Quarkonium measurements with the STAR experiment

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- *Introduction*
- *STAR experiment*
- *Charmonium*
- *Bottomonium*
- *Summary*

Why quarkonium?

- **Color-screening**: quark-antiquark potential is color-screened by the surrounding partons *-> dissociation*
  - J/ψ suppression was proposed as a direct proof of QGP formation *[T. Matsui and H. Satz, PLB 178 (1986) 416]*

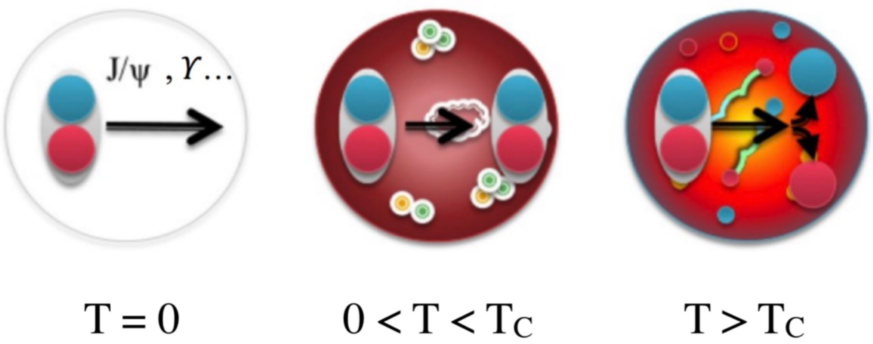
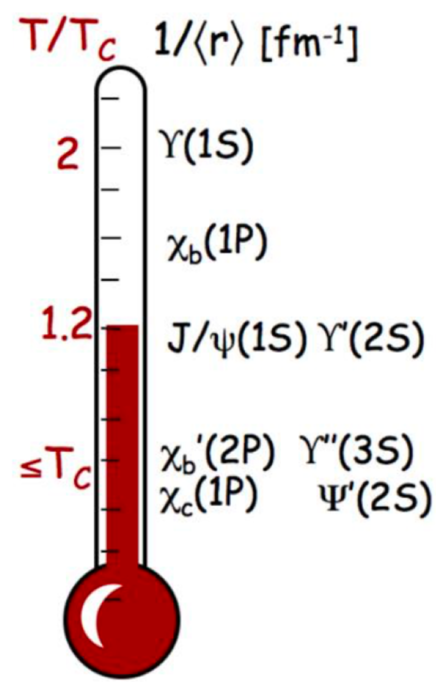


Illustration: A. Rothkopf

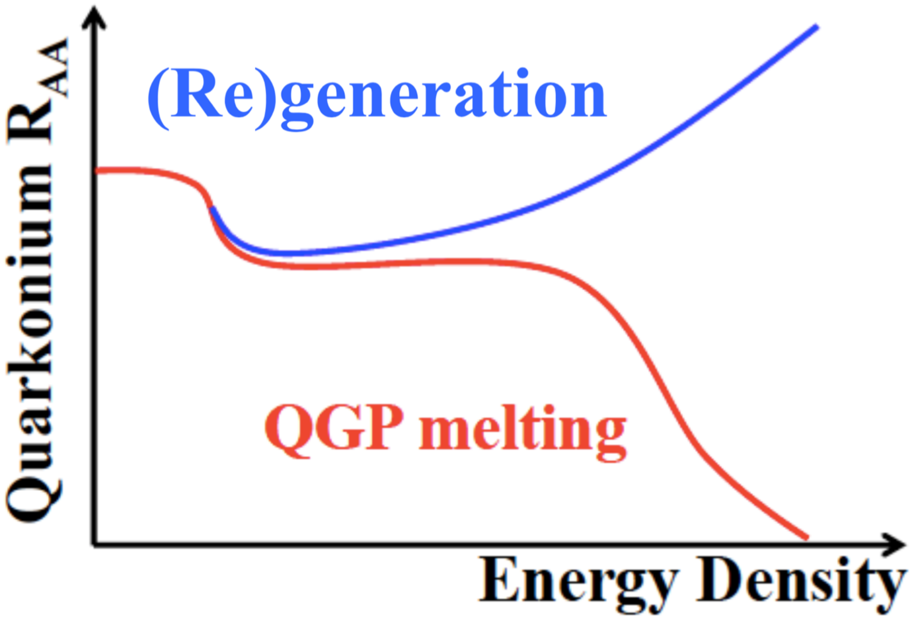


A. Mocsy, EPJ C61 (2009) 705

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

However, different effects in play…

➢ Hot medium effects:
- Dissociation
- Regeneration
- Medium induced energy loss
- Formation time

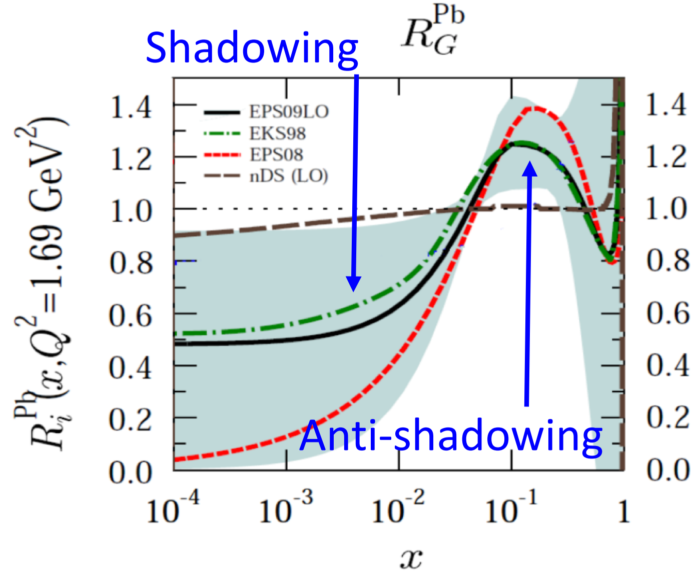


➢ Feed-down contributions

➢ Cold nuclear matter effects (CNM)

