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BROOKHAVEN NATIONAL LABORATORY

Measurements of quarkonium production in p+p, p+Au and Au+Au collisions with the STAR experiment

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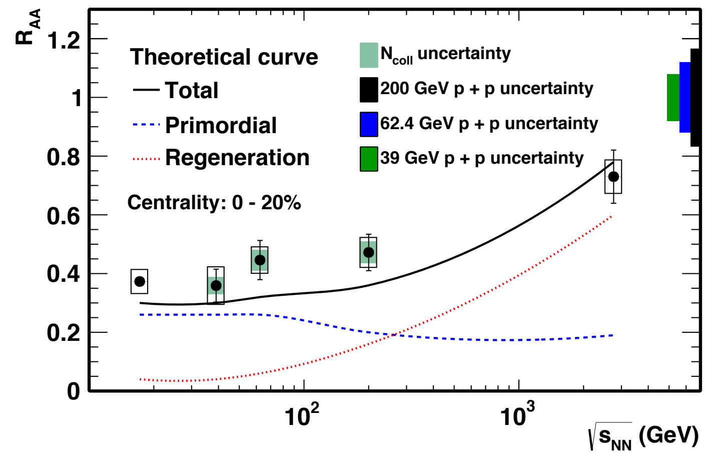
Probe QGP: Quarkonium

- **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**

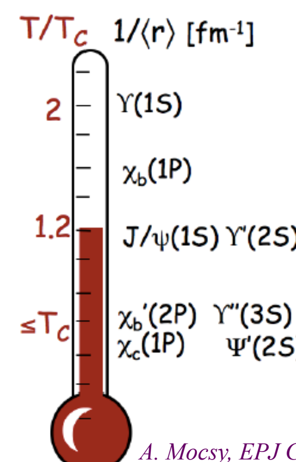
STAR arXiv:1607.07517

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



- **Thermometer**: different quarkonium states, e.g. ϒ family, dissociate at different temperatures
  - **Sequential melting**

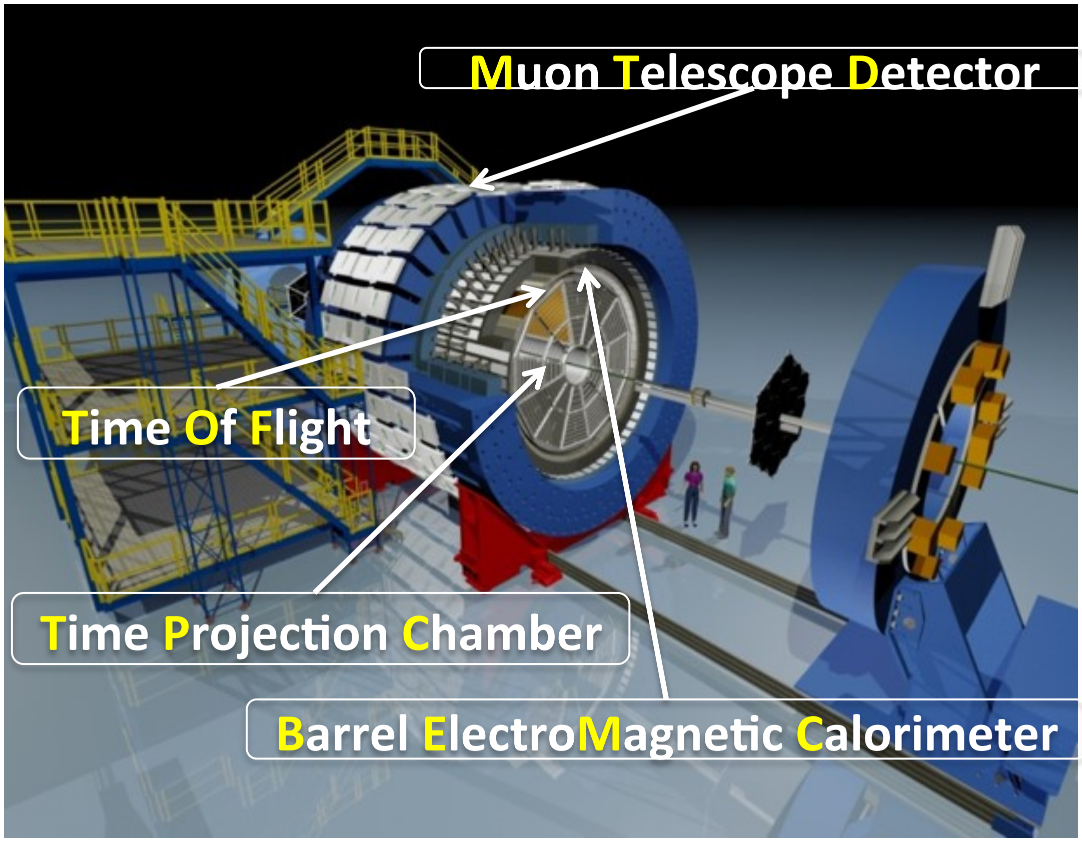
$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$



A. Mocsy, EPJ C61 (2009) 705

The Solenoid Tracker At RHIC

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

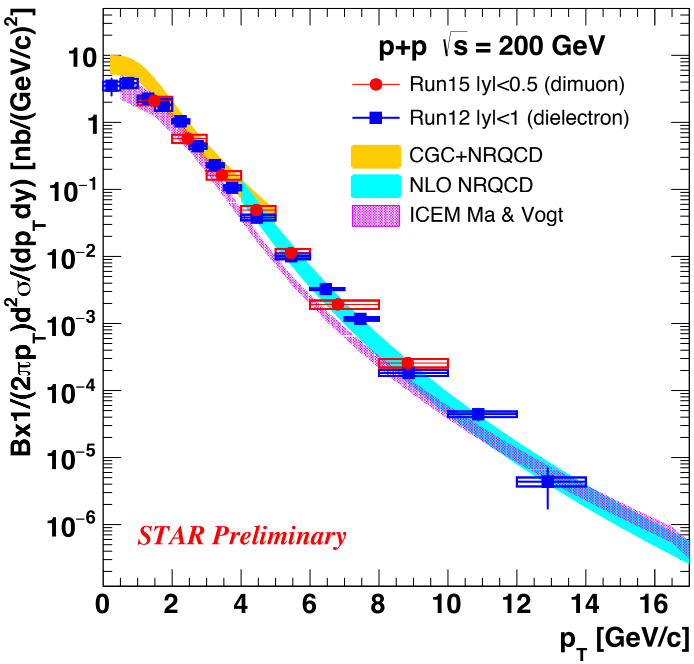


- **TPC**: measure momentum and energy loss
- **TOF**: measure particles' flight time to enhance PID at low p_T
- **BEMC**: trigger on and identify high-p_T electrons
- **MTD**: trigger on and identify muons
  - $|\eta| < 0.5$, $\varphi \sim 45\%$
  - $p_T >\sim 1.0$ GeV/c
  - Less bremsstrahlung

