Measurement of Transverse SSA for J/ψ Production in Polarized p+p Collisions at PHENIX

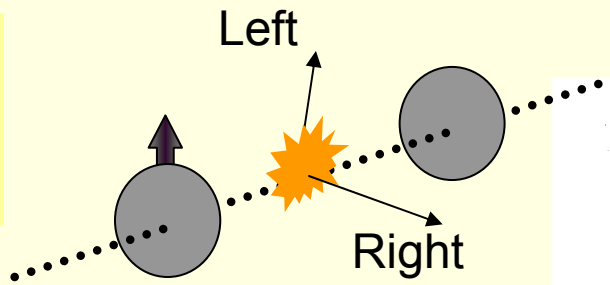
Xiaorong Wang
New Mexico State University

(arXiv: 0000000)

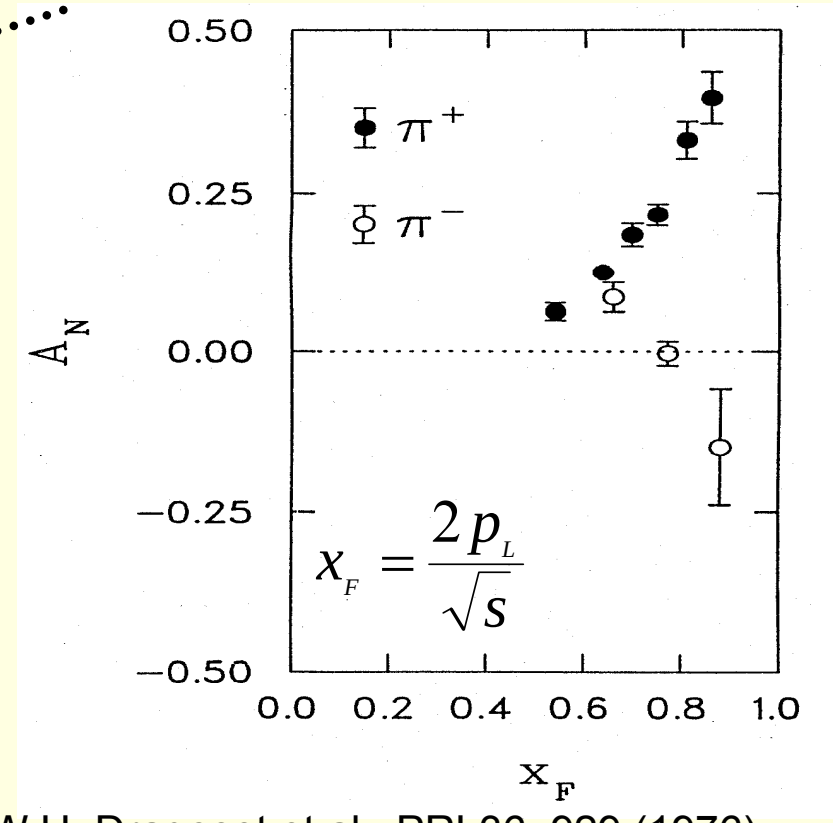
Surprise in Transverse Single Spin Physics

Transverse Single Spin Asymmetries A_N

$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}$$



Argonne ZGS, p_{beam} = 12 GeV/c



W.H. Dragoset et al., PRL36, 929 (1976)

Theory Expectation:

Small asymmetries at high energies

(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N ~ O(10^{-4}) theory

Experiments:

ZGS, AGS, FERMILAB to RHIC

$$pp^{\uparrow} \rightarrow \pi + X$$

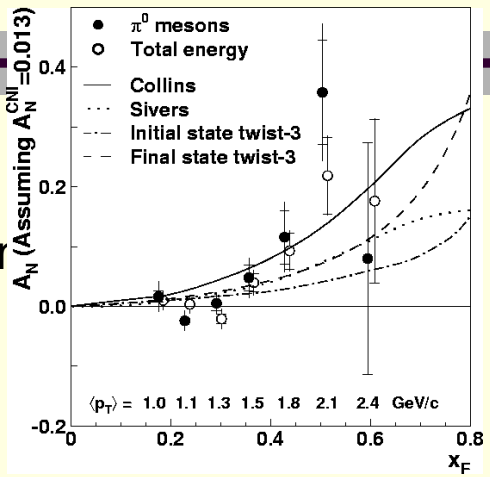
A_N ~ O(10^{-1}) observed

$$\sqrt{s} = 5 \sim 500 \text{ GeV}$$

Transverse SSA's

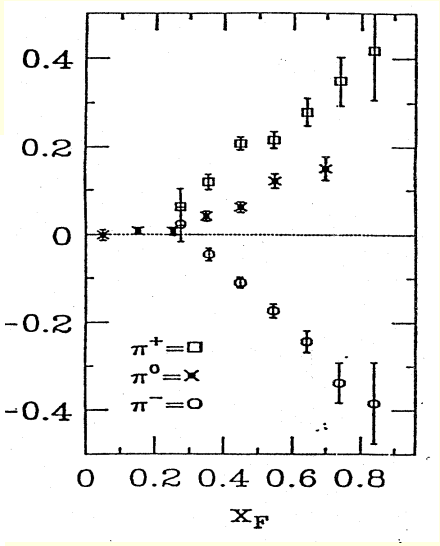
from low to high energies

RHIC 20,000 GeV beam



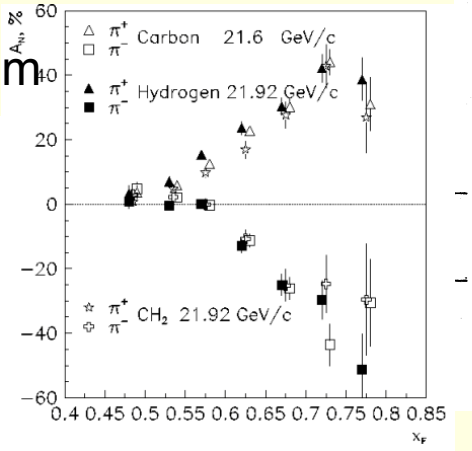
PRL (2004)

FNAL 200 GeV beam



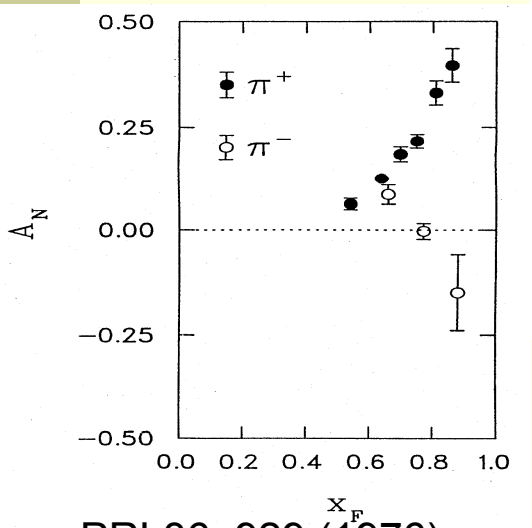
PLB261, 201 (1991)
PLB264, 462 (1991)

AGS 22 GeV beam



PRD65, 092008 (2002)

ZGS 12 GeV beam



PRL36, 929 (1976)

Non-Perturbative cross section → Perturbative cross section

Possible Origin of Large Single Spin Asymmetries

Can initial and/or final state effects generate large transverse spin asymmetries? ($A_N \sim 10^{-1}$)

Proton Structure

pQCD

$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \to \pi^+ X\right)}{dx_1 dx_2 dz} \propto q_i^{\uparrow}(x_1, k_{q,T}) \cdot G(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, p_{h,T})$$

small spin dependence

fragmentation function

Theory Study of Spin Asymmetries

1. Transversity quark distributions and Collins fragmentation function

Correlation between proton & quark spin + spin dependant fragmentation function $\propto \delta q(x) \cdot H_1^{\perp}(z_2, \bar{k}_{\perp}^2)$

2. Sivers quark-distribution

Correlation between proton-spin and transverse quark momentum

$$\propto \bar{f}_{1T}^{\perp q}(x, k_{\perp}^2) \cdot D_q^h(z)$$

3. Collinear factorization approach

At high transverse momenta : two twist-3 correlation functions

-- Quark-gluon correlation function $T_{q,F}$

-- Two independent tri-gluon correlation functions $T_G^{(f)}, T_G^{(d)}$

*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)*

The two mechanisms each have their own domain of validity, they describe the same physics in the kinematic region where they overlap.

