Measurements of the Υ meson production in Au+Au collisions by the STAR experiment

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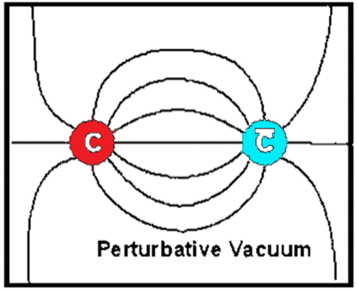
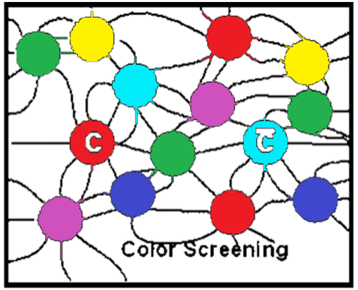
Outline

1. Heavy quarkonia in heavy-ion collisions
2. The STAR experiment
3. Measurements of the Υ production at STAR
4. Comparison with LHC results and model calculations
5. Summary

Heavy quarkonia in QGP





- $J/\psi, \Upsilon$ etc. are good candidates to probe QGP
  - $m_c \sim 1.3$ GeV$/c^2$, $m_b \sim 4.2$ GeV$/c^2$ → early production
  - Typically : $t^{Q\bar{Q}}_{\text{creation}} < t^{QGP}_{\text{creation}} < t^{QGP}_{\text{lifetime}} \ll t^{HQ}_{\text{lifetime}}$

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

- Suppression of production by colour screening
  - Quarkonium expected to *dissociate* if its radius is greater than the Debye radius:

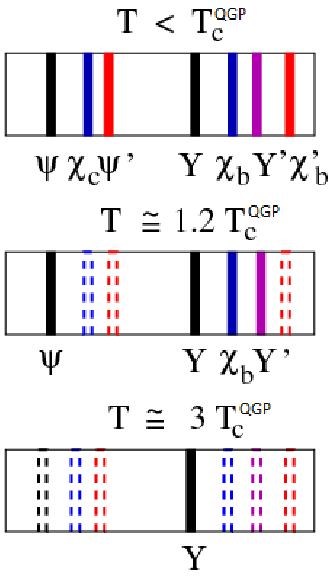
$r_{\text{Debye}} \propto 1/T$

- Sequential melting

A. Mocsy, EPJ C61 (2009) 705

  - Dissociation depends on the quarkonium binding energy
  - Different states expected to melt at different temperatures
  - QGP "*thermometer*"

$$R_{AA} \sim \frac{\#\text{HQ}\ in\ AA}{\#\text{HQ}\ in\ pp \quad \times\ \#\ binary\ coll.} = ?$$



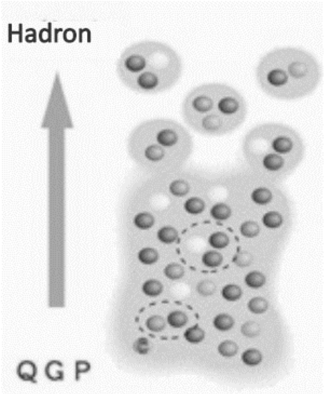
H. Satz, IJMPA 28 (2013) 1330043

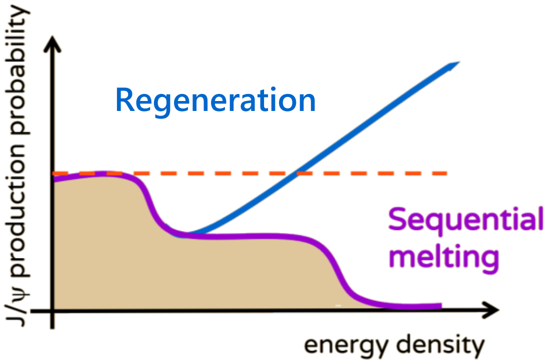
Other effects also play a role

- Other phenomena complicate interpretation of the measured quarkonium suppression
- ***Recombination***
  - Coalescence of deconfined quarks