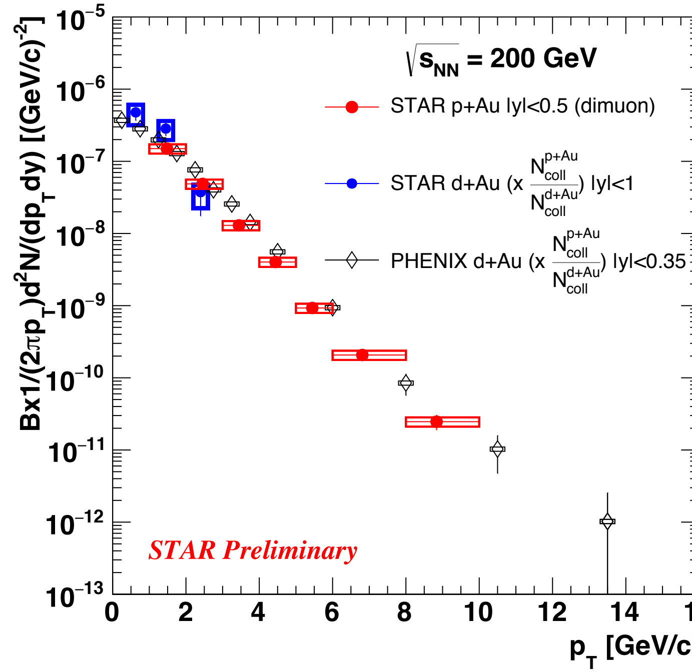
Charmonium

Inclusive J/ψ in p+p/A 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

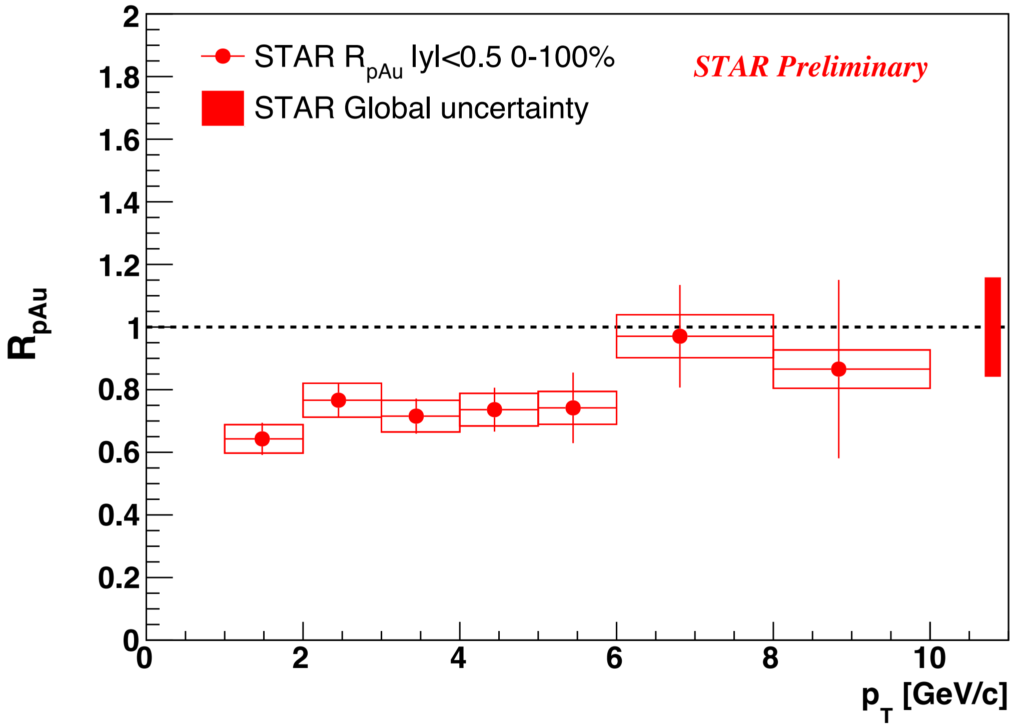


PHENIX, PRC 87 (2012) 034903
STAR d+Au, PRC 93 (2016) 064904



- p+p: inclusive J/ψ cross-section measured in $0 < p_T < 14$ GeV/c
  - CGC+NRQCD & NLO NRQCD (prompt) agree with data above 1 GeV/c
  - Improved CEM model (direct) is below data in 3.5 – 12 GeV/c
  - *B-hadron feed-down needs to be taken into account*
- N_{coll} scaling works reasonably well at high p_T for p/d+Au

Inclusive J/ψ R_{pAu} at 200 GeV



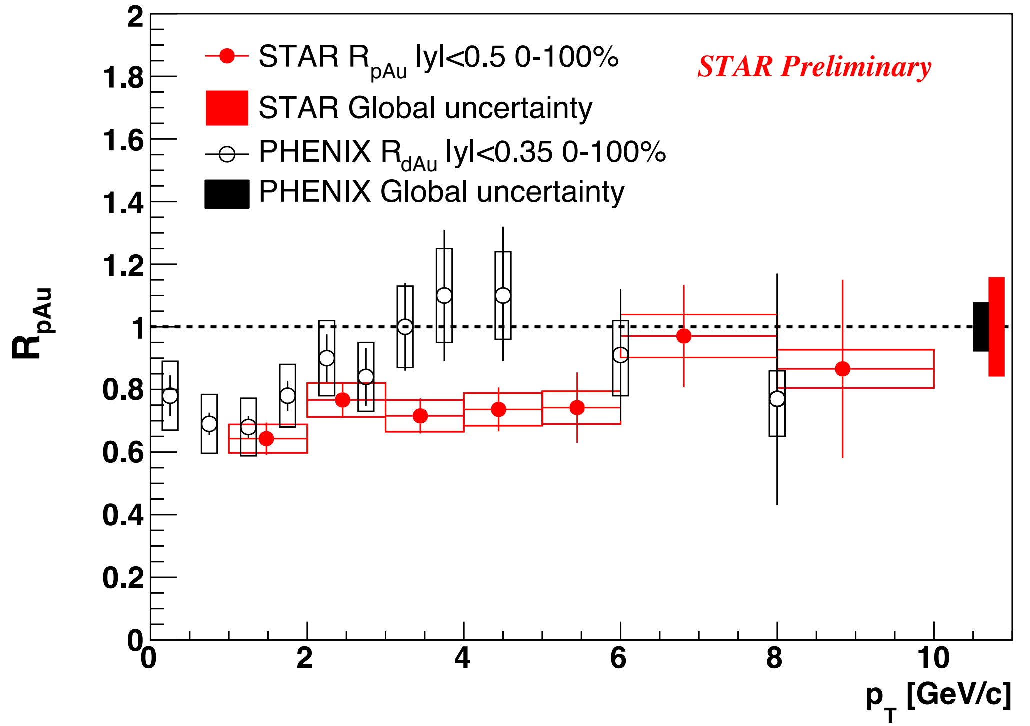
$$R_{pAu} = \frac{\sigma_{inel}^{pp}}{\langle N_{coll} \rangle} \frac{d^2 N_{pAu} / dydp_T}{d^2 \sigma_{pp} / dydp_T}$$

← **Global Uncertainty**

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

- First J/ψ R_{pAu} measurement at RHIC
- R_{pAu} ~ 1 at high p_T and is less than unity at low p_T

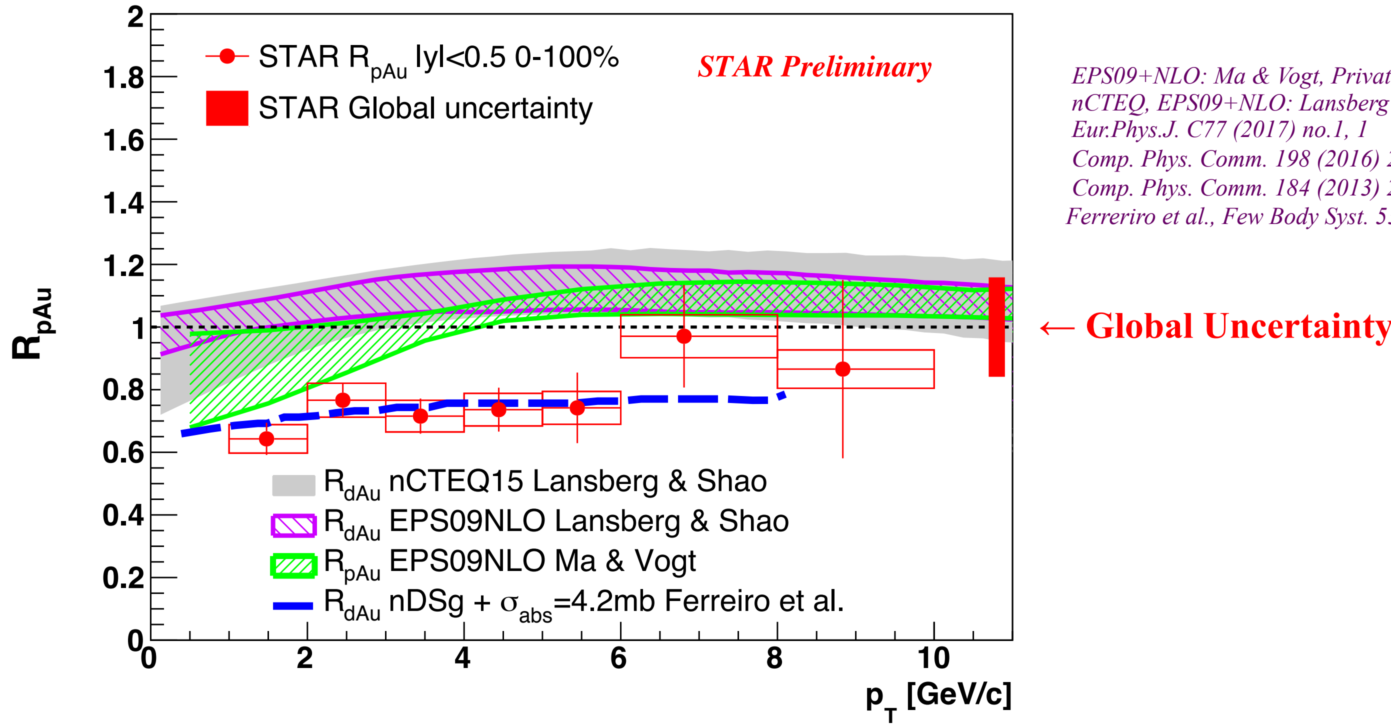
Inclusive J/ψ: R_{pAu} vs. R_{dAu}



PHENIX, PRC 87 (2012) 034903

- R_{pAu} is consistent with R_{dAu} within uncertainties
  - There seems to be tension at 3.5 – 5 GeV/c (1.4σ)

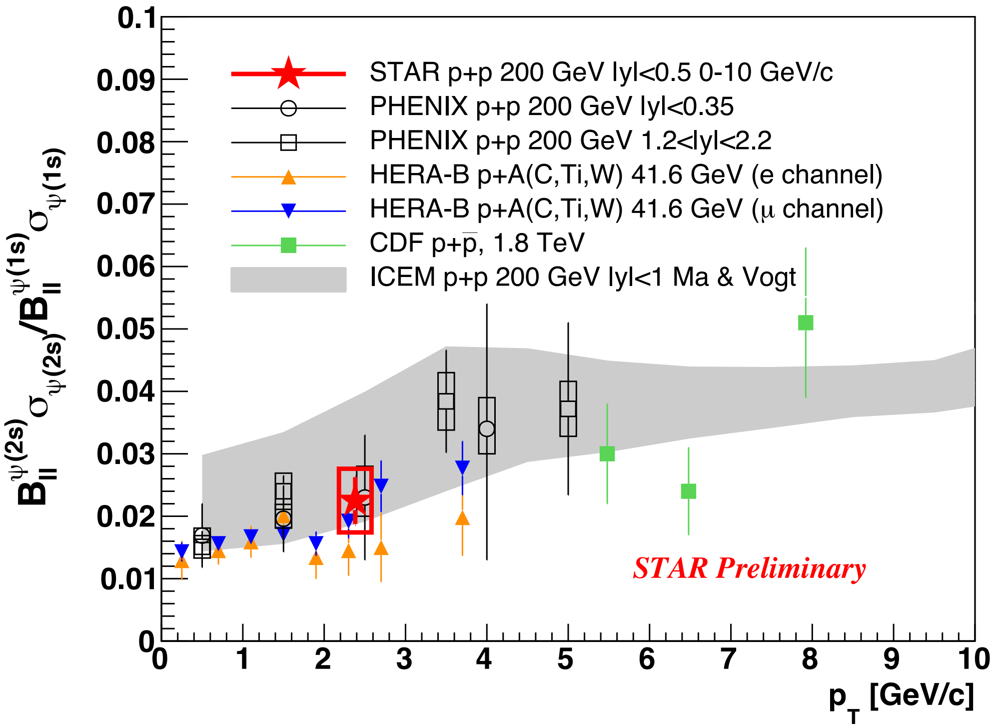
Inclusive J/ψ R_{pAu}: data vs. model



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

- **Data seem to favor additional nuclear absorption on top of nuclear PDF effects**
- However, models with only nPDF are not fully ruled out given the relatively large global uncertainty on data

