Measurements of charmonium production in p+p, p+Au and Au+Au collisions at 200 GeV with the STAR experiment

Takahito Todoroki (BNL)
for the STAR Collaboration

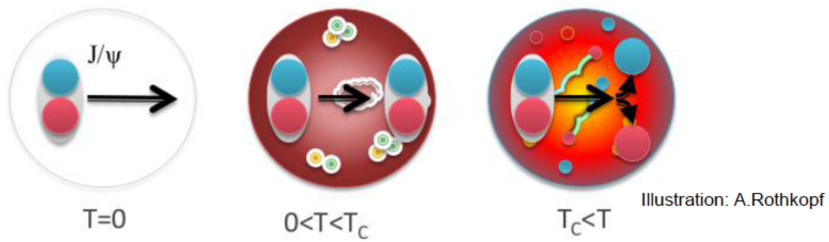
Quark Matter 2017
From Feb 5th to Feb 11st 2017
Hyatt Regency Chicago

U.S. DEPARTMENT OF ENERGY
Office of Science

BROOKHAVEN NATIONAL LABORATORY

Probe QGP with Charmonium

- **Color-screening** : J/ψ dissociates in the medium



J/ψ suppression was proposed as a direct proof of deconfinement

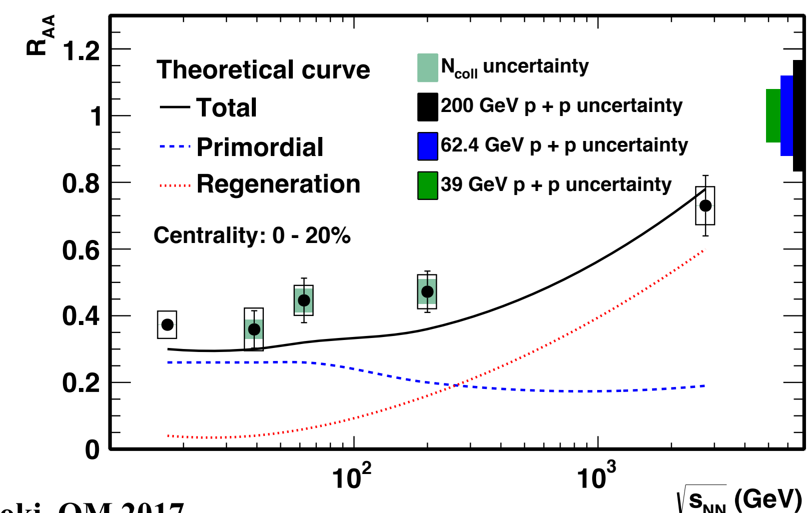
T. Matsui and H. Satz PLB 178 (1986) 416

HOWEVER

- **Various production mechanisms**
  - Prompt: direct production; decay of ψ(2S) and χ_c (40%)
  - Non-prompt: B-hadron decay (up to 10-15% at high p_T)

- **Different effects in play**
  - **Hot nuclear matter effects**
    - Dissociation
    - Regeneration
    - Medium-induced energy loss
  - **Cold nuclear matter effects**

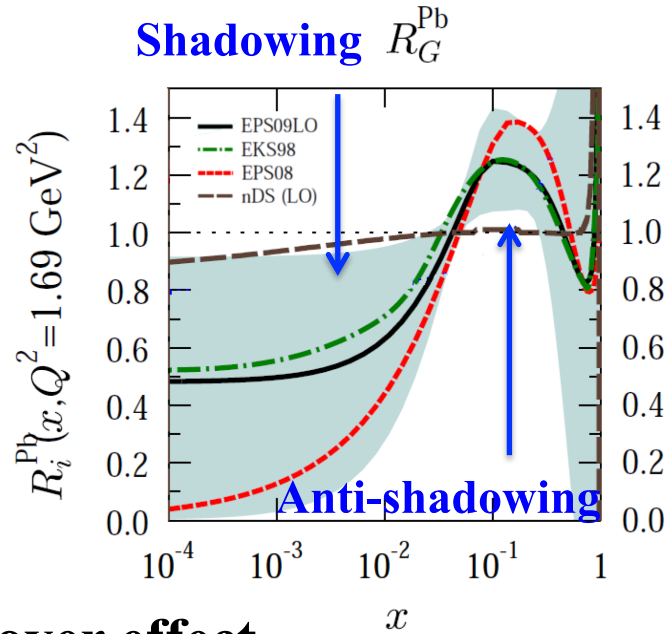
STAR arXiv:1607.07517v1



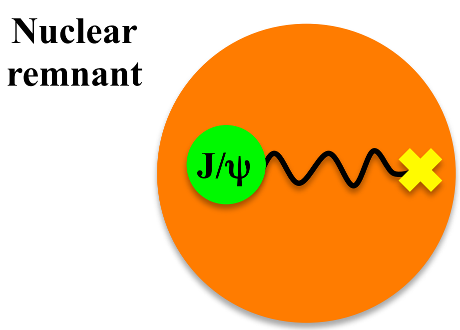
Cold Nuclear Matter Effects

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

- **nPDF effect**
  - Modification of gluon PDF distributions in nucleus
  - Shadowing : nPDF < proton PDF
  - Anti-shadowing : nPDF > proton PDF

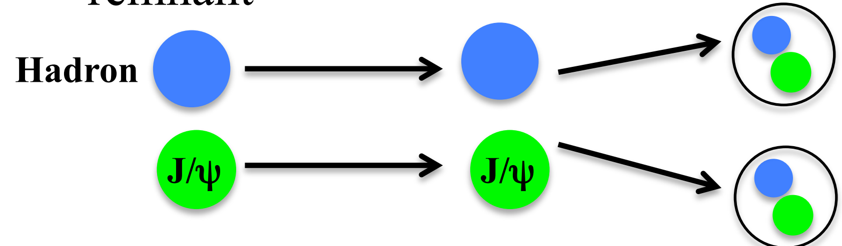


- **Nuclear absorption effect**
  - Absorption of charmonium by remnant of incident nuclei



Gavin et al., PRL 78 (1997) 1006
Capella et al., PLB 393 (1997) 431

- **Co-mover effect**
  - Break-up of charmonium by co-moving hadrons outside of nuclear remnant



Ferreiro et al., Eur.Phys. J. C61 (2009) 859–864
Ferreiro et al., PLB680 (2009) 50–55
Ferreiro, et al., PRC81 (2010) 064911

The Solenoid Tracker At RHIC (STAR)

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

➢ **TPC**: precisely measure momentum and energy loss

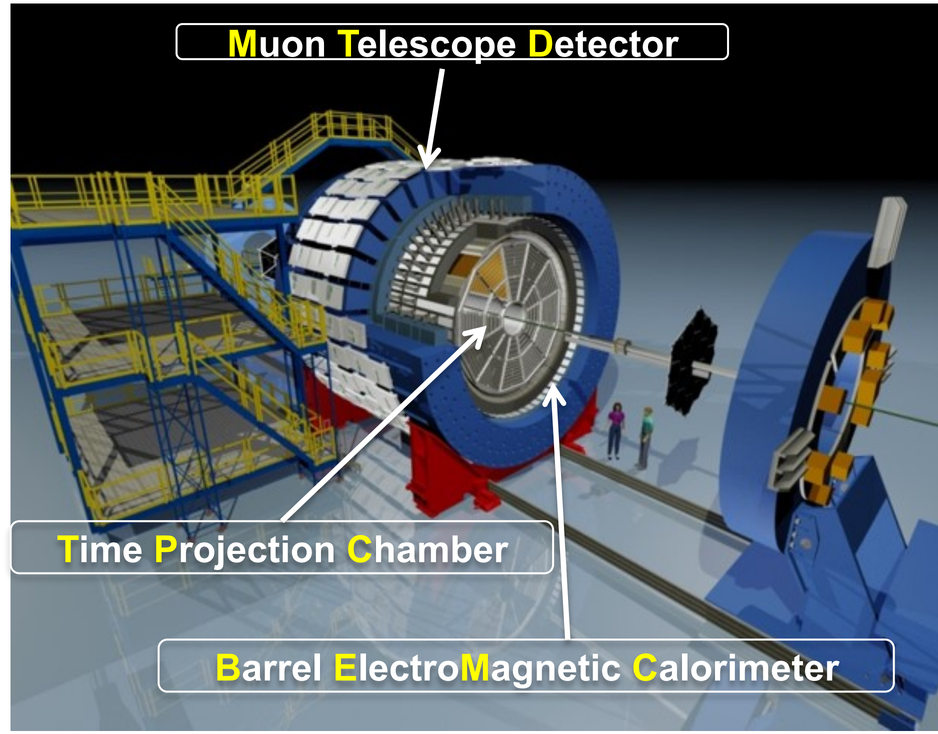
➢ **BEMC**: trigger on and identify electrons

