Recent quarkonium results in heavy-ion collisions at STAR

Nihar Ranjan Sahoo (for the STAR Collaboration)

IISER-Tirupati

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ENERGY

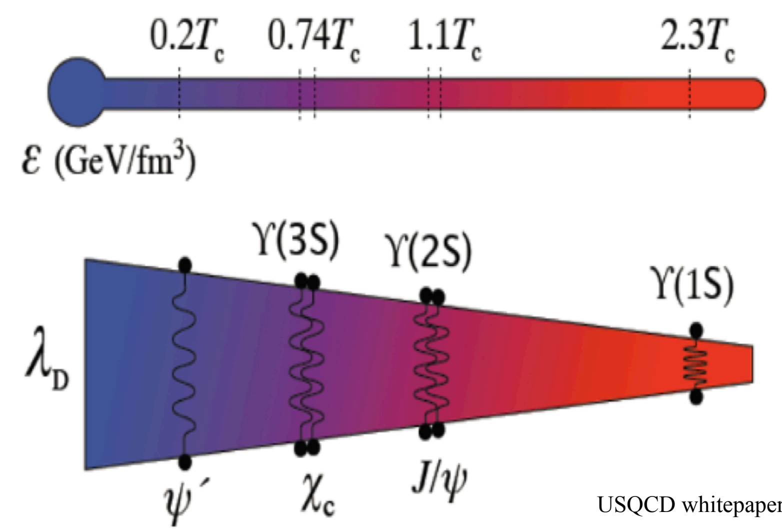
Quarkonia in heavy-ion collisions

Goal to probe finite temperature and baryon density in QCD medium

→ deconfined and chiral symmetric QCD phase: Quark-Gluon Plasma (QGP)

→ pseudo-critical temperature, T_{pc} = 155-160 MeV (lattice QCD simulation)

JHEP 09:073 (2010); PRL 113:082001 (2014)



USQCD whitepaper 2018

Quarkonia—bound states of $c\bar{c}$ (J/ψ) and $b\bar{b}$ (Υ)

In heavy-ion collisions

→ Dissociation of quarkonium

Color screening: quarkonium size > Debye screening length of medium

Dynamical dissociation: inelastic interaction between quarkonium and medium

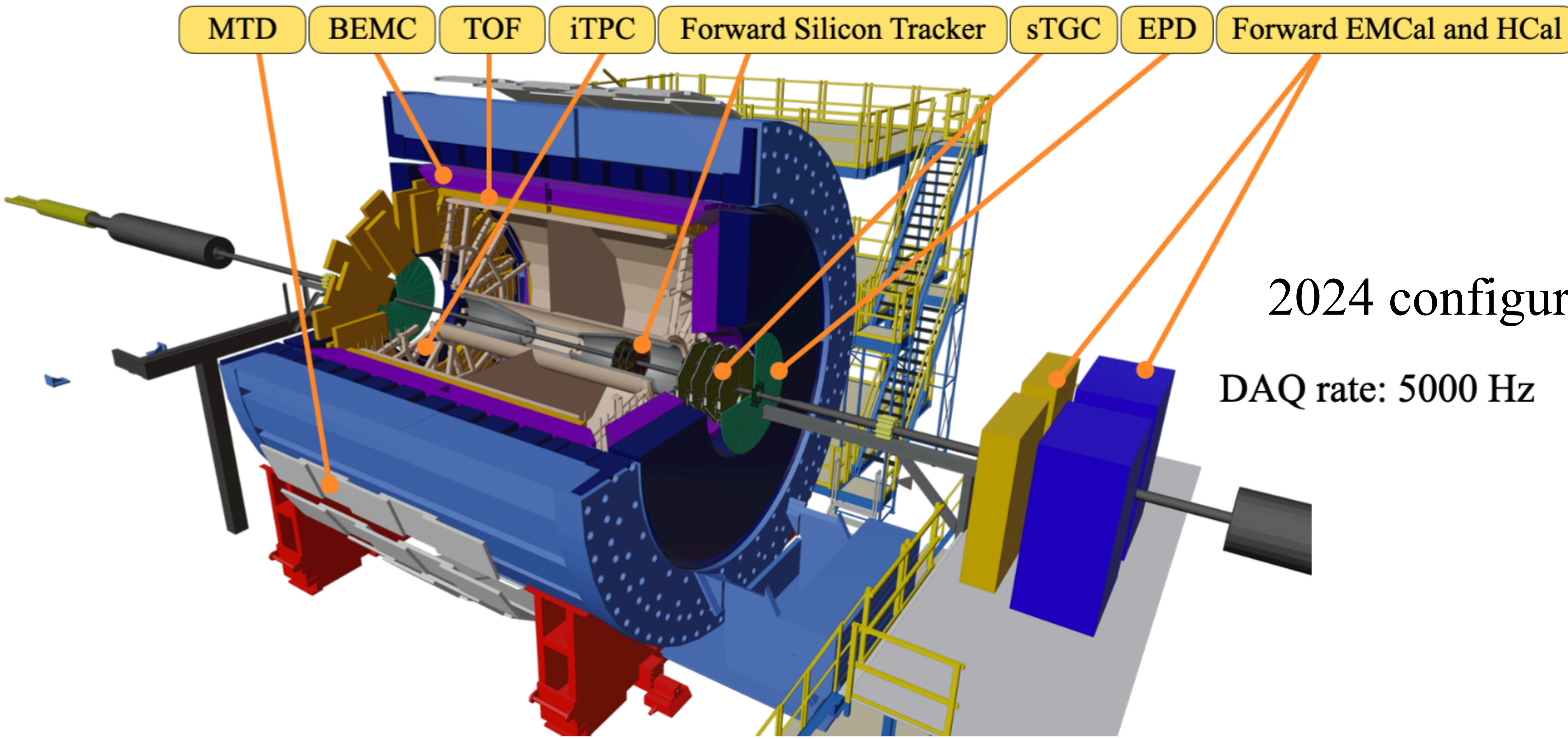
→ Regeneration of quarkonium : Important at high temperature and medium density

→ Cold Nuclear Matter (CNM) effect: nPDF modification, Cronin effect, dissociation due to co-mover, etc.

See Md. Nasim's talk on pp: 26 Feb, 5.00 PM

Let's discuss recent results from STAR experiment…

STAR detector



2024 configuration

DAQ rate: 5000 Hz

Key detectors for Quarkonia measurements:

- With Inner Time Projection Chamber, (i)TPC → $|\eta| < 1.5$ and $p_T > 0.15$ GeV/c
- Barrel Electromagnetic Calorimeter (BEMC) → $|\eta| < 1$
- Time of flight (TOF) → $|\eta| < 1$
- Muon Telescope Detector (MTD) → $|\eta| < 0.5$

Charmonium and its excited states in QGP

J/ψ suppression at different collision energy

Nuclear Modification factor:

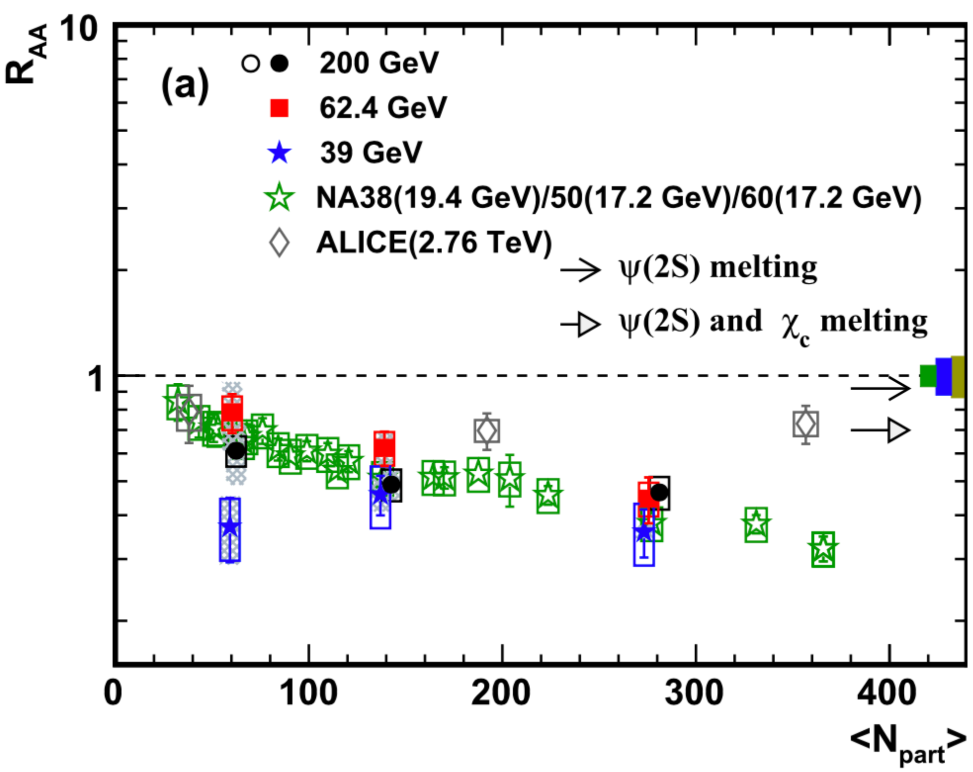
$$R_{AA} = \frac{1}{< T_{AA} >} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \qquad < T_{AA} > = \frac{N_{coll.}}{\sigma_{pp}^{incl.}}$$

