# Transverse Spin Physics at STAR

## RHIC Spin: Next Decade

Berkeley, Nov. 20-22, 2009

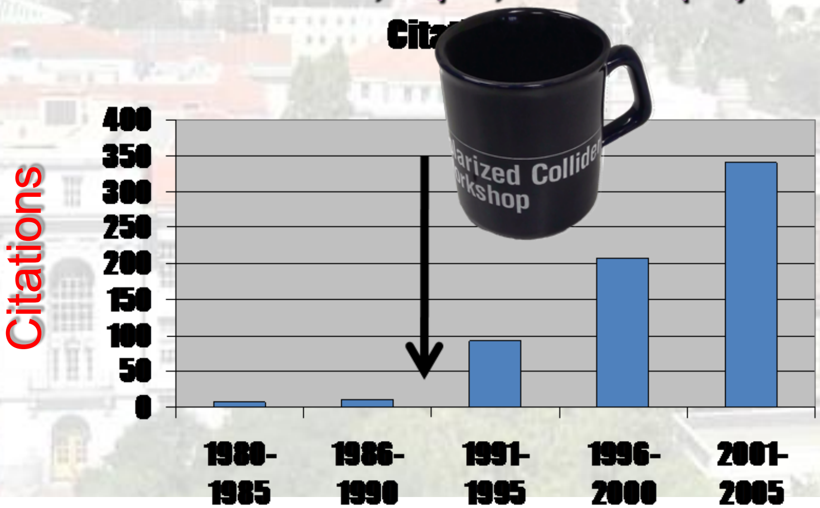
Steve Heppelmann Penn State University

Historically transverse spin has been a source of much controversy. Before 1980 transverse single spin asymmetries were such a challenge to the emerging QCD theory that they were systematically deemphasized by many. STAR and RHIC have made Giant Steps toward clarifying the nature of the Puzzle that is Transverse Spin.

This is what research is supposed to be!
The Citations tell the story.

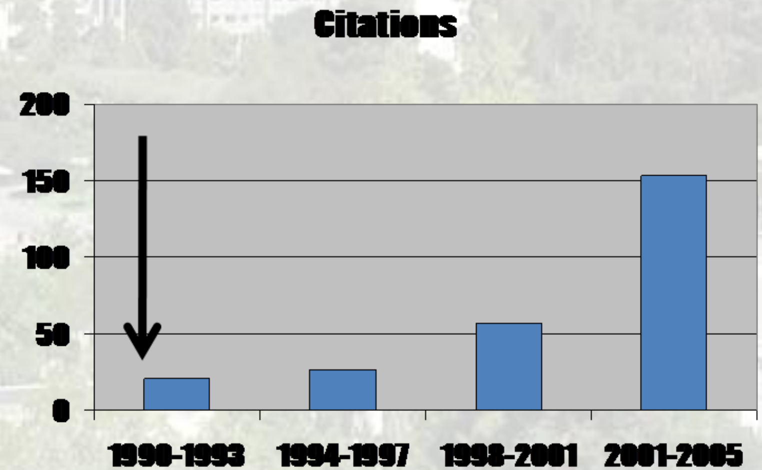
**Transversity: birth and growth**

*Ralston, Soper, NPB 152 (79)*




**Sivers function: birth and growth**

*D. Sivers, PRD41 (90)*




Compiled by: Alessandro Bacchetta (QCD N'06)

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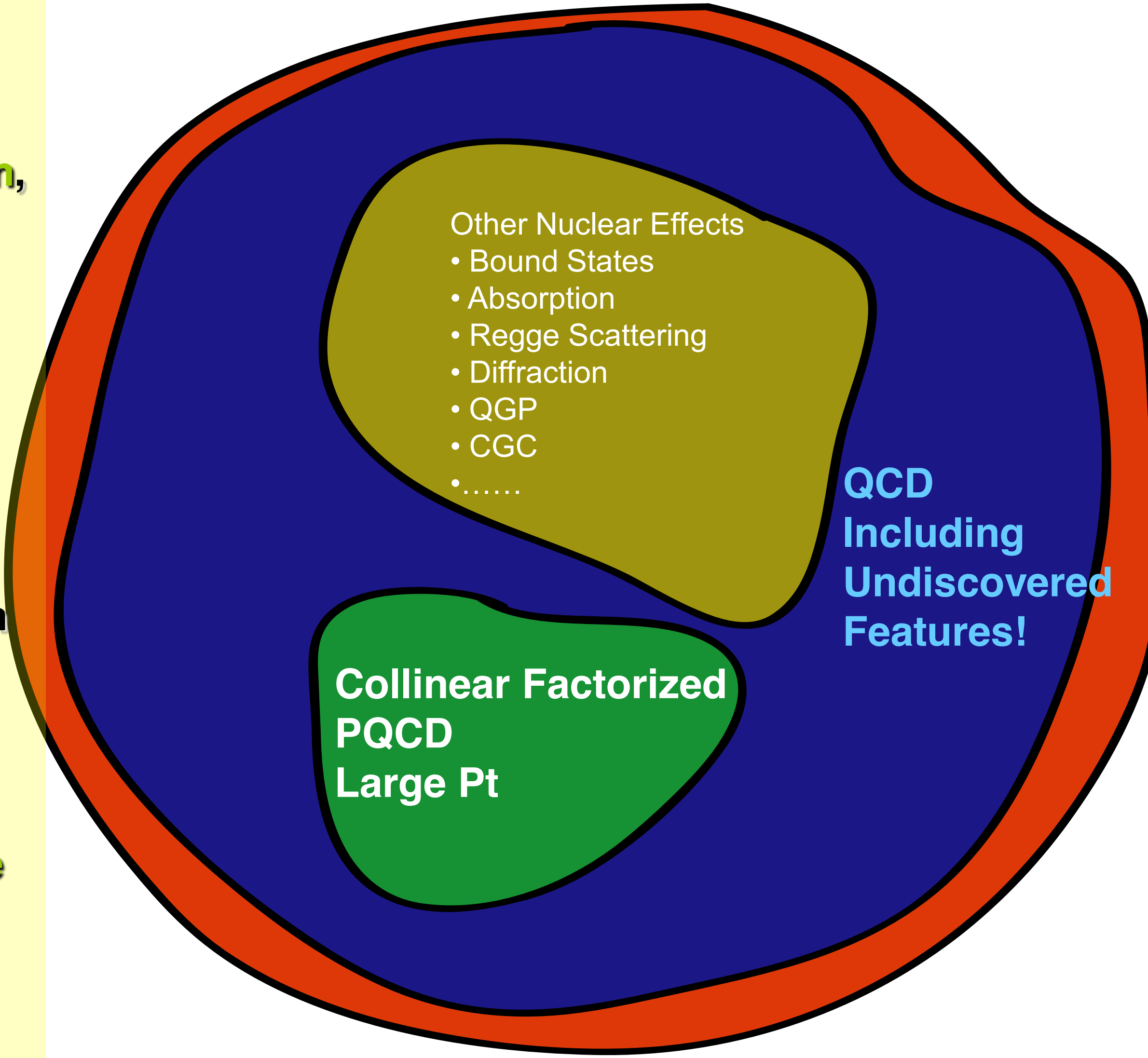
## PQCD Collinear Factorization

- 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, some hadrons, photons)
- Gives an experimental 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.




Strong Interactions

# Generalized Factorization PQCD++

- Applies to a wider variety of experimental measurements.

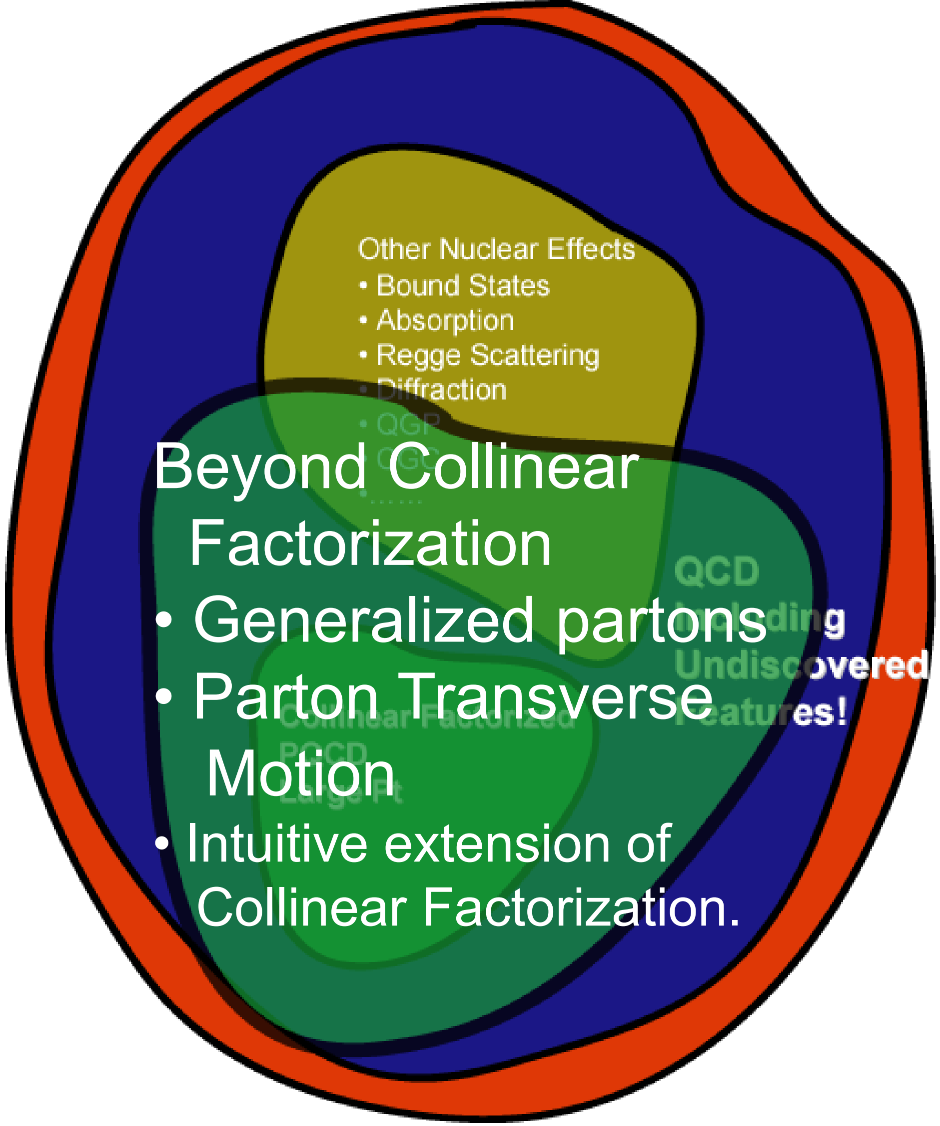
- Gives similar meaning to quark and gluon, the confined internal degrees of freedom (DOF) in QCD. **(same)**

