



# ***Recent Spin Physics Results from RHIC***

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**International Workshop on Structure and Spectroscopy  
March 19, 2007**



# *RHIC Physics*

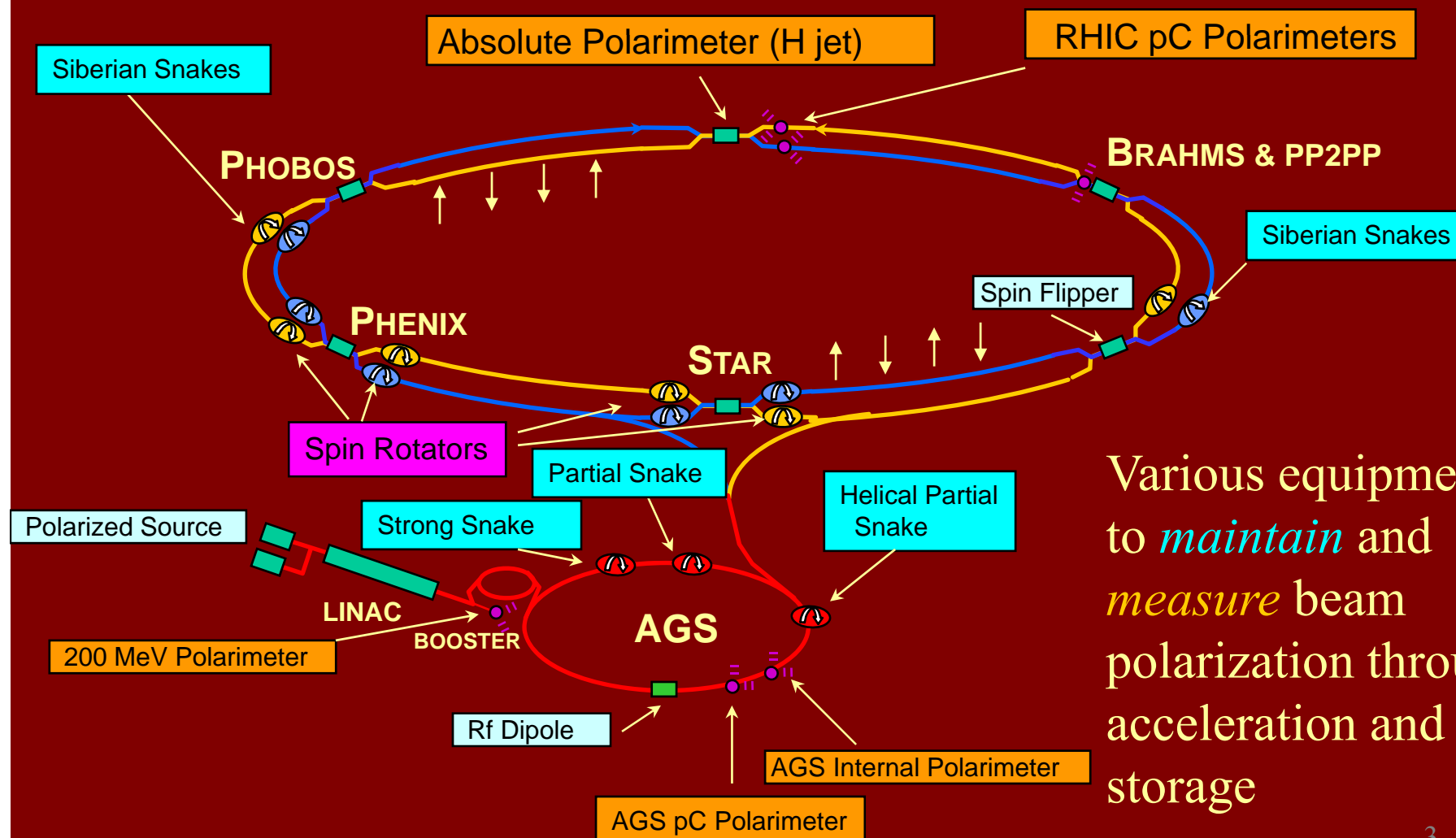
Broadest possible study of QCD in A+A, p+A, p+p collisions

- *Hadron structure in a nuclear environment*
  - Advantages of a polarized *hadron collider*
    - High energy  $\rightarrow$  factorization, new probes (W's)
    - Polarized hadrons  $\rightarrow$  gq, gg collisions
  - High energy
- *Nucleon structure in a nuclear environment*
  - Saturation physics
- *Proton spin structure*
  - In particular, contributions from
    - Gluon polarization ( $\Delta g$ )
    - Sea-quark polarization ( $\Delta \bar{u}, \Delta \bar{d}$ )





# *RHIC as a Polarized $p+p$ Collider*

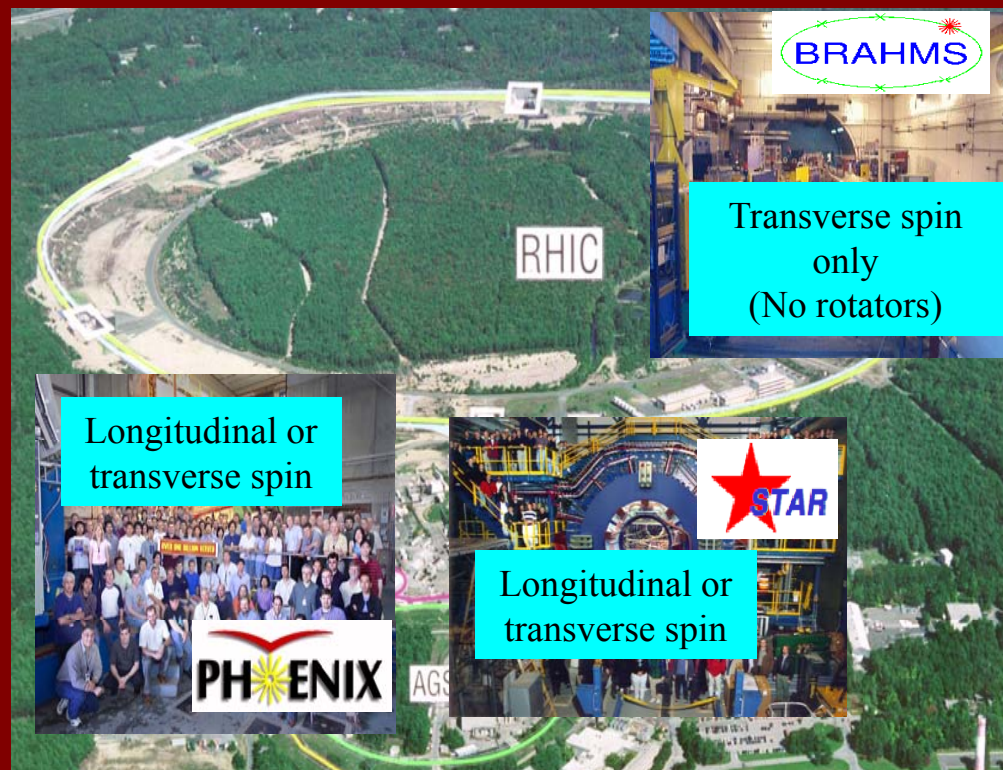


Various equipment to *maintain* and *measure* beam polarization through acceleration and storage



# Spin Physics at RHIC

- Variety of results out from STAR, PHENIX, and BRAHMS from 2002-2006 data sets
- 2006: STAR and PHENIX took significant transverse as well as longitudinally polarized data
- 2006: Polarized data at  $\sqrt{s} = 200$  and 62.4 GeV
- Future running only with STAR and PHENIX



2006 accelerator performance:

Avg. pol 62% at 200 GeV (design 70%).

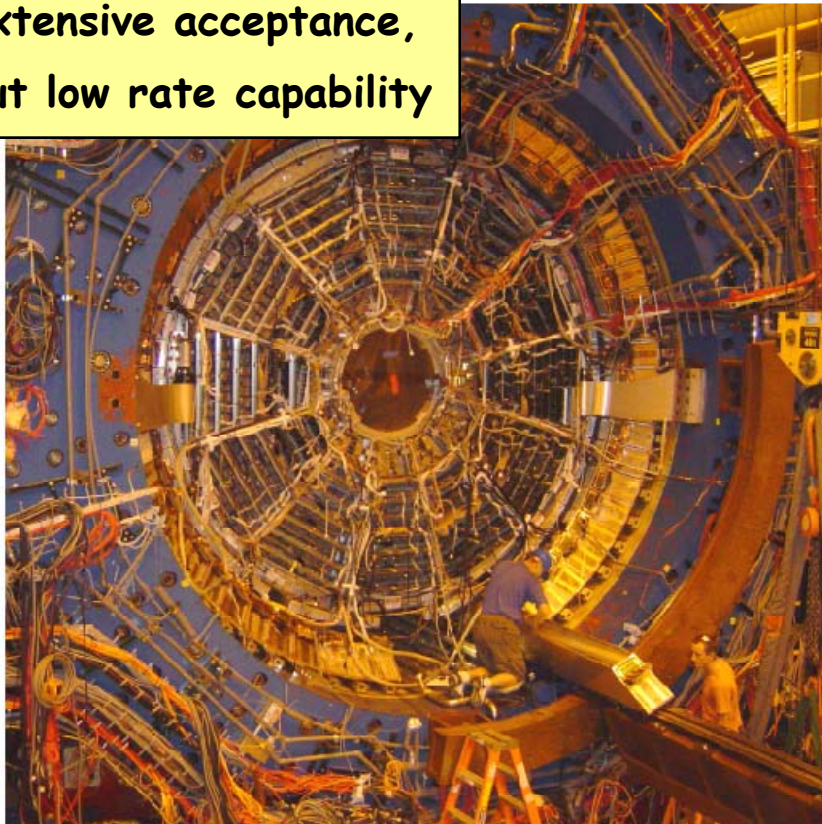
Achieved  $3.5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$  lumi (design  $\sim 5 \times$  this).



# STAR Detector

## Philosophy:

Extensive acceptance,  
but low rate capability



## Magnetron Tracker at RHIC

Time Projection Chamber,  $-1 < \eta < 1$

0.5 T magnetic field,



Barrel EM Calorimeter,  $0 < \eta < 1$

Endcap EM Calorimeter,  $1 < \eta < 2$

Beam-Beam Counters,  $2.2 < |\eta| < 5$

Forward Pion Detector  $|\eta| \sim 3.3/3.7/4.0$

...

Ongoing and proposed upgrades:

- DAQ-1000, Time-of-Flight barrel, Forward Meson Spectrometer,
- Heavy Flavor Tracker, Inner-Silicon Tracker, Forward Tracker.

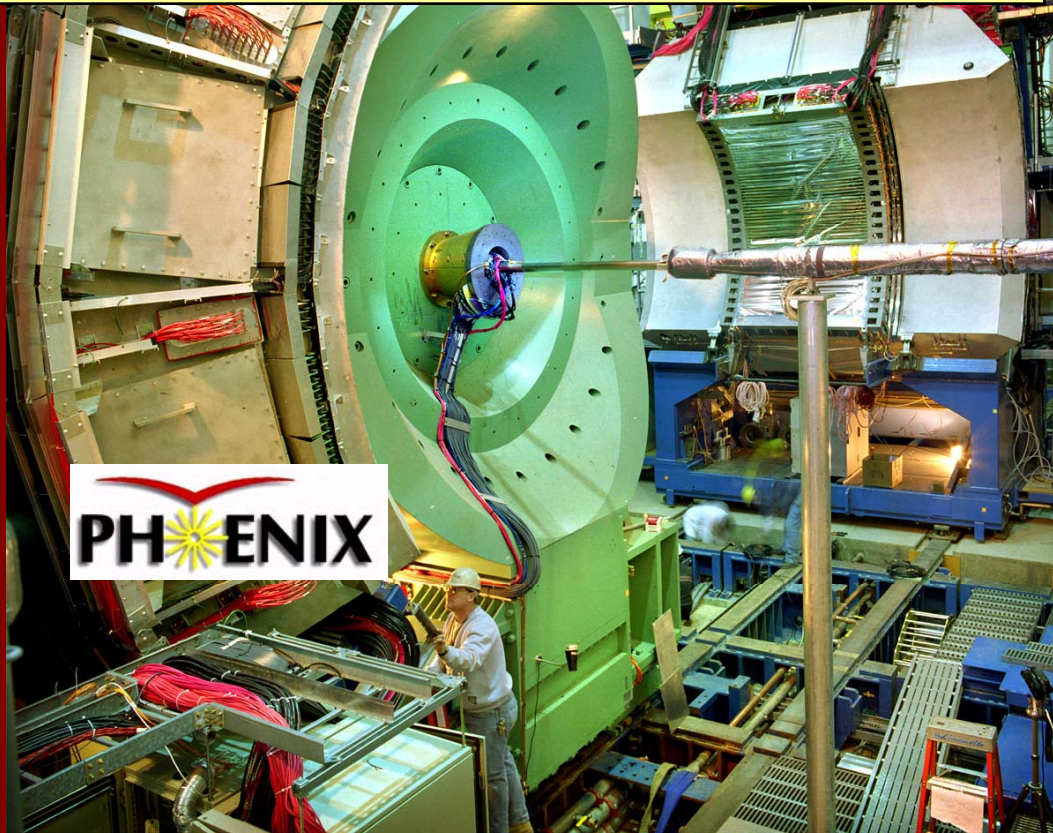




# *PHENIX Detector*

## Philosophy:

High rate capability to measure rare probes,  
but limited acceptance.



2 central  
spectrometers  
-Track charged  
particles and detect  
electromagnetic  
processes

$90^\circ + 90^\circ$  azimuth  
 $|\eta| < 0.35$

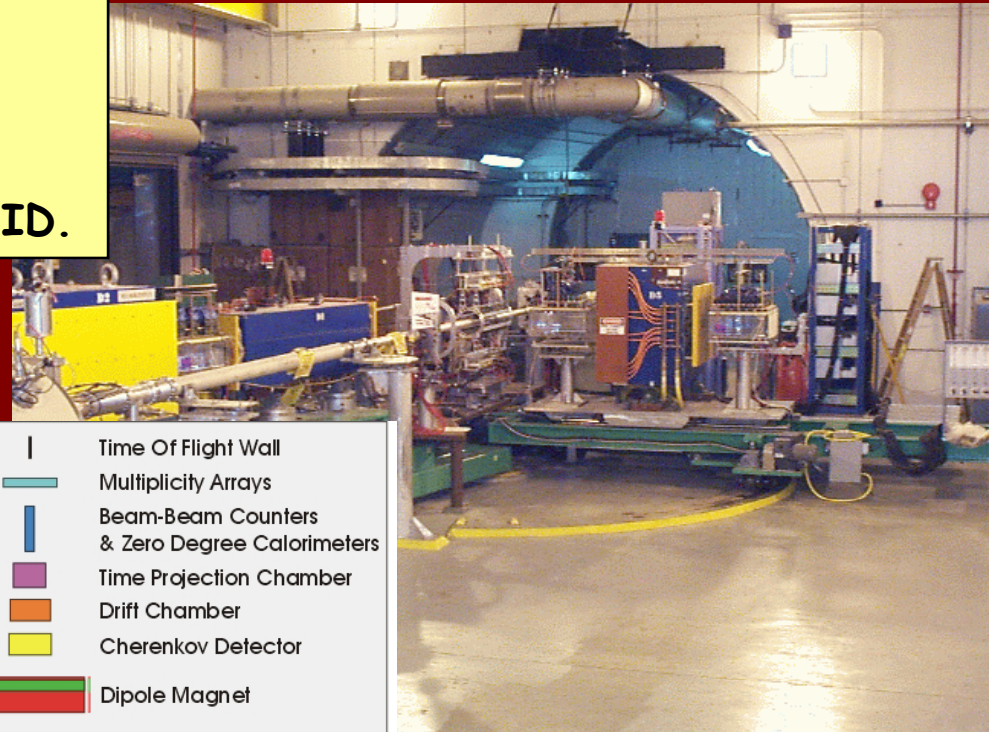
2 forward  
spectrometers  
- Identify and track  
muons



# BRAHMS Detector

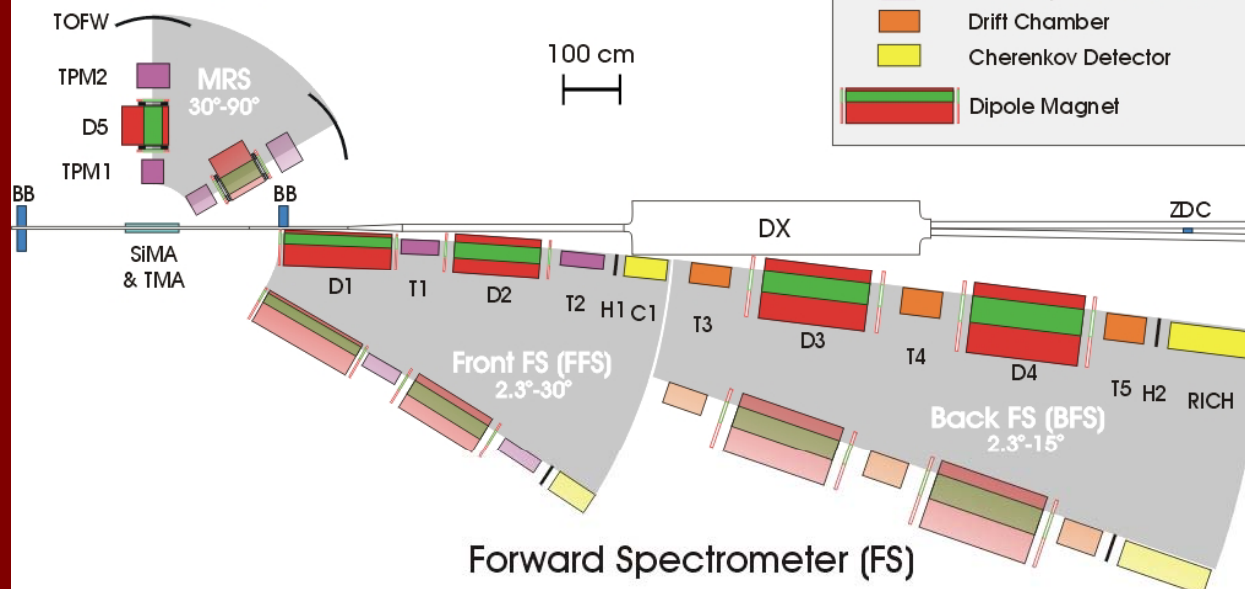
## Philosophy:

Small acceptance spectrometer arms  
designed with good charged particle ID.

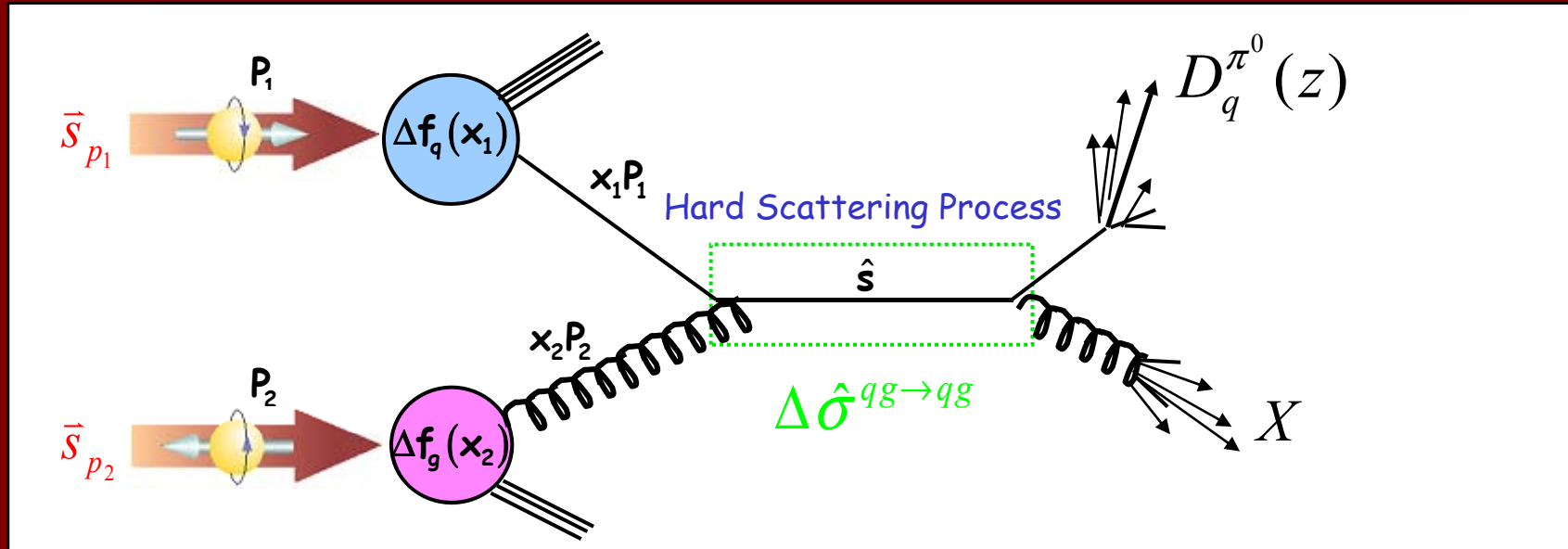


## BRAHMS Experimental Setup

### Mid Rapidity Spectrometer



# Hard Scattering in $p+p$ : $p$ QCD Factorization



$$\sigma(pp \rightarrow \pi^0 X) \propto q(x_1) \otimes g(x_2) \otimes \hat{\sigma}^{qg \rightarrow qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

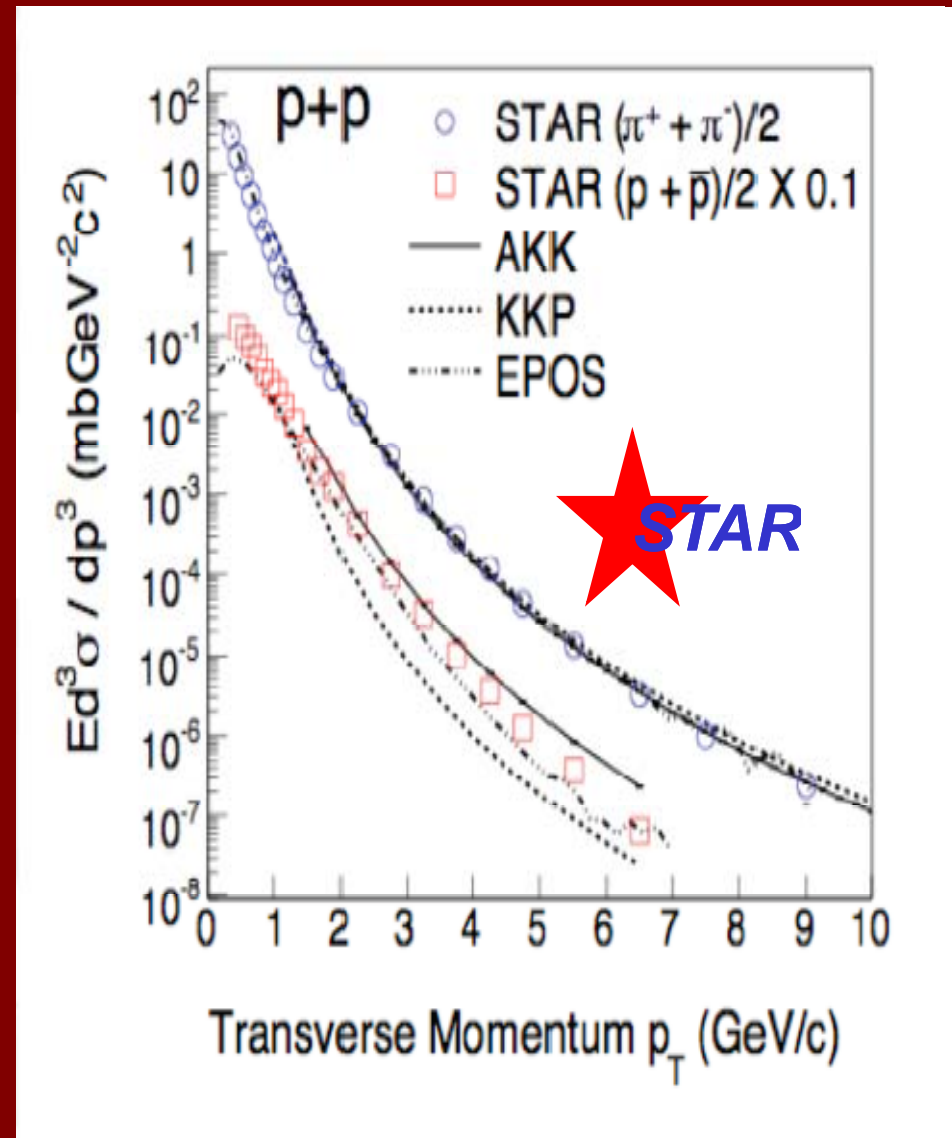
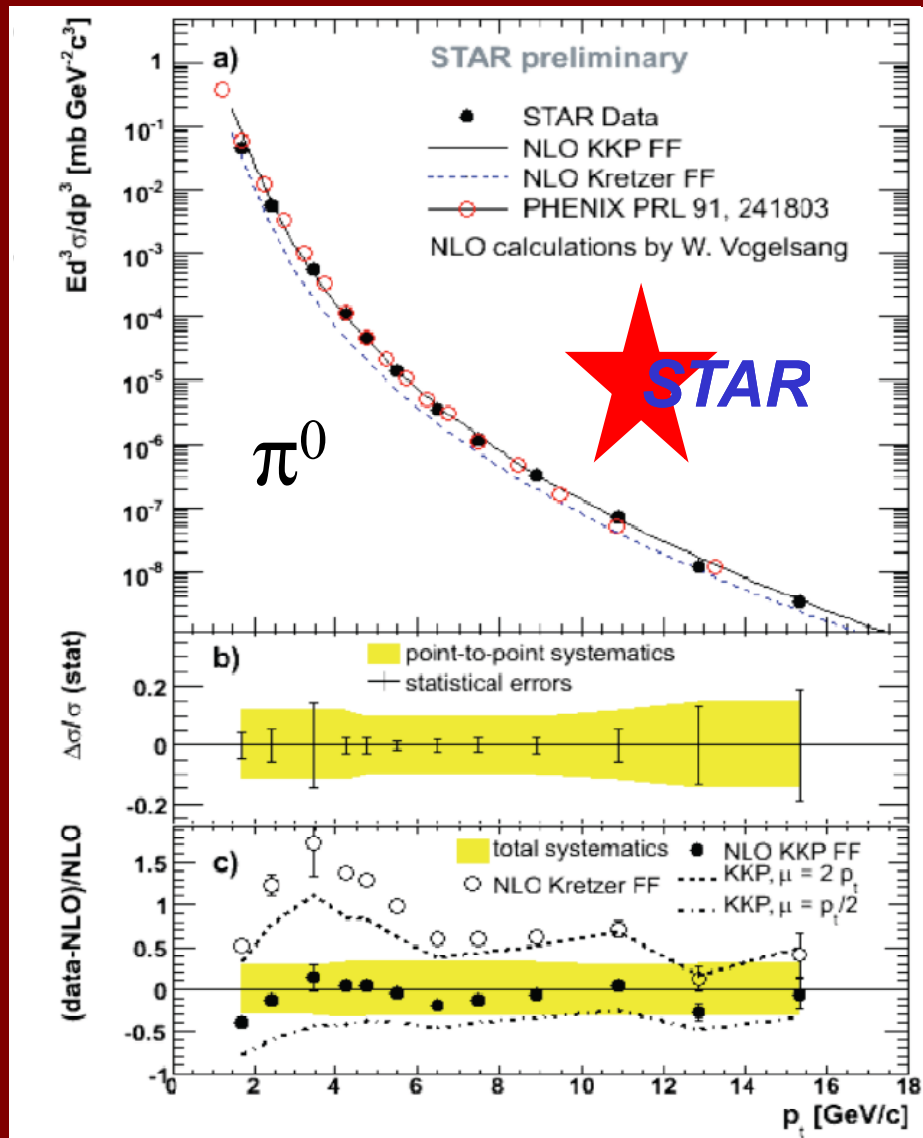


$$\Delta\sigma(pp \rightarrow \pi^0 X) \propto \Delta q(x_1) \otimes \Delta g(x_2) \otimes \Delta\hat{\sigma}^{qg \rightarrow qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

