极端条件下的QCD研讨会：探索极高温和极高密下的强相互作用物质
烟台大学，2026年8月18-20日

Heavy Quarkonium Measurements in Heavy Ion Collisions

-- with a focus on STAR

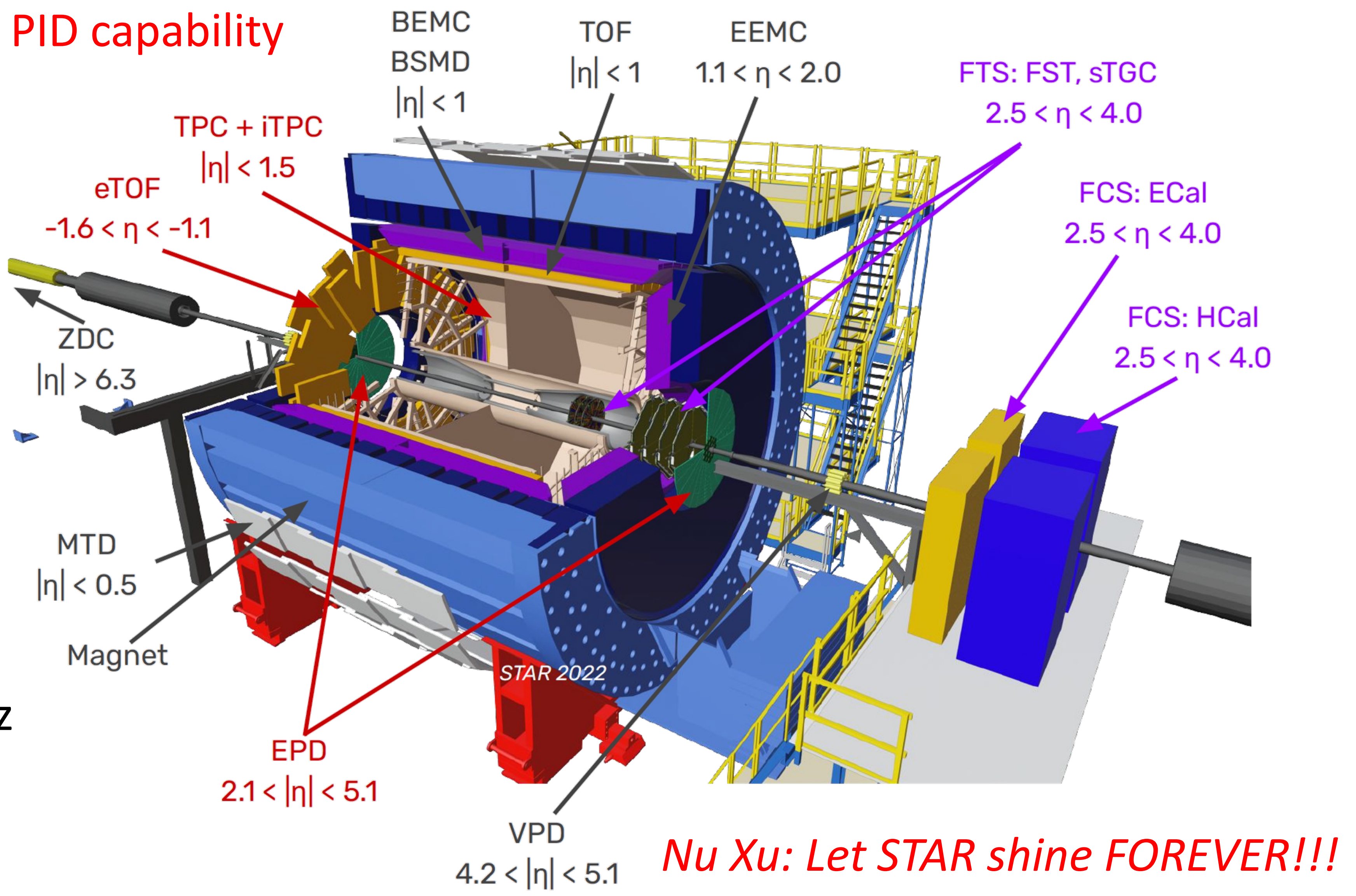
Zebo Tang
University of Science and Technology of China

The STAR Experiment

Large acceptance, excellent PID capability

Recent upgrades:

- 2018+:
  - iTPC
  - eTOF
  - EPD
- 2022+:
  - FTS
  - FCS
- DAQ rate: 10s Hz -> 5 kHz

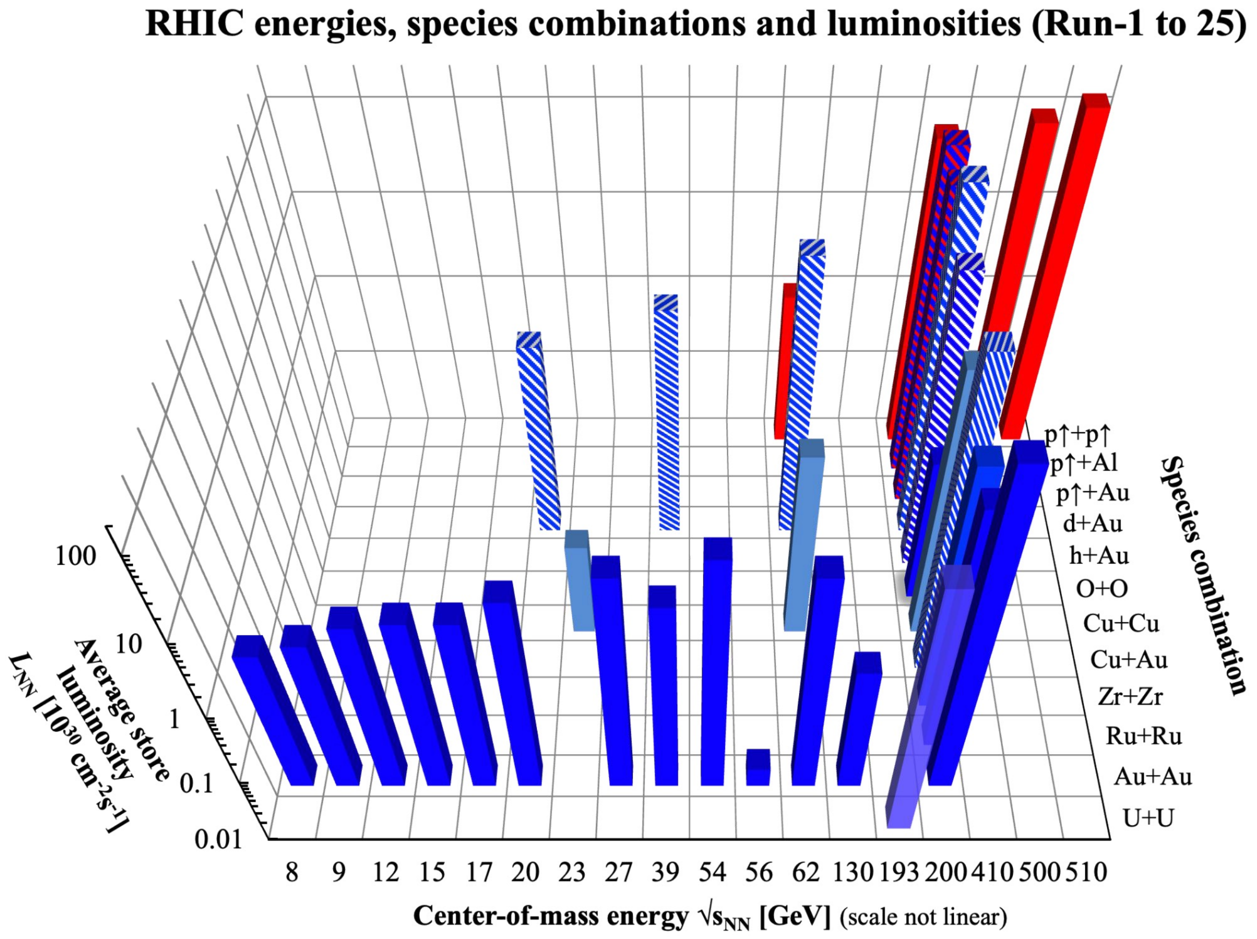


Decomissioned in 2026

Nu Xu: Let STAR shine FOREVER!!!

Relativistic Heavy Ion Collider (RHIC)

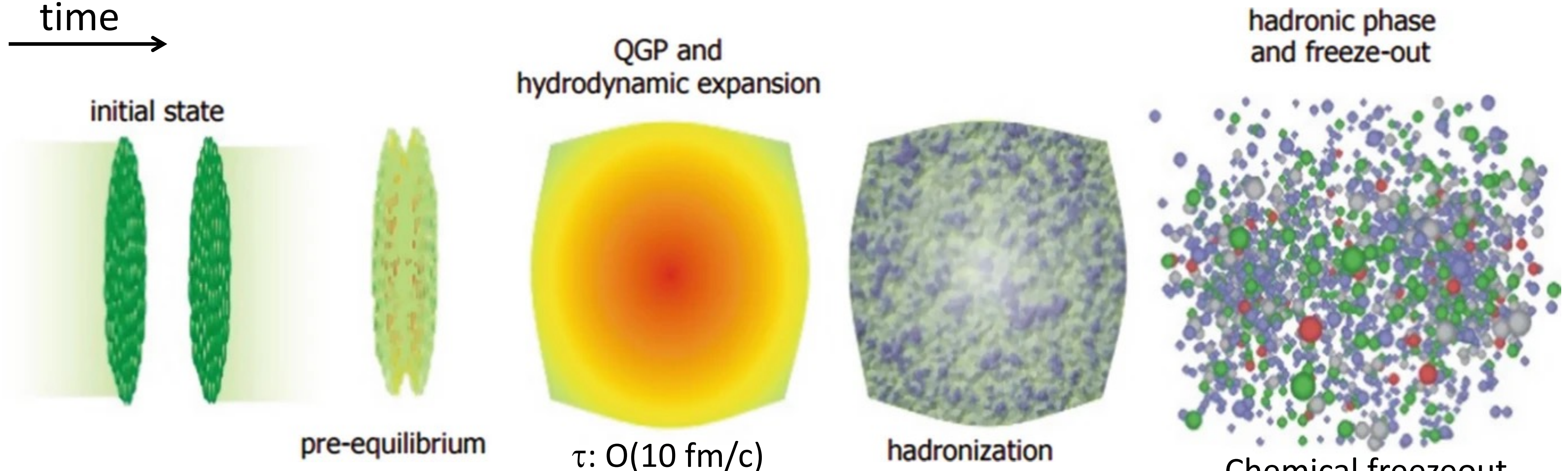
2000 - 2026



- Continuous and sign. improvement of *L*
- Various collision species at top energy
- Wide energy range of Au+Au collisions

Evolution of Heavy Ion Collision

time

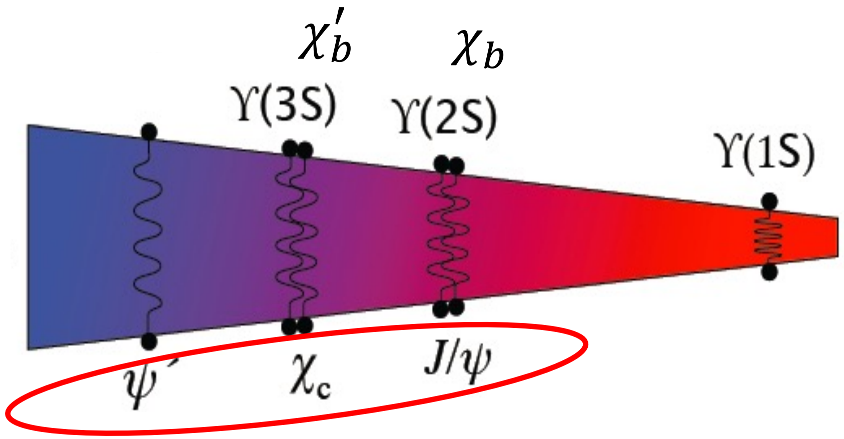


τ: O(10 fm/c)

