Charmonium production measurements through the dimuon channel at STAR

Zhen Liu

University of Science and Technology of China

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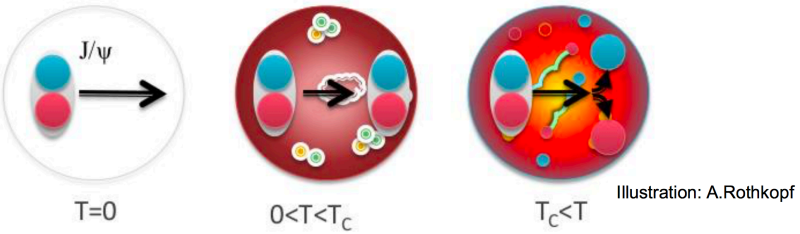
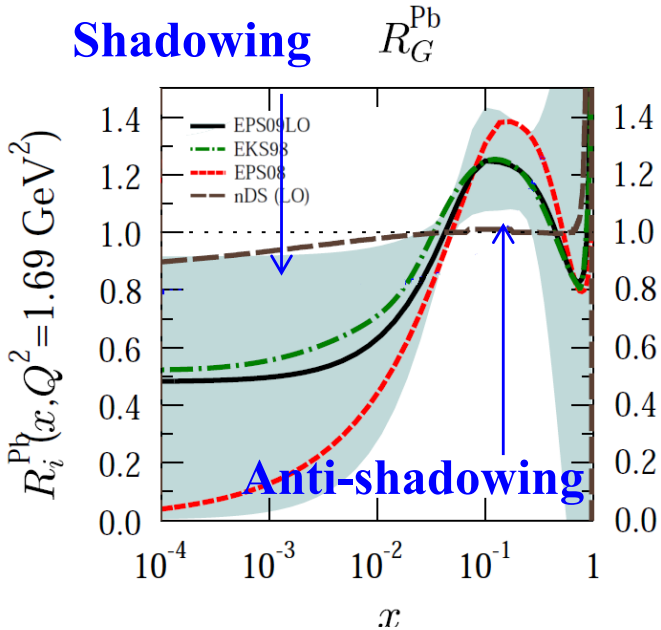
Outline

- **Introduction**
- **J/ψ production in elementary collisions**
  - Cross section
  - $\psi(2S)/\psi(1S)$ ratio
  - Polarization
- **J/ψ production in small system**
  - J/ψ R_{pAu} vs. p_T
  - $\psi(2S)/\psi(1S)$ double ratio
- **J/ψ production in Heavy-ion collisions**
  - R_{AA} vs. p_T
  - R_{AA} vs. centrality
- **Summary**

Use charmonium 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**

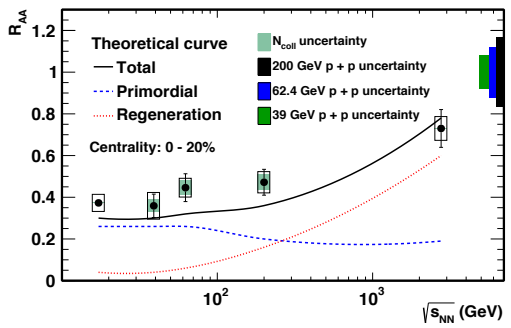




Ferreiro et al., PRC 81(2010) 064911
Eskola et al., Eur.Phys.J. C9 (1999) 61-68
Eskola. et al., JHEP 0807 (2008) 102
Eskola et al., JHEP 0904 (2009) 065
De Florian et al., PRD69 (2004) 074028

However

- **Other effects come into play**
  - Cold nuclear matter (CNM) effects
    →Measurements in p+A
  - Regeneration and dissociation
    ⟶R_{AA} measurements
  - Feed down
    ⟶ $\psi(2S), \chi_c$, B



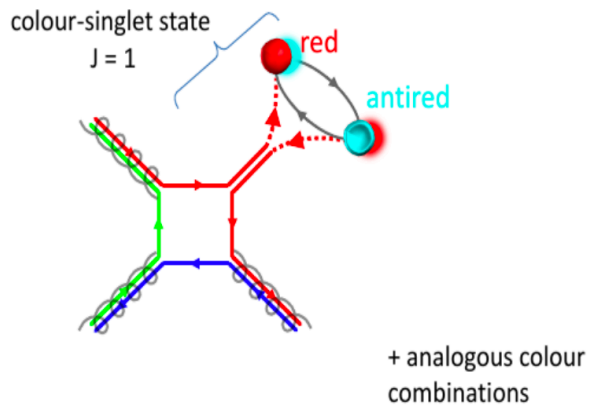
STAR Physics Letters B 771 (2017) 13–20

Charmonium production mechanism

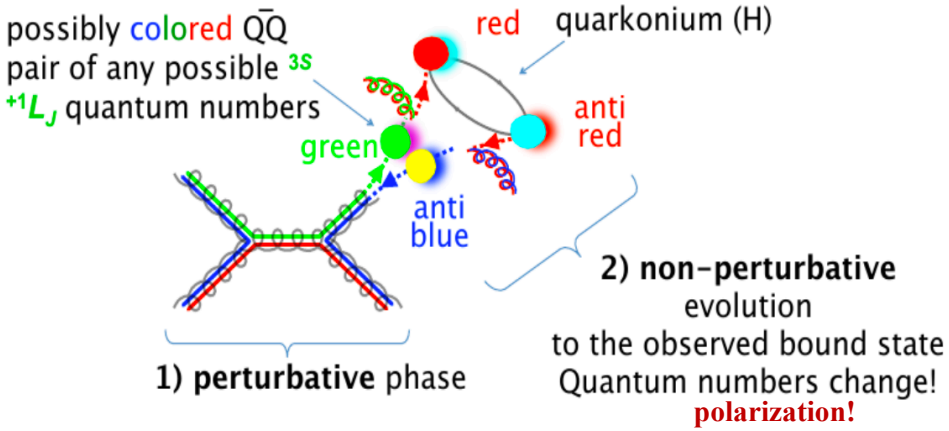
Charmonium production mechanism in elementary collisions is not fully understood

- **Hadronization:**

  formation of final state with hadron long distance process
  - non-relativistic
  - involve soft energy scales
  - **no full-QCD description**



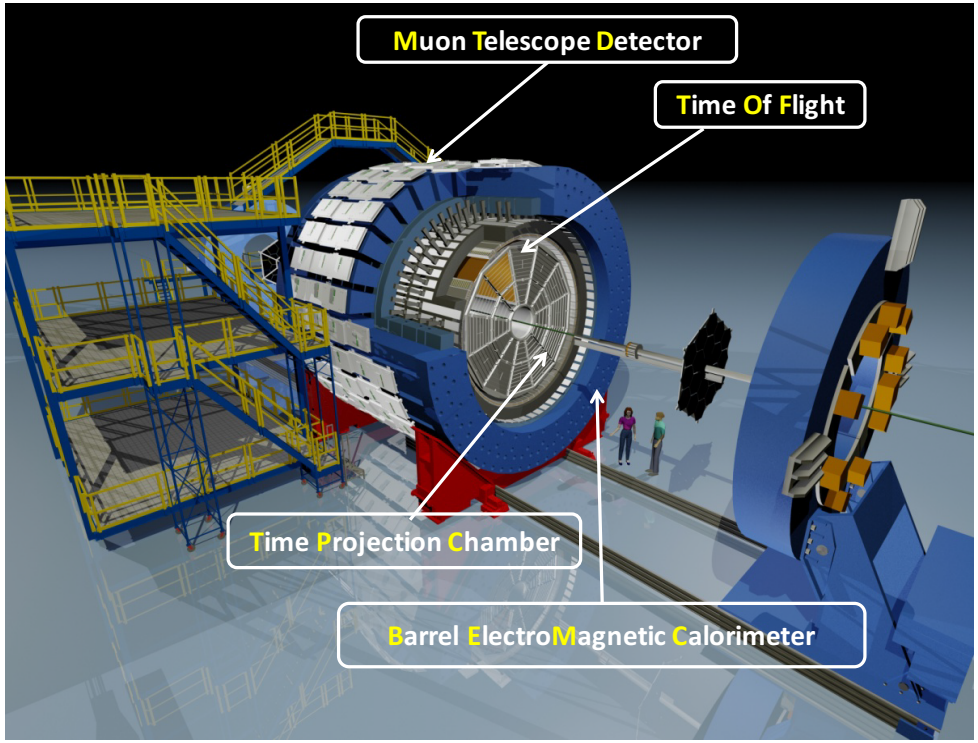
- **Different models on the market**
  - Color Singlet Model
  - Color Evaporation Model
  - NRQCD approach
  - CGC+NRQCD