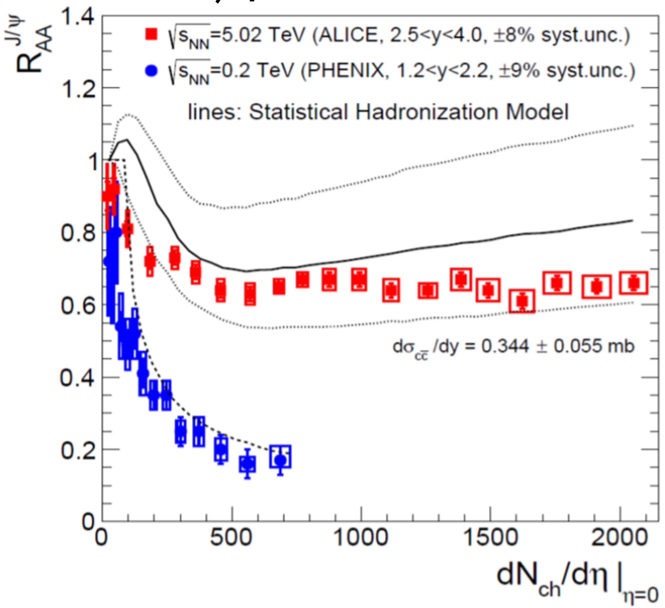
ALICE, PLB 766 (2017) 212

PHENIX, PRC 84 (2011) 054912





***J/ψ* in A+A at LHC vs RHIC**



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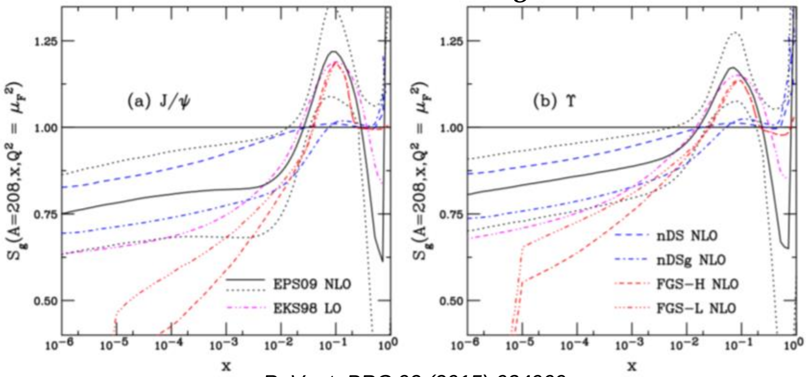
- ***Cold nuclear matter (CNM) effects***
  - ***Initial state: nuclear shadowing, energy loss***

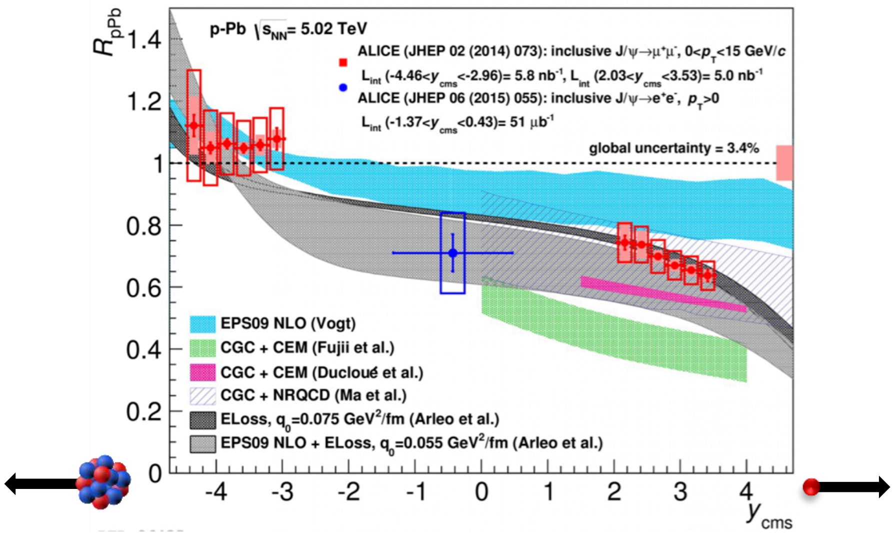
nuclear shadowing ratios



R. Vogt, PRC 92 (2015) 034909

ALICE, JHEP 02 (2014) 073

rapidity dependence for J/ψ in p+Pb



← higher x *lower x →*

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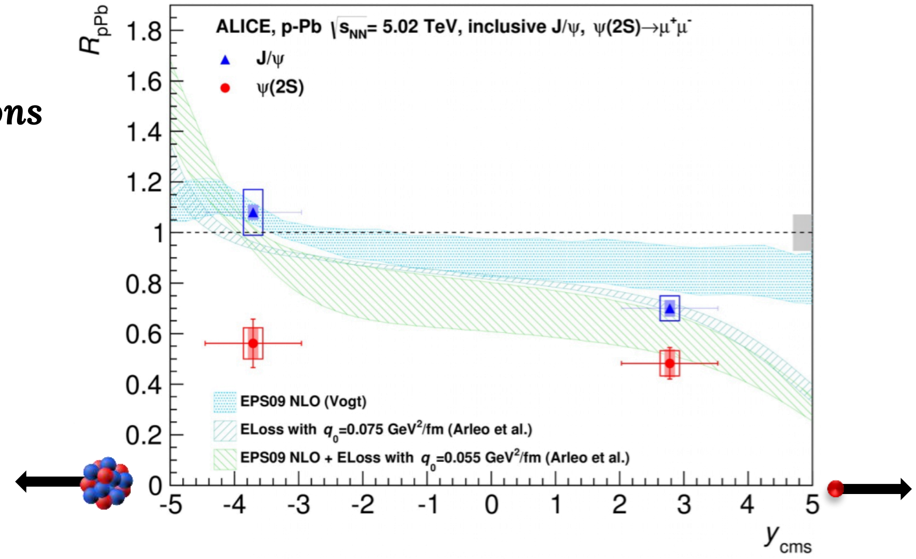
  - Initial state: nuclear shadowing, energy loss
  - ***Final state: inelastic interactions with hadrons***
    - → nuclear break-up
    - → co-mover absorption

ALICE, JHEP 12 (2014) 073

difference for J/ψ and $\psi(2S)$ in p+Pb



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- ***Feed-down***

$\Upsilon(1S)$ $p_T > 8$ GeV/c at $\sqrt{s} = 1.8$ TeV — *CDF, PRL 84 (2000) 2094*

Prompt $\Upsilon(1s)$	$\sim 51\%$
$\Upsilon(1s)$ from $\chi_b(1P)$ decays	$\sim 27\%$
$\Upsilon(1s)$ from $\chi_b(2P)$ decays	$\sim 10\%$
$\Upsilon(1s)$ from $\Upsilon(2S)$ decays	$\sim 11\%$
$\Upsilon(1s)$ from $\Upsilon(3S)$ decays	$\sim 1\%$

Why measure Υ at STAR?