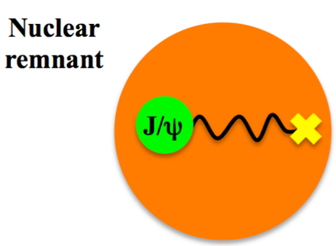
Cold nuclear matter effects

- nPDF: modification of parton distribution functions in nucleus



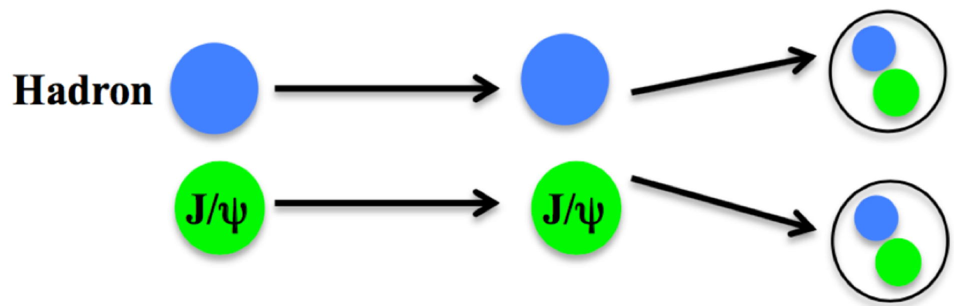
Ferreiro et al., PRC 81 (2010) 064911

- Nuclear absorption



Gavin et al., PRL 78 (1997) 1006

- Interaction with co-movers

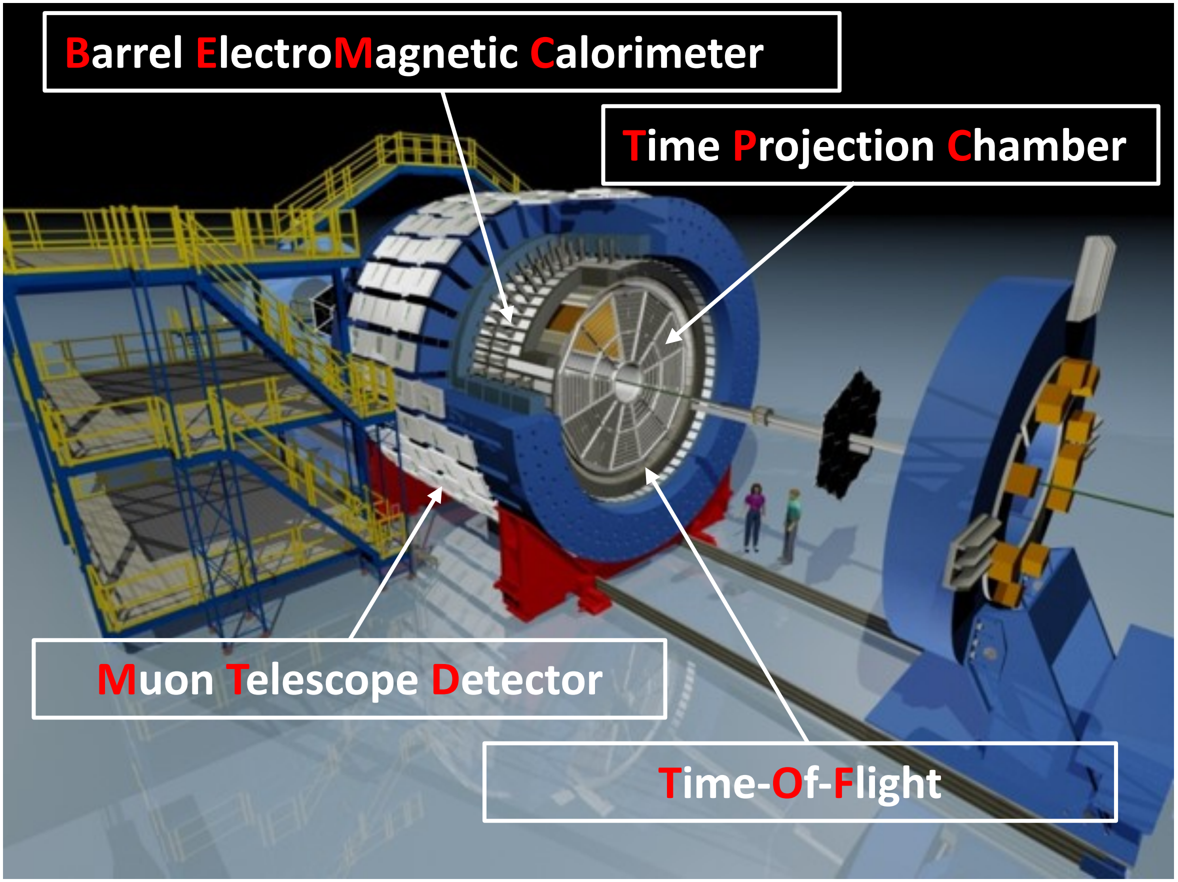


Capella and Ferreiro, EPJC 42 (2005) 419

- Energy loss

STAR detector

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



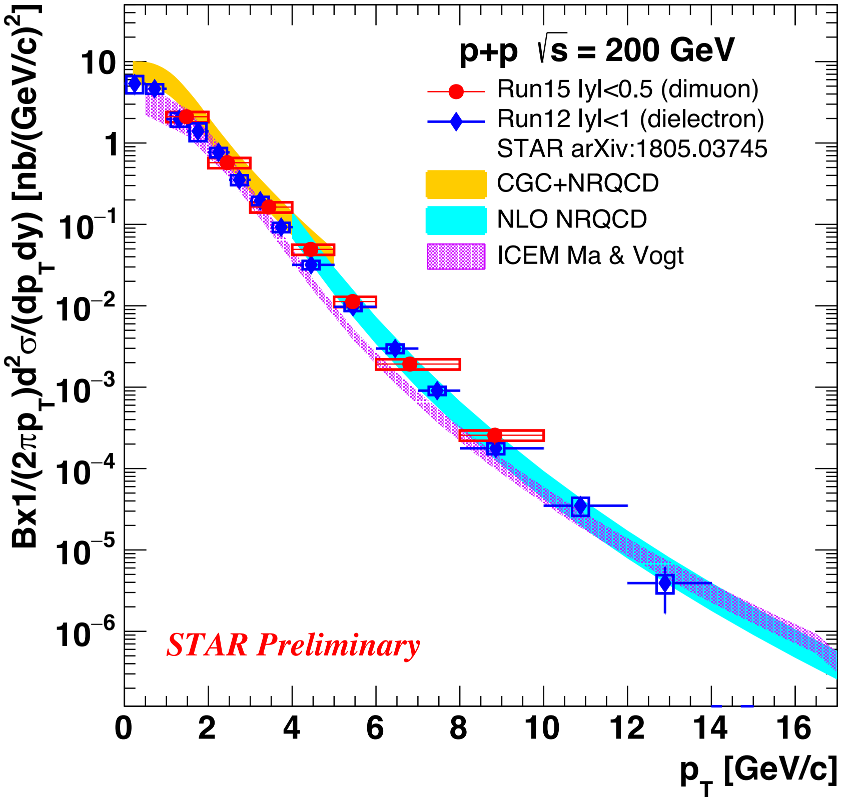
- TPC: tracking and PID (dE/dx)
- TOF: PID ($1/\beta$)
- BEMC: trigger on and identify high-p_T electrons
- MTD ($|\eta|<0.5$, 45% azimuthal coverage): trigger on and identify muons
  - Less bremsstrahlung: help separate ϒ(2S+3S) from ϒ(1S)

Charmonium

- **Advantage:** large cross section at RHIC energy
- **Disadvantage:** interplay of several effects

Inclusive J/ψ cross section in pp@200 GeV

STAR, arXiv:1805.03745

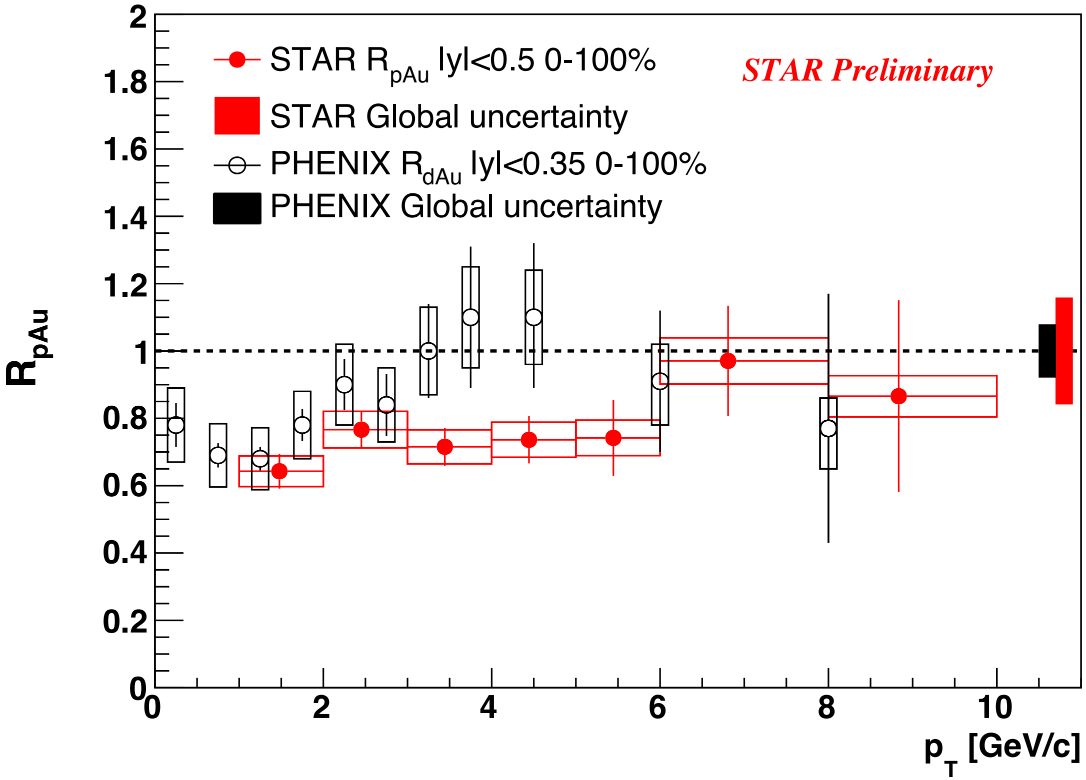


CGC+NRQCD, Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
ICEM, Ma & Vogt, PRD 94 (2016) 114029

- Inclusive J/ψ cross section is measured in $0< p_T < 14$ GeV/c
- CGC+NRQCD & NLO NRQCD (prompt J/ψ) model calculations can describe data in the full p_T range
- 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
- ~10-25% feed-down contribution from bottom hadrons in $4 < p_T < 14$ GeV/c. *[Bedjidian et al., arXiv:hep-ph/0311048; Cacciari, Nason, and Vogt, PRL 95 (2005) 122001]*

