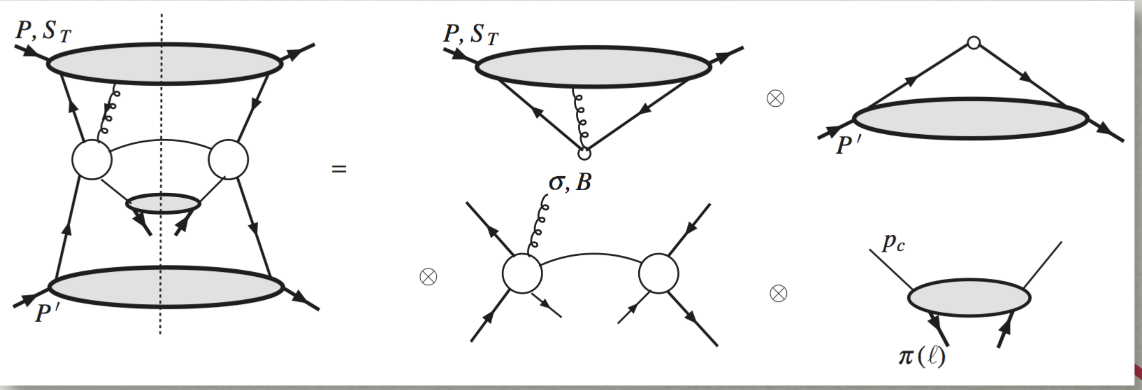
Sivers effect (TMD)
The orbital angular motion of the struck parton, correlated with the spin of the proton, generates the asymmetry.



Collins effect (TMD)
Asymmetry arises from the fragmentation process that depends on the **quark transversity**.

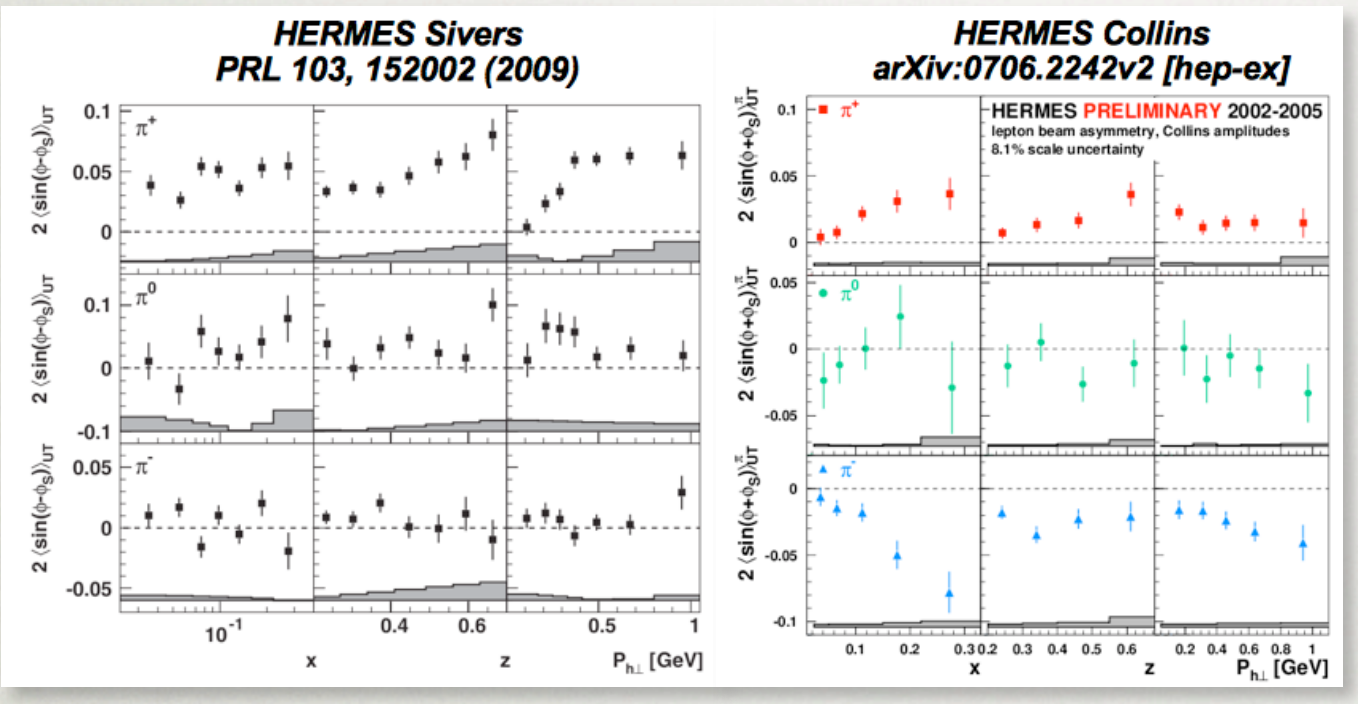


Twist-3 (Collinear)
Twist-3, **three-parton correlation/ fragmentation functions** can generate the asymmetry within collinear factorization.

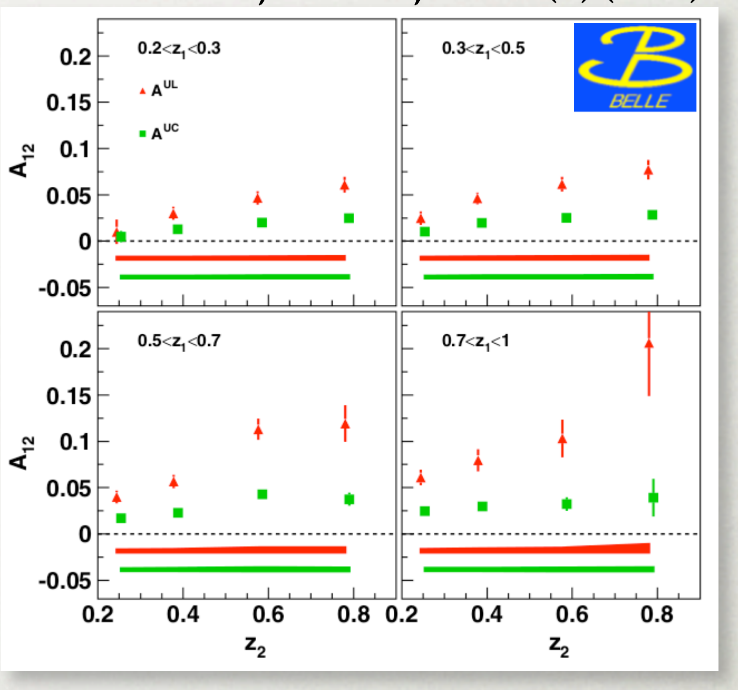


Sivers and Collins

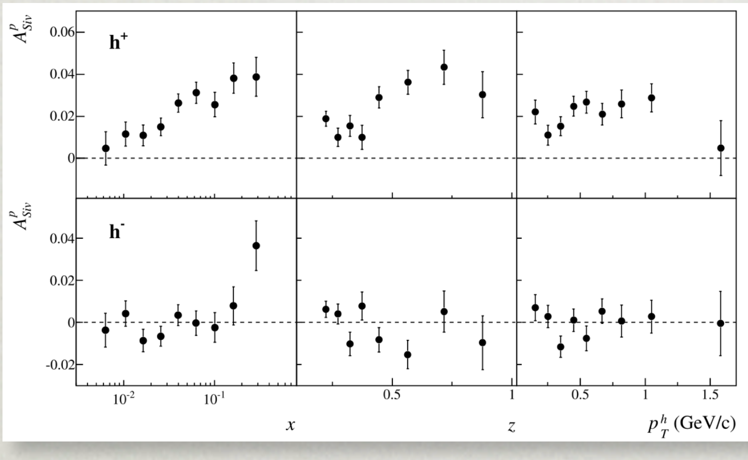
The TMD functions (Collins and Sivers) have been measured in various SIDIS experiments (HERMES, COMPASS, JLab) and e^+e^- (Belle), and shown to be non-zero.

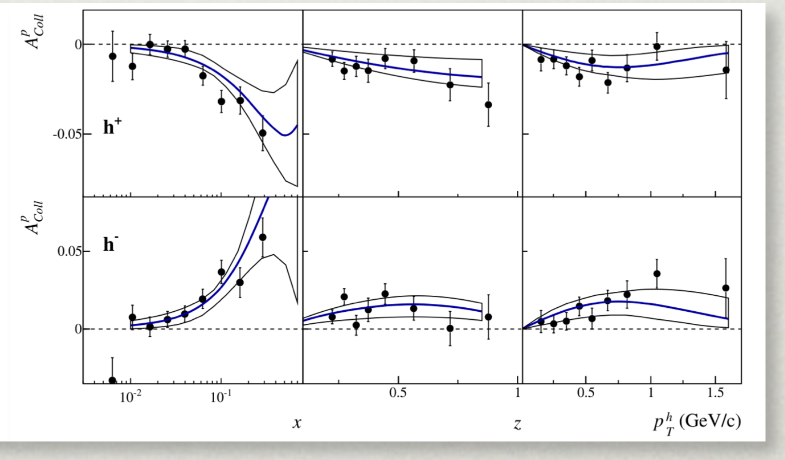


Belle Collins, PRD. 86, 039905(E) (2012)



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)*)

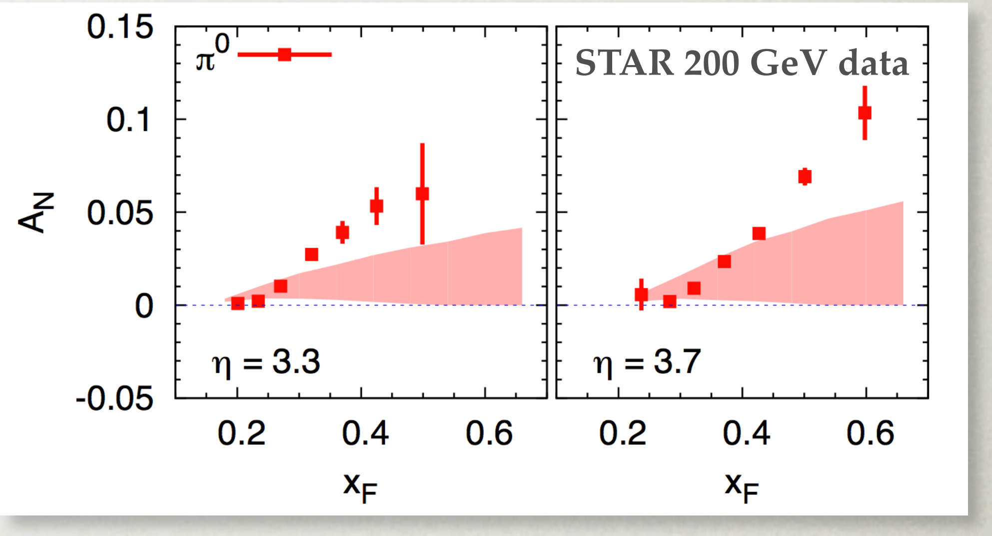
SIDIS vs. P+P

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

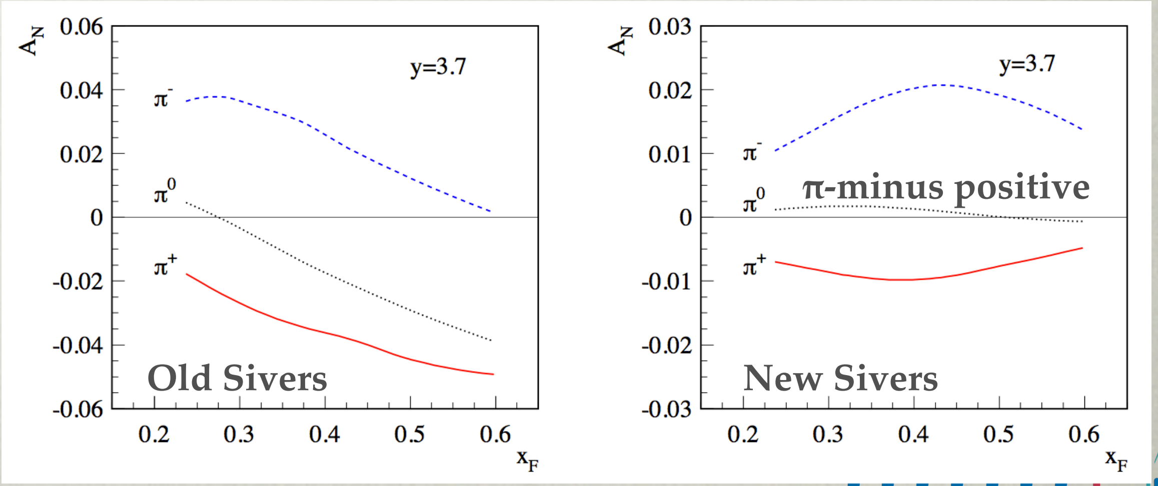
While the Sivers and Collins effects (or their twist-3 relatives) likely contribute, the SIDIS results do not provide quantitative understanding of A_N in p+p .