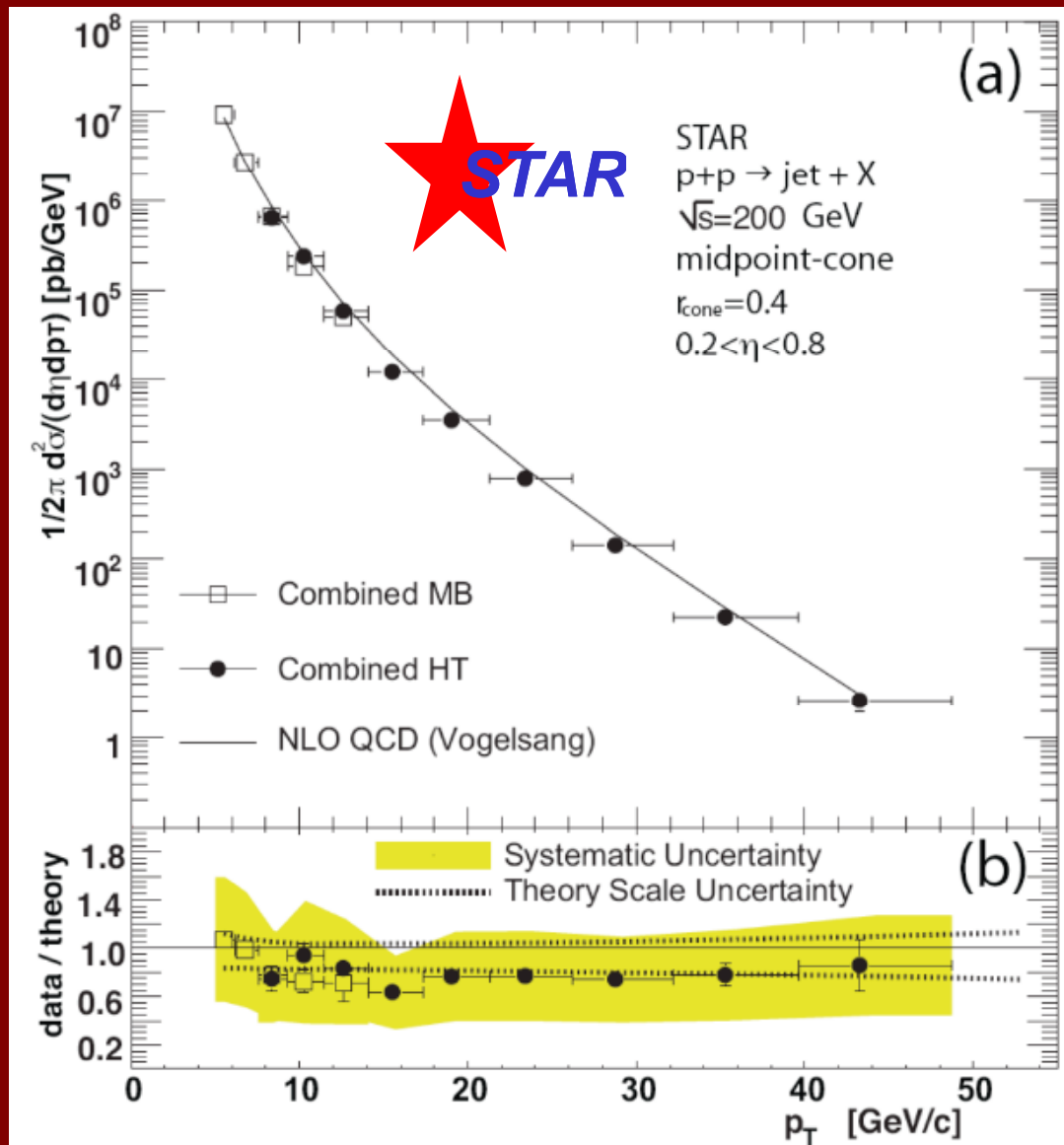




# Midrapidity Hadron Production at $\sqrt{s}=200$ GeV



# Midrapidity Jet Production at $\sqrt{s}=200$ GeV



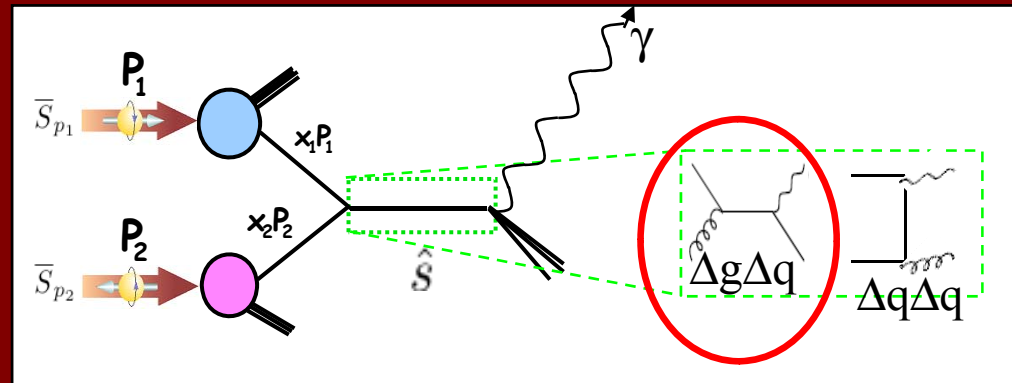
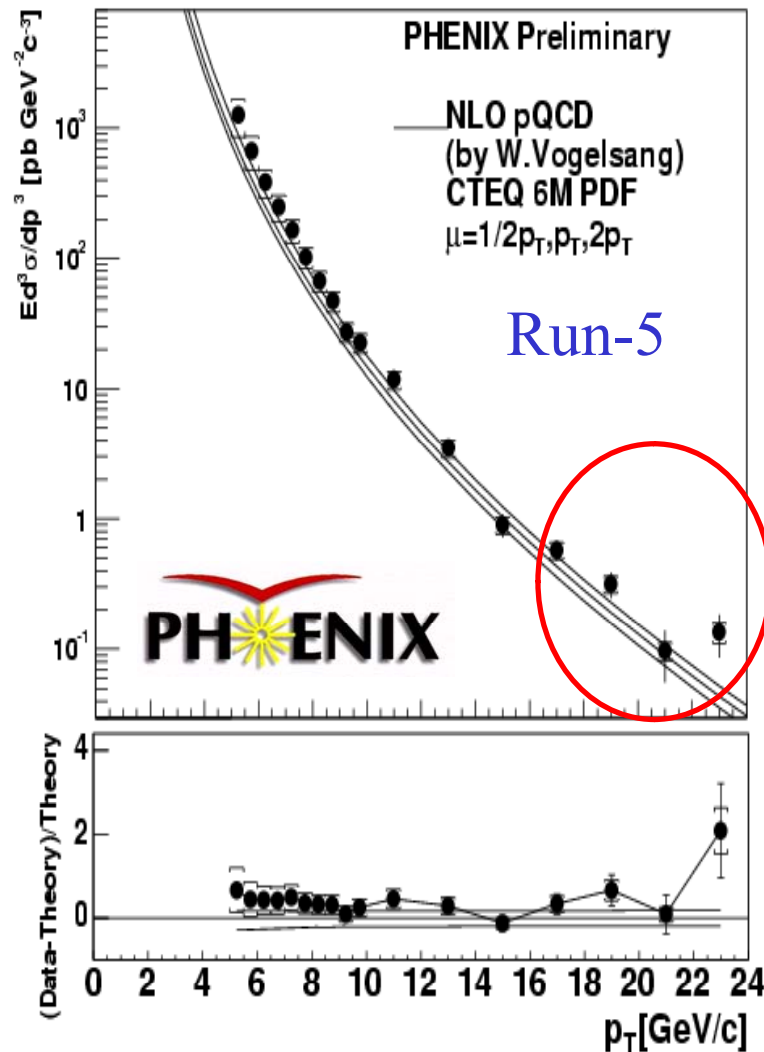
First measurement of inclusive jet cross section at RHIC

Good agreement with NLO pQCD, within large systematic uncertainties (dominated by energy scale uncertainty)

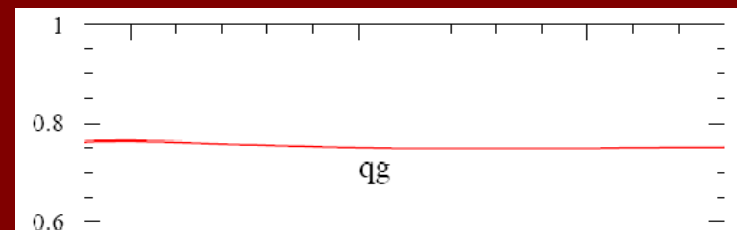




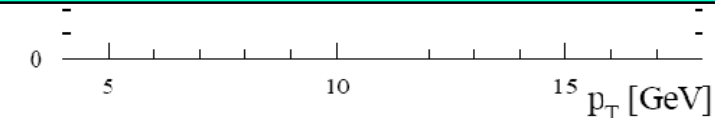
# Midrapidity Prompt $\gamma$ Production at $\sqrt{s}=200$ GeV



$$A_{LL} \propto \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta q(x_2)}{q(x_2)} \otimes \hat{a}_{LL}(gq \rightarrow \gamma q)$$

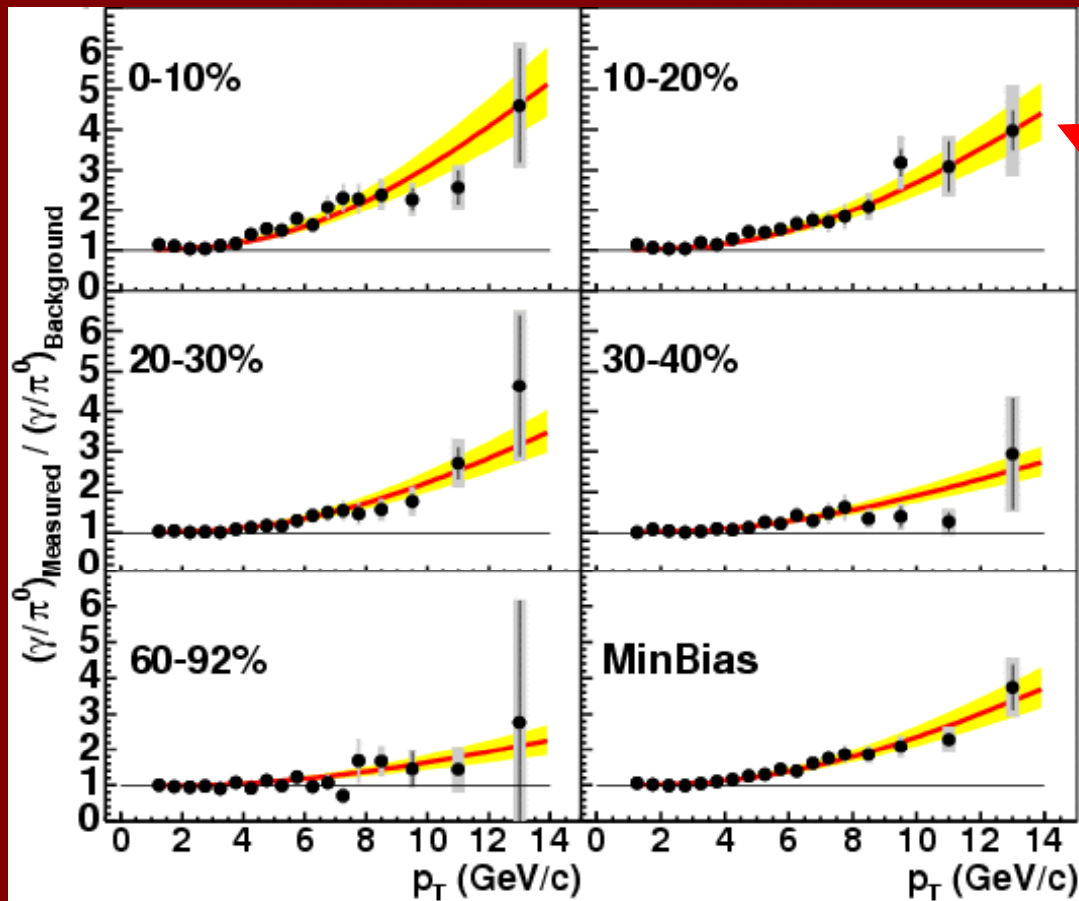


Will be an important channel for  $\Delta g$ !



# Prompt Photons in Au+Au Collisions

PRL 94, 232301



Expectation for  
 $N_{\text{collision}}$  scaling  
of direct  
photons

Prompt photons also  
a clean probe in  
Au+Au, unaffected  
by produced medium!

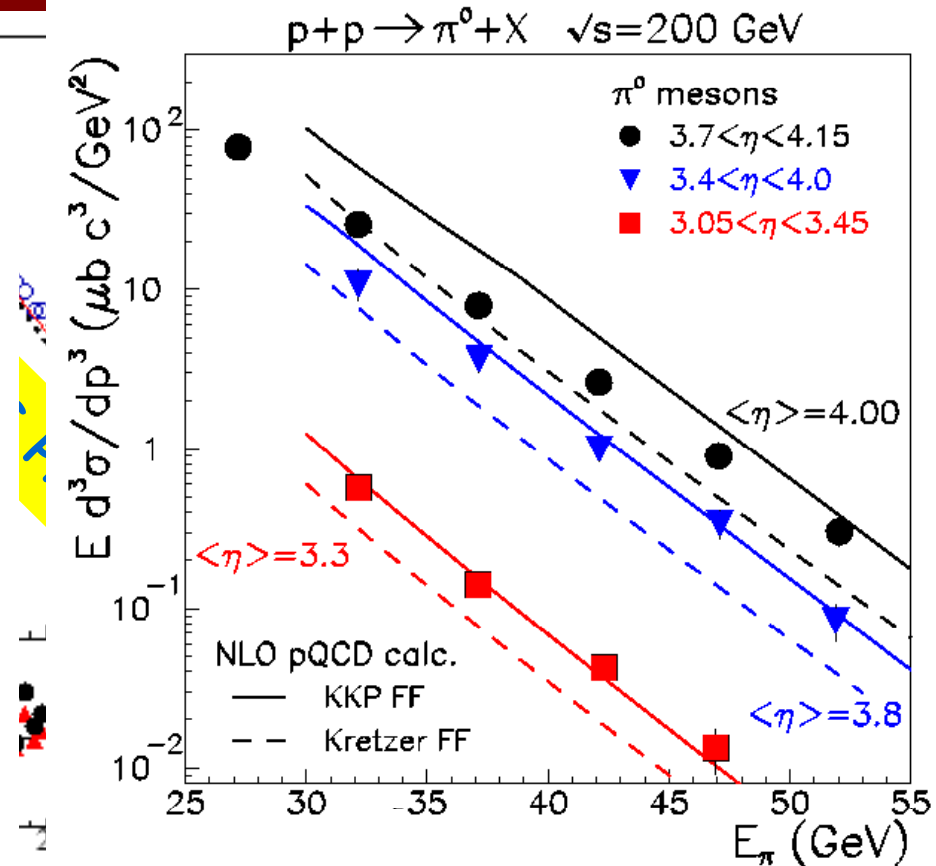
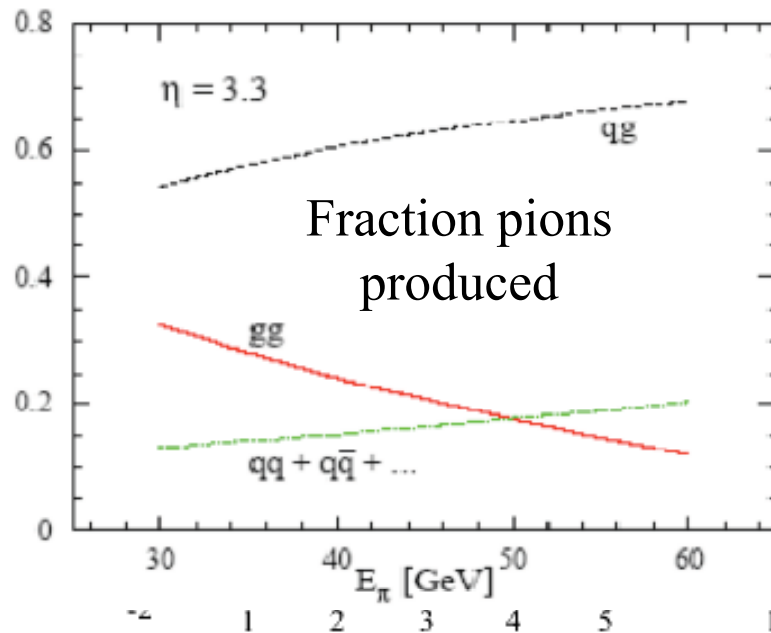




# Forward Hadron Production at $\sqrt{s}=200$ GeV

Good agreement between data and NLO pQCD at  $\sqrt{s}=200$  GeV, even at larger rapidities

PRL 97 (2006) 152302



# Probing the Gluon Polarization at RHIC

With factorized pQCD in hand as a theoretical tool, can probe  $\Delta g$  via double-helicity asymmetry measurements

$$\Delta\sigma(pp \rightarrow \pi^0 X) \propto \Delta q(x_1) \otimes \Delta g(x_2) \otimes \Delta\hat{\sigma}^{qg \rightarrow qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

*Now for some results . . .*

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}, \quad \delta_{A_{LL}} = \frac{1}{|P_1 P_2|} \frac{2RN_{++}N_{+-}}{(N_{++} + RN_{+-})^2} \sqrt{\left(\frac{\Delta N_{++}}{N_{++}}\right)^2 + \left(\frac{\Delta N_{+-}}{N_{+-}}\right)^2}$$

++ same helicity

+- opposite helicity

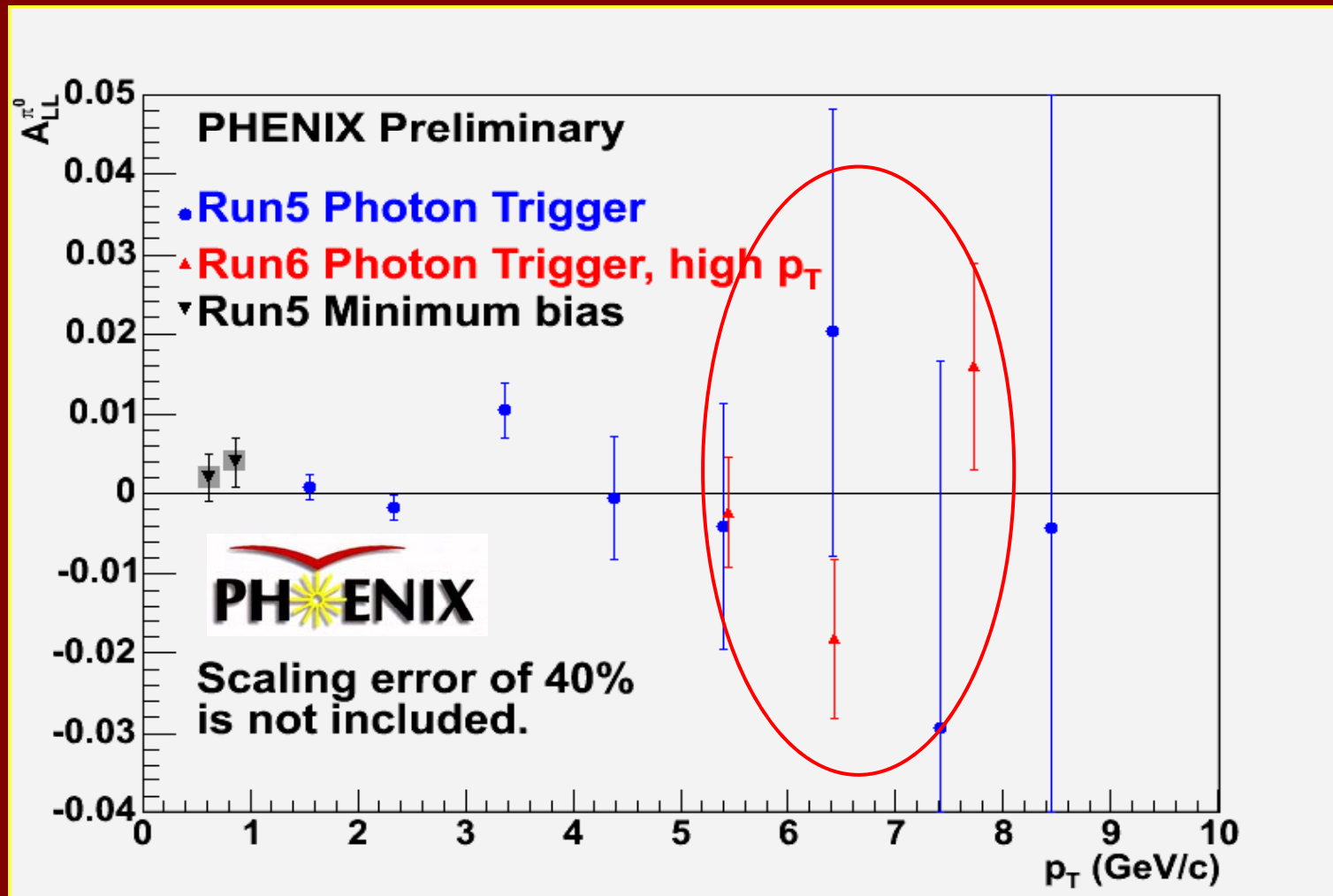
$N$ : yield

$R$ : luminosity $_{++}$ /luminosity $_{+-}$



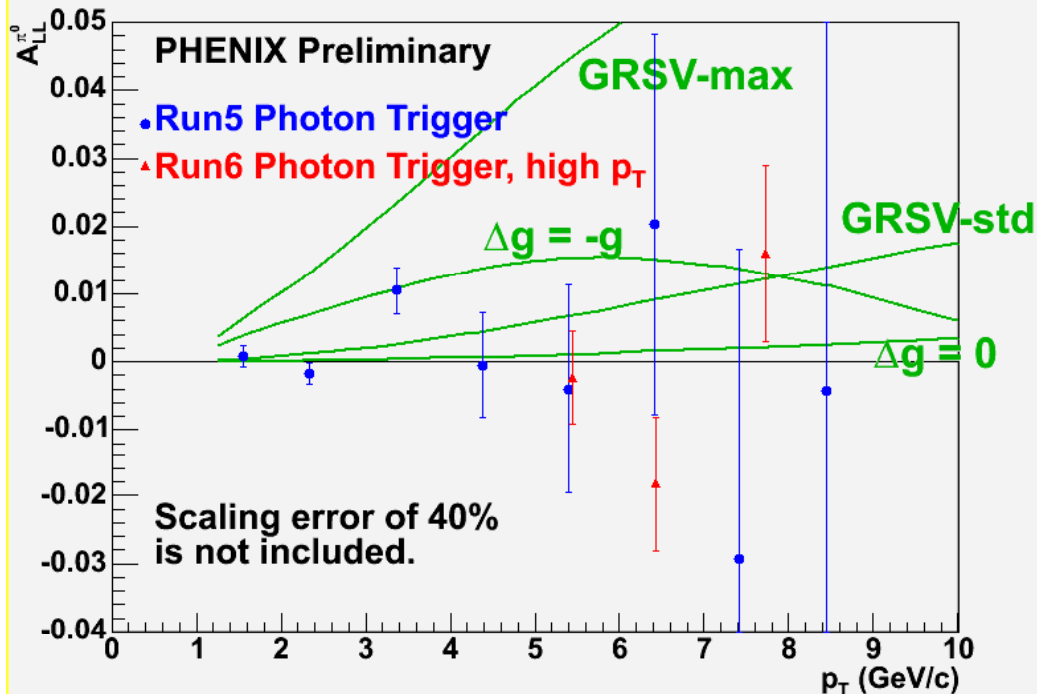


# $A_{LL}$ of $\pi^0$ at $\sqrt{s}=200$ GeV





# $A_{LL}$ of $\pi^0$ at $\sqrt{s}=200$ GeV



- Run-6 data set 2.0-2.7 times improvement on statistical uncertainties from Run-5.
  - Variation due to trigger turn-on

GRSV: M. Glueck, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. D 63 (2001) 094005.



Expect clearer statement when full data from Run-6 available and lower- $p_T$   $\pi^0$  points as well as other probes are measured

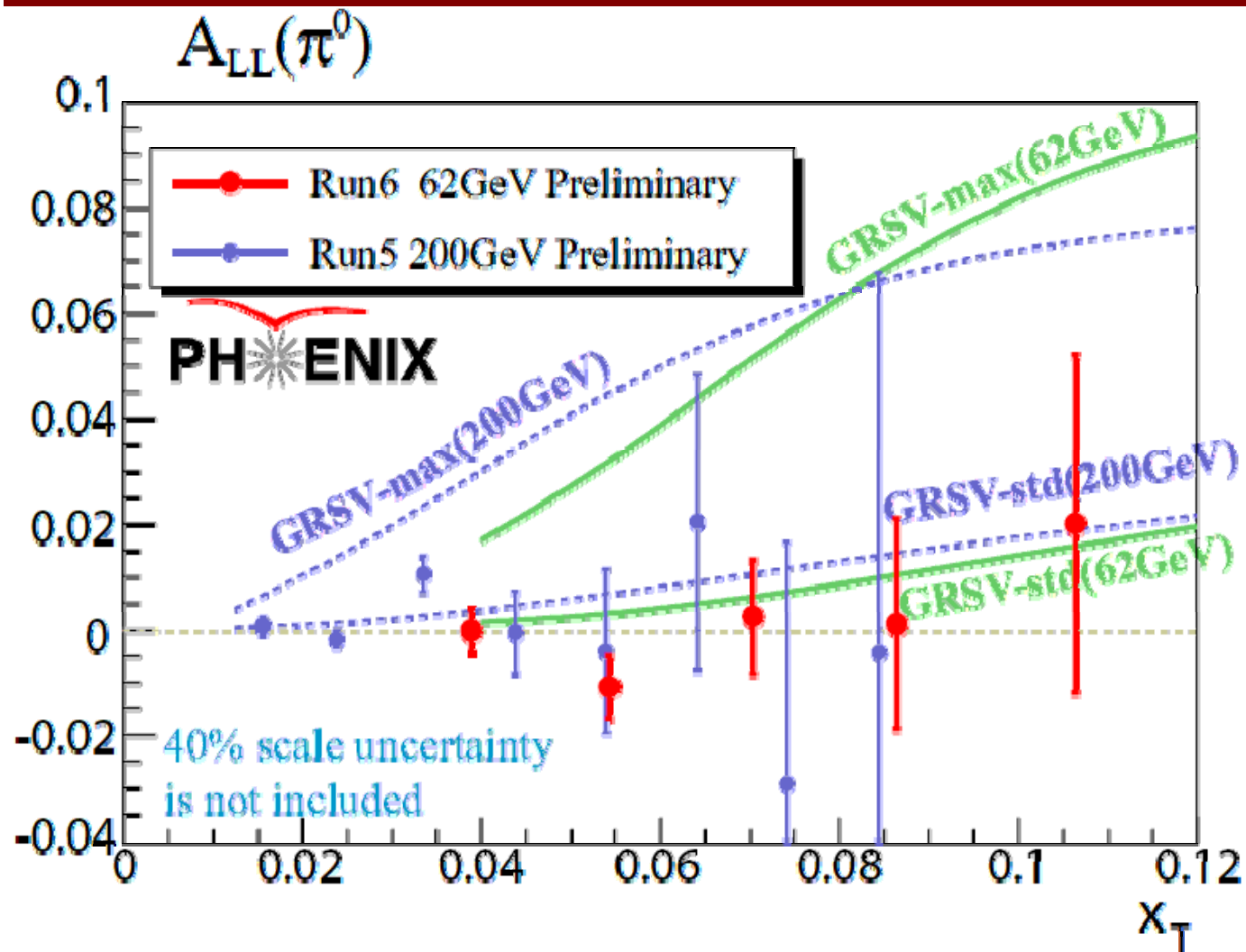
Confidence Levels	Run-5	Run-6	Run-5&Run-6
GRSV-std	18-22	0.5-7	1-9
GRSV $\Delta g=0$	17-19	14-17	11-12



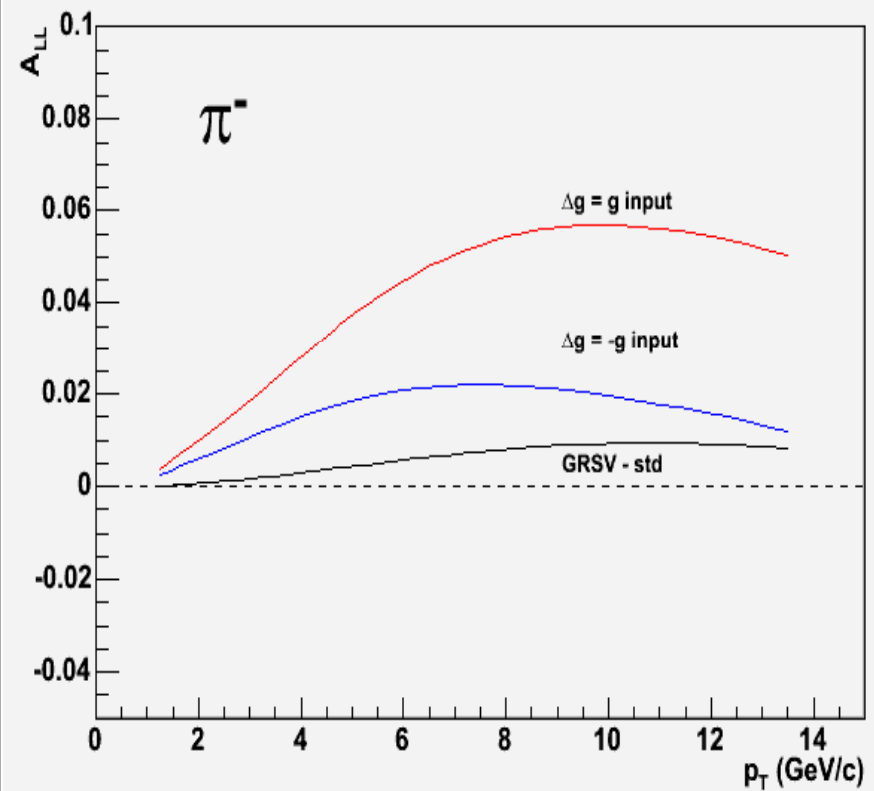
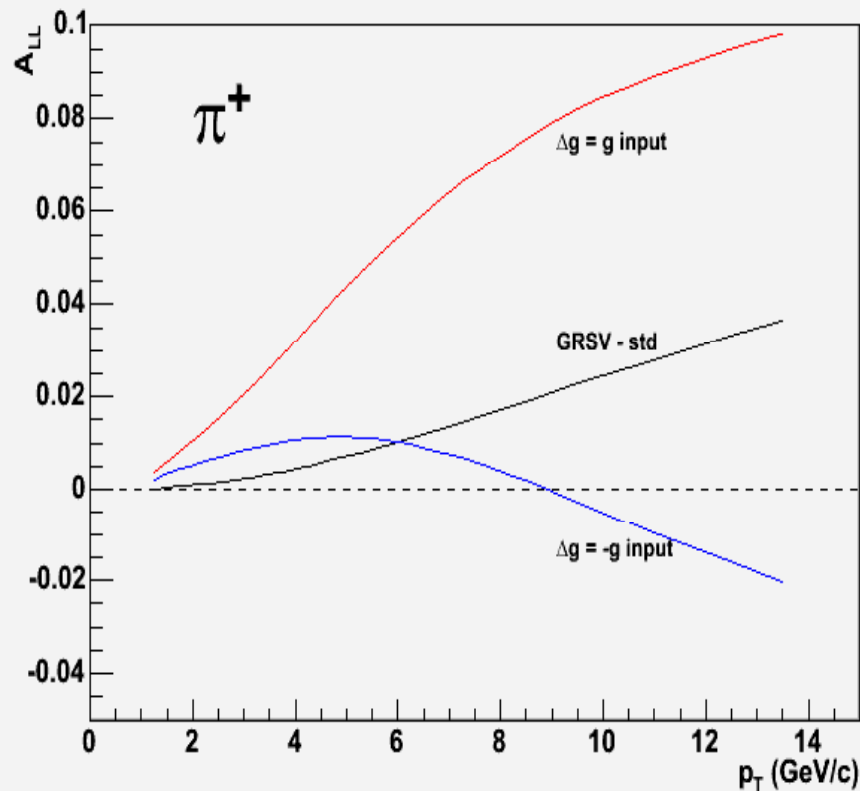
# $\pi^0 A_{LL}$ at $\sqrt{s}=62.4$ GeV

$$x_T = \frac{2p_T}{\sqrt{s}}$$

Converting to  $x_T$ , we can see the significance of the  $\sqrt{s}=62.4$  GeV data set compared to the Run-5 200-GeV preliminary data. Not bad for 2 weeks of 62-GeV running!