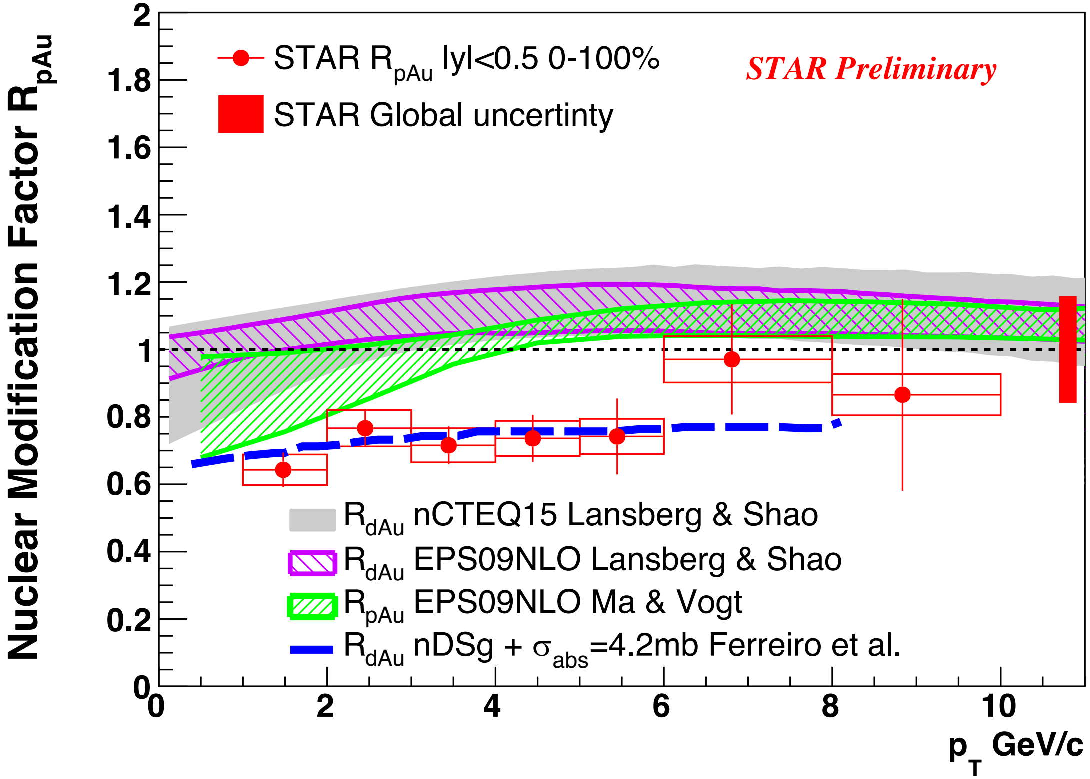
J/ψ R_{pAu} at 200 GeV

PHENIX, PRC 87 (2012) 034903



- 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
- R_{pAu} is consistent with R_{dAu} within uncertainty
  - There seems to be tension at 3< p_T <5 GeV/c with 1.4σ significance
- Suggests similar CNM effects in these collision systems

J/ψ R_{pAu} at 200 GeV



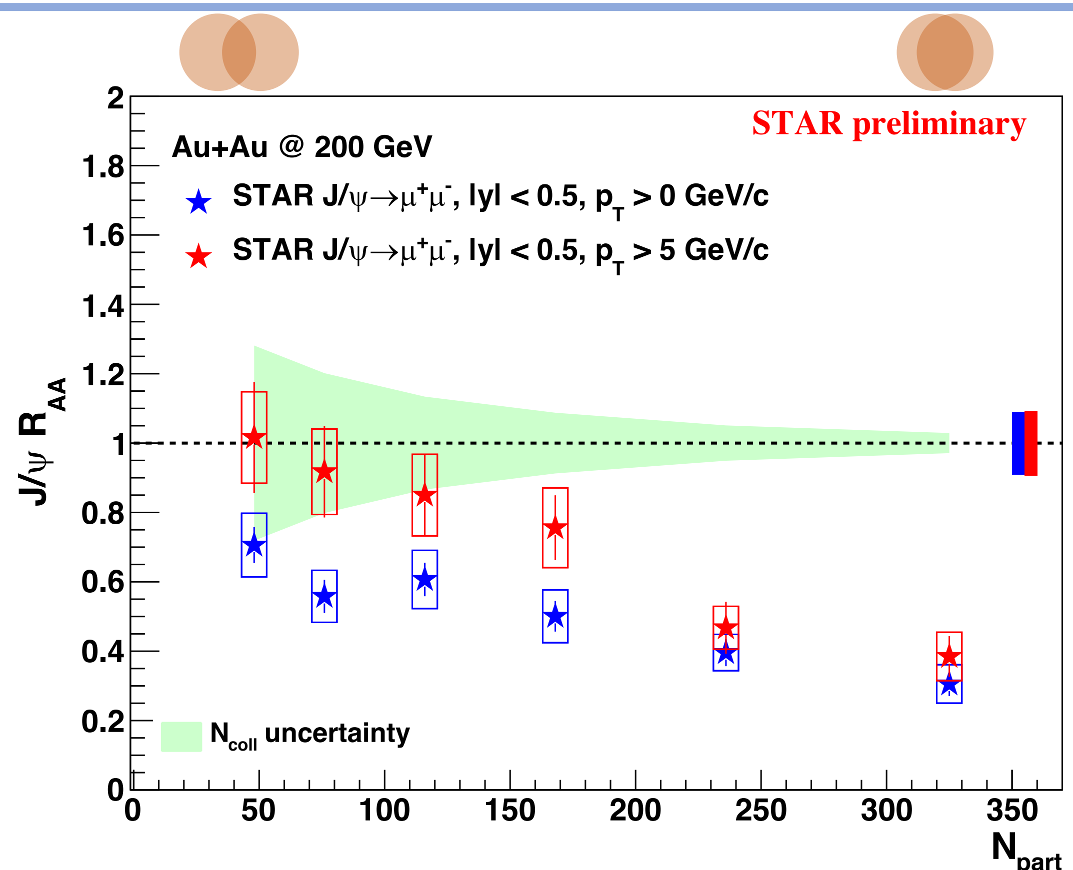
EPS09+NLO, Ma & Vogt, Private Comm.

nCTEQ, EPS09+NLO, Lansberg & Shao, Eur. Phys. J. C77 (2017) 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 shadowing effect can touch the upper limit of data within uncertainties
- Additional nuclear absorption is favored by data

J/ψ R_{AA} vs. centrality

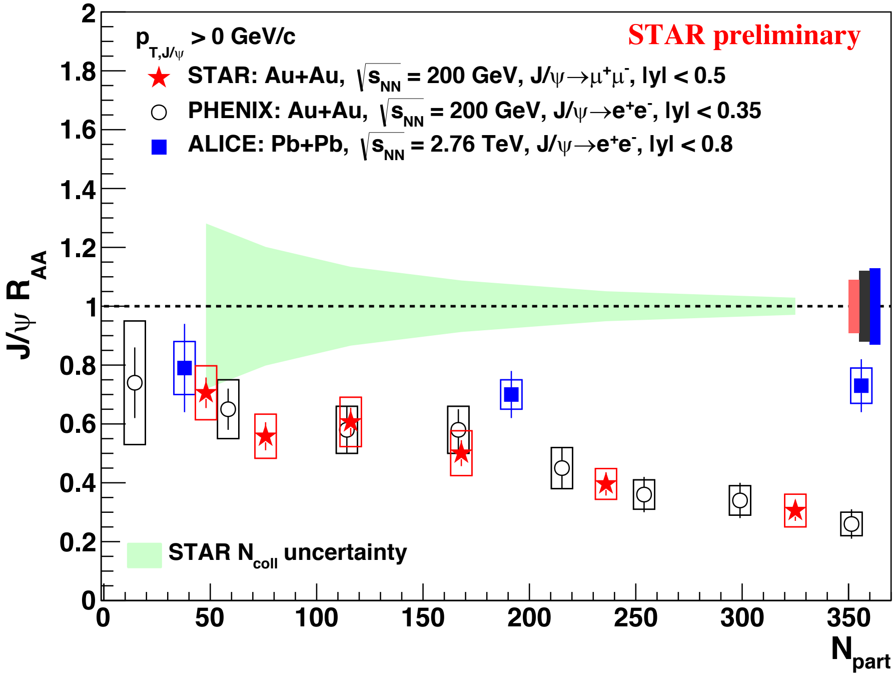


- Central collisions: significant suppression in both $p_T > 0$ and $p_T > 5$ GeV/c -> interplay of different effects
- Peripheral collisions: R_{AA} of J/ψ for $p_T > 0$ GeV/c is smaller than that for $p_T > 5$ GeV/c probably due to cold nuclear matter effects

Centrality dependence: RHIC vs. LHC

$p_T > 0$ GeV/c

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

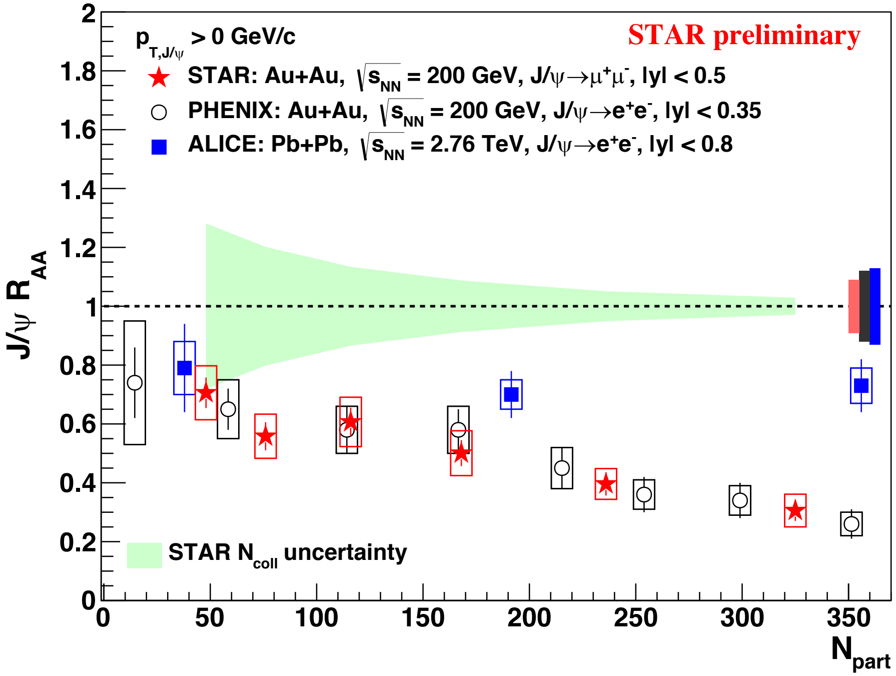


- STAR data are consistent with PHENIX
- $p_T > 0$ GeV/c: less suppressed at LHC in central events -> larger regeneration contribution due to larger charm cross-section at LHC

