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Overview of Open Heavy Flavor and Quarkonia Physics at STAR

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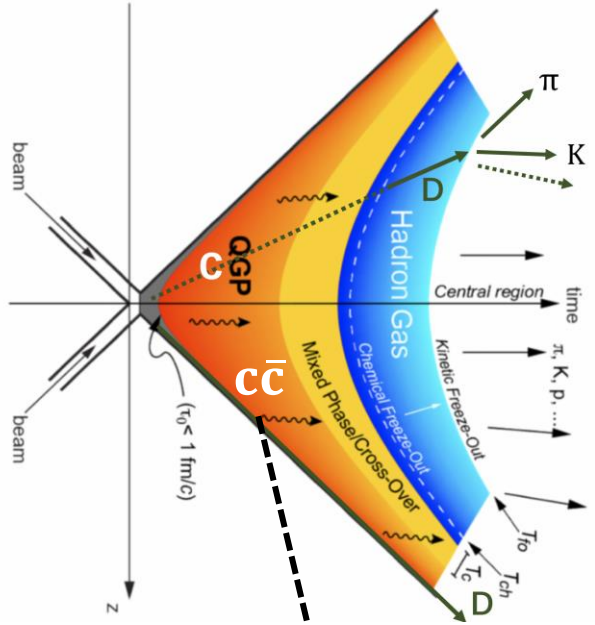
Outline

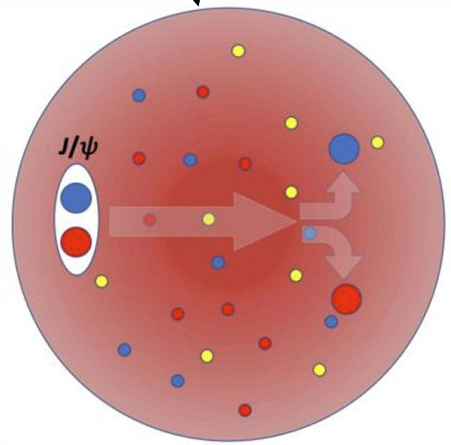
- Experimental Probes for Deconfinement
- Open Heavy Flavor Physics at STAR
- Quarkonia Physics at STAR
- Summary and Outlooks

Experimental Probes for Deconfinement

Heavy-flavour as probes of the QGP

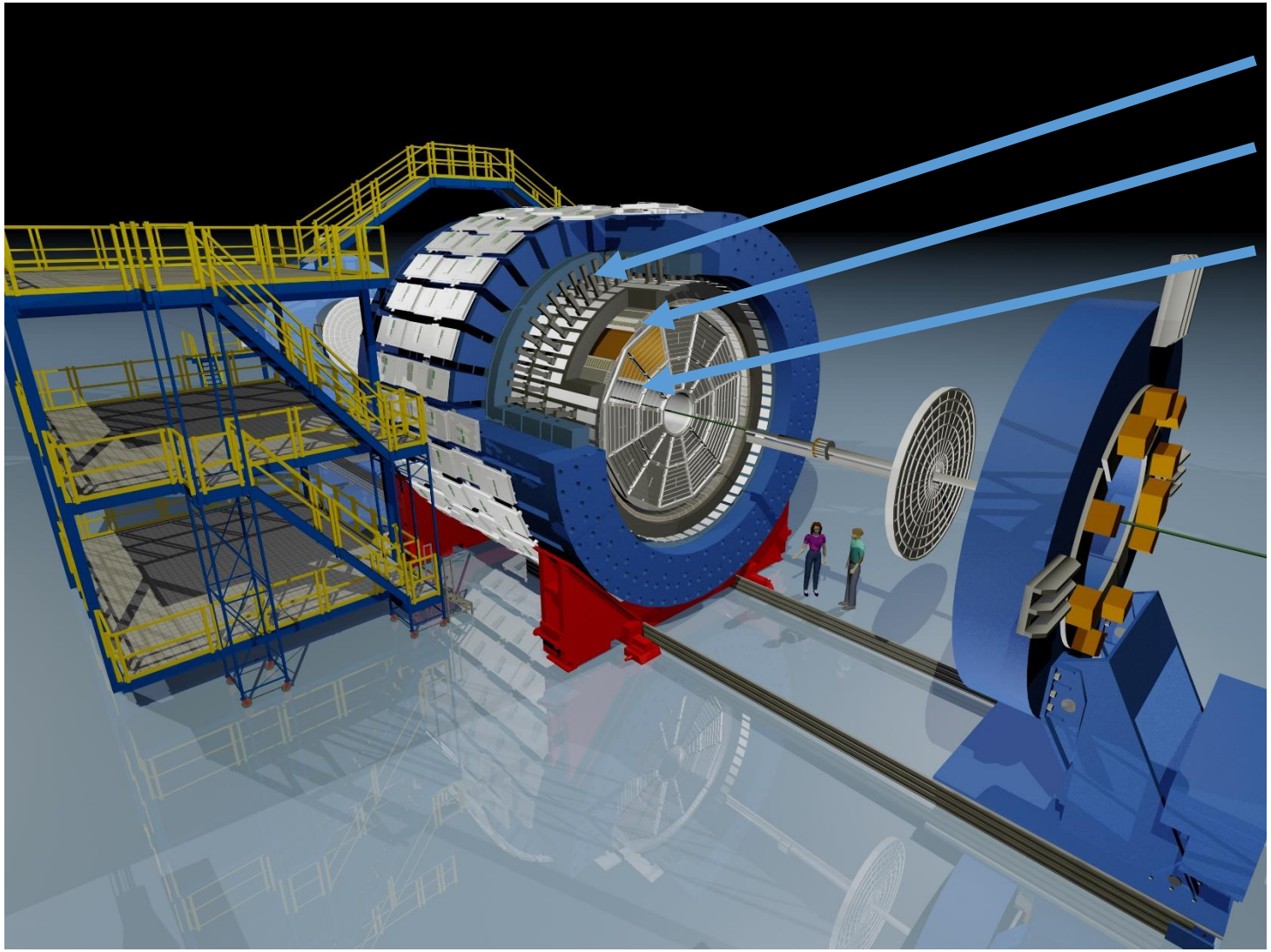
- Heavy quarks mainly produced from initial hard partonic scattering, $m_{c,b} > \Lambda_{\mathrm{QCD}}$
- Experience the entire evolution of the QPG, loss energy through Gluon radiation or Collisional energy loss
- The $Q\bar{Q}$ pair bound state can be dissociated or regenerated in the QGP





Credit: Boris Hippolyte & Qian Yang

The Solenoid Tracker At RHIC



- ✓ BEMC: Triggering, E_0/p, high p_T electron identification
- ✓ TOF: Time of flight, particle identification
- ✓ TPC: Tracking, momentum and particle identification(dE/dx)

Presented collision system:

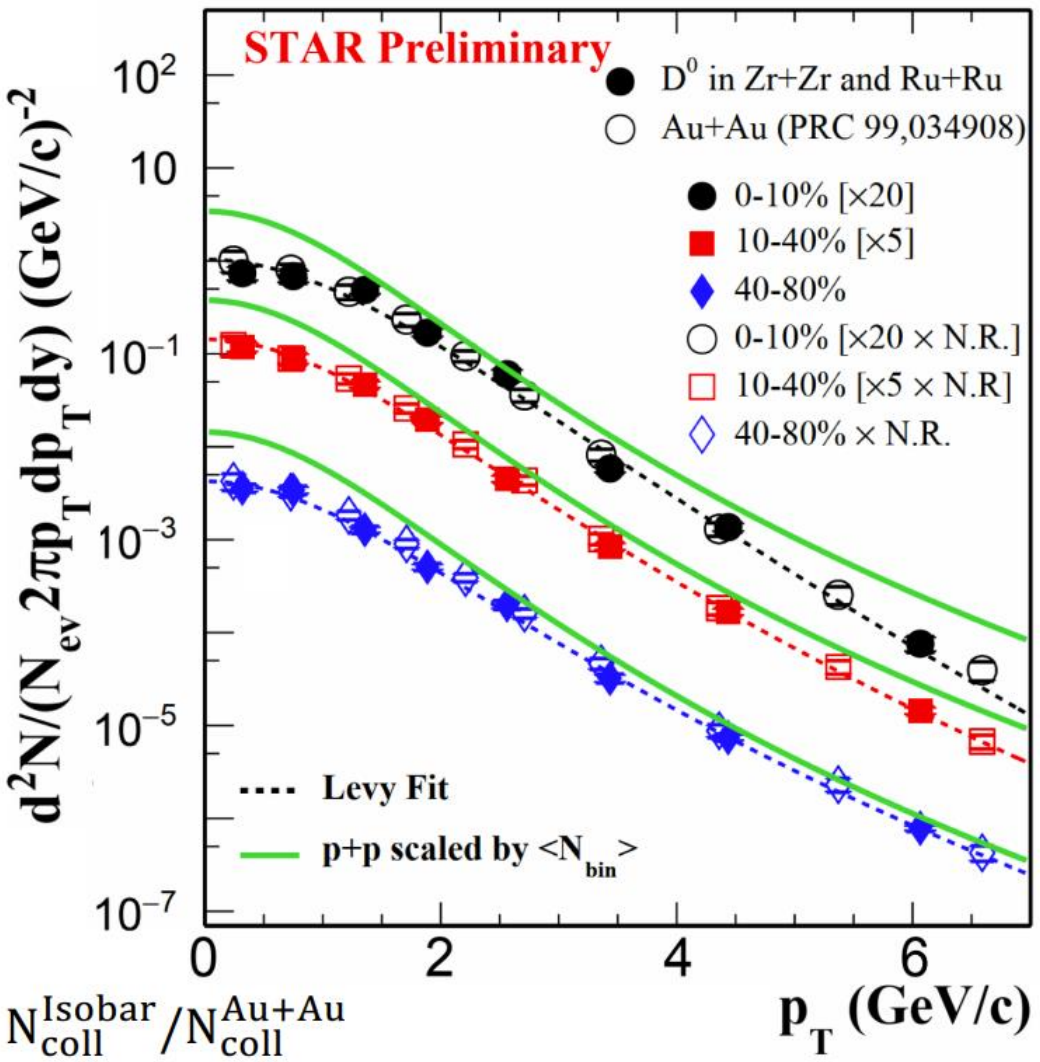
- Au+Au at $\sqrt{s_{NN}} = 14.6\text{-}200$ GeV
- Ru+Ru & Zr+Zr at $\sqrt{s_{NN}} = 200$ GeV
- p+p at $\sqrt{s} = 500$ GeV

Kinematic acceptance:

- $p_T > 0.2$ GeV/c
- $|\eta| < 1$

Open Heavy Flavor Physics at STAR

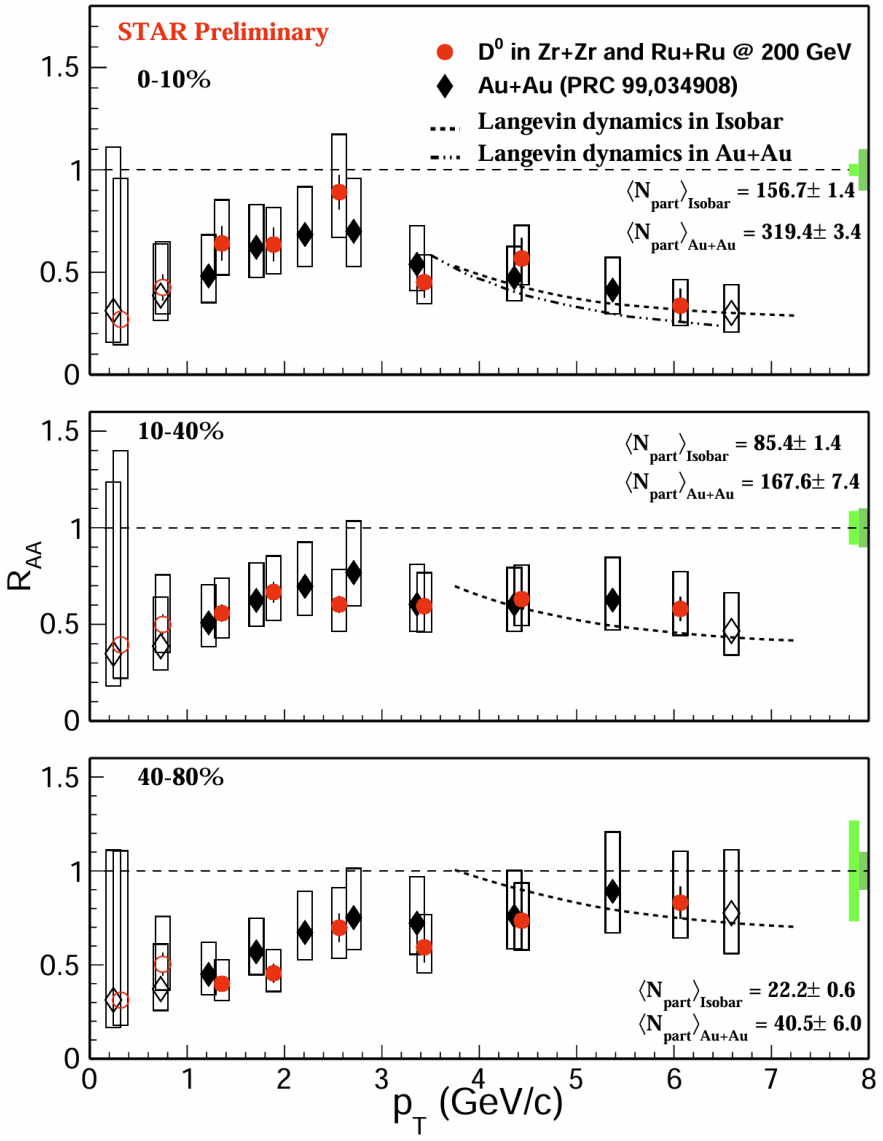
D^0 meson measured in different collision systems



$$N.R. = N_{coll}^{Isobar} / N_{coll}^{Au+Au}$$

- D^0 meson has been measured in isobaric collisions, and the N.R. scaling applied to the Au+Au data
- D^0 yield follows N_{coll} scaling within uncertainties between Zr+Zr, Ru+Ru and Au+Au collisions at 200 GeV