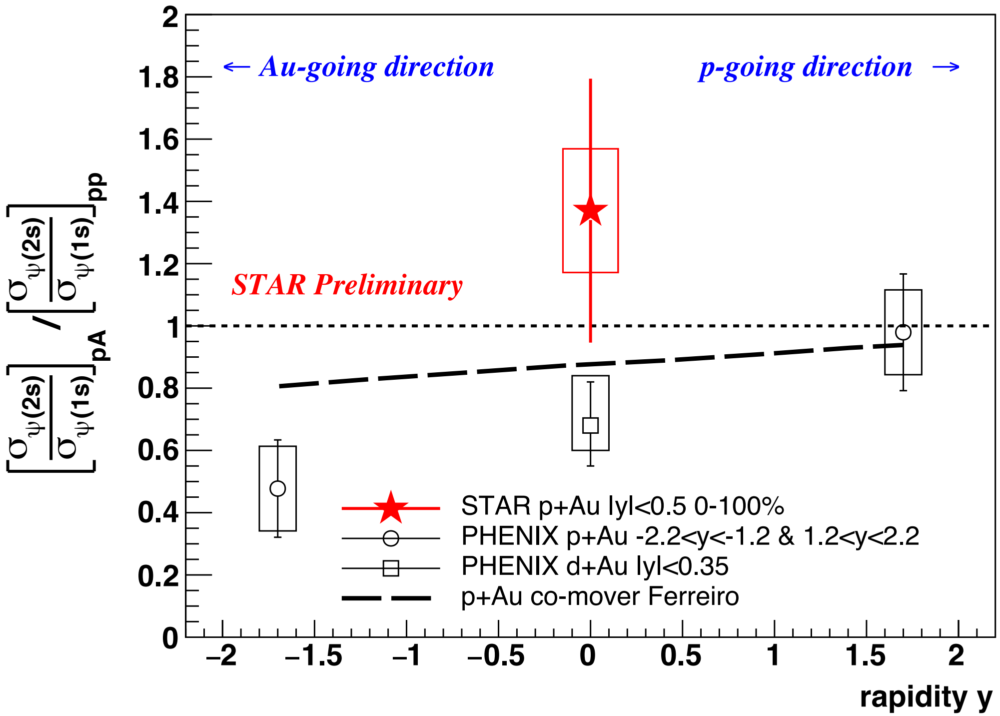
ψ(2S)/J/ψ ratio in 200 GeV p+p



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

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



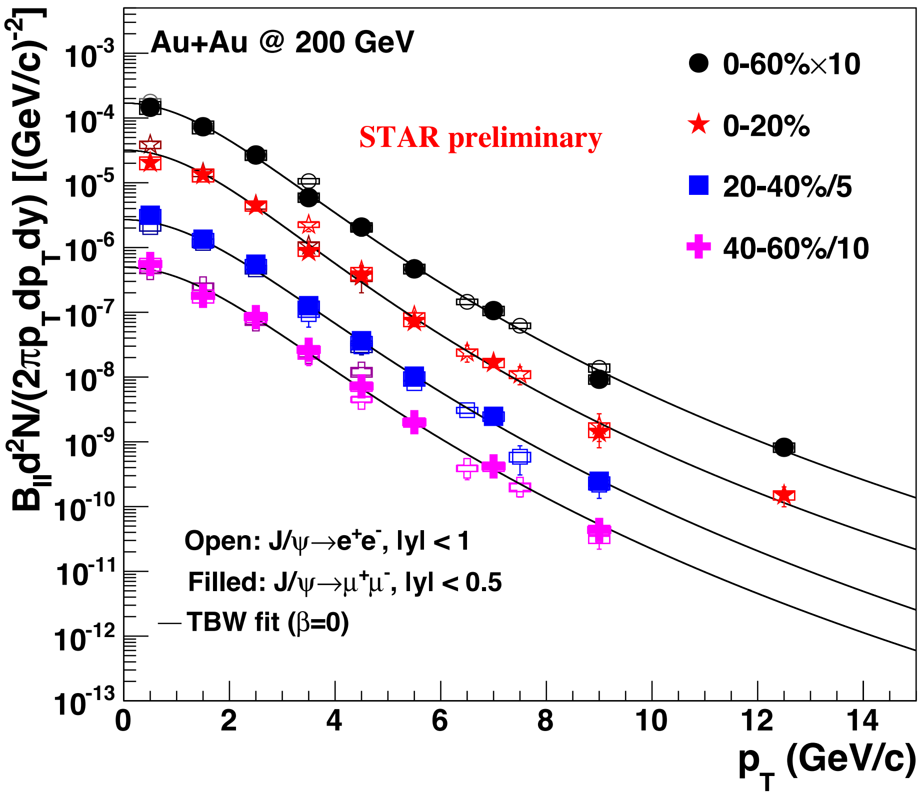
PHENIX p+Au, arXiv:1609.06550 (Accepted by PRC)
PHENIX d+Au, PRL111 (2013) 202301

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

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

1.37 ± 0.42(stat) ± 0.19(sys)

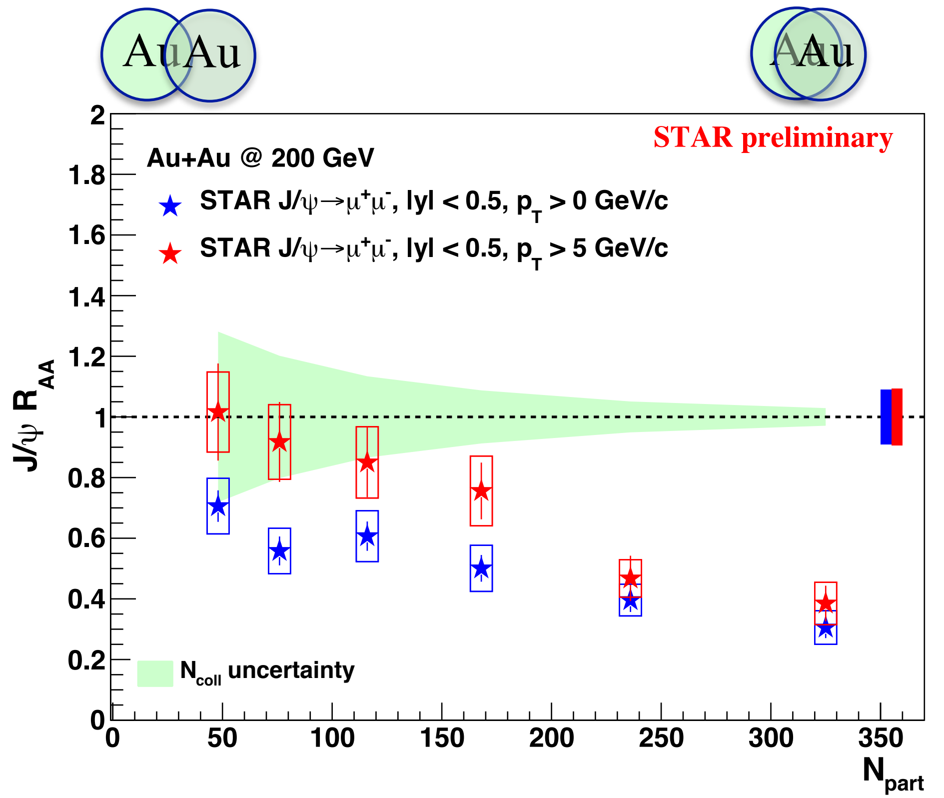
J/ψ yield in 200 GeV Au+Au collisions



Di-electron:
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

- Mid-rapidity J/ψ yield measured via the di-muon channel for 0–15 GeV/c
- Consistent with the published di-electron results over the entire kinematic range

J/ψ R_{AA} vs. centrality

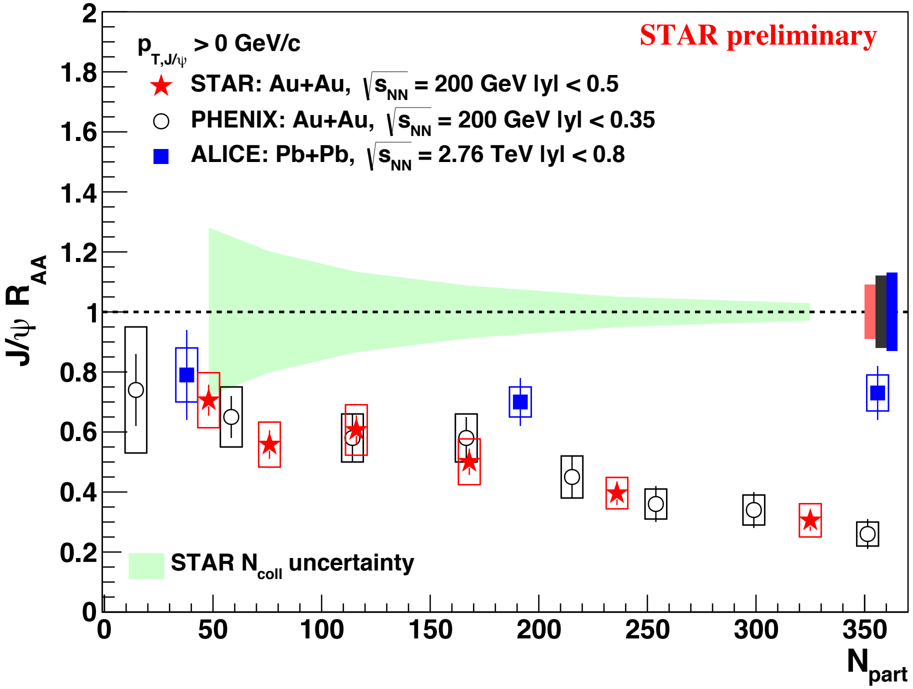


- Central collisions: **significant suppression for $p_T > 0$ GeV/c and $p_T > 5$ GeV/c** → interplay of different effects
- Peripheral collisions: R_{AA} of J/ψ for $p_T > 0$ GeV/c is smaller than that for $p_T > 5$ GeV/c; consistent with cold nuclear matter effects

