J/Psi Production and Asymmetry in Polarized p+p Collisions at RHIC

Ming Liu
Los Alamos National Laboratory

(for the PHENIX Collaboration)

Outline

- The challenge:
  - J/Psi production mechanisms in p+p
- J/Psi spin asymmetry:
  - New understanding of QCD process

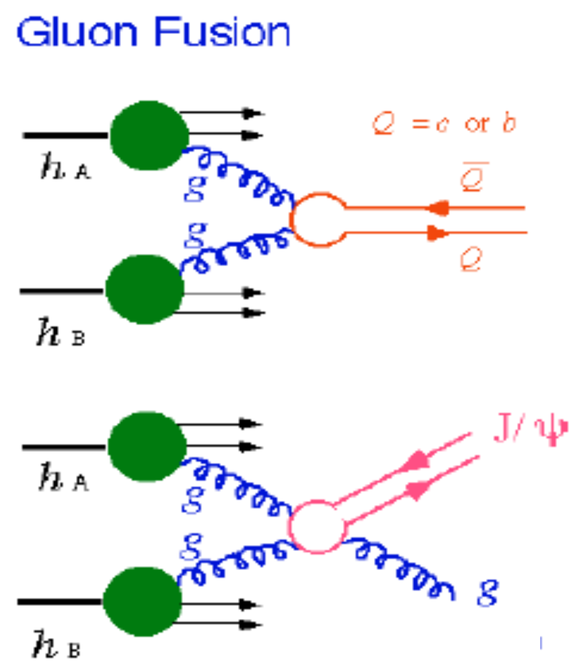
J/Psi & QCD

- J/Psi is considered one of the simplest hadrons
  - Charm and anti-charm "atom"
  - Non-relativistic movement of charm quarks, wave functions
  - Clean signature: di-lepton decay channel
- Produced through "hard" scattering in p+p
  - pQCD applicable: NRQCD

$$d\sigma \sim f(x_1)\otimes f(x_2)\otimes \hat{\sigma}^{x_1+x_2\to[c\bar{c}]+X} \otimes H^{[c\bar{c}]\to J/Psi}$$

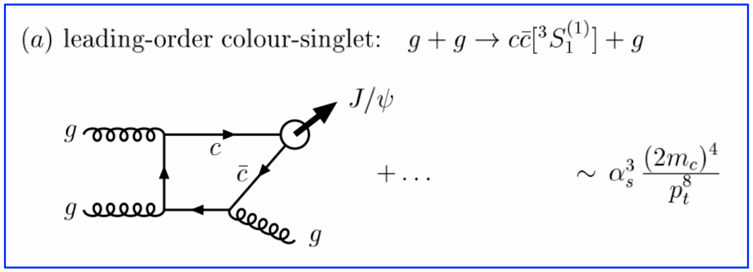
- An excellent test ground for our understanding of QCD processes

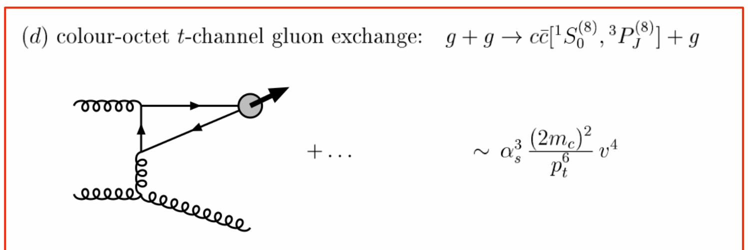
@RHIC, LHC

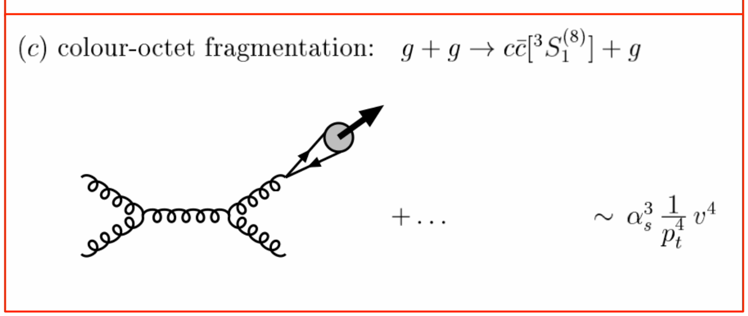


J/ψ Production in p+p Collisions

- NRQCD @high pT: $\sim \alpha_s^3$

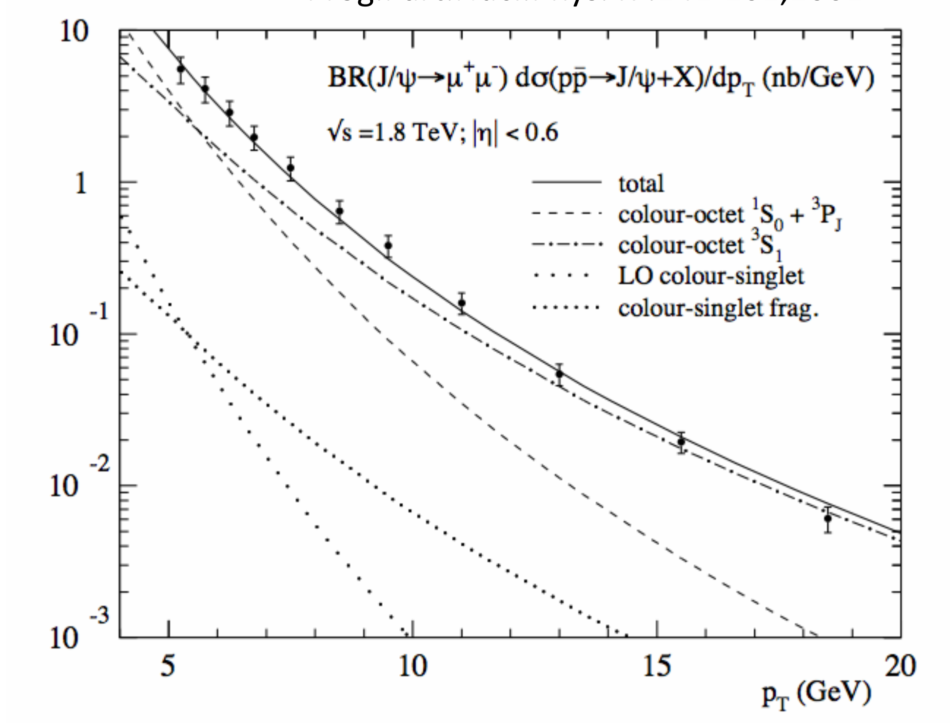






Fixed the relative contributions from Data (CDF)

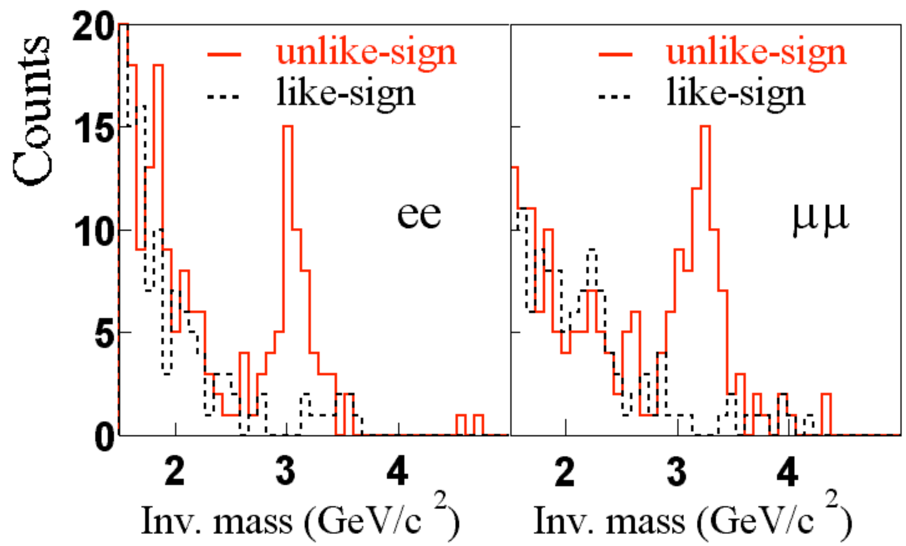
Prog.Part.Nucl.Phys.47:141-201,2001

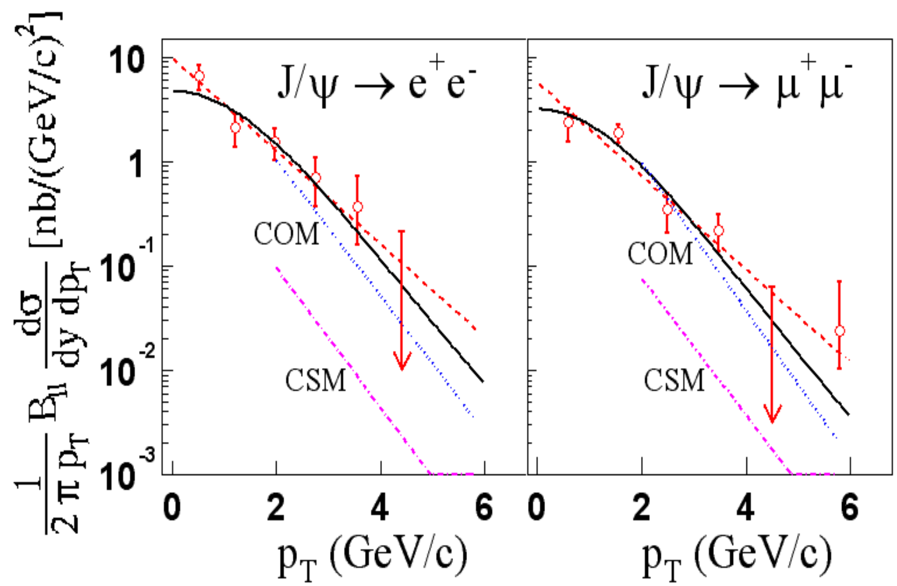


The First J/Psi Measurement @RHIC

NRQCD and J/ψ Cross Section

PHENIX, PRL 92, 051802 (2004)





