Quarkonium measurements with the STAR experiment

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on behalf of the STAR Collaboration

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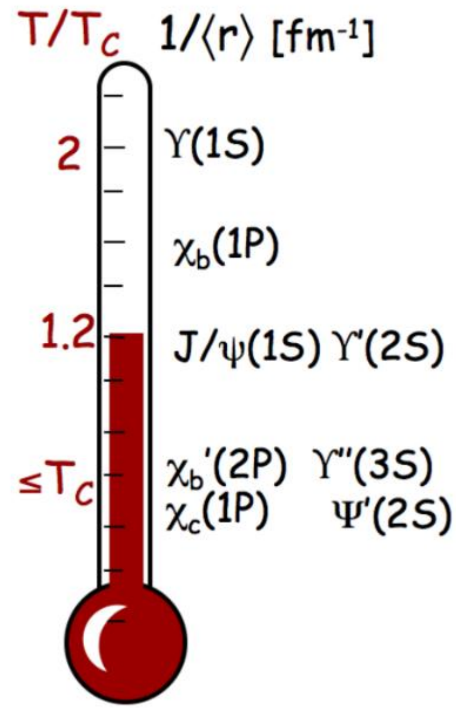
Heavy quarkonia in QGP

- Dissociation: quarkonia dissociate in QGP due to color-screening
  → Proposed as a direct proof of QGP formation
  T. Matsui and H. Satz, PLB 178 (1986) 416

- Sequential melting: different quarkonia dissociate at different temperatures
  → QGP thermometer

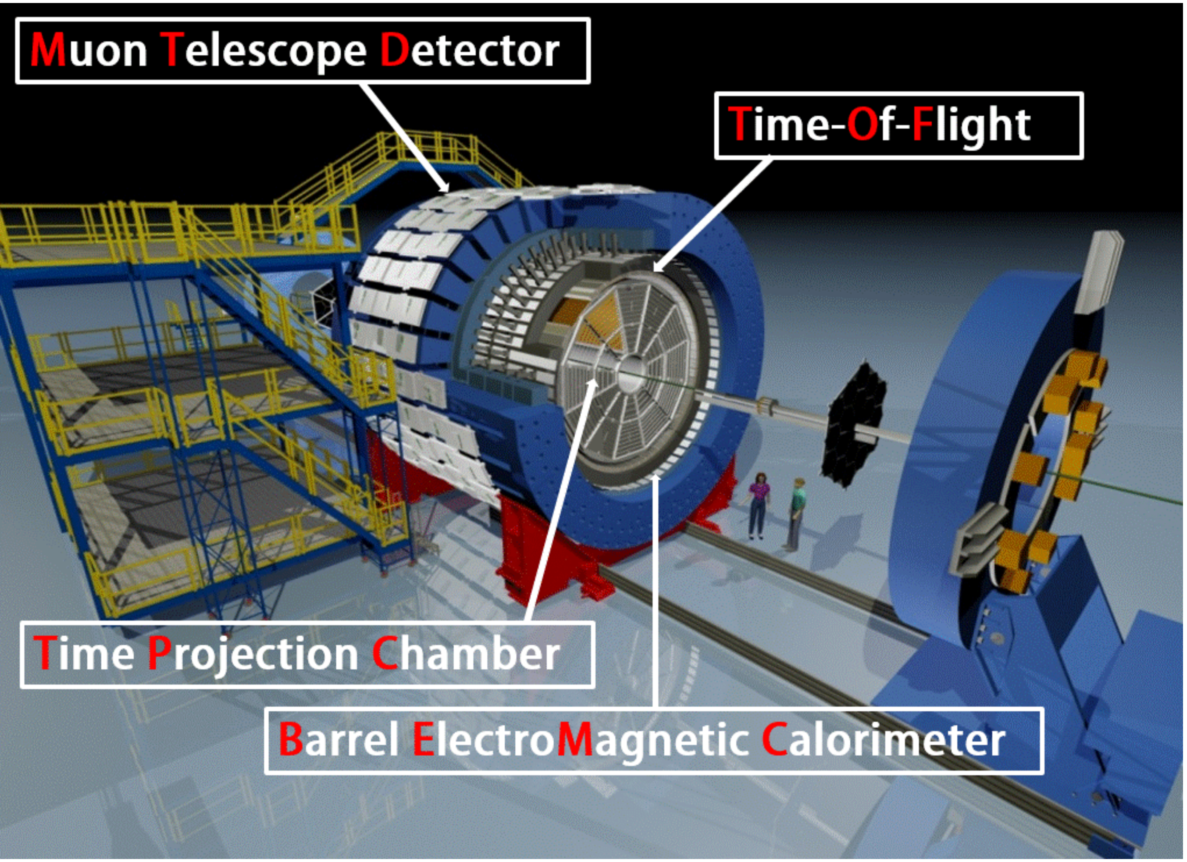
- Other effects add additional complications
  - Cold nuclear matter (CNM) effects
  → Measurements in p+A
  - Regeneration → Elliptic flow (v_2) measurements
  - Co-mover absorption
  → Υ is a cleaner probe
  - Feed down



