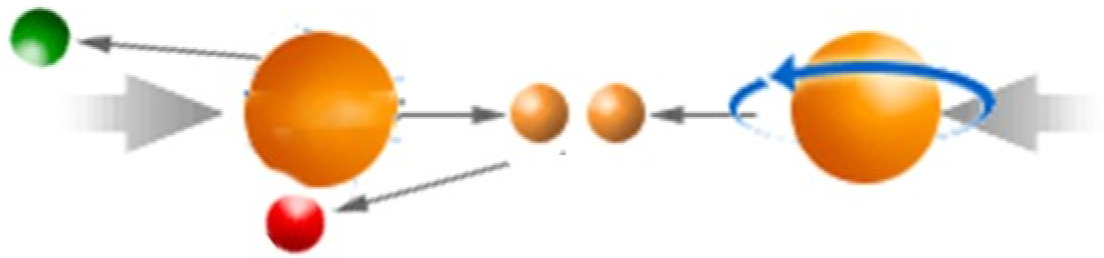
RHIC Spin: The Next Decade

Iowa State University, May 14-16, 2010

Man looking for his keys
under the light!



Transverse Spin with STAR (SSA)
Forward Production.

Steve Heppelmann
Penn State

Looking for spin effects where the asymmetries are large!
A high statistics characterization of what nature insists we measure and explain ….

and that we almost already understand

Longitudinal Spin Asymmetries are calculable in pQCD with ***Collinear Factorization.***

Cross sections are calculable, given parton densities and fragmentation functions.

Asymmetries derive from initial state **polarization of partons in a polarized proton** and from calculable spin dependence of parton hard scattering.
Measurements help to **characterize the parton structure** of the proton
.

within a well established pQCD framework

Transverse Single Spin Asymmetries vanish in leading order
For pQCD with ***Collinear Factorization***.
Asymmetry may derive from factorizable correlations of proton spin with

- initial state polarization of partons
- or from orbital angular momentum of partons
  (transverse orbital motion of partons)
- and/or from fragmentation of polarized partons (jets)

or SSA may result from non-factorized calculations, where universal parton structure is insufficient.
Large measured transverse SSA probe elements of QCD that must expand out knowledge of pQCD.

beyond our current comfort zone

What PQCD with Collinear Factorization Gave Us:

- Gives meaning to quark and gluon, the confined internal degrees of freedom (DOF) in QCD.

- Provides concrete connections between these internal DOF and experimental observables. (Jets, hadrons, photons)

- Gives an experimental (process independent) connection to a description of nucleon and non-perturbative bound state (Nucleon parton densities) .

- Provides a recipe for approximate calculation of cross sections for certain interactions in certain kinematic regions.

- Has a well defined kinematic region where calculations are most likely dependable.

Generalized Factorization PQCD++

- Applies to a wider variety of experimental measurements.
- Gives similar meaning to quark and gluon, the confined internal degrees of freedom (DOF) in QCD. (same)
- Provides concrete connections between these internal DOF and experimental observables. (Jets, some hadrons, photons) (same)
- Gives an experimental connection to a description of nucleon and non-perturbative bound state (Nucleon parton densities) . (same)
- Provides a recipe for approximate calculation of cross sections for certain interactions in certain kinematic regions??? (perhaps same)
- Has less clearly defined, evolving rules that tell us when calculations are most likely dependable.

Formal Definition of Factorization May Break Down!!!
Opportunity Experiment Driven Discovery

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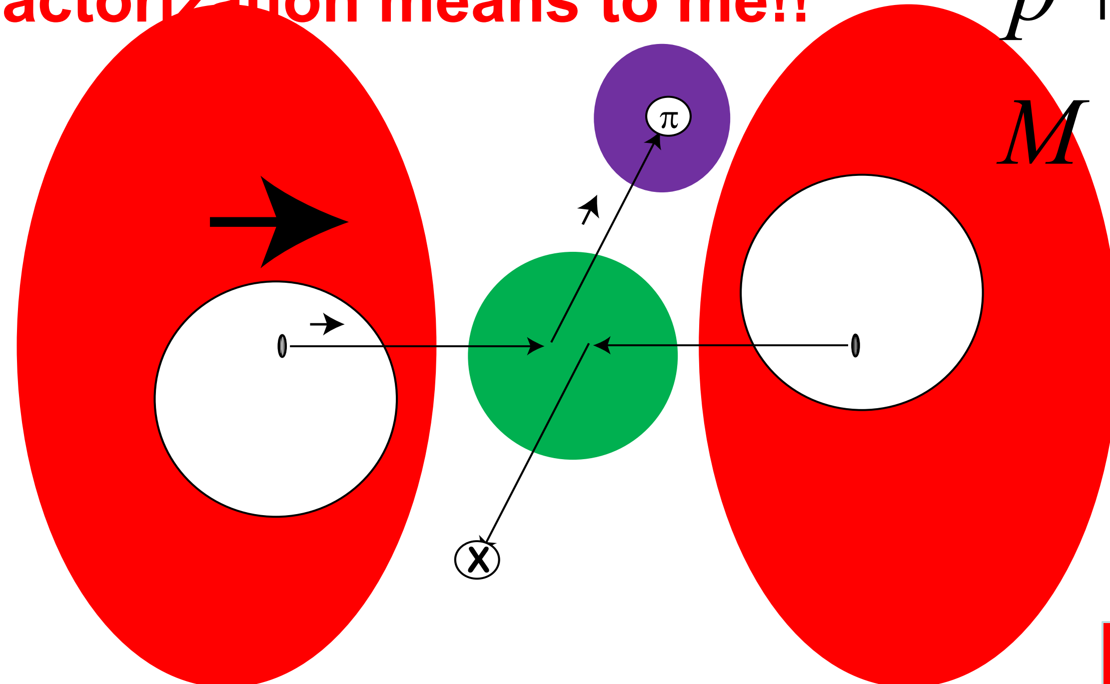
What **Factorization means to me!!**

$$p + p \rightarrow M + X$$

$$M : \{m_{\pi^0}, \eta, \eta'\}$$



Fragmentation

Real helicity conserving Hard Scattering

Parton Structure (polarized parton distribution)

Universality

- **Factorization:** *Parton Structure* **does not** depend on *Hard Scattering* or on *Fragmentation*
  Fragmentation **does not** depend on *Hard Scattering* or on *Parton Structure*
  Hard Scattering **does** not depend on *Fragmentation* or on *Parton structure*

Leading order Hard Scattering **does not flip the parton helicity** but the scattering amplitude "can and **does depend upon helicity**" in a predictable way.

Amplitudes are real (no phase delay difference between various contributing amplitudes)
(not like diffraction in optics)

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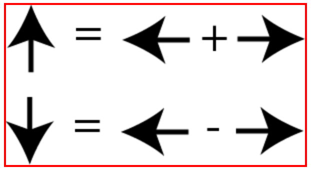
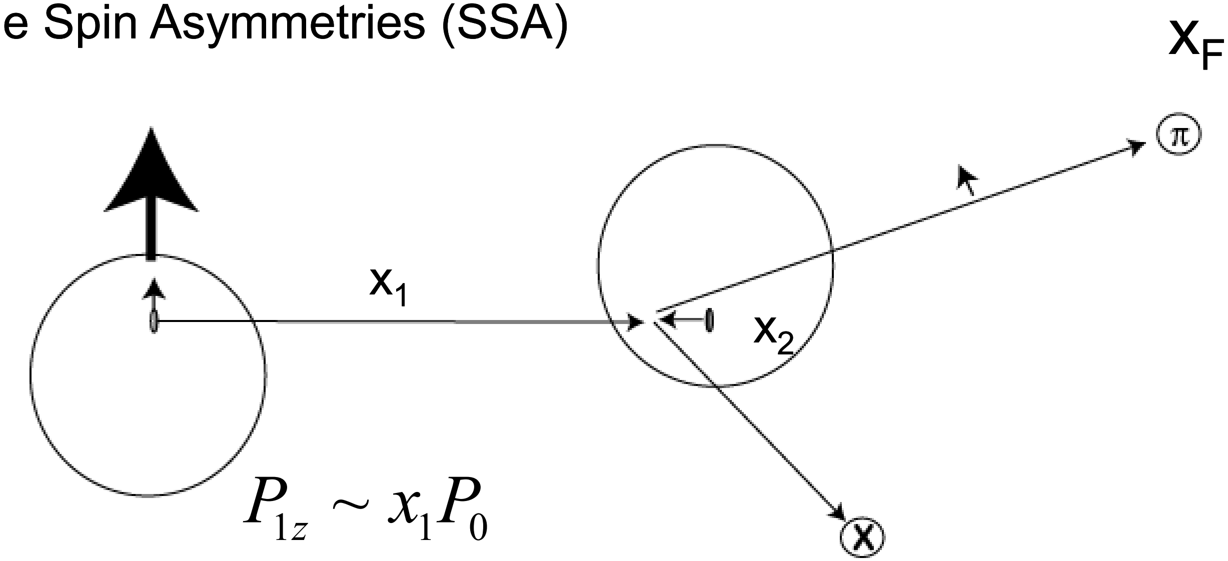
Forward Transverse Single Spin Asymmetries (SSA)



$$|\uparrow\rangle = |\rightarrow\rangle + |\leftarrow\rangle$$
$$|\downarrow\rangle = |\rightarrow\rangle - |\leftarrow\rangle$$



Surprising large SSA

Transversity?
Parton polarizations may be very large as $x_1 \rightarrow 1$.

Kinematic Conspiracy?
High statistics measurements
Of large SSA processes.