➢ **MTD (45% φ, $|\eta|<0.5$)** : trigger on and identify muons

  – ***Precise timing measurement (σ~100 ps)***

  – ***Spatial resolution (~1cm)***

  – ***Dimuon trigger for quarkonia***

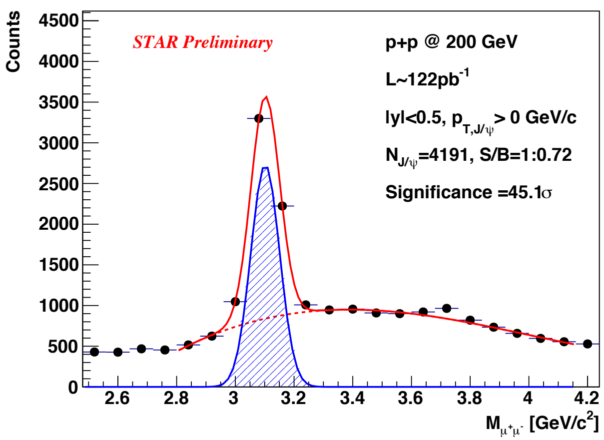


Sampled luminosity by the dimuon trigger

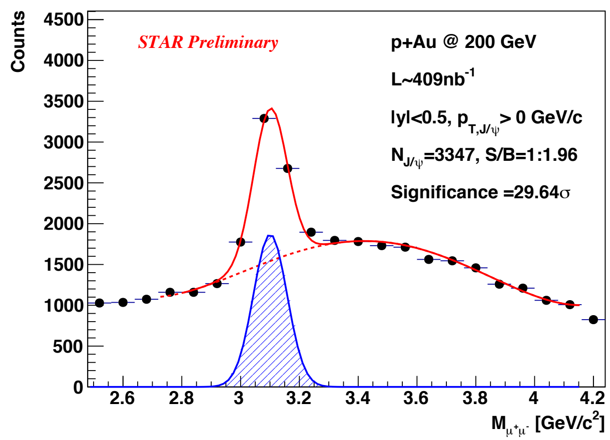
2013 p+p 500 GeV	~ 28.3 pb^{-1}
2014 Au+Au 200 GeV	**~ 14.2 nb^{-1}**
2015 p+p 200 GeV	**~ 122 pb^{-1}**
2015 p+Au 200 GeV	**~ 409 nb^{-1}**
2016 d+Au 200 GeV	~ 94 nb^{-1}
2016 Au+Au 200 GeV	~12.8 nb^{-1}