Case study: Drell-Yan

Heavy flavor A_N

Why heavy flavor?

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

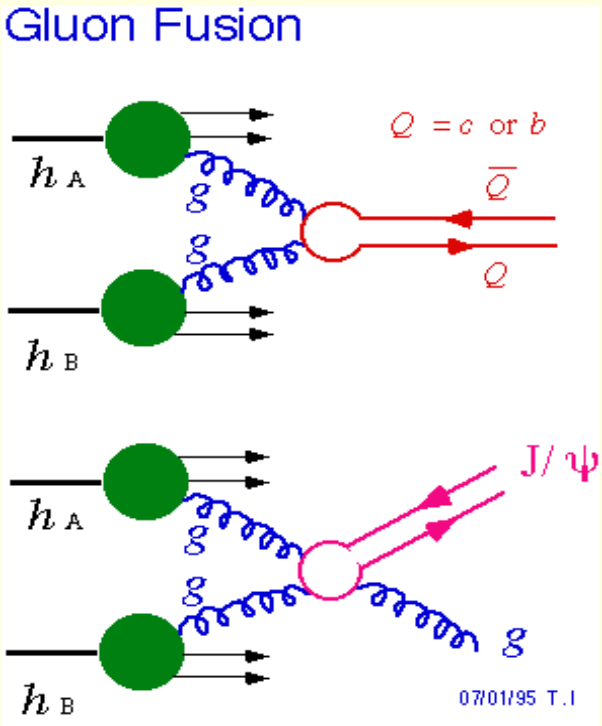
    Pythia 6.1 simulation

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

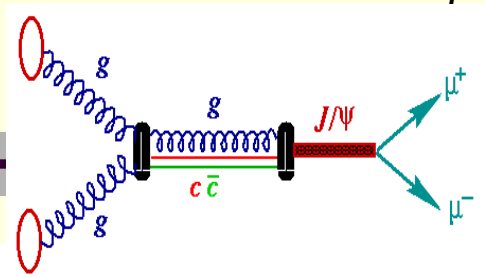
  - * gluon has zero transversity

- A perfect channel for gluon Sivers function
  - * Gluon's orbital angular momentum?

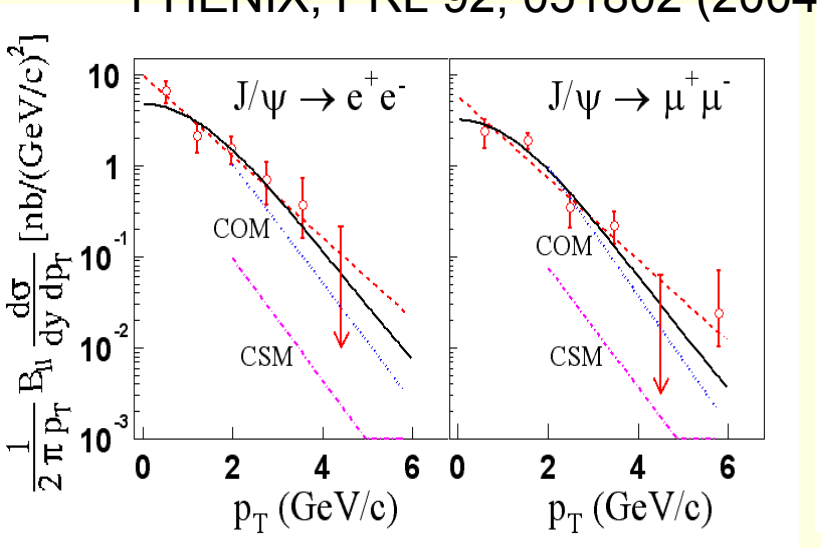
- Important to understand the origin of observed large A_N at large x_F

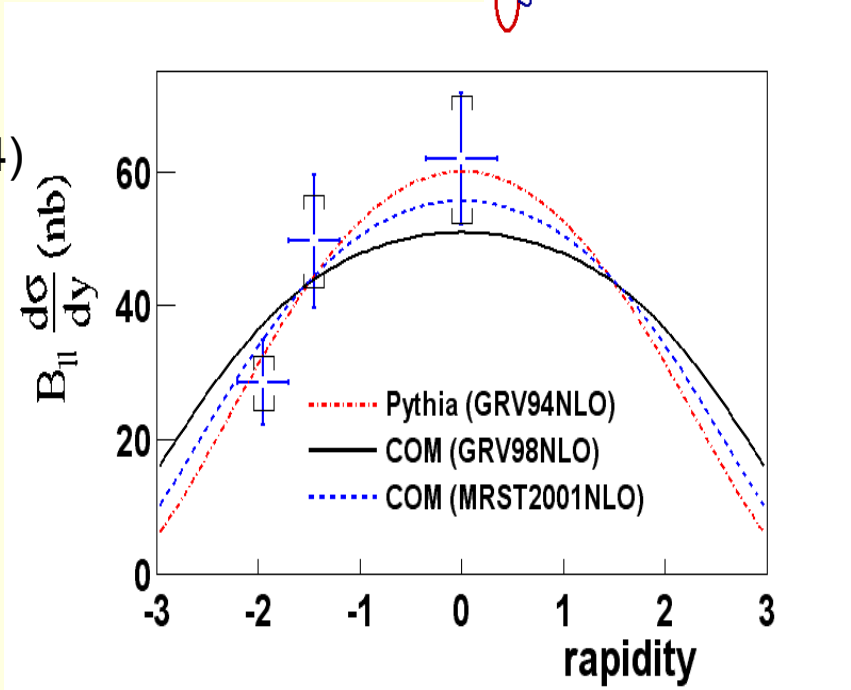


NrQCD and PHENIX J/ψ data



PHENIX, PRL 92, 051802 (2004)

