Quarkonium measurements in heavy-ion collisions at STAR

Pengfei Wang (*for the STAR Collaboration*)

University of Science and Technology of China

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

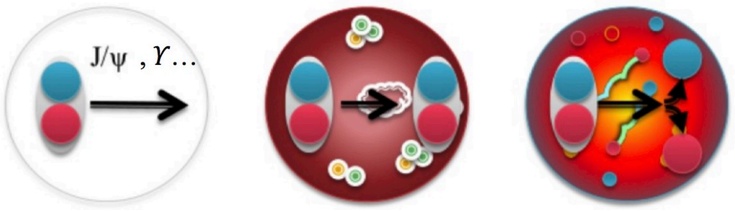
STAR

Outline

- Introduction
- STAR experiment
- Charmonium measurements
- Bottomonium measurements
- Summary

Why Quarkonium?

- **Color-screening: quark-antiquark potential is color-screened by the surrounding partons -> *dissociation***

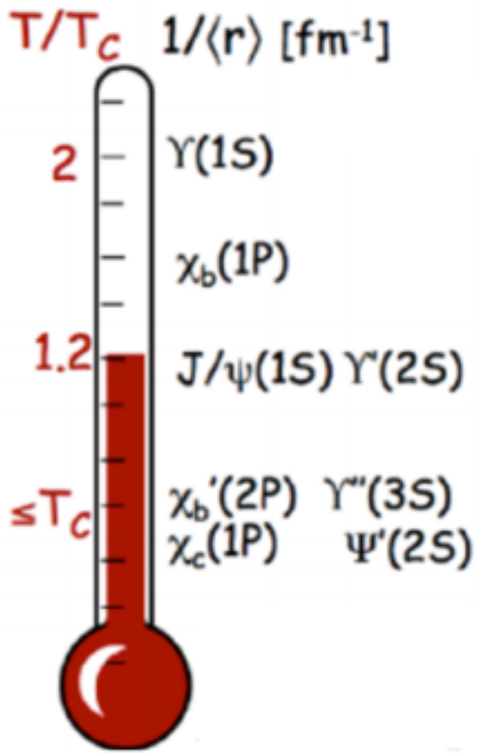


T = 0 **0 < T < T_C** **T > T_C**

Illustration: A. Rothkopf

- **However, other effects come into play**
  - **Regeneration**
  - **Medium-induced energy loss**
  - **Feed-down**
  - **Cold Nuclear Matter (CNM) effects**

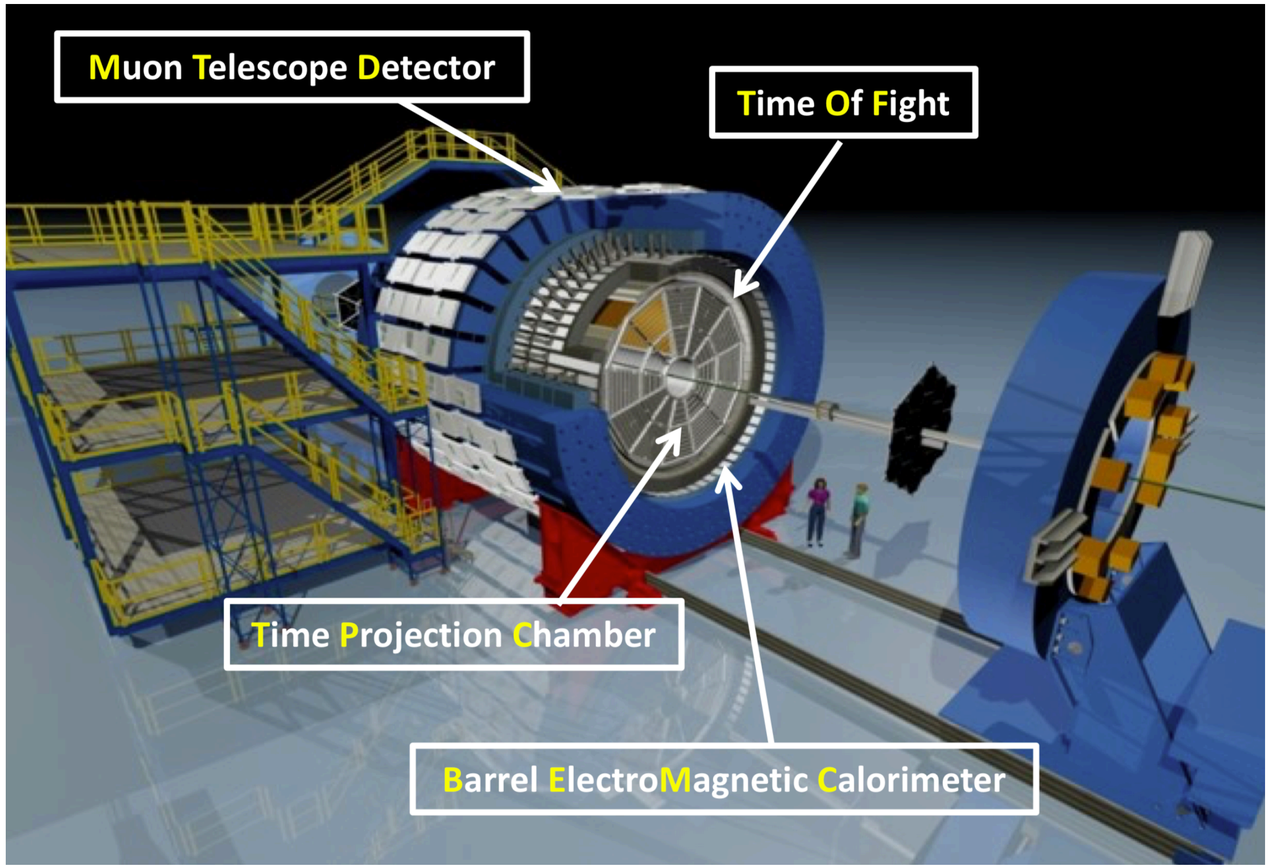
- **"Thermometer": different states dissociate at different temperatures -> *sequential melting***



A. Mocsy, EPJ C61 (2009) 705

The Solenoidal Tracker at RHIC

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



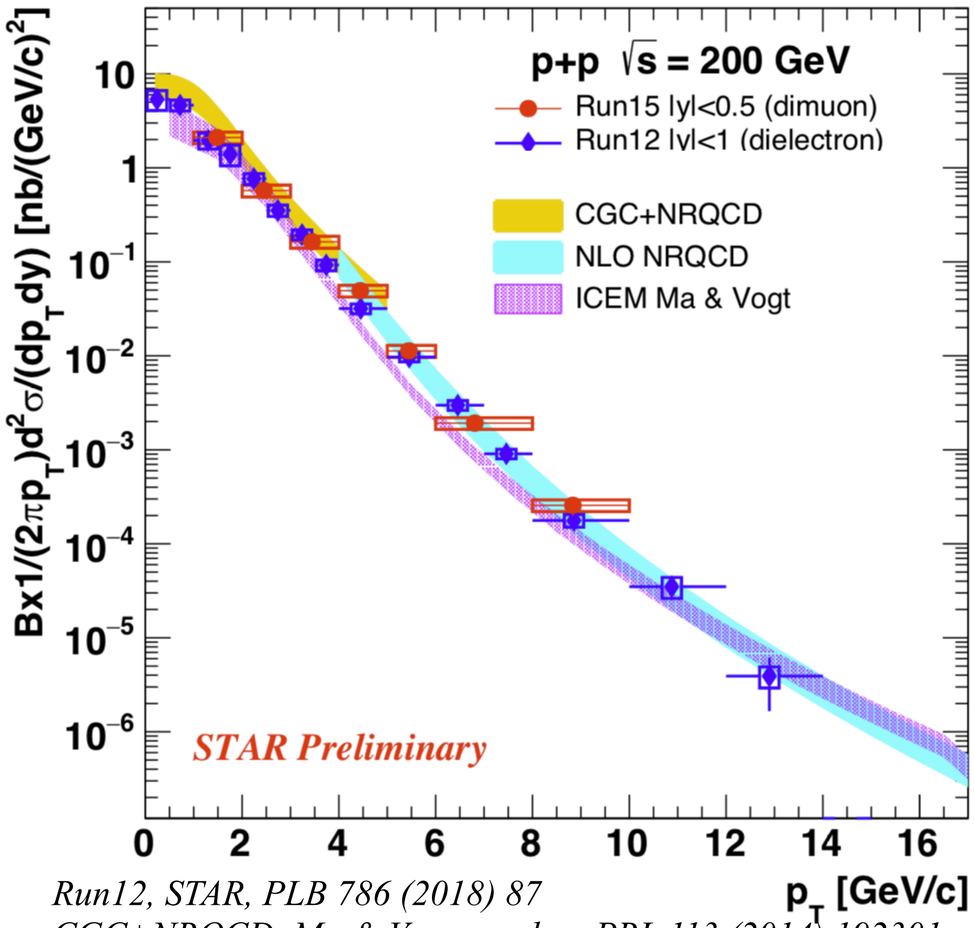
- **TPC**
  - Tracking, PID
- **TOF**
  - Measure time of flight
- **BEMC**
  - Trigger and identification of high-p_T electrons
- **MTD** ($|\eta| < 0.5$, 45% in φ)
  - Dimuon trigger and muon identification
  - Less bremsstrahlung: helps separate Υ(2S+3S) from Υ(1S)