Charmonium signal in the **dimuon** decay channel

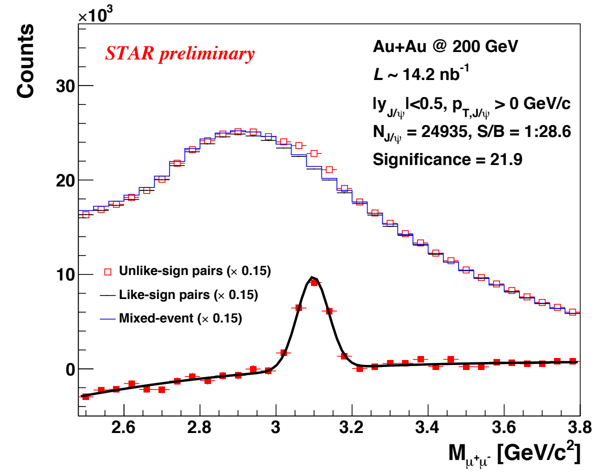
J/ψ in p+p ~45σ



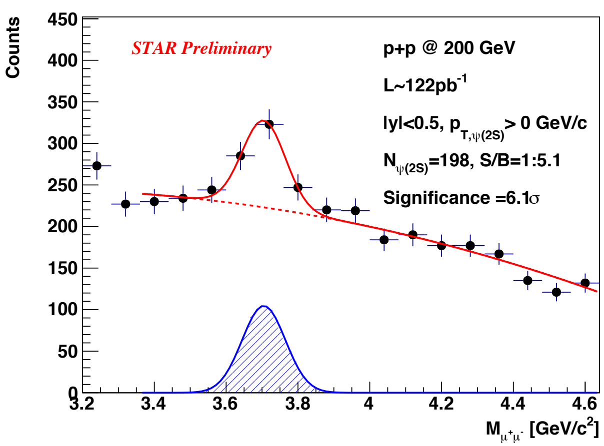
J/ψ in p+Au ~26σ



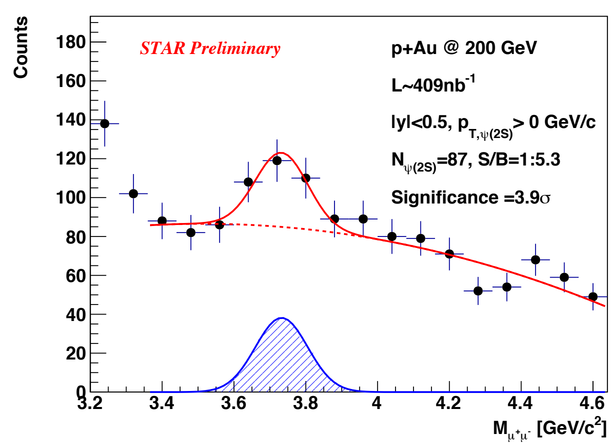
J/ψ in Au+Au ~22σ



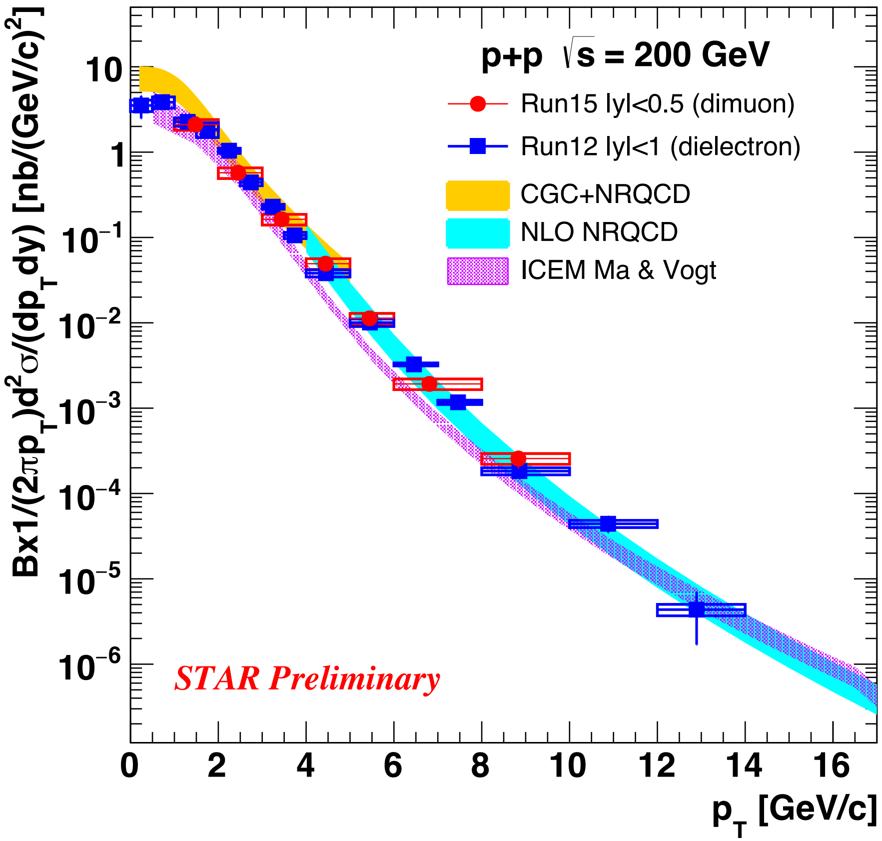
ψ(2S) in p+p ~6.1σ



ψ(2S) in p+Au ~3.9σ



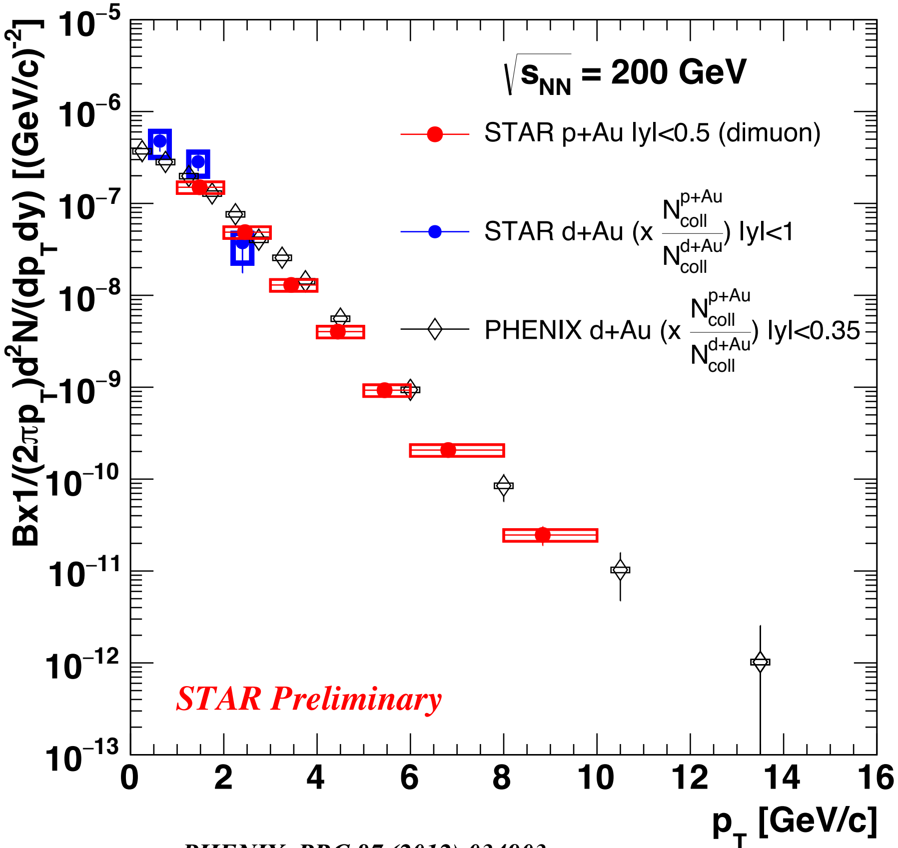
Inclusive J/ψ cross section in p+p collisions



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 in **$0 < p_T < 14$ GeV/c**
- CGC+NRQCD & NLO NRQCD describe data above 1 GeV/c
- Improved CEM model describes data well at low p_T
  - Data are above ICEM calculation at $3.5 < p_T < 12$ GeV/c

Inclusive J/ψ invariant yield in p+Au collisions

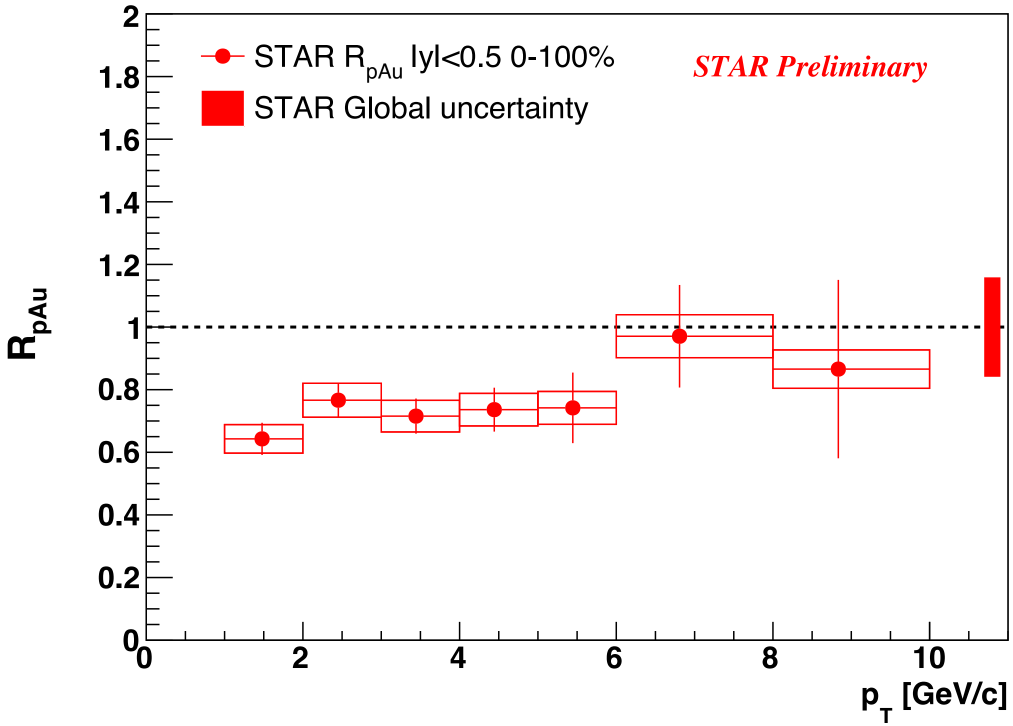


PHENIX, PRC 87 (2012) 034903
STAR d+Au, PRC 93 (2016) 064904

- **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

Centrality determination in p+Au collisions, Yanfang Liu, PosterID H12

J/ψ R_{pAu} at 200 GeV



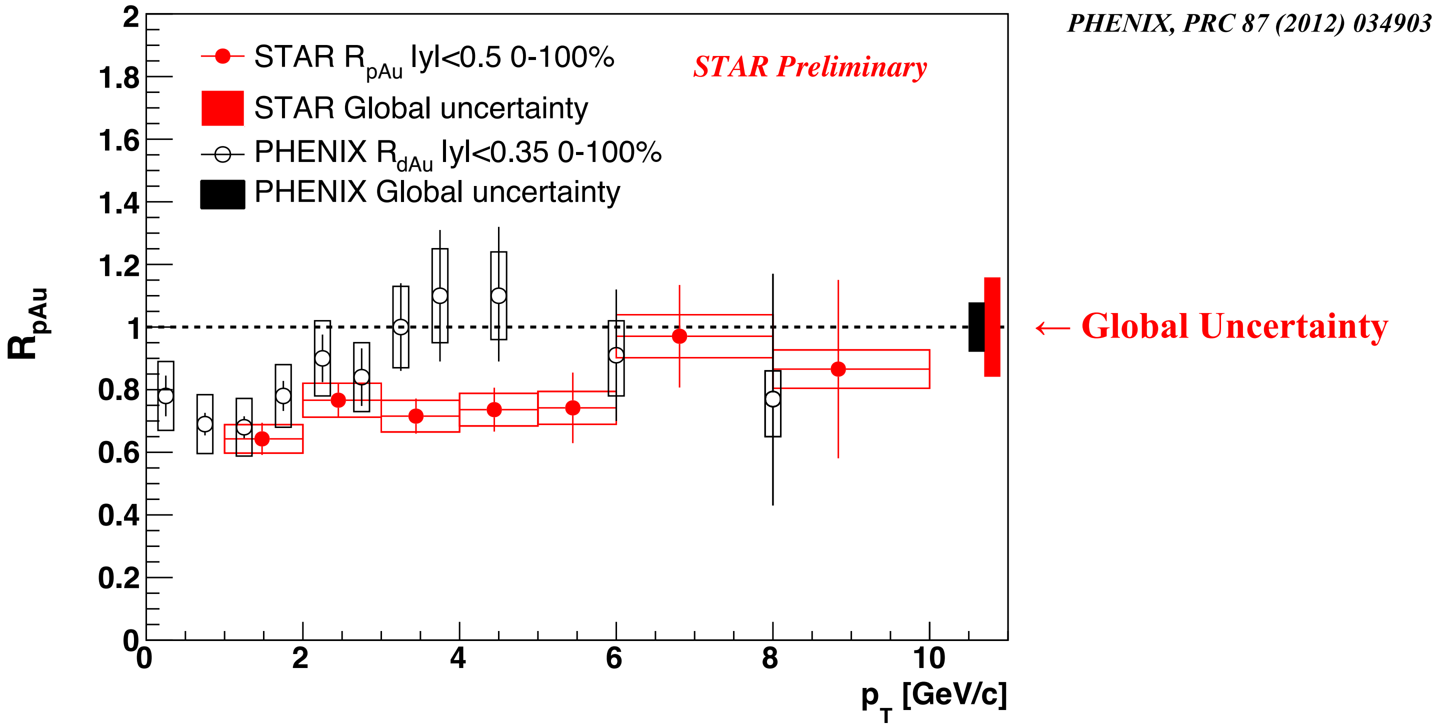
$$R_{pAu} = \frac{\sigma_{inel}}{\langle N_{coll} \rangle} \frac{d^2N_{pAu} / dydp_T}{d^2\sigma_{pp} / dydp_T}$$