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

The Solenoidal Tracker At RHIC

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

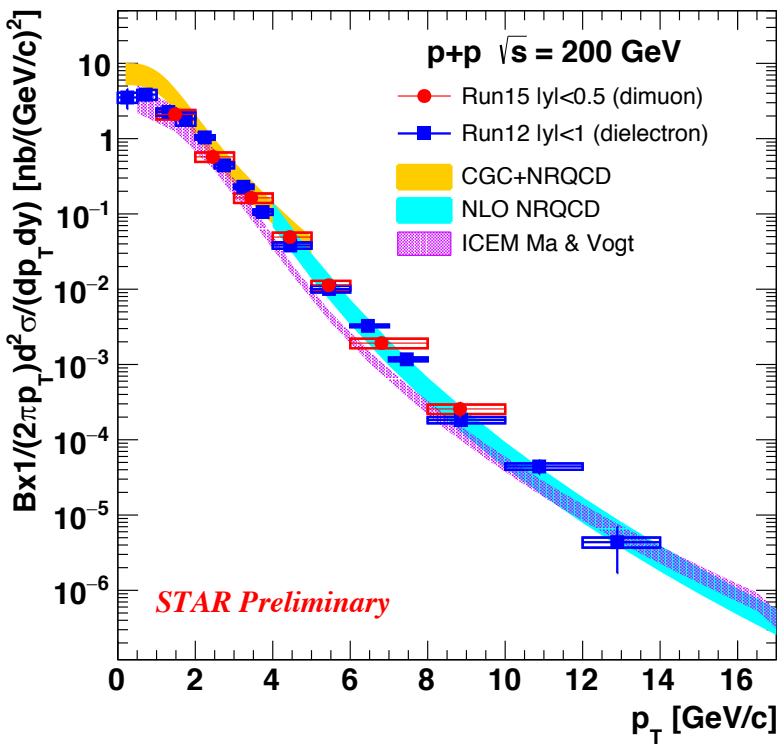


The MRPC modules for TOF and MTD are mainly developed and produced by USTC and Tsinghua.

- **TPC**: measure momentum and ionization 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

J/ψ production in elementary collisions

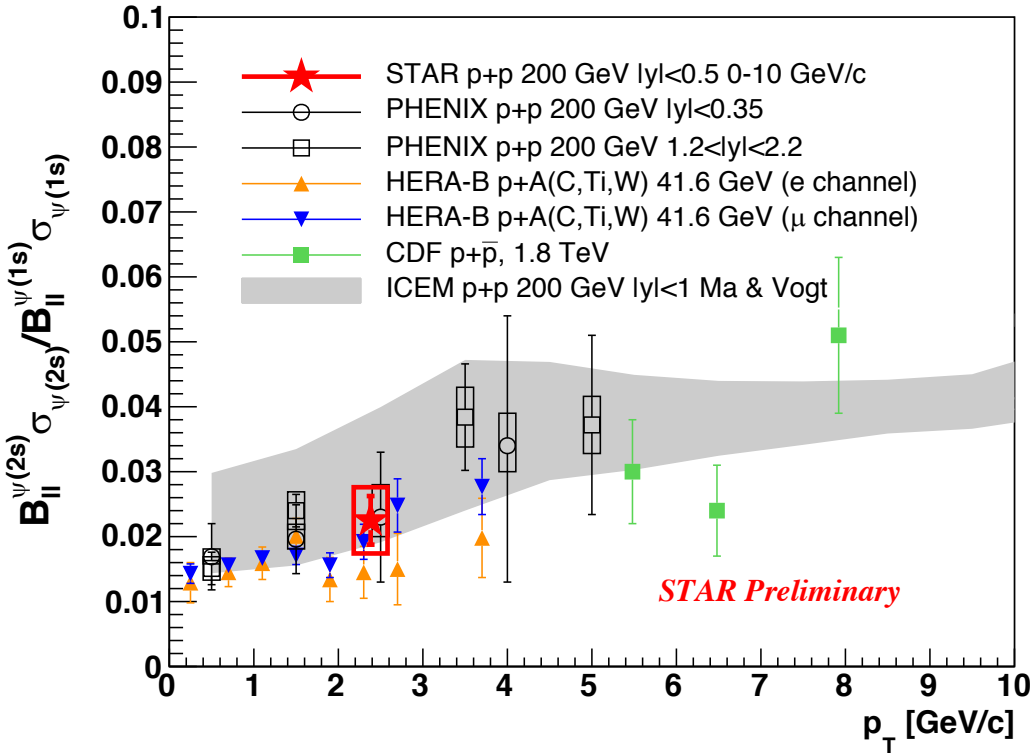
Inclusive J/ψ cross section in p+p collisions



