Measurement of Transverse spin effects with the Forward Pion detector at STAR in Polarized p+p Collisions at 200GeV

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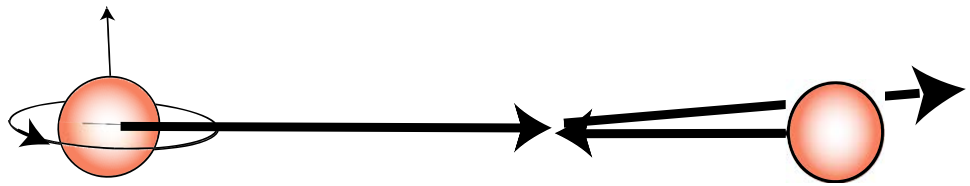
$$A_N(X_F, P_T)$$

Separating the Feynman "X_F" and Transverse Momentum "P_T" Dependence.



Forward π^0 Detected

Overview: The QCD Challenge

STAR has shown that the measured $\pi°$ cross sections at large rapidity $3<\eta<4$ and modest transverse momentum $P_T>1$ GeV/c for

$$p^{\uparrow} + p \Rightarrow \pi^0 + X$$

are in good agreement with NLO PQCD calculations.

Reproduction of spin averaged cross section
→ PQCD and Factorization in good shape.

Confirmation of these calculations validates the long held prejudice that events in this kinematic region involve the collisions between a large x quark in one proton and a soft parton (gluon) in the other proton with a factorized hard cross section. Single Transverse Spin asymmetry "A_N" for this process require the interference between the real part of a quark helicity non-flip amplitude and the imaginary part of a helicity flip amplitude. Such "T odd, helicity flip" terms are not present in the colinear parton leading twist calculations that now well describe the spin averaged cross section.

A QCD based description of the spin dependent cross sections leading to A_N .... will impact "next generation" investigations into perturbative QCD, probing the ultimate limit to the intuitive factorized parton distribution picture.

Transverse Single Spin Asymmetry for Small Angle

$$p^{\uparrow} + p \Rightarrow \pi^{0} + X$$

(100 GeV/c on 100 Gev/c) Proton Collisions @RHIC

The difference between spin **up** and **down** **(depends on Up vs Down Luminosity)**

$$A_N \equiv \frac{\sigma^{\uparrow}(x_F, p_t) - \sigma^{\downarrow}(x_F, p_t)}{\sigma^{\uparrow}(x_F, p_t) + \sigma^{\downarrow}(x_F, p_t)}$$

$$x_F \sim \frac{\left|\vec{P}_{\pi}\right|}{\left|\vec{P}_{proton}\right|}$$

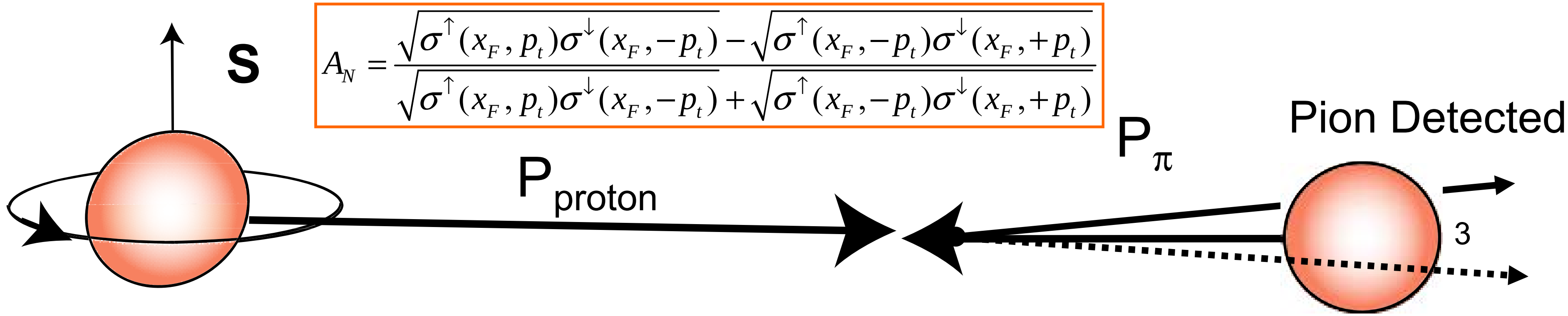
$$p_t = \vec{P}_{\pi} \cdot \left[\frac{\vec{P}_{proton} \times \vec{s}}{\left|\vec{P}_{proton} \times \vec{s}\right|} \right]$$

or the difference between **left** and **right** scattering **(Depends upon Left vs Right acceptance).**

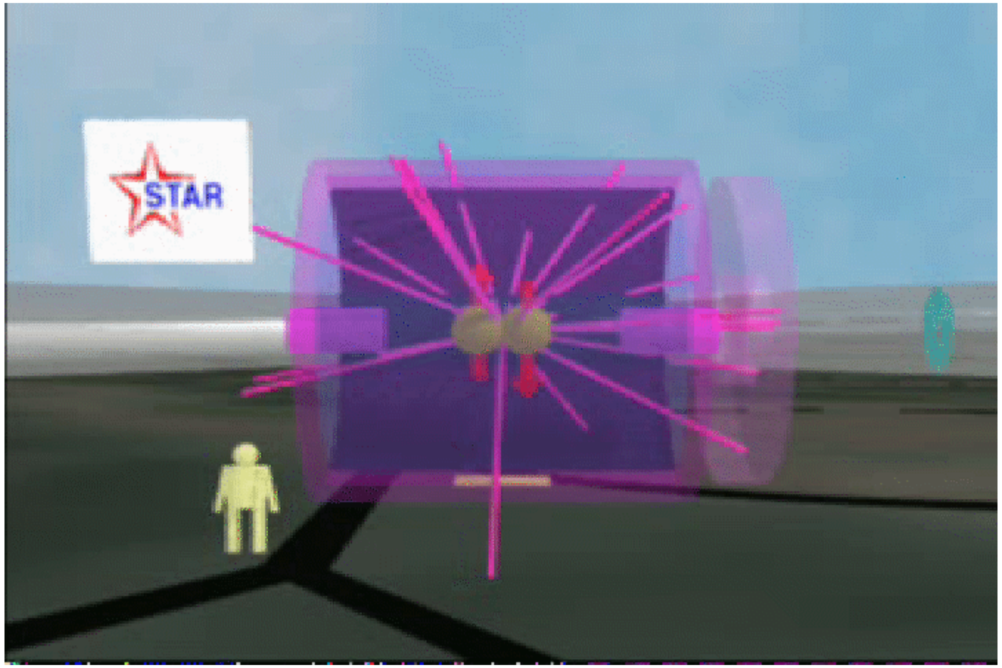
$$A_N = \frac{\sigma^{\uparrow}(x_F, p_t) - \sigma^{\uparrow}(x_F, -p_t)}{\sigma^{\uparrow}(x_F, p_t) + \sigma^{\uparrow}(x_F, -p_t)} = \frac{\sigma^{\downarrow}(x_F, -p_t) - \sigma^{\downarrow}(x_F, p_t)}{\sigma^{\downarrow}(x_F, -p_t) + \sigma^{\downarrow}(x_F, p_t)}$$

or the cross ratio
(Insensitive to Left/Right Acceptance or to Up/Down Luminosity).

$$A_N = \frac{\sqrt{\sigma^{\uparrow}(x_F, p_t)\sigma^{\downarrow}(x_F, -p_t)} - \sqrt{\sigma^{\uparrow}(x_F, -p_t)\sigma^{\downarrow}(x_F, +p_t)}}{\sqrt{\sigma^{\uparrow}(x_F, p_t)\sigma^{\downarrow}(x_F, -p_t)} + \sqrt{\sigma^{\uparrow}(x_F, -p_t)\sigma^{\downarrow}(x_F, +p_t)}}$$



