Recent Transverse Spin Results in Polarized p+p Collisions at PHENIX

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Outline

- Introduction
- The PHENIX Experiment
- Single Spin Asymmetry Measurements

  Light hadrons

  -- Mid-rapidity π^0 and charged hadrons (Run2, Run5)

  -- Forward π^0 at 62GeV (MPC, Run6)

  -- Forward neutron (Run5)

  Heavy Flavors

  -- J/Ψ (Run6)

  -- Muons from heavy flavor decay (Run6)
- Summary and Outlook

A brief history…

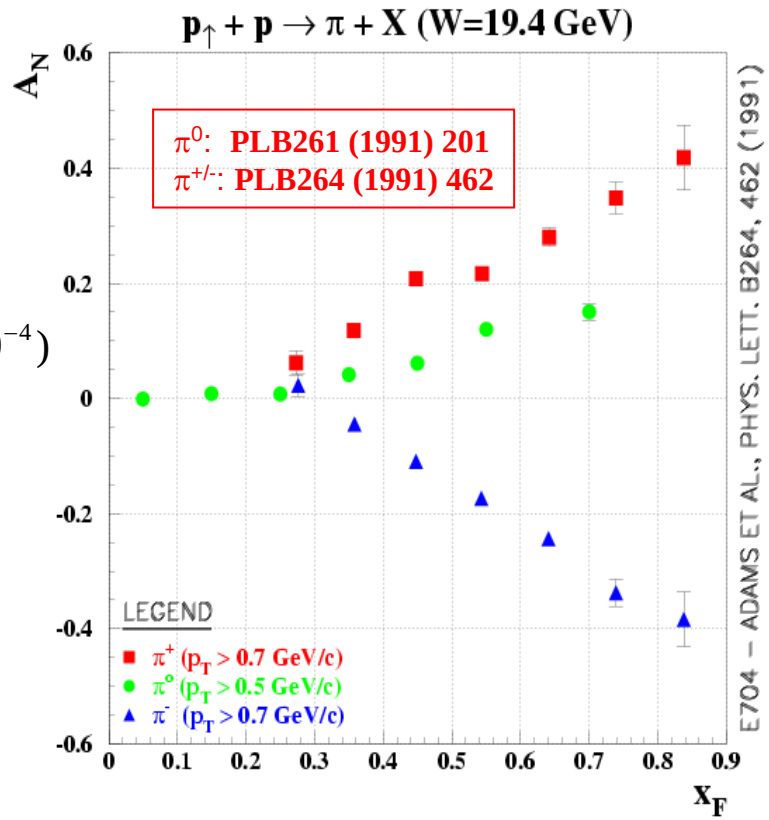
-- Kane, Pumplin, Repko '78

At leading twist and with collinear factorization, pQCD predicts small analyzing powers in transversely polarized p+p collisions

$$A_N \propto \frac{m_q}{\sqrt{s}} \text{ (for example, } m_q = 3MeV, \sqrt{s} = 20GeV, A_N \approx 10^{-4})$$

-- FermiLab E704 experiment

Found strikingly large transverse single-spin effects in p↑+p fixed-target collisions with 200 GeV polarized proton beam



-- Persists at RHIC energies

Theoretical efforts

Four different mechanisms have been proposed to explain these asymmetries

- Sivers effect

-- Transverse momentum dependent quark and gluon distributions give rise to correlation between transverse proton spin and the transverse momentum k_T of quarks and gluons

- Collins effect

-- Transversity distributions + spin dependent fragmentation functions

- Higher-twist effects

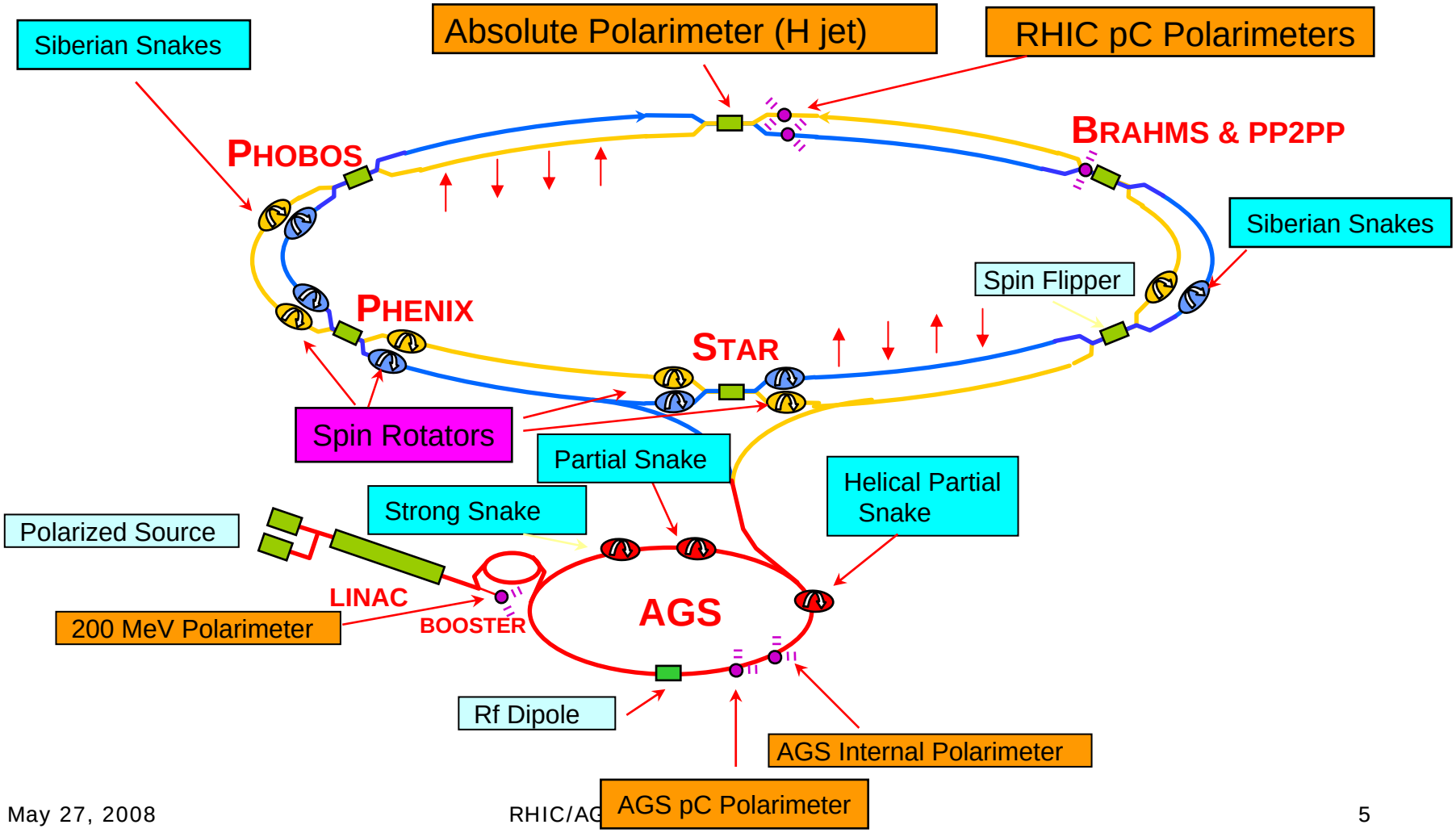
-- Quark gluon field interference

* Sterman and Qiu → Initial State Twist 3
* Koike → Final State Twist 3

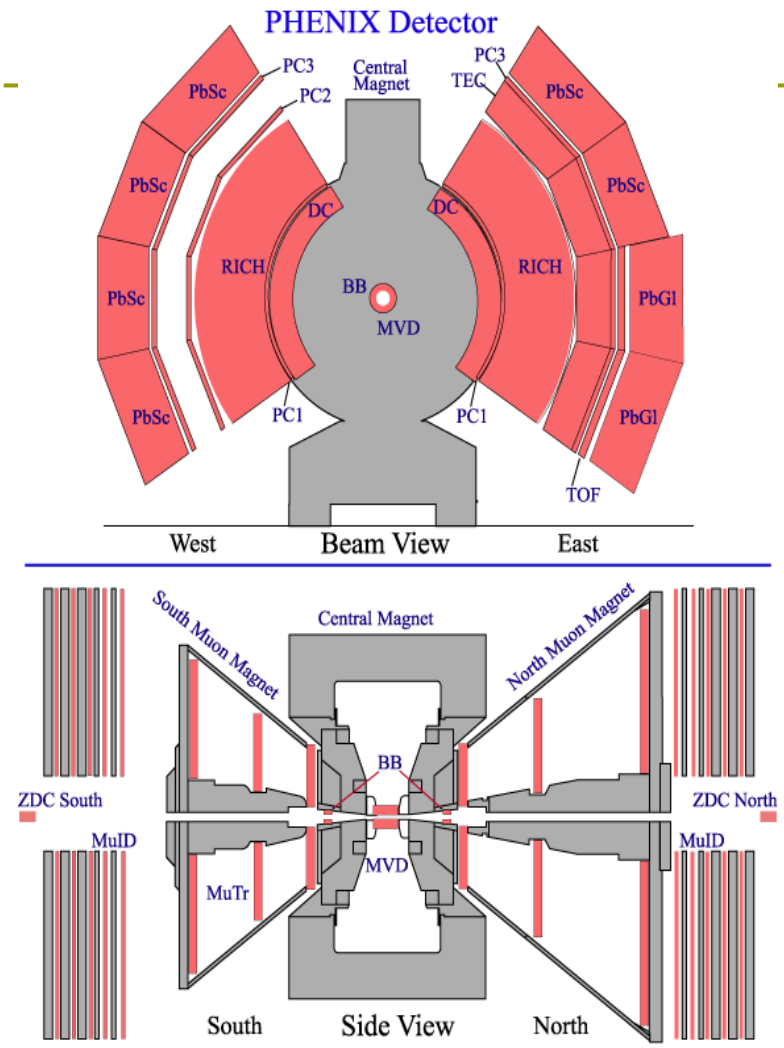
A coherent treatment of the Sivers effect and quark gluon correlations at higher twist has been provided by Ji, Qiu, Vogelsang and Yuan (**PRL97**:082002,2006)