D^0 meson: energy loss in QGP



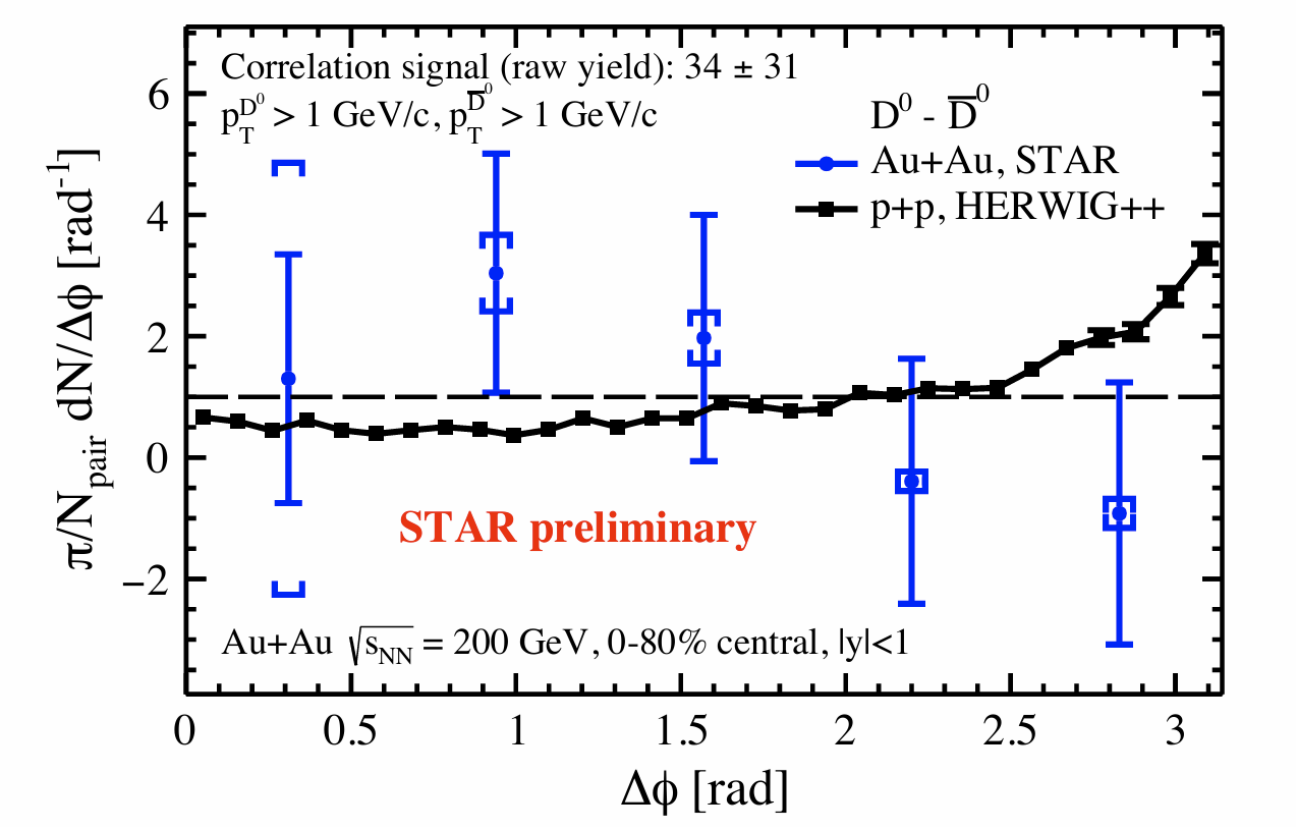
- D^0 meson R_{AA} is significantly suppressed at high-p_T in central collisions
- More suppression towards central collisions
- Similar suppression is observed between isobar and Au+Au collisions at same centrality class
- Consistent with model calculations based on radiative and collisional energy loss

Model calculation: G. Qin, private communication

D^0-$\overline{D^0}$ meson: azimuthal correlations

- Weaker correlation is expected in heavy ion collisions compared to that in p+p collisions at $\Delta\phi \approx \pi$, due to energy loss and thermalization in QGP

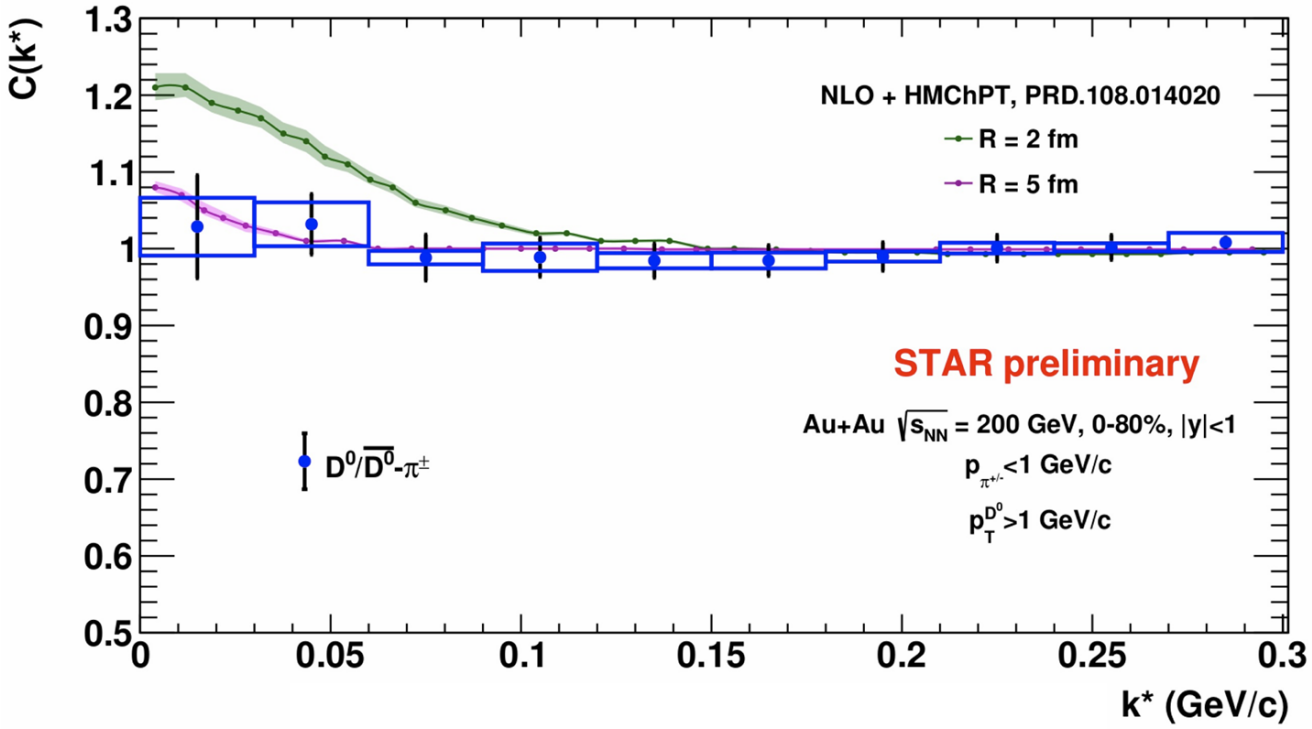
X. Zhu, et al., Phys. Lett. B 647 (2007) 366



- No azimuthal correlation is seen within current large uncertainties

D^0-$\pi^{\pm}$ femtoscopic correlations

- The final state interaction(FSI) measured in femtoscopic CFs

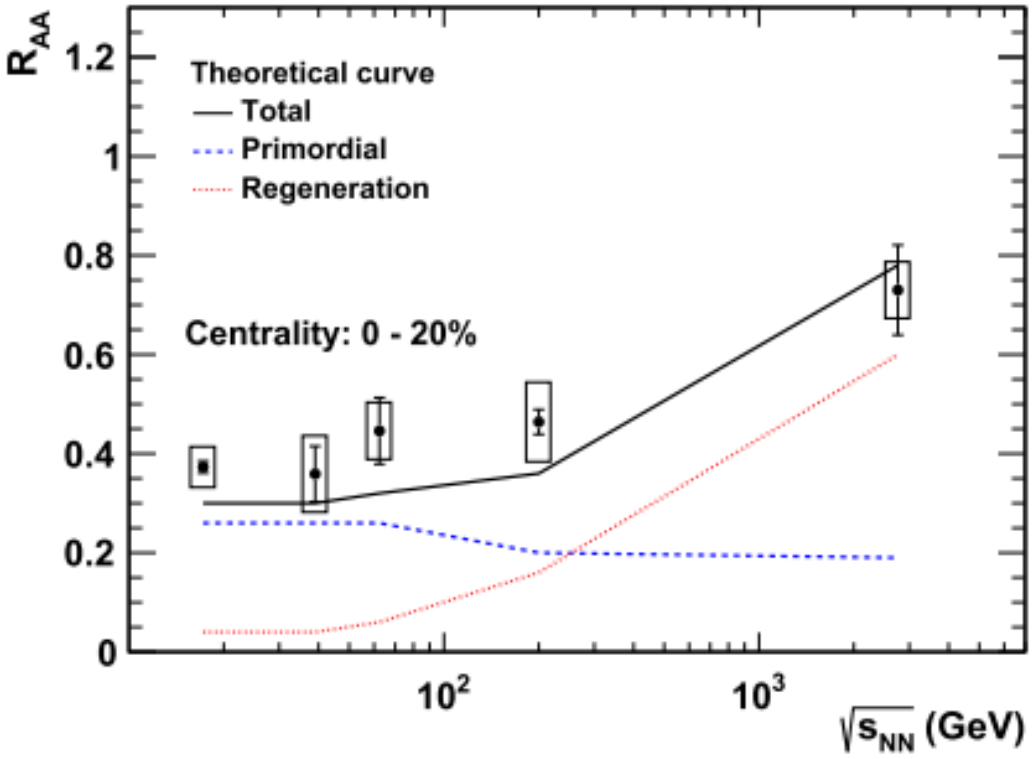


- No significant correlations is observed within current uncertainties
- Consistent with model calculation with R = 5 fm or larger