Transverse Polarization at RHIC



Frames from film clip, courtesy of BNL

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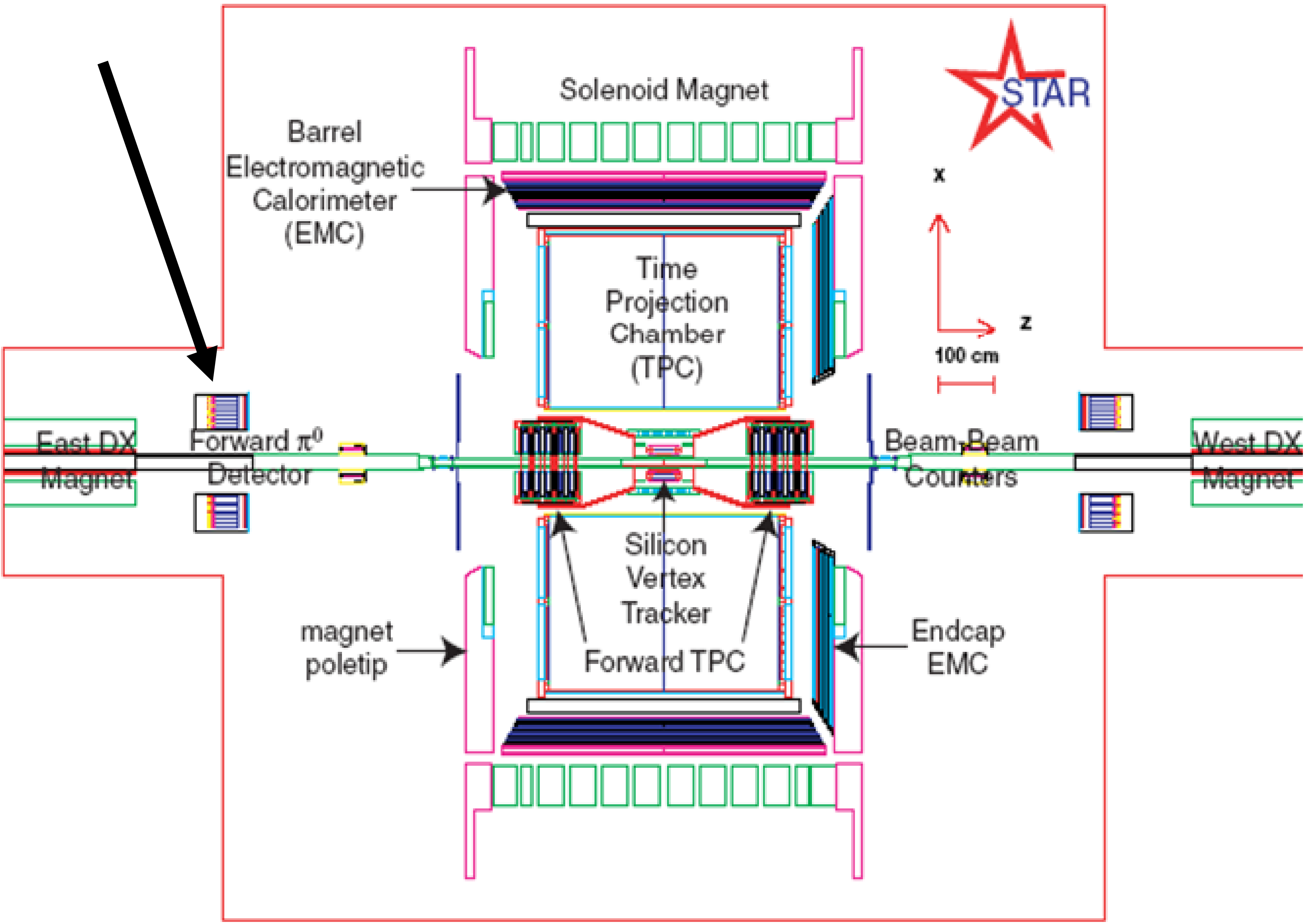
spin up x up

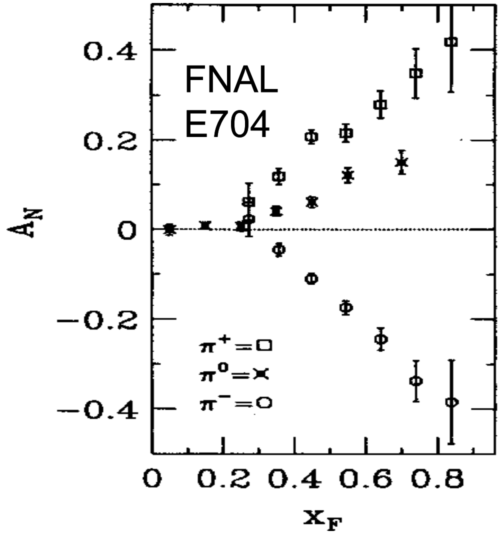
spin up x down

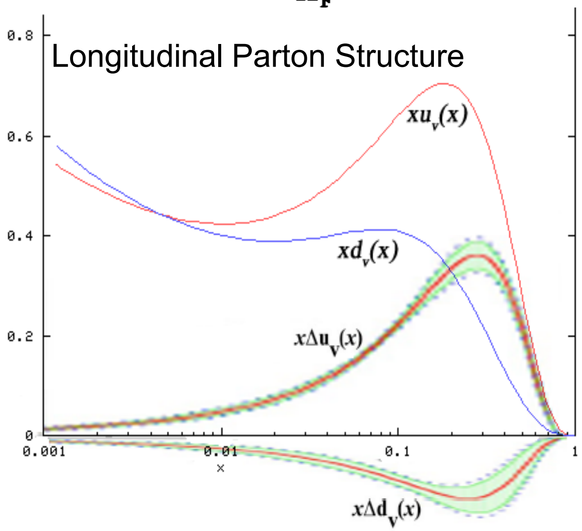
- **111 bunches** of protons in each RHIC Ring
- **Polarization of each bunch** prepared independently at injection.
- Half of the bunches are filled with spin up protons and half with spin down protons at injection.
- The polarization is kept transverse as beam circulates in RHIC.
- Bunch collisions every ~100 nS
- **Each bunch collision involves different but known spin combinations.** Spin pattern repeats after 111 bunch crossings.



Solenoid Magnet
STAR
Barrel
Electromagnetic
Calorimeter
(EMC)
x
z
Time
Projection
Chamber
(TPC)
100 cm
East DX
Magnet
Forward π^0
Detector
Beam-Beam
Counters
West DX
Magnet
Silicon
Vertex
Tracker
magnet
poletip
Forward TPC
Endcap
EMC

Single Spin Asymmetries (the historical context)





http://zebu.uoregon.edu/~parton/partongraph.html

HIRAI, KUMANO, AND SAITO

The naïve (but perhaps correct) interpretation of many single spin polarization effects in hadronic interaction is:

1. **Polarized Partons (transversity):** At large x (parton momentum fraction) … up /down quarks have their transverse spins aligned/opposite the spin of the proton.

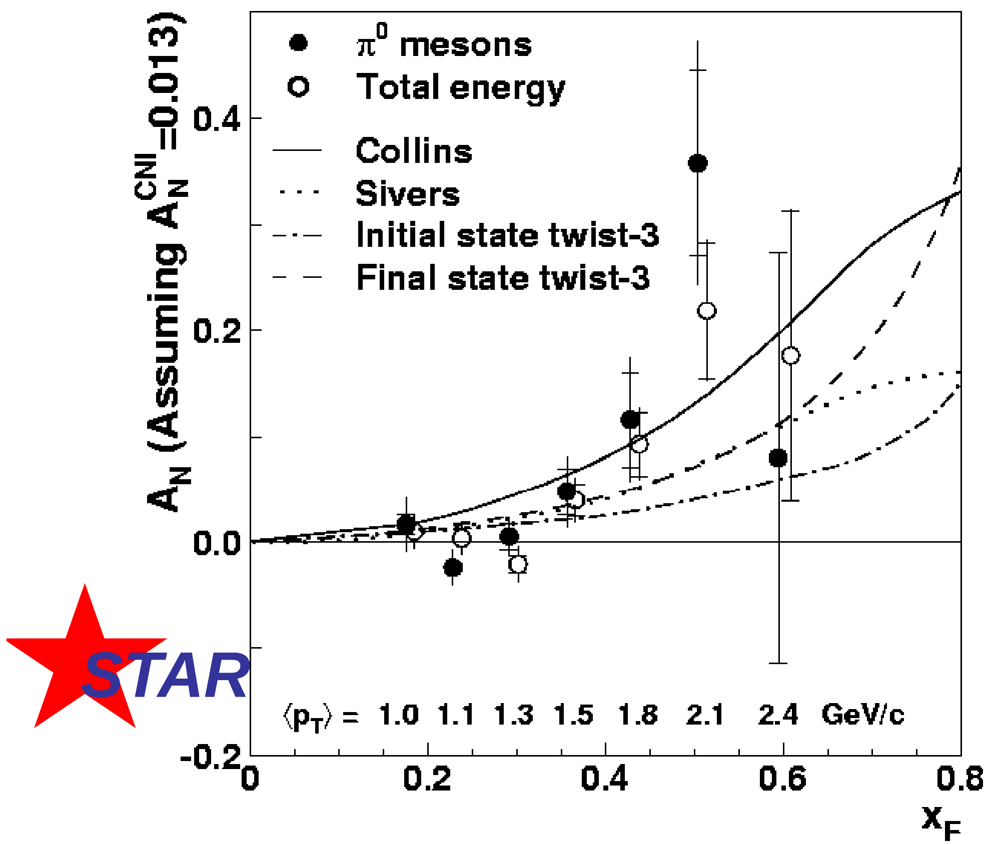
2. **Parton-parton sub-process**: involves scattering between a
   - hard up quark and soft parton for π^+ or π^0
   - hard down quark and soft parton for π^-