I. Das, QM2015, https://indico.cern.ch/event/355454/contributions/838966/

	RHIC 200 GeV	LHC 2.76 TeV
$\#c\bar{c}$ / event	13	115
$\#b\bar{b}$ / event	0.1	3

- Very ***small production by recombination***

  A. Emerick, X. Zhao, R. Rapp, EPJ A48 (2012) 72

- Precursor $b\bar{b}$ pair is more probable to survive propagation through a nuclear medium than $c\bar{c}$ since:

  $$\sigma_{\mathrm{eff}}^{\Upsilon} \sim \left(\frac{m_c}{m_b}\right)^2 \sigma_{\mathrm{eff}}^{J/\psi} \simeq 0.1\, \sigma_{\mathrm{eff}}^{J/\psi}$$

  E. Ferreiro, et al., PoS 157 (2012) 159

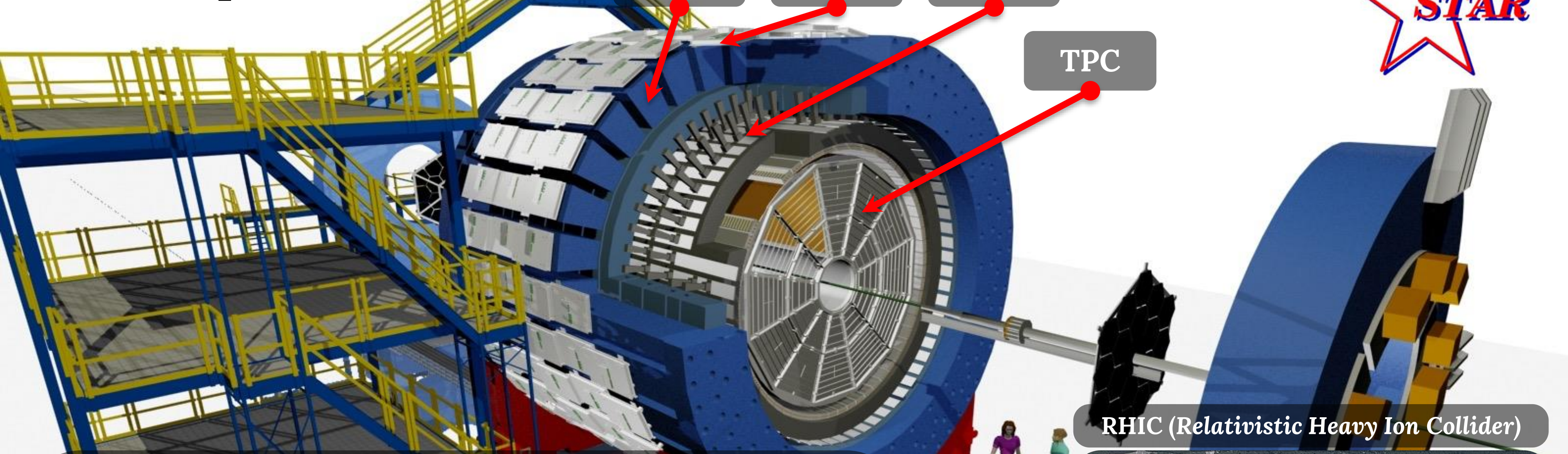
- For co-movers (pions): $\sigma^{co-\Upsilon(1S)} \ll \sigma^{co-J/\psi}$ → ***break-up by co-movers insignificant***

  Z. Lin, C. Ko, PLB 503 (2001) 104

> **→ Υ′*s* at RHIC $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV *are a cleaner probe of the screening effect!***

- Challenge: smaller production cross-section compared to the LHC

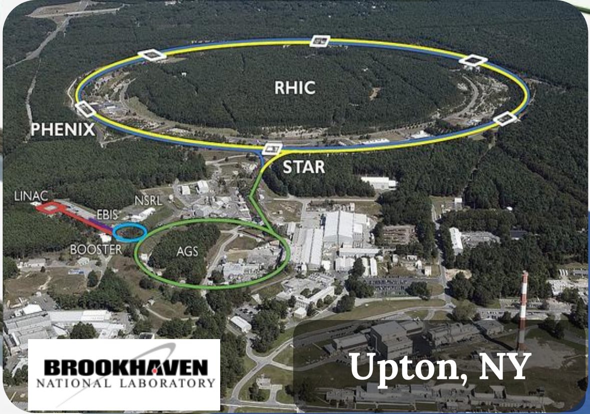
STAR experiment



Excellent charged-particle identification (PID), full 2π coverage at pseudo-rapidity $|\eta| < 1$

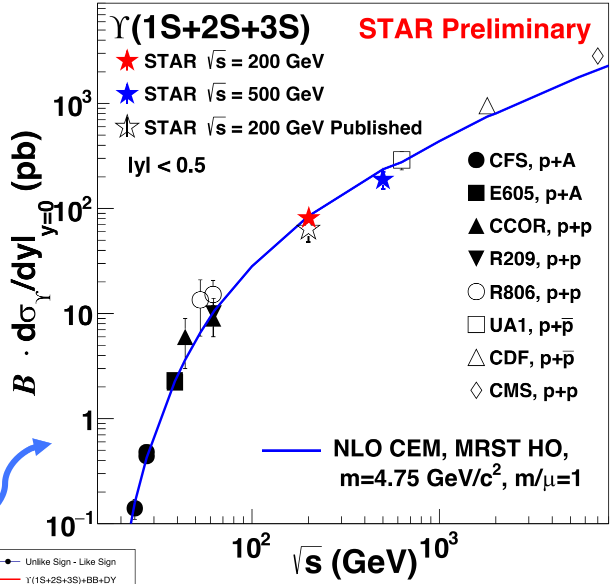
- **TPC (*Time Projection Chamber*)** : tracking, momentum measurement, dE/dx PID
- **BEMC (*Barrel Electromagnetic Calorimeter*)** : trigger on and identify high-p_T electrons
- **MTD (*Muon Telescope Detector*)** : $|\eta| < 0.5$ and φ ~ 45%, muon PID and triggering

