Quarkonium measurements in heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR experiment

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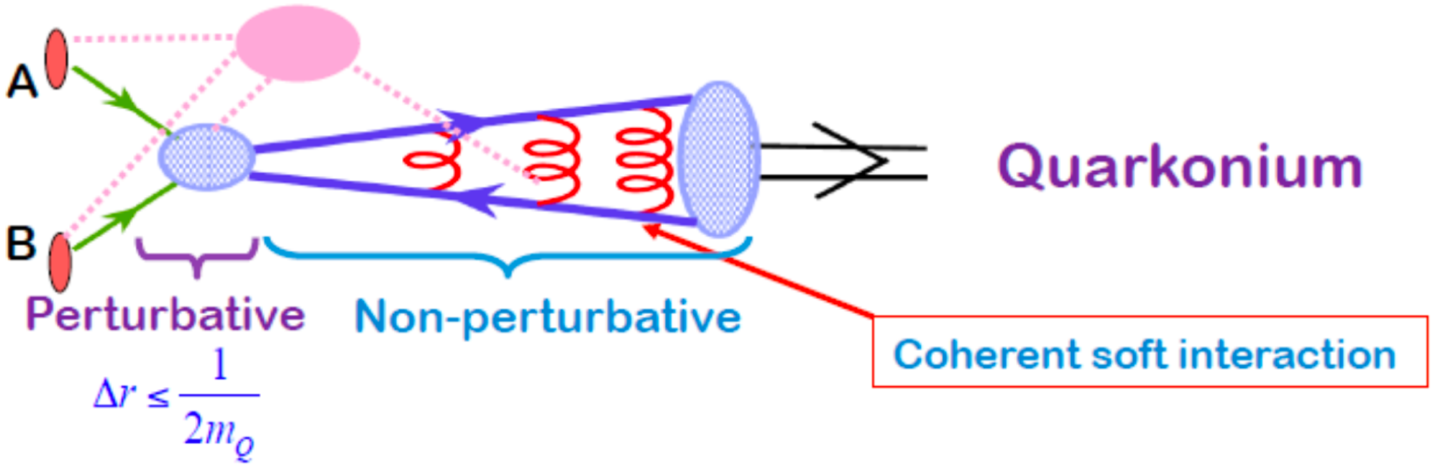
Quarkonium production mechanism

Jianwei Qiu, ECT workshop, 2016*



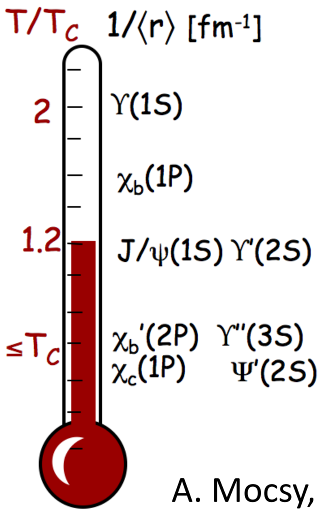
- Quarkonium production can be factorized into:
  - Perturbative: production of heavy $q\bar{q}$ pair
  - Non-perturbative: quarkonium formation; involves long distances and soft momentum scales
  - Models differ in the treatment of hadronization

Use quarkonium to probe QGP

- Heavy-quark pairs: early creation & long lived
  - Created mostly before the quark-gluon plasma (QGP) formation
  - Experience entire evolution of QGP

Illustration: A.Rothkopf

- Dissociation → evidence of deconfinement
  - Quark-antiquark potential is color-screened by surrounding partons



A. Mocsy, EPJ C61 (2009) 705

- Sequential suppression → constrain medium temperature
  - Different quarkonium states of different binding energies dissociate at different temperatures

The Complications

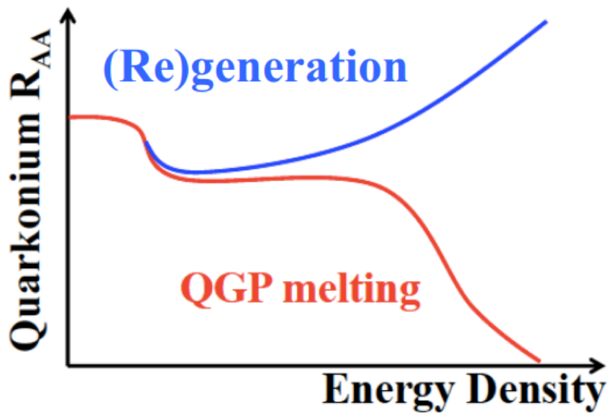
- Regeneration
  - Much smaller effect for $b\bar{b}$

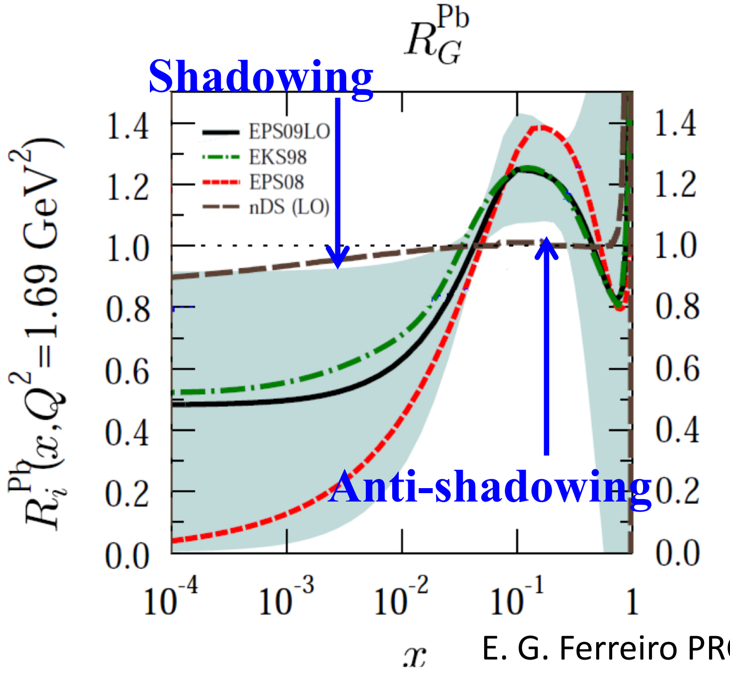
  → R_{AA} measurements

- Cold nuclear matter (CNM) effects:
  - Nuclear PDF: shadowing/anti-shadowing
  - Nuclear absorption
  - Interact with co-movers
  - ...