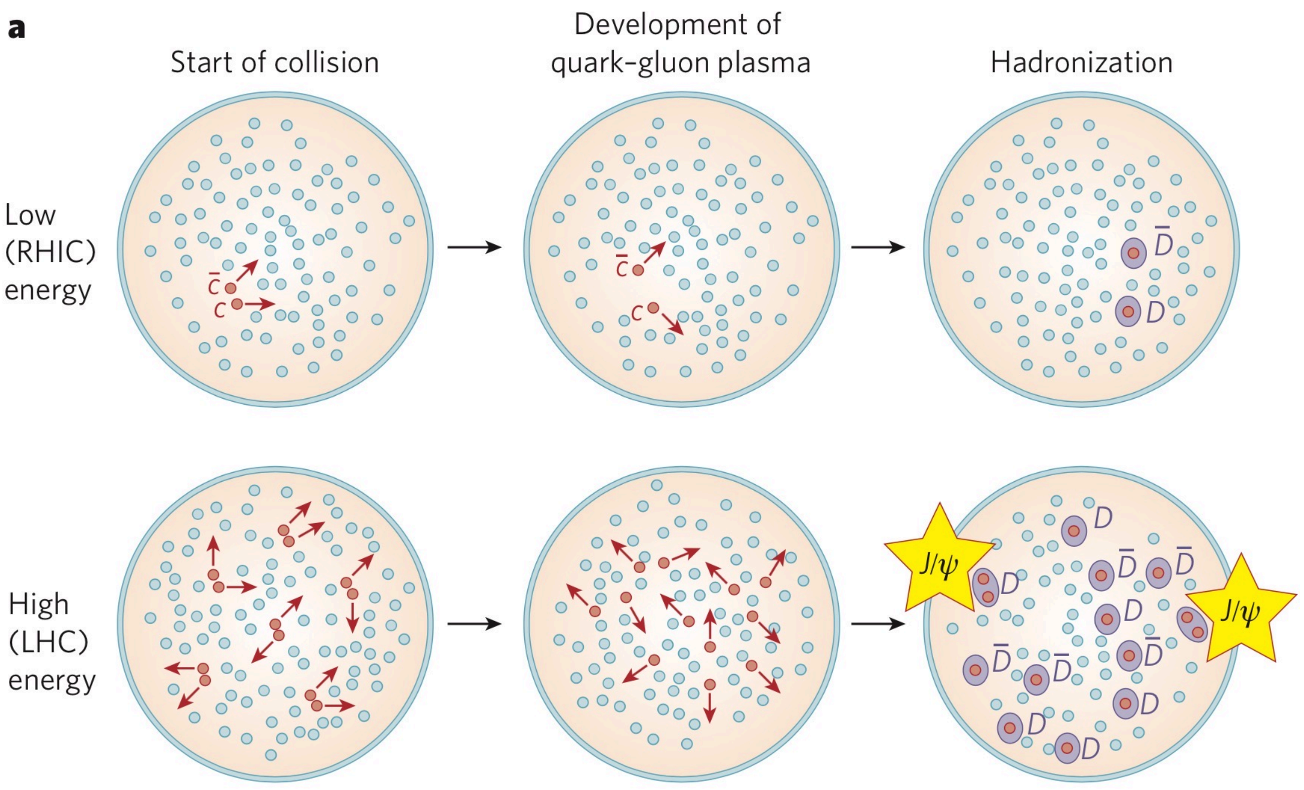
Chemical freezeout
Kinetic freezeout

What we can control → What we want to study ← What we can measure

Quarkonium in QGP



S. Digal, P. Petreczky, H. Satz, PLB514, 57 (2001)

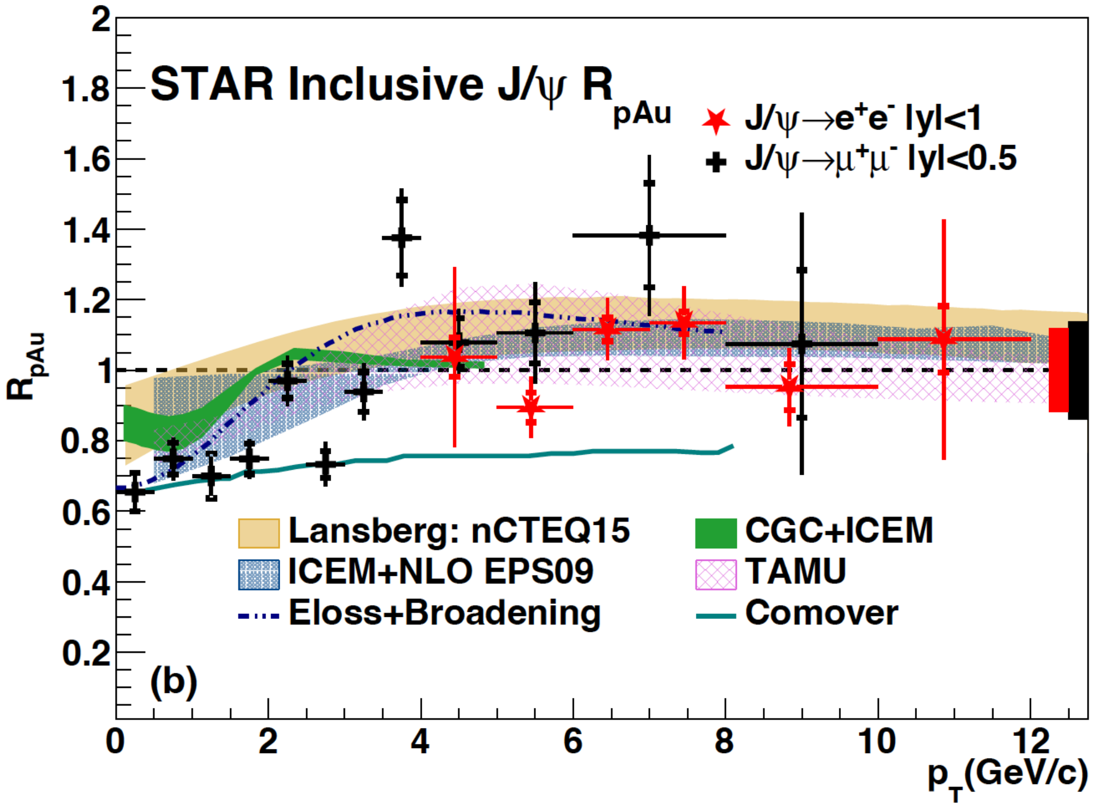


P. Braun-Munzinger, J. Stachel, Nature 448, 302 (2007)
A. Andronic et. al., Nature 561, 321 (2018)

Hot medium effects:

- Melting in QGP
- Regeneration
- Jet quenching?

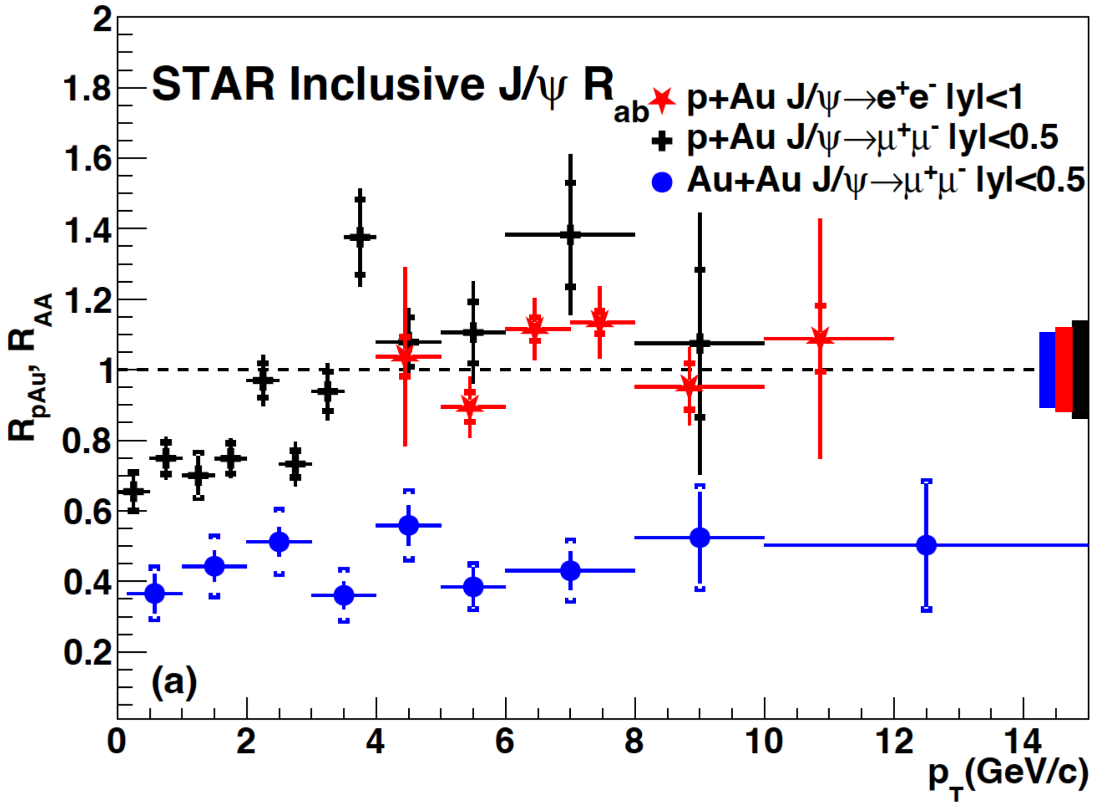
J/ψ Suppression in p+Au at 200 GeV



STAR, arXiv: 2604.22184 (2026)

- Measuremets from two decay channels are consistent in overlapping p_T range
- Significant suppression at low p_T
- Consistent with no suppression at high p_T
- Theoretical calculations incorporating nPDF and/or k_T broadening describe data
- Comover model overestimates suppression at high p_T, due to lack of p_T dependence

J/ψ Suppression in Au+Au at 200 GeV

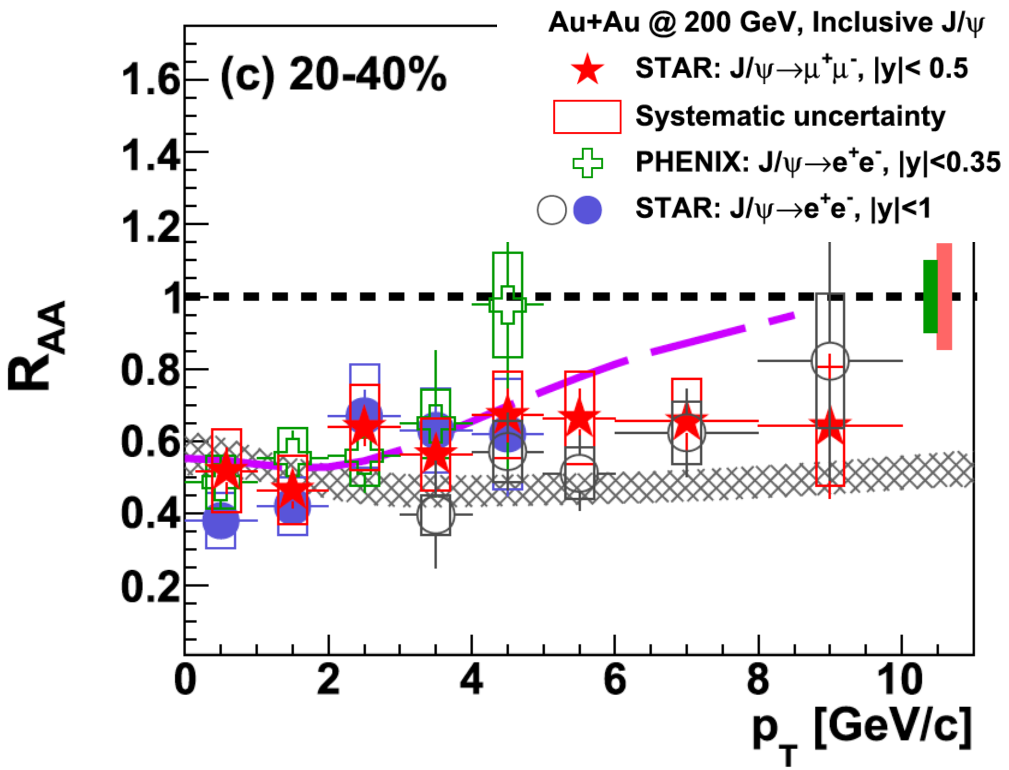


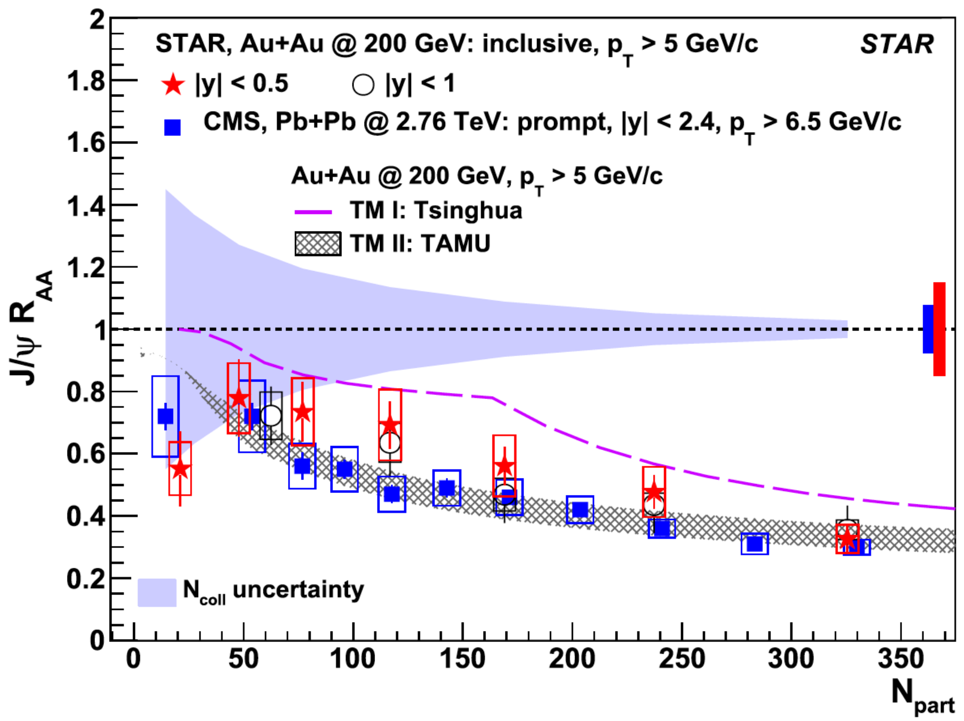
STAR, arXiv: 2604.22184 (2026); PLB797, 134917 (2019)

- Significant suppression observed at high p_T in Au+Au collisions
- CNM effects are minimal at high p_T
- Regeneration is negligible at high p_T

➔ "Providing strong evidence for the color-screening in the deconfined medium"

J/ψ Suppression in Au+Au at 200 GeV

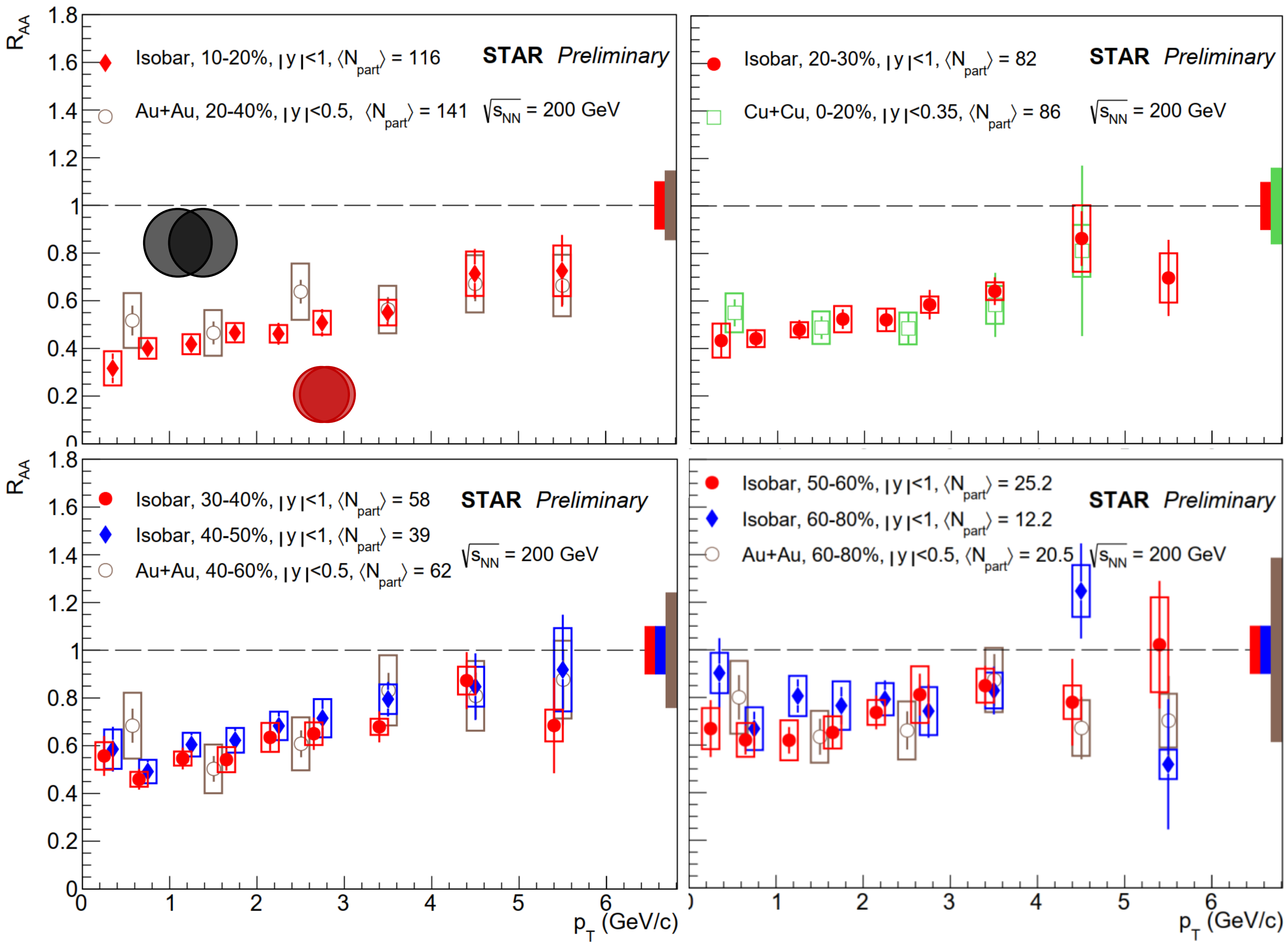




STAR, PLB722, 55 (2013) ; PLB797, 134917 (2019)