J/ψ R_{AA}: RHIC vs. LHC

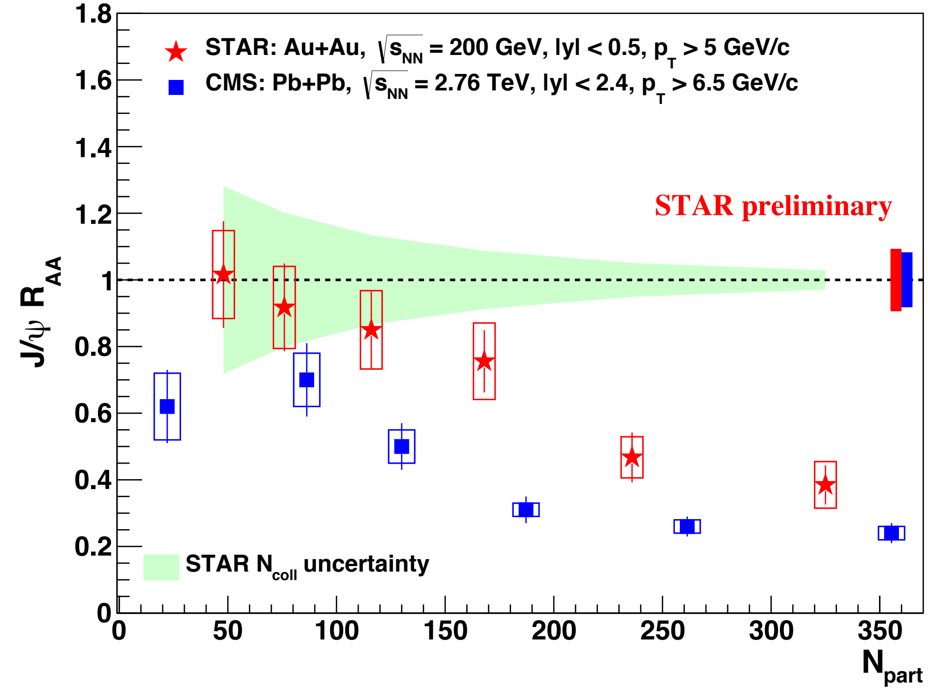
p_T > 0 GeV/c

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



p_T > 5 GeV/c

CMS: JHEP 05 (2012) 063



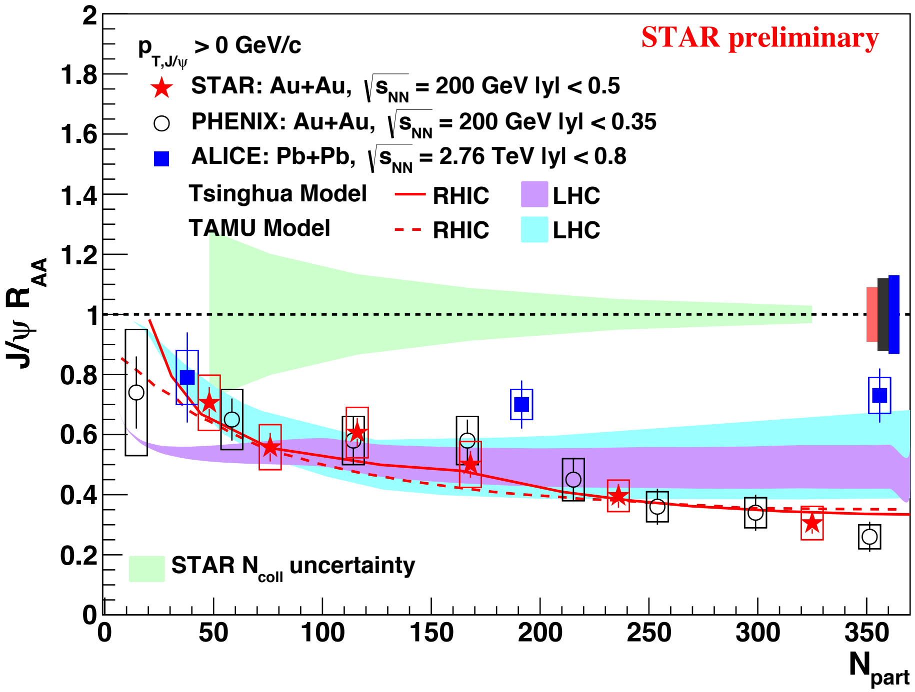
- p_T > 0 GeV/c: less suppressed at LHC in central events → **larger regeneration contribution due to higher charm cross-section**
- p_T > 5 GeV/c: more suppressed at LHC in all centralities → **larger dissociation rate due to higher temperature**