Dependence on kinematics:?
Relation to cross section?

$$P_{1z} \sim x_1 P_0$$

$$P_{2z} \sim -x_2 P_0$$

$$x_1 >> |x_2|$$

$$\frac{P_{\pi z}}{z_\pi} + P_{zX} \sim P_{1z} \sim x_1 P_0$$

$$x_F < x_1 \rightarrow 1$$

$$? : x_F << x_1 \rightarrow 1$$

Previous observation of Single Spin Transverse Asymmetry for Forward Production of

π^+	Meson
π^-	Meson
π^0	Meson
η	Meson
η'	Meson

by FNAL Exp 704
They reported:

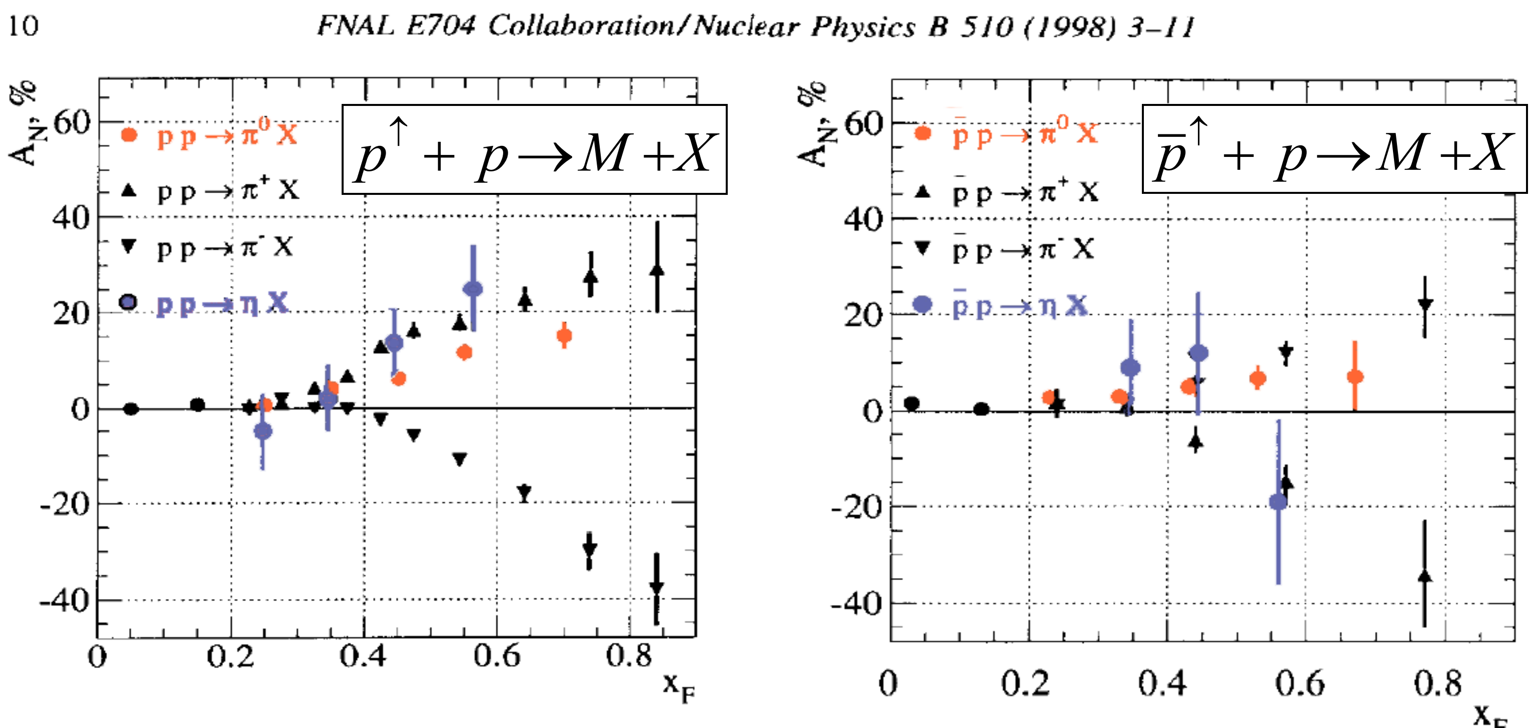
$$p^{\uparrow} + p \rightarrow M + X$$

$$\bar{p}^{\uparrow} + p \rightarrow M + X$$

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

1) Nominally (perhaps not significantly) larger asymmetry for η than π^0
2) Large Uncertainty in Eta A_N.

$\sqrt{s} = 19.4 GeV$ $\langle p_T \rangle \sim 1 GeV/c$



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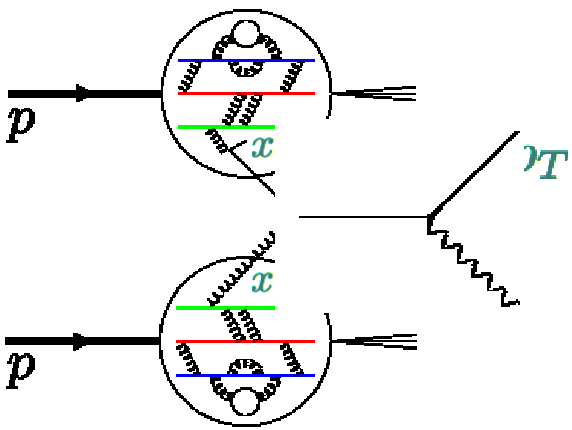
Collinear Factorization

Cross Section~ (Probability to select required parton A (x_1) from proton 1)
x (Probability to select required parton B (x_2) from proton 2)
x (Probability that partons A+B => C + X)
x (Probablity that parton C Fragments into observed final state)

$$f_1(x_1) \underset{x_1 \to 1}{\sim} (1-x_1)^3$$

$$f_2(x_2) \underset{x_2 \to small}{\sim} const$$

$$D^{\pi^0}_{parton} \underset{z \to 1}{\sim} (1-z)^1$$



$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D^h_f$$

For Forward Production of Pi/Eta ..

$$\sigma(x) \propto \int_{x_f}^{1} dz\, f_1\left(x \sim x_F / z\right) \sigma_{parton} \quad D^{\pi^0}_{parton}(z)$$

$$q(x) \sim (1-x)^3$$

$$d(z) \sim (1-z)$$

$$\sigma(x) \propto (1-x_F)^5 + Order[(1-x_F)^6]$$

$$\sigma(x) \propto (1-x_F)^5$$

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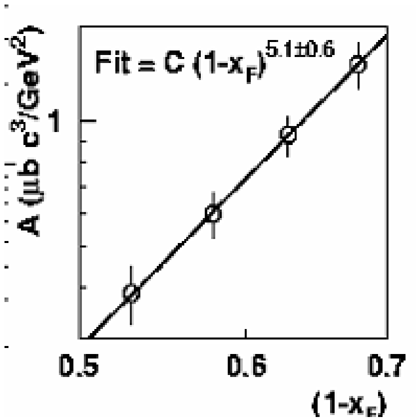
Forward Pi0 Cross Sections Scale Like seen in ISR.

At Large X_F (ie. X_F>0.4) , the Pi^0 fragment carries most of the of the jet momentum (<z> > 75%).



$$E\frac{d^3\sigma}{dp^3} \propto (1-x_F)^N p_T^{-B}$$

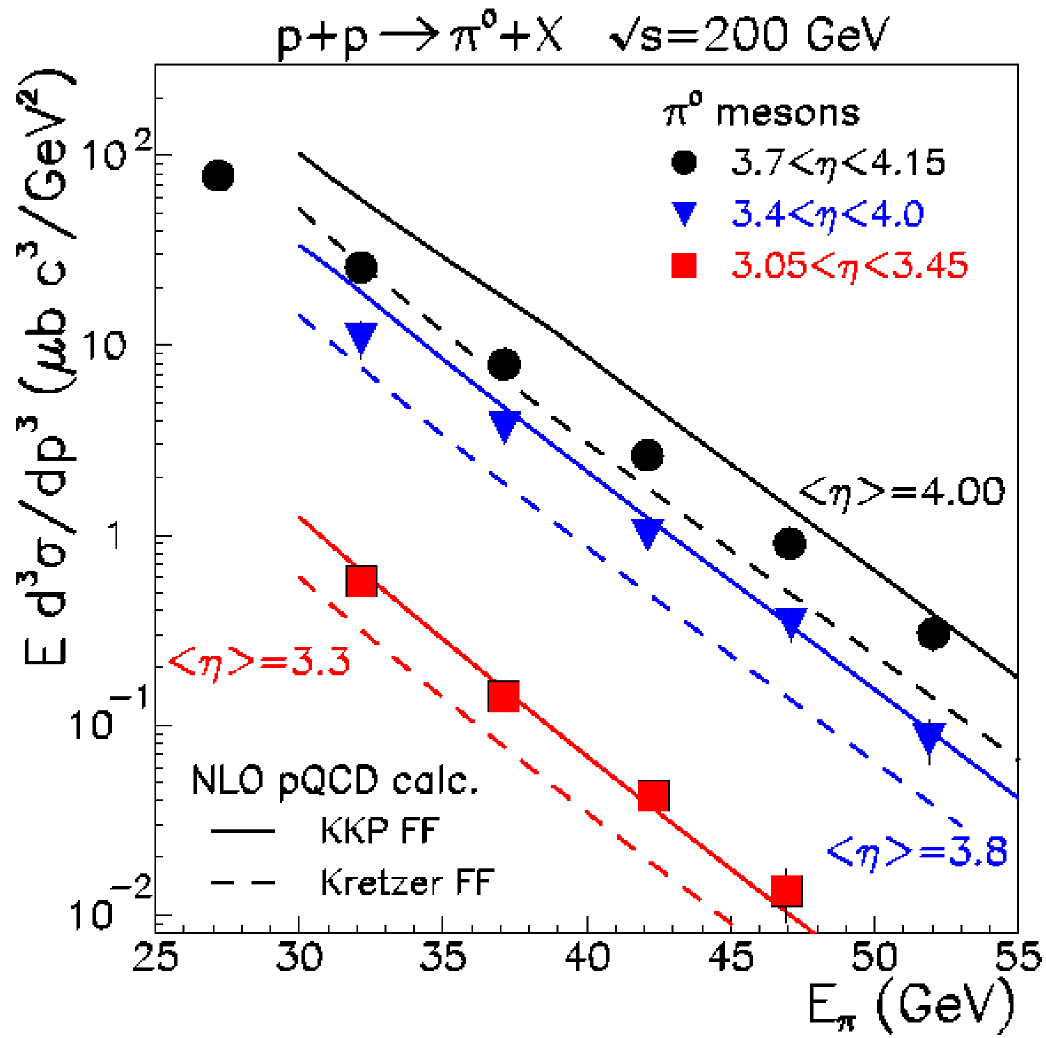
$$N \approx 5$$

$$B \approx 6$$

STAR Published Result is similar to to ISR analysis J. Singh, et al Nucl. Phys. B140 (1978) 189.

$$\propto e^{-\frac{2(N+B)}{100}E} = e^{-\frac{2(11)}{100}E} = e^{-.22\,E}$$

$$for\ \{20 < E < 80\} GeV$$



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Alternatives to Factorized PQCD Lead to very different cross sections

- Preliminary look at invariant cross section are likely consistent with conventional

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

- In contrast, analysis of low p_T **Regge type processes** lead to **to a different form** for the dependence of the cross section on $(1-x_F)$ as Feynman x_F approach unity.

Regge Cross Section $\propto (1-x_F)^2$

L.L.FrankFurt and M.I. Strikman, Vol. 94B2 Physics Letters, 28 July 1980.
and Private Communication.

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General Issues: Transverse SSA with Factorization in the Context of Collins/Sivers ….

$$P_T = p_T^{\,hard\,scattering} + k_T^{\,Collins/Sivers}$$

$k_T^{\,Collins/Sivers}$ changes sign if proton transverse spin changes sign.

Does $k_T^{\,Collins/Sivers}$ depend upon $p_T^{\,hard\,scattering}$?

By Definition Factorization Implies NO!!!!

$$A_N(P_T) = \frac{\sigma\left(p_T + \langle k_T \rangle\right) - \sigma\left(p_T - \langle k_T \rangle\right)}{2\sigma(P_T)}$$

$$\sim \frac{1}{\sigma}\frac{d\sigma}{dP_T}\langle k_T \rangle$$

pQCD: $\sigma \propto \left(\frac{1}{p_T}\right)^N \rightarrow A_N \propto \frac{1}{p_T}$

Exponential: $\sigma \propto e^{-k\,p_T} \rightarrow A_N \propto const$

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So factorization can *imply* a direct relation between p_T dependence of A_N

and the p_T dependence of cross section.