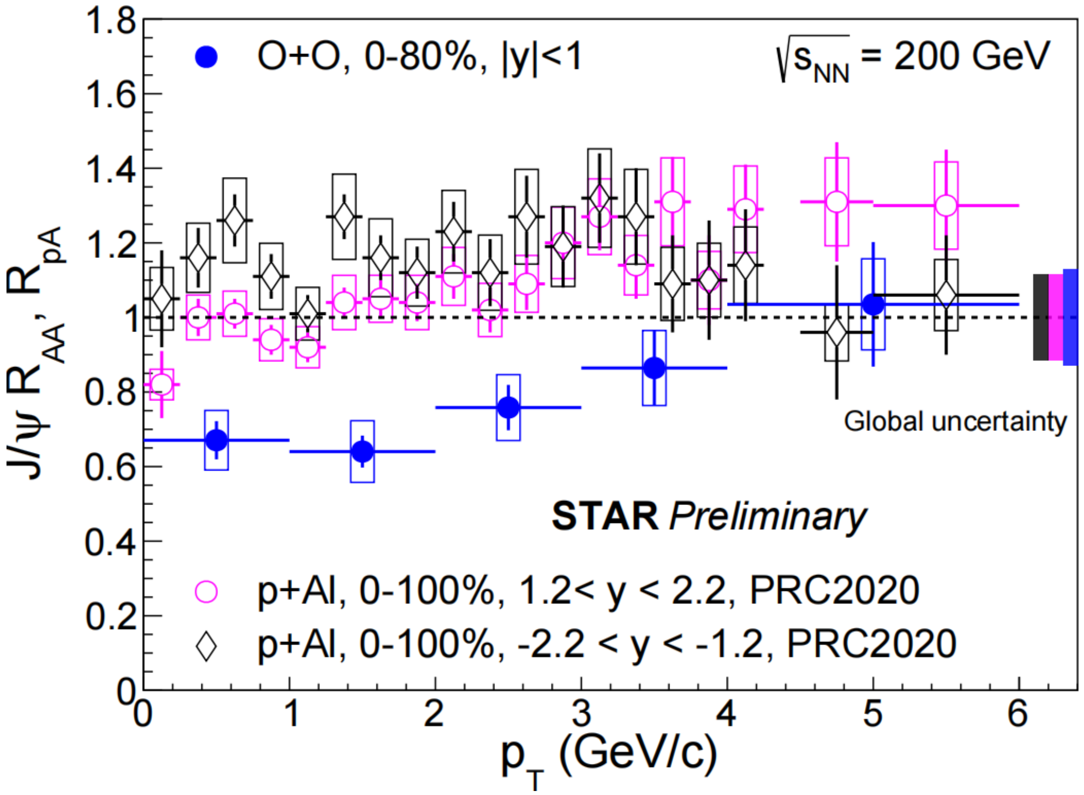
- Transport models incorporating hot medium and CNM effects describe data within uncer.
- p_T dependence of transport models to be examined with precise data

J/ψ Suppression in Ru+Ru/Zr+Zr at 200 GeV



- Most precise measurements to date at RHIC
- Significant suppression observed in (semi-)central isobar collisions
- Consistent with that in Cu+Cu and Au+Au for similar system size $<N_{part}>$
- Exhibits an increasing p_T dependence
- To be compared with models

J/ψ Suppression in O+O at 200 GeV



Wei Zhang, Hard Probes 2026

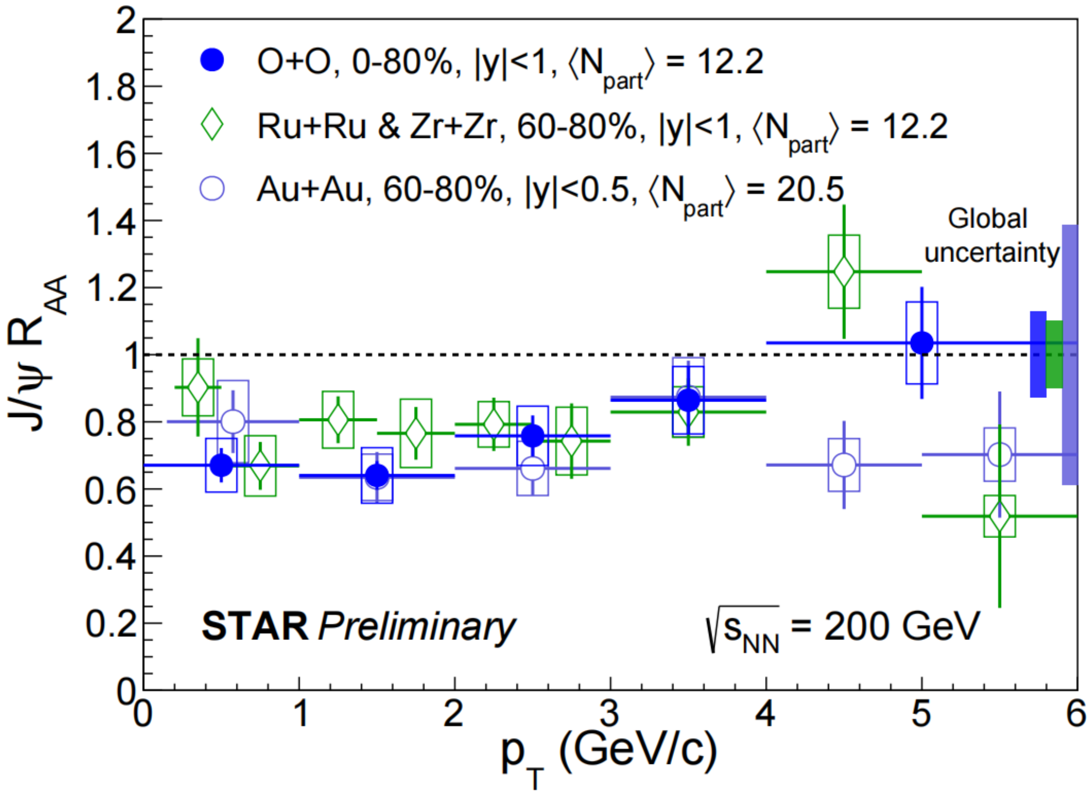
- Stronge suppression of J/ψ at mid-rapidity in O+O collisions at low p_T
- The nuclear modification factor in p+Al is consistent with unity in forward and larger than unity in backward rapidity

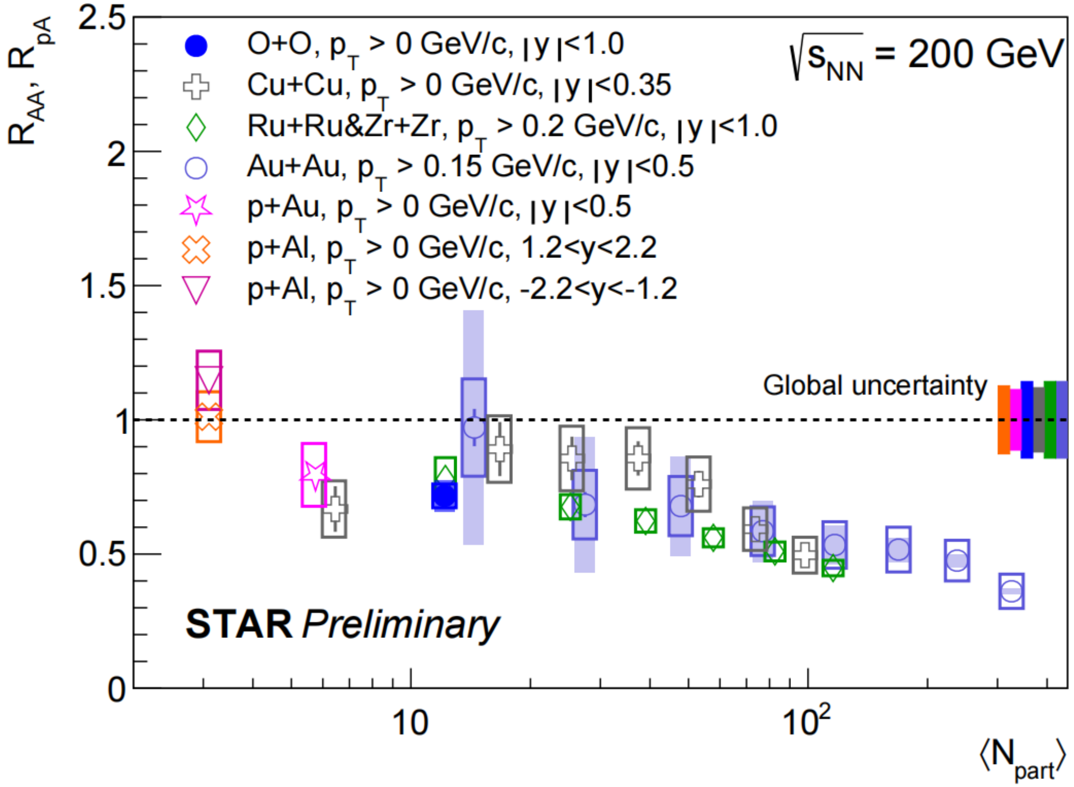
  → No suppression from CNM effects

Suggestion of QGP formation in O+O at 200 GeV

- p_T dependence may due to different time in the hot medium (leakage effect)

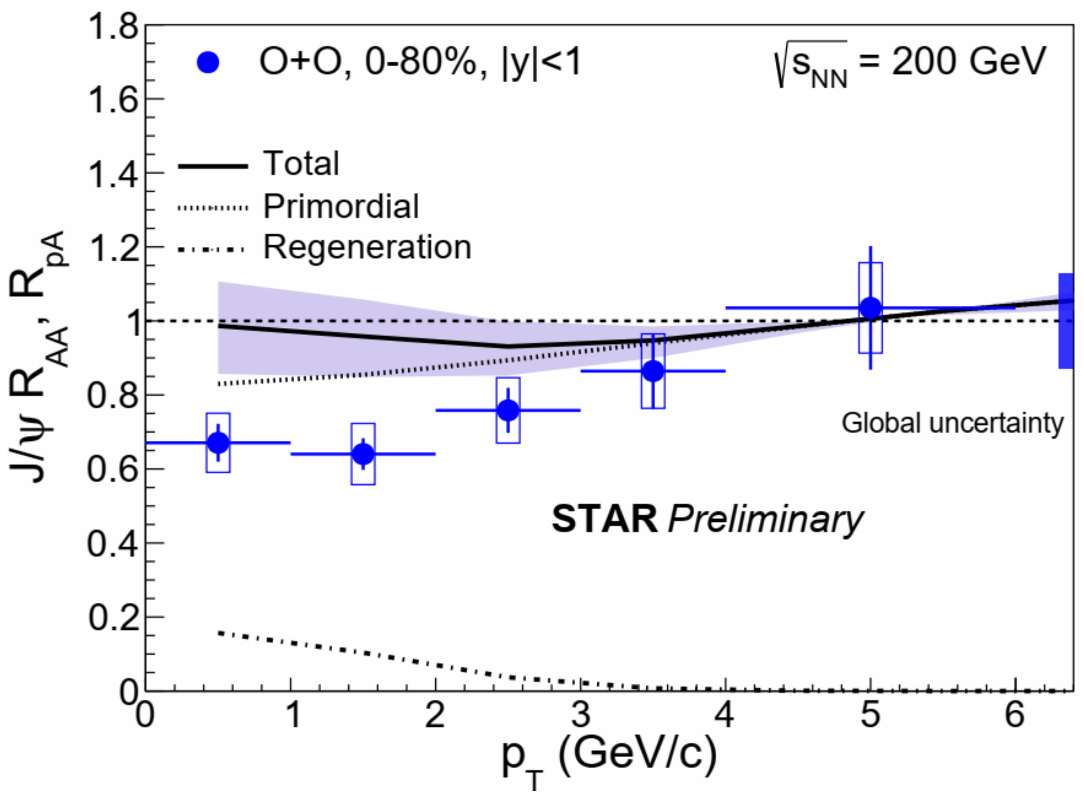
J/ψ Suppression in O+O at 200 GeV





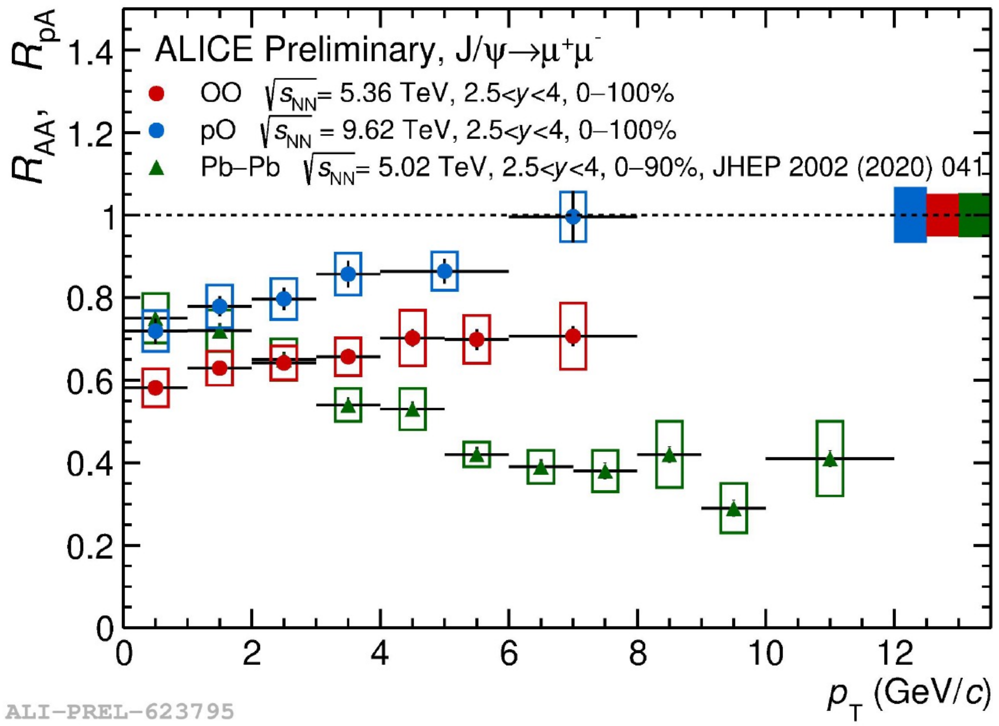
- Suppression is similar as in Au+Au and Isobar collisions with similar <N_{part}>