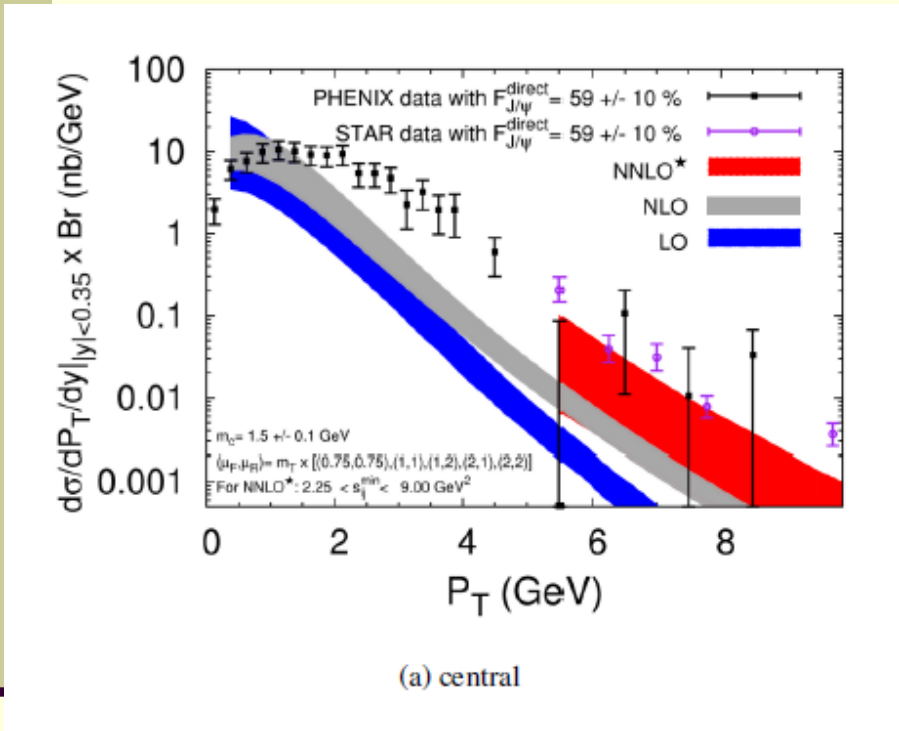




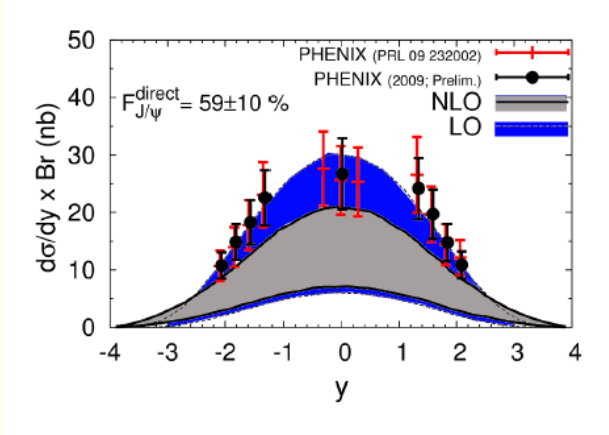
Theoretical predictions of J/Ψ production at RHIC are in good agreement with the PHENIX data: COM process dominant

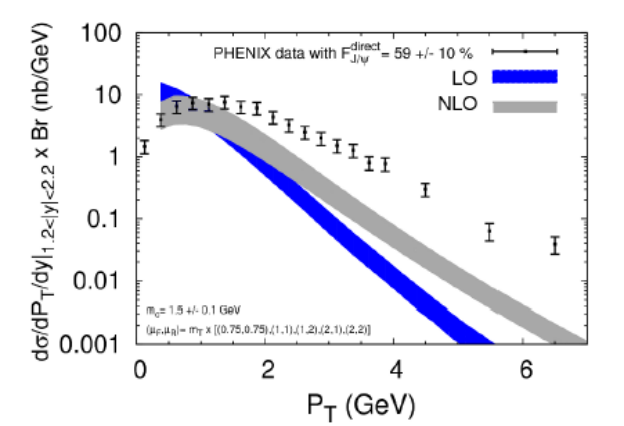
- PRD 68 (2003) 034003 G. Nayak, M. Liu, F. Cooper
- PRL 93 (2004) 171801 F. Cooper, M. Liu, G. Nayak

NRQCD and PHENIX data



(a) central





(b) forward

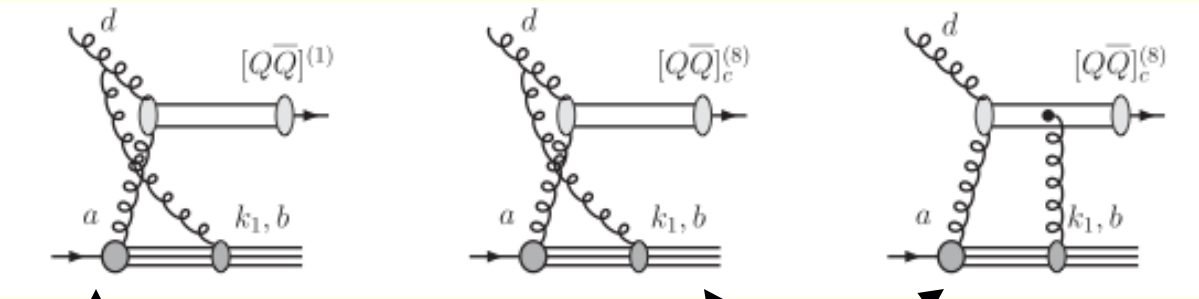
Even at NLO, the Color-Singlet Model undershoots the PHENIX data

How does J/Ψ production affect asymmetry prediction?

J/ψ SSA is very sensitive to the production mechanism

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

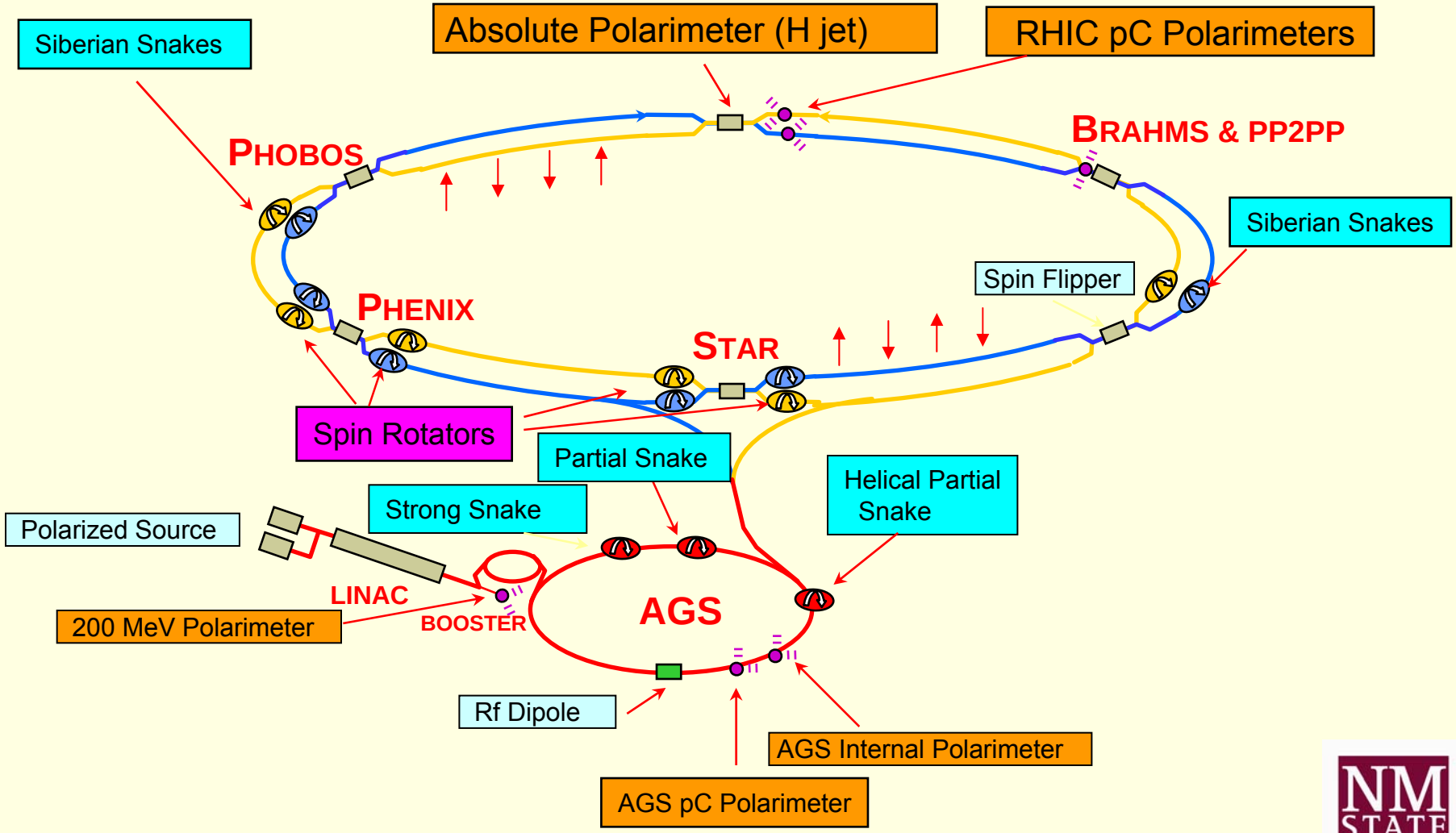
(Feng Yuan, Phys. Rev D78, 014024(2008)