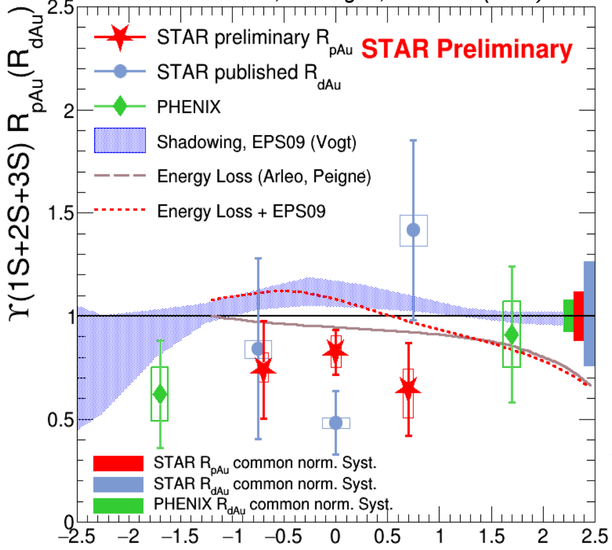
RHIC (*Relativistic Heavy Ion Collider*)



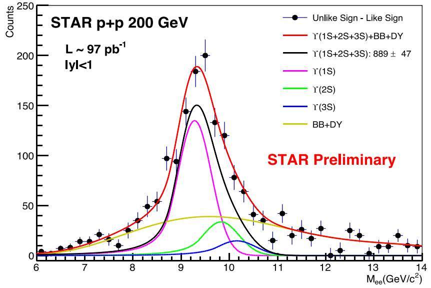
Results from p+p and p+Au collisions

STAR, PLB 735 (2014) 127
PHENIX, PRC 87 (2013) 044909
F. Arleo, S. Peigné, JHEP 03 (2013) 122

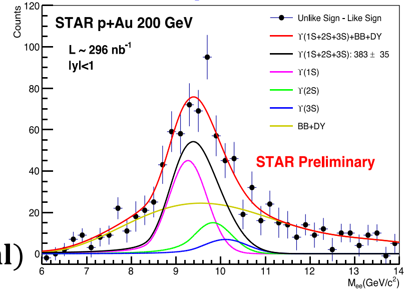




p+p: $\Upsilon \rightarrow e^+e^-$



p+Au: $\Upsilon \rightarrow e^+e^-$



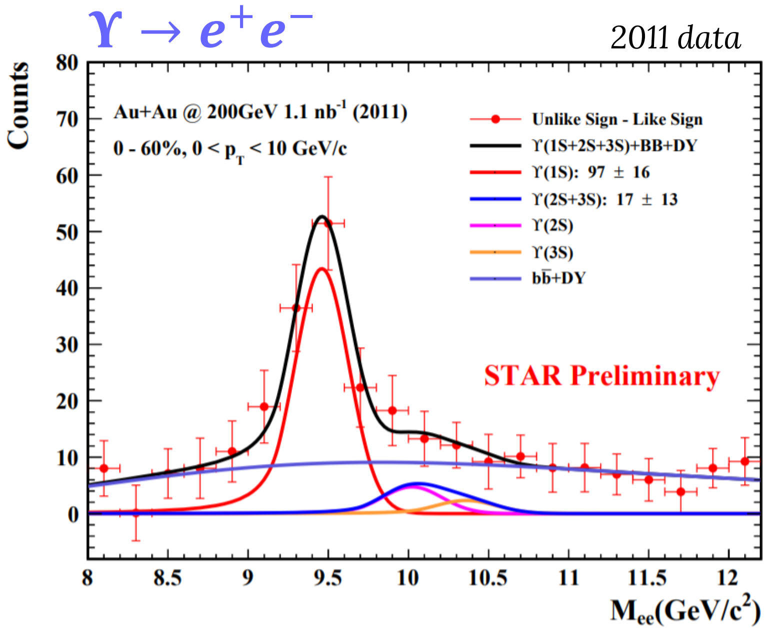
- **p+p:** precise baseline for comparison with Au+Au collisions

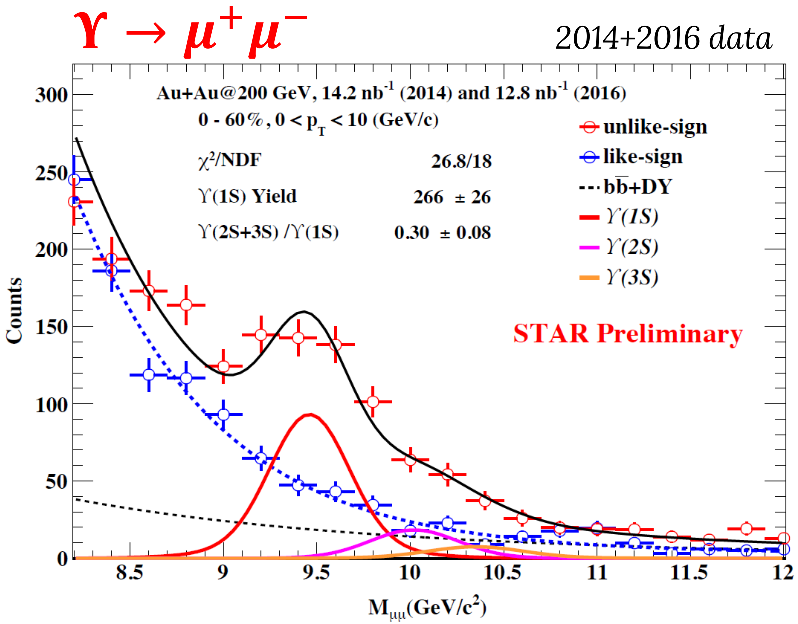
$$\sigma = 81 \pm 5\,(\text{stat.}) \pm 8\,(\text{syst.})\ \text{pb}$$