# $\pi^+, \pi^- A_{LL}$ and $\Delta g$



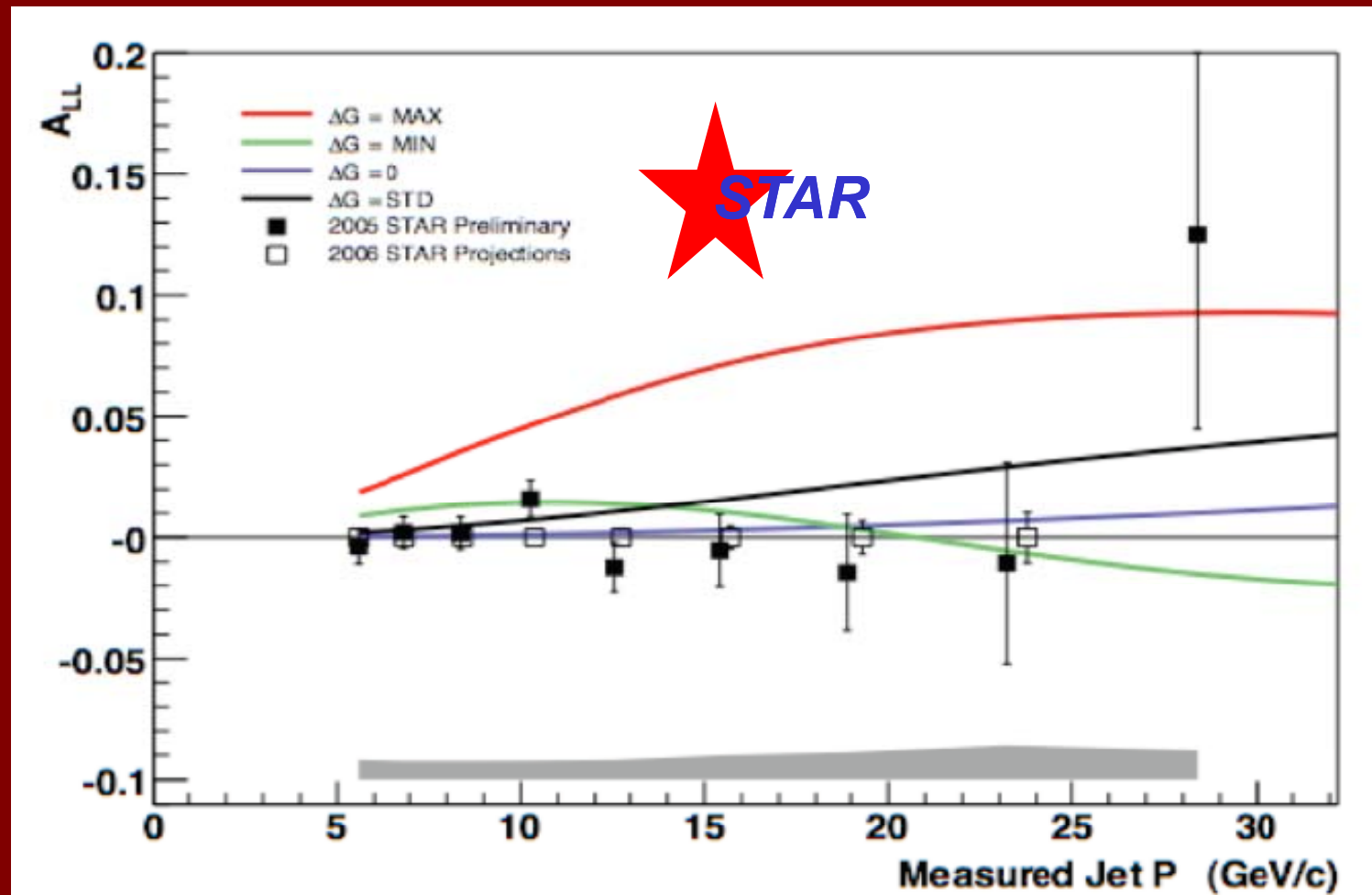
$$\Delta g > 0 \Rightarrow A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$$



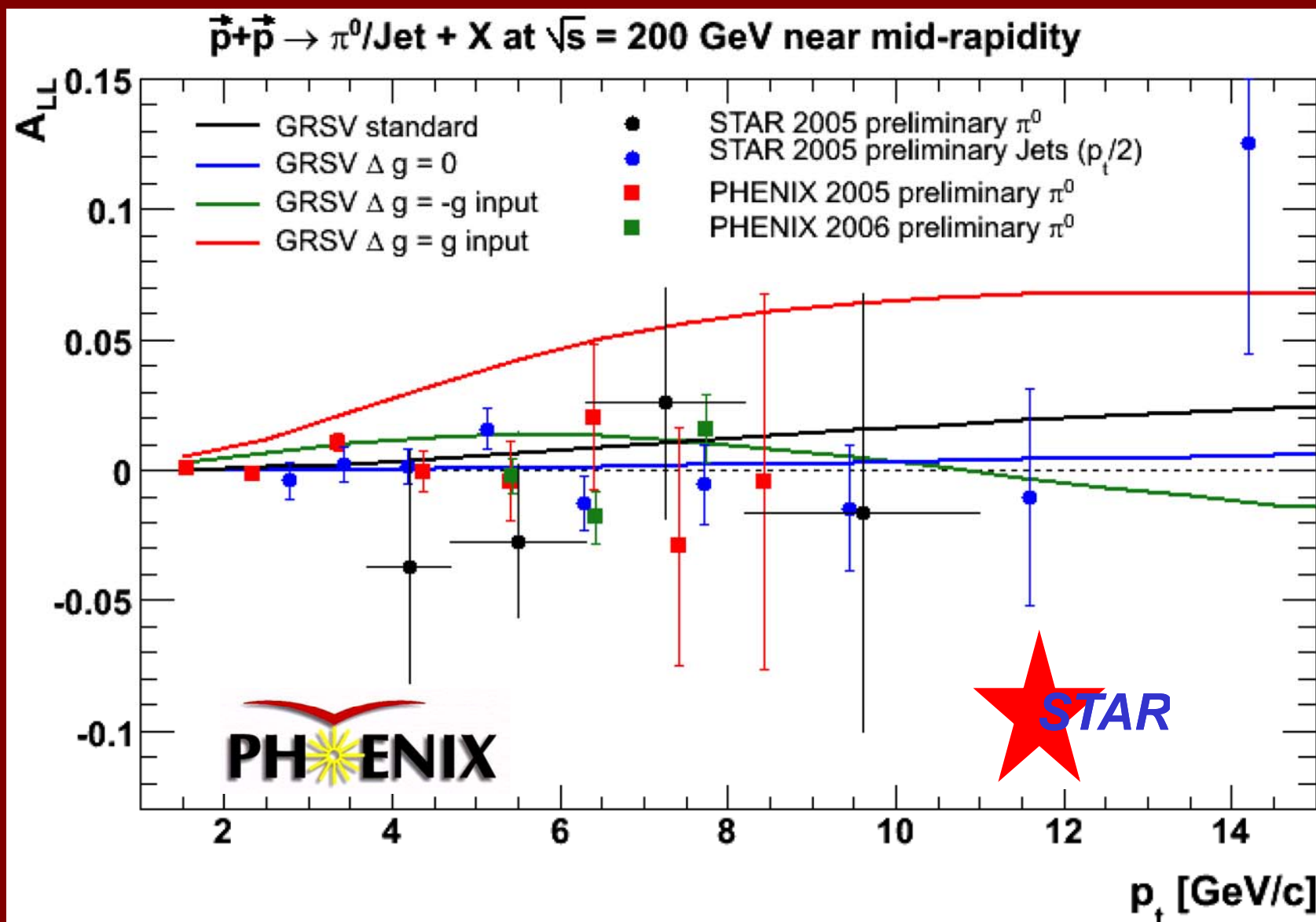


[illegible]

# $A_{LL}$ of Inclusive Jets at $\sqrt{s}=200$ GeV



# Combined $\pi^0$ and Jet $A_{LL}$

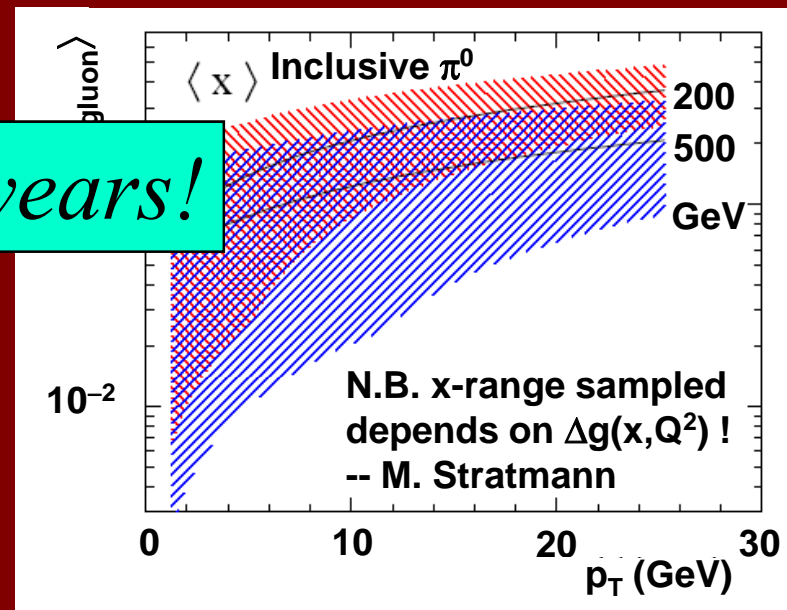


# Going Beyond Inclusive Measurements

- Inclusive channels suffer from integration over  $x \rightarrow$  model-

*Stay tuned in upcoming years!*

- Improved accelerator and detector performance will allow jet-jet and  $\gamma$ -jet coincidence measurements, placing better constraints on partonic kinematics



$$x_1 = \frac{x_T}{2} (e^{\eta_1} + e^{\eta_2}); \quad x_2 = \frac{x_T}{2} (e^{-\eta_1} + e^{-\eta_2})$$

$$x_T \equiv \frac{2p_T}{\sqrt{s_{pp}}}$$





# *Understanding Transverse Spin Measurements in Hadronic Collisions*

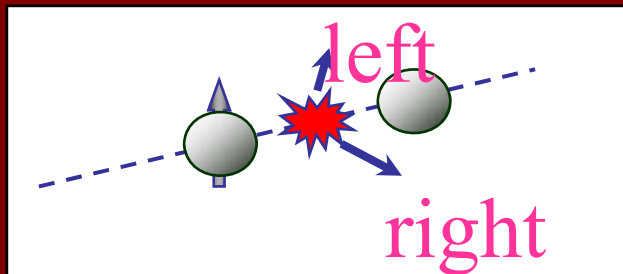
- Theoretical interpretation of longitudinally polarized measurements at RHIC relies on various assumptions
  - *Exciting progress in last five years, but lots of work still to be done, experimentally and theoretically!*
- Relativistic spin Hall of light calculations only starting to be measured the last couple years



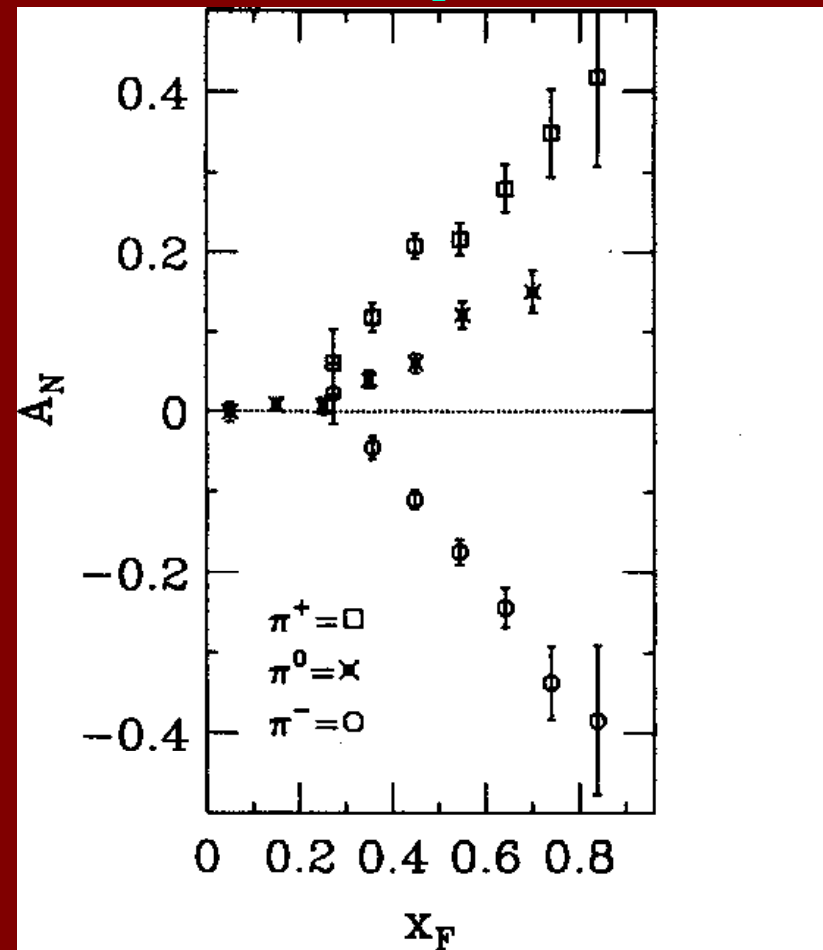
# Transverse Single-Spin Asymmetries $A_N$

- Large left-right asymmetries ( $\sim 20\text{-}40\%$ )

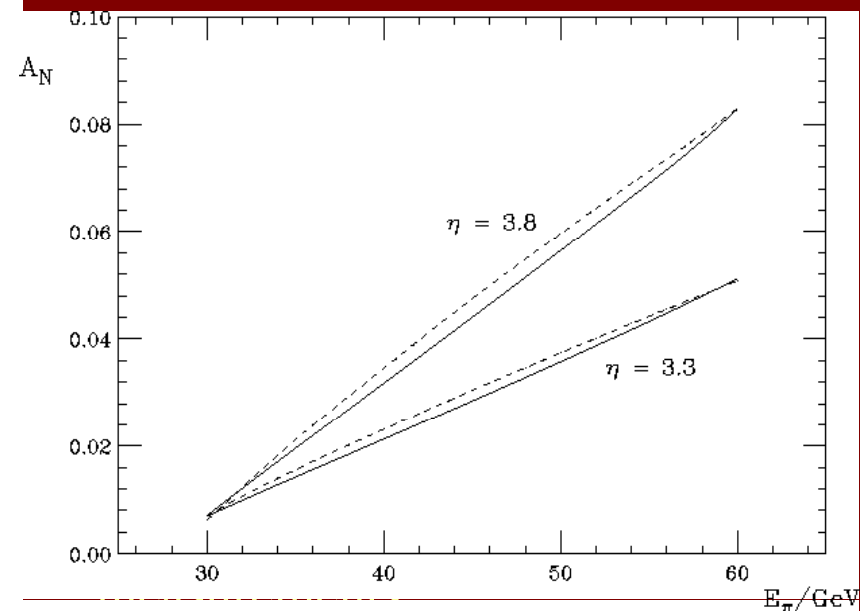
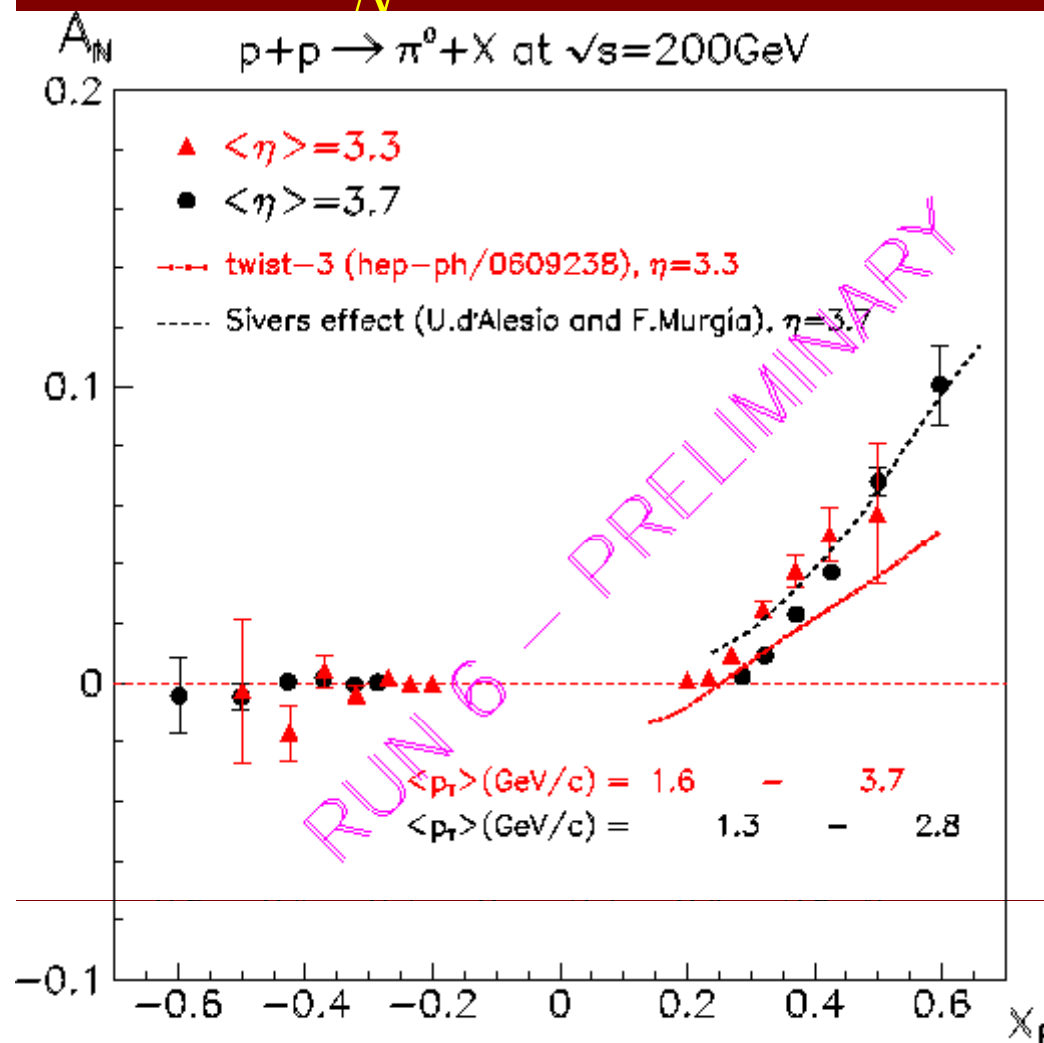
Large asymmetries found to persist at RHIC energies vertically polarized beam or target at AGS and Fermilab experiments



E704 at Fermilab  
at  $\sqrt{s}=19.4$  GeV,  $p_T=0.5\text{-}2.0$  GeV/c:



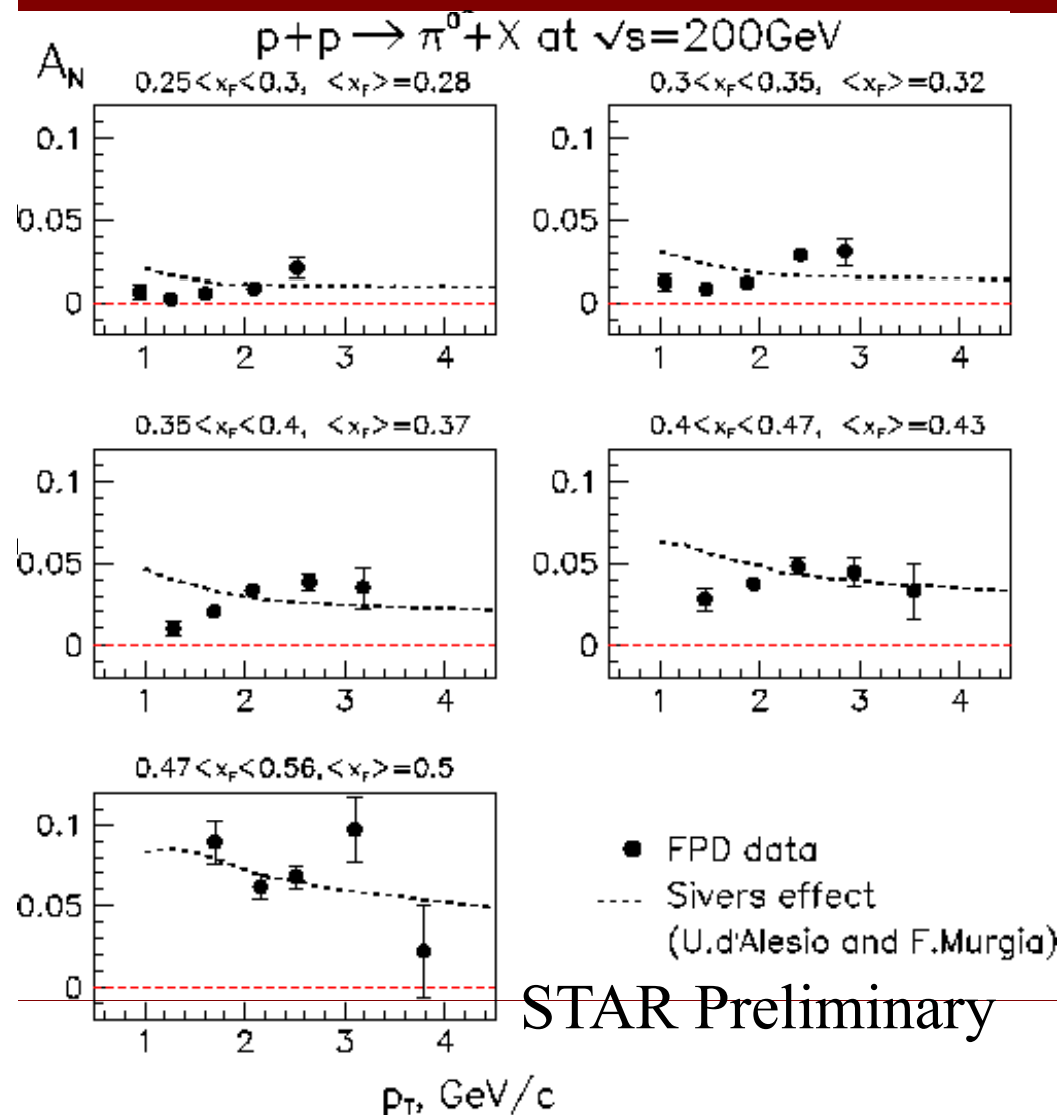
# $\pi^0 A_N$ at $\sqrt{s}=200$ GeV: $x_F$ dependence



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



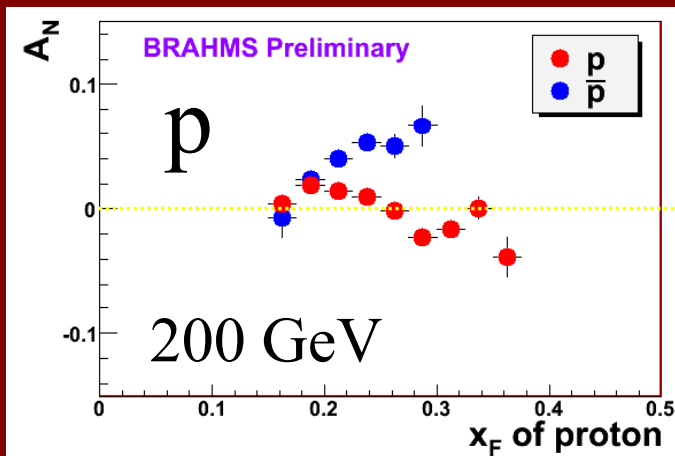
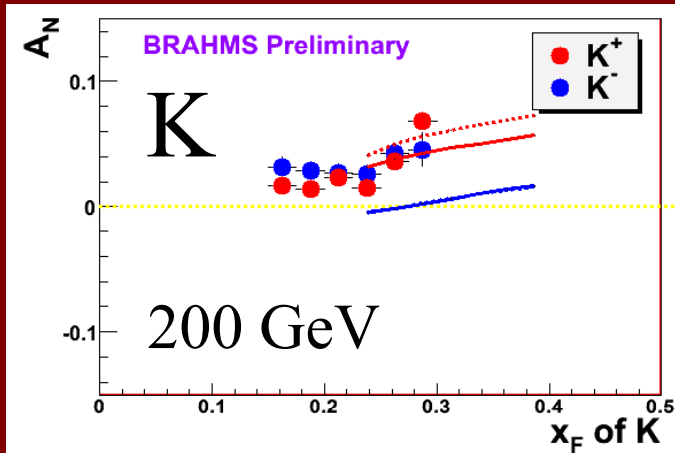
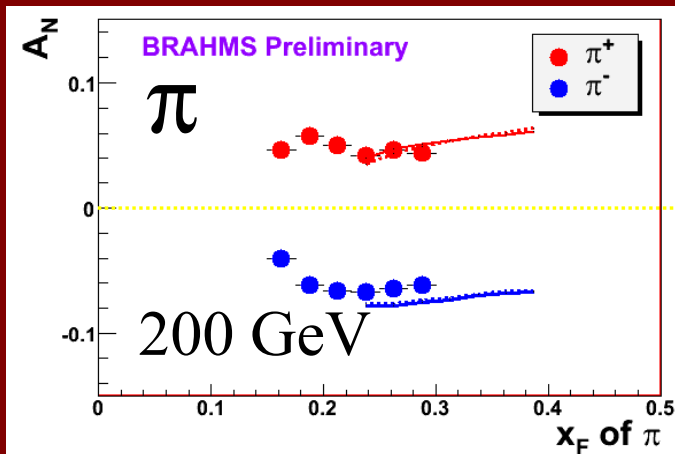
# $A_N$ vs. $p_T$ in $x_F$ Bins



- Combined data from three runs at  $\langle \eta \rangle = 3.3, 3.7$  and  $4.0$
- In each  $x_F$  bin,  $\langle x_F \rangle$  does not significantly change with  $p_T$
- Measured  $A_N$  is not a smoothly decreasing function of  $p_T$  as predicted by theoretical models!





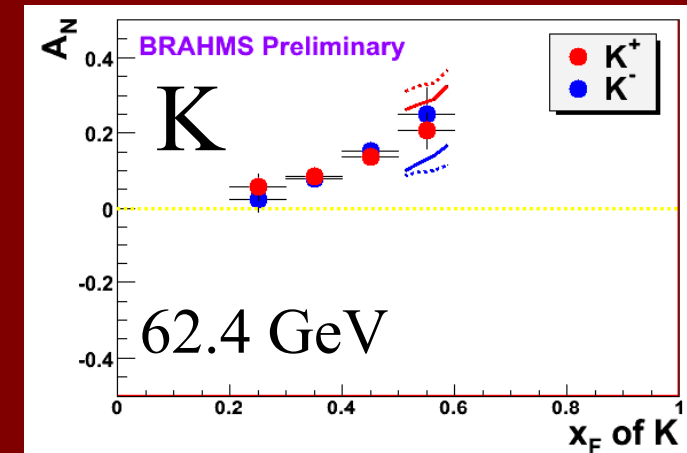
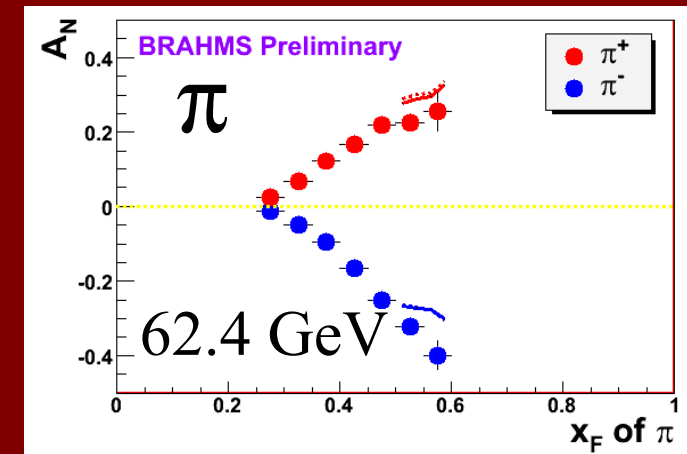


Curves:  
Twist-3  
calculations  
by F. Yuan

Note different scales

K- asymmetries  
underpredicted

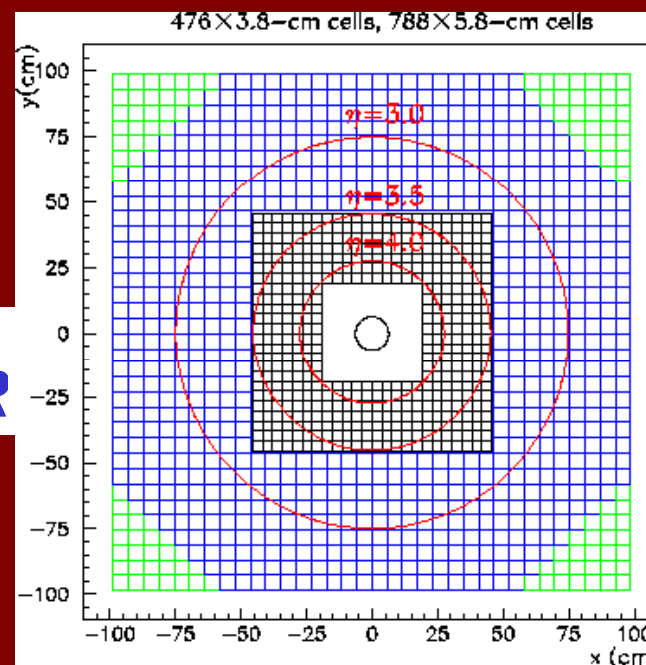
Proton and antiproton  
asymmetries puzzling!