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)

What Can We Learn in P+P?

Some things are ~universal:

The Collins and Interference Fragmentation Functions couple to quark transversity, and can be connected directly to SIDIS and e^+e^- measurements.

- Quark transversity is the least constrained of the 3 leading order PDFs.
- **Extract the quark transversity in p+p through Collins and Interference FF measurements, complementing the SIDIS extraction by covering higher x region with moderate upgrades. (arXiv:0812.4366 [hep-ph]).**

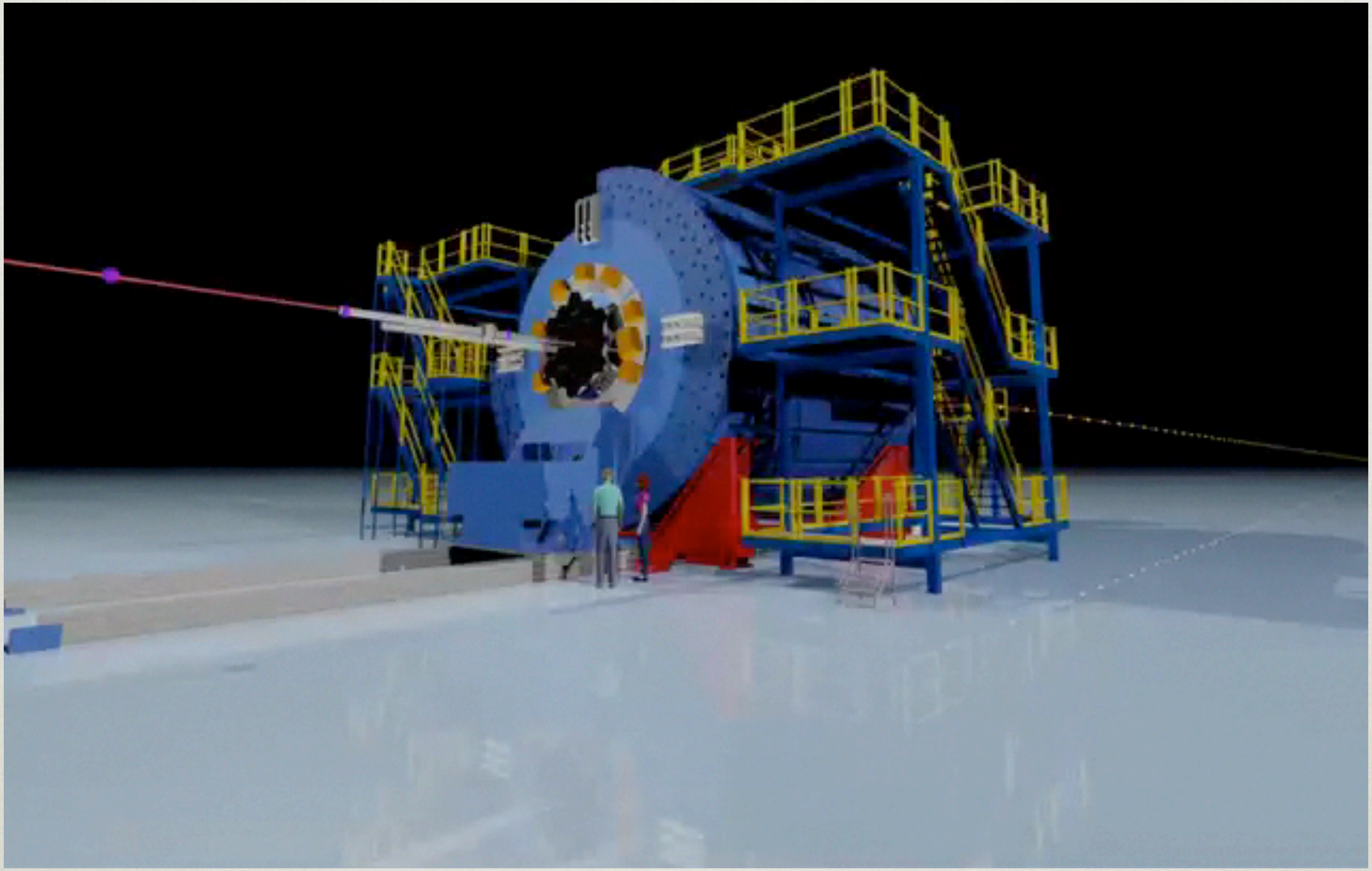
Others are process-dependent:

The full scope of A_N in hadronic interactions is difficult to interpret, but **it is also where the largest asymmetries have been measured**.

- Is the collider TSSA the same phenomenon as the fixed target TSSA?
- Are Collins, Sivers and/or twist-3 enough to understand it?
- Can we verify the connection between TMD and twist-3?
- **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 Detectors



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.

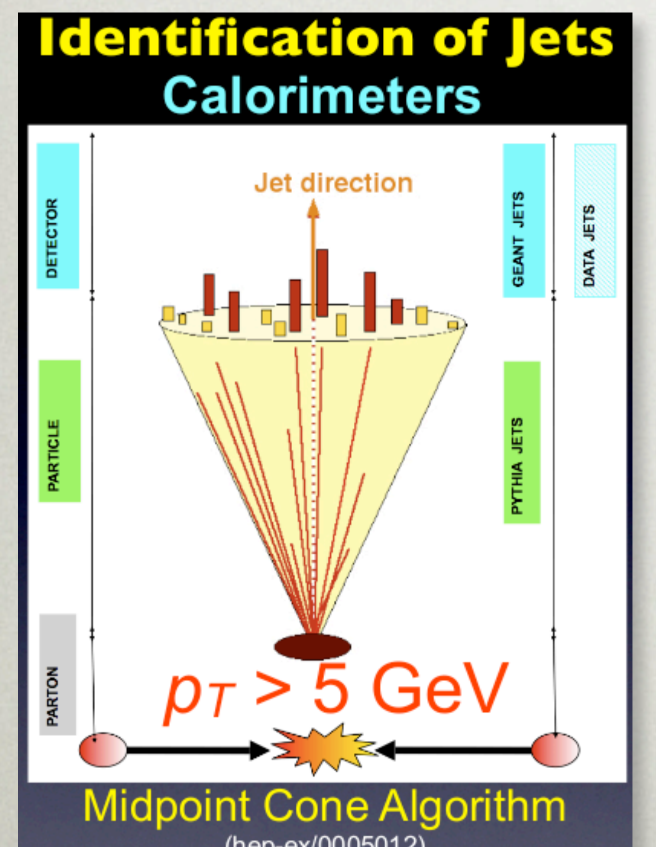
Transversity

Mid-rapidity Collins

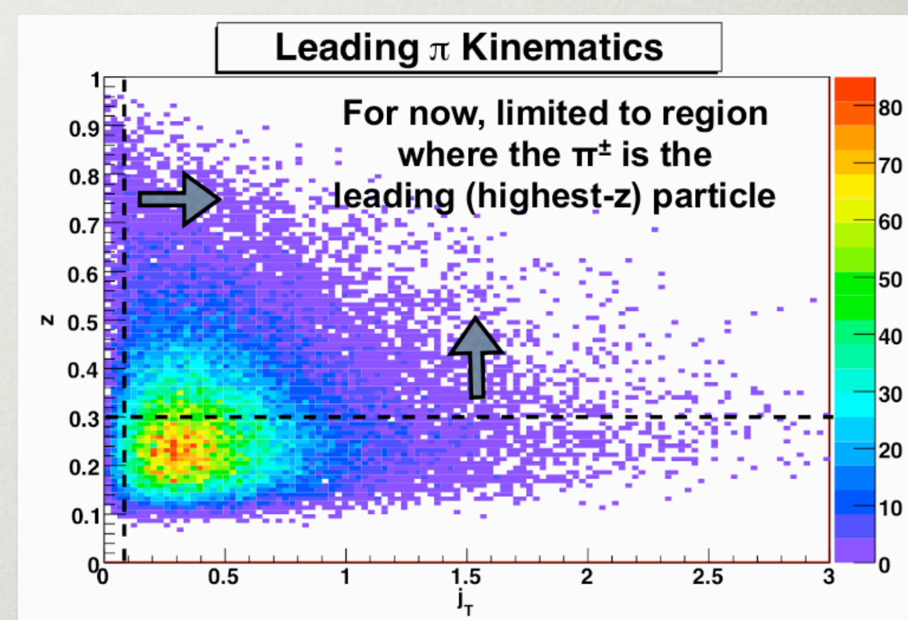
Unlike the Sivers function, **Collins function is thought to be universal** (*Phys. Rev. D77, 074019 (2008)*), and the SIDIS and e^+e^- results may be applied to p+p.

Therefore, **it is possible to measure proton transversity and Collins fragmentation function in p+p through the Collins effect.**

STAR has a full jet capability for $-1.0 < \eta < 1.4$.