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

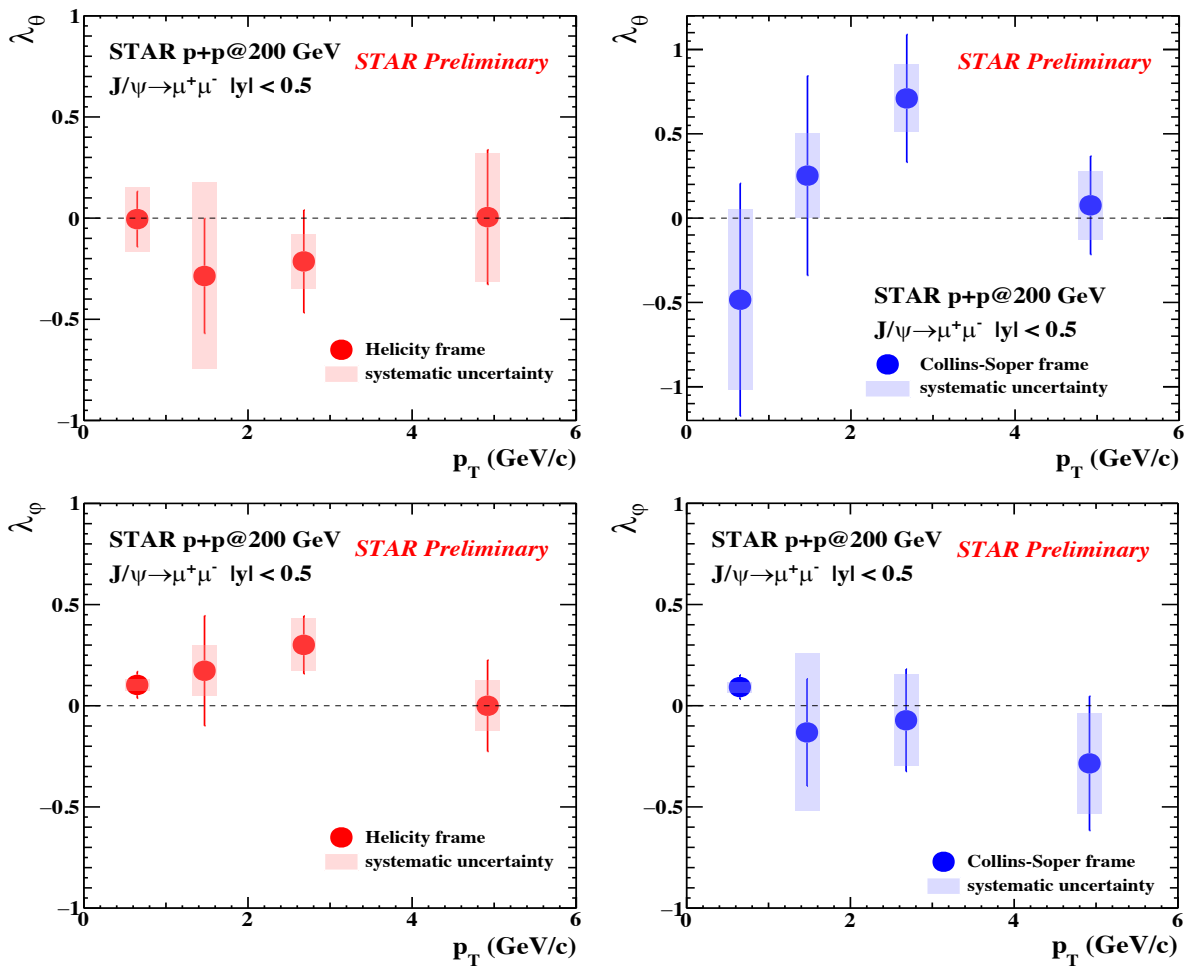
$\psi(2S)/\psi(1S)$ ratio



HERA-B, EPJC49, 545
PHENIX mid y, PRD85 (2012) 092004
PHENIX forward y, Phys. Rev. C 95, 034904 (2017)
CDF, 1.8TeV, PRL79 (1997) 572
ICEM, Ma & Vogt, PRD 94 (2016) 114029

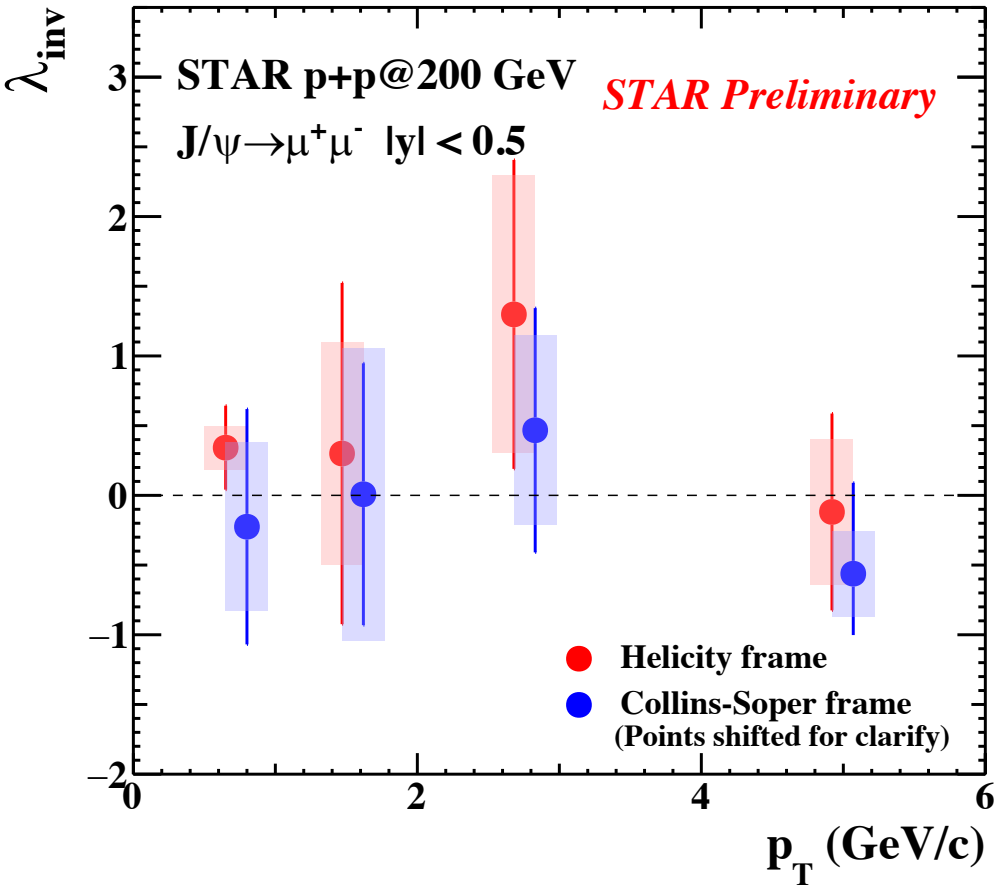
- Measured $\psi(2S)/J/\psi$ ratio in 200 GeV p+p collisions is consistent with world-wide data
- The ICEM model describes the increasing trend

J/ψ polarization measurement via the dimuon decay channel



- 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



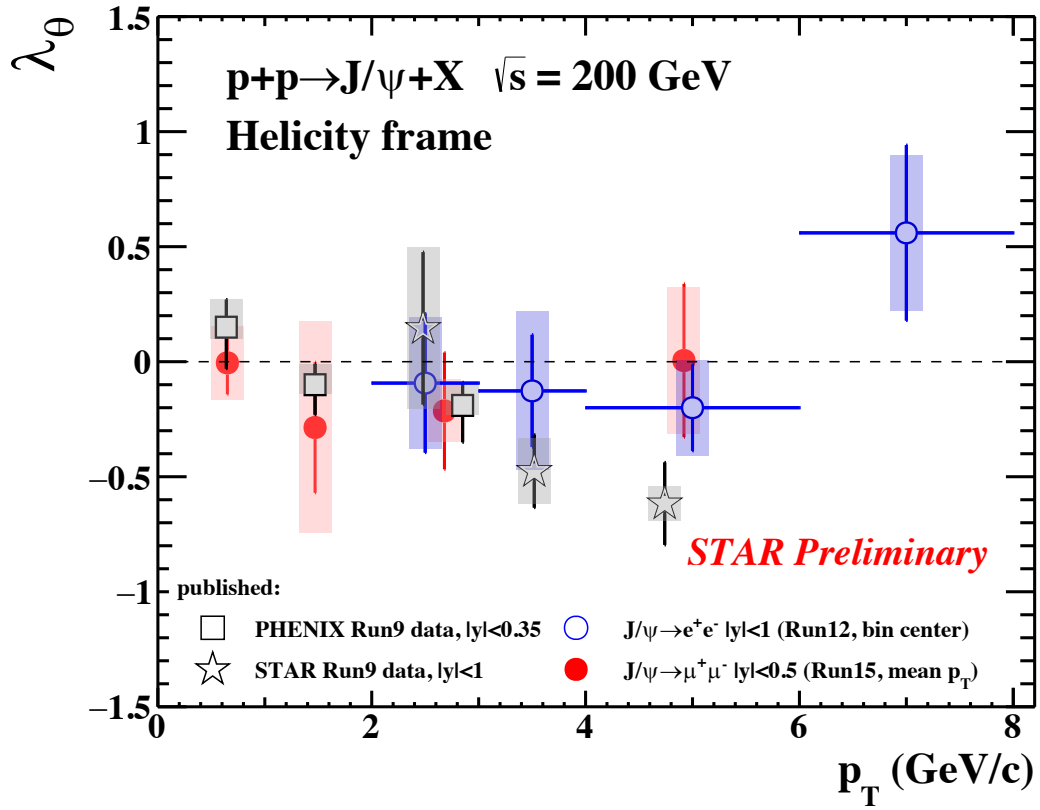
➢ **Frame invariant quantity:**

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

- 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 in 200 GeV p+p collisions

