# Study of $J/\psi$ spin alignment in proton-proton collisions at $\sqrt{s}$ = 200GeV in the PHENIX experiment at RHIC

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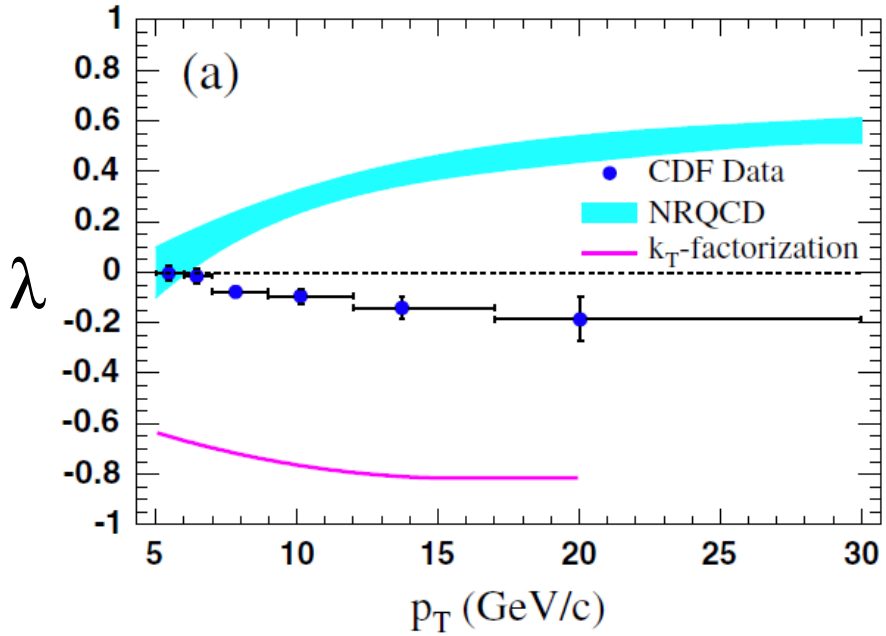
Contents

- introduction to spin alignment
- about RHIC PHENIX experiment
- acceptance study with simulation
- sensitivity at forward rapidity region
- summary

Used RSCC and RIKEN CCJ
for analysis and simulation

# $J/\psi$ spin alignment (polarization)

- Unknown part of the production mechanism of $J/\psi$
  - NRQCD calculations with color-octet mechanism succeed in describing $J/\psi$ production cross section but fail to explain its polarization
  - CDF measurements show small negative (longitudinal) polarization while NRQCD predicts positive (transverse) polarization at high $p_T$

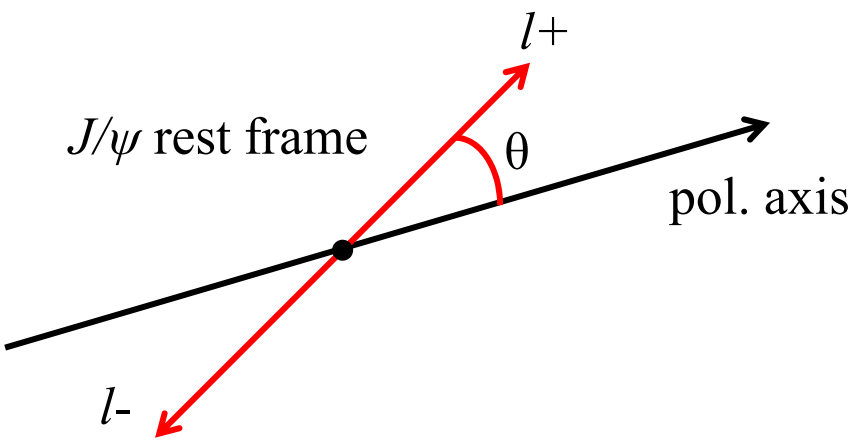


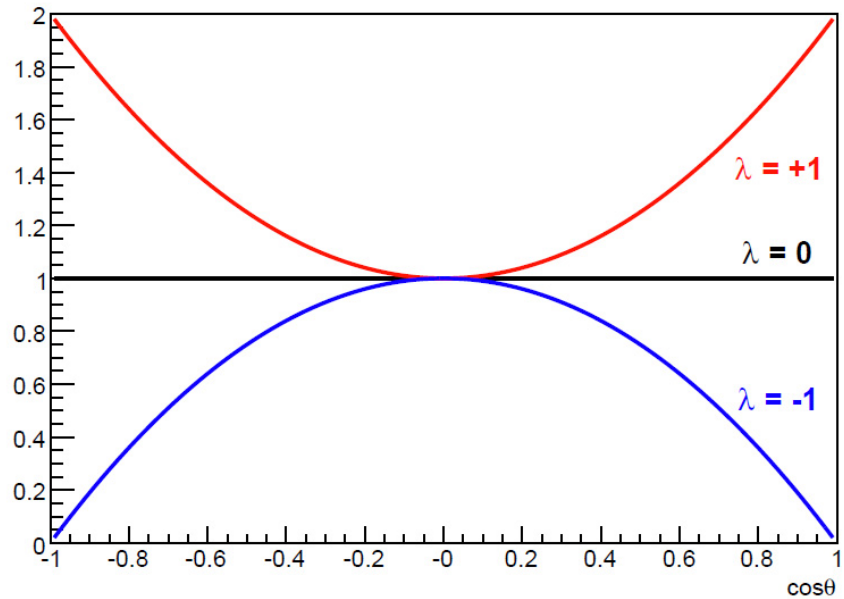

PRL 99, 132001 (2007)

- Measurements of $J/\psi$ polarization provide significant test of heavy quarkonia production models in hadronic collisions

# $J/\psi$ polarization

- $J/\psi$ polarization can be studied through the angular distribution of decay lepton pairs in $J/\psi$ rest frame
- The angular distribution is parameterized as $\frac{d\sigma}{d\cos\theta} \propto 1 + \lambda \cos^2\theta$
  - $\lambda$ is the polarization value
  - $\theta$ is the polar angle of decay lepton in $J/\psi$ rest frame with respect to the polarization axis




$\lambda = 0$ : no polarization

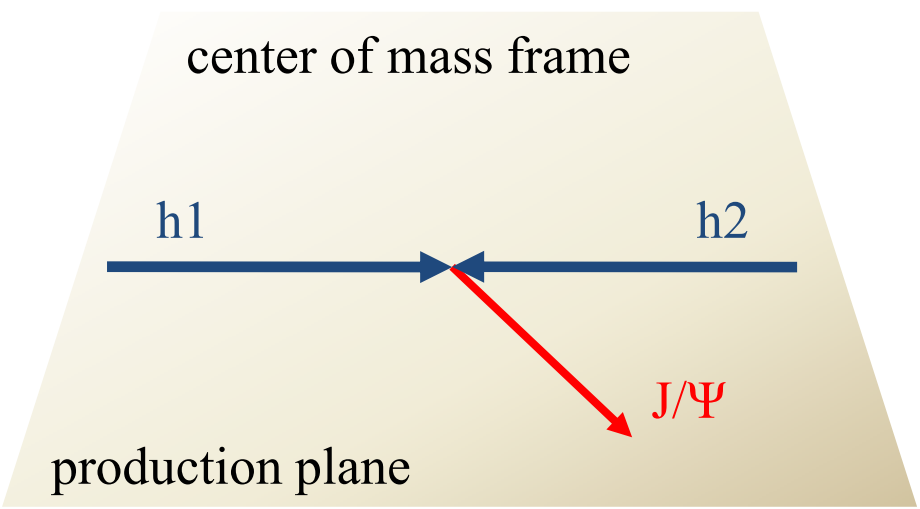
$\lambda = +1$ : transverse polarization → $J_z = +1$ or $-1$

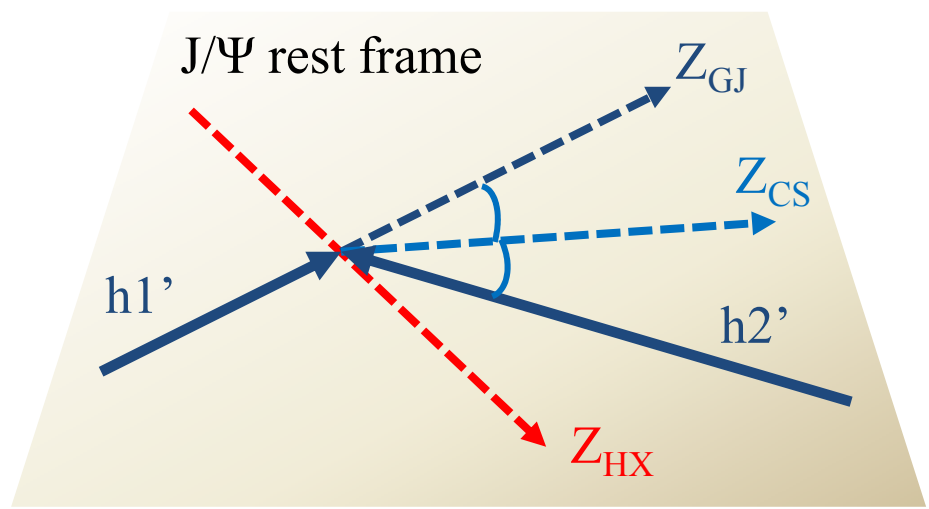
$\lambda = -1$ : longitudinal polarization → $J_z = 0$