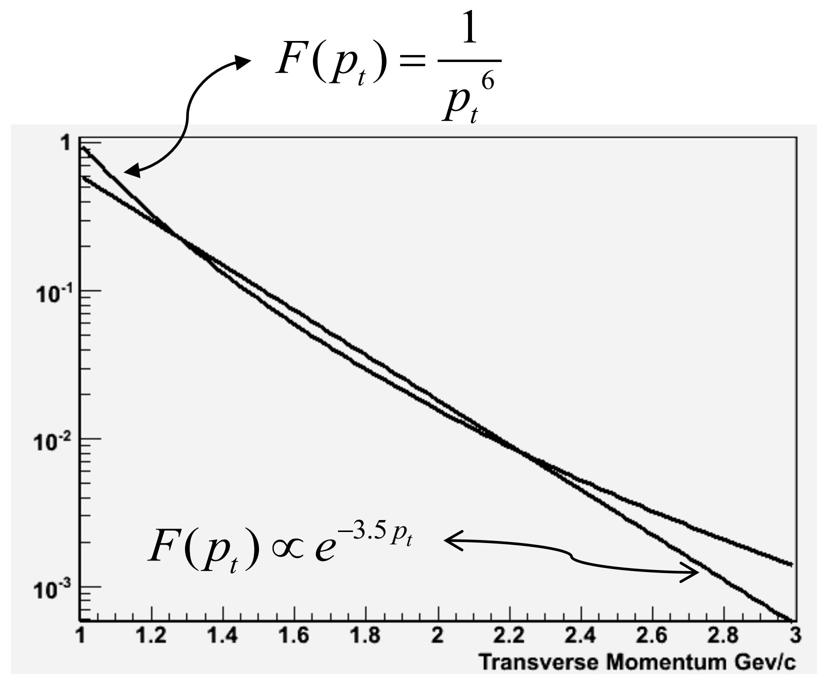
pQCD: $\sigma \propto \left(\frac{1}{p_T}\right)^N \rightarrow A_N \propto \frac{1}{p_T}$

Exponential: $\sigma \propto e^{-k\,p_T} \rightarrow A_N \propto const$

<u>**In FMS:**</u>

<u>p_T dependence</u>
Involves measurement of variation from cell to cell.

Requires all neighboring cells to have accurate gain determination.



<u>x_F dependence</u> involves energy distribution within one or a few cells

This is opposite in central region!!

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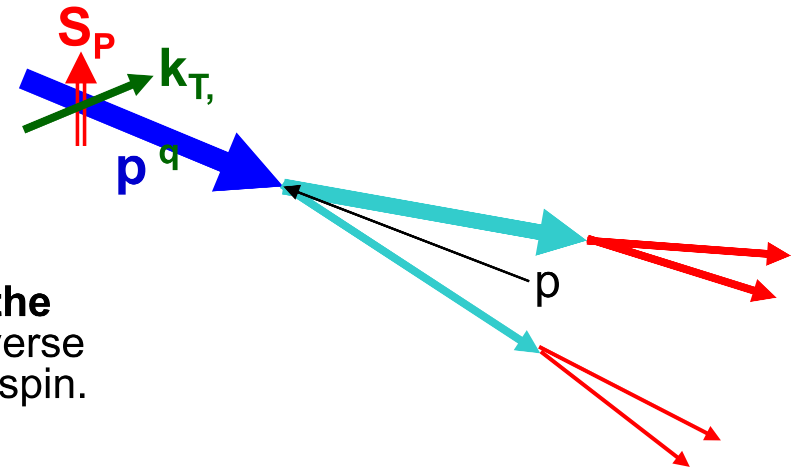
Sivers Model

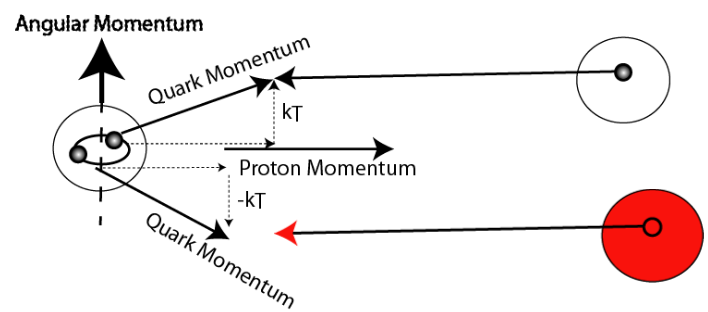
Difference Between π^0 and η A_N?



- A fast quark in the polarized proton (probably a u quark) has initial **transverse motion relative to the incident proton direction**. The sign of this transverse momentum is connected to the proton transverse spin.

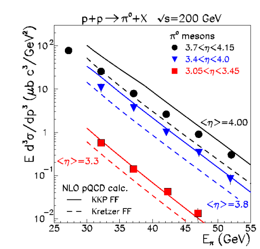
- The jet has transverse momentum

$$P_T = p_T^{\text{hard scattering}} + k_T$$



- $\langle k_T \rangle$ changes sign if the spin and angular momentum is reversed.

  "T" symmetrical "$-k_T$" amplitude absorbed as quark in one nucleon passes through gluon field of other nucleon. ("Wilson Line")
  Breaking of Factorization!!!!



- The jet fragments with large z to produce a **meson that is moving in the direction of the jet**, with nearly p_T of the jet.
- Dependence of **initial state k_T** upon proton spin leads to Sivers A_N.
- Shape of **cross section similar for pi0 and eta**.
- This situation should be the **same whether** the jet fragments into a **pi0 or an eta**.

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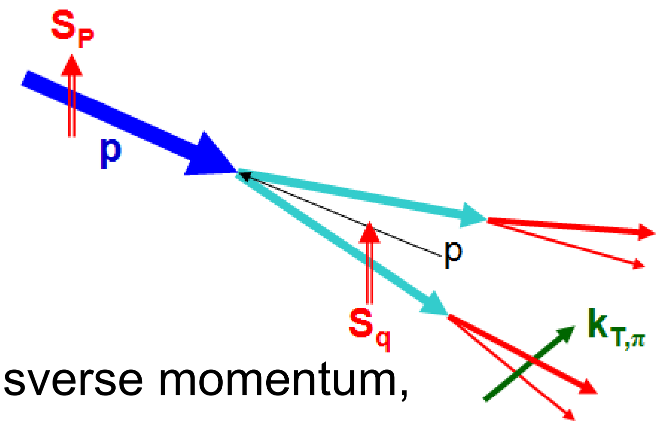
Collins Model



k_T and thus A_N vanishes as Z approaches 1

- Consider large eta A_N (perhaps of order unity)
  X_F~0.75 , **Z~ .9** and **p_T~3.9 GeV/c**.
- Any associated jet fragments will carry limited transverse momentum,

$$k_T \sim \frac{(1-Z)\, p_T}{2}$$

- If the cross section is given by $\dfrac{(1-x_F)^5}{p_T^{\;6}}$
- The Maximal asymmetry from fragmentation $p_T \rightarrow p_T + Sin(\phi) k_T$

$$\phi = fragmentation \;\; azimuthal \;\; angle \; from \; spin \; direction$$

- Leads to an **<u>extreme limit</u>** for A_N from fragmentation,

$$A_N < \frac{6k_T}{p_T} \sim 3(1-Z) \sim .6$$

This is the most extreme case including

- 100% transverse parton polarization
- the maximum possible Collins Fragmentation function.

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P_t Dependence in Calculations of A_N

•Sivers Effect / Collins Effect

•introduce transverse spin dependent **offsets in transverse momentum** ….

•independent of the hard scattering (definition of factorization).

$$P_T \Rightarrow P_T \pm k_T$$

"±" depending on the sign of proton transverse spin direction. **Using our (STAR) measured cross section form:**

$$d\sigma^{\uparrow} \propto \frac{1}{(P_T - k_T)^6} \qquad d\sigma^{\downarrow} \propto \frac{1}{(P_T + k_T)^6}$$

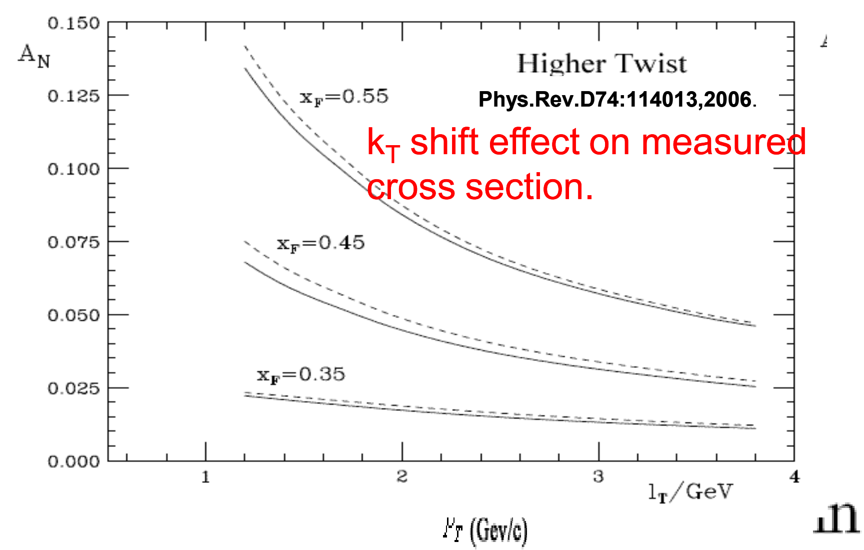
$$A_n \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{6k_T}{P_T} + O\left(\frac{k_T}{P_T}\right)^2$$

Higher Twist Effects:

Qiu and Sterman
Kouvaris et. al. **Phys.Rev.D74:114013,2006**.

A_N Fall as $1/P_T$ as required by definition of higher twist.

