中国科学技术大学
University of Science and Technology of China

Recent RHIC measurements on quarkonium production and suppression

Kaifeng Shen
University of Science and Technology of China
(skfwyl@ustc.edu.cn)

15th Conference on the Intersections of Particle and Nuclear Physics

11 June 2025

Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

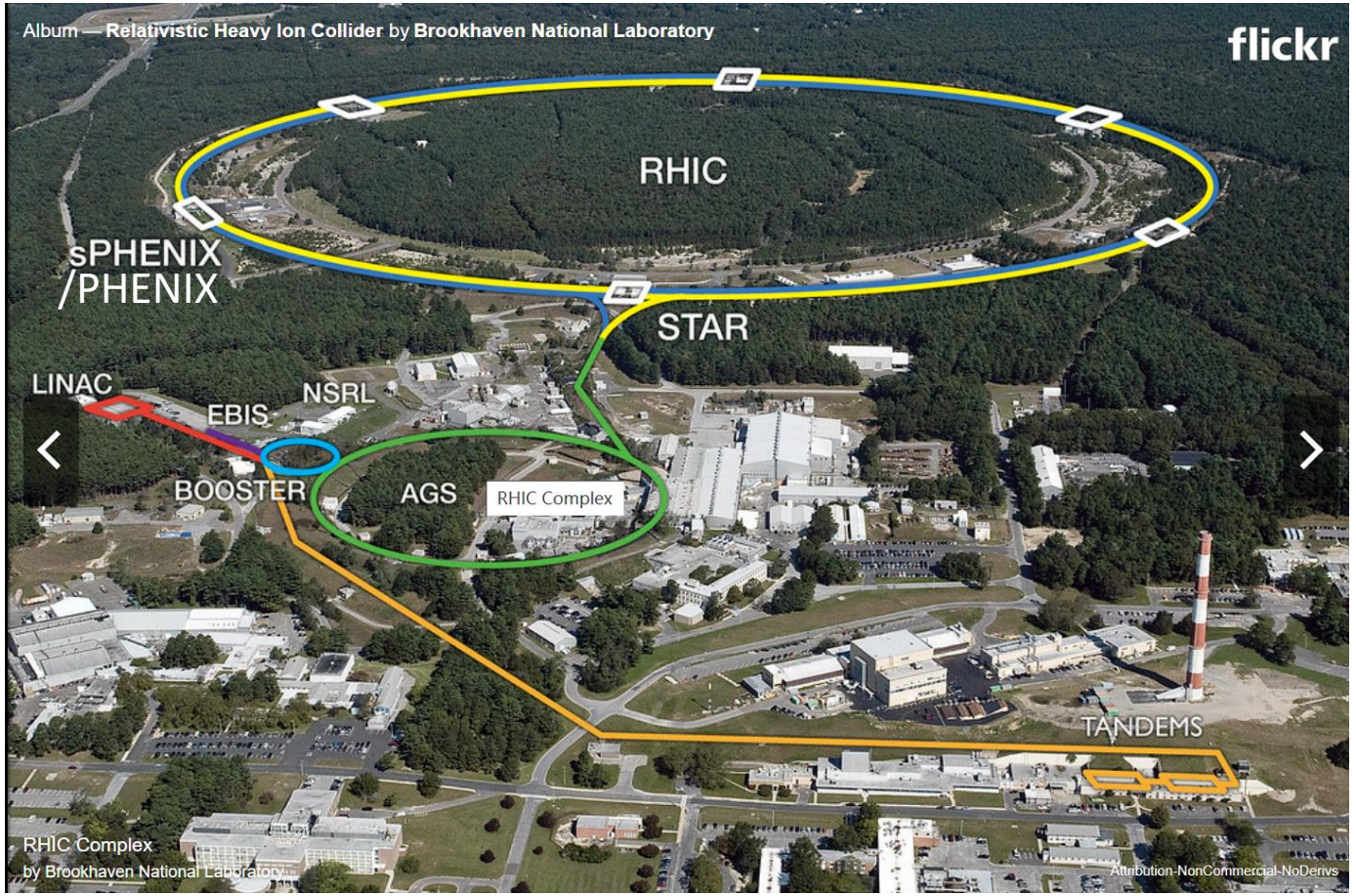
Outline

- Experimental Probes for Deconfinement
- Quarkonia Physics at RHIC
- Summary and Outlooks

Relativistic Heavy Ion Collider (RHIC)

- To explore some of Nature's most basic -- and intriguing -- ingredients and phenomena

Credit: the webpage of the physics of RHIC



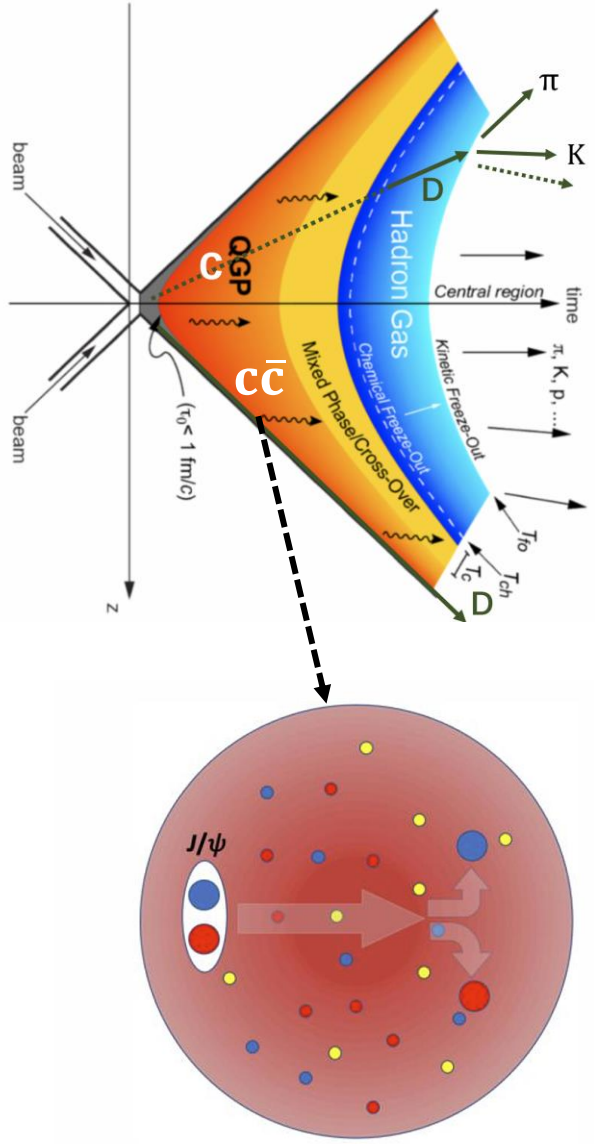
- Current experiments: STAR and sPHENIX

- Enters 25th and final run: RHIC science program will be completed and Transition to the Electron-Ion Collider

Experimental Probes for Deconfinement

Heavy-flavour as probes of the QGP

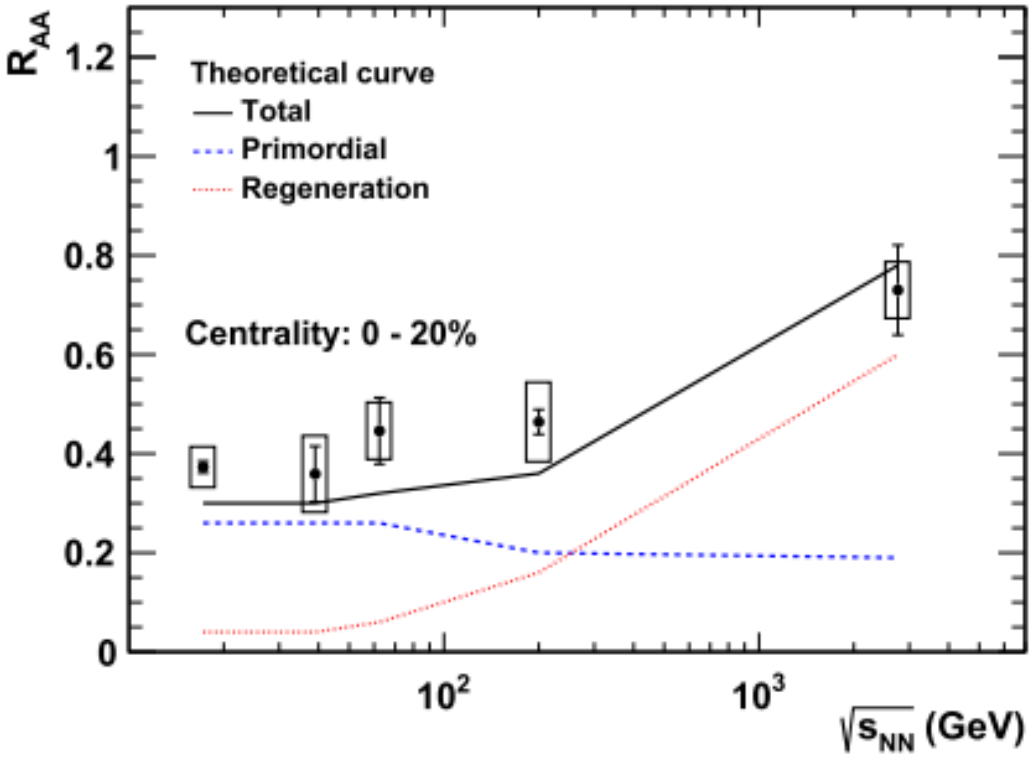
- Heavy quarks mainly produced from initial hard partonic scattering, $m_{c,b} > \Lambda_{\mathrm{QCD}}$
- Experience the entire evolution of the QPG, loss energy through Gluon radiation or Collisional energy loss
- The $Q\bar{Q}$ pair bound state can be dissociated or regenerated in the QGP



Credit: Boris Hippolyte & Qian Yang

Quarkonia production at RHIC

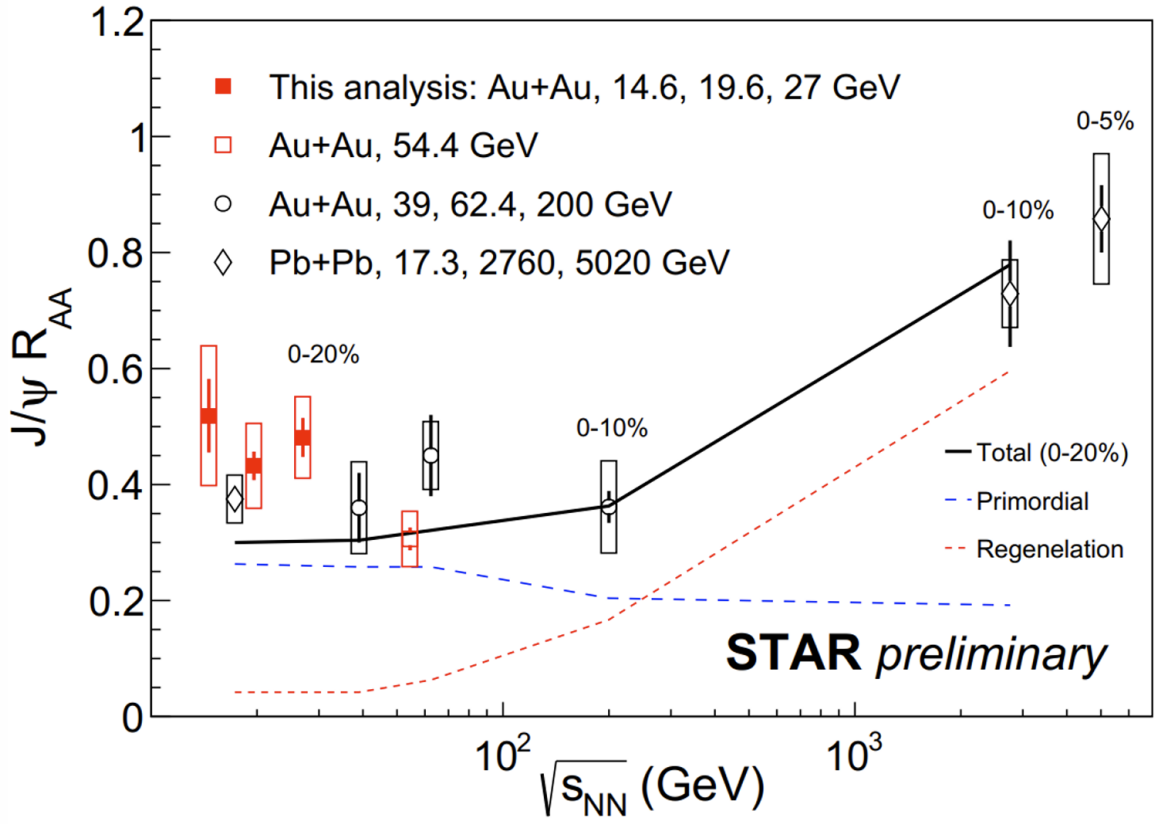
Collision energy dependence of QGP property