M. Albaladejo, et al., Phys. Rev. D 108 (2023) 014020

Quarkonia Physics at STAR

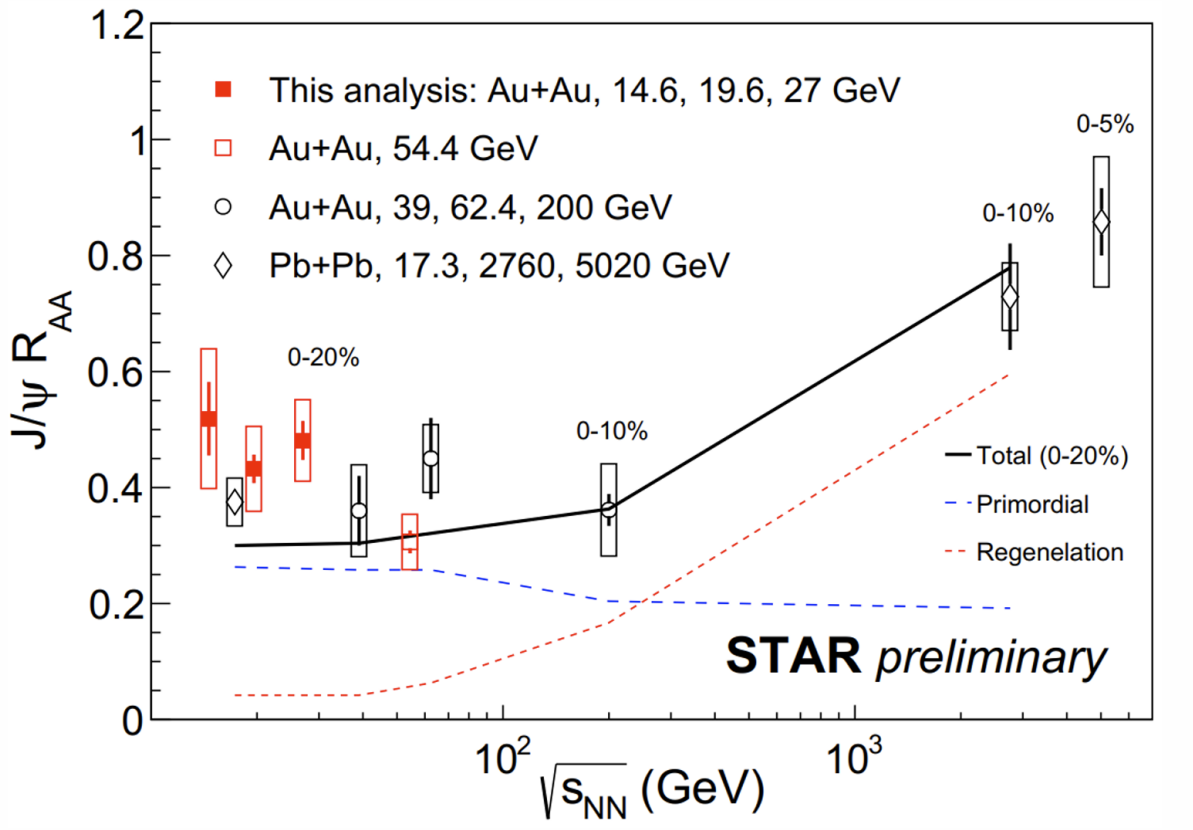
Collision energy dependence of QGP property



(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



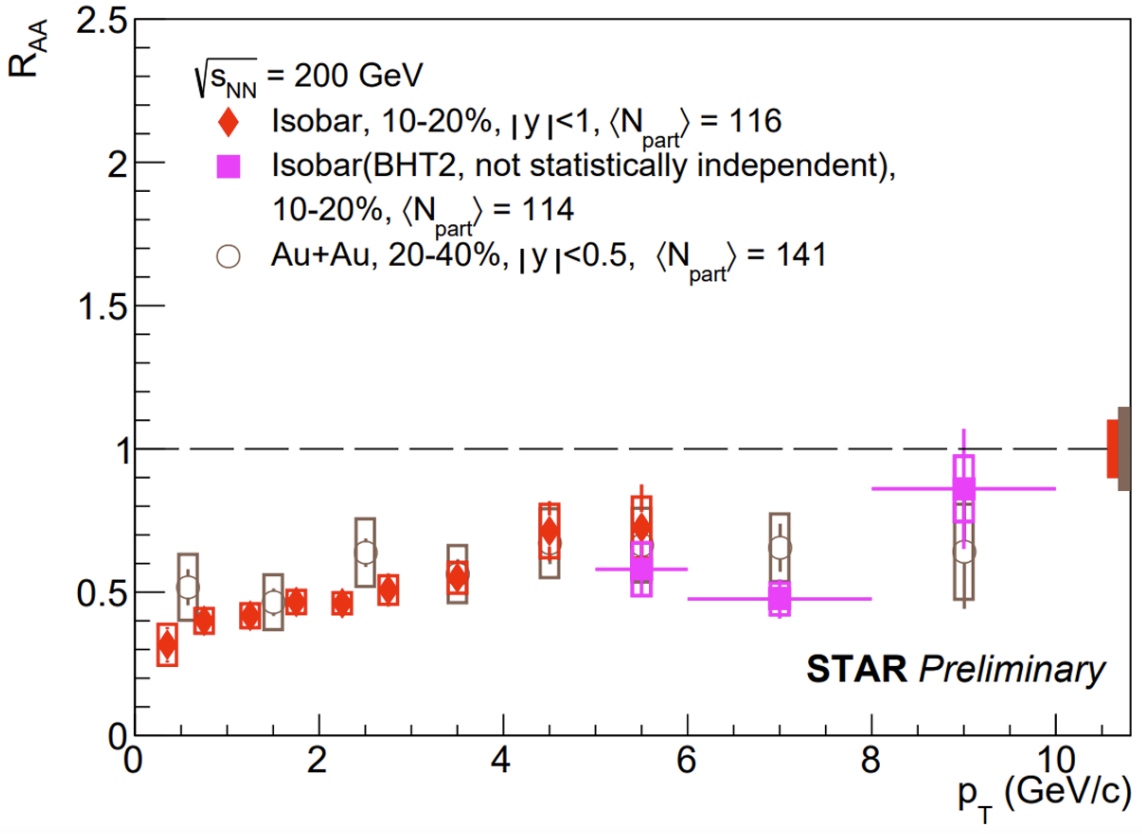
- No significant energy dependence of nuclear modification factor within uncertainties at $\sqrt{S_{NN}} \leq 200$ GeV

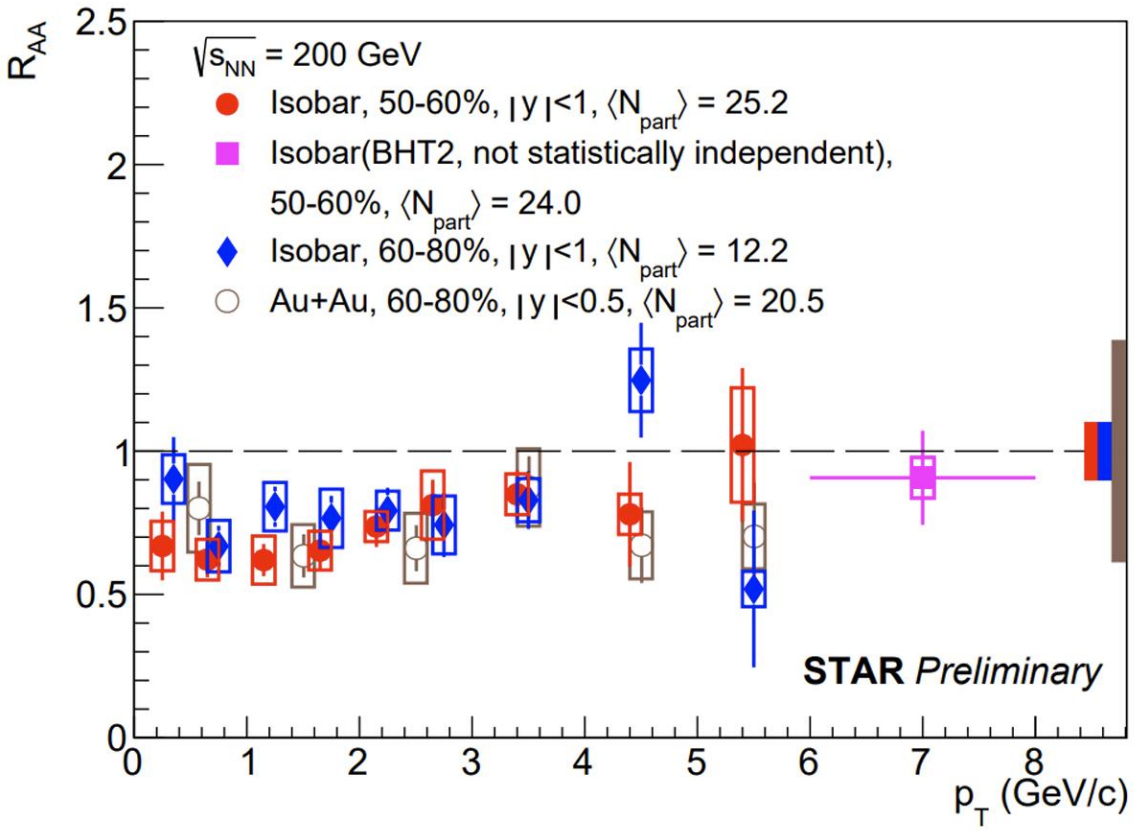
X. Zhao and R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication)