# Polarization axis

Decay angular distribution in $J/\psi$ rest frame could be measured with respect to several definitions of polarization axis

- Helicity (HX) $J/\psi$ momentum in center of mass system of the colliding hadrons
- Gottfried-Jackson (GJ) direction of beam momentum in $J/\psi$ rest frame
  - h1' : forward – positive $x_F$
  - h2' : backward – negative $x_F$
- Collins-Soper (CS) Bisector of h1' & -h2'
  - ~ (h1'-h2')/2 : relative velocity of two hadrons
- All frames are identical at $p_T = 0$ GeV/c

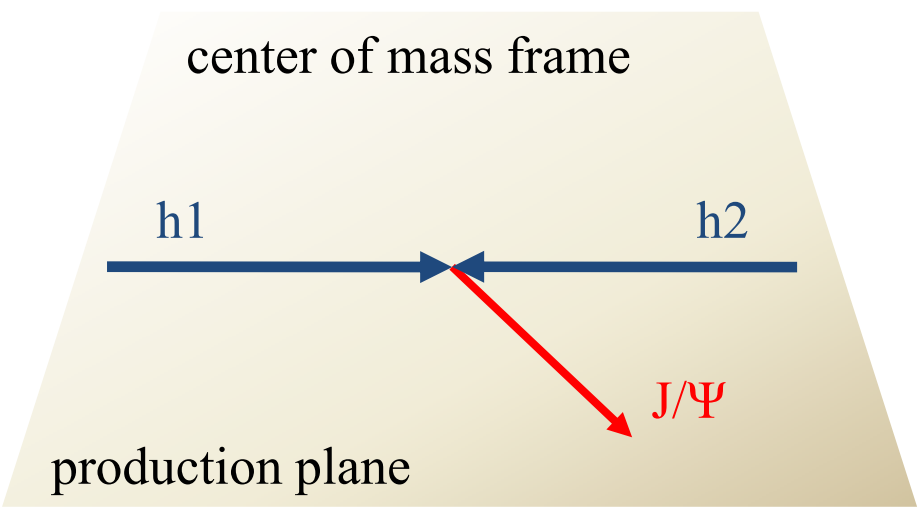


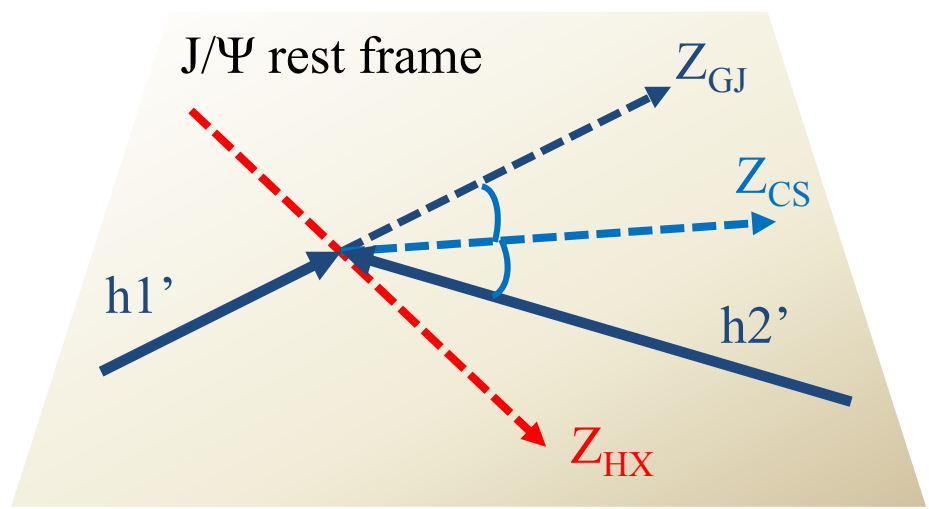



# Polarization axis

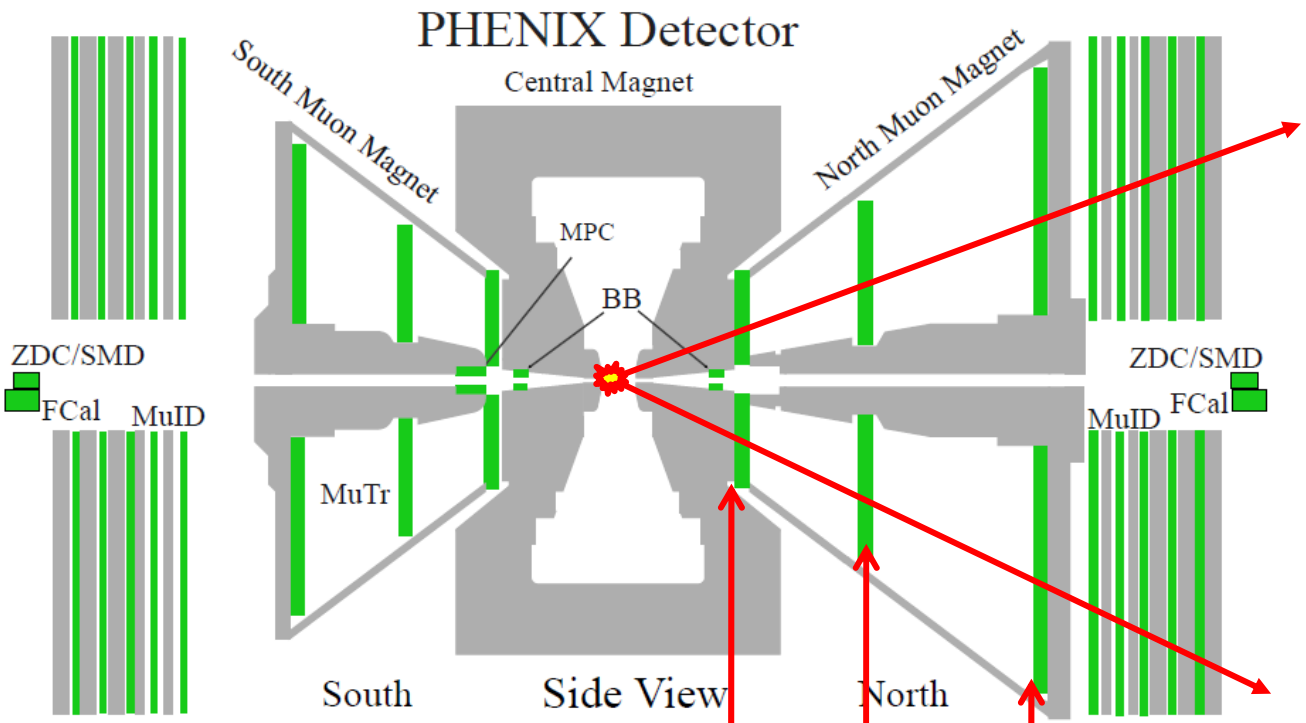
- Proper polarization axis which is sensitive to the physics phenomenon is not known well
  - Gluon fragmentation is dominant process in COM
    → helicity frame is natural frame to measure the polarization
  - Spin is inherited from initial hadron
    → Gottfried-Jackson frame is natural frame
  - Focus on both of colliding hadrons
    → Collins-Soper frame is natural frame
- Measurements at different polarization axis are important
  - Detector acceptances are not the same for all frames

Color-Octet Fragmentation:
$g + g \rightarrow c\bar{c}[^3S_1^{(8)}] + g$



# $J/\psi$ signal detection at forward rapidity region in the RHIC PHENIX experiment




- $J/\psi \rightarrow \mu^+\mu^-$
- $1.2 < |\eta| < 2.2$
- $\Delta\varphi = 2\pi$
- $p_\mu > 2$ GeV/c

Muon Tracker
momentum reconstruction
particle trajectory in magnetic field

Muon Identifier
muon identification
requiring particle penetration
through layers of chamber and steel