A. Mocsy, EPJ C61 (2009) 705

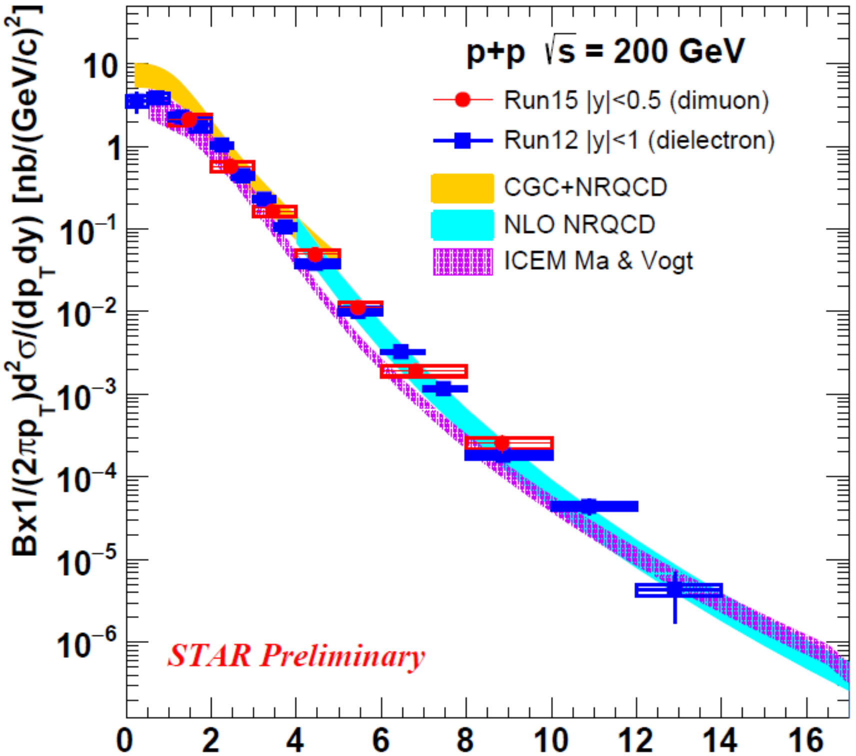
The Solenoid Tracker At RHIC

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

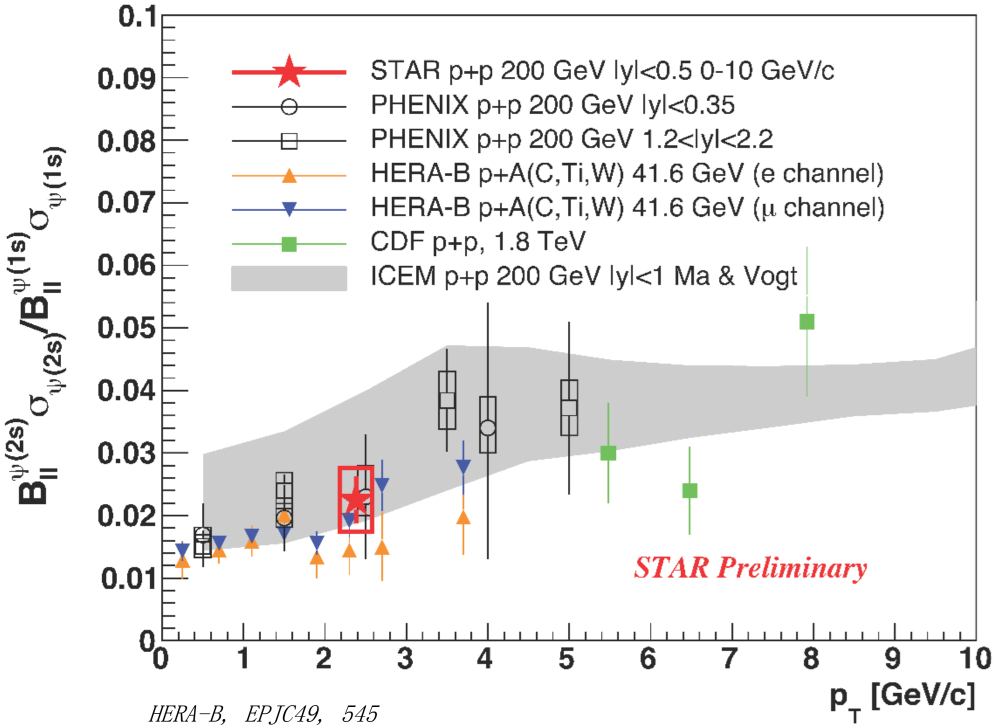


- TPC: Measure momentum and energy loss
- TOF: Measure time-of-flight
- BEMC: Trigger on and identify high p_T electrons
- MTD: Identify and trigger on muons
  - $|\eta| < 0.5$, $\phi \sim 45\%$
  - Less bremsstrahlung compared to electrons

p+p: inclusive J/ψ and $\psi(2S)/J/\psi$ ratio



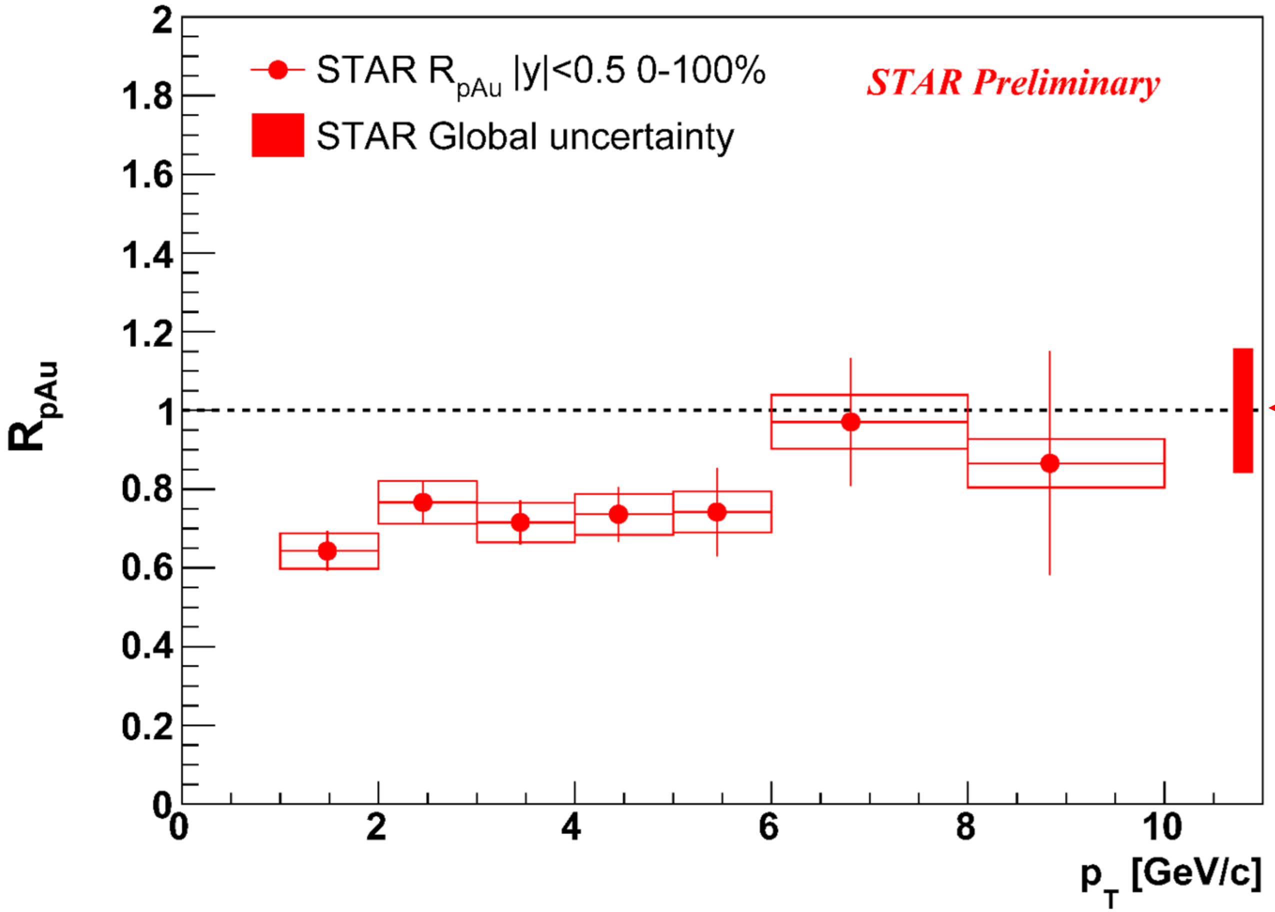
CGC+NRQCD: Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD: Shao et al., JHEP 05 (2015) 103
ICEM: Ma & Vogt, PRD 94 (2016) 114029



HERA-B, EPJC49, 545
PHENIX mid y, PRD85 (2012) 092004
PHENIX forward y, PRC(2017) 034904
CDF, 1.8TeV, PRL79 (1997) 572
ICEM, Ma & Vogt, PRD 94 (2016) 114029

- Inclusive J/ψ cross-section measured in $0 < p_T < 14$ GeV/c
  - CGC+NRQCD and NLO NRQCD (prompt) agree with data
  - Improved CEM model (direct) is below data in $3.5 < p_T < 12$ GeV/c
- Measured ψ(2S)/J/ψ ratio in p+p 200 GeV is consistent with world-wide data

Inclusive J/ψ R_{pAu}



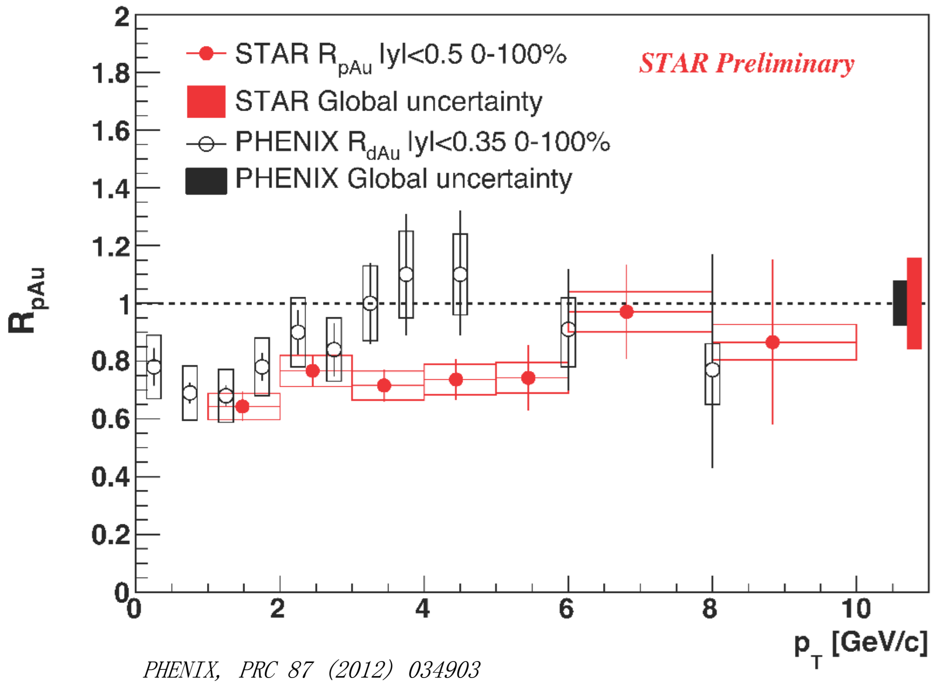
$$R_{pAu} = \frac{\sigma_{pp}^{inel}\ d^2N_{pAu}/dydp_T}{\langle N_{coll}\rangle\ d^2\sigma_{pp}/dydp_T}$$