# Improving Forward Coverage at RHIC

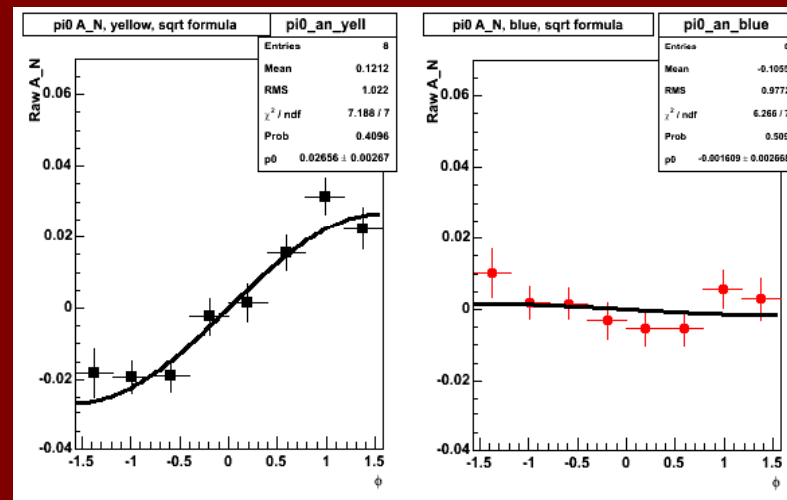
STAR Forward Meson Spectrometer will provide full azimuthal coverage for range  $2.5 \leq \eta \leq 4.0$

- Broad acceptance in  $x_F$ - $p_T$  plane for inclusive  $\pi^0$ ,  $\gamma$ , etc...production in p+p and d(p)+Au
- Broad acceptance for  $\gamma$ - $\pi^0$  and  $\pi^0$ - $\pi^0$  from forward jet pairs to probe low- $x$  gluon density in p+p and d(p)+Au collisions



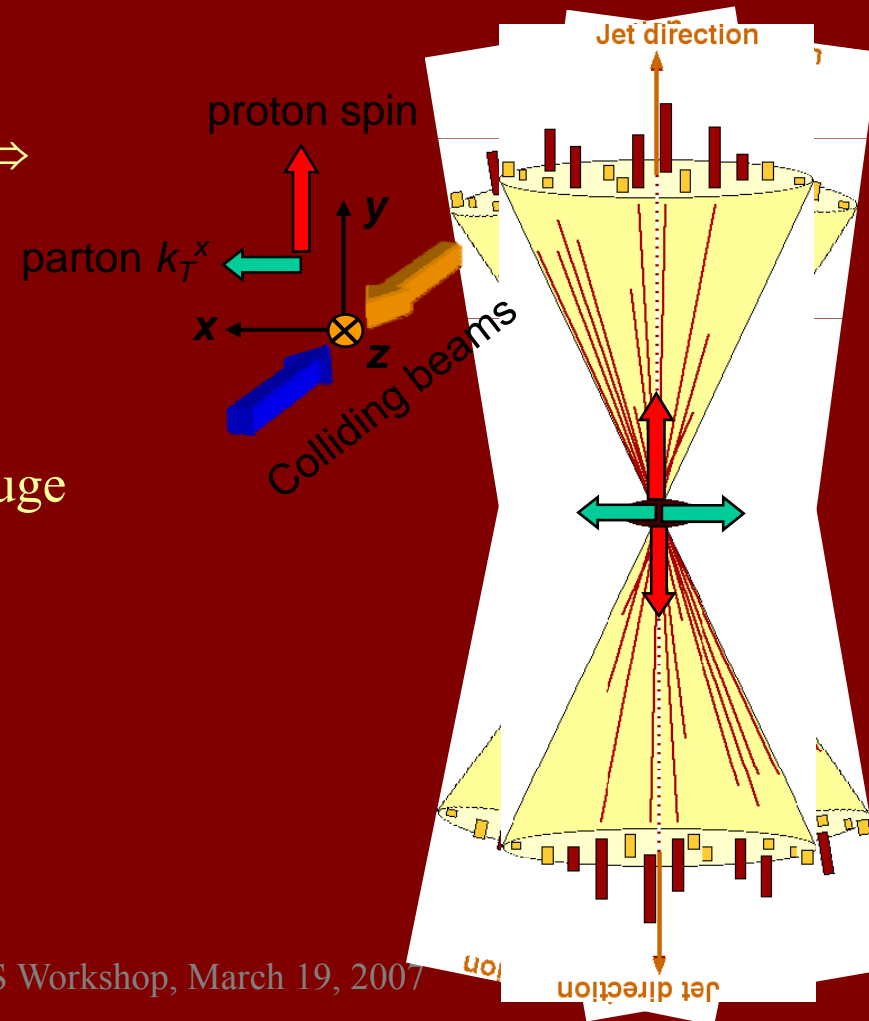
PHENIX Muon Piston Calorimeter will provide full azimuthal coverage for range  $3.1 \leq \eta \leq 3.7$  and  $2 < E(\pi^0) < 25\text{GeV}$

Raw  $A_N(\phi)$  of  $\pi^0$  from Run-6 MPC, 62.4 GeV



# Probing the Sivers Function via Dijets

- Sivers effect in  $p+p \Rightarrow$  spin-dependent sideways boost to dijets, suggested by Boer & Vogelsang (PRD 69, 094025 (2004))
- Both beams polarized,  $x+z \neq x-z \Rightarrow$  can distinguish high- $x$  vs. low- $x$  (primarily gluon) Sivers effects.
- Do we observe q Sivers consistent with HERMES, after inclusion of proper pQCD-calculable ISI/FSI gauge link factors for  $pp \rightarrow$  jets? Tests universality.
- First direct measurement of gluon Sivers effects.



# Quark Sivers Functions From SIDIS

HERMES positive Sivers SSA for  $\pi^+$ , but  $\sim 0$  for  $\pi^-$ , fitted by Vogelsang & Yuan with u and d quark Sivers functions of different sign and magnitude:

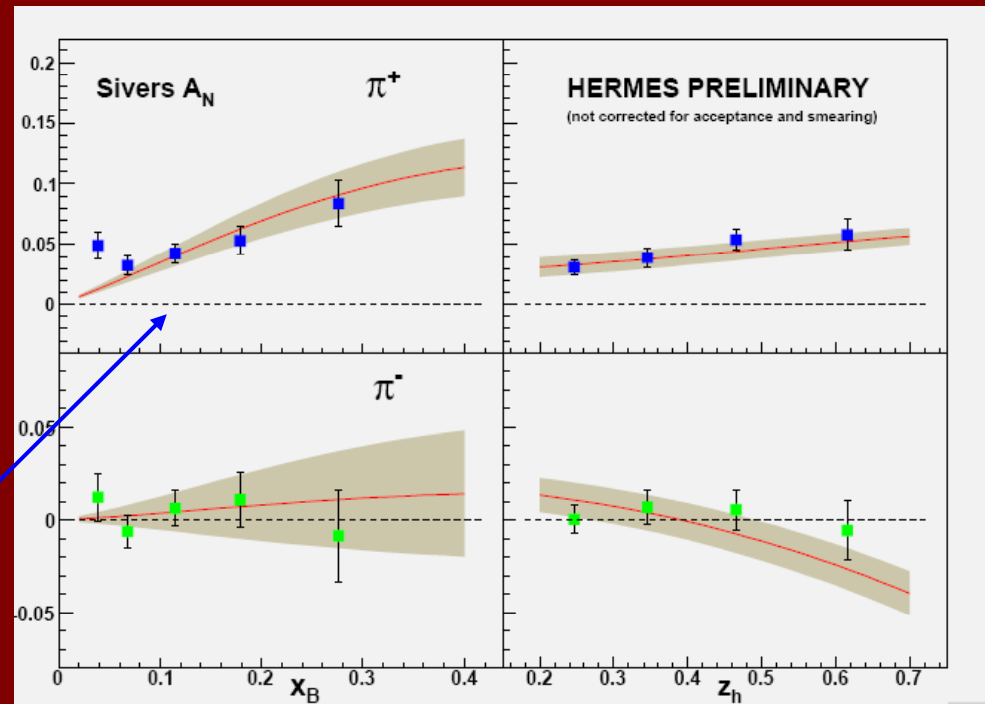
$$VY\ 1: u_T^{(1/2)} / u(x) = -0.81x(1-x)$$

$$d_T^{(1/2)} / u(x) = 1.86x(1-x)$$

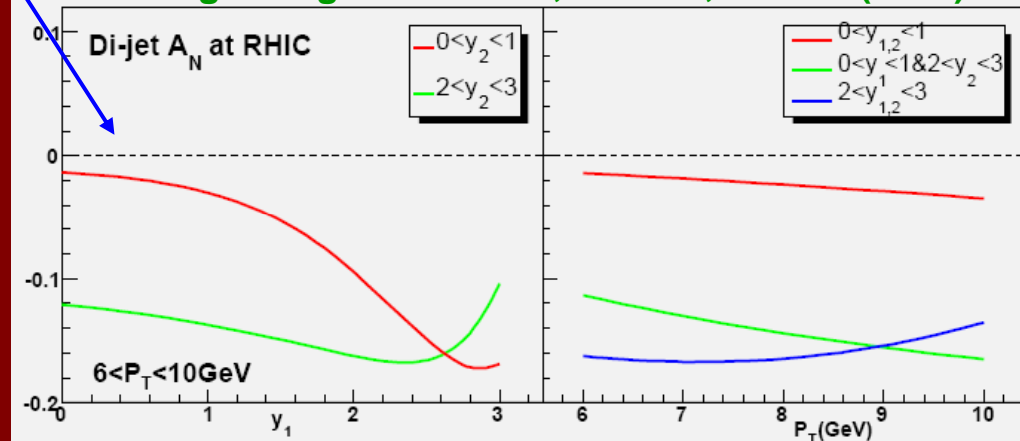
$$VY\ 2: u_T^{(1/2)} / u(x) = -0.75x(1-x)$$

$$d_T^{(1/2)} / d(x) = 2.76x(1-x)$$

V & Y use these Sivers fcn. (assuming zero gluon Sivers) to predict SSA for  $pp \rightarrow \text{dijet} + X$ , integrated over  $k_T$  distributions within both protons. Strong  $y$ - and weak  $p_T$ -dependence.



W. Vogelsang and F. Yuan, PRD 72, 054028 (2005).



Jet 1 rapidity

Jet  $p_T$  (GeV/c)

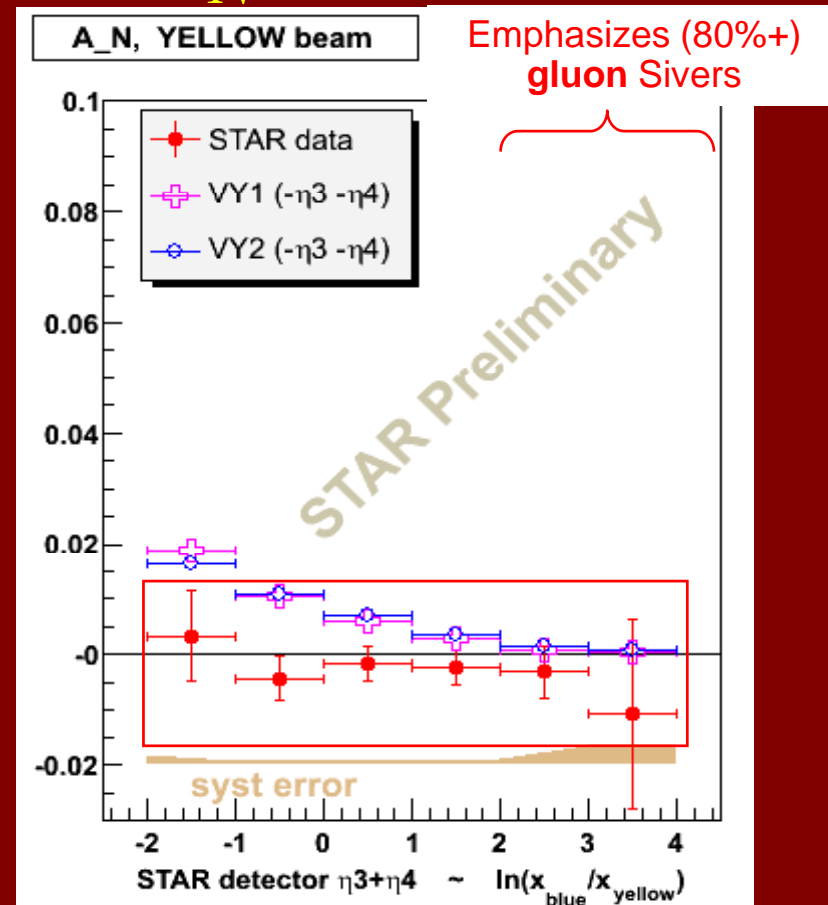
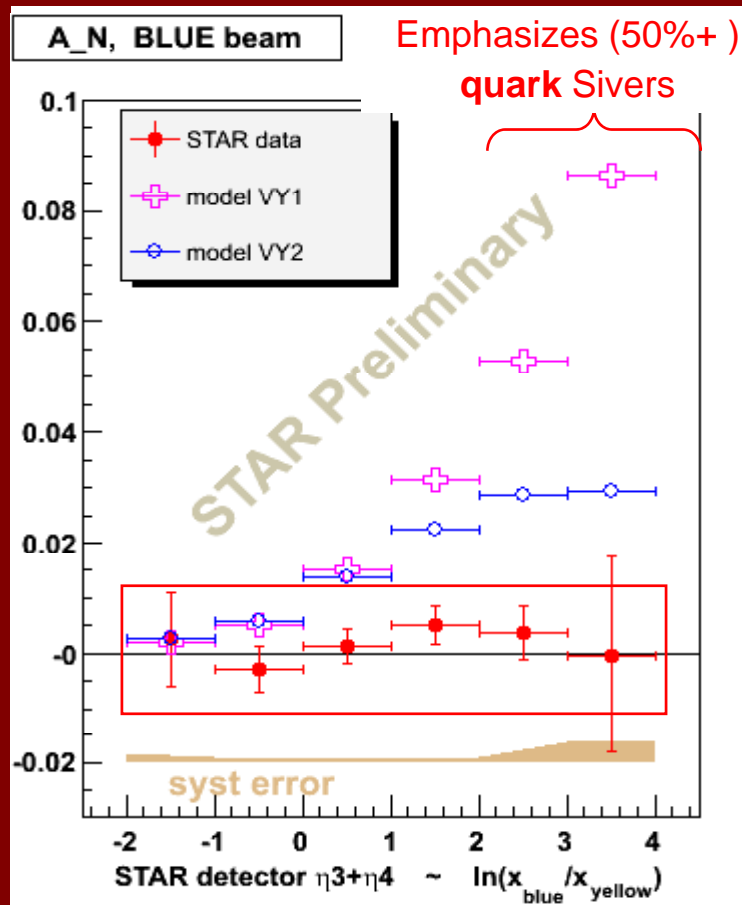
C. Aidala, COMPASS Workshop, March 19, 2007







# Measured Sivers $A_N$ for Dijets



Measured  $A_N$  consistent with zero  $\Rightarrow$  both quark and gluon Sivers effects much smaller in  $p+p \rightarrow$  dijets than in HERMES SIDIS!!



# *But Rapidly Progressing Theory!*

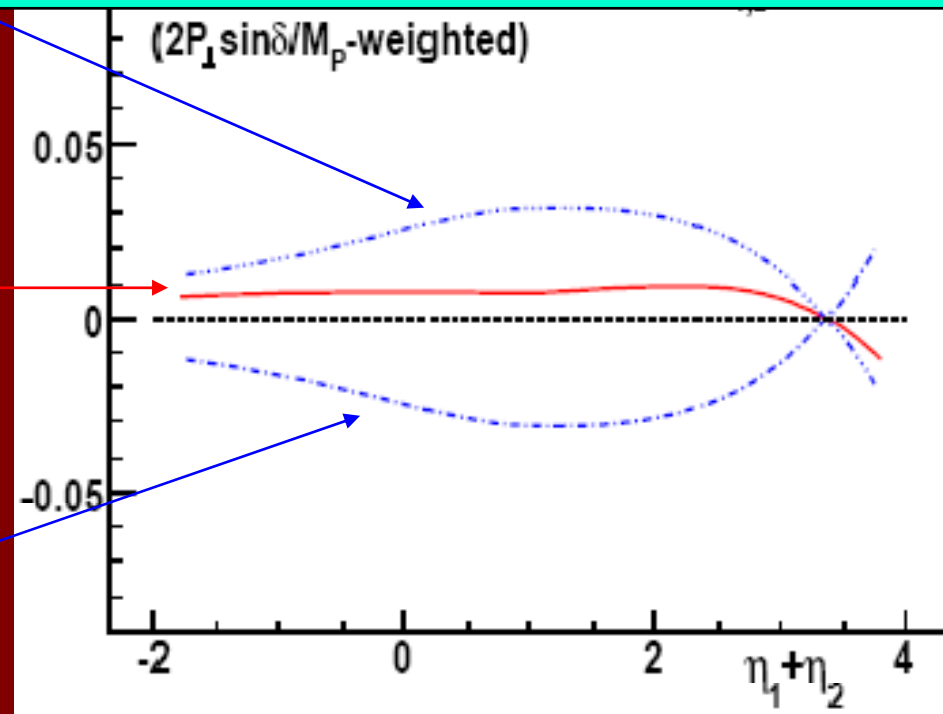
Bomhof, Mulders, Vogelsang, Yuan: hep-ph/0701277

Prediction for dijet SSA if  
Sivers contributions were  
same as for SIDIS (FSI)

Initial- and final-state  
cancellations in  $p+p \rightarrow$   
jet+jet found to reduce  
expected dijet asymmetry at  
RHIC.

Prediction for dijet SSA if  
Sivers contributions were  
same as for Drell-Yan (ISI)

*Asymmetries observed at STAR  
also consistent with SIDIS results!*



# *Accessing Transversity at RHIC*

BELLE FF measurements make it possible to learn more about the initial state in p+p collisions

- Probe transversity distribution at PHENIX via *interference fragmentation*
  - Collinear factorization! No need to assume  $k_T$ -factorization
  - Exploratory analysis using 2006 data already underway
- Probe transversity at STAR via *Collins effect*
  - Forward Meson Spectrometer will allow measurement of azimuthal distribution of  $\pi^0$ 's within jet



# *RHIC Data and Global Fits*

- Global fits of measurements sensitive to different processes and different kinematics essential to place tight constraints on nucleon pdf's
- DIS rescaled measurements  
Long road ahead of us . . .
  - Pions, jets, heavy flavor, prompt photons, gamma-jet and jet-jet correlations, . . .
- Two global fit papers published in 2006 including PHENIX  $\pi^0$   $A_{LL}$  data
  - M. Hirai et al., Phys. Rev. D74, 014015 (2006)
  - Navarro and Sassot, Phys. Rev. D74, 011502 (2006)



# *Summary and Prospects*

- The 2005 and 2006 RHIC runs have provided a wealth of additional data for spin physics, both longitudinal and transverse
  - Look for updated and additional results over the next months!
- Moving into new era where RHIC will make decisive contributions to knowledge of polarized gluon distribution and more

Beginning of an exciting period of measurements for RHIC spin—many more years of data and results to look forward to!





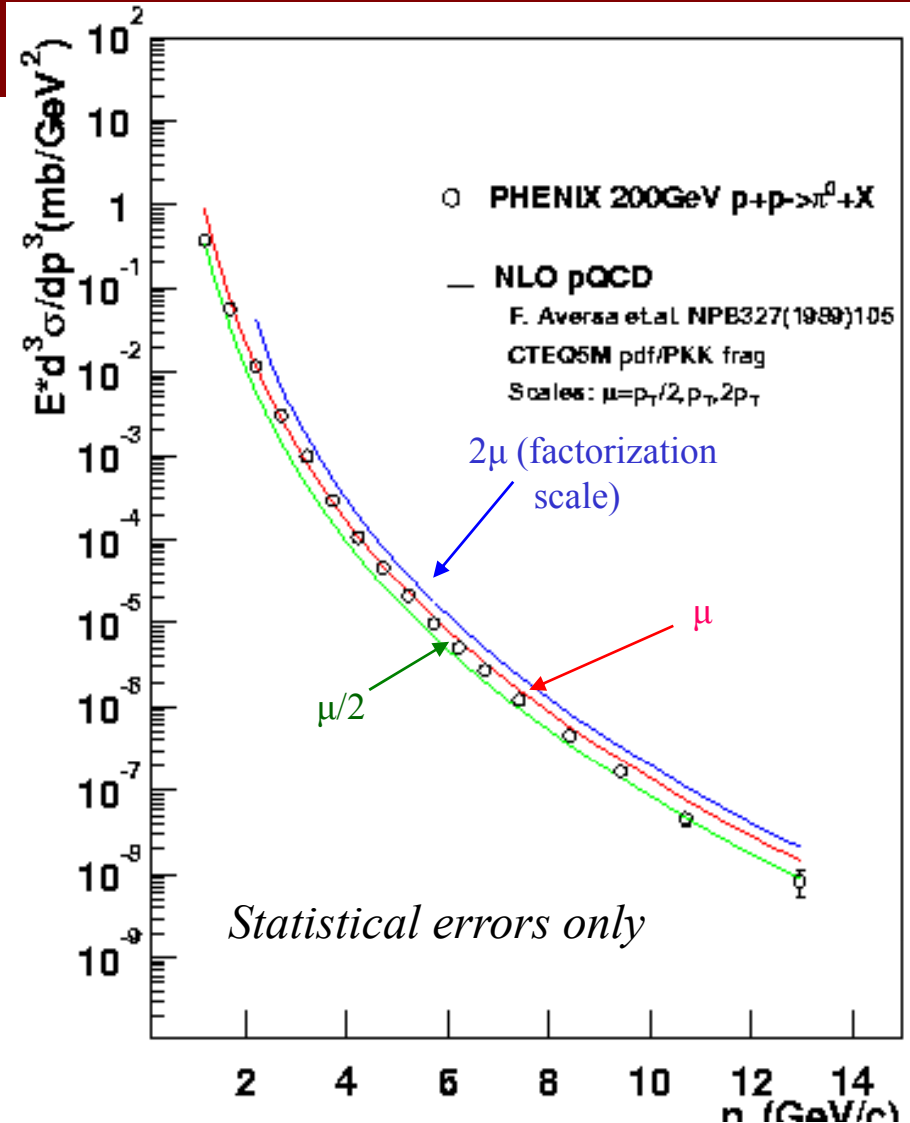
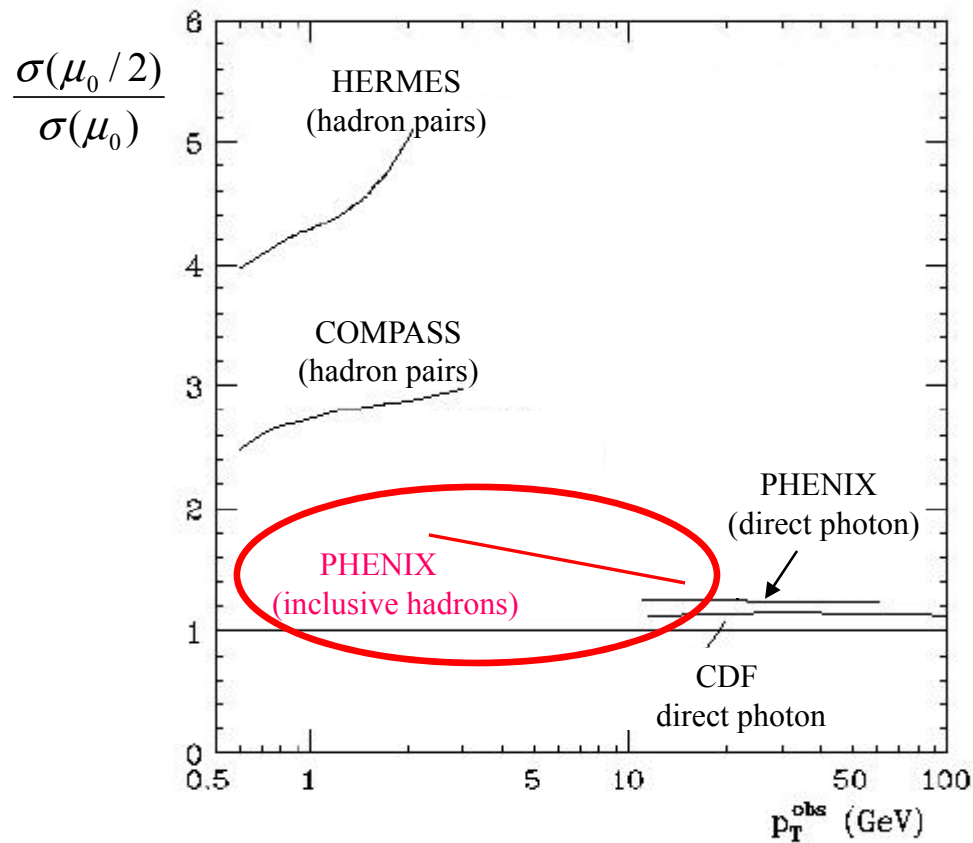
# *Extra Slides*



# *pQCD Scale Dependence at RHIC*

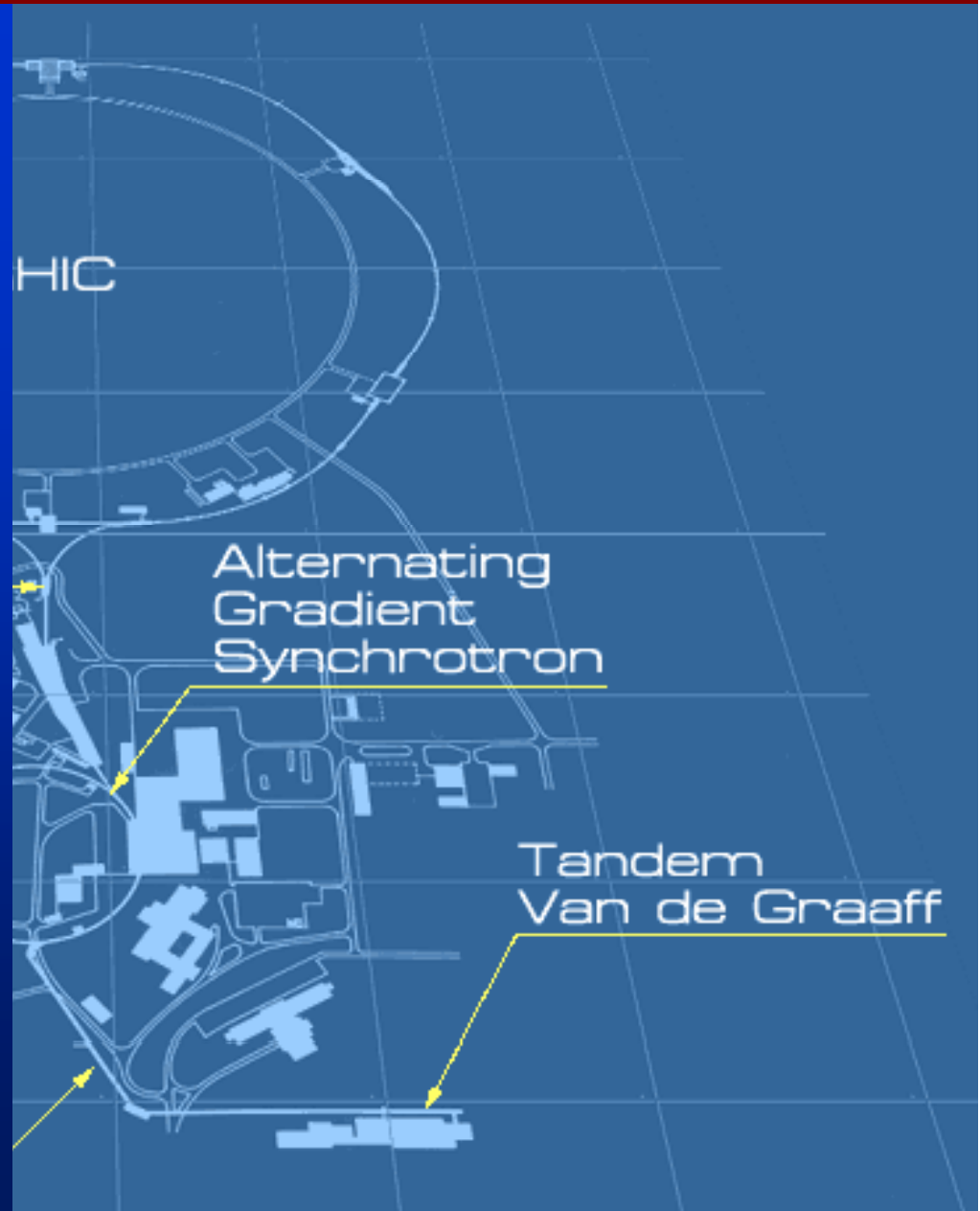
Theoretical uncertainty of pQCD calculations in channels relevant for gluon polarization measurements:

$\pi^0$  data vs pQCD with different factorization scales:



# *RHIC Specifications*

- 3.83 km circumference
- Two independent rings
  - Up to 120 bunches/ring
  - 106 ns crossing time
- Energy:
  - ➔ Up to 500 GeV for p+p
  - ➔ Up to 200 GeV for Au+Au (per N+N collision)
- Luminosity
  - Au+Au:  $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
  - p+p :  $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$   
(70% polarized)



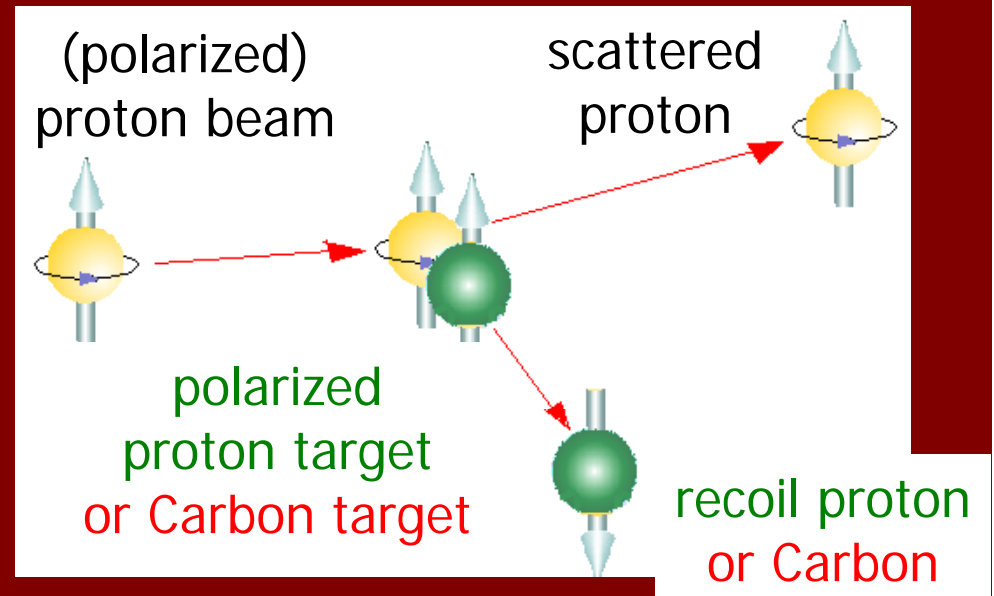
# *RHIC Polarimetry*

- Proton-carbon (pC) polarimeter
  - For *fast* measurements ( $< 10$  s!) of beam polarization
  - Take several measurements during each fill
- Polarized hydrogen-jet polarimeter
  - Dedicated measurements (weeks) to calibrate the pC polarimeter
- Three-fold purpose of polarimeters
  - Measurement of beam polarization to provide feedback to accelerator physicists
  - Measurement of beam polarization as input for spin-dependent measurements at the various experiments
  - Study of polarized elastic scattering



# *Polarimetry (cont.)*

- E950 experiment at AGS became RHIC pC polarimeter
  - Measure  $P_{\text{beam}}$  to  $\sim 30\%$
- H jet polarimeter expected to determine  $P_{\text{beam}}$  to 6-8% for final release of 2005 data
- Both take advantage of previously measured spin asymmetries to determine the beam polarization



See H. Okada et al., hep-ex/0601001, for most recent published jet polarimeter measurements.