Data vs. transport model

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

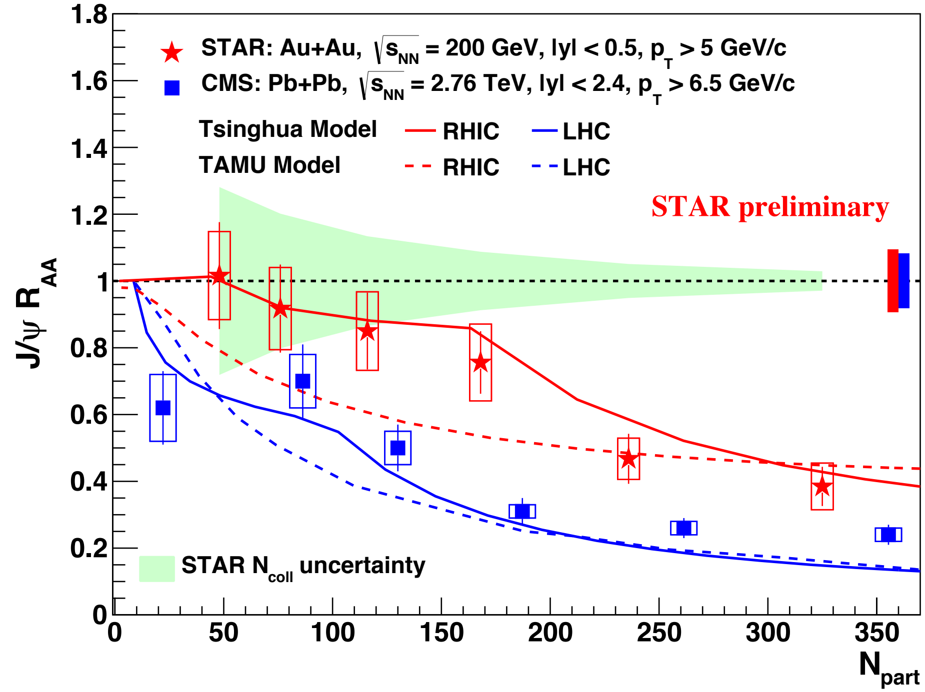
p_T > 0 GeV/c

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



p_T > 5 GeV/c

CMS: JHEP 05 (2012) 063

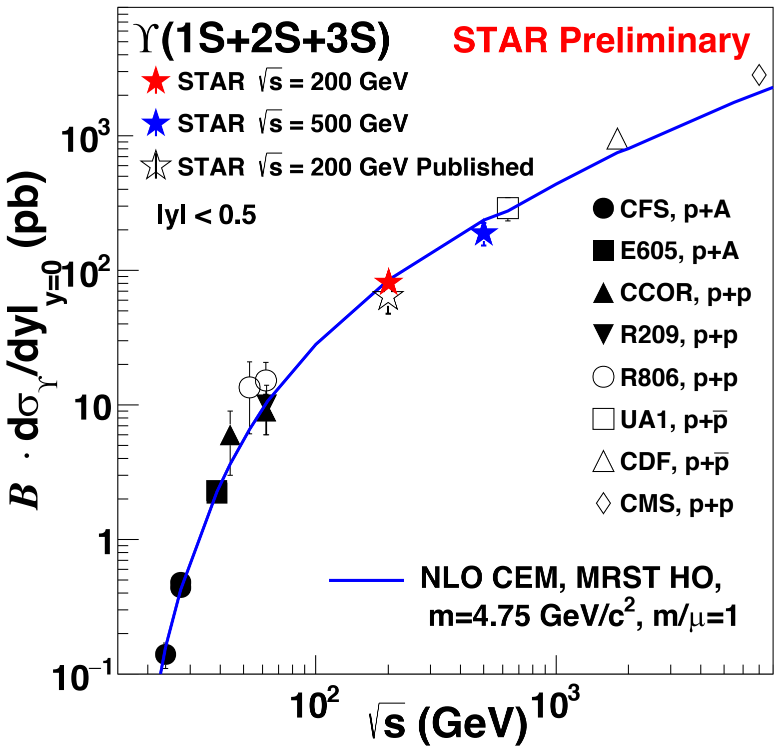


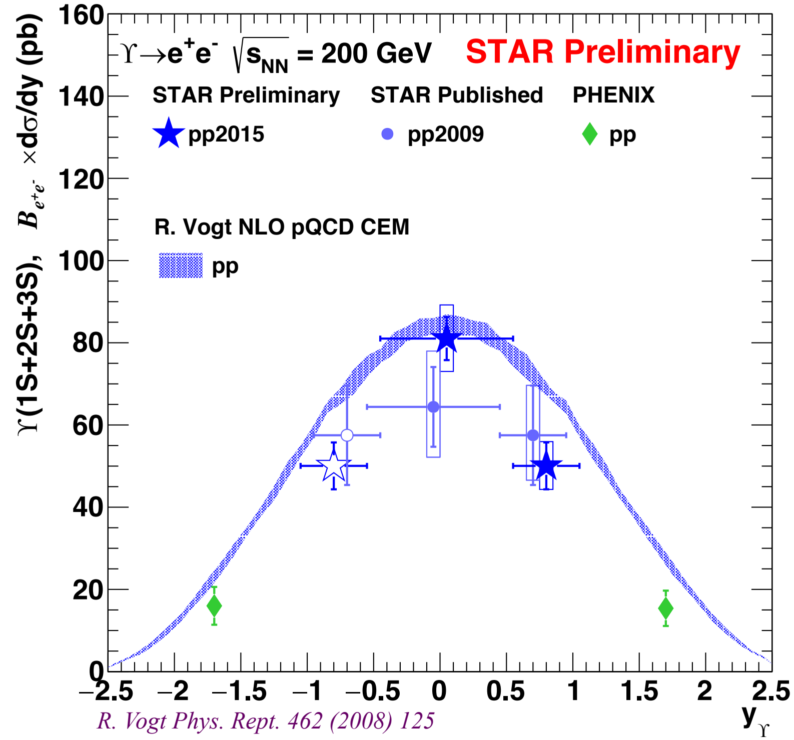
- p_T > 0 GeV/c: both models can describe centrality dependence at RHIC, but tends to overestimate suppression at LHC
- p_T > 5 GeV/c: there is tension among models and data
- Other models on the market: SHM, co-mover …

PBM, J. Stachel, PLB 490 (2000) 196, and PLB 652 (2007) 659
E.G. Ferreiro, PLB 731 (2014) 57–63

Bottomonium

ϒ cross-section in p+p collisions

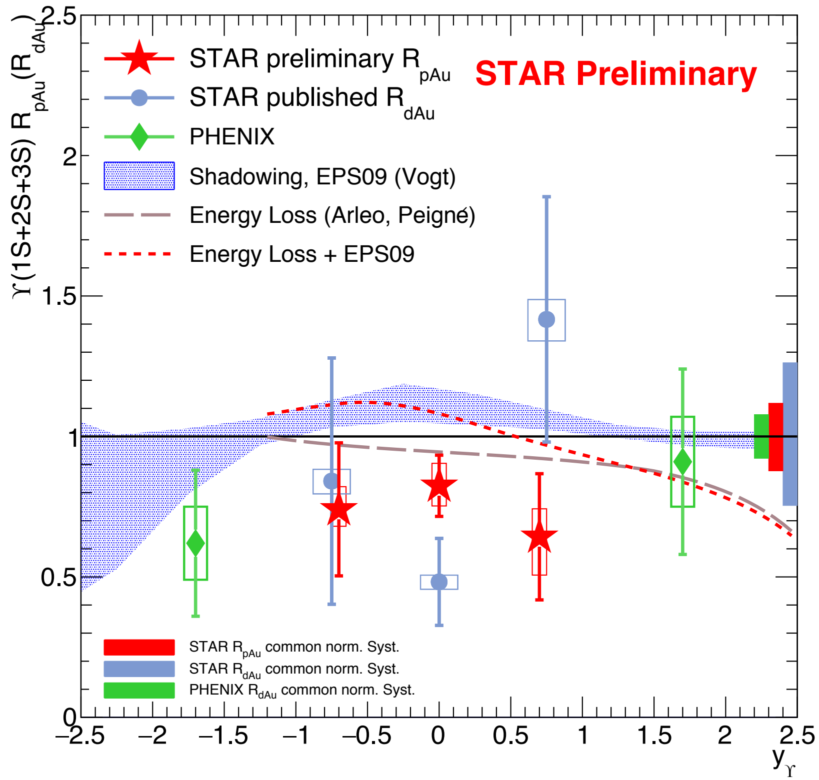




- p+p @ 200 and 500 GeV: ϒ cross-sections follow world-wide data trend predicted by CEM
- p+p @ 200 GeV: ϒ cross-section exhibit narrower rapidity distribution than NLO CEM calculation

Improved p+p reference for p+Au and Au+Au studies

Υ(1S+2S+3S) R_{pAu} at 200 GeV



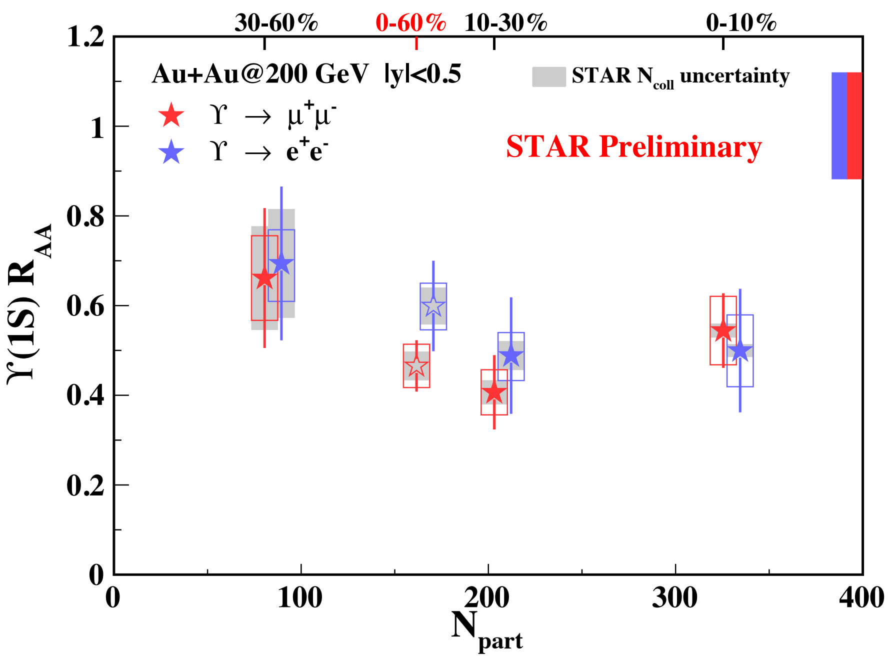
R. Vogt, et. al, PoS ConfinementX 203 (2012)
F. Arleo, S. Peigne, JHEP 1303 (2013) 122
K. J. Eskola, et. al, JHEP 0904 (2009) 065

STAR: PLB 735 (2014) 127
PHENIX: PRC 87 (2013) 044909

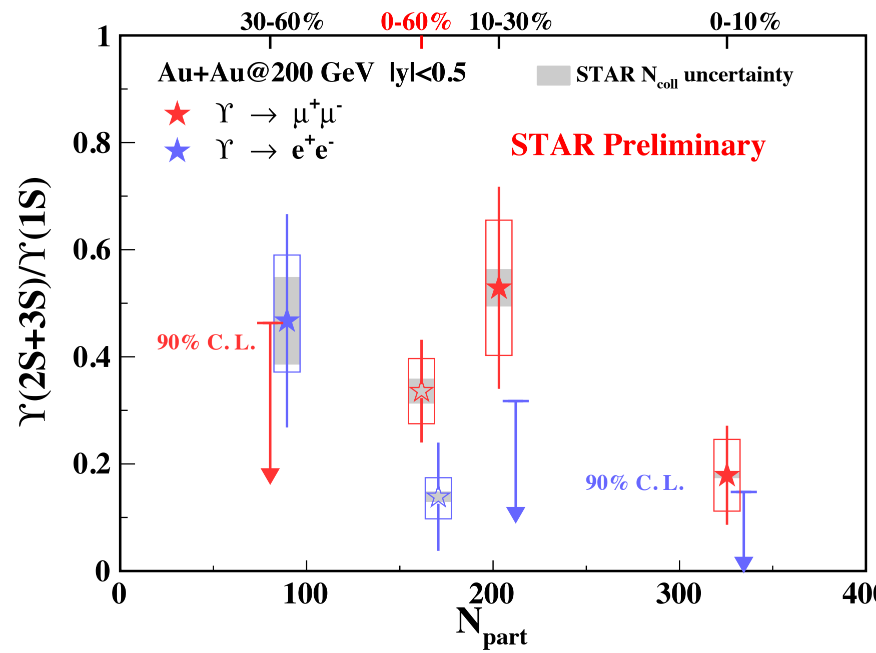
- **CNM: indication of Υ(1S+2S+3S) suppression in p+Au collisions**
  - $R_{pAu} = 0.82 \pm 0.10(\text{stat}) + 0.08(\text{syst}) - 0.07(\text{syst}) \pm 0.10(\text{global})$
  - A factor of two better precision than R_{dAu} measurement
- Additional suppression mechanism seems needed beyond shadowing effects