(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

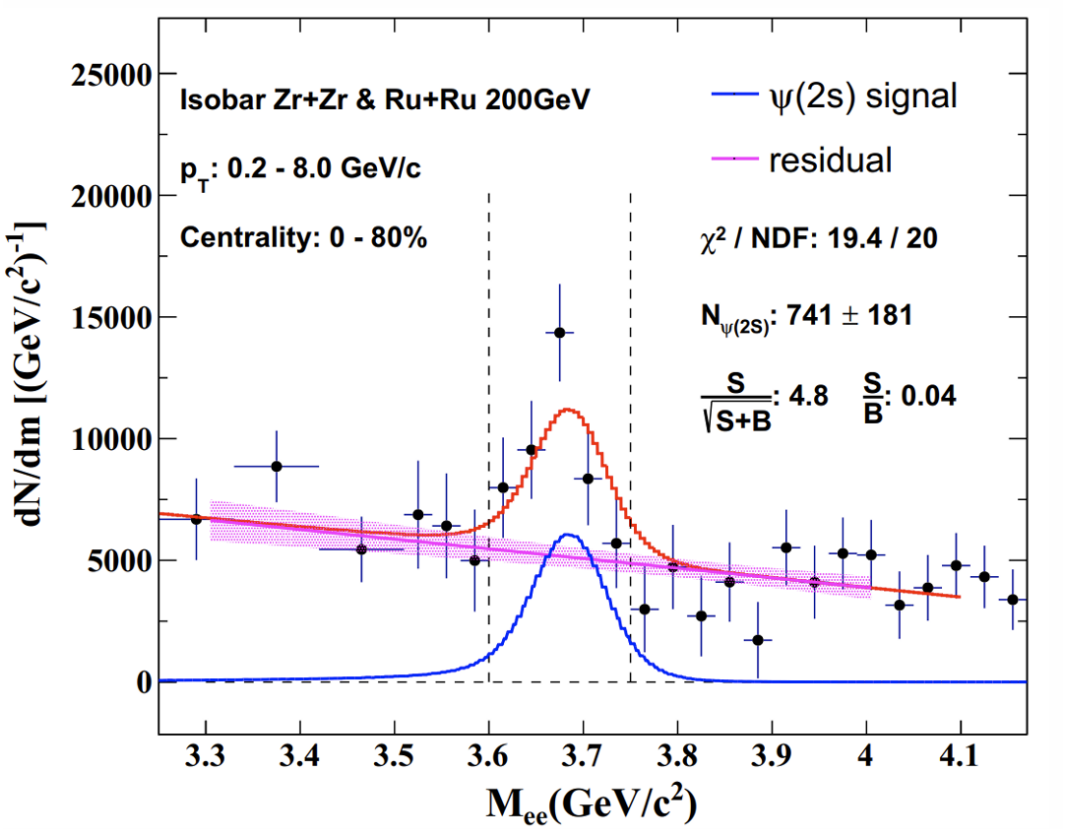


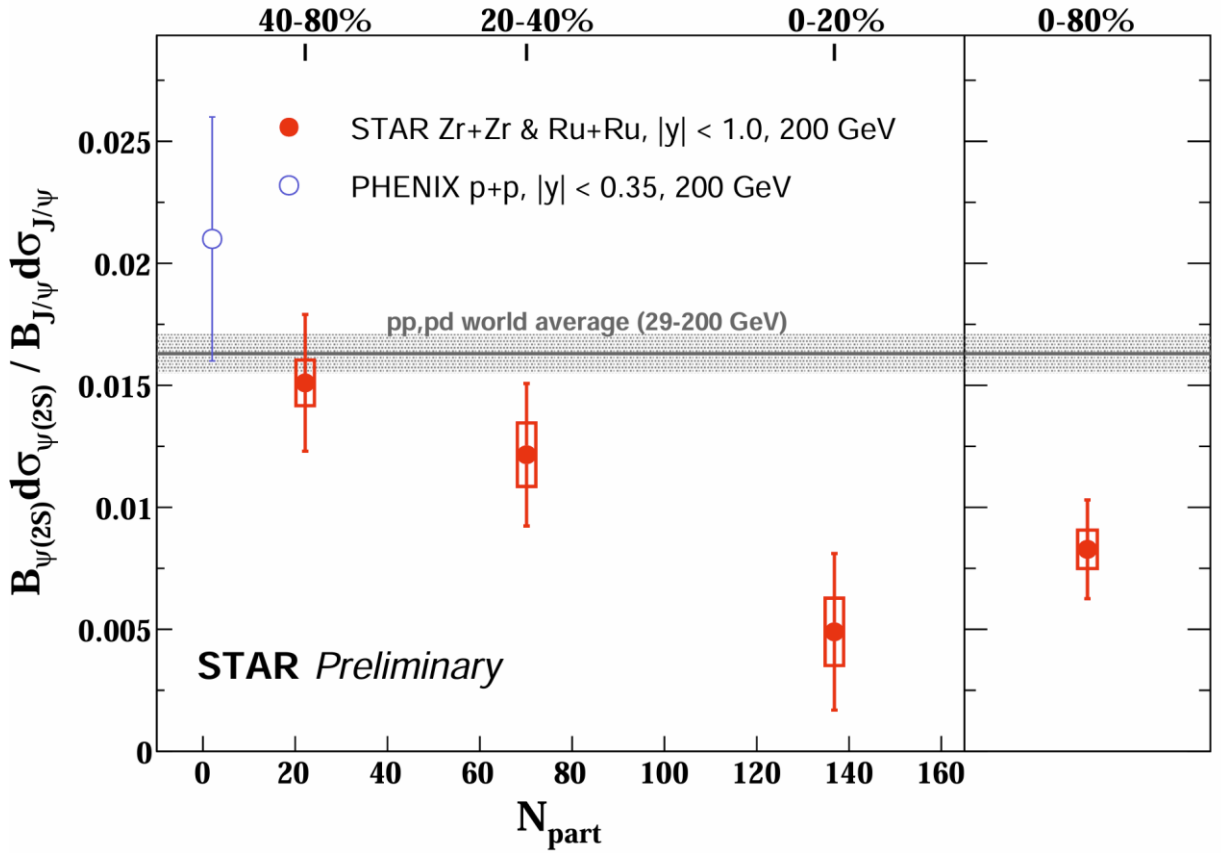


- In isobaric collisions, highest precision measurement at RHIC to date
- No significant collision system dependence of J/ψ suppression at similar $\langle N_{\mathrm{part}} \rangle$ range

Charmonium sequential suppression

- The suppression level related to the binding energy of charmonium



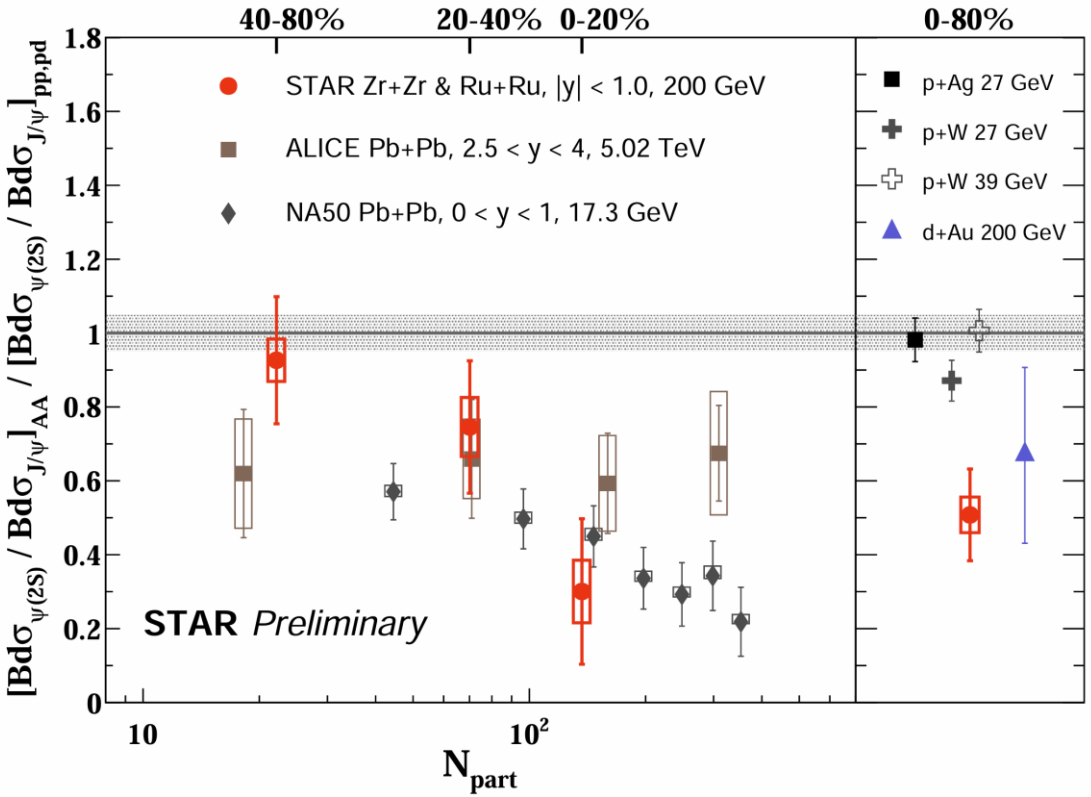


- A clear $\psi(2s)$ signal is observed in isobaric collisions

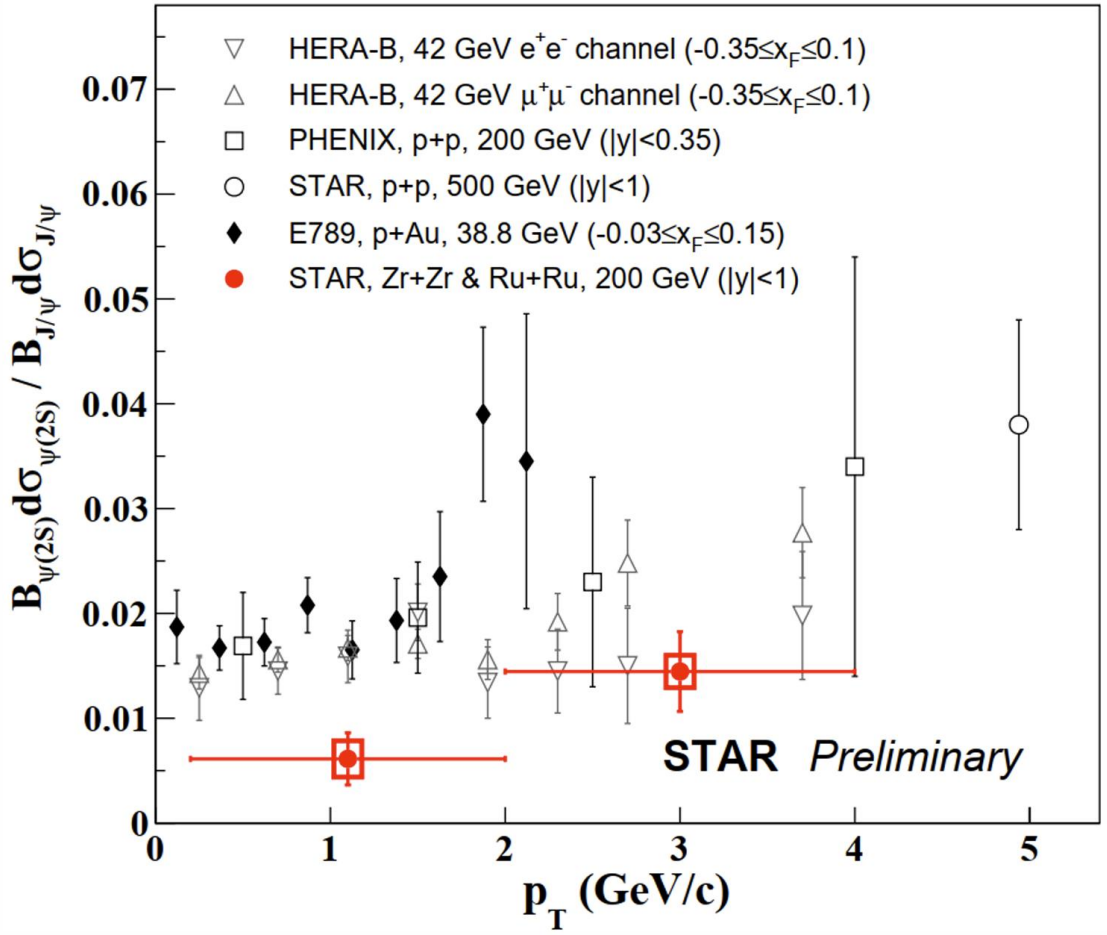
(PHENIX) Phys.Rev.D, 85,092004 (2012)
(NA51) Phys.Lett.B 438 (1998) 35-40

- 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}



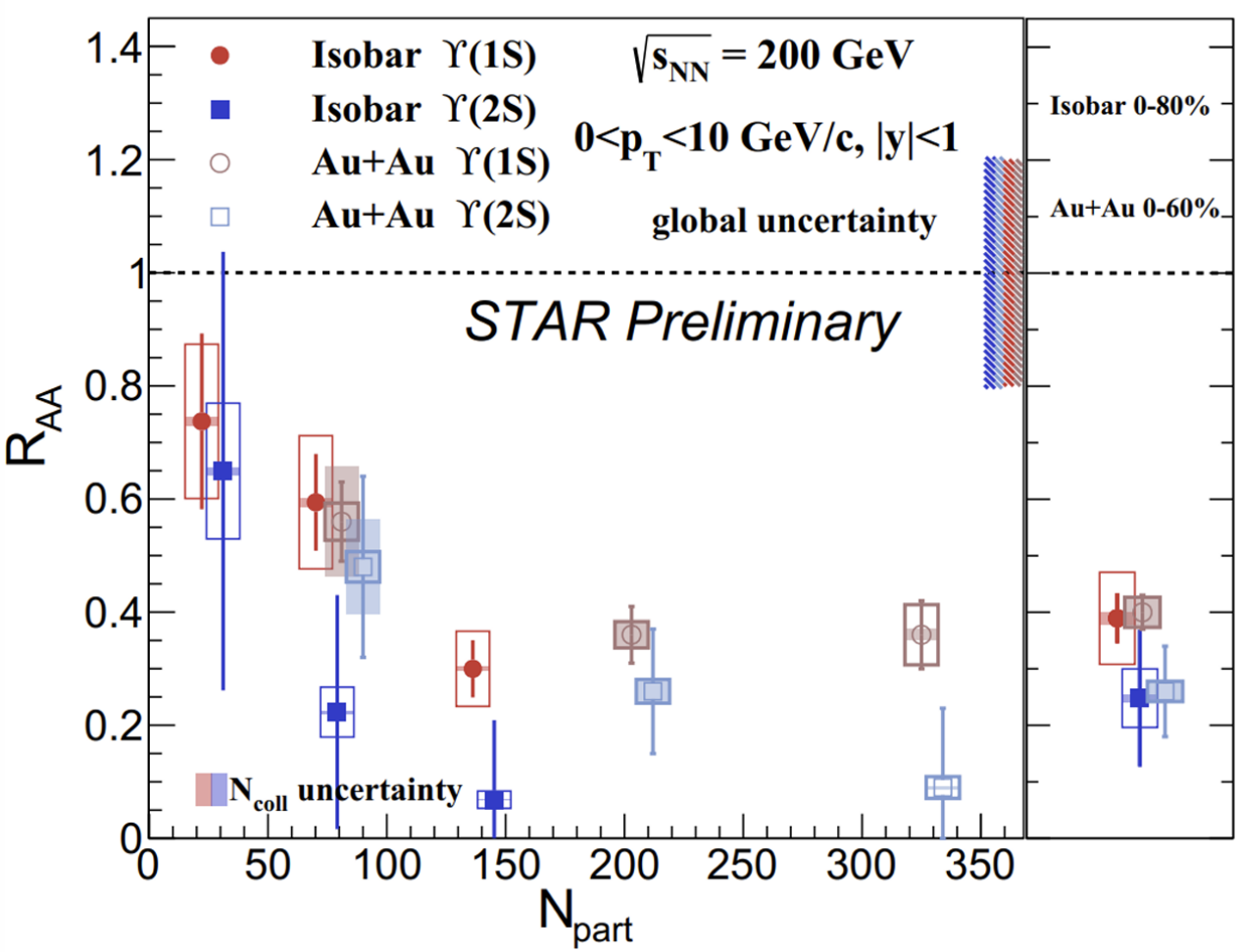
(PHENIX) Phys.Rev.D, 85,092004 (2012)
(NA51) Phys.Lett.B 438 (1998) 35-40