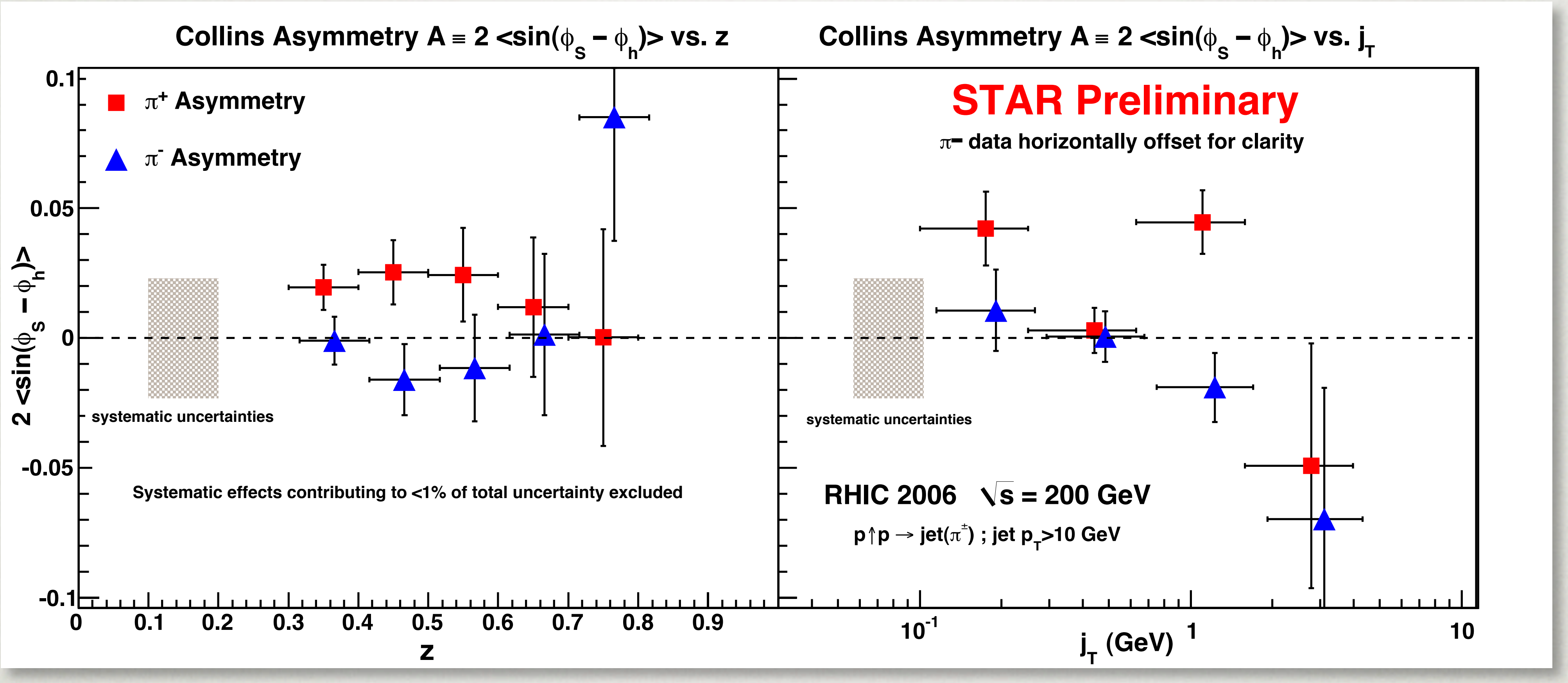


We use **mid-rapidity jets** (TPC+calorimeters), and measure the Collins effect for the **leading charged pions** (TPC).

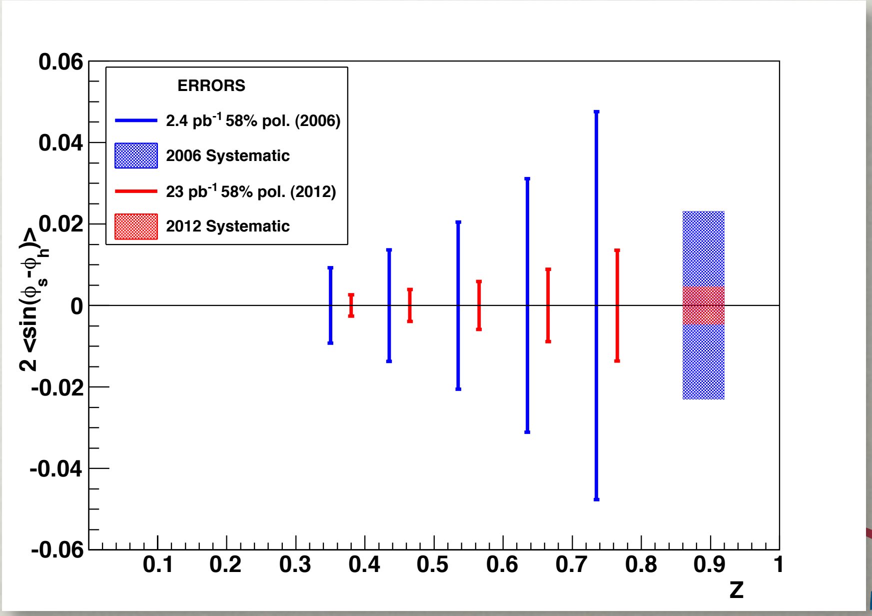


For z > 0.3, leading pions make up 95% of the inclusive pion sample.

Mid-rapidity Collins



Evidence of a sign difference between π^+ and π^- apparent – further reduction of systematic uncertainty will clarify this.



24 pb^{-1} of 200 GeV data were recorded during 2012, with ~60% polarization. Analysis is on-going.

A similar analysis is also underway based on 500 GeV data (2011).

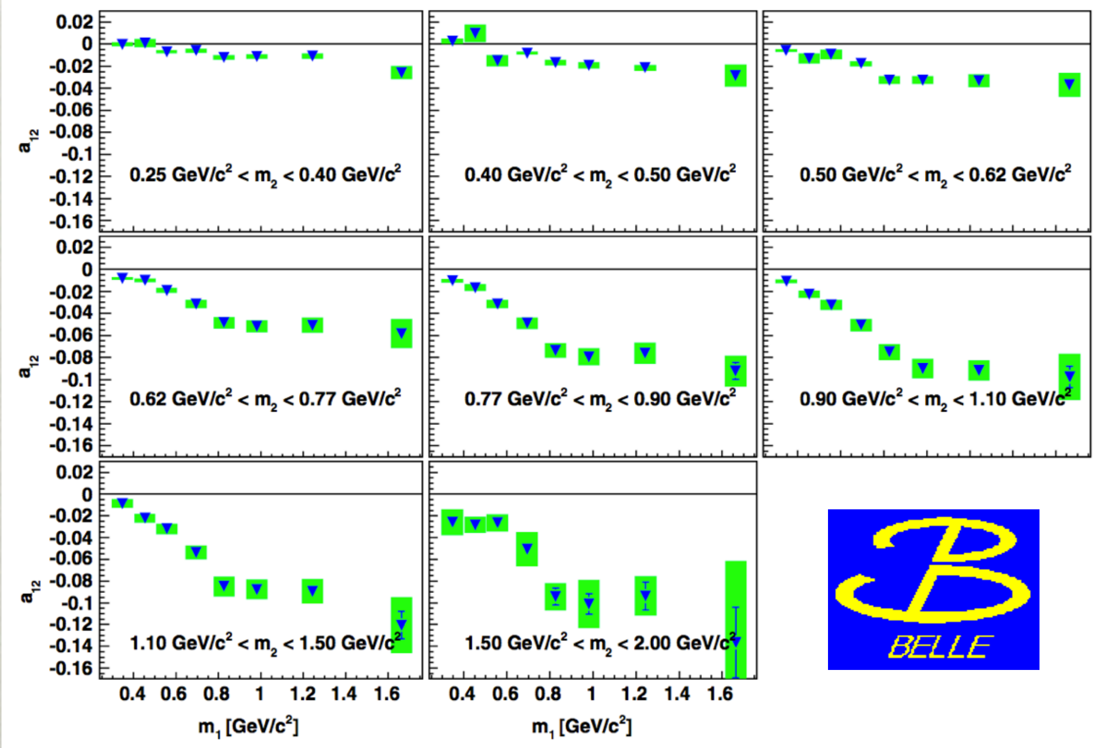
Mid-rapidity IFF

The Interference Fragmentation Function (IFF) involves **two hadrons in a jet**, where their relative transverse momentum encodes the information about **quark transversity**.

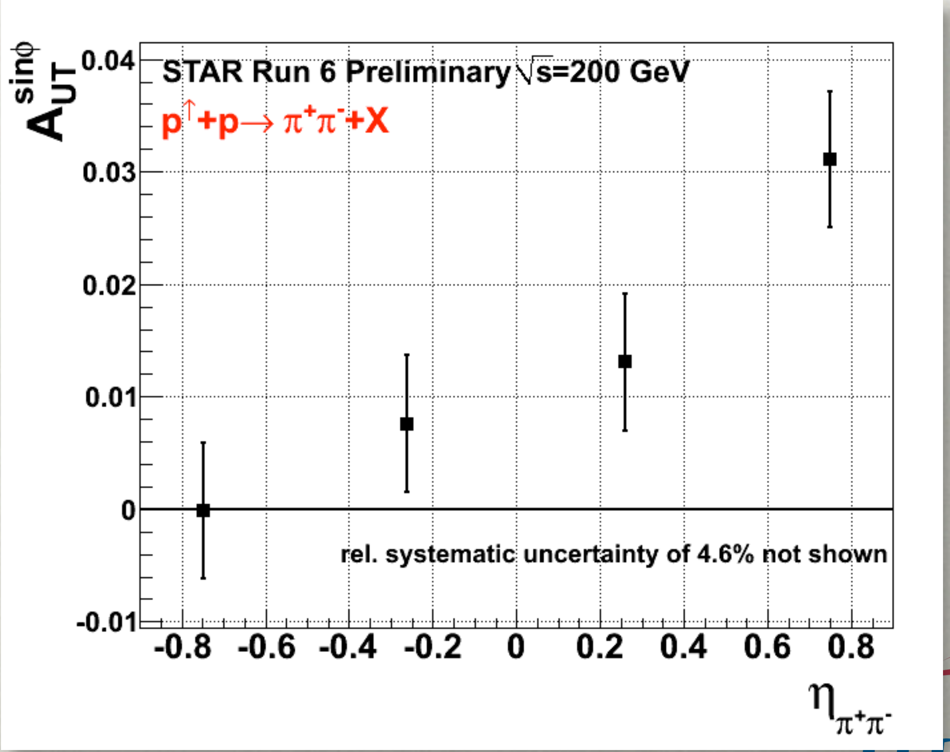
Since the relevant k_T is confined in the di-hadron system, **collinear factorization** is preserved. It is also a **leading twist** effect. *(Phys. Rev. D70, 094032 (2004))*
→ ***Theoretically much cleaner to interpret than the Collins FF.***

STAR recently released a preliminary result based on **mid-rapidity π^+ - π^- pairs**.

Phys. Rev. Lett. 107,072004 (2011)



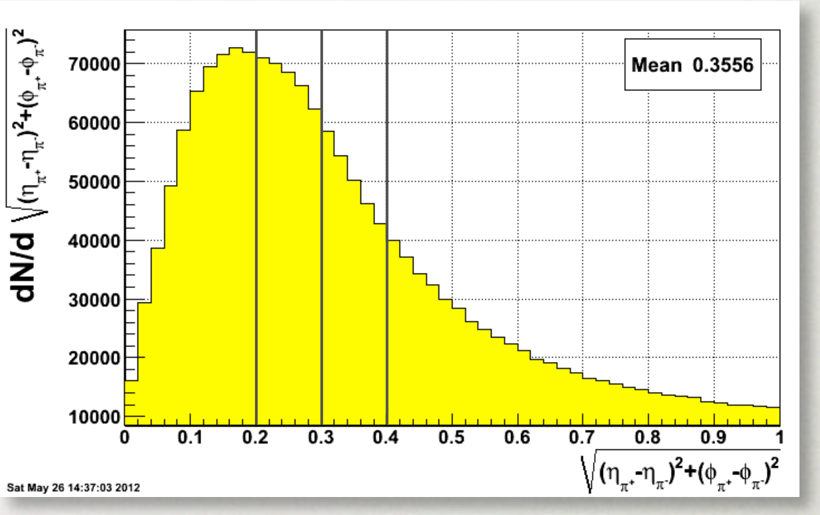
STAR Shows a significant signal!