- 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 rules as to when calculations are most likely dependable.**




**Strong Interactions**

## *Previous observation of Single Spin Transverse Asymmetry for Forward Production of*

***π⁺ Meson***
***π⁻ Meson***
***π⁰ Meson***
***η Meson***

**by FNAL Exp 704**
**They reported:**

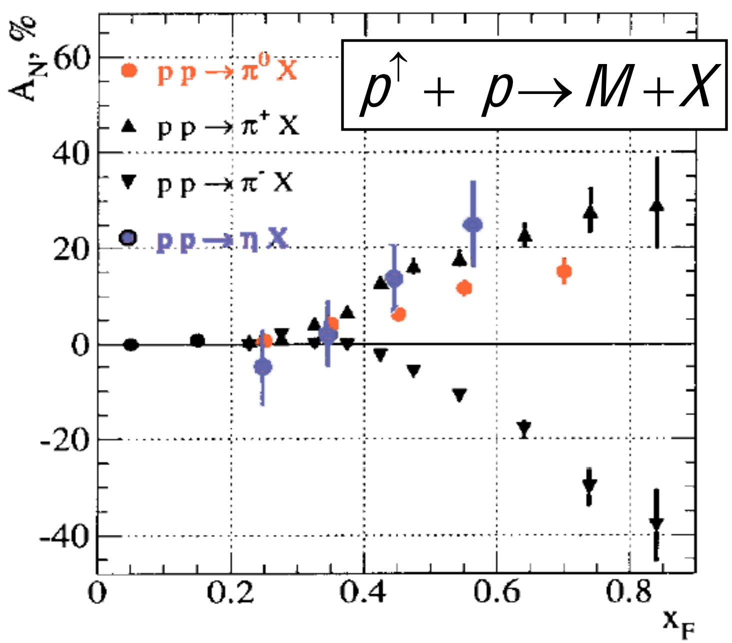
$$p^{\uparrow} + p \rightarrow M + X$$
$$\bar{p}^{\uparrow} + p \rightarrow M + X$$

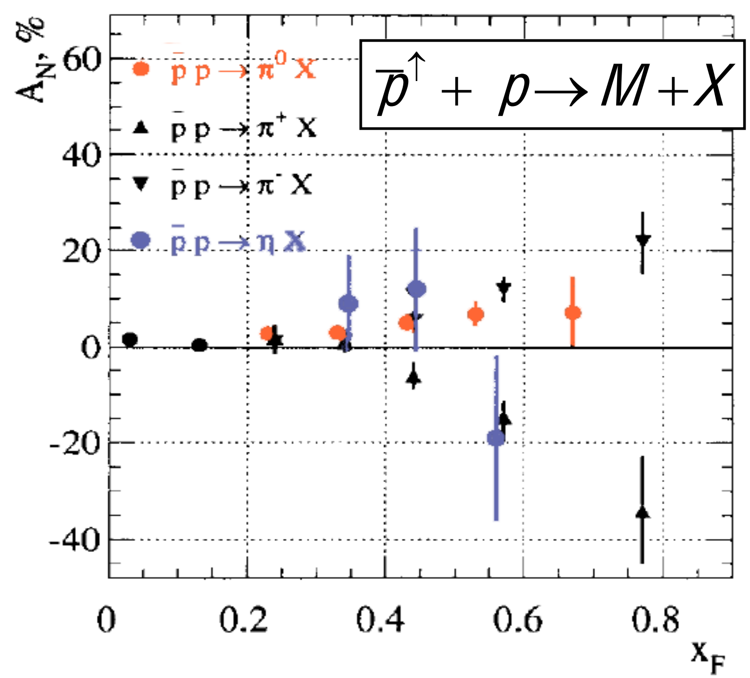
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

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

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

10 FNAL E704 Collaboration/Nuclear Physics B 510 (1998) 3–11



**Prior to 1980, much of the QCD establishment believed that Transverse Spin Asymmetries were a challenge to the broad applicability of QCD.**

**Then many PQCD proponents argued against the importance of these data.**

In this note we have pointed out that the asymmetry off a polarized target, and the transverse polarization of a produced quark in $e^+e^- \to q\bar{q}$, or in $qq \to qq$ at large $p_T$, or in leptoproduction, should all be calculable perturbatively in QCD. The result is zero for $m_q = 0$ and is numerically small if we calculate $m_q/\sqrt{s}$ corrections for light quarks. We discuss how to test the predictions. At least for the cases when $P$ is small, tests should be available soon in large-$p_T$ production [where currently $P(\Lambda) = 25\%$ for $p_T \gtrsim 2$ GeV/$c$], and $e^+e^-$ reactions. While fragmentation effects could dilute polarizations, they cannot (by parity considerations) induce polarization. Consequently, observation of significant polarizations in the above reactions would contradict either QCD or its applicability.

Kane, Pumpkin and Repko PRL 41 1978

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**Collins, Soper and Ellis Win Sakurai Prize**

**John Collins Wins 2009 J. J. Sakurai Prize for Theoretical Particle Physics**

17 October 2008 —**John Collins**, a Penn State distinguished professor of physics, has won the 2009 J. J. Sakurai Prize for Theoretical Physics for his work in perturbative quantum chromodynamics. The prize is given annually to physicists to recognize and encourage their outstanding achievements in particle theory. Collins shares the award with **Dave Soper**, a professor of physics at the University of Oregon, and **Keith Ellis**, a physicist at Fermi National Accelerator Laboratory.

A theoretical physicist, Collins focuses on the theory of strong nuclear interaction in elementary particles, known as quantum chromodynamics (QCD). He has played a vital role in formulating and proving many of the mathematical results that underly QCD calculations. Without the aid of these results, it would not be possible to interpret

**Past Recipients:**

In sharp contrast, 2009 PSU News!!!

# Transverse Spin is Starting to Get Respect

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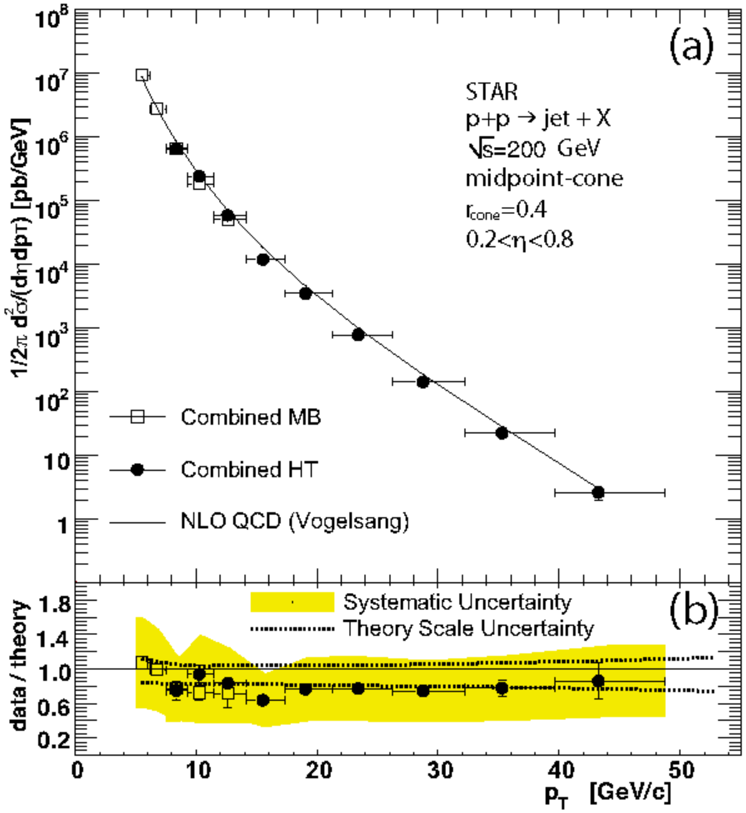
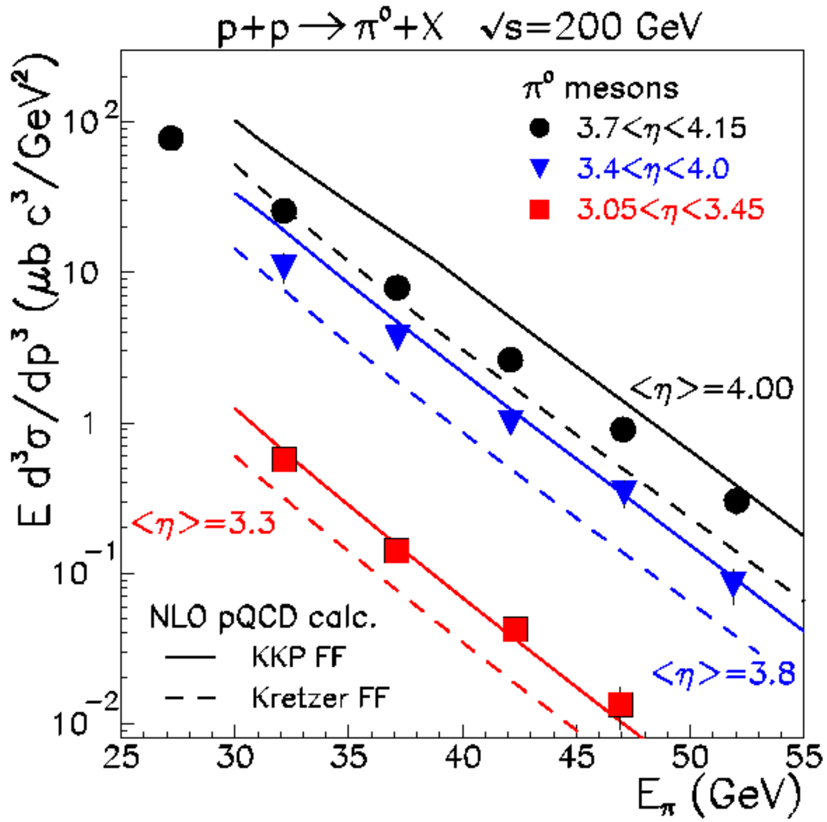
# Unpolarized Cross Sections agree with Colinear Factorization PQCD