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

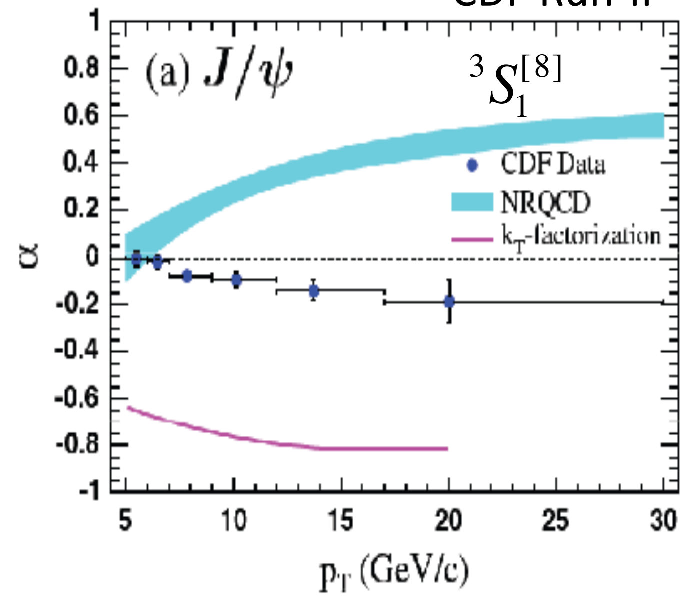
- PRD 68 (2003) 034003 G. Nayak, M. Liu, F. Cooper
- PRL 93 (2004) 171801 F. Cooper, M. Liu, G. Nayak

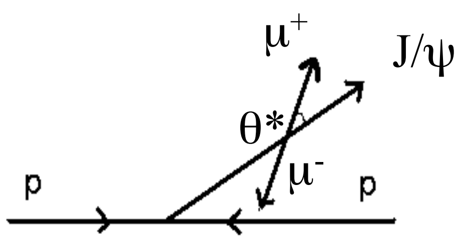
A Challenge to NRQCD: J/ψ Polarization

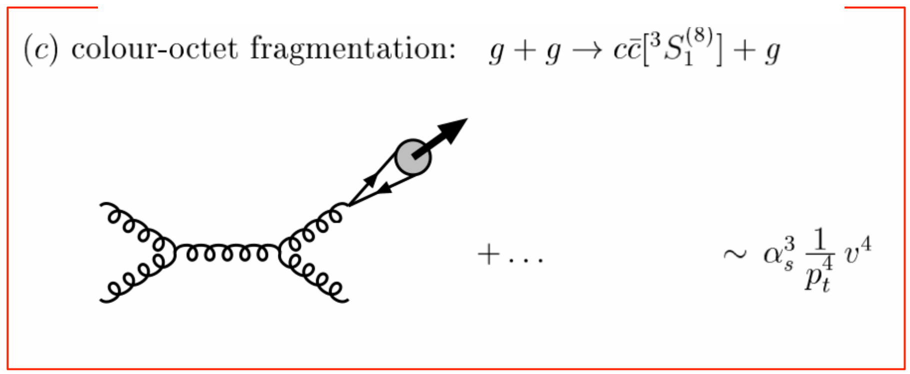
$$\frac{d\sigma}{d\cos\theta^*} \propto 1 + \alpha\cos^2\theta^*$$

α= +1: transversely polarized
α= -1: longitudinally polarized
α= 0: no polarization

CDF Run-II





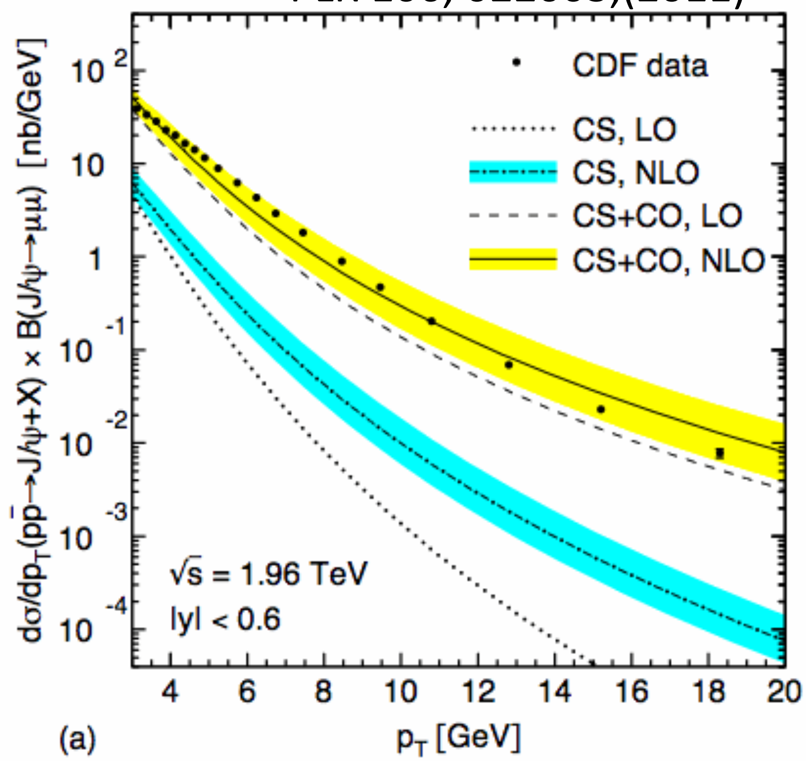


NRQCD failed badly on J/Psi polarization in pp
- HI connection: what happens in AA?

J/Psi pT Distr. and NRQCD Fit

- J/Psi pT distr. in CO and CS @LO NRQCD
  - COM
    $$\hat{\sigma}[^3S_1^{[8]}] \sim \frac{1}{p_T^4}$$
    $$\hat{\sigma}[^1S_0^{[8]},\ ^3P_J^{[8]}] \sim \frac{1}{p_T^6}$$
  - CSM
    $$\hat{\sigma}[^3S_1^{[1]}] \sim \frac{1}{p_T^8}$$
- NLO corrections sizable
  - change the pT shapes
  - Higher order contributions unknown
  - Hard to separate CO and CS contributions from pT fit alone
    - Y. Ma et al., PRL 106, 042002 (2011)
    - M. Buternschoen et al. PRL 106, 022003,(2011)
- Production mechanism – an open question
  - Any other new observables?

PLR 106, 022003,(2011)



A Possible New Observable to Study J/Psi Production Mechanisms

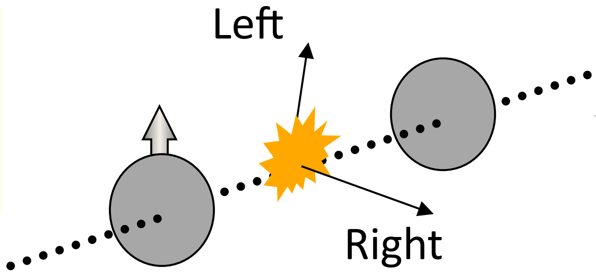
J/Psi Transverse Spin Asymmetry

A Puzzle in Spin Physics

A. Vossen's talk on Mon.

Transverse Single Spin Asymmetries A_N

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



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:

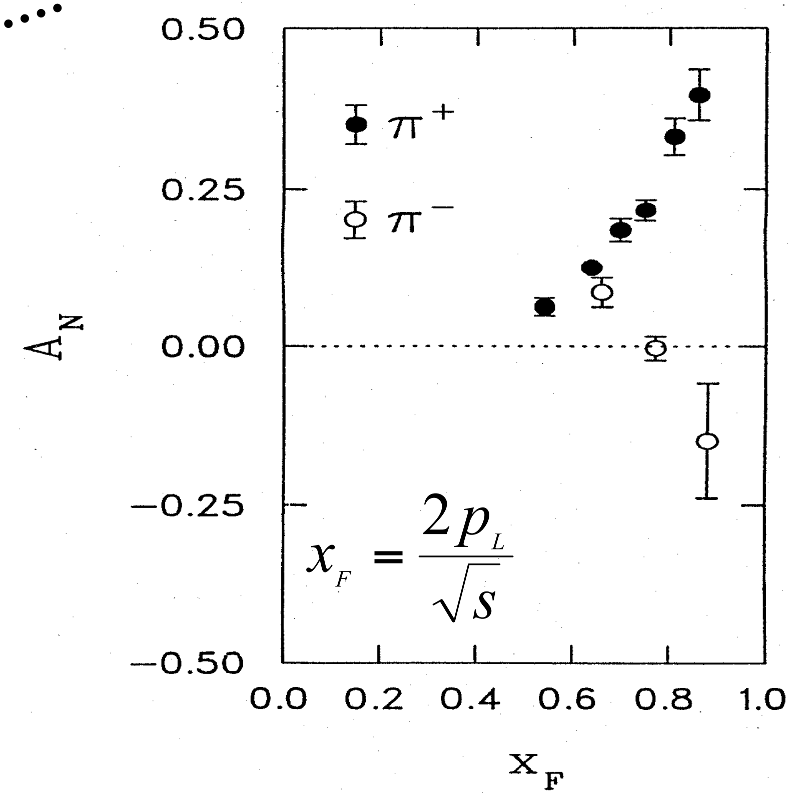
ZGS, AGS, FERMILAB to RHIC

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

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

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

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

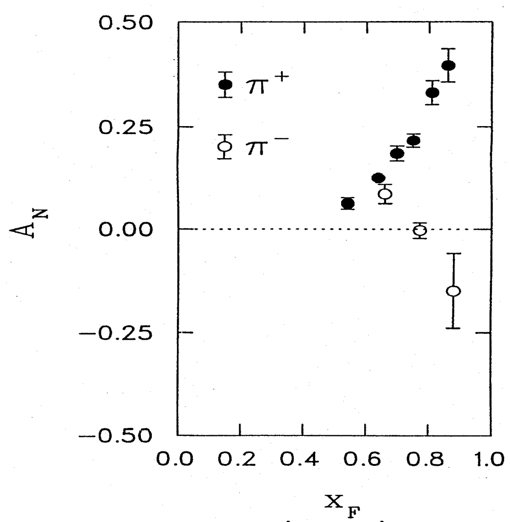


W.H. Dragoset et al., PRL36, 929 (1976)

Transverse SSA's : $\pi^{0,\pm}$

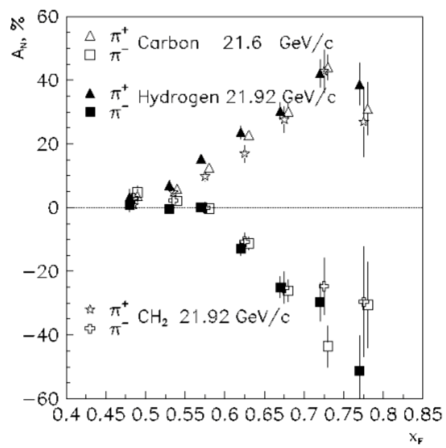
from low to high energies

ZGS 12 GeV beam



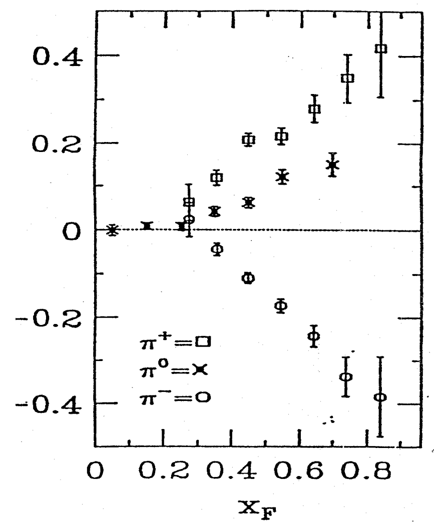
PRL36, 929 (1976)

AGS 22 GeV beam



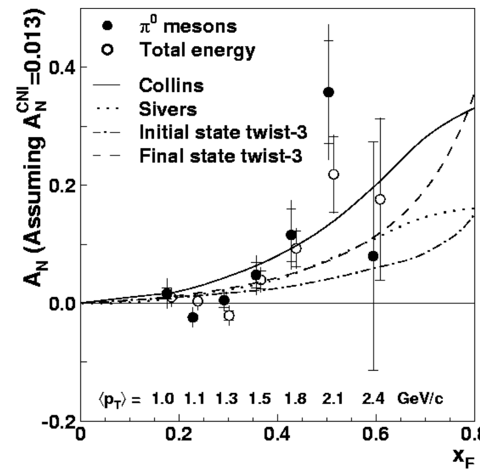
PRD65, 092008 (2002)

FNAL 200 GeV beam



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

RHIC 10,000 GeV beam



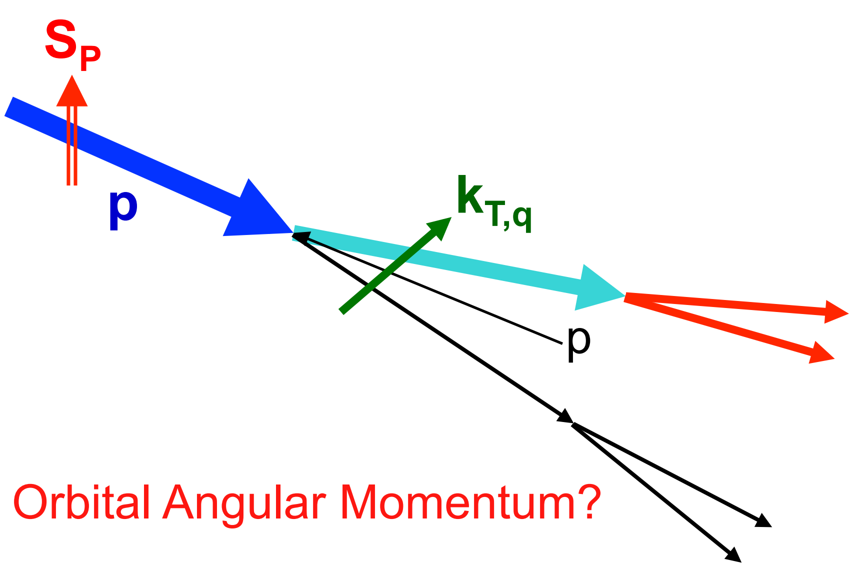
PRL (2004)

Non-Perturbative cross section → Perturbative cross section

Possible Mechanisms for large A_N …

Sivers mechanism: Correlation between nucleon spin and parton k_T

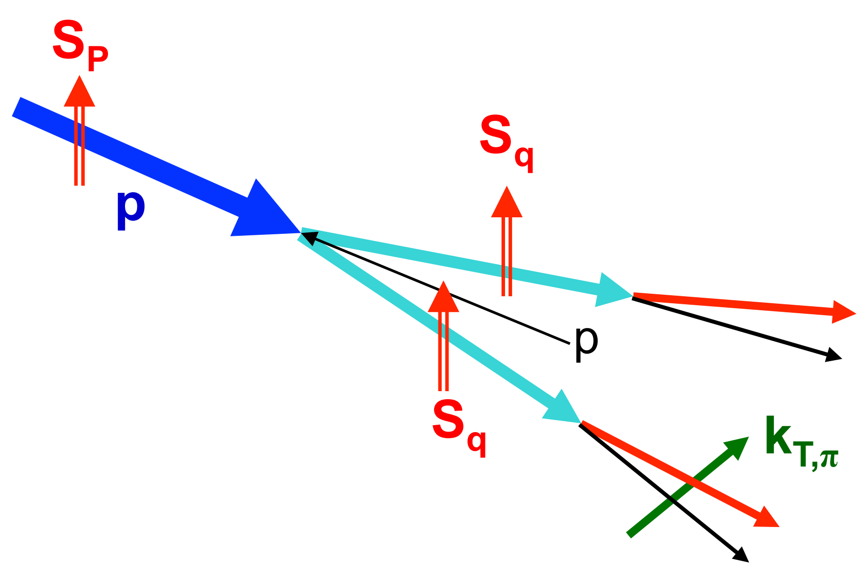
Phys Rev D41 (1990) 83; 43 (1991) 261



Orbital Angular Momentum?