Charmonium

- Large production cross-section at RHIC energy
- Interplay of several effects

.

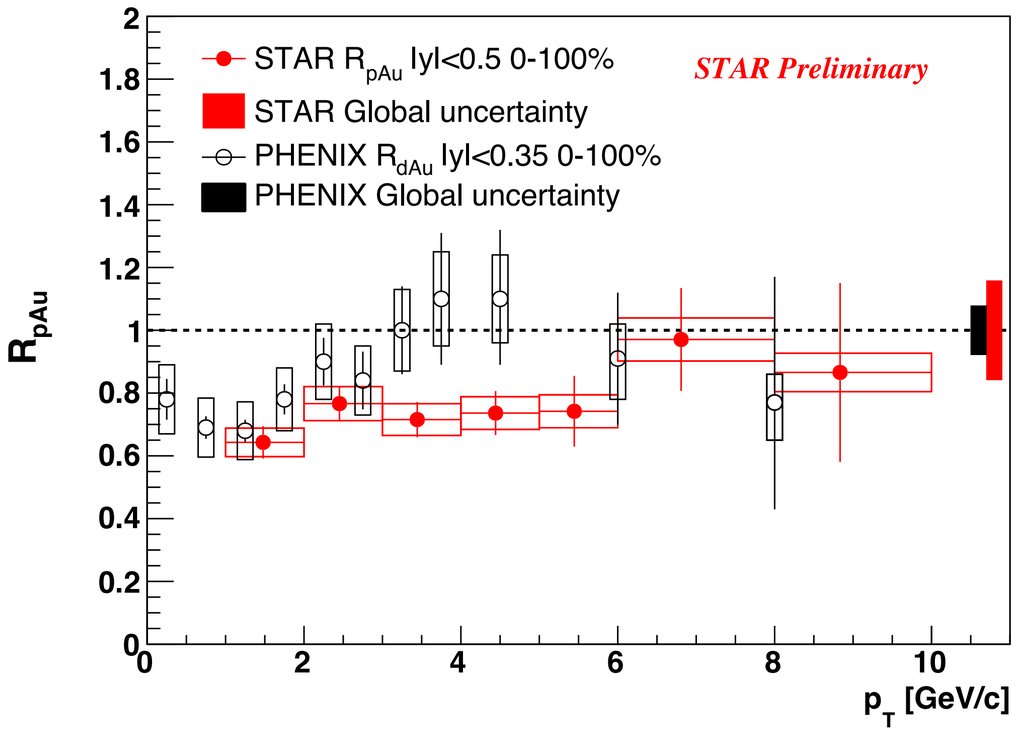
Inclusive J/ψ in p+p collisions



Run12, STAR, PLB 786 (2018) 87
CGC+NRQCD, Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
ICEM, Ma & Vogt, PRD 94 (2016) 114029
S. Digal, P. Petreczky & H. Satz, PRD 64 (2001) 094015

- **Inclusive J/ψ cross-section is measured in $0 < p_T < 14$ GeV/c**
- **CGC+NRQCD (prompt J/ψ) calculations are consistent with the data within uncertainties. However, the data are close to the lower uncertainty boundary of the theoretical calculation**
- **NLO NRQCD (prompt J/ψ) describes the data reasonably well in $4 < p_T < 14$ GeV/c**
- **Improved CEM model (direct J/ψ) describes data well at low p_T, but underpredicts data in 3.5 – 10 GeV/c**
  - **Feed-down contribution from excited charmonium states is about 40%**
- **Feed-down contribution from bottom hadrons is predicted to be approximately ~10-25% in $4 < p_T < 14$ GeV/c**

J/ψ R_{pAu} at 200 GeV

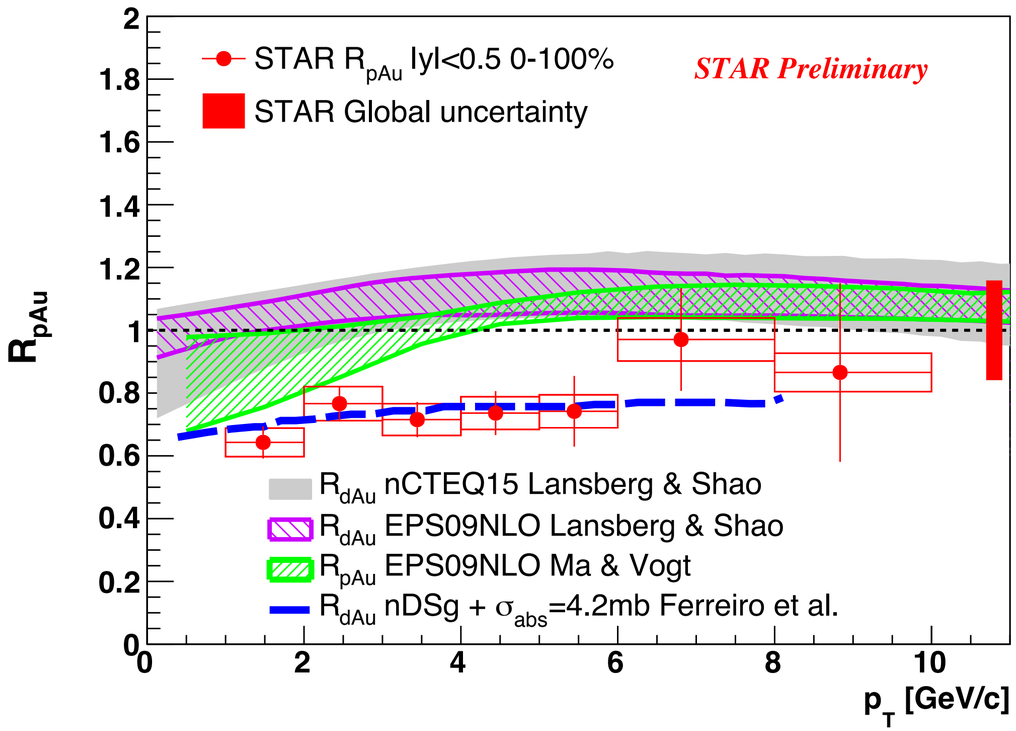


PHENIX, PRC 87 (2012) 034903

- **R_{pAu} is less than unity at low p_T and is consistent with unity at high p_T -> suppression at low p_T**
- **R_{pAu} is consistent with R_{dAu} within uncertainties -> similar CNM effects in these collision systems**