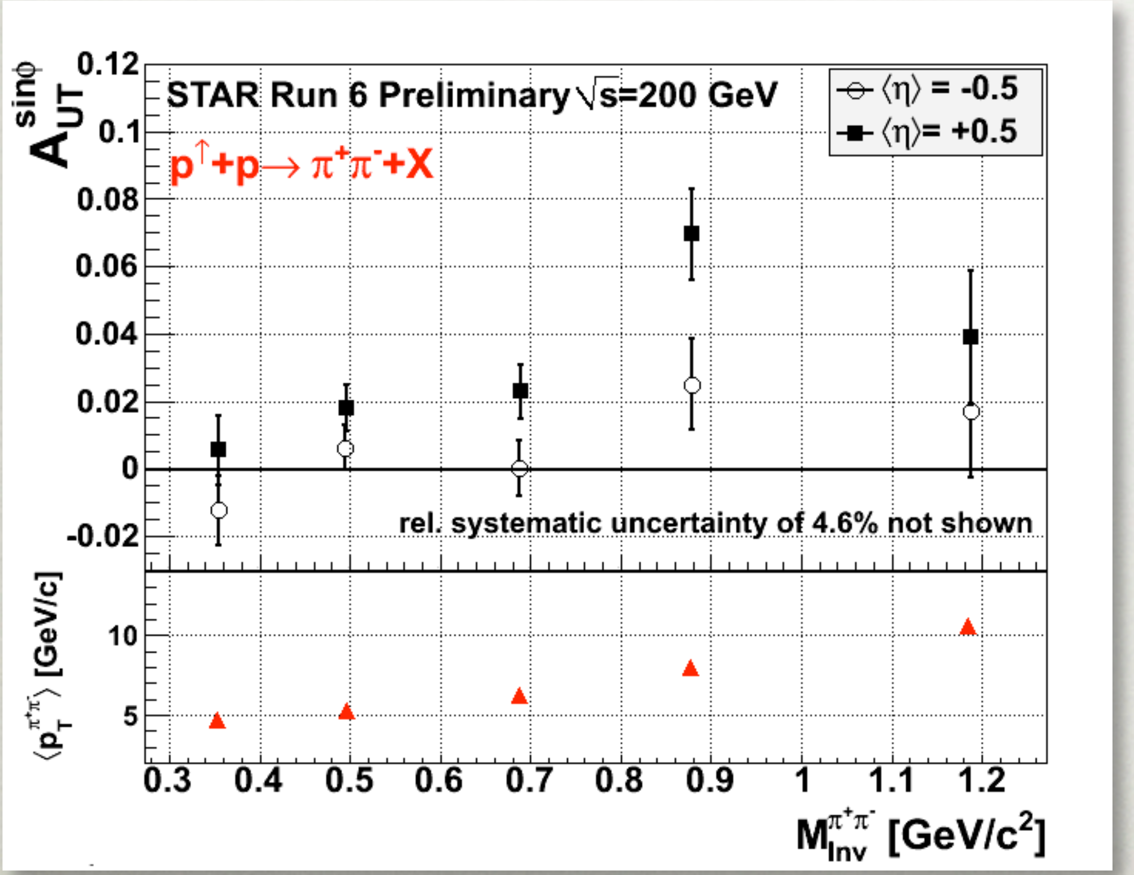


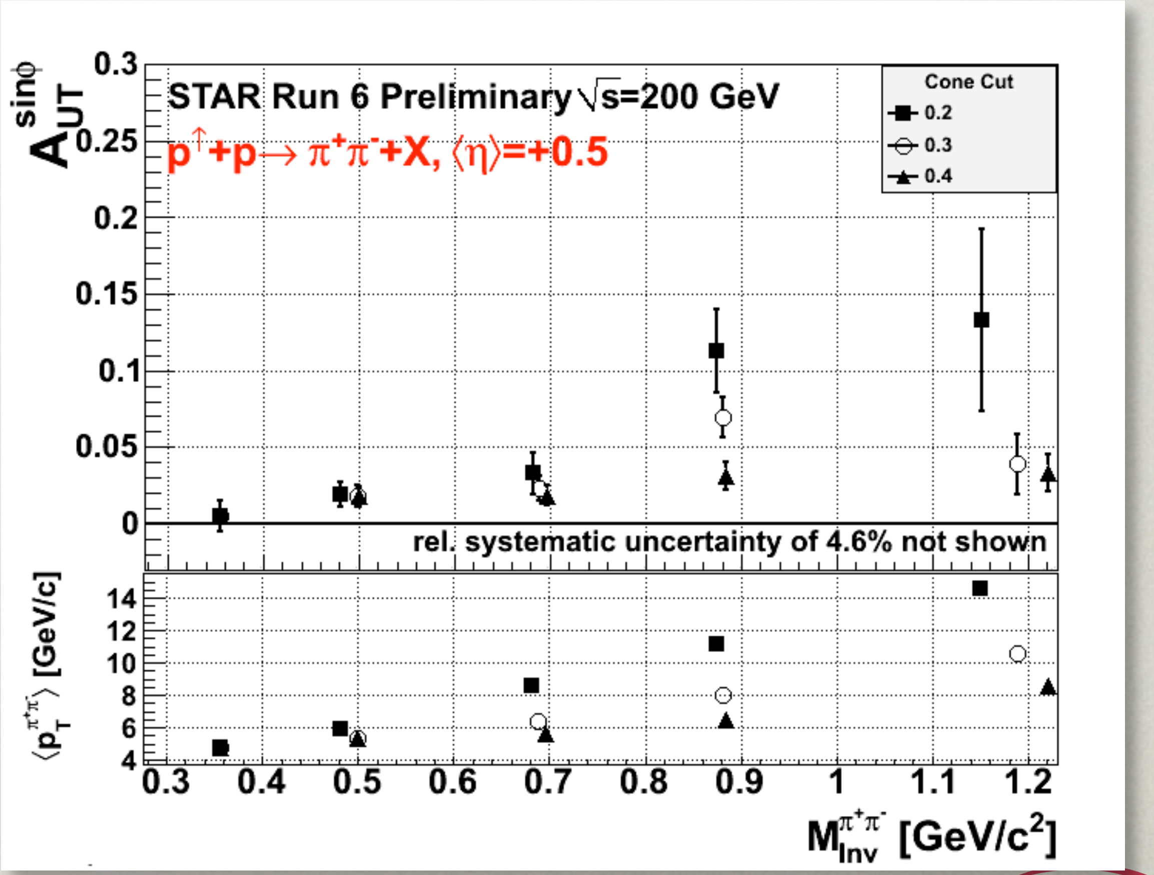
Mid-rapidity IFF

The dependence on the pion pair mass shows a peak at ϱ mass region.

The largest asymmetry is found with the smallest cone cut at high mass / high p_T region.







Characterizing A_N in p+p

Mid-rapidity Di-Jet Sivers

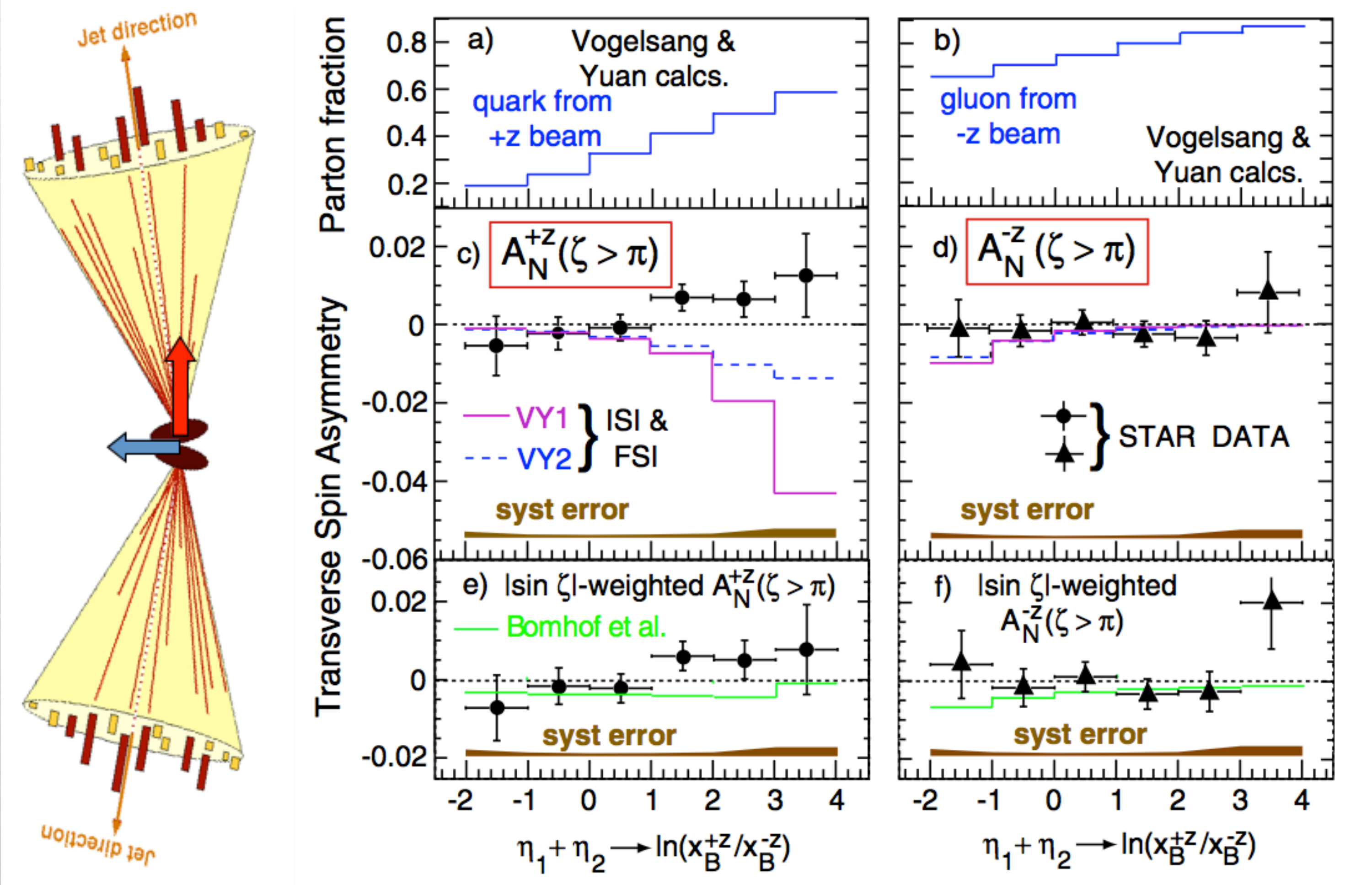
The Sivers effect produces spin dependent left/right bias in k_T due to parton orbital angular momentum. This leads to **di-jets being not precisely back-to-back**. The azimuthal opening angle depends on the spin of the proton.

In contrast, di-jet measurements are insensitive to the Collins effect, which produces an asymmetry within a jet.

The observed A_N is much smaller than SIDIS result, but the comparison is likely invalid due to factorization breaking in h + h → 2 Jets. (*PRD 81, 094006 (2010)*)

Twist-3 calculation based on fits to forward p+p predicts much smaller A_N, due to ISI-FSI & u-d cancellation.