# Reconstructed $J/\psi$ from proton-proton collisions at $\sqrt{s}$=200GeV

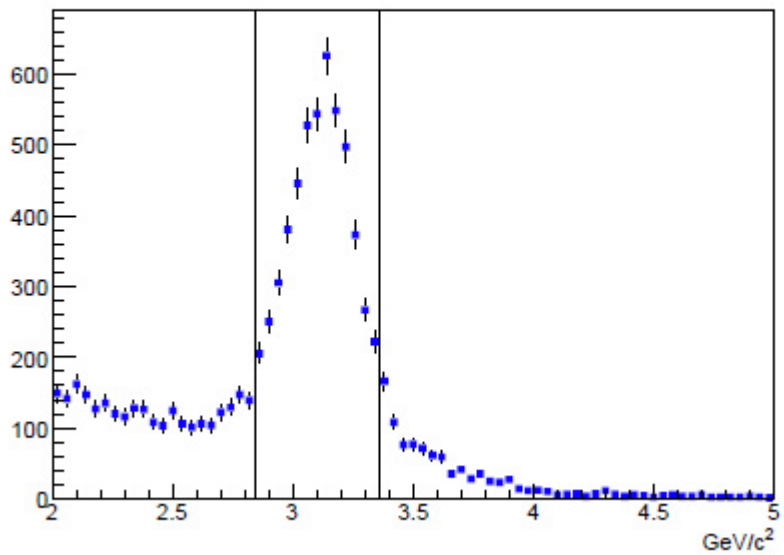
Data accumulated in 2006

Integrated luminosity of 7.5pb$^{-1}$

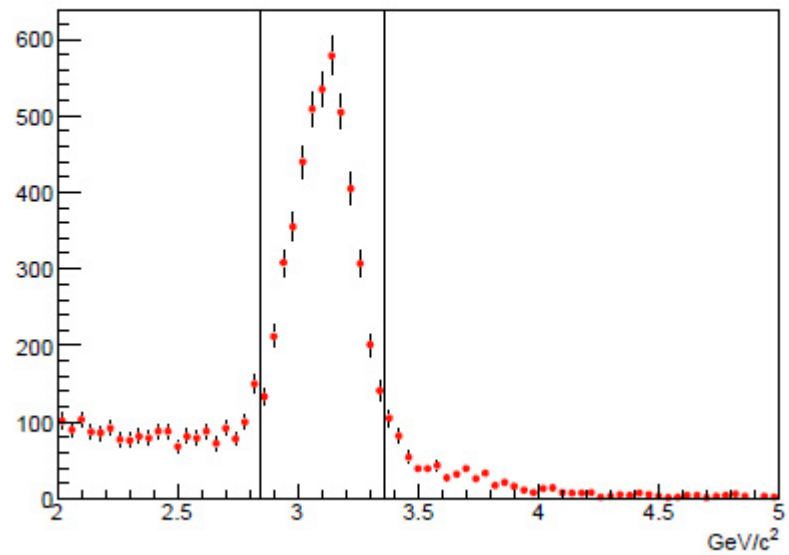
Reconstructed $J/\psi$ events

- 13.5k candidates for $1.2 < |y| < 2.2$, $p_T < 5.0$ GeV/c
- Include feed downs from $\psi(2S)$, $\chi_{cJ}$ and $B$
- $J/\psi$ candidates are selected in mass window of 2.84-3.36 GeV/c$^2$, which corresponds to ~2σ of mass resolution
- Background fraction is less than 10%

$-2.2 < y < -1.2$, $p_T < 5.0$ GeV/c




$1.2 < y < 2.2$, $p_T < 5.0$ GeV/c

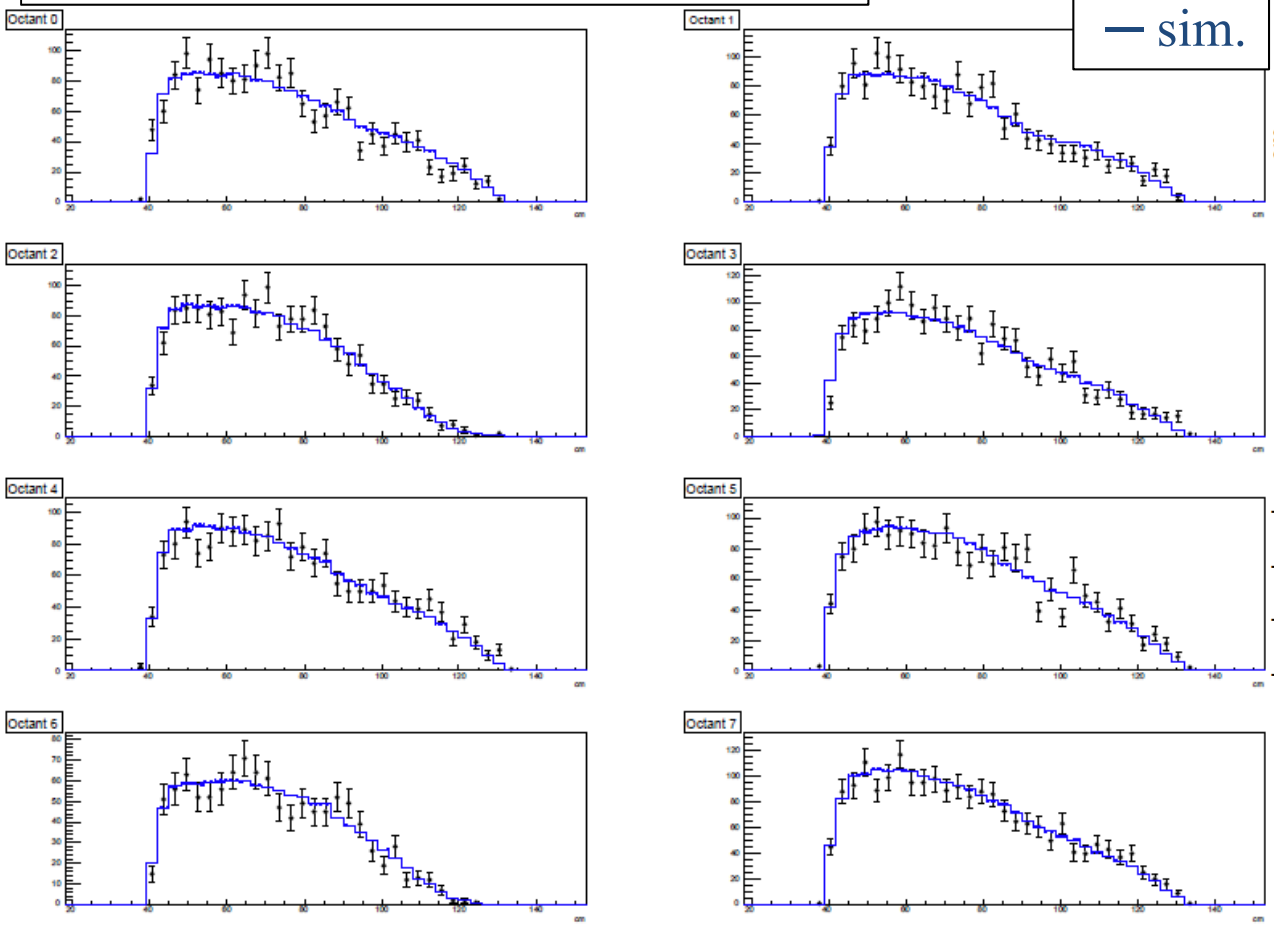


# Acceptance study with simulation

- Generate $J/\psi$ events

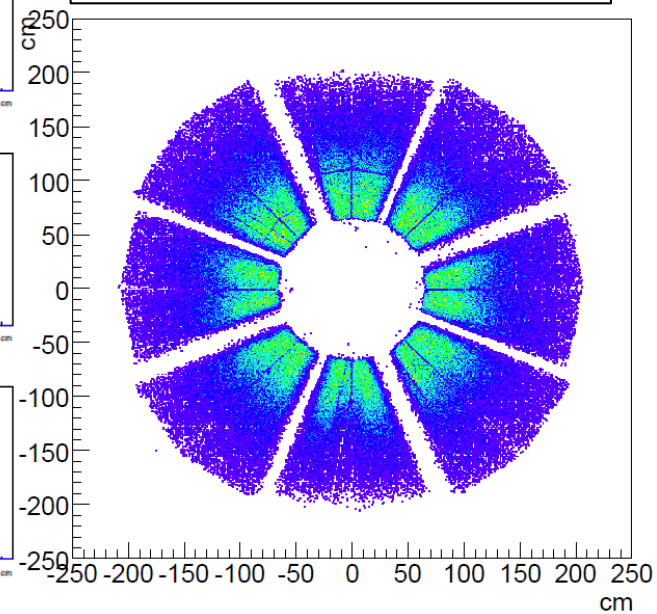
  as reconstructed $p_T$ and rapidity distributions reproduce real data
- Compare simulation to real data for muon hit profiles and kinematics

radial hit profiles at each 1/8 segment




● data
— sim.