- **p+Au:** quantification of CNM effects

$$R_{\text{pAu}}(|y| < 0.5) = 0.82 \pm 0.10\,(\text{stat.})\,^{-0.07}_{+0.08}\,(\text{syst.}) \pm 0.10\,(\text{global})$$

Signal in Au+Au collisions





- Background sources:
  - → combinatorial background (estimated as $N_{l^+l^+} + N_{l^-l^-}$)
  - → Drell-Yan process, $B\bar{B}$ semi-leptonic decays

Results from Au+Au collisions

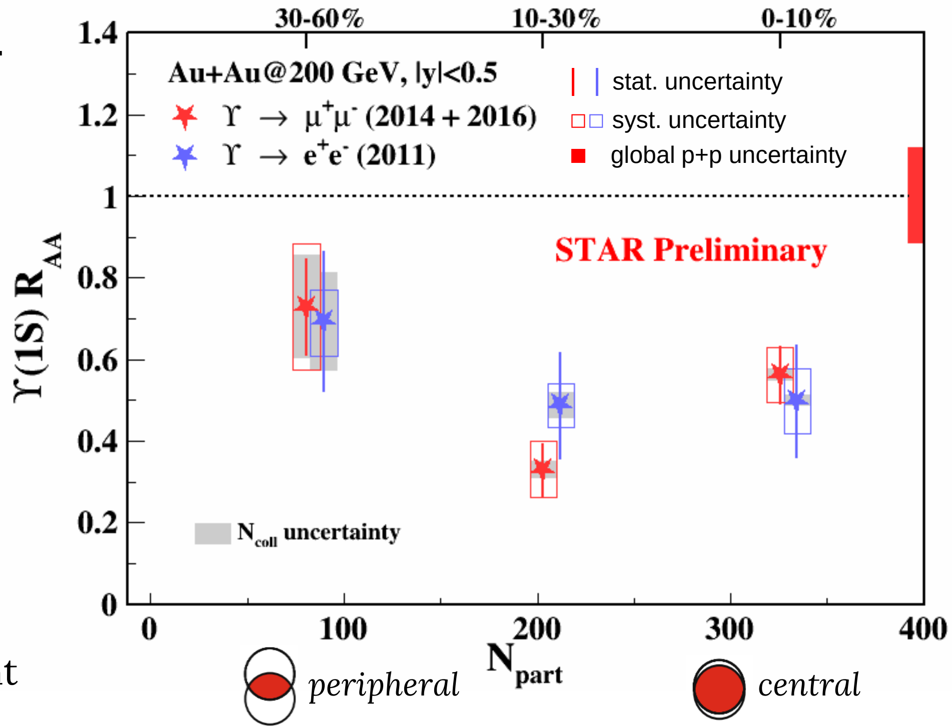
- Nuclear modification factor

  $R_{AA} = \frac{\sigma_{inel}^{pp}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T dy}{d^2 \sigma_{pp}/dp_T dy}$ as a function of mean number of participants N_{part}

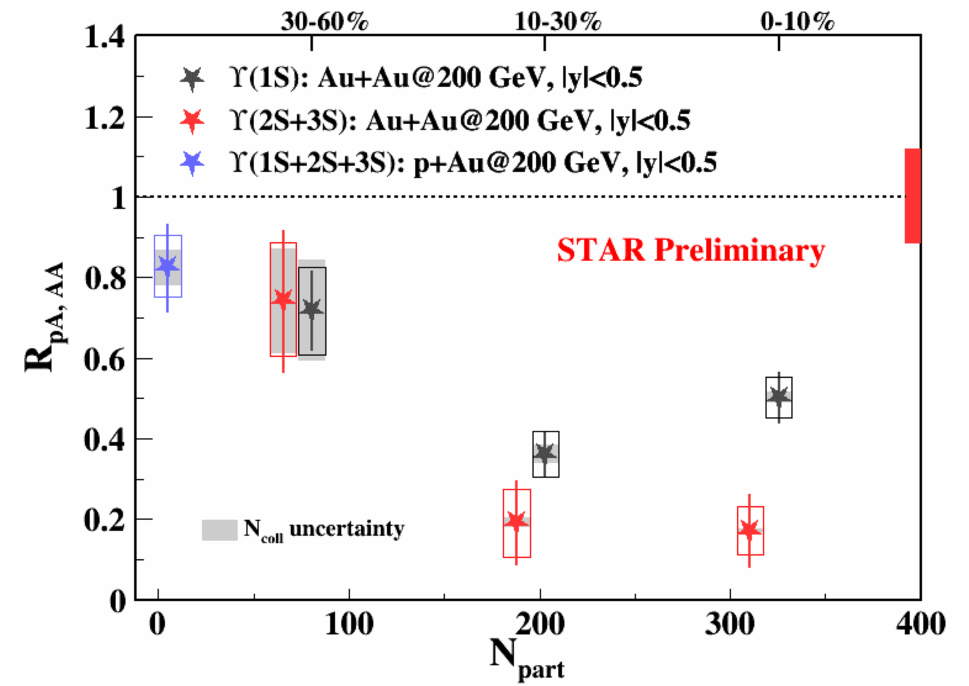
- σ_{pp} baseline taken from the Υ measurements in p+p collisions at STAR