(STAR) Phys. Lett. B 771 (2017) 13-20

- Measurement J/ψ suppression at different collision energies → understand collision energy dependence of QGP property
- Beam Energy Scan Ⅱ at STAR: Unique opportunity to study the collision energy dependence, 10-20 times higher statistics than BES-Ⅰ

J/ψ suppression measured at different energies



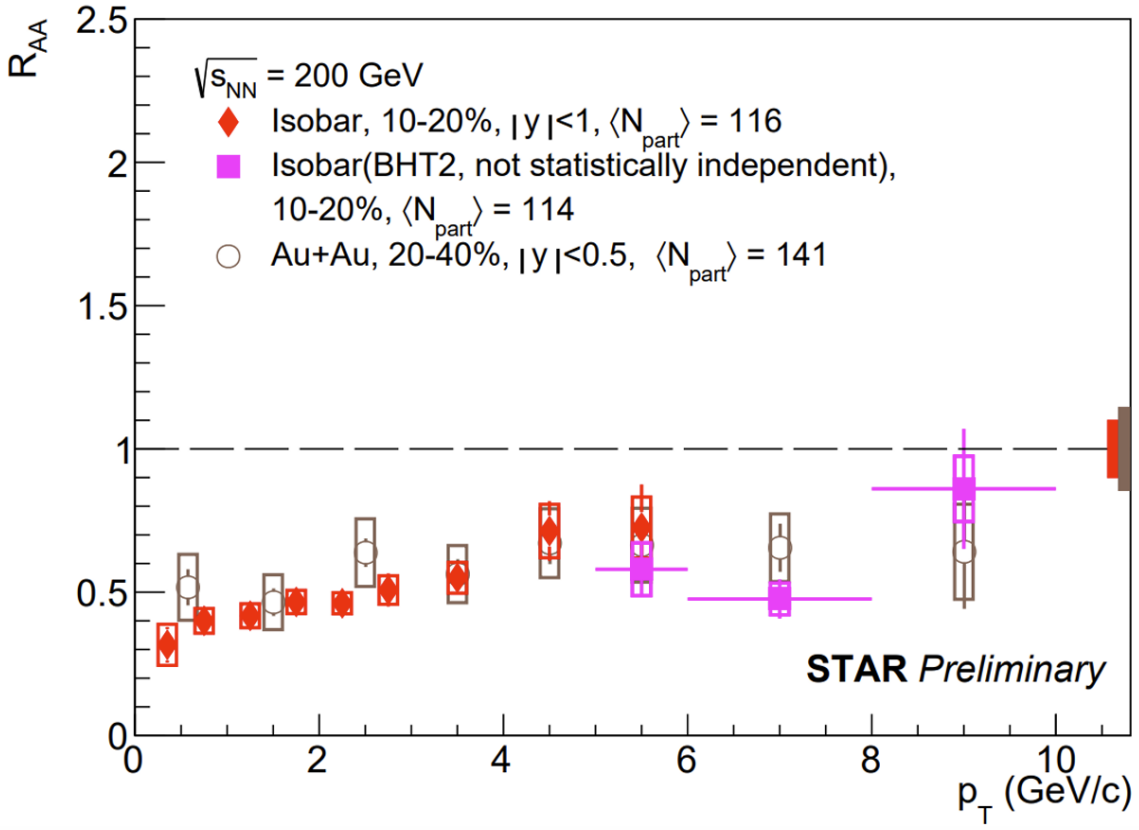
- No significant energy dependence of nuclear modification factor within uncertainties at $\sqrt{S_{NN}} \leq 200$ GeV

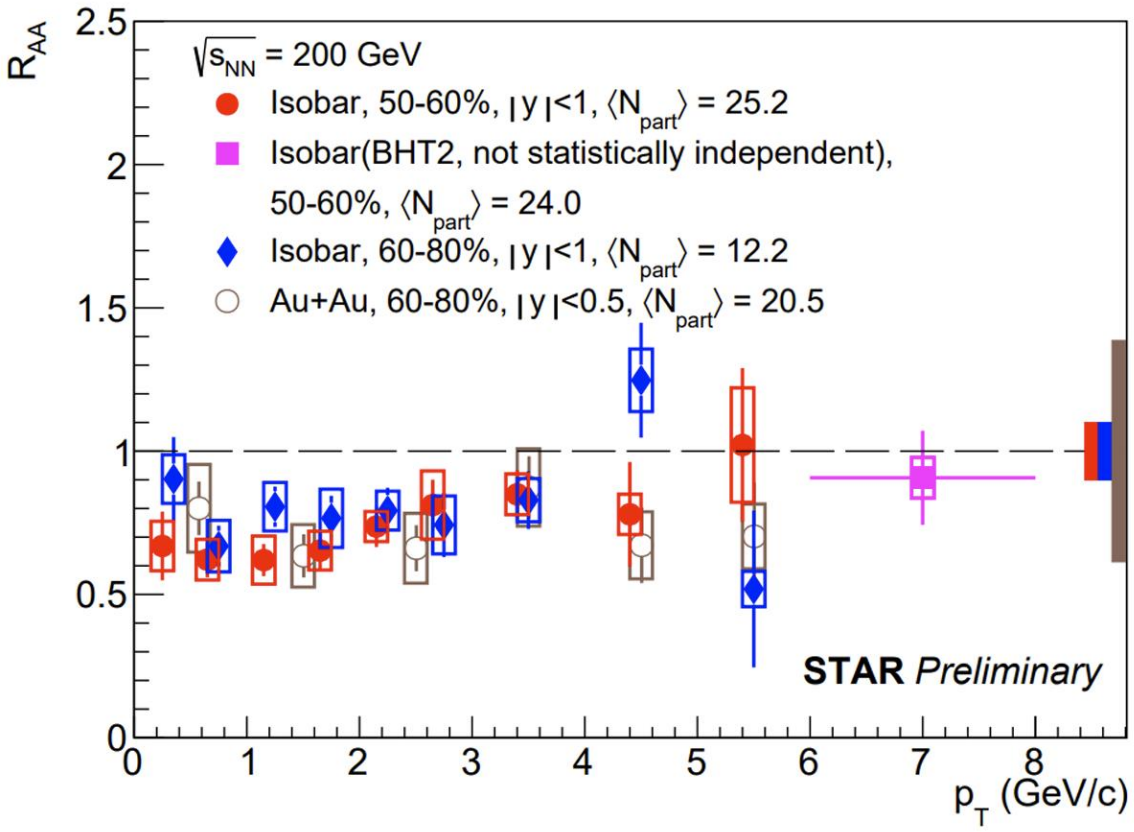
X. Zhao and R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication)

(NA50) Phys. Lett. B 477 (2000) 28
(ALICE) Phys. Lett. B 734 (2014) 314
(STAR) Phys. Lett. B 771 (2017) 13-20
(STAR) Phys. Lett. B 797 (2019) 134917
(ALICE) PLB 849 (2024) 138451