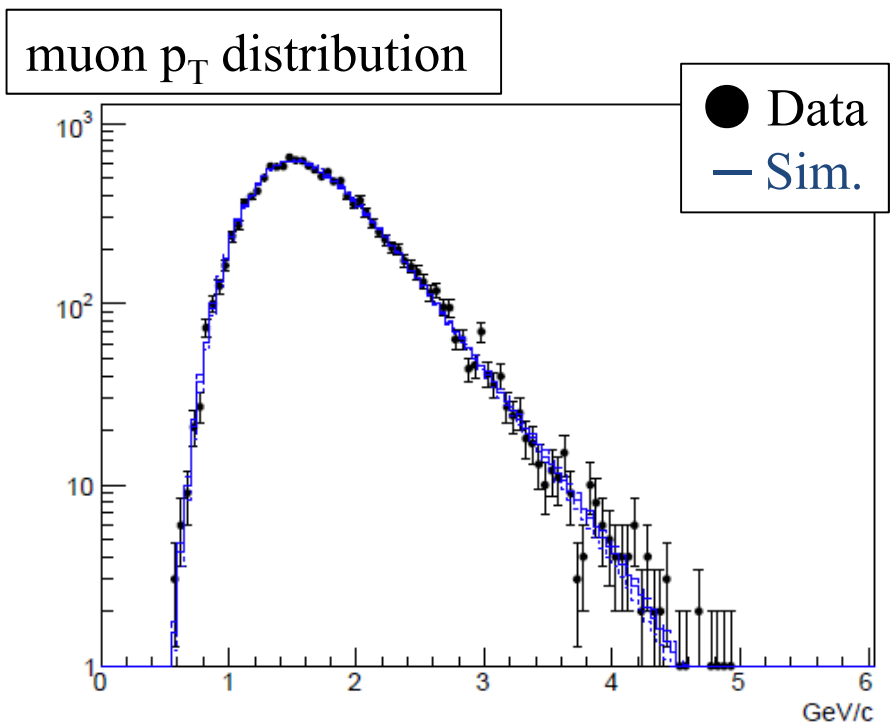
radiograph seeing from collision points

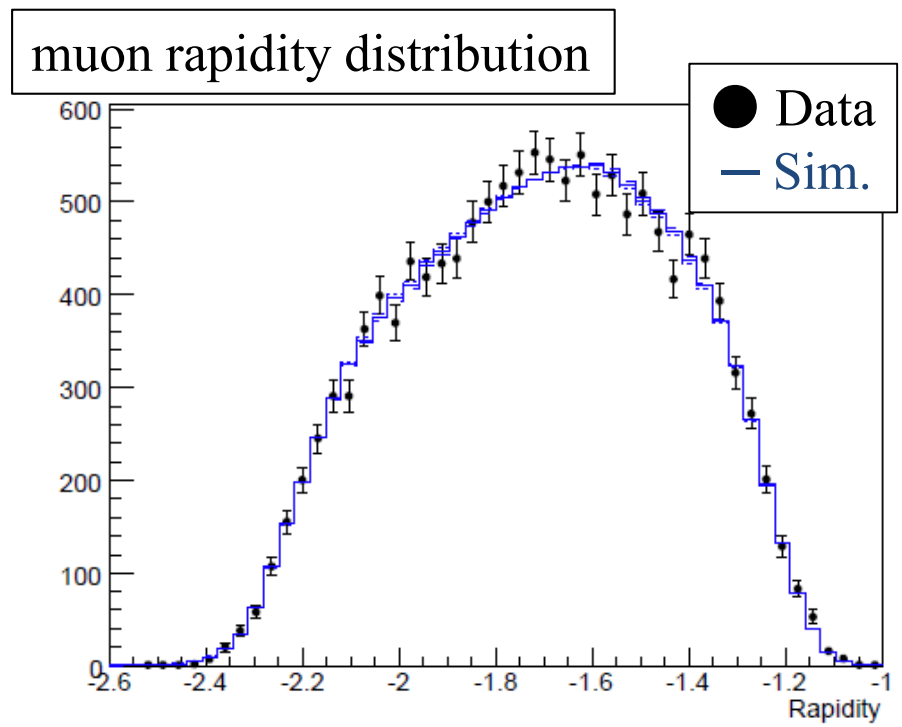


# Acceptance study with simulation

- Acceptance and reconstruction efficiency are well understood

  Trigger efficiency, chamber response, dead channels and HV status are properly included into simulation



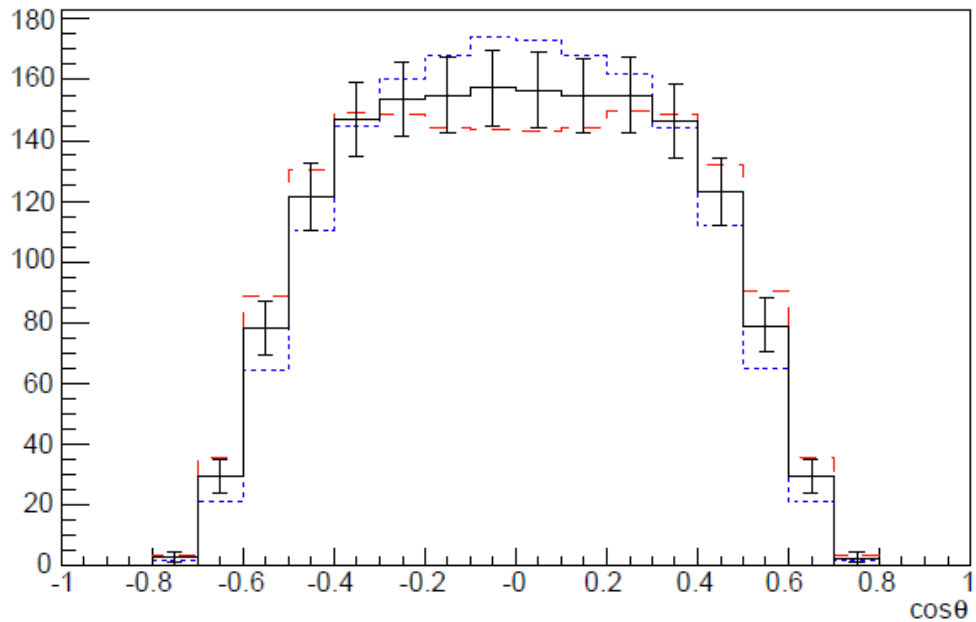



# Angular distribution

*J/ψ* polarization can be measured

- Calculate $\chi^2$ values between real data and simulations varying polarization $\lambda_{sim}$ of simulation input
- Find $\lambda_{sim}$ which minimize $\chi^2$ value

Angular distribution in helicity frame, $-2.2 < y < -1.2$, $2.0 < p_T < 5.0$ GeV/c

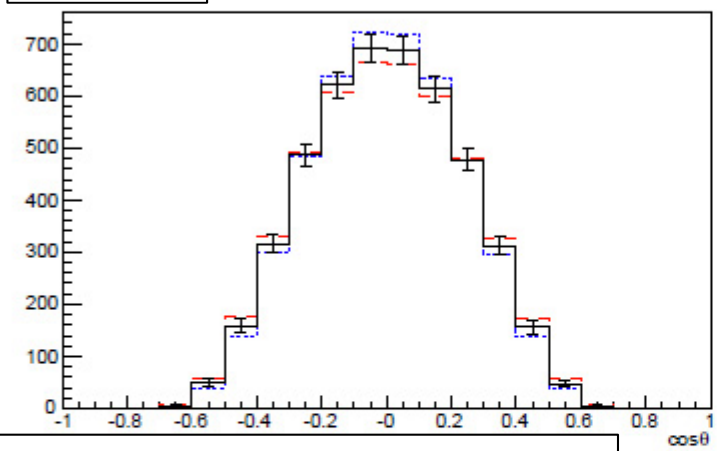



solid line : sim. with $\lambda_{sim}$=0, non-polarization
dashed (red) : sim. with $\lambda_{sim}$=+1, transverse polarization
dotted (blue) : sim. with $\lambda_{sim}$=-1, longitudinal polarization

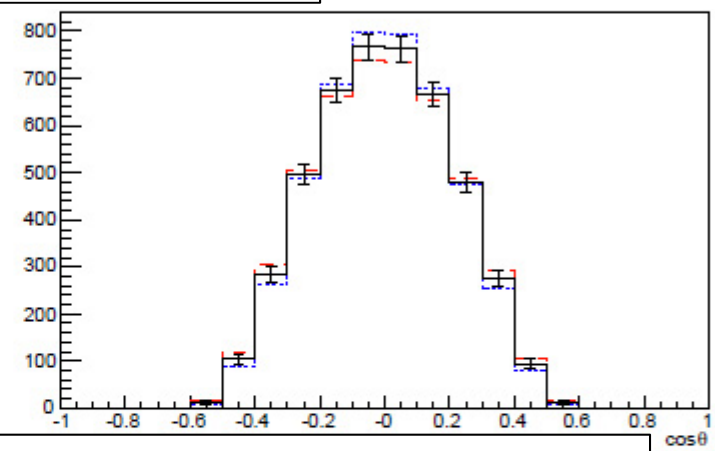
# Angular distributions – $p_T$ 0.0-2.0 GeV/c

- We have limited acceptances at low $p_T$ region for all frames
- Small differences appear for $\lambda_{sim}$ compared to statistical errors

