Measurements of J/ψ production in p+p and p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR experiment

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Use quarkonium to probe QGP

- **Color-screening:** quark-antiquark potential is screened by surrounding partons, leading to dissociation

T. Matsui and H. Satz, PLB 178 (1986) 416

J/ψ suppression was proposed as a proof of QGP formation

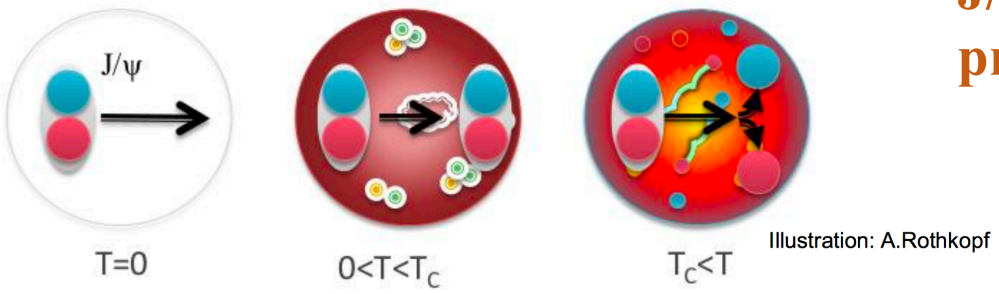


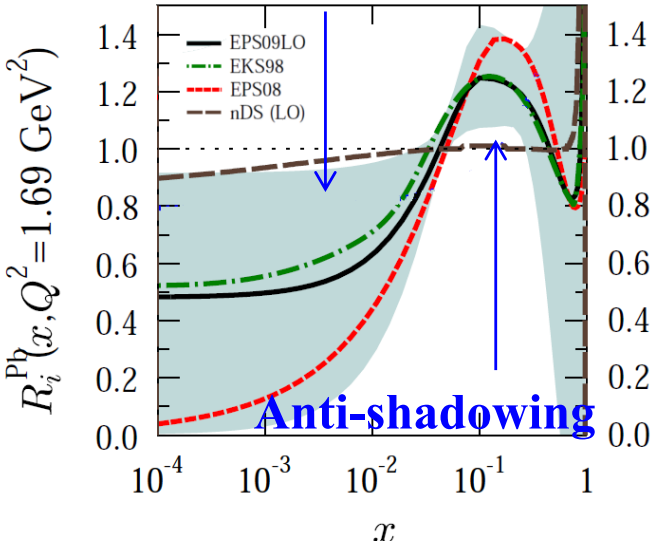
Illustration: A.Rothkopf

Ferreiro et al., PRC 81(2010) 064911
Eskola et al., Eur.Phys.J. C9 (1999) 61-68
Eskola. et al., JHEP 0807 (2008) 102
Eskola et al., JHEP 0904 (2009) 065
De Florian et al., PRD69 (2004) 074028

However

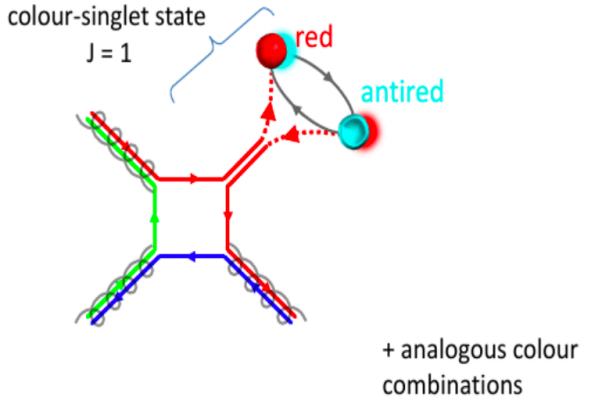
- **Cold nuclear matter effects also play an important role**
  - Nuclear PDF (nPDF) effect
  - Nuclear absorption effect
  - Co-mover effect
- **Quarkonium production mechanism** in elementary collisions **is not fully understood**

Shadowing R_G^{Pb}

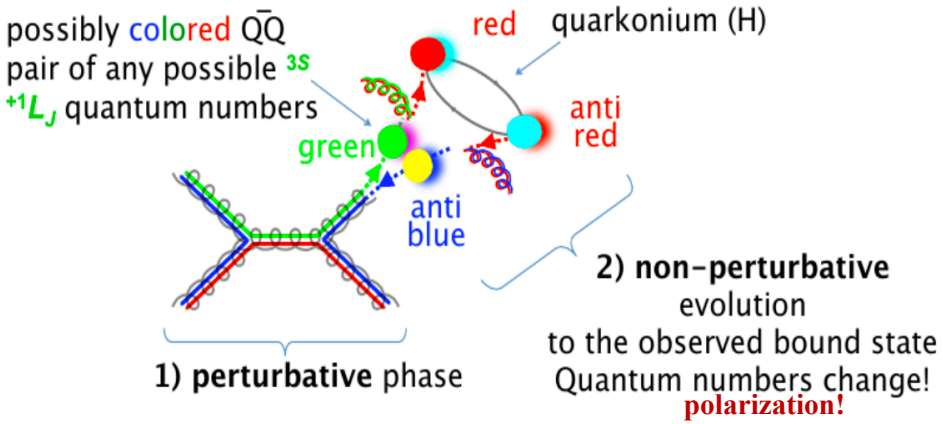


Quarkonium production mechanism

- **Various production mechanism**
  - Prompt J/ψ: direct production; decay of ψ(2S) and χ_c(~ 40%) *J. Phys. G 35, 104134 (2008)*
  - Non-prompt J/ψ : B-hadron decay (up to 10-15% at high p_T) *STAR: Phys. Lett. B722 (2013) 55*



- **Different models on the market**
  - Color Singlet Model
  - Color Evaporation Model
  - NRQCD approach
  - CGC+NRQCD