J/ψ suppression measured at different systems

- The size of hot and dense medium → the corresponding J/ψ suppression

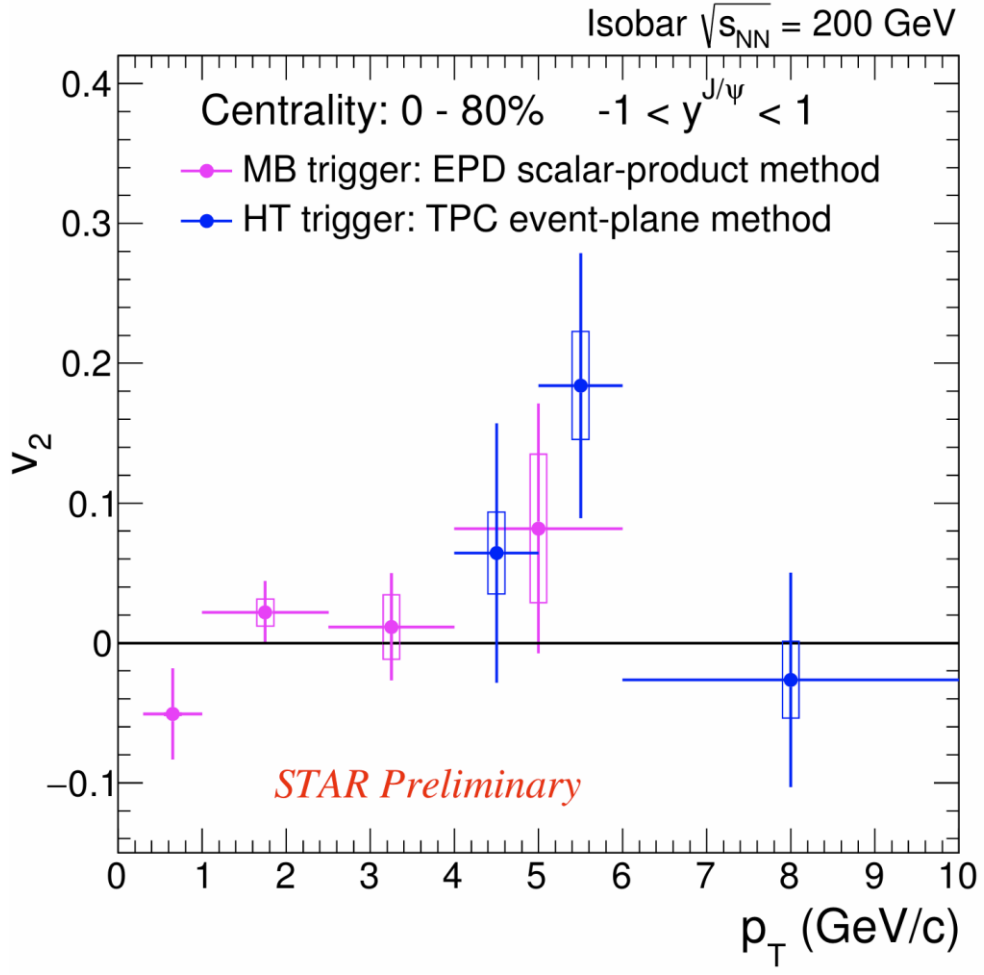




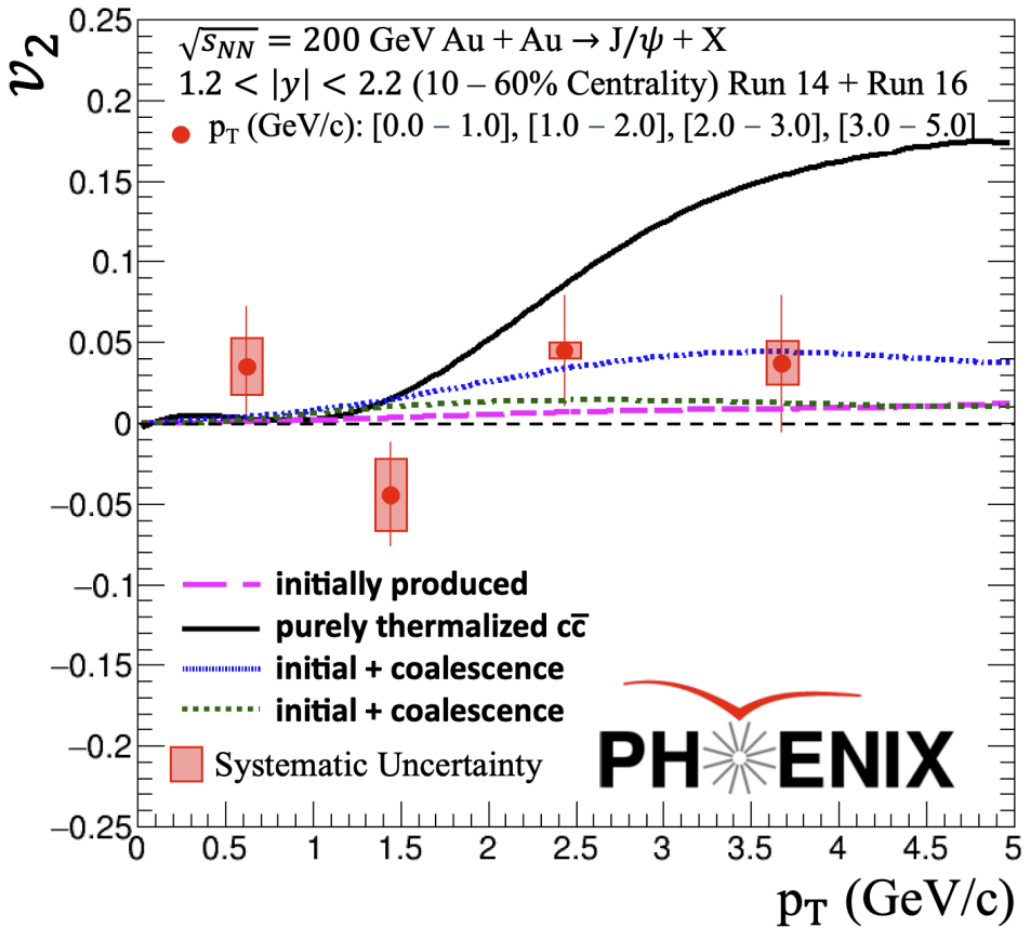
- In isobaric collisions, highest precision measurement at RHIC to date
- No significant collision system dependence of J/ψ suppression at similar $\langle N_{\mathrm{part}} \rangle$ range

J/ψ v_2 at RHIC top energy

- Charm quark thermalization level at RHIC



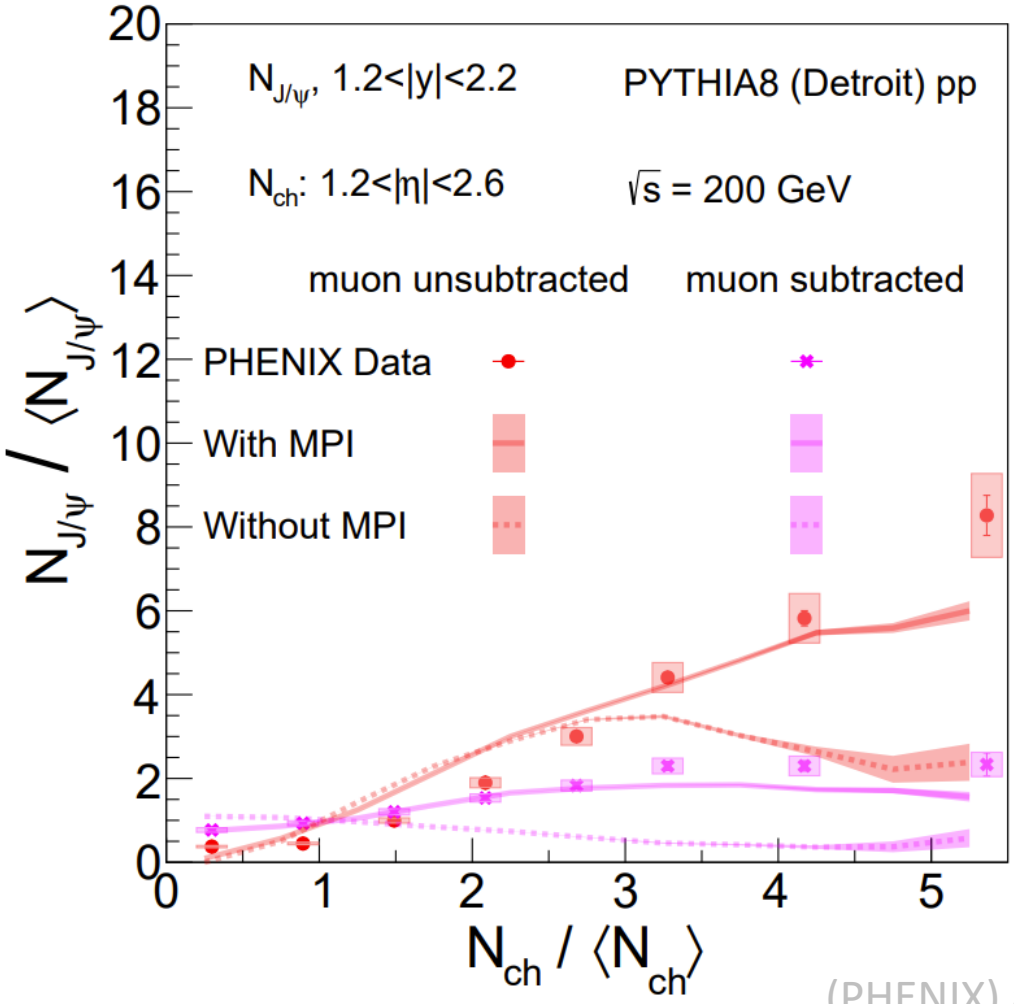
(PHENIX) arXiv:2409.12756



- Smaller regeneration effect at RHIC compared to that at LHC ?

J/ψ yield vs event multiplicity in p+p

- Sensitive to underlying event activities, MPI



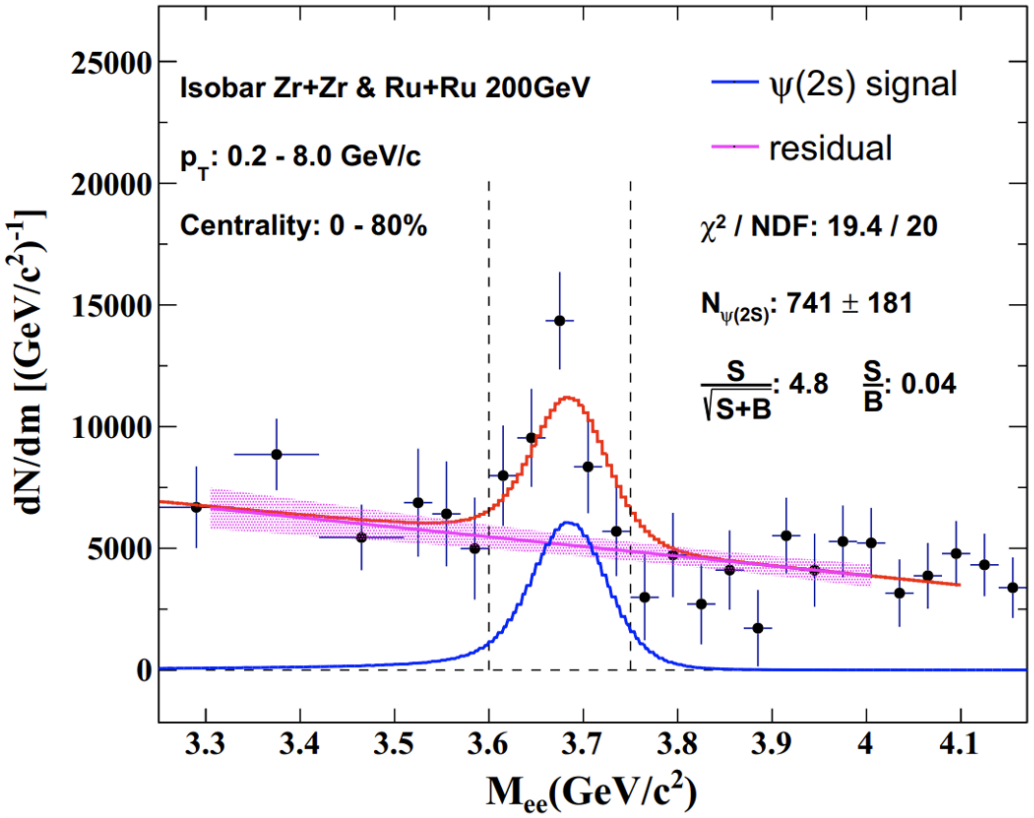
- After subtracting the J/ψ daughter-muon, the yields shift to lower $N_{\mathrm{ch}}/\langle N_{\mathrm{ch}} \rangle$

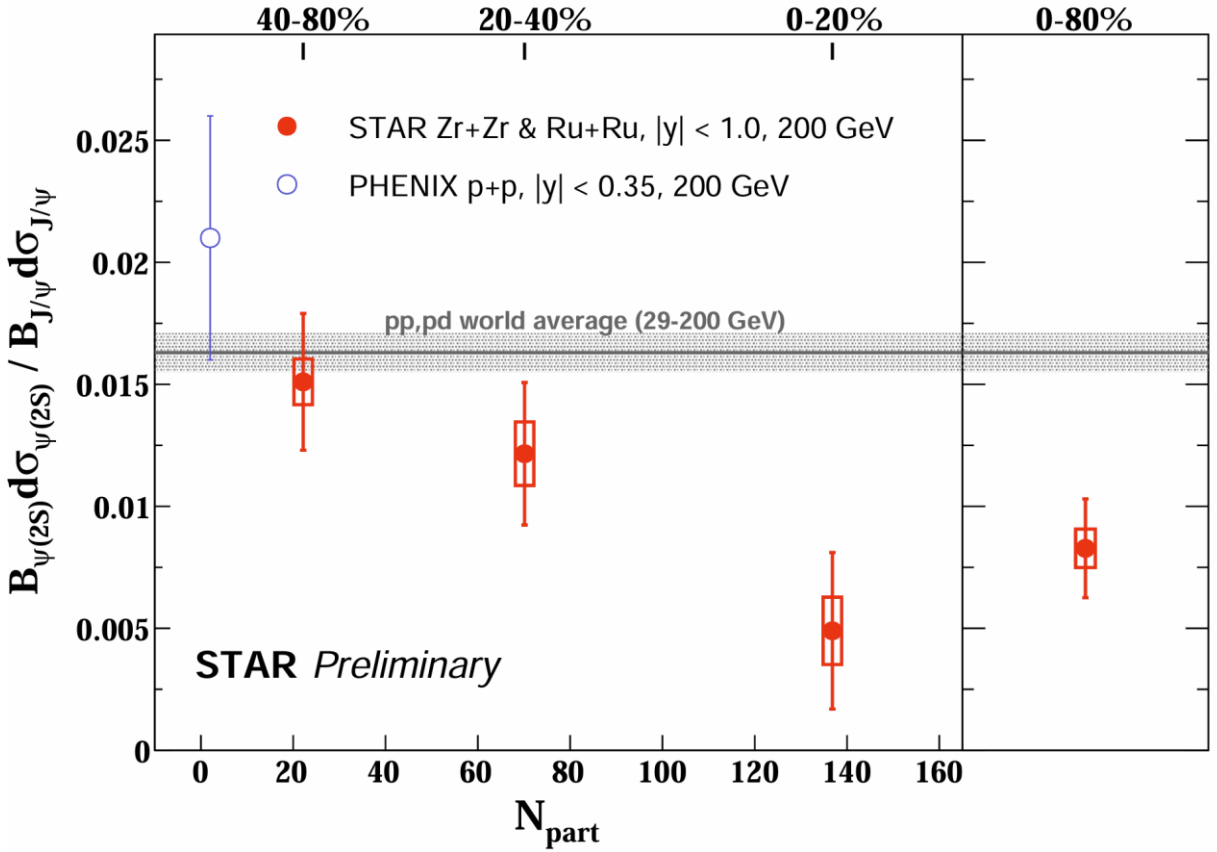
- The measurements are consistent with the PYTHIA 8 Detroit tuned with MPI calculations (within 1σ)