- 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

ϒ suppression at different systems

- Smaller regeneration effect compared to charmonia

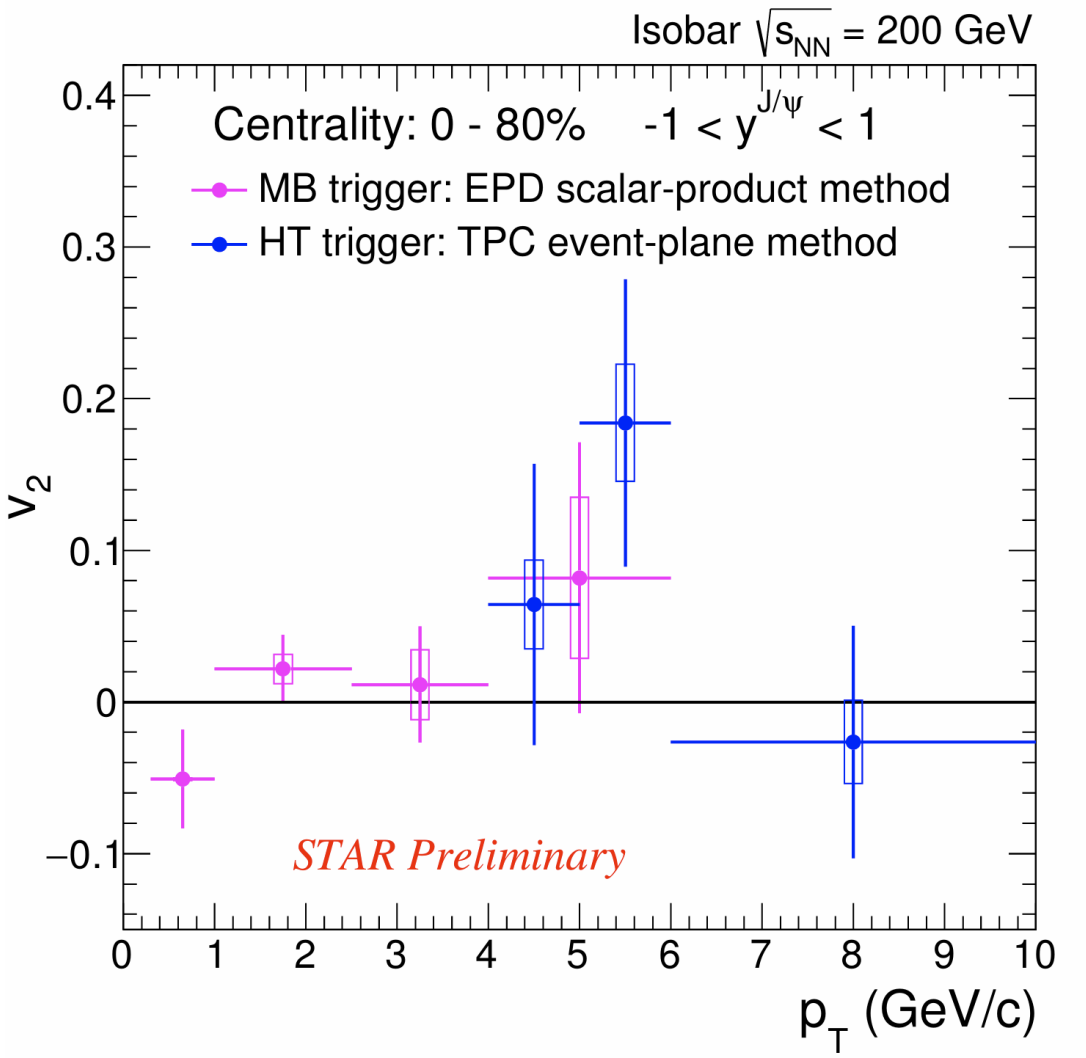


(STAR) Phys. Rev. Lett. 130 (2023) 112301

- 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

J/ψ v_2 in isobaric collisions at RHIC top energy

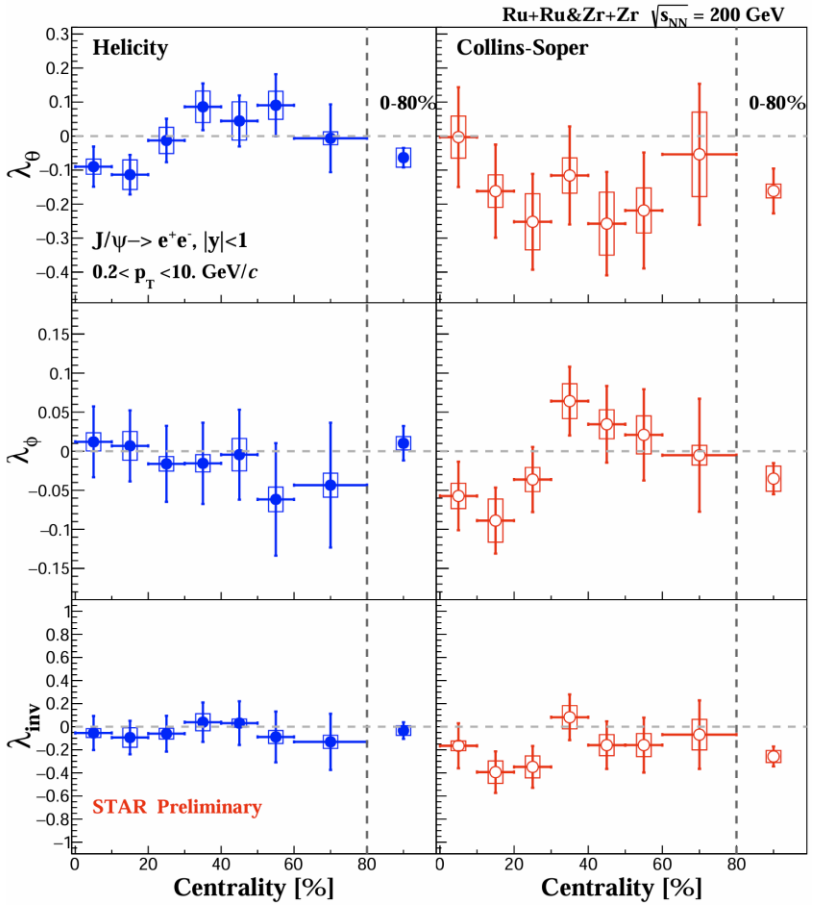
- Charm quark thermalization level at RHIC



- No significant J/ψ v_2 signal is observed under current uncertainties in isobaric collisions
- Smaller regeneration effect at RHIC compared to that at LHC ?

J/ψ polarization in isobaric collisions

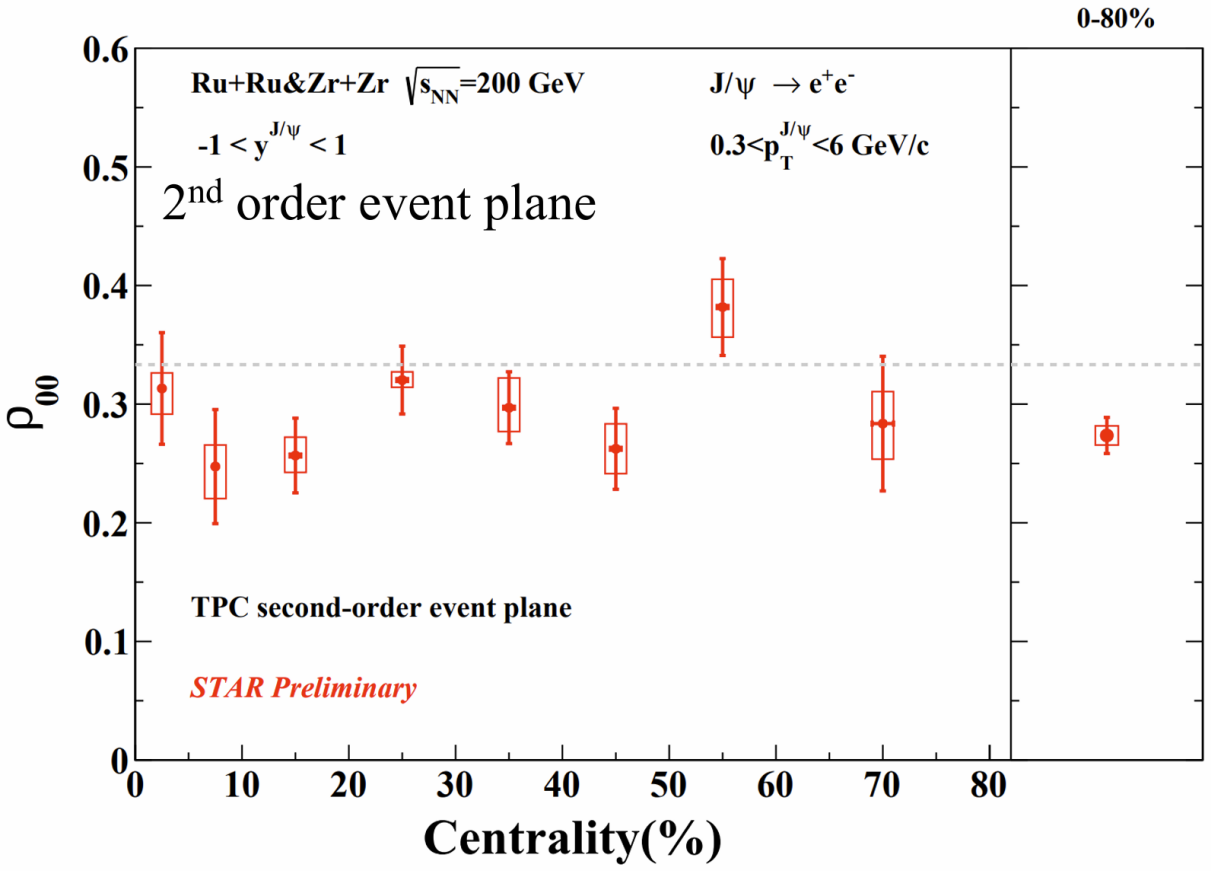
- J/ψ polarization → the production mechanism
- Possible difference between heavy ion collisions and p+p collisions
- The J/ψ decayed leptons: $w(\cos\theta, \phi) \propto 1 + \lambda_\theta cos^2\theta + \lambda_\phi sin^2\theta cos2\phi + \lambda_{\theta\phi} sin2\theta cos\phi$