- **Di-muon** and **di-electron** results consistent with each other within the uncertainties

  → ***results combined for increased statistical precision***



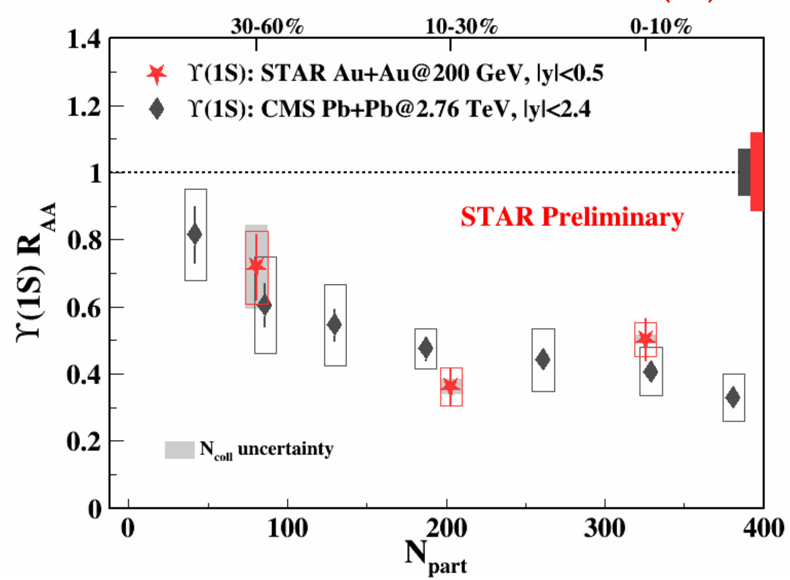
R_{AA} vs. N_{part} at RHIC

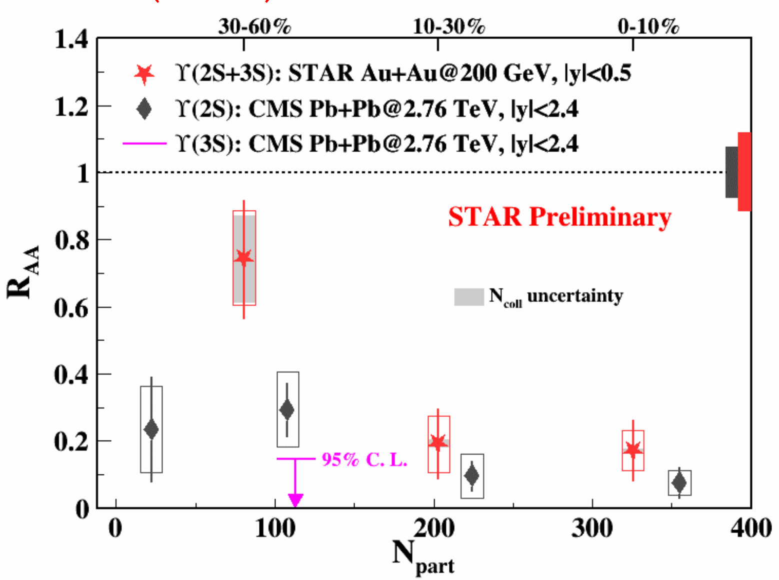


- $\Upsilon(2S{+}3S)$ ***more suppressed*** than $\Upsilon(1S)$ in central collisions