(PHENIX) arXiv:2409.03728

Charmonium sequential suppression

- The suppression level related to the binding energy of charmonium



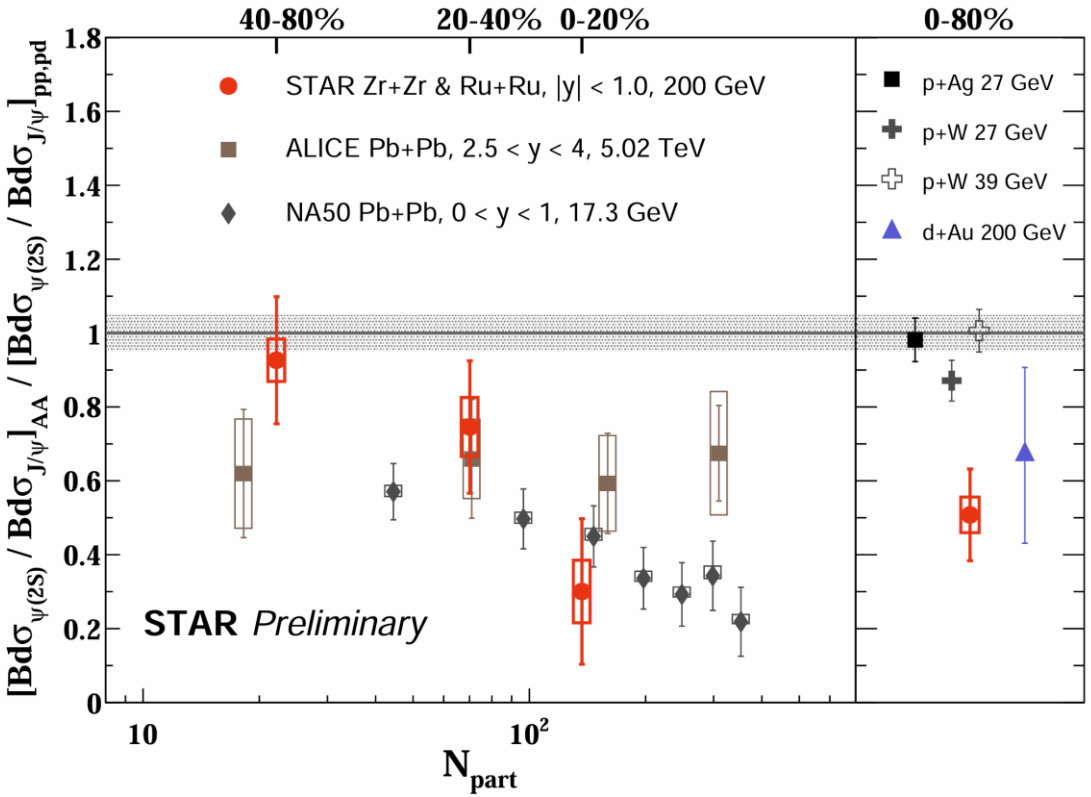


- A clear $\psi(2s)$ signal is observed in isobaric collisions

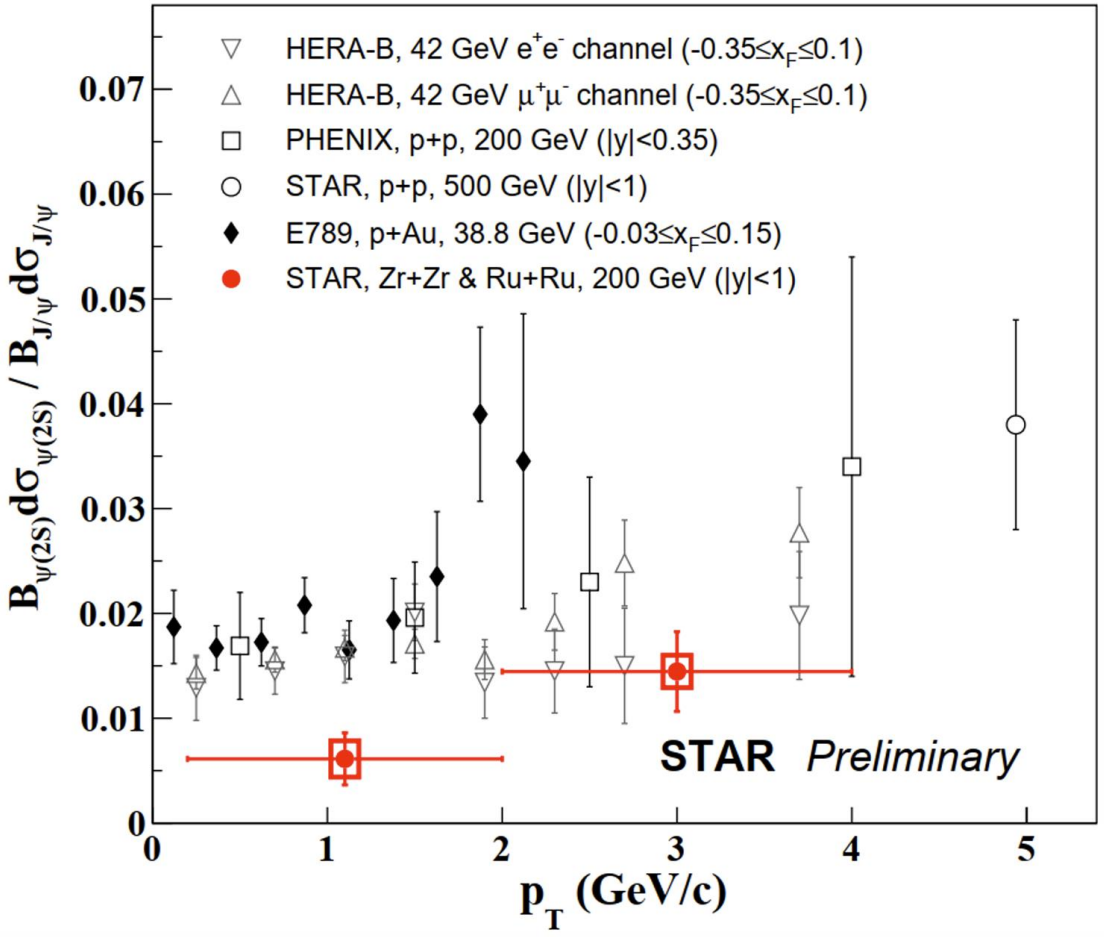
(PHENIX) Phys.Rev.D, 85,092004 (2012)
(NA51) Phys.Lett.B 438 (1998) 35-40

- First observation of charmonium sequential suppression in heavy ion collisions at RHIC (3.5σ)

$\psi(2s)$ over J/ψ ratio vs centrality and p_{T}

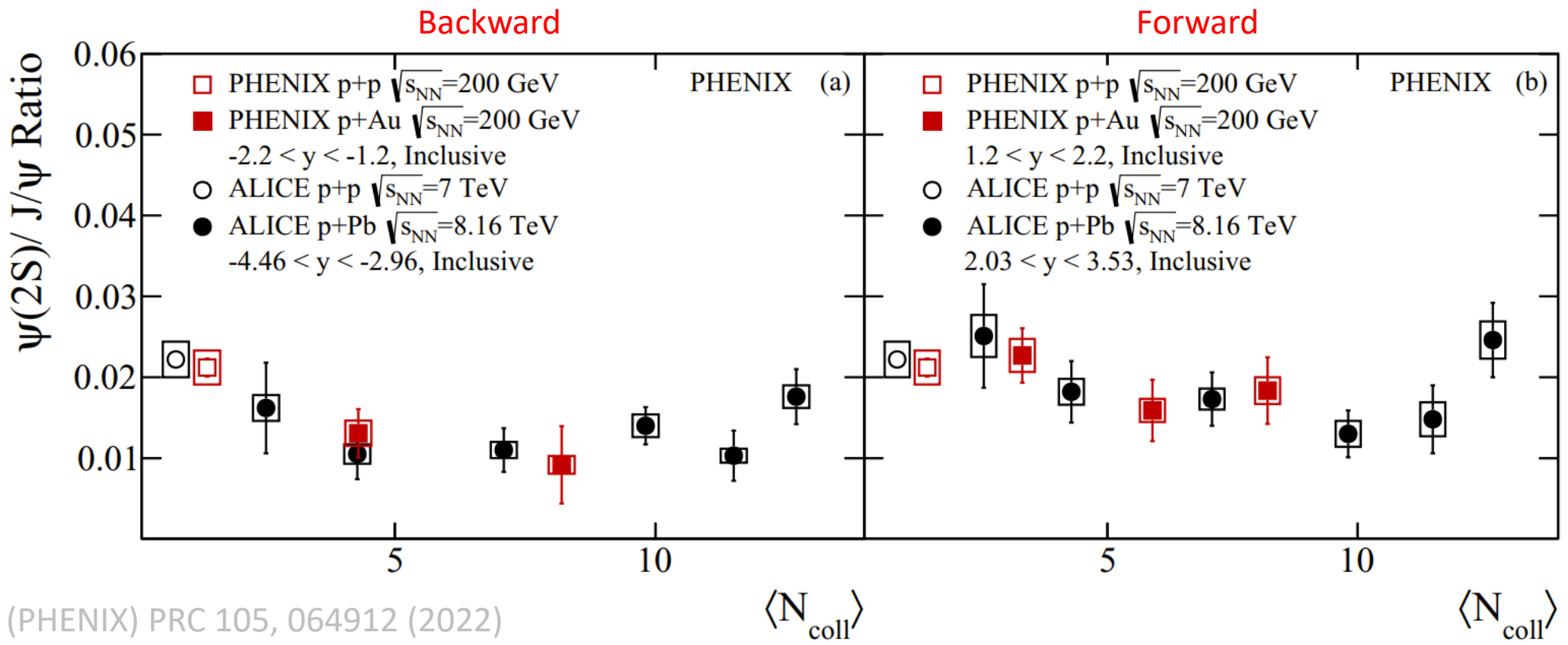


(PHENIX) Phys.Rev.D, 85,092004 (2012)
(NA51) Phys.Lett.B 438 (1998) 35-40



- Centrality dependence trend at RHIC seems more similar to that at SPS than at LHC
- Significantly lower than that in p+p and p+A collisions at p_{T} <2 GeV/c