All of these models lead to $A_N \sim\propto 1/P_T$



Observation of Eta Signal

- 3.5<Rapidity<3.8
- 3 columns for 3 energy bins
- 2 rows Log/Linear

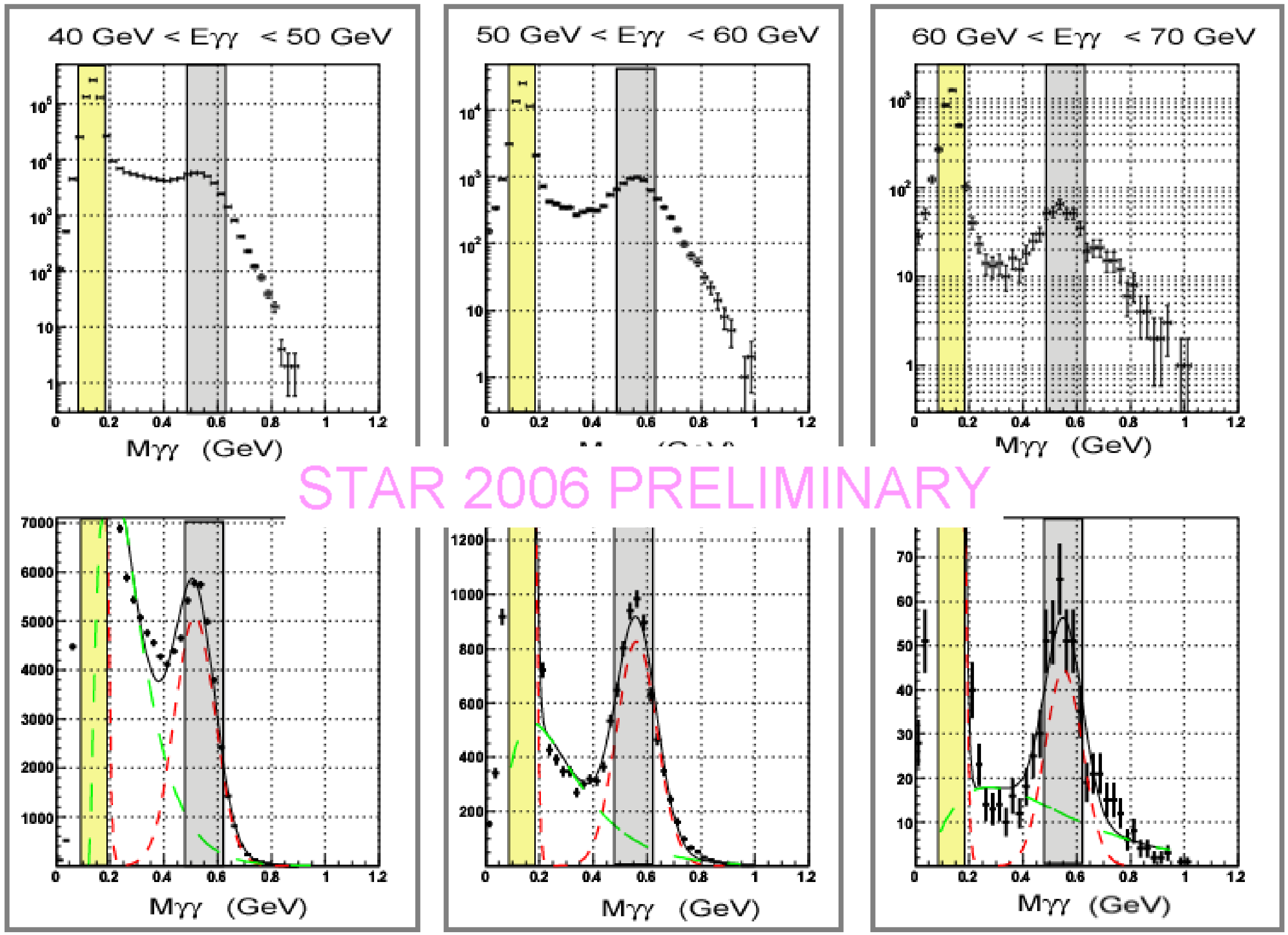
π^0 Mass Cut

$.085\,GeV < M_{\gamma\gamma} < .185\,GeV$

Eta Mass Cut

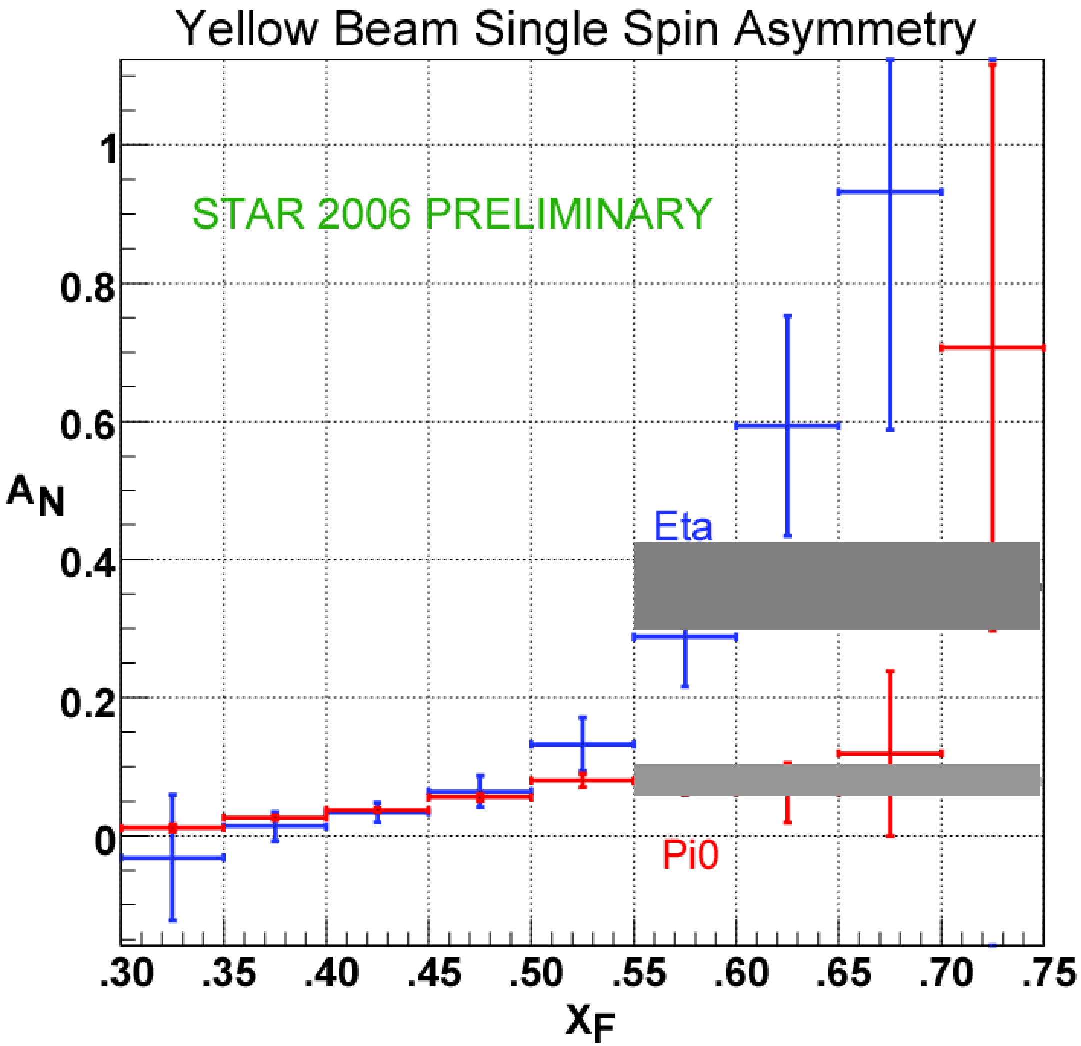
$.48\,GeV < M_{\gamma\gamma} < .62\,GeV$

Di-Photon Invariant Mass Spectra in 3 Energy Bins



$A_N(x_F)$ in π^0 and Eta Mass Regions

$$p^{\uparrow} + p \rightarrow M + X \qquad \sqrt{s} = 200\, GeV$$
$$M \rightarrow \gamma + \gamma$$



1. $N_{photon} = 2$
2. Center Cut (η and ϕ)
3. Pi0 or Eta mass cuts
4. Average Yellow Beam Polarization = 56%

$$.55 < X_F < .75$$
$$\langle A_N \rangle_{\eta} = 0.361 \pm 0.064$$
$$\langle A_N \rangle_{\pi} = 0.078 \pm 0.018$$

For $.55 < X_F < .75$, the asymmetry in the η mass region is greater than 5 sigma above zero, and about 4 sigma above the asymmetry in the π^0 mass region.

Comparison between *η* production and π^0 production?

- **Gluons** or ***η*** has **Isospin I=0**.
- **u quark** has **Isospin I=1/2**
- **π^0** has **Isospin I=1**.

- But we expect both mesons to come from **<u>fragmentation of quark jets</u>**.

$$I = 0 \quad \begin{cases} \eta \simeq \quad + d\bar{d} - s\bar{s}) \\ \eta' \simeq \quad + d\bar{d} + 2s\bar{s}) \end{cases}$$

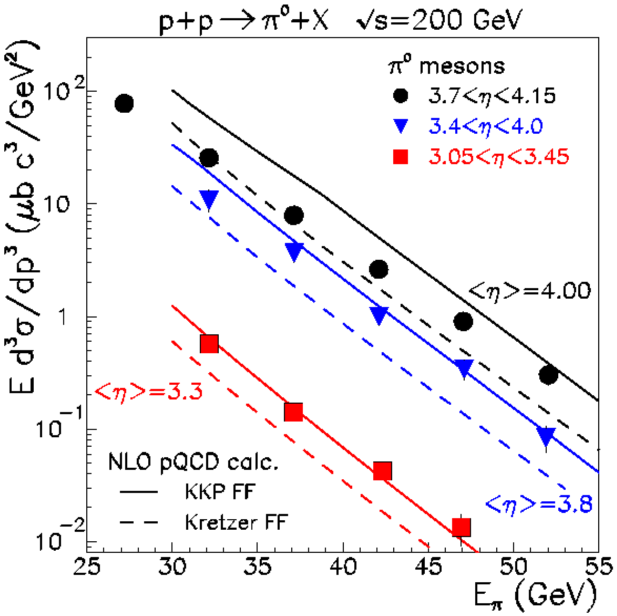
$$I = 1 \quad \left\{ \pi^0 = \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \right.$$

*Assume η, η' mixing angle: $\theta_P \sim -19.5°$

- **For Sivers Effect: Asymmetry is in the jet and should not depend on the details of fragmentation.**

- **For Collins Effect**: Asymmetry reflects fragmentation of the quark jet into a leading ***η*** or **π^0** meson. Differences in fragmentation could relate to:
  - Mass differences?
  - Isospin differences?
  - Role of Strangeness?
  - **But Collins Effect Should be suppressed when Z→1**