Global Uncertainty

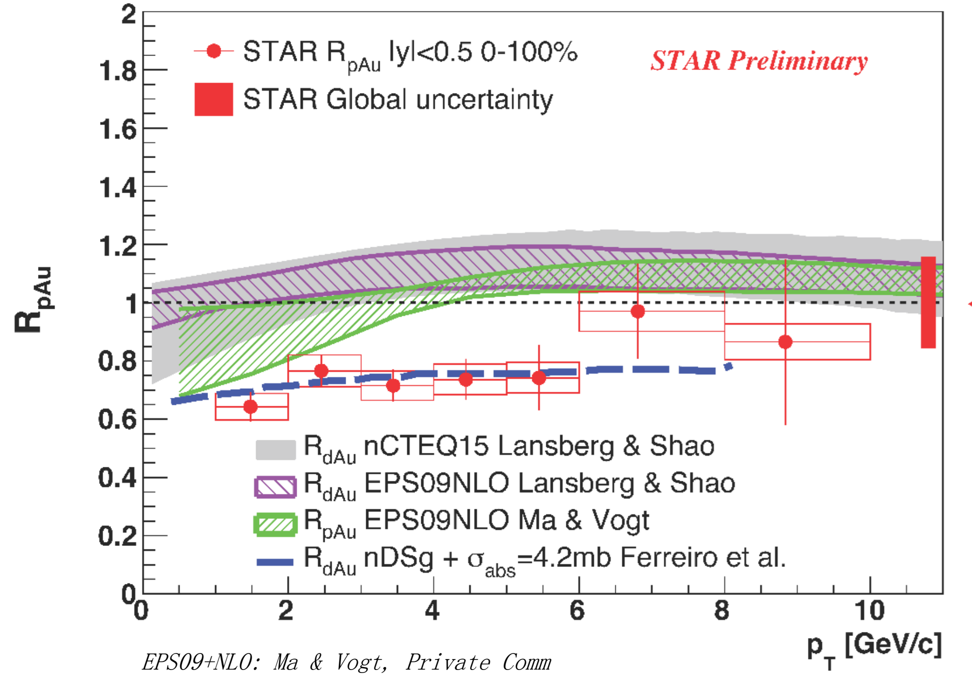
- p+p Luminosity
- N_{coll}
- Trigger efficiency
- Tracking efficiency

- First J/ψ R_{pAu} measurement at RHIC
- R_{pAu} is less than unity at low p_T, and consistent with unity within uncertainties at high p_T

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



PHENIX, PRC 87 (2012) 034903

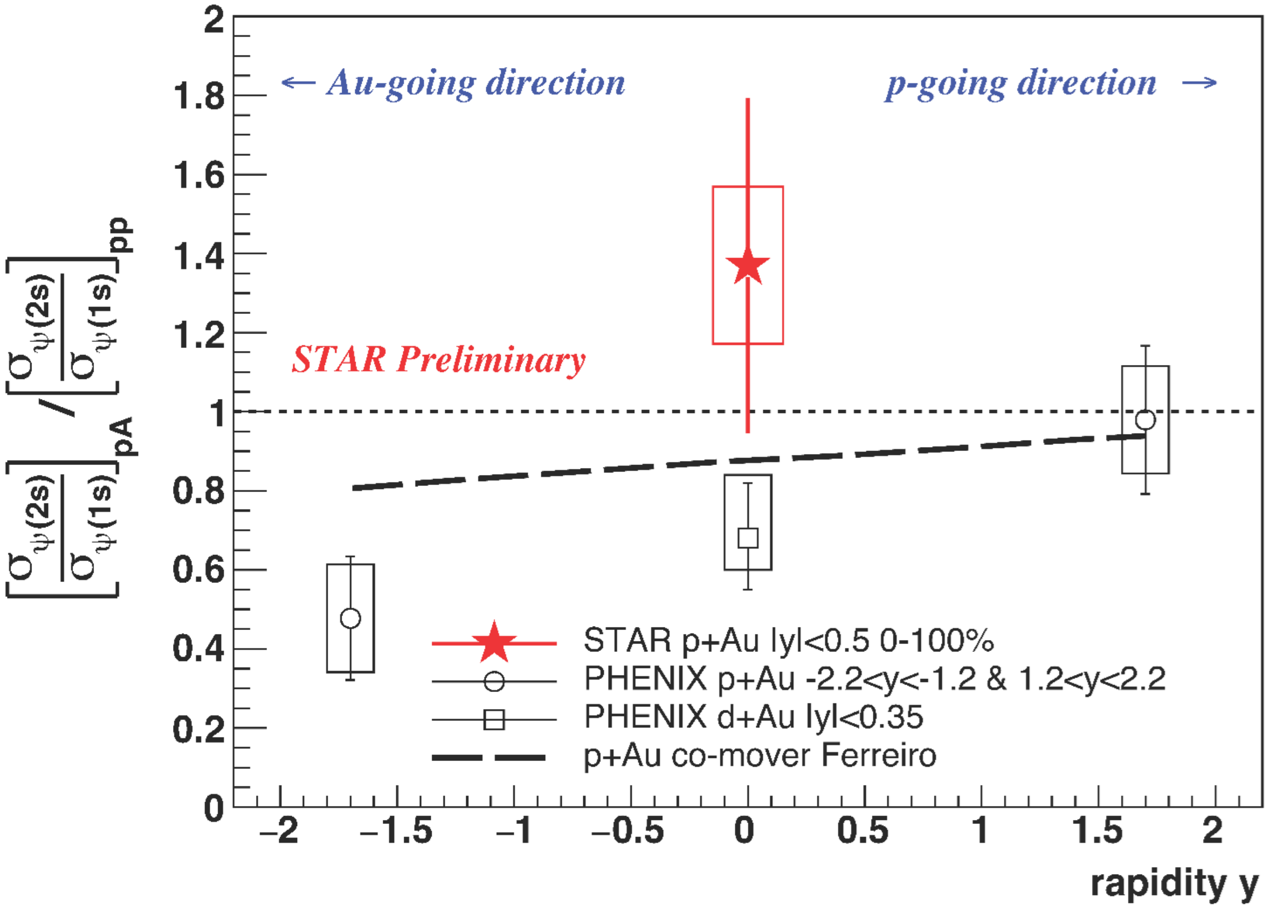


EPS09+NLO: Ma & Vogt, Private Comm
nCTEQ, EPS09+NLO: Lansberg Shao,
Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570
Ferreiro et al., Few Body Syst. 53 (2012) 27

- R_{pAu} vs. R_{dAu}: Consistent within uncertainties, but there seems to be a tension at $3.5 < p_T < 5$ GeV/c (1.4σ)
- Data vs. model: Data favor the model calculation with additional nuclear absorption effect on top of the nuclear PDF effect