STAR PRL 97, 252001

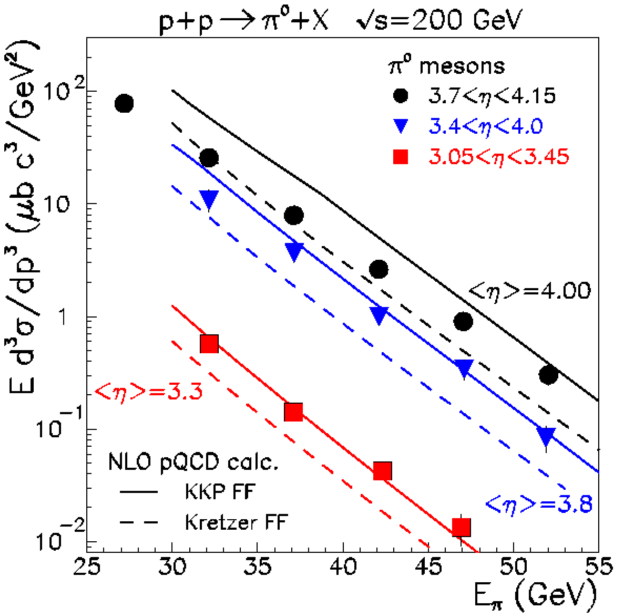



STAR PRL 97, 152302




- Jet Mid-rapidity (Left) and Pi0 Forward Rapidity (right)
- Cross section are consistent with NLO pQCD.

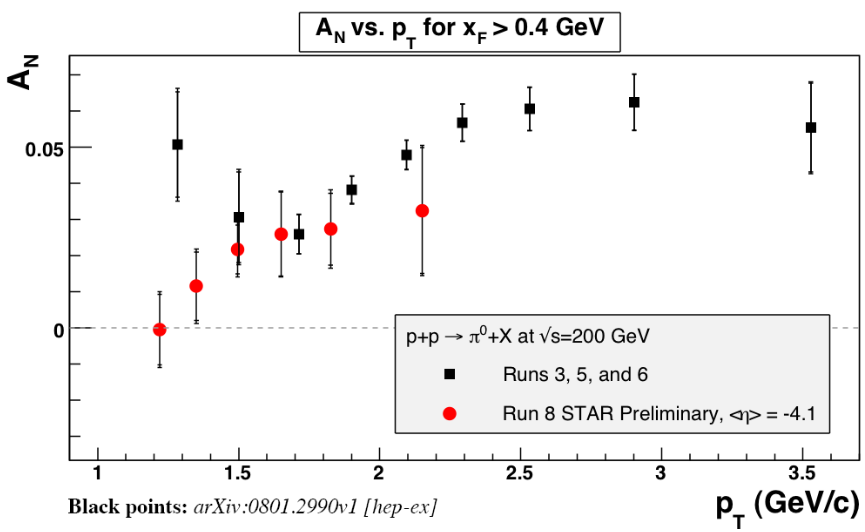
# Forward $\pi^0$ Single Spin Asymmetry




*Phys. Rev. Lett. 97 (2006) 152302*

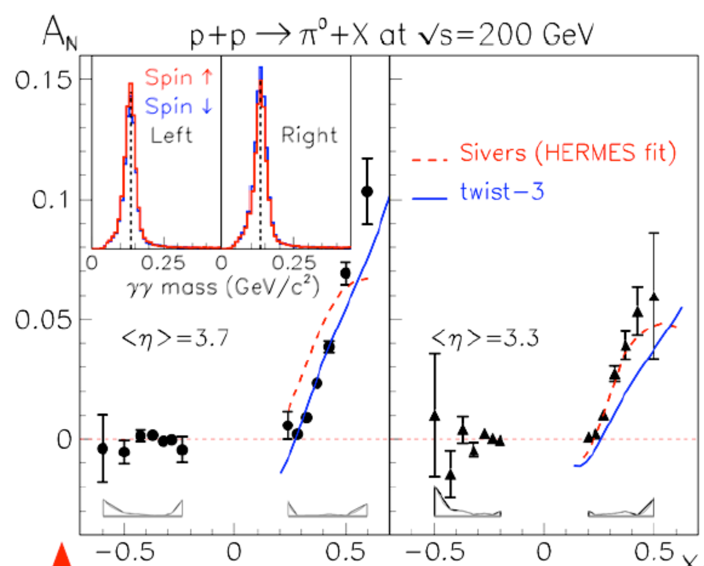
At √s=200GeV, $\pi^0$ cross-section measured by STAR FPD is consistent with the NLO pQCD calculation. Results at <η>=3.3 and <η>=3.8.

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




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

From Spin2008 talk by J.Drachenberg




STAR *arXiv:0801.2990v1 [hep-ex]*

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



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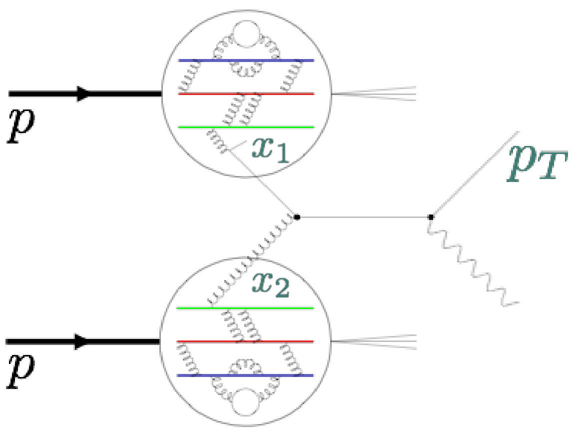
# Collinear Factorization

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)

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

$$f_2(x_2) \underset{x_2 \to small}{\sim} 1$$

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




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

## 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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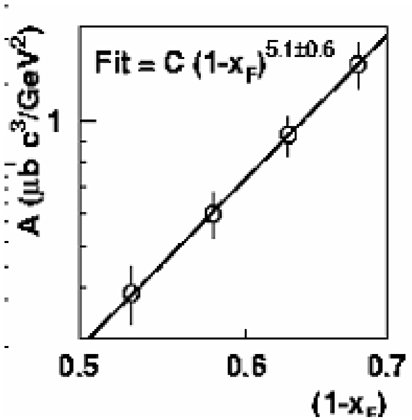
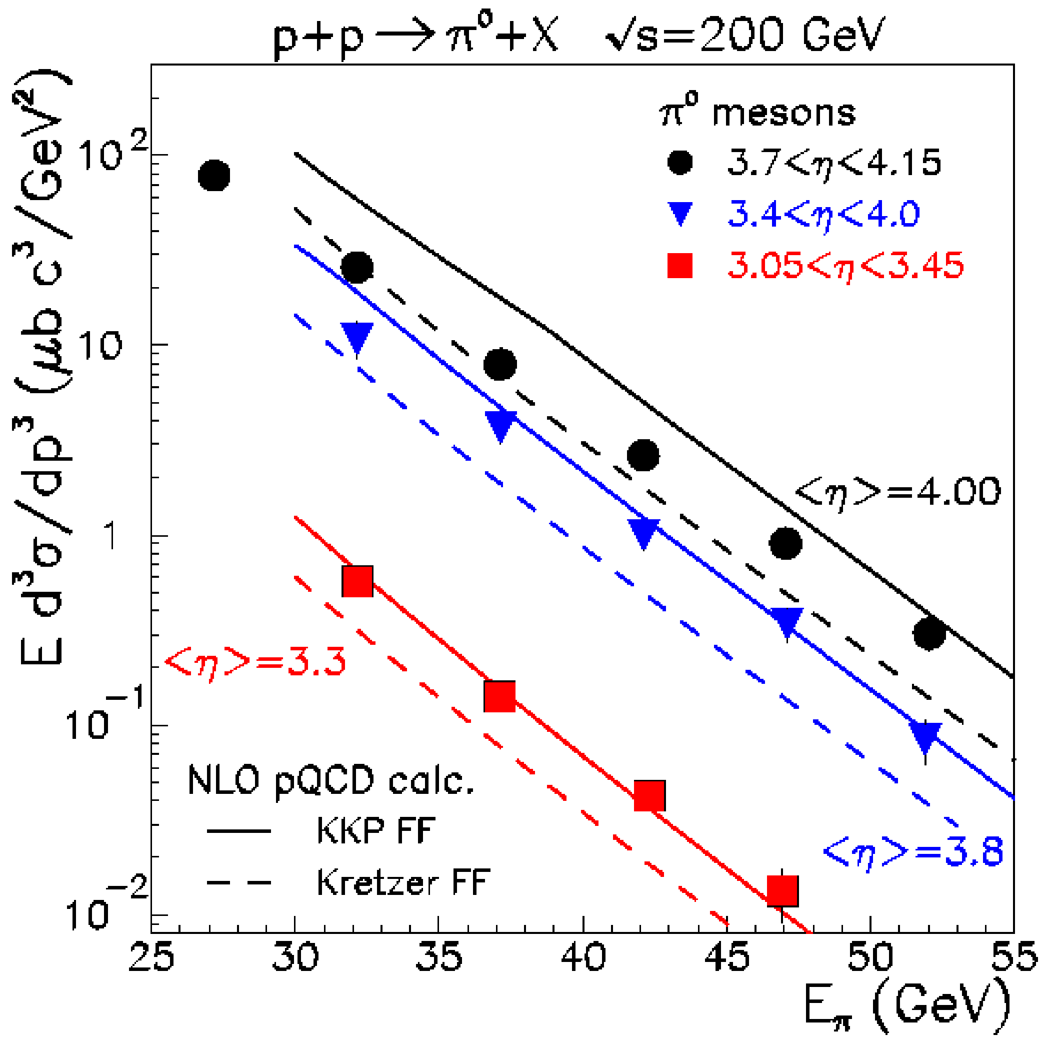
# Forward Pi0 Cross Sections Scale Like seen in ISR.