- Or some combination of above

RHIC as a polarized p+p collider



The PHENIX detectors

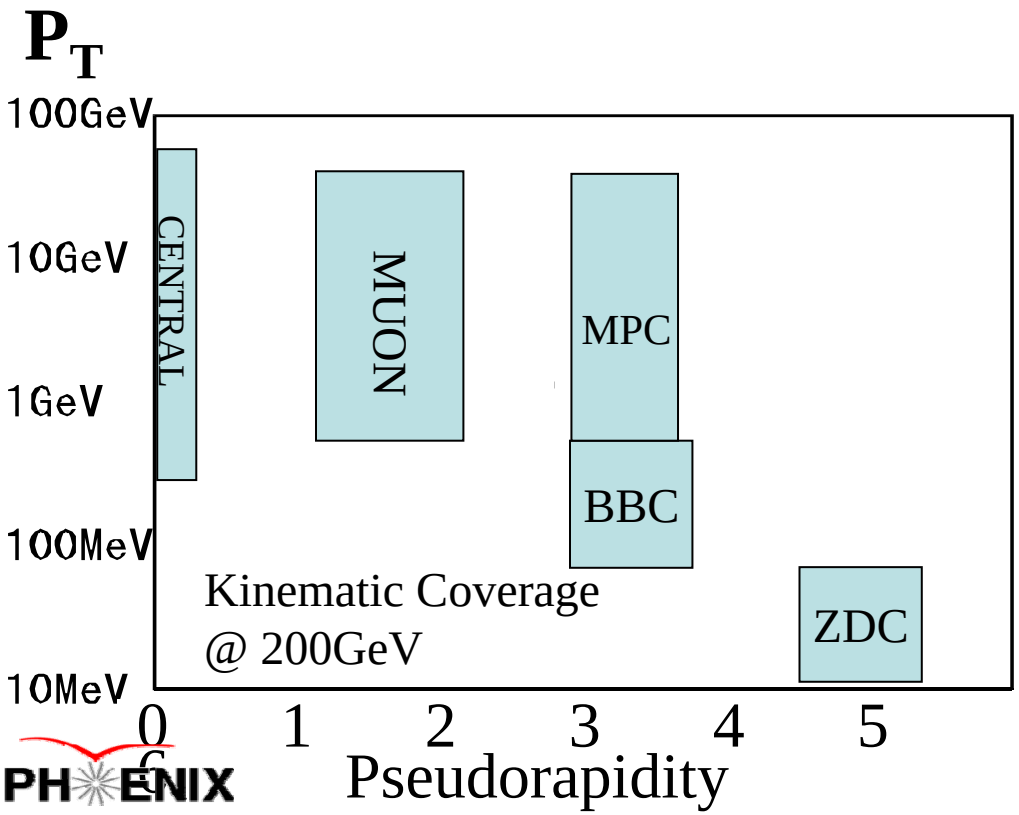


- **Central Arm Tracking** **$|\eta| < 0.35$, $x_F \sim 0$**
  - Drift Chamber (DC)
    - momentum measurement
  - Pad Chambers (PC)
    - pattern recognition, 3d space point
  - Time Expansion Chamber (TEC)
    - additional resolution at high pt
- **Central Arm Calorimetry**
  - PbGl and PbSc
    - Very Fine Granularity
      - Tower $\Delta\phi x \Delta\eta \sim 0.01x0.01$
    - Trigger
- **Central Arm Particle Id**
  - RICH
    - electron/hadron separation
  - TOF
    - π/K/p identification
- **Global Detectors (Luminosity,Trigger)**
  - BBC **$3.0 < |\eta| < 3.9$**
    - Quartz Cherenkov Radiators
  - ZDC/SMD (**Local Polarimeter)**
    - Forward Hadron Calorimeter
- **Forward Calorimetry** **$3.1 < |\eta| < 3.7$**
  - MPC
    - $PbWO_4$ Crystal
- **Forward Muon Arms**

  South arm: $-2.0 < \eta < -1.2$

  North arm: $1.2 < \eta < 2.4$

PHENIX Kinematic Coverage



Transverse spin running at PHENIX

Year	√s [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2001 (Run 2)	200	.15 pb^{-1}	15	3.4 nb^{-1}
2005 (Run 5)	200	.16 pb^{-1}	47	38 nb^{-1}
2006 (Run 6)	200	2.7 pb^{-1}	51	700 nb^{-1}
2006 (Run 6)	62.4	.02 pb^{-1}	48	4.6 nb^{-1}
2008 (Run 8)	200	5.2 pb^{-1}	46	1100 nb^{-1}

Analysis technique

- Square root formula

$$A_N = \frac{1}{P}\frac{\sqrt{N_L^+ N_R^-} - \sqrt{N_L^- N_R^+}}{\sqrt{N_L^+ N_R^-} + \sqrt{N_L^- N_R^+}}$$

- Luminosity formula

$$A_N = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{1}{P}\frac{N^+ - RN^-}{N^+ + RN^-},$$

$$R = \frac{L^+}{L^-}$$

N – Particle yields from up(down) polarized bunches

P – Beam polarization (CNI and jet polarimetry)

R – Relative luminosity (BBC, ZDC)

$$A_N = \frac{A^{incl} - r \cdot A^{BG}}{1 - r}$$

$$\delta A_N = \frac{\sqrt{(\delta A^{incl})^2 + r^2 \cdot (\delta A^{BG})^2}}{1 - r}$$

$$r = \frac{N^{BG}}{N^{incl}}$$

π^0 and charged hadrons at mid-rapidity

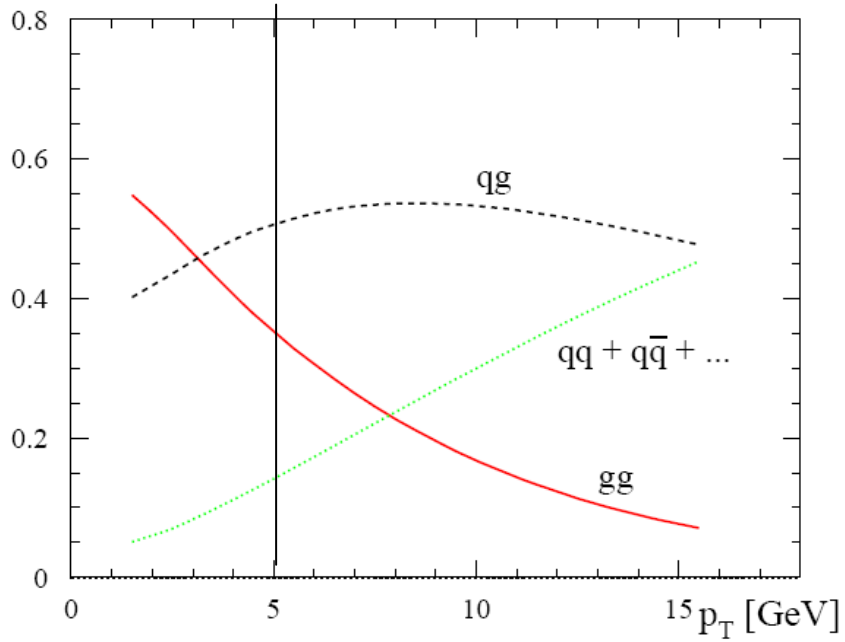
- Why Measure A_N of Different Particle Species at Mid-rapidity in PHENIX?

-- Different kinematic regions

-- Currently dominated by gg and gq scattering, mainly probes the Sivers effect

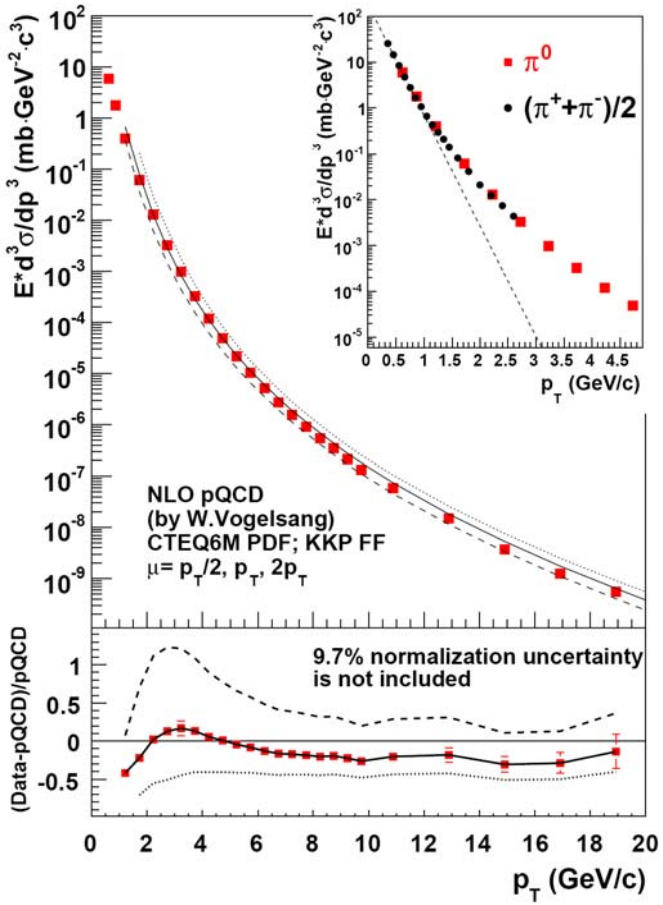
-- Future measurements will be dominated by quark scattering, more sensitive to transversity + Collins

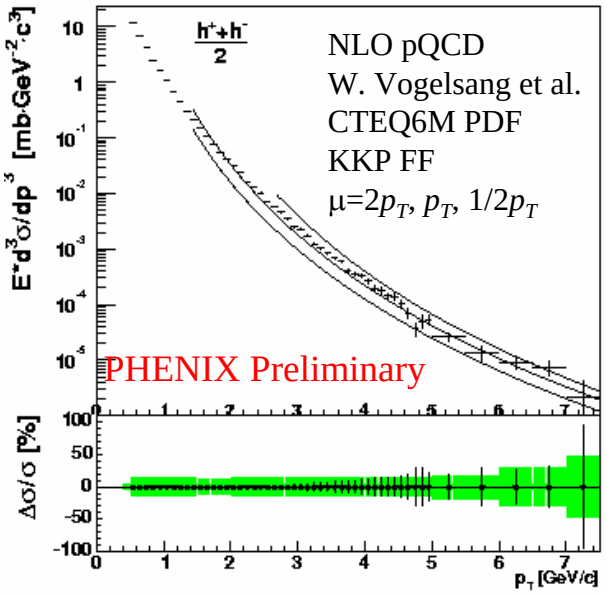
Fraction of pion production



Cross section measurement

PRD 76(2007)051106

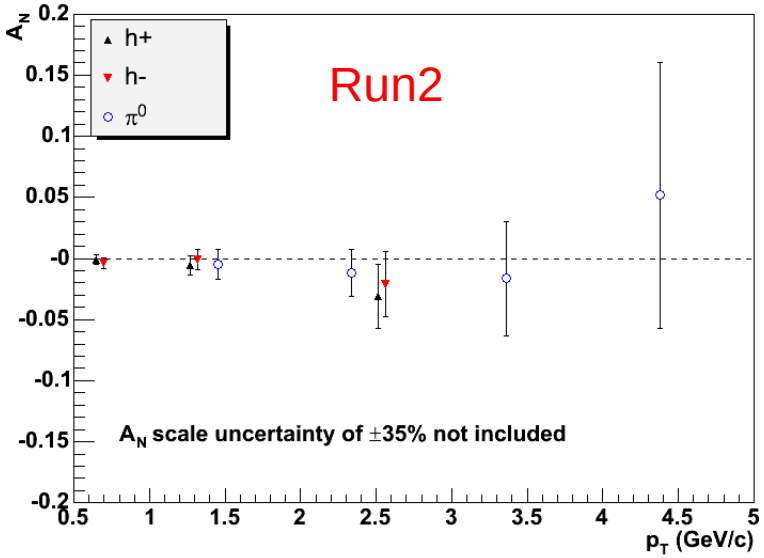




* NLO QCD Calculation Cross-sections consistent with Data
  - --- CTEQ6M pdf
  - --- KKP and Kretzer Fragmentation Fcns
* Necessary Confirmation that pQCD can be used successfully at RHIC to extract spin dependent pdf's