Centrality dependence: RHIC vs. LHC

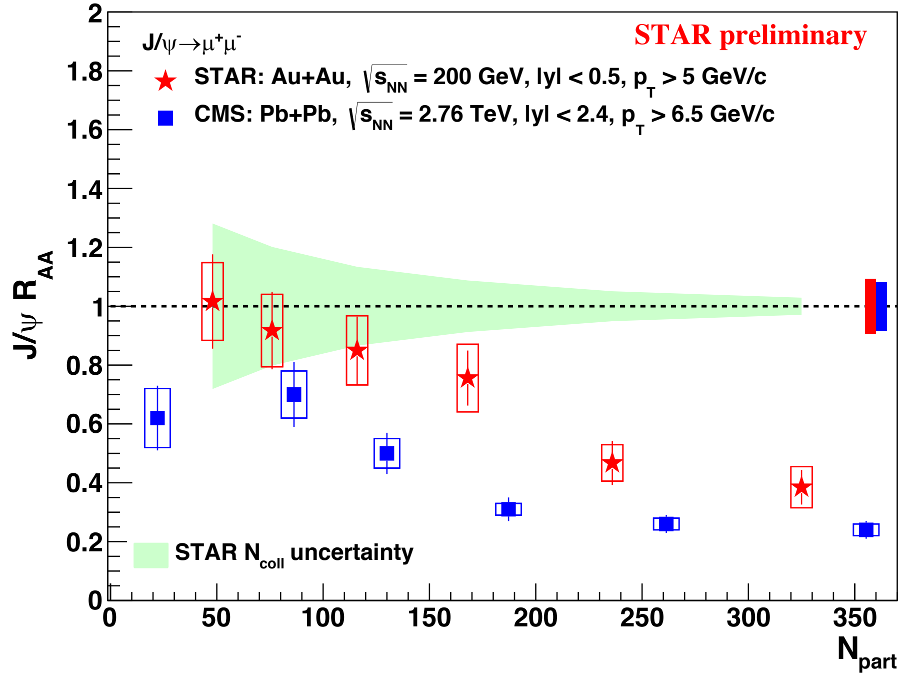
$p_T > 0$ GeV/c

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



$p_T > 5$ GeV/c

CMS, JHEP 05 (2012) 063

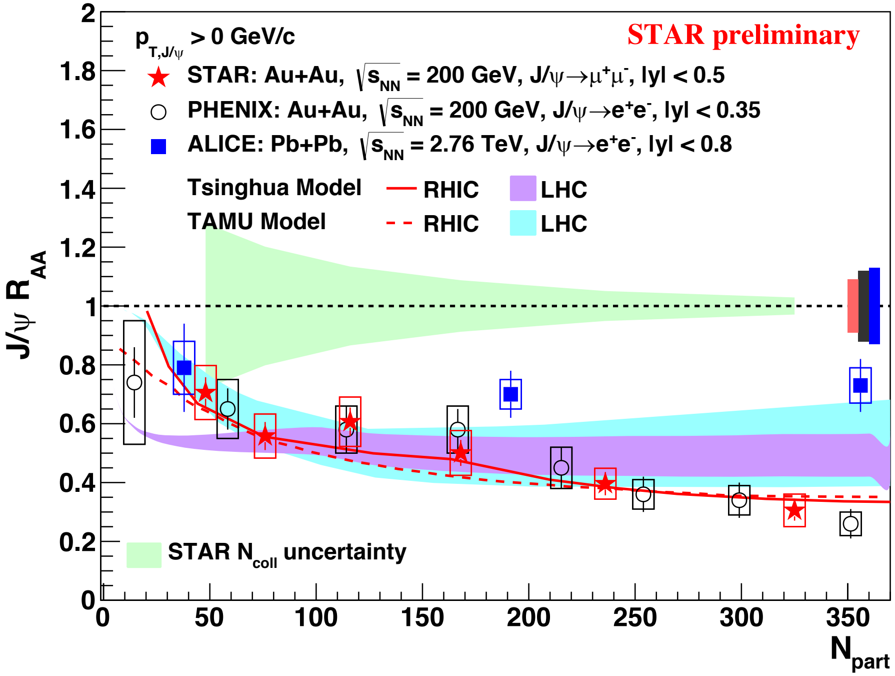


- STAR data are consistent with PHENIX
- $p_T > 0$ GeV/c: less suppressed at LHC in central events -> larger regeneration contribution due to higher charm cross-section
- $p_T > 5$ GeV/c: more suppressed at LHC in all centralities -> higher dissociation rate due to higher temperature

Comparison to models

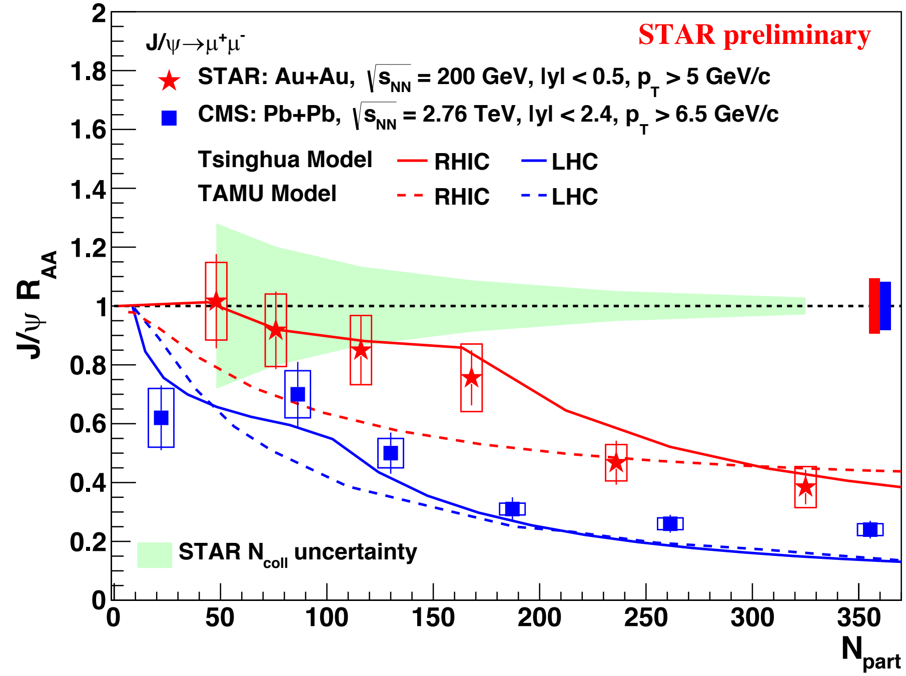
$p_T > 0$ GeV/c

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



$p_T > 5$ GeV/c

CMS, JHEP 05 (2012) 063



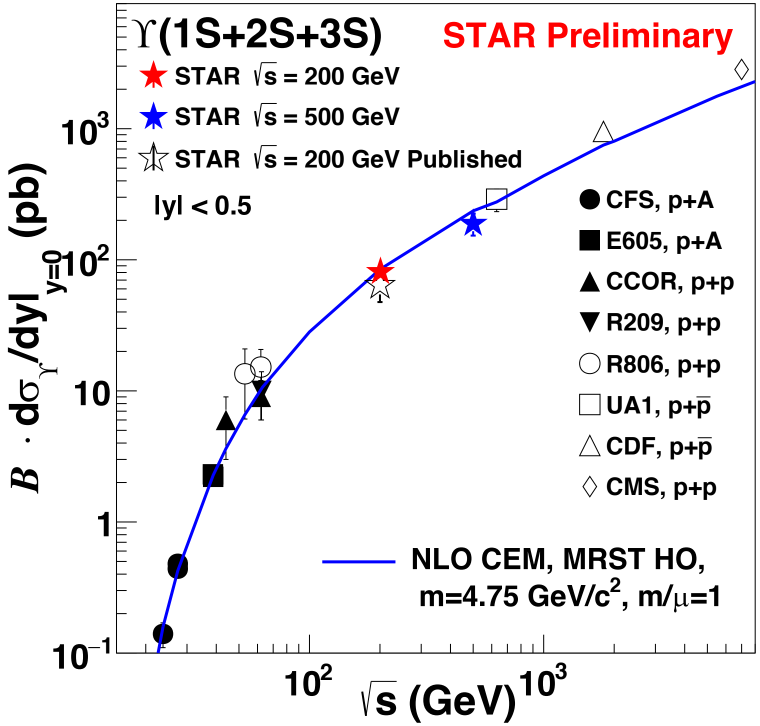
Tsinghua at RHIC: PLB 678 (2009) 72, Tsinghua at LHC: PRC 89 (2014) 054911
TAMU at RHIC: PRC 82 (2010) 064905, TAMU at LHC: NPA 859 (2011) 114