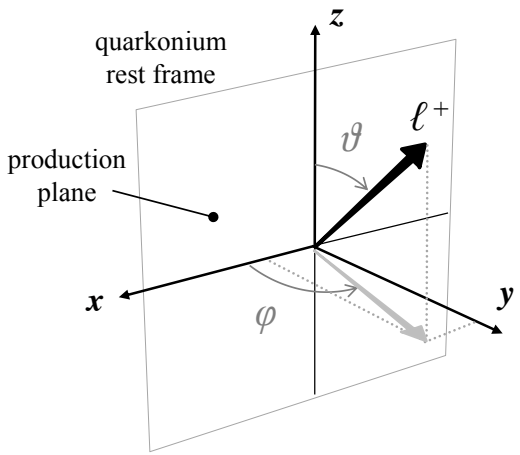


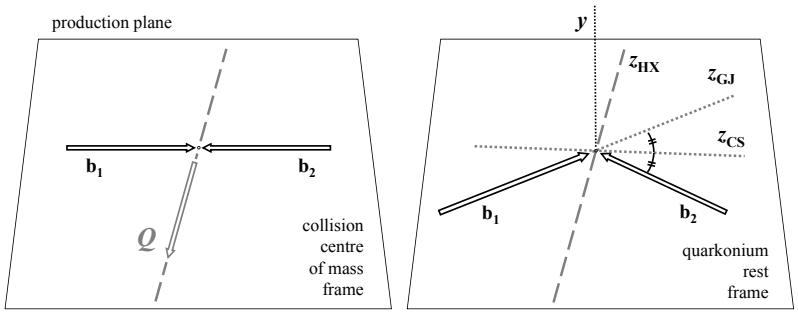
- **Measurements of quarkonium polarization** provide further constraints on production models
  - **Competing theoretical approaches predict similar production cross-sections, but different polarizations**

J/ψ polarization measurement

- J/ψ polarization can be analyzed via the angular distribution of the decayed positively charged leptons, which can be expressed as:

$$W(cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta} \cdot (1+\lambda_\theta cos^2\theta + \lambda_\varphi sin^2\theta cos2\varphi + \lambda_{\theta\varphi} sin2\theta cos\varphi)$$



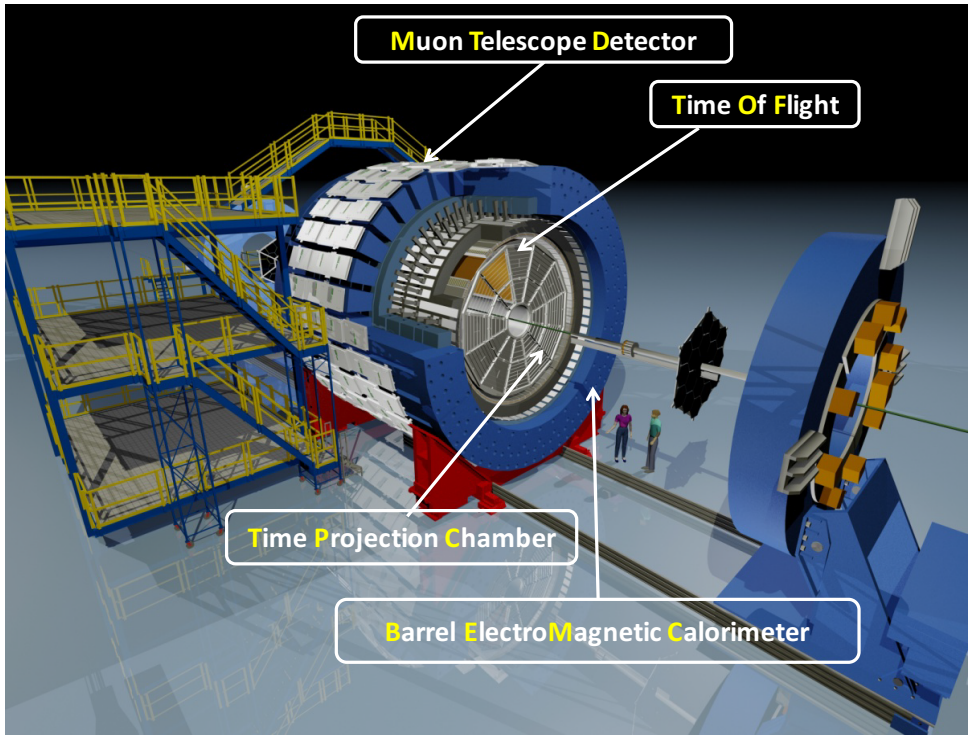


- **θ - polar angle** between momentum of a positive lepton in the J/ψ rest frame and the polarization axis z
- **φ -** corresponding **azimuthal angle**

  - **Polarization axis z**
    - **Helicity (HX) frame:** along the J/ψ momentum in the center-of-mass of the colliding beams
    - **Collins-Soper (CS) frame:** bisector of the angle formed by one beam direction and the opposite direction of the other beam in the J/ψ rest frame

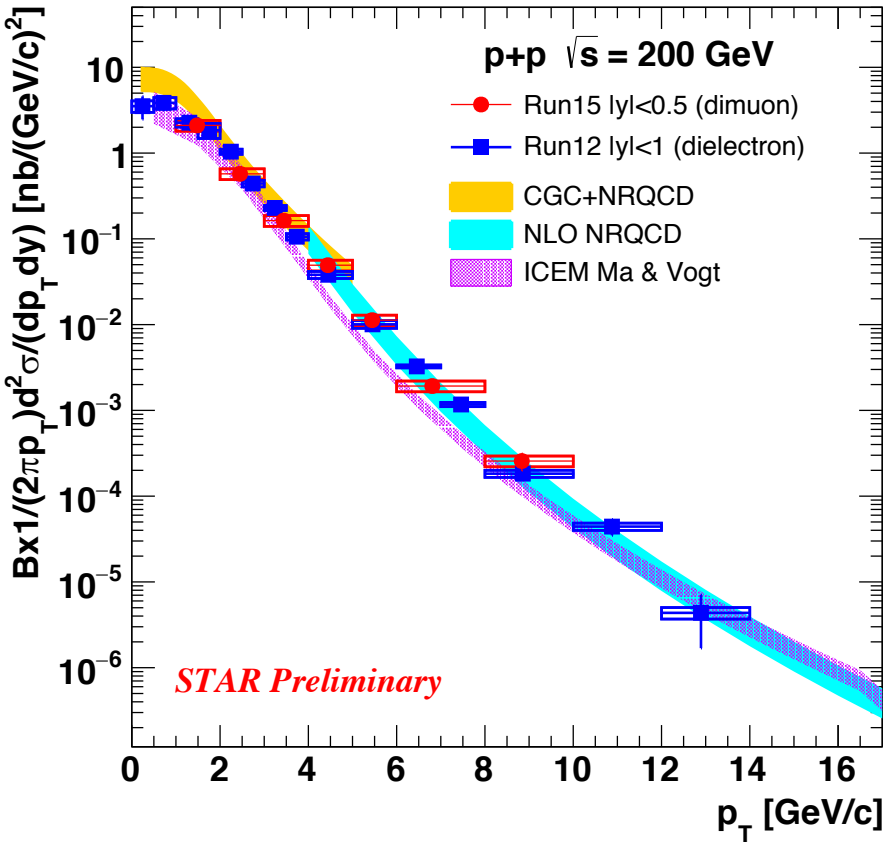
The Solenoidal Tracker At RHIC

- Mid-rapidity detector: $|\eta| < 1, 0 < \varphi < 2\pi$



- **TPC**: measure momentum and energy loss
- **TOF**: measure particle's time of flight. Extend PID to higher p_T.
- **BEMC**: trigger on and identify electrons
- **MTD (45% in φ, $|\eta| < 0.5$)** : trigger on and identify muons
  - precise timing measurement ($\sigma \sim 100ps$)
  - spatial resolution (~1cm)
  - reduced Bremsstrahlung radiation compared to electrons