← **Global Uncertainty**

- Luminosity p+p
- N_{coll}
- Trigger efficiency
- Tracking efficiency

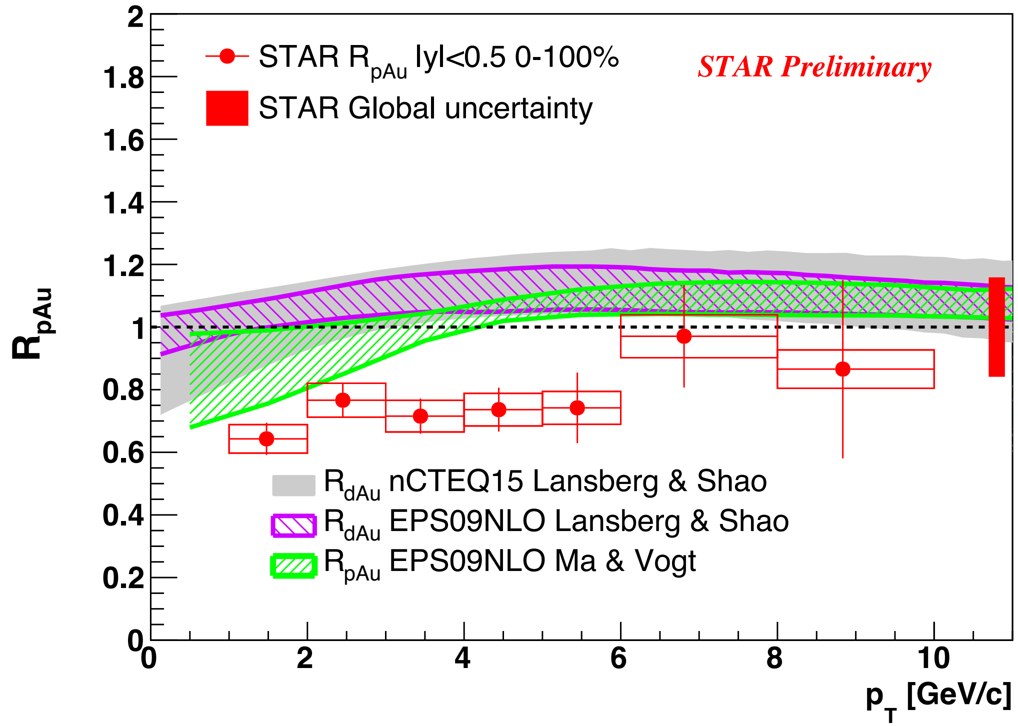
- **First J/ψ R_{pAu} measurement at RHIC**
- R_{pAu} is consistent with unity at high p_T and is less than unity at low p_T

J/ψ R_{pAu} at 200 GeV



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

J/ψ R_{pAu} at 200 GeV



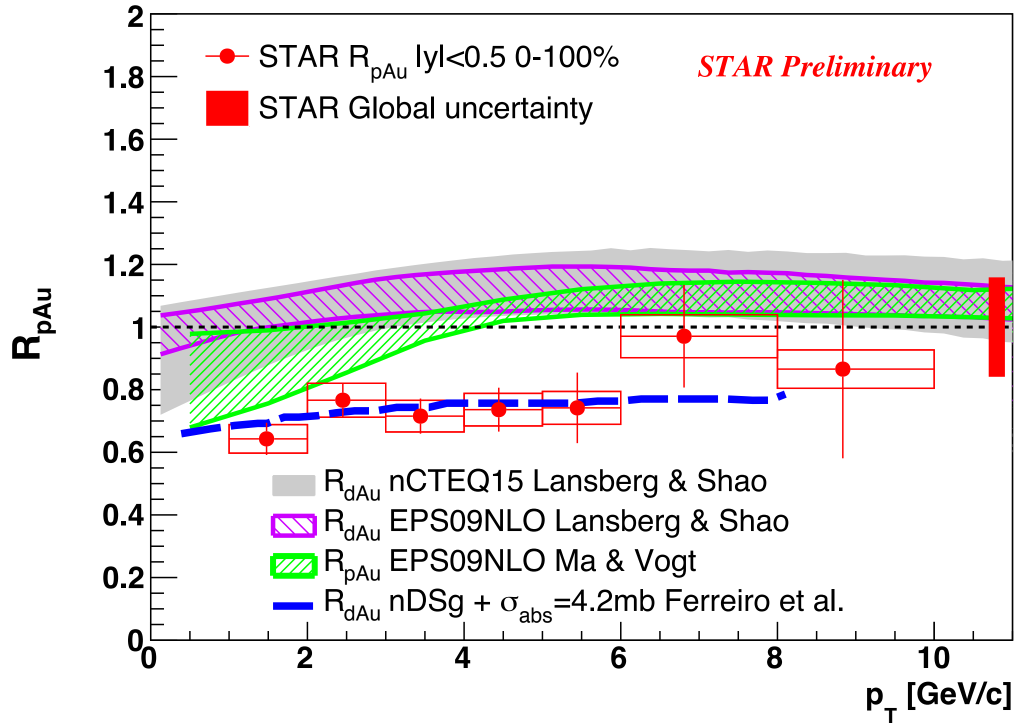
EPS09+NLO, Ma & Vogt, Private Comm.

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 shadowing effect can touch the upper limit of data within uncertainties**

J/ψ R_{pAu} at 200 GeV



EPS09+NLO, Ma & Vogt, Private Comm.

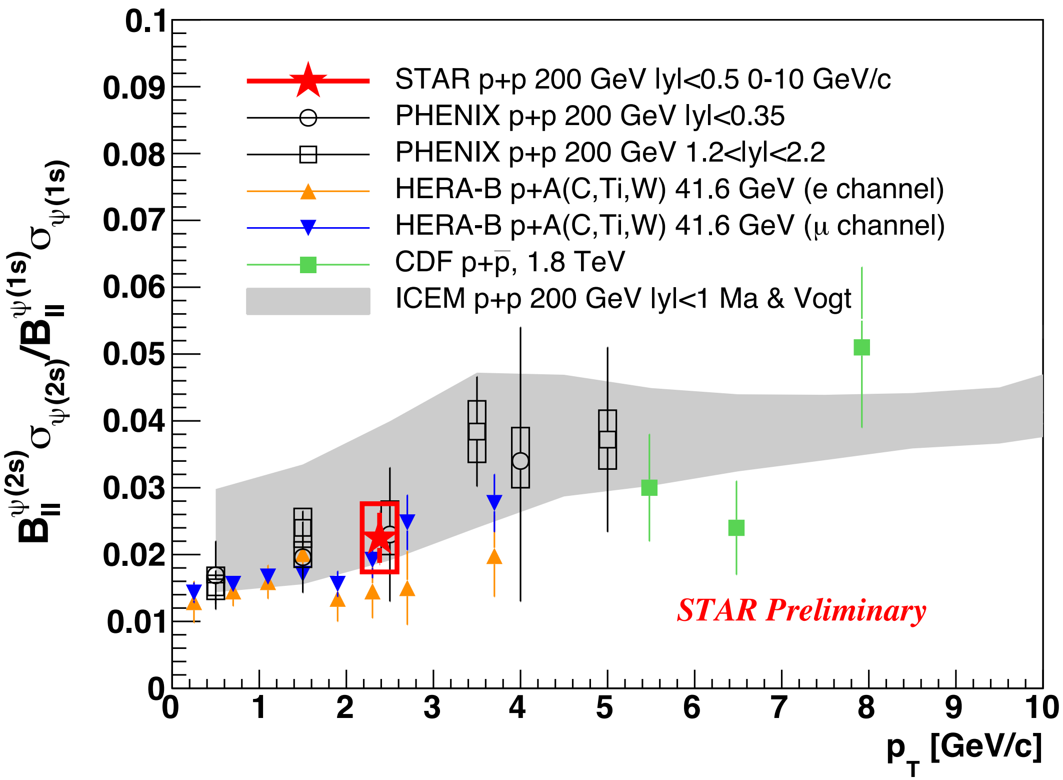
nCTEQ, EPS09+NLO, Lansberg Shao, Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570

Ferreriro et al., Few Body Syst. 53 (2012) 27

← **Global Uncertainty**

- Model calculations with only shadowing effects can touch the upper limit of data within uncertainties
- **However additional nuclear absorption is favored by data**