Consistency check

Υ(1S) R_{AA}



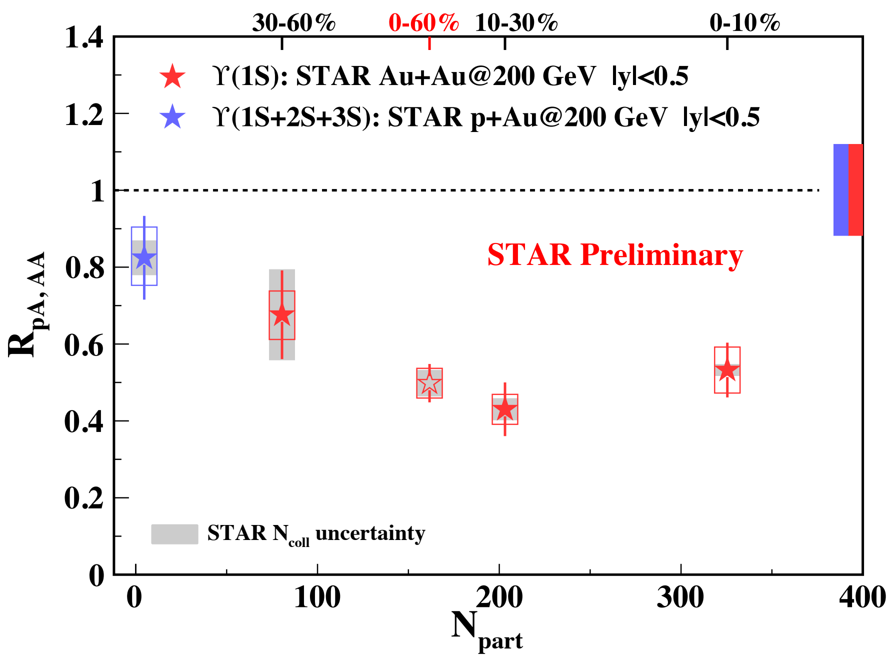
Υ(2S+3S)/Υ (1S)



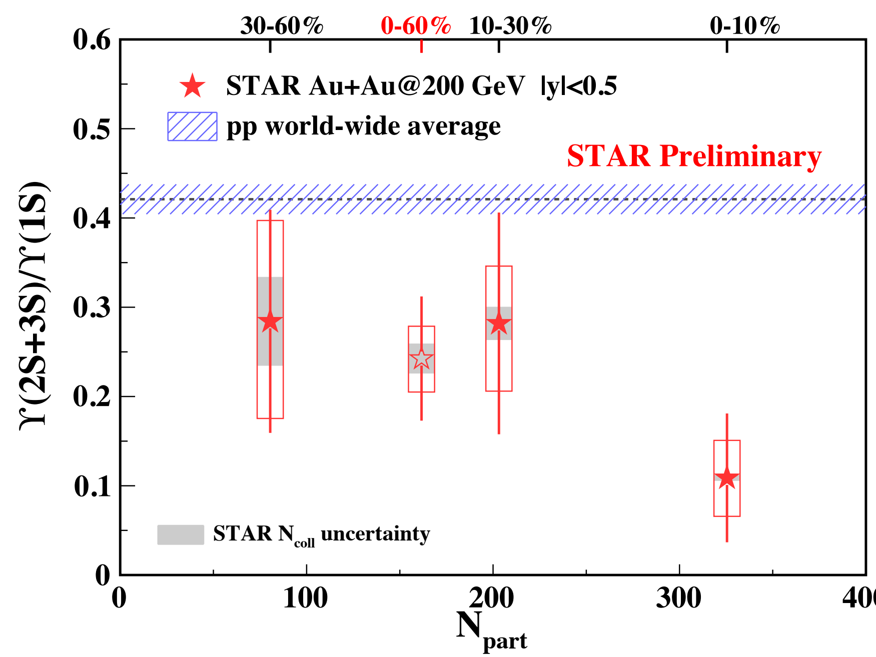
- Di-muon: 2014 data; di-electron: 2011 data
- Consistent results from the two channels → Combine

ϒ suppression at RHIC

ϒ(1S) R_{AA}



ϒ(2S+3S)/ϒ(1S)

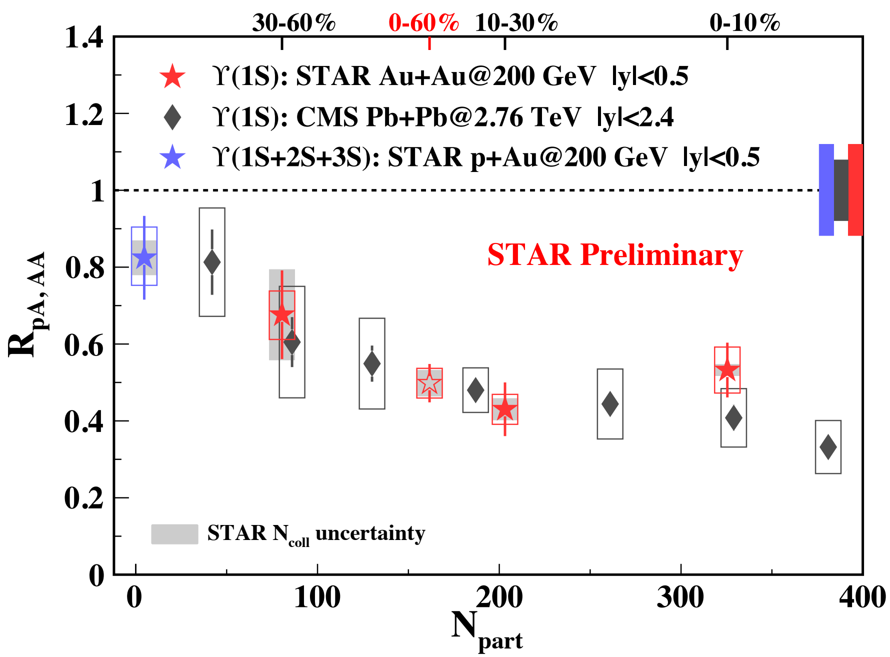


World-wide p+p: W. Zha, et. al, PRC 88 (2013) 067901

- **Direct ϒ(1S) could be suppressed**
  - 0-60% ϒ (1S) $R_{AA} = 0.50 \pm 0.04(\text{stat}) \pm 0.05(\text{syst}) \pm 0.07(\text{global})$
  - Indication of more suppression with increasing centrality
- **Central: ϒ(2S+3S) is more suppressed → sequential melting**

Υ(1S): RHIC vs. LHC

CMS: arXiv:1611.01510

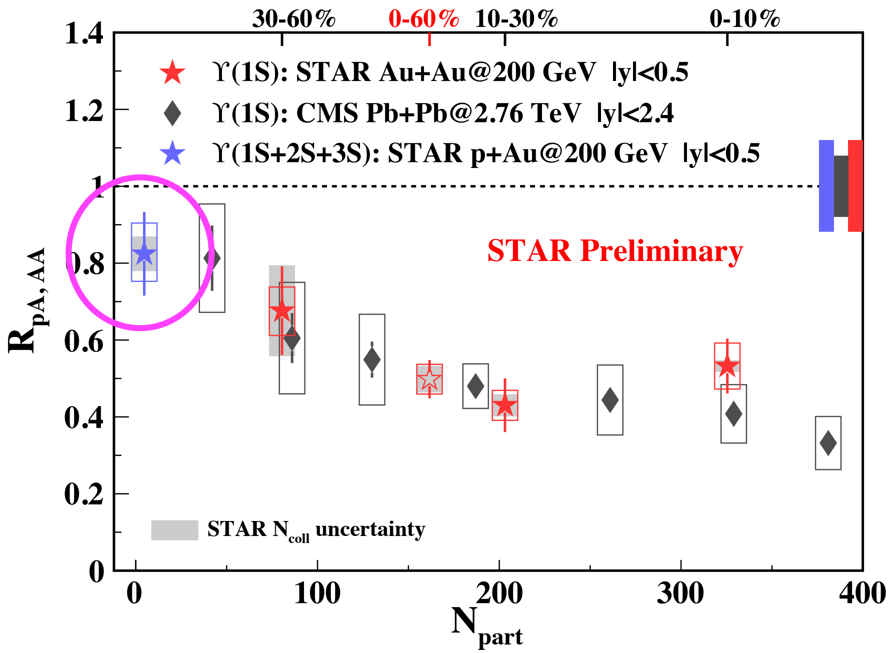


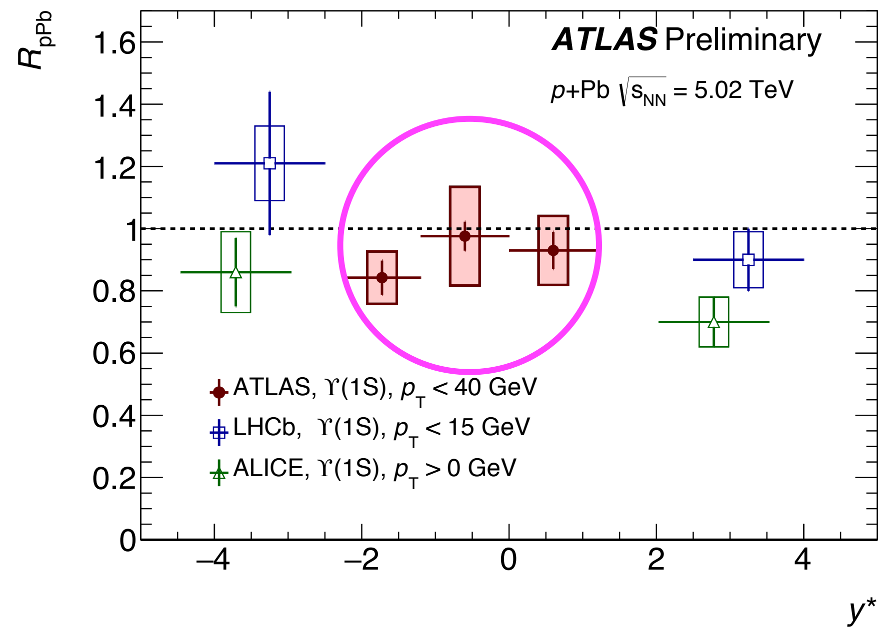
- **Υ(1S) suppression: similar at RHIC and LHC**

ϒ(1S): is it CNM?