3. **Parton scattering amplitude:** Proportional to interference between real non-helicity flip and imaginary helicity flip amplitudes (properties that exclude the leading and simplest terms of PQCD calculations).

4. **Asymmetry vs X_f thought to be related to** initial-final state (Sivers), final state (Collins) effects or higher twist effects.

pp → π^0 + X cross sections at 200 GeV

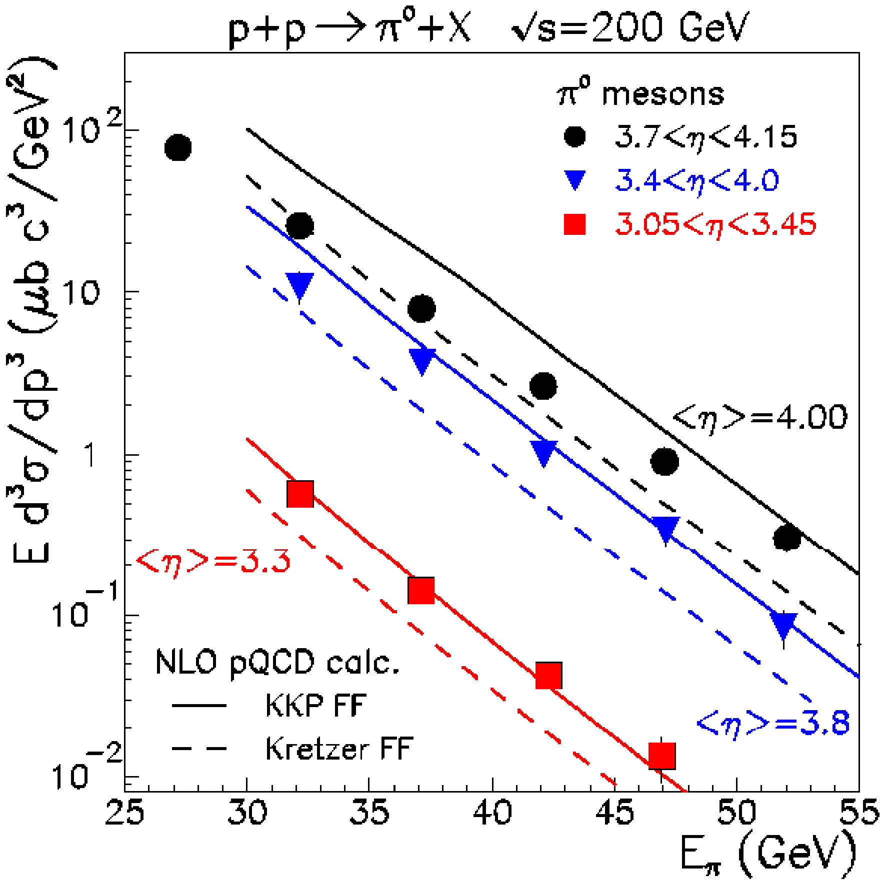
PRL 92, 171801 (2004)



Asymmetry revealed at lower energies persists at $\sqrt{s}$=200 GeV

$\sqrt{s}$=200 GeV, <η> = 3.8

PRL97:152302,2006



- Consistent with NLO pQCD calculations at 3.3 < η < 4.0. NLO pQCD calculations by Vogelsang, et al.
- Data at low p_T trend from KKP fragmentation functions toward Kretzer. PHENIX observed similar behavior at mid-rapidity.

Pions identified in this region with severe x_F and p_T dependence
(measured here by STAR in forward region)
tend to carry most of the of the jet momentum (<z>~ 60% to 80%).

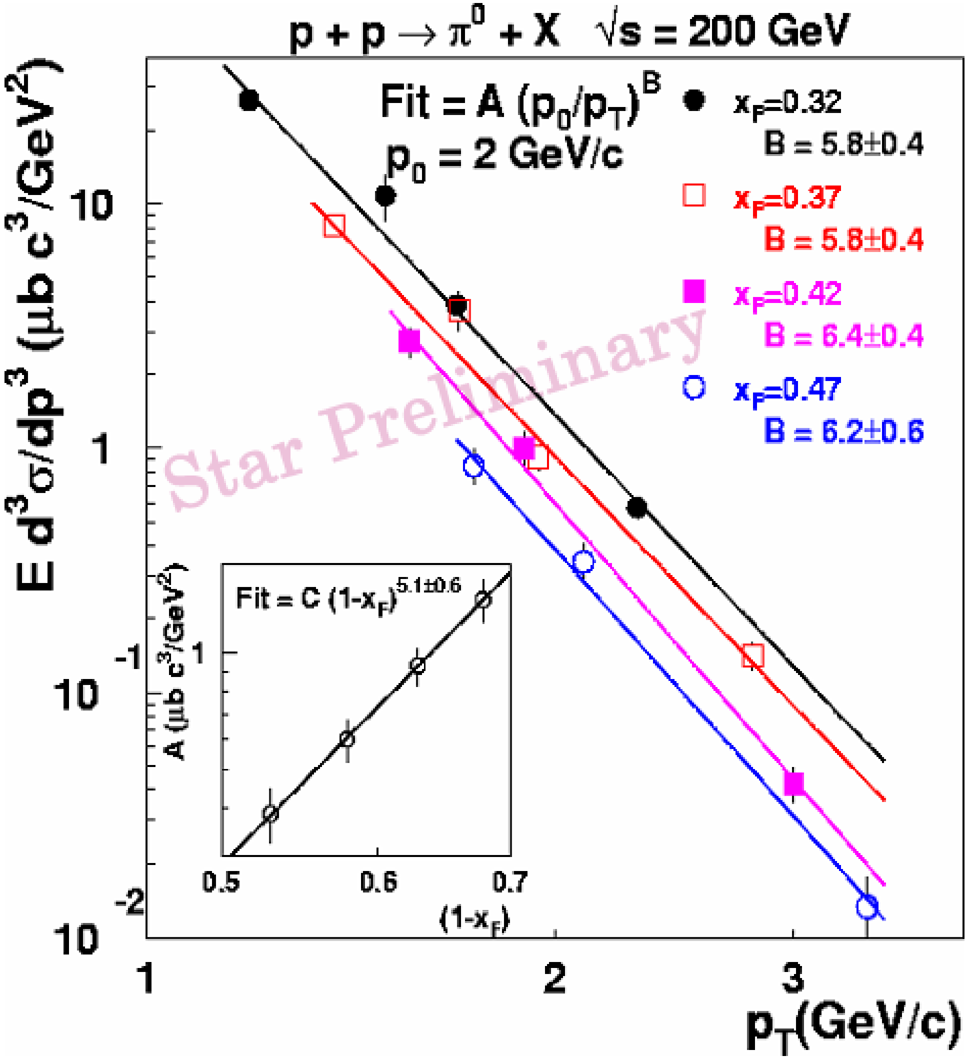
$$x_F \sim x\, z$$

$$\sigma(x) \propto q\left(x \sim {x_F}/{z}\right)\, \sigma_{parton}\quad d\,(z)$$

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

$$N \approx 5$$

$$B \approx 6$$



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

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P_t Dependence in Calculations of A_N

•Sivers Effect / Collins Effect

these types of models involve:

- •<u>initial state parton distribution</u> (Sivers)
- •or <u>final state fragmentation</u> distributions (Collins)

that introduce transverse spin dependent <u>offsets in transverse</u> 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. **<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:

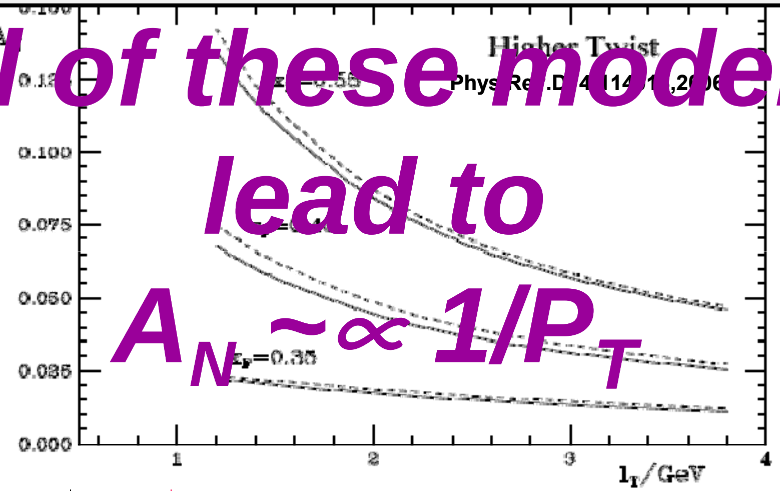
Off diagonal initial state parton density for hard quark

$$\rho_{quark}(x, x') \quad x' = x + x_{gluon} \quad x_{gluon} \to 0$$

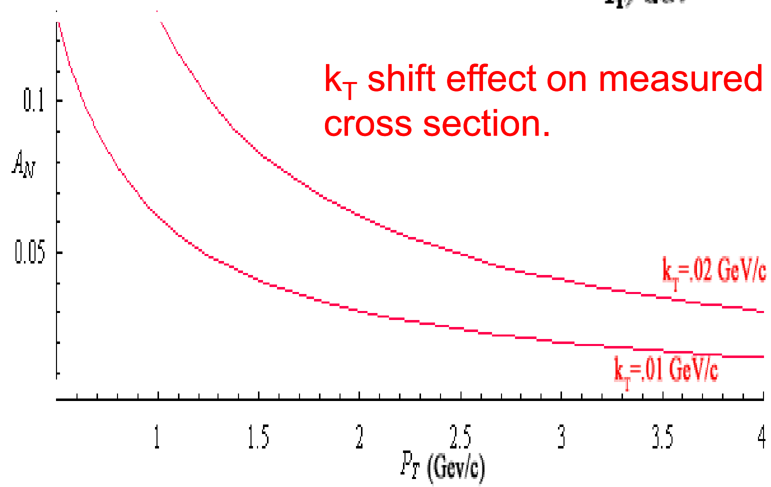
Qiu and Sterman

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

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



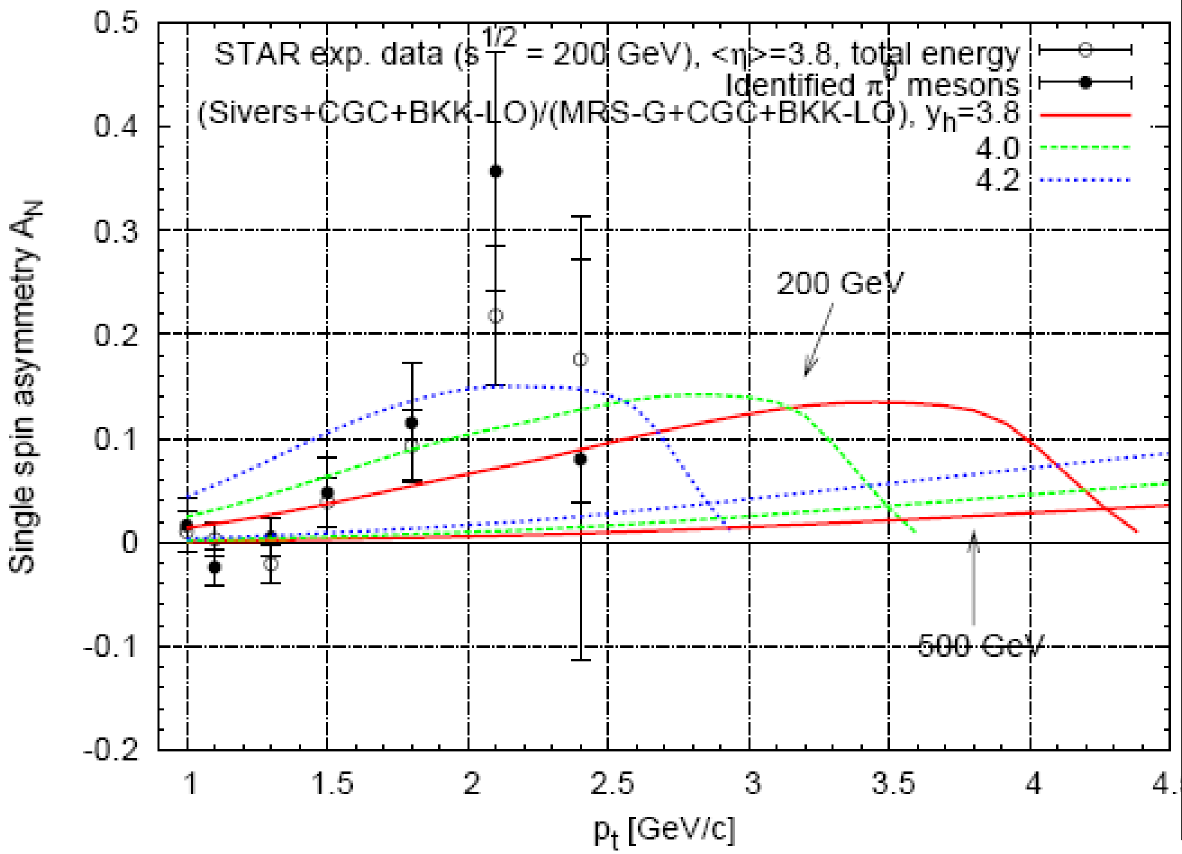
All of these models lead to $A_N \sim\propto 1/P_T$



Calculations Involving Traditional Factorization in PQCD seems to require A_N falling with P_T for fixed large X_F

What about other approaches?

Early STAR data and theory: Highly correlated X_F and P_T acceptance.



Boer, Dumitru, Hayashigaki

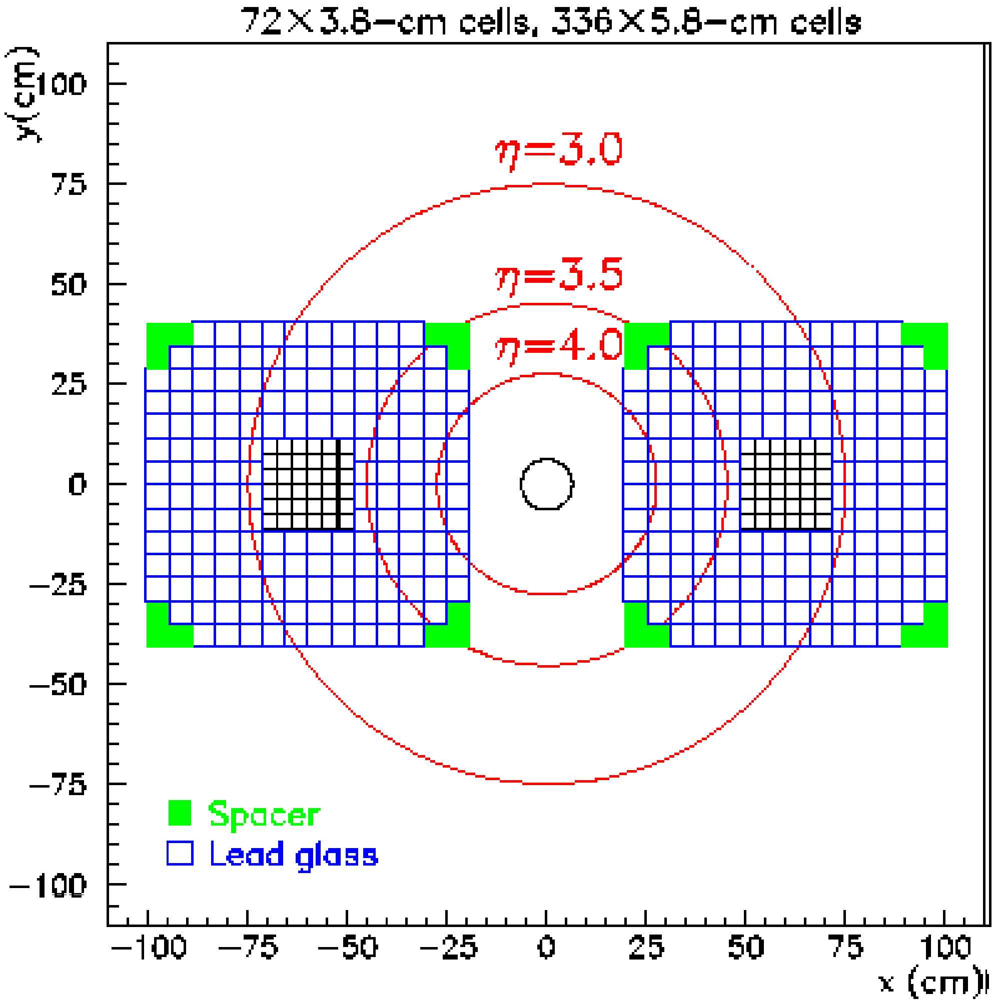
Small x gluon modification for unpolarized proton