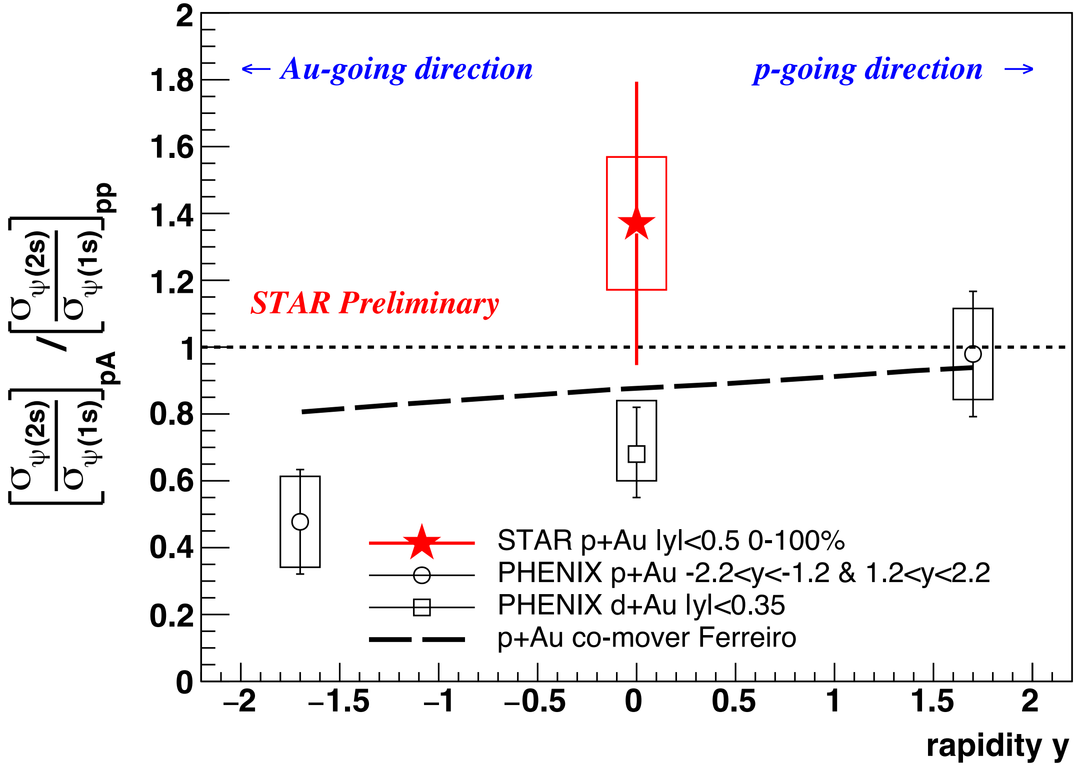
$\psi(2S)/\psi(1S)$ ratio in p+p



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

- New STAR $B^{\psi(2S)}\ \sigma_{\psi(2S)}\ /B^{\psi(1S)}\ \sigma_{\psi(1S)}$ ratio in p+p collisions is consistent with world-wide data
- The ICEM model can describe the increasing trend at RHIC

ψ(2S)/ψ(1S) double ratio between p+p and p+Au



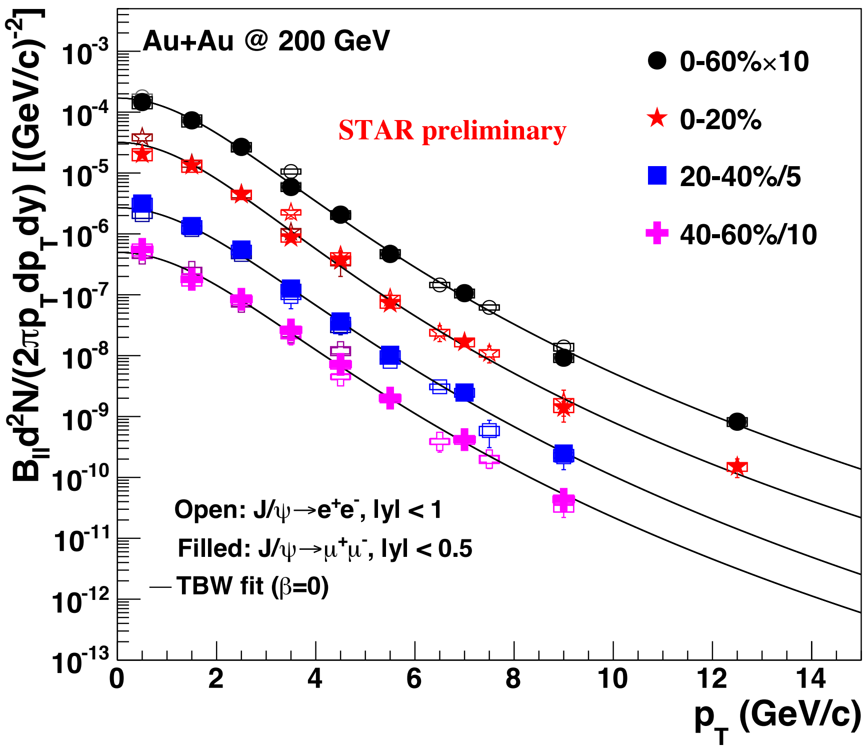
PHENIX p+Au, arXiv:1609.06550 (Accepted by PRC)
PHENIX d+Au, PRL111 (2013) 202301

Co-mover calculation, Ferreiro (2016) private communication Calculation based on PLB749 (2015) 98-103

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

1.37 ± 0.42(stat) ± 0.19(sys)

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

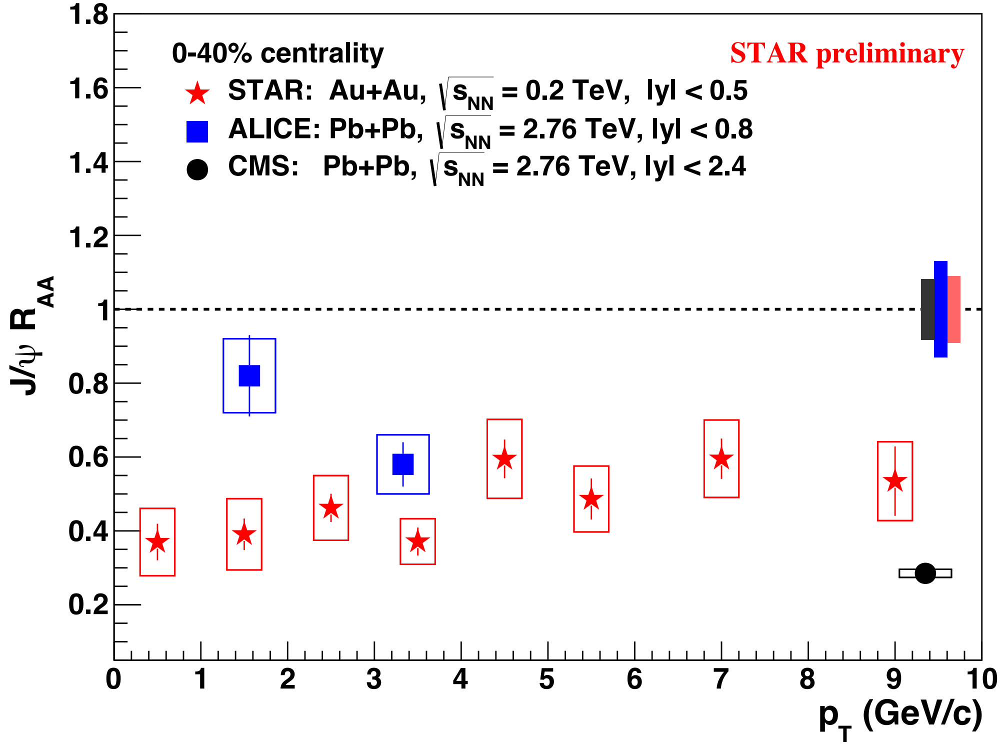


dielectron:
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

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 di-muon channel for $0 < p_T < 15$ GeV/c**
- Consistent with the published di-electron results using Run10 data over the entire kinematic range.