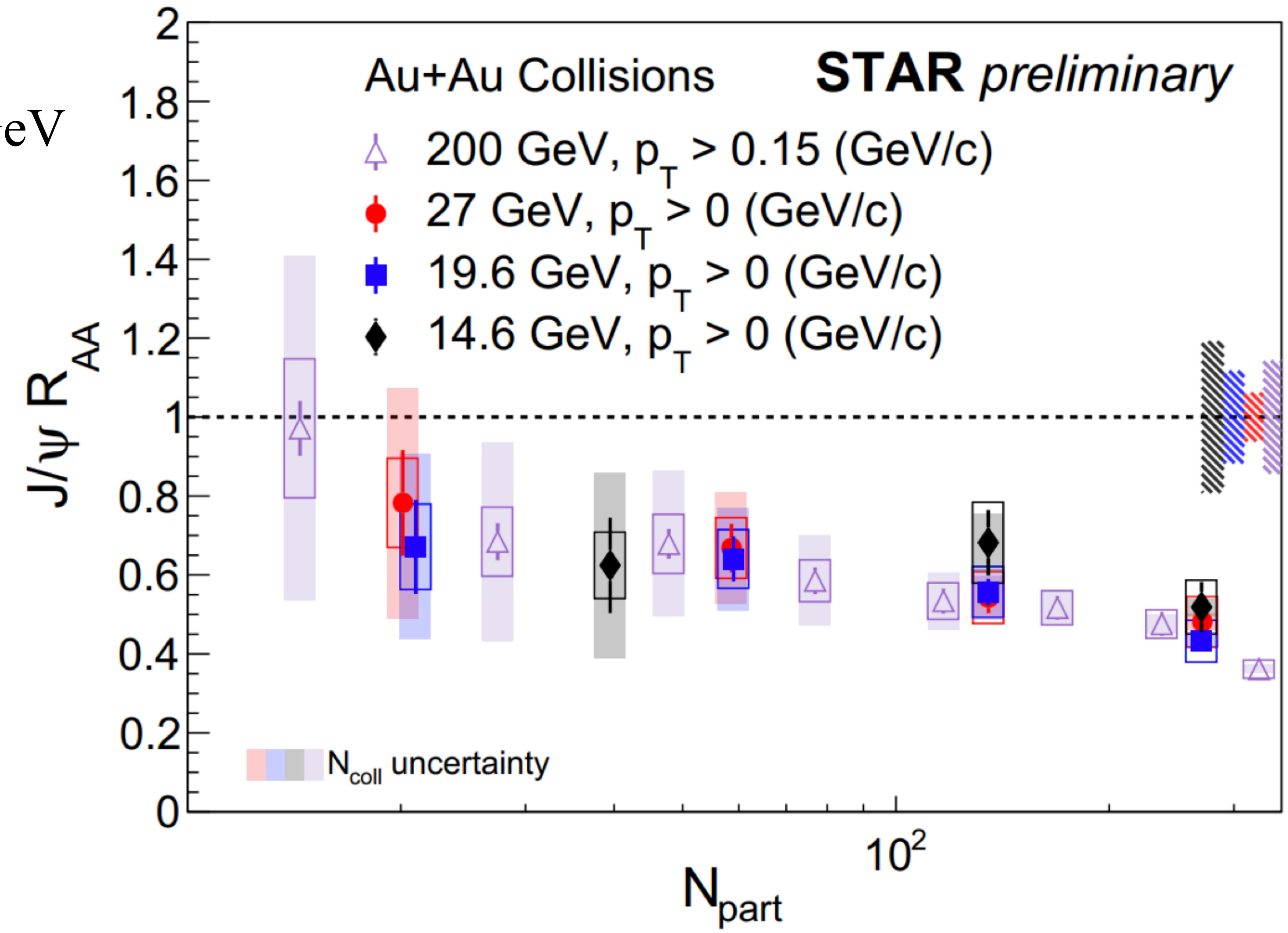
Using Beam Energy Scan-II data

$\sqrt{s_{NN}}$ = 27, 19.6, and 14.6 GeV

Previous measurements $\sqrt{s_{NN}}$ = 200 - 39 GeV

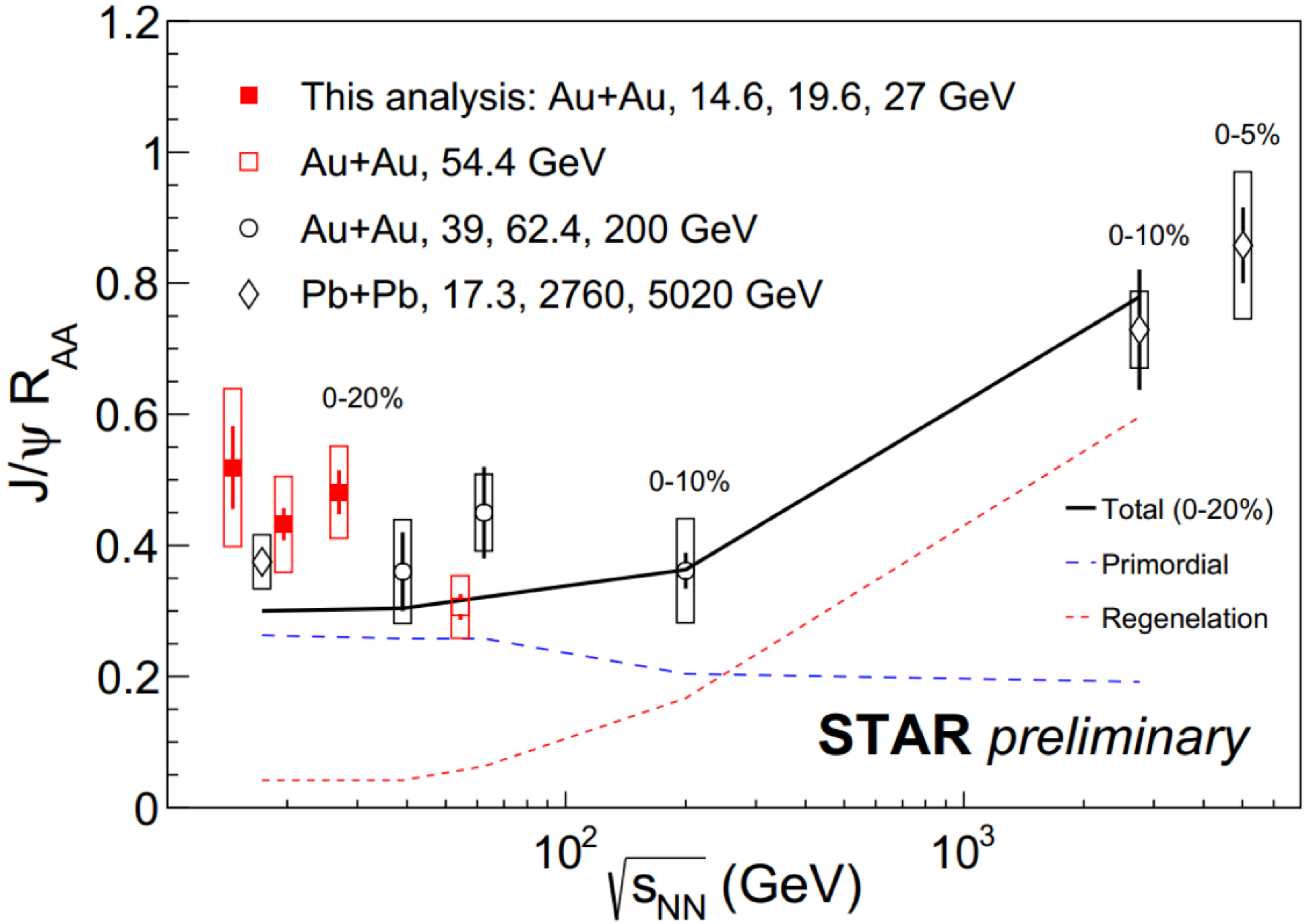
STAR: PLB 771 (2017) 13





→ Similar J/ψ suppression for similar <N_{part}> at RHIC energies in Au+Au collisions