π^0 and charged hadrons A_N at mid-rapidity

PRL 95(2005)202001



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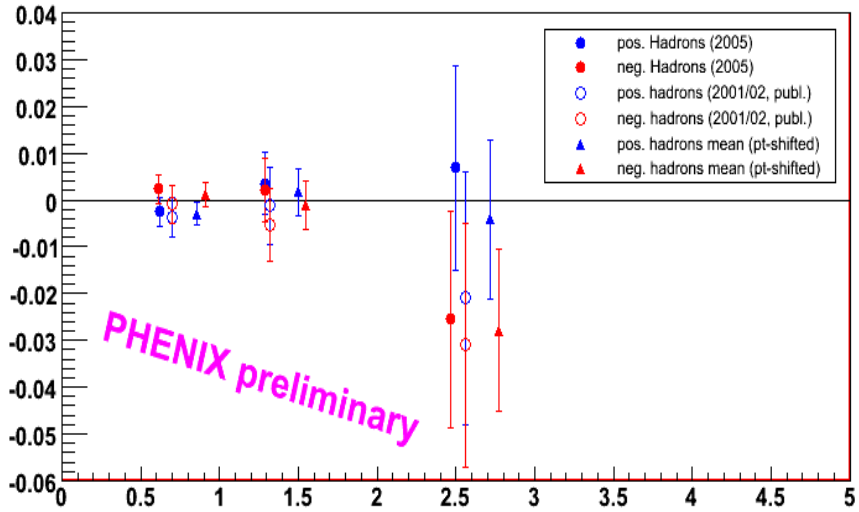
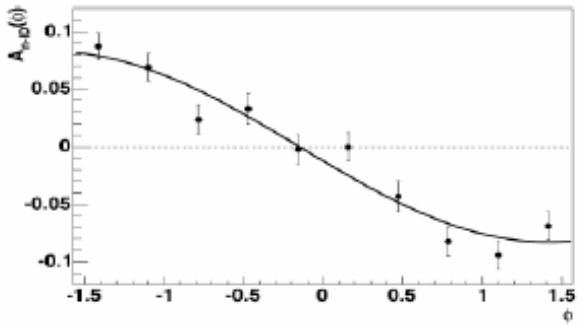


--A_N for π^0 and charged hadrons at mid-rapidity consist with zero within 1% → contrast with forward pions
--Constrains Sivers distribution function for gluons (Anselmino et al., PRD74(2006)094011)
--Updated π^0 analysis with ~200x improvement(!) in statistical figure-of-merit underway . . .

Forward neutron asymmetries

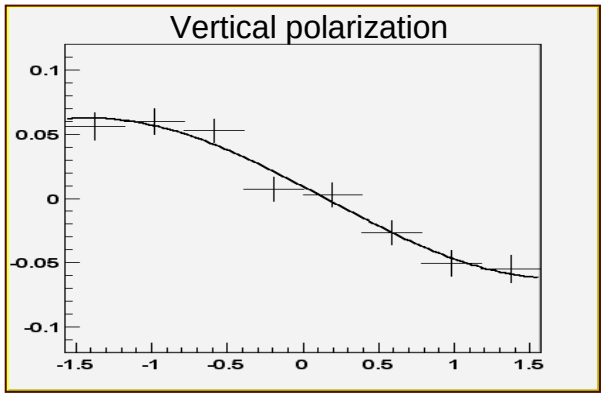
- A_N measurement at IP12 (Y.Fukao et.al., PLB650(2007)325)
  - large A_N was discovered for forward neutrons

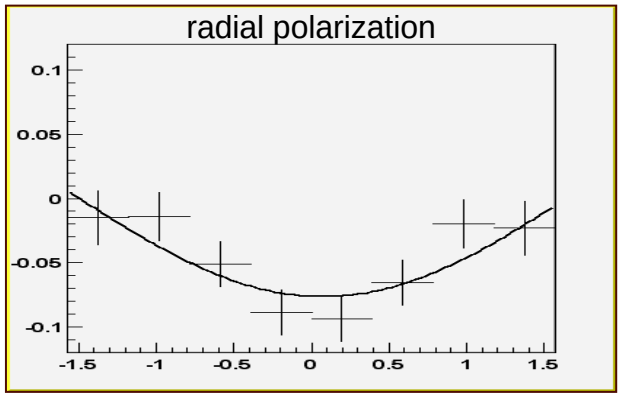


Asymmetries measured by the EMCal. The errors are statistical and systematic, respectively. There is an additional scale uncertainty, due to the beam polarization uncertainty, of $(1.0^{+0.47}_{-0.24})$

	Forward	Backward
Neutron	$-0.090 \pm 0.006 \pm 0.009$	$0.003 \pm 0.004 \pm 0.003$
Photon	$-0.009 \pm 0.015 \pm 0.007$	$-0.019 \pm 0.010 \pm 0.003$
π^0	$-0.022 \pm 0.030 \pm 0.002$	$0.007 \pm 0.021 \pm 0.001$

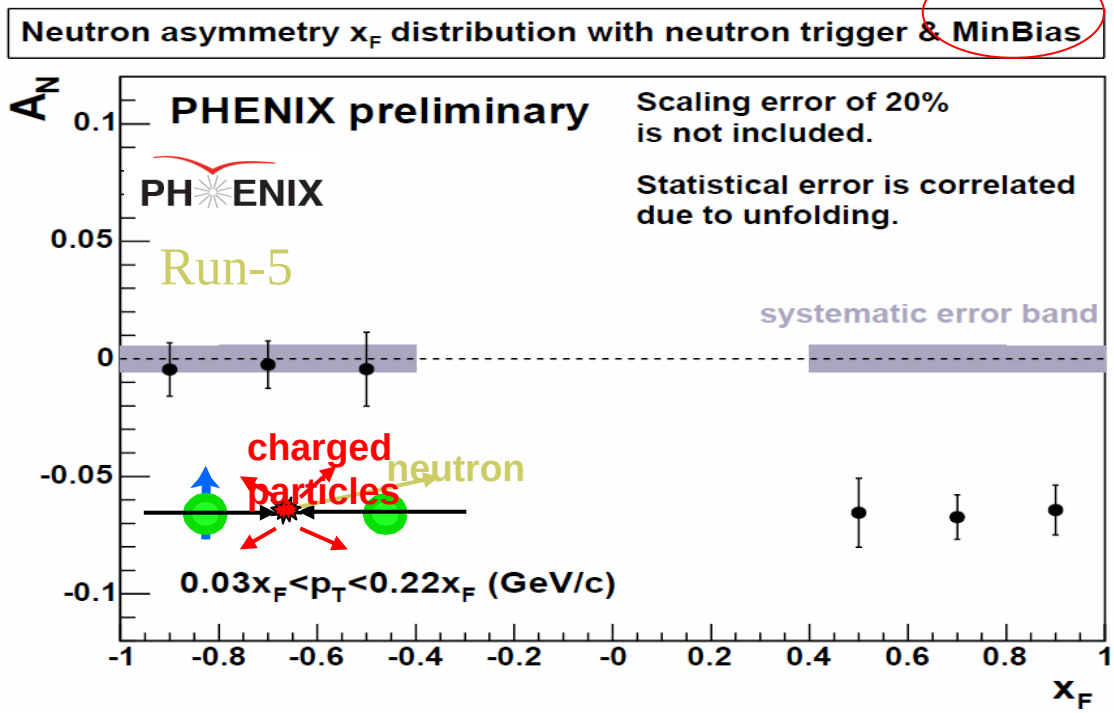
➔ Local polarimeter at PHENIX
  - ZDC + position sensitive counters to measure the neutron A_N





Forward neutrons at 200GeV

detecting charged particles in BBC (3.0<| η |<3.9)



$\langle p_T \rangle$ (Estimated by simulation assuming ISR p_T distribution)

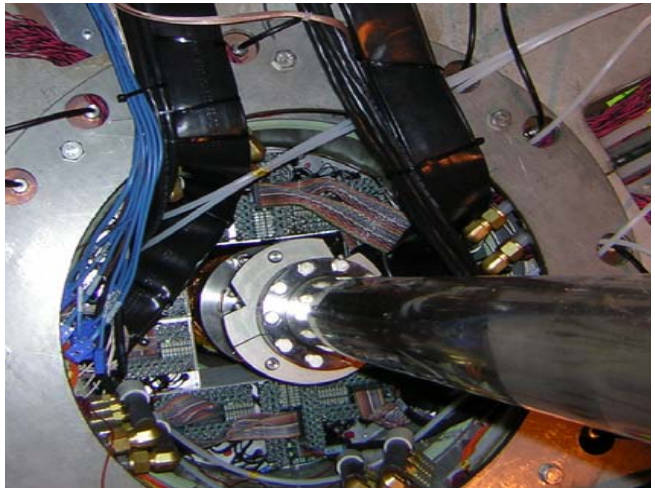
$0.4<|x_F|<0.6$ 0.088 GeV/c
$0.6<|x_F|<0.8$ 0.118 GeV/c
$0.8<|x_F|<1.0$ 0.144 GeV/c

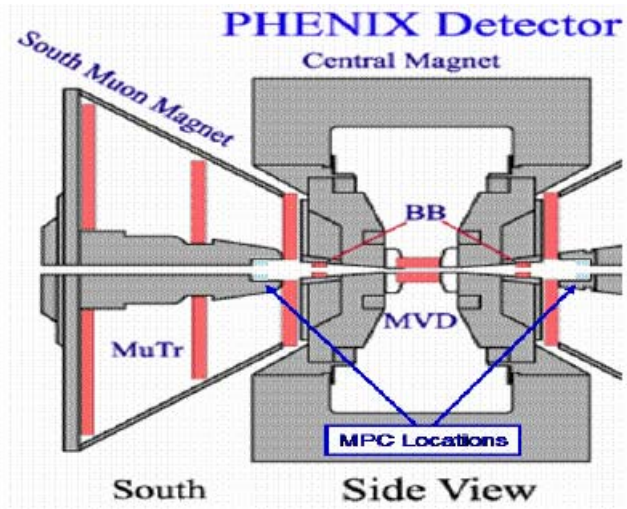
preliminary	A_N
Without MinBias	-6.6 ±0.6 %
With MinBias	-8.3 ±0.4 %

-- A_N consistent with zero for $x_F<0$, large asymmetry for $x_F>0$
-- A_N enhanced by requiring coincidence with forward charged particles ("MinBias" trigger)
-- No x_F dependence observed
-- Significant forward neutron asymmetries observed down to 62.4 and up to 410 GeV!