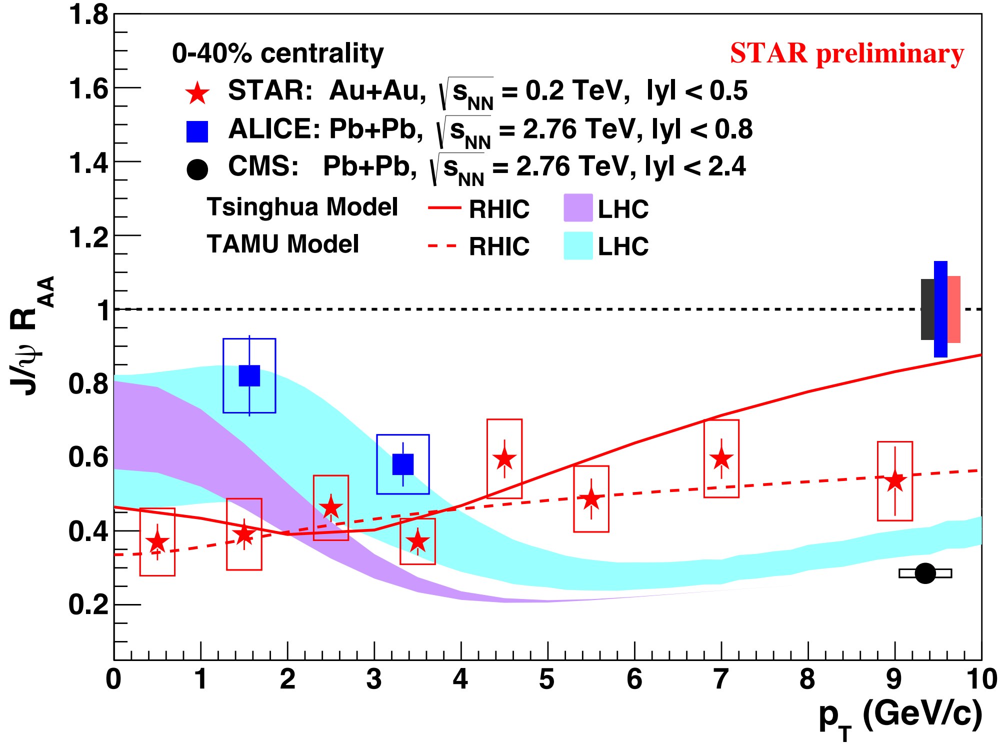
J/ψ R_{AA} vs. p_T: RHIC vs. LHC



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**

J/ψ R_{AA} vs. p_T: RHIC vs. LHC

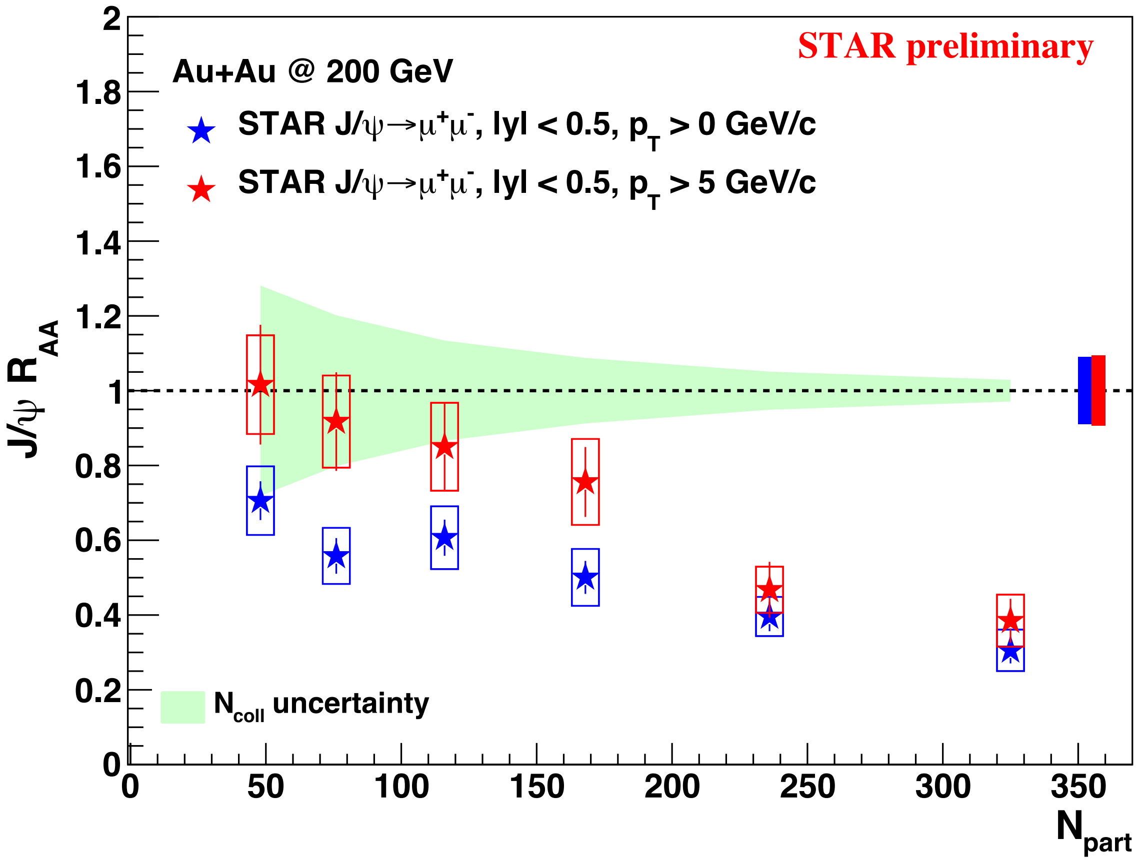


Transport model:
Tsinghua at RHIC: PLB 678 (2009) 72
Tsinghua at LHC: PRC 89 (2014) 054911
TAMU at RHIC: PRC 82 (2010) 064905
TAMU at LHC: NPA 859 (2011) 114

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

R_{AA} vs. centrality

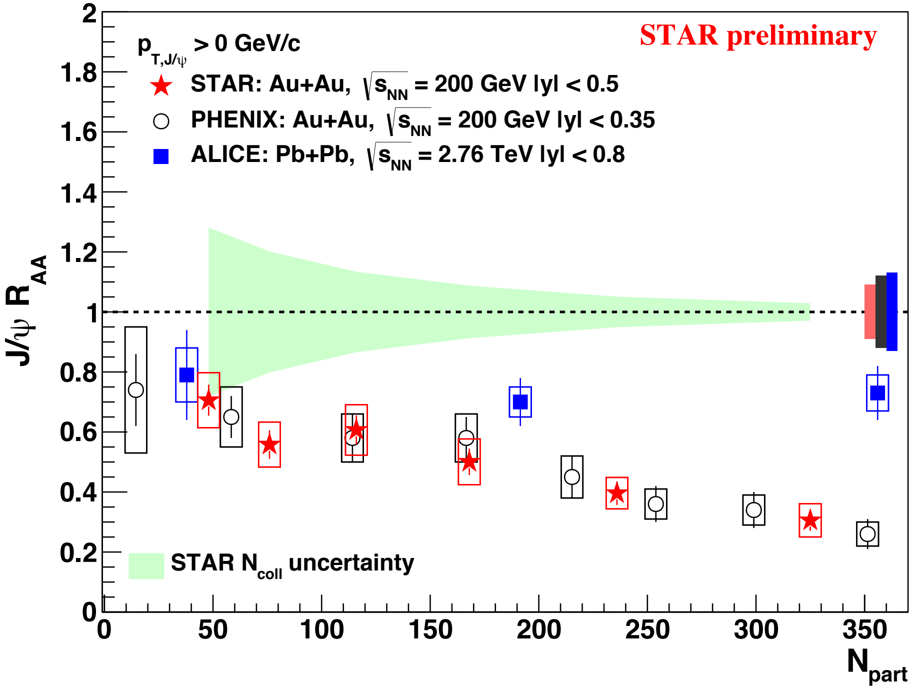


- Central collisions: **significant suppression is observed for $p_T > 0$ GeV/c and $p_T > 5$ GeV/c** → interplay of different effects
- Peripheral collisions: **R_{AA} of J/ψ for $p_T > 0$ GeV/c is smaller than that for $p_T > 5$ GeV/c probably due to cold nuclear matter effects**