  → Measurements in p+A

- Feed-down

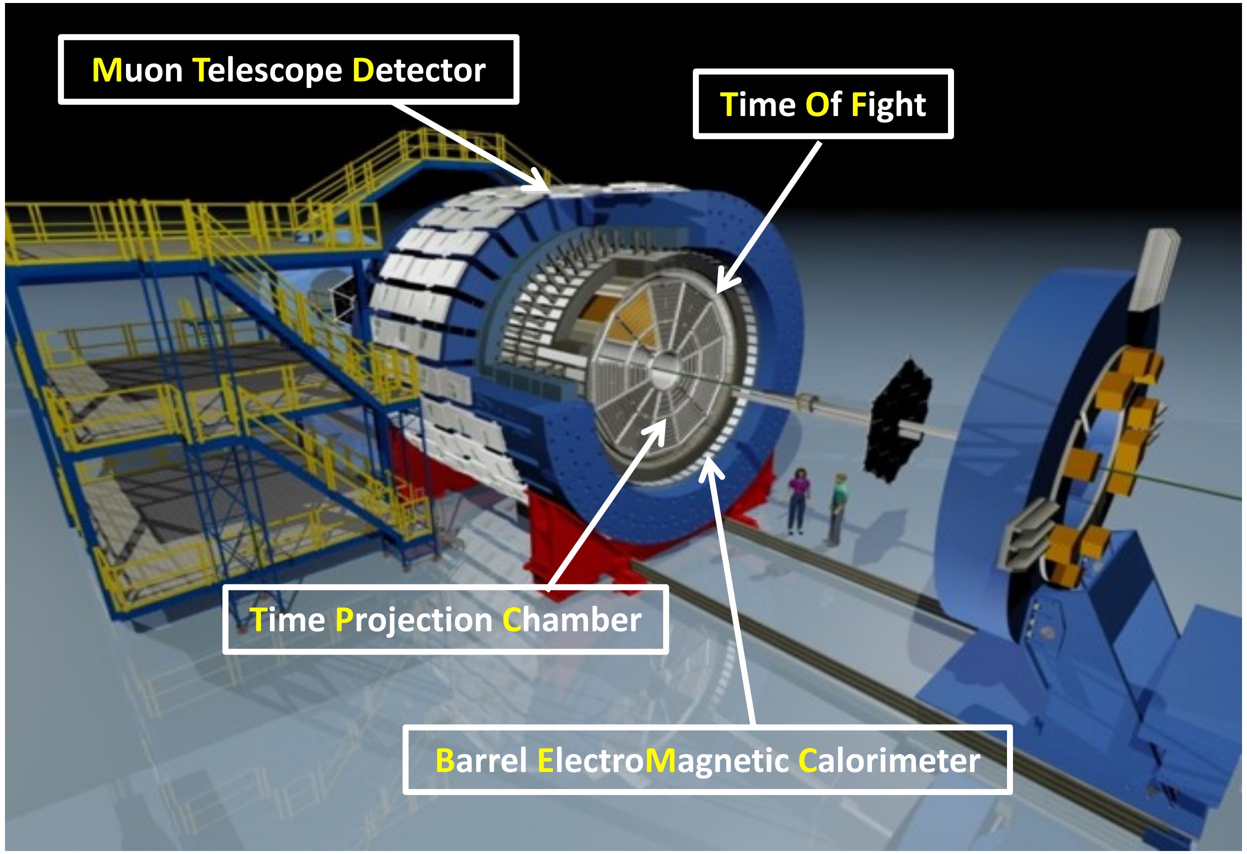




E. G. Ferreiro PRC 81 (2010) 064911

The Solenoid Tracker At RHIC (STAR)

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



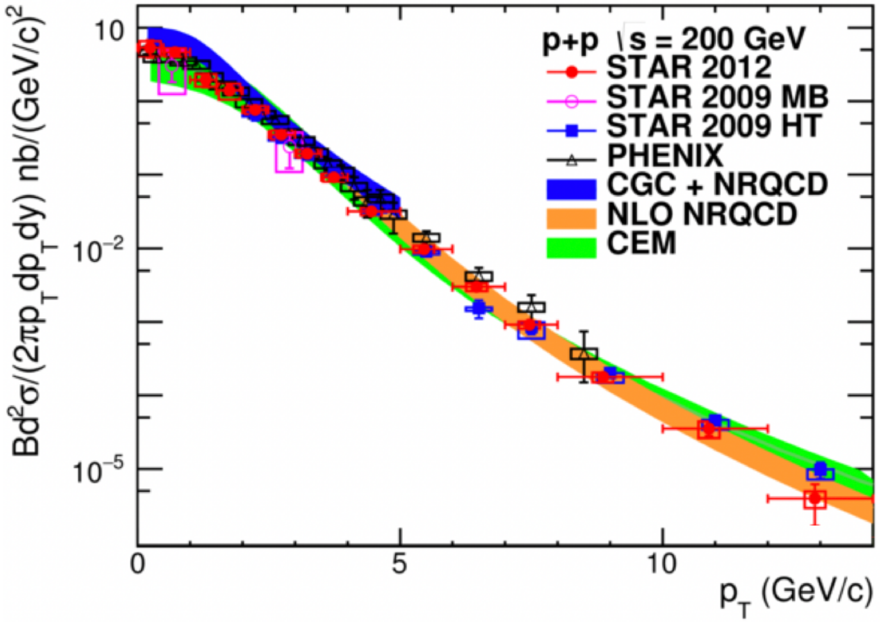
- **TPC**: measure momentum and energy loss
- **TOF**: measure time of fight
- **BEMC**: trigger on and identify electrons
- **MTD** (45% in φ, $|\eta|<0.5$) : trigger on and identify muons
  - Timing measurement (σ~100 ps) and spatial resolution (~1 cm)
  - Facilitate separation of ground and excited ϒ states