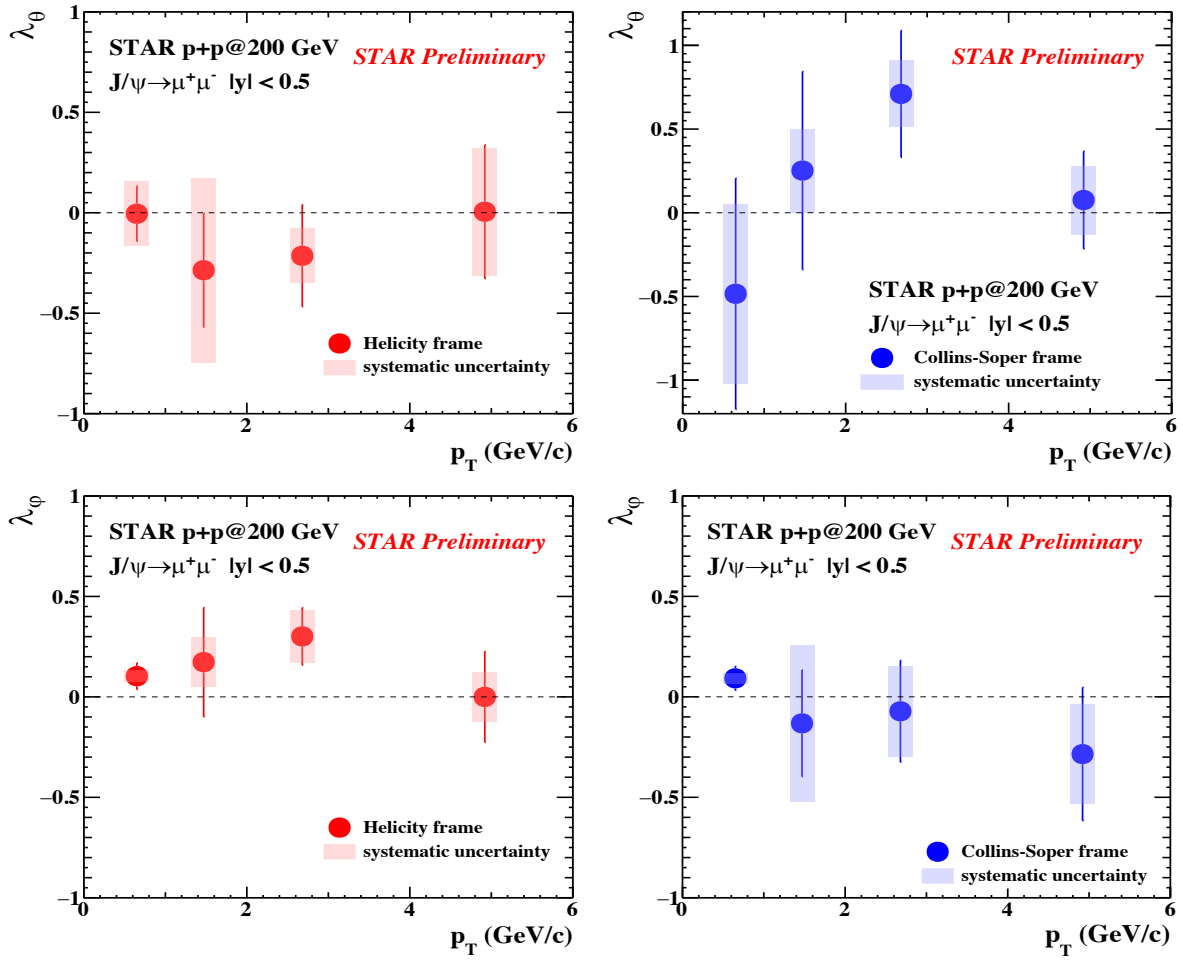
Inclusive J/ψ cross section in p+p collisions



CGC+NRQCD, Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
ICEM, Ma & Vogt, PRD 94 (2016) 114029

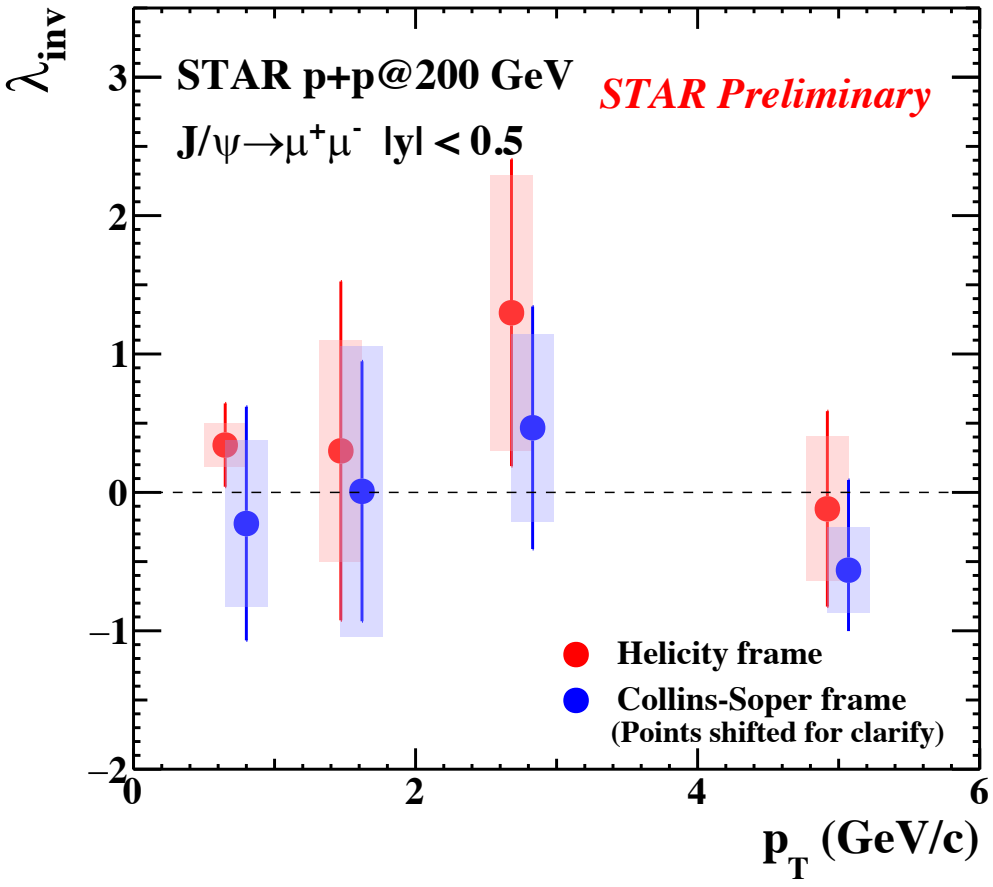
- Inclusive J/ψ cross section is measured for $0 < p_T < 14$ GeV/c
- CGC+NRQCD together with NLO NRQCD (prompt J/ψ) can qualitatively describe data in the full p_T range within uncertainties
  - There seems tension towards very low p_T
- Improved CEM model (direct J/ψ) describes data well at low p_T
  - Data are above ICEM calculation at $3.5 < p_T < 12$ GeV/c
- B-hadron feed-down needs to be taken into account