– There seems to be tension at $3.5 < p_T < 5$ GeV/c with a significance of 1.4σ

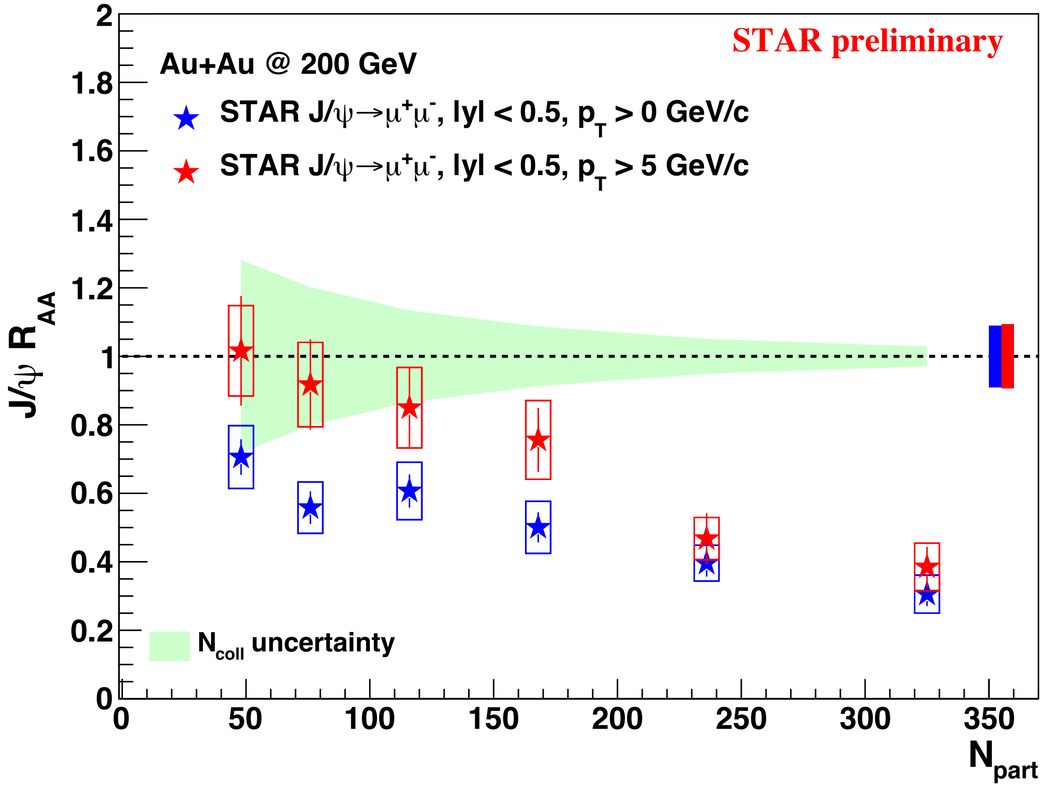
J/ψ R_{pAu} at 200 GeV



EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg & Shao, Eur. Phys. J. C77 (2017) 1
Comp. Phys. Comm. 198 (2016) 238
Comp. Phys. Comm. 184 (2013) 2562
Ferreriro et al., Few Body Syst. 53 (2012) 27

- **Model calculations with only nPDF effects describe the data at high p_T, but underpredicts the suppression at low p_T**
- **Additional nuclear absorption is favored by data**

J/ψ R_{AA} vs. centrality

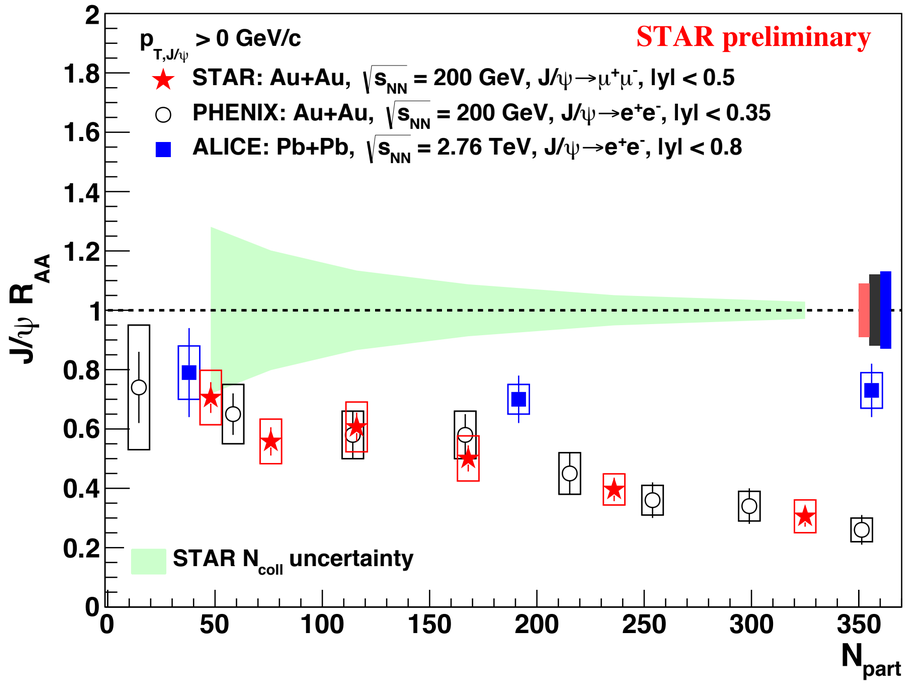


- Central collisions: significant suppression is observed for both low p_T and high p_T (> 5 GeV/c) J/ψ -> interplay of different effects
- Peripheral collisions: R_{AA} of J/ψ for p_T > 0 GeV/c is smaller than that for p_T > 5 GeV/c probably due to CNM effects