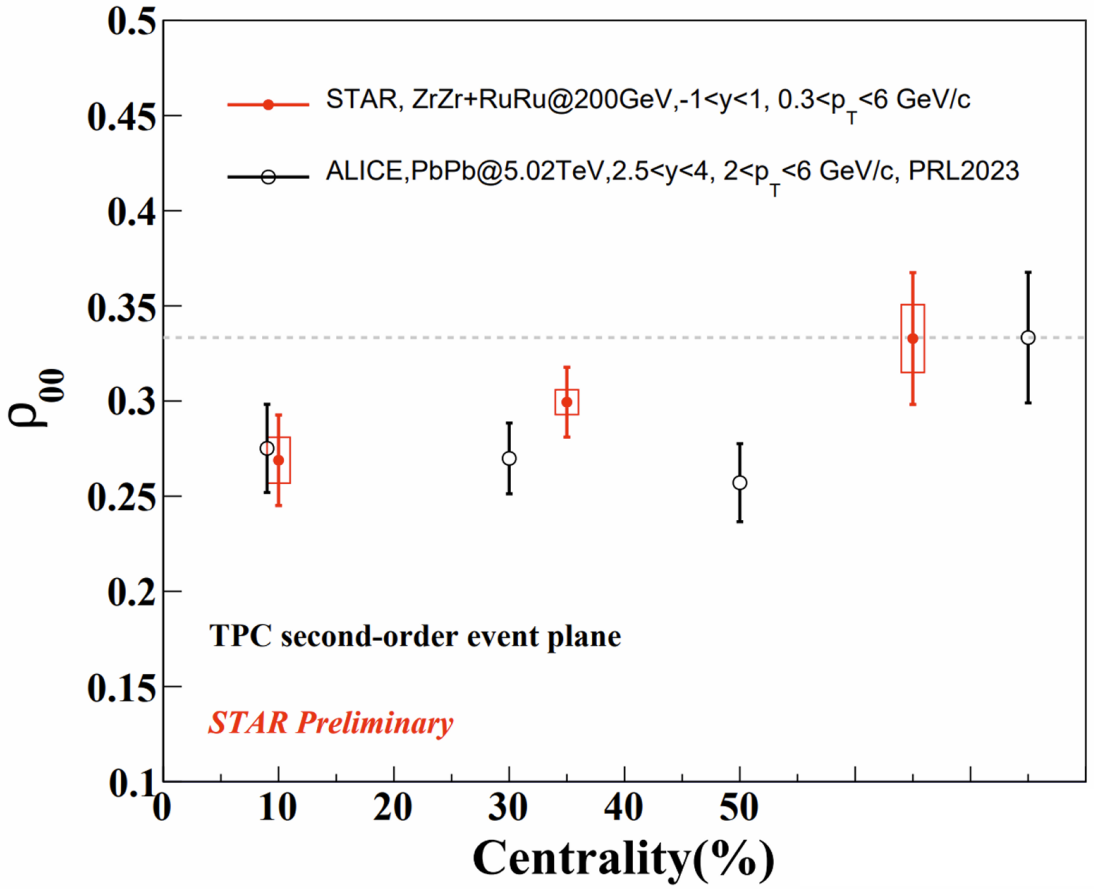


- λ_θ and λ_ϕ are consistent with zero within uncertainties, indicate that no polarization is observed within current uncertainties
- No significant centrality dependence is observed

J/ψ global spin alignment in isobaric collisions

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

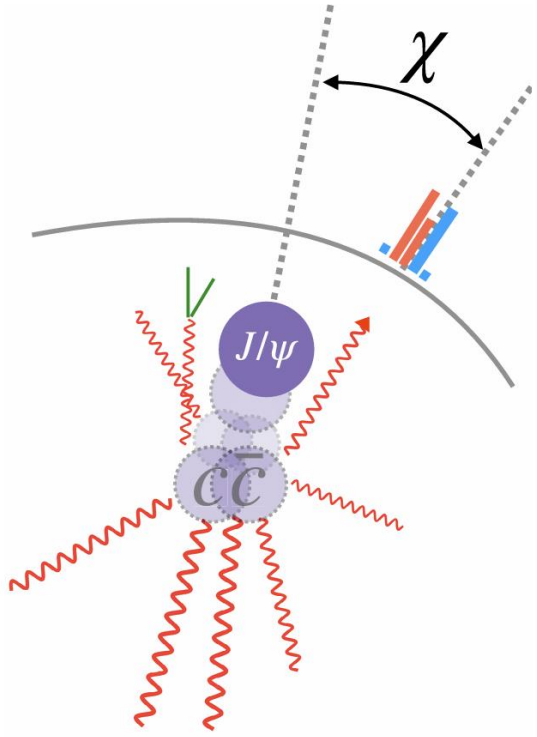




(ALICE) Phys. Rev. L 131 4, 042303 (2023)

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

J/ψ energy correlator

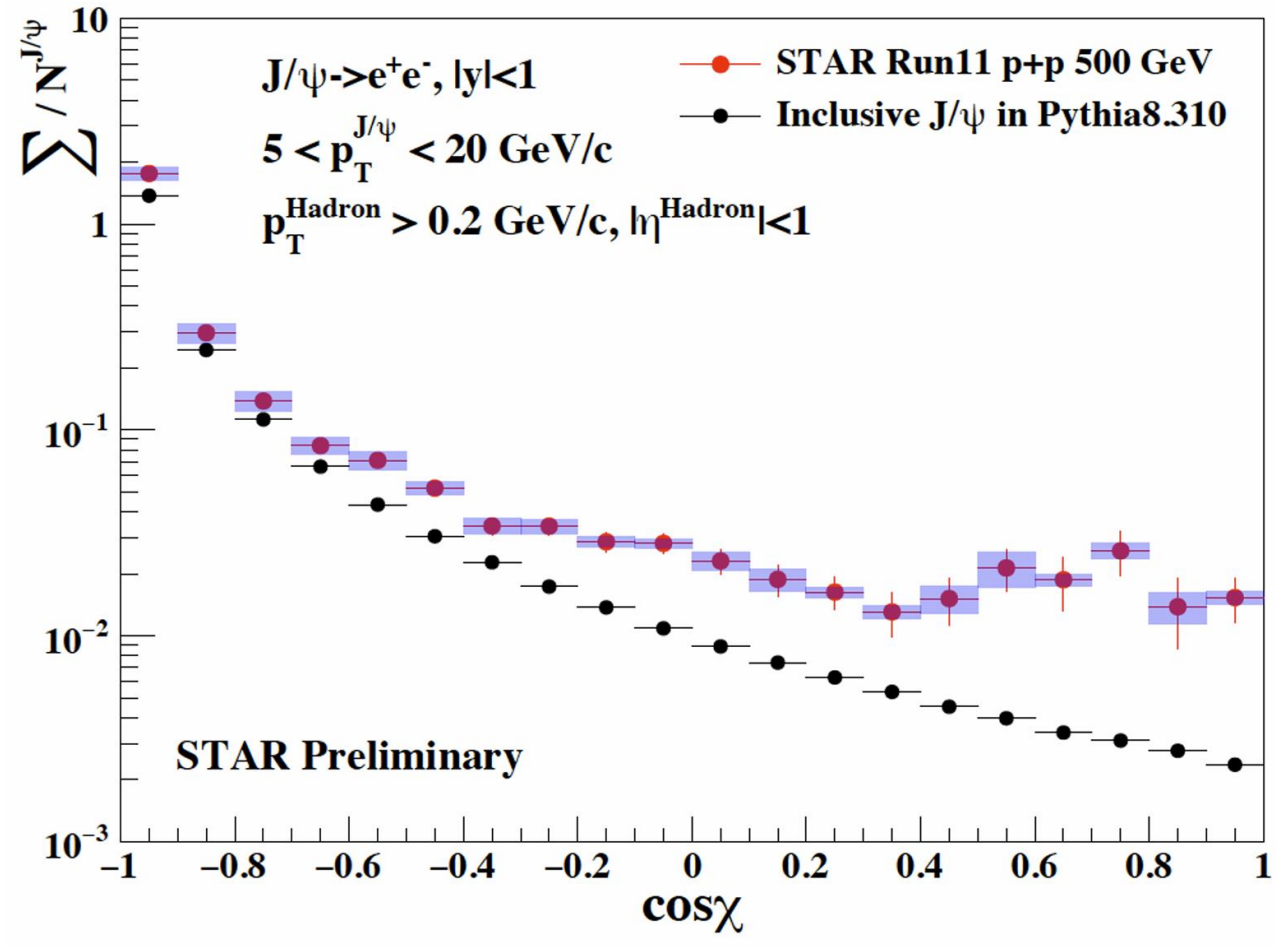


$$\Sigma(\cos\chi) = \int d\sigma \sum_i \frac{E_i}{M} \delta(\cos\chi - \cos\theta_i),$$

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 $\cos(\chi) \geq 0$

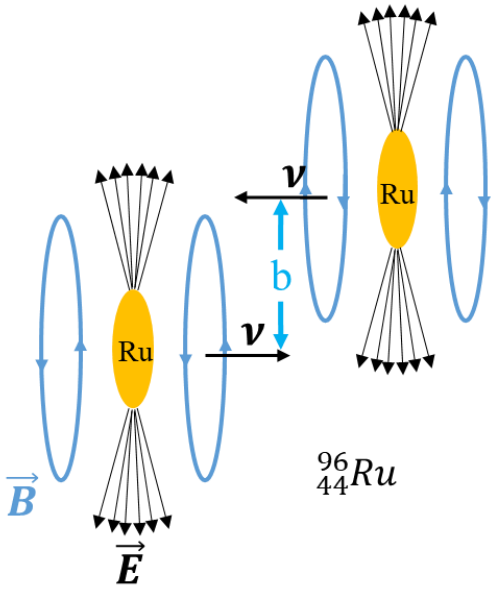
J/ψ energy correlator measured at RHIC-STAR

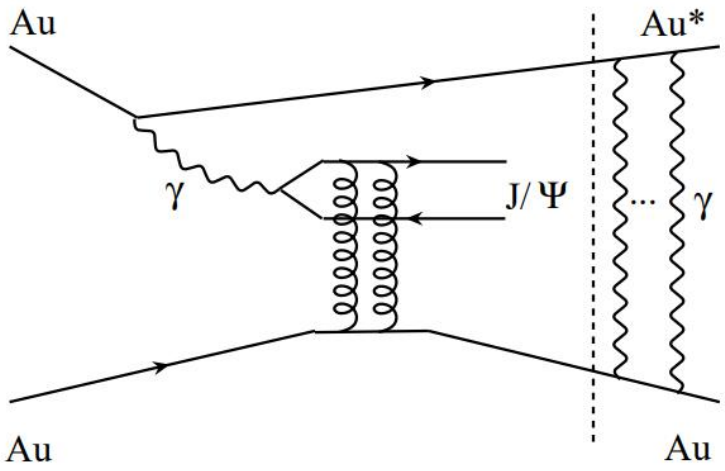


- The J/ψ energy correlator has been measured firstly at STAR in p+p collisions at $\sqrt{s} = 500$ GeV
- No significant $\cos(\chi)$ dependence of the J/ψ energy correlator at $\cos(\chi) > 0$, while the measurement is different compared to that in Pythia8 ($\sim 7\sigma$)

Coherent J/ψ photoproduction

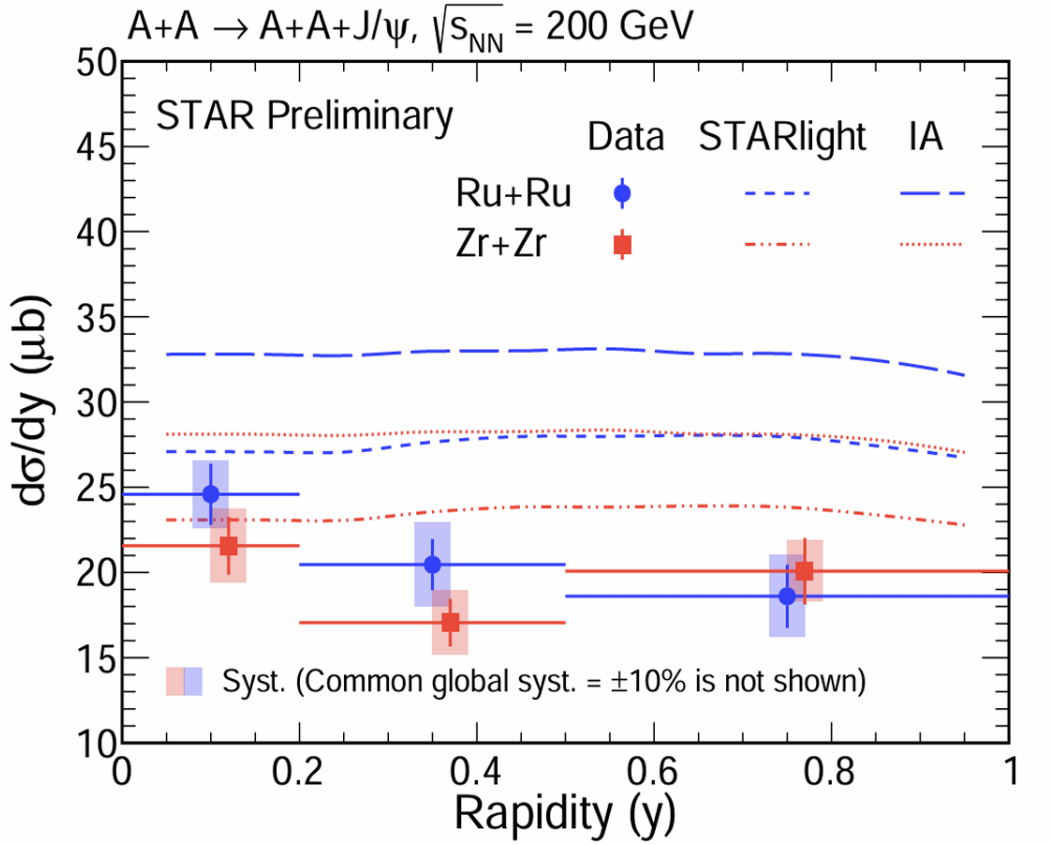
- Transverse EM fields can be equal to a flux of quasi-real photon ($\propto Z^2$, and $q^2 < (\hbar/R_A)$)
- These photons are linearly polarized