J/ψ polarization parameters in p+p collisions



- First inclusive J/ψ polarization measurement via the dimuon decay channel in both HX and CS frames in 200 GeV p+p collisions at RHIC
- λ_θ and λ_φ parameters are consistent with 0 in HX and CS frames

Frame invariant quantity



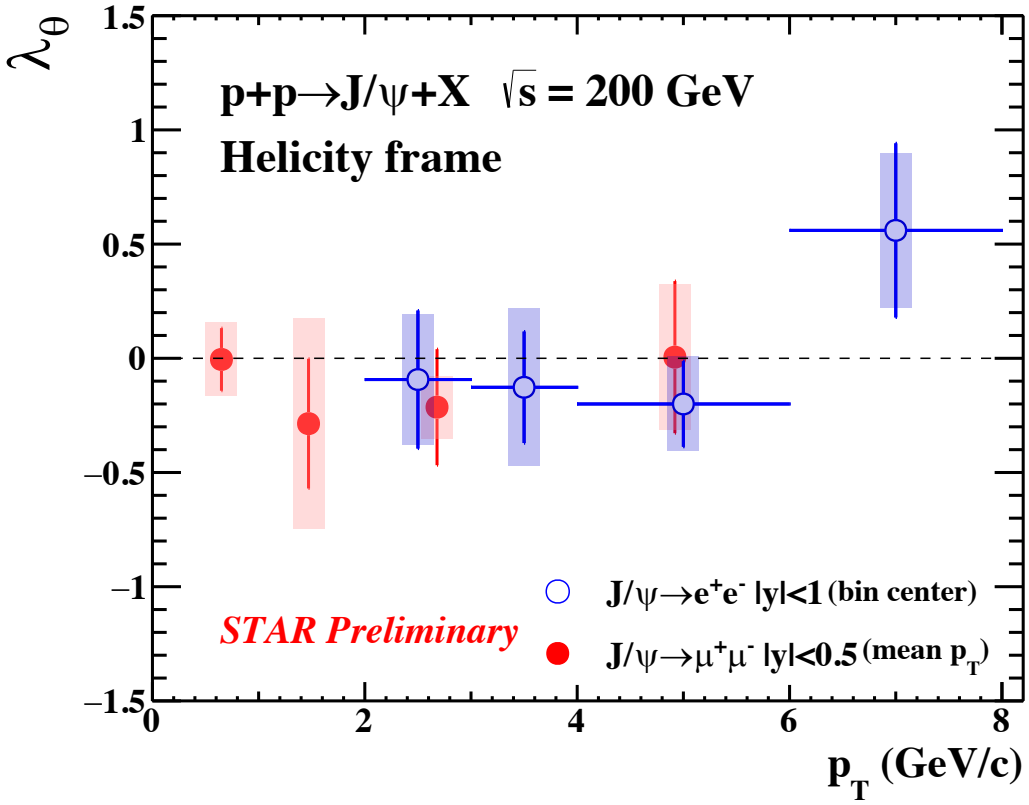
➢ **Frame invariant quantity:**

$$\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

- Any arbitrary choice of the experimental observation frame will give the same value of this quantity
- Good cross-check on measurements performed in different frames

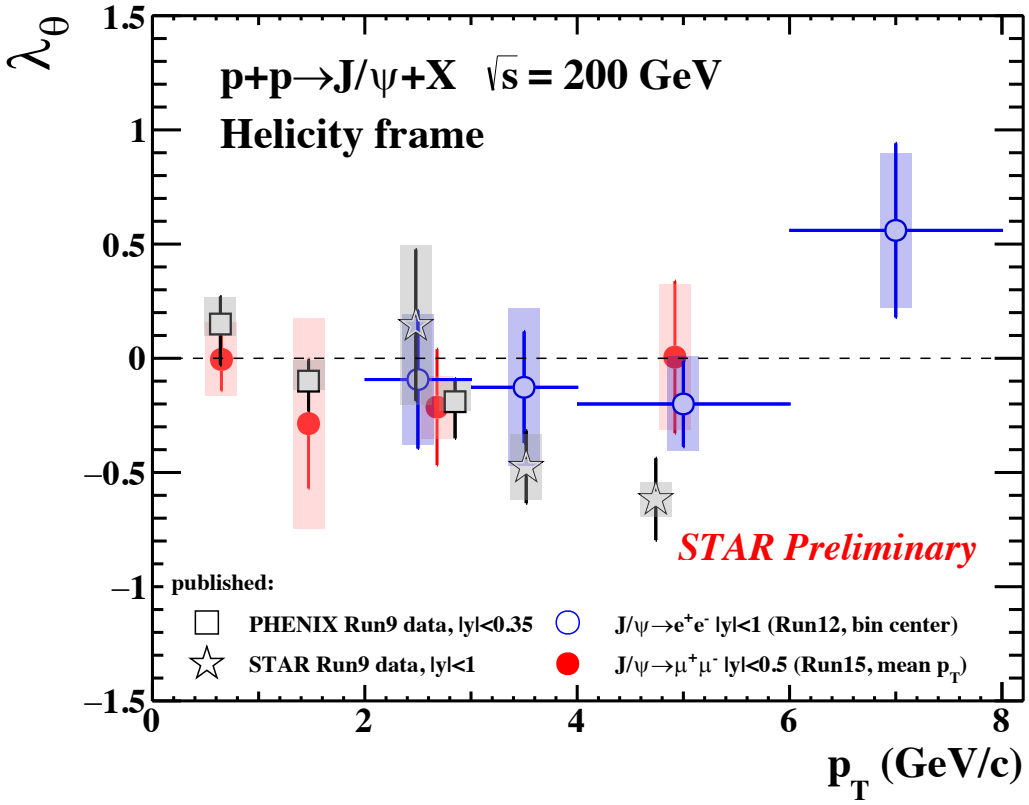
- λ_{inv} as a function of p_T are consistent between HX and CS frames

J/ψ polarization: dimuon vs. dielectron



- Consistent results from the two decay channels in overlapping region
  - The dimuon results have different acceptance, efficiency and systematics compared to dielectron results
- The λ_θ parameters are consistent with 0 at $0 < p_T < 8$ GeV/c.