Collins mechanism: Transversity (quark polarization) * spin-dependent fragmentation

Nucl Phys B396 (1993) 161



- Quark's Sivers and Collins functions well measured from polarized DIS
- Gluon's Sivers poorly known; no Collins effect due to zero tranversity

Heavy Flavor TSSA and Gluon's Sivers Function

- Heavy flavor production dominated by gluon gluon fusion at RHIC energy

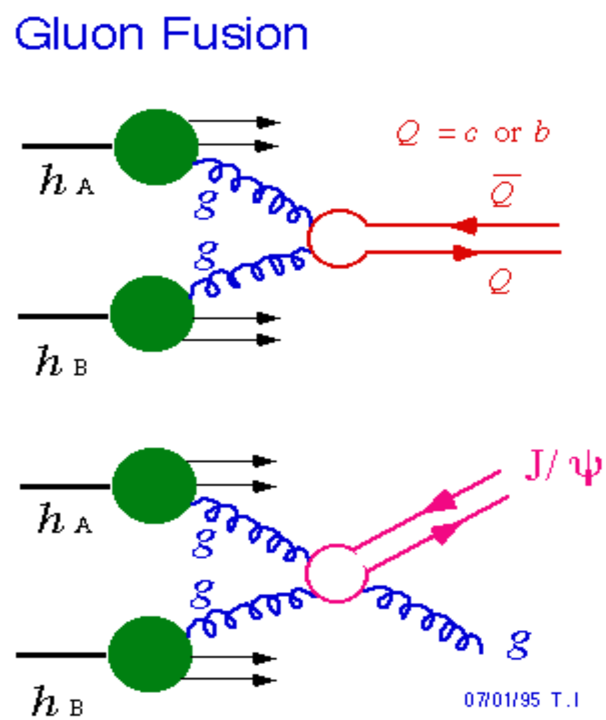
  Pythia 6.1 simulation (LO) @200GeV

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

- Gluon has zero transversity
  - Minimize Collins' effects

- Sensitive to the poorly known gluon Sivers functions
  - corresponding to the twist-3 tri-gluon correlation functions in the collinear approach

- Sensitive to J/ψ production mechanisms if gluon's Sivers function is non-zero

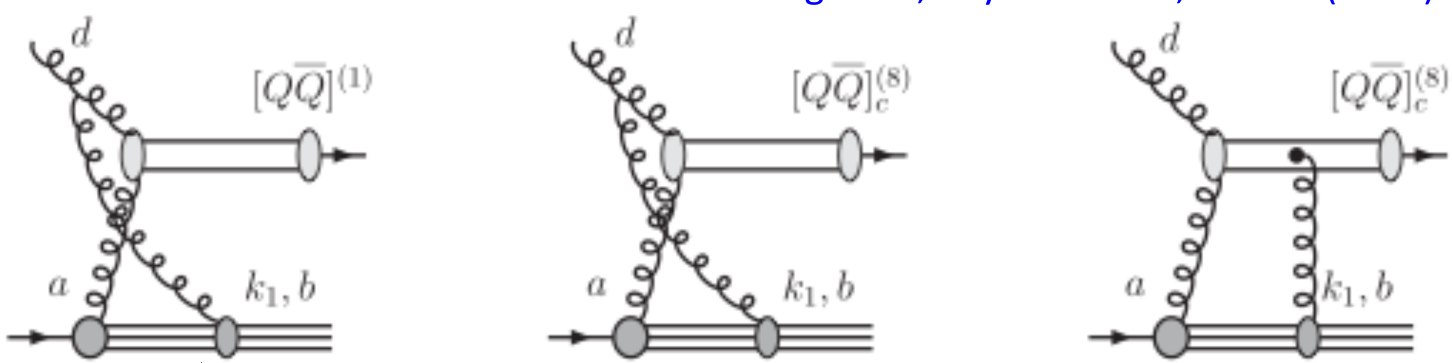


A new Theoretical Development about J/Psi TSSA

J/ψ TSSA is sensitive to the production mechanisms

Assuming a non-zero gluon sivers function, In pp scattering, TSSA 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)

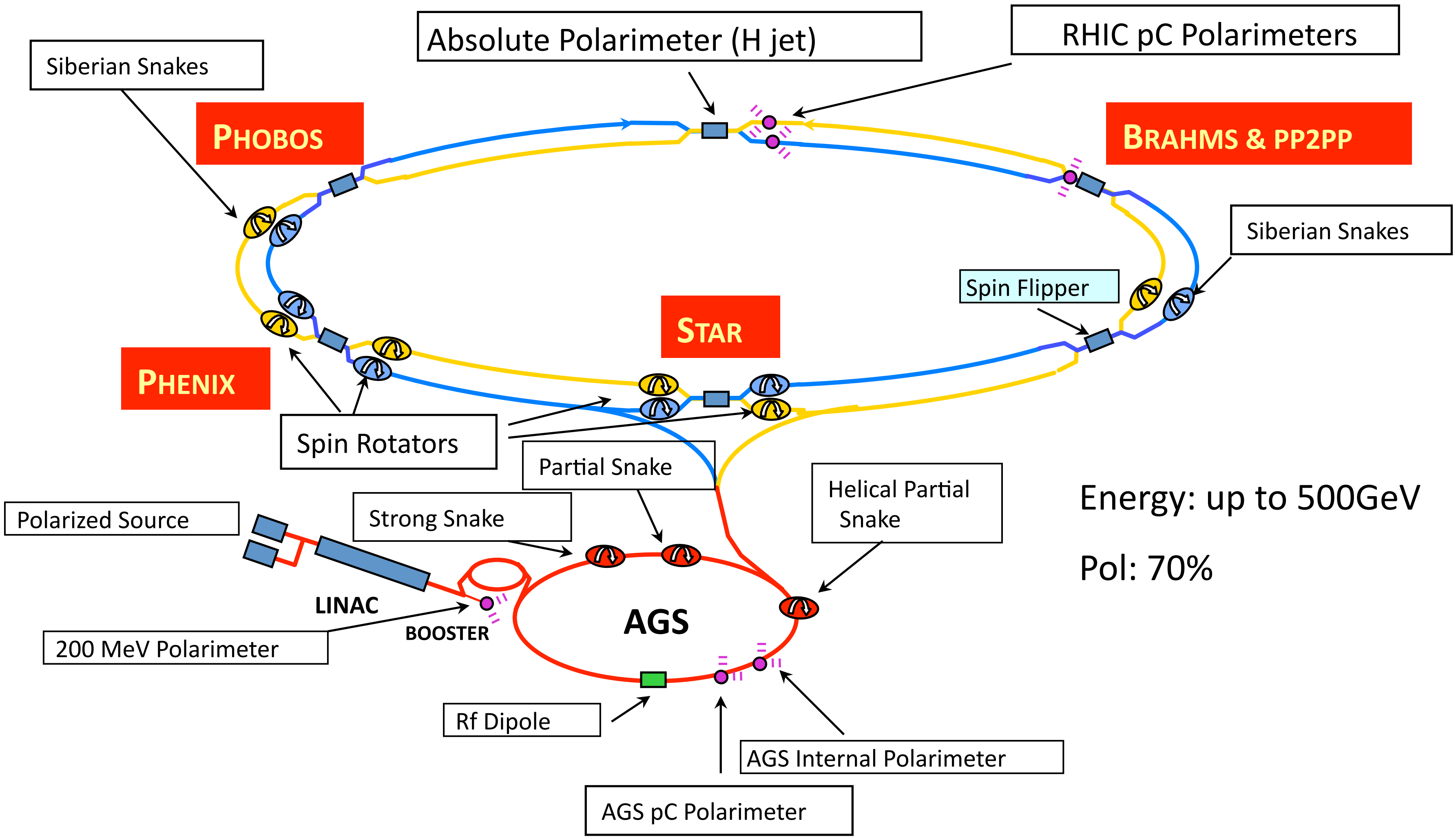


One color-singlet diagram
— no cancellation, asymmetry generated by the initial state interaction

Two color-octet diagrams
— cancellation between initial and final state interactions, no asymmetry

Let's measure it!