CMS: arXiv:1611.01510

ALTAS-CONF-2015-050
ALICE: PLB 740 (20115) 105
LHCb: JHEP 07 (2014) 094

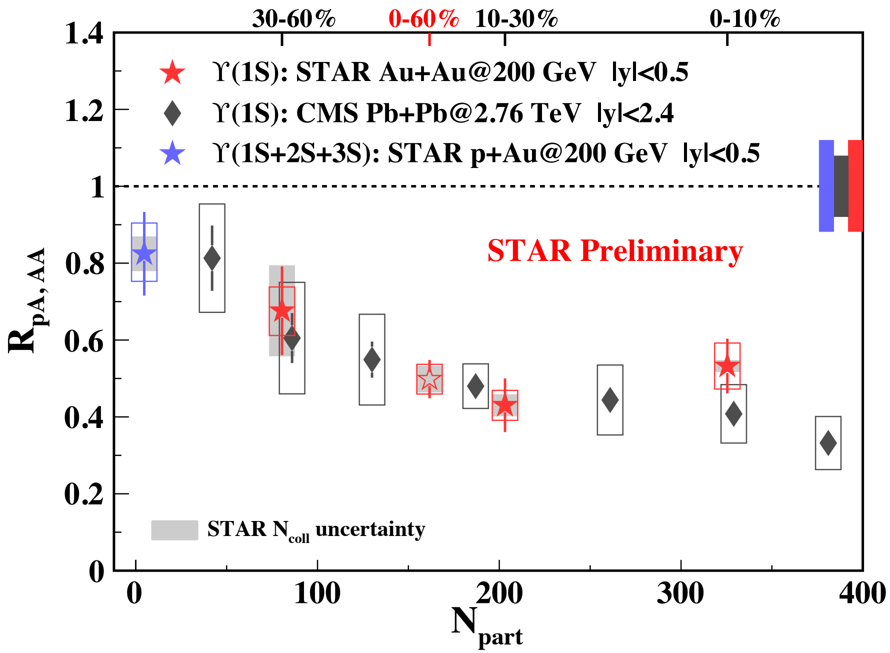




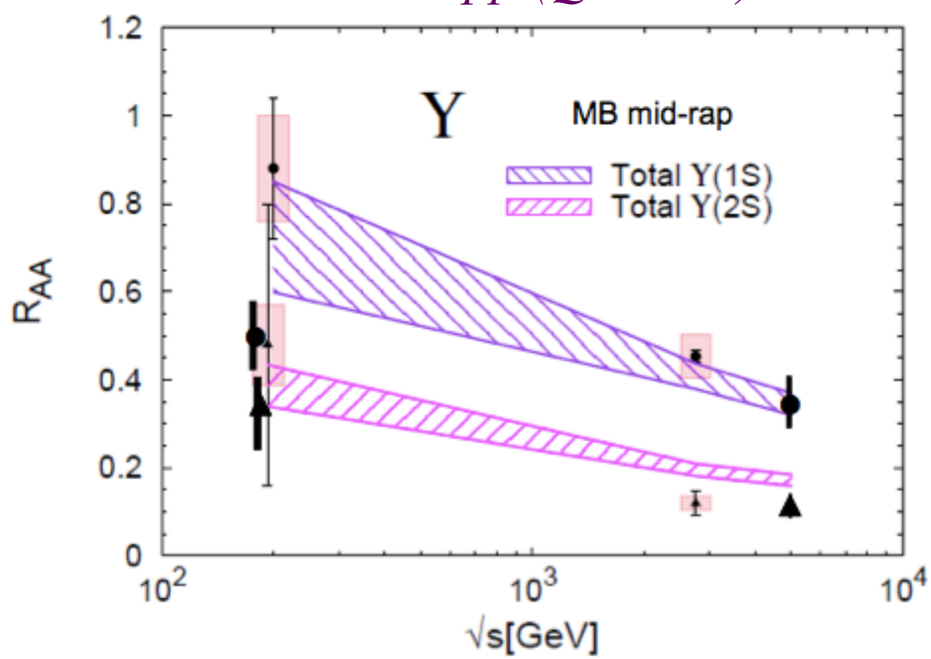
- ϒ(1S) suppression: similar at the RHIC and the LHC
- The CNM effects seem compatible. But need results with better precision from experiments.

ϒ(1S): is it regeneration?

CMS: arXiv:1611.01510



R. Rapp (QM2017)

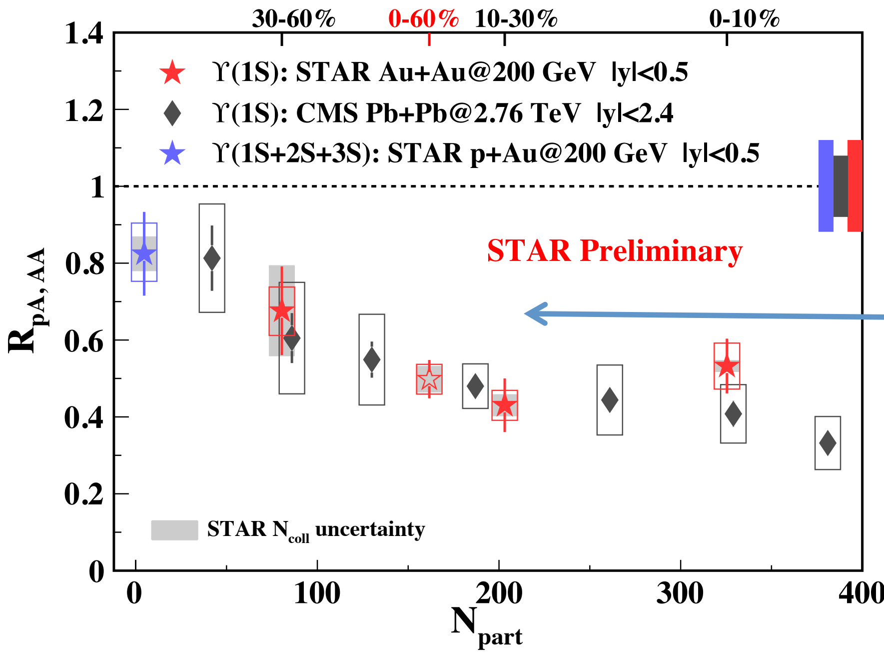


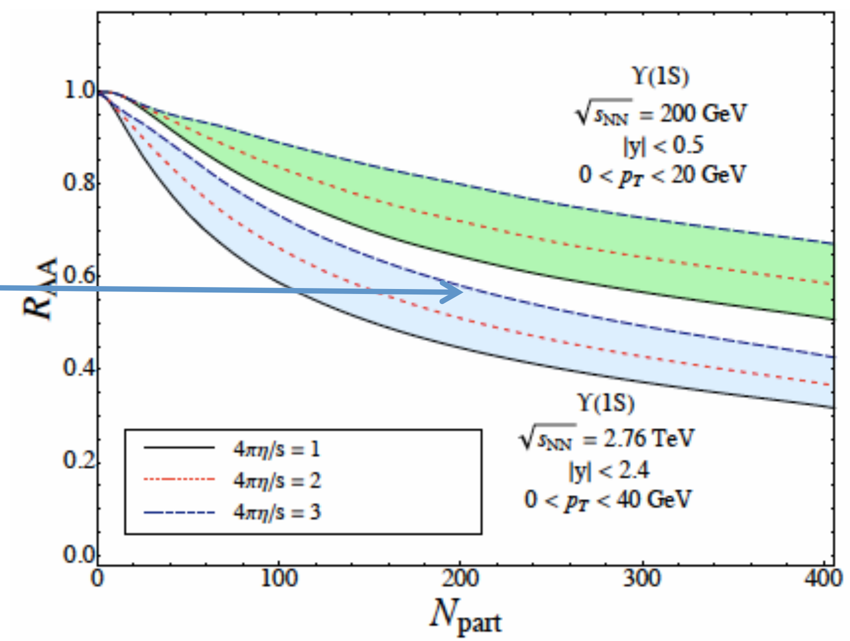
- ϒ(1S) suppression: similar at the RHIC and the LHC
- R. Rapp model: including regeneration cannot describe STAR and CMS data simultaneously.
  - Is the magnitude of regeneration right?

What does other model say?

CMS: arXiv:1611.01510

M. Strickland (QM2017)

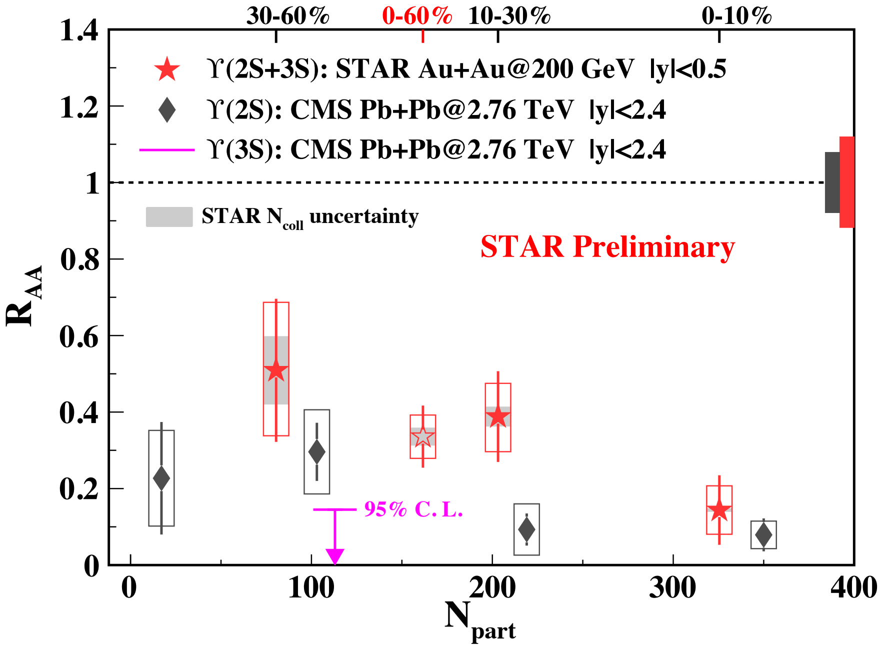




- ϒ(1S) suppression: similar at the RHIC and the LHC
- M. Strickland model: describes CMS but under-predicts suppression seen by STAR
  - Anisotropic hydrodynamic medium; no CNM or regeneration.