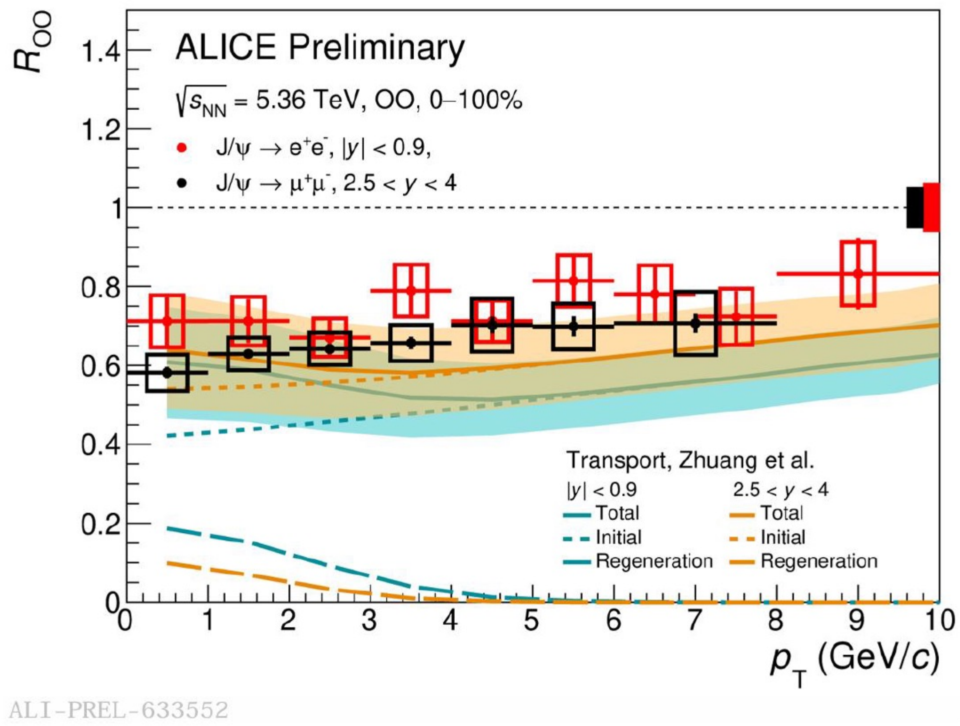
J/ψ Suppression in O+O at 200 GeV



- Transport model describes the data at high p_T
- But underestimates the suppression at low p_T
- Sizeable regeneration contribution at low p_T?

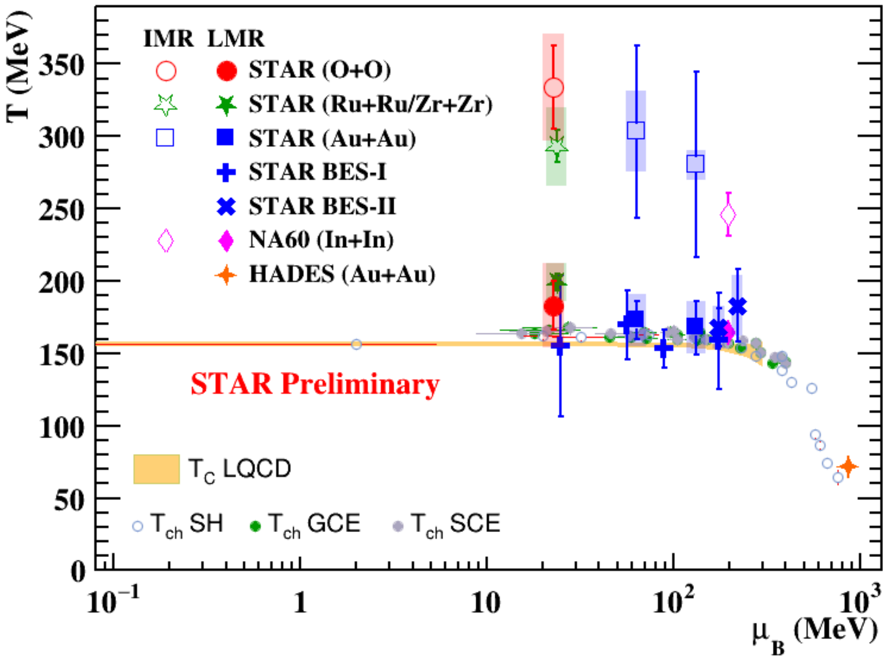
J/ψ Suppression in O+O at 5.36 TeV

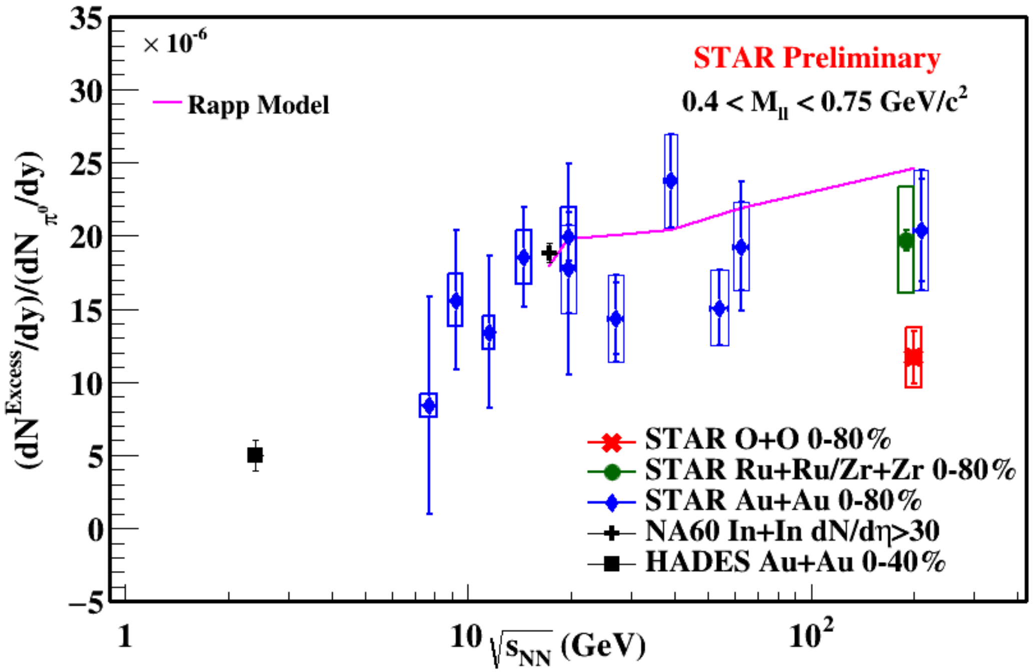




Liang Dong, Hard Probes 2026

- Significant suppression in O+O at 5.36 TeV
- Systematically lower than in p+O at 9.62 TeV
- Different p_T dependence from Pb+Pb at 5.02 TeV
- Described by transport models
- CNM effects : EPS09 + Cronin





Temperature extracted from intermediate-mass dilepton is similar as in Ru+Ru/Zr+Zr and Au+Au collisions

➔ Similar hot medium initial T

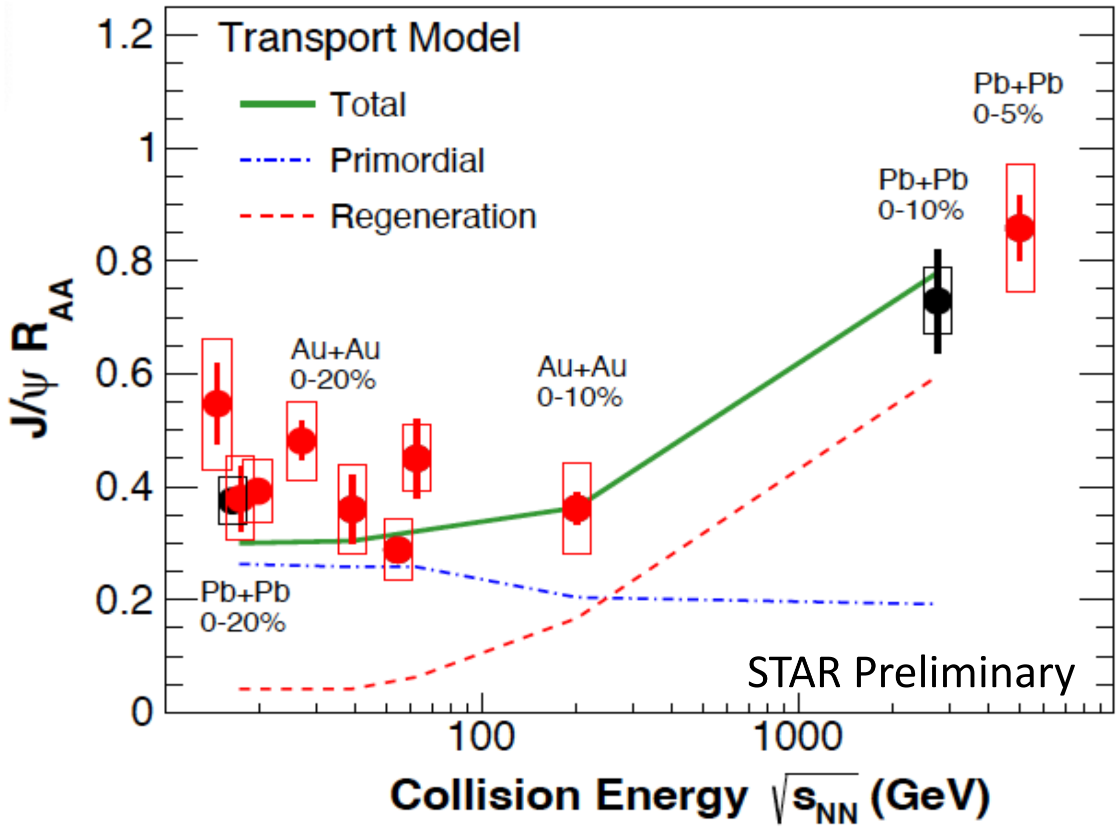
Normalized integrated excess yield of low-mass (ρ-like) dilepton is smaller than in Ru+Ru/Zr+Zr and Au+Au

➔ Shorter system lifetime

Provides additional constraints to the QGP properties

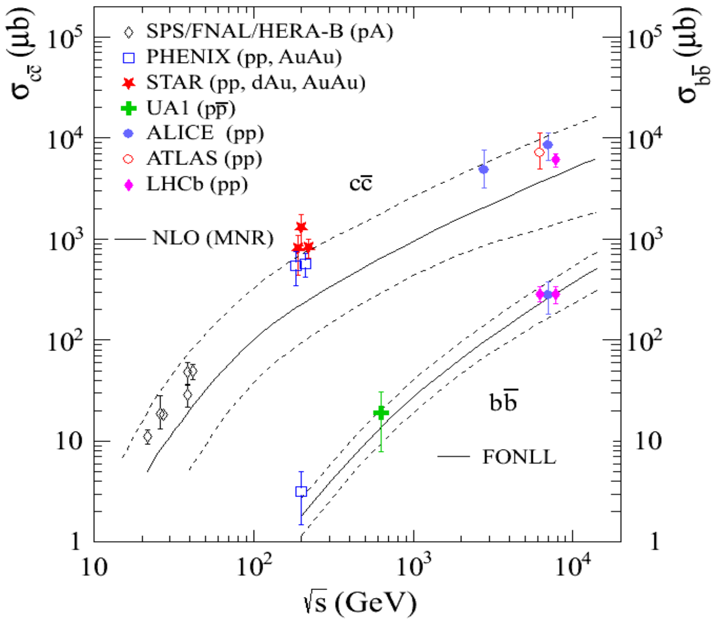
Zihan Wang, SQM2026

Energy Dependence of J/ψ Suppression



NA50, PLB 477, 28 (2000)
Wei Zhang, Hard Probes 2026
STAR, PLB 722, 55 (2013)
STAR, PLB 771, 13 (2017)
STAR, PLB 877, 140405 (2026)
ALICE, PLB 734, 314 (2014)
ALICE, PLB 849, 138451 (2024)