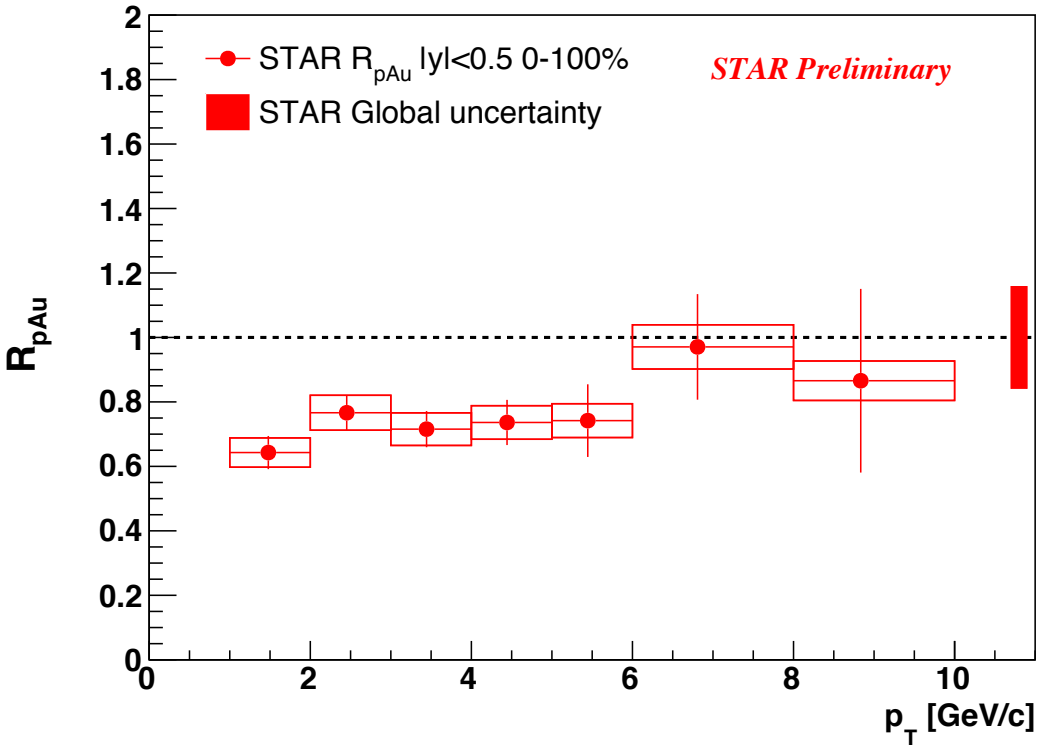
J/ψ polarization in 200 GeV p+p collisions



STAR:Phys.Lett. B739 (2014) 180
PHENIX: Phys. Rev. D 82, 012001 (2010)

- Newly measured λ_θ parameters using 2012 and 2015 data are consistent with previous publication with 2009 data
- But the overall trend seems a bit different:
  - Current data are compatible with 0 without strong p_T dependence, while the published data seem to indicate a decreasing trend towards high p_T

J/ψ R_{pAu} at 200 GeV p+Au collisions



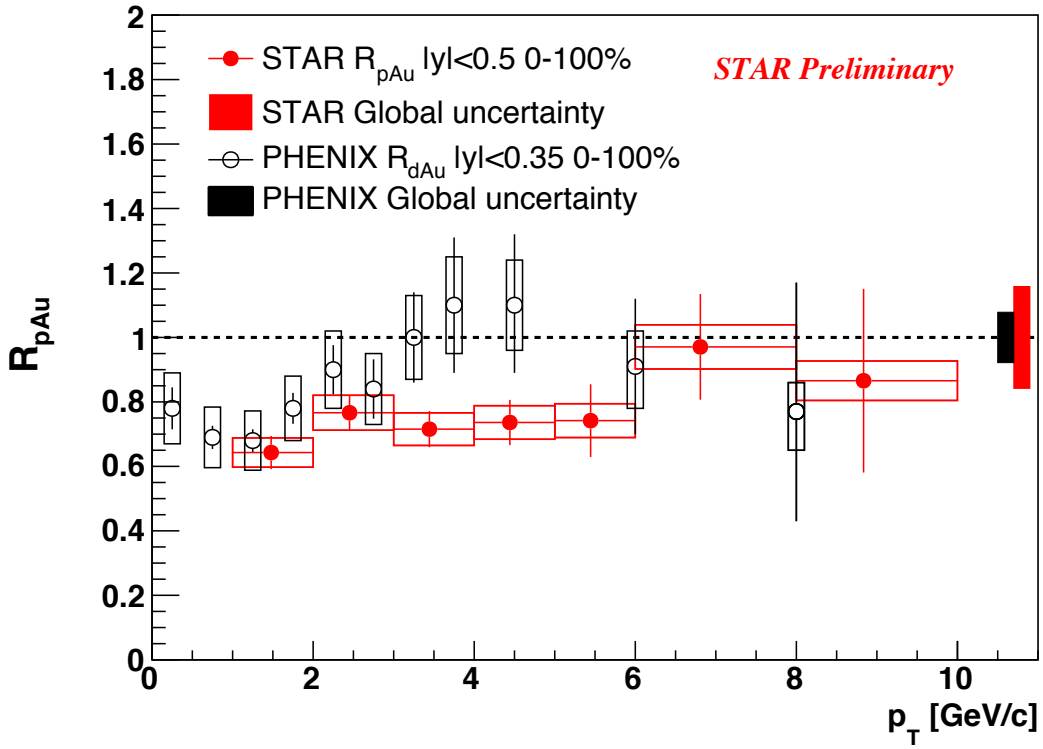
$$R_{pAu} = \frac{\sigma_{inel}}{<N_{coll}>} \frac{d^2N_{pAu}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

← **Global Uncertainty**

Luminosity p+p
Ncoll
Trigger efficiency
Tracking efficiency

- First J/ψ R_{pAu} measurement at RHIC
- R_{pAu} is consistent with unity at high p_T and is less than unity at low p_T