Color Glass Condensate

Needs to be analyzed to separate X_F and P_T Dependence.

??If plotted for fixed X_F, still seems to be falling with P_T??

FPD → FPD++ for Run 6 (2006)



Run 6

West end of the ***STAR*** interaction region

Caveats:

- -RHIC CNI Absolute polarization still preliminary.
- -Result Averaged over azimuthal acceptance of detectors.
- -Positive X_F (small angle scattering of the polarized proton).

Run 2 Published Result.

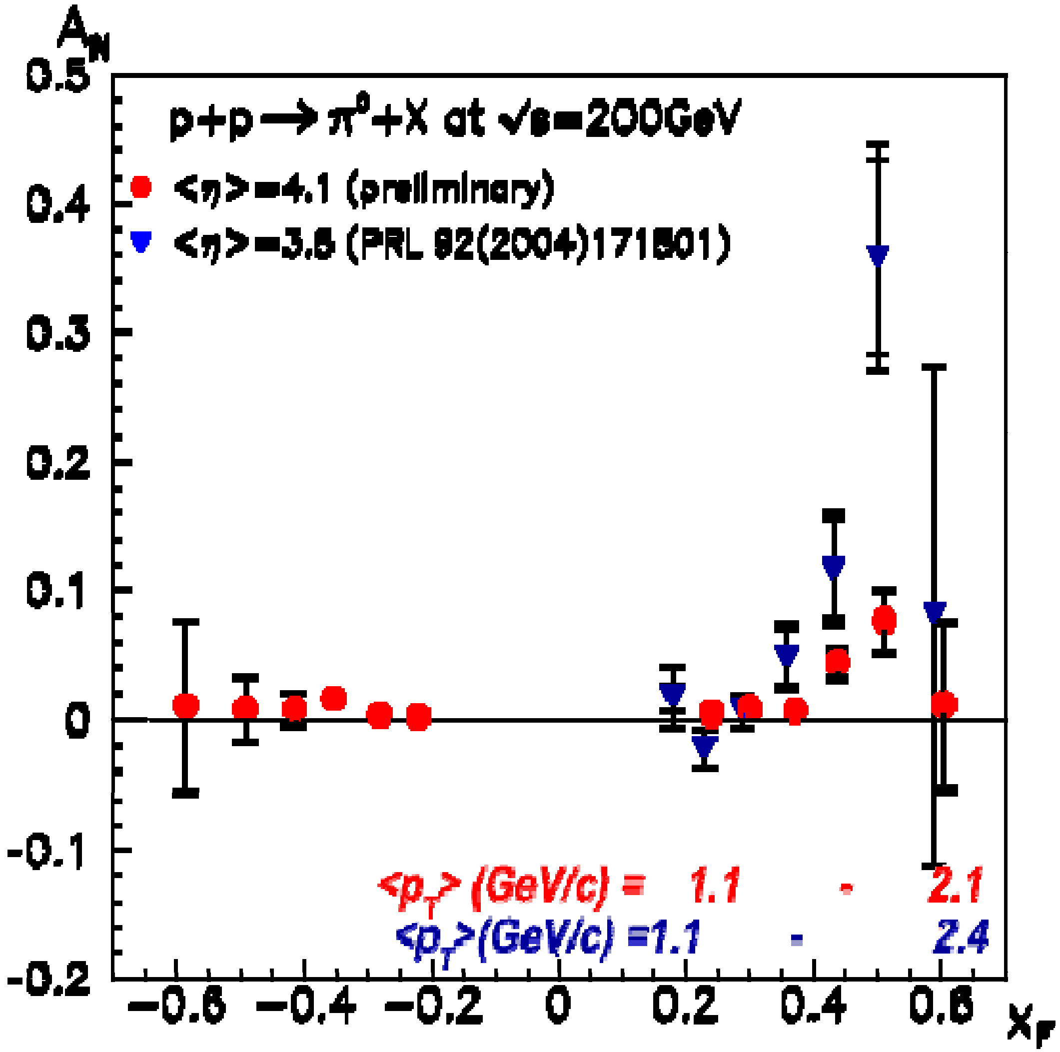
Run 3 Preliminary Result.

- **-More Forward angles.**
- **-FPD Detectors.**

Run 3 Preliminary Backward Angle Data.

- **-No significant Asymmetry seen.**

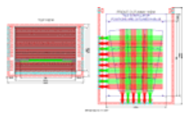
(Presented at Spin 2004: hep-ex/0502040)



Run 3 + Run 5 Preliminary

$\langle\eta\rangle$=3.7,4.0

(Presented SPIN 2005 Dubna Sept 27-Oct 1)



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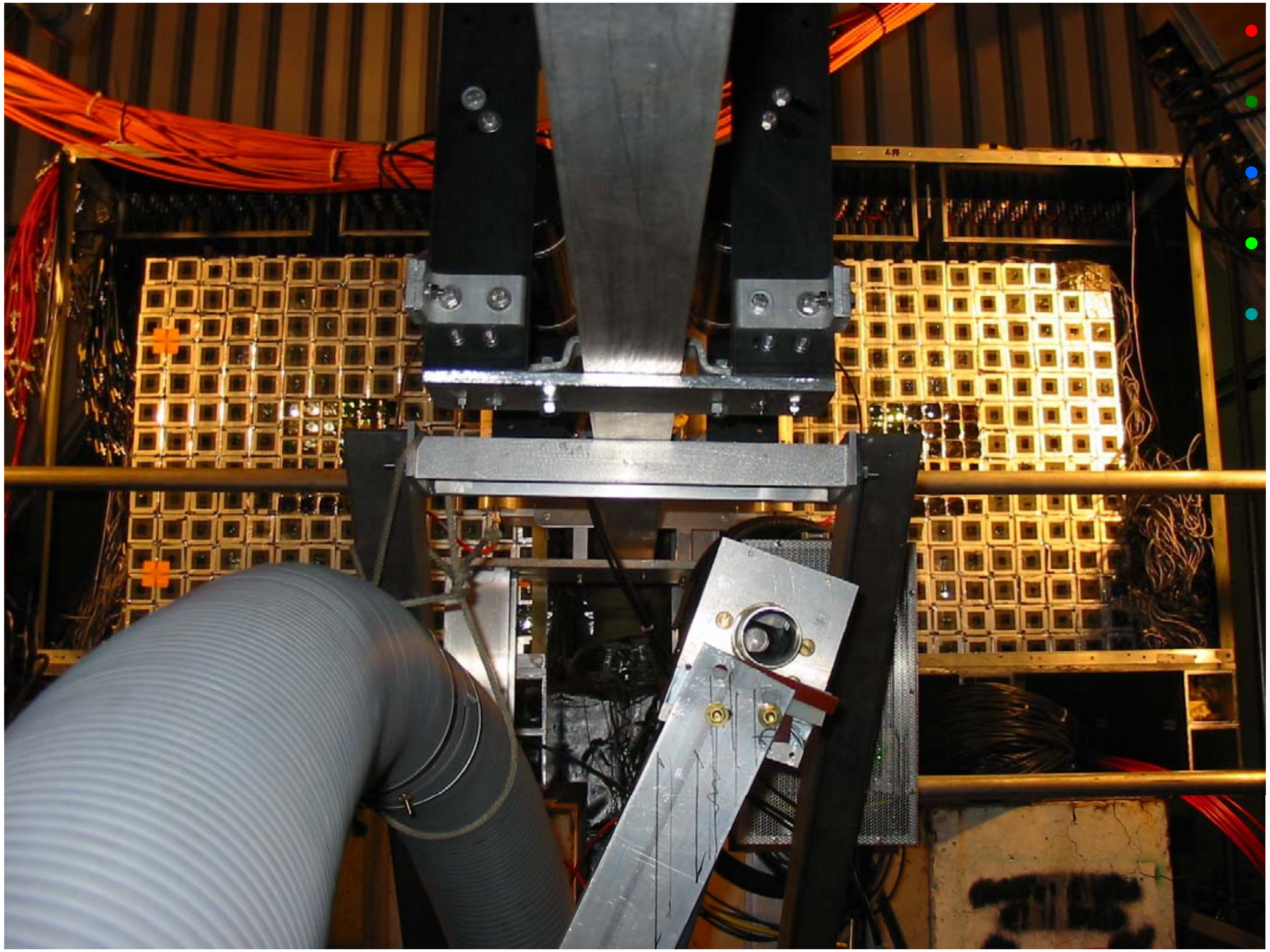
Run 6 (2006) – FPD++