J/ψ suppression at different collision energy

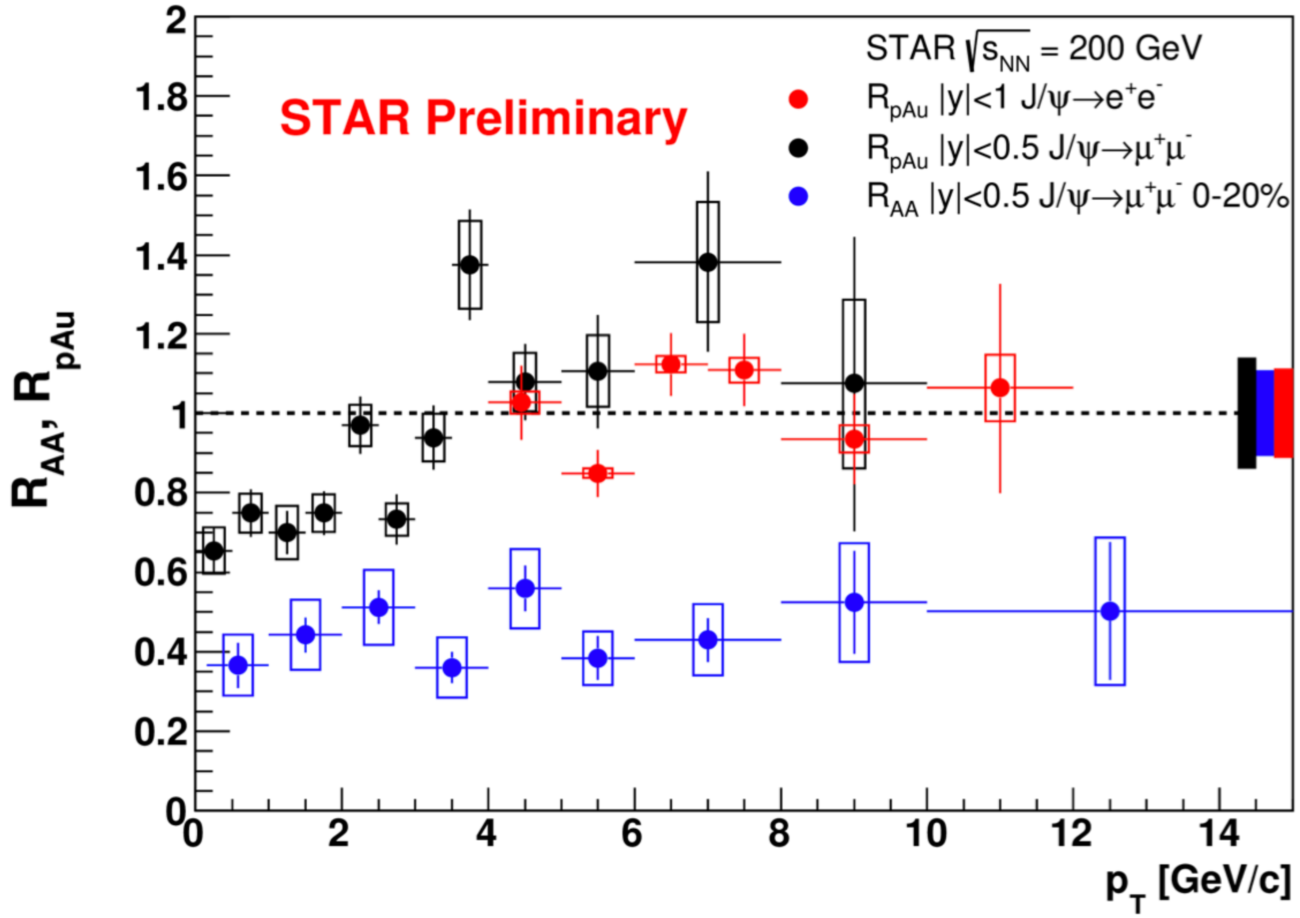


No collision energy dependence of R_{AA} at RHIC

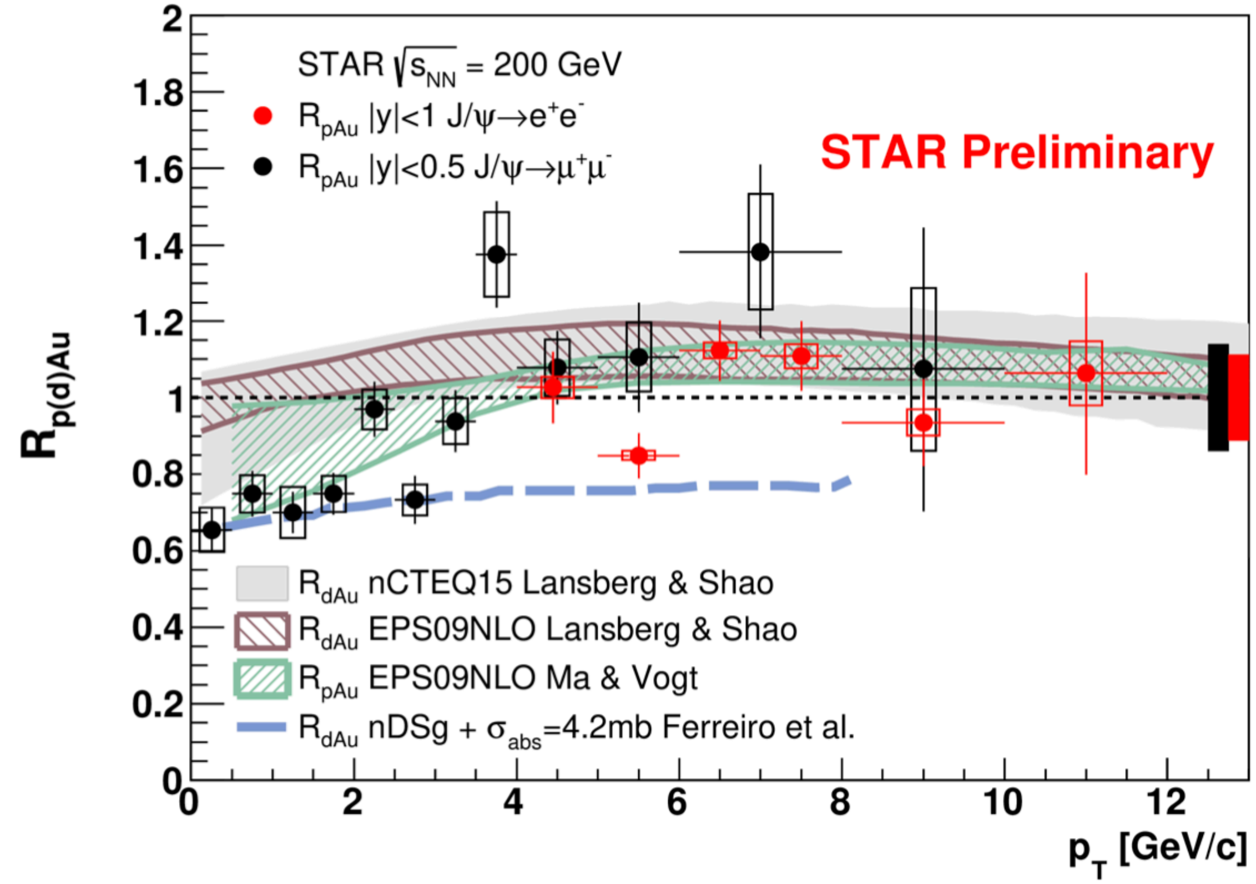
Interplay of dissociation and regeneration effects at RHIC energies

What about in p+Au collisions?

J/ψ in hot-dense vs. cold QCD medium



STAR, Phys. Lett. B 825 (2022) 136865
STAR, Phys. Lett. B 797 (2019) 134917



STAR, Phys. Lett. B 825 (2022) 136865
Ma & Vogt, EPS09+NLO, Private Comm.
Lansberg & Shao, nCTEQ15, EPS09+NLO, Eur.Phys.J. C77 (2017) no.1, 1
Ferreriro et al., nDSg+σ_{abs}, Few Body Syst. 53 (2012) 27