Forward π^0 with MPC at 62GeV

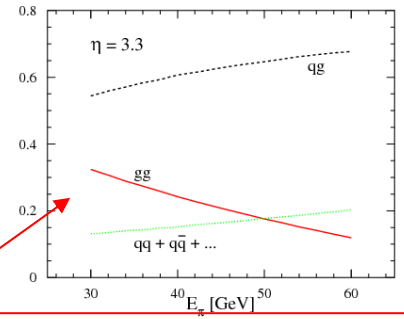
- New calorimeter (Muon Piston Calorimeter) added in Run6
- 192 2.2x2.2x18 cm^3 $PbWO_4$ crystals, 220 cm from vertex (behind Beam-Beam counter)
- $3.1 < |\eta| < 3.65$ (Region of large observed asymmetries)
- Only south arm in Run6
- Expect 200GeV longitudinal and 62.4GeV longitudinal & transverse results (very little useful 200GeV transverse data due to late electronics)



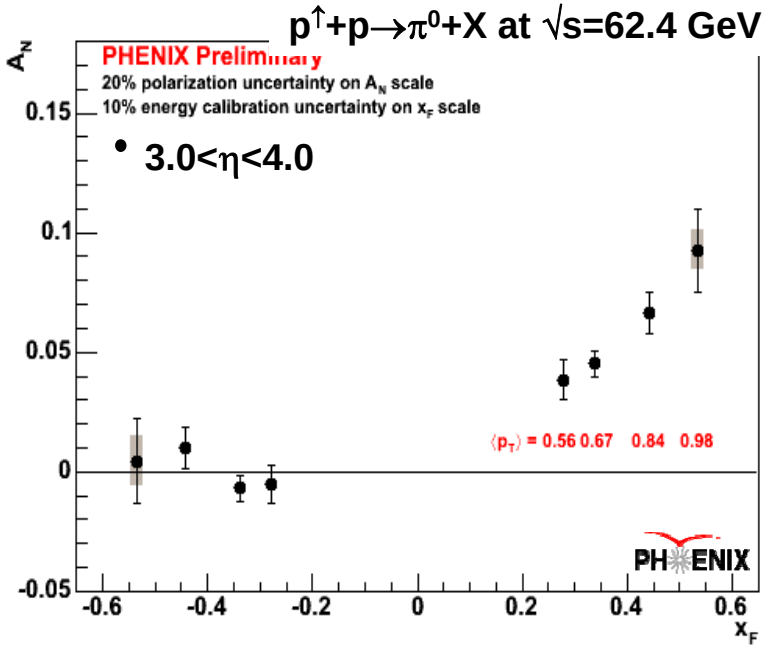


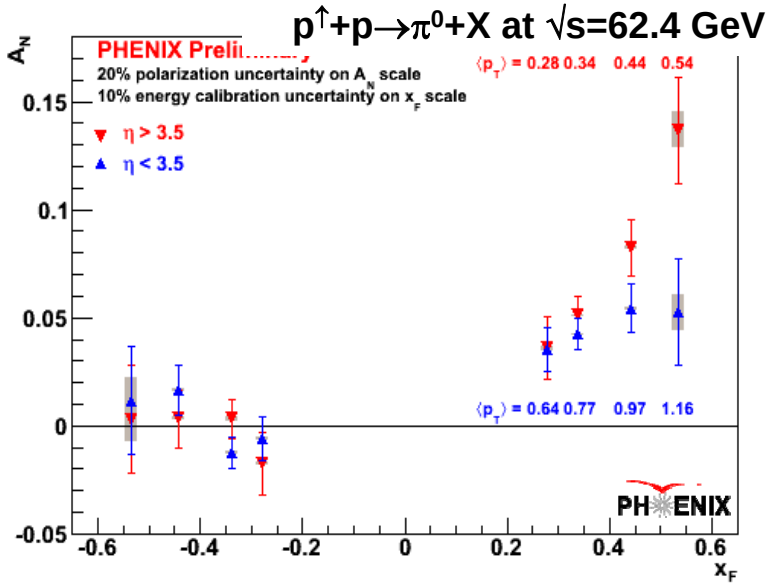
PLB **603**,173 (2004)

π^0 A_N at large x_F



process contribution to π^0, η=3.3, $\sqrt{s}$=200 GeV





-- Asymmetry seen in yellow beam (positive x_F), but not in blue (negative x_F)

-- Sizable asymmetries in forward direction

-- Indication of larger forward asymmetries at higher rapidity →Need more data to understand pT dependence

-- x_F, p_T, $\sqrt{s}$, and η dependence provide quantitative tests for theories

Heavy flavor A_N at forward rapidity with muon spectrometers

Why heavy flavor?

- Eliminate Collins' effects
  * heavy flavor production dominated by gluon gluon fusion at RHIC energy

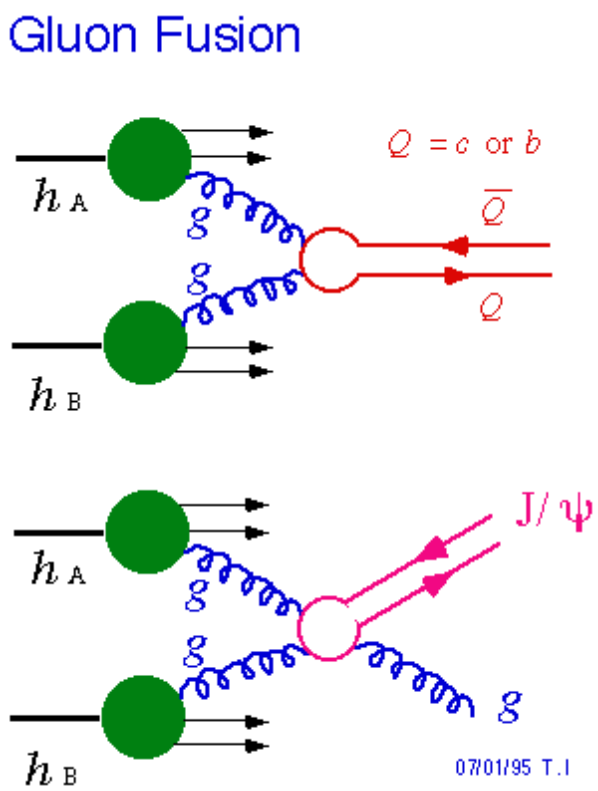
    Pythia 6.1 simulation

$$c\bar{c}: \; gg \rightarrow c\bar{c} \quad 95\%$$
$$b\bar{b}: \; gg \rightarrow b\bar{b} \quad 85\%$$

  * gluon has zero transversity

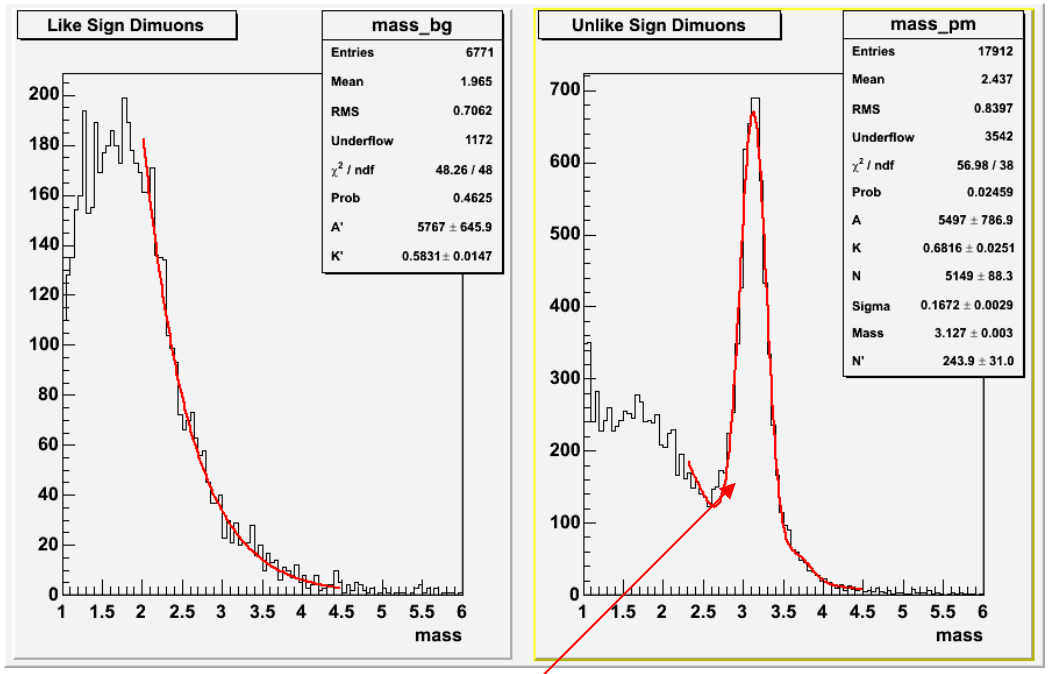
- A perfect channel for gluon Sivers function

- Important to understand the origin of observed large A_N at large x_F



J/Ψ

Like/Unlike charge signed dimuon mass spectra



Run6 Lvl2 data

$$\frac{dN}{dM} = A \cdot e^{-K \cdot M} + N \cdot \frac{1}{2\pi\sqrt{\sigma}} e^{-\frac{(M - M_{J/\psi})^2}{2\sigma^2}} + N' \cdot \frac{1}{2\pi\sqrt{\sigma}} e^{-\frac{(M - M_{\psi'})^2}{2\sigma^2}}$$

How does J/Ψ production affect asymmetry prediction?

Very sensitive to the production mechanism

(Feng Yuan, hep-ph:0801.4357)

- NRQCD (non-relativistic QCD) can describe some experimental observations

  -- the heavy quark pairs are produced at short distance in a color-singlet or color-octet configurations

- Two processes:

  -- ep scattering: (only final state interaction)

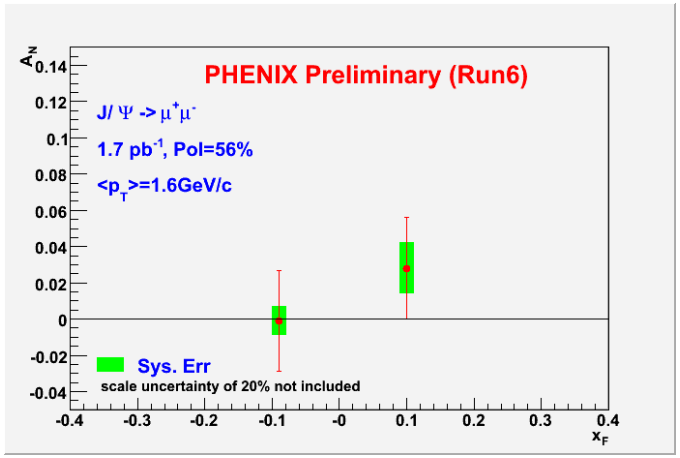
  SSA vanishes if the pair are produced in a color-singlet model but survives in the color-octet model

  -- pp scattering: (both initial and final state interactions)

  SSA vanishes if the pair are produced in a color-octet model but survives in the color-singlet model