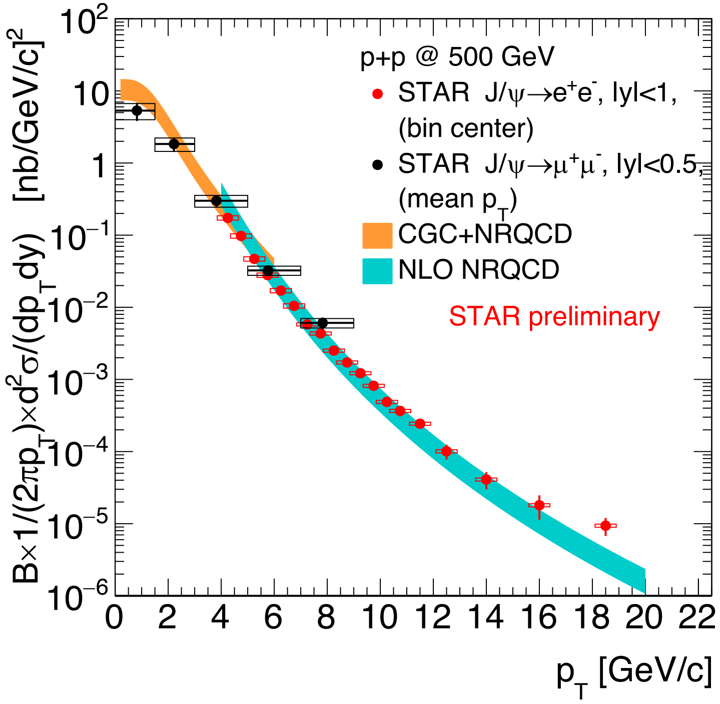
Quarkonium cross section in p+p collisions

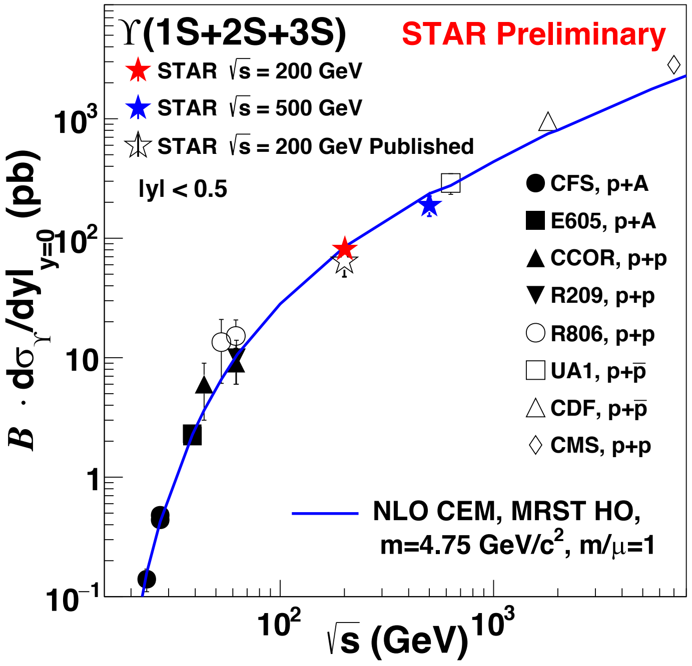
STAR 2012: arXiv:1805.03745
STAR 2009: PLB 722 (2013) 55;
PRC 93 (2016) 064904
PHENIX: PRD 82 (2010) 012001