One color-singlet diagram
— no cancellation, only initial state interaction
Asymmetry set (essentially) by Gluon orbital angular momentum

Two color-octet diagrams
— cancellation between initial and final state interactions
Orbital angular momentum terms cancel

Polarized p+p collider -- RHIC



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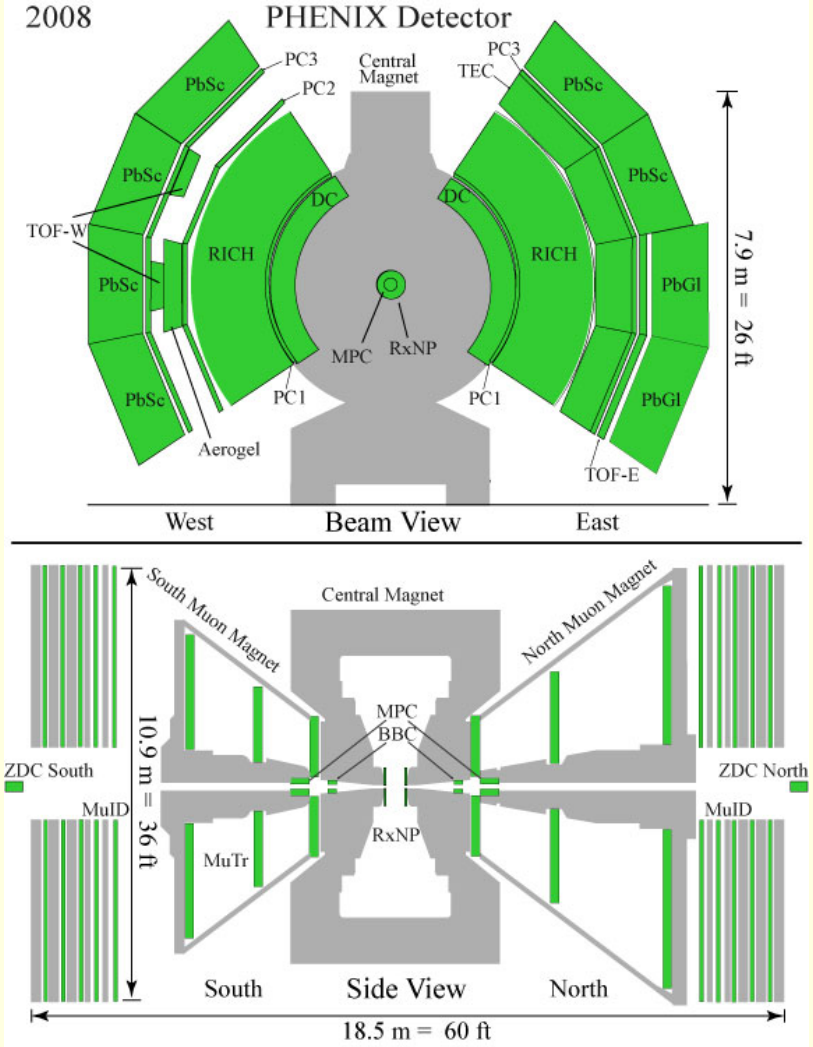
The PHENIX detectors



- **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: **$1.2 < \eta < 2.4$**

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}

Asymmetry Formulae

Define Left: $\vec{p} \bullet (\vec{S} \times \vec{P}) > 0$ Right: $\vec{p} \bullet (\vec{S} \times \vec{P}) < 0$

Square root formula

$$A_N = \frac{1}{P}\langle f(\phi)\rangle \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}},$$

P: beam polarization
f: Acceptance Correction Factors

Luminosity formula

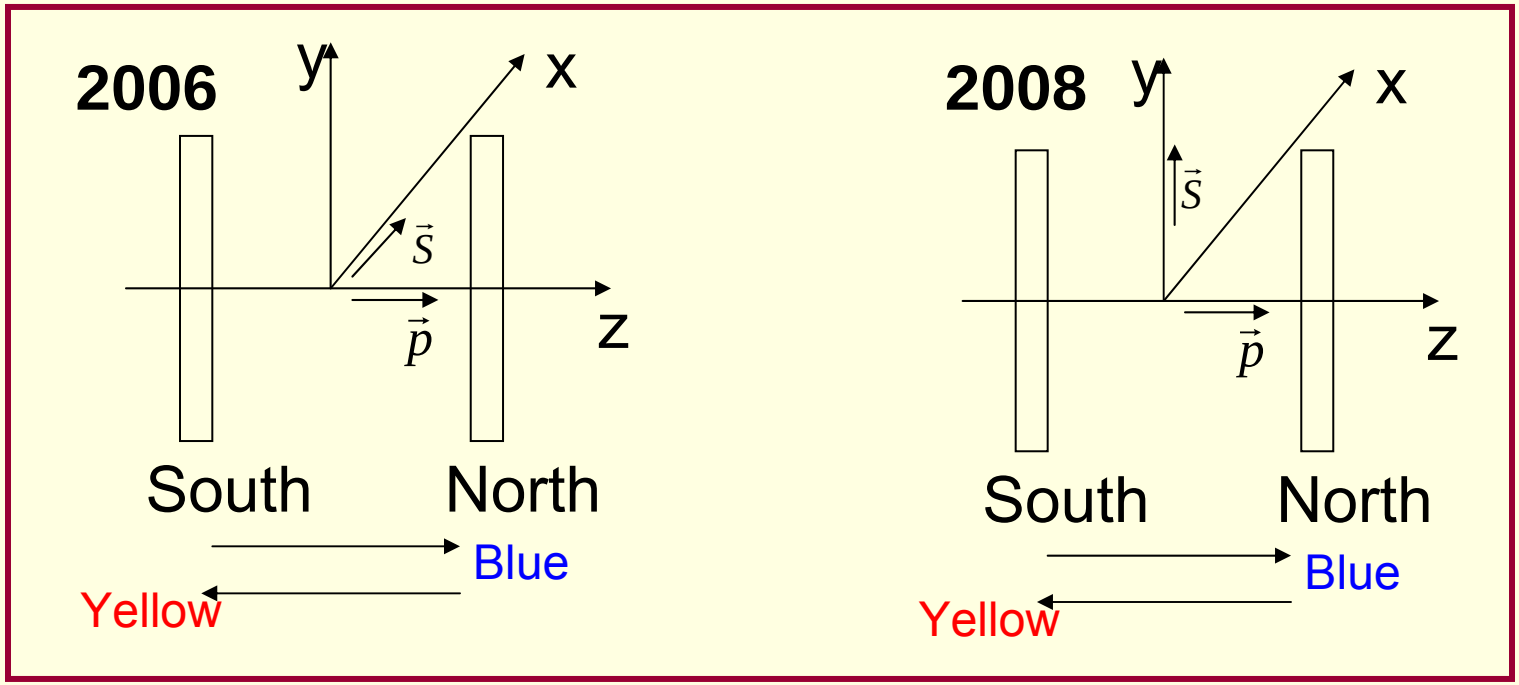
$$A_{l(r)} = \frac{1}{P}\langle f(\phi)\rangle_{left(right)} \frac{N_{l(r)}^{\uparrow} - RN_{l(r)}^{\downarrow}}{N_{l(r)}^{\uparrow} + RN_{l(r)}^{\downarrow}},$$

R = L+/L-;

$$f = \left(\frac{\int_0^{\pi} \varepsilon(\phi)\sin\phi d\phi}{\int_0^{\pi} \varepsilon(\phi) d\phi}\right)$$

Φ: Azimuthal angle between the outgoing particle and the proton spin.
ε(Φ): efficiency for J/ψ at given Φ.