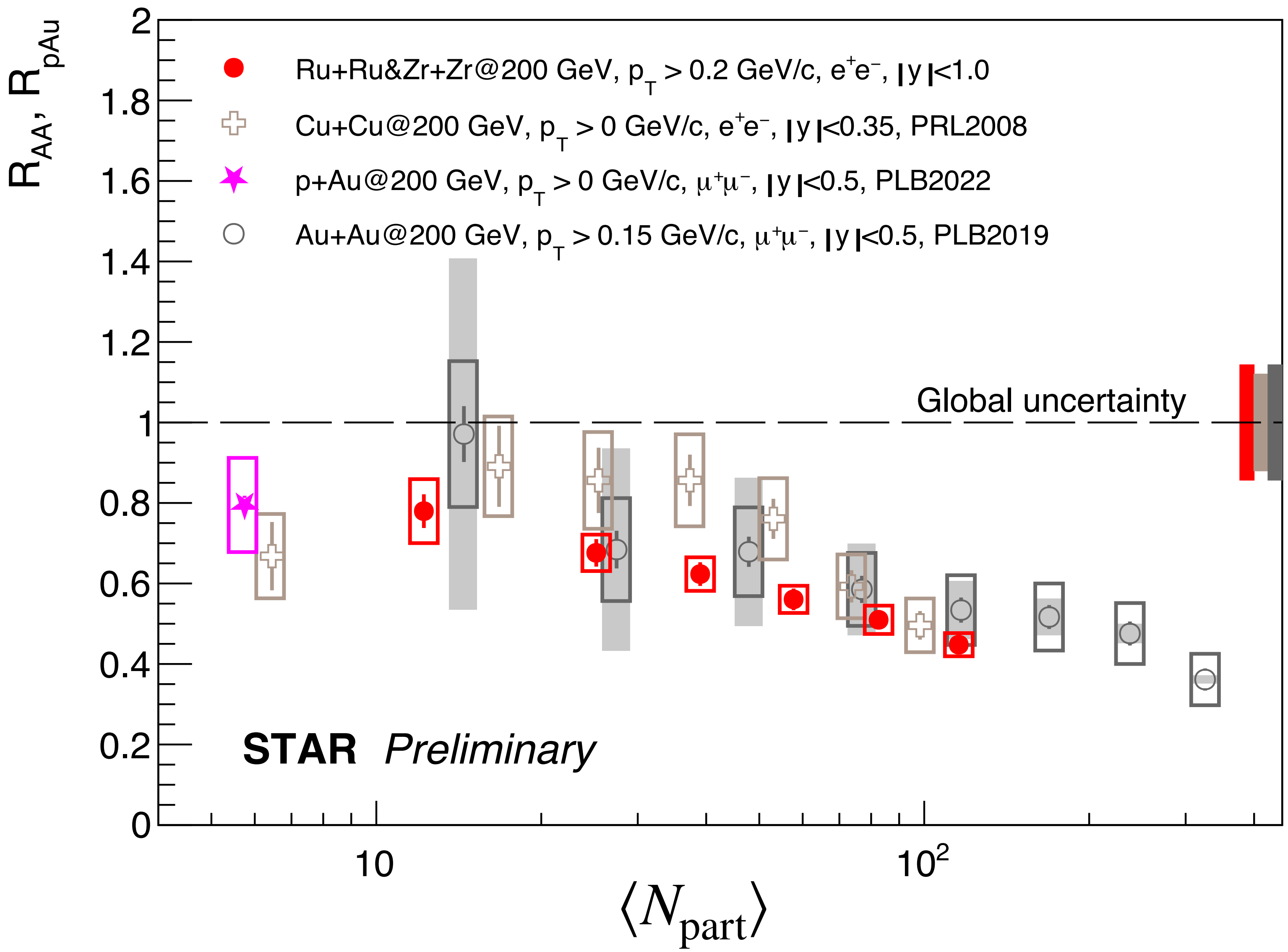
→Au+Au: strong evidence of the QGP formation

→p+Au: at high-p_T (> 3 GeV/*c*) no suppression; low-p_T suppression due to CNM effects

→p+Au data help to quantify the CNM effect in Au+Au collisions

Collision system size dependence of J/ψ suppression

p+Au, Cu+Cu, Zr+Zr, Ru+Ru and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

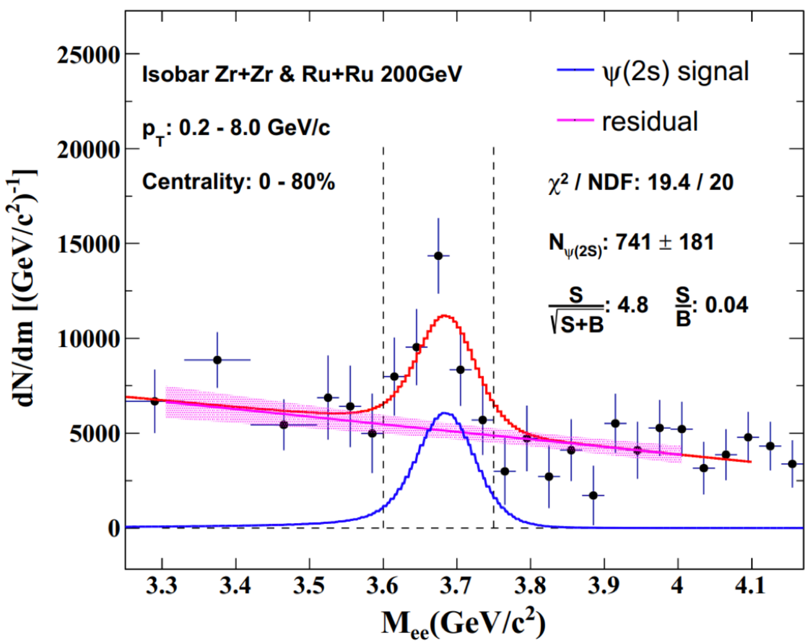


Same J/ψ R_{AA} with similar N_{part} , independent of collision system

Charmonium excited states in QGP

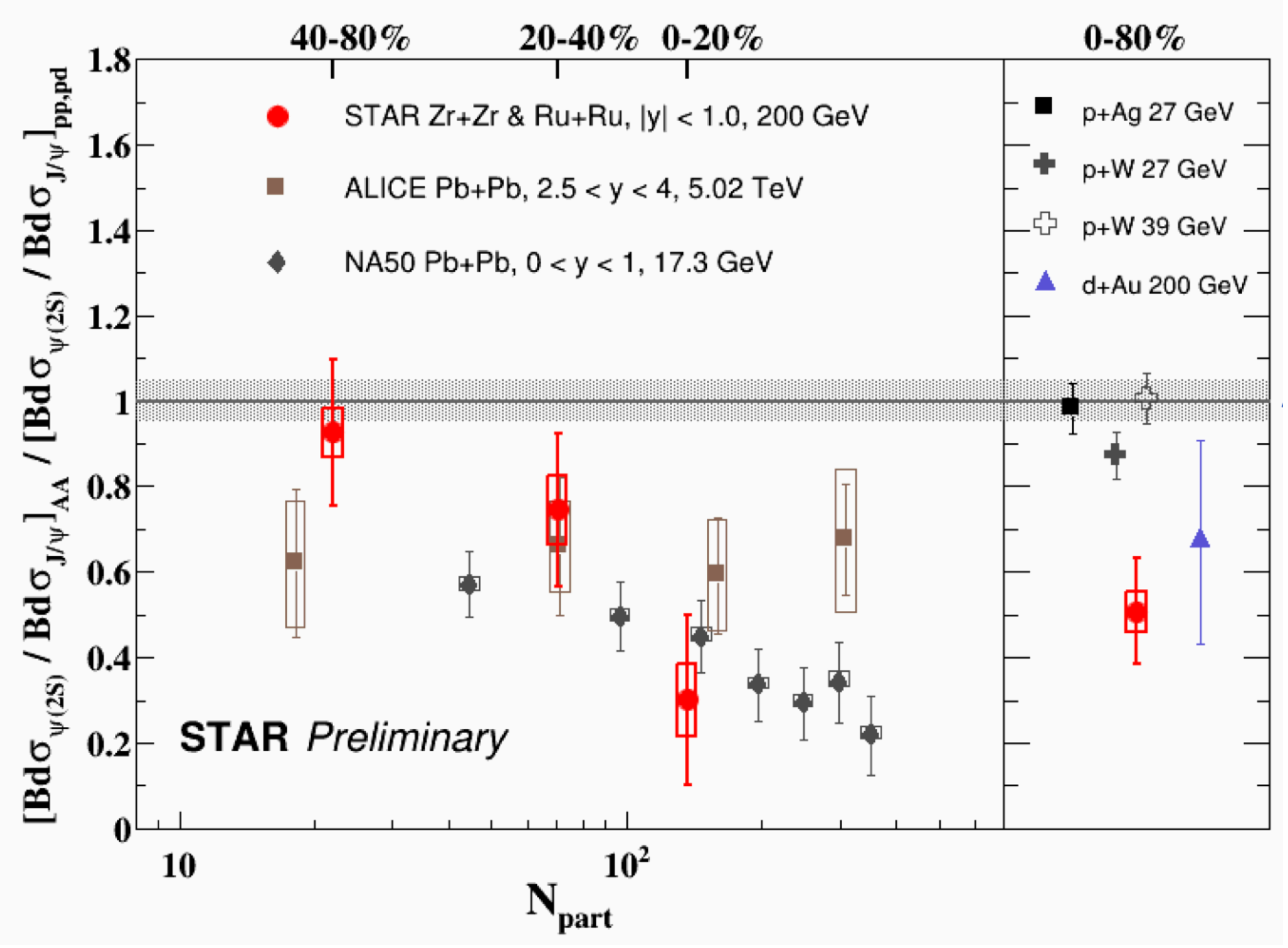
Charmonium ψ(2S) suppression at RHIC in Zr+Zr and Ru+Ru collisions

ψ(2S) signal reconstructed using Boosted Decision Tree (ML method)