$\psi(2s)$ over J/ψ ratio in p+A collisions at RHIC

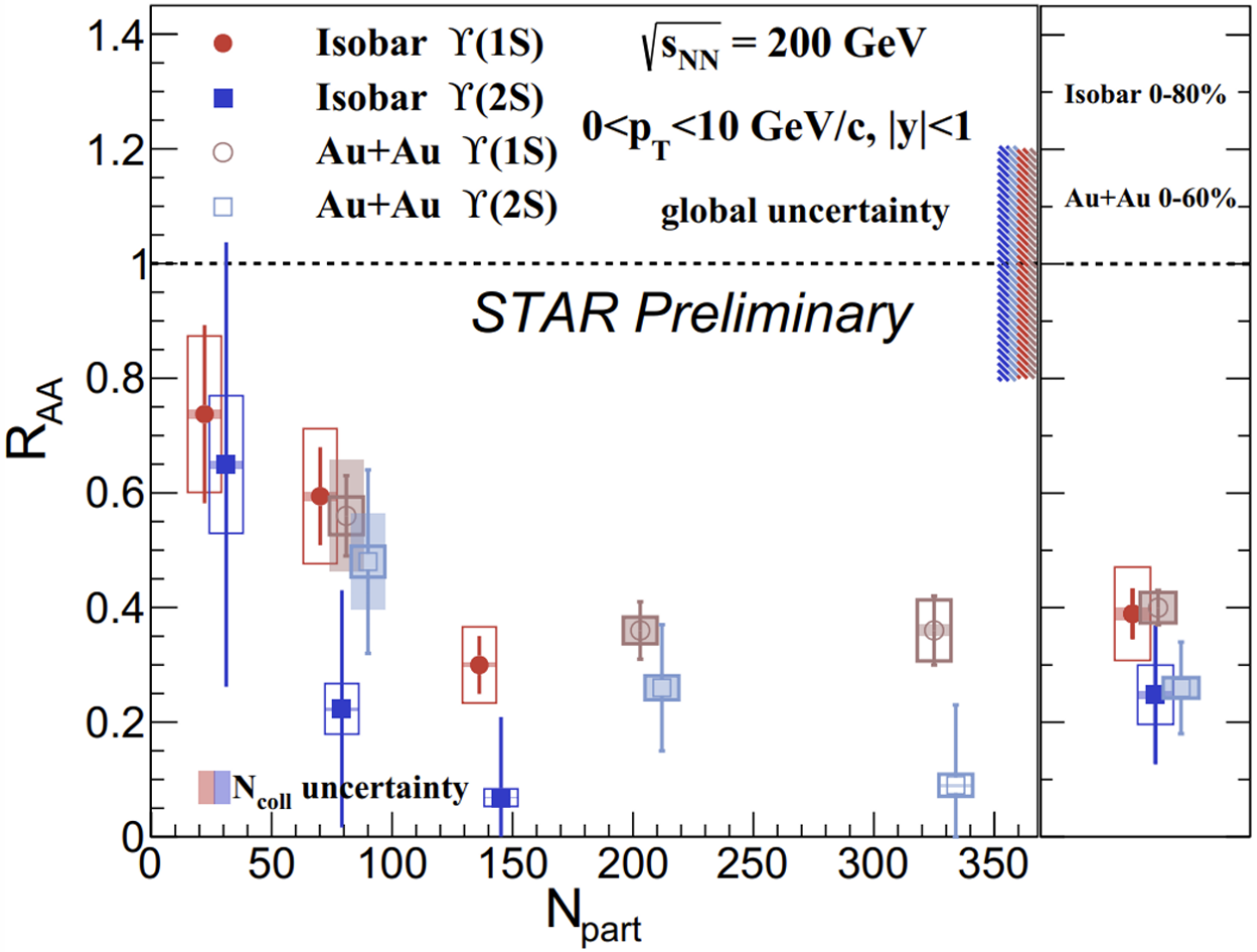


(PHENIX) PRC 105, 064912 (2022)
(ALICE) JHEP 02 (2021), 002

- Final stat effect is significant, and larger in the backward rapidity where multiplicity is higher
- Similar suppression pattern, weak energy dependence

ϒ suppression at different systems

- Smaller regeneration effect compared to charmonia



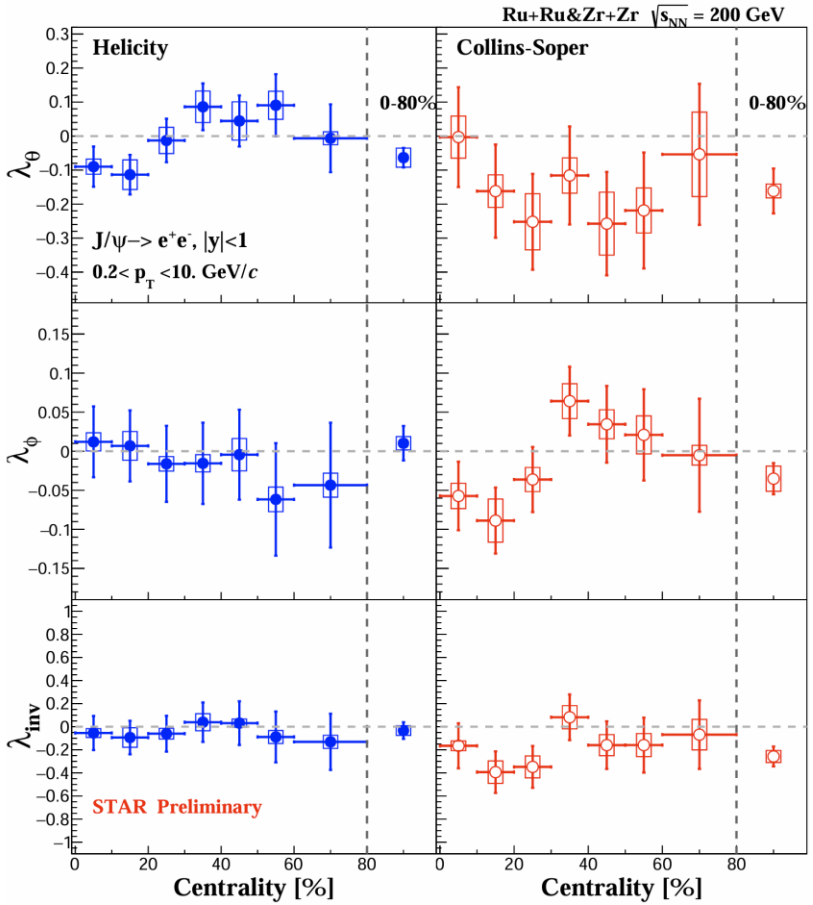
(STAR) Phys. Rev. Lett. 130 (2023) 112301

- Consistent suppression is observed between isobar and Au+Au collisions in similar $\langle N_{\mathrm{part}} \rangle$ range
- Hint of sequential suppression in isobaric collisions

Polarization and global spin alignment at RHIC

J/ψ polarization in isobaric collisions

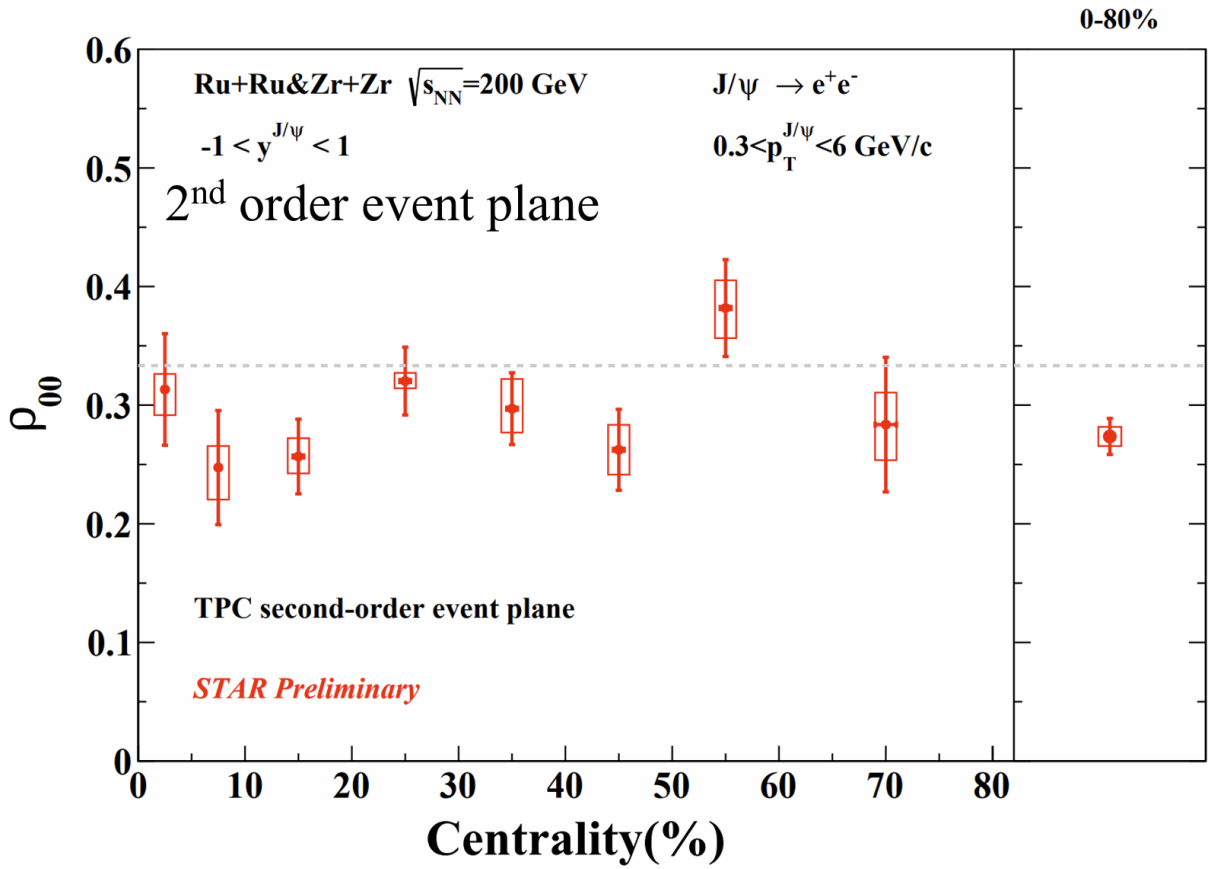
- J/ψ polarization → the production mechanism
- Possible difference between heavy ion collisions and p+p collisions
- The J/ψ decayed leptons: $w(\cos\theta, \phi) \propto 1 + \lambda_\theta cos^2\theta + \lambda_\phi sin^2\theta cos2\phi + \lambda_{\theta\phi} sin2\theta cos\phi$