$\psi(2S)/J/\psi$ double ratio

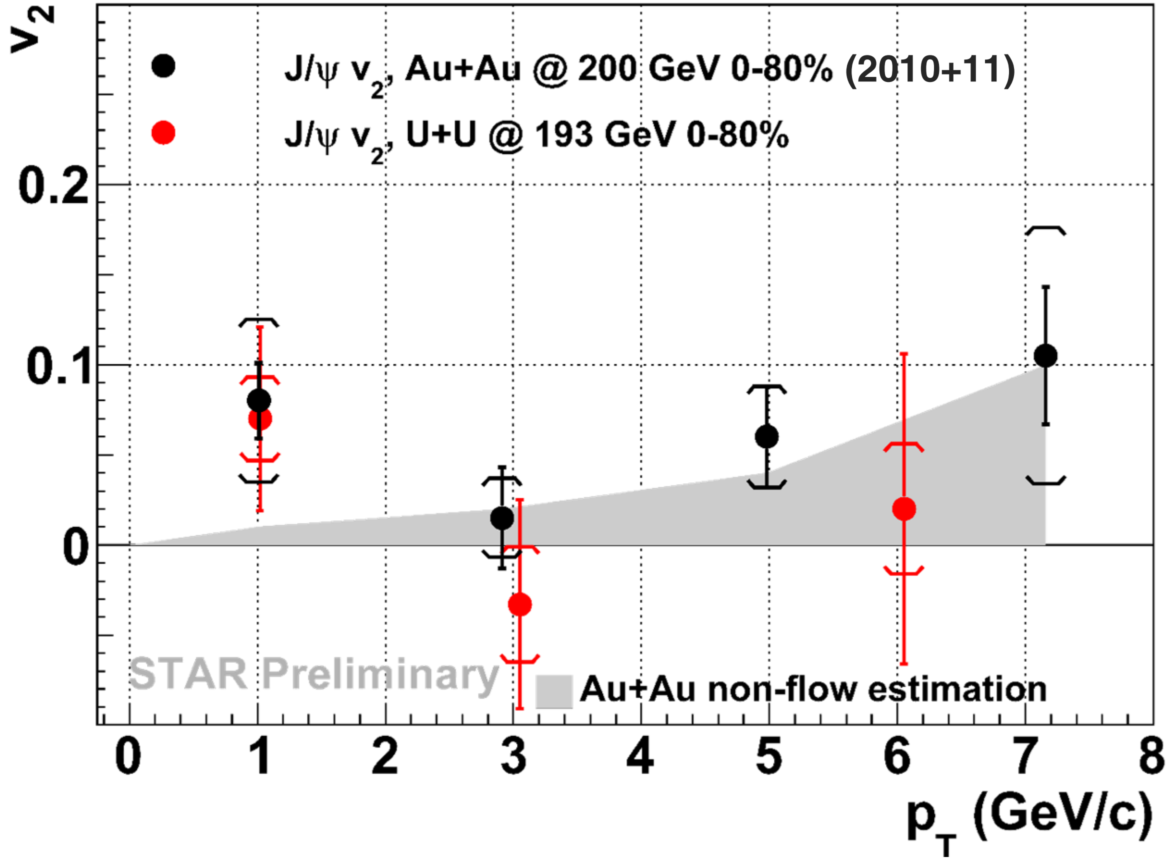
PHENIX p+Au, PRC(2017) 034904
PHENIX d+Au, PRL111 (2013) 202301
Co-mover calculation, Ferreiro, private comm.



- First mid-rapidity $\psi(2S)$ to J/ψ double ratio measurement in p+Au to p+p collisions at RHIC, $[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pAu}/\ [\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pp}$ =

$$1.37 \pm 0.42(\text{stat.}) \pm 0.19(\text{syst.})$$

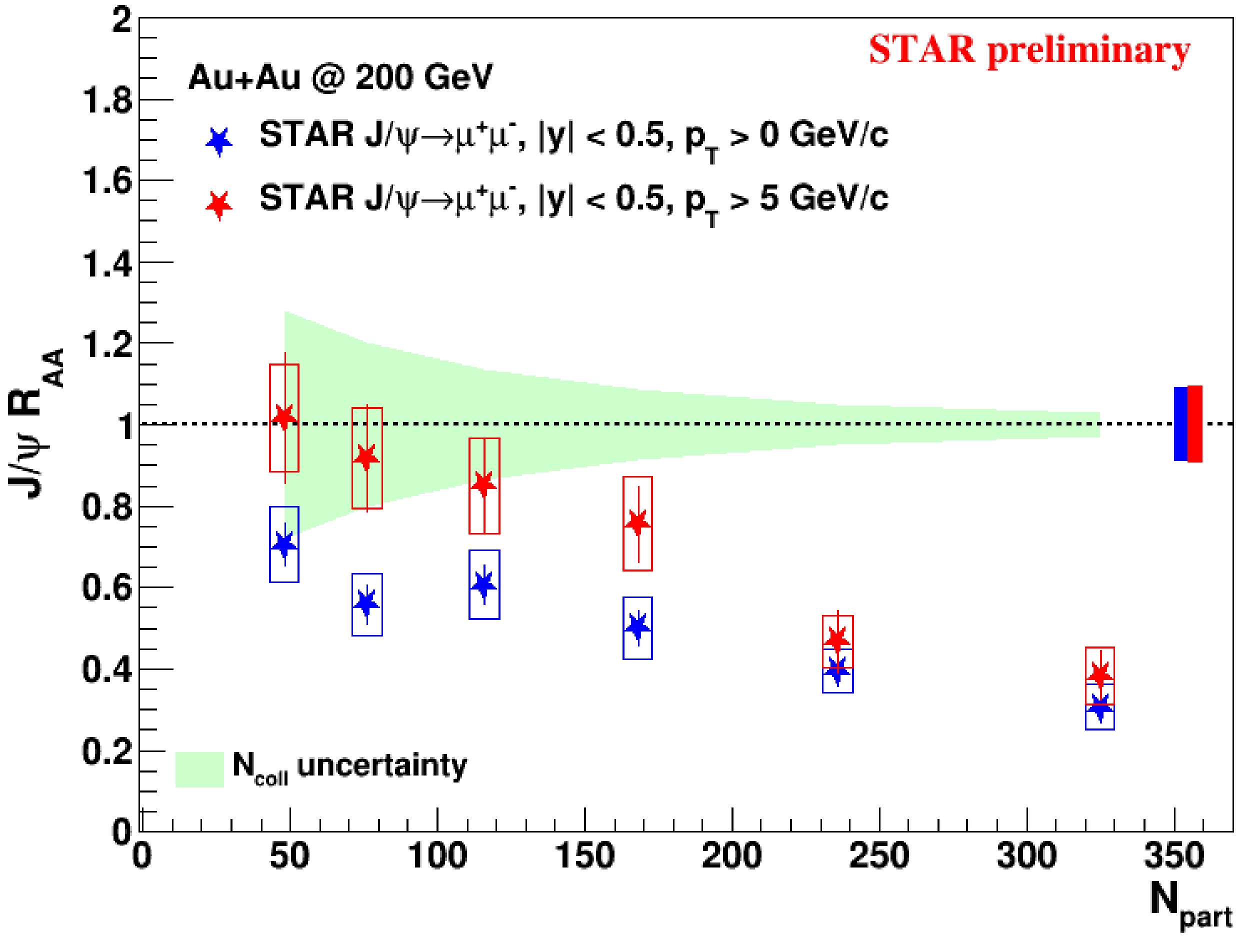
J/ψ v_2 results at STAR



STAR Au+Au 2010
PRL 111 (2013), 052301

- First measurement of J/ψ v_2 in U+U collisions at $\sqrt{s_{\mathrm{NN}}}$ = 193 GeV
  - U+U result is consistent with Au+Au result within uncertainties
- J/ψ v_2 is consistent with zero within uncertainties above 2 GeV/c
  -> Disfavor the scenario that the regeneration is the dominant contribution in this kinematic range