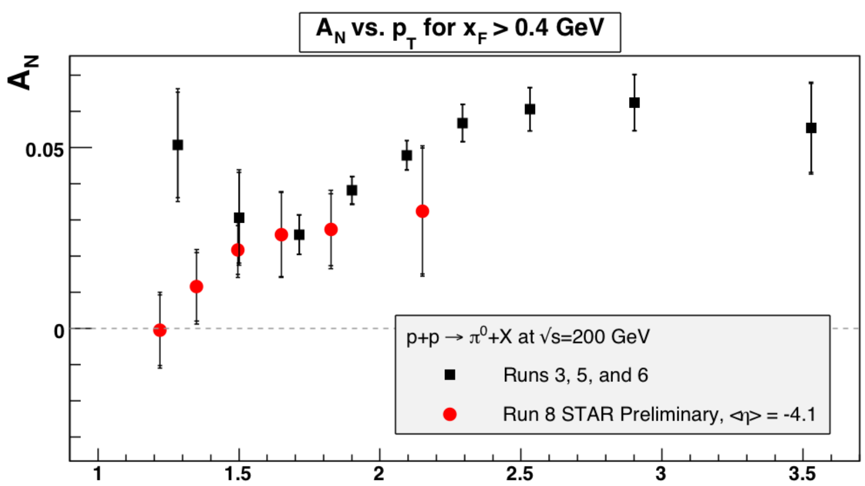
Forward π^0 Single Spin Asymmetry



Phys. Rev. Lett. 97 (2006) 152302

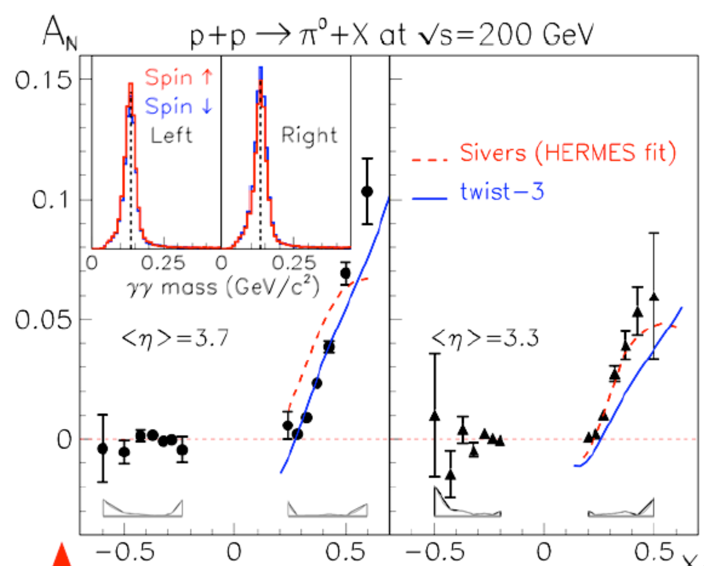
At $\sqrt{s}$=200GeV, π^0 cross-section measured by STAR FPD is consistent with the NLO pQCD calculation. Results at <η>=3.3 and <η>=3.8.

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



Black points: *arXiv:0801.2990v1 [hep-ex]*

From Spin2008 talk by J.Drachenberg



arXiv:0801.2990v1 [hep-ex]

Phys.Rev.Lett.101:222001,2008.

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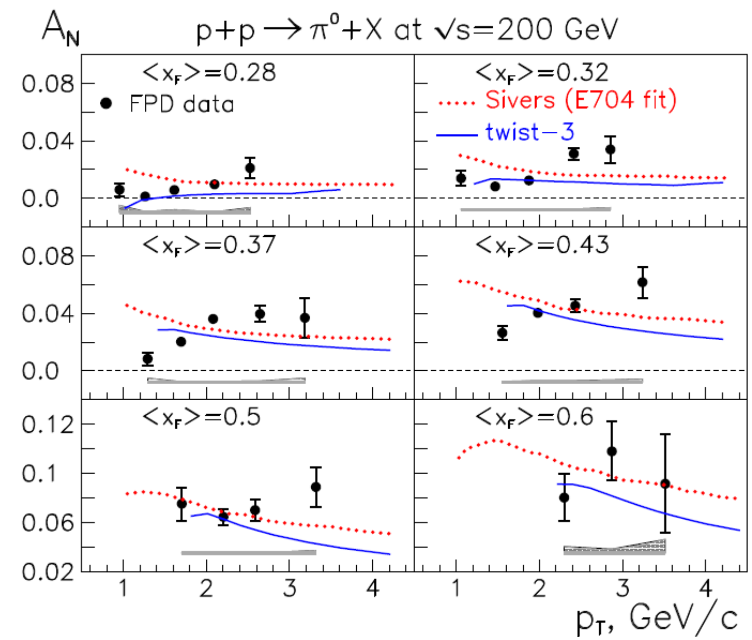
For Fixed X_F, the asymmetry A_N does not fall with P_t as predicted by models.

- NLO PQCD **does describe** the size and shape of this forward pp cross section.
- Model calculations (Sivers, Collins or twist-3) **can explain** the X_F dependence of A_N.
- Flat or increasing dependence of A_N on P_T



U. D'Alesio, F. Murgia, Phys. Rev. D **70**, 074009 (2004).
J. Qiu, G. Sterman, Phys. Rev. D **59**, 014004 (1998).

Theory Score Card For Factorized QCD Picture for Pi & Eta Transverse A_N

✓ Cross Section for Pi0 agrees with PQCD (Normalization and Shape)	✓ Dependence of cross section on X_F and Pt may be similar for Pi0 and Eta at large X_F as expected.	✓? Ratio Eta/Pi0 nominal 40% - 50% Yet to be determined.	✗ Pt Dependence of Pi0 A_N . Inconsistent with $A_N \sim 1/p_T$.

Can a large difference in asymmetry between Pi0's and Eta's be understood in either Collins or SIvers Model?

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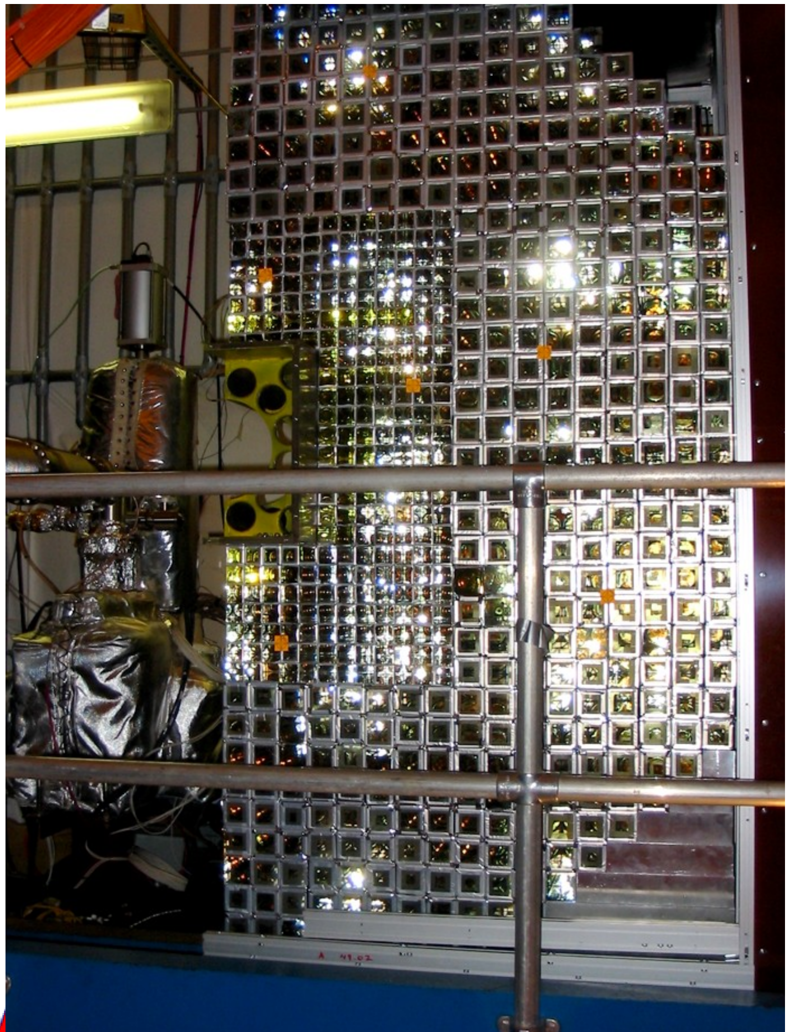
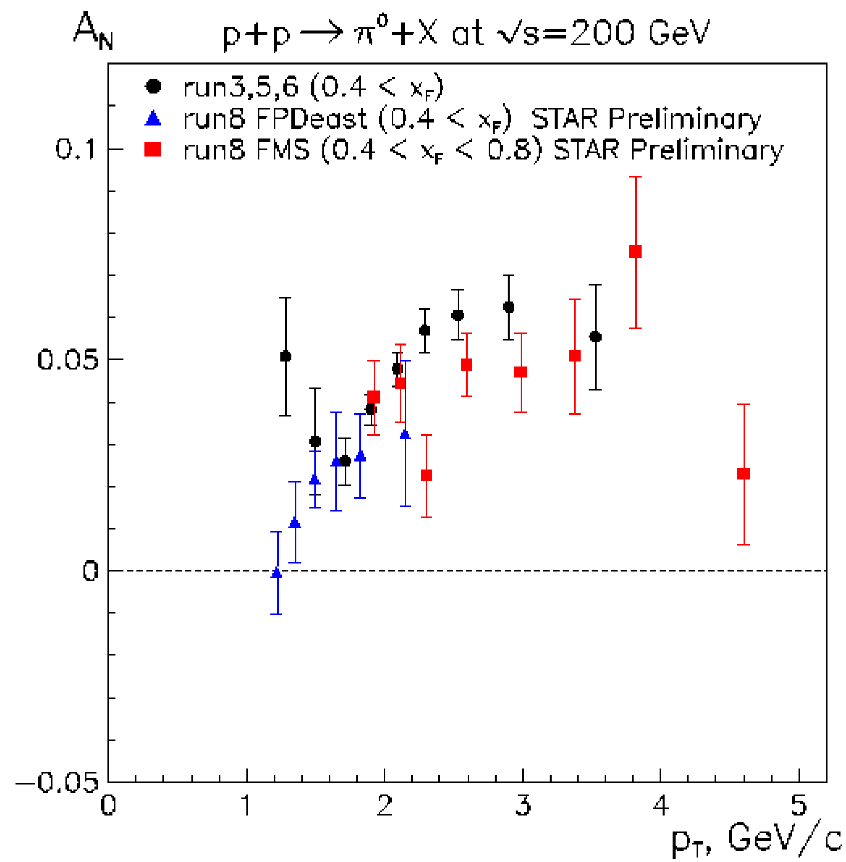
With FMS, STAR has Expanded Rapidity Coverage -1<Y<4.2

STAR Forward Meson Spectrometer
2.5 < Y < 4.0





arXiv:0901.2763 +
A.Ogawa @CIPANP09

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Sensitivity for Future STAR Forward Measurements

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200 GeV Transverse Spin Program

$\sqrt{s}$	Transverse Process	Collins	Sivers	Sivers SIDIS Sign Change	$\int L$	Detectors
200 GeV	$p^{\uparrow} + p \rightarrow \pi^0 + X$	*	*		30 pb^{-1}	FMS
	$p^{\uparrow} + p \rightarrow \eta + X$	*	*			
	$p^{\uparrow} + p \rightarrow \gamma + X$		*	*		
	$p^{\uparrow} + p \rightarrow \pi^0 + \pi^0 + X$	*	*			
	$p^{\uparrow} + p \rightarrow \gamma + \pi^0 + X$		*	*		
	$p^{\uparrow} + p \rightarrow \pi^0 + \pi^0 + X$	*	*			FMS+EMC
	$p^{\uparrow} + p \rightarrow jet + X$	*	*			FMS+HCAL
	$p^{\uparrow} + p \rightarrow jet + \pi^0 + X$	*	*			
	$p^{\uparrow} + p \rightarrow \Lambda + X$	*	*			
	$p^{\uparrow} + p \rightarrow jet + jet + X$	*	*			FMS+EMC
	$p^{\uparrow} + p \rightarrow \gamma + jet + X$		*	*		HCAL +Tracking