Phys. Rev. Lett. 99, 142003 (2007)

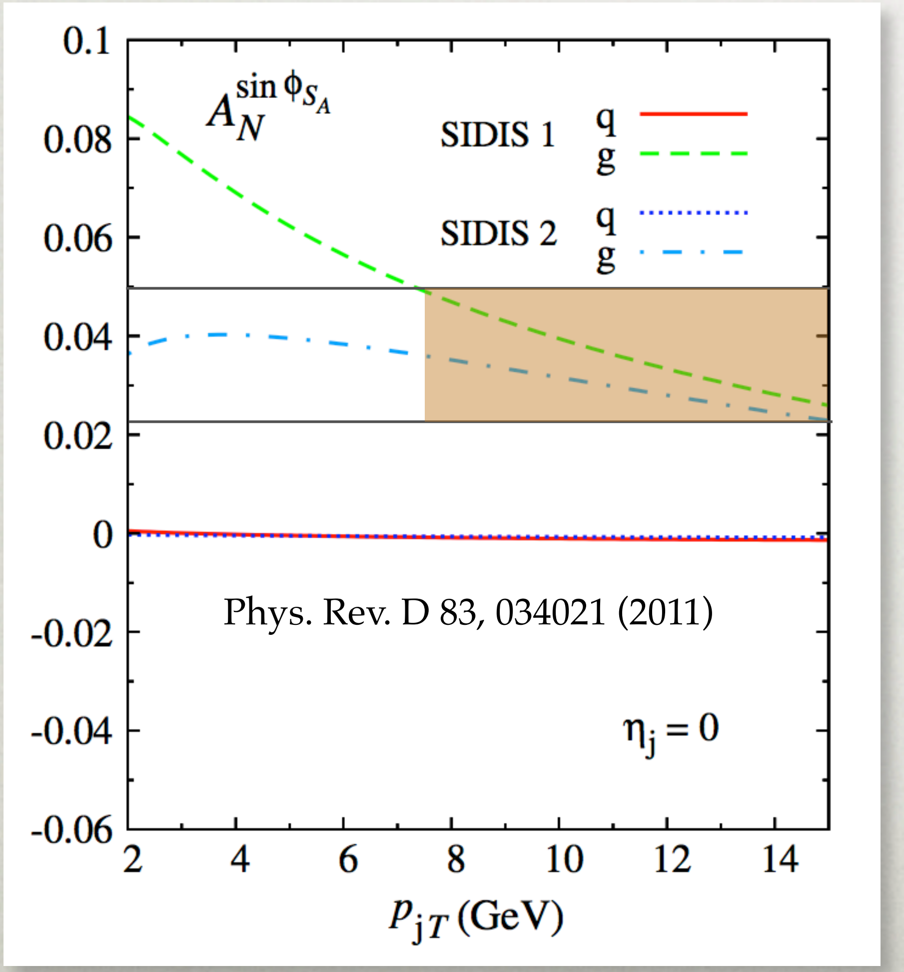


Berkeley Lab

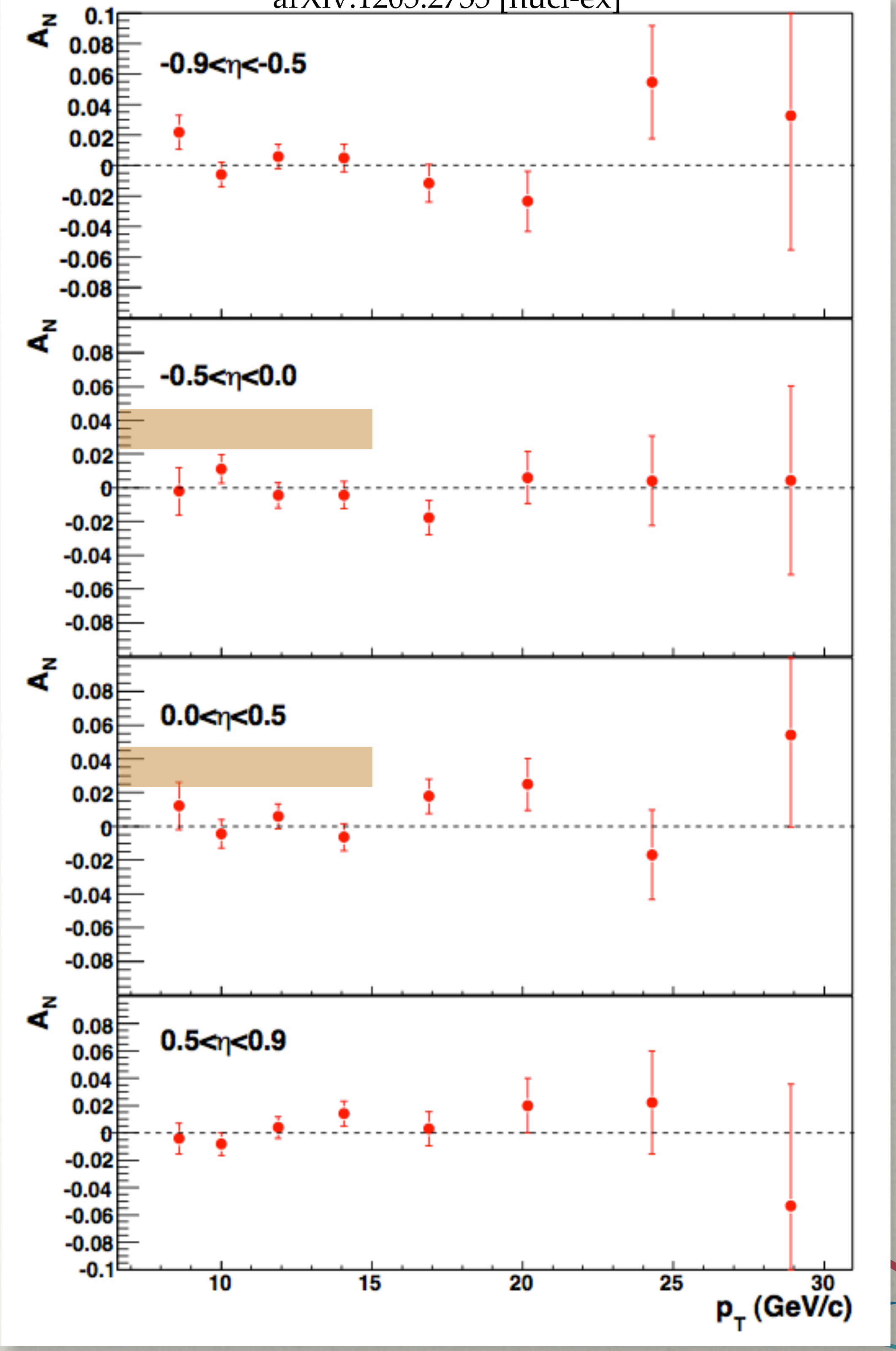
Mid-Rapidity Incl. Jet A_N

Mid-rapidity inclusive jet A_N is expected to originate almost entirely from **gluon Sivers** function. (*Phys. Rev. D 83, 034021 (2011)*)

The current **upper limit** for the gluon Sivers results in **A_N of 2.5 ~ 5%** in the measured p_T region, **significantly larger than the data**.

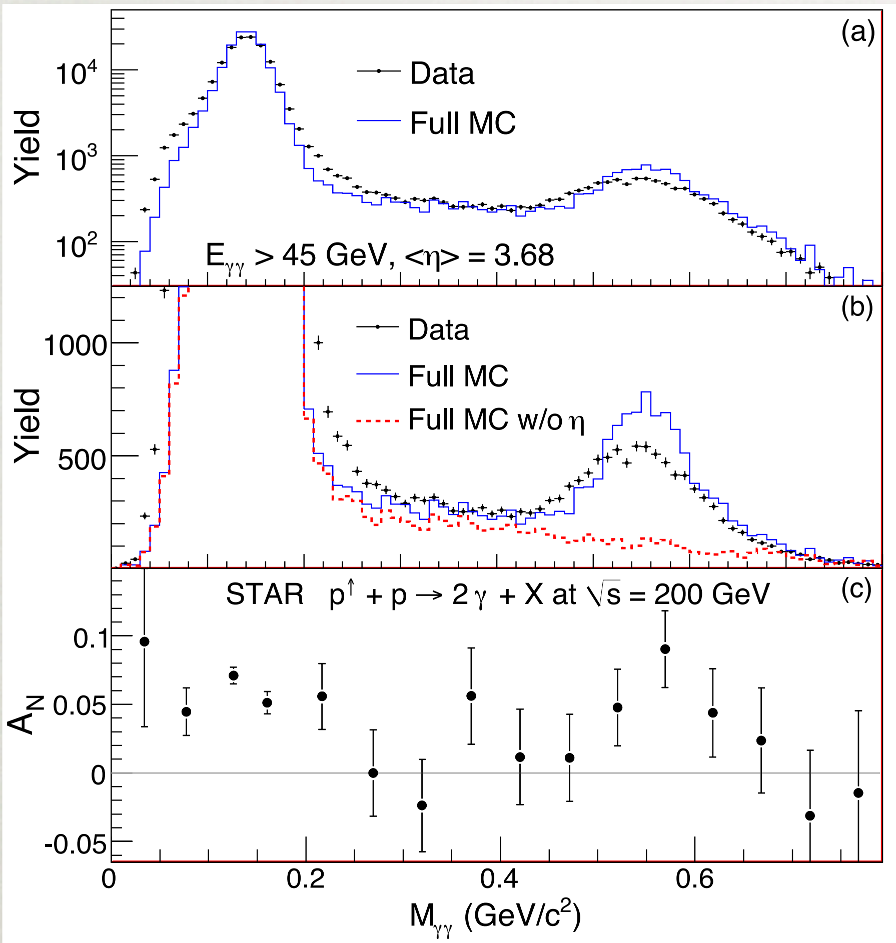


arXiv:1205.2735 [nucl-ex]

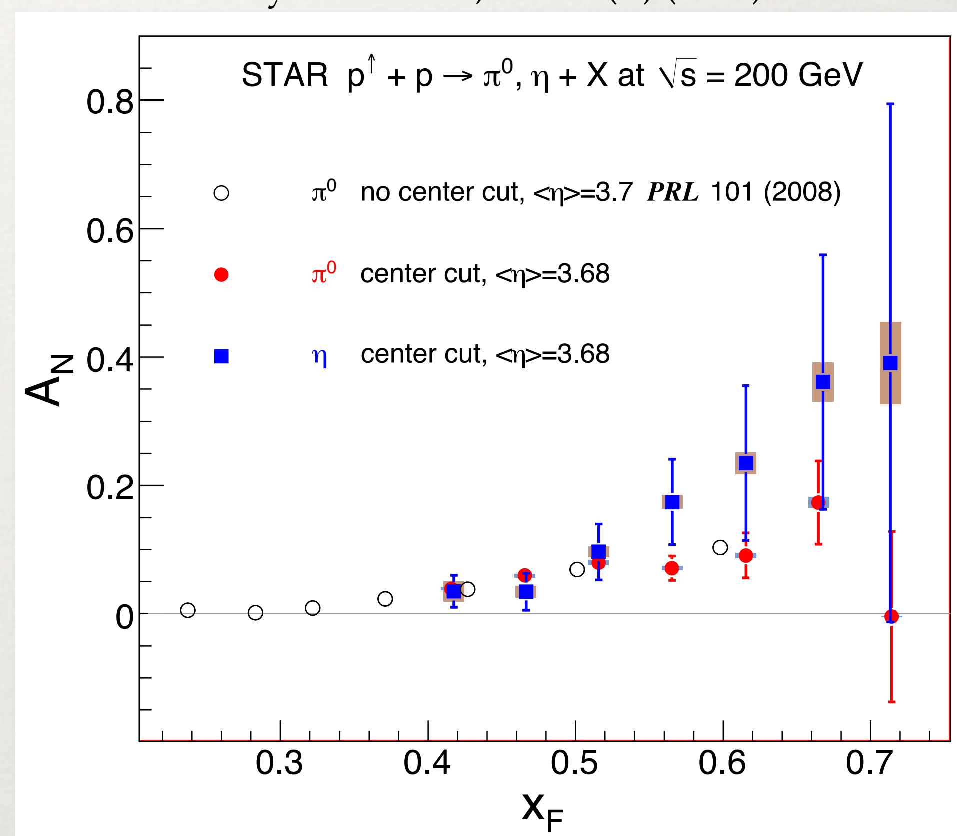


Forward η A_N at 200 GeV

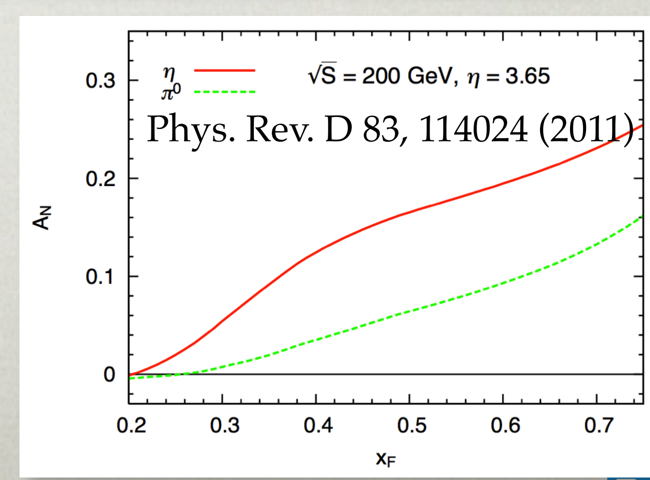
In addition to the π^0's, STAR has measured the forward cross-section (slide 4) and A_N for the η mesons. At high x_F ($x_F > 0.55$), the A_N for the η is very large, and may not be consistent (~3%) with that of the π^0.