Shall shed light on the production mechanism for the heavy quarkonium production

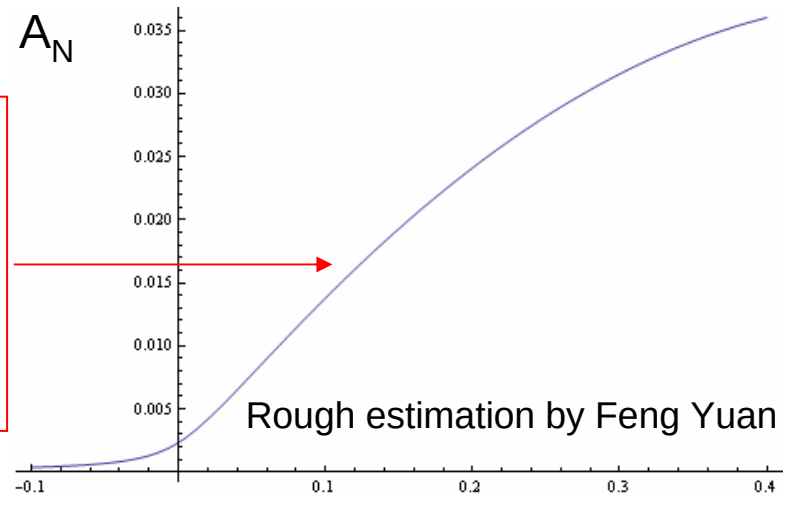
Rough estimate at RHIC



- At RHIC, color-octet dominate the production cross section
- 30%-40% J/Ψ comes from Ψ' and χ_c feeddown

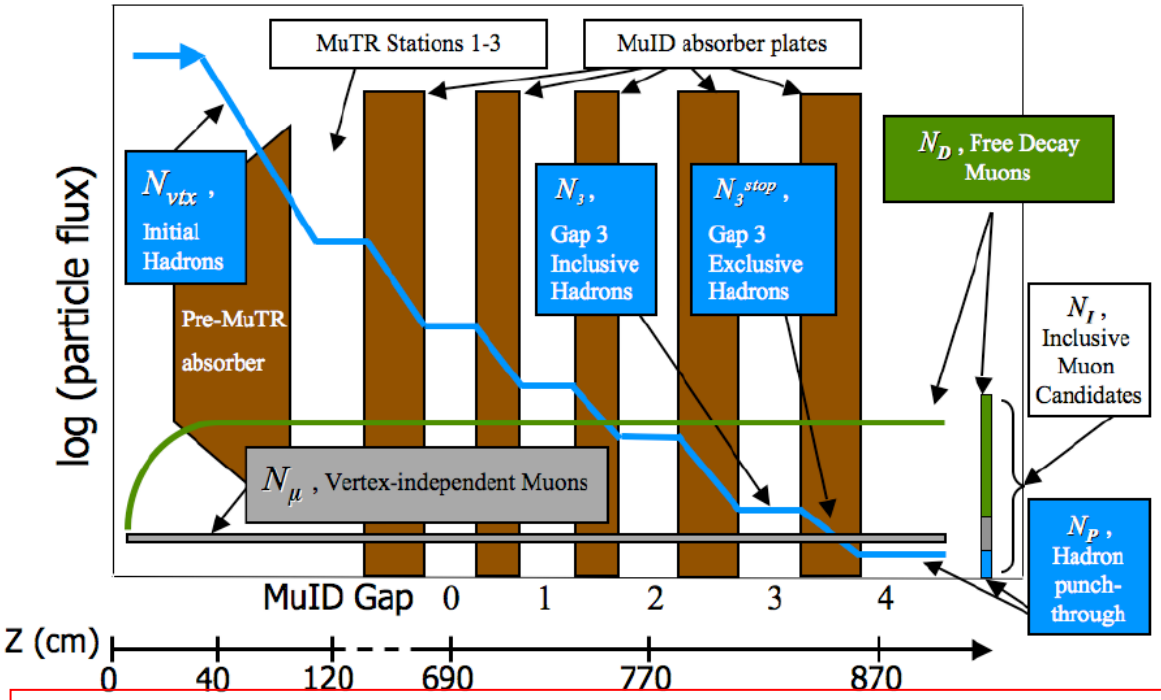
Assume:
--Gluon Sivers function ~ 0.5 x(1-x) times unpolarized gluon distribution (expect large-x and small-x suppression of the Sivers function as compared to the unpolarized one)

-- 30% J/Ψ comes from χ_c feeddown



Prompt muons from open heavy flavor decay

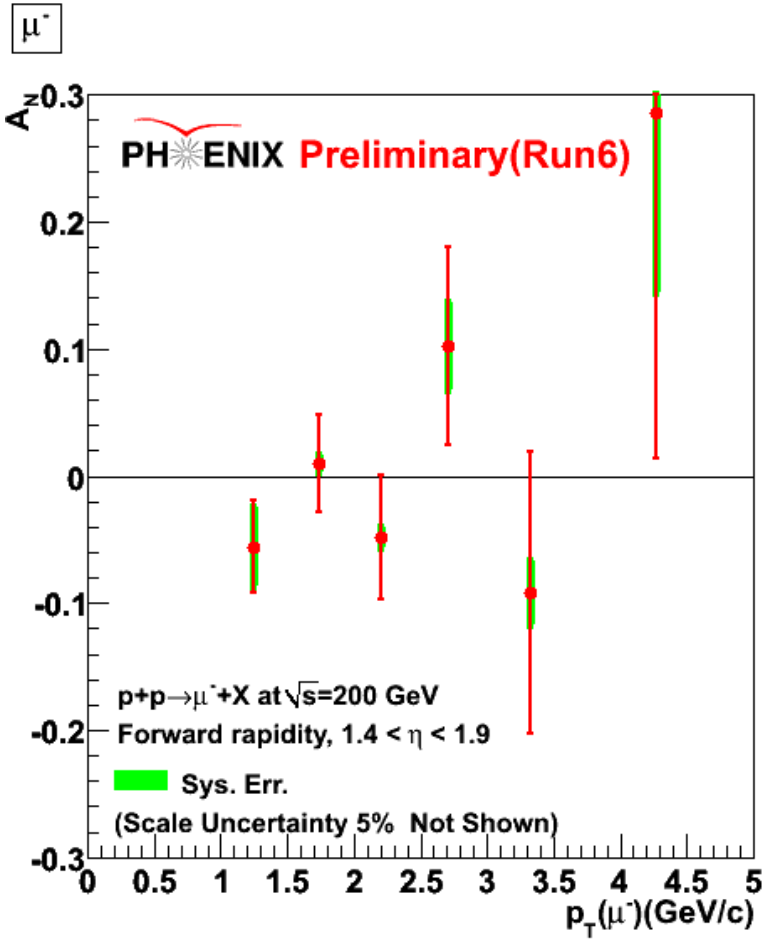
Cartoon depiction of the relative flux of particles in the PHENIX muon arm

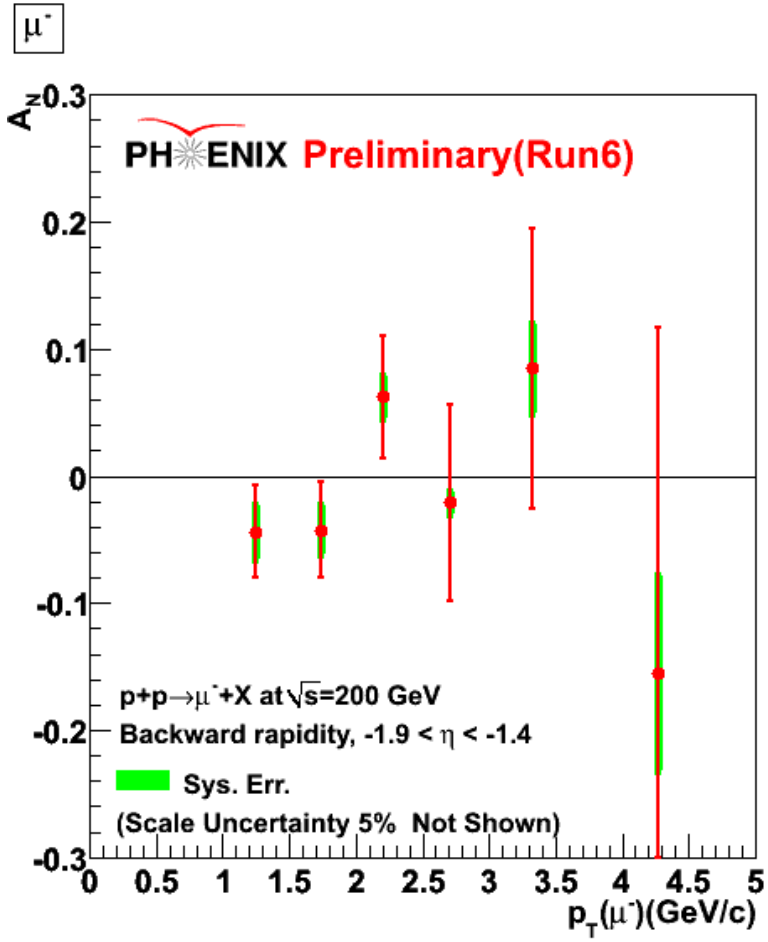


-- p_T<3GeV, decay muons dominant and exhibit a well known linear z-vertex dependence

-- p_T>3GeV, punch through hadrons dominate and can not be directly distinguished from prompt muons

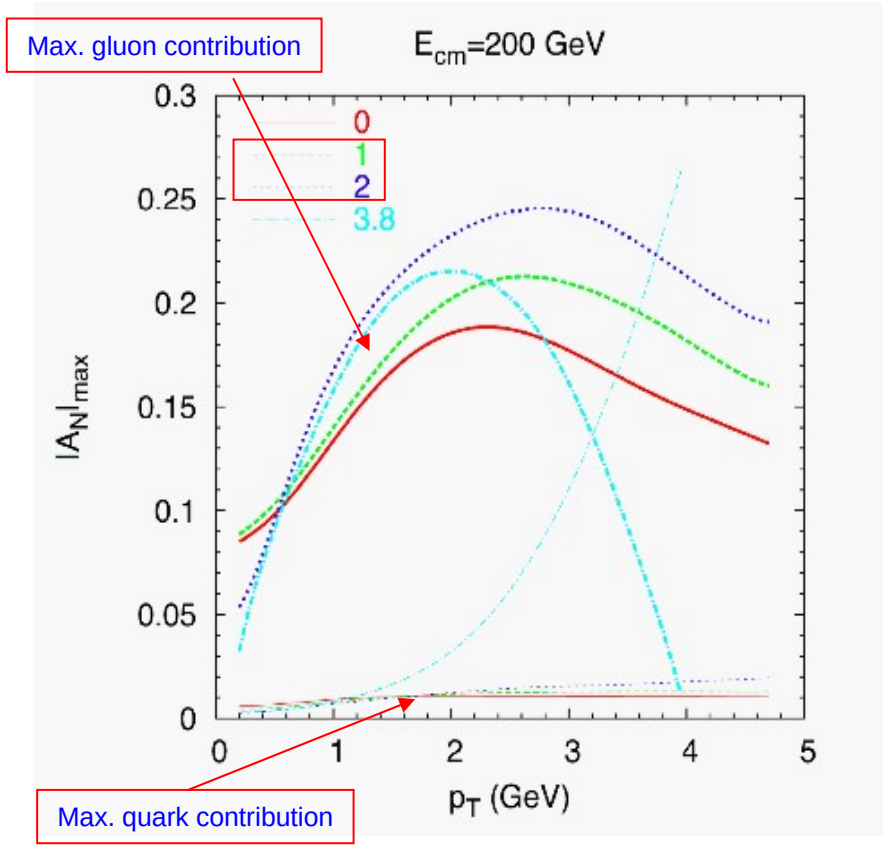
A_N vs. p_T in forward and backward rapidities