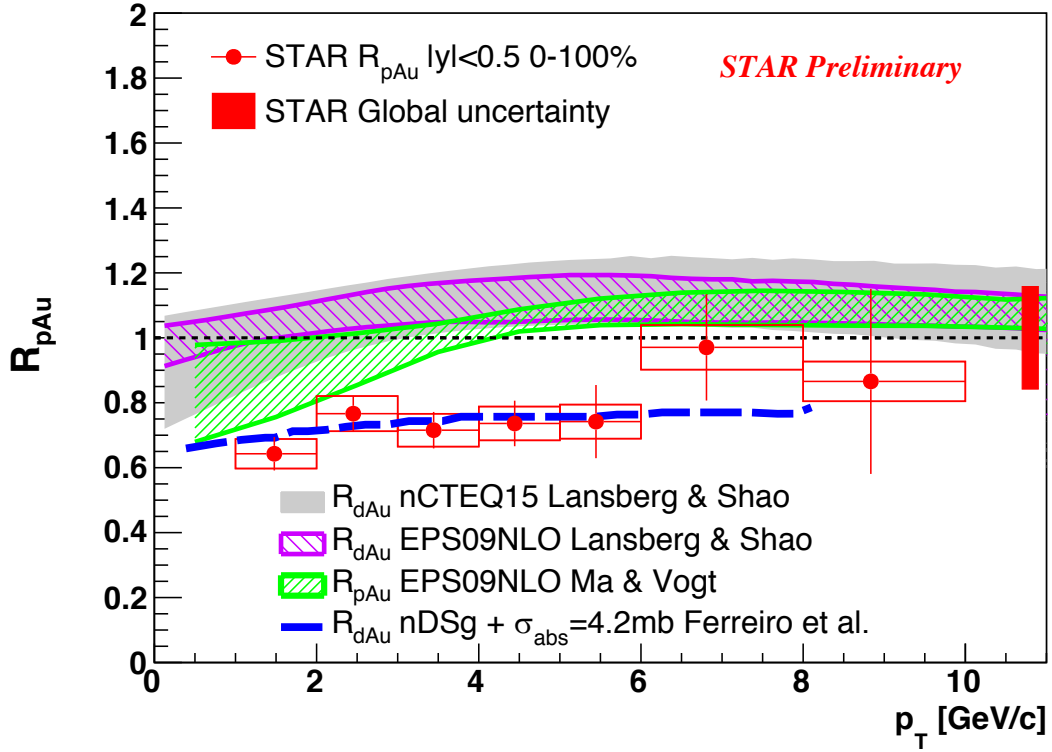


STAR:Phys.Lett. B739 (2014) 180
PHENIX: Phys. Rev. D 82, 012001 (2010)

- Newly measured λ_θ parameters consistent with previous publication
  - The new results are consistent with 0 at 0 < pT < 8 GeV/c without strong p_T dependence
  - The published data seem to indicate a decreasing trend towards high p_T

J/ψ production in small system

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

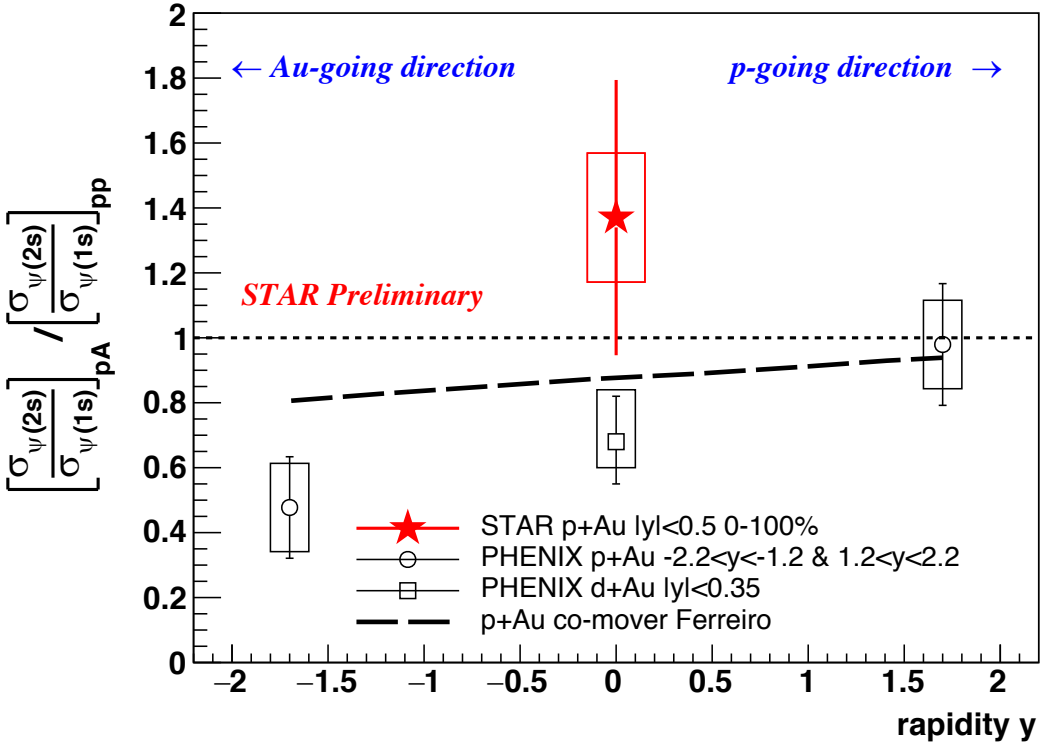


EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg Shao,
Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570

← Global Uncertainty

- First J/ψ R_{pAu} measurement at RHIC
- 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**

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



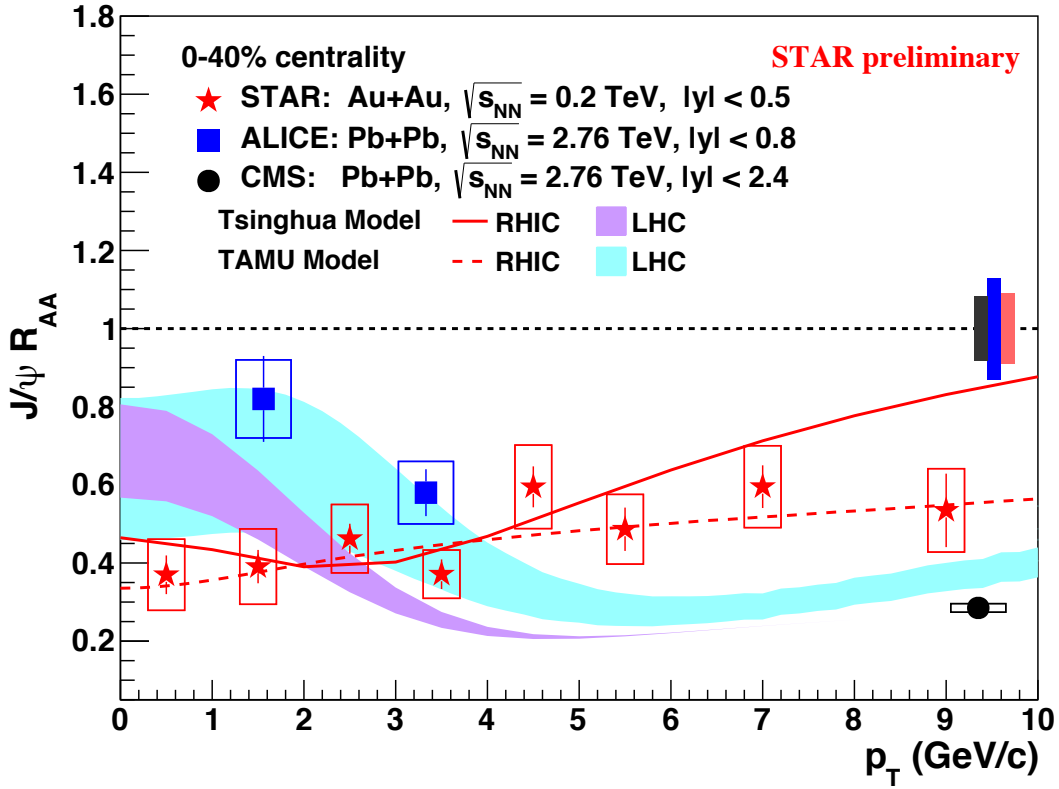
PHENIX p+Au, arXiv:1609.06550 (Accepted by PRC)
PHENIX d+Au, PRL111 (2013) 202301
Co-mover calculation, Ferreiro (2016) private communication
Calculation based on PLB749 (2015) 98-103