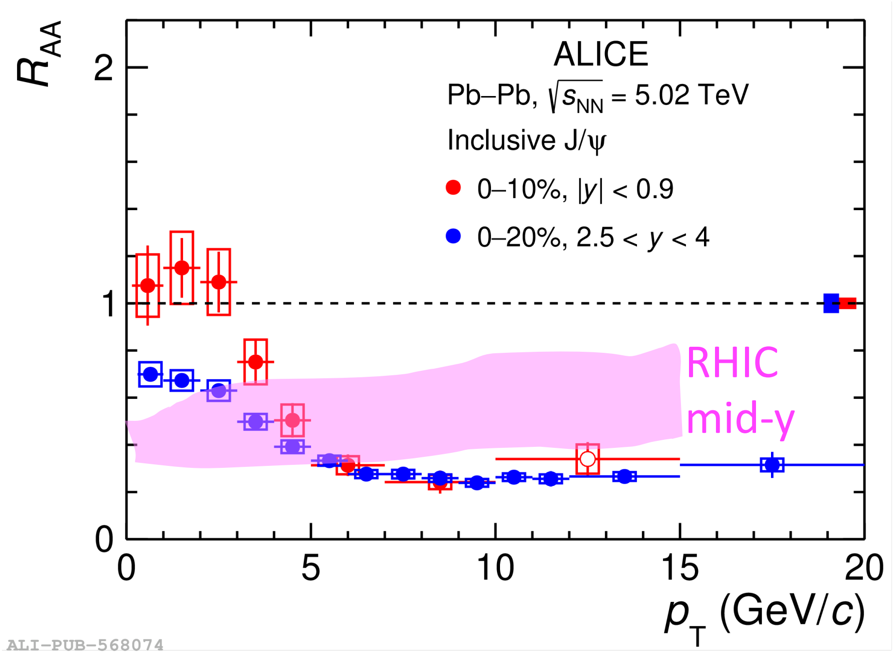
20 years efforts at STAR and the LHC

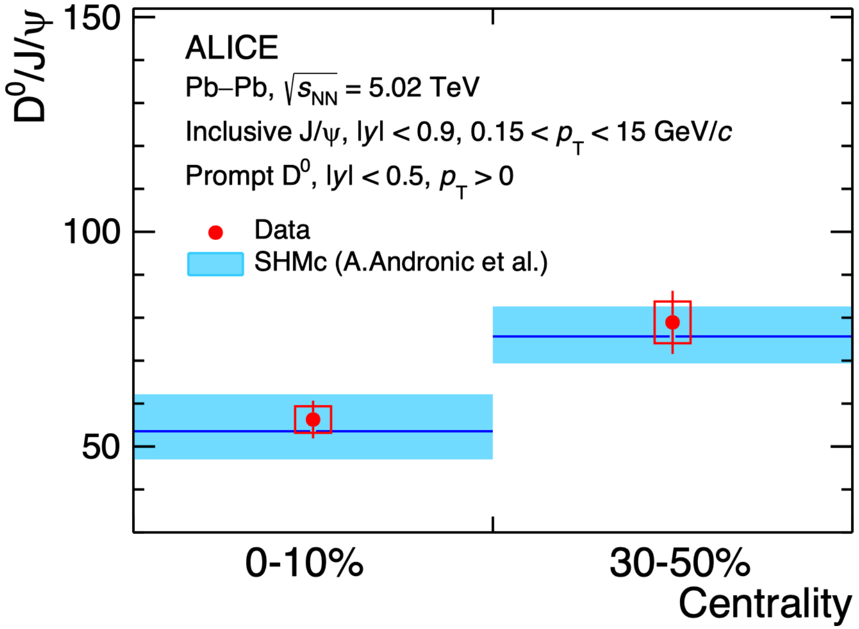


SPS → RHIC → LHC

Melting | Melting + regeneration | Regeneration domain

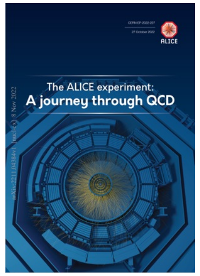
ALICE, PLB 849, 138451 (2024)





- Strong p_T dependence, unlike at RHIC
- Clear rapidity dependence at low p_T

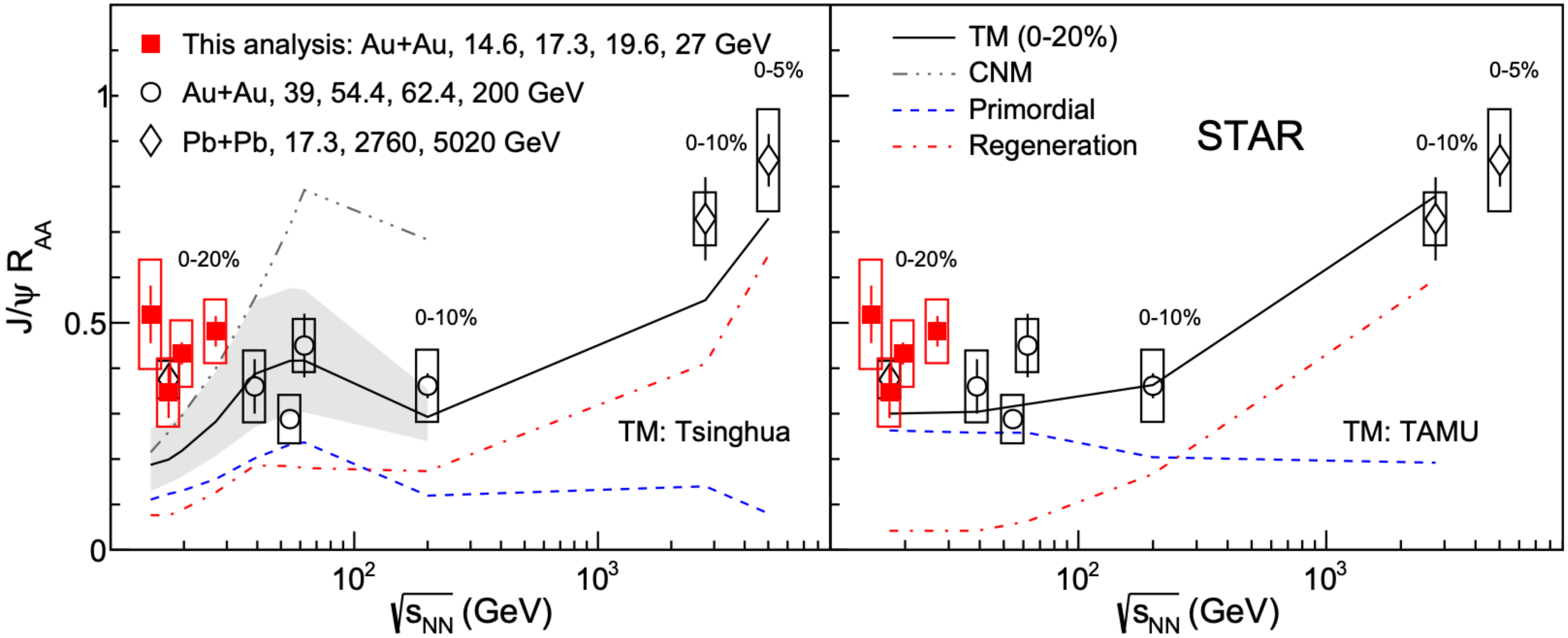
- Increase of J/ψ yield with respect to D-meson in central collisions



2.5.1 Study of the charmonium ground state: evidence for the (re)generation and demonstration of deconfinement at LHC energies

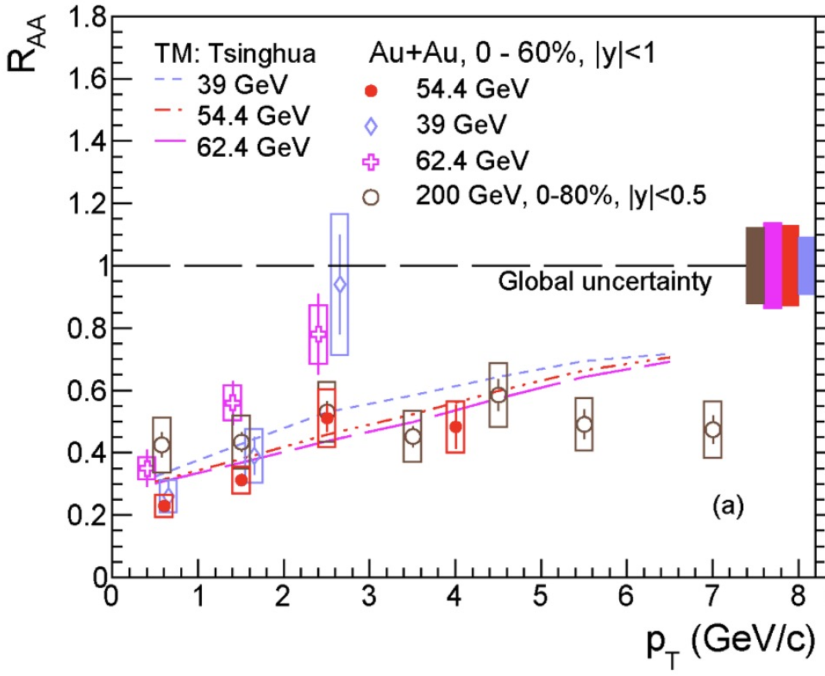
ALICE, EPJC 84, 813 (2024)

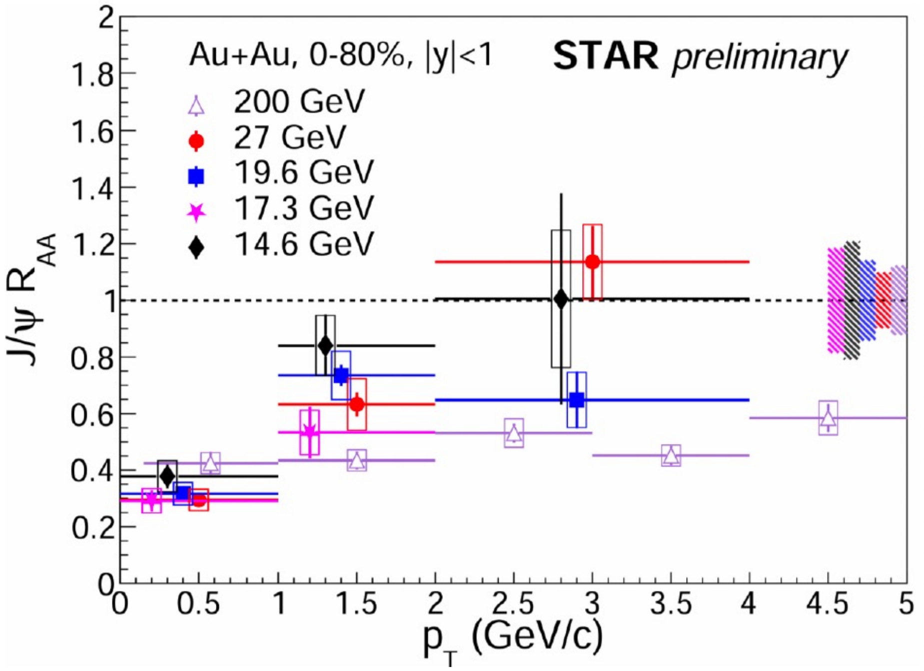
J/ψ Measurements at RHIC BES–II



- Both transport models capture the overall trend
  - Describe data above 27 GeV and systematically lower than data at lower energies
- But the relative contribution of primordial and regenerations are quite different

Transverse Momentum Dependence

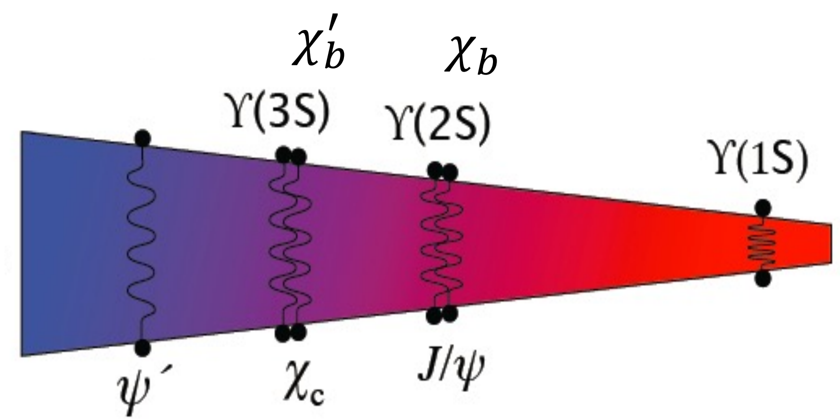


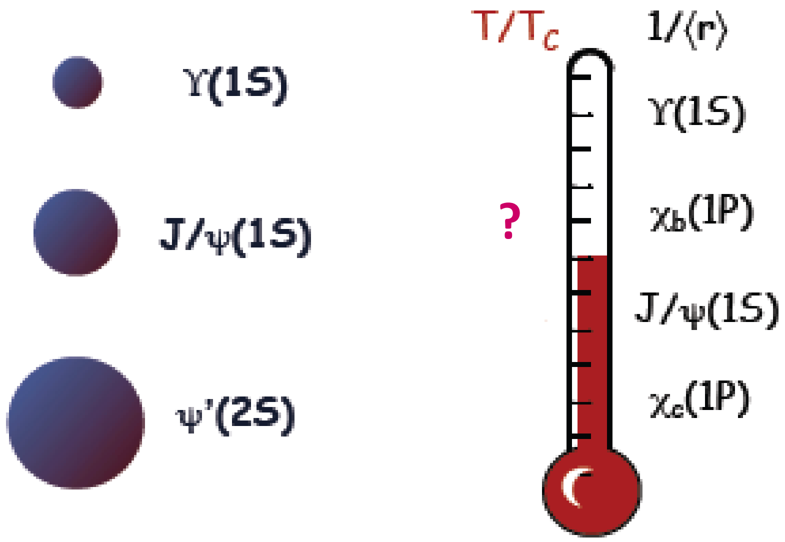


- An clear increasing p_T dependence is observed at RHIC BES energies
- Dominantly attribute to CNM effects (absorption) in transport model