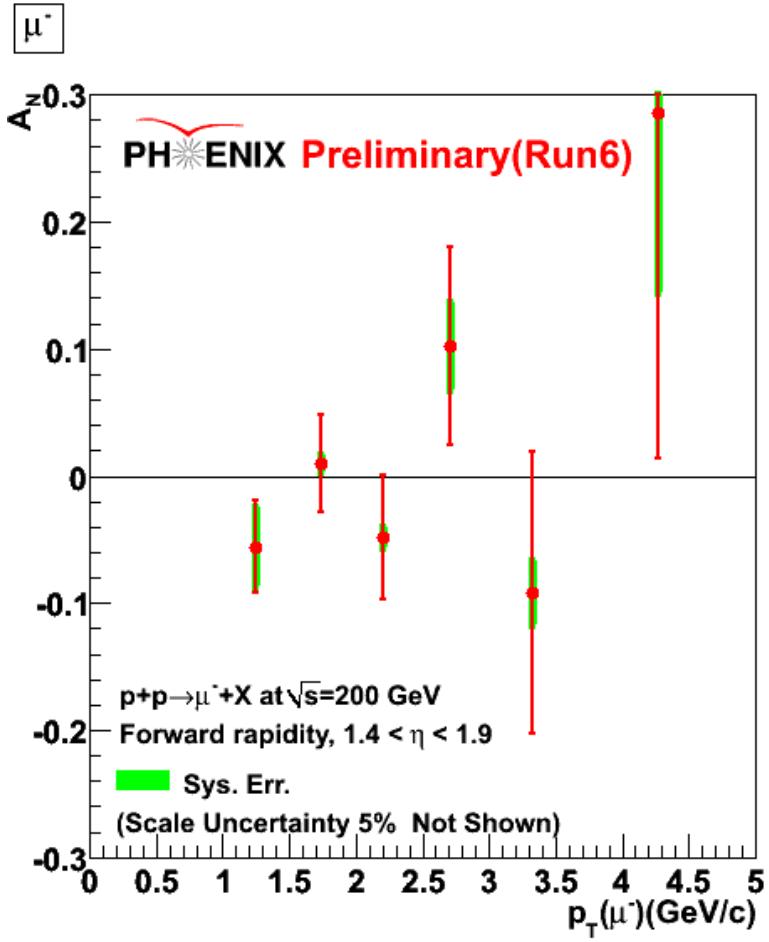




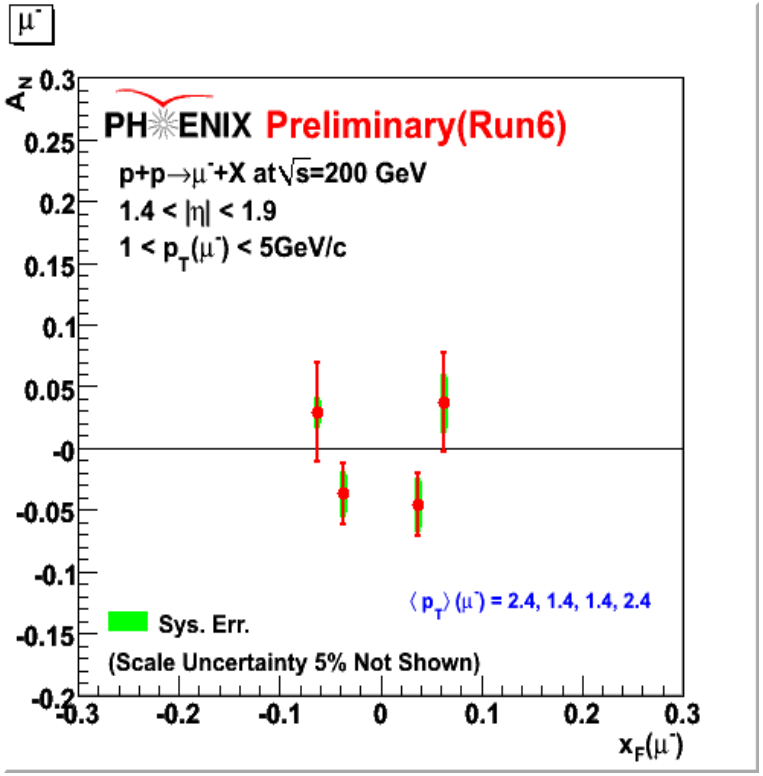
Anselmino's prediction on open charm A_N

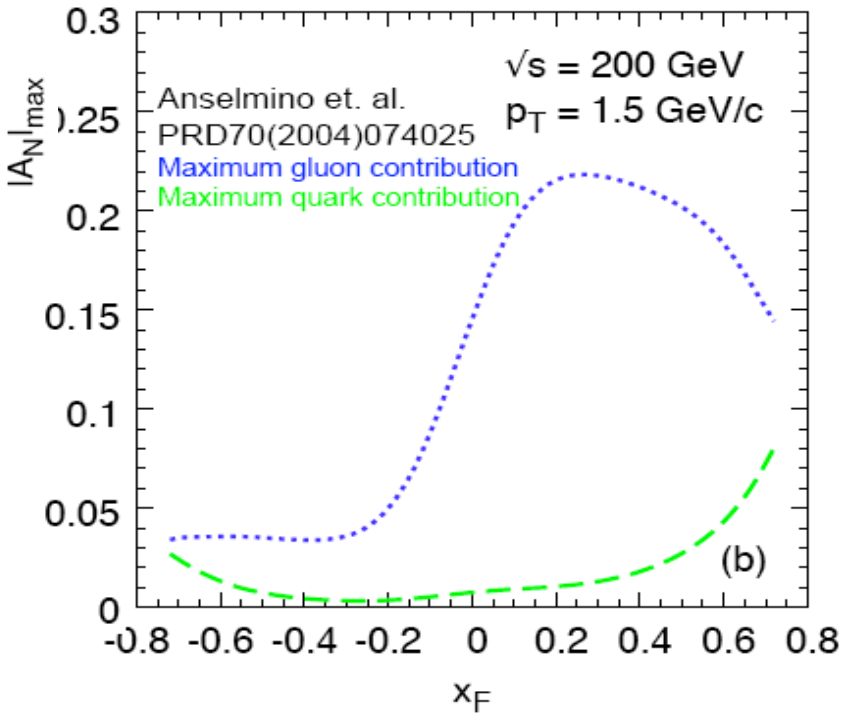
Inclusive D meson production at RHIC energy





A_N vs. x_F

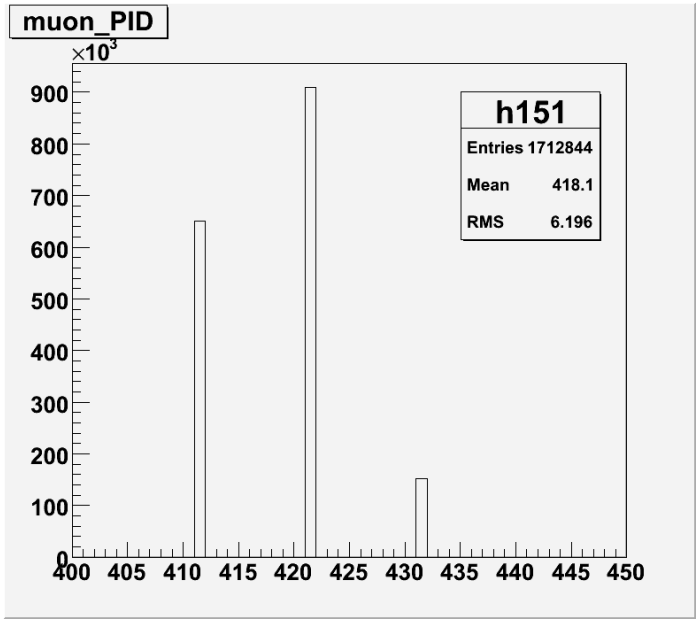


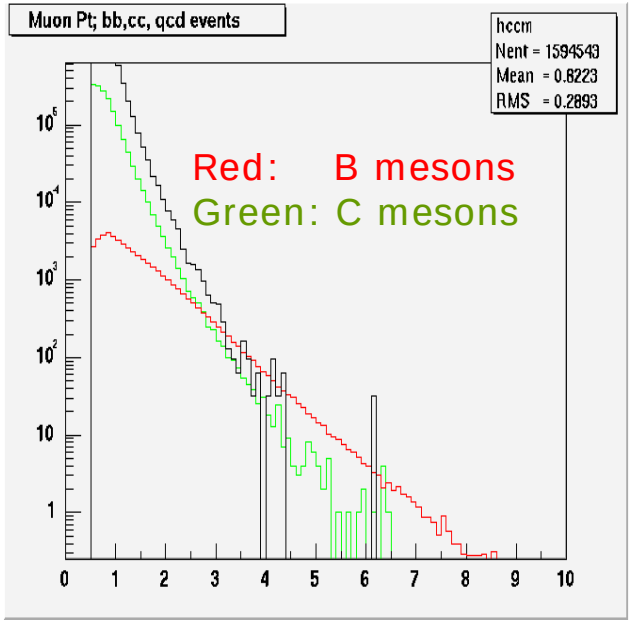


-- Qualitative conclusion: Data constrain the gluon Sivers function to be significantly smaller than the maximal allowed
-- Translation between D meson and muon kinematics and estimate of charm vs. bottom components underway (next slide)

Translation between muon and D and B meson kinematics

- D^0, $D^{+/-}$ hadron relative fraction
- D/B fractions





More quantitative comparison will come in the future

Theoretical effort on open charm single spin asymmetries

G.D. Zacarias et. al., EPJC 51(2007)619

- Two component model (has been used to describe the production asymmetry of charm productions successfully)

$$\frac{d\sigma^{D}}{dx_F dp_T} = \frac{d\sigma^{D}_{rec}}{dx_F dp_T} + \frac{d\sigma^{D}_{frag}}{dx_F dp_T}$$

-- Recombination process: a quark from the sea joins a valence quark in the initial state

$$\overline{D}^{0} : u\overline{c} \qquad D^{-} : d\overline{c}$$

-- Fragmentation process: assume particles created by the fragmentation process lose information about the spin polarization of the proton in the initial state

$$\frac{d\sigma^{\uparrow}_{frag}}{dx_F dp_T} = \frac{d\sigma^{\downarrow}_{frag}}{dx_F dp_T}$$