R_{AA} vs. N_{part} at RHIC + comparison with the LHC

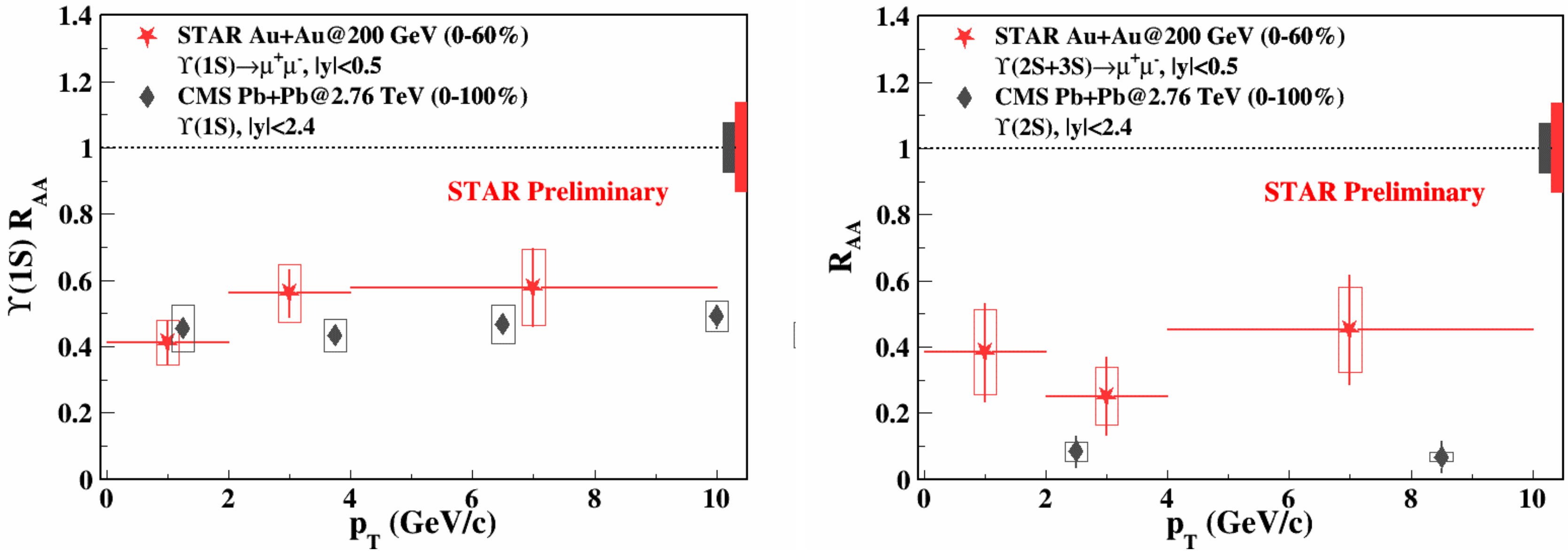
ϒ(1S) *vs.* **ϒ(2S+3S)**





- Comparison with the LHC: *CMS, PLB 770 (2017) 357*
  → comparable suppression for inclusive ϒ(1*S*)
  → hint of ***less suppression*** for ϒ(2*S*+3*S*) at RHIC than at LHC

Suppression vs. p_T



RHIC vs. LHC

CMS, PLB 770 (2017) 357

- Comparable suppression for inclusive $\Upsilon(1S)$
- Signs of ***less suppression*** at high-p_T for $\Upsilon(2S{+}3S)$ at RHIC

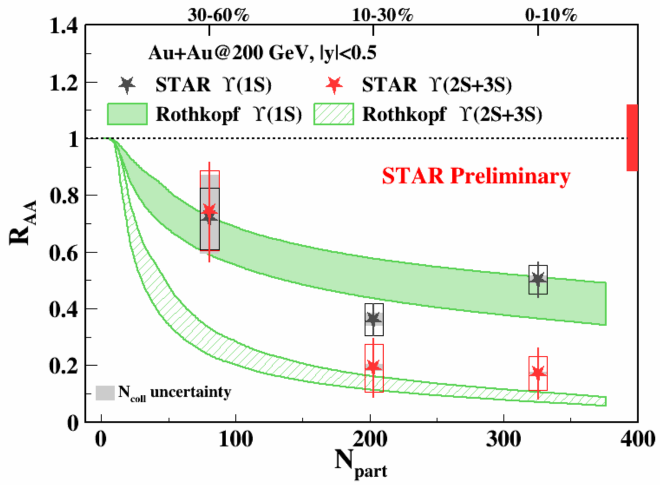
Comparison with models

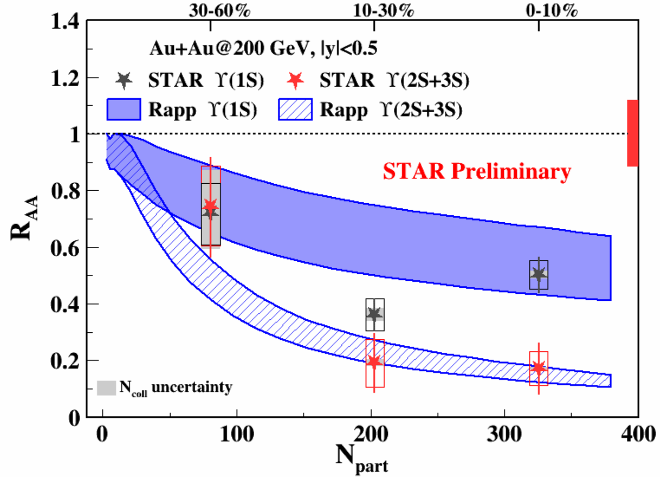
- **Krouppa, Rothkopf, Strickland:** *PRD 97 (2018) 016017*
  - No CNM effects, no regeneration
  - Uses a lattice QCD vetted complex potential embedded in a hydrodynamically evolving medium

- **Du, He, Rapp:** *PRC 96 (2017) 054901*
  - Incorporates regeneration as well as CNM effects
  - Uses in-medium binding energies predicted by thermodynamic T-matrix calculations with internal-energy potentials

→ Both models show agreement with the Υ(1S) data from STAR

→ Rothkopf model seems to underestimate the Υ(2S+3S) R_{AA} in the 30-60% centrality





Summary

- **Physics of heavy quarkonia**
  - Quarkonia can be used to constrain the QGP temperature thanks to the *colour screening effect*
  - ϒ's at RHIC are a cleaner probe than e.g. the J/ψ, due to lesser influence of CNM effects and regeneration