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

CEM: R. Vogt, Phys. Rept. 462 (2008) 125
STAR 200 GeV: PRD 82 (2010) 12004

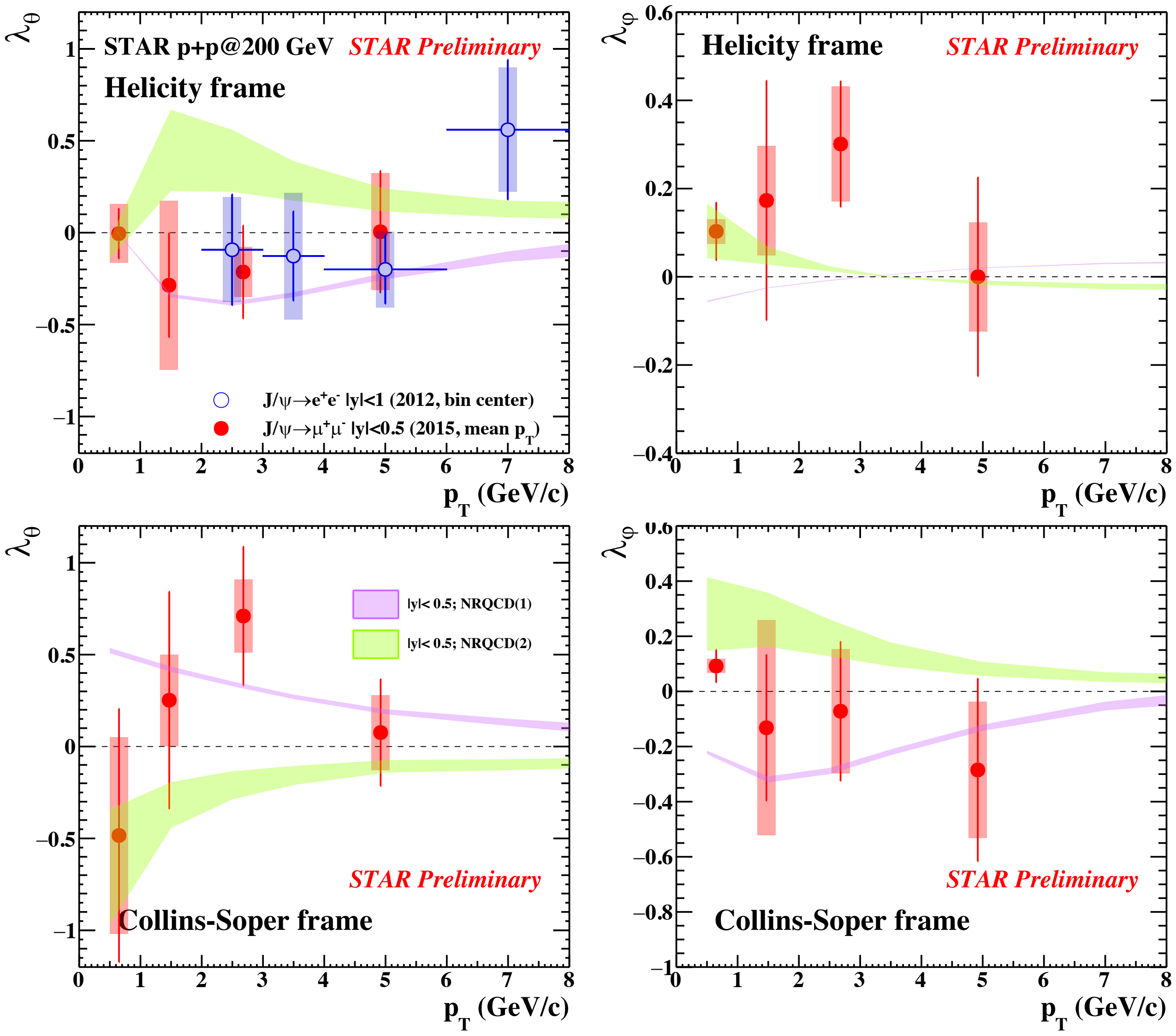






- Inclusive J/ψ and ϒ measurements at 200 and 500 GeV:
  - J/ψ: models describe the quarkonium production cross-section reasonably well
  - ϒ : follow world-wide data trend predicted by CEM

J/ψ polarization in p+p Collisions



- J/ψ polarization parameters in helicity and Collins-soper frames compared with NRQCD calculations using two sets of Long Distance Matrix Elements (LDMEs)

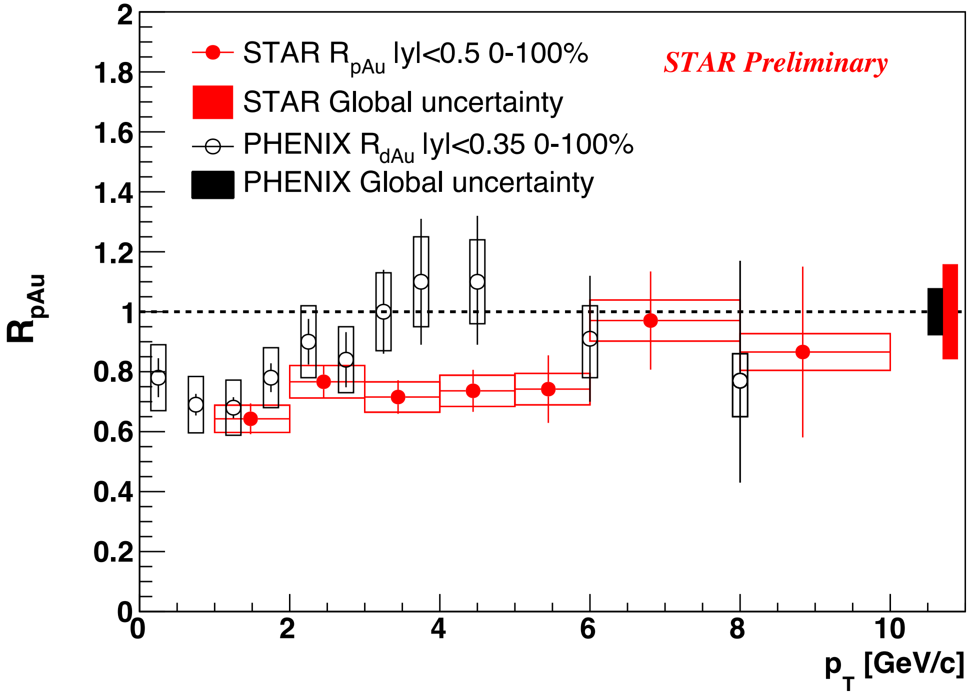
- NRQCD calculations are consistent with data within uncertainties