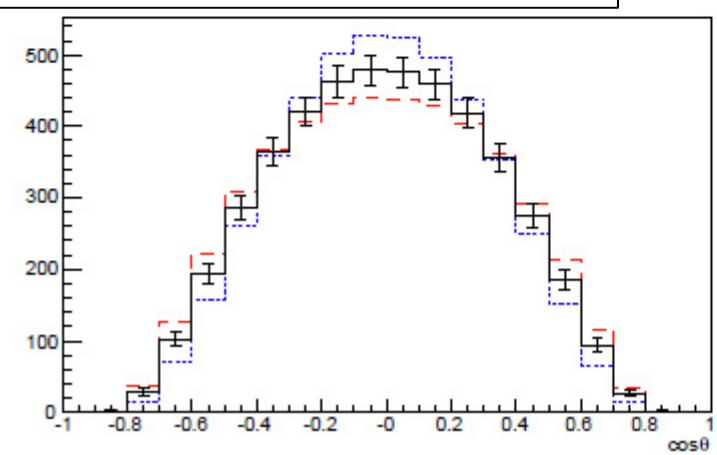
helicity



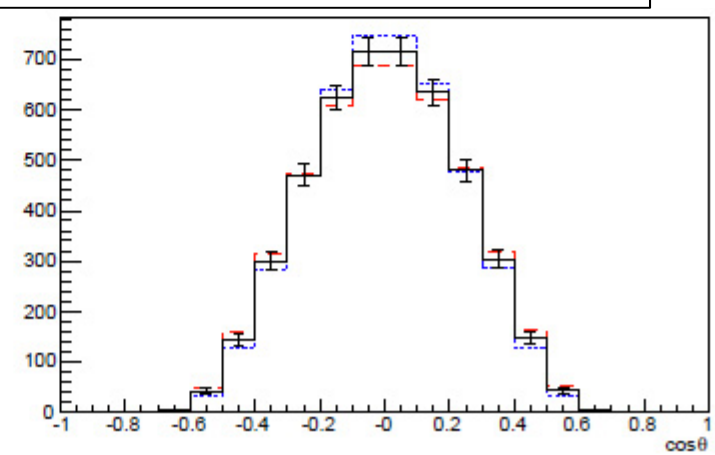

Collins-Soper




Gottfried-Jackson : forward



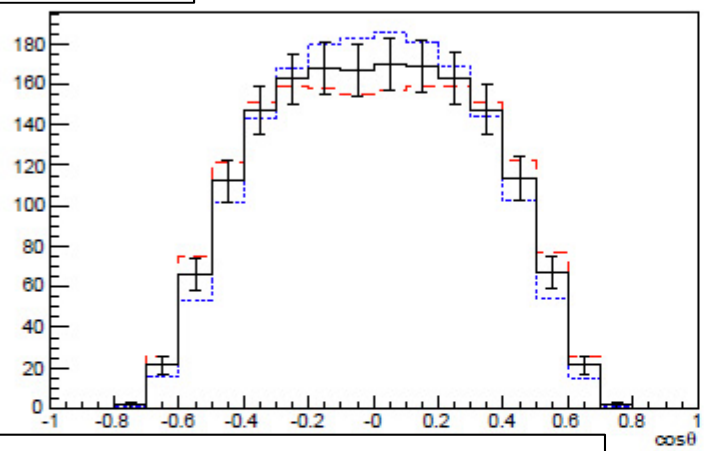

Gottfried-Jackson : backward



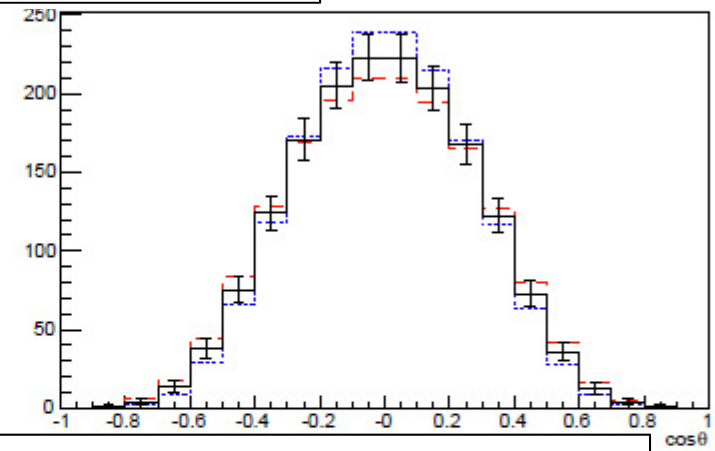
# Angular distributions – $p_T$ 2.0-5.0 GeV/c

- Acceptances get wider at high $p_T$ region for all frames
- The PHENIX Muon Arm is most sensitive to GJ forward frame