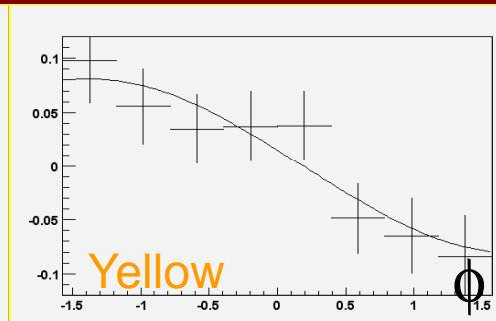
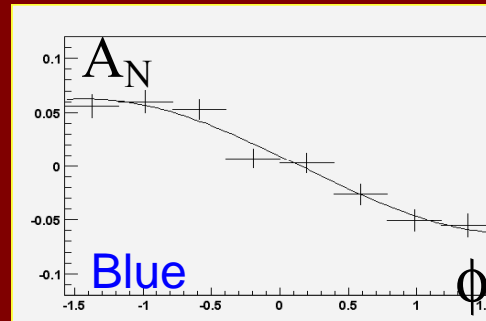




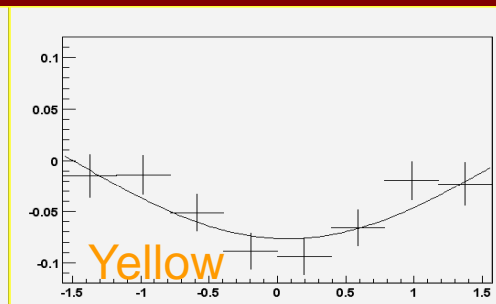
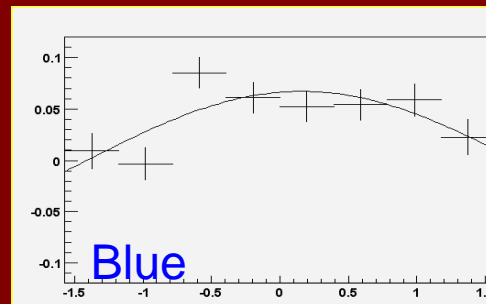
# Single-Spin Asymmetries for Local Polarimetry

Take advantage of previously measured transverse single-spin asymmetry in forward neutron production (PHENIX); forward charged hadron production (STAR)

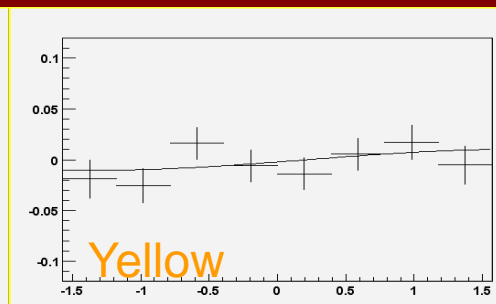
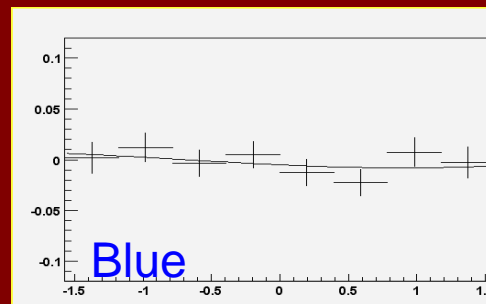
Spin Rotators OFF  
Left-right asymmetry  
→ Vertical polarization



Spin Rotators ON  
Up-down asymmetry  
→ Radial polarization



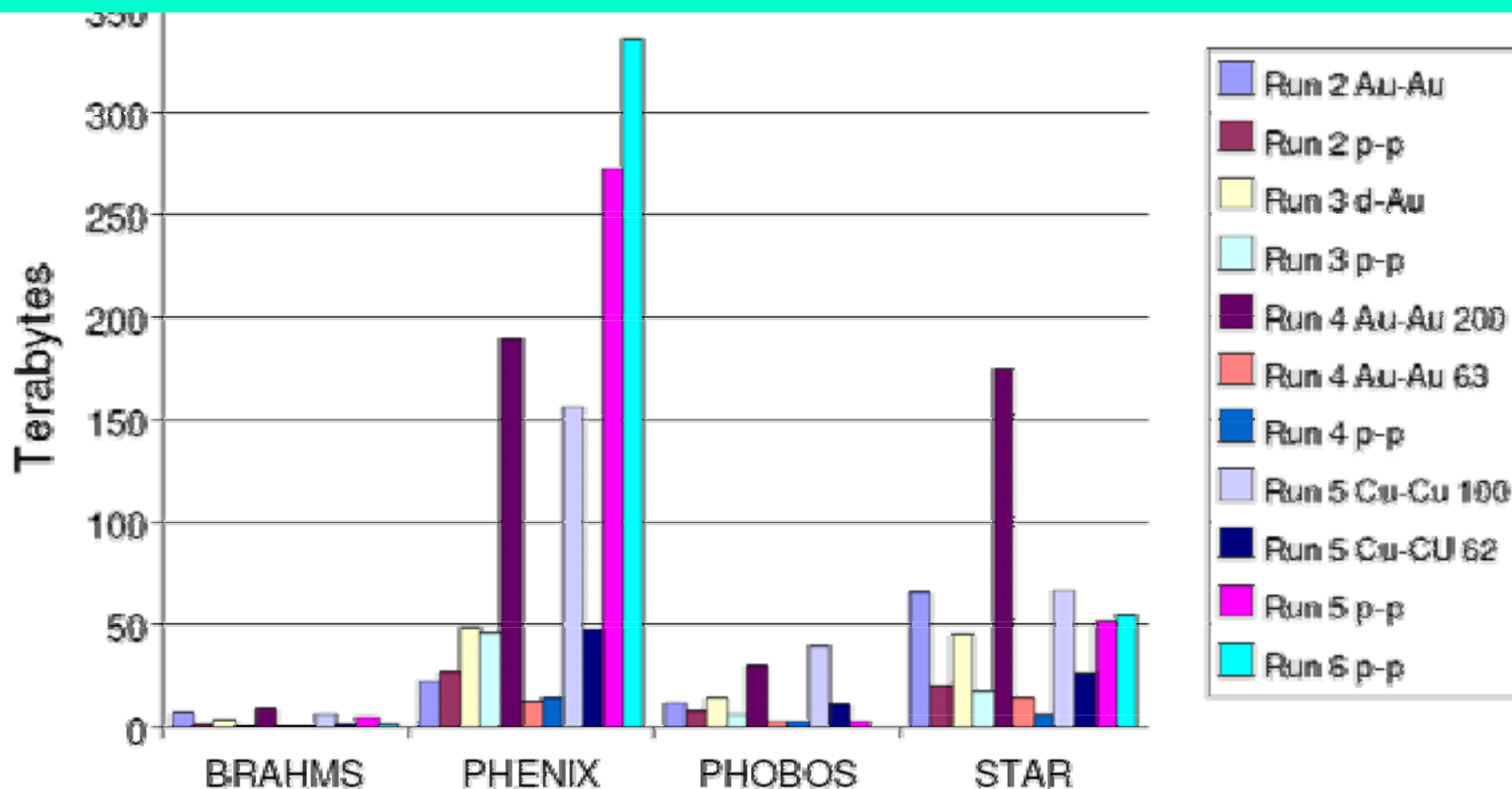
Spin Rotators ON  
No asymmetry  
→ Longitudinal polarization



# *Total Raw Data Volumes*

WAN data transfer and p+p data production at CC-J in RIKEN, Wako Japan

- » 60 MB/s sustained rate using Grid technology
- » 570 TB transferred in Runs 5 & 6



# $x_T$ Scaling

- $x_T$  scaling—can parametrize cross sections for particle production in hadronic collisions by:

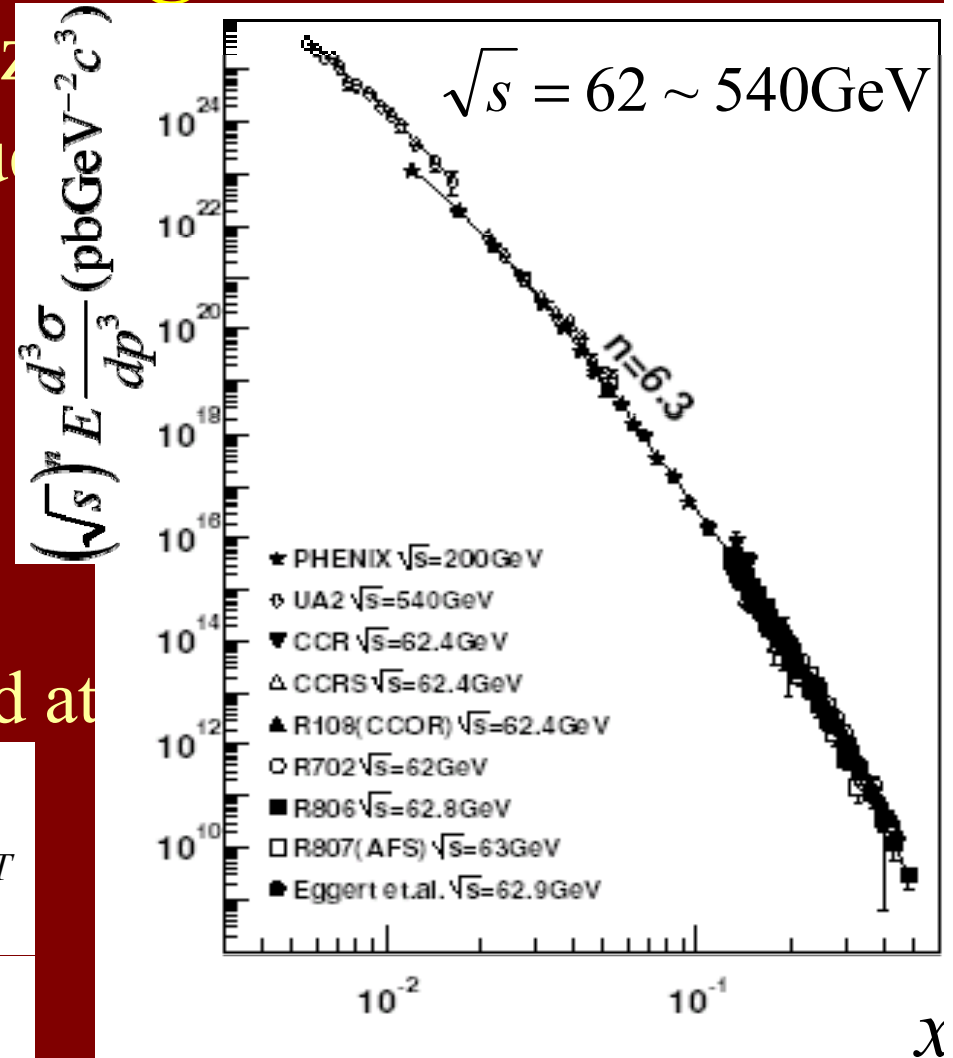
$$E \frac{d^3\sigma}{dp^3} \sim (\sqrt{s})^{-n} F(x_T)$$

$$x_T = \frac{2p_T}{\sqrt{s}}, n = \text{constant}$$

- Lower energy has higher yield at

$$L \int E \frac{d^3\sigma}{dp^3} dp_T = L \int E \frac{d^3\sigma}{dp^3} \frac{\sqrt{s}}{2} dx_T$$

$$\propto L \sqrt{s}^{-5.3}$$



We can probe higher  $x_T$  with better statistics even with a short run at 62.4 GeV!! (compared to 200 GeV)



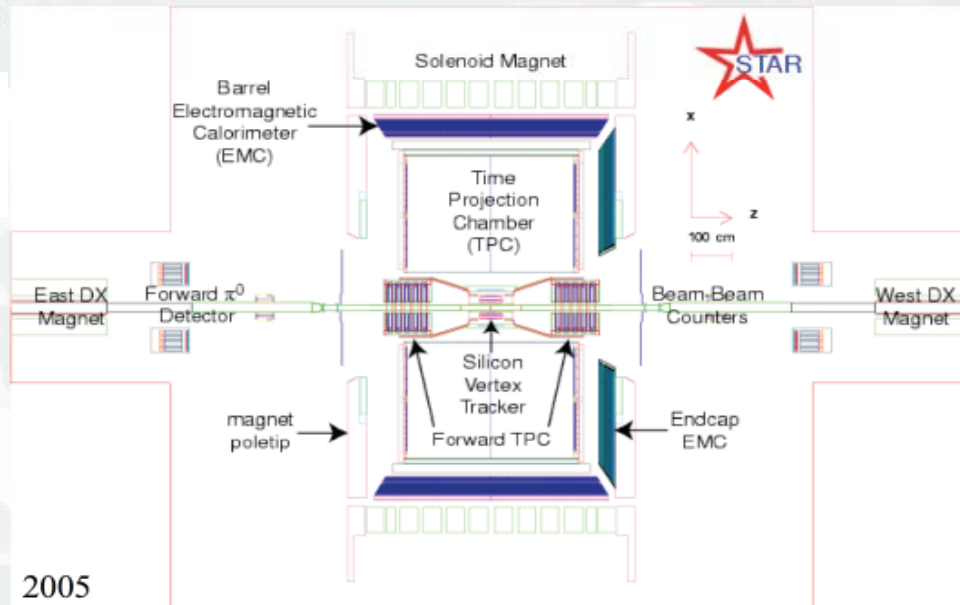
# *Polarized Collider Development*

Parameter	Unit	2002	2003	2004	2005	<b>2006</b>
No. of bunches	--	55	55	56	106	<b>111</b>
bunch intensity	$10^{11}$	0.7	0.7	0.7	0.9	<b>1.4</b>
store energy	GeV	100	100	100	100	<b>100</b>
$\beta^*$	m	3	1	1	1	<b>1</b>
peak luminosity	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	2	6	6	10	<b>35</b>
average luminosity	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	1	4	4	6	<b>20</b>
Collision points	--	4	4	4	3	<b>2</b>
average polarization, store	%	15	35	46	47	<b>60-65</b>



# STAR Detector

## Overview



- **Forward-Pion Detector (FPD)** ( $3 < |\eta| < 4$ )
- **FPD++** (Extended coverage for Run 6 with  $3 < \eta < 4$ )
- **FMS** upgrade (Run 7 and beyond with  $2.5 < \eta < 4$ )

- **Beam-Beam Counter (BBC)**: ( $3.4 < |\eta| < 5$ )

- Relative luminosity measurement
- Absolute luminosity measurement
- Local polarimeter ( $A_N$  for charged particles)

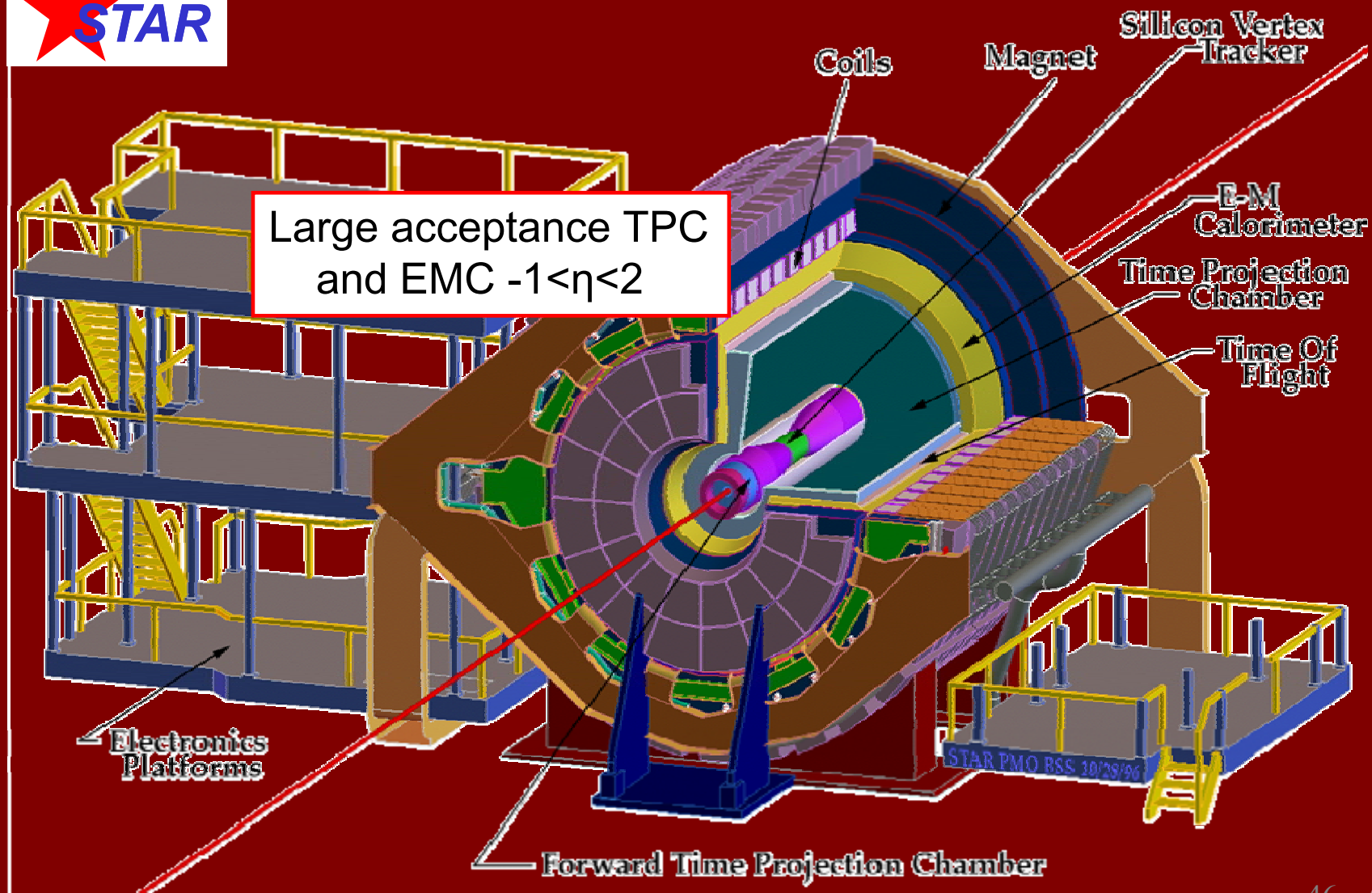
- **EM-Calorimeter**: (**Barrel - BEMC**:  $-1 < \eta < 1$  & **Endcap - EEMC**:  $1.09 < \eta < 2$ )

- Reconstruction of  $\gamma$ ,  $e^\pm$  and  $\pi^0$
- Jet-reconstruction in combination with TPC





# STAR Detector



# STAR Integrated Luminosities



RHIC RUN	$\sqrt{s}$ [GeV]	$L_{\text{recorded}}$ [pb <sup>-1</sup> ] (Transverse)	$L_{\text{recorded}}$ [pb <sup>-1</sup> ] (Longitudinal)	Polarization [%]
RUN 2	200	0.15	0.3	15
RUN 3	200	0.25	0.3	30
RUN 4	200	0	0.4	40-45
RUN 5	200	0.1	3.1	45-50
RUN 6	200	3.4/6.8	8.5	60

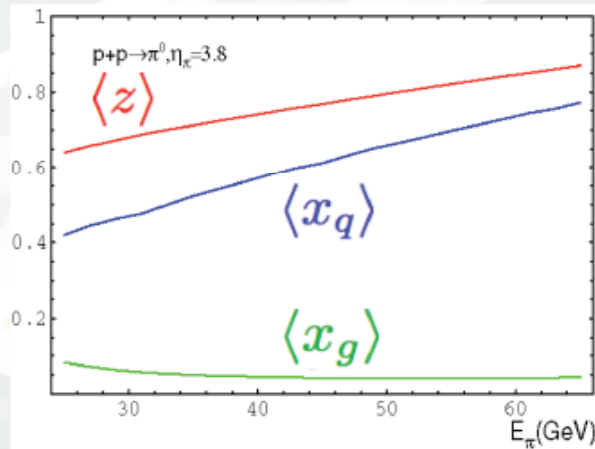


# Forward Neutral Pions at STAR

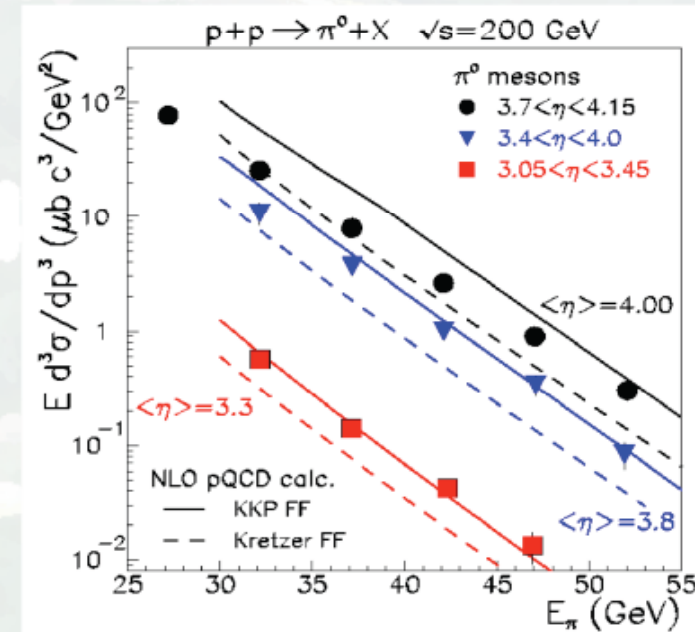
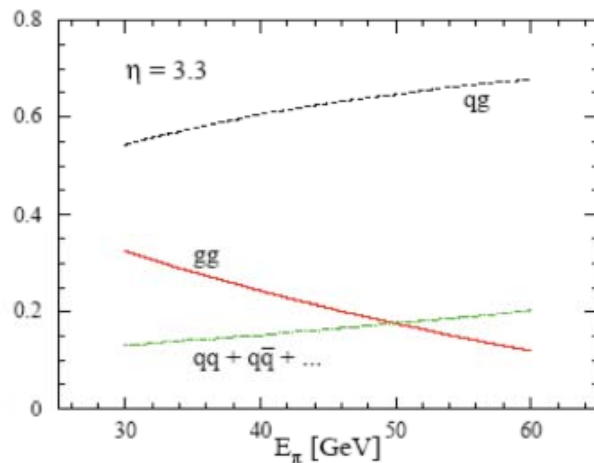
## ■ Cross-section measurement: Forward neutral pion production

L. Nogach (IHEP-Protvino)

Jaeger, Stratmann, Vogelsang  
and Kretzer



V. Guzey, M. Strikman and W. Vogelsang,  
Phys. Lett. B603 (2004) 173.



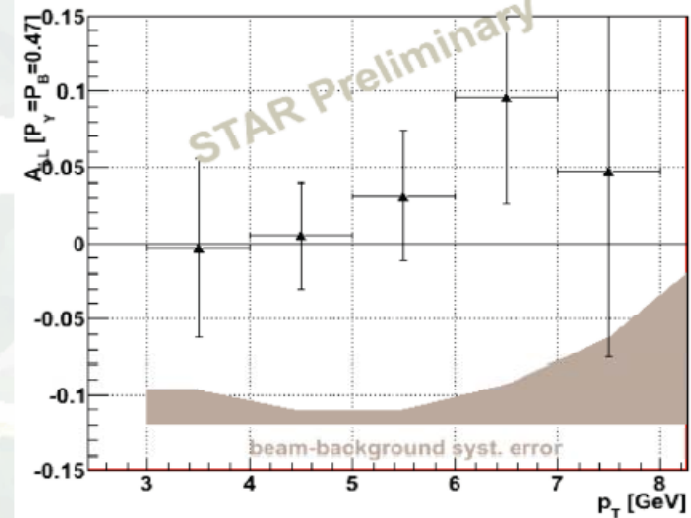
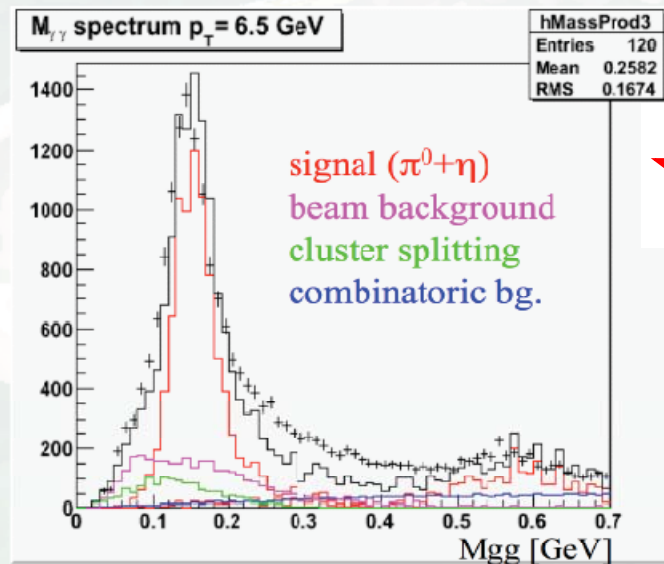
- Forward  $\pi^0$  production : Dominated by asymmetric  $qg$  collisions
- NLO pQCD calculations for two sets of fragmentation functions
- Data compares favorably to NLO pQCD at  $\sqrt{s} = 200\text{GeV}$  in contrast to fixed-target or ISR energies



# Neutral Pion $A_{LL}$ at STAR ( $1.09 < \eta < 2.0$ )

## ■ $A_{LL}$ measurement: Neutral pion production (STAR EEMC)

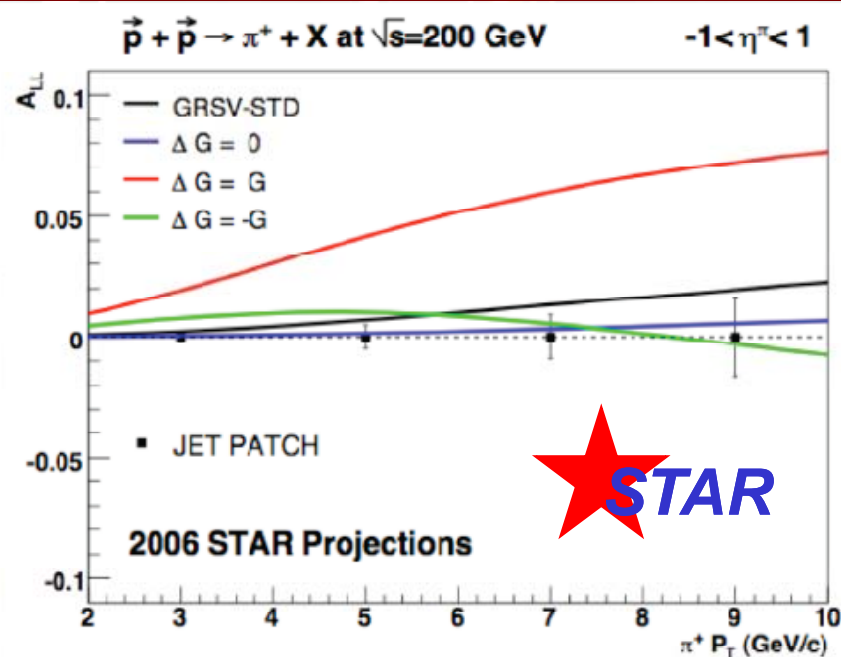
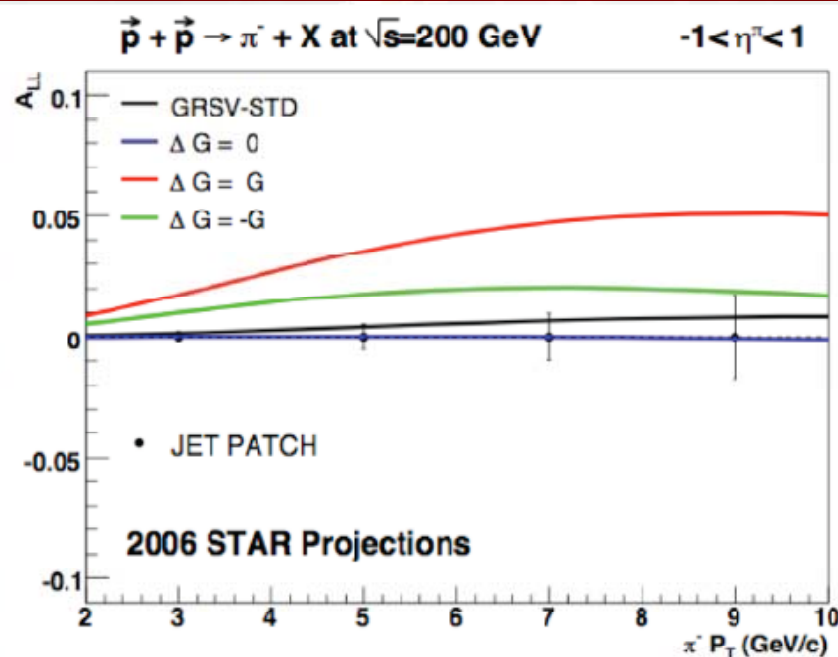
J. Webb (Valparaiso University)



- Forward direction probes different  $q/g$  sub-process mixture
- Current analysis (Run 5) in STAR EEMC region ( $1.09 < \eta < 2$ ) dominated by beam background
- Several improvements in Run 6 such as reduction in beam background
- Important baseline measurement for future prompt photon measurements



# STAR Run-06 Charged Pion Projections



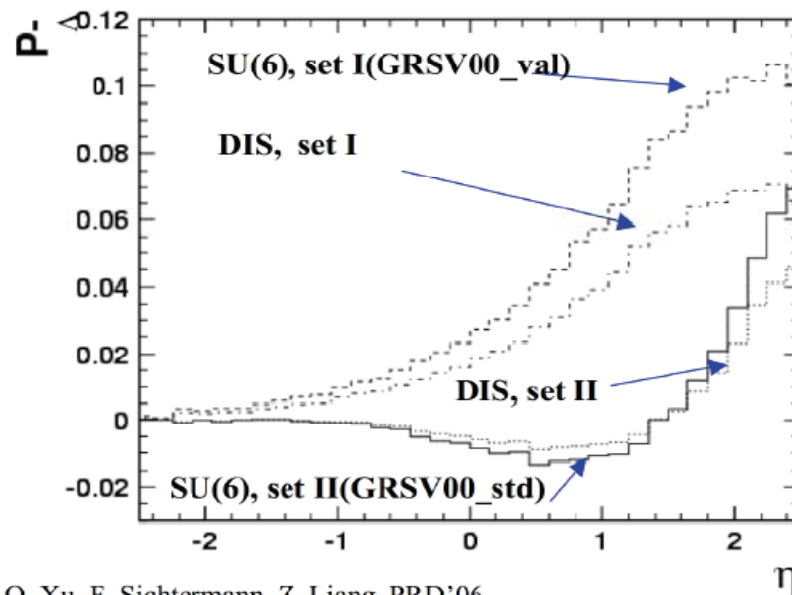


# Longitudinal Spin Transfer to $\Lambda$

## ■ Lambda production

Q. Xu (LBL)

- The measurement of  $\Lambda$  polarization at RHIC can give insights into polarized fragmentation and parton distribution functions



Q. Xu, E. Sichtermann, Z. Liang, PRD'06

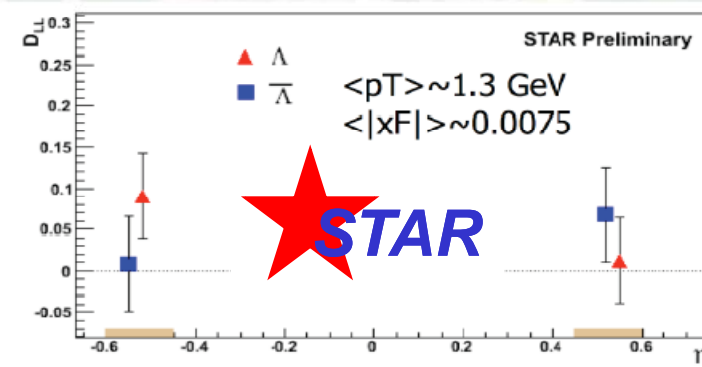
- Lambda-bar polarization is sensitive to  $\Delta\bar{s}(x)$  at large  $p_T$  ( $p_T > 5 \text{ GeV}/c$ )

$$\vec{p}p \rightarrow \vec{\Lambda}X$$

$$(\Lambda \rightarrow p + \pi)$$

$$D_{LL} \equiv \frac{\sigma_{p^+p \rightarrow \Lambda^+X} - \sigma_{p^+p \rightarrow \Lambda^-X}}{\sigma_{p^+p \rightarrow \Lambda^+X} + \sigma_{p^+p \rightarrow \Lambda^-X}}$$

- Longitudinal spin transfer  $D_{LL}$



- Proof-of-principle measurement from 2005 minimum-bias data



# What Did We Expect? Constraints from SIDIS Results

Fits to HERMES SIDIS Sivers asymmetries constrain  $u$  and  $d$  quark Sivers functions, for use in  $pp \rightarrow \text{dijet} + X$  predictions.