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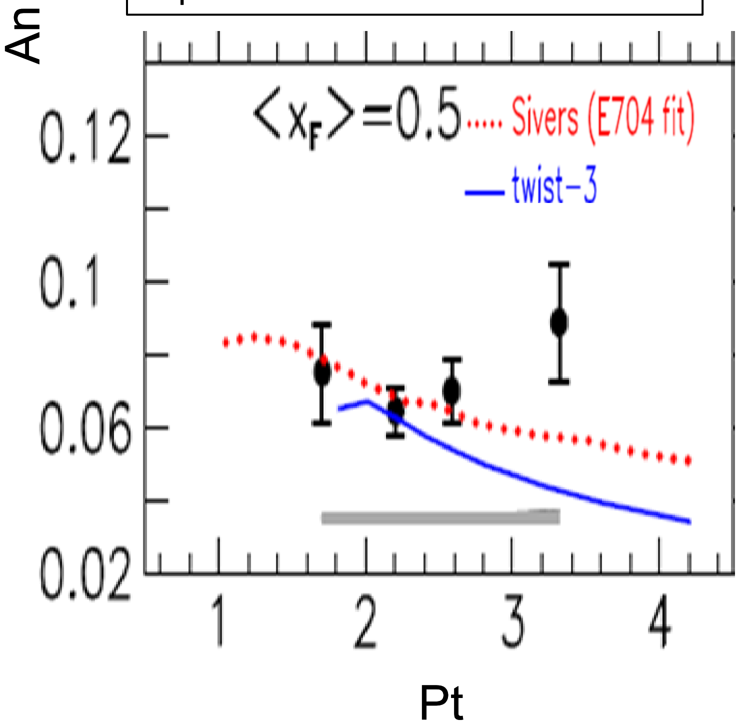
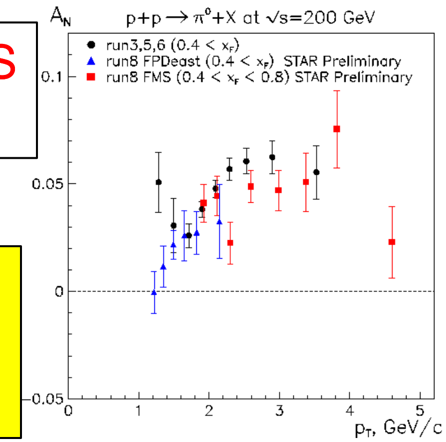
$A_N \ \pi^0$

$\sqrt{s} = 200\,GeV$

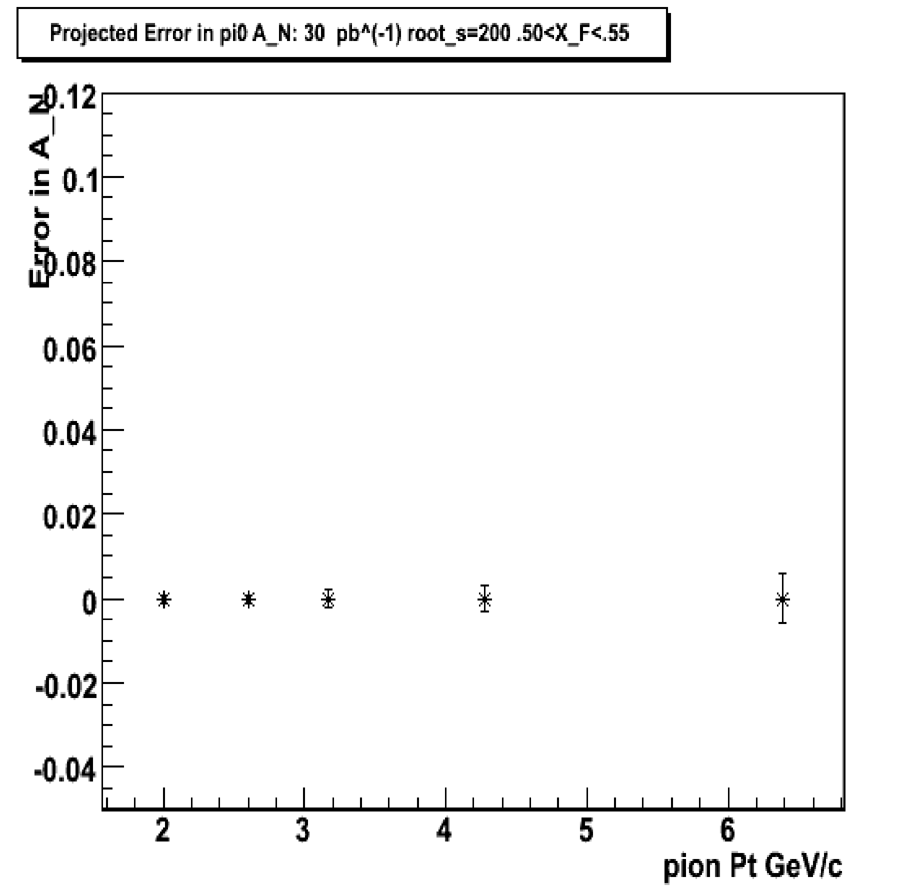
Run 6 FPD Pt Dependence
$X_F \sim 0.5$



Run 6 FPD+ Run 8 FMS
Pt Dependence X_F>0.4



Errors for Projected
FMS Pt dependence
0.5< X_F <0.55



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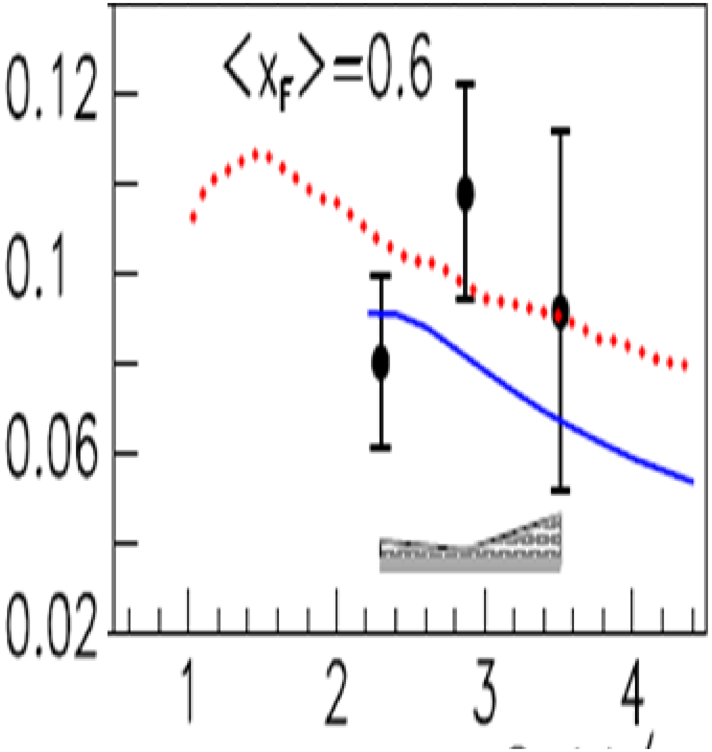
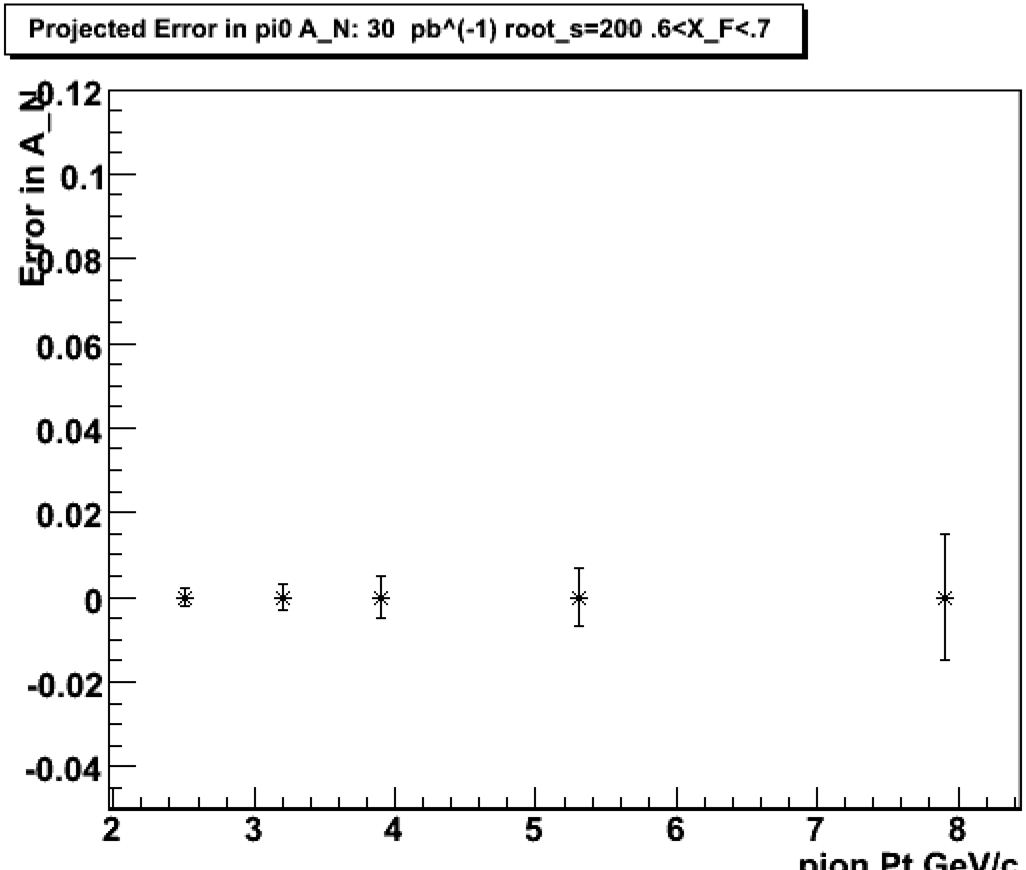
$A_N \; \pi^0 \quad \sqrt{s} = 200\,GeV$