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 somewhat.



Phys. Rev. D 83, 114024 (2011)

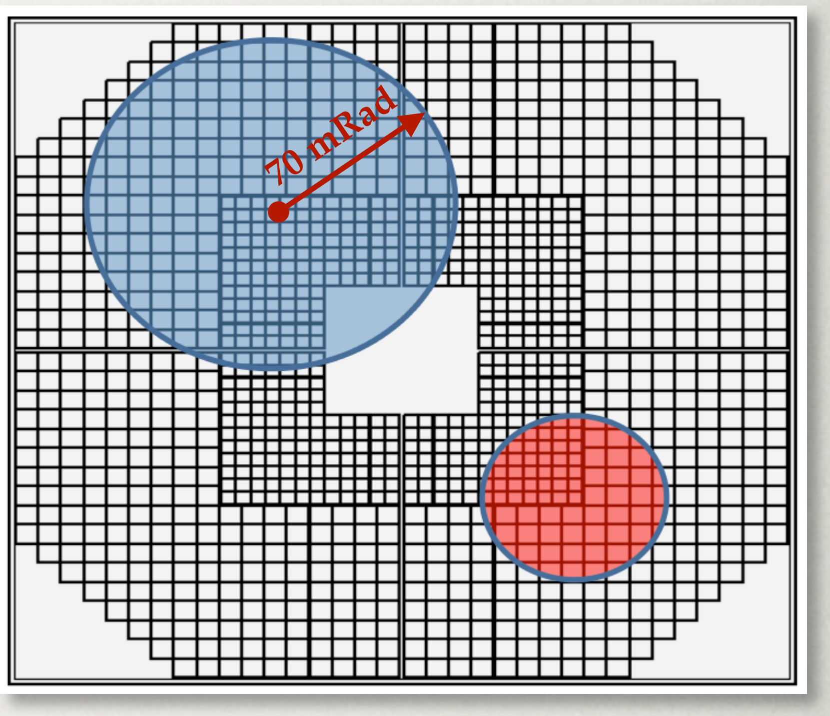
Forward π^0 A_N at 500 GeV

STAR Forward Meson Spectrometer (**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)

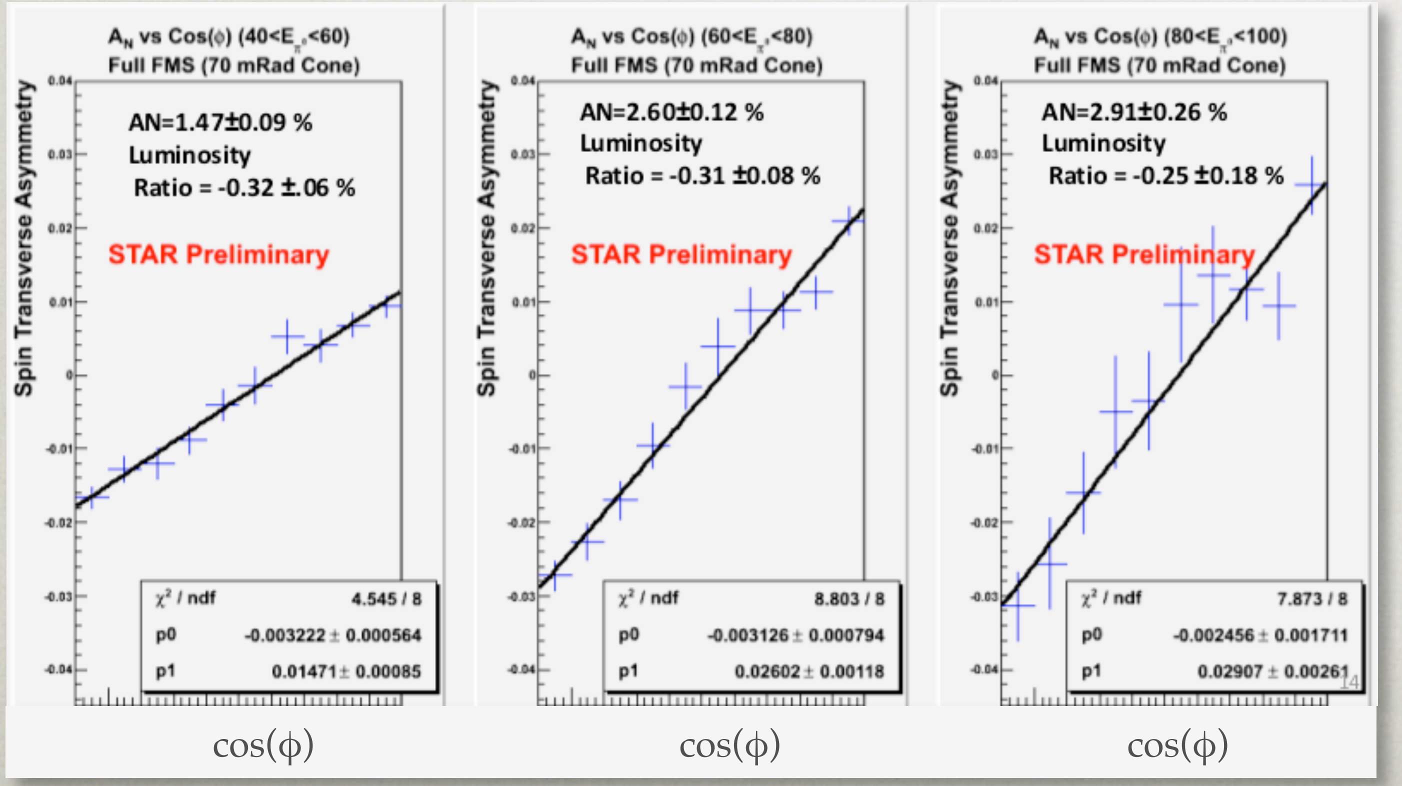
The π^0 recon. is effective up to ~100 GeV ($x_F = 0.4$).

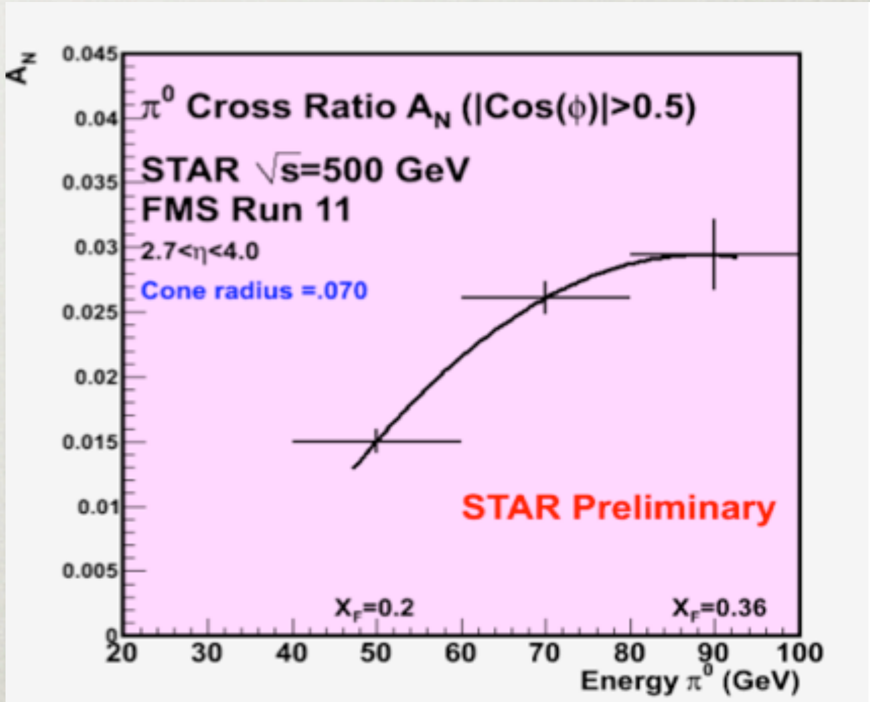
The **onset of positive A_N is lower in x_F** compared to 200 GeV, and the **magnitude is comparable**.

Isolation cut = 70 mRad



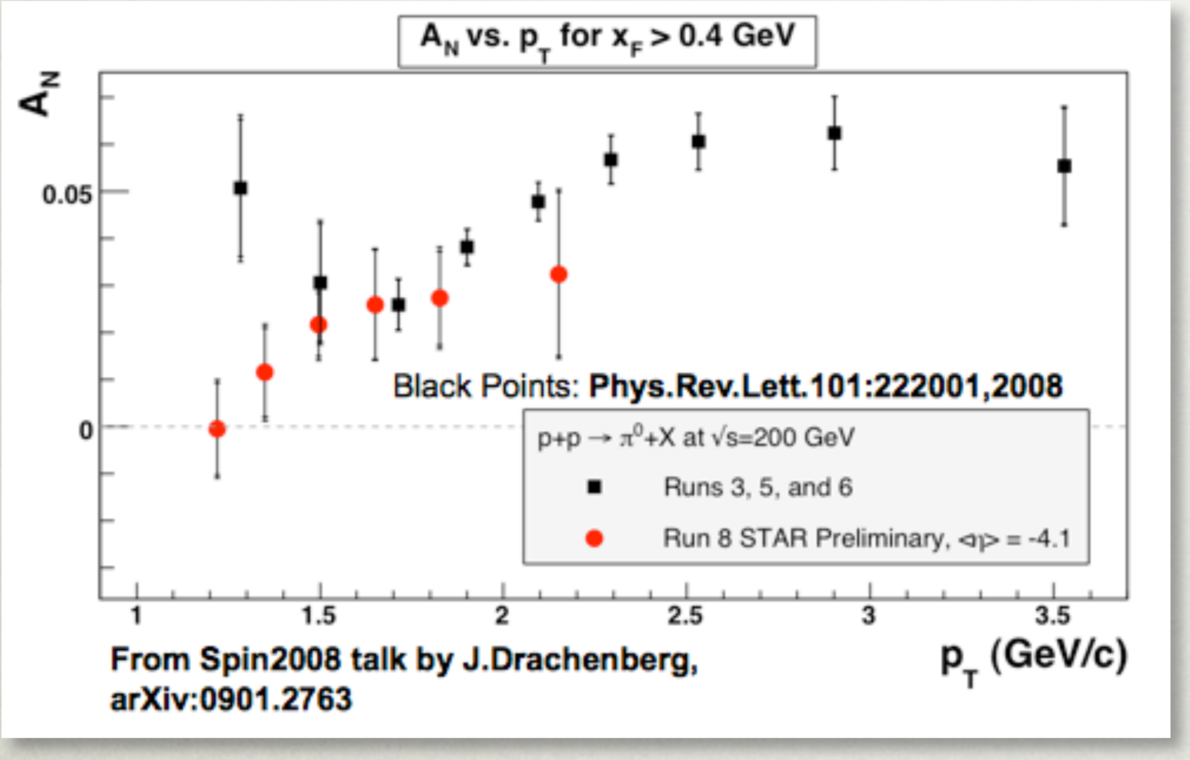
Slope =A_N , Intercept = Luminosity Ratio (for all data ~ - 0.31 ± .05 %)