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 ISR analysis
J. Singh, et al Nucl. Phys. B140 (1978) 189.



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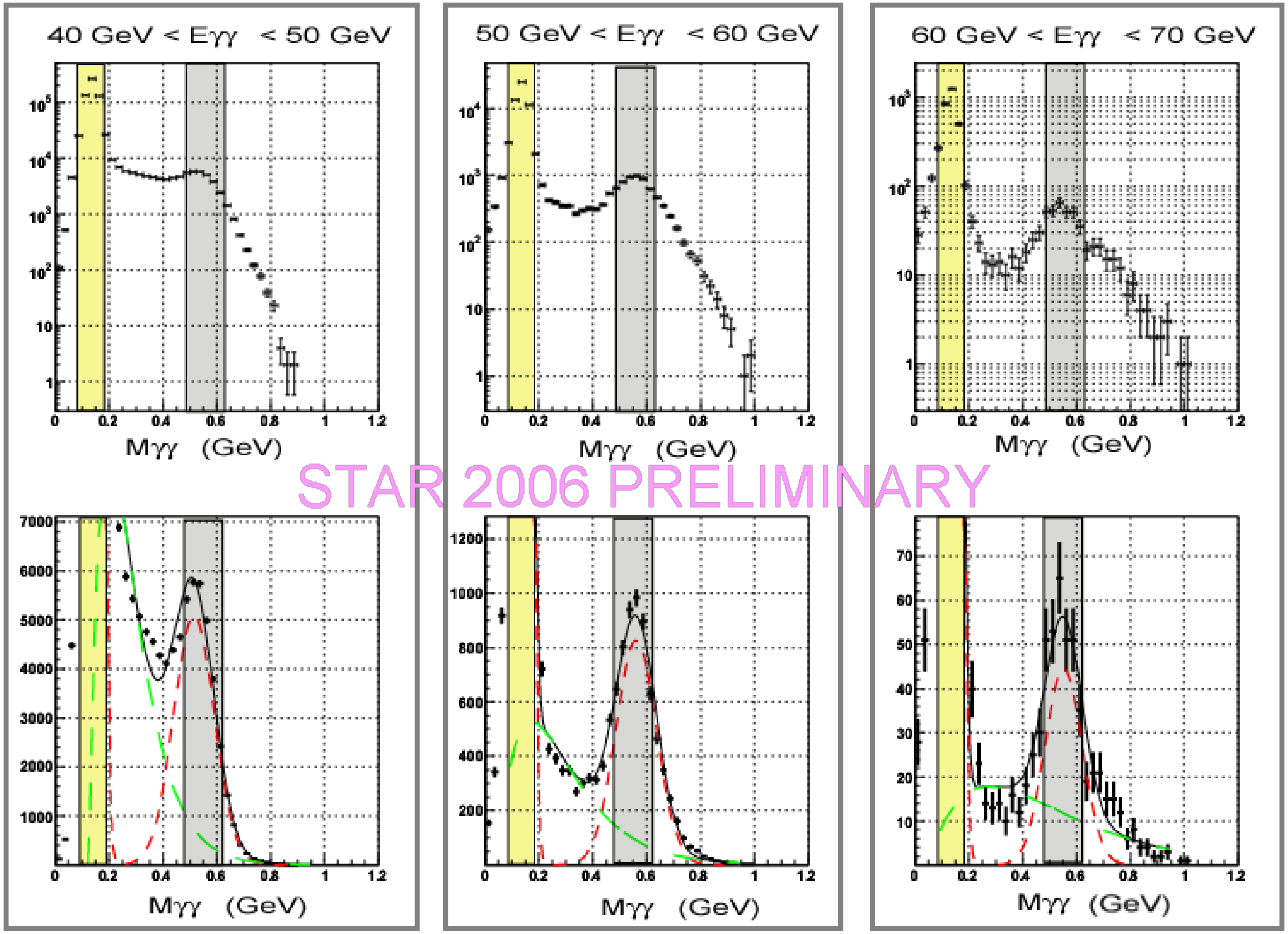
# Observation of Eta Signal

Di-Photon Invariant Mass Spectra in 3 Energy Bins




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

**$\pi^0$ Mass Cut**

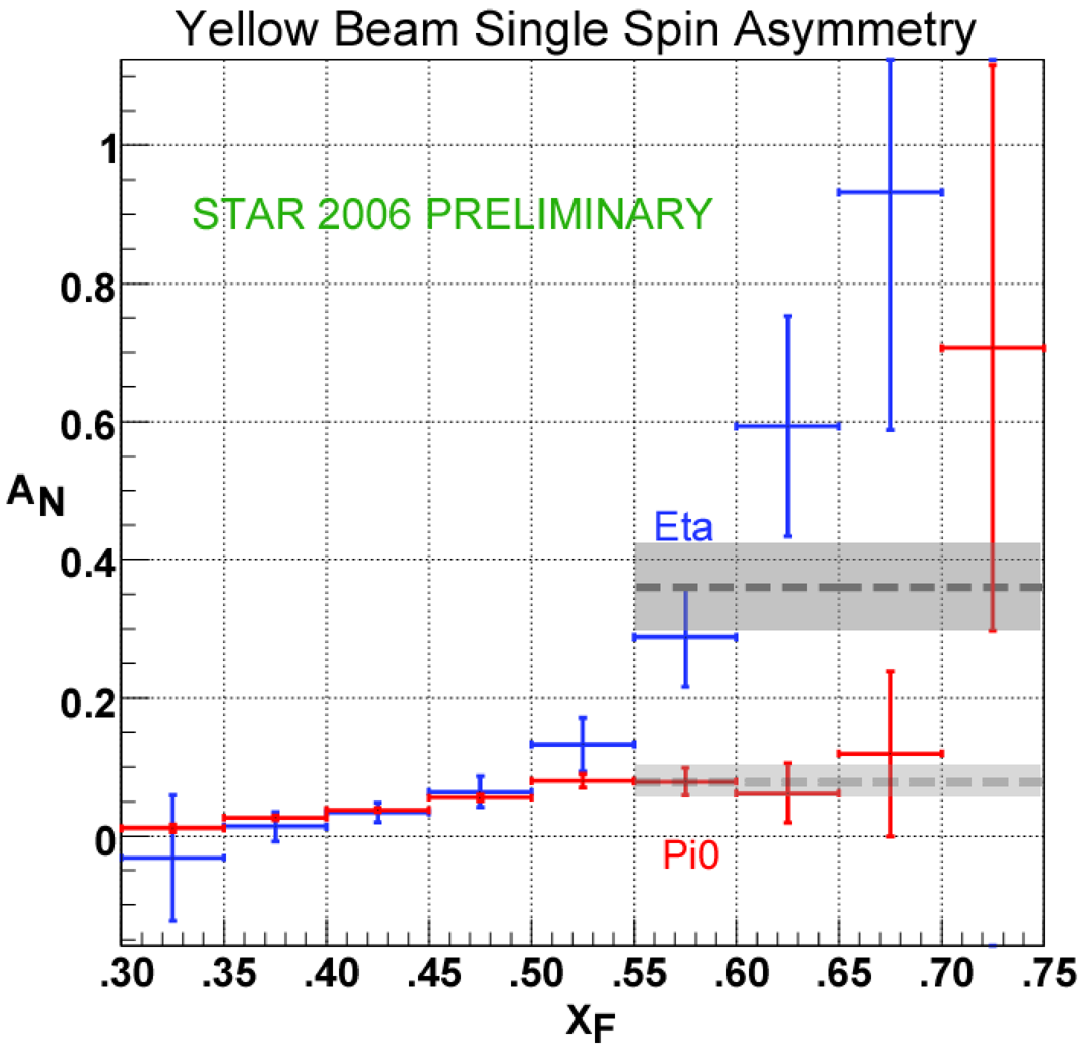
$.085\ GeV < M_{\gamma\gamma} < .185\ GeV$

**Eta Mass Cut**

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

# $A_N(x_F)$ in $\pi^0$ and Eta Mass Regions

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




1. $N_{photon} = 2$
2. Center Cut ($\eta$ and $\phi$)
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 $\eta$ mass region is greater than 5 sigma above zero, and about 4 sigma above the asymmetry in the $\pi^0$ mass region.