Run 6 FPD Pt Dependence
$X_F \sim 0.6$



Errors for Projected FMS Pt dependence
$0.6 < X_F < 0.65$



$A_N(x_F)$ in π^0 and Eta Mass Regions

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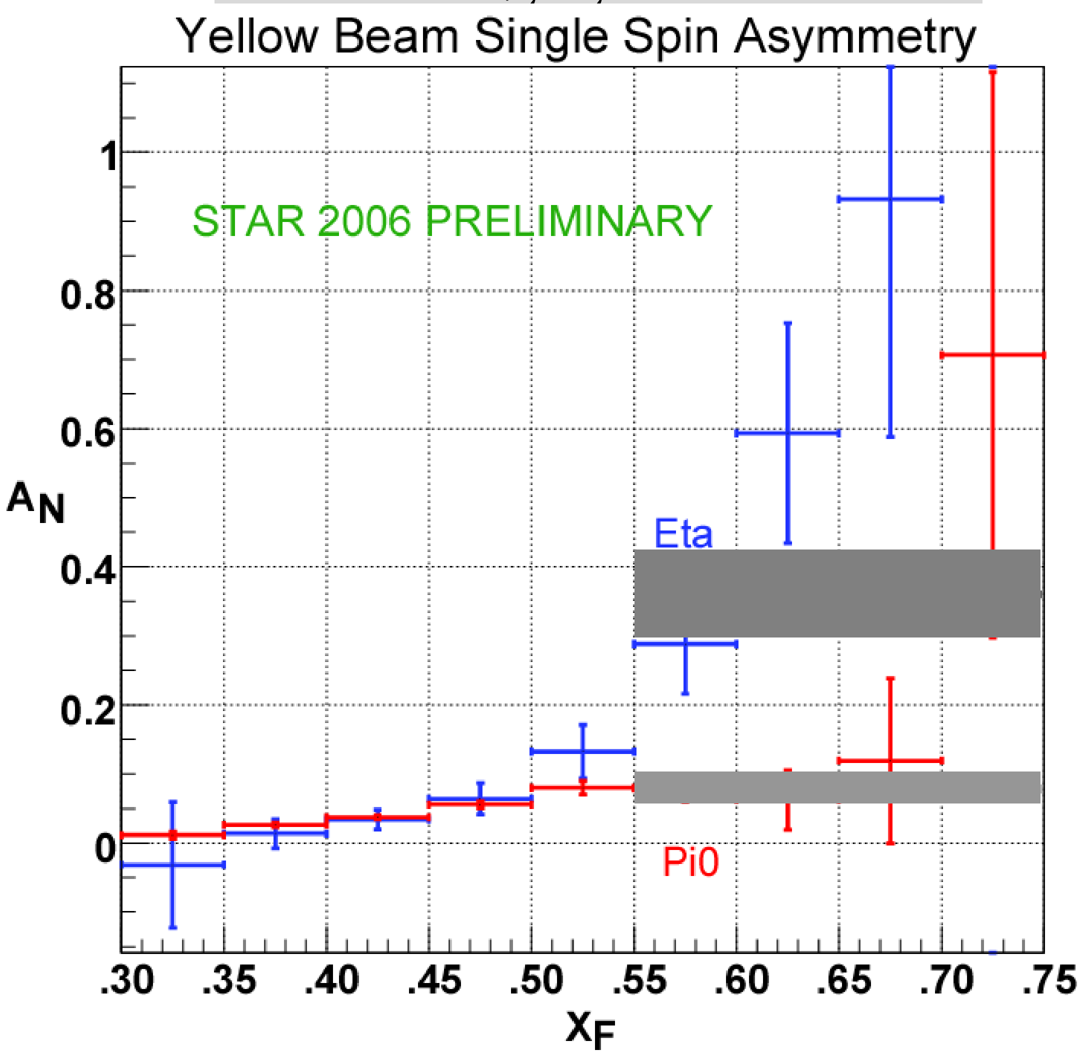

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$$\langle A_N \rangle_\eta = 0.361 \pm 0.064$$
$$\langle A_N \rangle_\pi = 0.078 \pm 0.018$$

For $.55 < X_F < .75$, the asymmetry in the η mass region is greater than 5 sigma above zero, and about 4 sigma above the asymmetry in the π^0 mass region.

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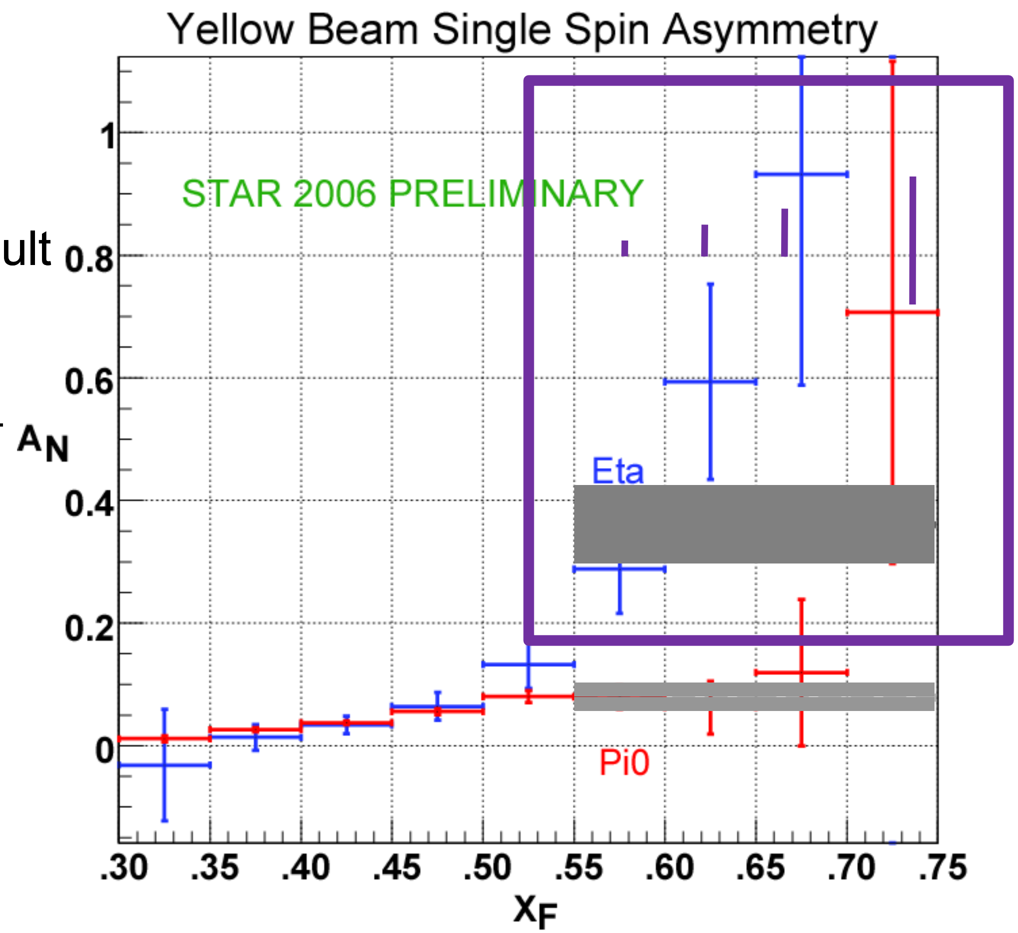
Run 6 FPD Result

$.55 < X_F < .75$

$\langle A_N \rangle_\eta = 0.361 \pm 0.064$

$\langle A_N \rangle_\pi = 0.078 \pm 0.018$

Projected Errors
For Eta A_N
200 GeV
30 pb^{-1}



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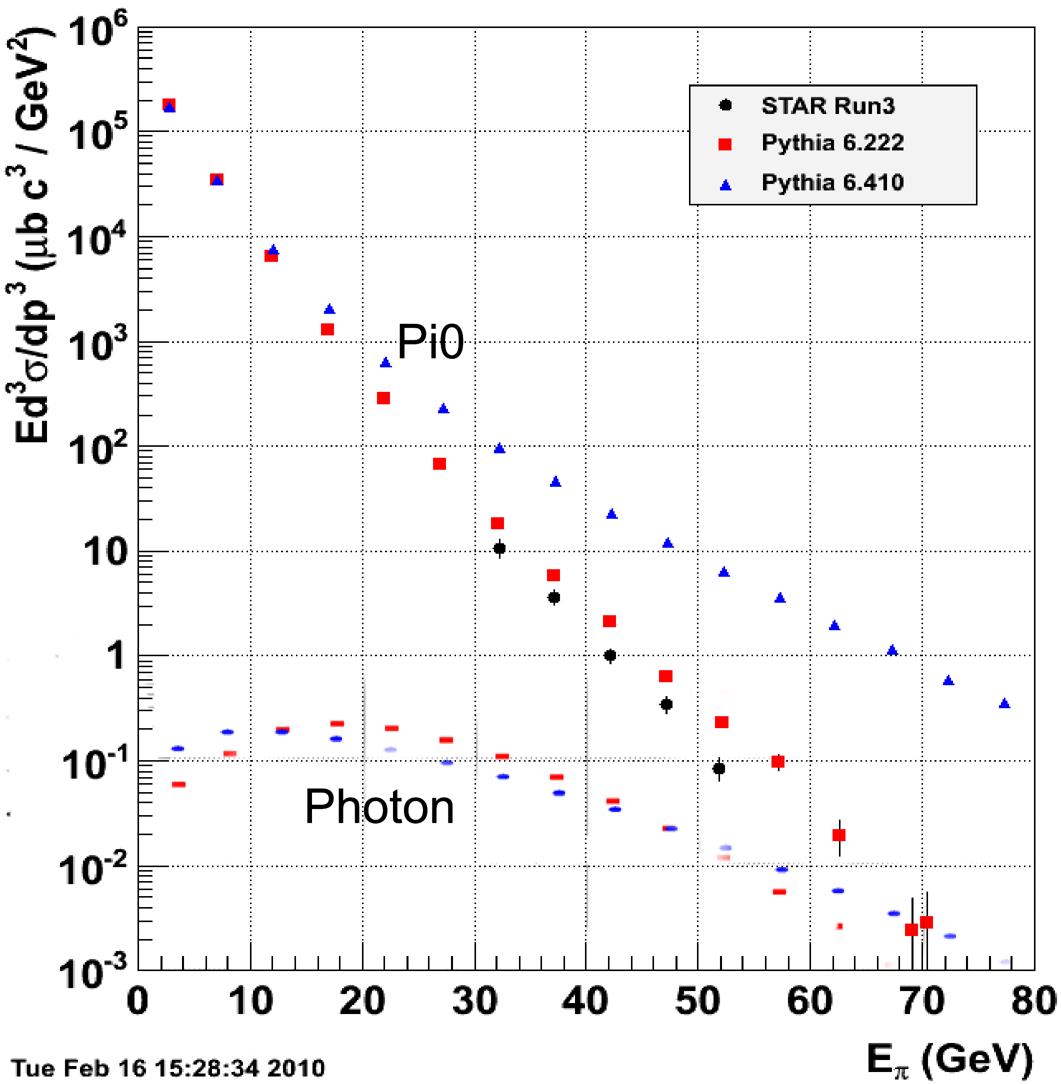
Photons: 200 GeV