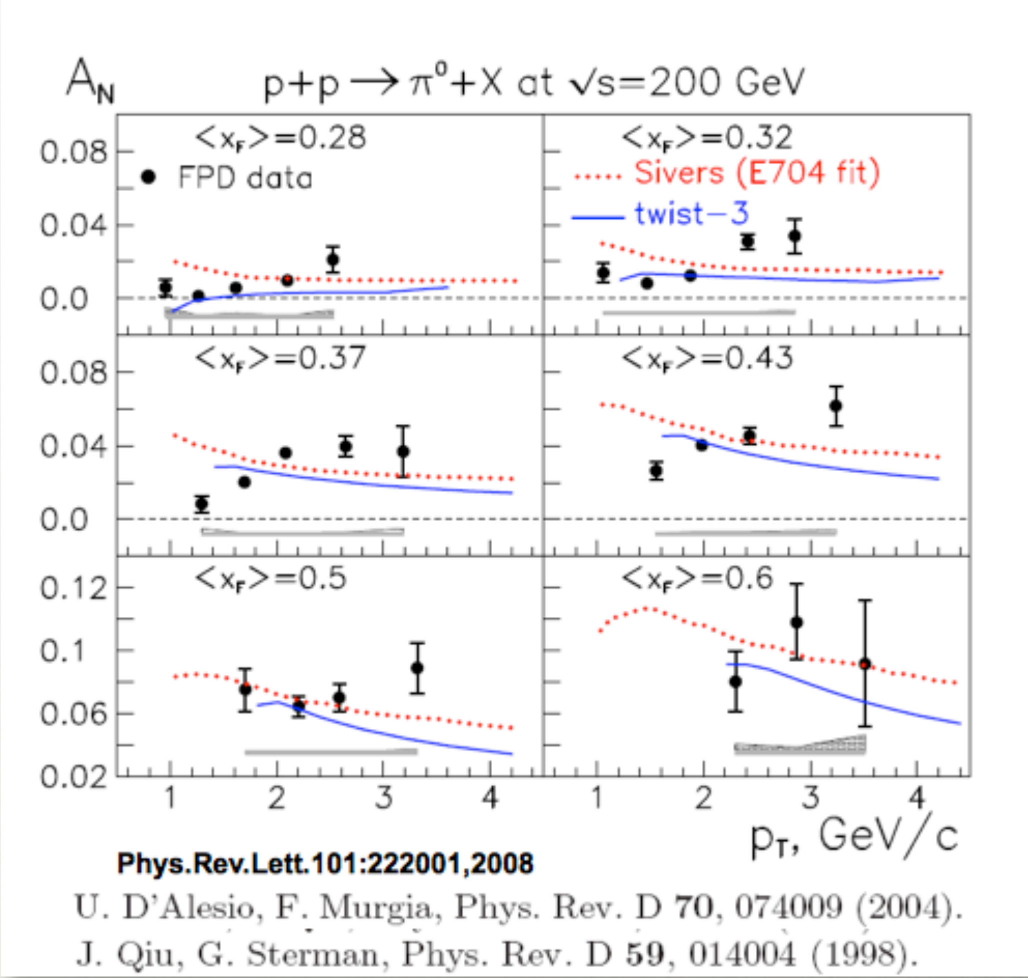




p_T Dependence of π^0 A_N

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.

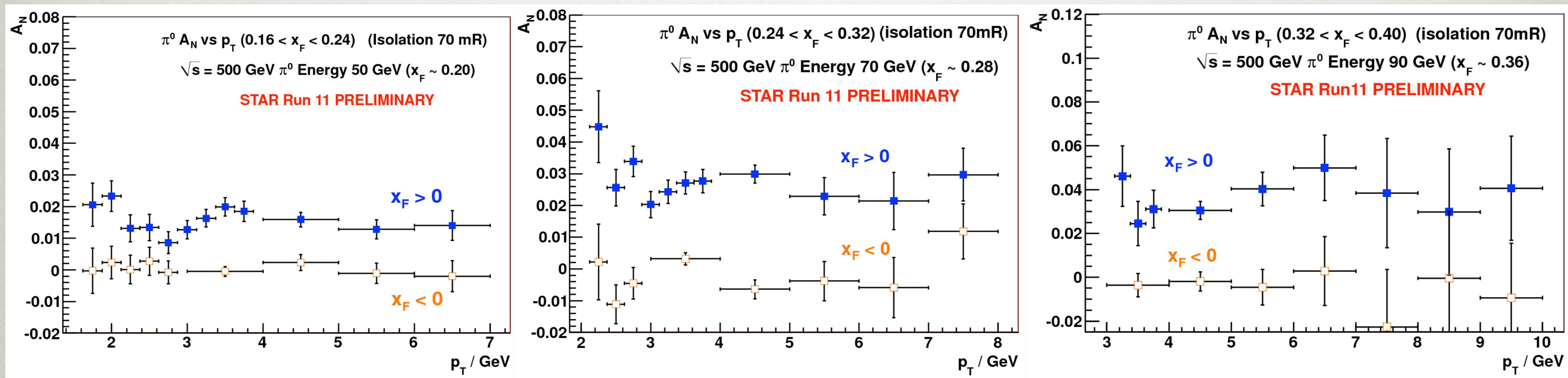




However, STAR has previously reported the p_T dependence of forward π^0 A_N at $\sqrt{s}$=200 GeV that shows **no sign of falling out to ~3.5 GeV/c.**

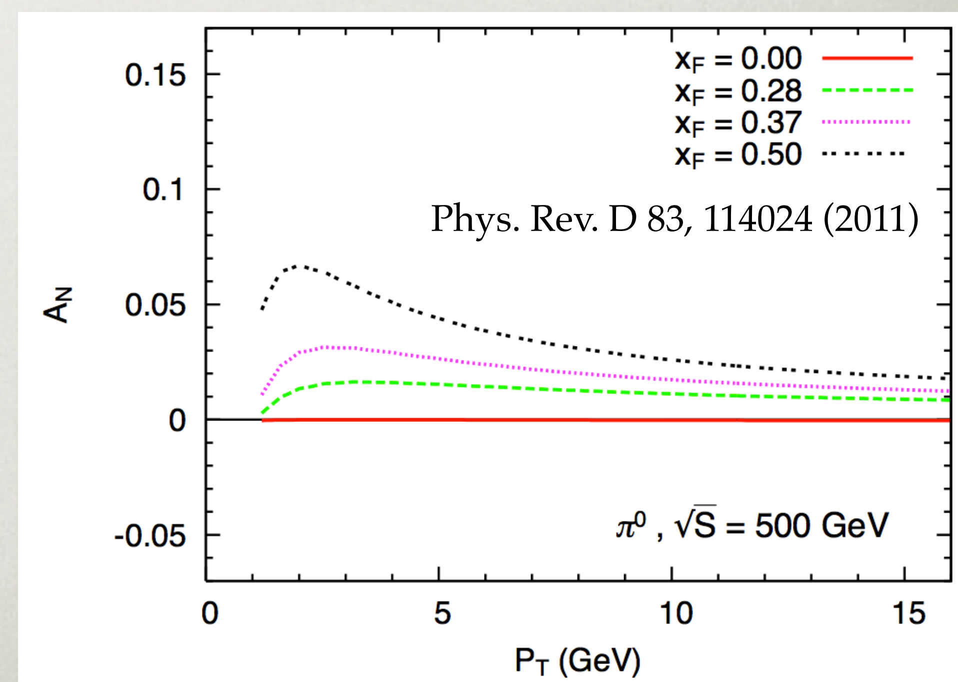
p_T Dependence of π^0 A_N

Based on a much larger detector (FMS) and a newer data set (run 11), STAR has measured the **p_T dependence of forward π^0 A_N at $\sqrt{s}$=500 GeV, up to ~10 GeV.**

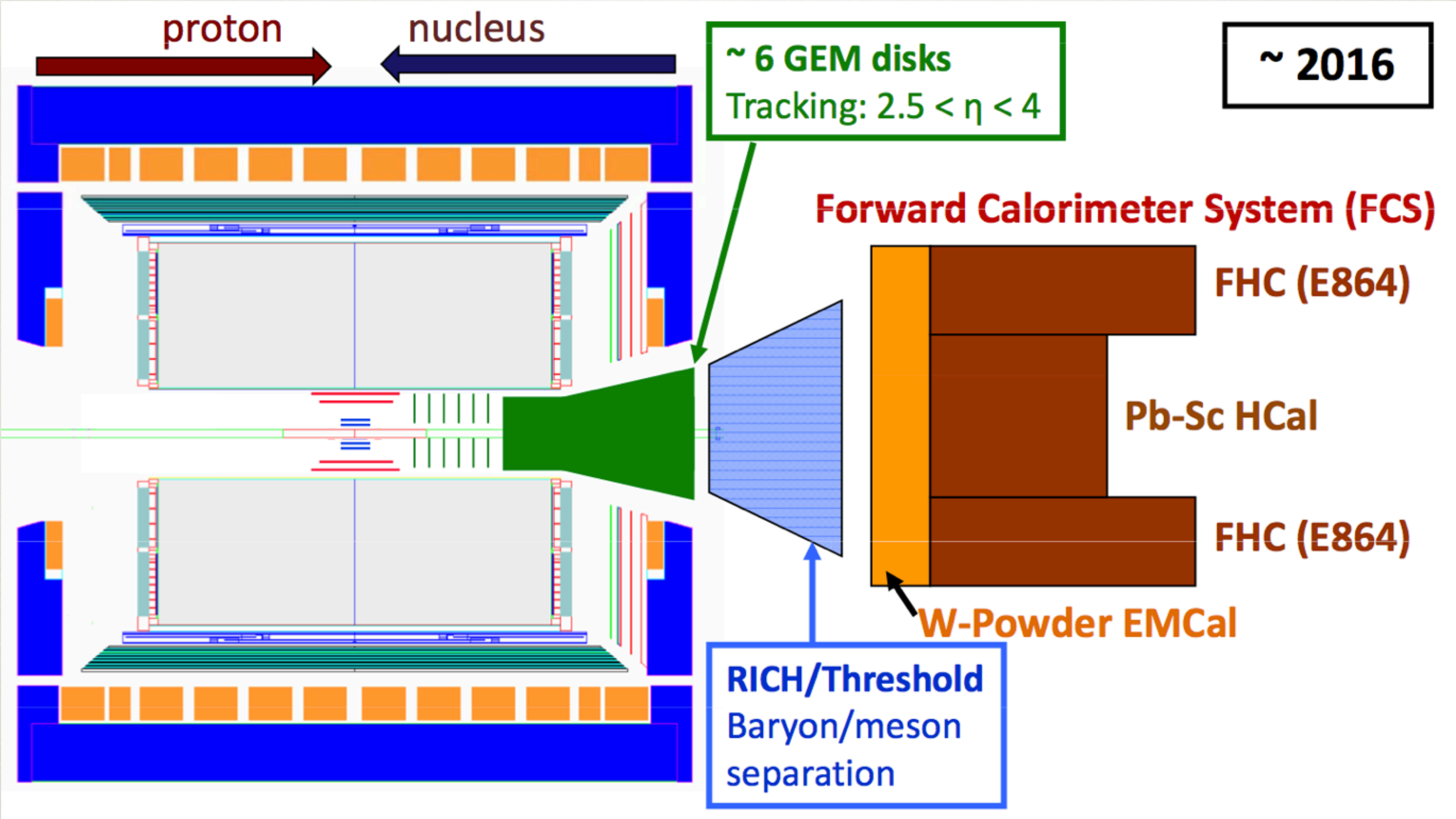


Even at 7~10 GeV, we see no sign of $1/p_T$ like fall.

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.