## Uncorrected Energy Distributions from Run 6 East FPD for pi0 and eta @ Y ~ 3.65 Sqrt [s]=200 GeV

If the <u>Invariant Cross Section</u> is proportional to

$$\frac{(1-x_F)^n}{{p_T}^m}$$

Then near E=50, with a little calculus, we can show that:

$$\frac{dN}{d\Omega} \propto e^{-\left(\frac{(n+m)}{50\,GeV}\right)E}$$

$$= e^{-(n+m)\left(0.02\,GeV^{-1}\right)E}$$

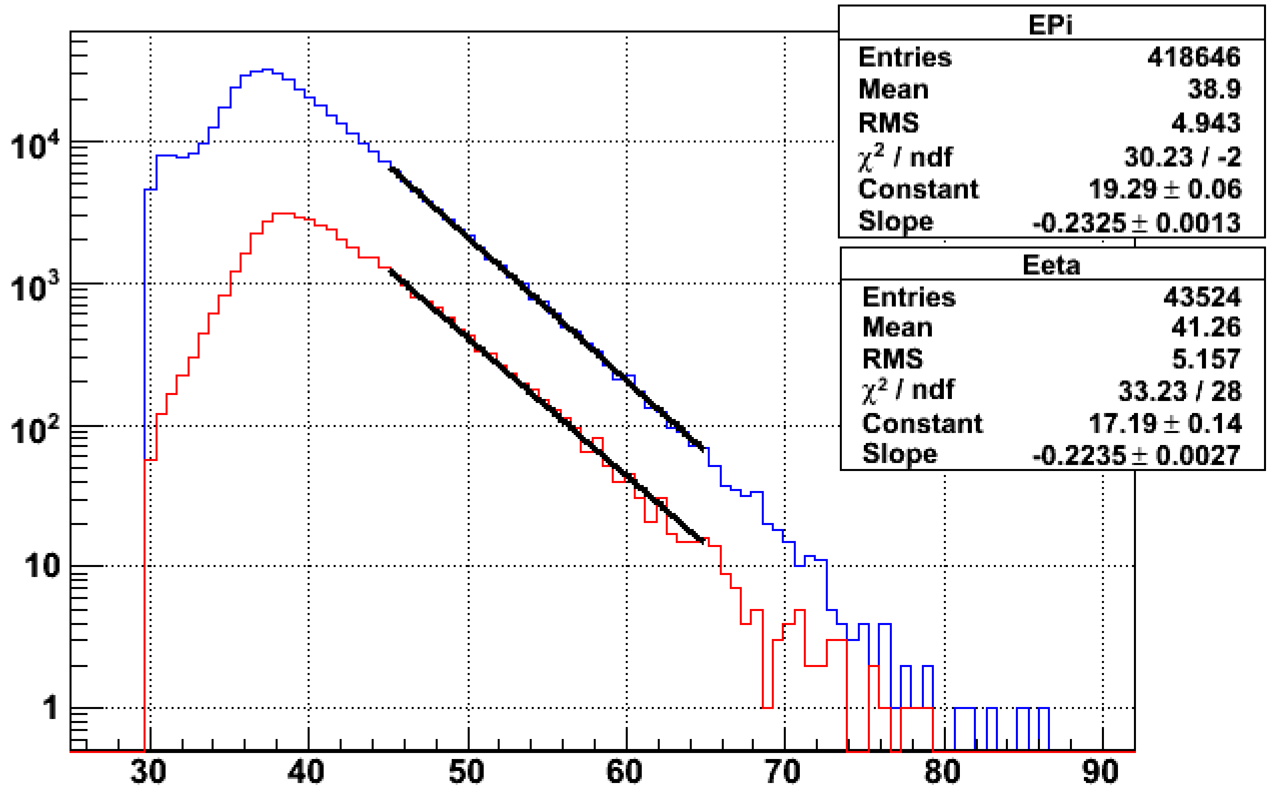
$$if \;\; n+m=11$$

$$\frac{dN}{d\Omega} \propto e^{-\left(0.22\,GeV^{-1}\right)E}$$

Z=|(E1-E2)/(E1+E2)|<.4

.07 GeV < $M_{gg}$ <.20 GeV

0.4 GeV < $M_{gg}$ <0.7 GeV




E=E1+E2 GeV

=(100 GeV) ($X_F$)

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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 **<u>to a different form</u>** 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.

# $P_t$ Dependence in Calculations of $A_N$

**•Sivers Effect / Collins Effect**

•introduce transverse spin dependent **<u>offsets in transverse momentum</u>** ….

•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. **<u>Using our (STAR) measured cross section form:</u>**

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

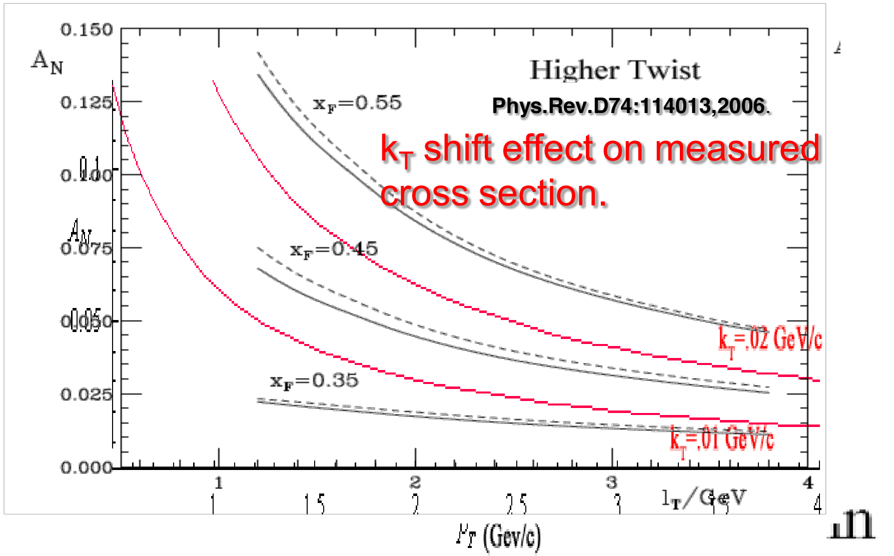
$$A_n \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{6k_T}{P_T} + O\left(\frac{k_T}{P_T}\right)^2$$

**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 $A_N \sim\propto 1/P_T$***

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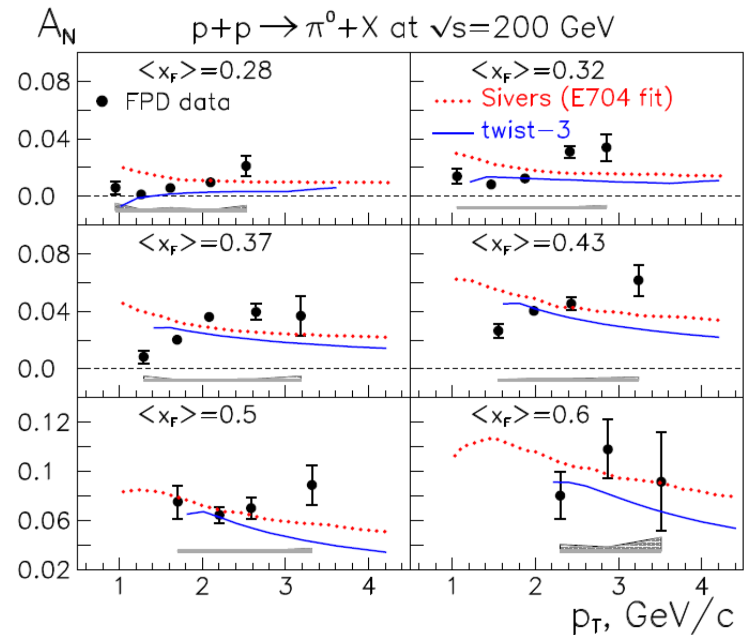
# For Fixed $X_F$, the asymmetry $A_N$ does not fall with $P_t$ as predicted by models.

- 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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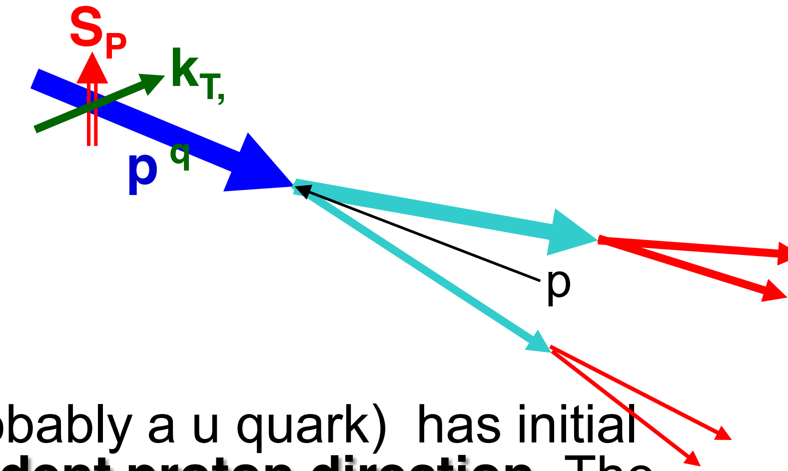
# Sivers Model

## Difference Between pi0 and eta $A_N$?




- 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, **(apparently a u quark)** has a transverse direction that is biased relative to the nominal transverse momentum.