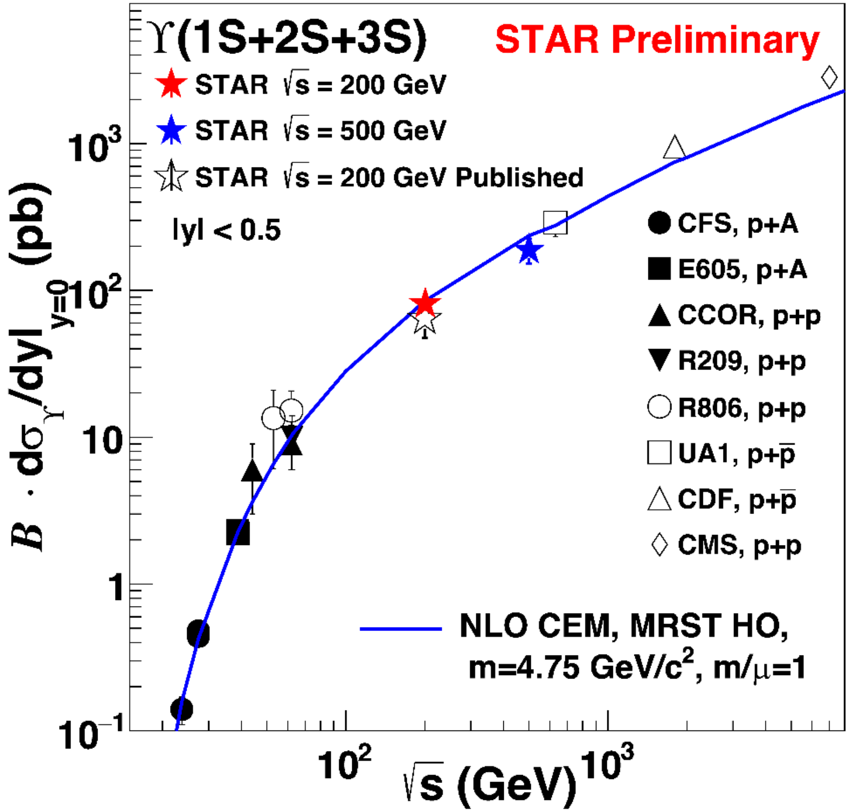
J/ψ suppression: R_{AA} vs. centrality

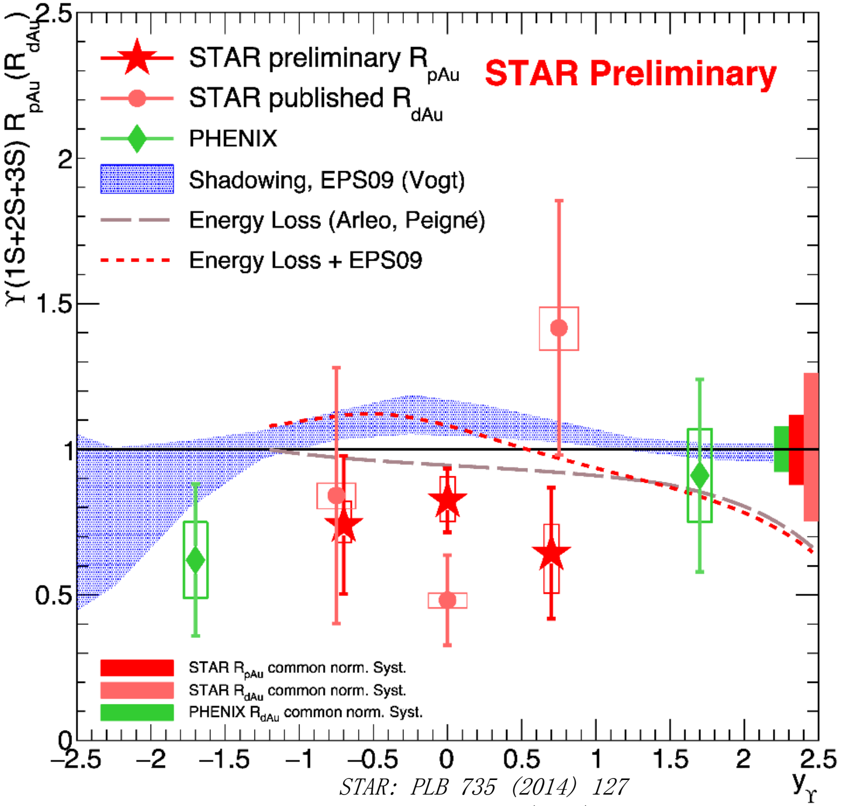


$$R_{AA} = \frac{\sigma_{pp}^{inel} \; d^2N_{pAu}/dydp_T}{\langle N_{coll}\rangle \; d^2\sigma_{pp}/dydp_T}$$

- Strong suppression of J/ψ above 5 GeV/c in central collisions
  → Dissociation in effect

Υ results in p+p and p+Au collisions

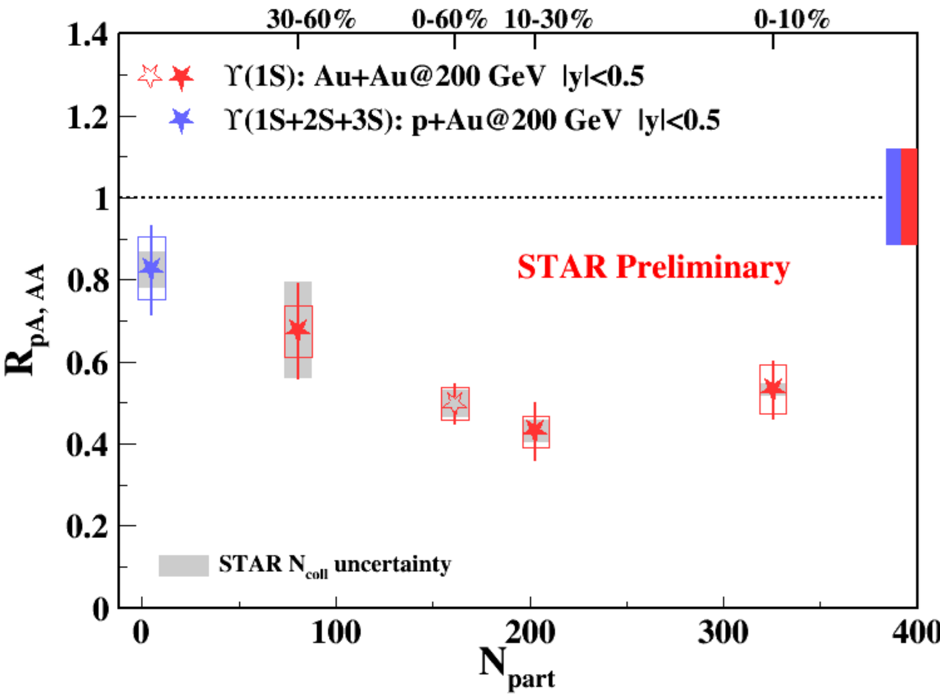


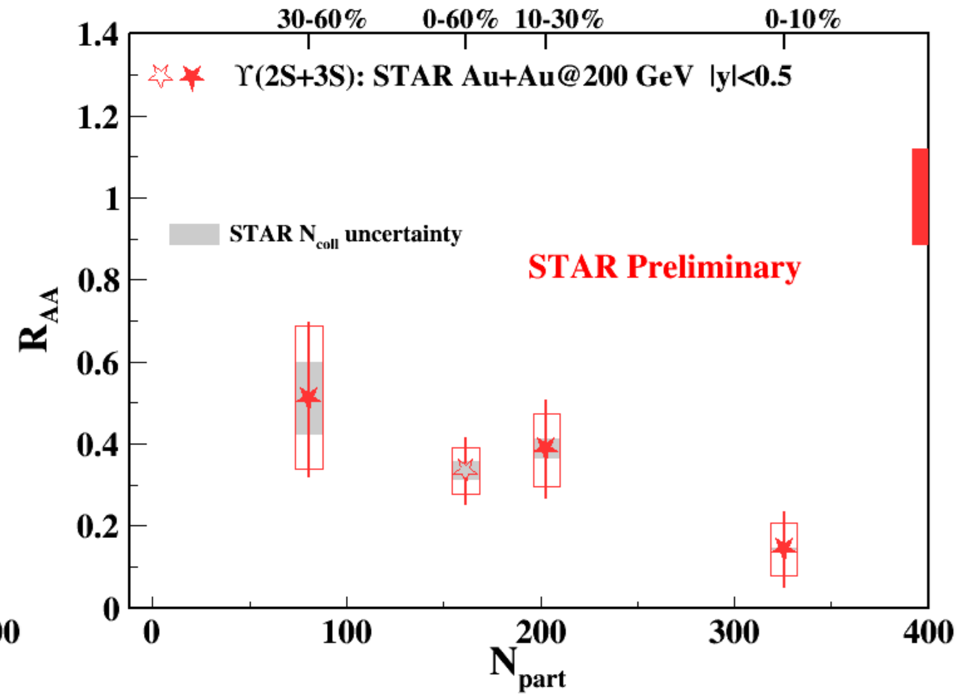


STAR: PLB 735 (2014) 127
PHENIX: PRC 87 (2013) 044909
R. Vogt, et. al, PoS ConfinementX 203 (2012)
F. Arleo, S. Peigne, JHEP 1303 (2013) 122
K. J. Eskola, et. al, JHEP 0904 (2009) 065

- p+p: σ = 81 ± 5(stat.) ± 8(syst.) pb
  - Baseline for A+A collisions with improved precision
  - Consistent with the Color Evaporation Model (CEM) prediction
- p+Au: R_{pAu} = 0.82 ± 0.10(stat.) $^{-0.07}_{+0.08}$ (syst.) ±0.10(global)
  - Quantify CNM effects