Sequential Melting of Quarkonium

Plasma thermometer



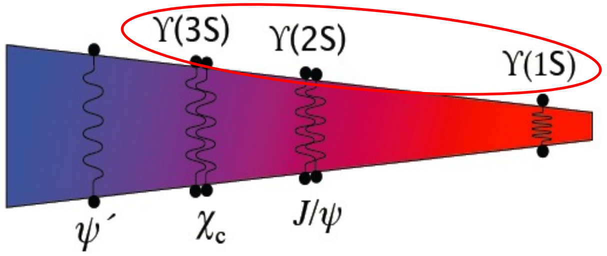


Debye radius is inversely proportional to the temperature of QGP

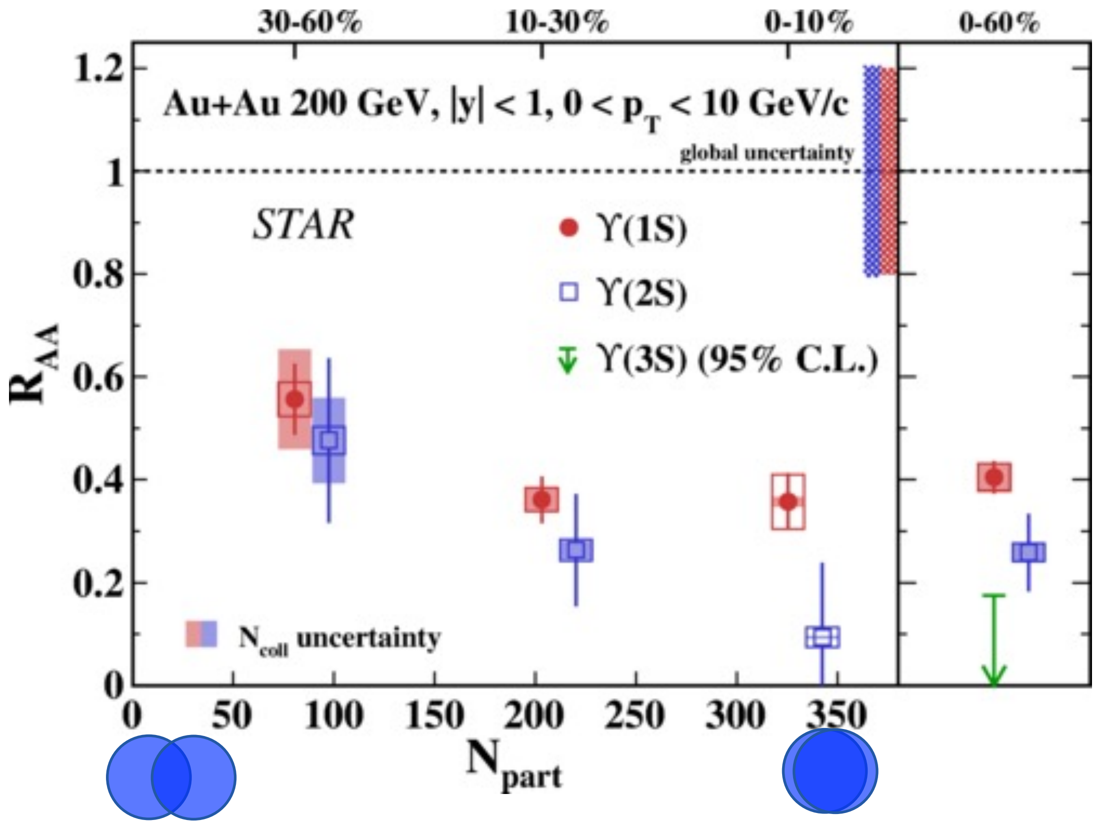
Different quarkonium states dissociate at different temperatures
→ Sequential melting

Sequential melting confirms deconfinement and provides information about T_{QGP}

Sequential Melting in Bottom Sector

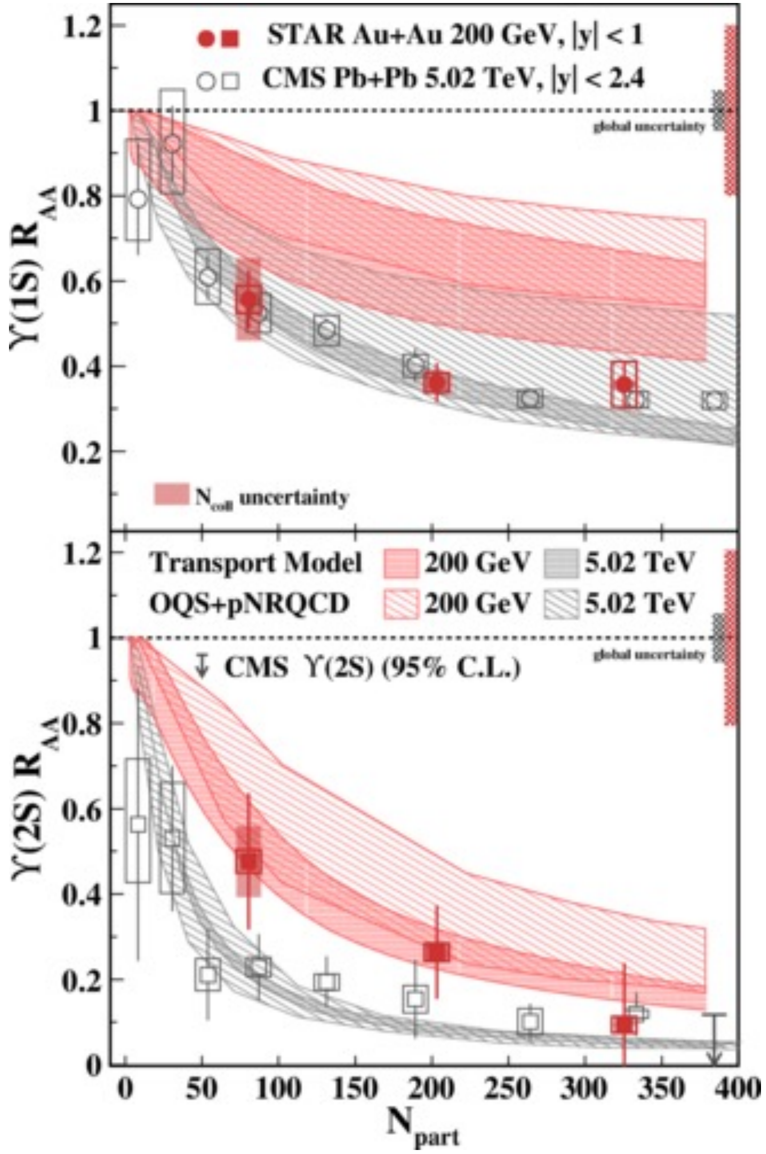


STAR, PRL 130, 112301 (2023)



First observation of “sequential melting” at RHIC

Sequential Melting in Bottom Sector



Upsilon(1S):

- Strong suppression, and similar at RHIC and LHC

→ Arises mainly from the suppression of excited states feed down to Upsilon(1S)

→ Primordial Upsilon(1S) not significantly suppressed

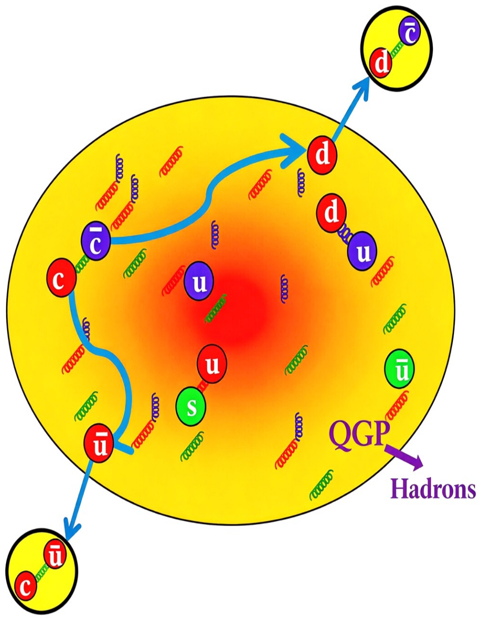
Upsilon(2S):

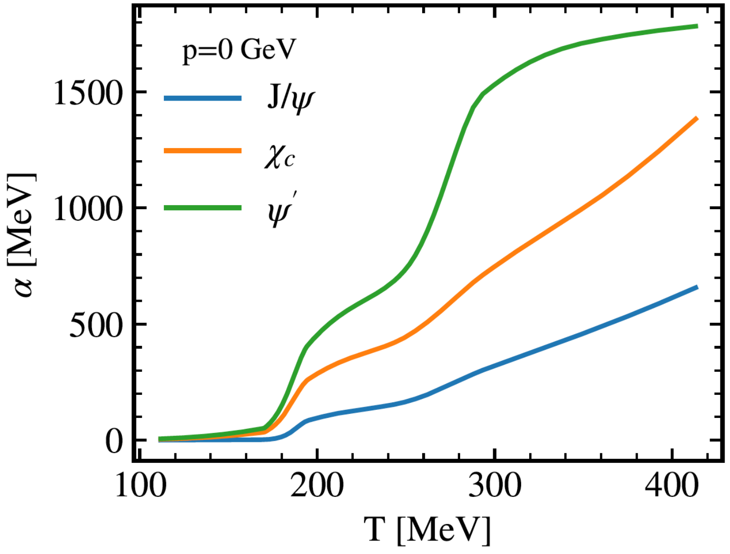
- Stronger suppression than 1S state
- Hints of less suppression at RHIC in peripheral collisions

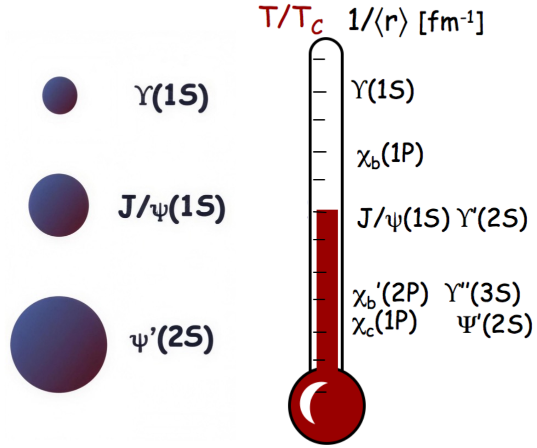
QGP is formed, and its temperature is high enough to melt excited bottomonium states!!!

STAR, PRL130, 112301 (2023)

Sequential Melting in Charm Sector





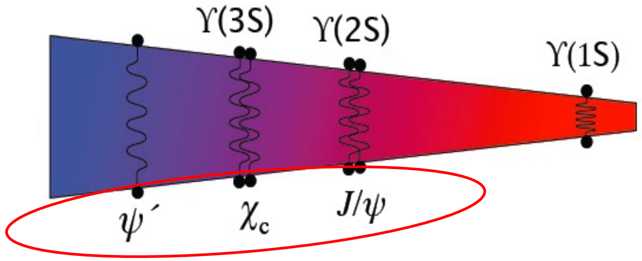


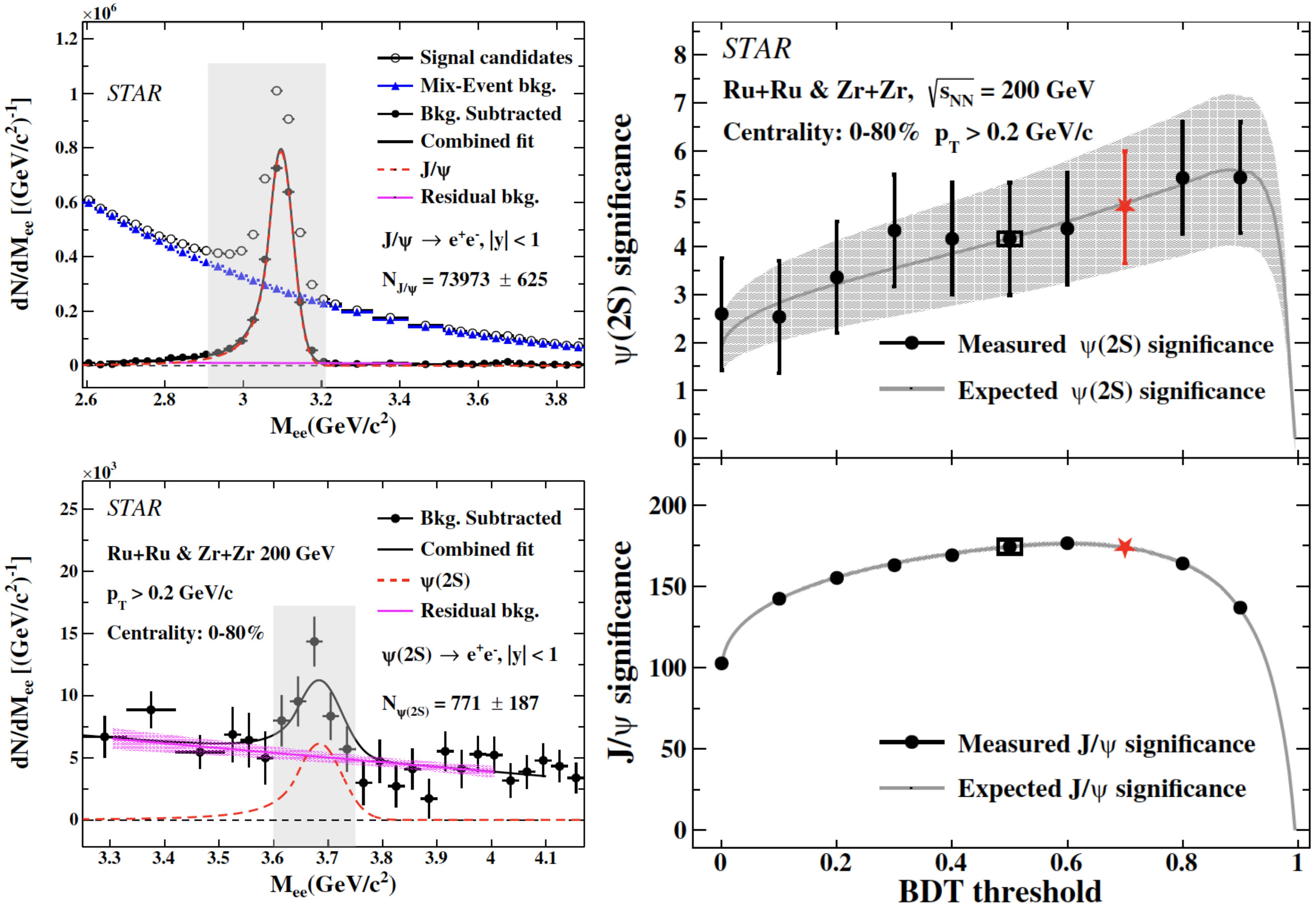
K. Fu, B. Wu and R. Rapp, arXiv:2603.0467

Suppression of loosely-bounded ψ(2S) is very sensitive to the space and time profile of the QGP temperature