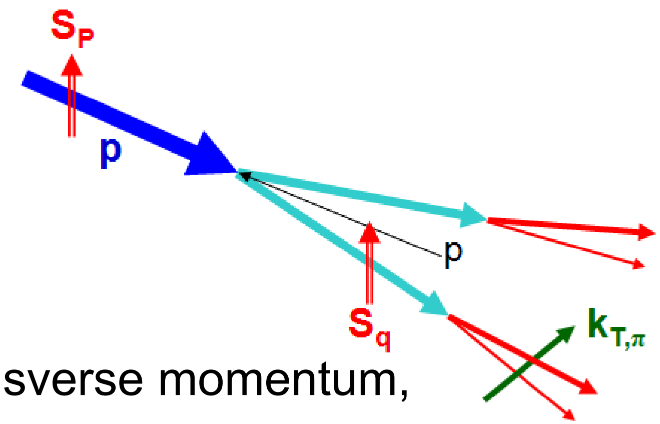
- The jet fragments with large z to produce a **meson that is moving in the direction of the jet**, with nearly $p_T$ of the jet.

- Dependence of **initial state $p_T$** 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**.

# Collins Model




## $A_N$ 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,

$$k_T \sim (1-Z)\, p_T$$

- If the cross section is given by $\frac{(1-x_F)^5}{p_T^{\,6}}$
- The Maximal asymmetry from fragmentation $p_T \to p_T + (1+Sin(\phi))\frac{k_T}{2}$

$$\phi = \textit{fragmentation azimuthal angle from spin direction}$$

- Leads to an **extreme limit** for $A_N$ from fragmentation,

$$A_N < \frac{6\,k_T}{2\,p_T} \sim 3(1-Z) \sim .3$$

This is the most extreme case including

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



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# Comparison between *η* production and π⁰ production?

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

- But we expect both mesons to come from **fragmentation of quark jets**.

$$I=0 \begin{cases} \eta \simeq \frac{1}{\sqrt{3}}\left(u\bar{u}+d\bar{d}-s\bar{s}\right) \\ \eta' \simeq \frac{1}{\sqrt{6}}\left(u\bar{u}+d\bar{d}+2s\bar{s}\right) \end{cases}$$

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

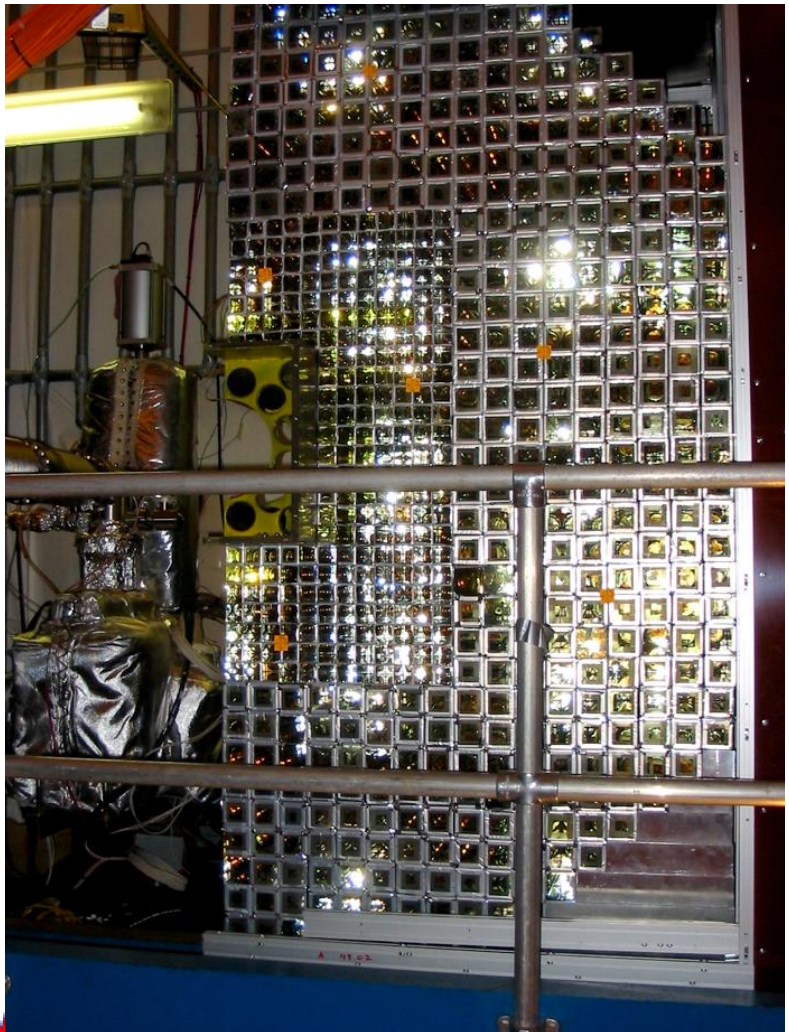
*Assume $\eta,\eta'$ mixing angle: $\theta_P \sim -19.5°$

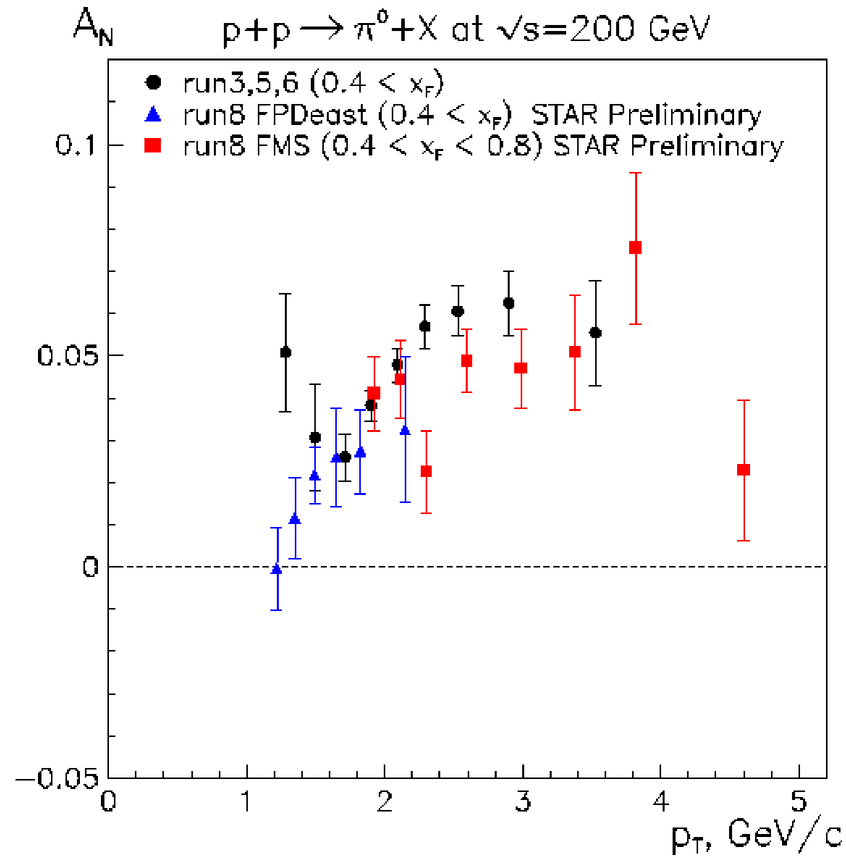
- **For Sivers Effect: Asymmetry is in the jet and should not depend on the details of fragmentation.**

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

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

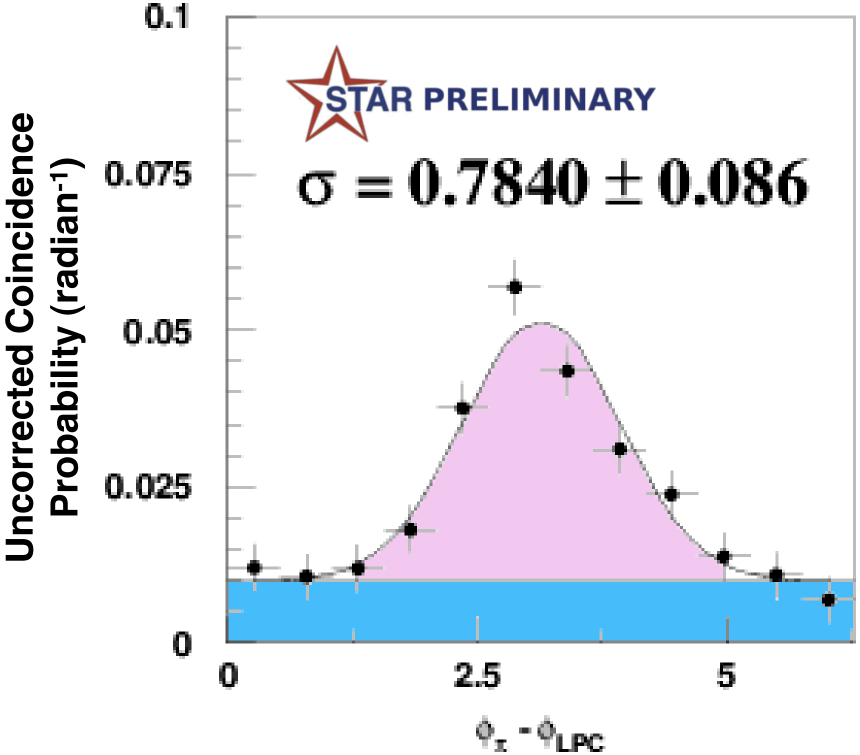
***STAR*** Forward Meson Spectrometer
2.5 < Y < 4.0