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

1.37 ± 0.42(stat) ± 0.19(sys)

J/ψ production in Heavy-ion collisions

J/ψ R_{AA} vs. p_T: RHIC vs. LHC

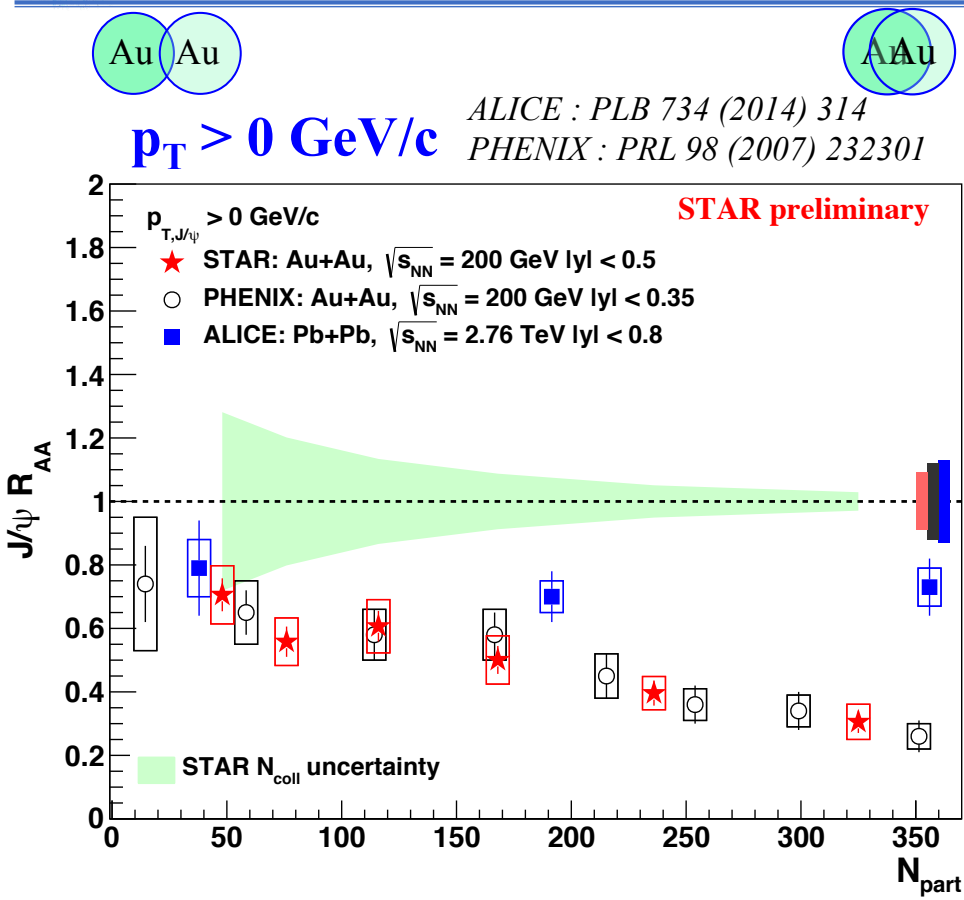


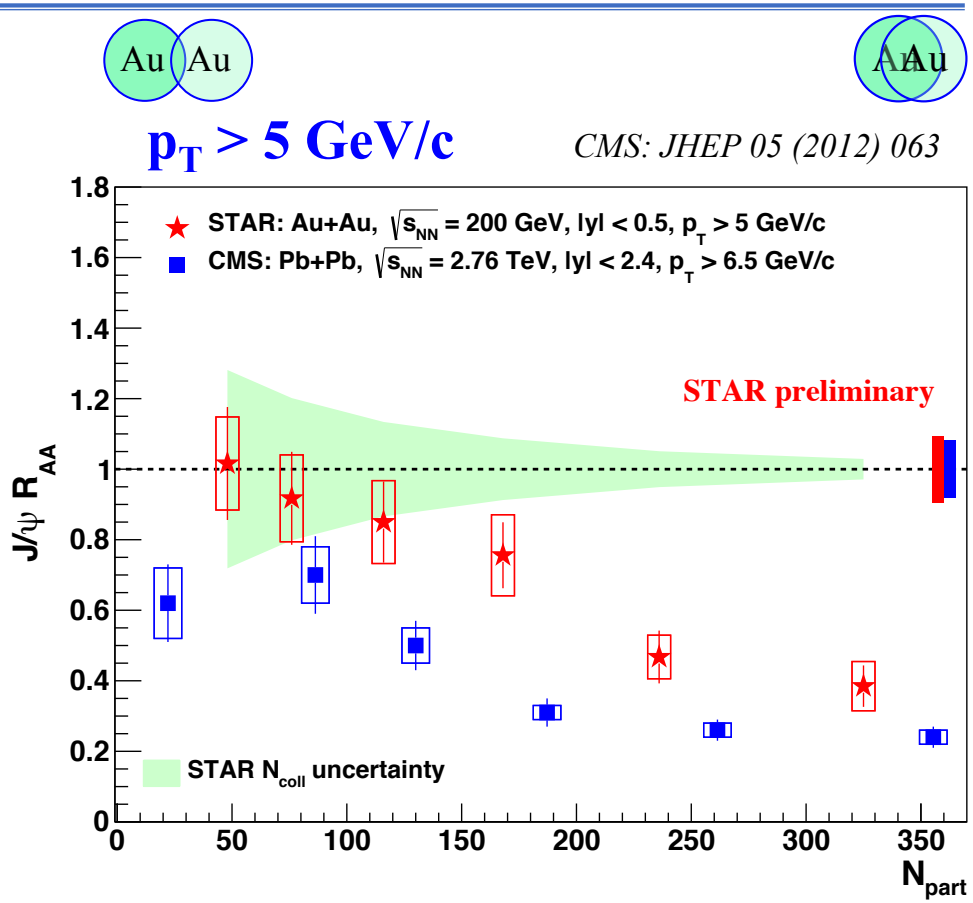
Transport model:
Tsinghua at RHIC: PLB 678 (2009) 72
Tsinghua at LHC: PRC 89 (2014) 054911
TAMU at RHIC: PRC 82 (2010) 064905
TAMU at LHC: NPA 859 (2011) 114

ALICE : PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063

- Smaller R_{AA} at RHIC in low p_T → smaller regeneration contribution due to lower charm cross section
- Larger R_{AA} at RHIC in high p_T → smaller dissociation rate due to lower temperature
- Transport models including dissociation and regeneration effects qualitatively describe p_T dependence of data