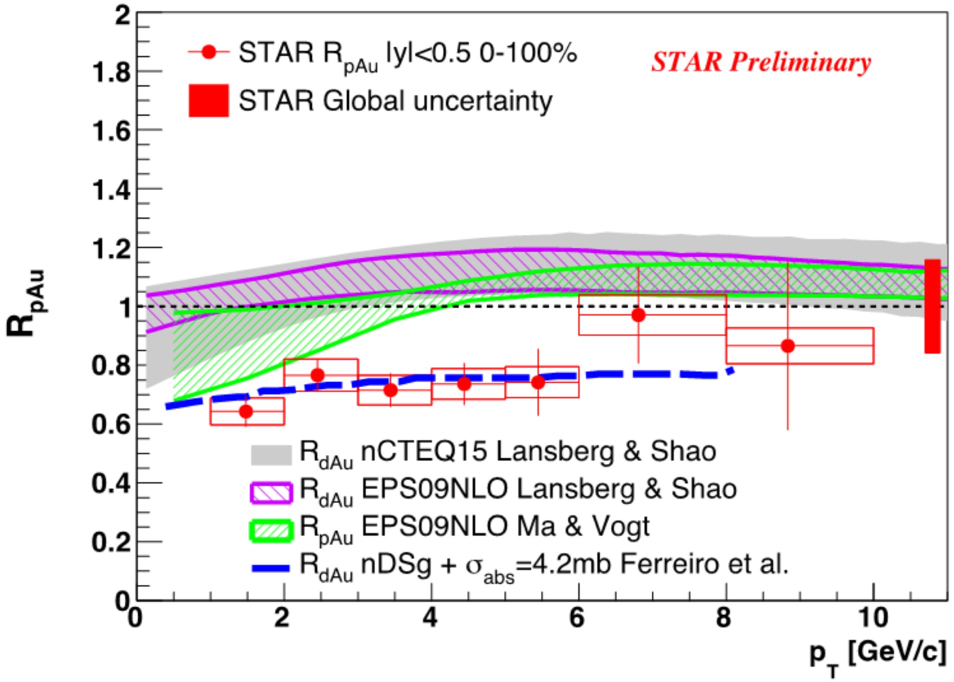
- J/ψ polarization at low p_T can be used to constrain the LDMEs

NRQCD1: Hong-Fei Zhang et al. Phys. Rev. Lett 114 (2015) 092006
NRQCD2: Bin Gong et al. Phys. Rev. Lett 110 (2013) 042002

Inclusive J/ψ R_{pAu} vs. R_{dAu} vs. model

PHENIX, PRC 87 (2012) 034903

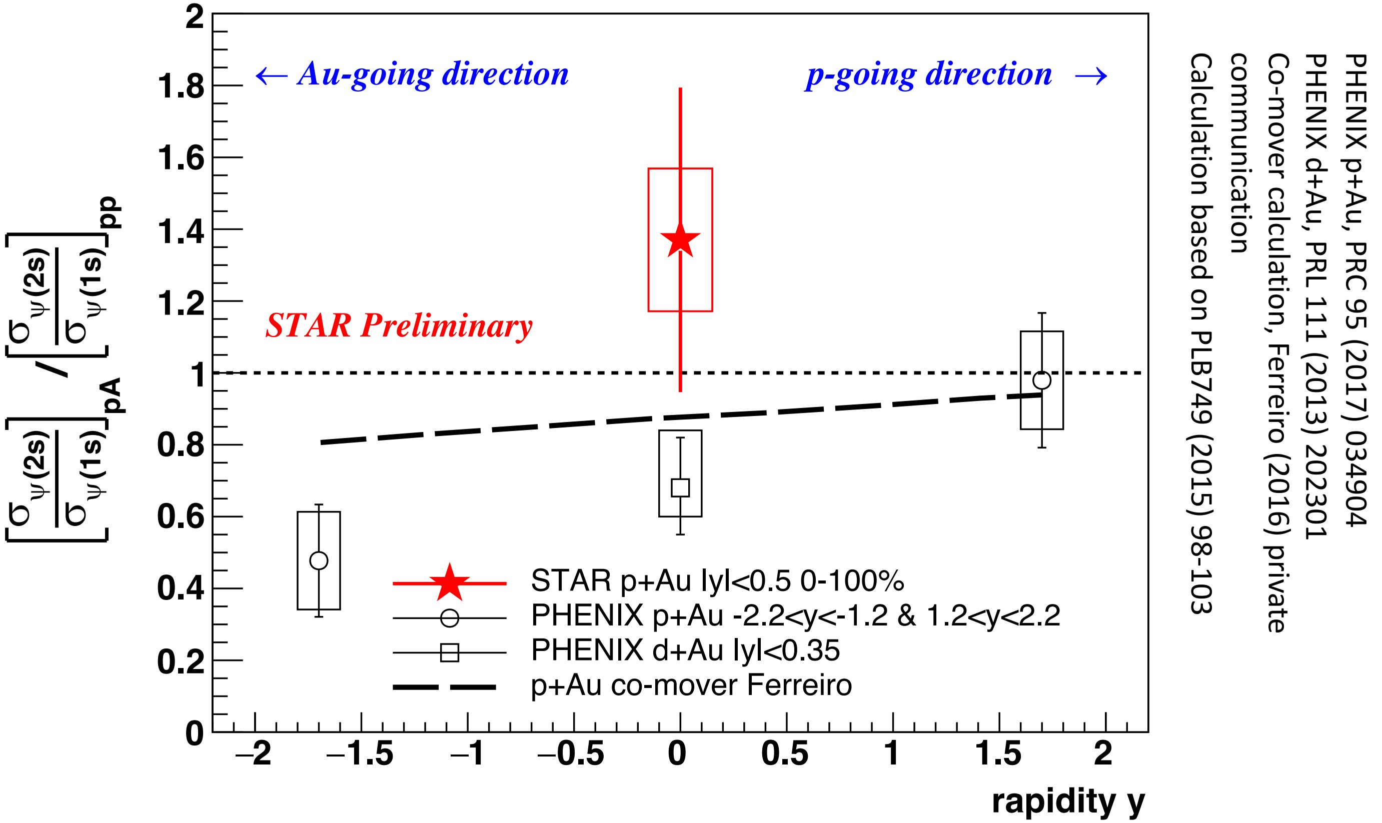




EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg Shao,
Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570
Ferreiro et al., Few Body Syst. 53 (2012) 27