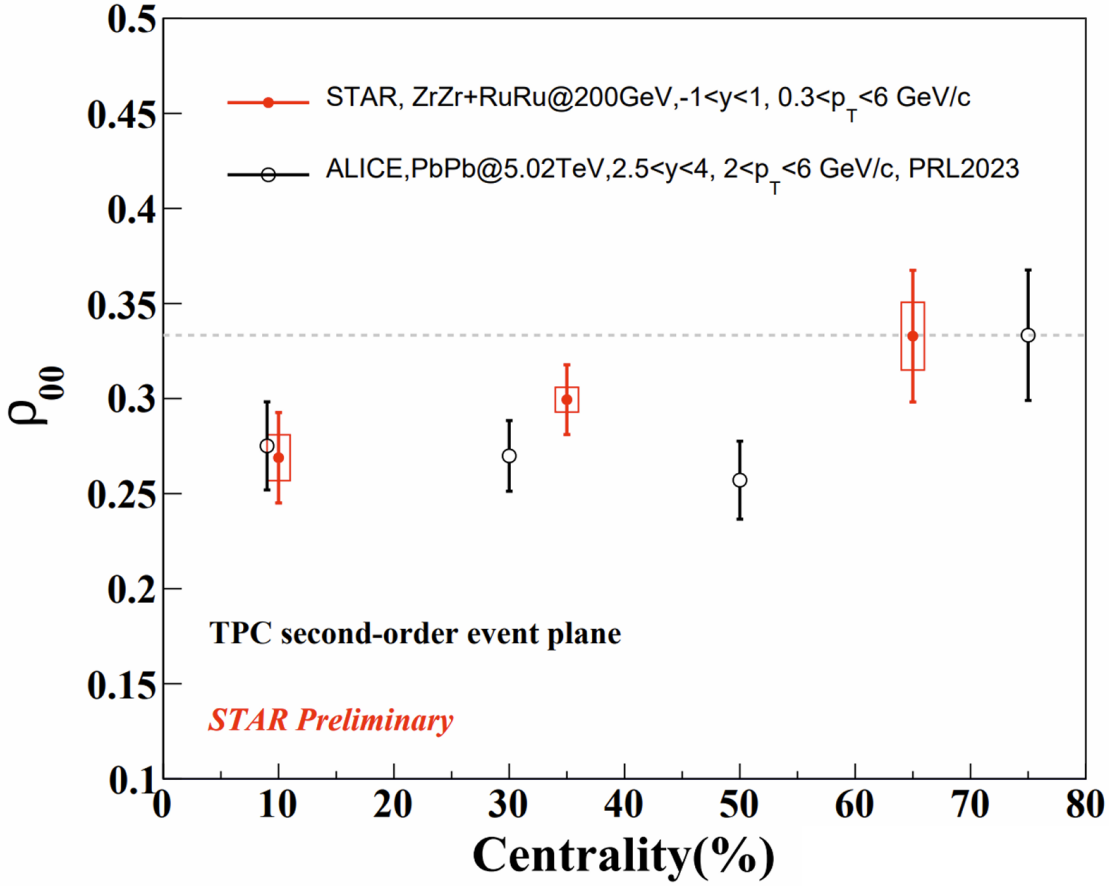


- λ_θ and λ_ϕ are consistent with zero within uncertainties, indicate that no polarization is observed within current uncertainties
- No significant centrality dependence is observed

J/ψ global spin alignment in isobaric collisions

- Respect to the Event Plane： axis orthogonal to reaction plane



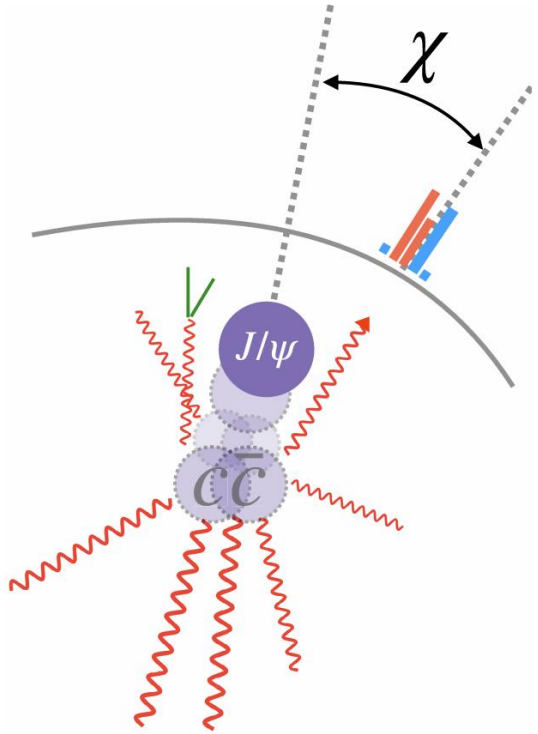


(ALICE) Phys. Rev. L 131 4, 042303 (2023)

- The ρ_{00} at RHIC is lower than 1/3 (3.5σ), and comparable to LHC results

Energy correlator with Quarkonia tagged at RHIC

J/ψ energy correlator

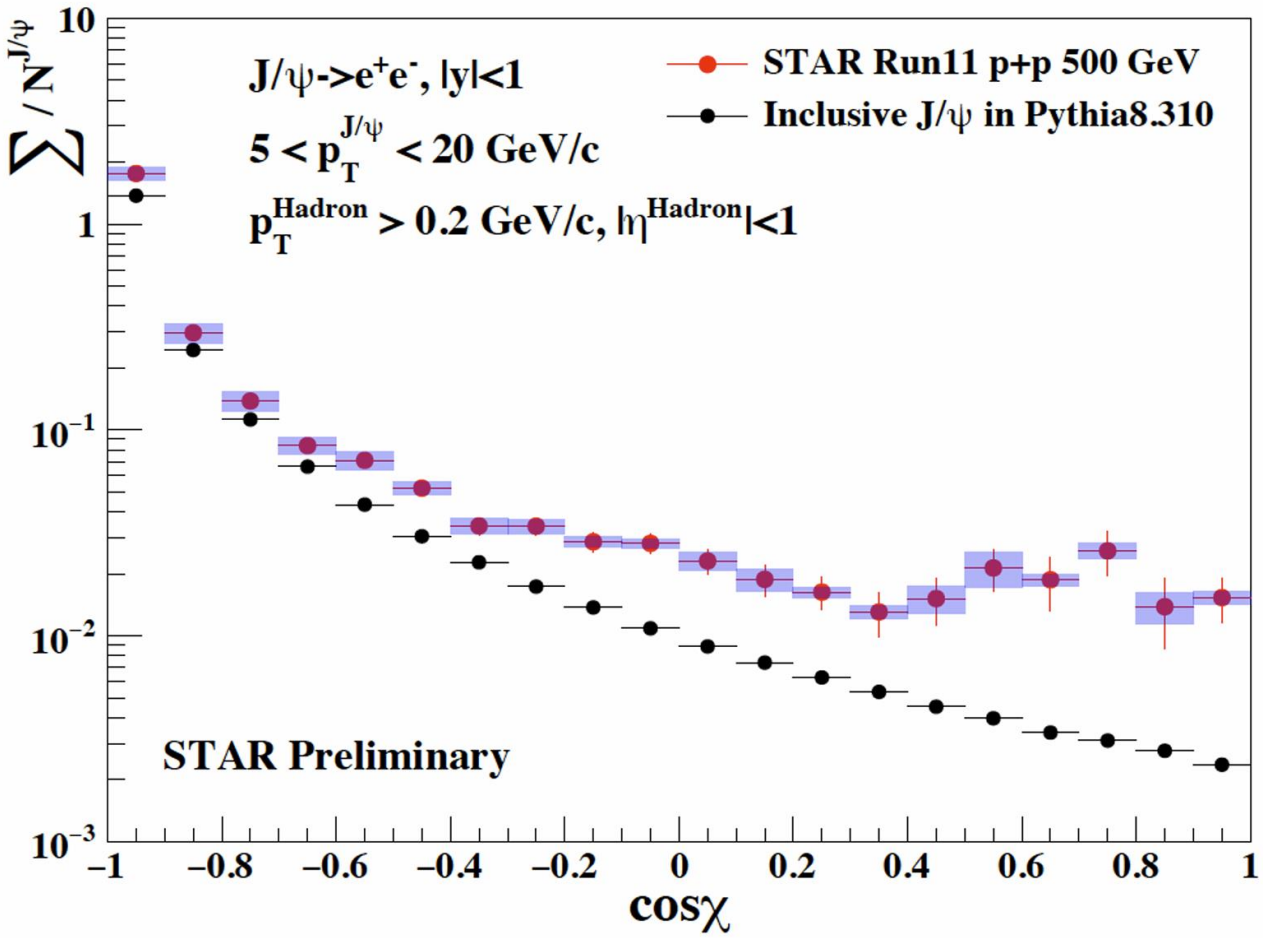


$$\Sigma(\cos\chi) = \int d\sigma \sum_i \frac{E_i}{M} \delta(\cos\chi - \cos\theta_i),$$

Phys. Rev. L 133, 191901 (2024)

- J/ψ as a tagged meson, sensitive to hadronization of $c\bar{c} \rightarrow$ J/ψ +X
- χ is measured in the J/ψ rest frame:
  - Perturbative processes contribution dominate at $\cos(\chi) < 0$
  - Non-perturbative processes contribution dominate at $\cos(\chi) \geq 0$

J/ψ energy correlator measured at RHIC-STAR



- The J/ψ energy correlator has been measured firstly at STAR in p+p collisions at $\sqrt{s} = 500$ GeV

- No significant $\cos(\chi)$ dependence of the J/ψ energy correlator at $\cos(\chi) > 0$, while the measurement is different compared to that in Pythia8 ($\sim 7\sigma$)

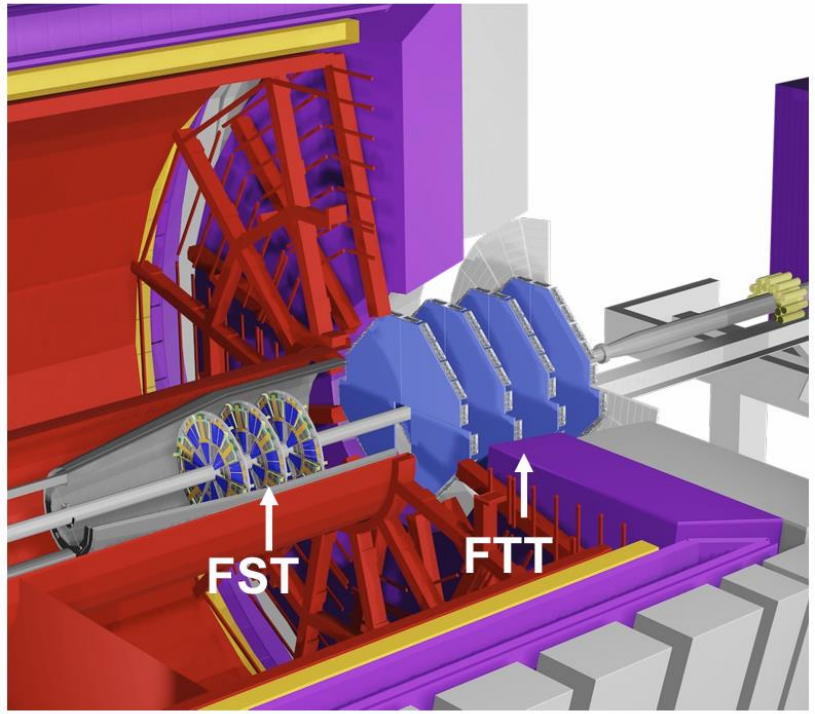
Summary

◘ Quarkonia at RHIC:

- Collision energy and system dependence: no significant dependence has been observed; first measured charmonium sequential suppression in heavy ion collisions at RHIC
- Polarization and spin alignment in heavy-ion collisions: J/ψ polarization around zero, ρ_{00} at RHIC is lower than 1/3 (3.5σ)
- Hadronization process: first measured J/ψ energy correlator in p+p collisions
- Photo-nuclear production: coherent J/ψ strongly suppressed; evidence of decay anisotropy