What Pythia says For π^0 and γ

STAR data

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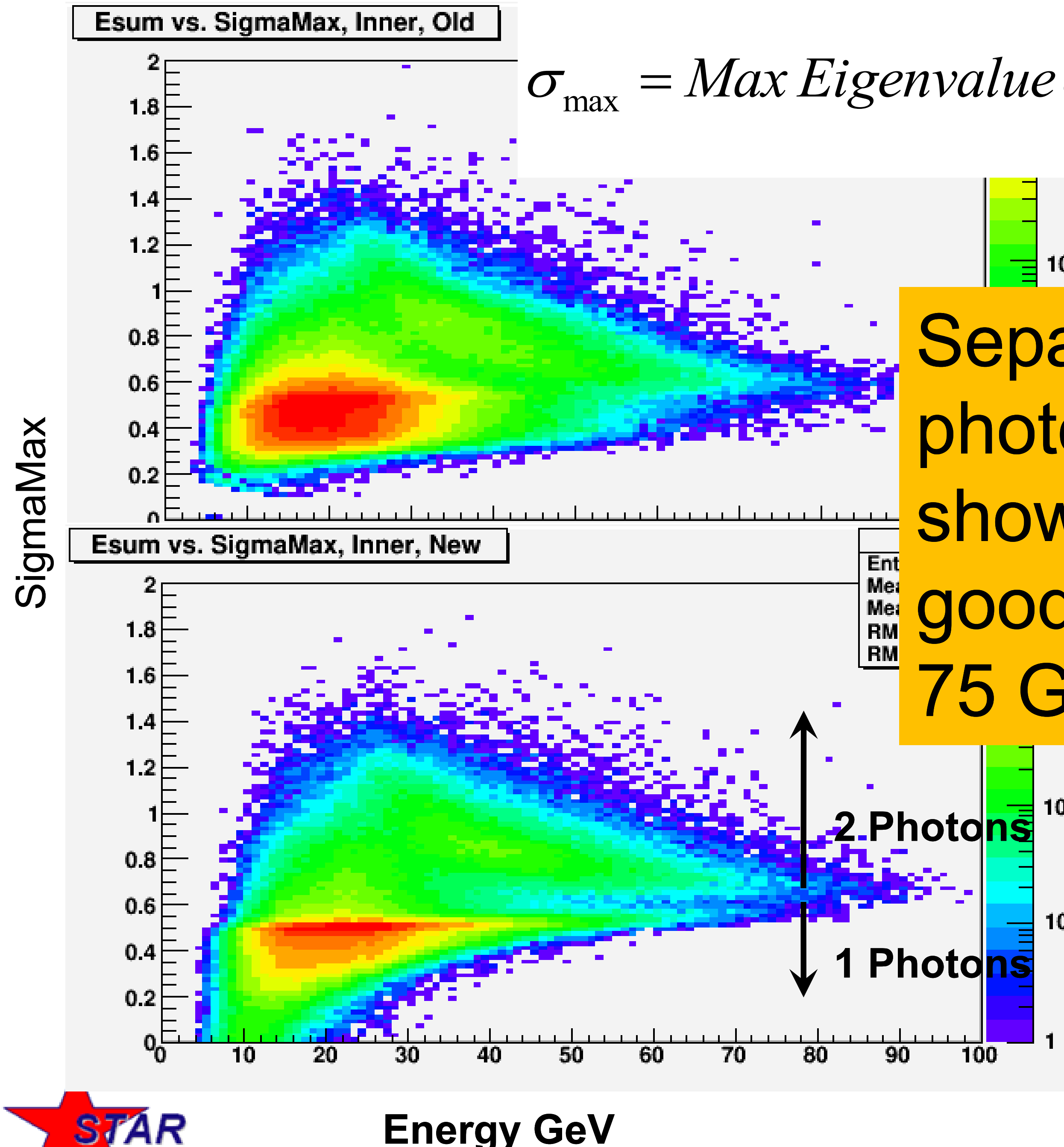
$$\sigma_{\max} = Max\ Eigenvalue\ of \begin{bmatrix} \Delta\sigma_x{}^2 & \Delta\sigma_x\Delta\sigma_y \\ \Delta\sigma_y\Delta\sigma_x & \Delta\sigma_y{}^2 \end{bmatrix}$$



Separation of 1 vs 2 photons based on shower shape good to beyond 75 GeV

<u>Separation of single photon from two photon cluster based upon shower shape.</u>

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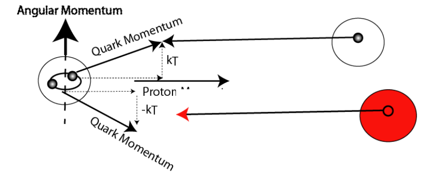
Direct Photon A_N Measurement



- <u>Predicted violation of factorization</u>
  - If Sivers is mechanism: a sign change is predicted between Direct Photon and DIS.
  - No Collins effect in Direct Photon A_N.
- **Measurement of predicted sign change vs A_N in DIS is a milestone goal from Nuclear Science Advisory Committee.**
- For X_F>.5, single photon cross section similar to π^0 cross section.
- Separation of 1 photon from 2 photon clusters based upon shower shape.
- Statistical errors similar to that for π^0.
- Full errors dominated by background subtraction. (π^0 and η).

500 GeV Transverse Spin Program

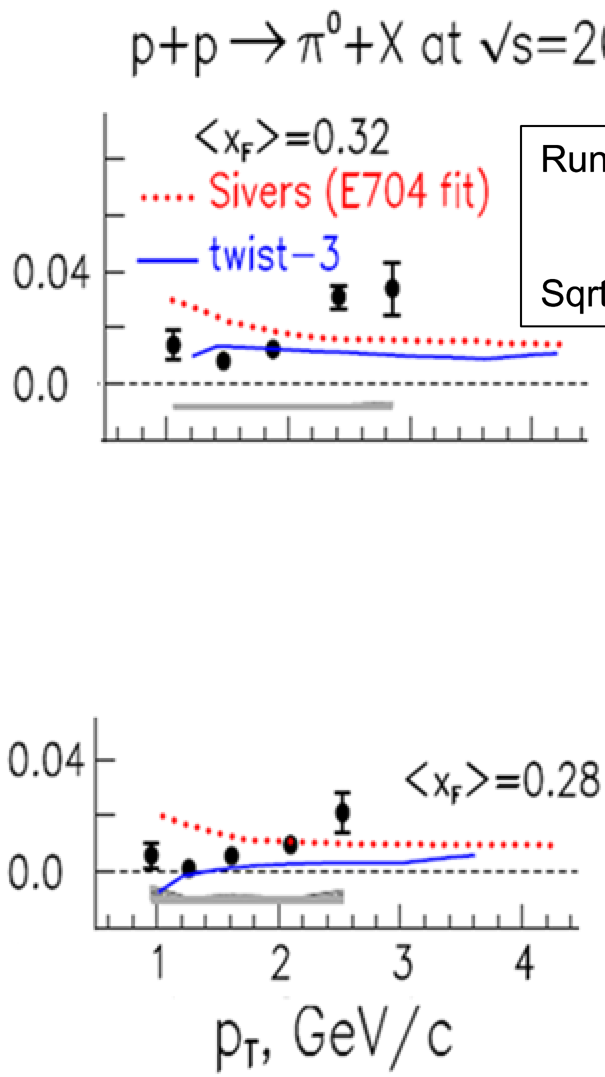
$\sqrt{s}$	Transverse Process	Collins	Sivers	Sivers SIDIS Sign Change	$\int L$	Detectors
500 GeV	$p^{\uparrow} + p \rightarrow \pi^0 + X$	*	*		20 pb^{-1}	West FMS East FPD +Shower Max
	$p^{\uparrow} + p \rightarrow \eta + X$	*	*			
	$p^{\uparrow} + p \rightarrow \gamma + X$		*	*		
	$p^{\uparrow} + p \rightarrow \pi^0 + \pi^0 + X$	*	*			
	$p^{\uparrow} + p \rightarrow \gamma + \pi^0 + X$		*	*		
	$p^{\uparrow} + p \rightarrow \pi^0 + \pi^0 + X$	*	*			FMS+EMC
	$p^{\uparrow} + p \rightarrow jet + X$	*	*			FMS+HCAL
	$p^{\uparrow} + p \rightarrow jet + \pi^0 + X$	*	*			
	$p^{\uparrow} + p \rightarrow \Lambda + X$	*	*			
	$p^{\uparrow} + p \rightarrow jet + jet + X$	*	*			FMS+EMC HCAL +Tracking
	$p^{\uparrow} + p \rightarrow \gamma + jet + X$		*	*		
	$p^{\uparrow} + p \rightarrow e^+ + e^- + X$		*	*	250 pb^{-1}	FMS+EMC +Tracking +PID

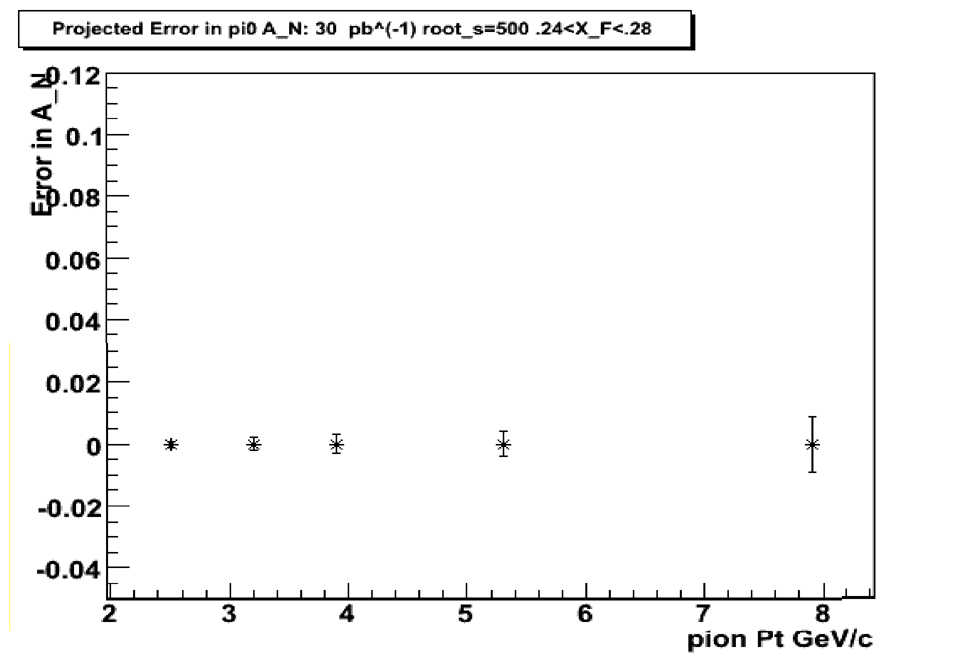
Comparison between 200 GeV Measurement and 500 GeV Projections

Projections for A_N
statistical errors
.24 < xF < .28
Sqrt(s) = 500 GeV
20 pb^{-1}

Run 6 FPD Published measurement

Sqrt(s) = 200 GeV





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Summary: About STAR Transverse SSA Measurements

- Forward and Central Rapidity Cross Sections consistent with PQCD with collinear factorization. This encourages new theoretical modeling **expanding on the essential PQCD framework**.

- In contrast to expectations, forward single spin asymmetries measured by STAR for Pi^0 mesons at fixed Feynman X_F **do not seem to fall with p_T** in the range 1GeV/c< p_T<5 GeV/c.

- At large X_F, the **Eta asymmetry may be much larger** that the Pi^0 asymmetry, which is again surprising.

- STAR will make significant high statistics measurements in the near future of transverse Single Spin Asymmetries, **with EMCal coverage over a very wide range of rapidity (-1<Y<4)** and these measurements will significantly enhance our understanding about the role of Collins, Sivers or "other" model variations of the PQCD.

Courage to Follow the Data

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