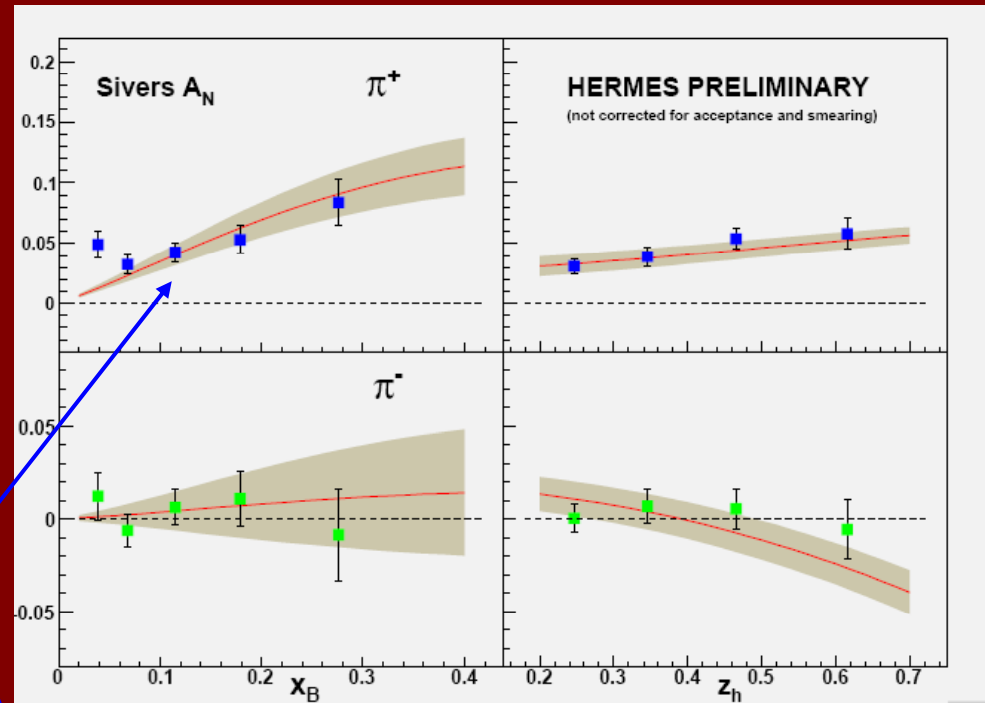
E.g., Vogelsang & Yuan use two different models of Sivers fcn.  $x$ -dependence:

$$\boxed{\text{VY 1:}} \quad \begin{aligned} u_T^{(1/2)} / u(x) &= -0.81 x(1-x) \\ d_T^{(1/2)} / u(x) &= 1.86 x(1-x) \end{aligned}$$

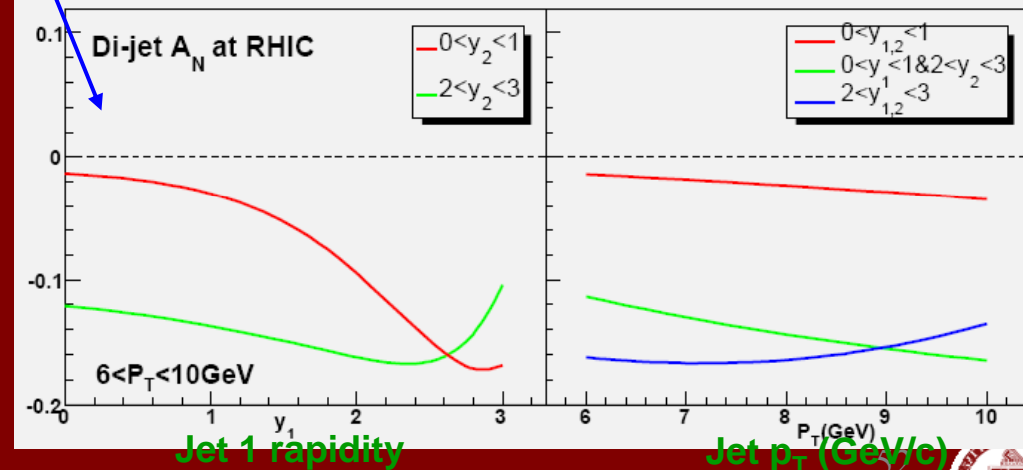
$$\boxed{\text{VY 2:}} \quad \begin{aligned} u_T^{(1/2)} / u(x) &= -0.75 x(1-x) \\ d_T^{(1/2)} / d(x) &= 2.76 x(1-x) \end{aligned}$$

Dijet calcs. include:

- no hadronization
- no gluon Sivers fcns.
- $5 < p_T^{\text{parton}} < 10 \text{ GeV}/c$
- Initial-state interactions only (à la Drell-Yan)
- Trento sign convention (opposite Madison)



W. Vogelsang and F. Yuan, PRD 72, 054028 (2005).



Jet 1 rapidity

Jet  $p_T$  (GeV/c)

C. Aidala, COMPASS Workshop, March 10, 2007

$\geq 1$  jet forward, expected  $|A_N| \sim 0.1$ , little  $p_T$ -dep.



# Theory of Transverse SSA Developing Very Rapidly!

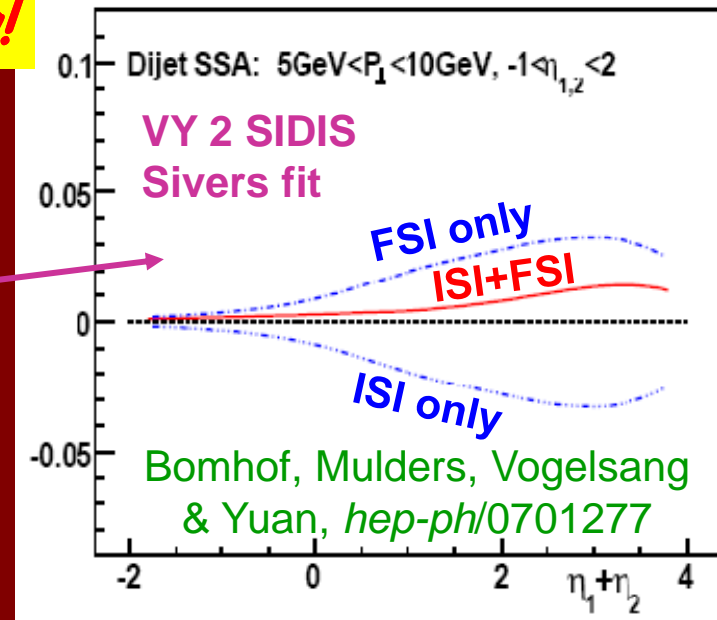
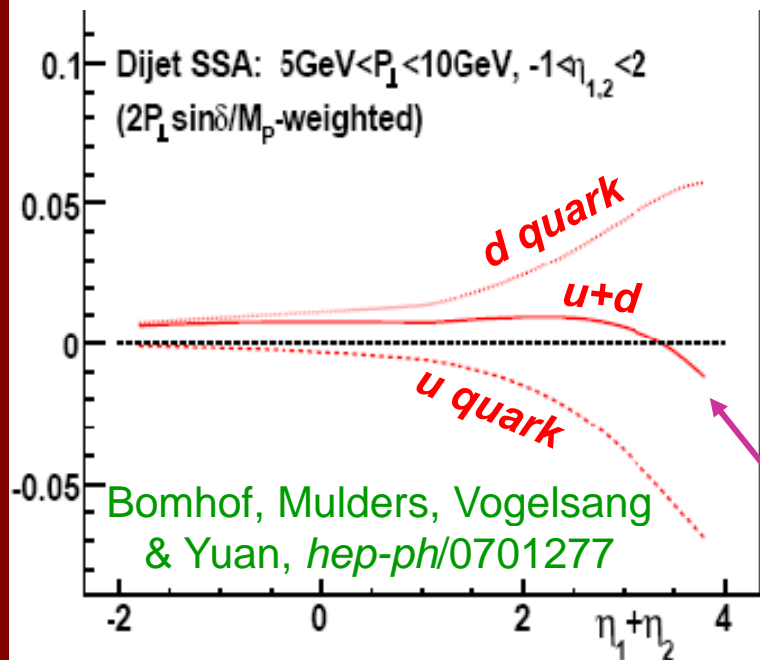
## Di-jet SSA Post-dictions shrinking!

Bacchetta, Bomhof, Mulders & Pijlman  
[PRD 72, 034030 (2005)] deduce gauge link  
structure for  $pp \rightarrow \text{jets, hadrons}$ :

$$\Rightarrow A_N(\text{ISI+FSI}) \approx -0.5 A_N(\text{ISI})$$

$\Rightarrow$  Gauge links more robust for SSA  
weighted by  $\sum p_T$  for 2 jets, or  $|\sin \zeta|$

Sivers fcns. from twist-3 qg correl'n  
fits to  $\vec{p}p \rightarrow \text{forward hadron}$



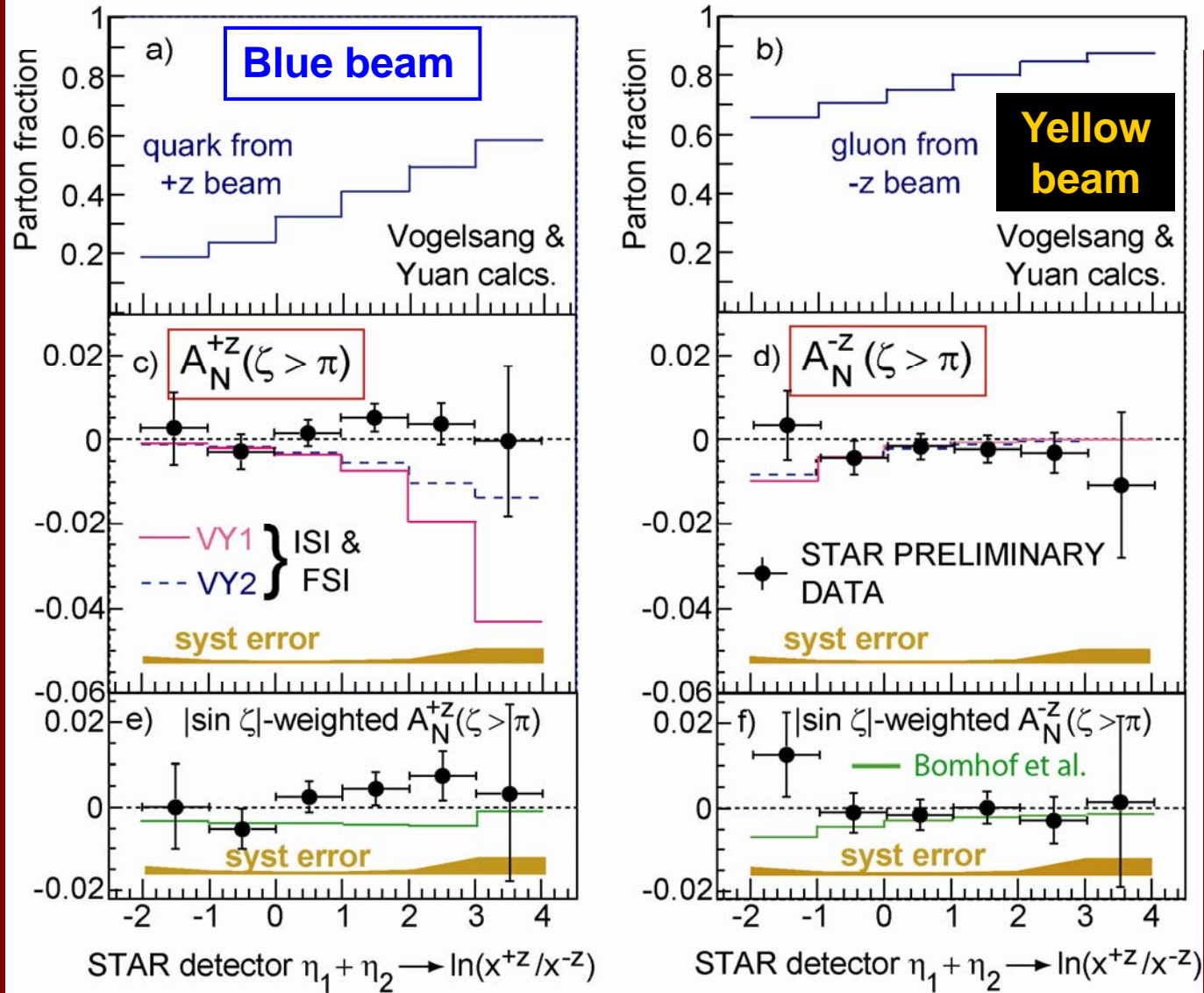
Ji, Qiu, Vogelsang & Yuan [PRL 97, 082002 (2006)] show strong overlap  
between Sivers effects & twist-3 quark-  
gluon (Qiu-Sterman) correlations:

$\Rightarrow$  twist-3 fits to  $A_N(\vec{p}+p \rightarrow \text{fwd. } h)$  can  
constrain Sivers fcn. moment relevant  
to weighted di-jet SSA

$\Rightarrow$  Kouvaris et al. [PRD 74, 114013  
(2006)] fits give nearly complete u vs. d  
cancellation in weighted di-jet SSA



# STAR Di-Jet Sivers Results vs. Jet Pseudorapidity Sum



- All calcs. for STAR  $\eta$  acceptance
- Reverse calc.  $A_N$  signs for Madison convention
- Scale Bomhof calcs by  $1/\langle |\sin \zeta| \rangle \approx 3.0$  to get  $A_N$  of unit max. magnitude
- $u$  vs  $d$  and FSI vs ISI cancellations  $\Rightarrow$  sizable SSA in inclusive fwd.  $h$  prod'n and SIDIS (weighted SSA) compatible with small weighted di-jet SSA -- test via LCP flavor select

**STAR  $A_N$  all consistent with zero  $\Rightarrow$  both net high- $x$  parton and low- $x$  gluon Sivers effects  $\sim 10\times$  smaller in  $\rightarrow pp \rightarrow$  di-jets than SIDIS quark Sivers asym.!**



# *$\pi/K/p$ SSA Measurements at 200 and 62 GeV*

BRAHMS measures identified hadrons ( $\pi, K, p, pbar$ )  
in the kinematic ranges of

- $0 < x_F < 0.35$  and  $0.2 < p_T < 3.5$  GeV/ $c$  at  $\sqrt{s}=200$  GeV
- $0 < x_F < 0.6$  and  $0.2 < p_T < 1.5$  GeV/ $c$  at  $\sqrt{s}=62$  GeV for
  - $x_F, p_T$ , flavor,  $\sqrt{s}$  dependent SSA
  - cross-section of unpolarized hadron production  
(constraint for theoretically consistent description)

Data:

- Run-5:  $\sqrt{s} = 200$  GeV  $2.5 \text{ pb}^{-1}$  recorded (polarization:45-50%)
- Run-6:  $\sqrt{s} = 62$  GeV  $0.21 \text{ pb}^{-1}$  recorded (polarization:45-65%)

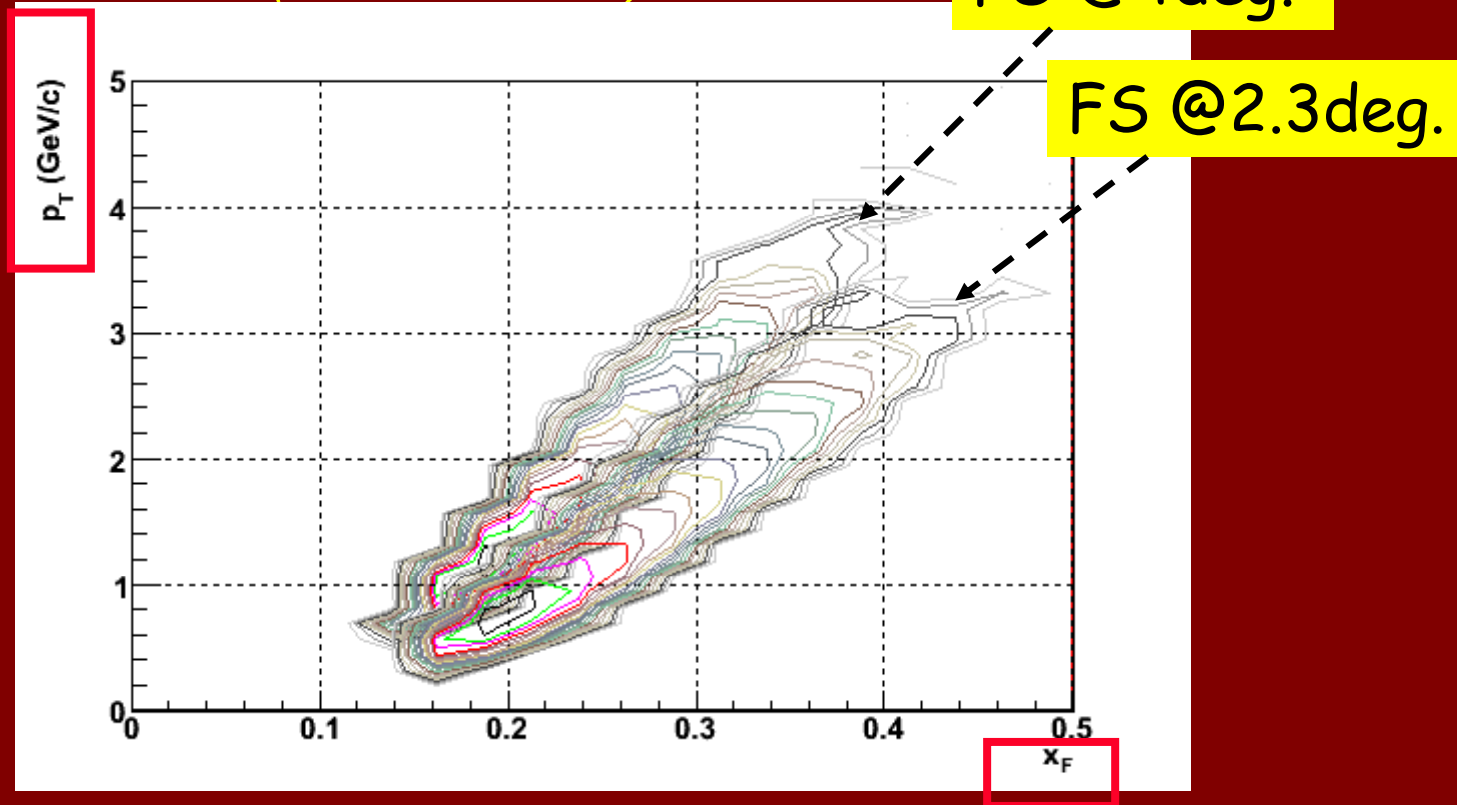
Data from Forward Spectrometer at 2.3-4 deg. covering  
"high"- $x_F$  ( $0.15 < x_F < 0.6$ ) are presented.





*DIRAFMS FS Acceptance at 2.3 deg.  
and 4 deg.*

*/Full Field (7.2 Tm) at  $\sqrt{s} = 200 \text{ GeV}$*

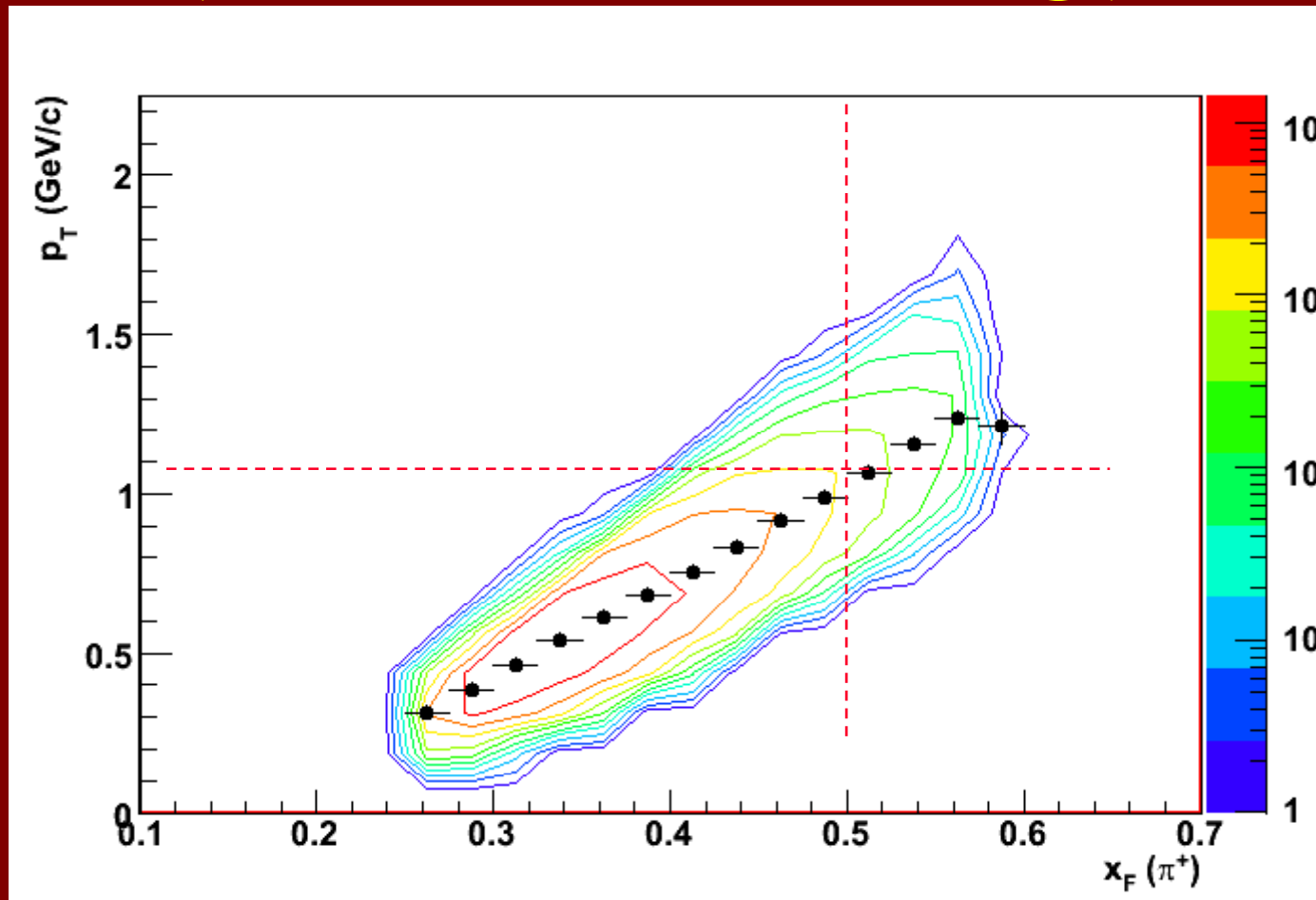


- Strong  $x_F$ - $p_T$  correlation due to limited spectrometer solid angle acceptance

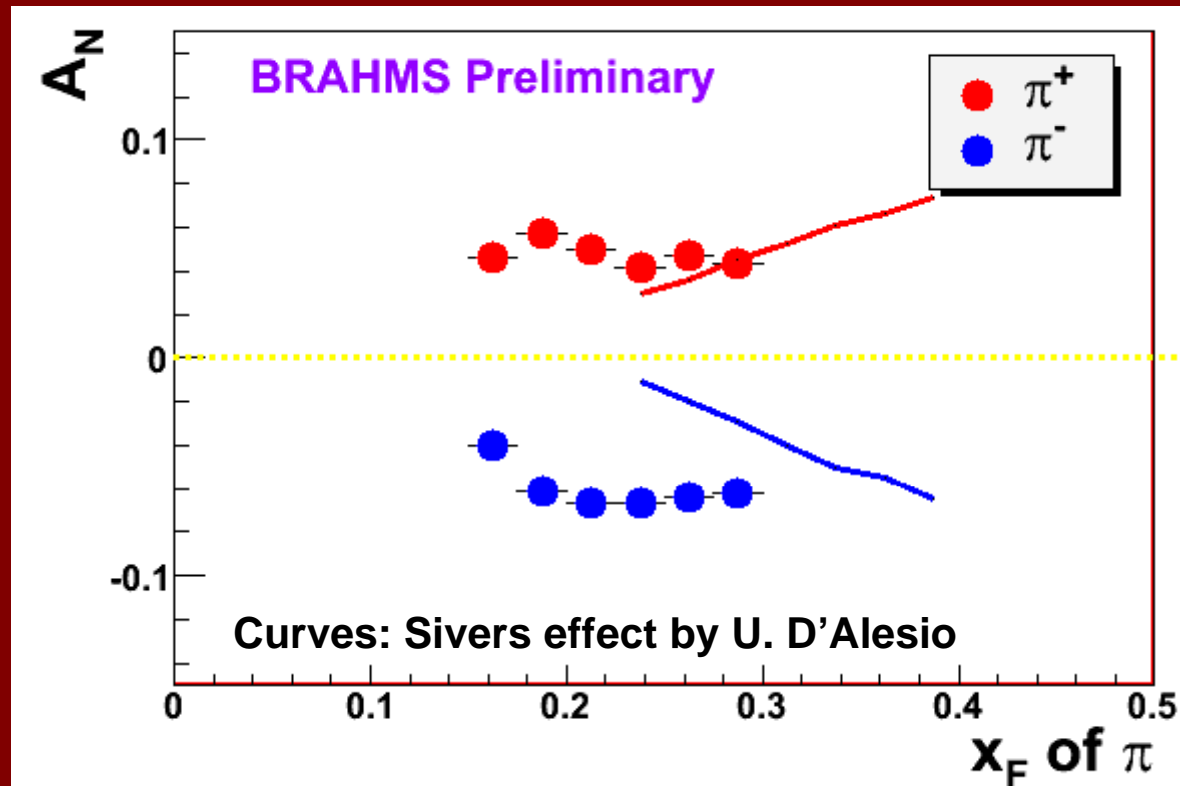




# *Kinematic coverage at $\sqrt{s} = 62 \text{ GeV}$ (FS at 2.3 and 3 deg.)*



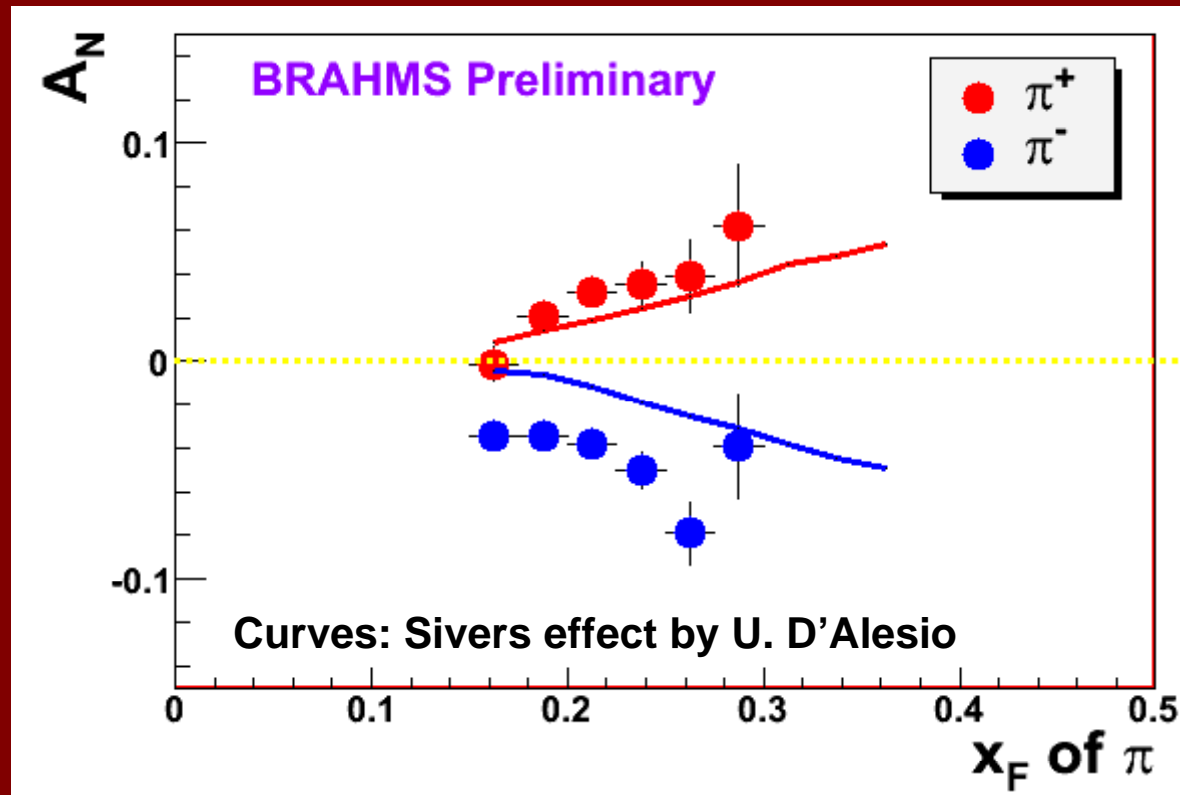
# $A_N(\pi)$ at 2.3 deg. at $\sqrt{s} = 200$ GeV