- TPC: -1.0 < η < 1.0
- FTPC: 2.8 < |η| < 3.8
- BBC : 2.2 < |η| < 5.0
- EEMC: 1 < η < 2
- BEMC: -1 < η < 1
- FPD++/FPD:
  η ~ 3.3/-3.7

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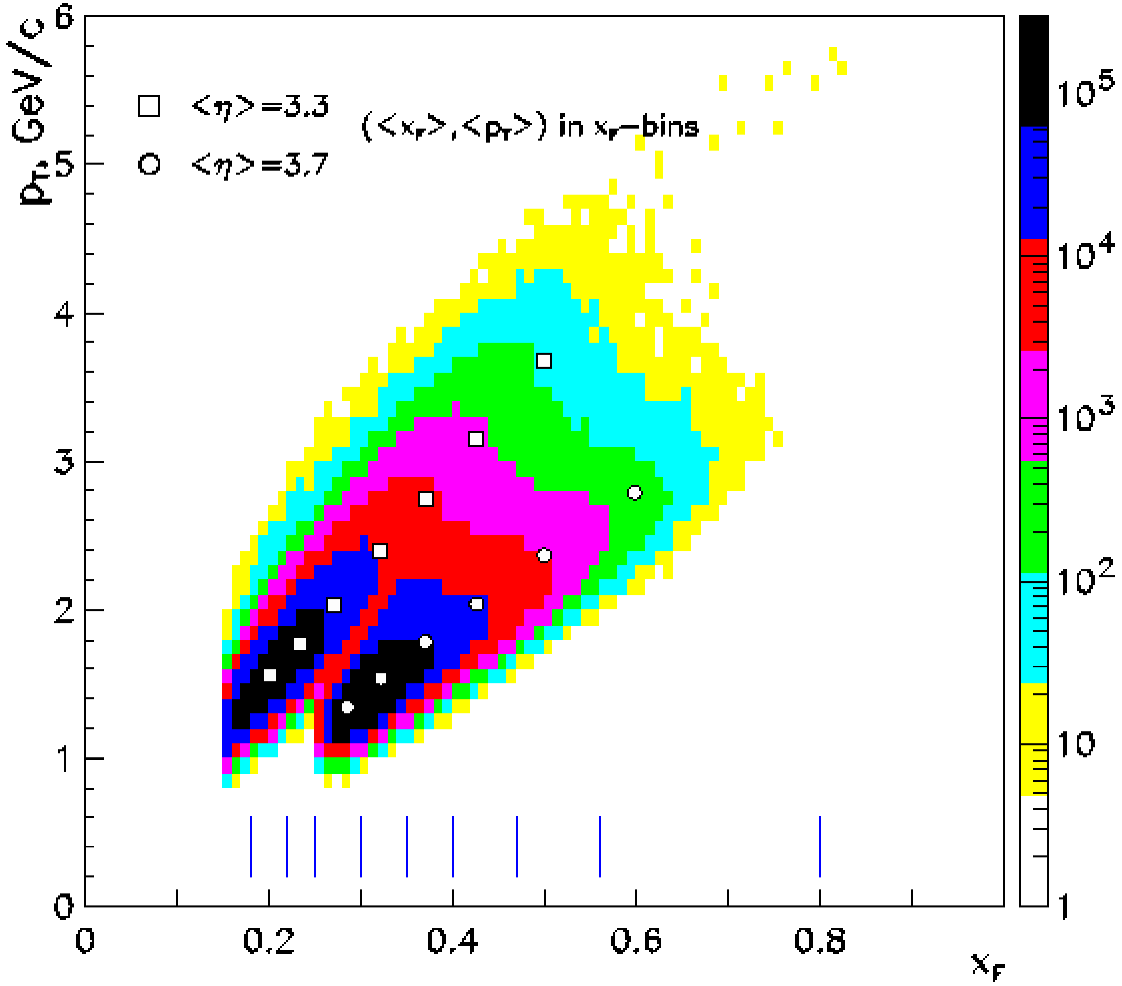
Detector acceptance



- Strong correlation between x_F and p_T in the individual detectors
- Rapid change in number of events for either increasing p_T at fixed x_F or increasing x_F at fixed p_T
- Broader p_T range in x_F bins when combining data at <η>=3.3 and 3.7

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Transverse spin runs at STAR with forward calorimetry: 2001→2006

	Run2	Run3	Run5	**Run6**
detector	EEMC and FPD prototypes	6 matrices of FPD	full FPD (8 matrices)	**East FPD West FPD++**
$P_{BEAM}, \%$	~15	~30	~45	**~60**
$\int^{\text{sampled}} Ldt,\ pb^{-1}$	0.15	0.25	0.1	**6.8**
$< \eta >$	3.8	±3.3/±4.0	±3.7/±4.0	**-3.7/3.3**

Figure of Merit

(P_{BEAM}^2 x L) in Run 6 is ~50 times larger than from previous STAR runs combined