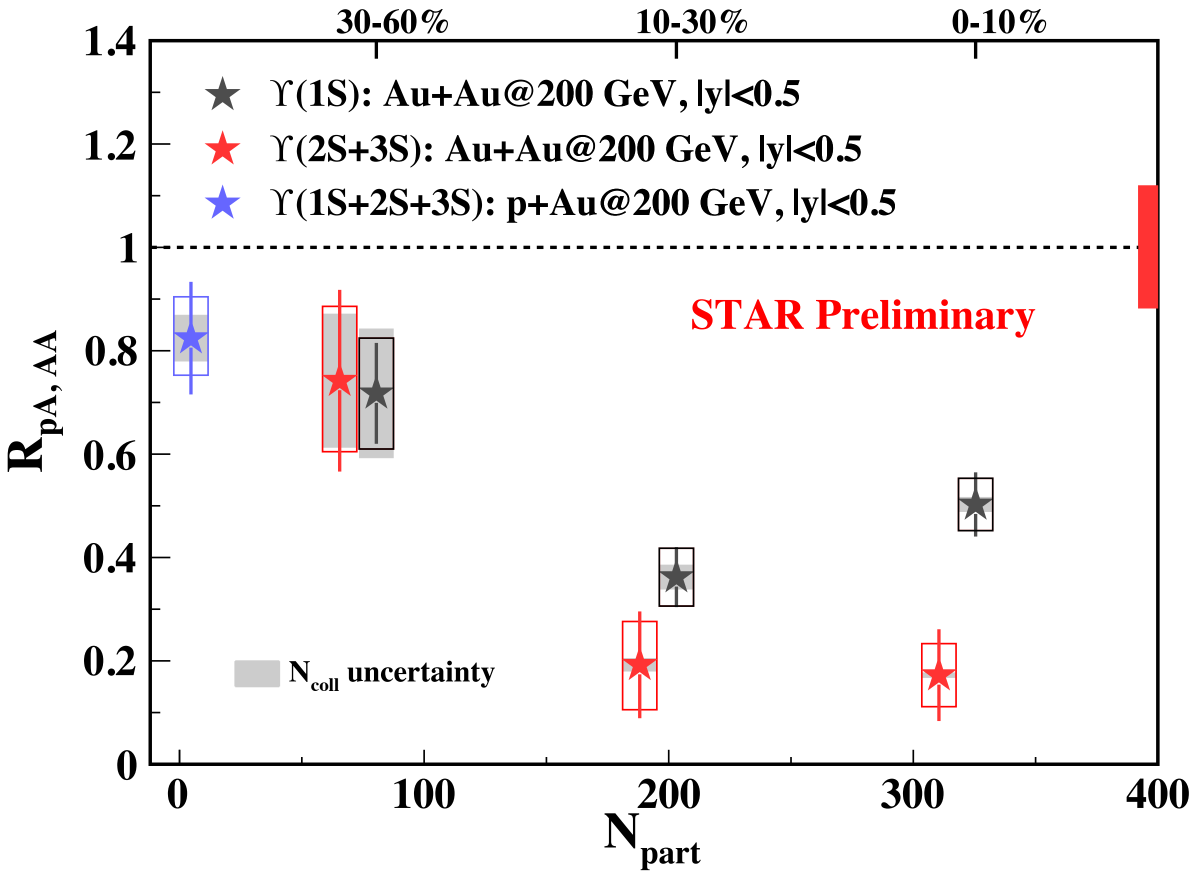
- R_{pAu} is consistent with R_{dAu} within uncertainties
  - 1.4σ difference at 3 – 6 GeV/c
- Data favor additional suppression mechanism on top of nPDF effects