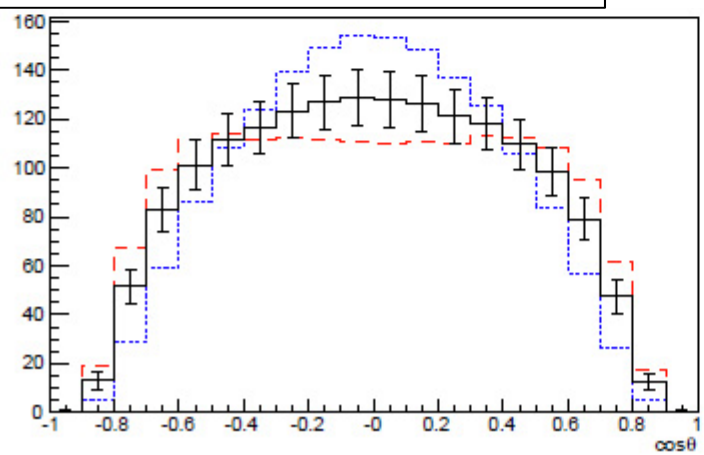
helicity



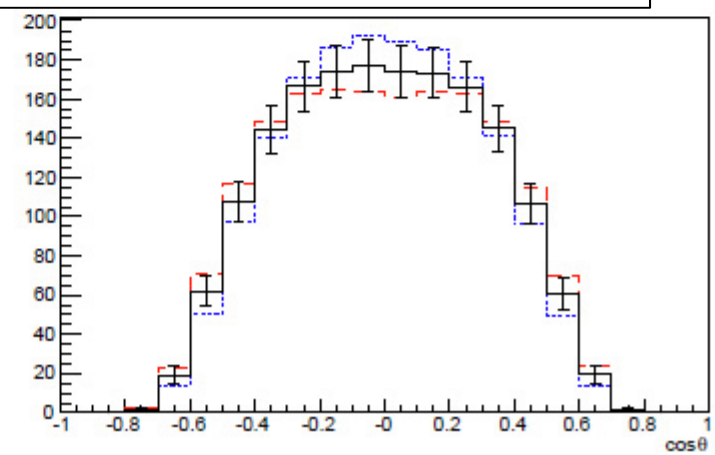

Collins-Soper




Gottfried-Jackson : forward

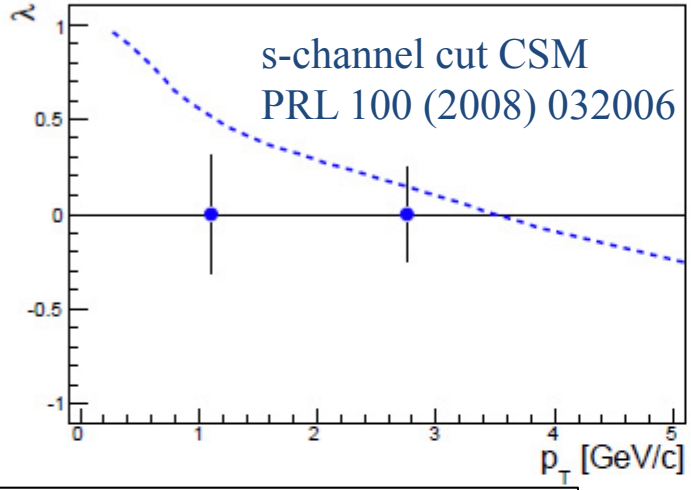



Gottfried-Jackson : backward

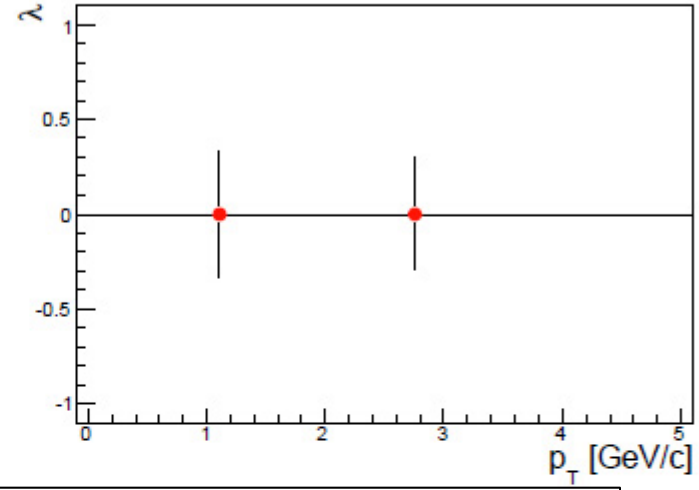


# Sensitivities

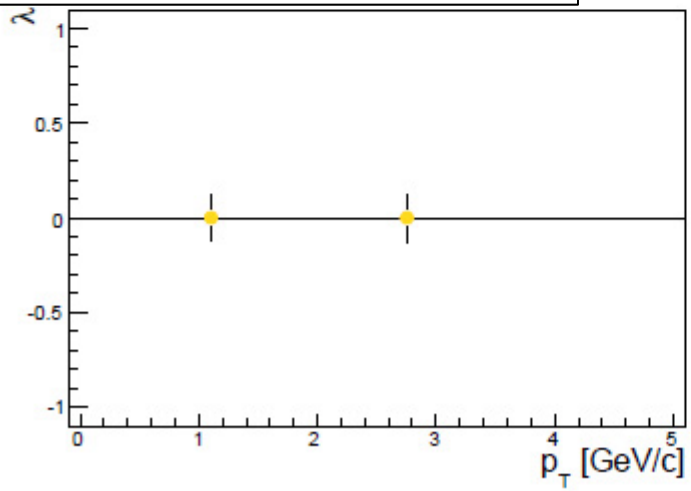
helicity



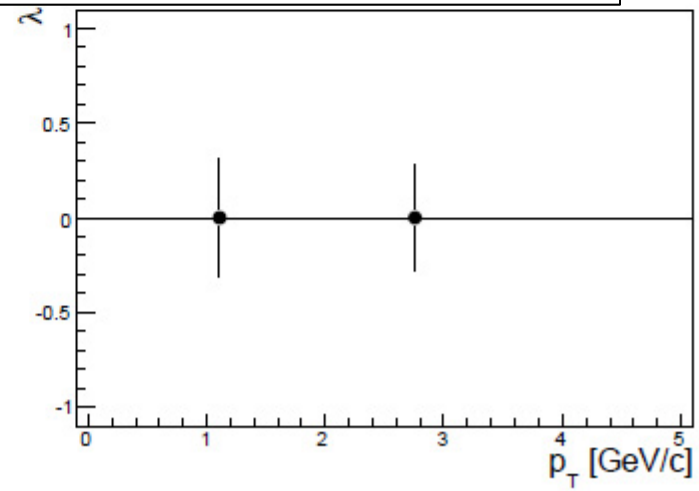

Collins-Soper




Gottfried-Jackson : forward



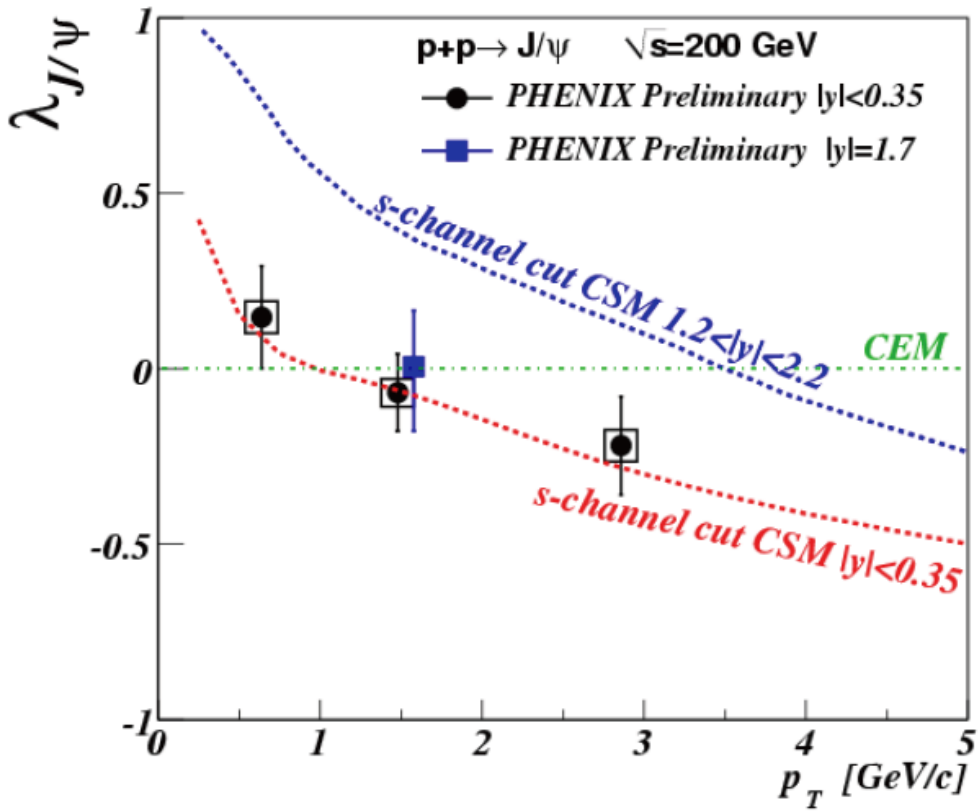

Gottfried-Jackson : backward




- Only statistical errors are shown
- Better sensitivities at higher $p_T$ due to the wider acceptances

# Results at mid rapidity and forward rapidity

- The PHENIX experiment has preliminary results
  - for mid-rapidity region
  - for forward rapidity region with data accumulated in 2005
- Combined results of forward and mid-rapidity can help to test different production mechanism models



# Summary

- Measurements of $J/\psi$ spin alignment (polarization) provide the significant test of production models of heavy quarkonia
- RHIC PHENIX experiment allow us to measure $J/\psi$ polarization at forward rapidity region
  - proton-proton collision data at $\sqrt{s}$=200GeV obtained in 2006
  - 13.5k reconstructed $J/\psi$ events for $1.2 < |y| < 2.2$, $p_T < 5.0$ GeV/c
  - include feed downs from $\psi(2S)$, $\chi_{cJ}$ and $B$
- Understanding of acceptance and efficiency is quite important
- Sensitivities for helicity, Gottfried-Jackson and Collins-Soper frame are estimated
  - Measurements for different polarization axis are important because "natural" frame is not well-known
  - Expected statistical errors of 0.1 ~ 0.3 depending on the frames
  - The PHENIX Muon Arm is most sensitive to Gottfried-Jackson frame
- We are working for systematic error estimation

- Measurements of anisotropy for azimuthal direction in $J/\psi$ rest frame would be also important
- Can the $J/\psi$ spin alignment measured in different proton spin states reveal additional information about the spin structure ?

# Back ups

# BG correction

$$\frac{dN}{d\cos\theta} \propto N_{SIG}(1+\lambda_{SIG}\cos^2\theta) + N_{BG}(1+\lambda_{BG}\cos^2\theta)$$

$$\propto 1 + \frac{N_{SIG}\lambda_{SIG} + N_{BG}\lambda_{BG}}{N_{SIG}+N_{BG}}\cos^2\theta$$

$$= 1 + (R\lambda_{SIG} + (1-R)\lambda_{BG})\cos^2\theta \qquad R = \frac{N_{SIG}}{N_{SIG}+N_{BG}}$$

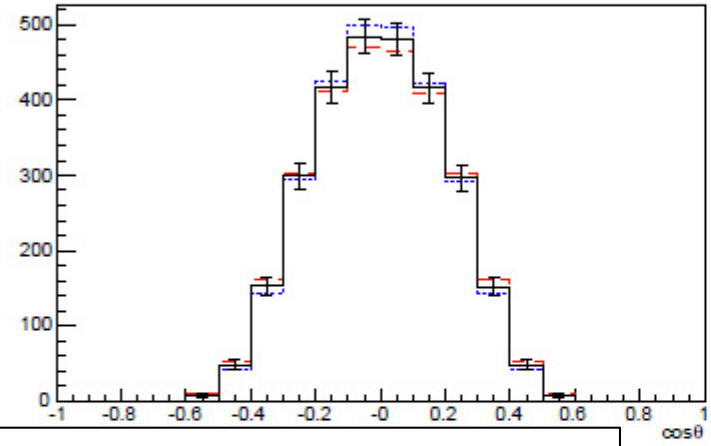
$$\lambda_{SIG} = \frac{\lambda_{measured} - (1-R)\lambda_{BG}}{R}$$

- Ratio obtained from mass fit is ~0.9
- $\lambda_{BG}$ would be zero
  → correction of ~+10% is applied to results

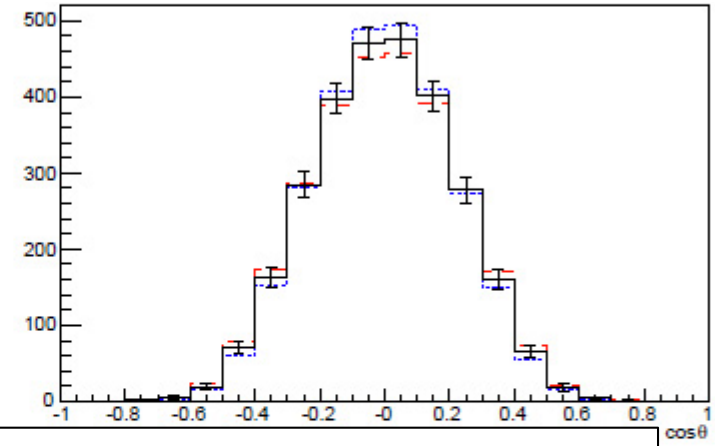
- If we think the case of $\lambda_{BG} = \pm 1$, we need an additional error of $\pm 0.1$