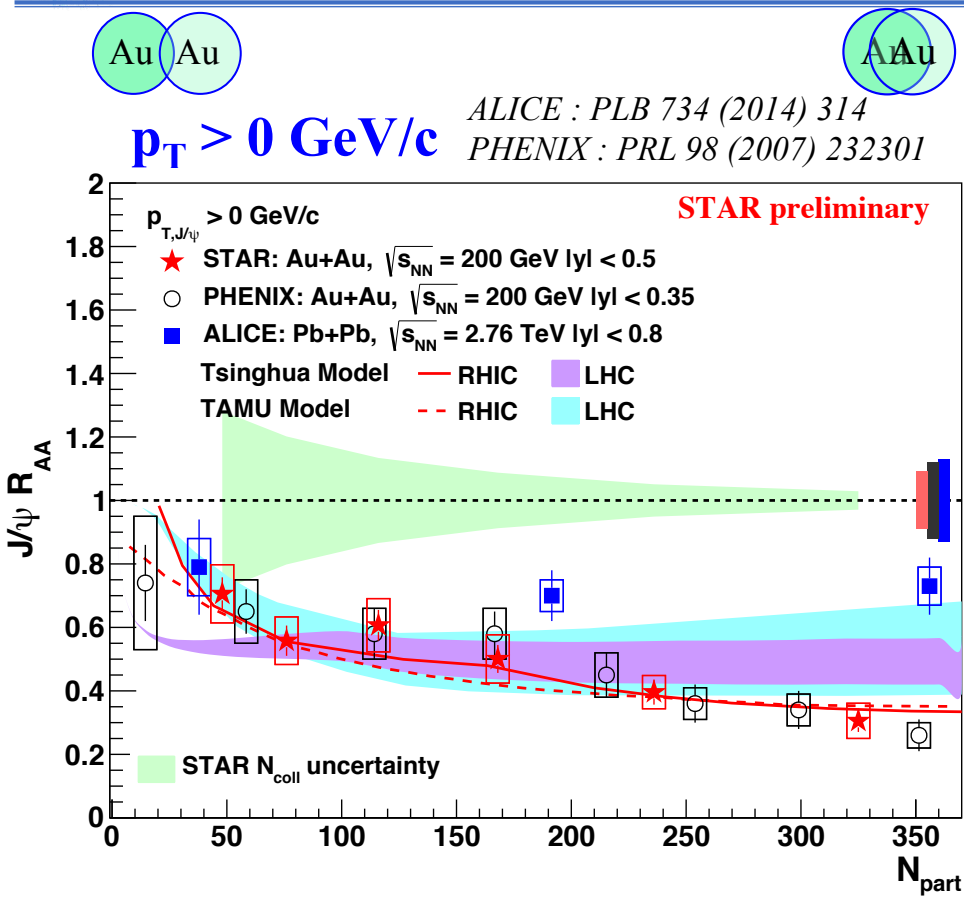
J/ψ R_{AA} vs. centrality: RHIC vs. LHC

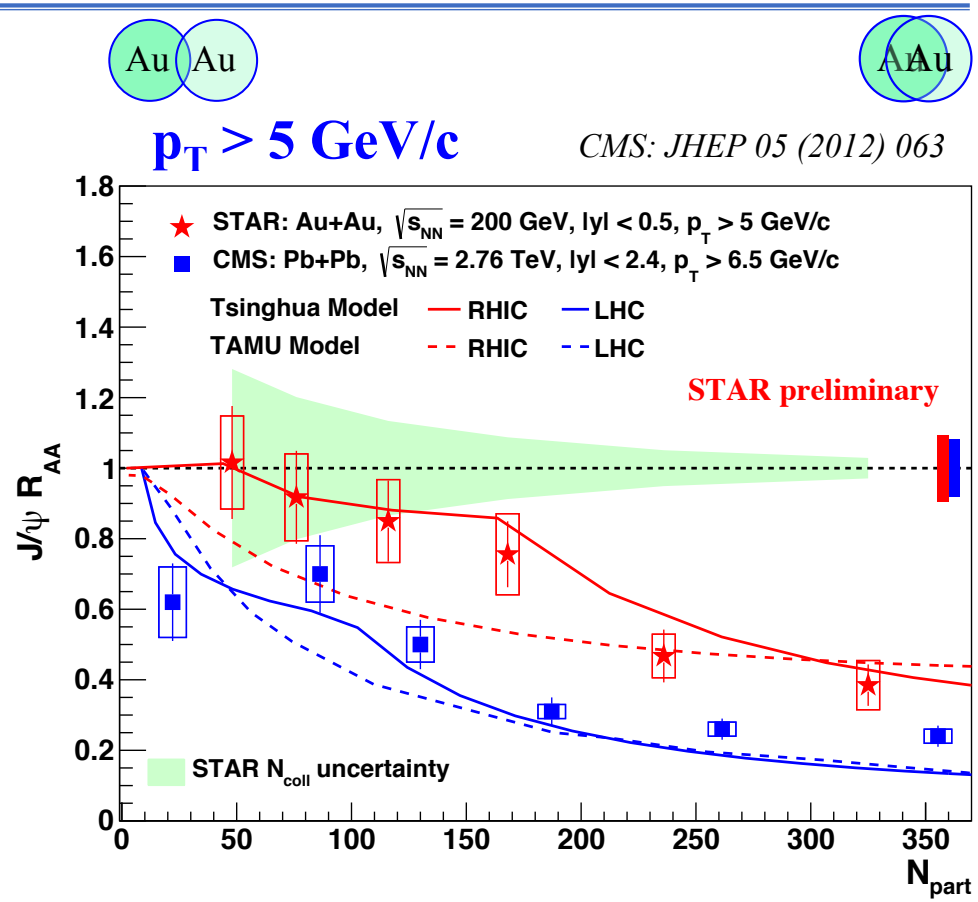




- p_T > 0 GeV/c: less suppressed at LHC in central events → **larger regeneration contribution due to higher charm cross section**
- p_T > 5 GeV/c: more suppressed at LHC in central events → **larger dissociation rate due to higher temperature**

J/ψ R_{AA} vs. centrality: data vs. transport model





- Transport models: dissociation and regeneration effects
- $p_T > 0$ GeV/c: both models can describe centrality dependence at RHIC, but tends to overestimate suppression at LHC
- $p_T > 5$ GeV/c: there is tension among models and data

Summary

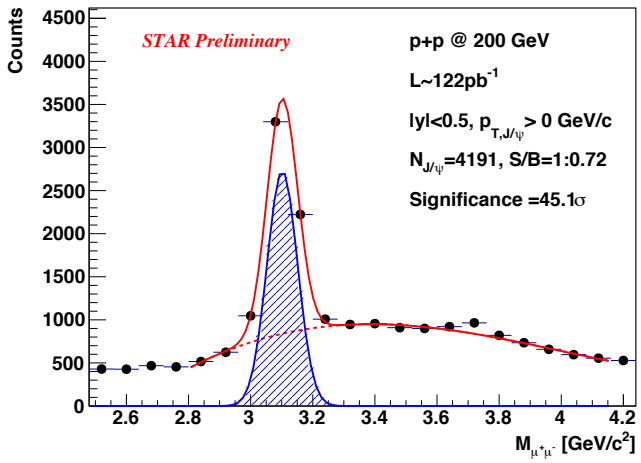
- **p+p collisions at $\sqrt{s}$ = 200 GeV**
  - Inclusive J/ψ cross section can be described reasonably well by model calculations
  - J/ψ polarization parameters λ_θ and λ_φ are consistent with 0 in the HX and CS frames from the dimuon channel for $0 < p_T < 5$ GeV/c
- **p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV**
  - J/ ψ R_{pAu} favors additional nuclear absorption effect on top of nPDF effect
  - First mid-rapidity double ratio of $\sigma_{\psi(2S)}/\sigma_{\psi(1S)}$: 1.37 ± 0.42(stat) ± 0.19(sys)
- **Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV**
  - Clear J/ψ suppression above 5 GeV/c in central collisions → Dissociation
  - Smaller R_{AA} at RHIC in low p_T → smaller regeneration contribution due to lower charm cross section
  - Larger R_{AA} at RHIC in high pT → smaller dissociation rate due to lower temperature
  - J/ψ R_{AA} can be qualitatively described by transport models including dissociation and regeneration contributions