Take ratio to J/ψ can mimic the experimental and theoretical uncertainties

Sequential Melting in Charm Sector



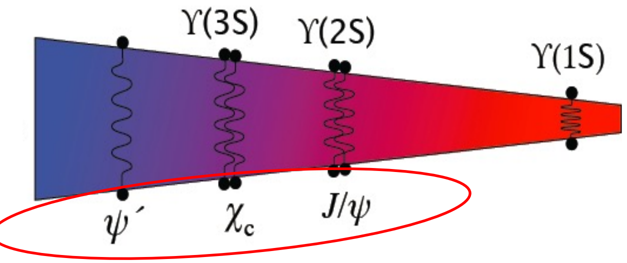


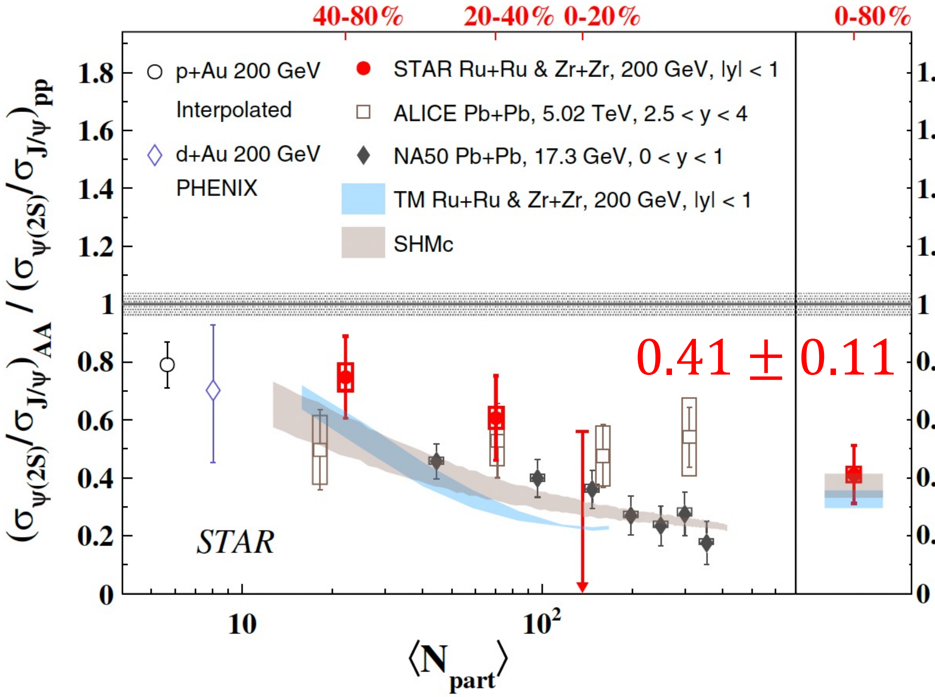
First measurement of $\psi(2S)$ in HIC at RHIC

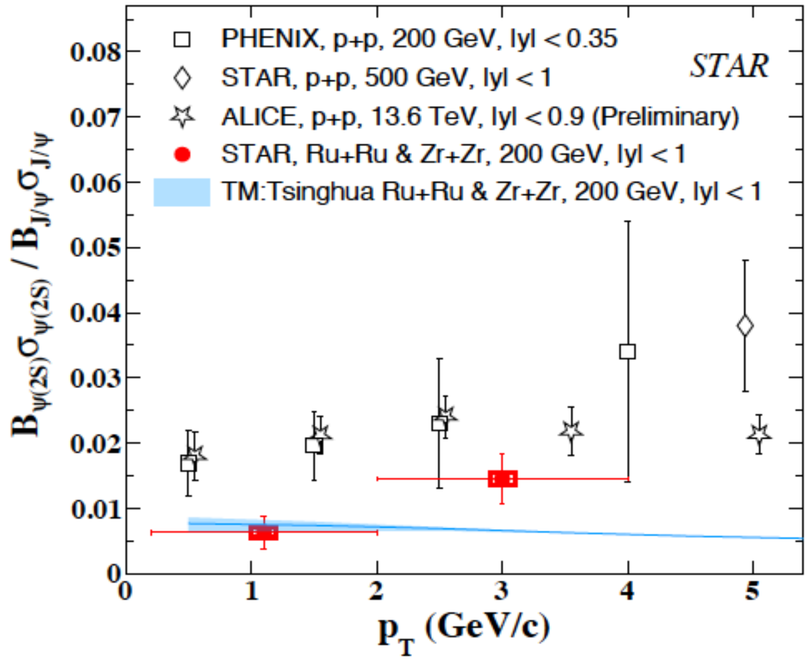
- Very challenging measurement in heavy ion experiment
- Enabled by ML techniques and high statistics

Y. Wang et al., NST 37, 145 (2026)

Sequential Melting in Charm Sector





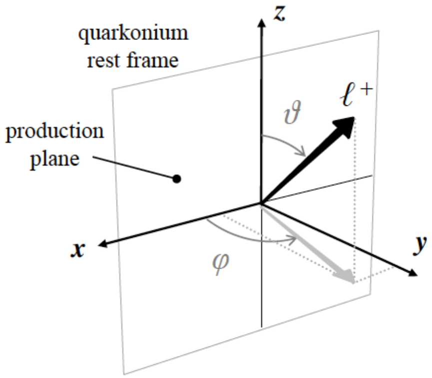


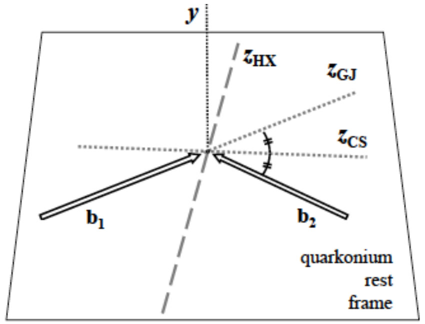
STAR, PRL 136, 122302 (2026)

- Clearly stronger suppression for ψ(2S) than J/ψ from SPS to LHC
- Consistent with model calculations → Constraints on QGP properties

J/ψ Polarization in Heavy Ion Collisions

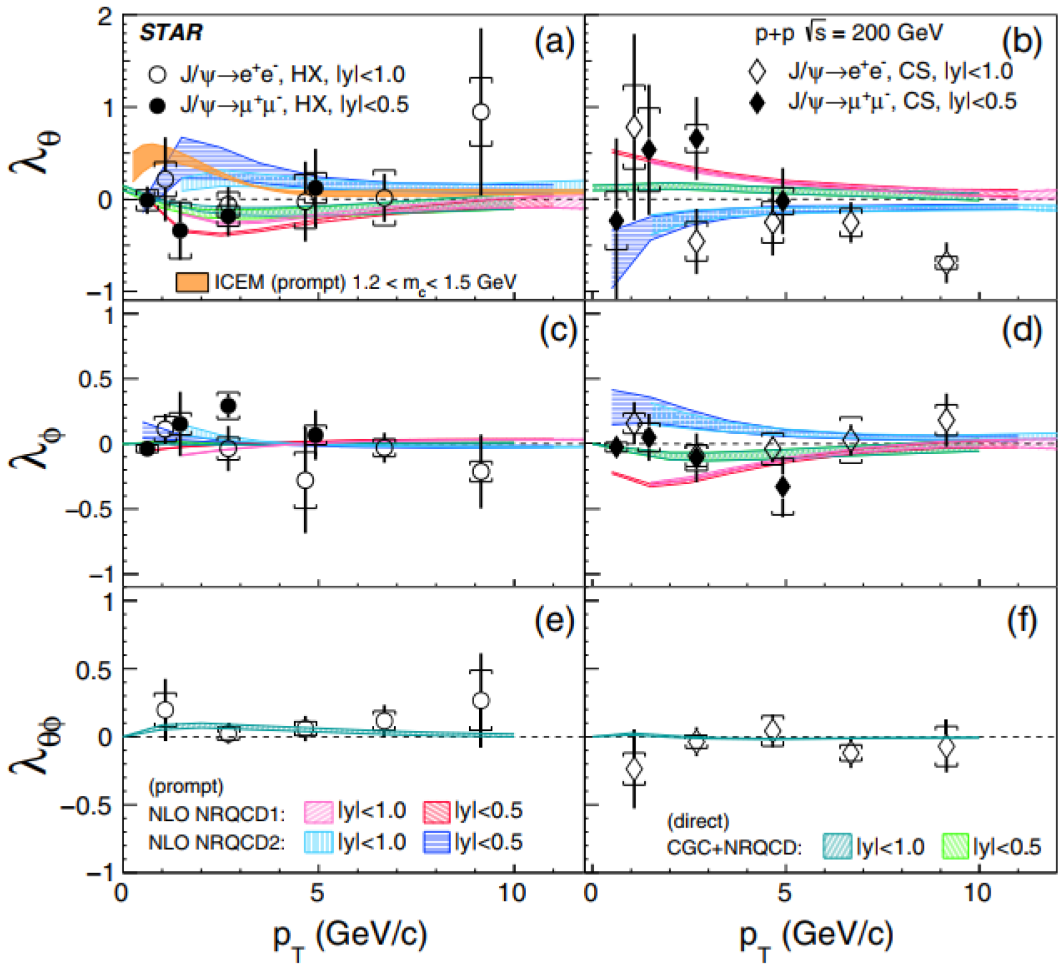
- Quarkonium polarization in p+p collisions provides crucial constraints on production mechanism
- Quarkonium polarization in heavy ion collisions may be subject to hot medium modification
  - Regeneration contribution
  - Suppression of feeddown contribution
  - Magnetic field effect
- Can be measured via decay daughters' angular distributions





$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\cos 2\varphi+\lambda_{\theta\varphi}\sin 2\theta\cos\varphi).$$

J/ψ Polarization in p+p at 200 GeV

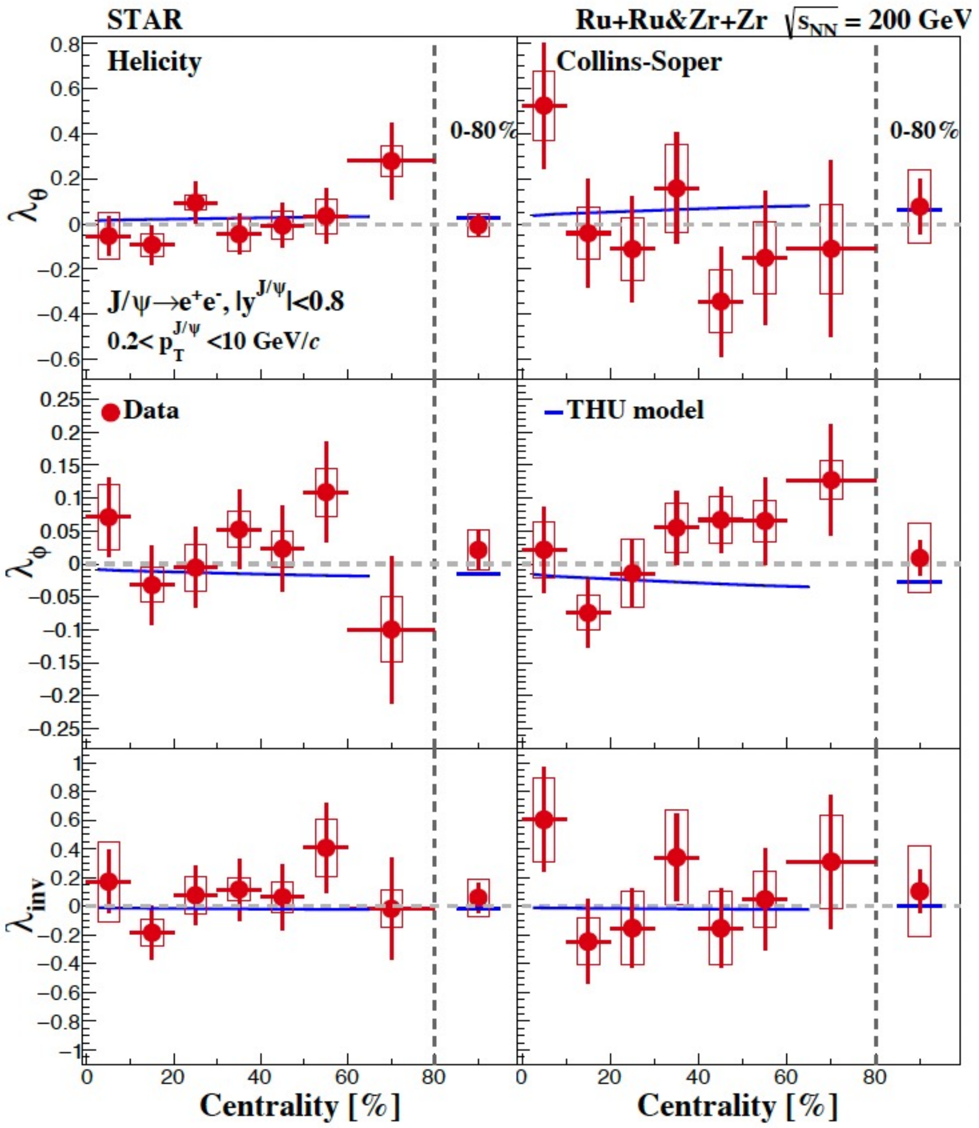


STAR, PRD102, 092009 (2020)

- J/ψ polarization measured in both Helicity and Collins-Soper frames
- Provides reference for measurements in heavy ion collisions
- Compared to ICEM, NLO NRQCD and CGC+NRQCD calculations, none of them can be ruled out definitively
- Better precision needed to distinguish models or constrain LDMEs

ICEM: V. Cheung and R. Vogt, PRD98, 114029 (2018)
CGC+NRQCD: Y. Ma et al., JHEP12, 57 (2018)
NRQCD1: H.-F. Zhang et al., PRL114, 092006 (2015) 092006
NRQCD2: B. Gong et al., PRL110, 042002 (2013)

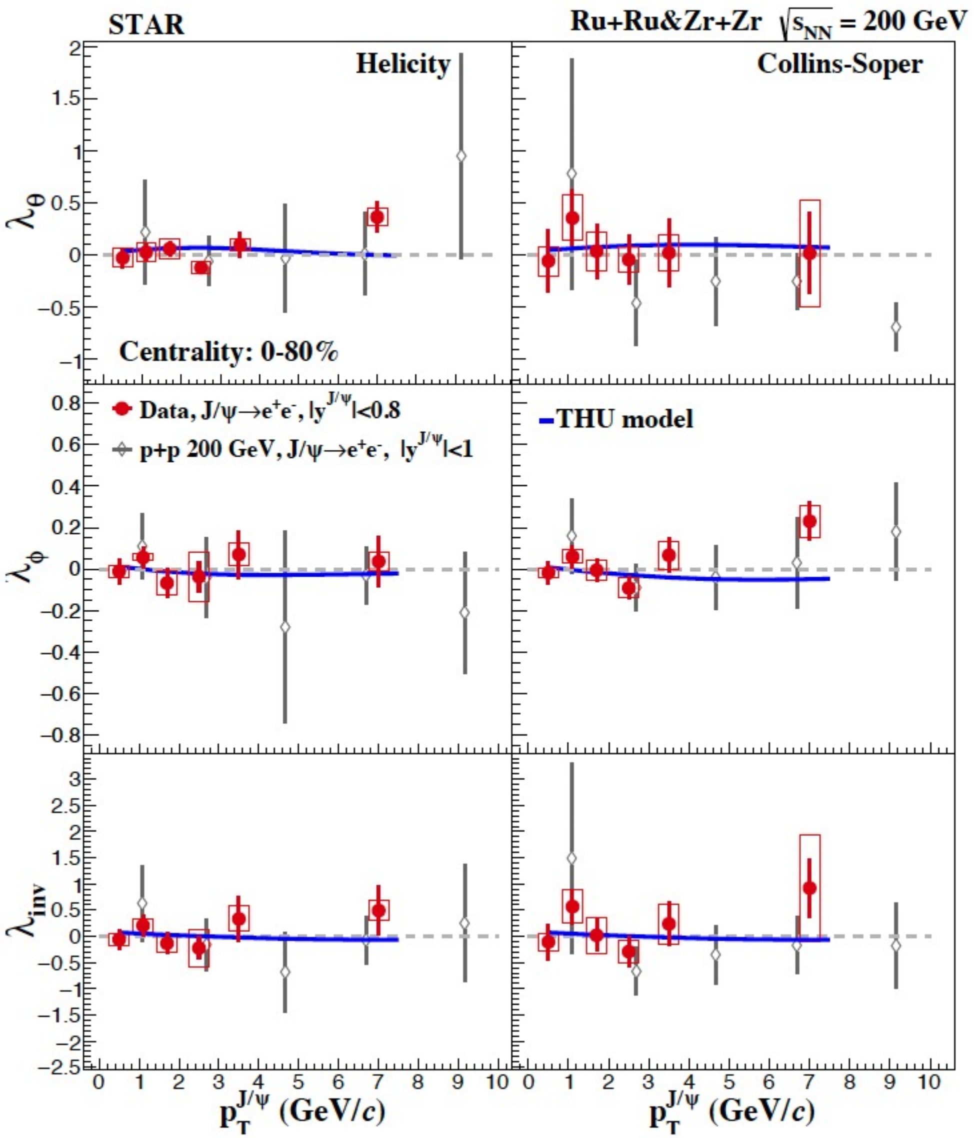
J/ψ Polarization in Ru+Ru/Zr+Zr Collisions at 200 GeV