Mixed event: for combinatorial background subtraction

$\psi(2S)$ over J/ψ double ratio of AA relative to pp,pd



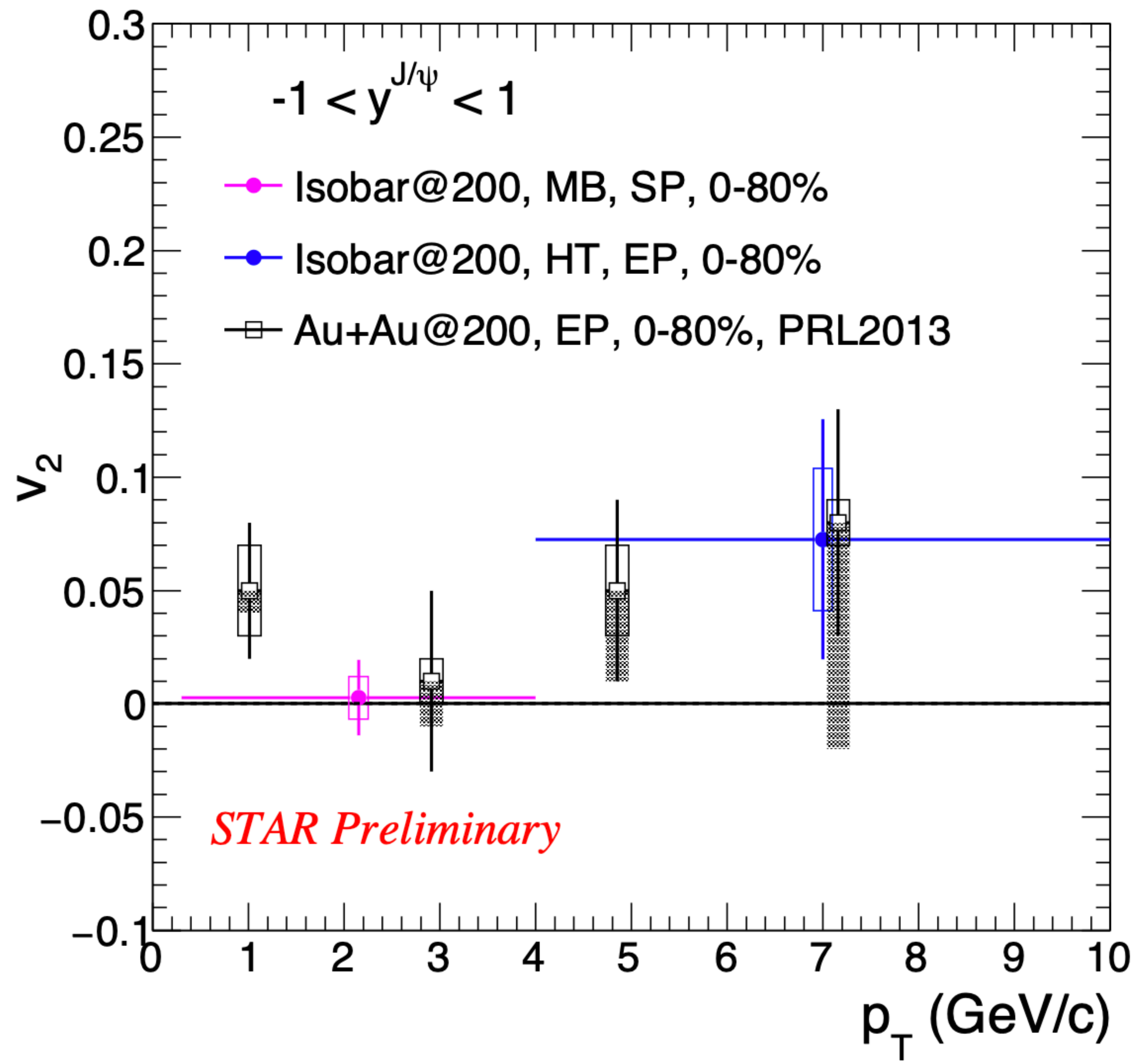
PHENIX: PRL 111 (2013); PHENIX: PRD, 85,092004 (2012)
NA50: EPJC 48, (2006); E772: PRL 66 (1991) 133

→ First observation of charmonium sequential suppression in A+A at RHIC (3.5σ, 0-80%)

→ Double ratio is smaller in A+A than that in p+A collisions

Collectivity and spin coupling of J/ψ in QGP

J/ψ flow in QGP at RHIC



Using TPC event plane method:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1 + \sum_{n=1}^{\infty} 2v_n cos[n(\phi - \Psi_n)])$$

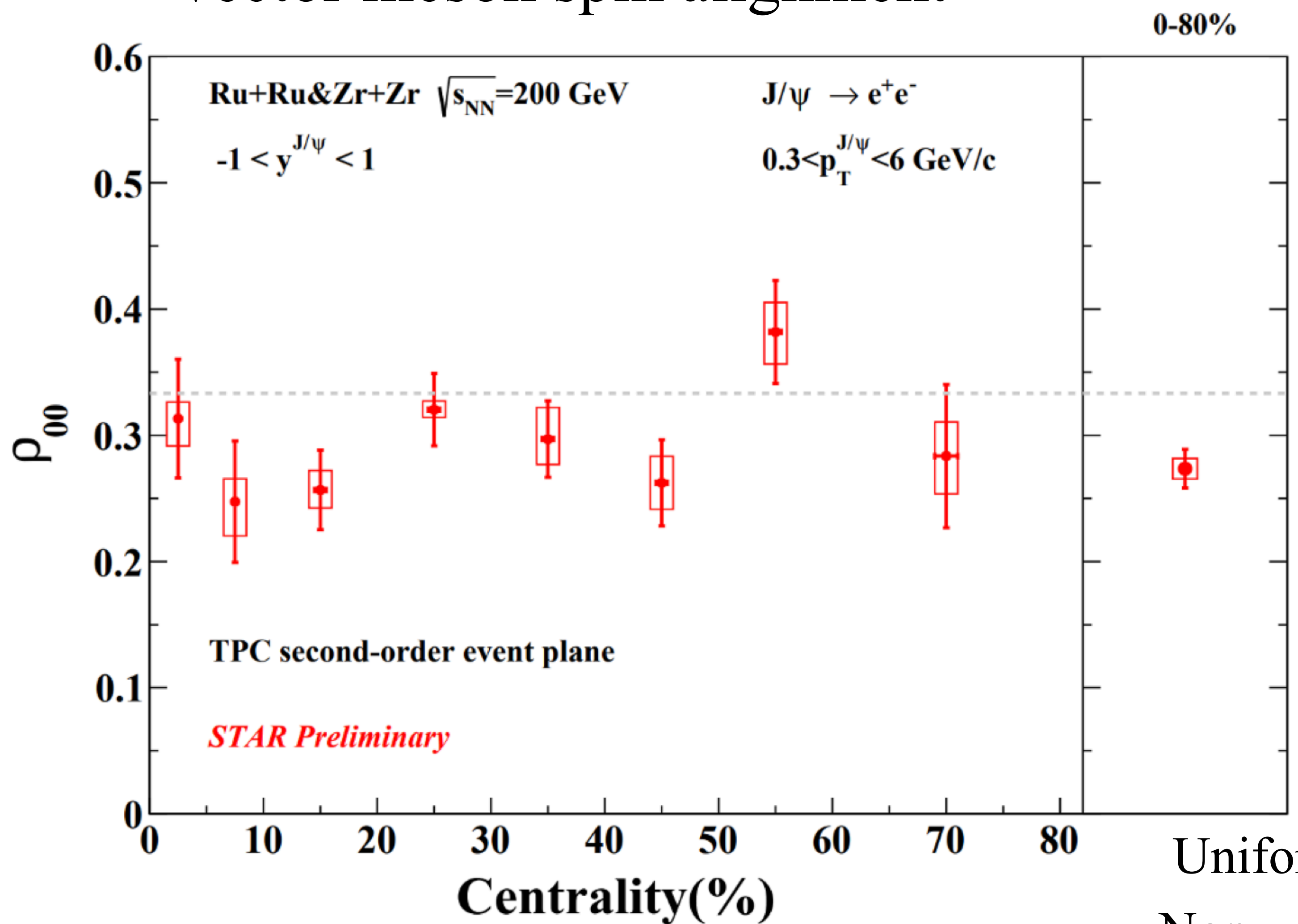
→ At low J/ψ p_T (0.3-4 GeV/c): zero elliptic flow coefficient

→ Hinting smaller regeneration effect or/and charm flow in QGP at RHIC

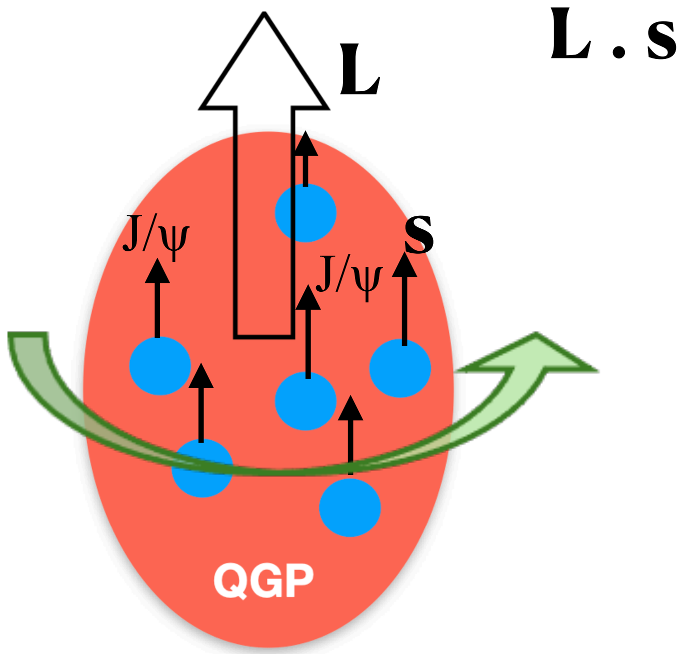
QGP global angular momentum and J/ψ spin coupling