J/ψ R_{pAu} vs. R_{dAu} at 200 GeV p+Au collisions

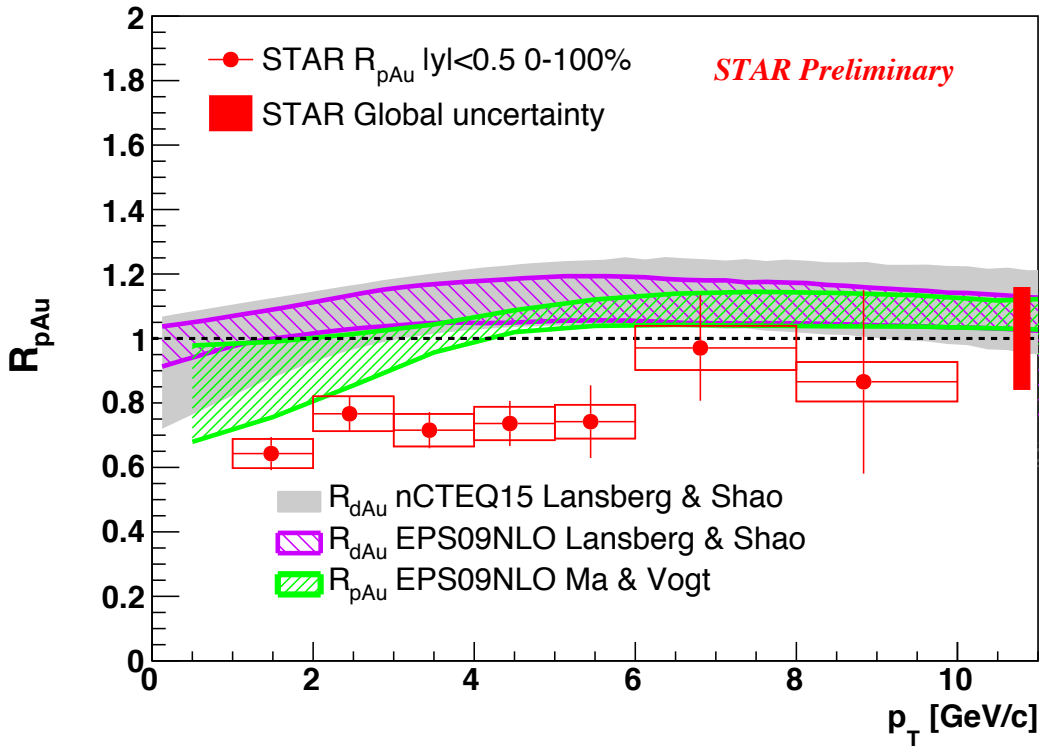


PHENIX, PRC 87 (2012) 034903

← **Global Uncertainty**

- R_{pAu} is consistent with R_{dAu} within uncertainties
  - There seems to be tension at 3.5-5 GeV/c with a significance of 1.4σ
- Suggest similar CNM effects in these collision systems

Inclusive J/ψ R_{pAu} : data vs. models

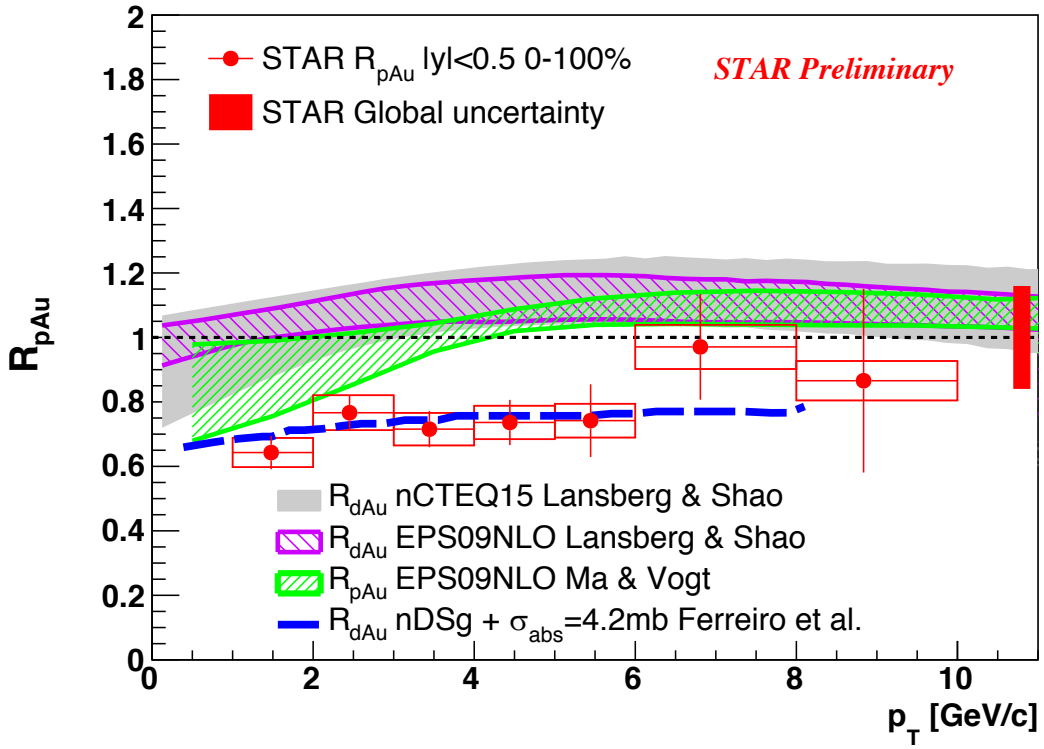


EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg Shao, Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570

← Global Uncertainty

- **Model calculations with only nPDF effect can touch the upper limit of data within uncertainties**

Inclusive J/ψ R_{pAu} : data vs. models



EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg Shao, Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570