Centrality dependence: RHIC vs. LHC

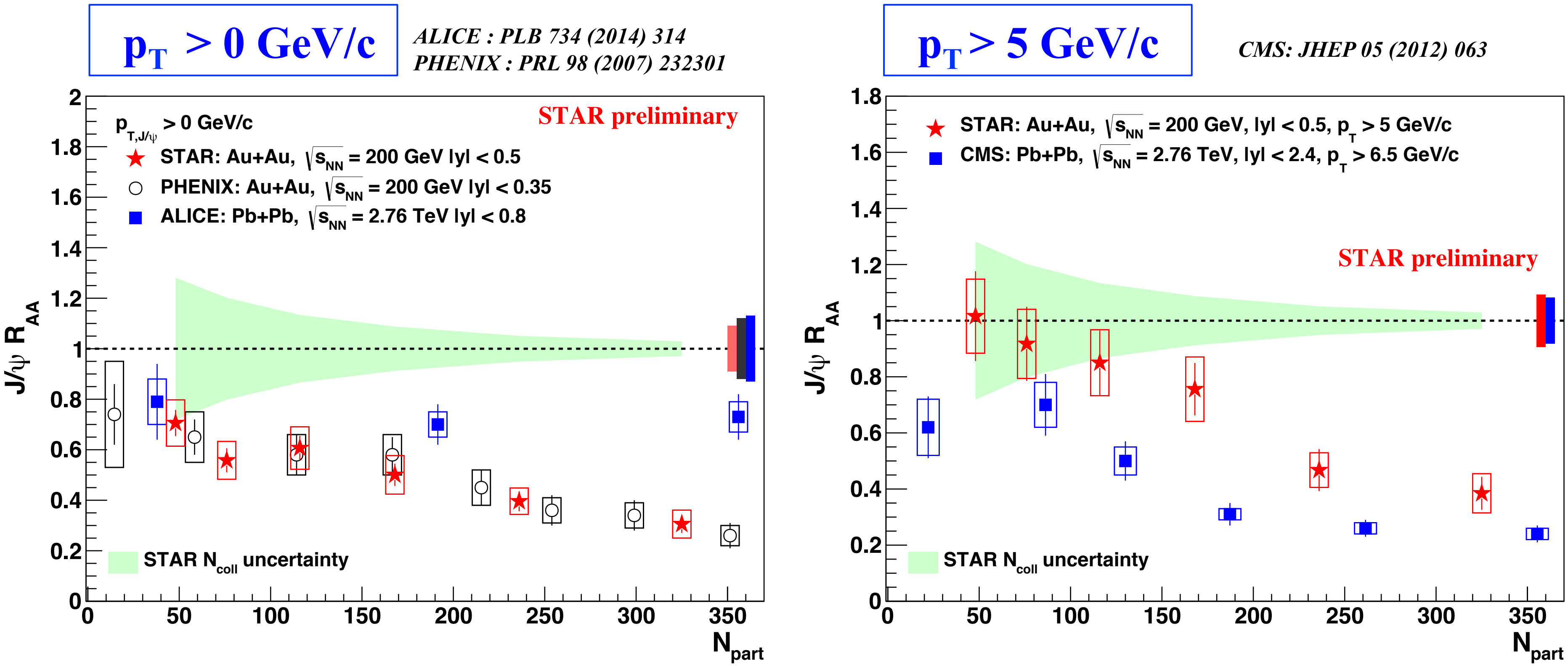
p_T > 0 GeV/c

ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301



- p_T > 0 GeV/c: smaller R_{AA} at RHIC in central collisions

Centrality dependence: RHIC vs. LHC

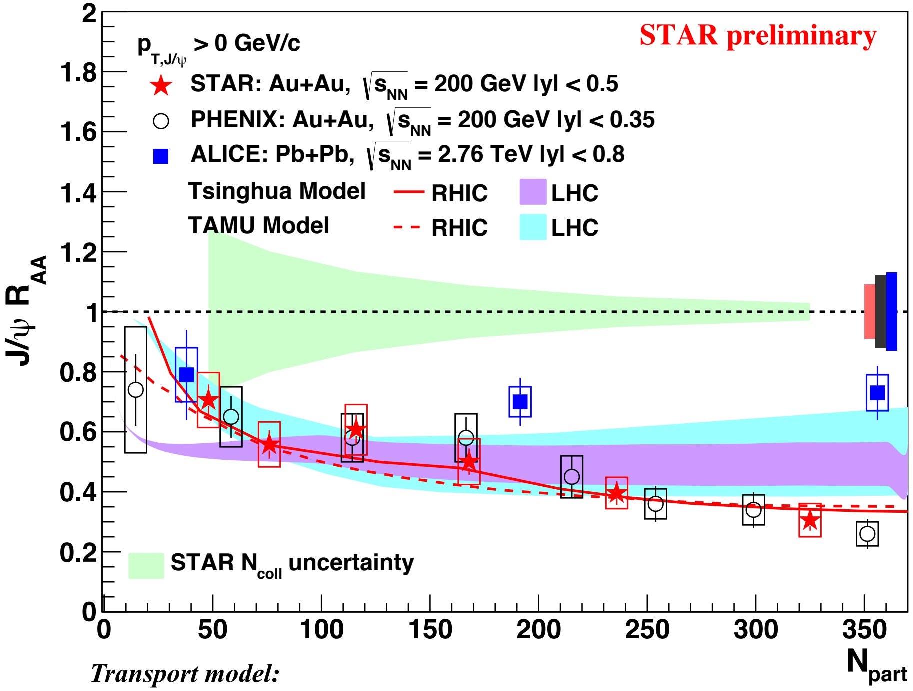


- $p_T > 0$ GeV/c: smaller R_{AA} at RHIC in central collisions
- $p_T > 5$ GeV/c: larger R_{AA} at RHIC in all centralities

Centrality dependence: RHIC vs. LHC

p_T > 0 GeV/c

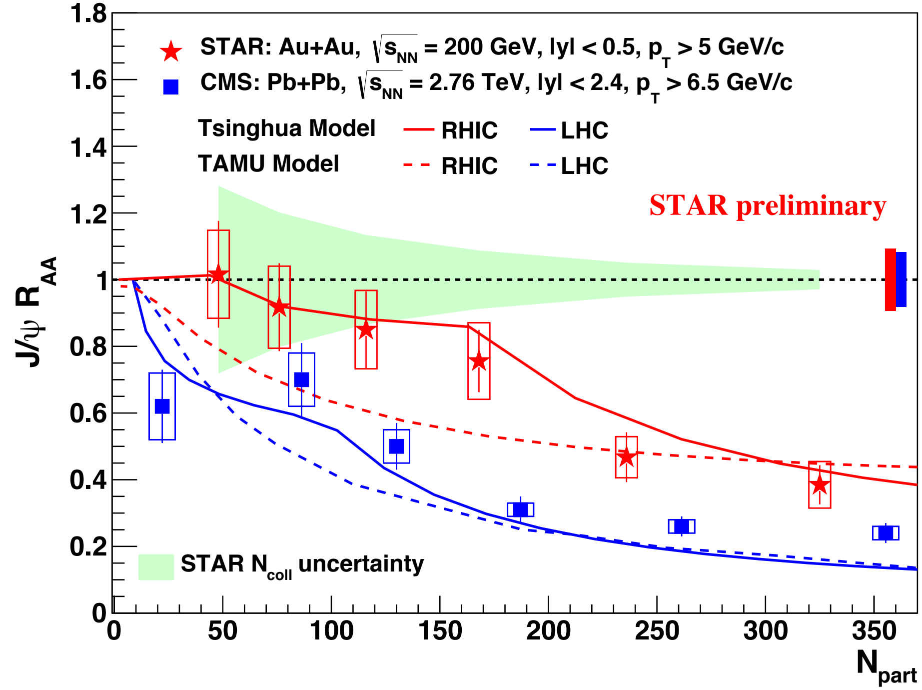
ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301



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

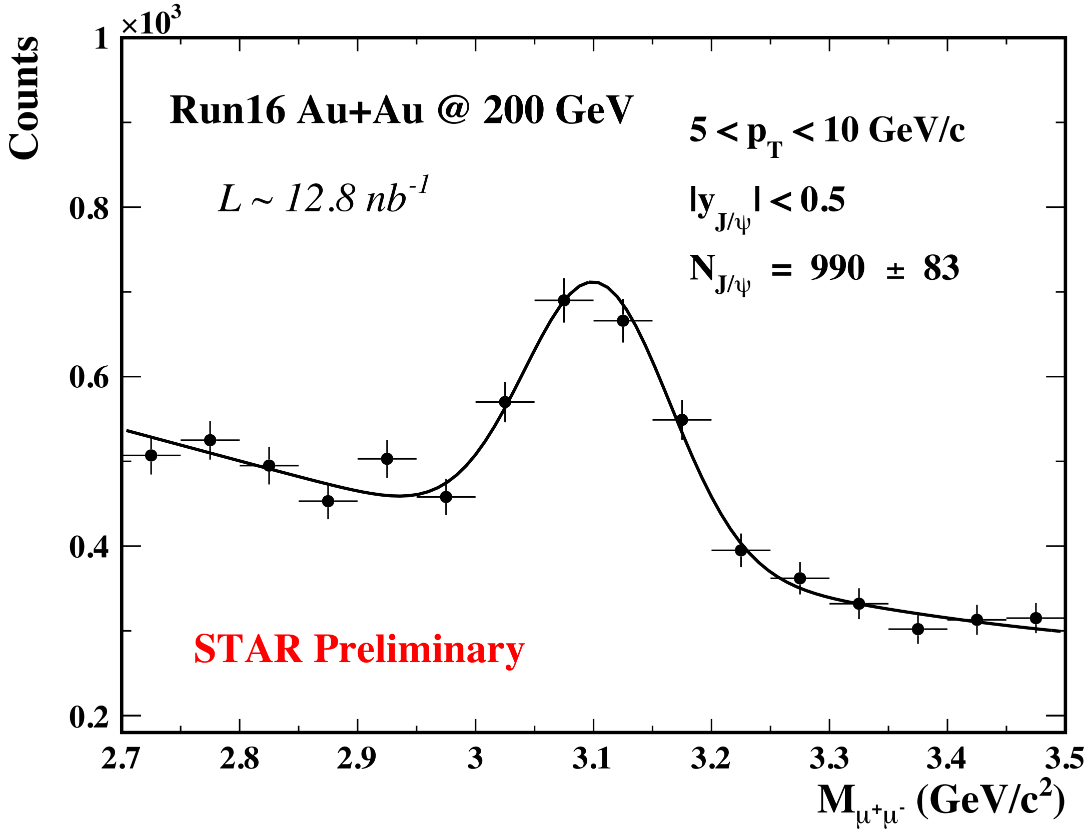
p_T > 5 GeV/c

CMS: JHEP 05 (2012) 063



- **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: both models can qualitatively describe data