J/ψ R_{AA}: RHIC vs. LHC

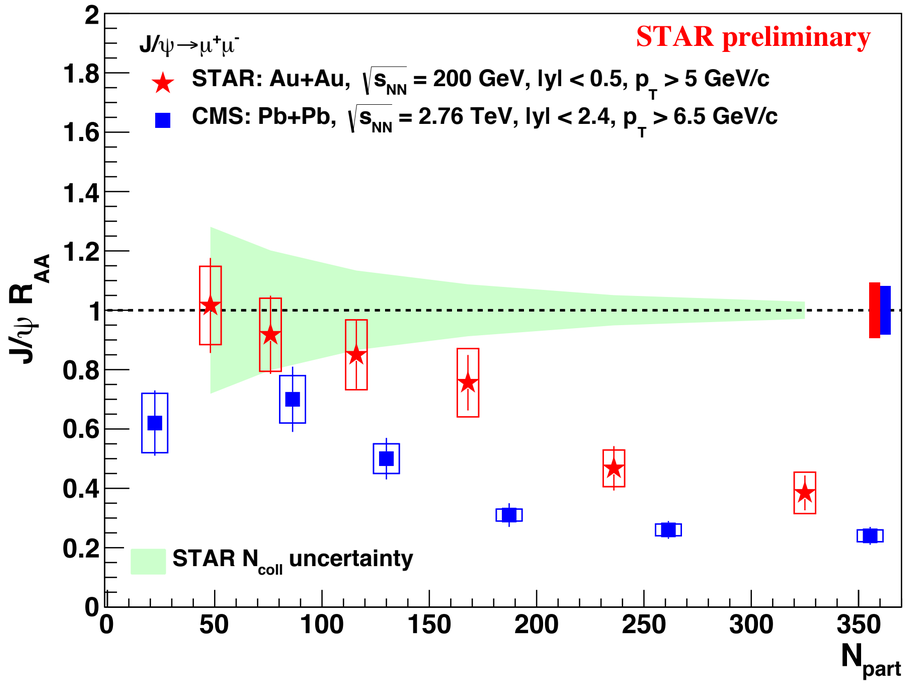
p_T > 0 GeV/c

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



p_T > 5 GeV/c

CMS, JHEP 05 (2012) 063

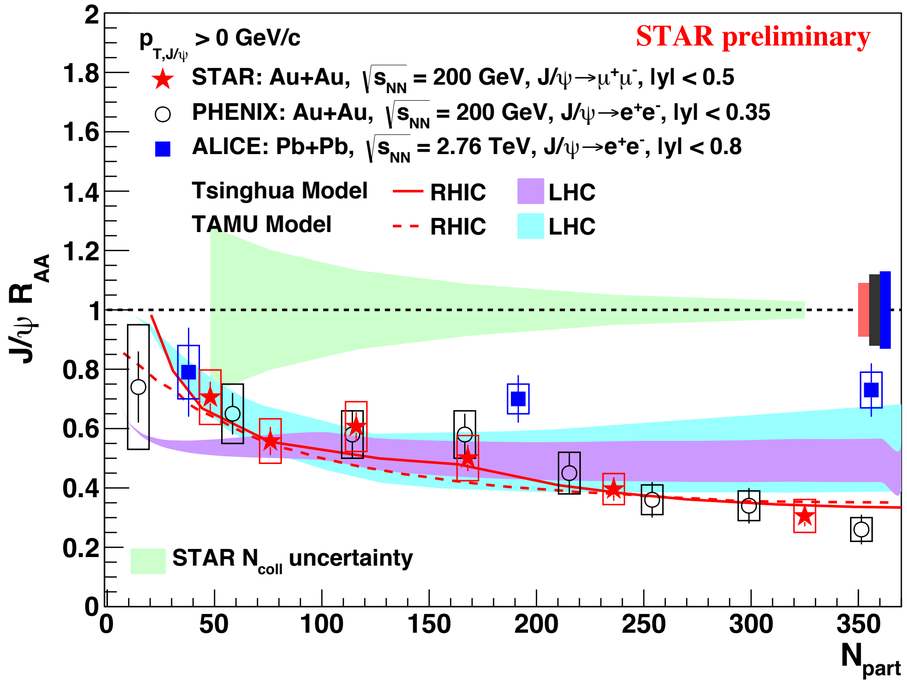


- **p_T > 0 GeV/c: less suppressed at the LHC in central events -> larger regeneration contribution due to higher charm cross-section**
- **p_T > 5 GeV/c: more suppressed at the LHC in all centralities -> higher dissociation rate due to higher temperature**

J/ψ R_{AA}: data vs. models

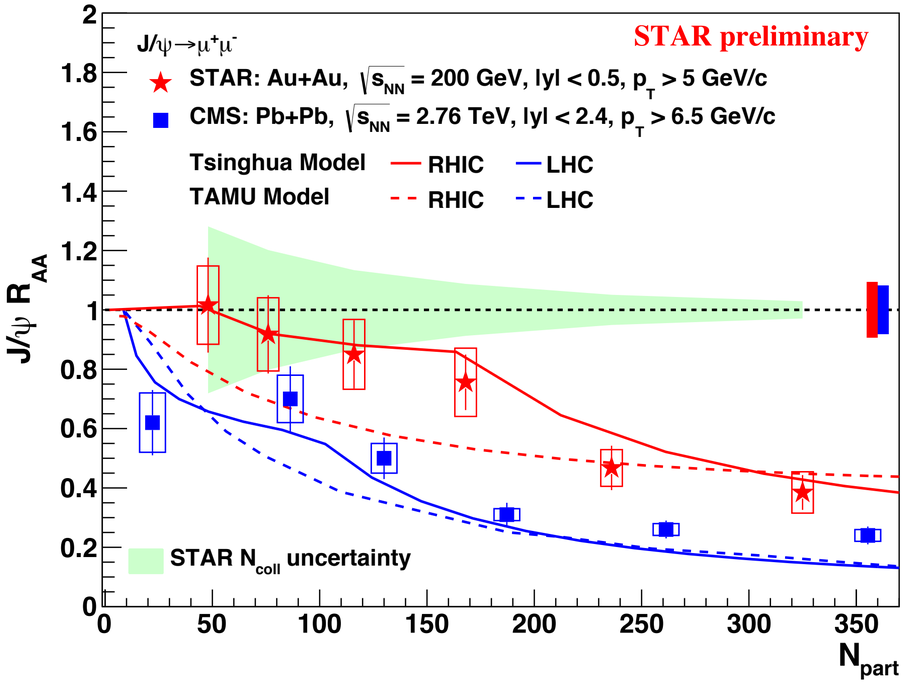
p_T > 0 GeV/c

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



p_T > 5 GeV/c

CMS, JHEP 05 (2012) 063



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 > 0 GeV/c: both models can describe centrality dependence at RHIC, but tends to overestimate suppression at the LHC**
- **p_T > 5 GeV/c: both models can qualitatively describe data**

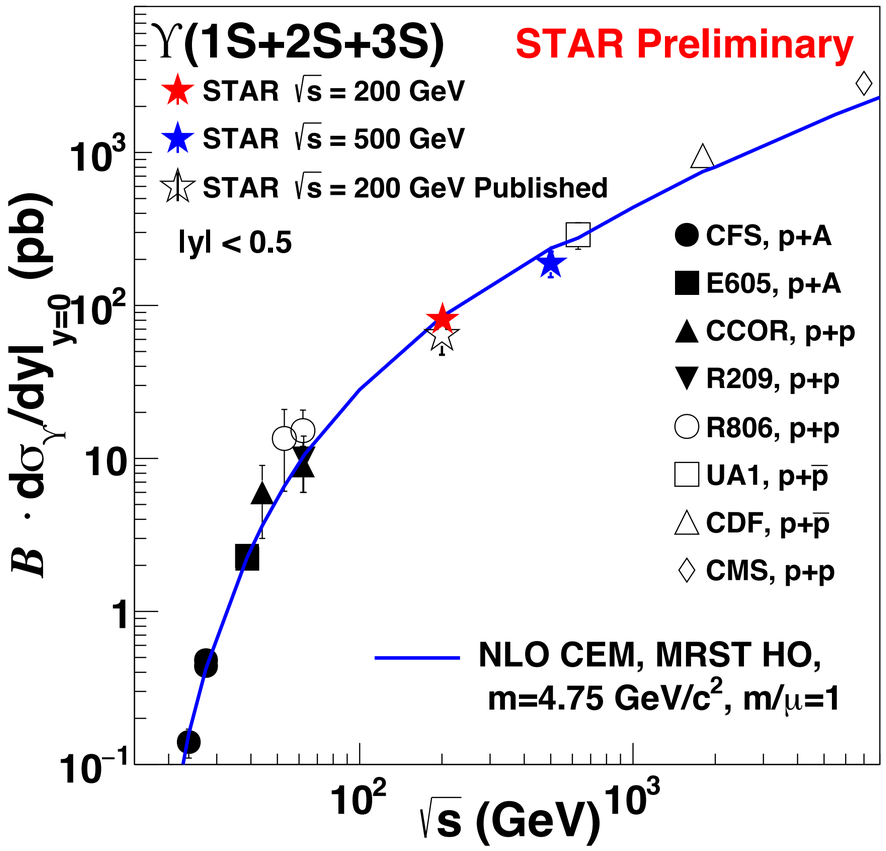
Bottomonium

- **Small production cross-section at RHIC energy**
- **A cleaner probe at RHIC**
  - Regeneration is smaller compared to J/ψ

    A. Emerick, X. Zhao and R. Rapp: EPJ A48 (2012) 72
    X. Du, M. He, and R. Rapp: PRC 96 (2017) 054901
  - Co-mover absorption for Υ(1S) is expected to be small