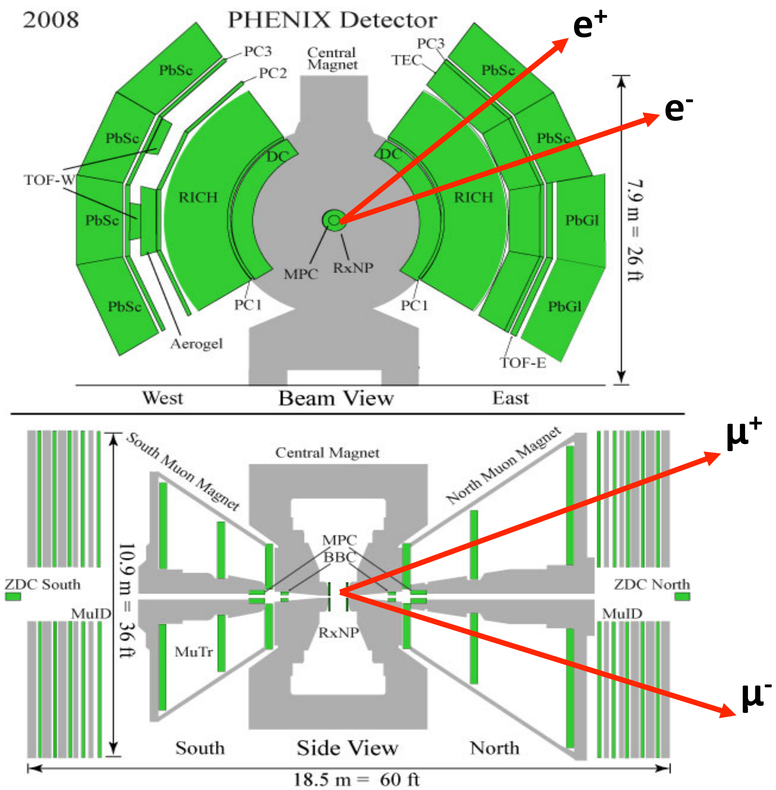
RHIC Polarized Proton Collider



Energy: up to 500GeV

Pol: 70%

PHENIX Detectors



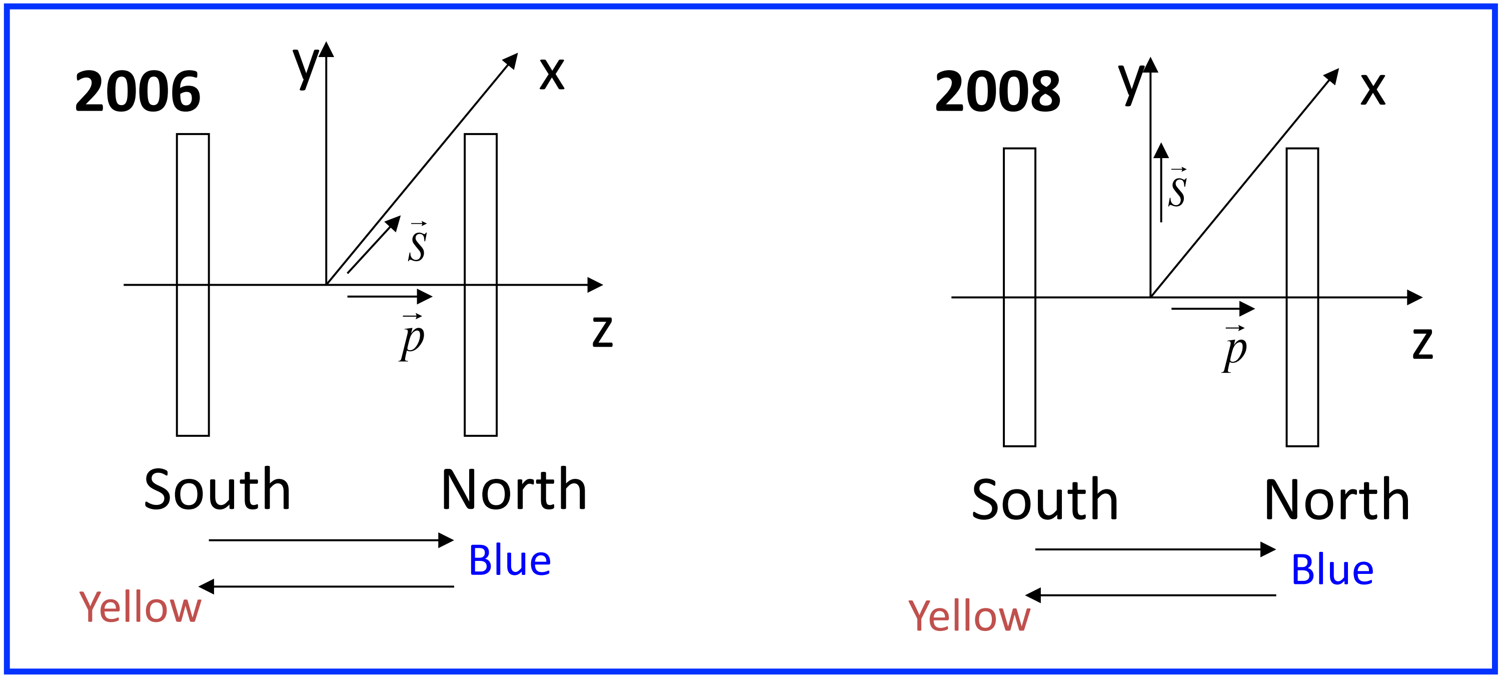
- **Central Arm** $|\eta| < 0.35$
  - Drift Chamber (DC)
  - PbGl and PbSc
  - Ring Imaging Cherenkov Detector (RICH)
  - Pad Chambers (PC)
  - Time Expansion Chamber (TEC)
- **Global Detectors (Luminosity,Trigger)**
  - BBC
  - ZDC
- **Muon Arms** $1.2 < |\eta| < 2.4$
  - **Muon tracker (MuTr)**
  - **Muon Identifier (MuID)**

$$A_N = \frac{1}{P_{Beam}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{1}{P_{Beam}} \frac{N^{\uparrow} - R \cdot N^{\downarrow}}{N^{\uparrow} + R \cdot N^{\downarrow}}$$

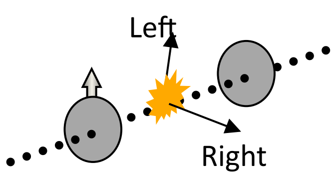
$$R = \frac{L^{\downarrow}}{L^{\uparrow}}$$

Year	√s [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2006 (Run 6)	200	2.7 pb^{-1}	51	700 nb^{-1}
2008 (Run 8)	200	5.2 pb^{-1}	46	1100 nb^{-1}

Transverse p + p Runs in 2006 and 2008



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



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

Asymmetry Measurements

- **TSSA**

$$A_N^{L(R)} = \frac{\sigma^{\uparrow}_{L(R)} - \sigma^{\downarrow}_{L(R)}}{\sigma^{\uparrow}_{L(R)} + \sigma^{\downarrow}_{L(R)}},$$

If both beams are polarized $\sigma^{\uparrow}_{L(R)} = \sigma^{\uparrow\uparrow}_{L(R)} + \sigma^{\uparrow\downarrow}_{L(R)}, \sigma^{\downarrow}_{L(R)} = \sigma^{\downarrow\uparrow}_{L(R)} + \sigma^{\downarrow\downarrow}_{L(R)}$

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

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

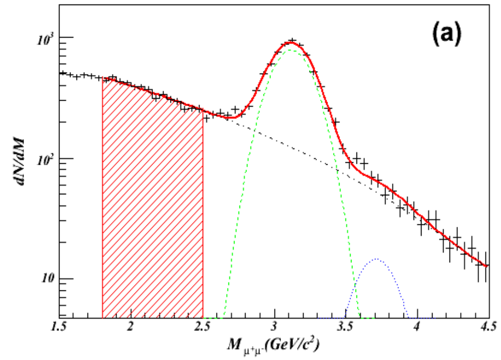
- **Final asymmetry**

$$A_N = \frac{\dfrac{\langle f(\phi)\rangle_L}{P}\dfrac{\frac{N_L^{\uparrow} - RN_L^{\downarrow}}{N_L^{\uparrow} + RN_L^{\downarrow}}}{\delta A_L^2} - \dfrac{\langle f(\phi)\rangle_R}{P}\dfrac{\frac{N_R^{\uparrow} - RN_R^{\downarrow}}{N_R^{\uparrow} + RN_R^{\downarrow}}}{\delta A_R^2}}{\dfrac{1}{\delta A_L^2} + \dfrac{1}{\delta A_R^2}}$$

J/ψ Measurements in the Muon and Central Arms

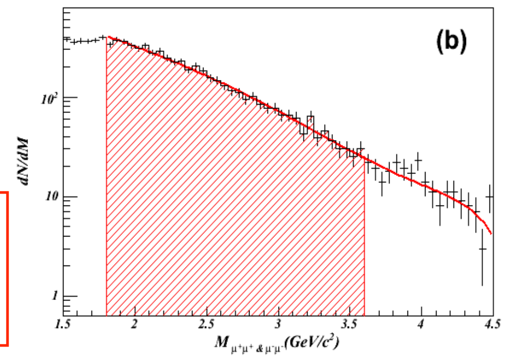
In Muon Arm

$$J/\psi \rightarrow \mu^+\mu^-$$



$A_N^{Incl.}$: 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 (2.0 run8) < *m* <2.5 along with charged pairs of the same sign in invariant mass range 1.8 (2.0 run8) < *m* < 3.6