STAR, Nature 614 (2023) 244 → φ-meson spin alignment

Vector meson spin alignment



Global angular momentum (**L**) and J/ψ spin (**s**) coupling



$$\frac{dN}{dcos\theta^*} \propto (1-\rho_{00}) + (3\rho_{00}-1)cos^2\theta^*$$

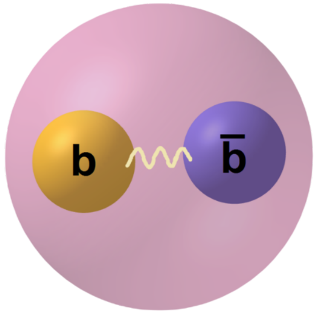
Uniform distribution: $\rho_{00} = 1/3$ → No spin alignment

Non-uniform distribution: $\rho_{00} \neq 1/3$ → spin alignment

ρ_{00} lower than 1/3 with a significance of 3.5σ in 0-80% centrality

No significant centrality dependence within uncertainty

Bottomonium and its excited states in QGP

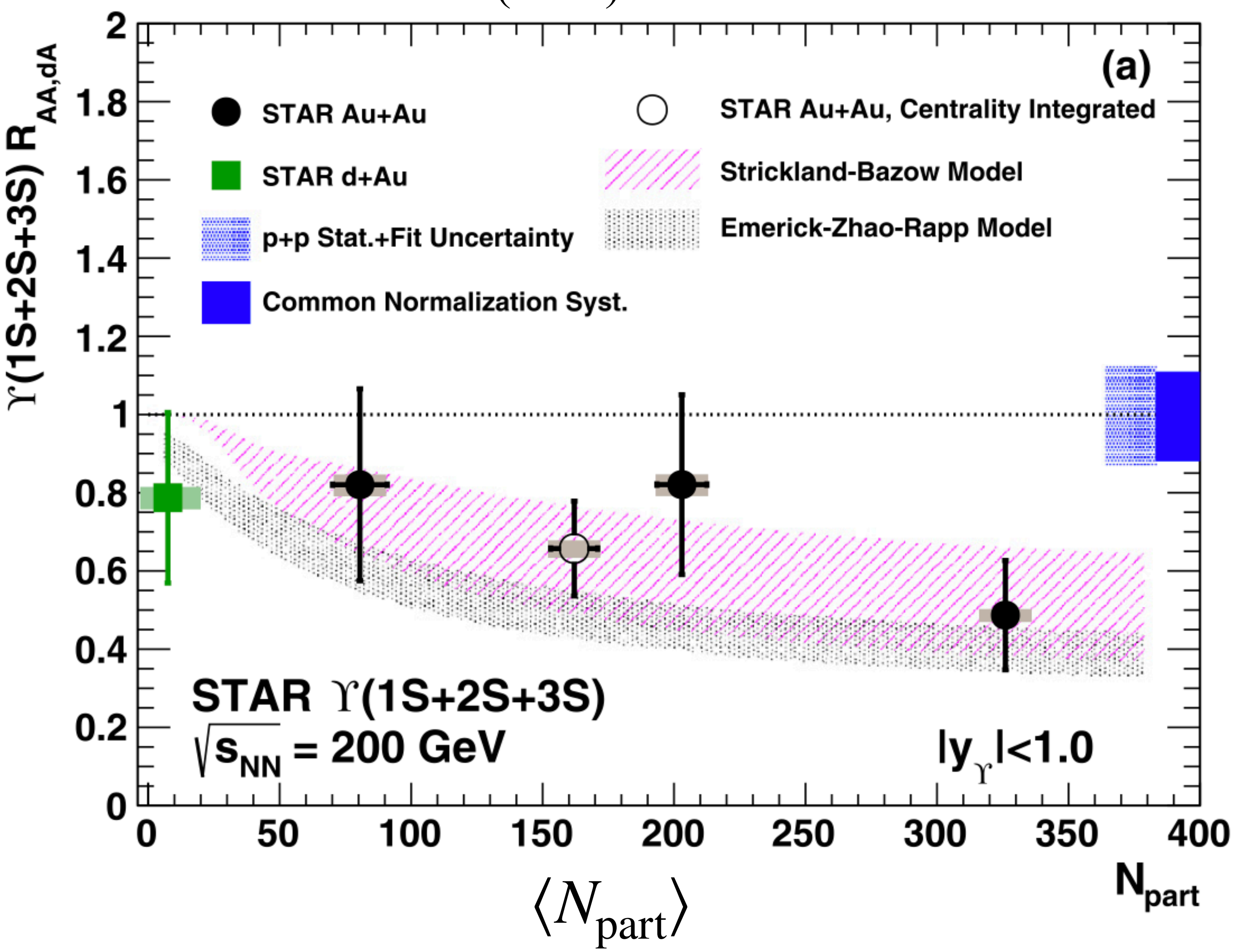


Bottomonium states in QGP

Υ(1S+2S+3S) suppression measurement in STAR

Au+Au and d+Au $\sqrt{s_{NN}} = 200$ GeV

STAR: PLB 735 (2014) 127



Using dielectron channel

→ p+Au collisions: R_{pA} = 0.79±0.22 indicting CNM effect

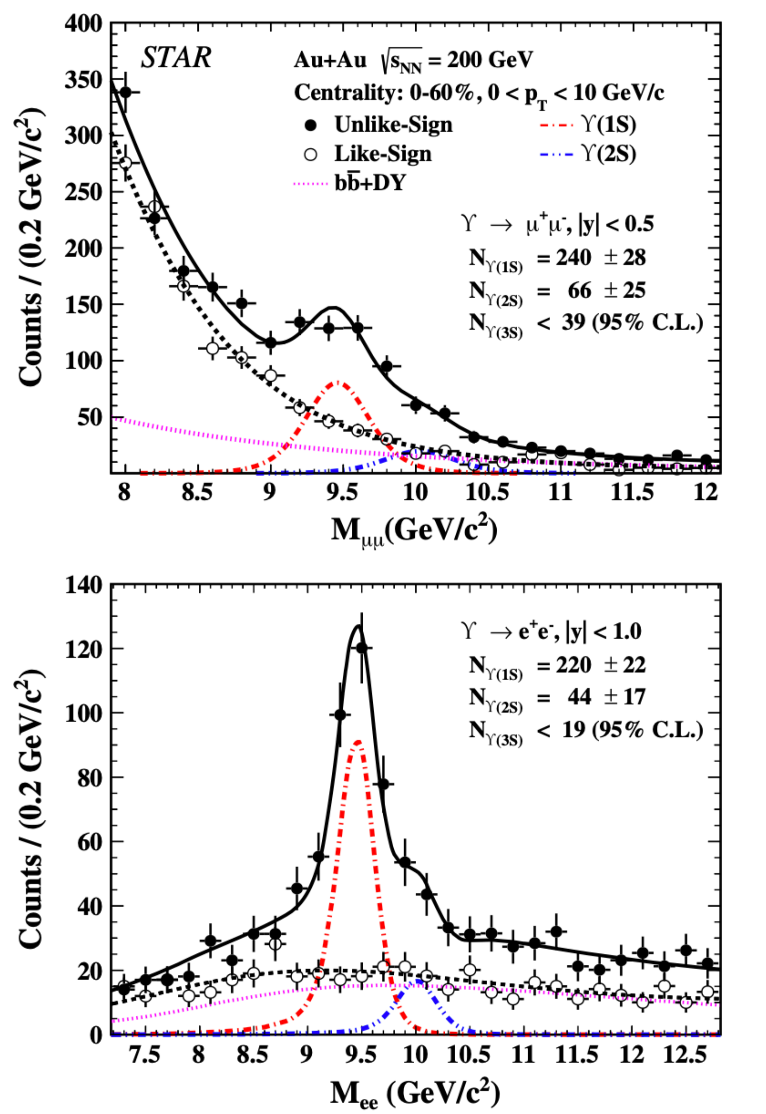
→ 0-10% central Au+Au collisions $R_{AA} < R_{pA}$ implying hot nuclear matter effect