J/ψ signal from 2016 Au+Au 200 GeV data



- Similar luminosity sampled by the dimuon trigger in 2016 as in 2014
- **2016 data also show excellent J/ψ signal!!**

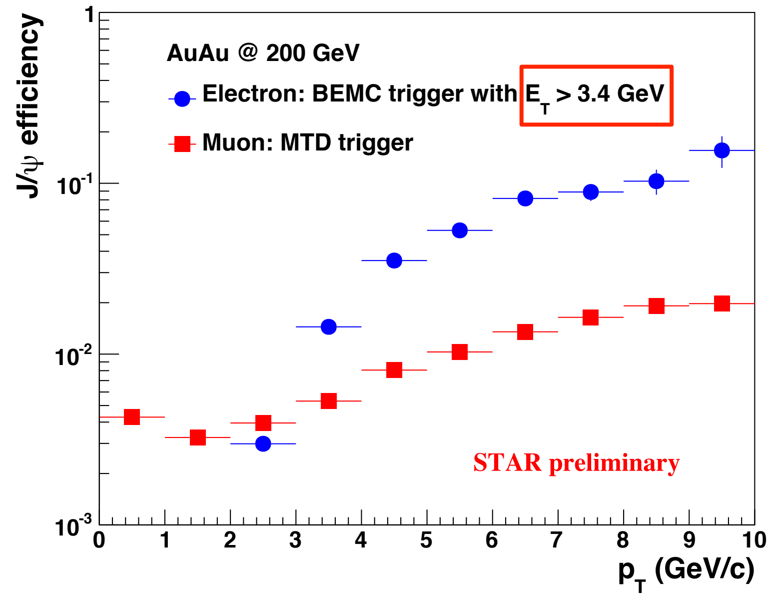
Summary

- **p+p collisions at $\sqrt{s}$ = 200 GeV**
  - Inclusive J/ψ cross section can be described by CGC+NRQCD and NLO NRQCD above 1 GeV/c
  - ICEM describes data at low p_T while underestimates data at $3.5 < p_T < 12$ GeV/c
- **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 shadowing 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-p_T → **smaller dissociation rate due to lower temperature**
  - J/ψ R_{AA} can be qualitatively described by **transport models** including **dissociation and regeneration contributions**

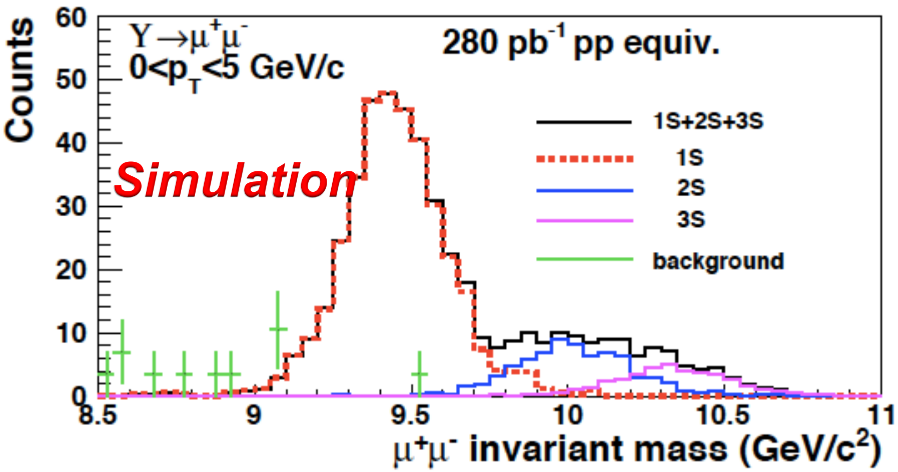
Back Up

Muon Telescope Detector (MTD)

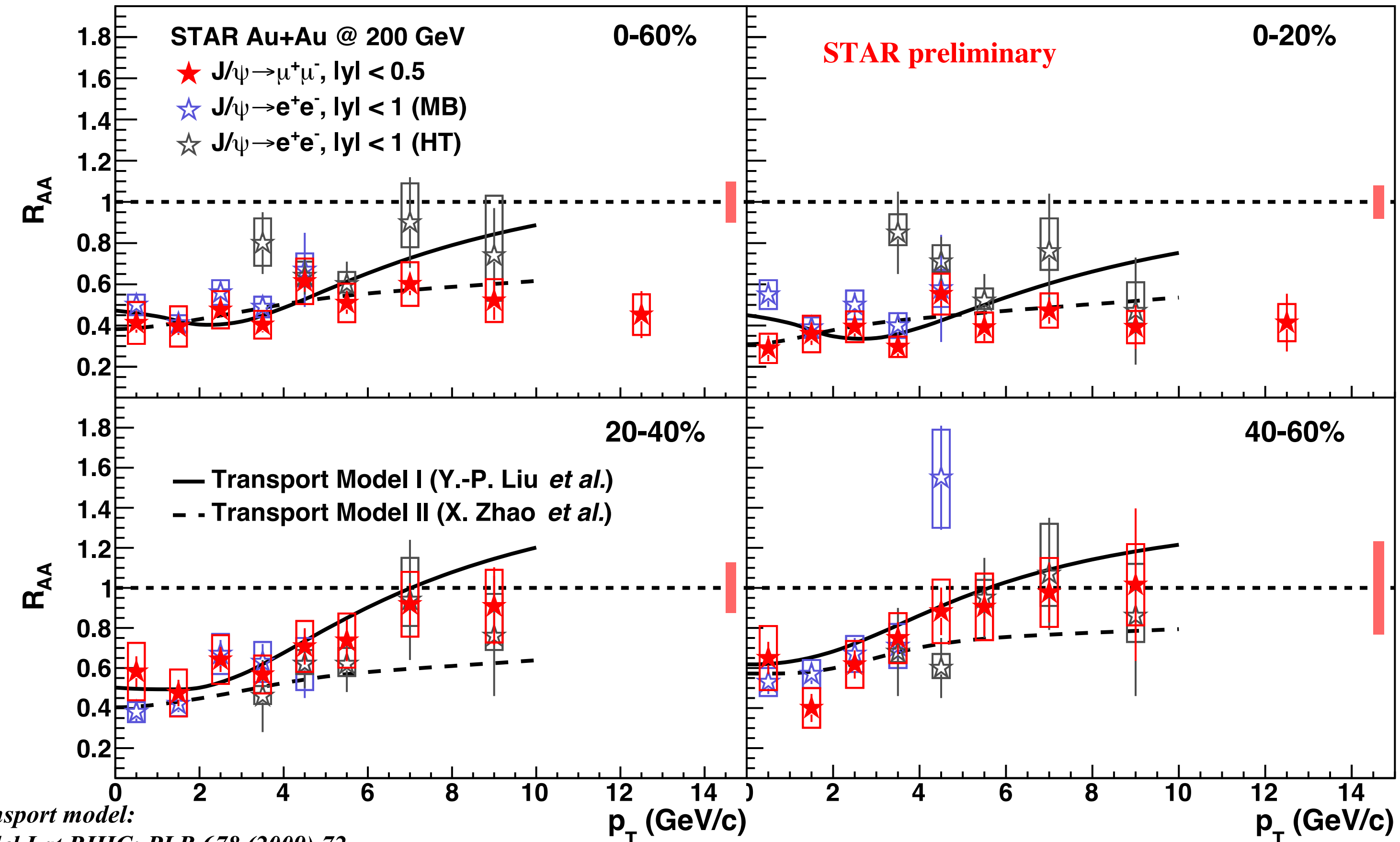
- **Relatively high efficiency for J/ψ at low p_T** → cover wide kinematic range



- **Separate Υ(2S+3S) from Υ(1S)**
- **Potential to separate Υ(2S) and Υ(3S)** states as muons suffer less from bremsstrahlung



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



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

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