Transverse p + p collison in 2006 and 2008



Beam Polarization: 2006: 0.53 ± 0.02 (syst.) (clockwise)
0.52 ± 0.02 (syst.) (counterclockwise)
2008: 0.48 ± 0.02 (syst.) (clockwise)
0.41 ± 0.02 (syst.) (counterclockwise)

Asymmetry Formula for $J/\Psi \rightarrow \mu^+\mu^-$

- **Modified Luminosity Formula**

$$A_N^{L(R)} = \frac{1}{P}\langle f(\phi)\rangle \frac{(N^{\uparrow\uparrow} + R_1 N^{\uparrow\downarrow}) - (R_2 N^{\downarrow\uparrow} + R_3 N^{\downarrow\downarrow})}{(N^{\uparrow\uparrow} + R_1 N^{\uparrow\downarrow}) + (R_2 N^{\downarrow\uparrow} + R_3 N^{\downarrow\downarrow})}$$

$$R_1 = \frac{L^{\uparrow\uparrow}}{L^{\uparrow\downarrow}}, R_2 = \frac{L^{\uparrow\uparrow}}{L^{\downarrow\uparrow}}, R_3 = \frac{L^{\uparrow\uparrow}}{L^{\downarrow\downarrow}}$$

- **Final asymmetry**

$$A_N = \frac{\frac{\langle f(\phi)\rangle_{Left}}{P}\frac{\frac{N_l^{\uparrow} - RN_l^{\downarrow}}{N_l^{\uparrow} + RN_l^{\downarrow}}}{\delta A_l^2} - \frac{\langle f(\phi)\rangle_{Right}}{P}\frac{\frac{N_r^{\uparrow} - RN_r^{\downarrow}}{N_r^{\uparrow} + RN_r^{\downarrow}}}{\delta A_r^2}}{\frac{1}{\delta A_l^2} + \frac{1}{\delta A_r^2}}$$

Analysis Method for $J/\Psi \rightarrow \mu^+\mu^-$ (I)

Effective Luminosity: 35cm vertex

Run6: S: 1.63pb^{-1} , N: 1.75pb^{-1},
Run8: S: 4.30pb^{-1}, N: 4.33pb^{-1}

Trigger selection:

Run6: MUID1D1S
Run8: MUID2D

Fill-by-fill analysis

No need fill by fill muon efficiency correction
Fix mass range to extract the number of J/Ψ (2σ)

Track/Event Quality Cuts

Rapidity range: 1.2 < |y| < 2.2
Event vertex cut: < 35cm
J/ψ P_T cut : < 6 GeV/c
J/ψ vertex fitting χ^2 <5
Muon Track p_Z cut: 1.4 < p_Z < 20
Muon Track id hits >= 64
Muon track fitting χ^2 < 30
Muon Track and Road matching angle <10 deg
Muon Track and Road matching distance
< 25cm (North) < 30cm (South)

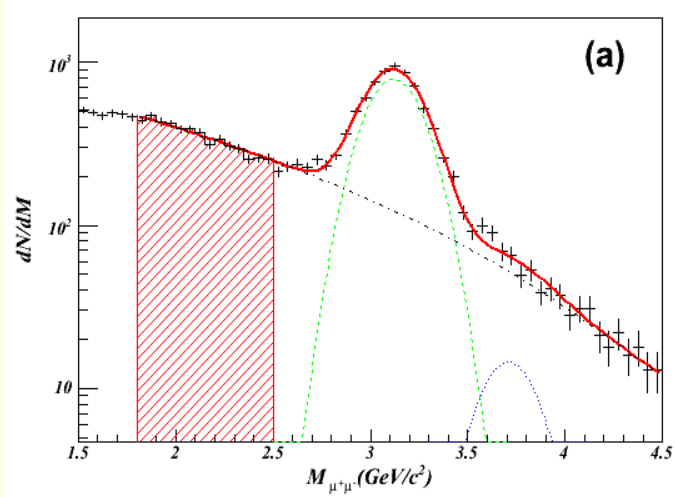
$$A_N = \frac{A^{incl} - r \cdot A^{BG}}{1-r}, r = \frac{N^{BG}}{N^{incl}} = \frac{N^{incl} - N^{signal}}{N^{incl}}$$

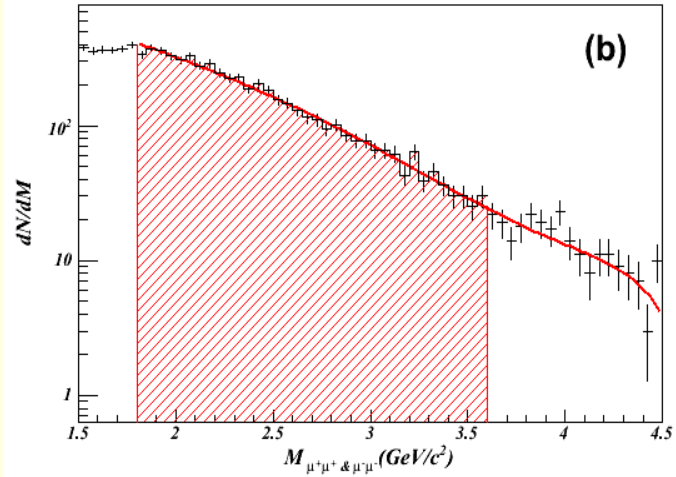
$$\delta A_N = \sqrt{\frac{(\delta A^{incl})^2 + r^2 \cdot (\delta A^{BG})^2 + (\delta r)^2 (A_N^{BG})^2}{(A_N^{incl} - r A_N^{BG})^2} + (\frac{\delta r}{1-r})^2}$$

Analysis Method for $J/\Psi \rightarrow \mu^+\mu^-$ (II)

$$\frac{dN}{dM} = (A + BM + CM^2 + DM^3) + N_{J/\Psi} \cdot \frac{1}{2\pi\sqrt{\sigma}} e^{-\frac{(M - M_{J/\Psi})^2}{2\sigma^2}} + N' \cdot \frac{1}{2\pi\sqrt{\sigma'}} e^{-\frac{(M - M_{\Psi'})^2}{2\sigma'^2}}$$

Two Gaussian + Exponential: Use to estimate the background fraction under the J/ψ peak.





A_N^{Incl}: oppositely-charged muon pairs in the invariant mass range ±2σ around J/ψ mass.