ψ(2S)/ψ(1S) double ratio in pAu



- First double ratio measurement at mid-rapidity at STAR

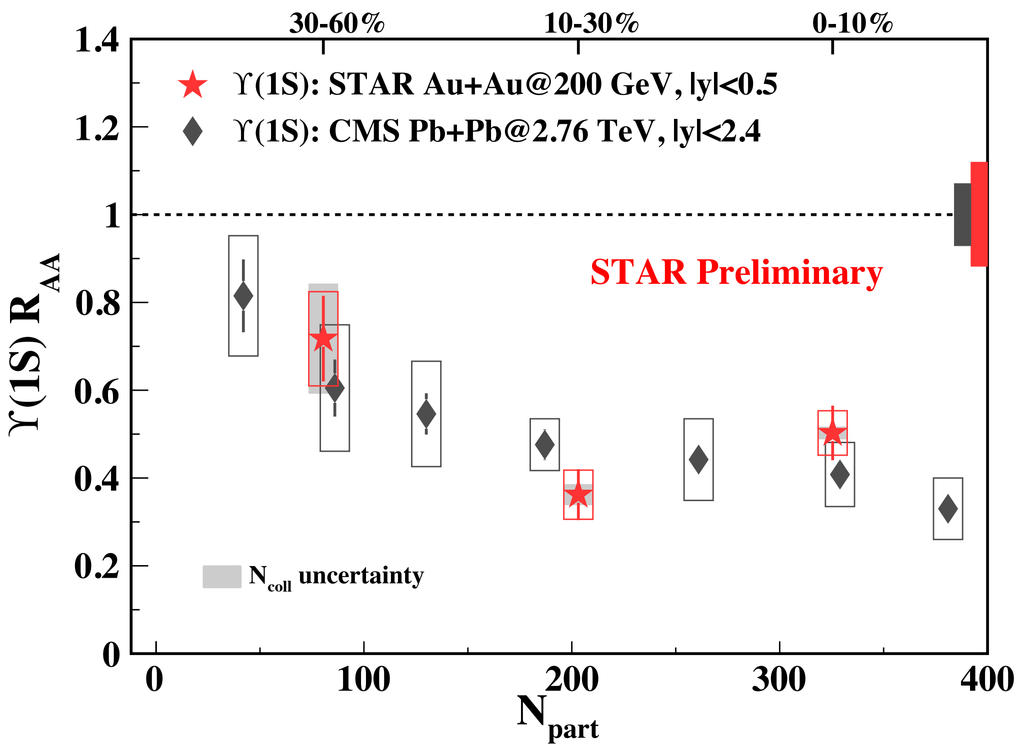
Upsilon suppression at STAR

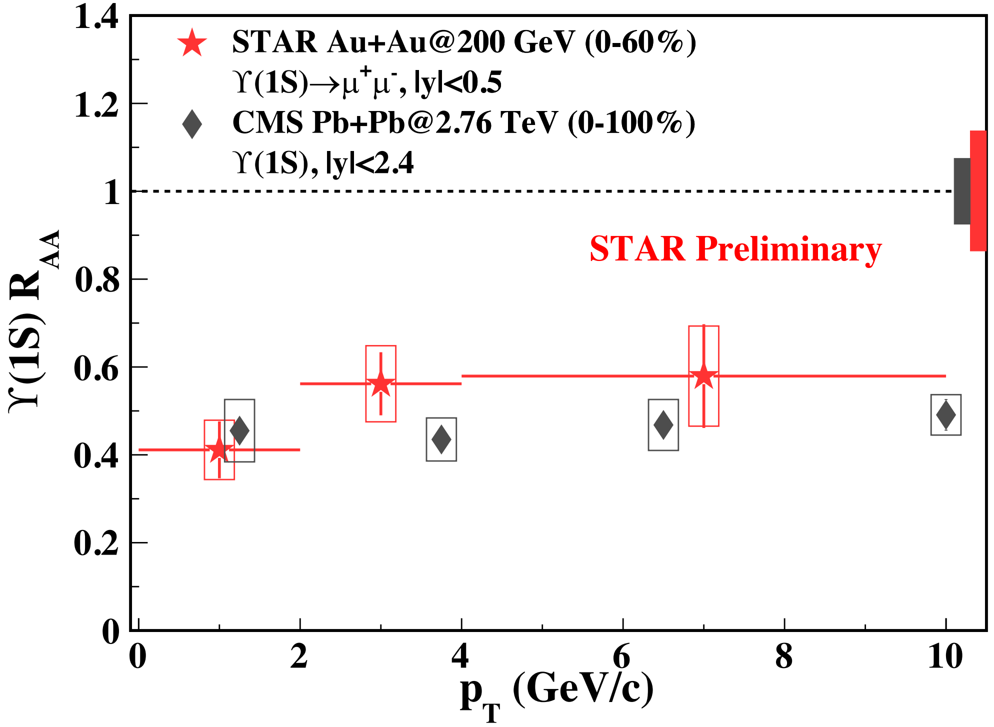


- Improved precision of ϒ measurements
  - Additional 2016 data are combined with those taken in 2014 and 2011 (di-muon and di-electron results are combined)
- ϒ(2S+3S) more suppressed than ϒ(1S) in central collisions → sequential melting
- Suppression increases from peripheral to central collisions