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

Transverse spin physics in p+p offers unique challenges and opportunities. The STAR collaboration continues to play an integral role in the field through the measurements of transverse spin asymmetries and forward cross-sections in p+p.

STAR has released its first measurements of Collins and Interference FF, which can be used to extract proton transversity. They utilize the jet/PID capability of the STAR mid-rapidity region. A large sample of 200 GeV transverse data taken in 2012 will significantly improve the precision for both measurements.

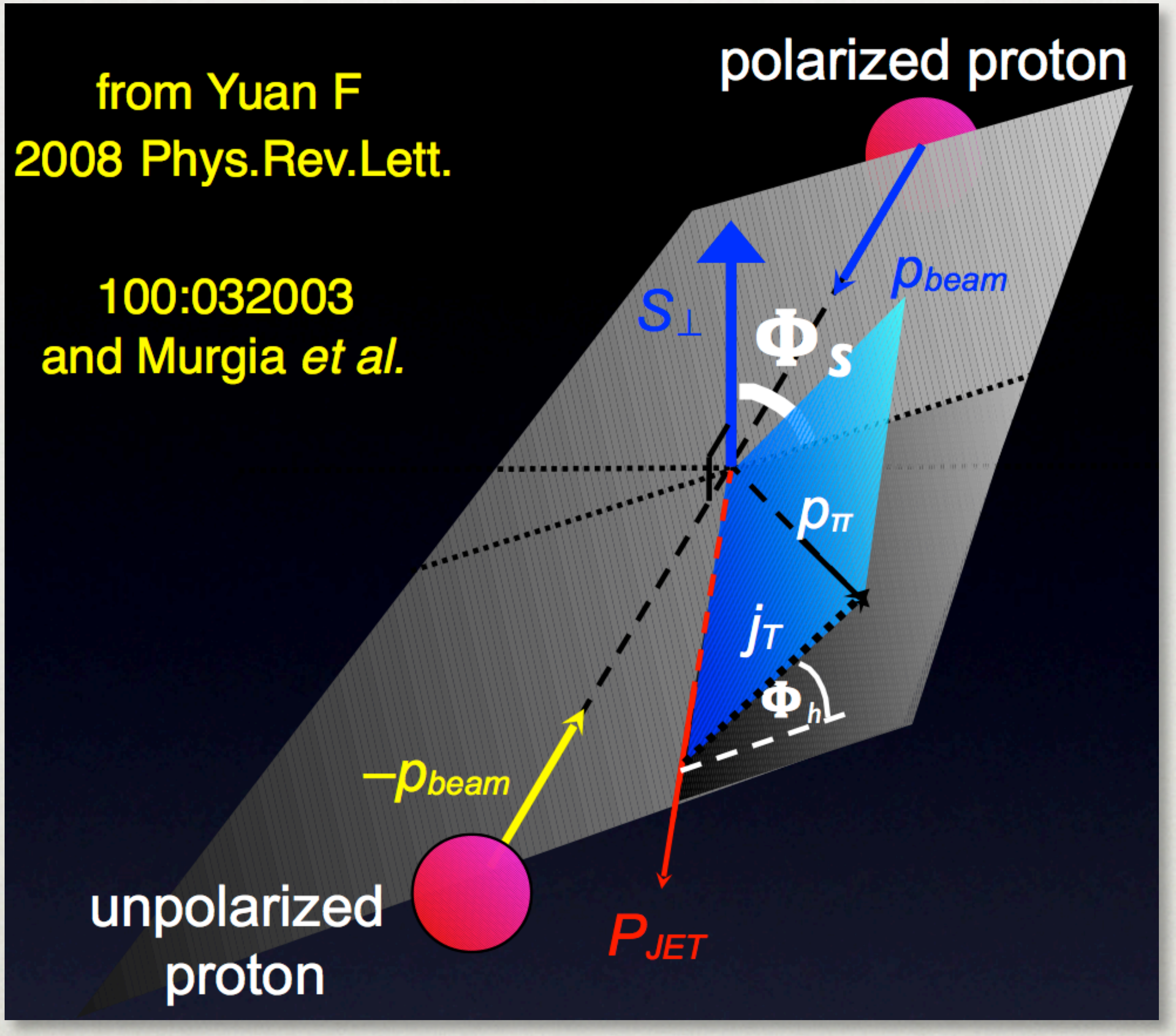
STAR is continuing its effort to map out the kinematic dependence of A_N in the forward region, and to expand the measurements beyond inclusive pions. The goal is to provide the data necessary to bring the theoretical understanding of the large A_N in p+p to the quantitative level.

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.

Backup

Mid-rapidity Collins Sign

From Rob Fersch's talk

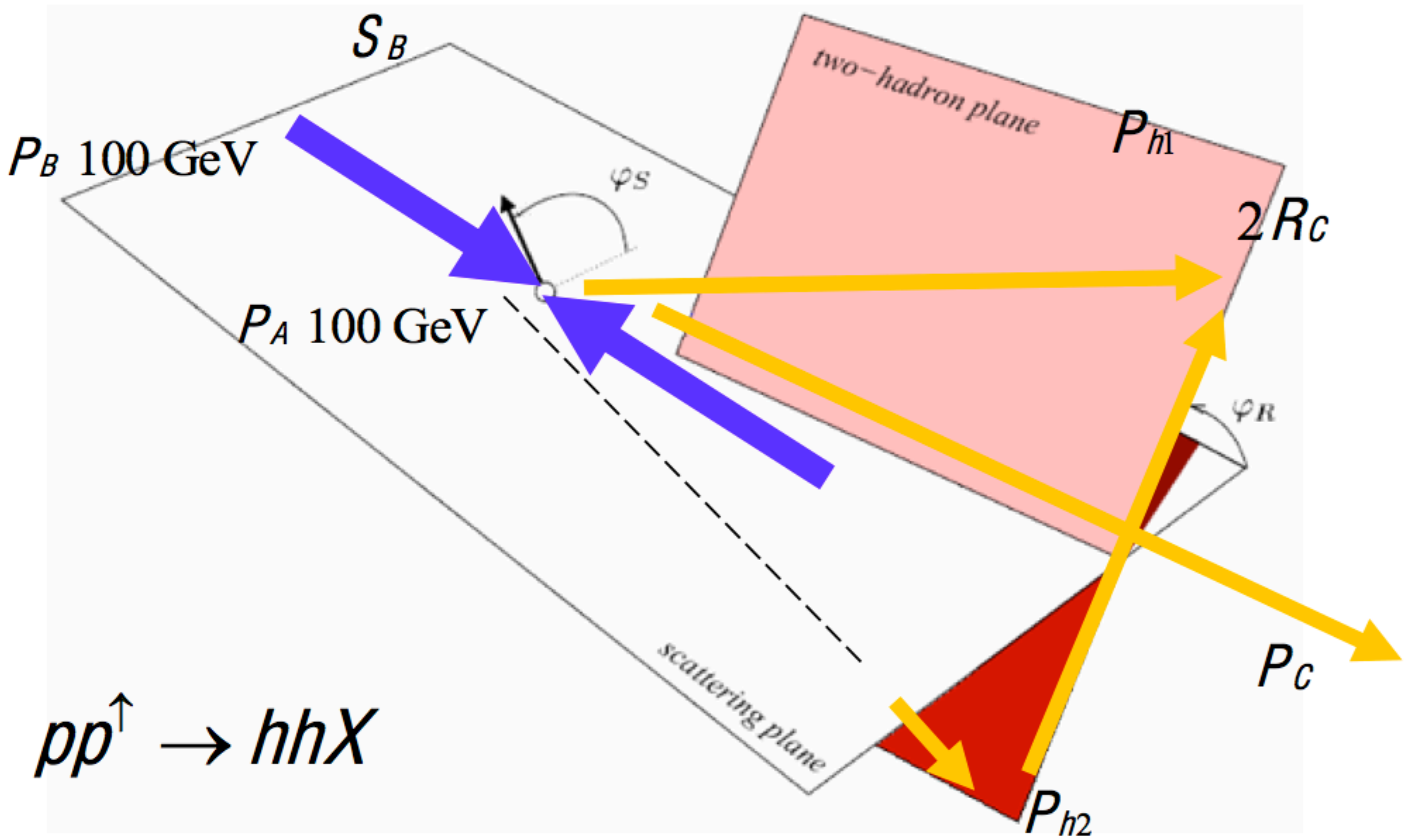


Asymmetry calculated as sin($\phi_S - \phi_h$).

Positive asymmetry = Spin up → Hadron going to the left when looking down the jet

Mid-rapidity IFF Sign

From Anselm Vossen's talk



p+p c.m.s. = lab frame

P_A, P_B : momenta of protons

P_{h1}, P_{h2} : momenta of hadrons

$P_C = P_{h1} + P_{h2}$

$R_C = (P_{h1} - P_{h2})/2$

S_B : proton spin orientation

Asymmetry calculated as $\sin(\phi_S - \phi_R)$,

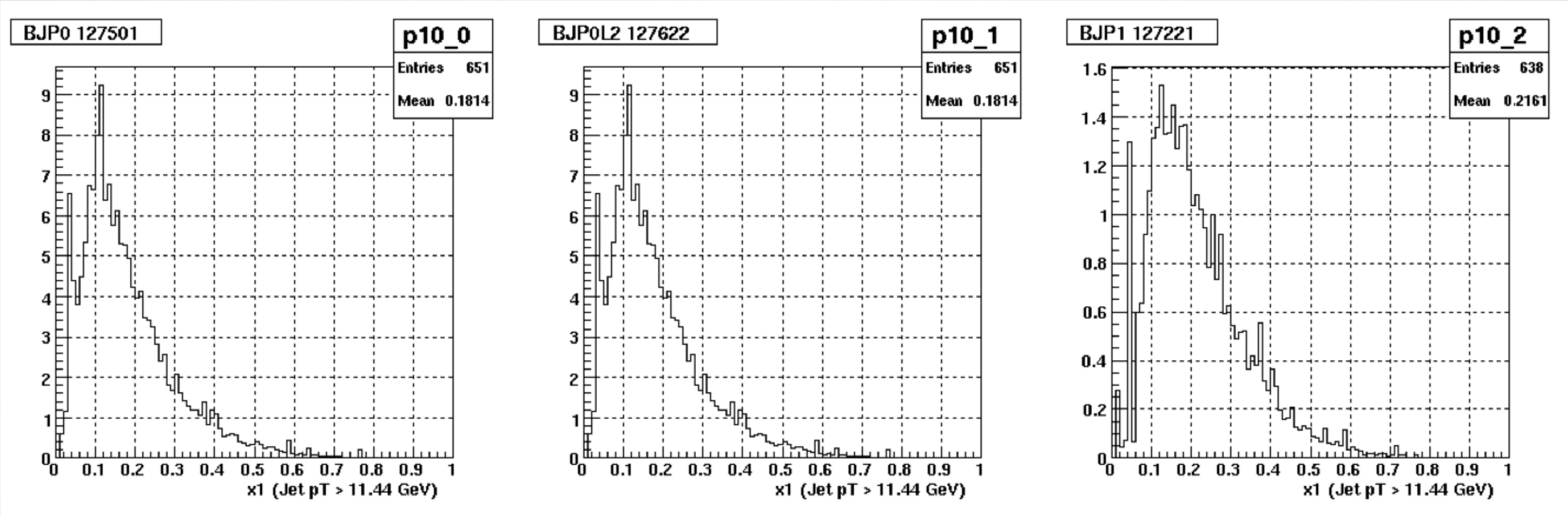
where $\phi_R = \phi_{(\pi+)} - \phi_{(\pi-)}$.

Positive asymmetry = Spin up → π^+ going to the left

when looking down the pair momentum (P_C)

Transversity Kinematics

Mid-rapidity jets (<x$_B$>~0.2)



Mid-rapidity π^0

Forward π^0