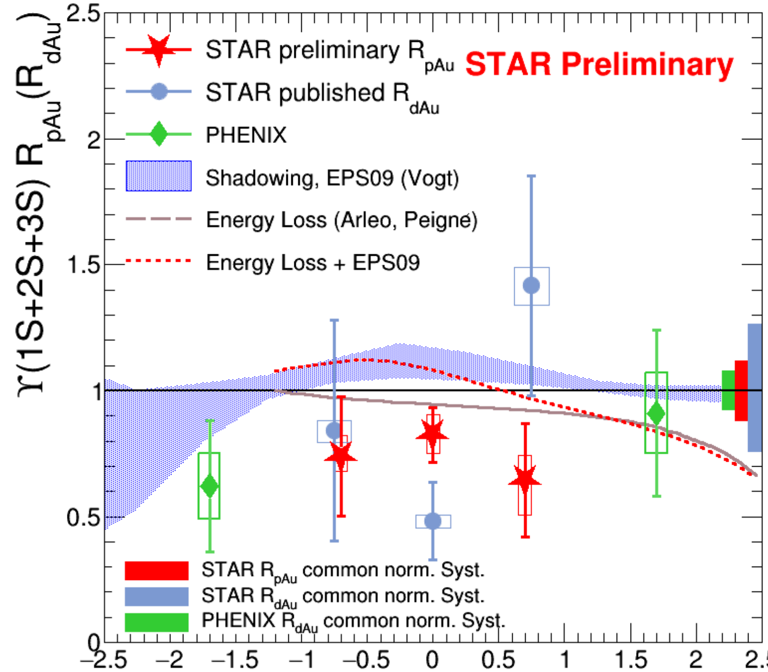
- $p_T > 0$ GeV/c: both models can describe centrality dependence at RHIC, but tend to overestimate suppression at LHC
- $p_T > 5$ GeV/c: there is tension among models and data

Bottomonium

- Advantage: a cleaner probe at RHIC
- Disadvantage: small production cross section

Υ results in pp and pAu collisions

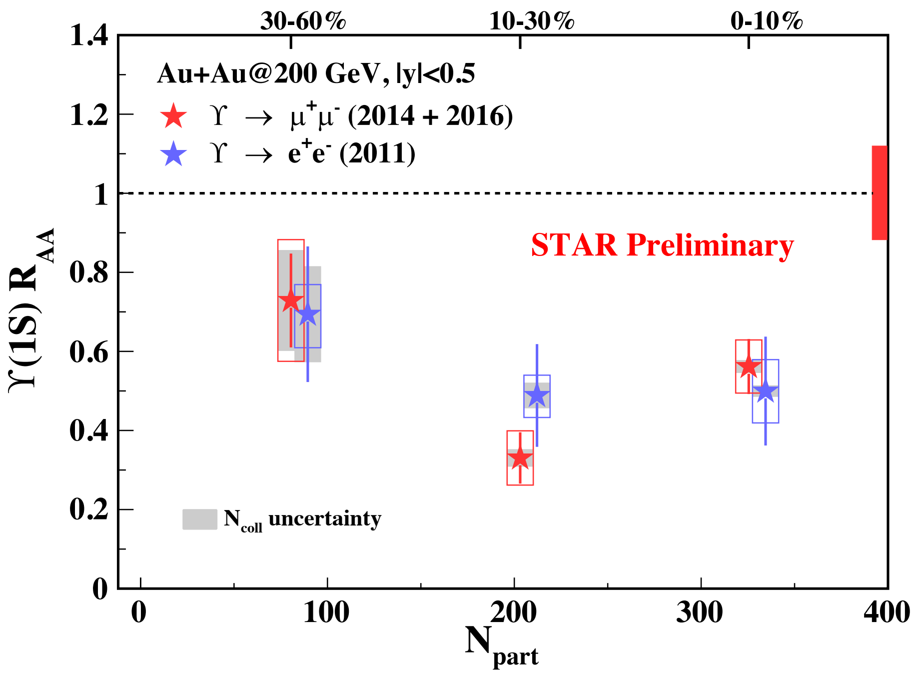


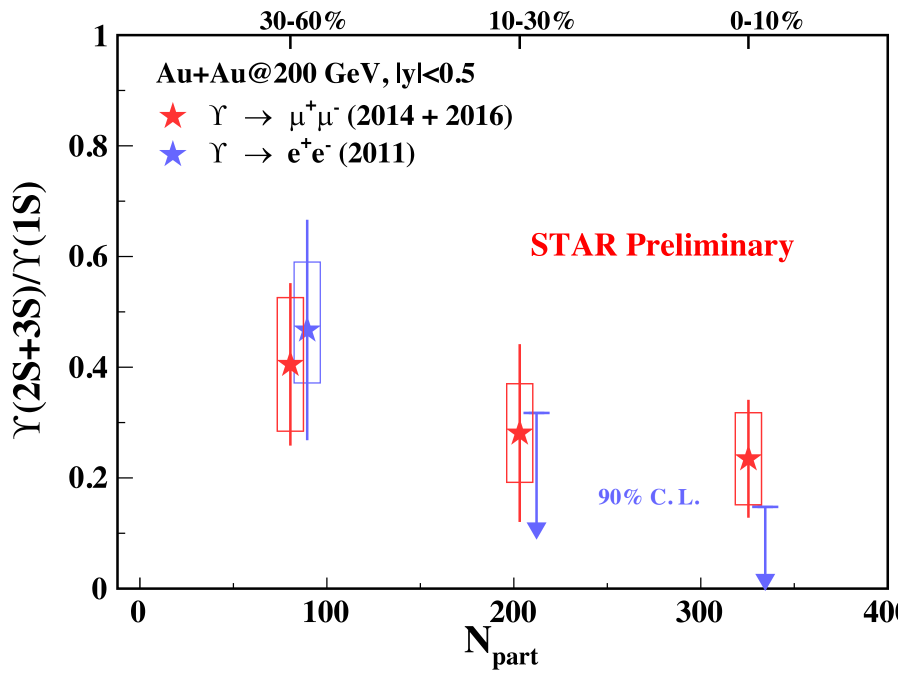


STAR, PLB 735 (2014) 127
PHENIX, PRC 87 (2013) 044909
R. Vogt et al., PoS ConfinementX 203 (2012)
F. Arleo and S. Peigne, JHEP 1303 (2013) 122
K. J. Eskola et al., JHEP 0904 (2009) 065

- p+p@200 GeV: $\sigma = 81 \pm 5(\text{stat.}) \pm 8(\text{syst.})$ pb
  - Baseline for p+A/A+A collisions with improved precision
  - Consistent with the Color Evaporation Model (CEM) prediction
- 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 seems needed beyond nPDF effects

ϒ results: dielectron vs. dimuon



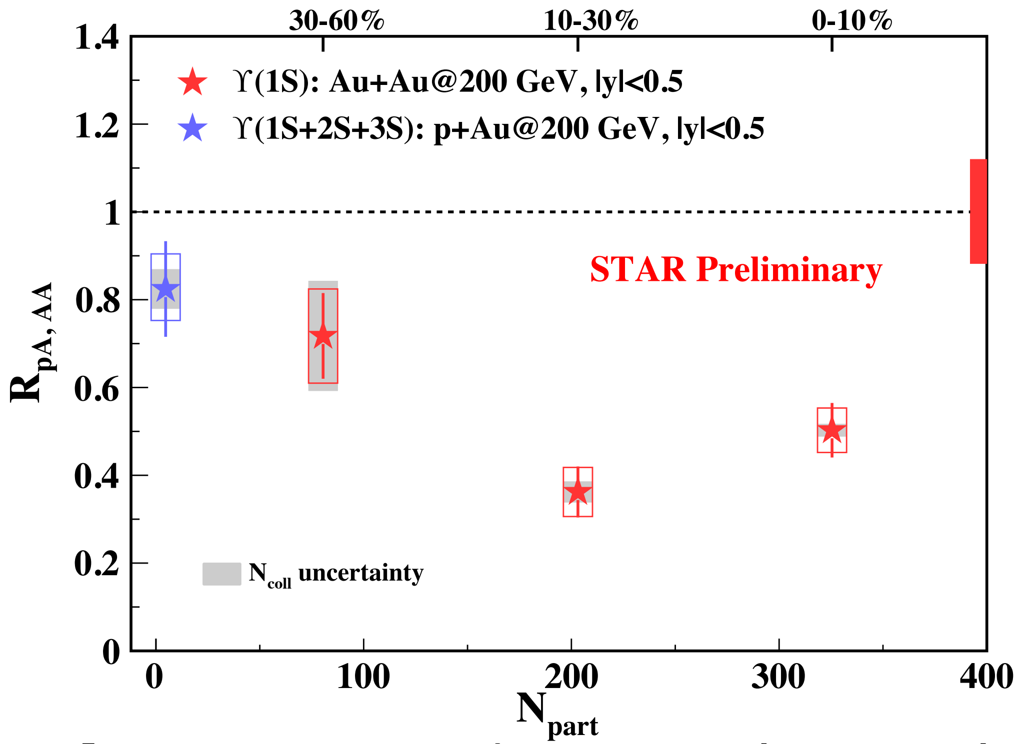


- Results from di-muon and di-electron channels are consistent within uncertainty
  - Statistics hungry -> combine results from two decay channels

$\Upsilon \rightarrow \mu^+ + \mu^-$:

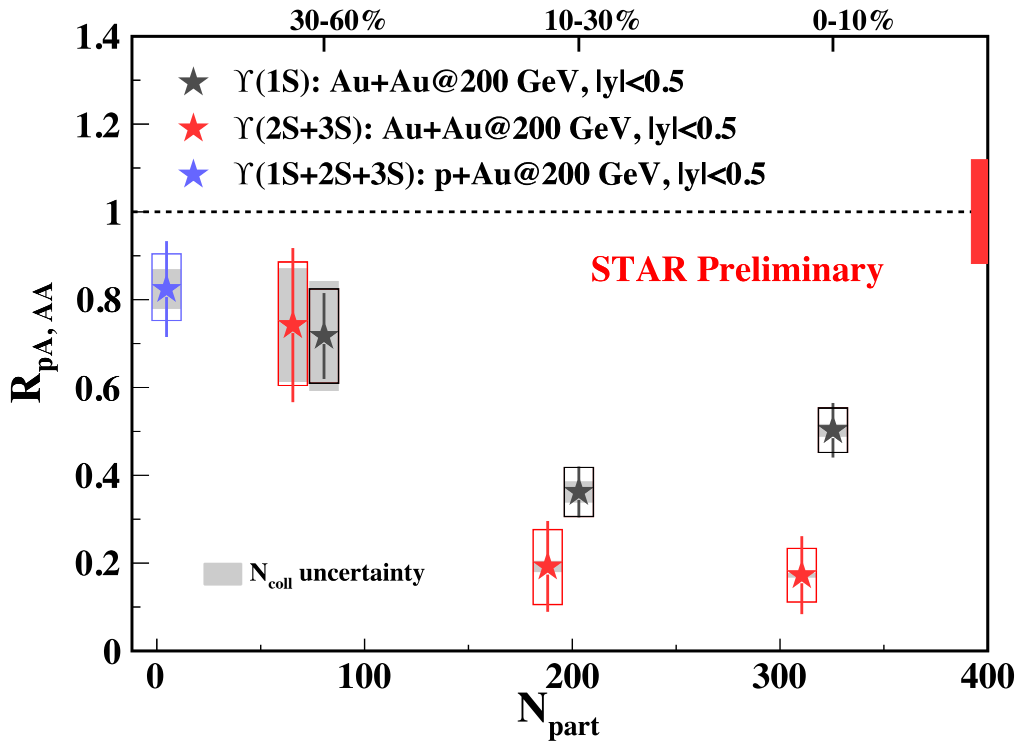
Datasets	2014	2014+2016
Integrated luminosity	14.2 nb^{-1}	27 nb^{-1}
ϒ(1S)	149±18	266±26

ϒ(1S) R_{AA} vs. centrality at RHIC



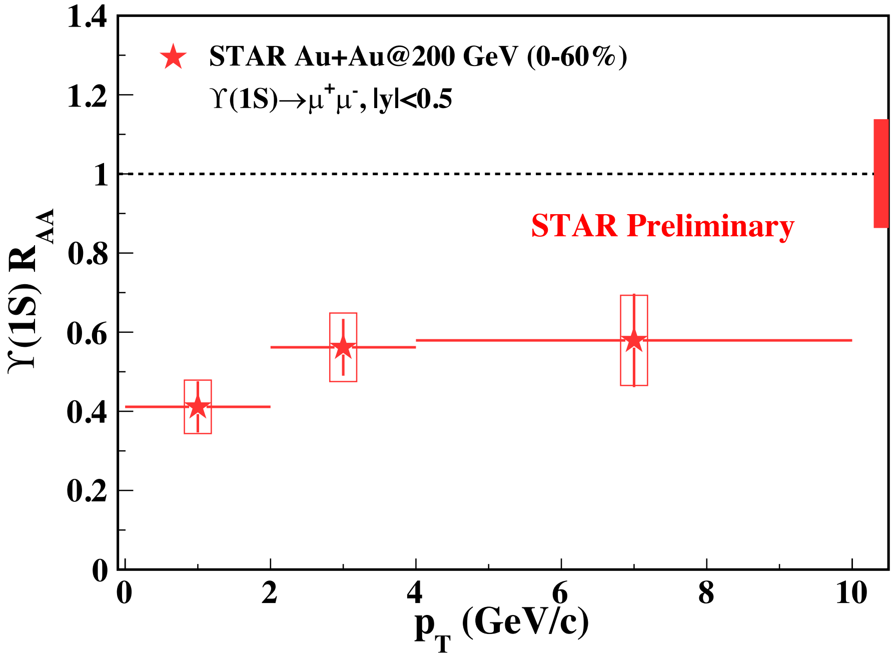
- ➢ Indication of more suppression towards central collisions
- ➢ Is direct ϒ(1S) suppressed?
  - ϒ(1S) R_{AA} in 0-10% central collisions: 0.50 ± 0.06(stat.) ± 0.05(syst.) ± 0.06 (global)
  - ~30% ϒ(1S) from feed down contribution of excited states
  - R_{pAu}(1S+2S+3S) = $0.82 \pm 0.10(\mathrm{stat.})\ ^{+0.08}_{-0.07}\ (\mathrm{syst.})\ \pm 0.10\ (\mathrm{global})$
  - Unlikely to happen at top RHIC energy

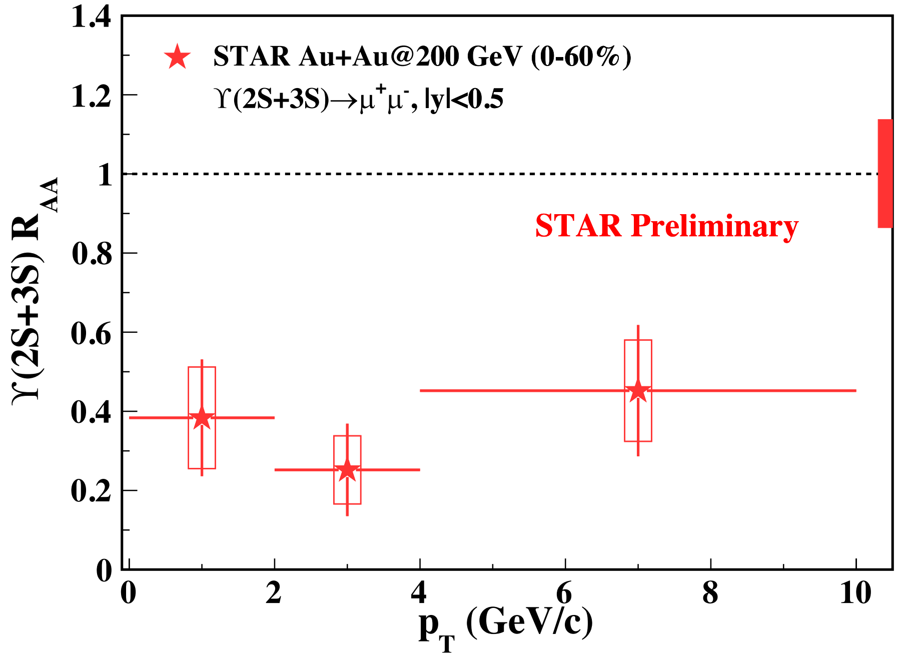
ϒ(2S+3S) R_{AA} vs. centrality at RHIC



- More suppression in 0-30% central collisions than 30-60%
- More suppression compared to ϒ(1S) in 0-10% centrality -> consistent with "sequential melting" expectation

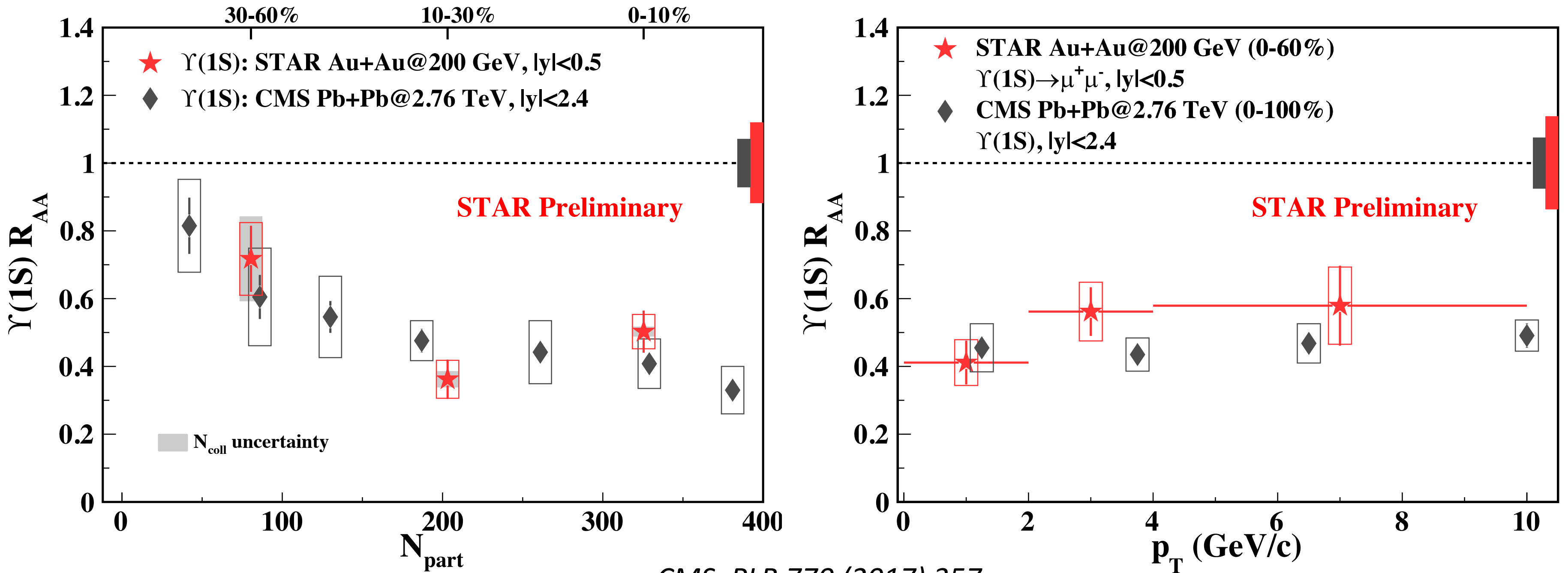
Υ(1S) and Υ(2S+3S) R_{AA} vs. p_T at RHIC