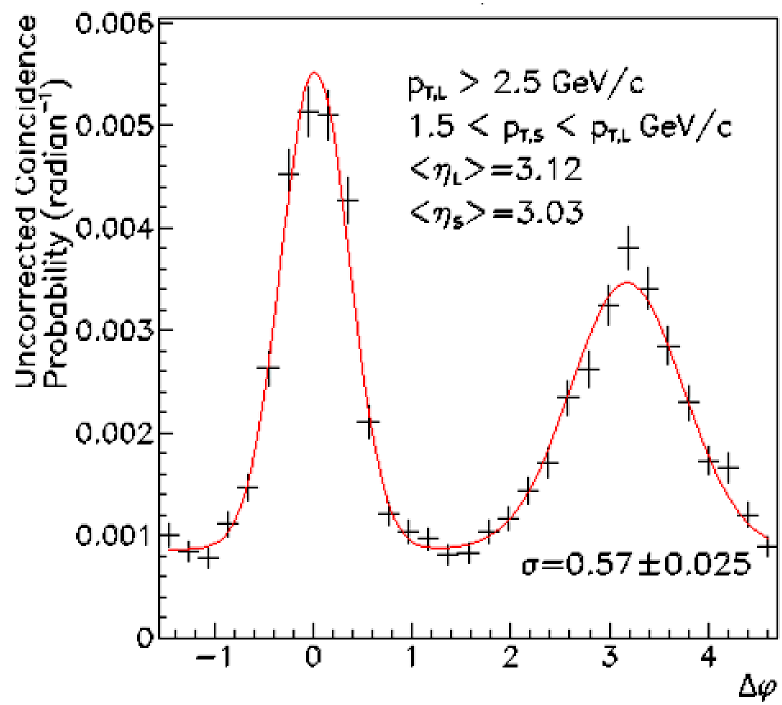





***arXiv:0901.2763 +***
***A.Ogawa @CIPANP09***

# Run 8 forward $\pi^0$ + hadron correlation measurements

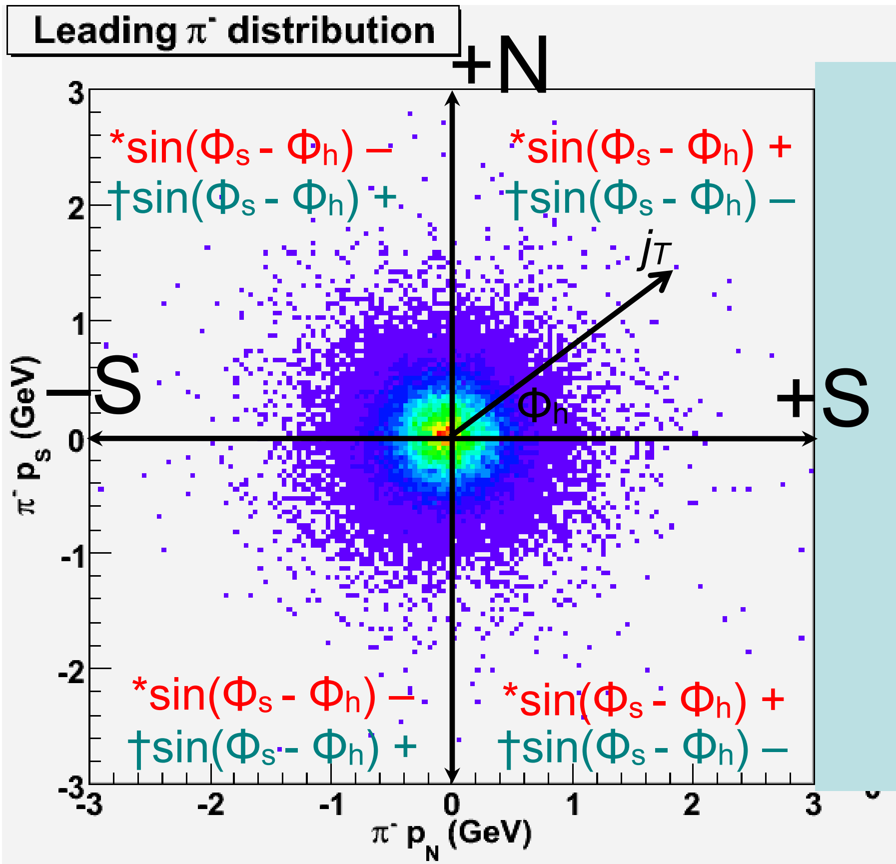



- FMS-TPC and FMS-FMS back-to-back correlations enable di-hadron / di-jet Sivers effect measurements
- FMS-FMS near-side correlations sensitive to Collins effect & transversity
- FMS-TPC: key step toward future transverse spin $\gamma$ + jet study

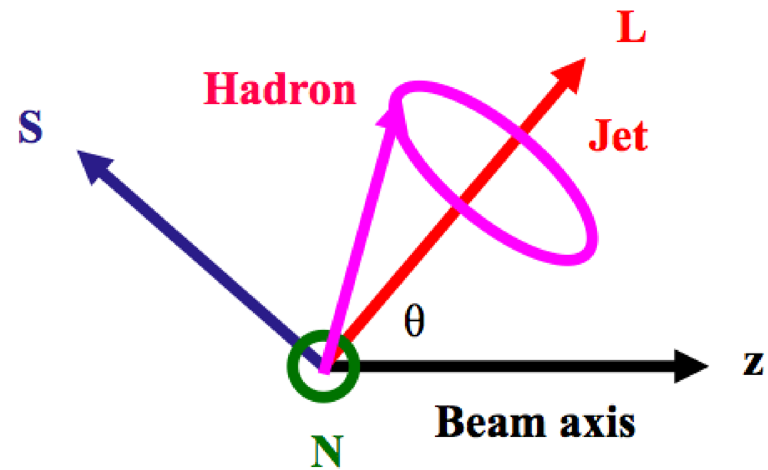
# In Progress: Mid Rapidity Measurement of Collins Fragmentation $A_N$

For blue beam polarized:




–N

(L is 3rd axis; L = S × N)




*For proton spin ↑↑ N axis, $\Phi_S = 90°$

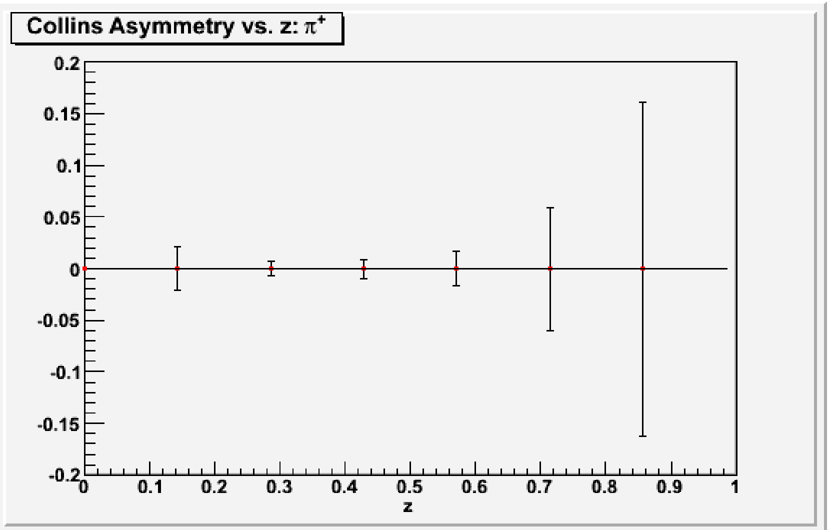
†For proton spin ↑↓ N axis, $\Phi_S = –90°$

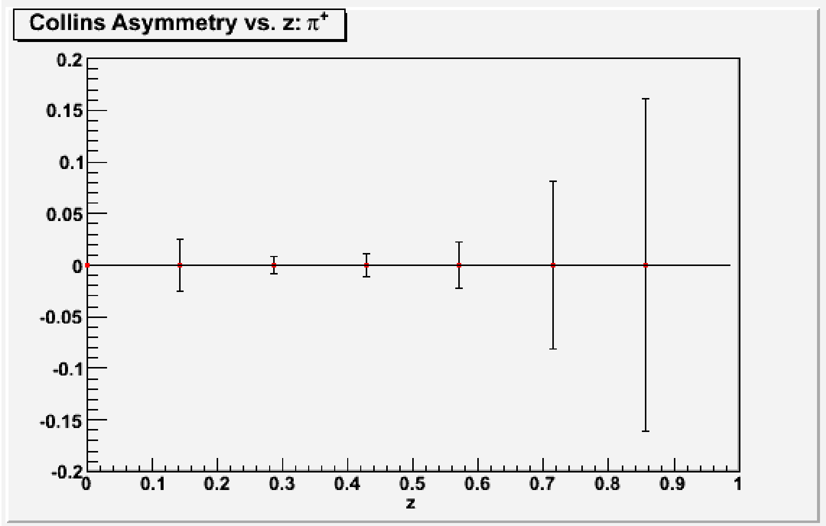
see F. Yuan, Phys Rev Lett 100, 032003(2008)