ϒ(2S+3S): RHIC vs. LHC

CMS: arXiv:1611.01510

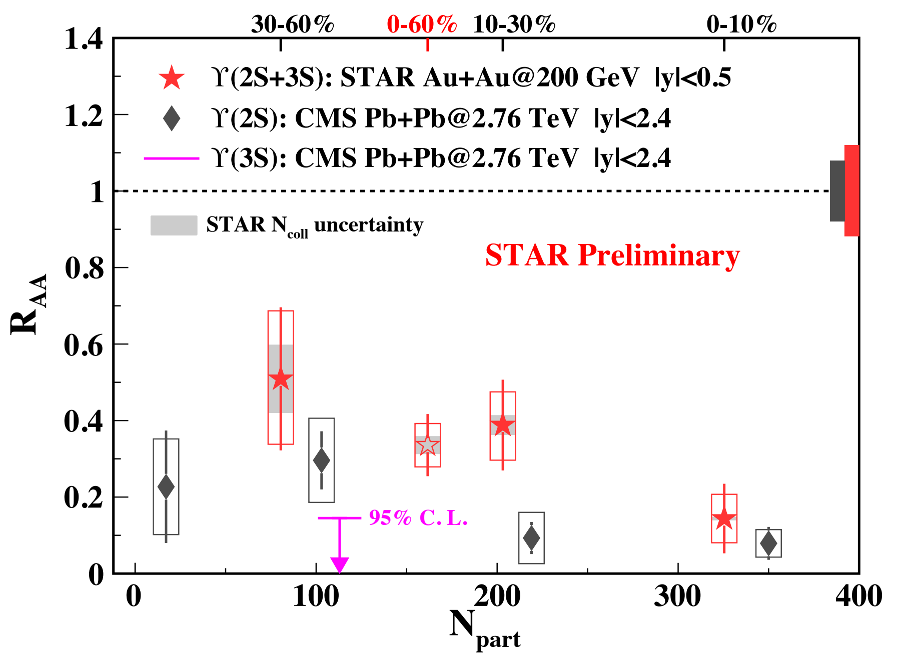


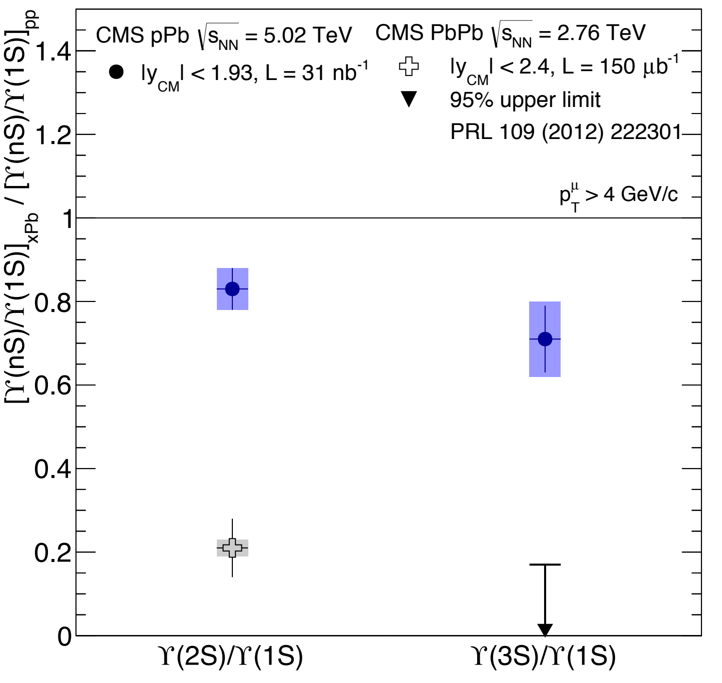
- **ϒ(2S+3S): hint of less suppression at RHIC than at the LHC**

ϒ(2S+3S): what about CNM?

CMS: JHEP 04 (2014) 103

CMS: arXiv:1611.01510

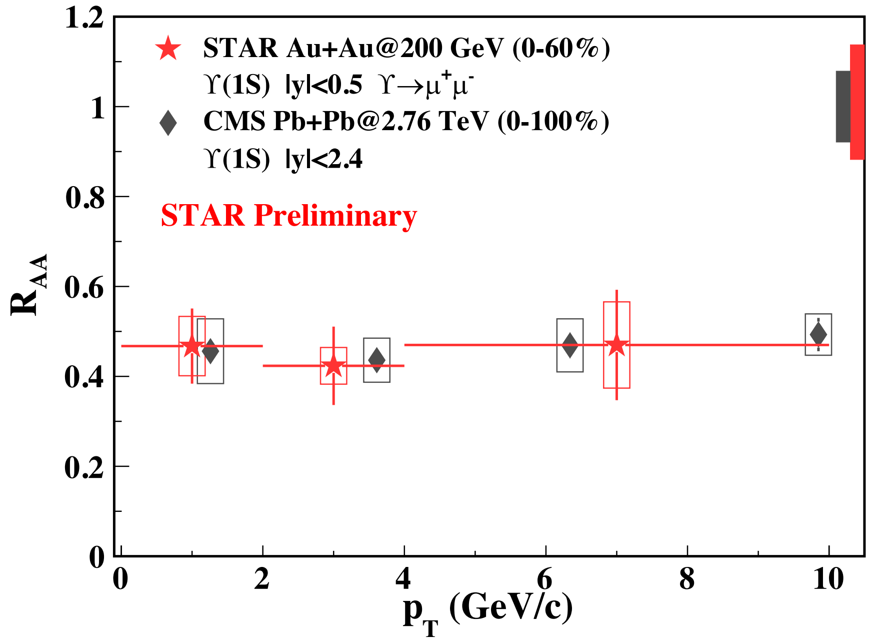




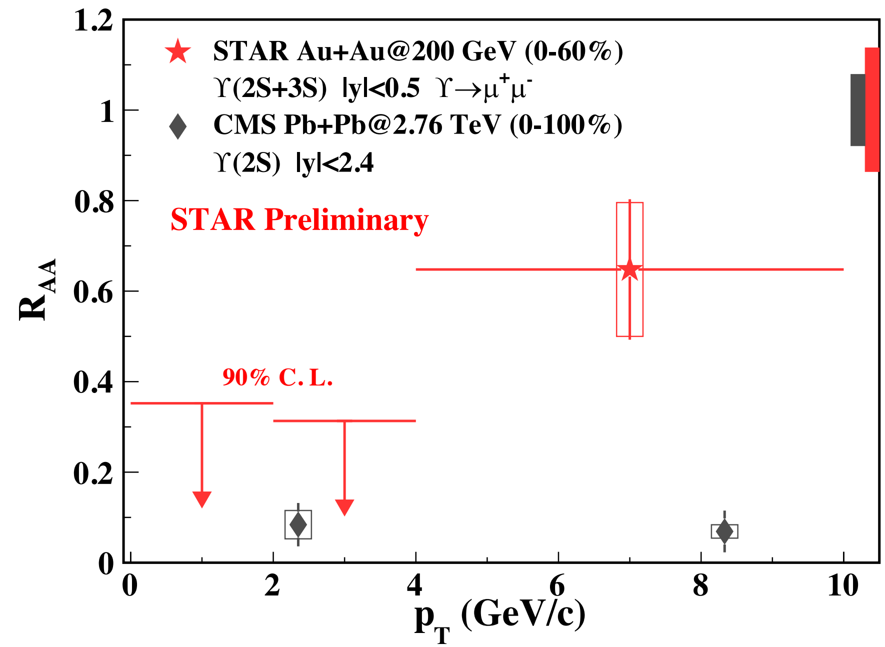
- ϒ(2S+3S): hint of less suppression at RHIC than at the LHC
- CNM: ϒ(2S+3S) states are more suppressed than ϒ(1S) at the LHC. What about RHIC?

Υ R_{AA} vs. p_T

Υ(1S)



Υ(2S+3S)



- Υ(1S): no obvious dependence on p_T; similar to CMS
- Υ(2S+3S): hint of less suppression at high p_T

Summary & Outlook

- p+p collisions
  - Models describe data reasonably well (e.g. CEM, NRQCD, etc)
- p+Au collisions
  - In general, quarkonia $R_{pAu} < 1$
  - Additional suppression mechanisms are supported by data, even though nPDF effects only cannot be fully ruled out yet.
- Au+Au collisions
  - J/ψ $R_{AA} < 1$ with $p_T > 5$ GeV/c → **dissociation in effect**
  - Direct Υ(1S) may be suppressed at RHIC → constrain medium T
  - 0-10%: Υ(2S+3S) R_{AA} < Υ(1S) R_{AA} → **sequential melting**
  - *Υ(1S) R_{AA}: STAR ≈ CMS. CNM? regeneration? other effects?*
- Outlook: 2x Au+Au data on tape for Υ analyses at STAR