A_N^{BG}: oppositely-charged muon pairs in the invariant mass range 1.8 (2.0run8) < *m* <2.5 along with charged pairs of the same sign in invariant mass range 1.8 (2.0run8) < *m* < 3.6

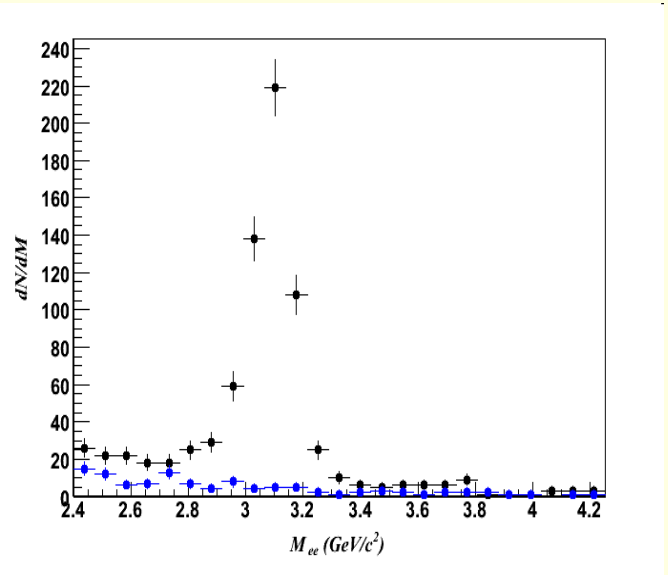
Analysis Method for $J/\Psi \rightarrow e^+e^-$

Effective Luminosity

Run6: 1.36pb^{-1}

Trigger selection:

BBCLL1 && ERT2*2



BG subtraction: $2\sqrt{N_{e^+e^+}N_{e^-e^-}}$

Remaining continuum background

Is small, not enough statistics

Assuming: $A_N^{BG}=0$

Too small statistics in central arm to calculate asymmetry for each store.

$$A_N = \frac{1}{n}\sum_{i=1}^{n}\frac{f_i}{P_i}\frac{N_i^{\uparrow} - R_i N_i^{\downarrow}}{N_i^{\uparrow} + R_i N_i^{\downarrow}} = \frac{1}{n}\sum_{i=1}^{n} A_{N,i.}$$

$$A_N = \frac{\sum_{i=1}^{n} f_i (N_i^{\uparrow} - R_i N_i^{\downarrow})}{\sum_{i=1}^{n} P_i (N_i^{\uparrow} + R_i N_i^{\downarrow})}$$

$$A_N = \frac{\langle f \rangle \sum_{i=1}^{n} (N_i^{\uparrow} - \langle R \rangle N_i^{\downarrow})}{\langle P \rangle \sum_{i=1}^{n} (N_i^{\uparrow} + \langle R \rangle N_i^{\downarrow})}$$

It require: $R_i = \langle R \rangle$, $f_i = \langle f \rangle$, $P_i = \langle P \rangle$ for all i

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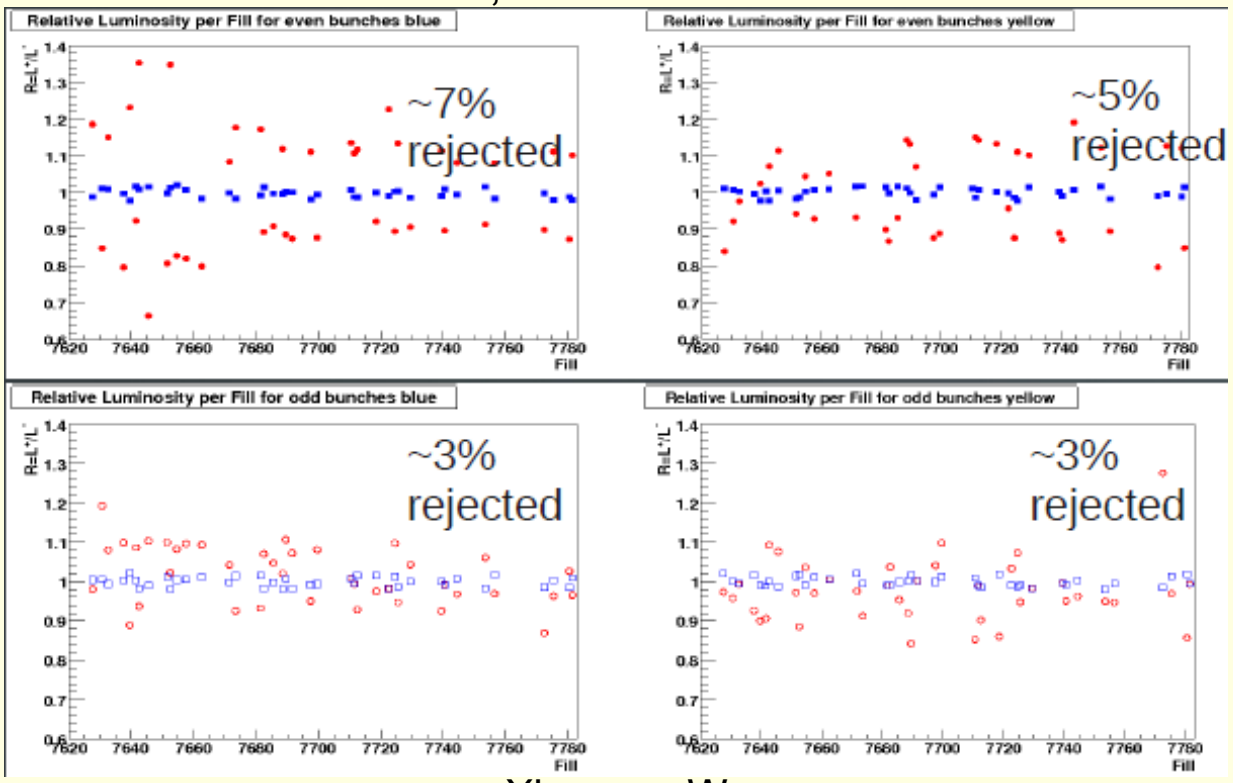
Analysis Method for $J/\Psi \rightarrow e^+e^-$

Stabilize relative luminosities method:

Several bunches of colliding protons are removed from the analysis so that the relative luminosity within each store is brought as close to unity as possible.

Before Correction, After Correction



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J/ψ Background Fraction

Muon Arms

p_T (GeV/c)	data set	detector	background fraction (%)
0–6	2006	South	21.7±0.6
	2006	North	19.1±0.4
	2008	South	16.4±0.2
	2008	North	14.2±0.2
0–1.4	2006	South	23.2±0.7
	2006	North	22.0±0.7
	2008	South	16.1±0.3
	2008	North	15.5±0.3
1.4–6	2006	South	20.1±0.8
	2006	North	14.1±0.5
	2008	South	15.6±0.4
	2008	North	10.5±0.2