Thank you

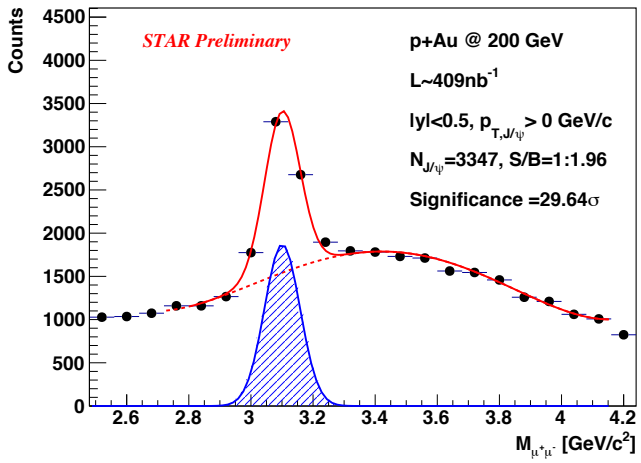
Back Up

Charmonium signal in the dimuon decay channel

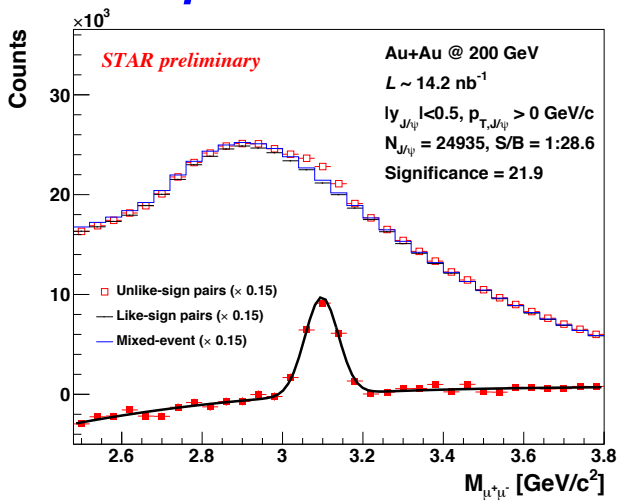
J/ψ in p+p ~45σ



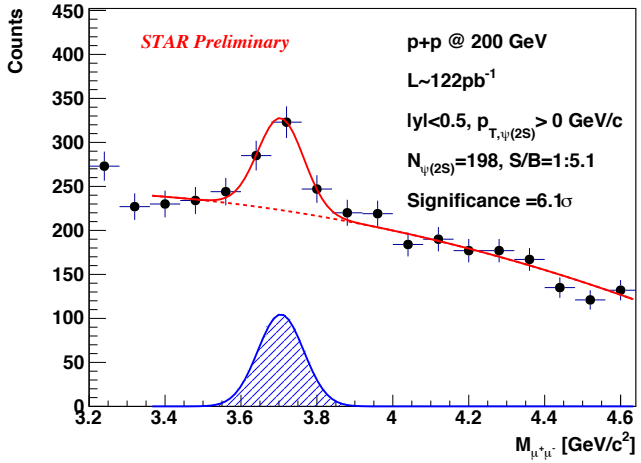
J/ψ in p+Au ~26σ



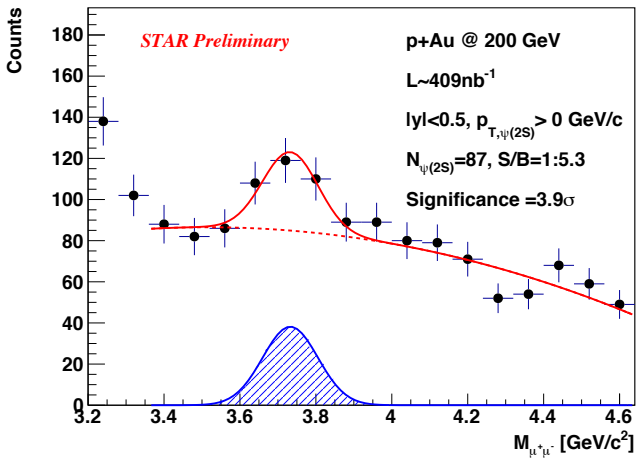
J/ψ in Au+Au ~22σ



ψ(2S) in p+p ~6.1σ



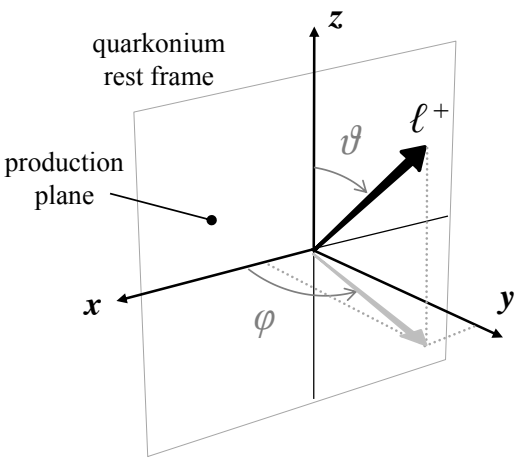
ψ(2S) in p+Au ~3.9σ



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:

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

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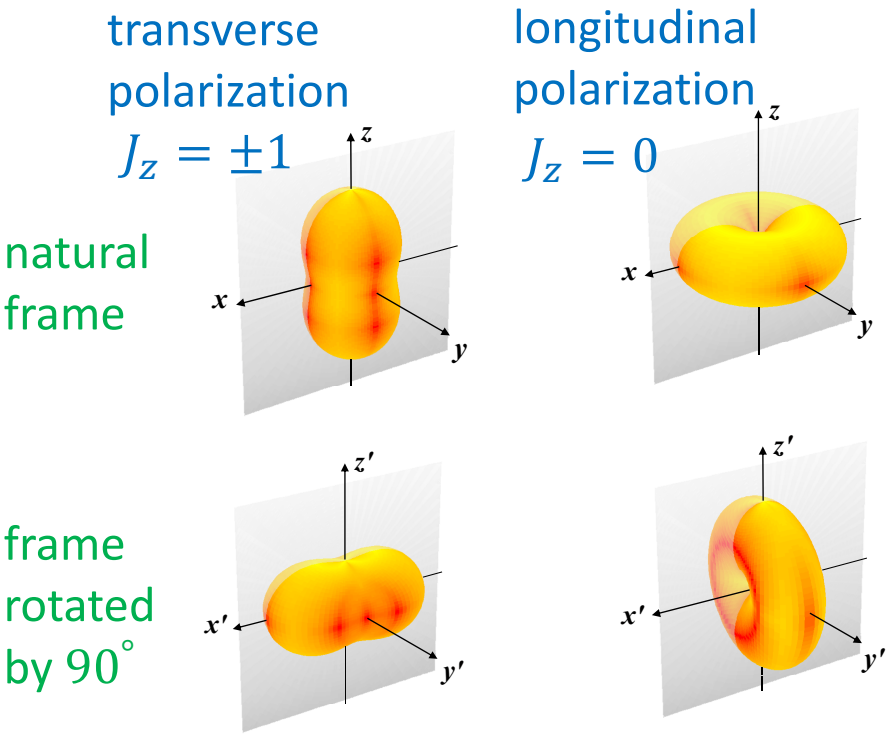

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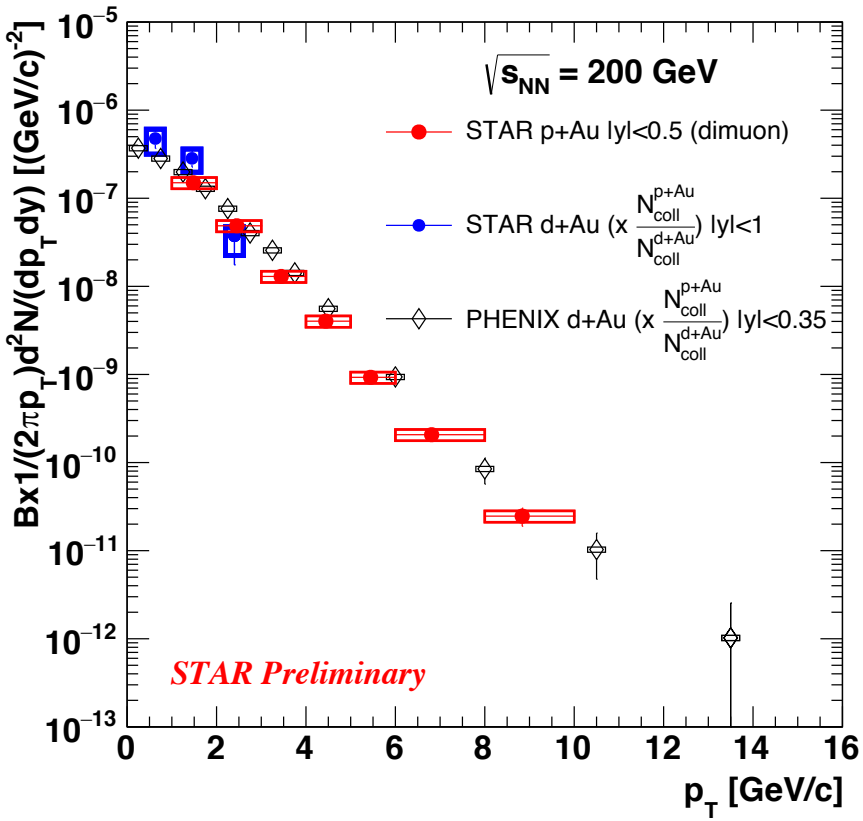
- Good cross-check on measurements performed in different frames