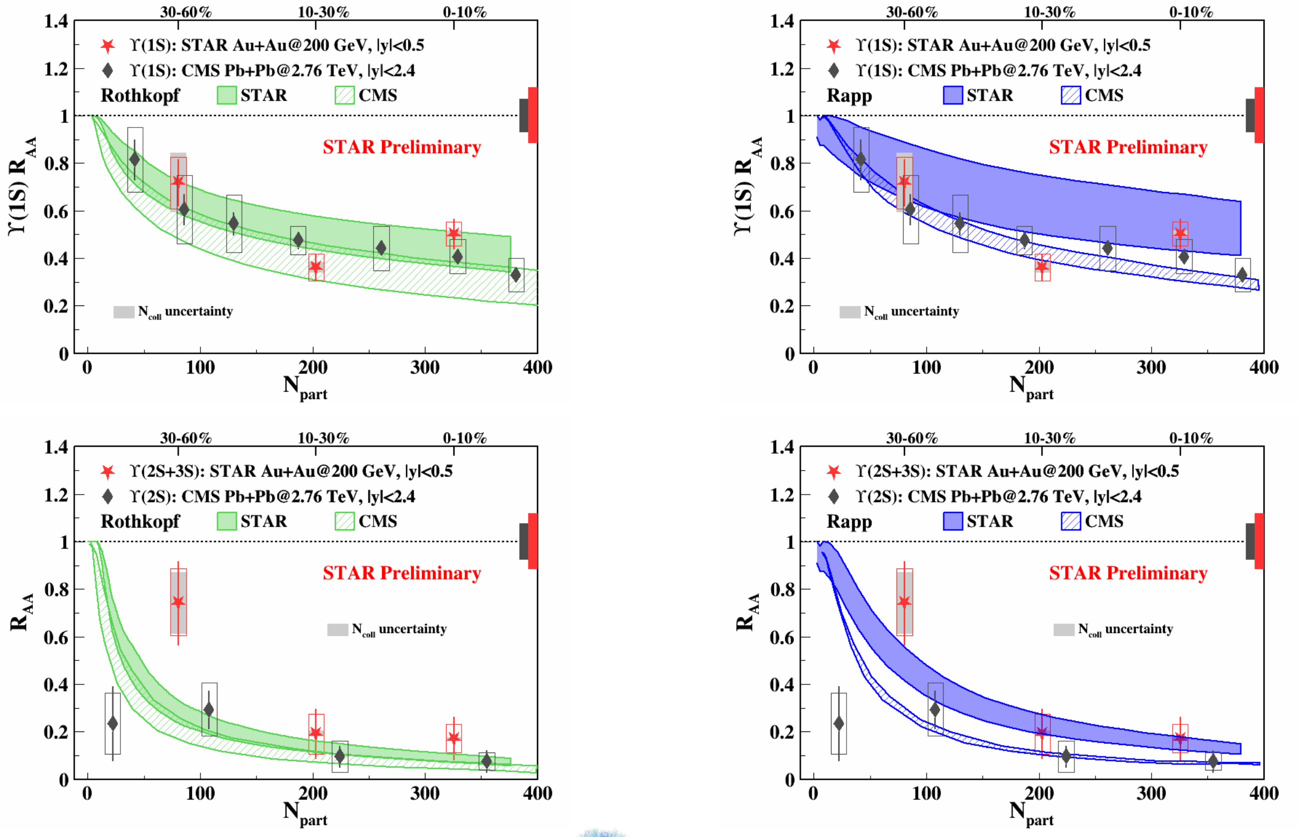
- **ϒ measurements at STAR**
  - ϒ's are reconstructed in the *di-electron channel* and *di-muon channel* in Au+Au *collisions* at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV
  - ϒ's are also measured in p+p and p+Au collisions to provide a baseline and a quantification of the CNM effects
  - Inclusive ϒ(1S) at RHIC are strongly suppressed in semi-central and central collisions
  - Excited states ϒ(2S+3S) at RHIC are more suppressed than ϒ(1S) in central collisions (*sequential melting*)
  - R_{AA} for ϒ(1S) at RHIC is similar to the LHC, but ϒ(2S+3S) seems to be less suppressed

- These results can be used to test models of different quarkonium behaviour in QGP and to help infer the medium temperature

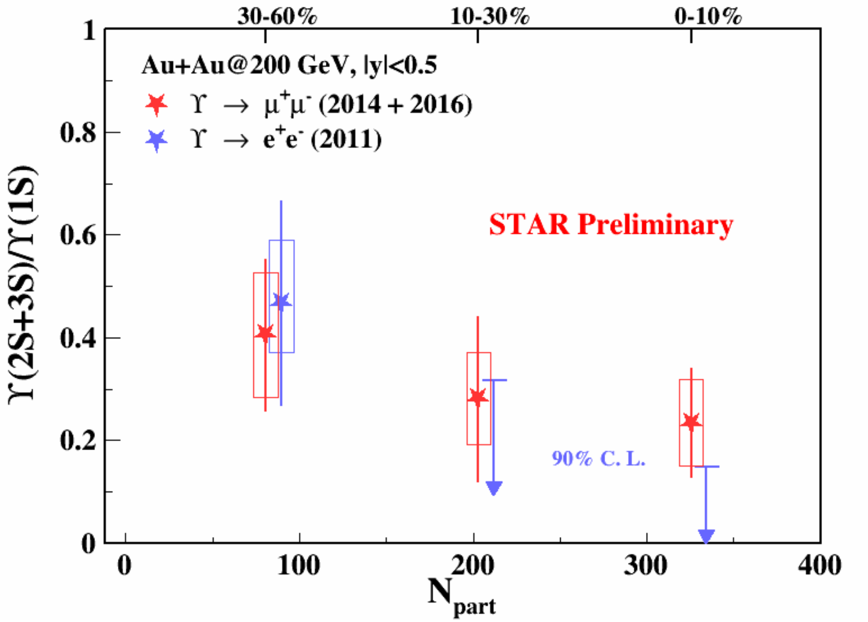
Thanks for your attention!

Back-up slides

Models at the LHC



Excited-to-ground ratio



world-wide measured ratio in p+p:

$\Upsilon(2S+3S)/\Upsilon(1S) = 0.423 \pm 0.009$ *PRC 88 (2013) 067901*