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

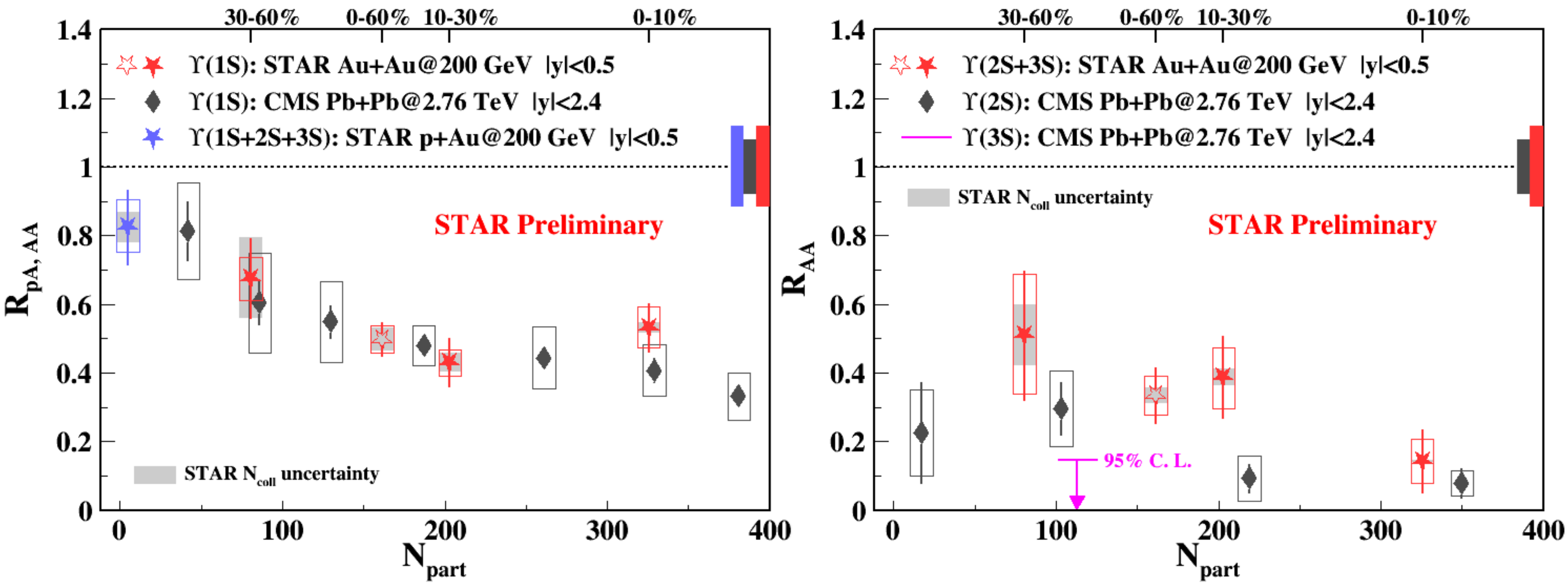




- Di-muon result from 2014 data and di-electron result from 2011 data are combined
- Indication of more suppression with increasing centrality
- $\Upsilon(2S{+}3S)$ is more suppressed than $\Upsilon(1S)$ in central collision → Sequential melting

Compare RHIC with LHC

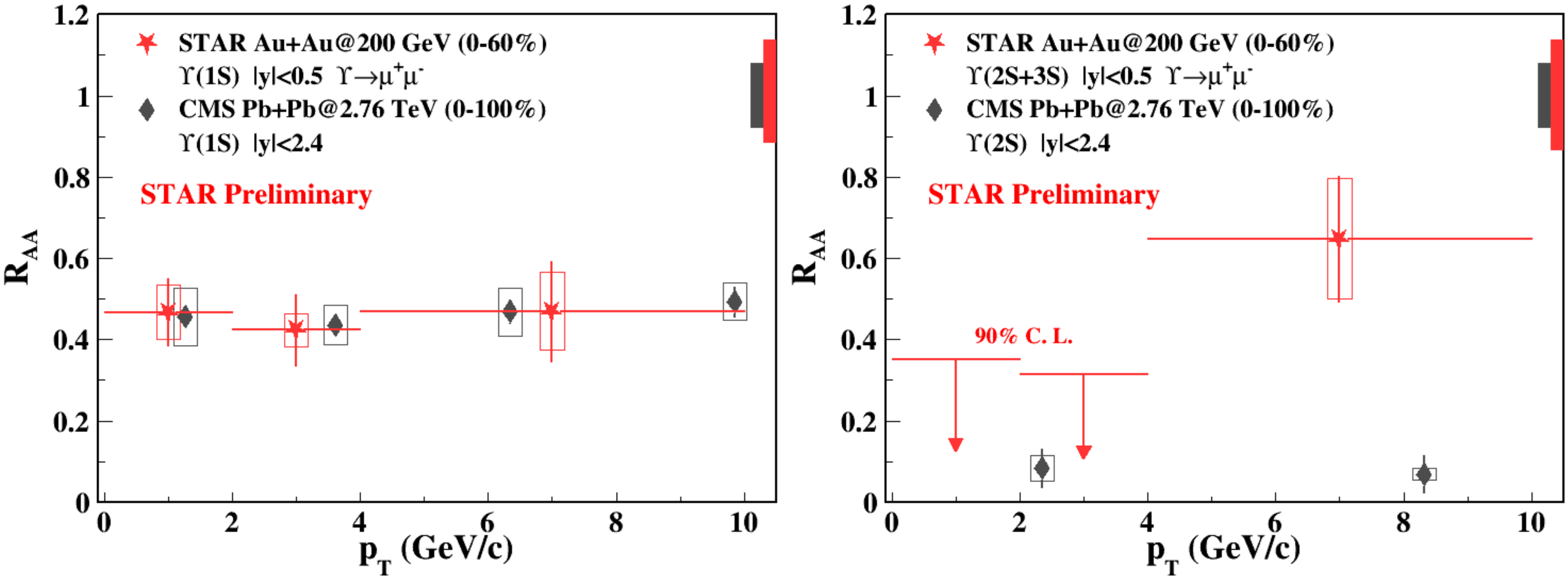
CMS Collaboration, arXiv:1611.01510



CMS: PLB 770 (2017) 357

- $\Upsilon(1S)$: Consistent with CMS result.
- $\Upsilon(2S+3S)$: Indication of less suppression at RHIC than at LHC