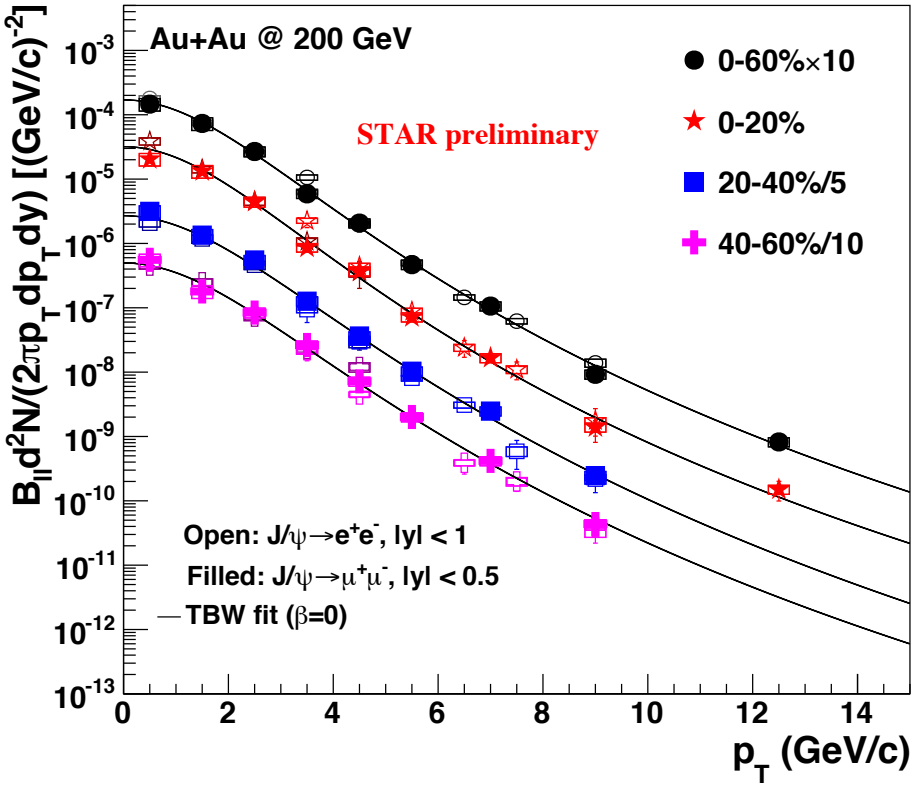
Inclusive J/ψ invariant yield in p+Au collisions



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

- First inclusive J/ψ invariant yield measurement in p+Au collisions at RHIC
- Number of binary collision scaling works reasonably well at high p_T between p+Au and d+Au collisions

Invariant yield of Inclusive J/ψ in Au+Au collisions



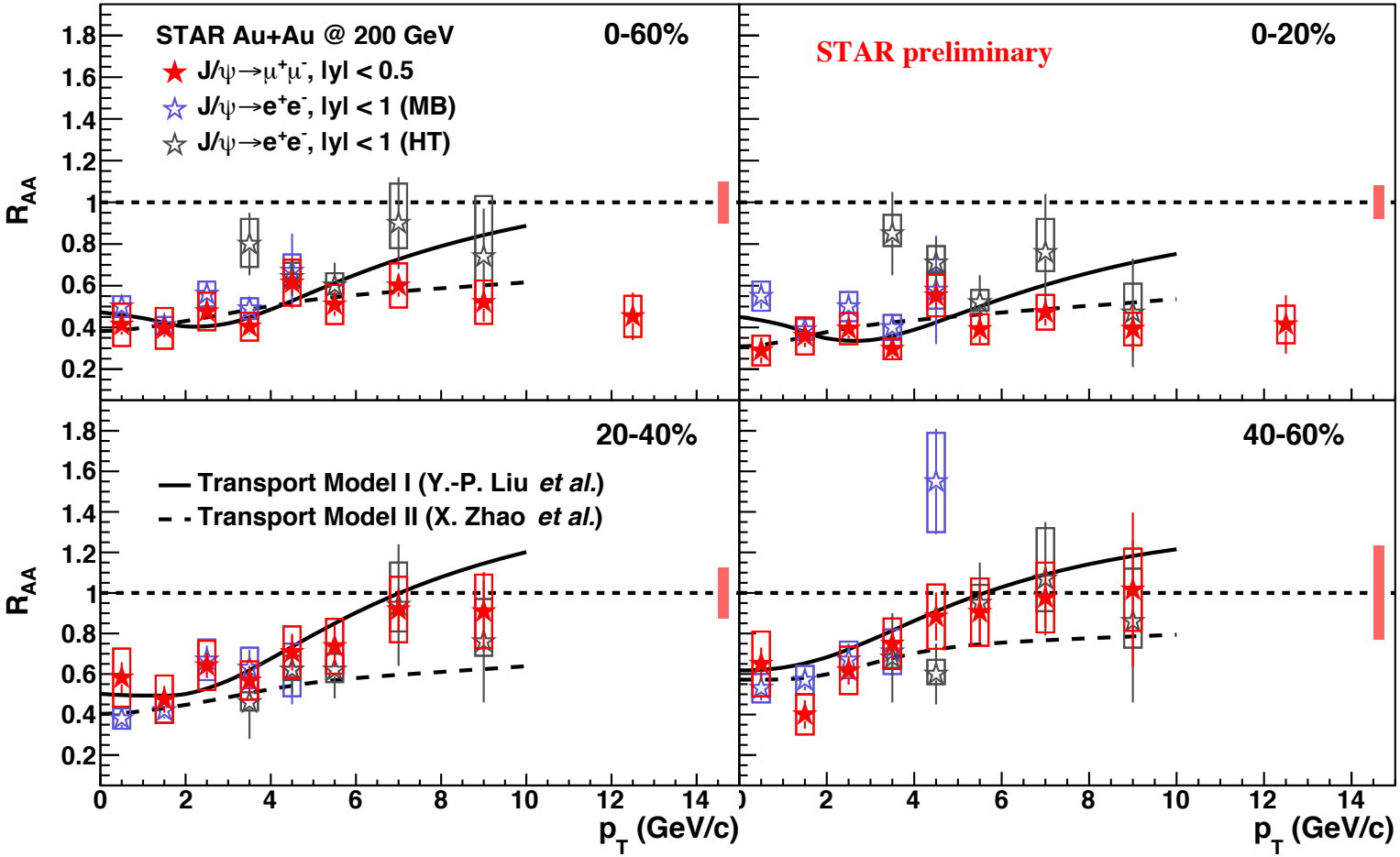
dielectron:
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

Tsallis Blast-Wave
Tang et al., PRC 79, (2009) 051901(R)

- Measurement of inclusive J/ψ yield at mid-rapidity in Au+Au collisions via the dimuon channel for $0 < p_T < 15$ GeV/c

- Consistent with the published dielectron results using Run10 data over the entire kinematic range

J/ψ R_{AA} vs. p_T: STAR vs. Transport Models



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