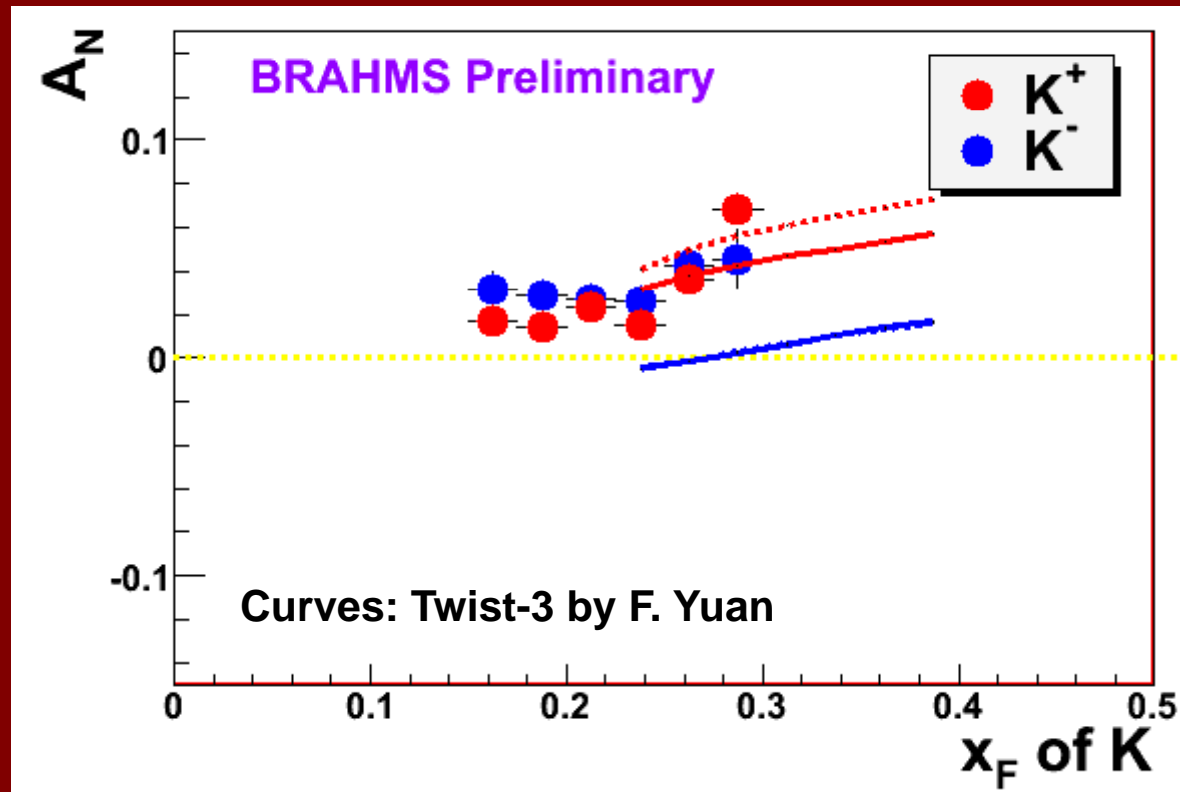
- Poor agreement between data and Siverson effect calculation



# $A_N(\pi)$ at 4 deg. at $\sqrt{s} = 200 \text{ GeV}$



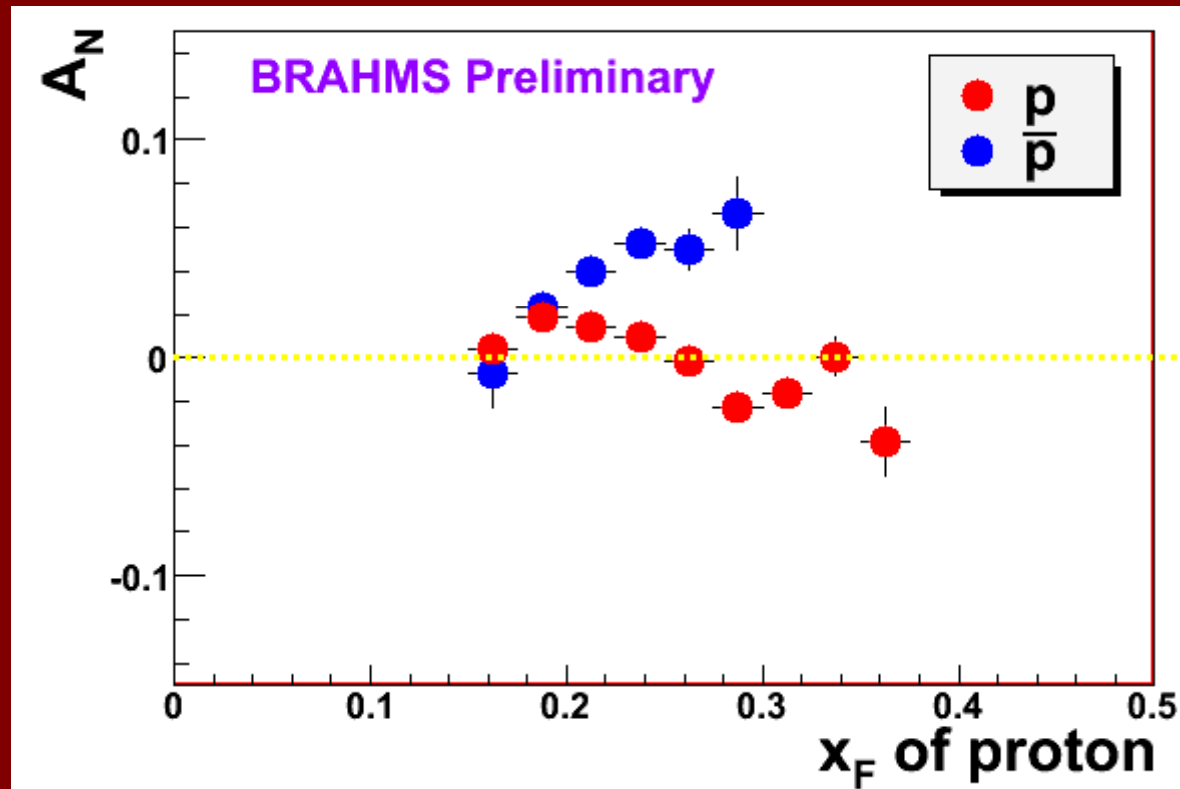
# $A_N(K)$ at 2.3 deg at $\sqrt{s} = 200$ GeV



- Solid lines: two-flavor ( $u, d$ ) fit
- Dashed lines: valence + sea, anti-quark
- Calculations done only for  $\langle p_T(\pi) \rangle > 1$  GeV/c



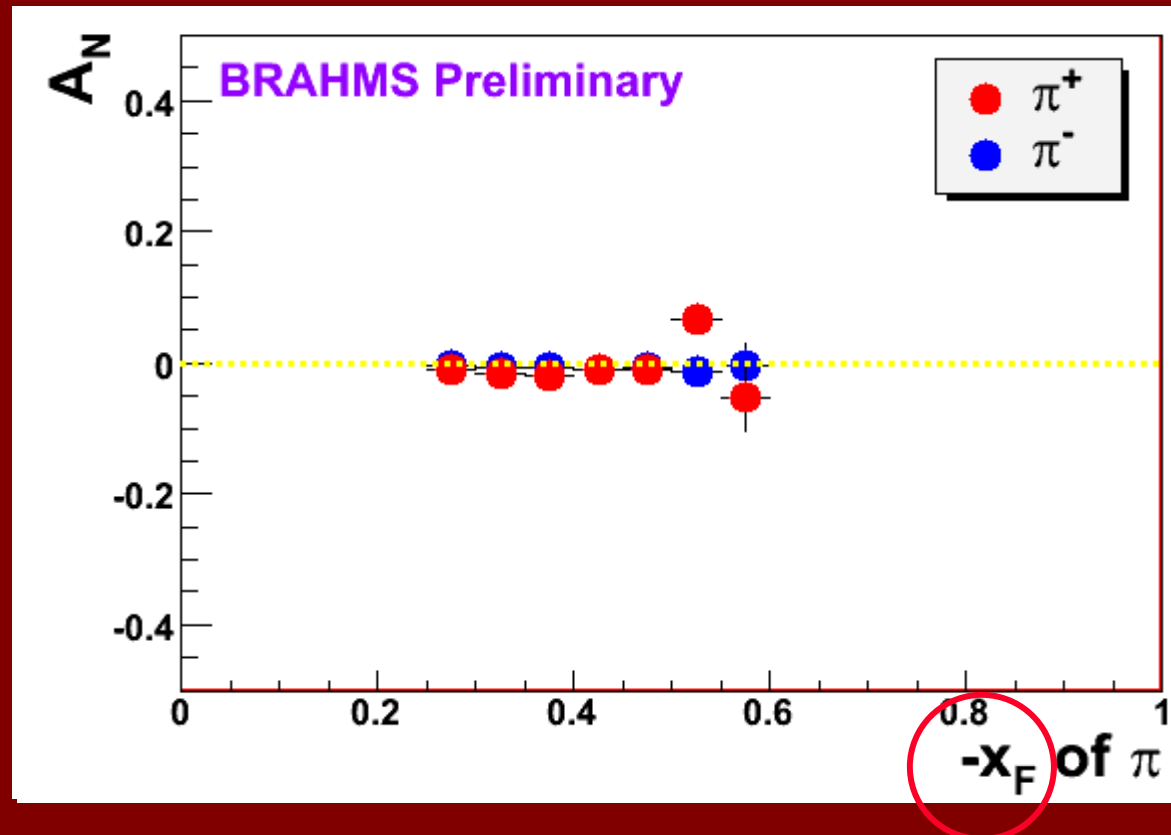
# *Proton at 2.3 deg. at $\sqrt{s} = 200 \text{ GeV}$*



- $A_N(pbar), A_N(K^-) > 0$ : Accidental? Or contribution from sea-quarks
- $A_N(p) \sim 0$ : At this kinematic region, significant fraction of proton are mostly from polarized beam proton, but only ones showing  $A_N \sim 0$

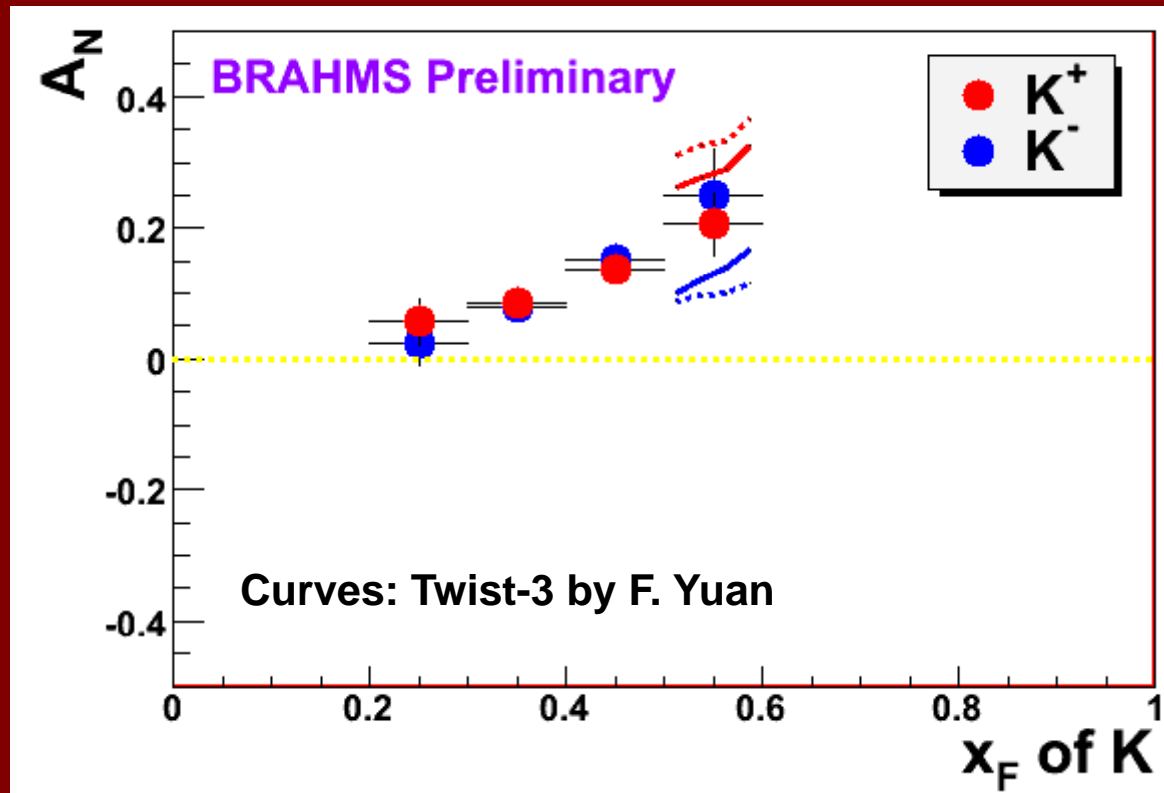


# $A_N(\pi)$ at $\sqrt{s} = 62 \text{ GeV}$





# $A_N(K)$ at $\sqrt{s} = 62 \text{ GeV}$

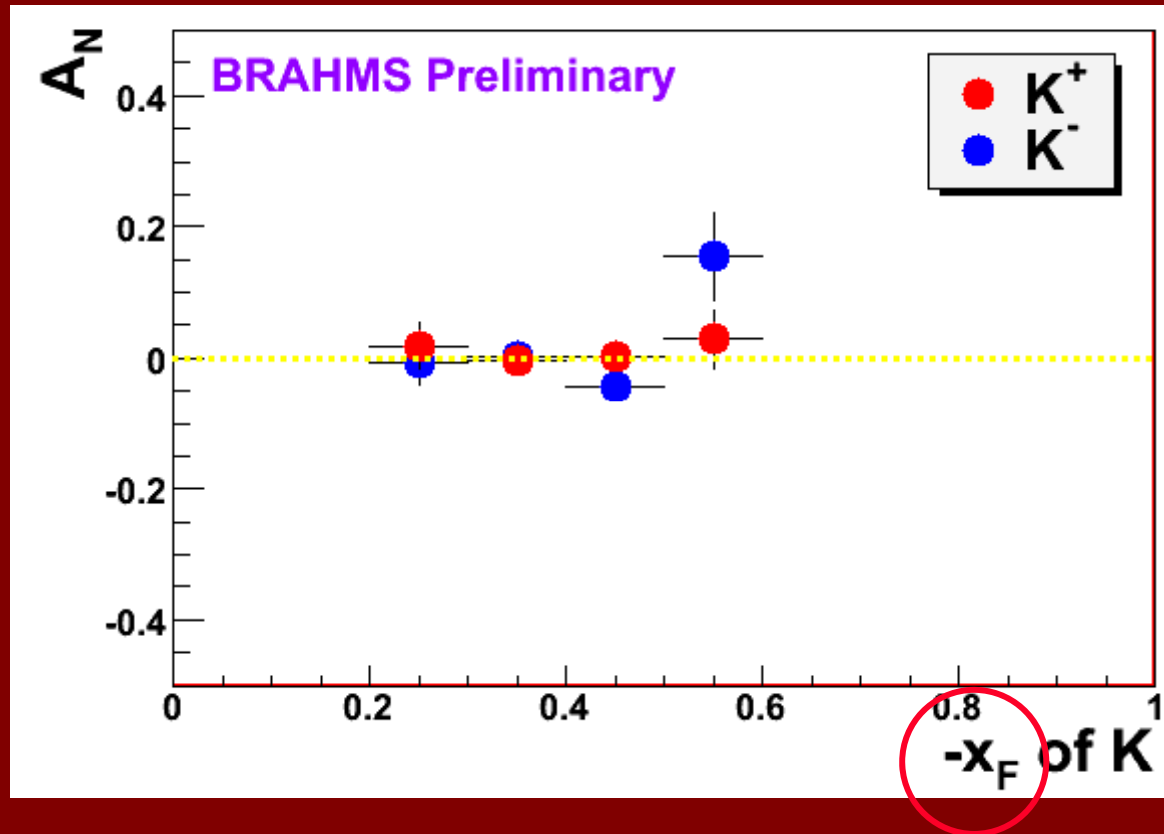


- Solid lines: two-flavor ( $u, d$ ) fit
- Dashed lines: valence + sea, anti-quark
- Calculations done only for  $\langle p_T(\pi) \rangle > 1 \text{ GeV}/c$

C. Aidala, COMPASS workshop, March 19, 2007

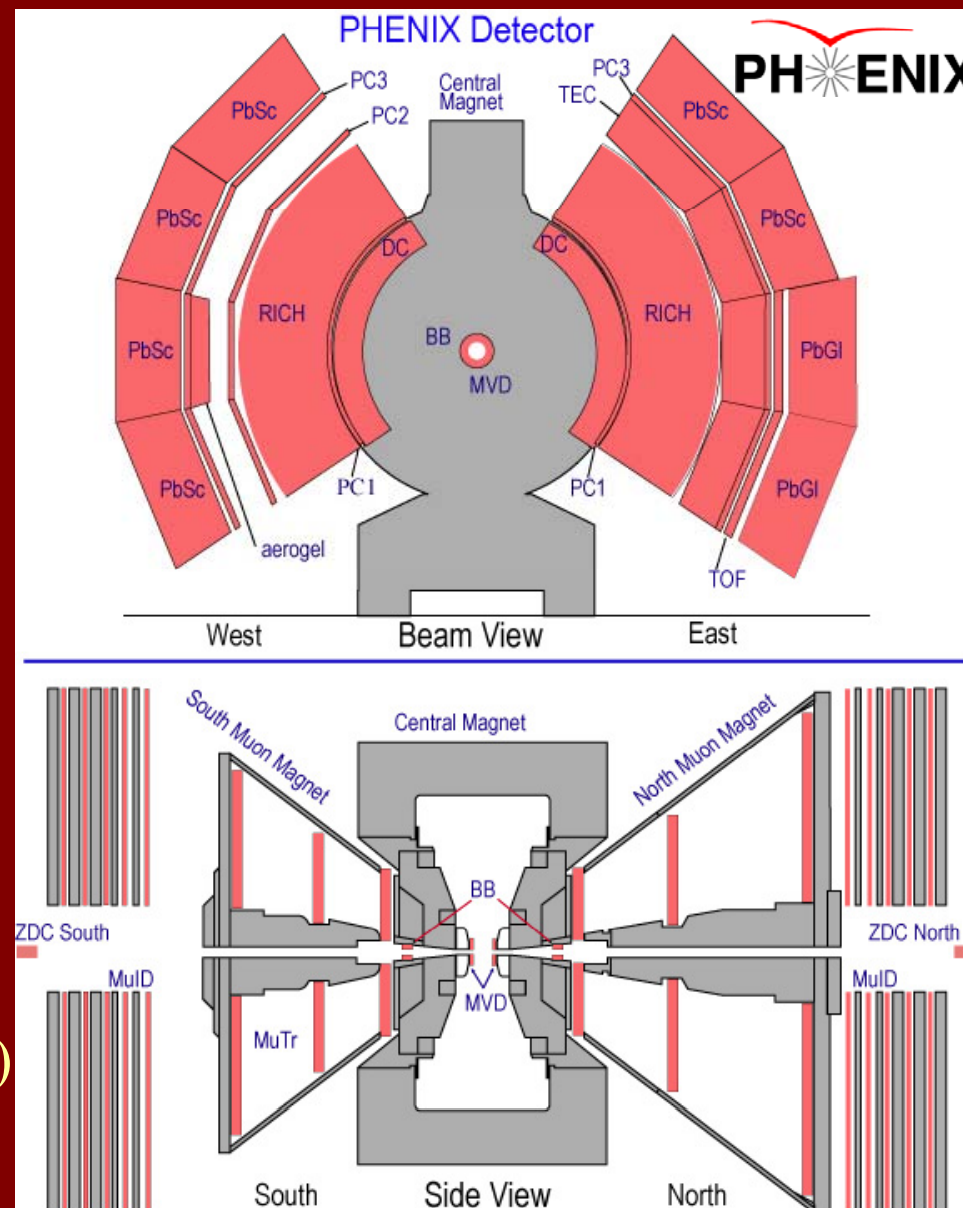


# $A_N(K)$ vs $-x_F$ at $\sqrt{s} = 62 \text{ GeV}$



# *The PHENIX Detector for Spin Physics*

- $\gamma/\pi^0/\eta$  detection
  - Electromagnetic Calorimeter
- $\pi^+/\pi^-$ 
  - Drift Chamber
  - Ring Imaging Cherenkov Detector or TOF
- $J/\psi$ 
  - Muon ID/Muon Tracker ( $\mu^+\mu^-$ )
  - EMCal ( $e^+e^-$ )
- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)
- Local Polarimetry - ZDC



# *RHIC Performance, Longitudinal Polarization (PHENIX integrated luminosities shown)*

Year	$\sqrt{s}$ [GeV]	Recorded L	Pol [%]	FOM (P <sup>4</sup> L)
2003 (Run-3)	200	.35 pb <sup>-1</sup>	27	1.5 nb <sup>-1</sup>
2004 (Run-4)	200	.12 pb <sup>-1</sup>	40	3.3 nb <sup>-1</sup>
2005 (Run-5)	200	3.4 pb <sup>-1</sup>	46	150 nb <sup>-1</sup>
2006 (Run-6)	200	7.5 pb <sup>-1</sup>	62	1100 nb <sup>-1</sup>
2006 (Run-6)	62.4	.08 pb <sup>-1</sup> **	48	4.2 nb <sup>-1</sup> **

\*\* initial estimate



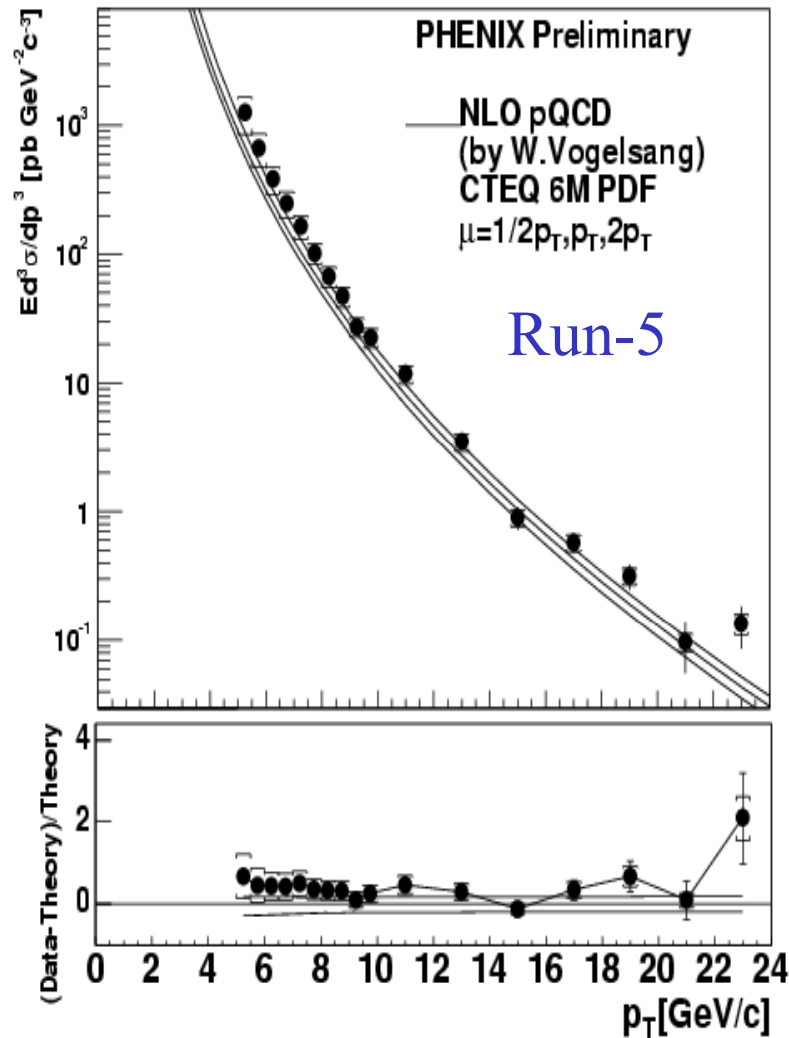
# *PHENIX Polarized-Proton Runs: Transverse Polarization*

Year	$\sqrt{s}$ [GeV]	Recorded L	Pol [%]	FOM (P <sup>2</sup> L)
2001 (Run-2)	200	.15 pb <sup>-1</sup>	15	3.4 nb <sup>-1</sup>
2005 (Run-5)	200	.16 pb <sup>-1</sup>	47	38 nb <sup>-1</sup>
2006 (Run-6)	200	2.7 pb <sup>-1</sup>	57	880 nb <sup>-1</sup>
2006 (Run-6)	62.4	.02 pb <sup>-1</sup> **	48	4.6 nb <sup>-1</sup> **

\*\* initial estimate



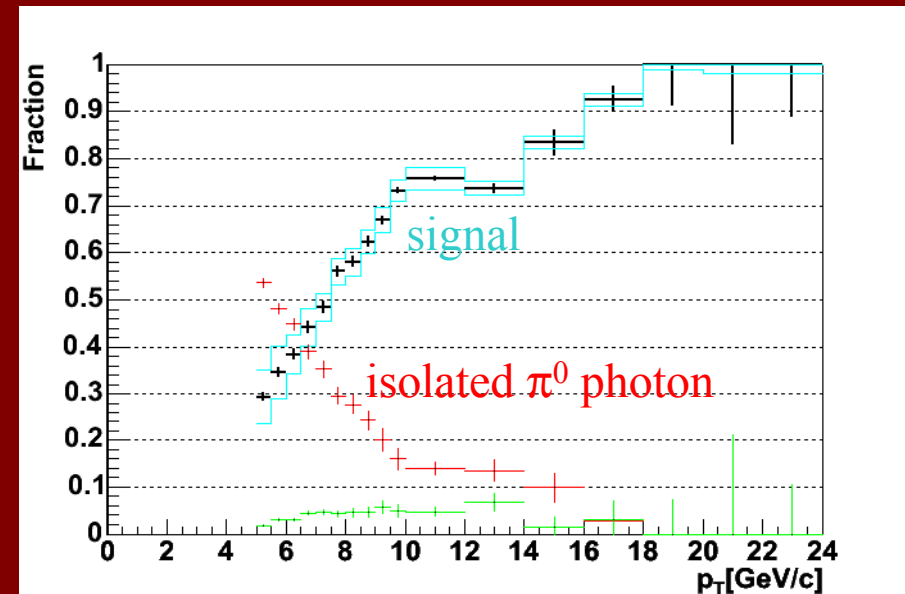
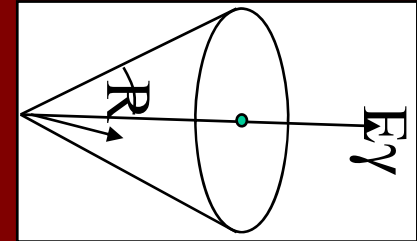
# Prompt $\gamma$ at $\sqrt{s}=200$ GeV (Run-5)



Isolation cut to  
reduce background

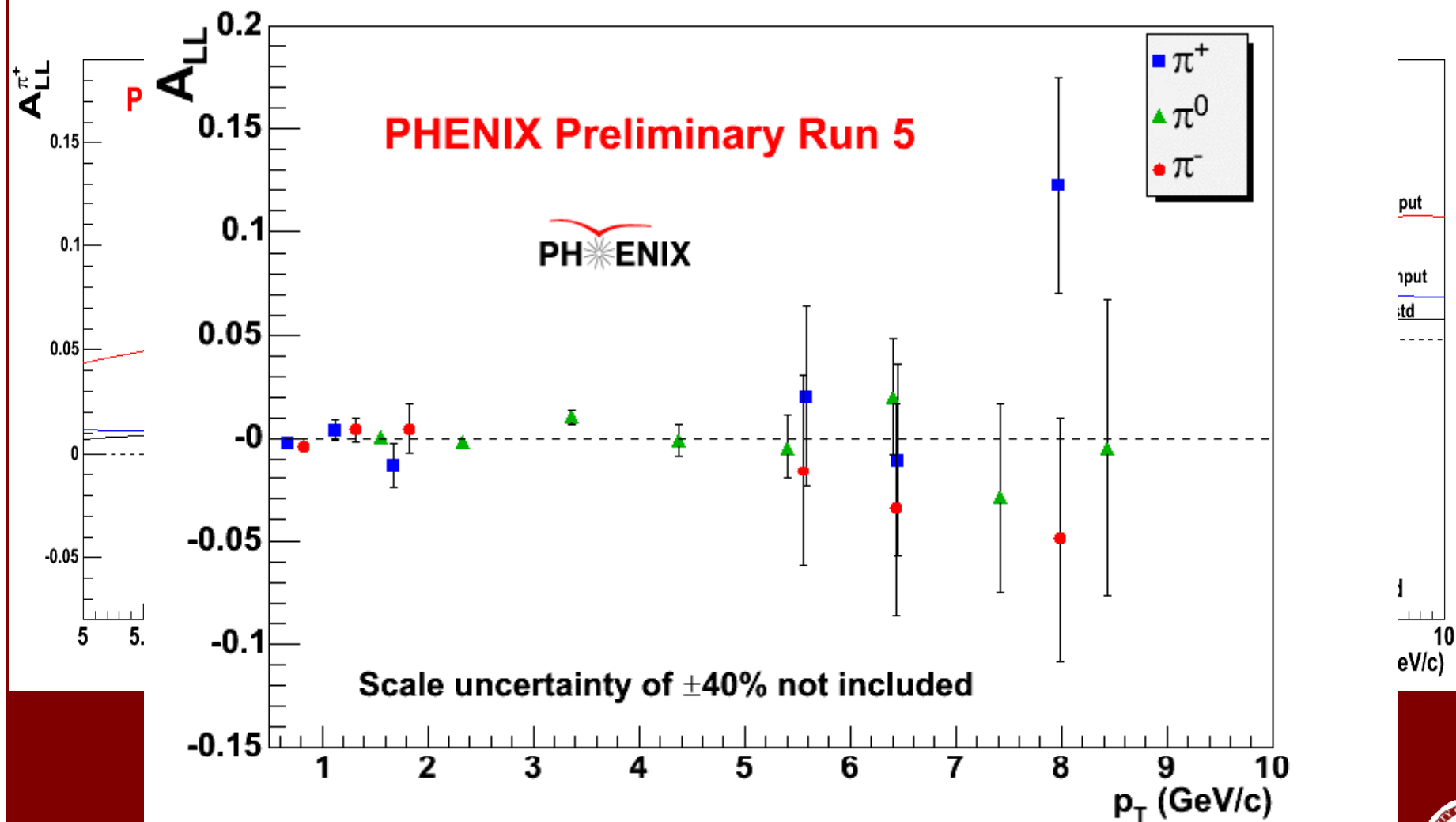
$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.5$$

$$E_{sum}(R < 0.5) < E_\gamma \times 0.1$$

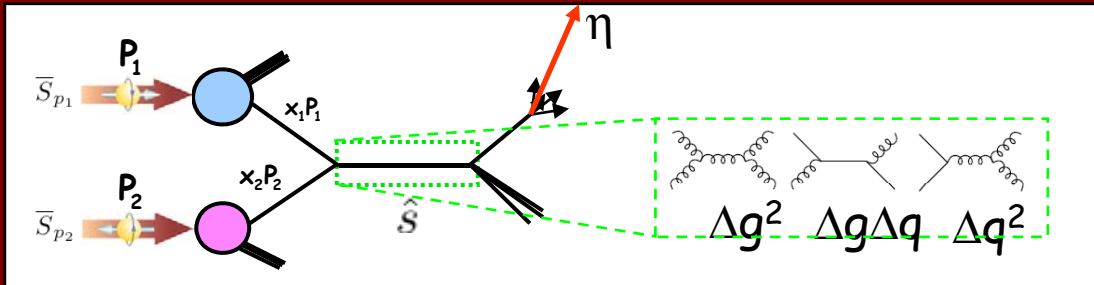




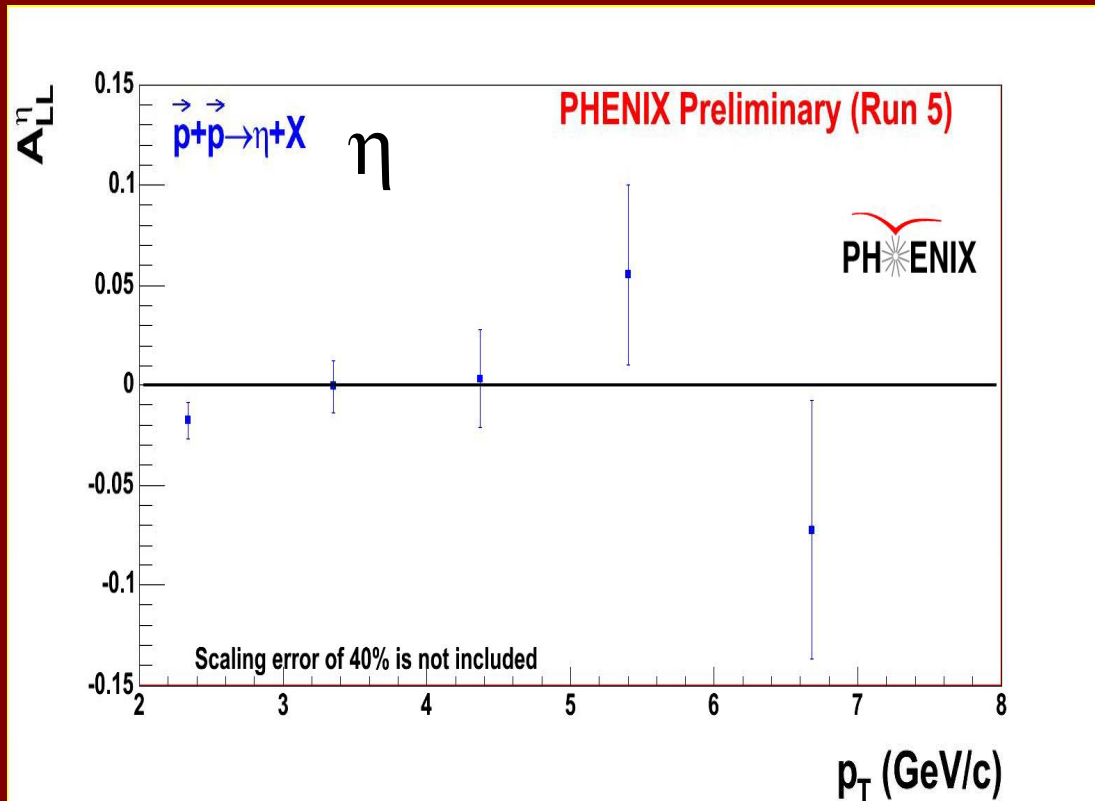
# $A_{LL}$ of $\pi^\pm$ at $\sqrt{s}=200$ GeV