Central Arm

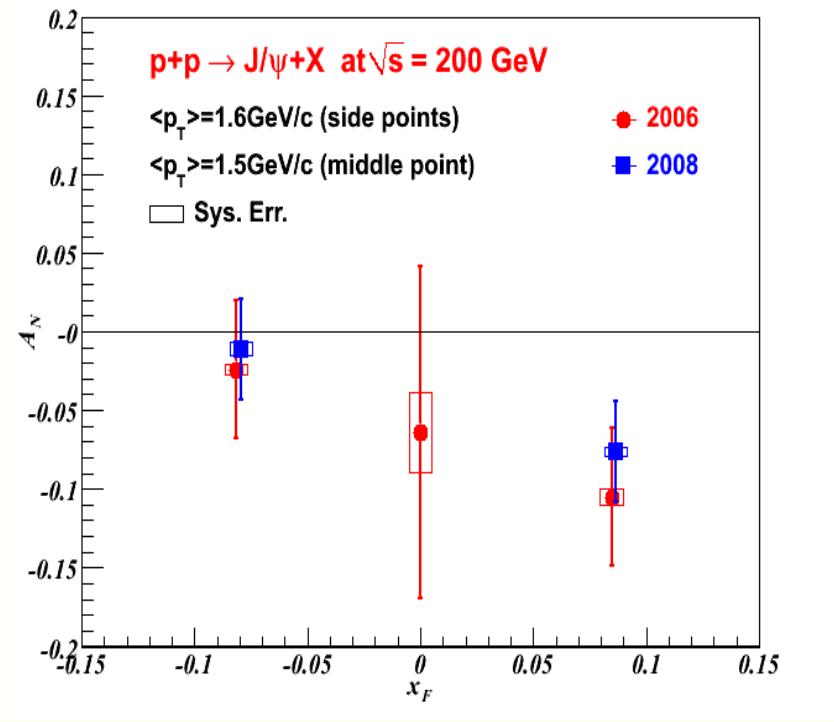
p_T (GeV/c)	r (%)
0–6	6.6±0.4
0–1.4	5.6±0.5
1.4–6	7.8±0.7

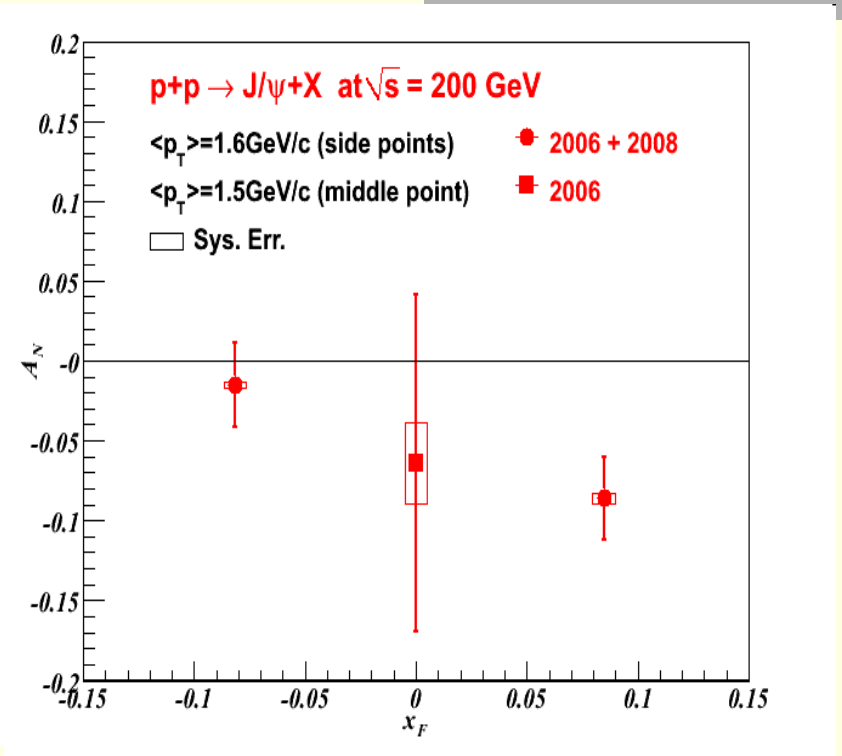
Background Asymmetry

- **Central Arm: assume: $A_N^{BG} = 0$**
- **Muon Arm**

p_T (GeV/c)	$< x_F >$	data set	A_N^{BG}
0–6	-0.081	2006	-0.003±0.028
	-0.082	2008	-0.072±0.034
	0.084	2006	-0.008±0.028
	0.086	2008	-0.003±0.035
0–1.4	-0.081	2006	-0.021±0.034
	-0.081	2008	-0.089±0.042
	0.085	2006	0.002±0.034
	0.087	2008	-0.008±0.043
1.4–6	-0.081	2006	0.001±0.053
	-0.082	2008	-0.041±0.068
	0.084	2006	-0.039±0.053
	0.086	2008	0.024±0.066

Results: A_N vs x_F

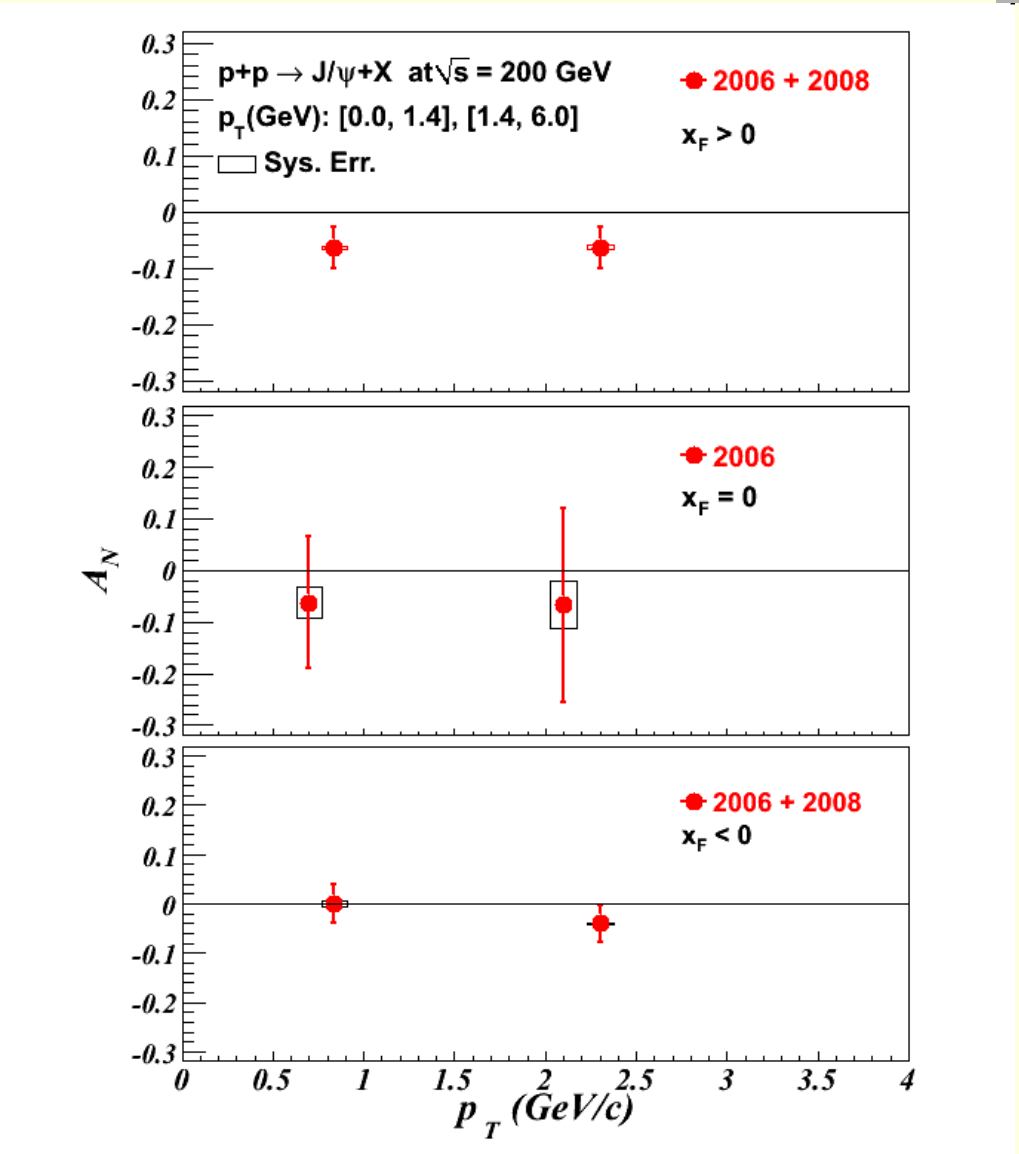




Asymmetries were obtained as a function of J/Psi Feynman-x, with a value of -0.086 ± 0.026 (stat.) ± 0.003 (sys.) in the forward region.