    Z. Lin and C. Ko: PLB 503 (2001) 104

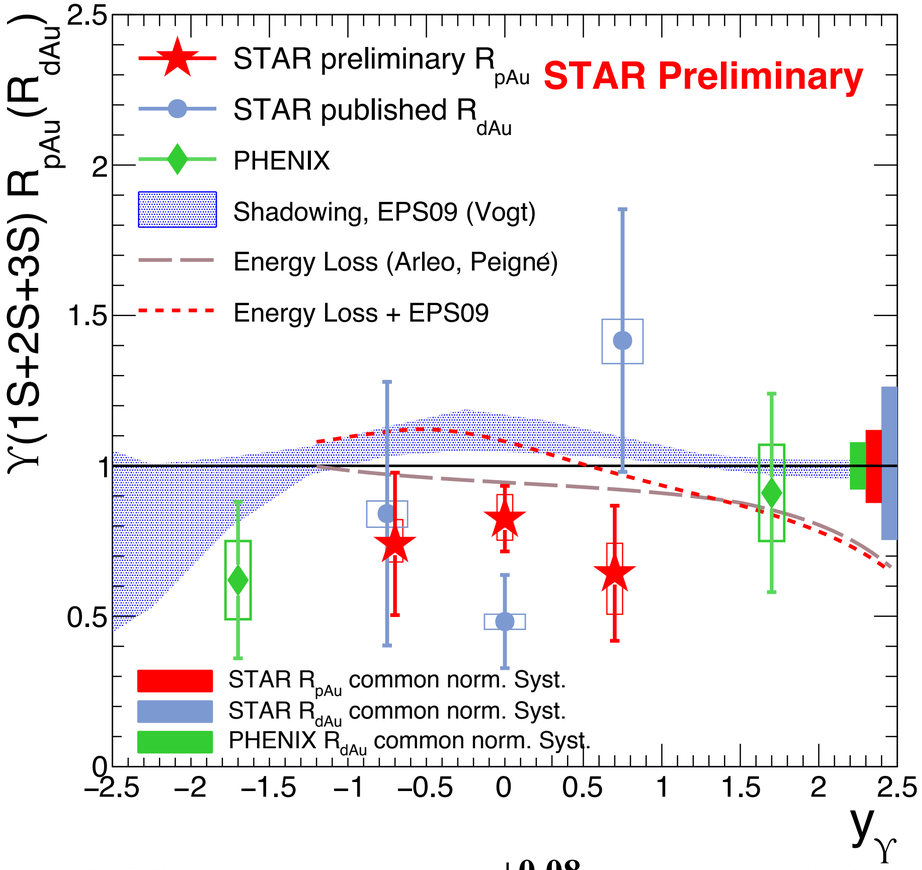
ϒ cross-section in p+p collisions



p+p@200 GeV: σ = 81 ± 5(stat.) ± 8(syst.) pb

- **Baseline for p+A and A+A collisions with improved precision**
- **Consistent with the Color Evaporation Model (CEM) prediction**

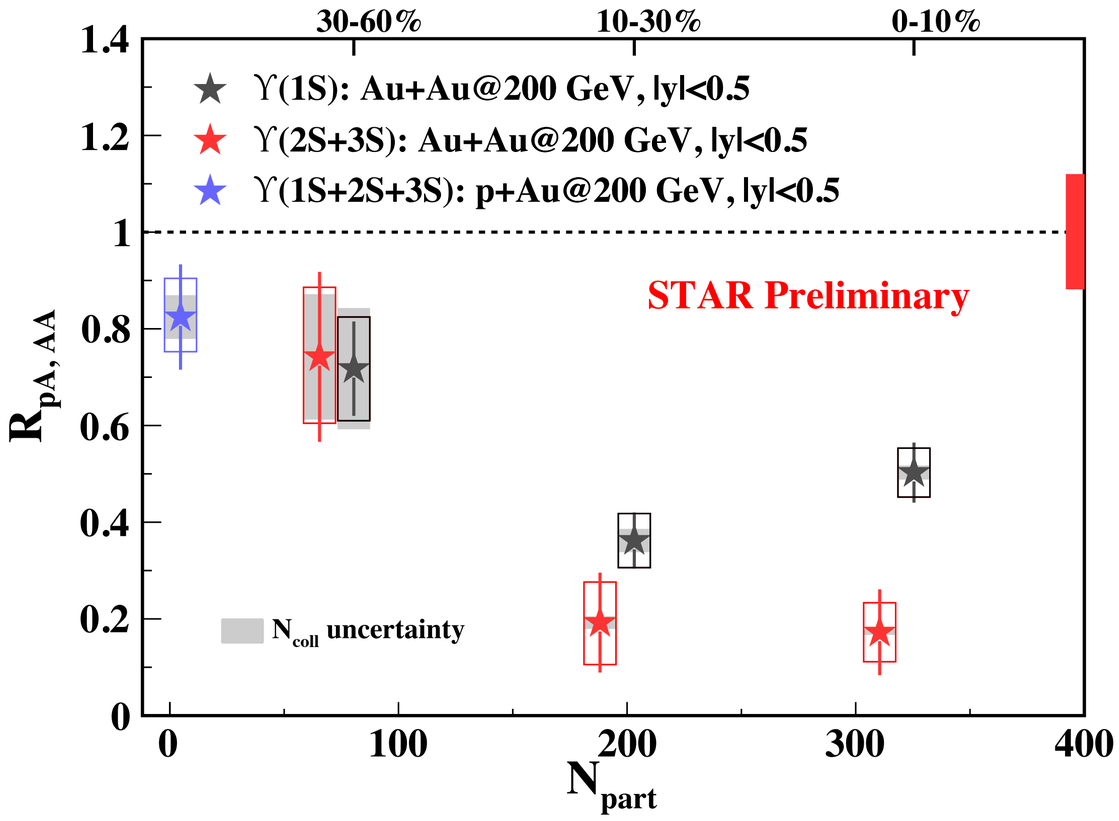
Υ(1S+2S+3S) R_{pAu} at 200 GeV



p+Au@200 GeV: $R_{pAu} = 0.82 \pm 0.10(\text{stat.})^{+0.08}_{-0.07}(\text{syst.}) \pm 0.10\ (\text{global})$

- **Indicates CNM effects**
- **Additional suppression mechanism beyond nPDF effects seems to be needed**

ϒ suppression at RHIC



- **Improved precision of ϒ measurements**
  - **Combining 2016 data with those taken in 2014 and 2011 (di-muon and di-electron results are combined)**

ϒ(1S):

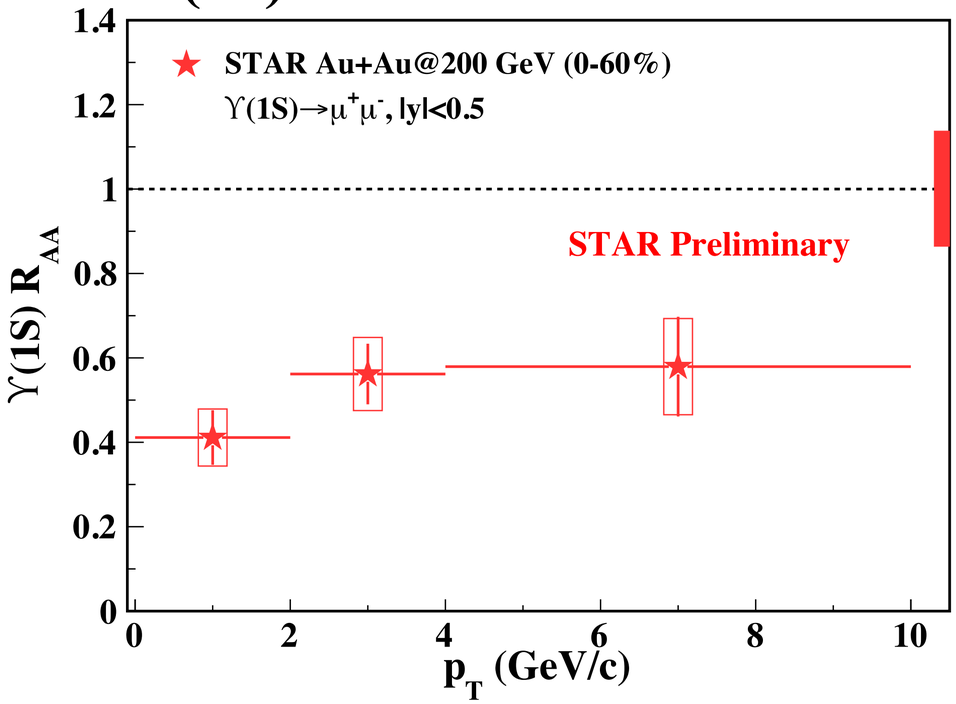
- **Stronger suppression towards central collisions**