Outlook： STAR experiment

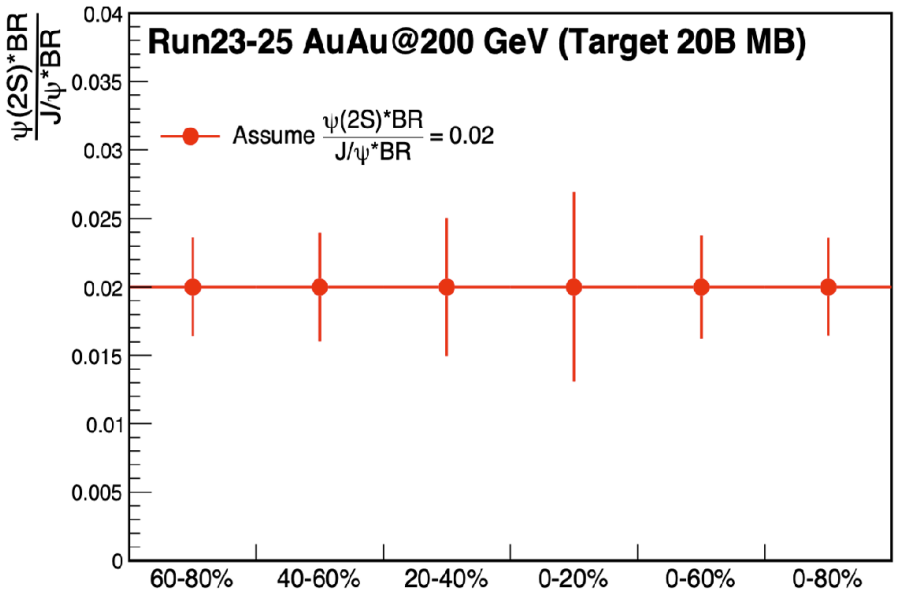
- Run23-25: large samples of p+p, (p+Au), and Au+Au collisions
- STAR forward upgrade(2.5<|η|<4): Forward Tracking System & Forward Calorimeter System



2.5 < η < 4

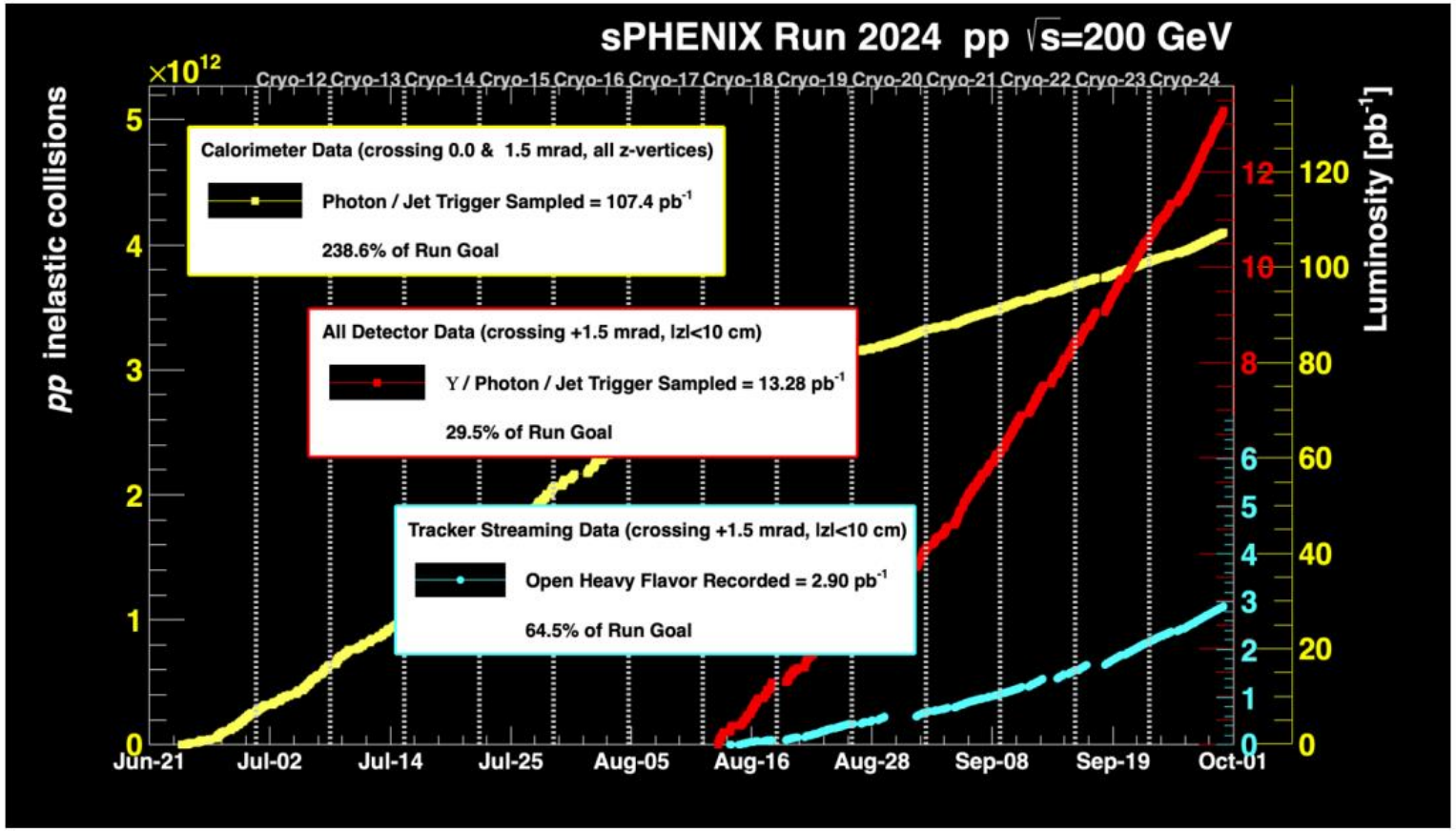
Zhen Wang@QM2023

STAR BUR Run25 2024



$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	8B+**5B** / 1.2 nb^{-1}+**20.8 nb^{-1}**	2023+2024+**2025 (20 cryo-weeks)**
200	Au+Au	8B+**9B** / 1.2 nb^{-1}+**28.6 nb^{-1}**	2023+2024+**2025 (28 cryo-weeks)**

Outlook： sPHENIX experiment

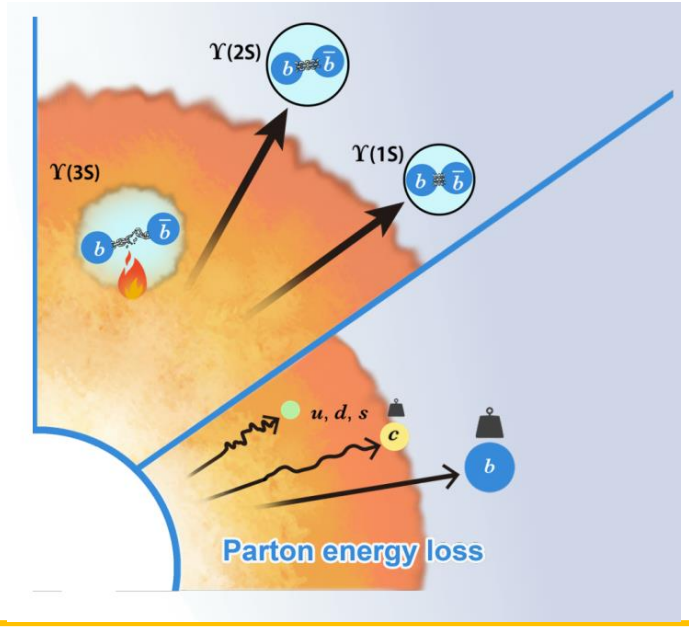


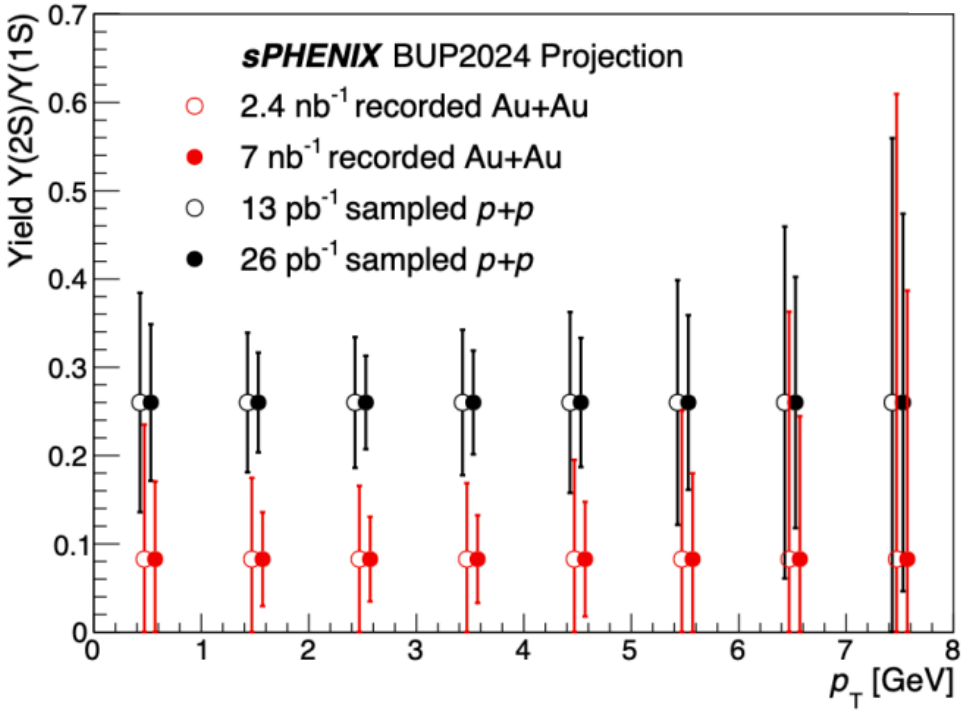
Alex Patton @ RHIC&AGS 2025

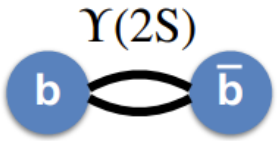
- During Run24, 107 pb^{-1} photon/Jet calorimeter data, 13.28 pb^{-1} photon/Jet full detector data, as well as 2.9 pb^{-1} of streaming tracker data in p+p collisions
- The full physics Run25 are ongoing (7 nb^{-1} in Au+Au)

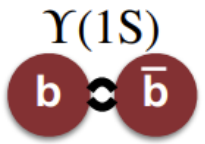
Outlook： Quarkonia at sPHENIX

- Quarkonia physics at sPHENIX:
  - Probing transport coefficients
  - Heavy-quark potential
  - (p)NRQCD formalism
  - …