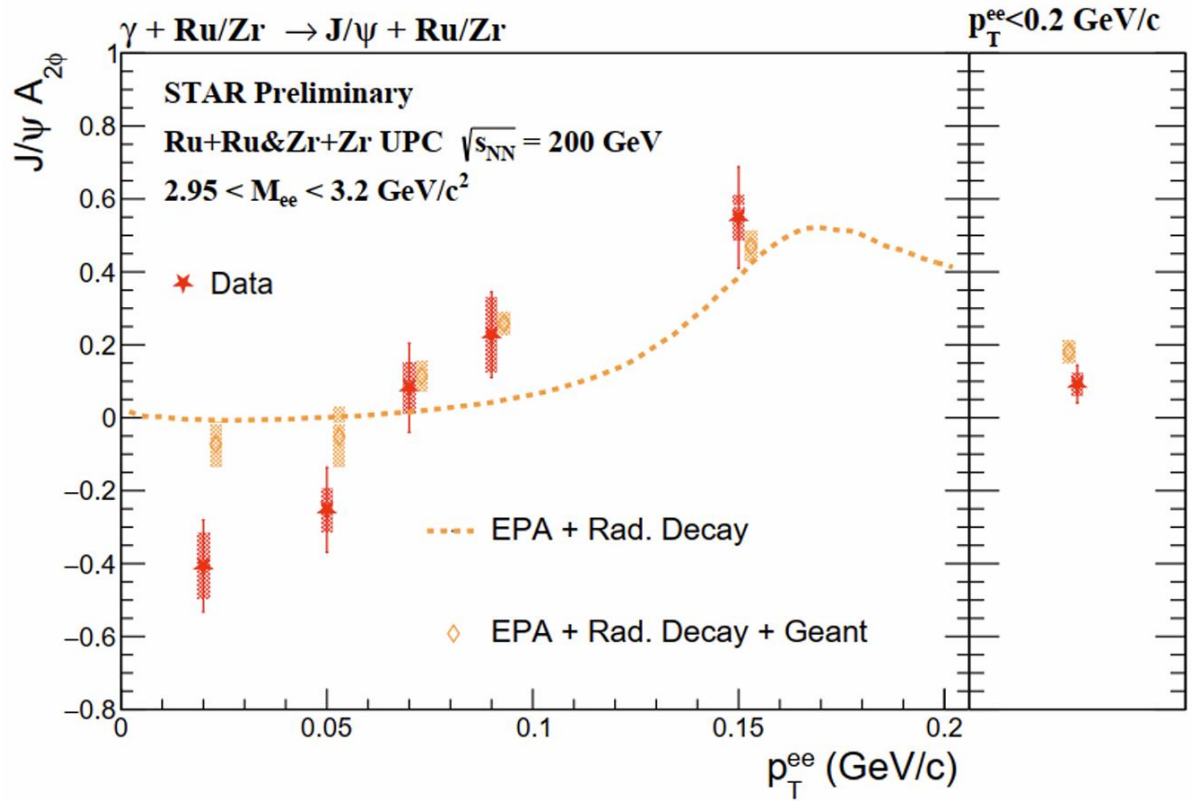




- Coherent: J/ψ production at low p_T^2 (≤0.02 (GeV/c)^2), while both nuclei stay intact
- Insightful probe of initial state of nucleus

Coherent J/ψ photoproduction in isobar UPCs

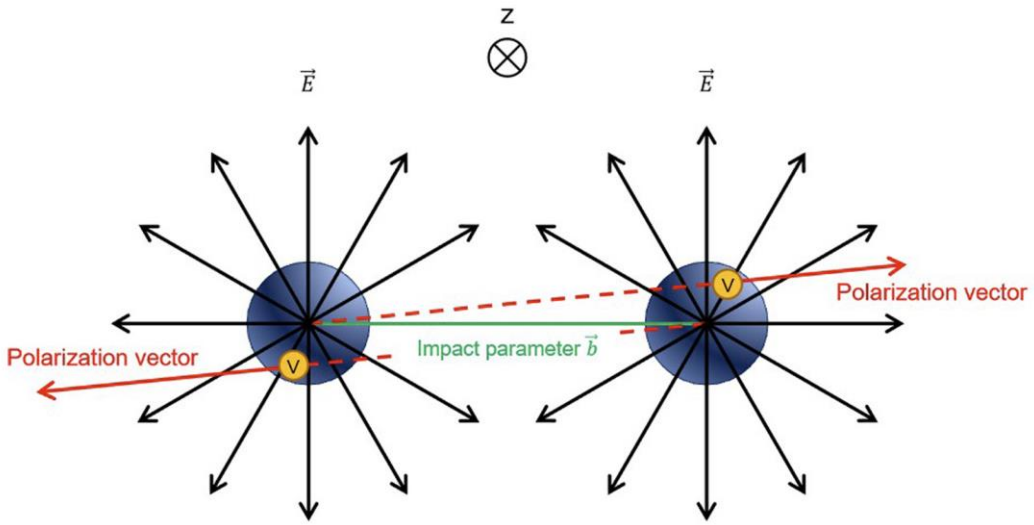




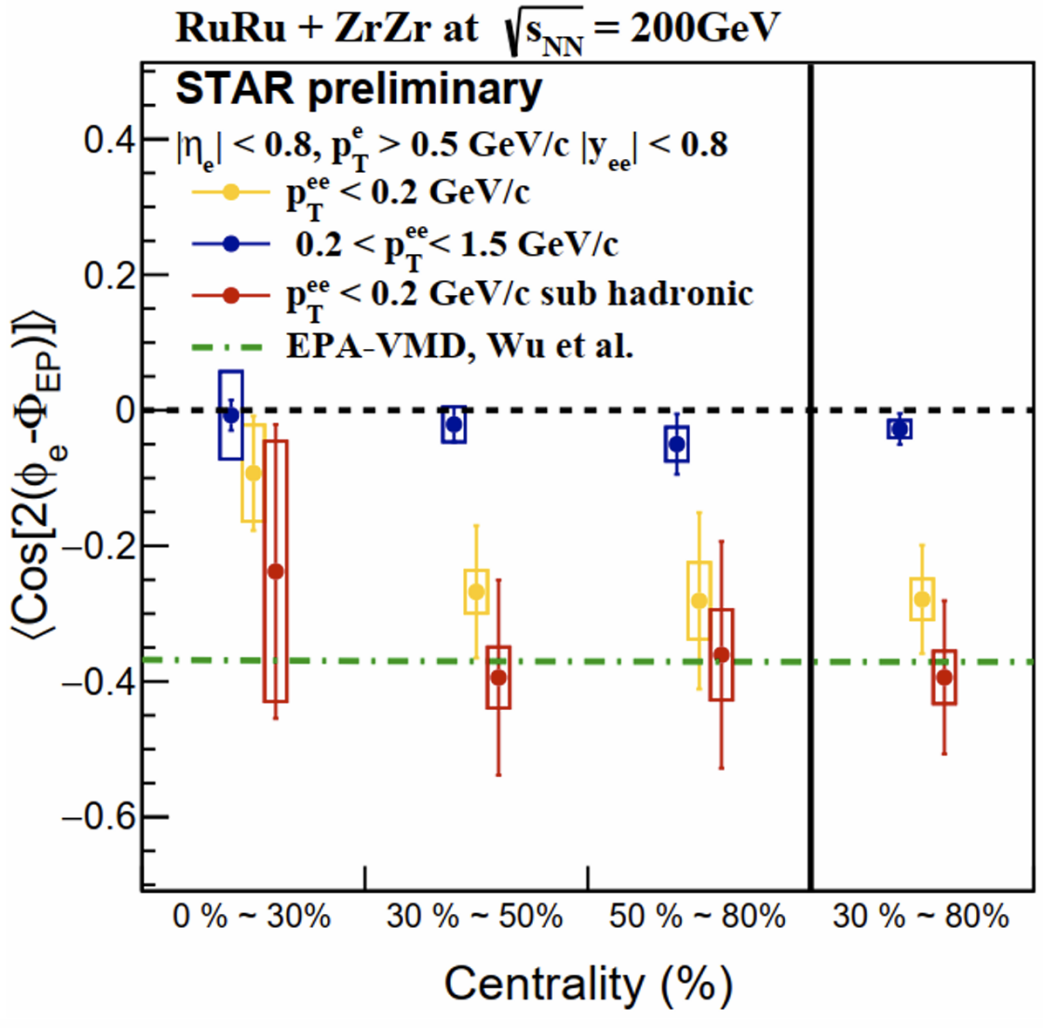
- Data ~20% lower than STARlight (with nucleon shadowing)
- Data ~30% lower than IA, strongly suppressed

- The J/ψ $A_{2\phi}$ changes from negative to positive with increasing p_{T}

Coherent J/ψ decay anisotropy in isobar PCs



X. Wu, et al., Phys. Rev. Res. 4, L042048 (2022)



- The evidence of decay anisotropy from photon polarization aligned with impact parameter

Summary and Outlook

Open heavy flavor:

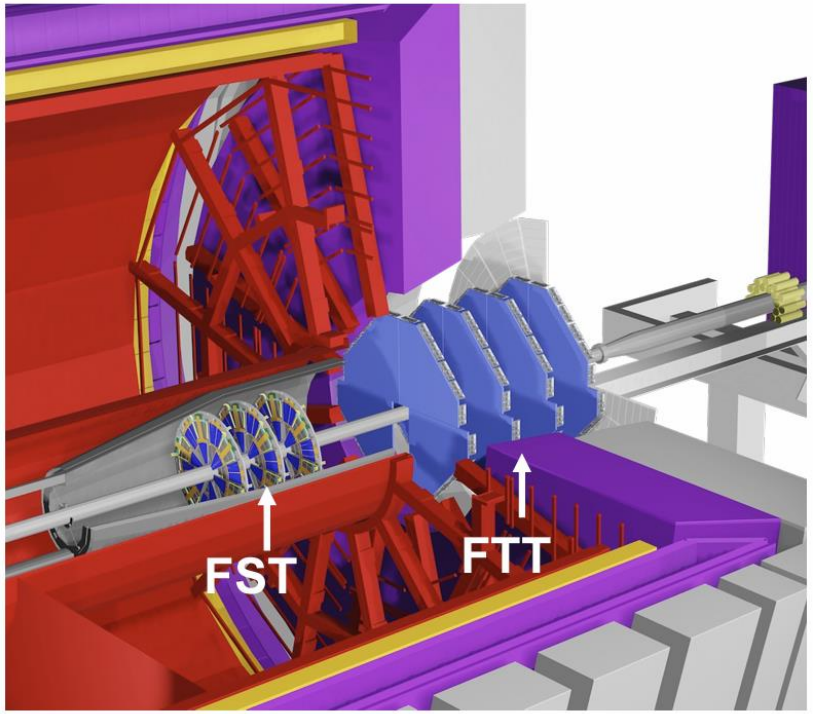
- Energy loss: similarity of D^0 in isobar and Au+Au collision
- Final state interaction: no clear azimuthal correlation and D^0-$\pi^{\pm}$ femtoscopic correlations

Quarkonia:

- 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

Summary and Outlook

- 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

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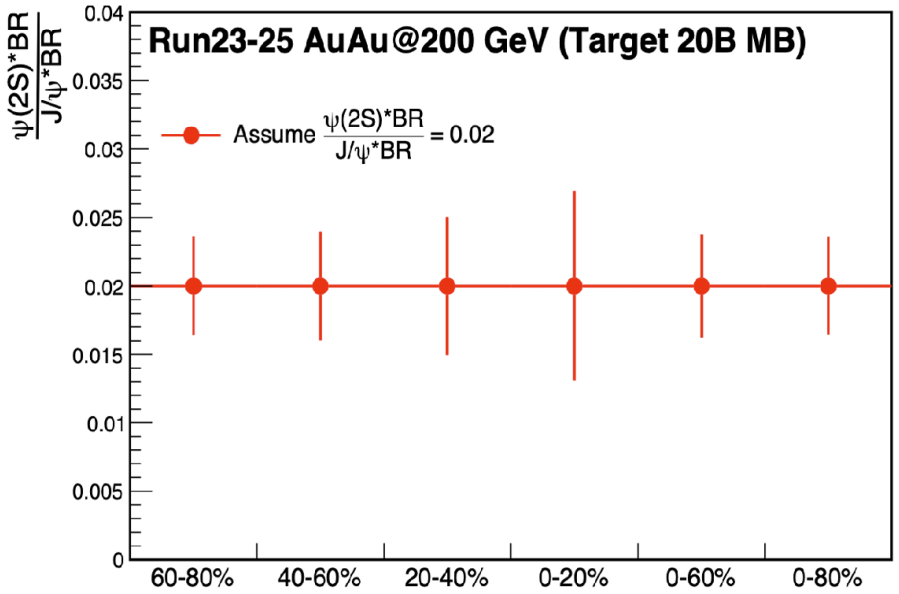
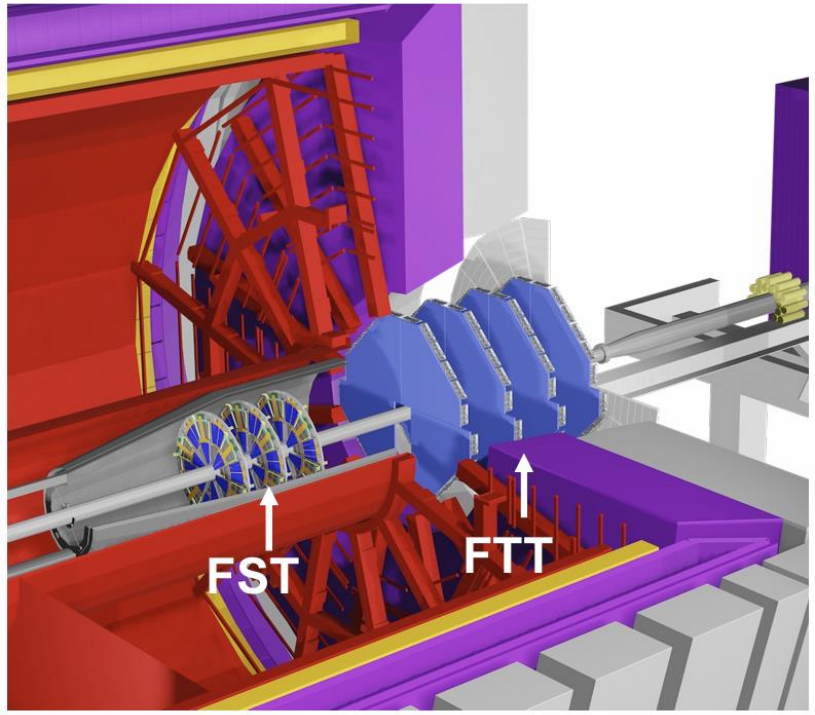


STAR BUR Run25 2024

Summary and Outlook

- 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

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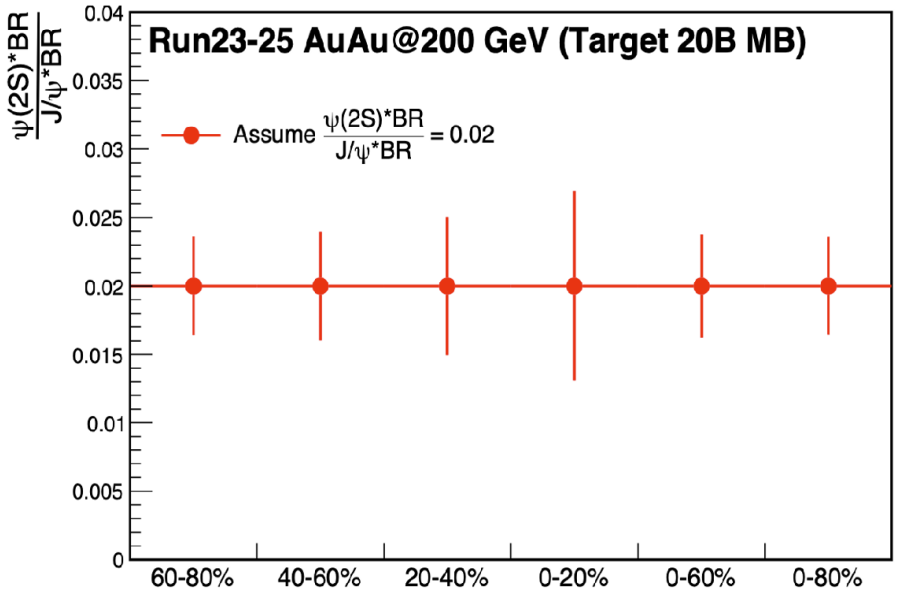
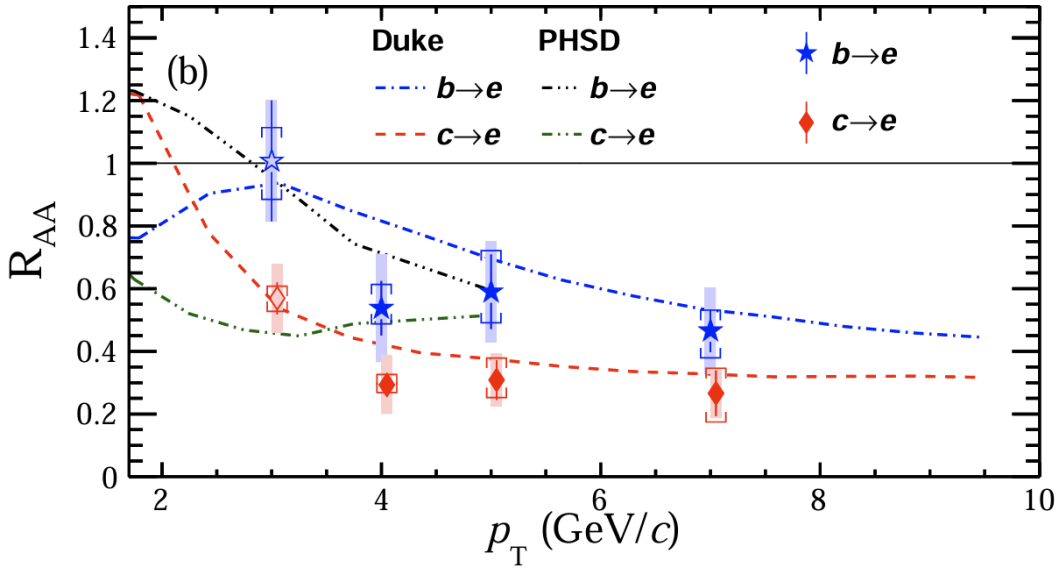
Thanks!

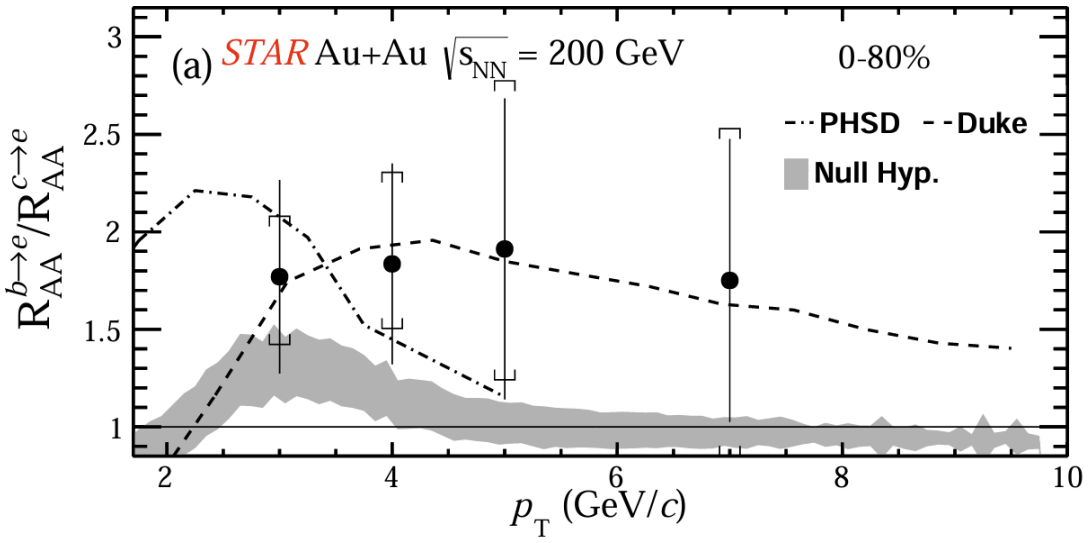


STAR BUR Run25 2024

Back up

b/c → e: energy loss in QGP

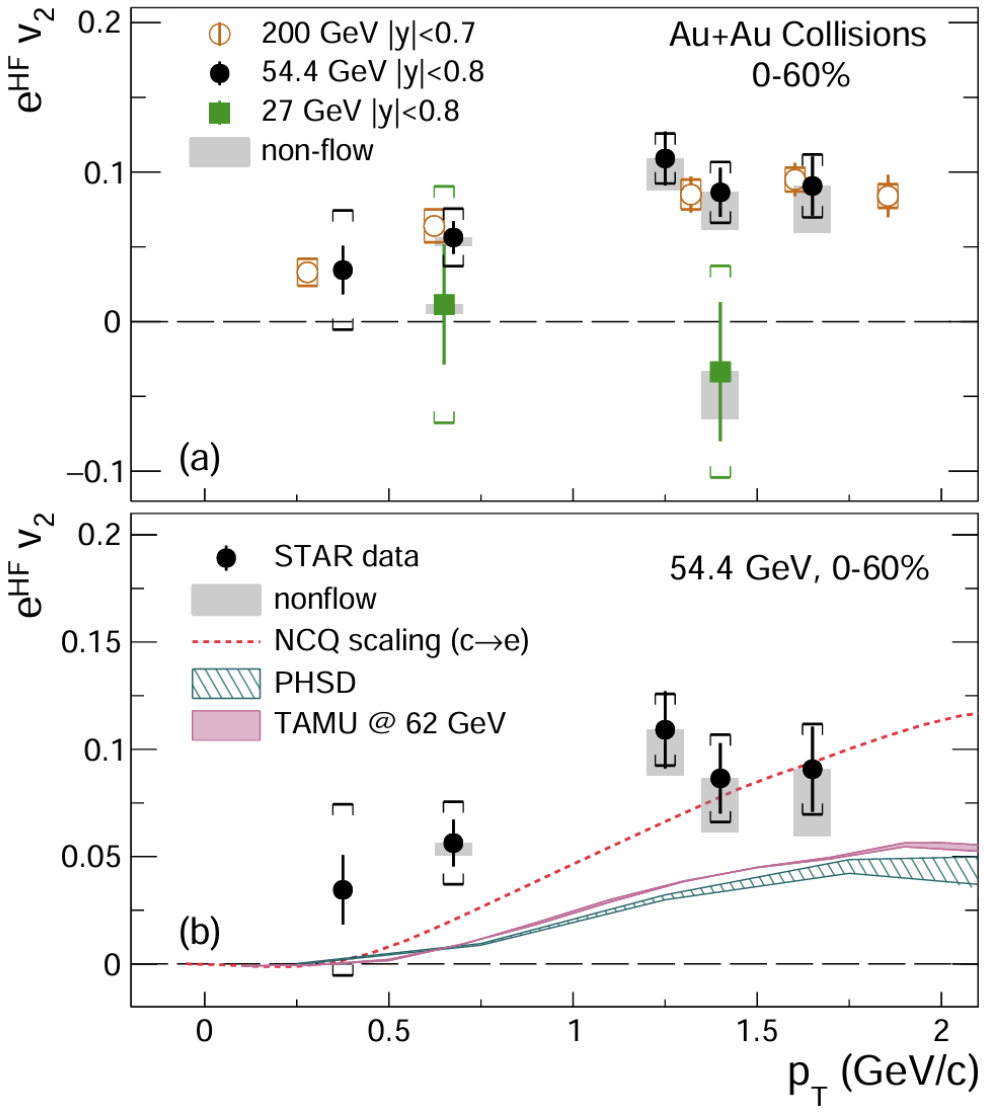




- The b/c-decay electron R_{AA} are suppressed at high-p_T in Au+Au collisions at 200 GeV
- The b-decay electron R_{AA} are systematically larger than c-decay R_{AA}, consistent with mass hierarchy of parton energy loss
- Consistent with model calculations including mass-dependent energy loss mechanisms

(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)