Suggests possible non-zero tri-gluon correlation functions in transversely polarized protons, and, if well defined in this reaction, a non-zero gluon Sivers distribution function.

Results: A_N vs p_T



Summary and discussions

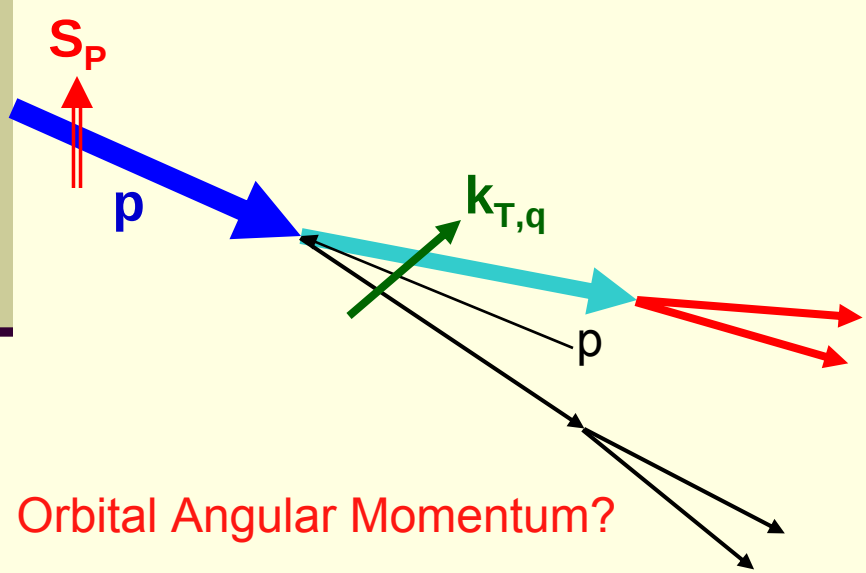
- PHENIX measured transverse SSA as a function of J/ψ transverse momentum and Feynman-x.
- In the forward region, 3.3σ away from 0 asymmetry was observed.
- It suggests possible non-zero trigluon correlation functions in transversely polarized protons, and, if well defined in this reaction, a non-zero gluon Sivers distribution function.
- It shall shed light on the production mechanism for the heavy quarkonium production, which is long standing puzzle in the field.
- We hope this measurement will stimulate further theoretical work in the future.

backups

Possible Mechanisms …

Sivers mechanism: Correlation between nucleon spin and parton k_T

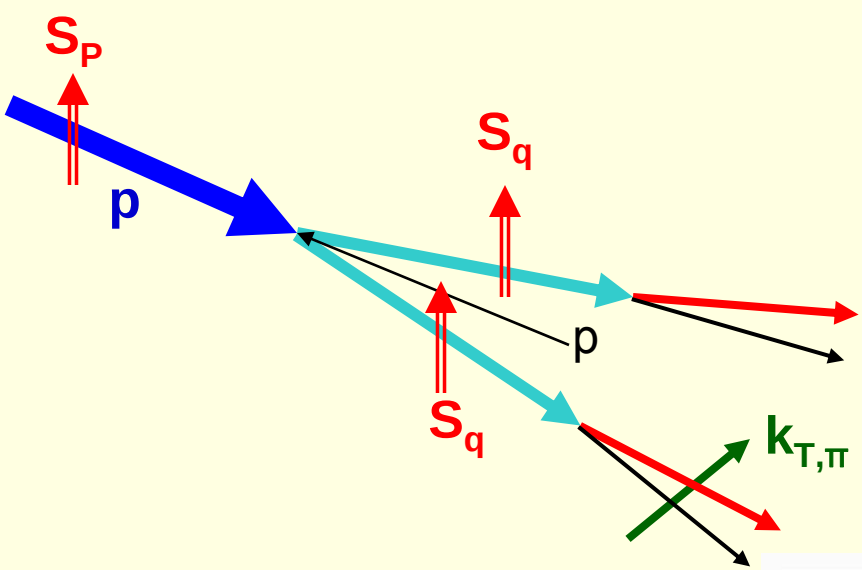
Phys Rev D41 (1990) 83; 43 (1991) 261



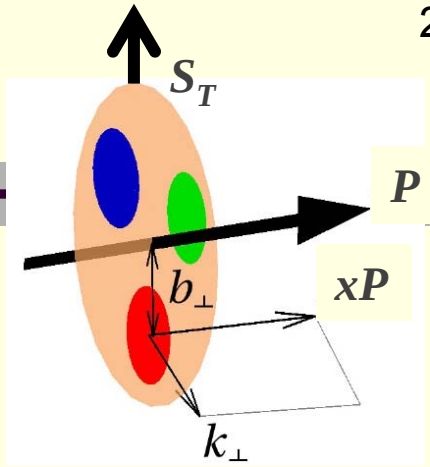
Orbital Angular Momentum?

Collins mechanism: Transversity (quark polarization) * asymmetry in the jet fragmentation

Nucl Phys B396 (1993) 161



Mechanisms in QCD



I. Transverse momentum dependent (TMD) functions approach Sivers function, Collins function ...

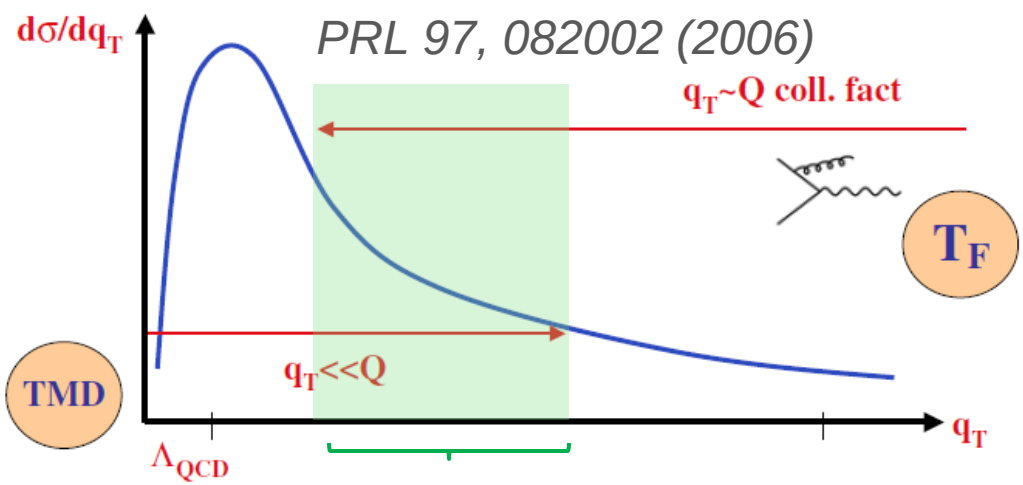
II Collinear factorization approach

At high transverse momenta : two twist-3 correlation functions

1. Quark-gluon correlation function $T_{q,F}$ $T_G^{(f)}, T_G^{(d)}$
2. Two independent trigluon correlation functions

$k_\perp$ is integrated ⇒ represent integrated spin dependence of the partons transverse motion

Are the two mechanisms related?



- $T_{q,F}, T_G^{(f)}$ related to a moment in $k_\perp$ of the corresponding quark/gluon Sivers function

Case study : Drell-Yan

In the overlap region both approaches give the same physics