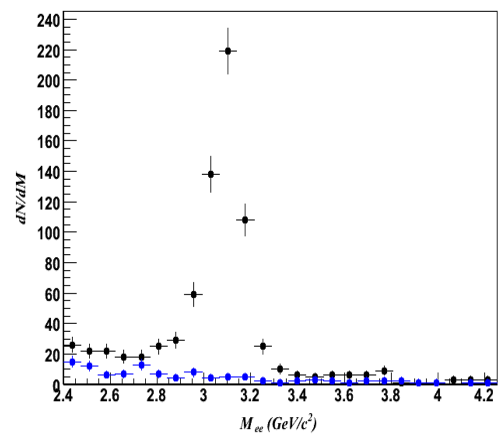


$$A_N^{J/\psi} = \frac{A_N^{Incl.} - r \cdot A_N^{BG}}{1 - r}$$

In Central Arm

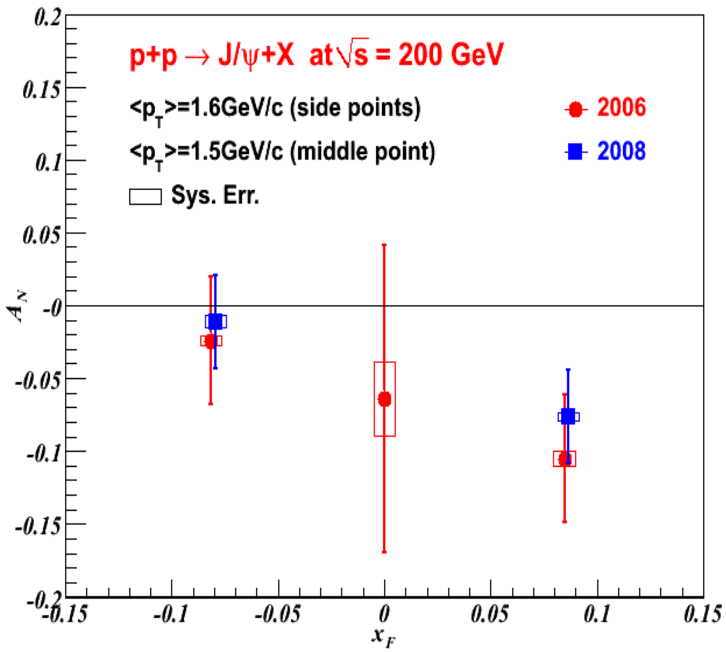
$$J/\psi \rightarrow e^+e^-$$

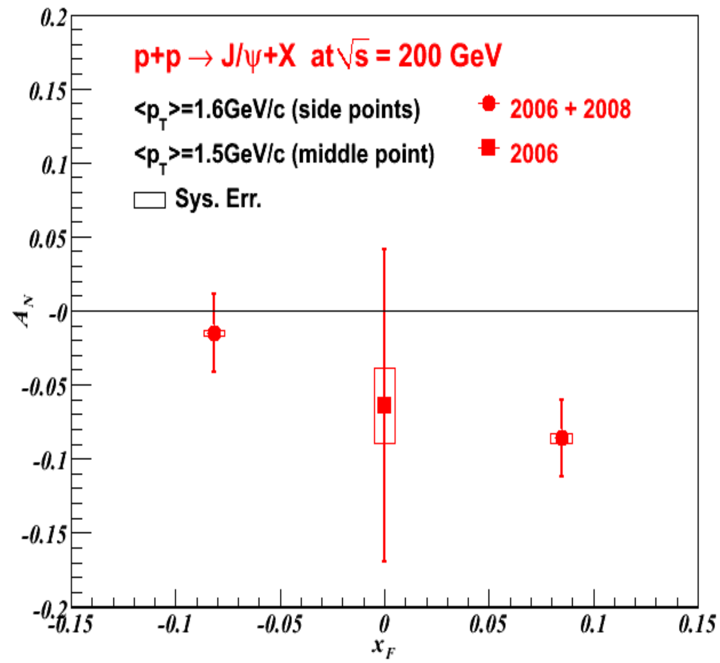
BG subtraction: $2*sqrt\{N_{e+e+}N_{e-e-}\}$
Remaining continuum background
Is small, not enough statistics
Assuming: $A_N^{BG}=0$



J/ψ A_N vs x_F

PHENIX PRD 82, 112008 (2010)

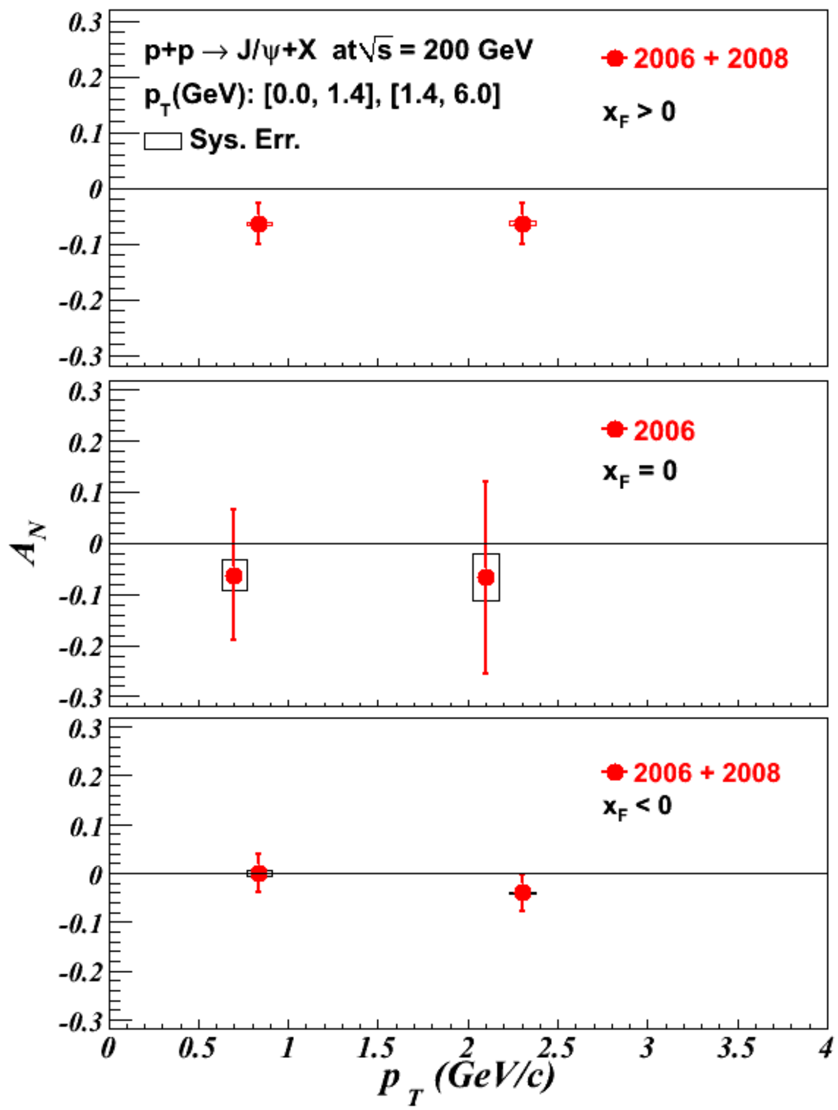




Asymmetries were obtained as a function of J/Psi Feynman-x, with a value of -0.086 ± 0.026 (stat.) ± 0.003 (sys.) in the forward region.

- Suggests possible non-zero tri-gluon correlation functions (gluon Sivers functions) in transversely polarized protons.
- Possible significant Color Singlet channel contribution?
- More theoretical and experimental investigations are needed!