Fit the π^0 A_N at different collision energy

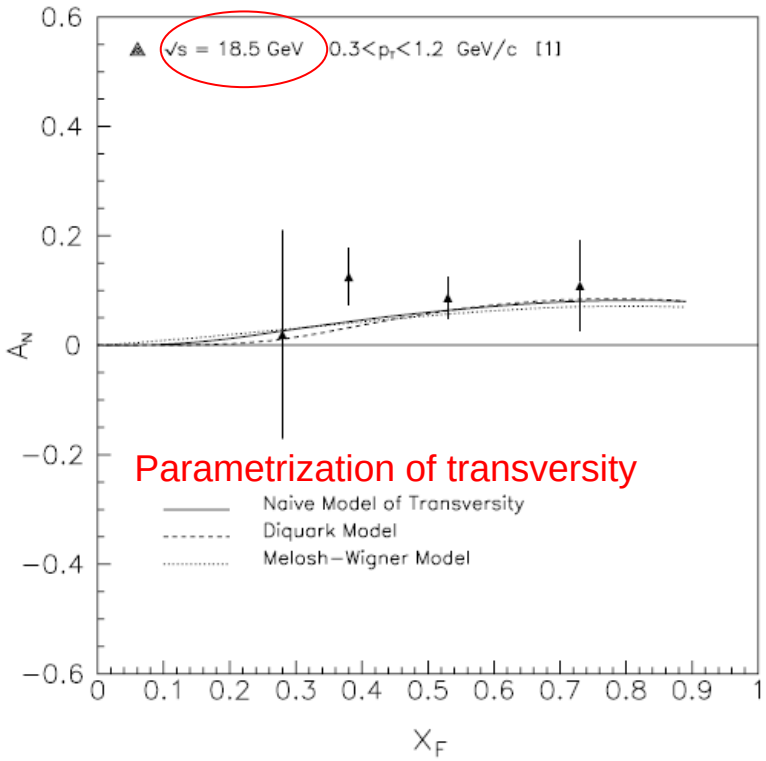


Fig. 3. Single spin asymmetry for π^0 [2–4] in the framework of the two component model with three different transversity parametrizations [15–18, 31–40]. The center of mass energy of the reaction is $\sqrt{s} = 18.5$ GeV

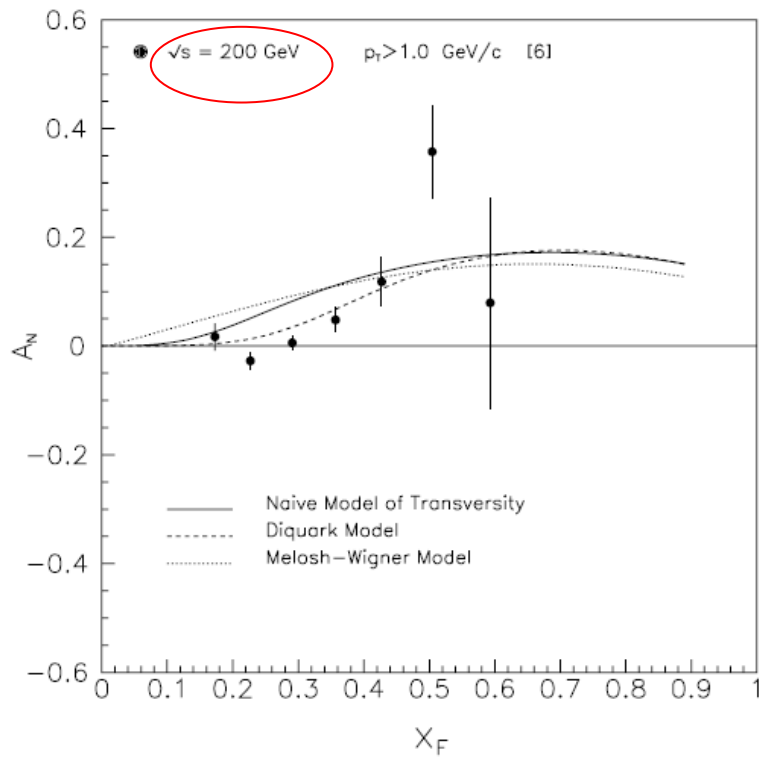


Fig. 4. Single spin asymmetry for π^0 [20] in the framework of the two component model with three different transversity parametrizations [15–18, 31–40]. The center of mass energy of the reaction is $\sqrt{s} = 200$ GeV

Anselmino's prediction

Prediction of two component model

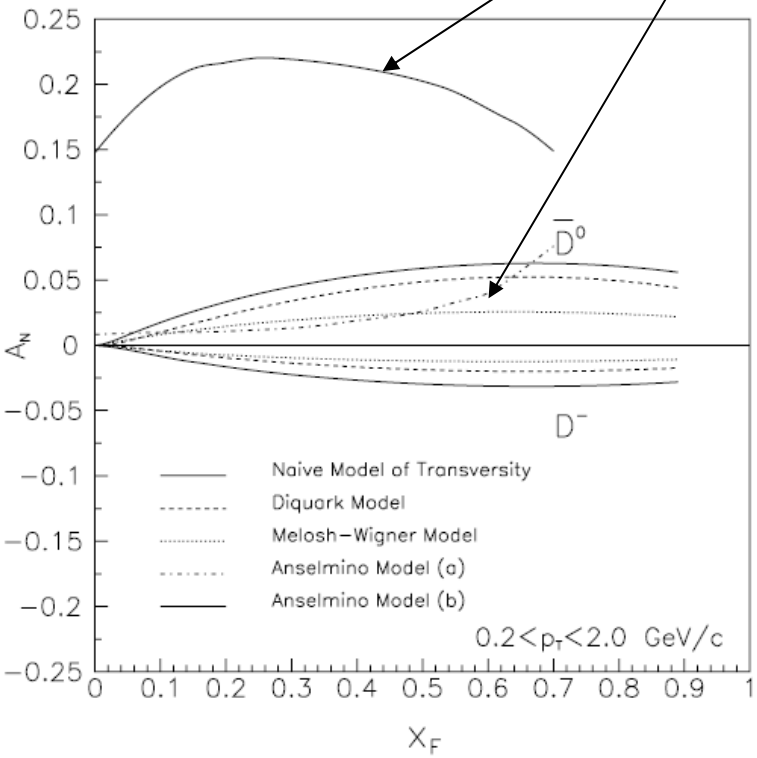


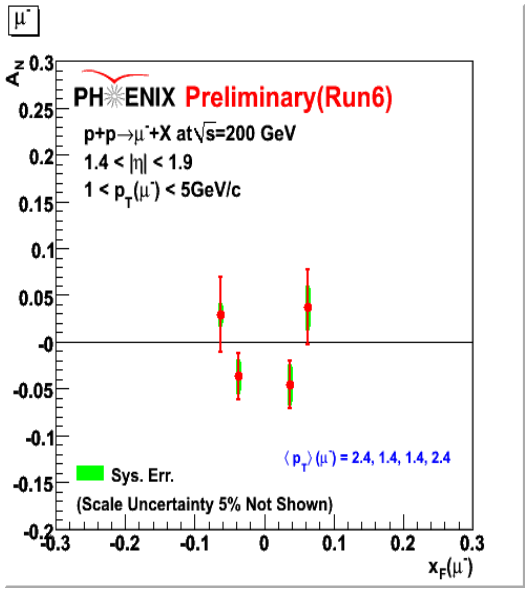
Fig. 6. Comparison of the single spin asymmetries obtained with the model presented here (*solid*, *dash* and *dotted curves*) with those obtained by Anselmino et al. [19] (*solid* in the upper part and *dot dashed curve*)

Prediction:

$\bar{D}^0(u\bar{c}), D^-(d\bar{c})$ → Sizable A_N

$D^0(\bar{u}c), D^+(\bar{d}c)$ → $A_N = 0$

Signal: μ^-



Summary

- PHENIX has measured the transverse asymmetry of π^0, $h^{\pm}$, J/Ψ, prompt muon and neutron at two different collision energies (200GeV and 62GeV)

  -- Cross sections agree with pQCD calculations, large SSA only observed at large x_F

  -- In central rapidity, $A_N \sim 0$ within statistics

  -- π^0 A_N at large rapidity consistent with low energy results

  -- Large negative asymmetry in neutron production at forward rapidity and backward asymmetry consistent with zero

  -- First measurement in J/Ψ production at $x_F \approx \pm 0.1$

  -- First measurement in open heavy flavor production at forward rapidity
  gluon-fusion dominates, possibly sensitive to gluon's sivers effects

Outlook

Much new data coming from transversely polarized proton interactions (Run6 and Run8)

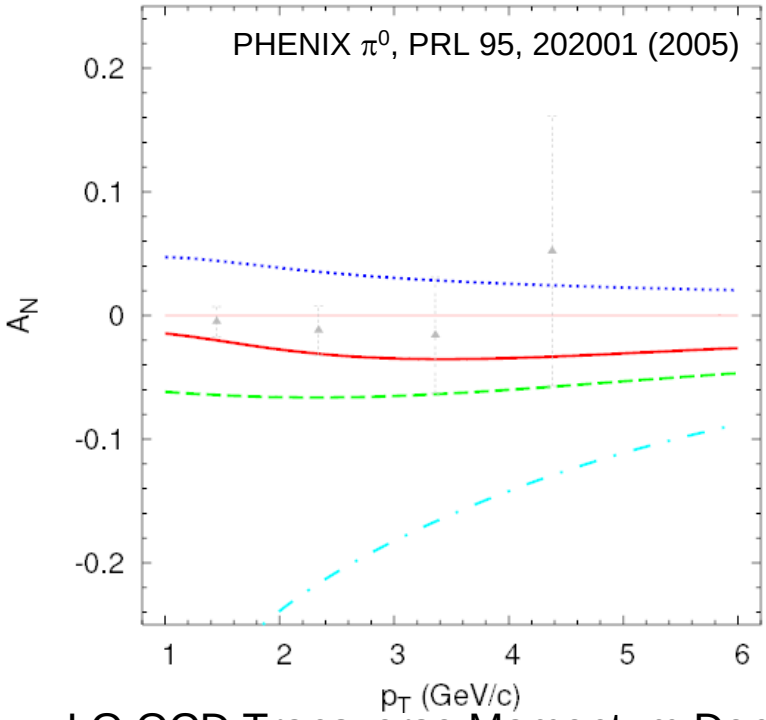
- Updated π^0 analysis with ~200x improvement(!) in statistical figure-of-merit underway
- Two-hadron back-to-back correlations
  (Boer and Vogelsang, Phys.Rev.D69:094025,2004)
  Idea: Non-zero Sivers function implies spin-dependence in k_T distributions of partons within proton and would lead to an asymmetry in $\Delta\phi$ of back-to-back jets
- Di-hadron ($\pi^0 h^+$,$\pi^0 h^-$ and h^+h^-) Interference fragmentation function study
- J/Ψ --> di-electron channel at $x_F=0$
- New upgrade detectors should significantly enhance physics reach
  -- Nose Cone Calorimeter
  χ_c-->J/Ψ

  -- Silicon Detectors (SVTX and FVTX)
  Heavy flavor measurement (Ψ', open heavy flavor)
  Drell-Yan (See Gerry's talk)