- No clear p_T dependence

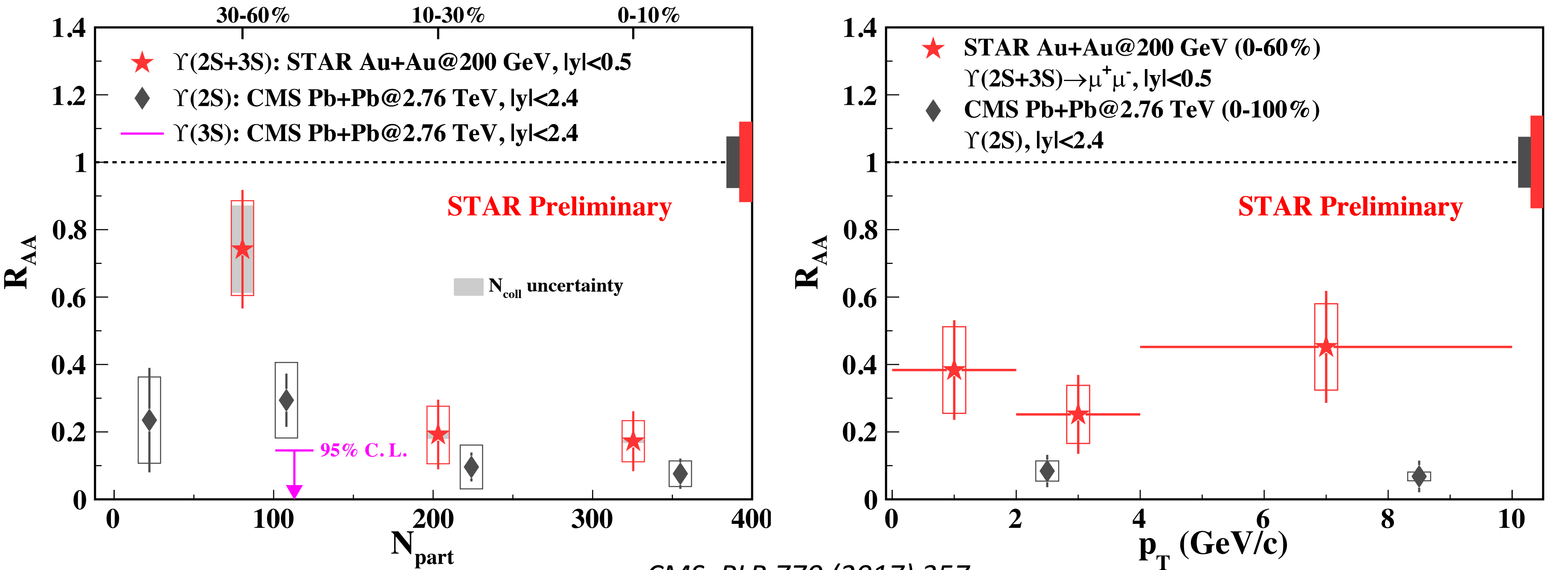
Υ(1S) R_{AA} : RHIC vs. LHC



CMS, PLB 770 (2017) 357

- Υ(1S) suppression: similar at RHIC and LHC energies!
  - CNM + suppression of excited states?

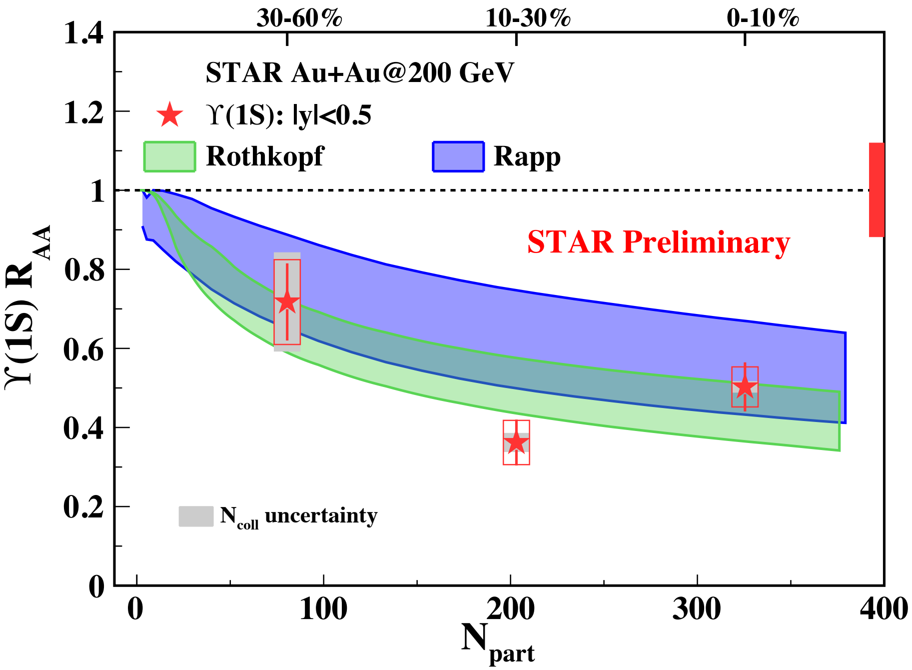
Υ(2S+3S) R_{AA} : RHIC vs. LHC

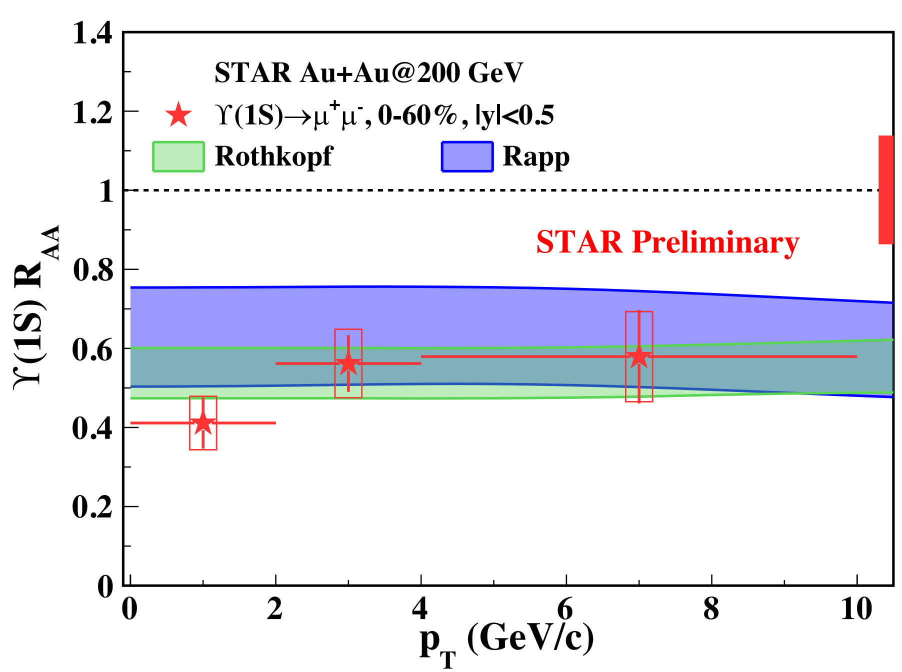


CMS, PLB 770 (2017) 357

- R_{AA}^{RHIC} are consistent with R_{AA}^{LHC} within uncertainty, but systematically higher
  - Indication of less suppression at RHIC than at LHC?