# Angular distributions – 1.2 < y < 1.7

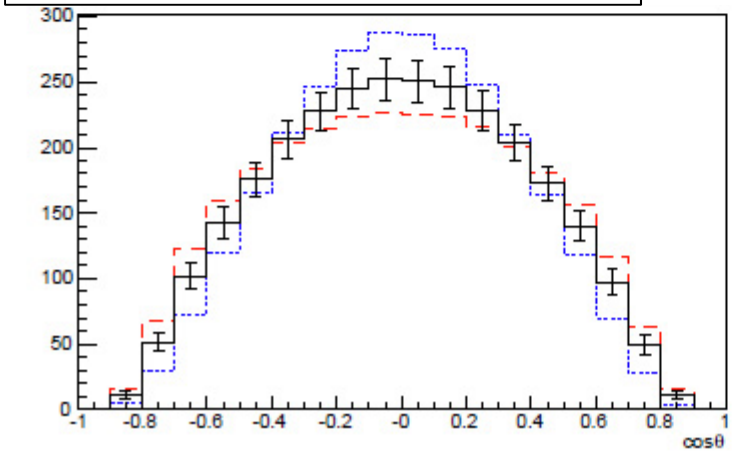
helicity



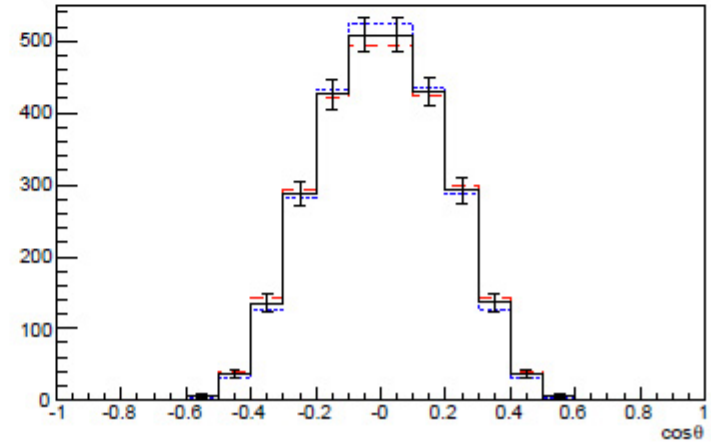

Collins-Soper




Gottfried-Jackson : forward

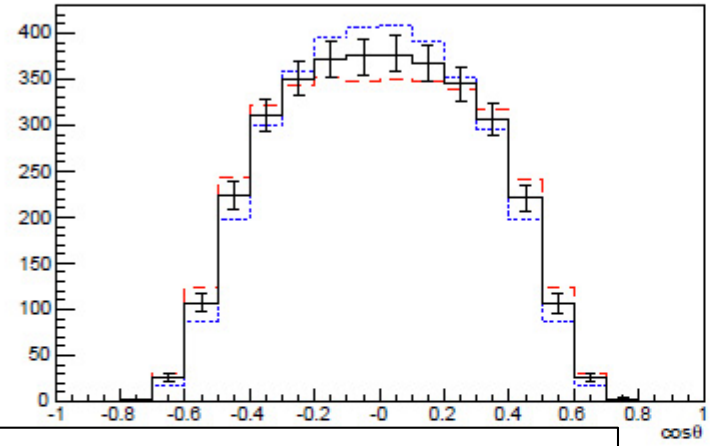



Gottfried-Jackson : backward

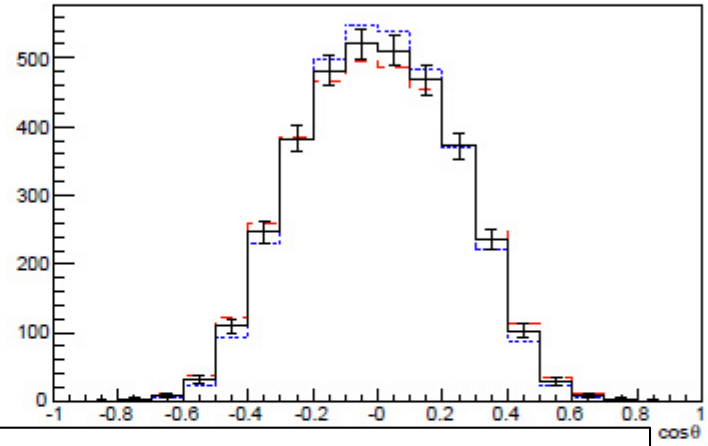


# Angular distributions – 1.7 < y < 2.2

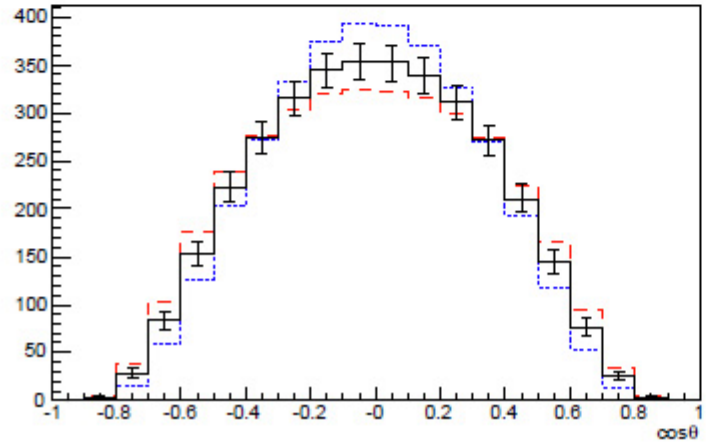
helicity



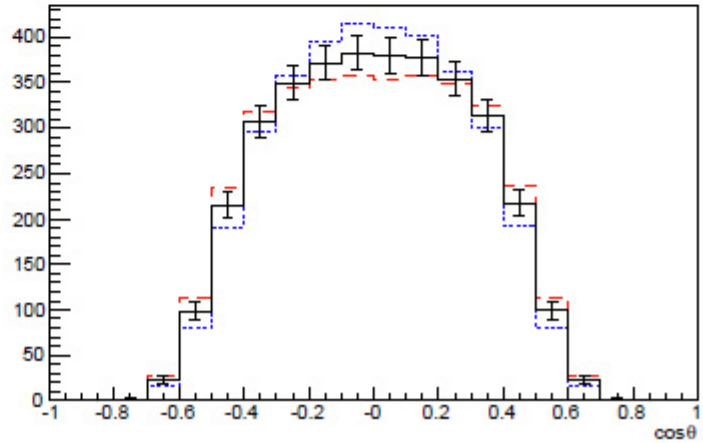

Collins-Soper



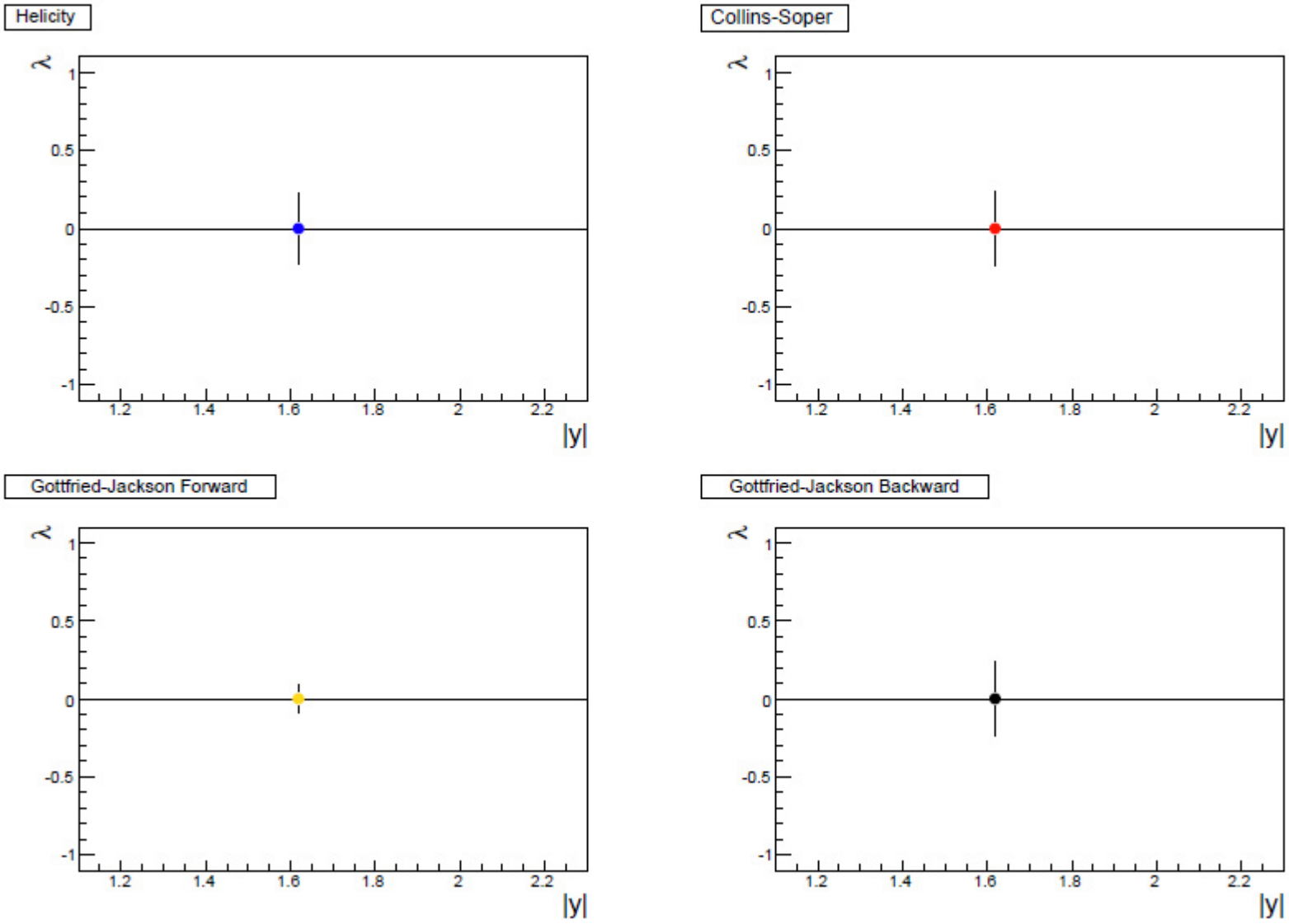

Gottfried-Jackson : forward




Gottfried-Jackson : backward

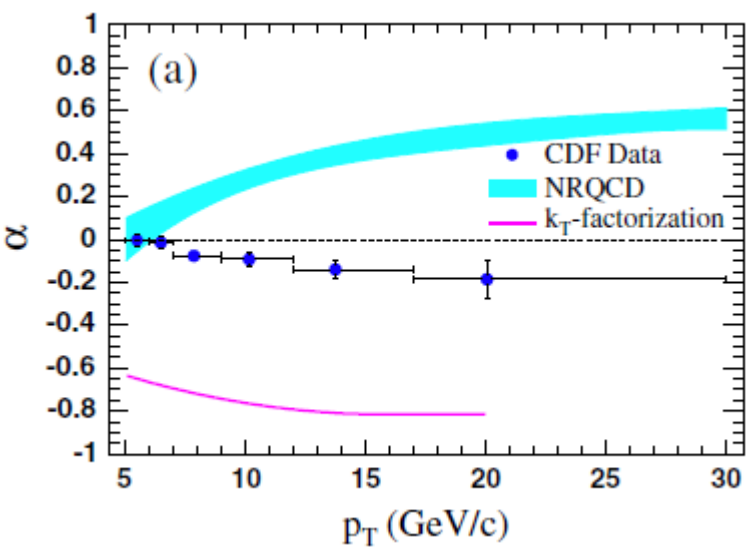


# Sensitivities



# Experimental situation I

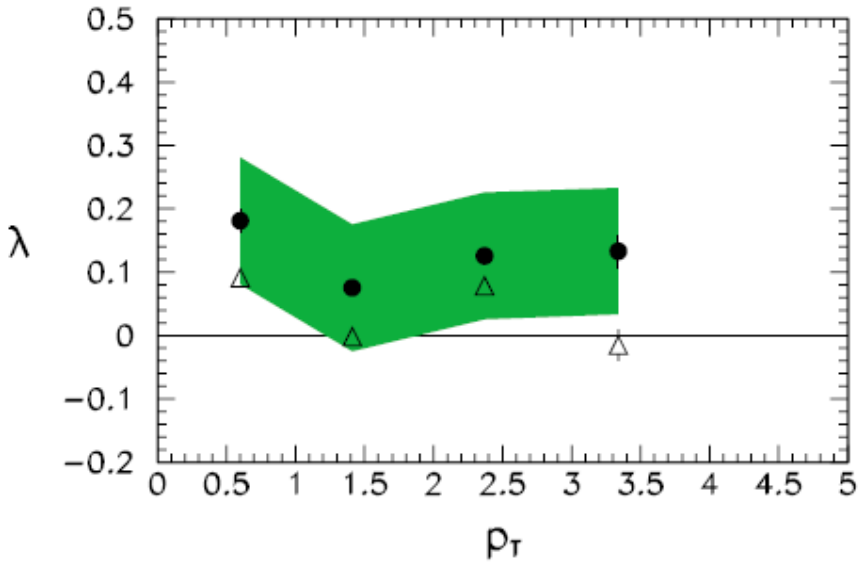
CDF
- helicity frame
- ppbar at $\sqrt{s} = 1.96$TeV
- $5 < p_T < 30$ GeV/c
- $|y| < 0.6$
- Phys. Rev. Lett. 99 (2007) 132001

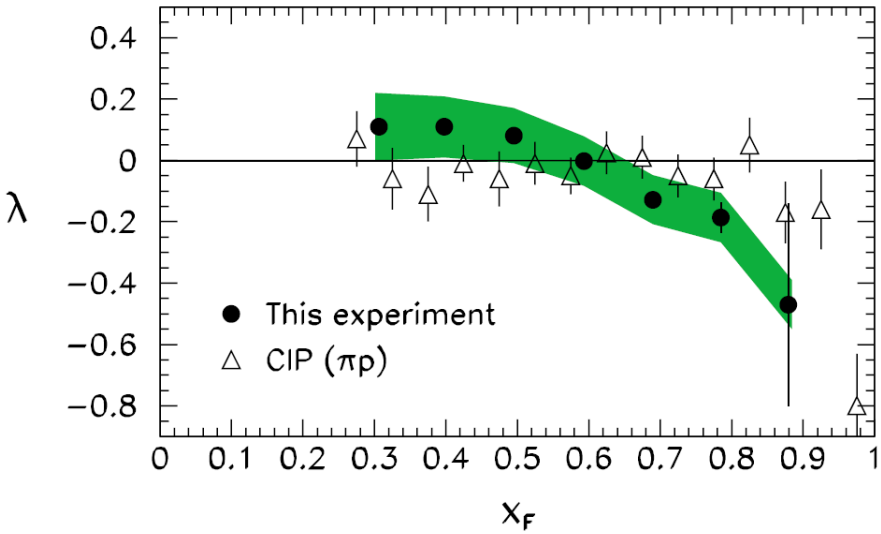


# Experimental situation II

E866

- Collins-Soper frame
- p-Cu at 800GeV, $\sqrt{s}$ = 38.8 GeV
- $p_T$ < 5 GeV/c
- 0.25 < $x_F$ < 0.45 (●), 0.45 < $x_F$ < 0.85 (△)
- Phys. Rev. Lett. 91 (2003) 211801

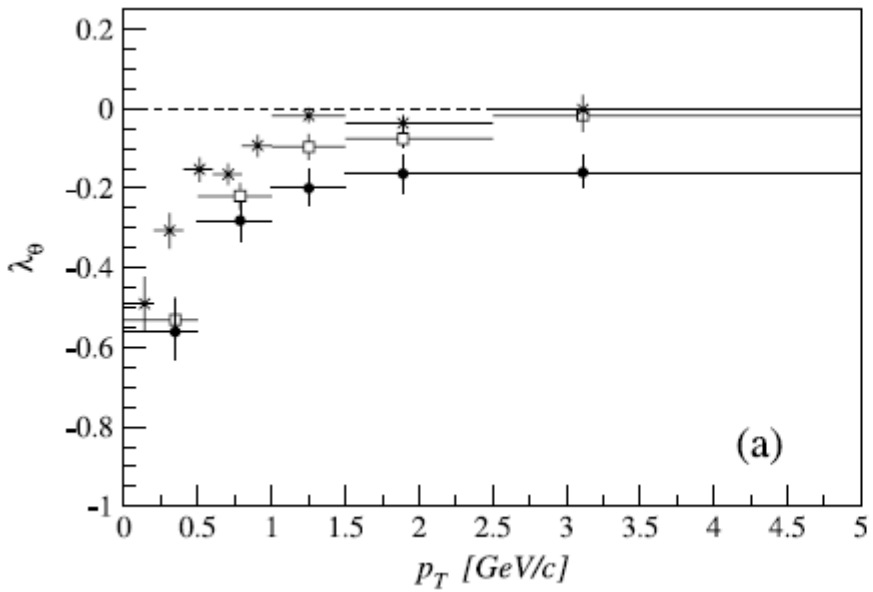


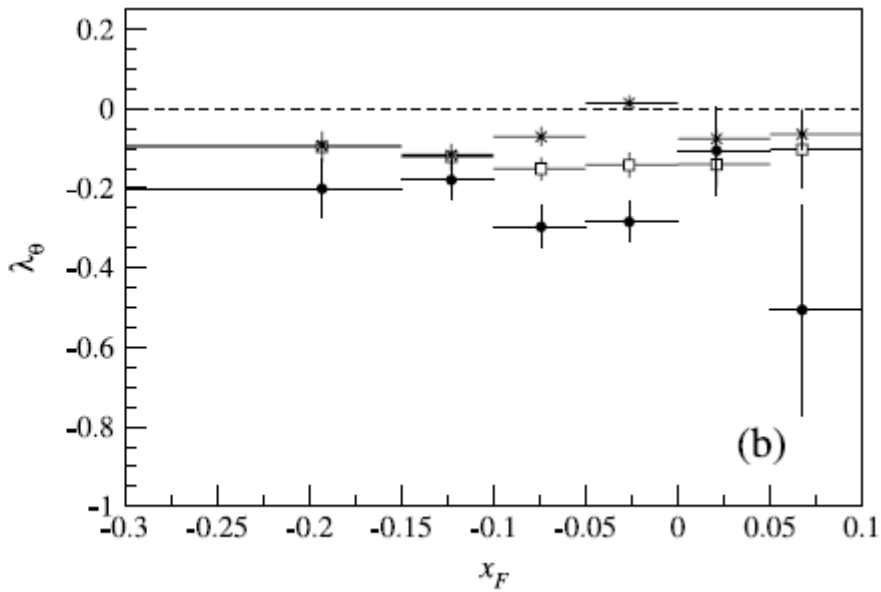



# Experimental situation III

HERA-B