ϒ(2S+3S):

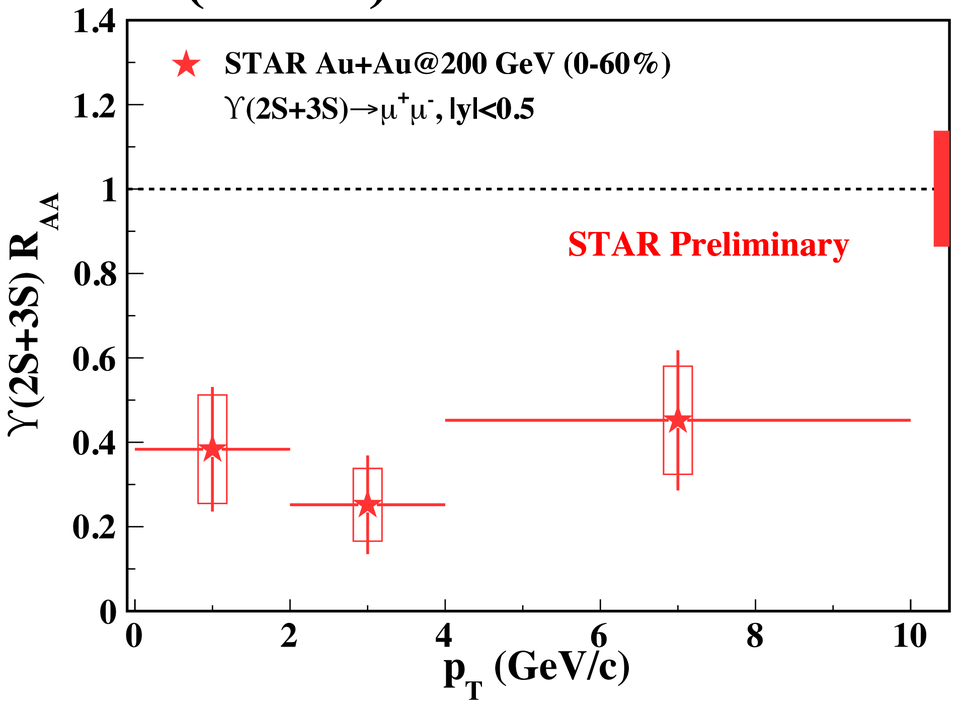
- **Stronger suppression in more central collisions**
- **More suppressed than ϒ(1S) in 0-10% central collisions -> sequential melting**

ϒ suppression at RHIC

ϒ(1S):



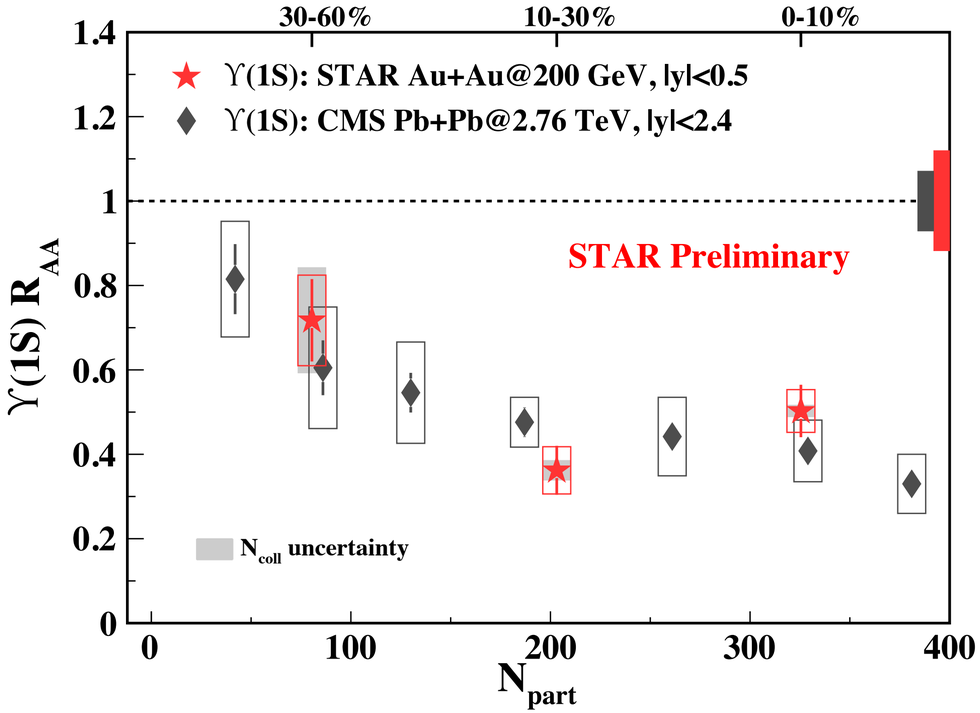
ϒ(2S+3S):

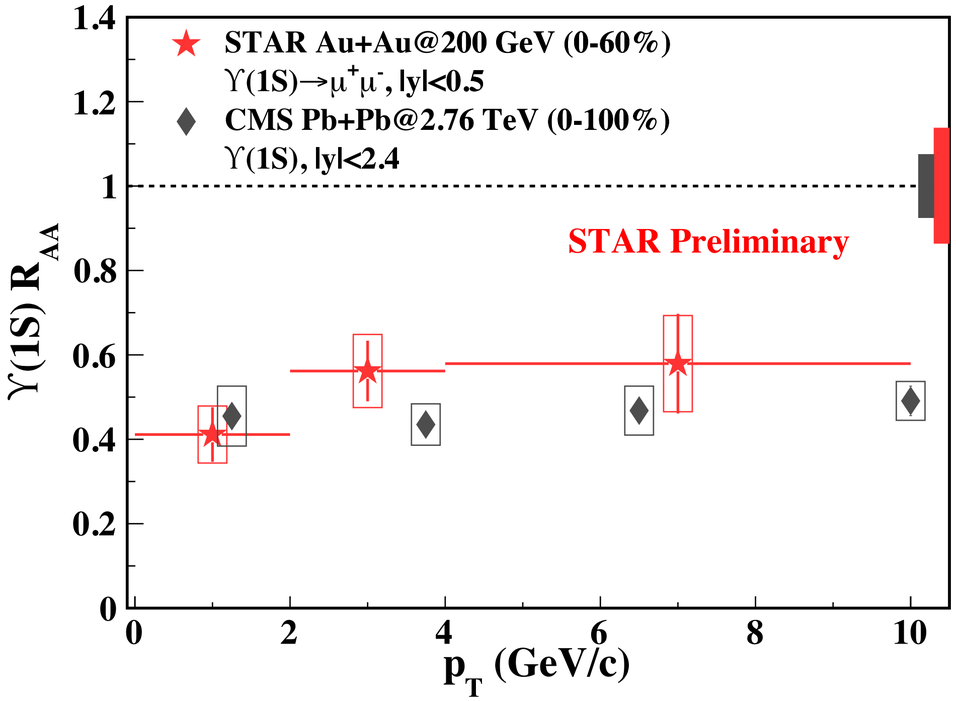


ϒ(1S) and ϒ(2S+3S):