← Global Uncertainty

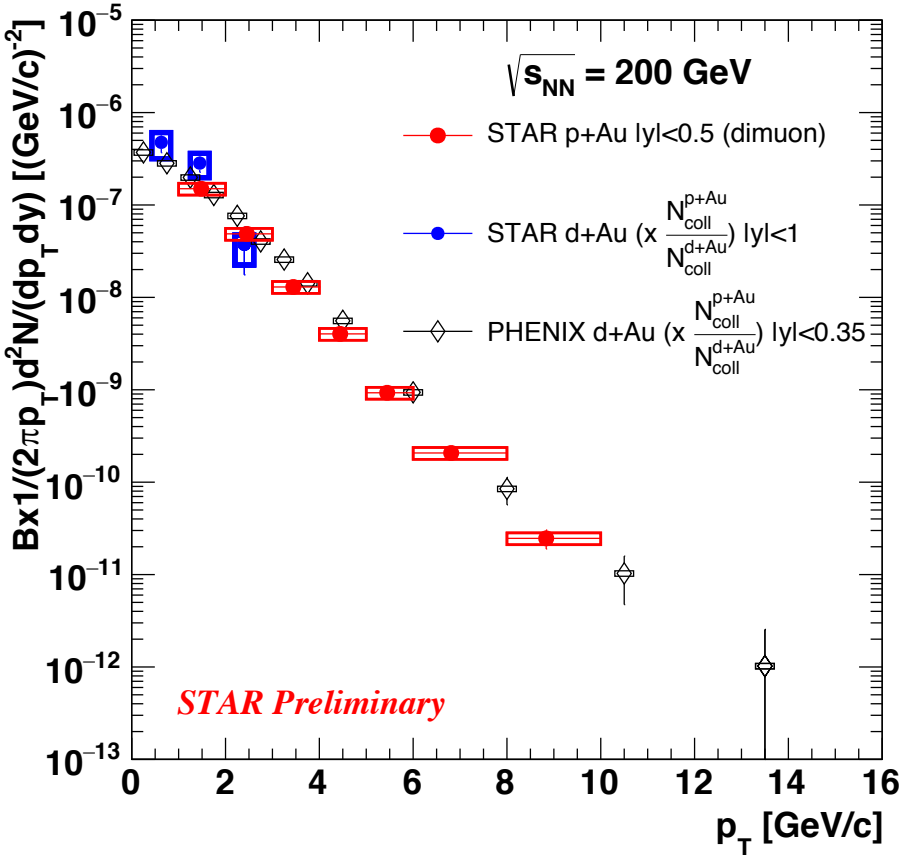
- Model calculations with only nPDF effect can touch the upper limit of data within uncertainties
- **Data favor a model calculation including an additional nuclear absorption effect on top of the nPDF effect**

Summary and outlook

- **p+p collisions at $\sqrt{s_{NN}}$ = 200 GeV**
  - Inclusive J/ψ cross section is measured for $0 < p_T < 14$ GeV/c
    - Can be described by CGC+NRQCD and NLO NRQCD (prompt J/ψ) in the full p_T range within uncertainties
    - ICEM (direct J/ψ) describes data at low p_T while underestimates data at $3.5 < p_T < 12$ GeV/c
  - First measurements of J/ψ polarization in the HX and CS frames from the dimuon channel for $0 < p_T < 5$ GeV/c
    - Both λ_θ and λ_φ parameters are consistent with 0 in the both frames
    - The λ_θ parameter in the HX frame is consistent with the dielectron result ($2 < p_T < 8$ GeV/c) in the overlapping region
- **p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV**
  - J/ψ $R_{pAu} \sim R_{dAu}$: suggests similar CNM effects between p+Au and d+Au collisions
  - J/ψ R_{pAu} favors additional nuclear absorption effect on top of nPDF effect
- **Outlook:** the measurement of J/ψ polarization parameters in p+Au collisions is underway

Back Up

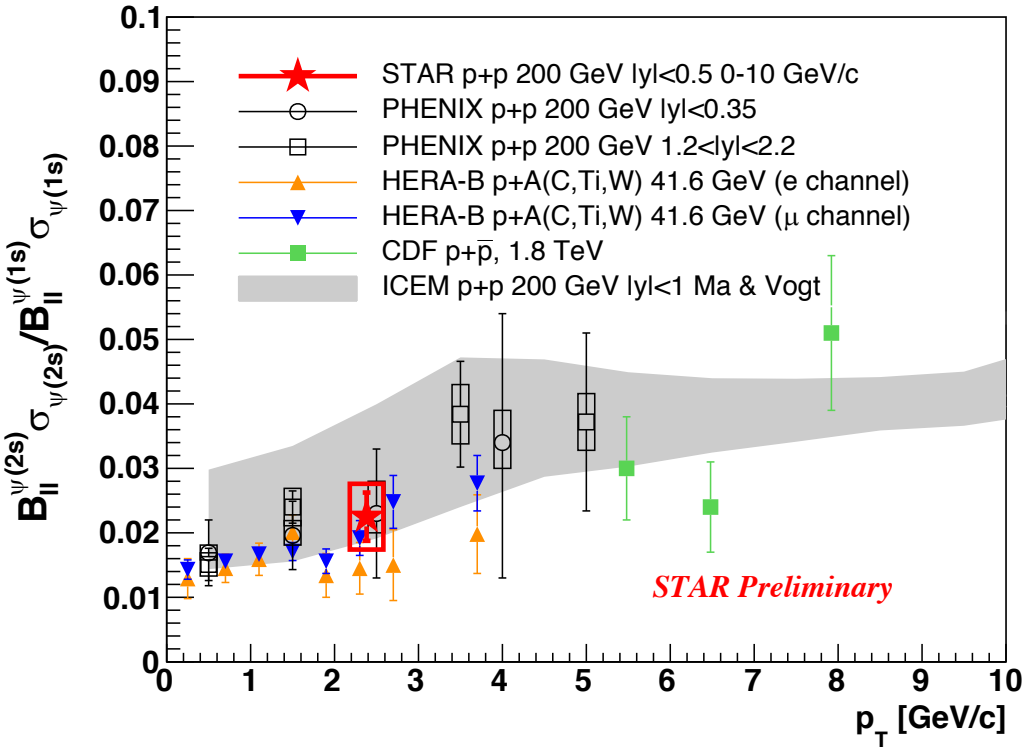
Inclusive J/ψ cross section in p+Au collisions



PHENIX, PRC 87 (2012) 034903
STAR d+Au, PRC 93 (2016) 064904

- First inclusive J/ψ invariant yield measured in p+Au collisions at RHIC
- N_{coll} scaling works reasonably well at high p_T for p/d+Au