R_{AA} vs. p_T at RHIC

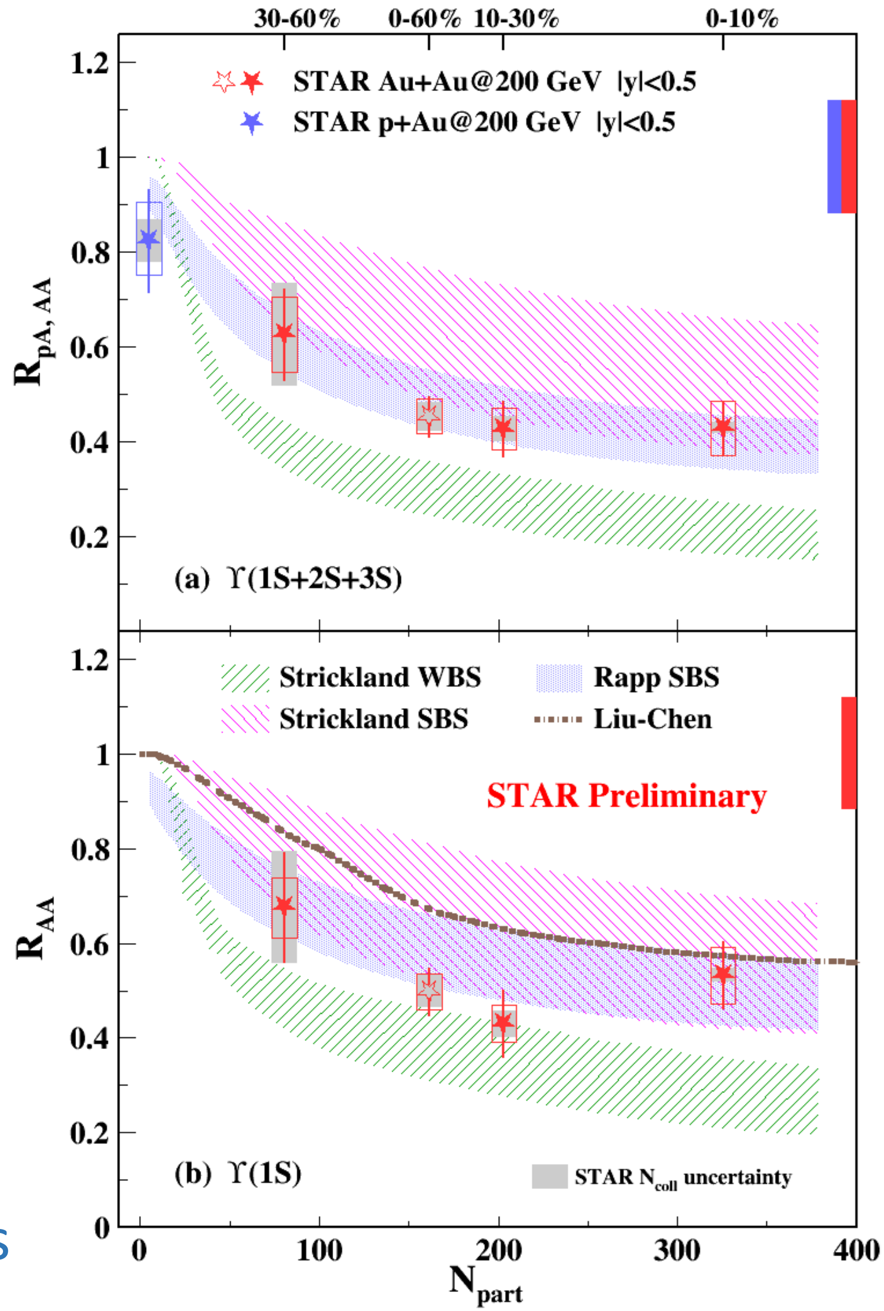


- $\Upsilon(1S)$: No obvious dependence on p_T; consistent with CMS result.
- $\Upsilon(2S+3S)$: Indication of less suppression at RHIC at high p_T

Compare with models

- SBS (Strongly Binding Scenario): Fast dissociation—potential based on internal energy
- WBS (Weakly Binding Scenario): Slow dissociation—potential based on free energy
- Strickland, Bazov: *NPA 879 (2012) 25*
  No CNM; no regeneration
- Liu, Chen, Xu, Zhuang: *PLB 697 (2011) 32*
  Dissociation only for excited states; suppression of ground state due to feed-down; SBS
- Emerick, Zhao, Rapp: *EPJ A48 (2012) 72*
  Includes CNM; SBS case

→ Data seem to favor the SBS models



Summary and Outlook

- **p+p**
  - Models describe the quarkonium production cross-section reasonably well
  - Baseline with improved precision for Υ
- **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
  - Quantify CNM effects for Υ,

    $R_{pAu} = 0.82 \pm 0.10(\text{stat.})\ ^{-0.07}_{+0.08}(\text{syst.}) \pm 0.10(\text{global})$
- **A+A**
  - J/ψ v_2 in U+U collisions: Consistent with zero above 2 GeV/c within uncertainties as for Au+Au collisions → Small regeneration contribution
  - Strong high-p_T J/ψ suppression in central Au+Au collisions

    → Dissociation in effect
  - $\Upsilon(2S+3S)$ is more suppressed than $\Upsilon(1S)$ in central Au+Au collisions at RHIC

    → Sequential melting
  - RHIC vs. LHC

    $\Upsilon(1S)$: Consistent results

    $\Upsilon(2S+3S)$: Hint of less suppression at RHIC than at LHC
- **Outlook:** Analyses from 2x Au+Au data are underway

Back up

v_2 measurment in U+U collisions

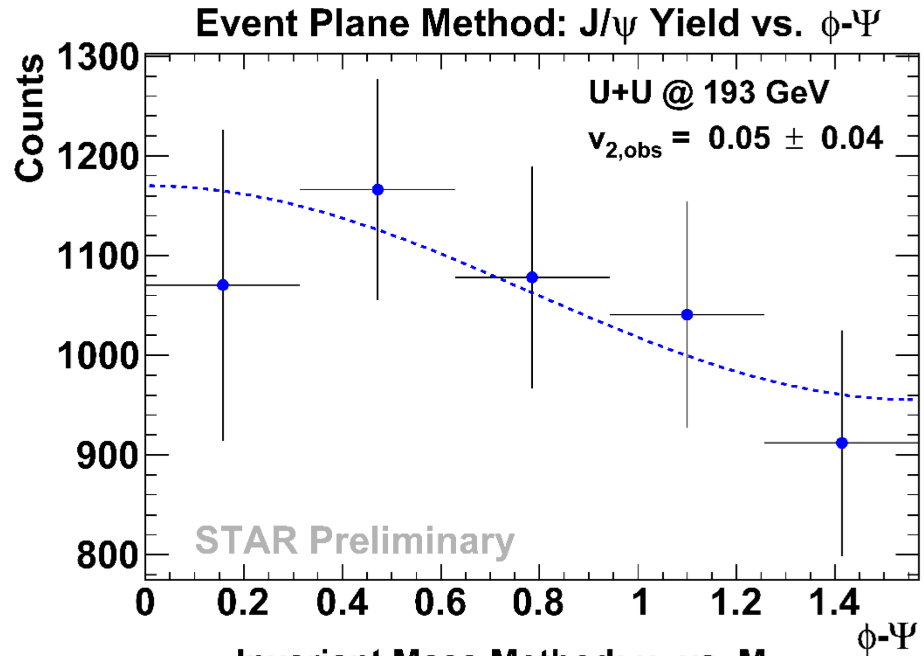
- Event plane method:
  fit J/ψ yield as the function of the relative angle between J/ψ (ϕ) and the event plane (Ψ) by the function

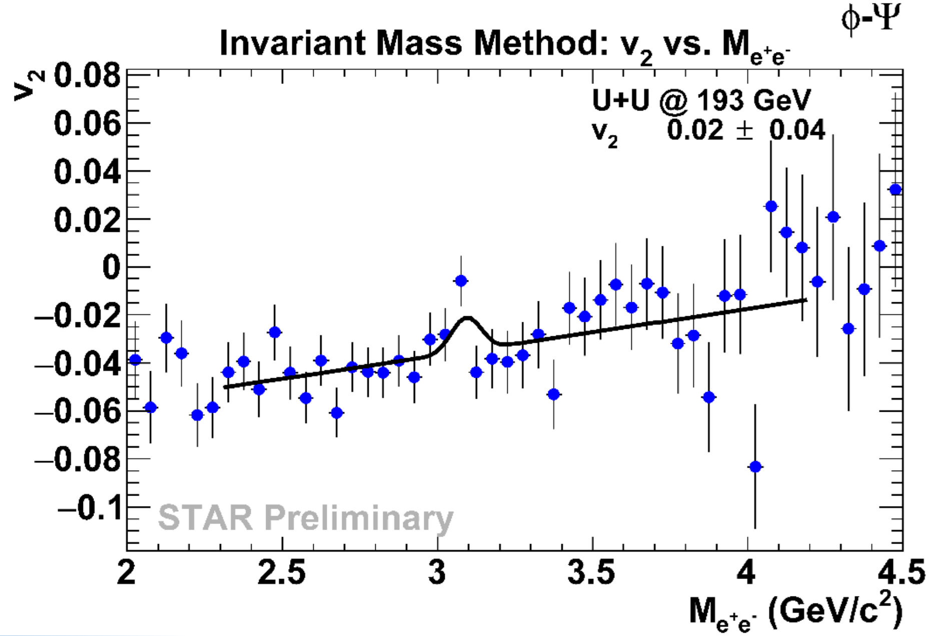
  $$N \cdot (1 + 2 \cdot v_{2,obs} \cdot \cos(2 \cdot (\phi - \Psi)))$$

- Invariant mass method:
  fit v_2 vs. m by

  $$\frac{v_2^{J/\psi} \cdot \mathrm{Sig(m)} + (a_0 + a_1 \cdot m) \cdot Bg(m)}{(\mathrm{Sig(m)} + Bg(m))}$$