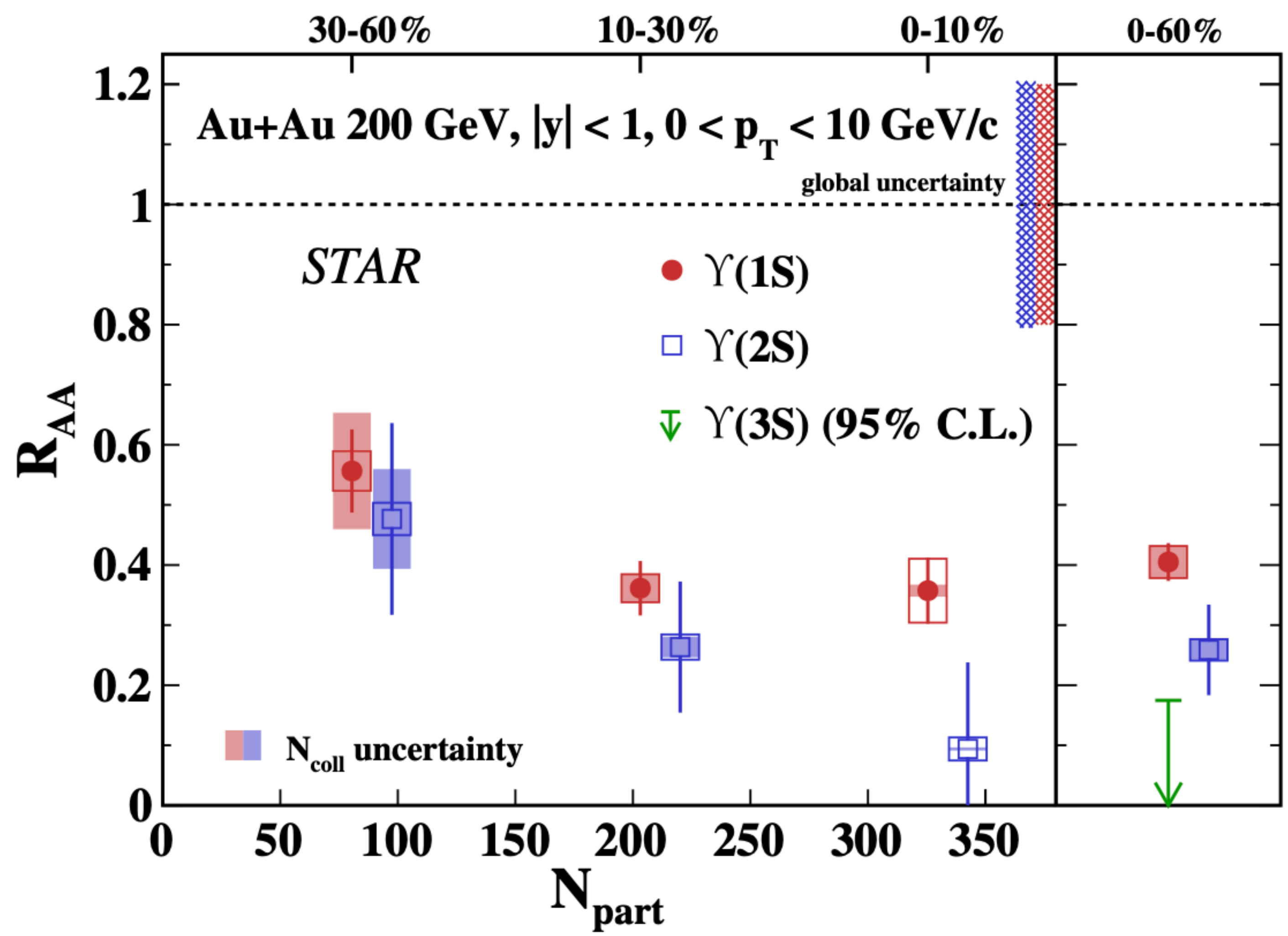
Need precision measurement to observe sequential suppression of excited states

Quarkonium states in QGP

Bottomonium ϒ(nS) suppression in Au+Au collisions

STAR, PRL 130 (2023) 112301





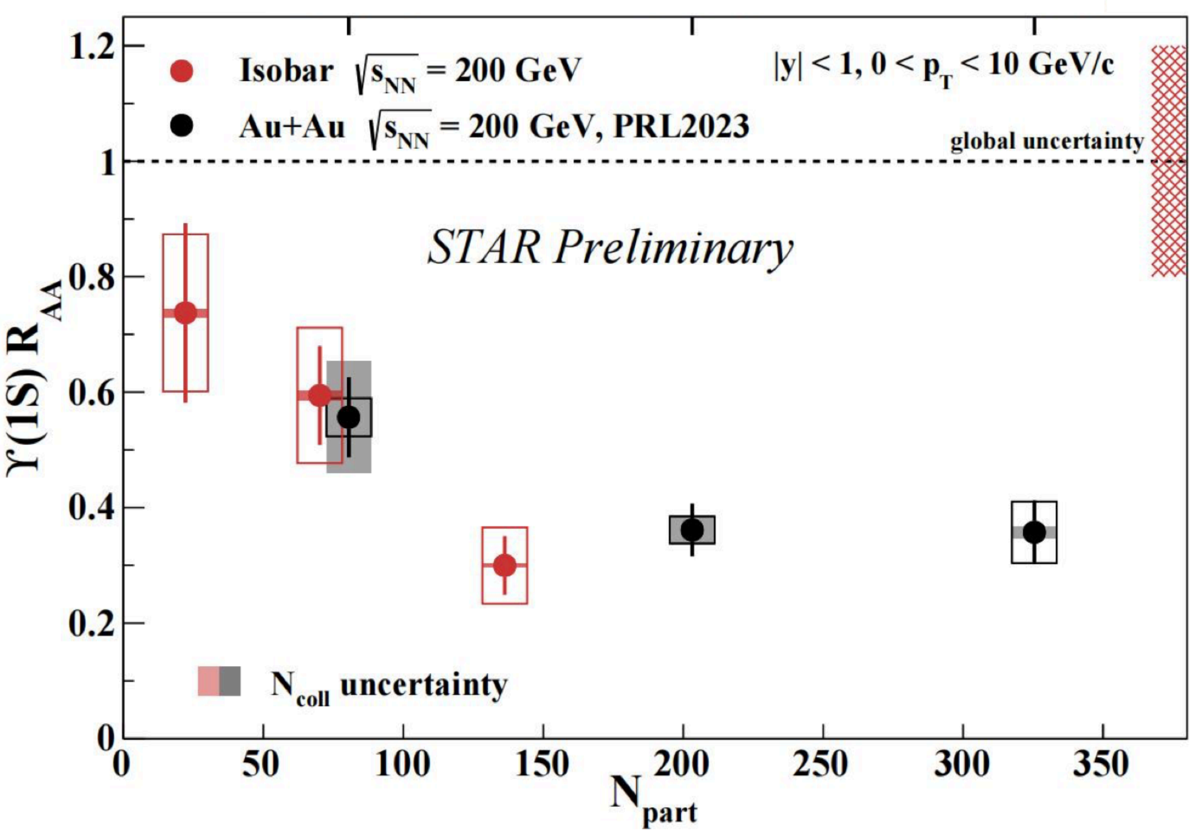
→ Sequential suppression pattern R_{AA}, ϒ(1S) > ϒ(2S) > ϒ(3S)