- No significant p_T dependence

ϒ(1S) suppression: RHIC vs. LHC



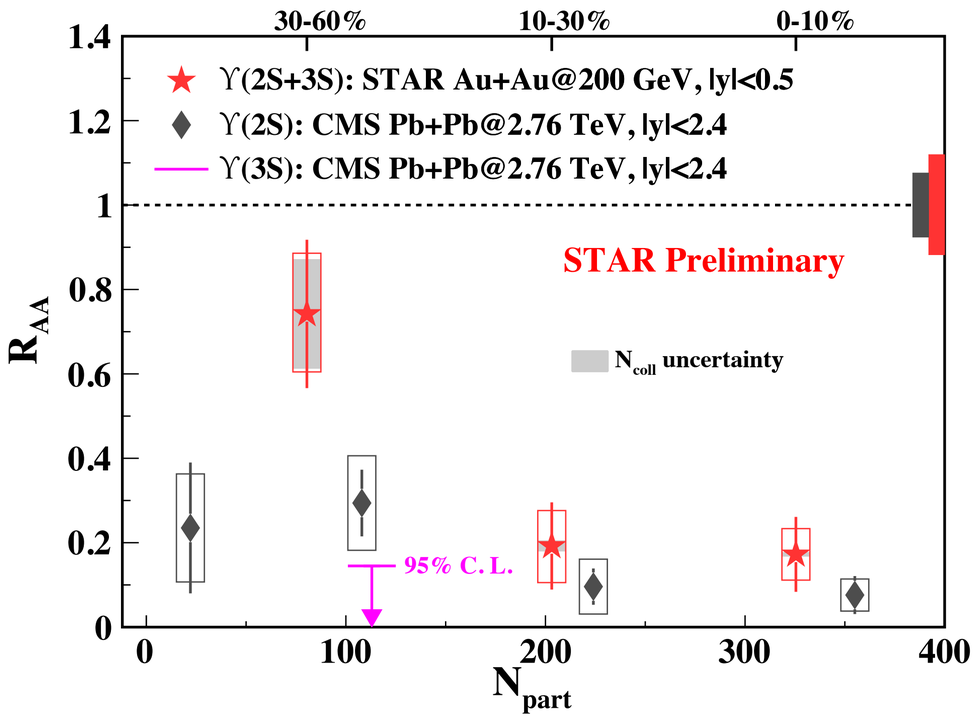


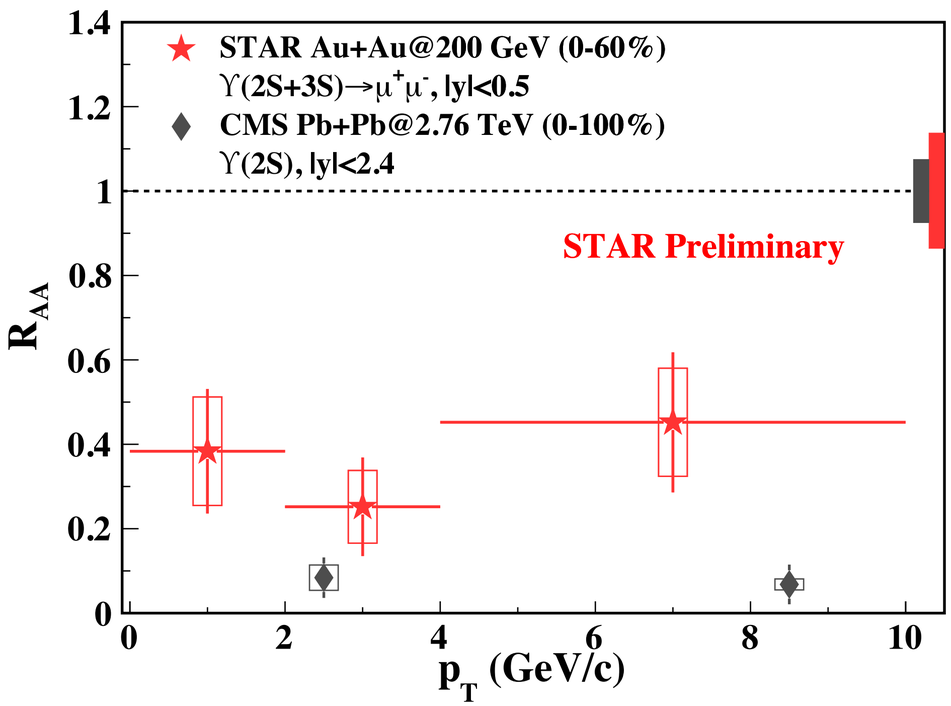
CMS, PLB 770 (2017) 357

ϒ(1S) suppression is similar at RHIC and the LHC:

- **Similar CNM effects (~ 20-30%)**
- **Suppression of excited ϒ states**

ϒ(2S+3S) suppression: RHIC vs. LHC



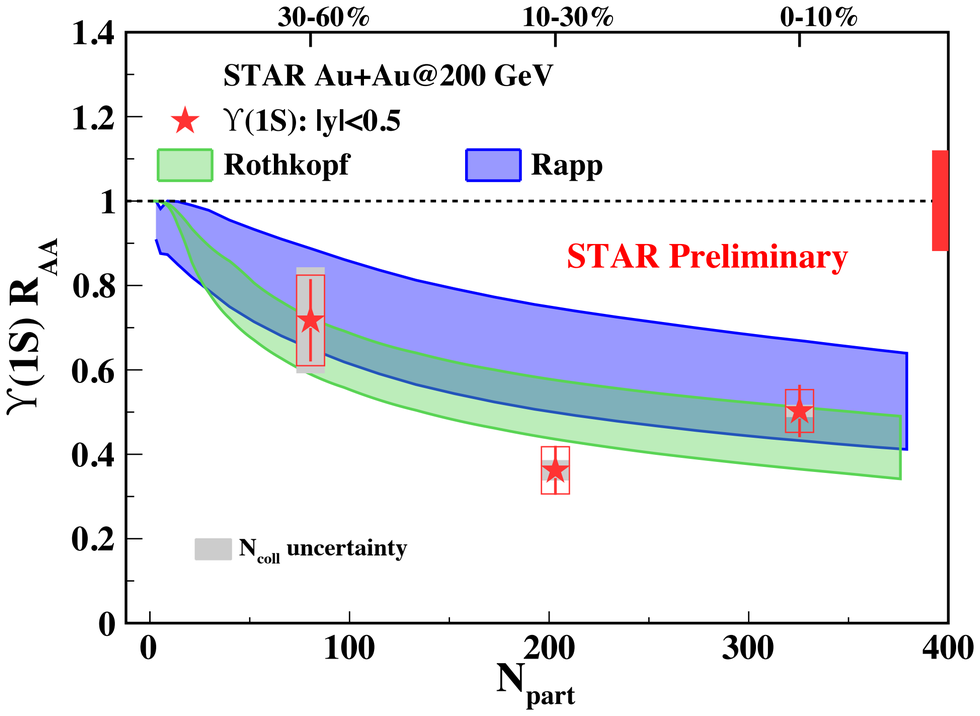


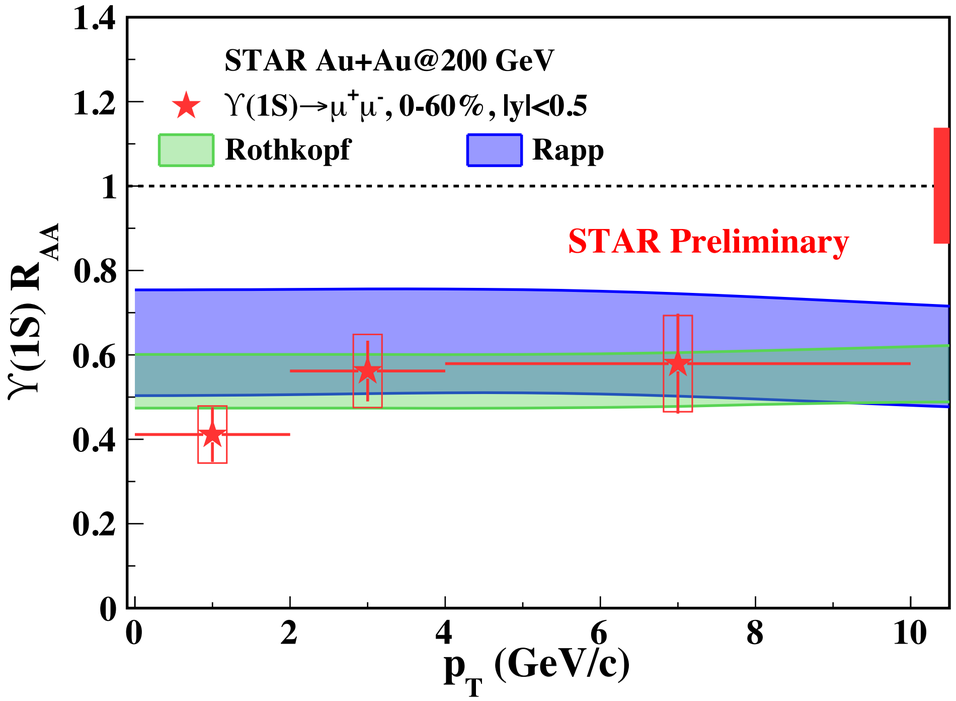
CMS, PLB 770 (2017) 357

ϒ(2S+3S):

- **Indication of less suppression at RHIC than at the LHC in peripheral collisions**

ϒ(1S) suppression: data vs. models



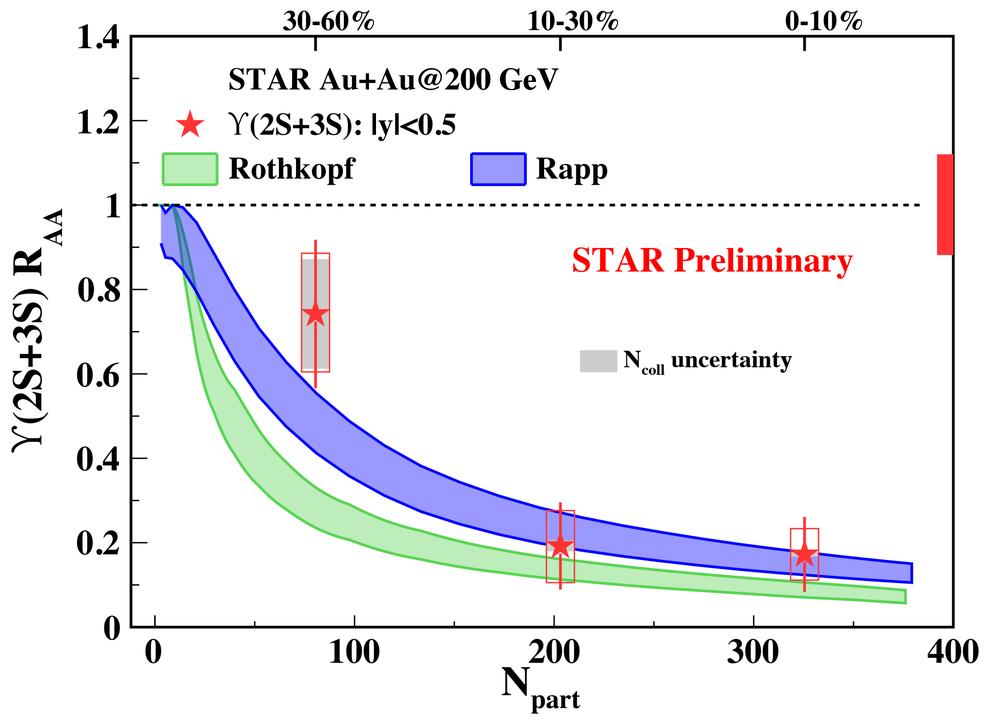


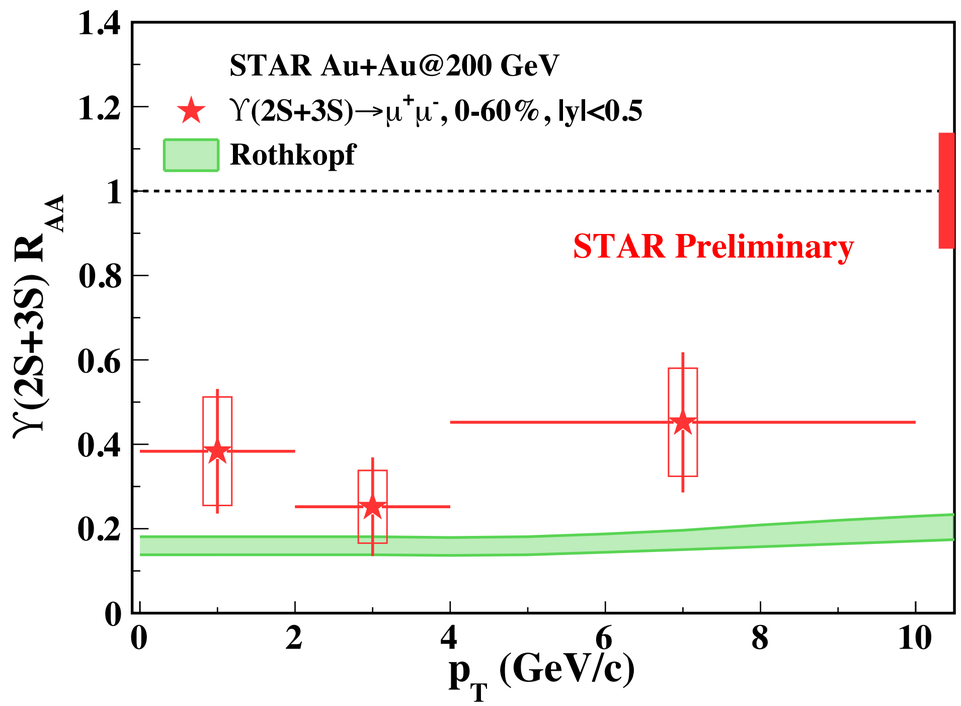
B. Krouppa, A. Rothkopf, M. Strickland: PRD 97, 016017 (2018)
X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)

Both models show good agreement with data:

- **Rothkopf: Complex potential (lattice QCD); No CNM or regeneration effects**
- **Rapp: T-dependent binding energy; Includes CNM and regeneration effects**

ϒ(2S+3S) suppression: data vs. models





- Rapp model describes data
- Rothkopf model calculation is lower than data in 30-60%

Summary

- p+p collisions
  - Models describe the quarkonium production cross-section reasonably well (e.g. CEM, NRQCD, etc)
- p+Au collisions
  - J/ψ R_{pA} favors additional nuclear absorption on top of nPDF effect
  - Υ(1S+2S+3S) R_{pA}: indication of Υ suppression due to CNM effects
- Au+Au collisions

J/ψ:

- Clear J/ψ suppression at $p_T > 5$ GeV/c in central collisions -> dissociation
- J/ψ R_{AA} can be qualitatively described by transport models including dissociation and regeneration

Υ(1S):

- Indication of increasing suppression towards central collisions
- Similar suppression as that at the LHC
- Model predictions are consistent with data

Υ(2S+3S):

- More suppressed than Υ(1S) in 0-10% central collisions -> sequential melting