What do models say at RHIC? - Υ(1S)



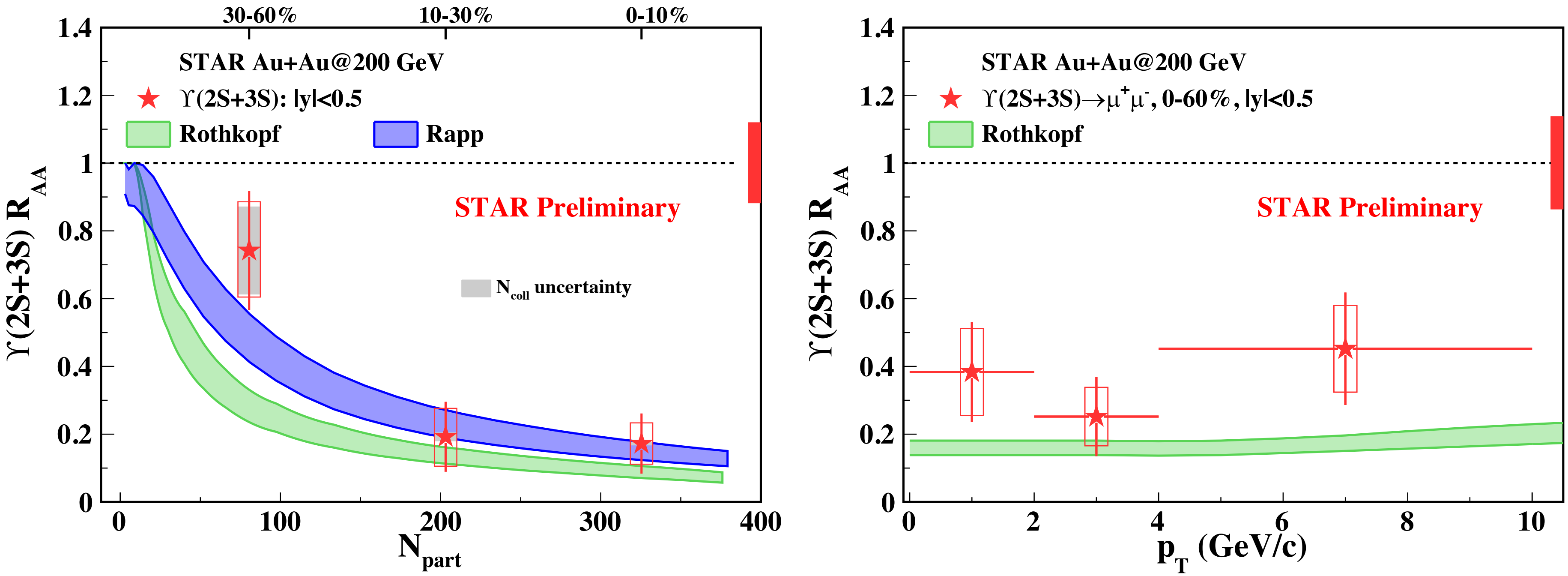


B. Krouppa, A. Rothkopf, and M. Strickland, PRD 97, 016017 (2018)

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 effect
  - Rapp: T-dependent binding energy; Includes CNM and regeneration effects

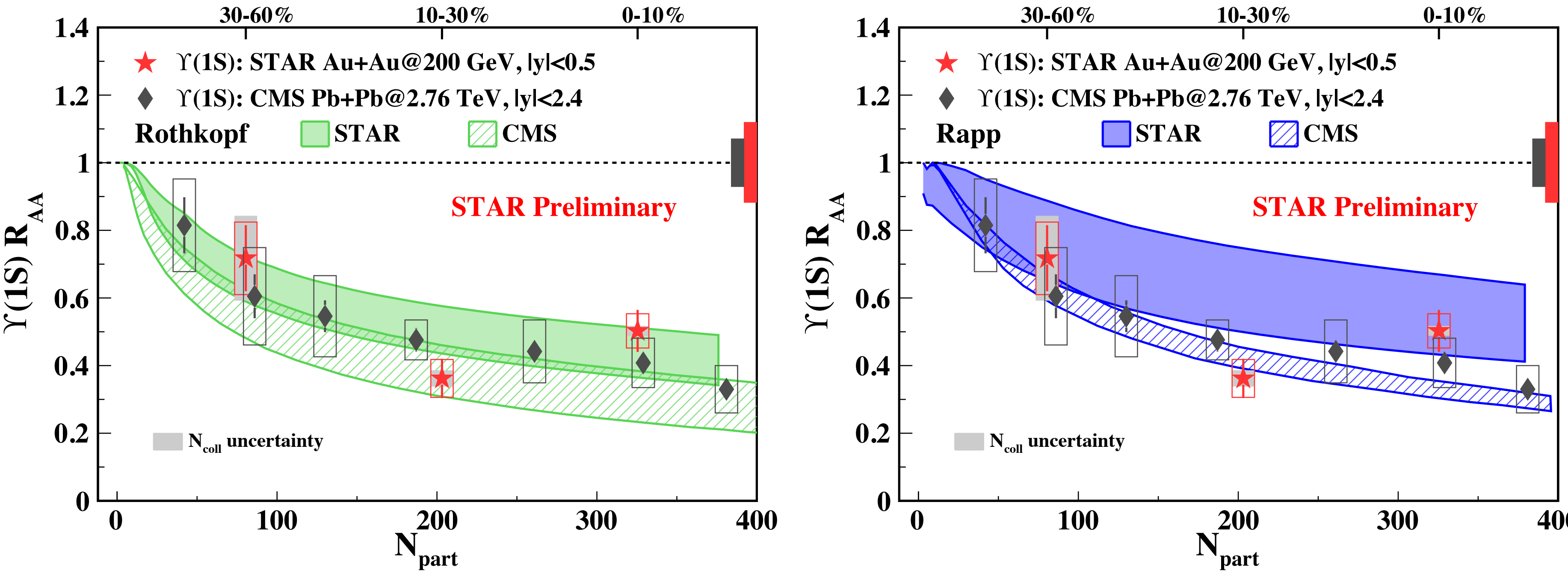
What do models say at RHIC? - Υ(2S+3S)



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

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

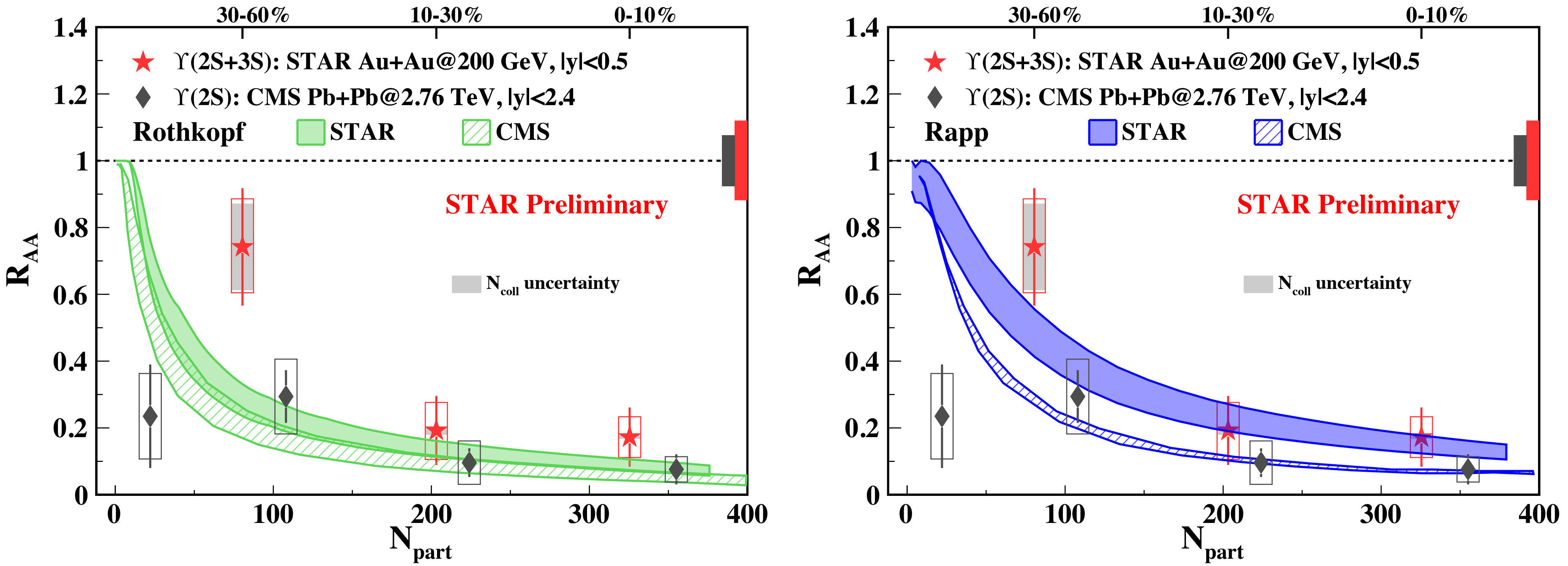
Can models consistently describe the data at RHIC and at LHC? - ϒ(1S)



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 description of ϒ(1S) suppression from RHIC to LHC energies.

Can models consistently describe the data at RHIC and at LHC? - ϒ(2S+3S) or ϒ(2S)



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

- Both models consistently describe RHIC and LHC excited ϒ states suppression in semi-central and central collisions

Summary

- p+p collisions at $\sqrt{s}$ = 200 GeV
  - ❑ Inclusive J/ψ cross section can be described by CGC+NRQCD and NLO NRQCD
  - ❑ NLO CEM model describes the total Υ cross section -> more precise baseline
- p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - ❑ J/ψ $R_{pAu} \approx R_{dAu}$: suggests similar CNM effects between p+Au and d+Au collisions
  - ❑ Υ(1S+2S+3S) R_{pAu}: indication of Υ suppression due to CNM effects
- Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - ❑ 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 more suppression towards central collisions
    - Similar suppression as at LHC
    - Both Rothkopf and Rapp models consistently describe the data from RHIC to LHC energies
  - ❑ Υ(2S+3S):
    - Stronger suppression in central collisions
    - More suppressed than Υ(1S) in 0-10% centrality -> sequential melting
    - Indication of less suppression at RHIC than at LHC
    - Both Rothkopf and Rapp models describe RHIC and LHC data in semi-central and central collisions