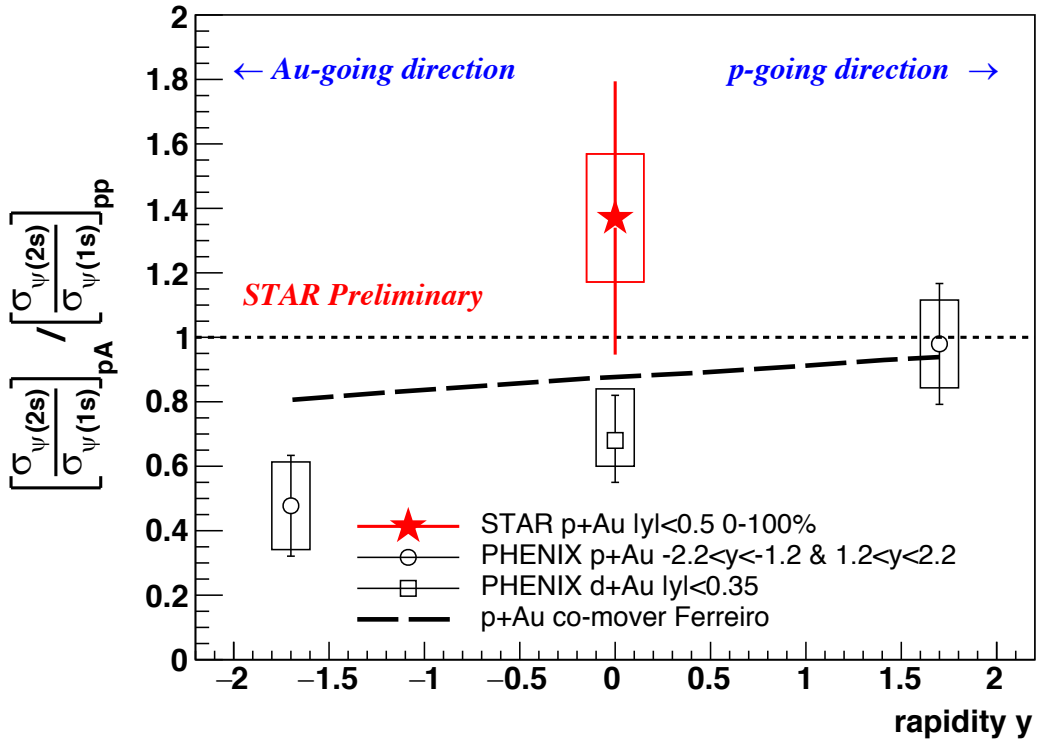
$\psi(2S)/\psi(1S)$ ratio in p+p



HERA-B, EPJC49, 545
PHENIX mid y, PRD85 (2012) 092004
PHENIX forward y, arXiv:1609.06550 (Accepted by PRC)
CDF, 1.8TeV, PRL79 (1997) 572
ICEM, Ma & Vogt, PRD 94 (2016) 114029

- Measured $\psi(2S)/J/\psi$ ratio in 200 GeV p+p collisions is consistent with world-wide data
- The ICEM model describes the increasing trend

$\psi(2S)/\psi(1S)$ double ratio between p+p and p+Au



PHENIX p+Au, arXiv:1609.06550 (Accepted by PRC)
PHENIX d+Au, PRL111 (2013) 202301
Co-mover calculation, Ferreiro (2016) private communication
Calculation based on PLB749 (2015) 98-103

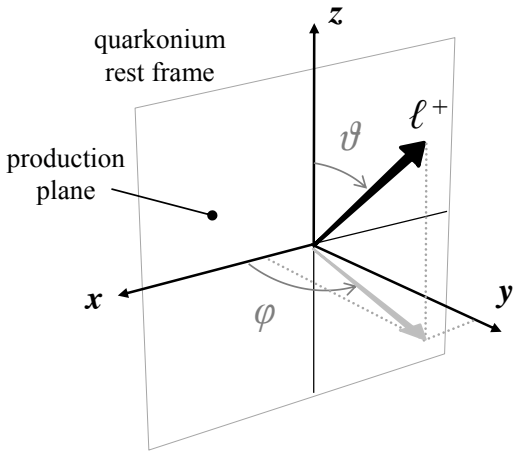
- First $[\sigma_{\psi(2S)}/\sigma_{\psi(1S)}]_{\mathrm{pAu}}/[\sigma_{\psi(2S)}/\sigma_{\psi(1S)}]_{\mathrm{pp}}$ measurement at midrapidity at RHIC

$1.37 \pm 0.42(\mathrm{stat}) \pm 0.19(\mathrm{sys})$

J/ψ polarization measurement

- J/ψ polarization can be analyzed via the angular distribution of the decayed positively charged leptons, which can be expressed as:

$$W(cos\theta, \varphi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta cos^2\theta + \lambda_\varphi sin^2\theta cos2\varphi + \lambda_{\theta\varphi} sin2\theta cos\varphi)$$



- θ **- polar angle** between momentum of a positive lepton in the J/ψ rest frame and the polarization axis z
- φ **-** corresponding **azimuthal angle**

- The angular distribution, integrated over

azimuthal angle:

$$W(cos\theta) \propto 1 + \lambda_\theta cos^2\theta$$

polar angle:

$$W(\varphi) \propto 1 + \frac{2\lambda_\varphi}{3+\lambda_\theta} cos2\varphi$$

J/ψ polarization measurement

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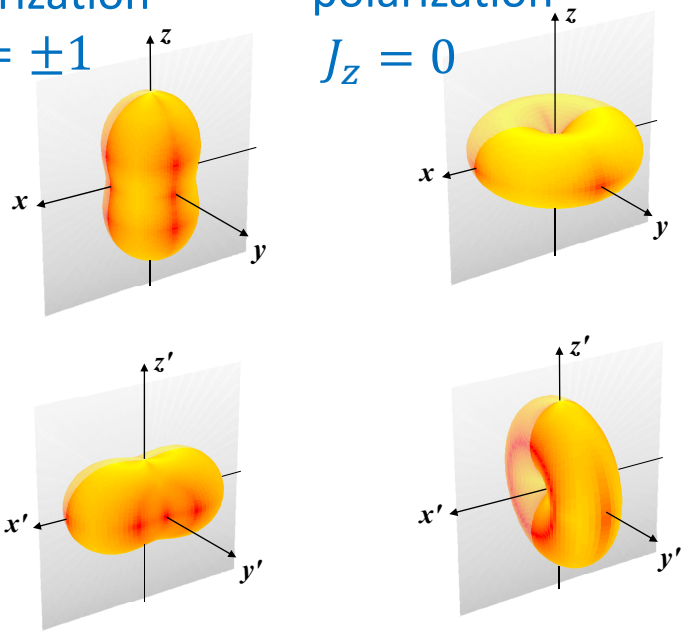
$$W(cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}\cdot(1+\lambda_\theta cos^2\theta+\lambda_\varphi sin^2\theta cos2\varphi+\lambda_{\theta\varphi} sin2\theta cos\varphi)$$

transverse polarization $J_z = \pm 1$

longitudinal polarization $J_z = 0$

natural frame

frame rotated by 90°



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$$\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\varphi}{1-\lambda_\varphi}$$

- Any arbitrary choice of the experimental observation frame will give the same value of this quantity
- Good cross-check on measurements performed in different frames