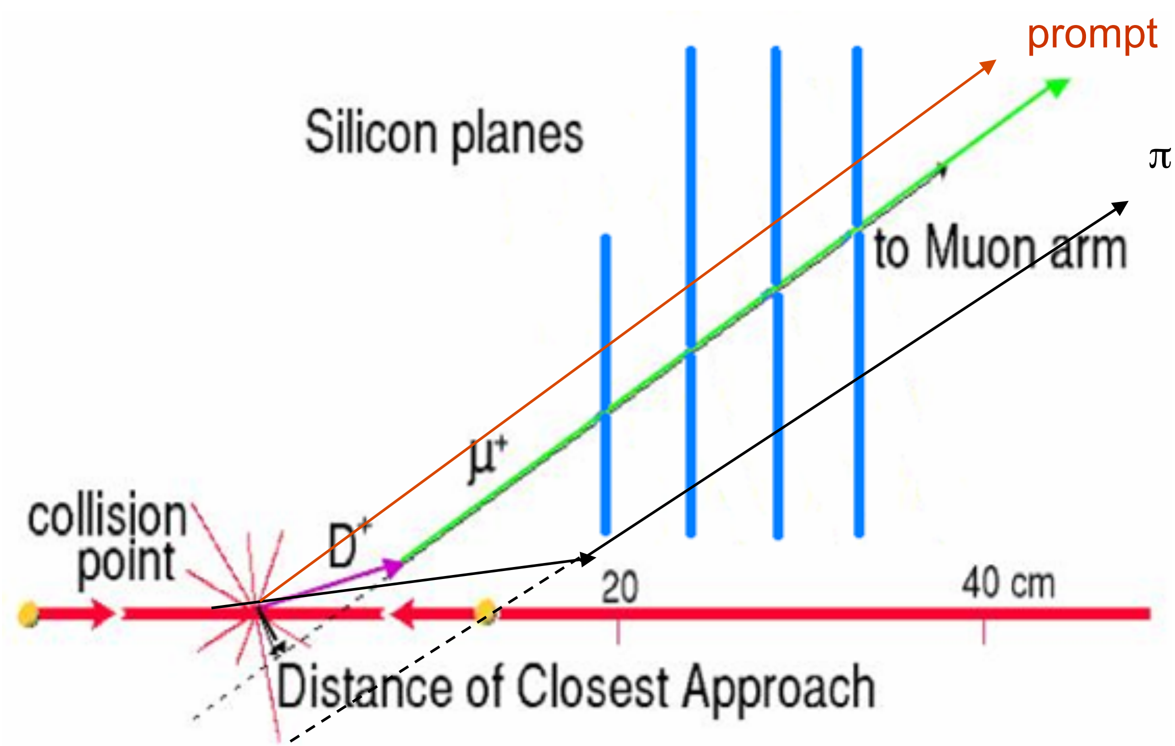
Results: A_N vs p_T

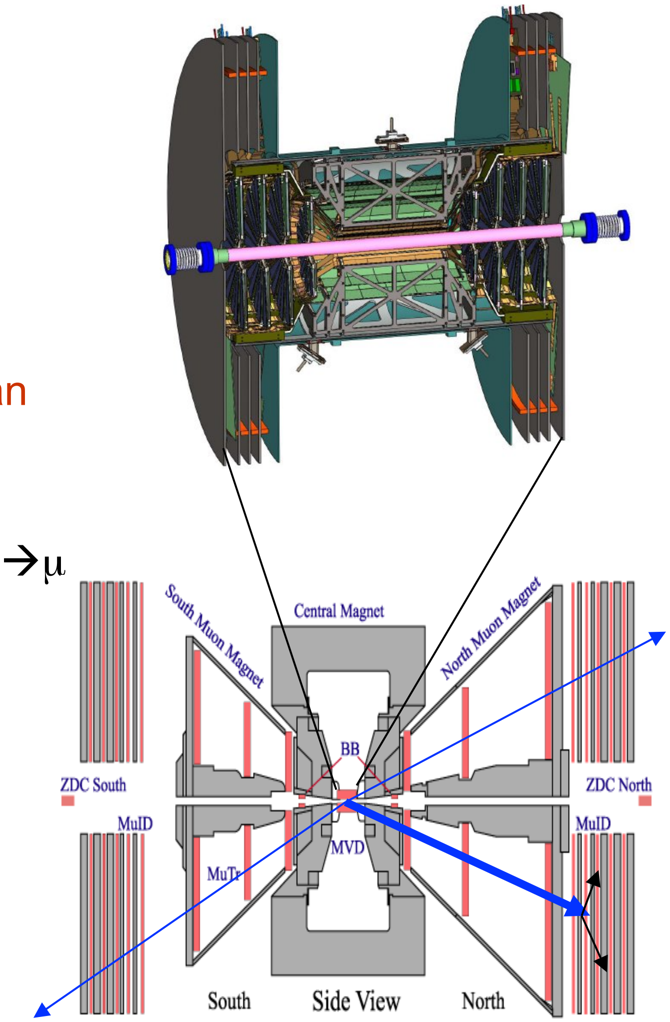


Future Prospects

PHENIX Forward Silicon VTX Upgrades: by 2011

- Precision Charm/Beauty Measurements
- B→J/ψ, Drell-Yan, ψ'

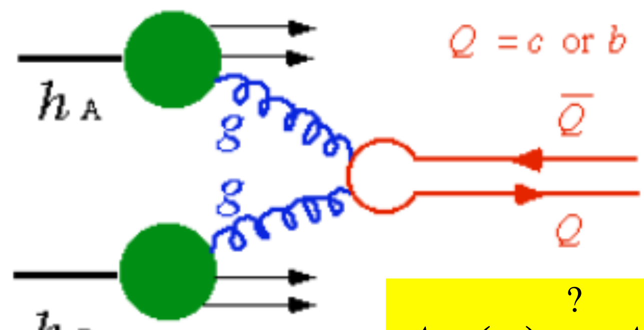




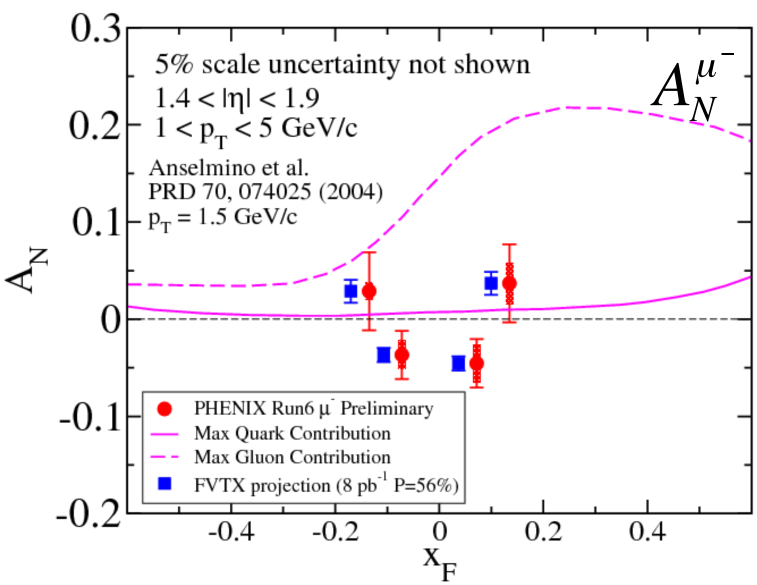
Charm SSA to Probe Gluon Sivers Distribution

D meson Single-Spin Asymmetry:

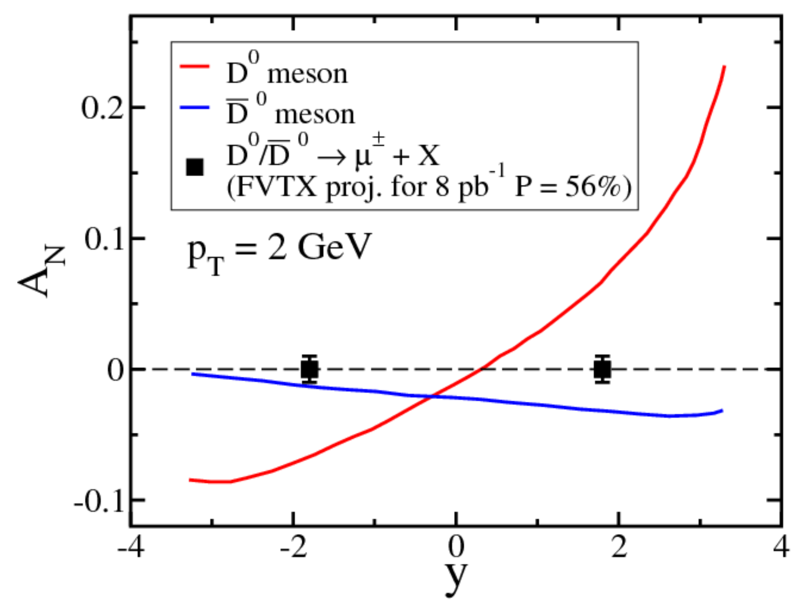
- Production dominated by gluon-gluon fusion
- Sensitive to gluon Sivers distribution
  - PHENIX-2006 data ruled out the max. gluon Sivers
  - Much improved results expected with VTX detectors



$$A_N(c) \overset{?}{\neq} A_N(\bar{c})$$



Kang, Qiu, Yuan, Vogelsang, Phys. Rev. D 78,114013(2008)