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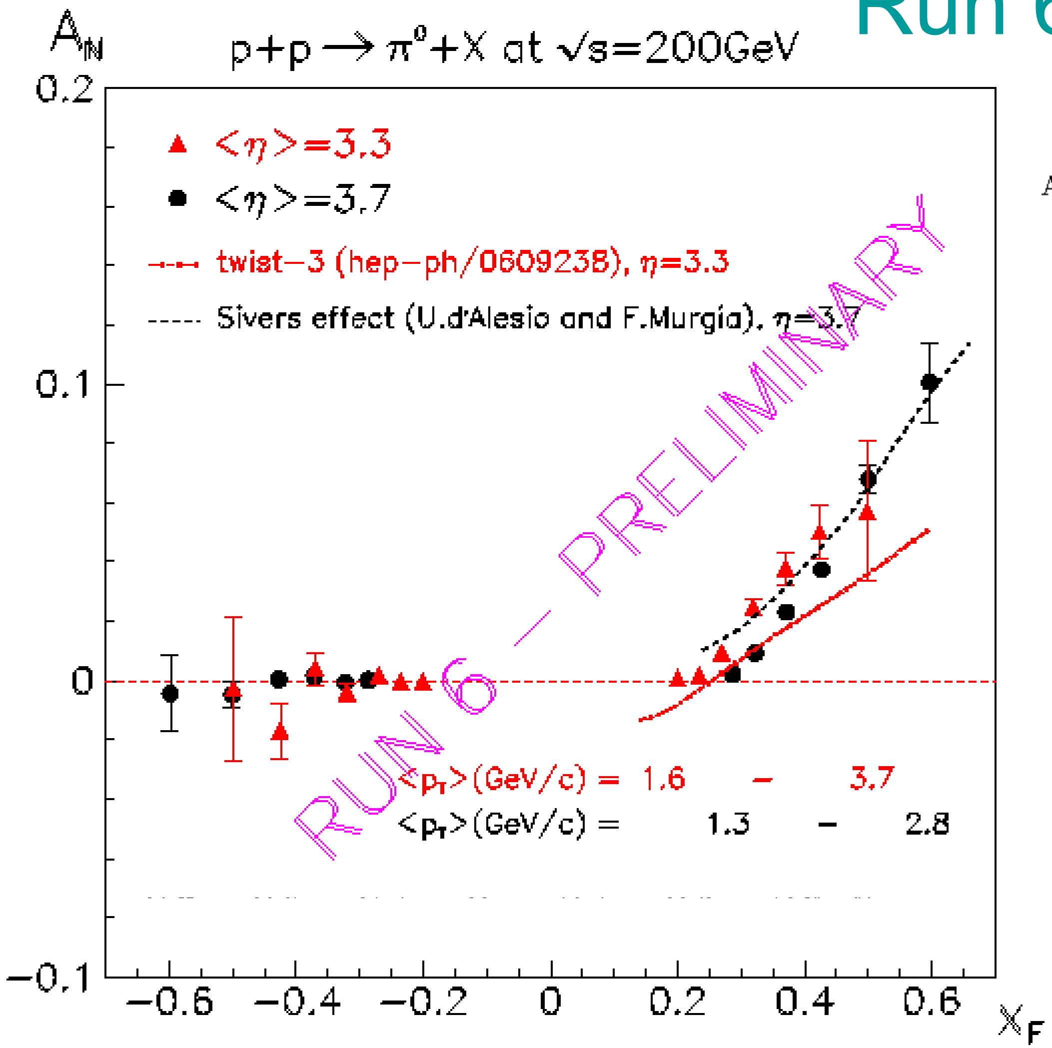
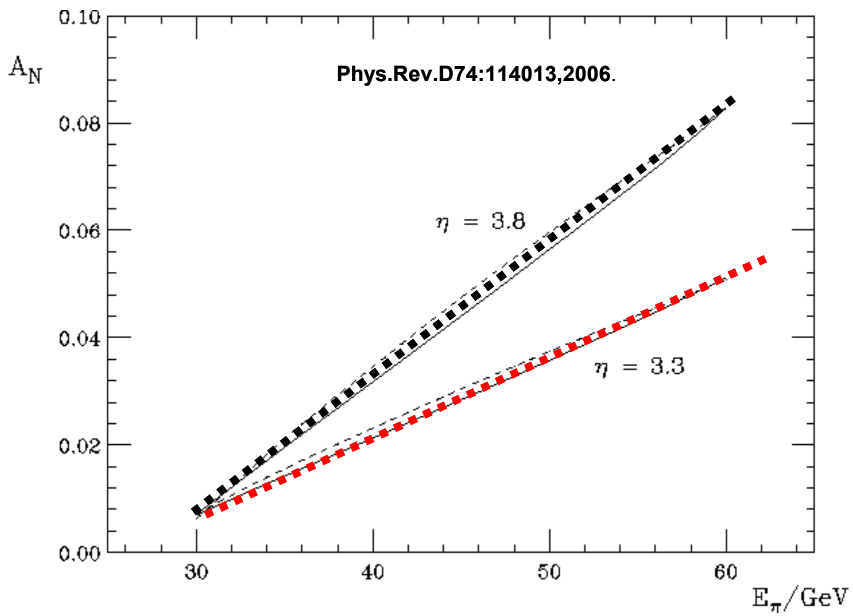
π^0 A_N at $\sqrt{s}$=200 GeV – x_F-dependence Run 6





- Small errors of the data points allow quantitative comparison with theory predictions
  - Theory expects the reverse dependence on η

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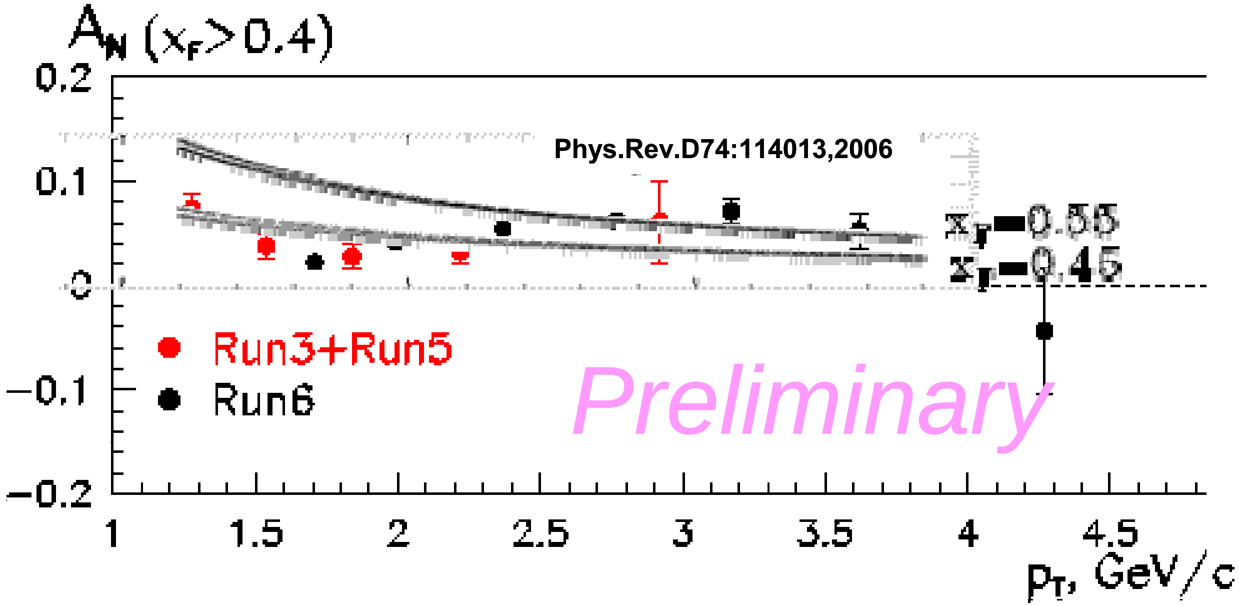
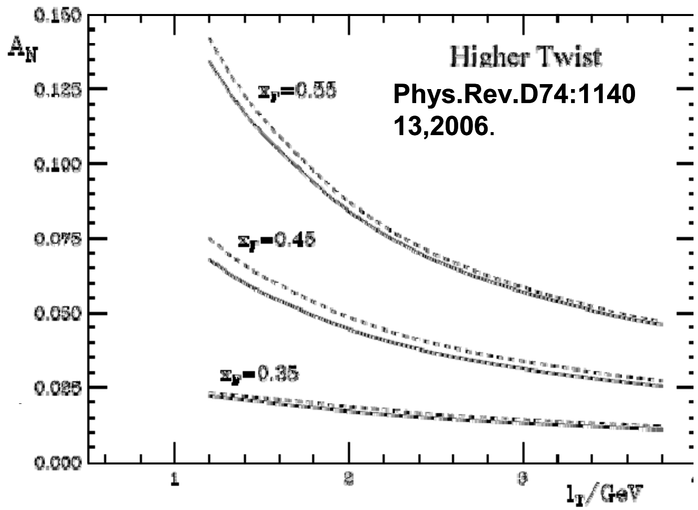
$A_N(p_T)$ at $x_F > 0.4$

Run3+Run5 data (hep-ex/0512013):





Run 6 data:

- *consistent with the previous runs in the overlapping p_T region*
- *complicated dependence on p_T (not $1/p_T$)*
- *more precise measurements*