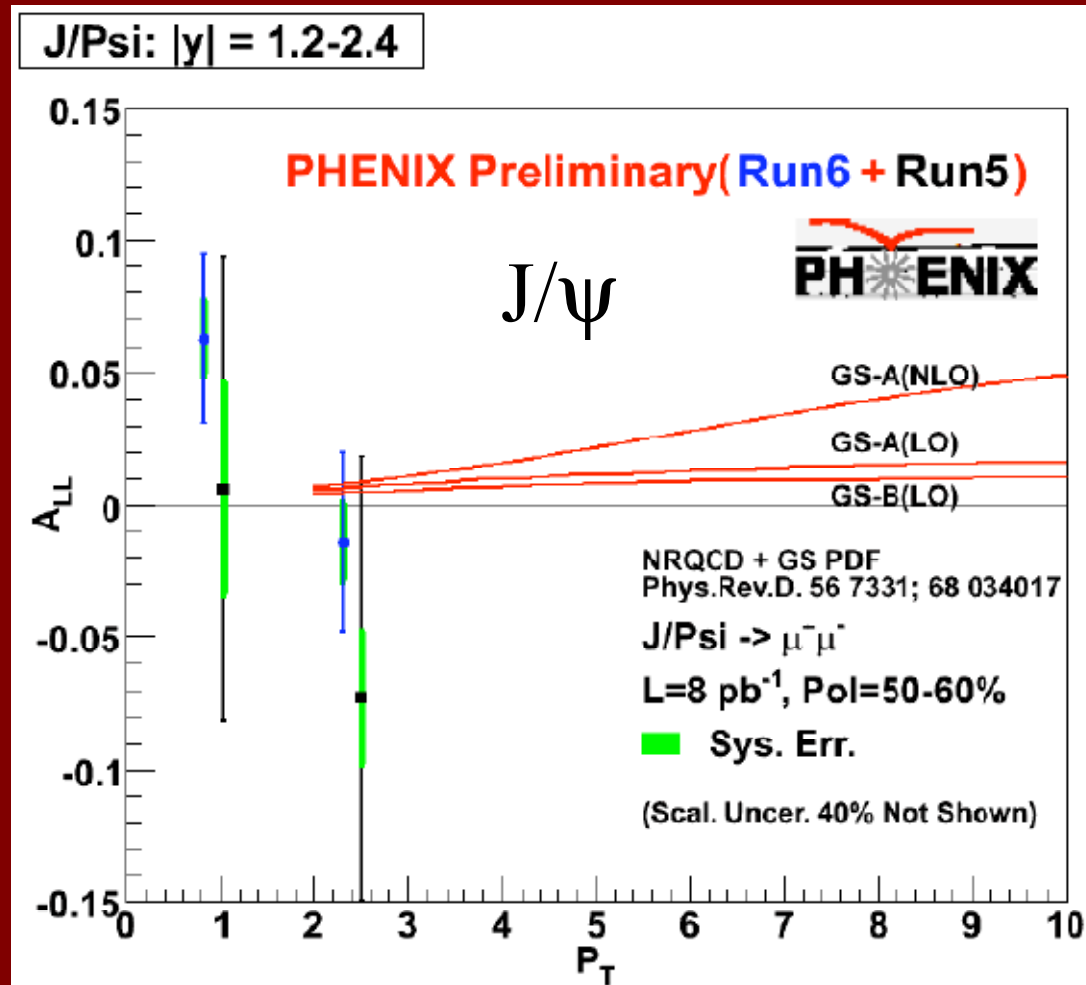
# $A_{LL}^{\eta}$ of $\eta$ at $\sqrt{s}=200$ GeV



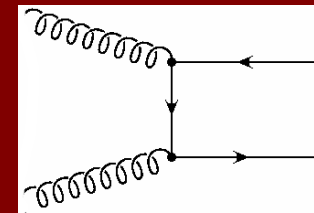
$\eta$  fragmentation  
function not yet  
available—  
needed for  
pQCD  
calculations!



# $A_{LL}$ of $J/\psi$ at $\sqrt{s}=200$ GeV



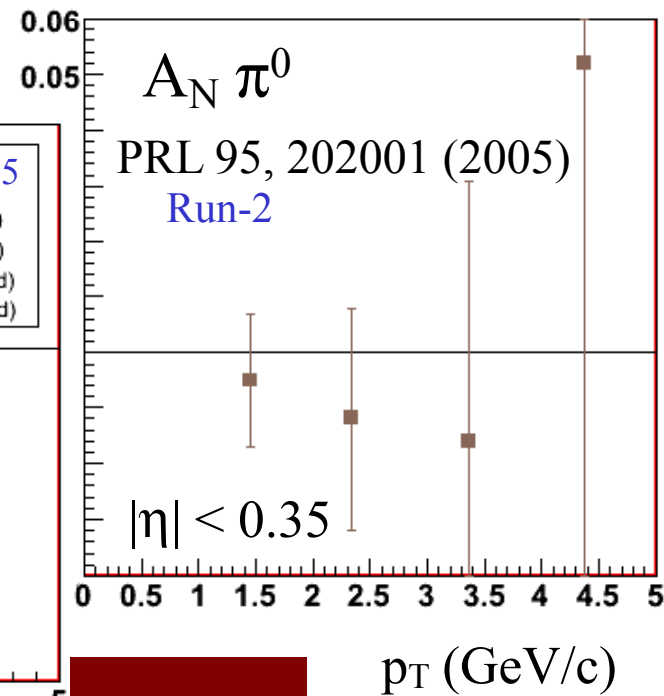
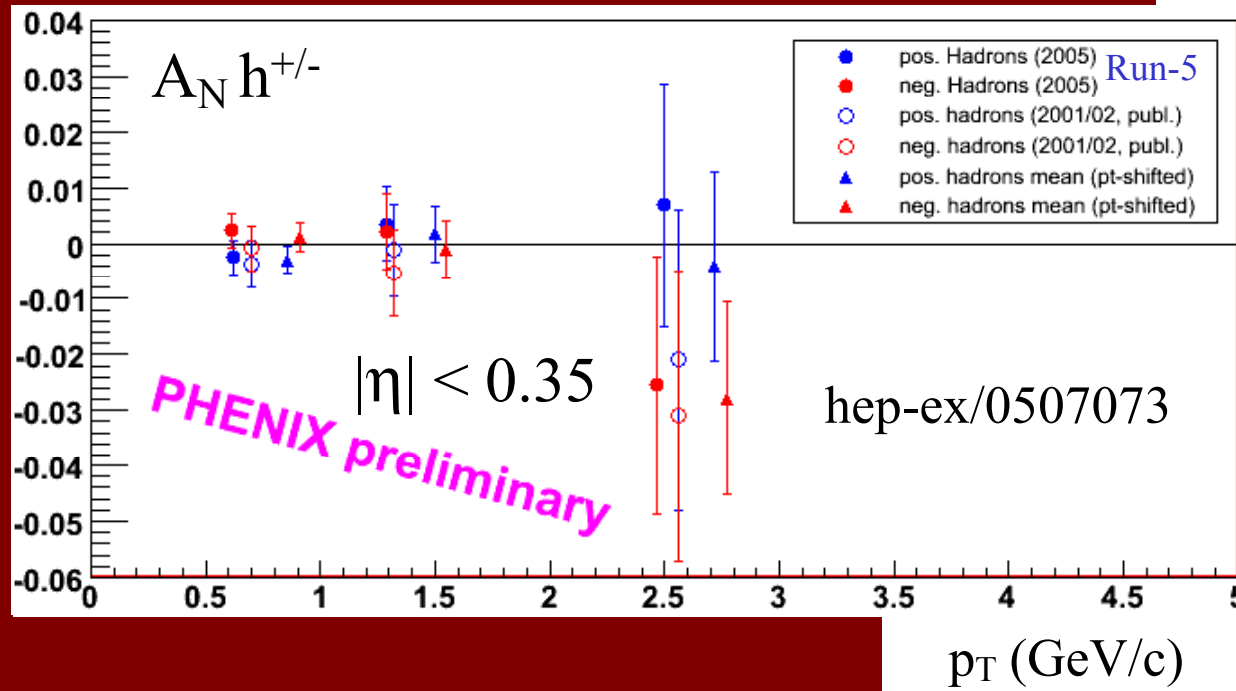
$$gg \rightarrow Q\bar{Q}$$



$$\propto \frac{\Delta g}{g} \frac{\Delta g}{g}$$



# $A_N$ of Mid-rapidity $\pi^0$ and $h^{+/-}$ at $\sqrt{s}=200$ GeV

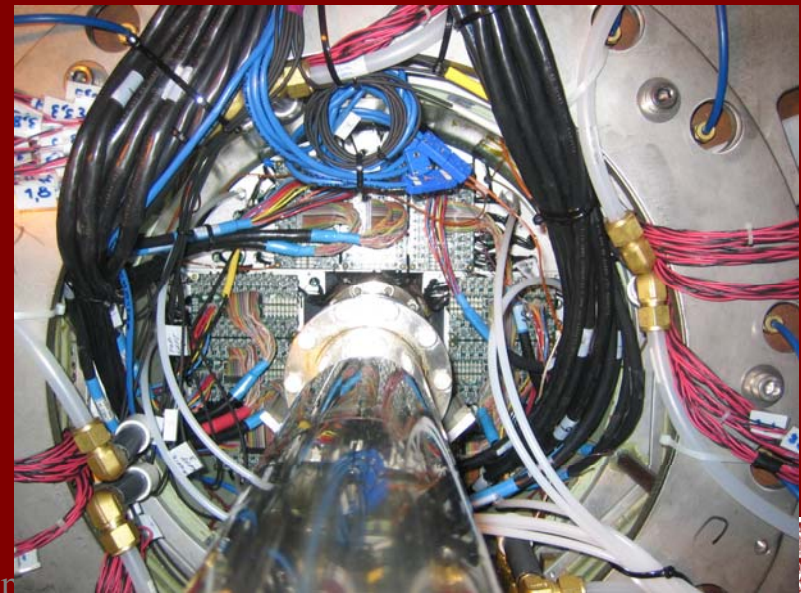
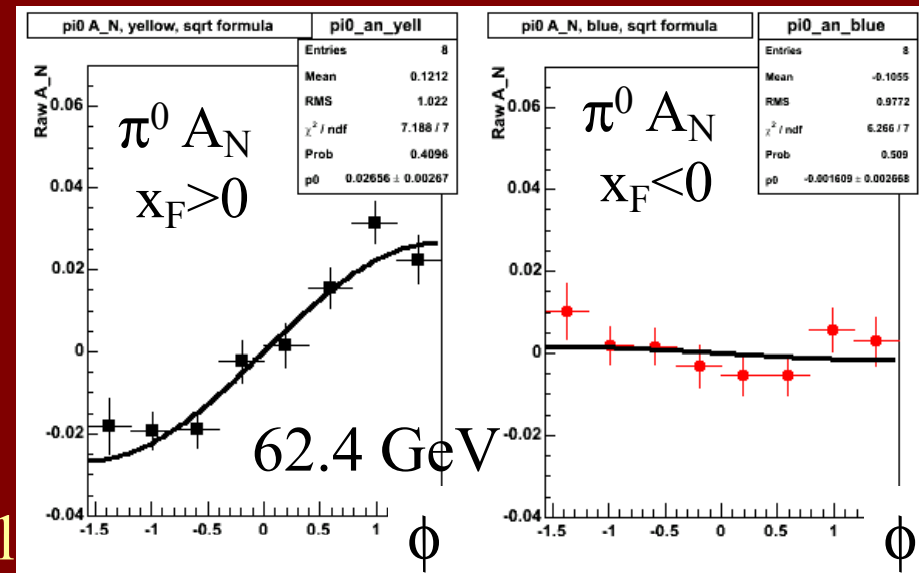


- $A_N$  is zero within 1%  $\rightarrow$  contrast with forward pions
- Constrains Sivers distribution function for gluons (Anselmino et al., hep-ph/0608211)

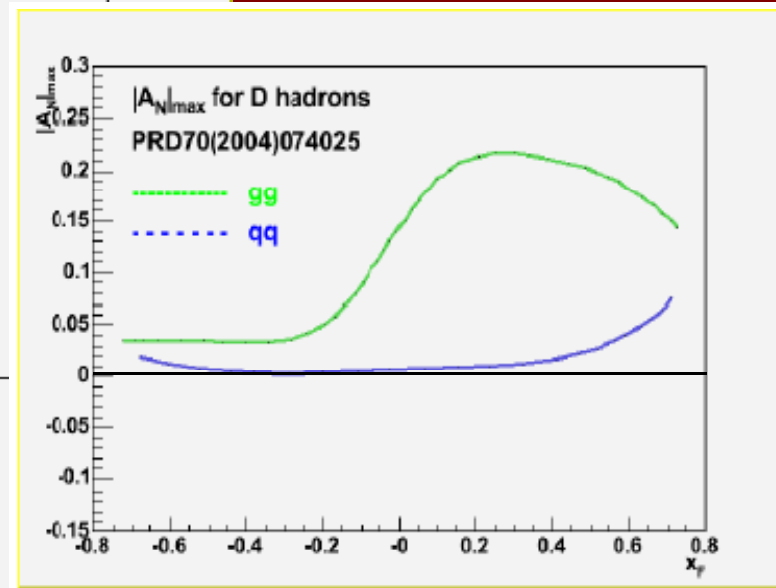
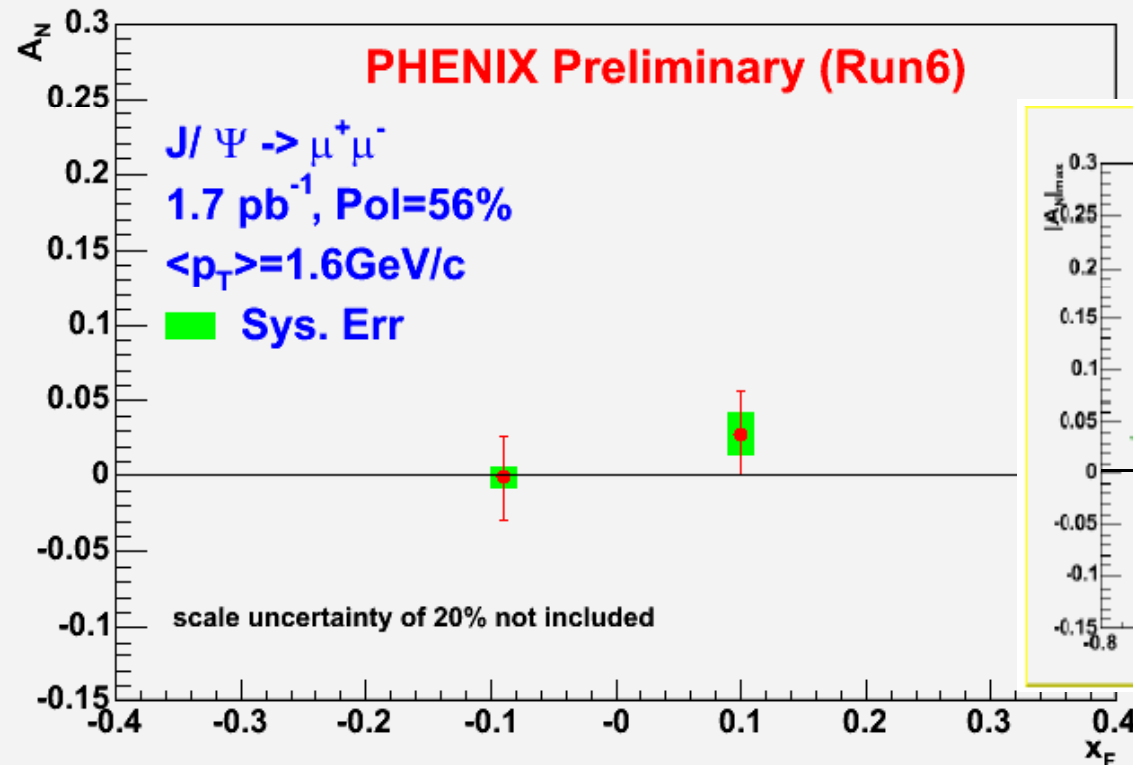


# Muon Piston Calorimeter (MPC)

- PbWO<sub>4</sub> calorimeter
- $3.1 < |\eta| < 3.7$ 
  - Region of large observed asymmetries
- South arm installed for Run-6 commissioning
  - Expect 200-GeV longitudinal and 62.4-GeV longitudinal & transverse results
  - Non-zero raw  $\pi^0$  transverse asymmetry already observed in 62.4-GeV data for  $x_F > 0$
- North arm installed and ready for Run-7!



# $A_N$ of $J/\psi$ at $\sqrt{s}=200$ GeV

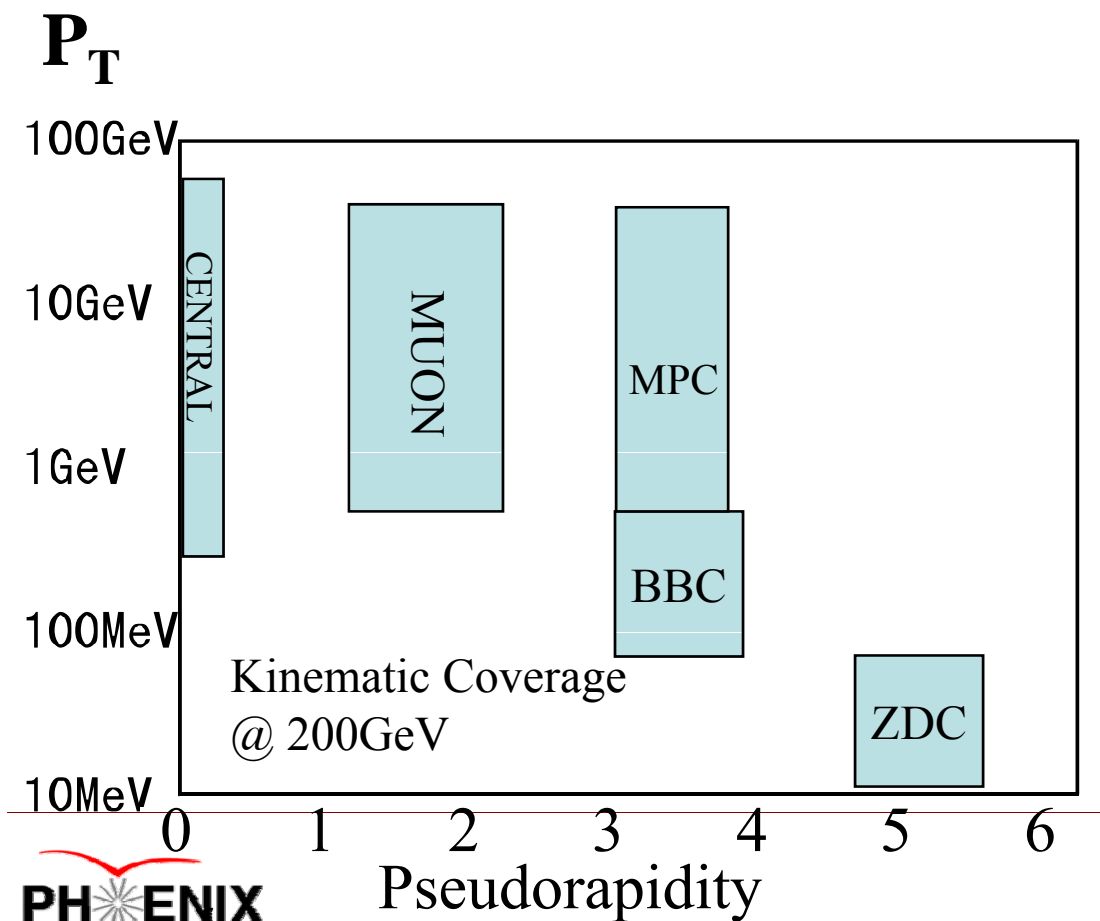
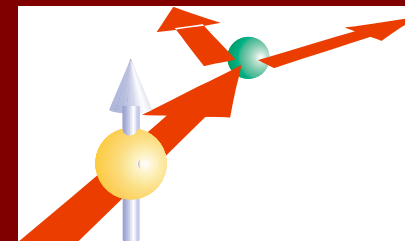


- Sensitive to gluon Sivers function  $gg \rightarrow Q\bar{Q}$
- Open charm theory prediction available from Anselmino et al.
  - How does  $J/\psi$  production affect prediction?? Waiting for theoretical calculation.





# PHENIX Kinematic Coverage

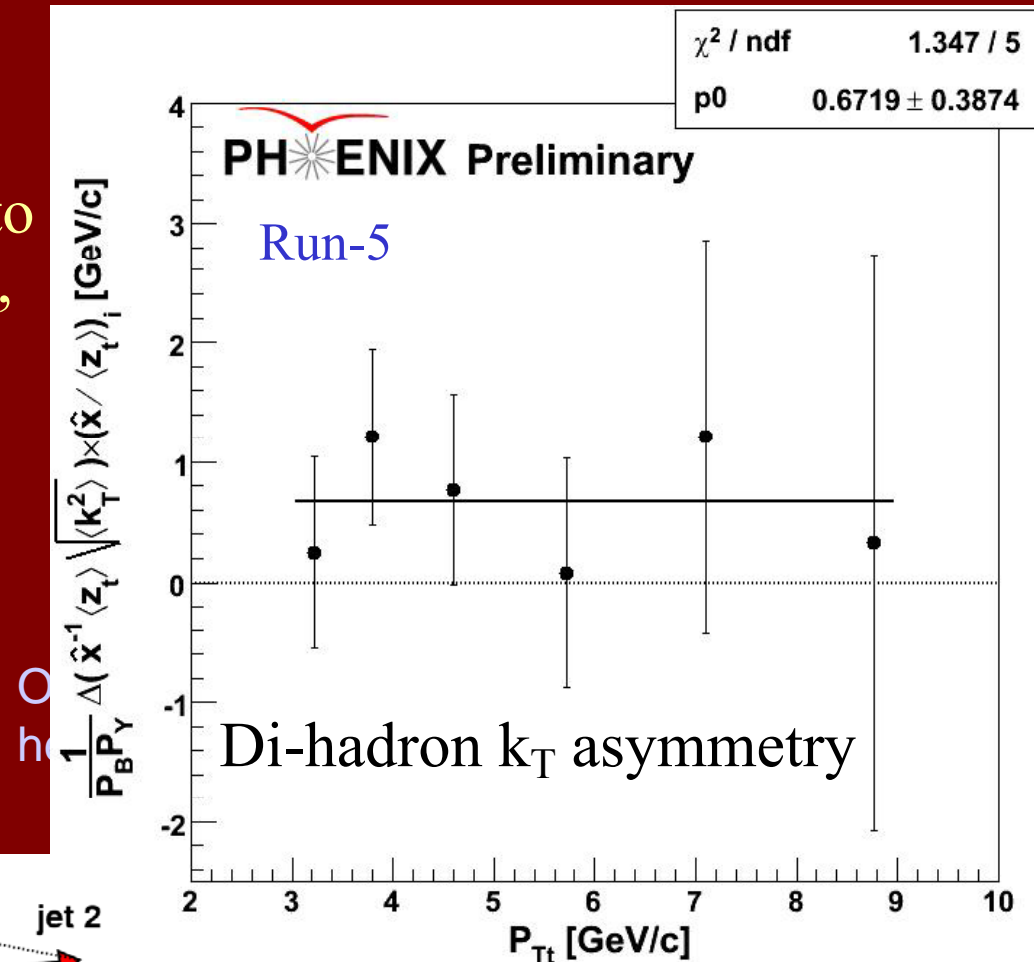
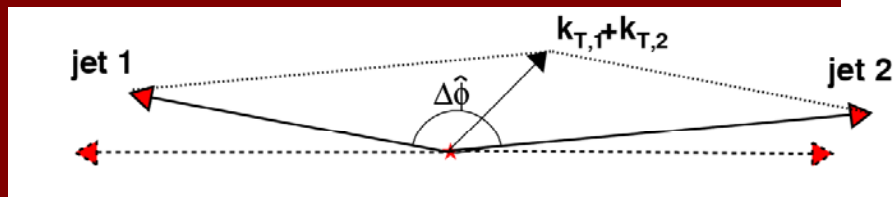


- Forward  $\pi^0$  now possible with Muon Piston Calorimeter
  - Kinematic region where large asymmetries have been observed by STAR and BRAHMS!



# Attempting to Probe $k_T$ from Orbital Motion

- Spin-correlated transverse momentum (orbital angular momentum) may contribute to jet  $k_T$ . (Meng Ta-chung et al., Phys. Rev. D40, 1989)
- Possible helicity dependence
- Would depend on (unmeasured) impact parameter, but may observe net effect after averaging over impact parameter

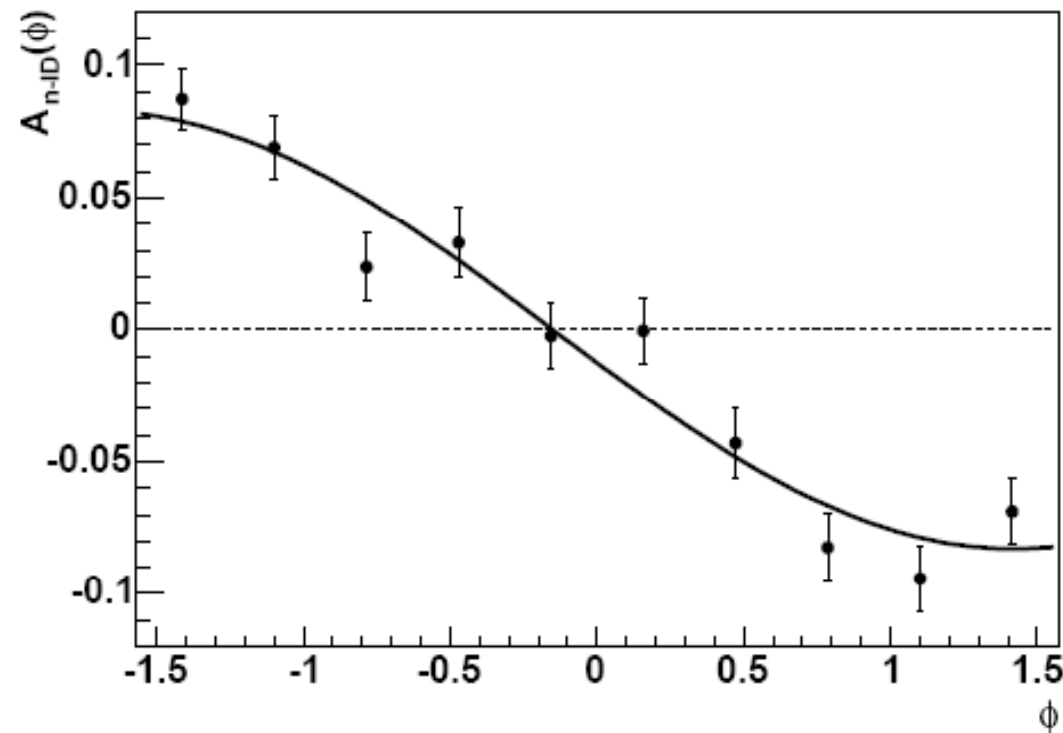


# Forward Neutral Particles at IP12

	forward	backward
neutron	$-0.090 \pm 0.006 \pm 0.009$	$0.002 \pm 0.004 \pm 0.003$
photon	$-0.009 \pm 0.015 \pm 0.007$	$-0.020 \pm 0.010 \pm 0.003$
$\pi^0$	$-0.022 \pm 0.030 \pm 0.002$	$0.005 \pm 0.021 \pm 0.0005$

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

hep-ex/0610030



Forward neutron  $A_N$



# Forward Neutrons at $\sqrt{s}=200$ GeV at PHENIX

Large asymmetry for  $x_F > 0$  at  $\sqrt{s}=200$  GeV,  
no  $x_F$  dependence observed.

Neutron asymmetry  $x_F$  distribution with neutron trigger & MinBias