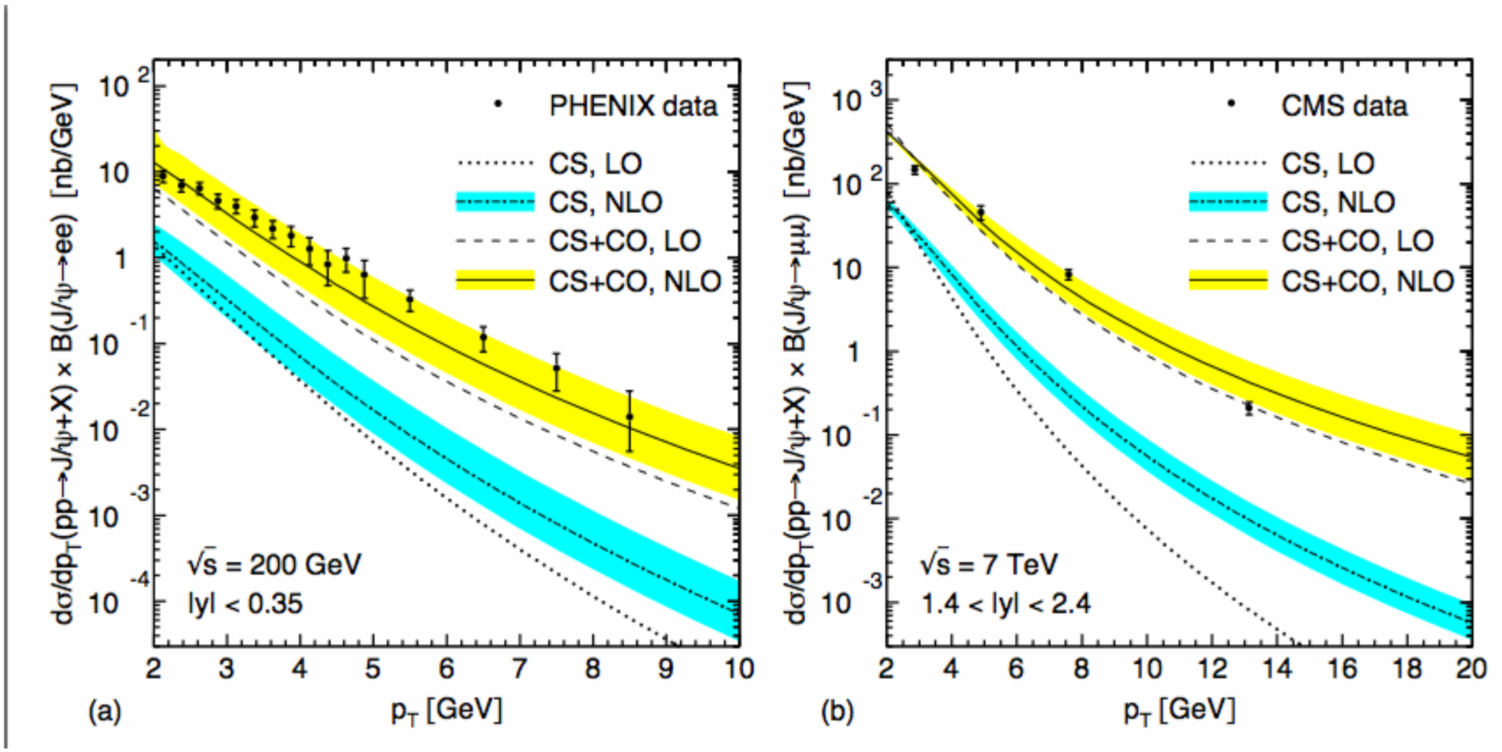
Summary and Outlook

- First measurements of TSSA in J/Psi production in p+p collisions at RHIC
  - In the forward direction, 3.3σ effect observed

    A_N = -0.086 ± 0.026 (stat.) ± 0.003 (sys.)
  - Possible none-zero Gluon Sivers (or Twist-3 funcs)
  - Suggesting possible significant Color Singlet contribution at RHIC
- Much improved results expected in near future
  - Future high luminosity runs
  - FVTX upgrade:
    - Psi', DY asymmetry possible
    - Open charm to constrain gluon's Sivers (or Twist-3)functions
- Active theoretical work ongoing for better understanding of J/psi production mechanisms.

backup

NRQCD @NLO



PHENIX data
CS, LO
CS, NLO
CS+CO, LO
CS+CO, NLO
√s = 200 GeV
lyl < 0.35
dσ/dp_T(pp→J/ψ+X) × B(J/ψ→ee) [nb/GeV]
p_T [GeV]
(a)
CMS data
CS, LO
CS, NLO
CS+CO, LO
CS+CO, NLO
√s = 7 TeV
1.4 < lyl < 2.4
dσ/dp_T(pp→J/ψ+X) × B(J/ψ→μμ) [nb/GeV]
p_T [GeV]
(b)

Theoretical Models of TSSA (I)

1. Transverse momentum dependent (TMD) function approach

Proton Structure | pQCD

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

Assuming TMD factorization….

small spin dependence

fragmentation function

-- Quark transversity distributions and Collins spin dependant fragmentation function

$$A_N \propto \delta q(x)\cdot H_1^{\perp}(z_2,\bar{k}_{\perp}^2)$$

-- Sivers quark-distribution

Correlation between proton-spin and quark transverse momentum

$$A_N \propto f_T^q(x,k_\perp^2)\cdot D_q^h(z)$$

TMD factorization is not valid for process involving more than two hadrons.

T.Rogers, P Mulders, PRD81, 094006(2010)

Theoretical Models of TSSA (II)

2. Collinear factorization approach

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

Twist-3 factorization works at Q >>Λ_{QCD},

$$d\sigma(S_T) \propto H(Q, l_T) \otimes f_3(x_1, x_2) \otimes f_2(x')$$

-- Twist-3 quark-gluon correlation function T_F

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

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

$$T_F(x,x) = -\int \frac{d^2\vec{k}_\perp}{2\pi} \frac{\vec{k}_\perp^2}{M^2} f_T(x,k_\perp)|_{DIS}$$

TMDs and Collinear Twist-3 Functions

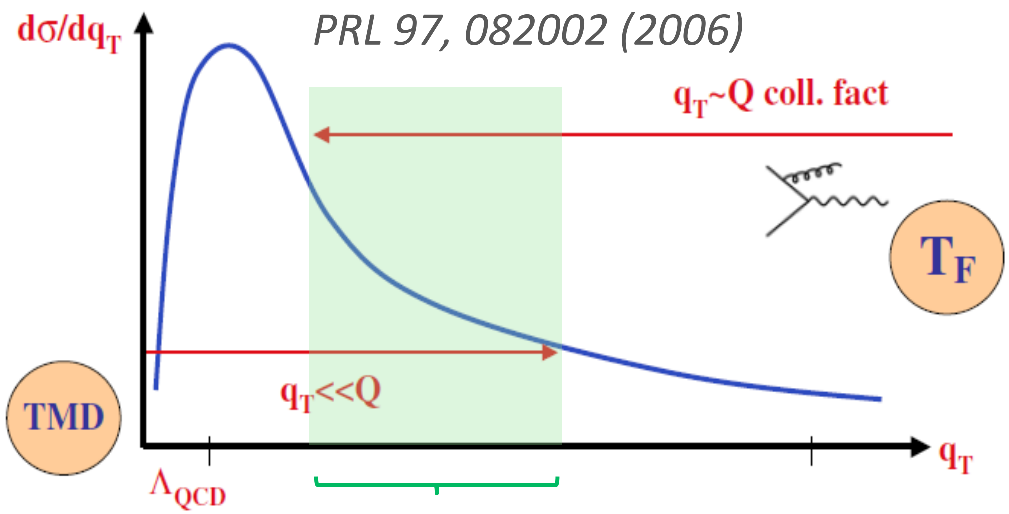
For DY process, when $Q \sim q_T >> \Lambda_{QCD}$, TMDs can be calculated in pQCD and expressed in terms of twist-3 functions.

$$f_{1T}^{\perp}|_{\rm DIS}(x_B, k_\perp) = \frac{-\alpha_s}{\pi} \frac{M^2}{(\vec{k}_\perp^2)^2} \int \frac{dx}{x} \left[A_{f_{1T}^\perp} + C_F T_F(x,x) \delta(1-\xi) \left(\ln \frac{x_B^2 \zeta^2}{\vec{k}_\perp^2} - 1 \right) \right]$$

$$A_{f_{1T}^\perp} = \frac{1}{2N_c} T_F(x,x) \frac{1+\xi^2}{(1-\xi)_+} + \frac{C_A}{2} T_F(x, x_B) \frac{1+\xi}{(1-\xi)_+} + \frac{C_A}{2} \tilde{T}_F(x_B, x)$$

Ji, Qiu, Vogelsang and Yuan

PRL 97, 082002 (2006)



In the overlap region both approaches give the same physics
Case study: Drell-yan

$$J/\Psi \to \mu^+\mu^-$$

Effective Luminosity:

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

Fill-by-fill analysis

Asymmetry measured fill by fill
Fix mass range to extract the number of J/Ψ (2σ)

Track/Event Selection

Rapidity range: 1.2 < |y| < 2.2
Event vertex cut: < 35cm
J/ψ P_T range : 0 - 6 GeV/c
Muon Track p_Z cut: 1.4 < $|p_Z|$< 20

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

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

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$J/\Psi \rightarrow e^{+}e^{-}$

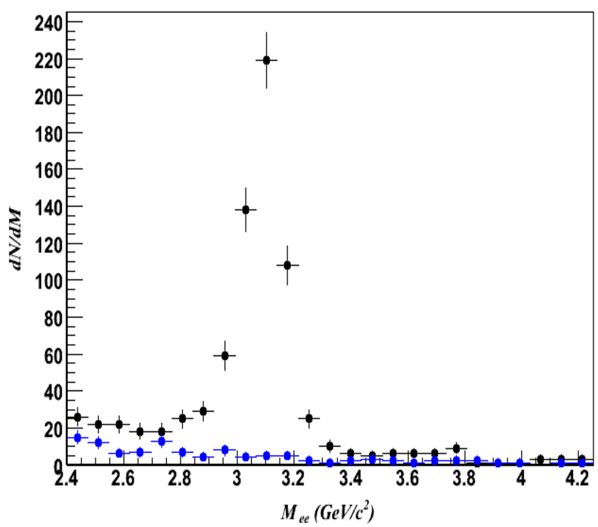
PHENIX

Effective Luminosity

Run6: $1.36pb^{-1}$

Rapidity range:

$|\eta| < 0.35$



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.

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

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

It require: R_i =<R>, f_i = <f>, P_i = <P> for all i

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.