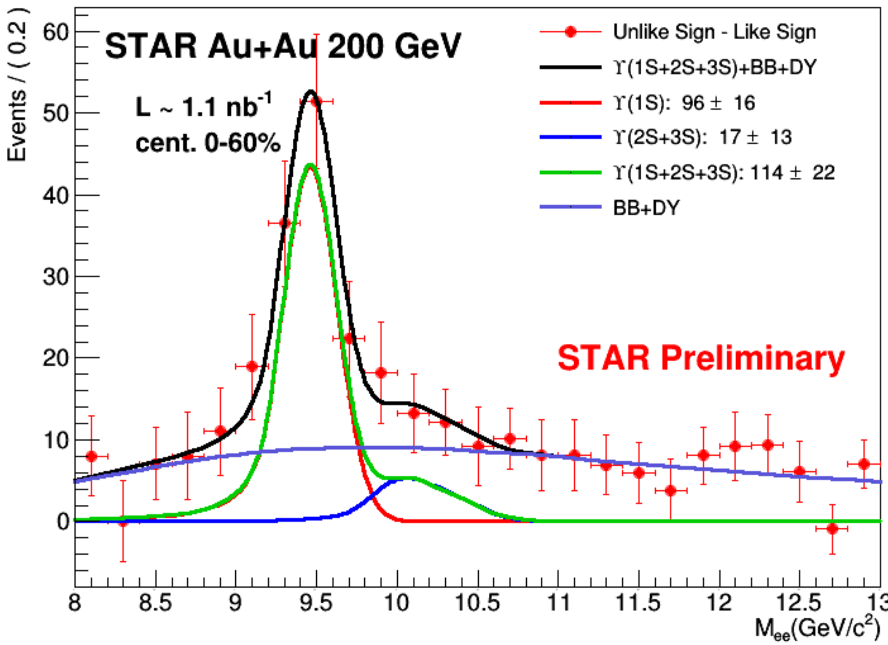
  Where $Sig(m)/Bg(m)$ is the unlike-sign/like-sign yield



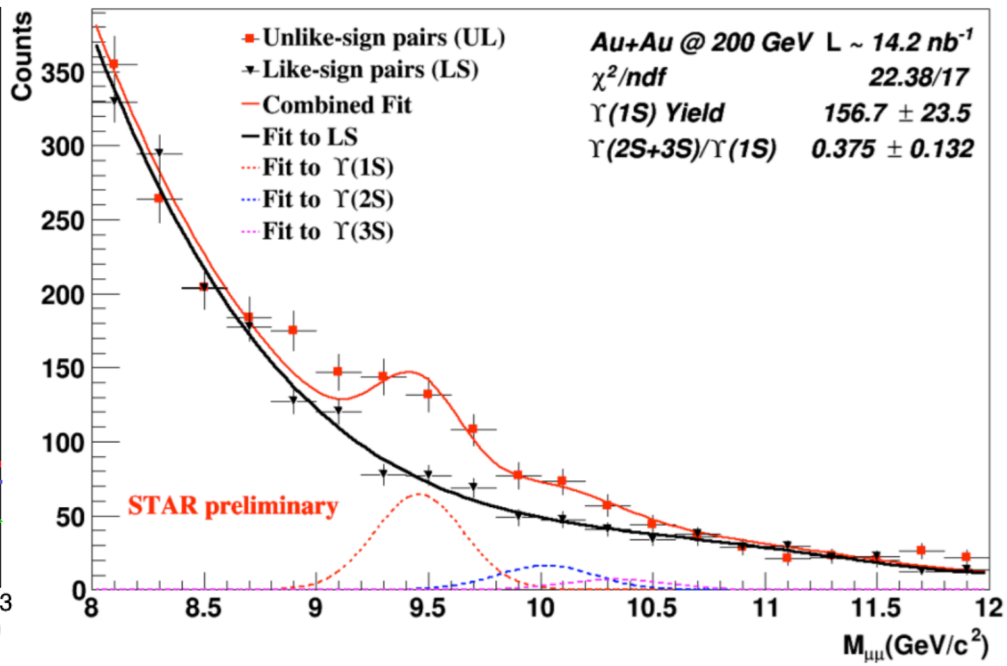


Υ signal in Au+Au collisions

$\Upsilon \rightarrow e^+e^-$, 2011 data

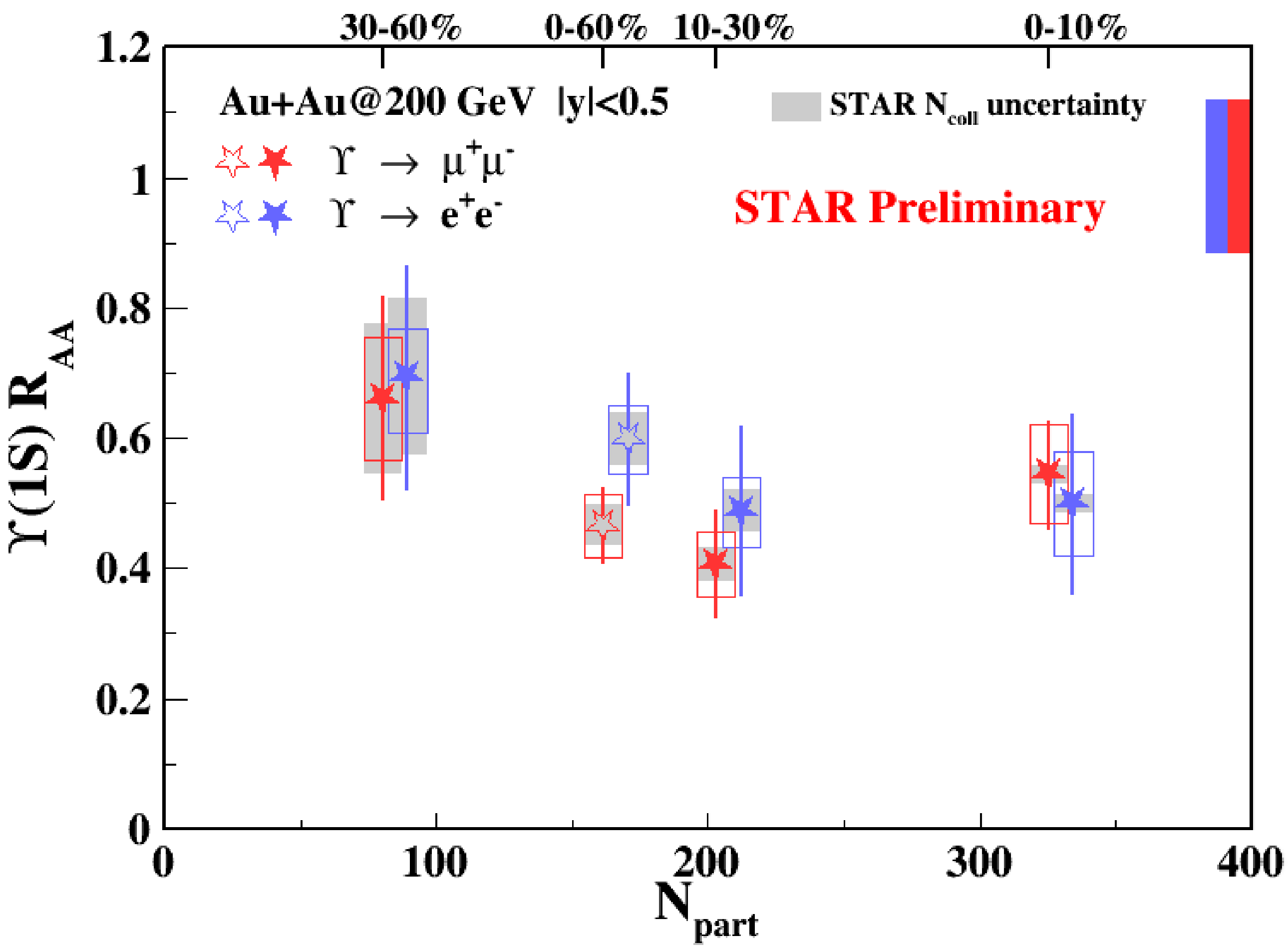


$\Upsilon \rightarrow \mu^+\mu^-$, 2014 data



- Background sources:
  - Combinatorial background (estimated with $N_{l^+l^+} + N_{l^-l^-}$)
  - $b\bar{b}$ and Drell-Yan contributions

Υ nuclear modification factor in Au+Au collisions



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

- ☆ are combinations of ★ results
- Di-muon and di-electron results consistent with each other
  → Results combined for higher statistical precision