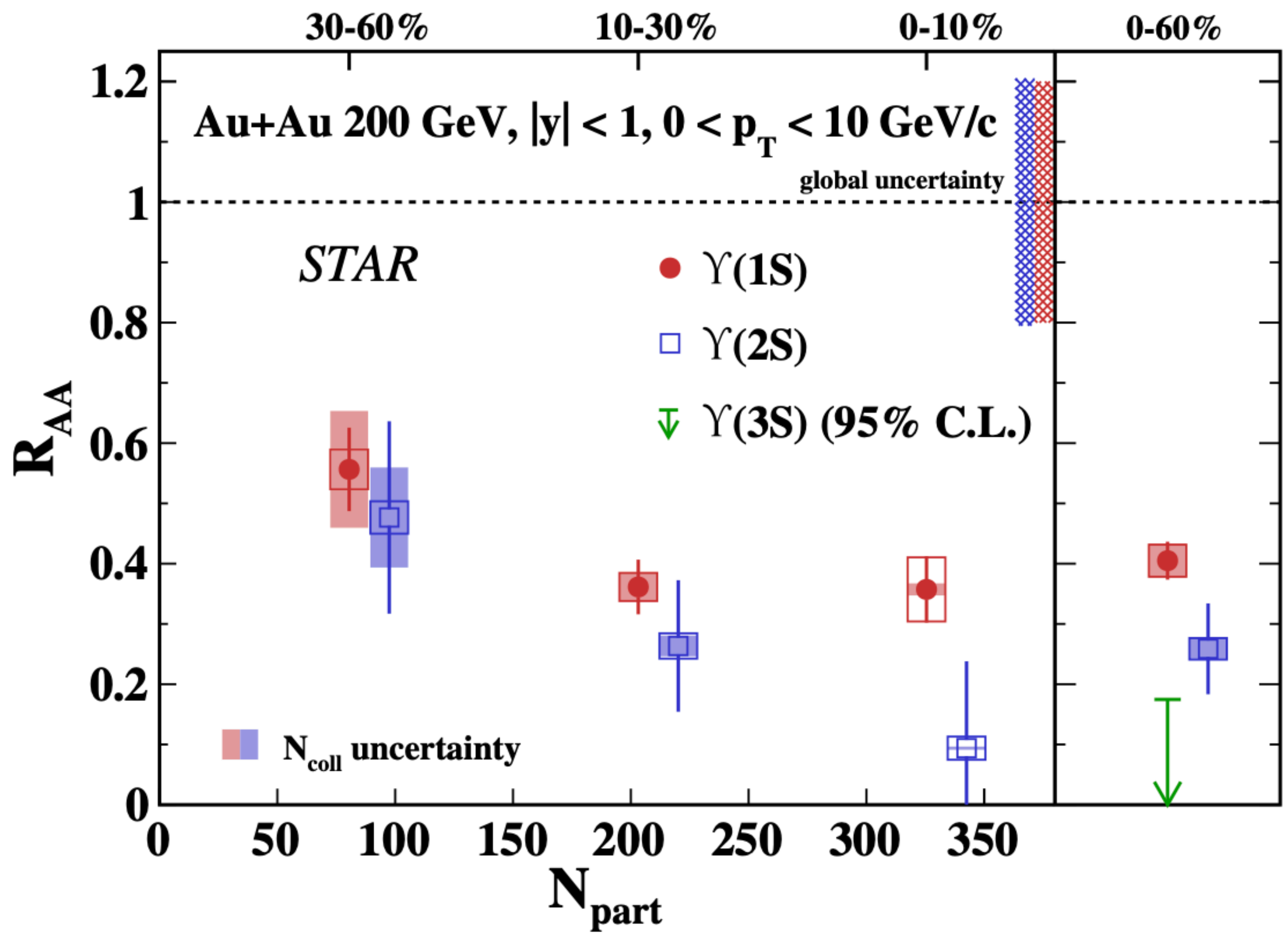
→ Sufficiently high QGP temperature to strongly suppress excited ϒ states

Quarkonium states in QGP

Bottomonium ϒ(nS) suppression in Au+Au and Isobar collisions

STAR, PRL 130 (2023) 112301



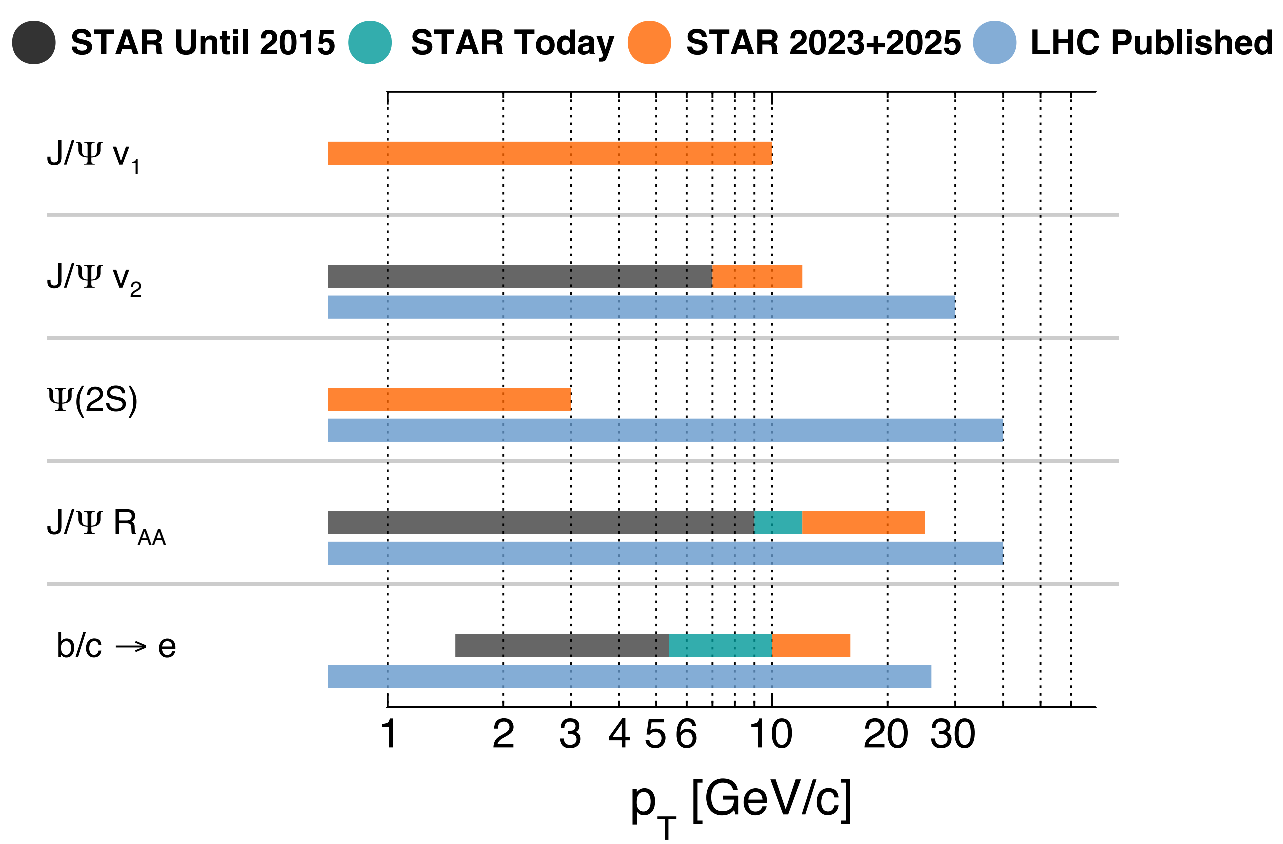


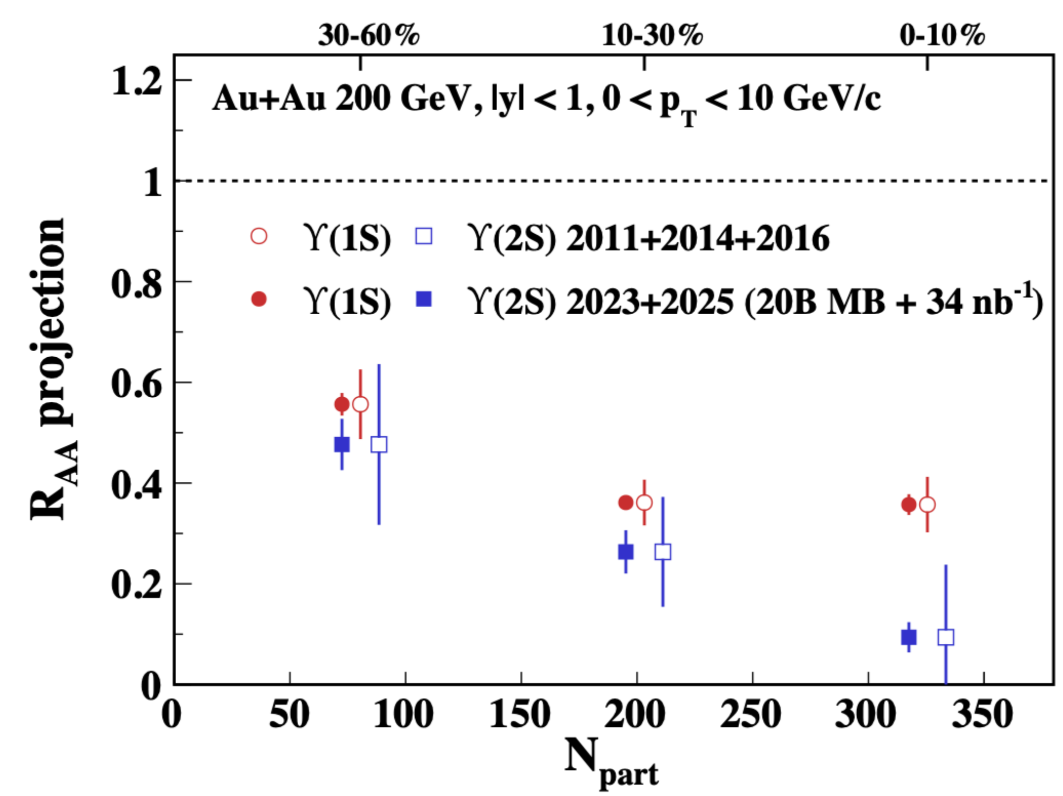
Same ϒ(1S) R_{AA} with similar N_{part} , independent of collision system

Summary and outlook

- Quarkonia—J/ψ, ψ(2s), Υ(nS)—sequential suppression in heavy-ion collisions
  → Informing QGP thermal properties at RHIC
  → Interplay of dissociation and regeneration effects at RHIC energies
  → Same R_{AA} with similar N_{part}, independent of collision system and energy

STAR 2023-2025 data taking plan for precision quarkonia measurements





Thank you!