Υ(1S) suppression: STAR vs. CMS

CMS: PLB 770 (2017) 357

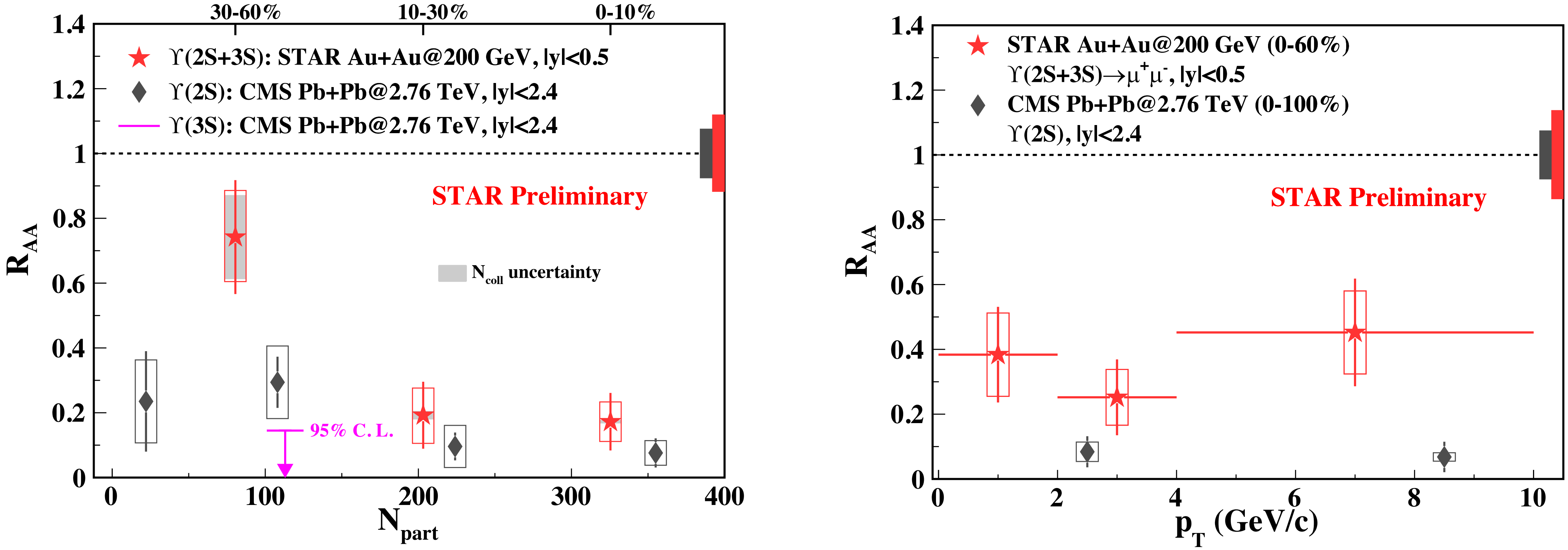




- Υ(1S): compatible with CMS result

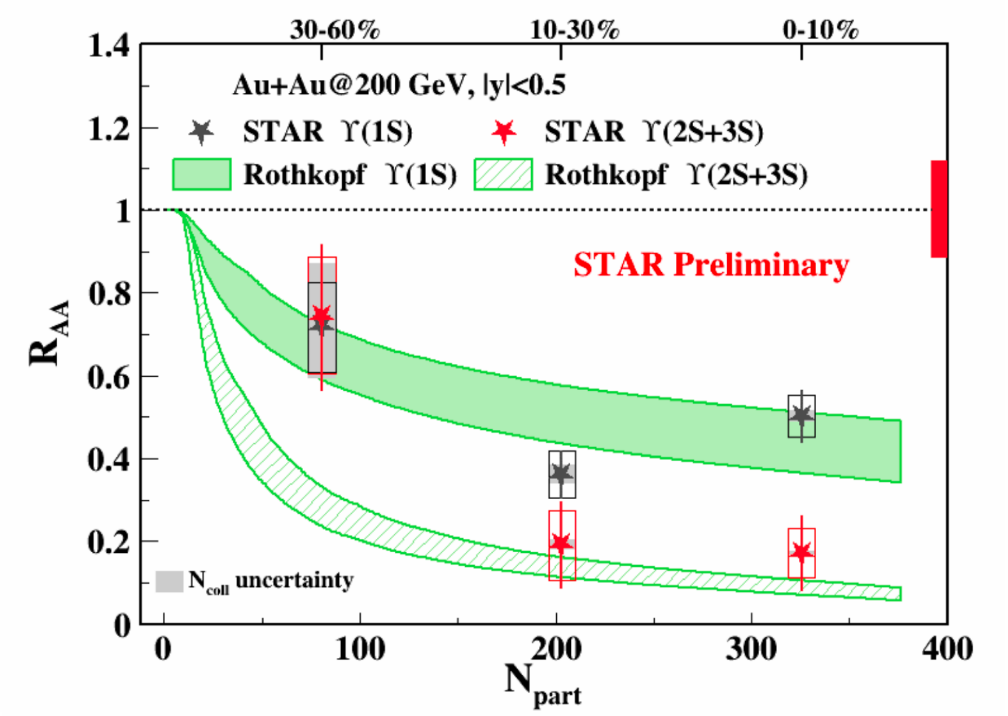
ϒ(2S+3S) suppression: STAR vs. CMS

CMS: PLB 770 (2017) 357

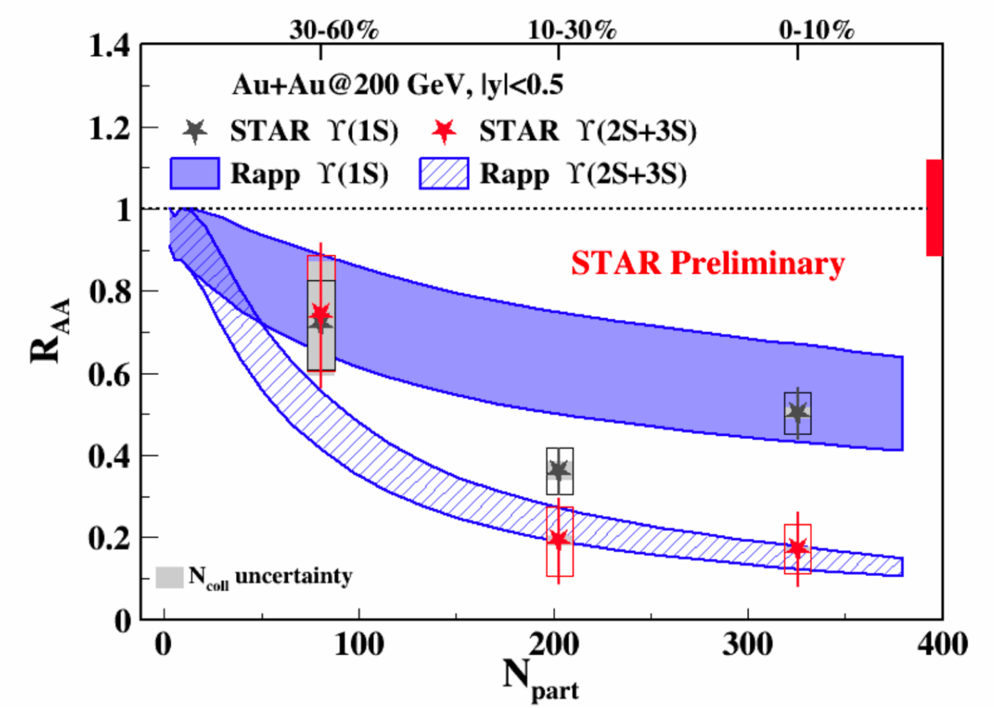


- ϒ(2S+3S): indication of less suppression at RHIC than at LHC in peripheral collisions

Υ suppression: data vs. models



- Rothkopf: PRD 97 (2018) 016017
  - Lattice-vetted heavy-quark potential embedded in a hydrodynamically evolving medium
  - No CNM or regeneration effect



- Rapp: PRC 96 (2017) 054901
  - T-dependent binding energy; Kinetic rate equation
  - Includes CNM and regeneration effects

- 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

- p+p
  - Models describe the quarkonium production cross-section reasonably well
  - J/ψ polarization at low p_T can be used to constrain the LDMEs
- p+Au
  - J/ψ R_{pAu} measurement: additional suppression mechanisms seem to be favored by data, but nPDF effects only cannot be fully ruled out yet
- A+A

  ϒ(1S):
    - Indication of stronger suppression towards central collisions
    - Similar suppression as that at the LHC
    - Consistent with model predictions

  ϒ(2S+3S):
    - More suppressed than ϒ(1S) in 0-10% central collisions → sequential melting
    - Indication of less suppression at RHIC than at the LHC in peripheral collisions

Thank you!