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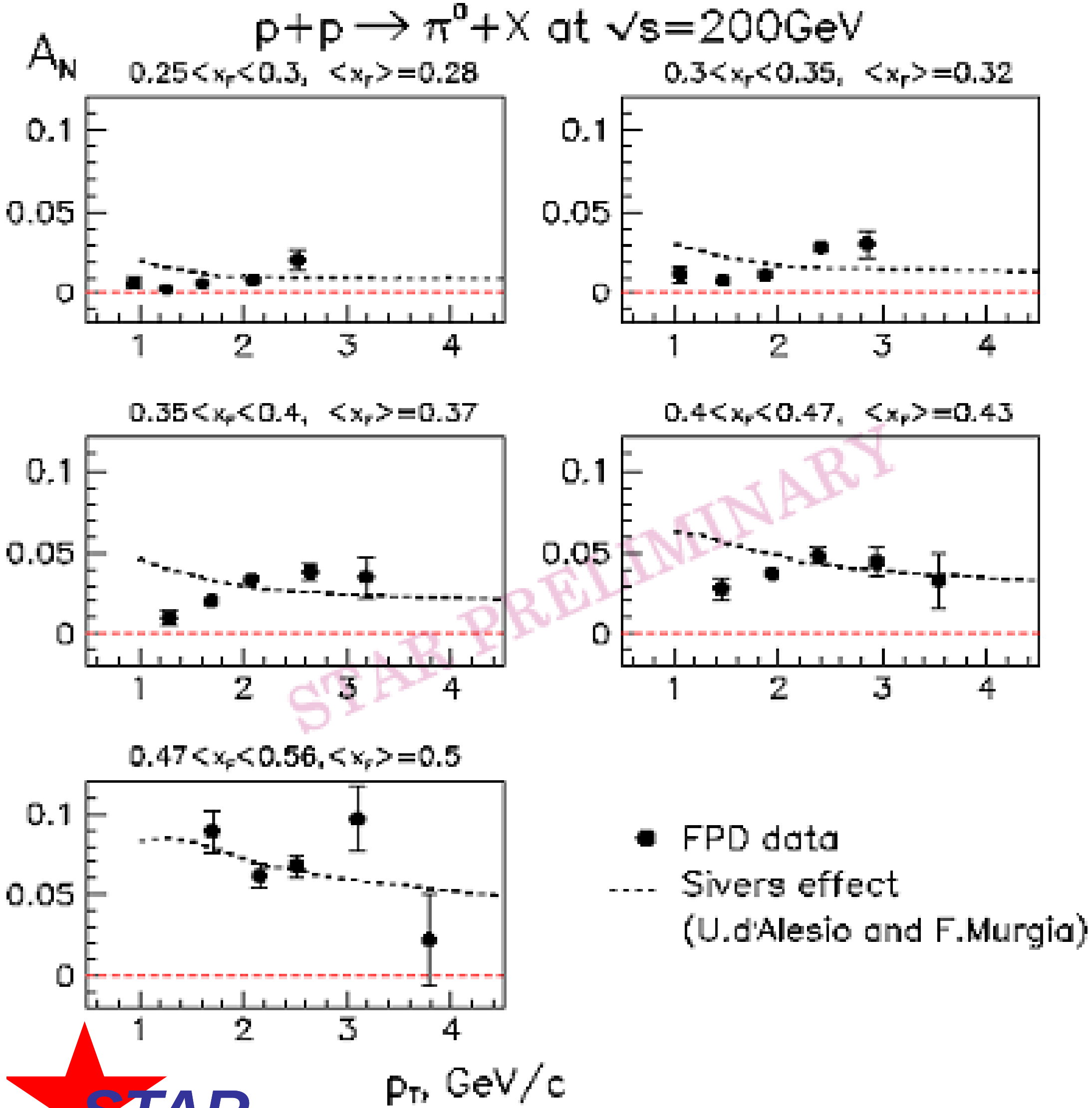
$A_N(p_T)$ in x_F-bins



- Combined data from three runs at <η>=3.3, 3.7 and 4.0
- Within each x_F bin, $\langle x_F \rangle$ does not significantly change with p_T
- Measured A_N is not a smooth decreasing function of p_T

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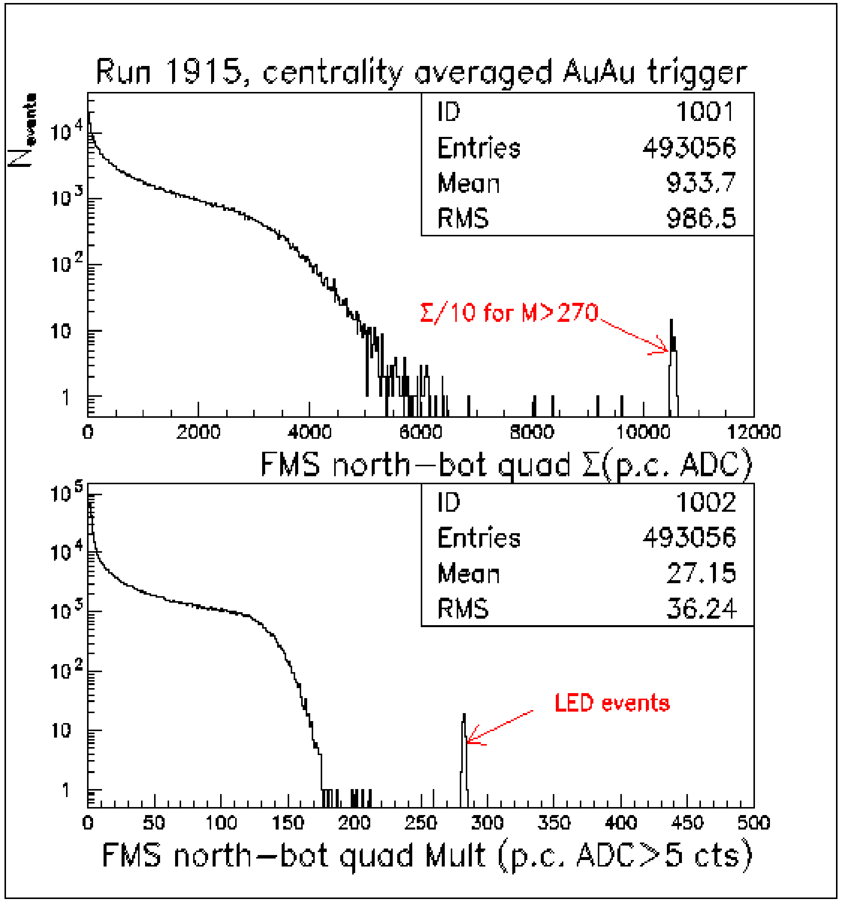
PHYSICS OBJECTIVES

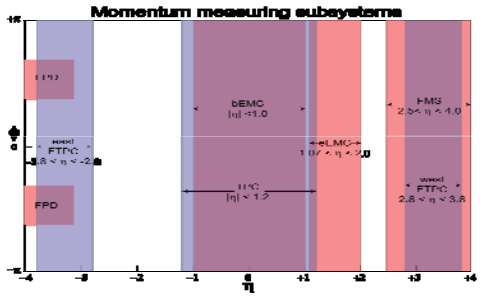
Au Au

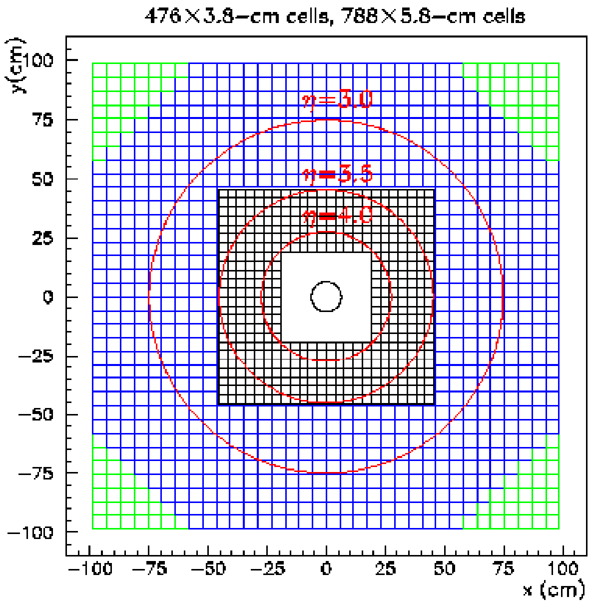
FMS Commissioning Apr 2007

- Summed Energy (ADC cnts)
- Cell multiplicity



FMS for Run 7 NOW!!





FMS ½ Wall

FMS Wall

1 Large Pb. Glass Cell

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Conclusions

- STAR collected 6.8 pb^{-1} of data for p+p collisions at $\sqrt{s}$=200 GeV with transversely polarized beam. With average polarization ~60%, this represents 50 fold increase in analyzing power sensitivity in comparison to all previous RHIC runs.

- We present the P_T dependence of A_N for restricted bins of X_F in a kinematic region where the spin summed pion cross section is well described by NLO PQCD.

- In contrast to predictions of conventional calculations, the asymmetry is "NOT" falling with P_T for $1 GeV/c < P_T < 3 GeV/c$ and may indeed be rising.

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