- helicity (*), Gottfried-Jackson (□), Collins-Soper (●)
- p-C, p-W at 920 GeV, $\sqrt{s}$ = 41.6 GeV
- $p_T < 5.4$ GeV/c
- $-0.34 < x_F < 0.14$
- Eur. Phys. J. C 60 (2009) 517



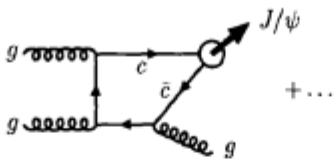
# Theoretical situation

Production models and predictions for helicity frame

- NRQCD
  - Transverse polarization at high $p_T$
  - Phys. Rev. D 62 (2000) 094005
- Color evaporation
  - No polarization
- $k_T$ factorization
  - Longitudinal polarization
  - Phys. Rev. D 66 (2002) 114003
- s-channel cut contribution to $J/\psi$ hadroproduction
  - Longitudinal polarization
  - Phys. Rev. Lett. 100 (2008) 032006

# Theoretical situation

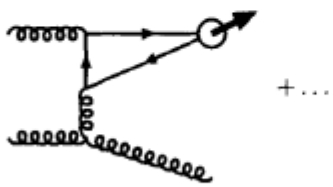
Colour-Singlet Model
(Baier,Ruckl, PLB102,364(1981))




Leading Order Color-Singlet:
$g + g \rightarrow c\bar{c}[^3S_8^{(1)}] + g$

Color-Singlet Fragmentation:
$g + g \rightarrow c\bar{c}[[^3S_1^{(1)}] + gg] + g$

Colour-Octet (NRQCD) Model
(Bodwin,Braaten,Lepage, PRD51,1125 (1996))




Color-Octet t-channel Gluon Exchange:
$g + g \rightarrow c\bar{c}[^1S_0^{(8)}, ^3P_J^{(8)}] + g$

Color-Octet Fragmentation:
$g + g \rightarrow c\bar{c}[^3S_1^{(8)}] + g$

And others... Color Evaporation Model, s-channel cut, 3-Gluon Fusion, etc.