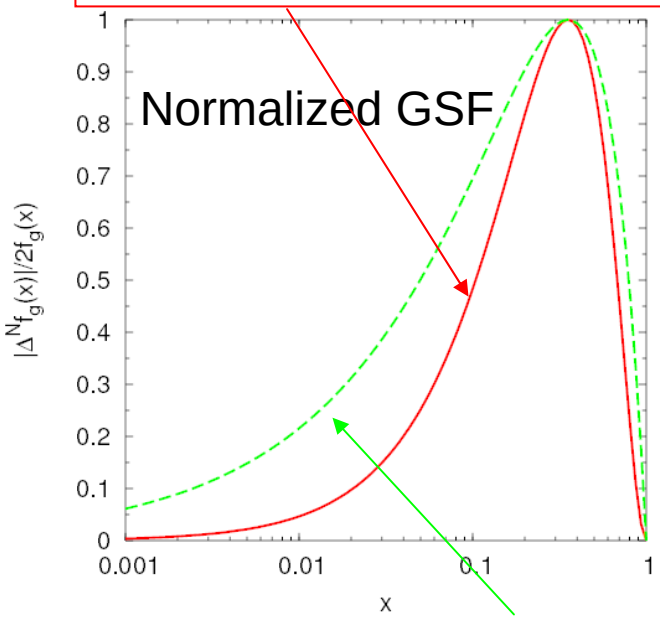
Backup Slides

Anselmino et al, **PRD74**:094011,2006

Constraints on Gluon Sivers?



vanishing sea quark contribution

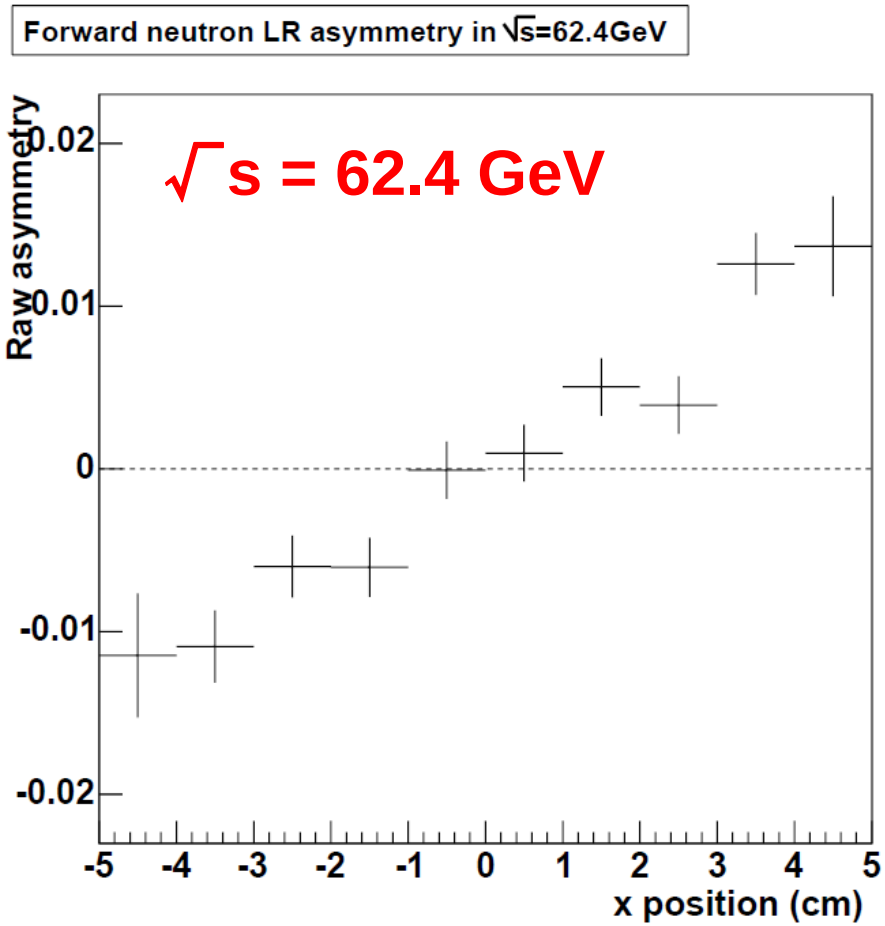


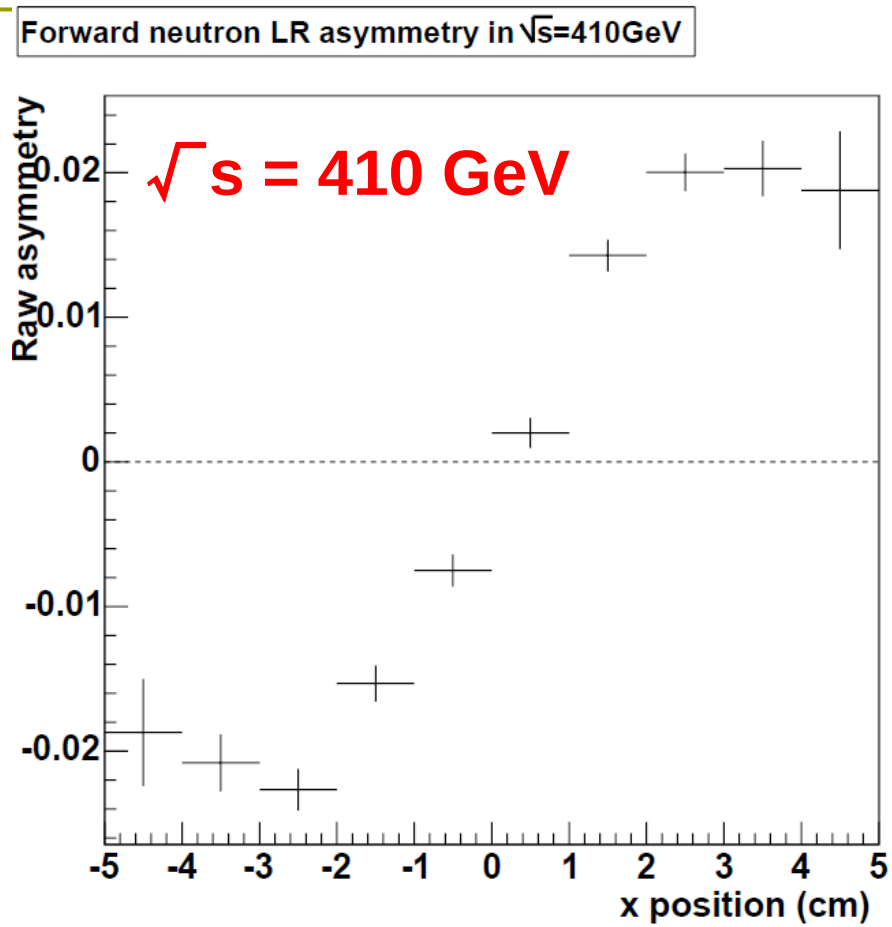
Valence + sea quark contributions at positivity bound

LO QCD Transverse Momentum Dependent parton scattering calculations

- Thin Red: valence u and d Sivers alone
- Cyan: Gluon Sivers Function at positivity bound, no sea quark Sivers
- Thick Red: Gluon Sivers parameterized to be 1 sigma from PHENIX π^0 A_N, no sea quark Sivers
- Blue: valence + sea quark Sivers at positivity bound
- Green: Gluon Sivers function and valence + sea quark at positivity bound → the largest gluons Sivers function compatible with our data

Finite asymmetry persists at 62 and 410GeV





Why such large asymmetries?

- A_N is produced via interference of spin non-flip and spin-flip amplitudes
- In Regge theory

  -- A spin non-flip amplitude contribution can be described due to Reggeon and Pomeron exchange

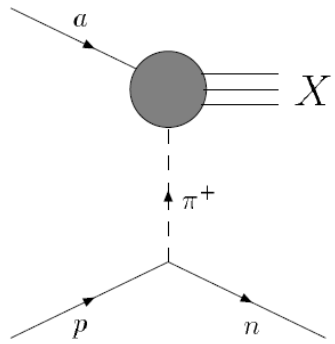
  -- We need spin-flip amplitude –> one pion exchange amplitude

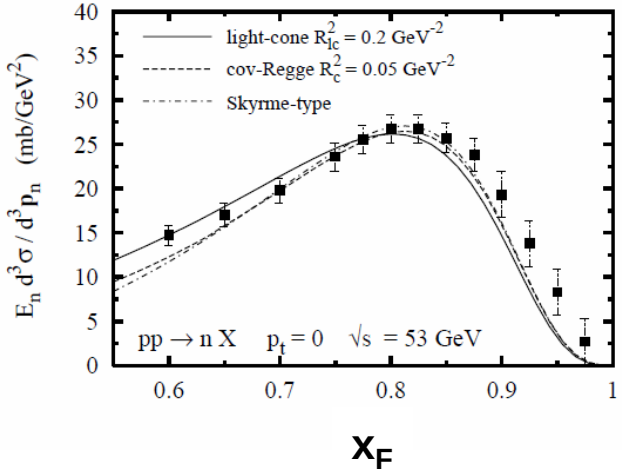
- One pion exchange model (OPE) may explain the result

  -- OPE has been used to describe exclusive diffractive neutron production

  -- The cross-section at ISR is well described by spin-flip OPE

Eur.Phys.J.A7:109-119,2000





Parameterization of the transversity (two component model)

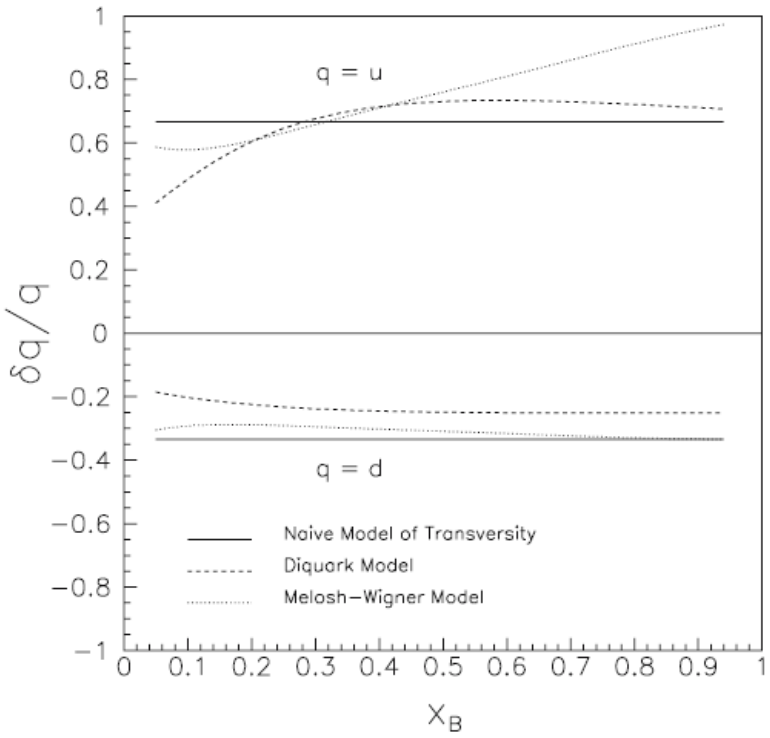


Fig. 1. Transversities of the proton according to the three models in [15–18, 31–40], discussed in the text

$$\frac{\delta q}{q} = \frac{q^{\uparrow} - q^{\downarrow}}{q^{\uparrow} + q^{\downarrow}}$$

→Difference in the number of quarks with transverse polarization parallel and anti-parallel to the proton transverse polarization