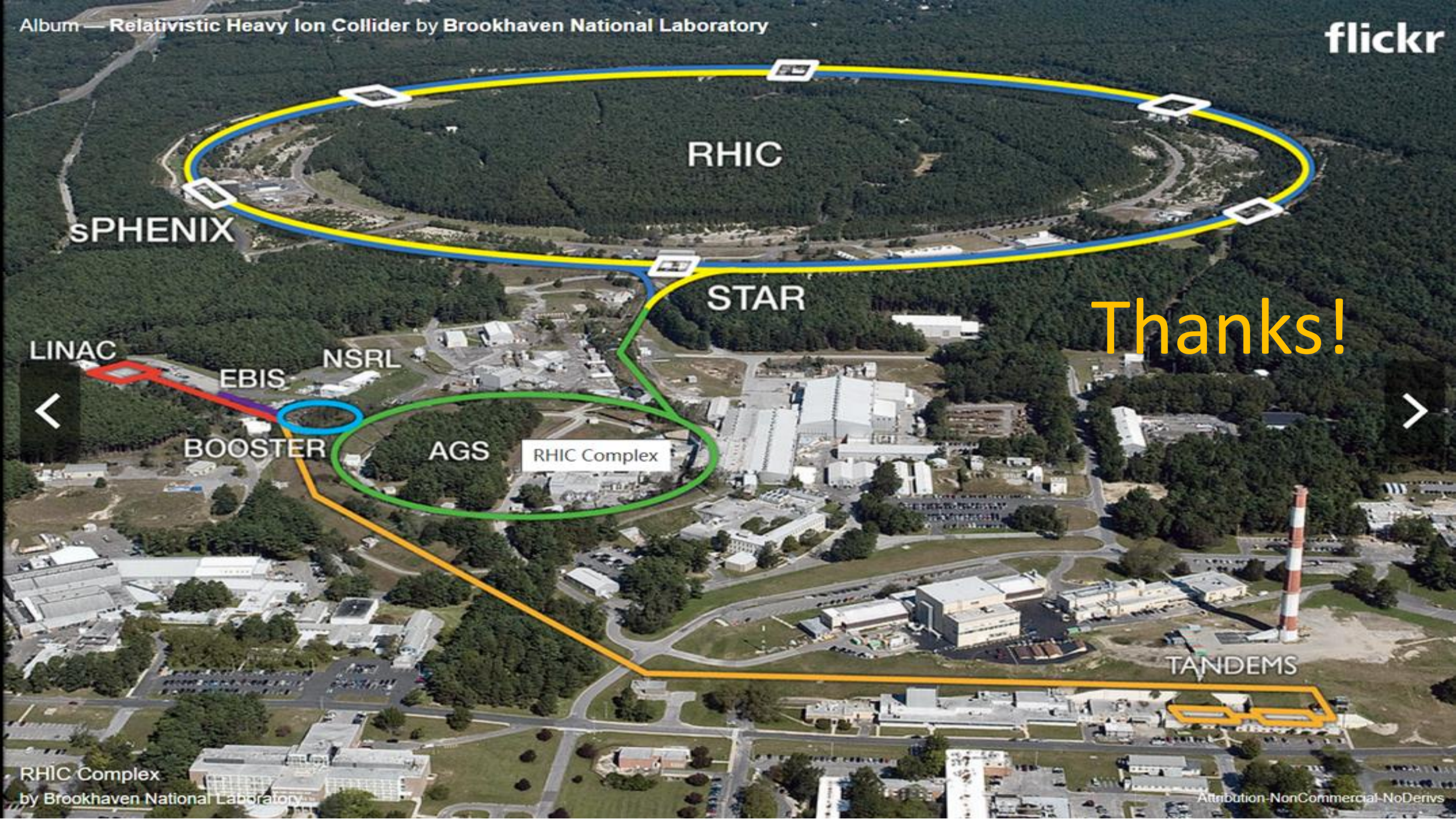






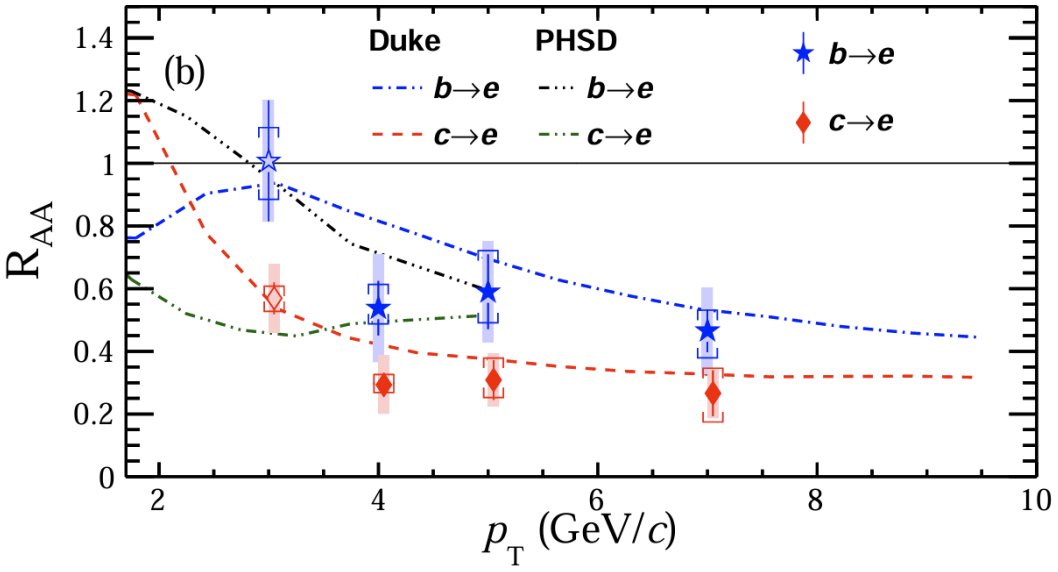


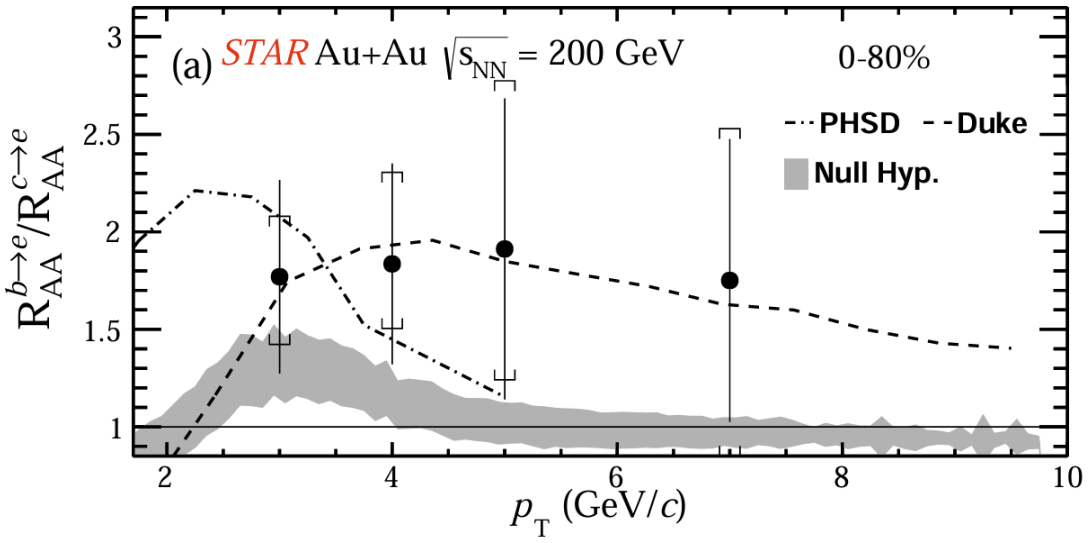
JaeBeom Park @ RHIC&AGS 2025


Album — Relativistic Heavy Ion Collider by Brookhaven National Laboratory
flickr
RHIC
sPHENIX
STAR
Thanks!
LINAC
EBIS
NSRL
BOOSTER
AGS
RHIC Complex
TANDEMS
RHIC Complex
by Brookhaven National Laboratory
Attribution-NonCommercial-NoDerivs

Back up

b/c → e: energy loss in QGP

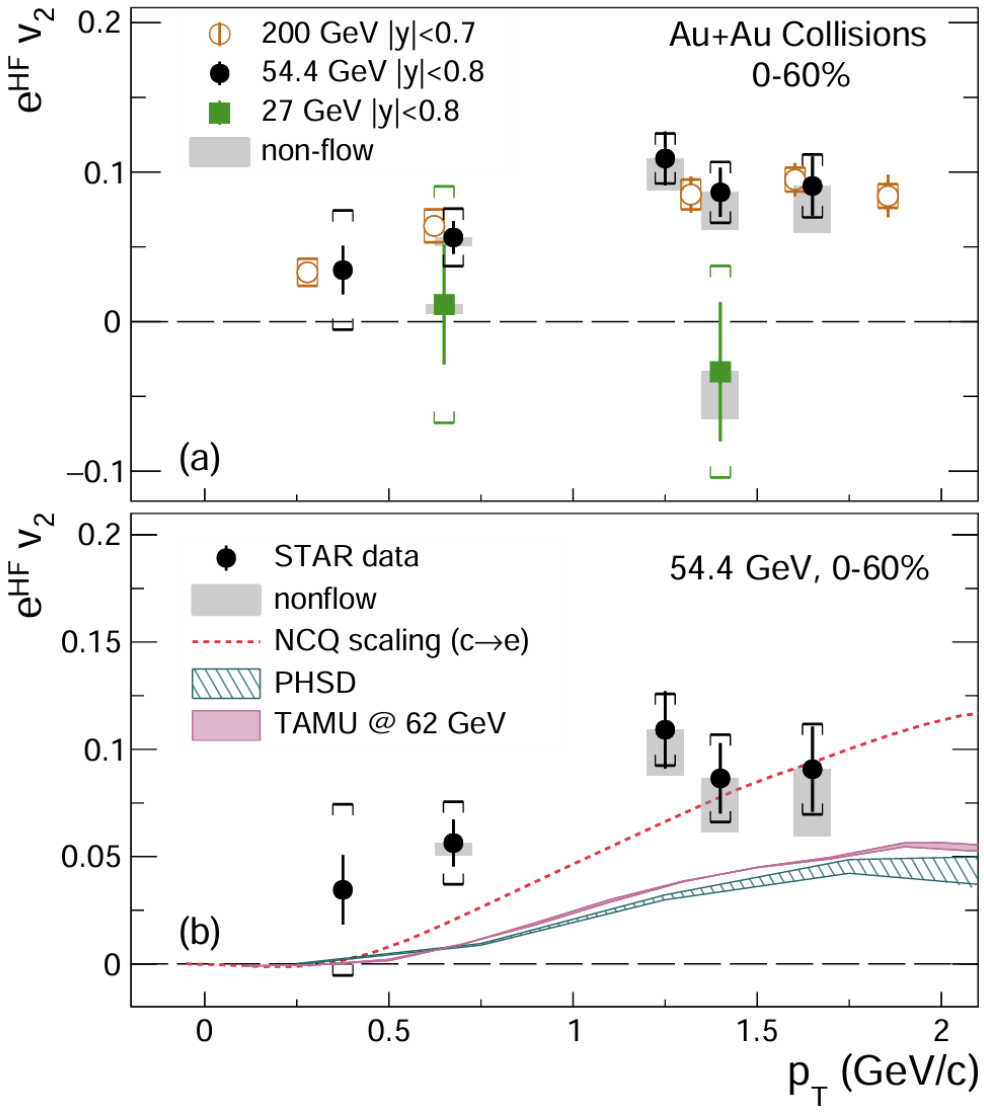




- The b/c-decay electron R_{AA} are suppressed at high-p_T in Au+Au collisions at 200 GeV
- The b-decay electron R_{AA} are systematically larger than c-decay R_{AA}, consistent with mass hierarchy of parton energy loss
- Consistent with model calculations including mass-dependent energy loss mechanisms

(STAR) EPJC 82 (2022) 1150
Duke: Phys. Rev. C 92, 024907 (2015)
PHSD: Phys. Rev. C 78, 034919 (2008), Nucl. Phys. A 831, 215 (2009)

b/c → e: collectivity in QGP



- The e^{HF} have non-zero and comparable v_2 in Au+Au collisions at 54.4 and 200 GeV → indicates that charm quarks interact strongly with the QGP medium
- The e^{HF} v_2 at 27 GeV Au+Au collisions are consistent with zero
- The e^{HF} v_2 at 54.4 GeV Au+Au collisions are Consistent with model calculations, which assume that elastic collision scattering dominated

(STAR) Phys. Lett. B 844 (2023) 138071
TAMU: Phys. Rev. C 91,024904 (2015).
PHSD: Phys. Rev.C 92, 014910 (2015), Phys. Rev. C 96,014905 (2017)