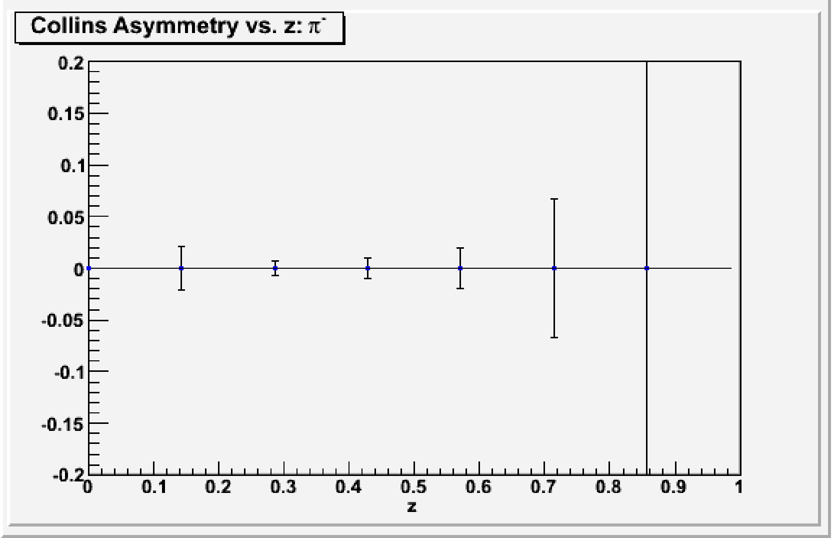
# Expected Asymmetry Statistical Errors (Run 6 Transverse Data)

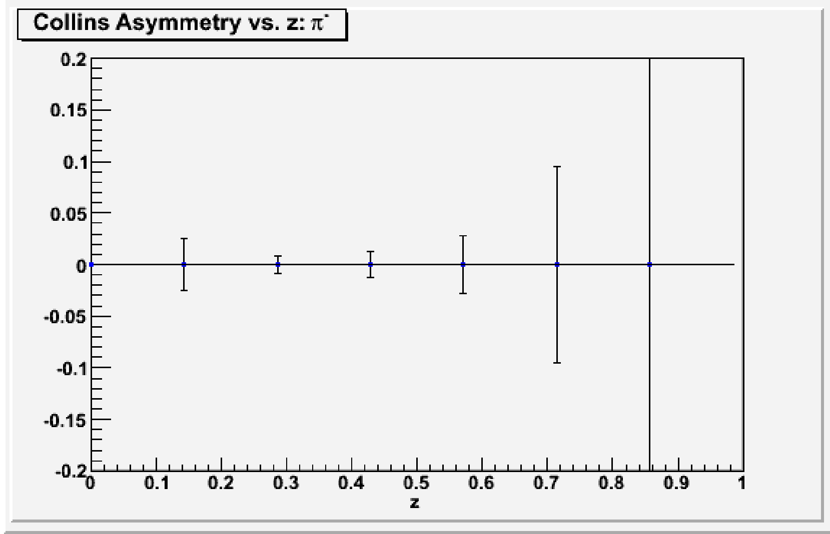
**BLUE BEAM POLARIZED**

**YELLOW BEAM POLARIZED**



# First Look at Eta Mass Region in FMS Detec

## 2 photon Mass Distributions in four Pseudo-Rapidity Y Regions (Preliminary Energy Calibration)

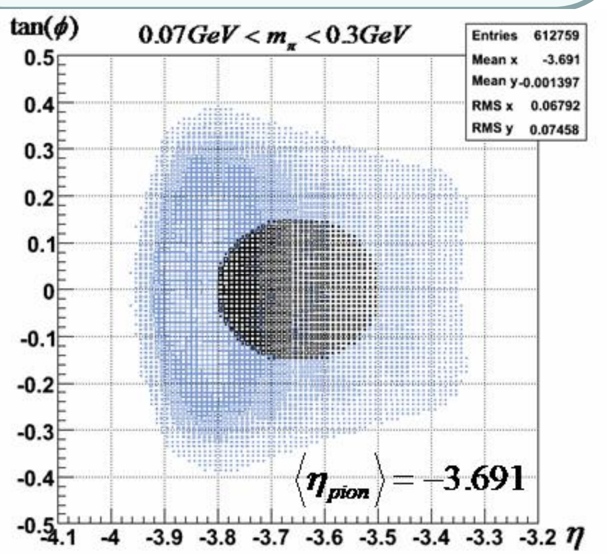
### Event Selection

2 Photons within cone

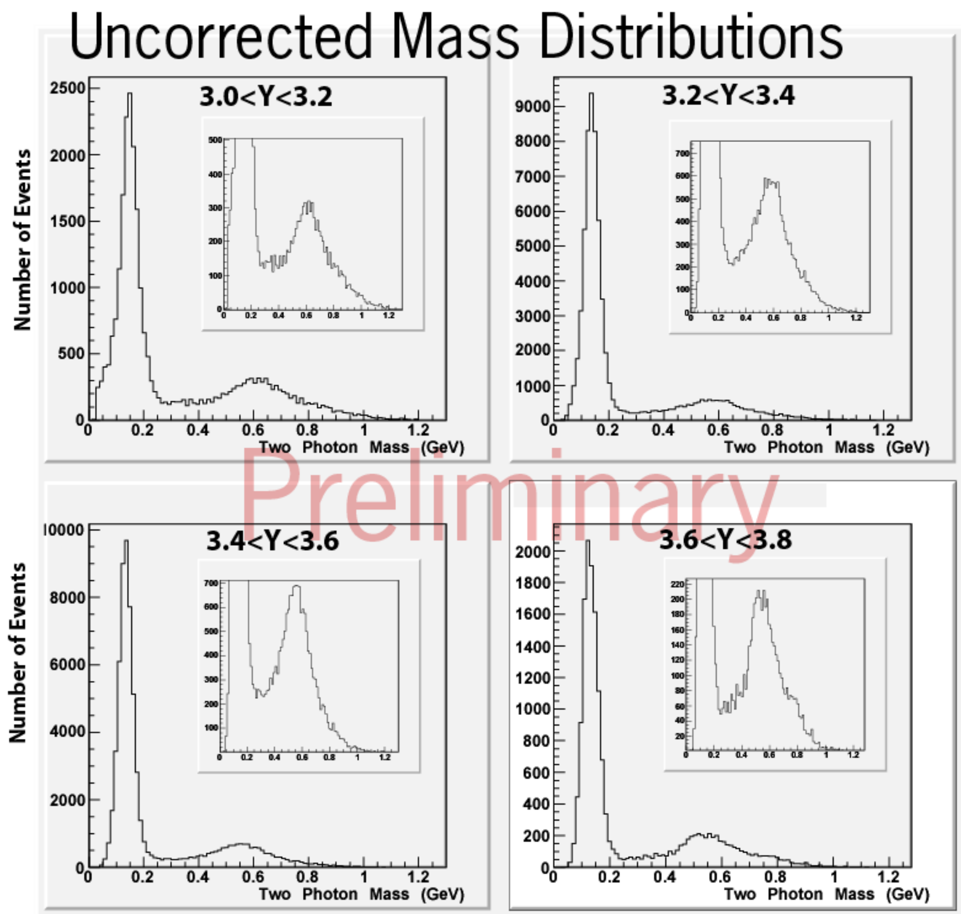
$$\sqrt{(Y_{Photons} - Y_{Eta})^2 + (\phi_{Photons} - \phi_{Eta})^2} < .85$$

$P_t > 2$ GeV/c

Z < .7




Comparison to FPD Center Cut




(~1/3 of Run 8 Transverse Data Set)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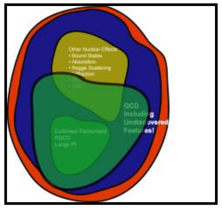
Steve Heppelmann

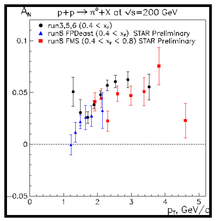
# Possible Future Star Transverse Single Spin Measurements

| Energy $\sqrt{s}$ | Transverse pp Measurement | Collins | Sivers | Sivers: SIDIS sign change | Luminosity | Detectors |
|---|---|---|---|---|---|---|
| 200 GeV | $p^{\uparrow} + p \rightarrow \pi^0 + X$ | ✓ | ✓ | | 30 pb$^{-1}$ | FMS |
| | $p^{\uparrow} + p \rightarrow \eta + X$ | ✓ | ✓ | | | FMS |
| | $p^{\uparrow} + p \rightarrow jet + X$ | ✓ | ✓ | | | FMS+EMC +(HCAL?) |
| | $p^{\uparrow} + p \rightarrow \pi^0 + \pi^0 + X$ | ✓ | ✓ | | | FMS+EMC |
| | $p^{\uparrow} + p \rightarrow jet + jet + X$ | ✓ | ✓ | | | FMS+EMC +(HCAL?) |
| | $p^{\uparrow} + p \rightarrow \gamma + X$ | | ✓ | ✓ | | FMS |
| | $p^{\uparrow} + p \rightarrow \Lambda + X$ | ✓ | ✓ | | | FMS+HCAL |
| 500 GeV | $p^{\uparrow} + p \rightarrow \gamma + X$ ( $p^{\uparrow} + p \rightarrow \pi^0 + X$ ) | | ✓ | ✓ | 20 pb$^{-1}$ | East FPD +Shower Max |
| | $p^{\uparrow} + p \rightarrow \Lambda + X$ | ✓ | ✓ | | | FMS+HCAL |
| | $p^{\uparrow} + p \rightarrow \eta + X$ | ✓ | ✓ | | | FMS |
| | $p^{\uparrow} + p \rightarrow e^+ + e^- + X$ | | ✓ | ✓ | 250 pb$^{-1}$ | STAR with FMS |
| | $p^{\uparrow} + p \rightarrow W + X$ | | ✓ | ✓ | | STAR with FMS |

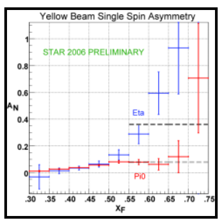
# Conclusion About STAR Transverse SSA Measurements



- Forward and Central Rapidity Cross Sections consistent with PQCD with collinear factorization. This encourages theoretical models **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.

"Collins"
"Sivers"
"Beyond"

- STAR will make significant 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.