- J/ψ polarization measured in both Helicity and Collins-Soper frames
- Consistent with no polarization in all centralities

STAR, arXiv: 2604.22184 (2026)

J/ψ Polarization in Ru+Ru/Zr+Zr Collisions at 200 GeV



- J/ψ polarization measured in both Helicity and Collins-Soper frames
- Consistent with no polarization in all centralities and all p_T bins
- No difference between p+p and A+A collisions within experimental uncertainties is observed
- Transport model prediction in A+A is different from various theoretical calculations in p+p, dominantly due to hot medium effect
- Can not be distinguished with current data precision and looking forward high statistics in Au+Au taken in 2023-2025

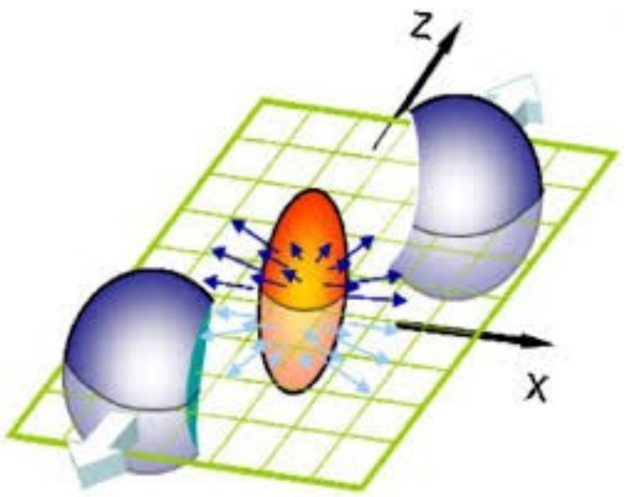
STAR, arXiv: 2604.22184 (2026)

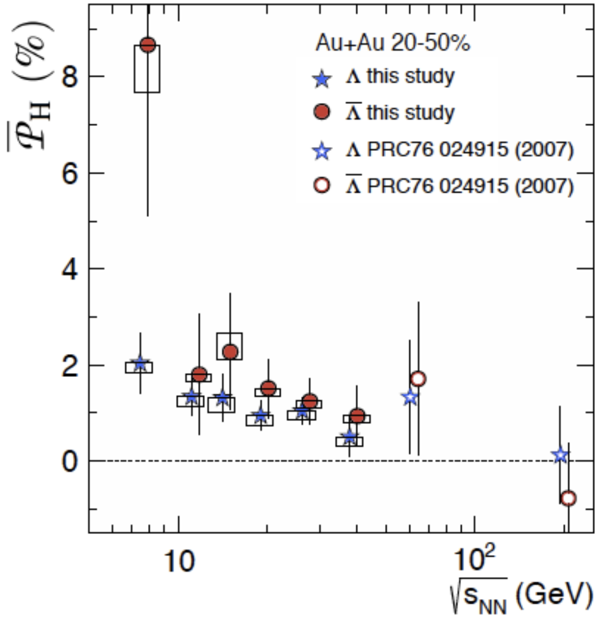
Global Spin Polarization in Heavy Ion Collisions

- Non-central heavy ion collisions produced huge orbital angular momentum
- Largest vorticity fluid in nature
- Can transfer to quark spin polarization and thus hadron spin polarization
- ϕ spin alignment significantly larger than expected from Λ global polarization measurement

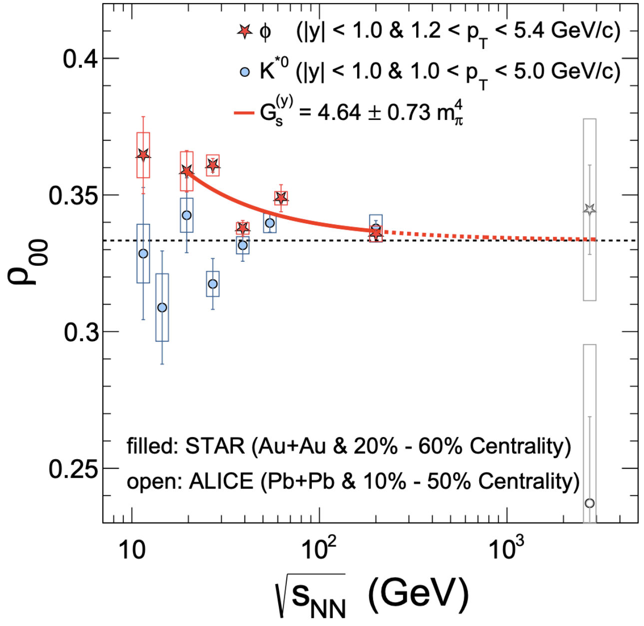
→ Spin correlation X.-L. Sheng et al., PRL 131, 042304 (2023)

→ J/ψ spin alignment?



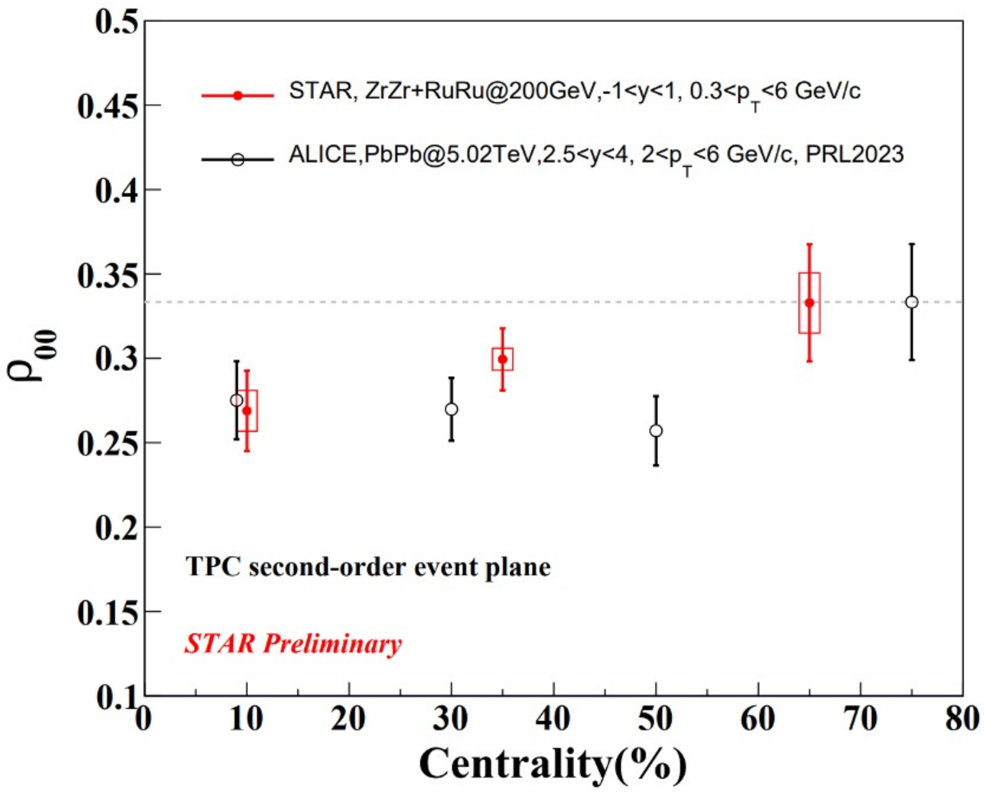


STAR, Nature 548, 62(2017)

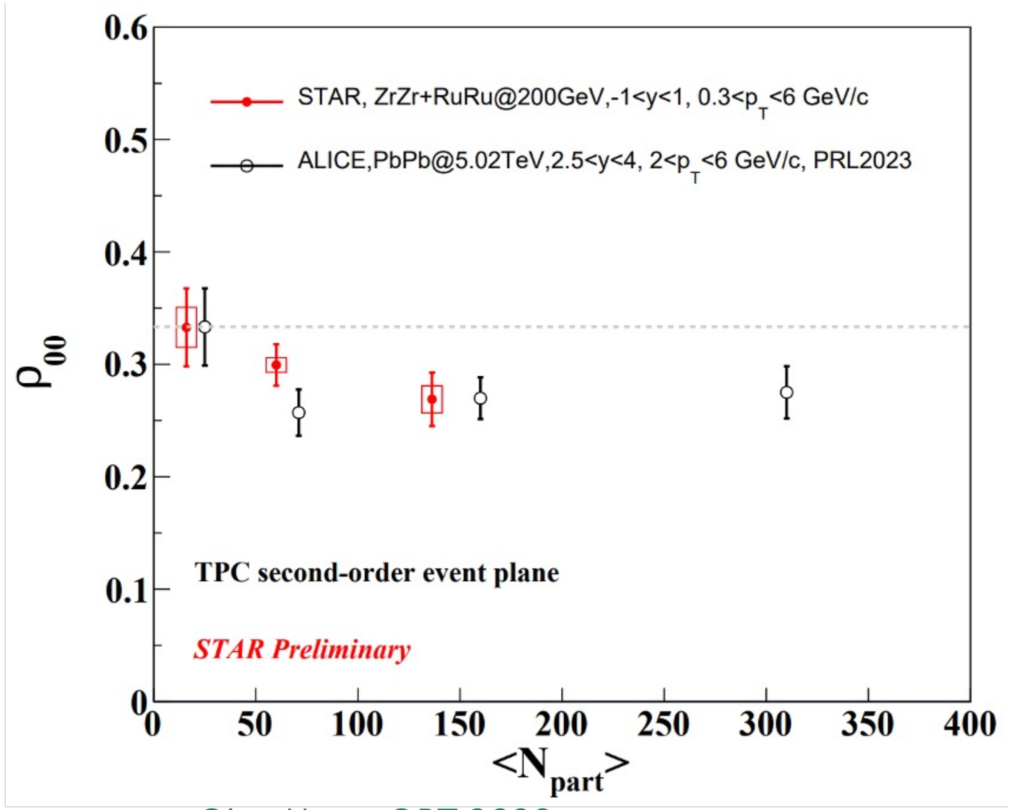


STAR, Nature 614, 244 (2023)

J/ψ Spin Alignment in Heavy Ion Collisions



ALICE, PRL 131, 042303 (2023)



Qian Yang, QPT 2023

- ρ_{00}-1/3 for J/ψ is measured to be negative at RHIC and LHC, opposite to ϕ at RHIC
- Comparable between RHIC and LHC, despite different contribution from coalescence
- Looking forward to RHIC Run 2023-2025 Au+Au and ALICE Run3 Pb+Pb results

Electromagnetic Field in Heavy Ion Collisions

- Fast moving charge generates strong EM filed, especially for heavy ions

$$B \sim \frac{1}{4\pi} \frac{\gamma Z e \beta r}{[\gamma^2 (z - \beta t)^2 + r^2]^{3/2}} \sim O(10^{14-16}\ T)$$

- The Lorentz contracted EM field can be expressed in terms of equivalent photon flux

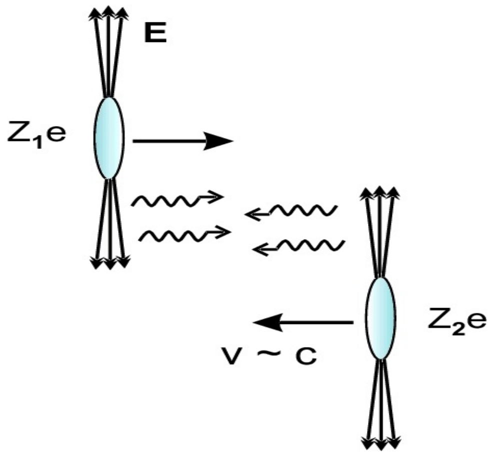
$$E \perp B \perp z, E = B$$

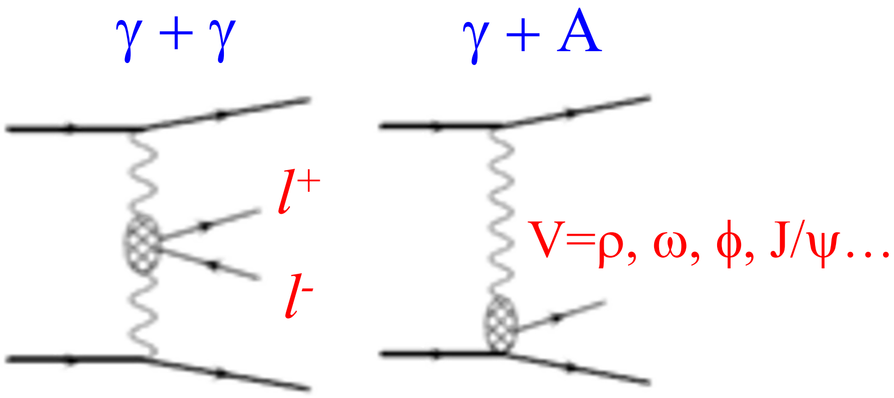
$$\omega_{max} \sim 3\ \text{GeV @ RHIC}, \sim 80\ \text{GeV @ LHC}$$

E. Fermi, Z. Phys. 29, 315 (1924)

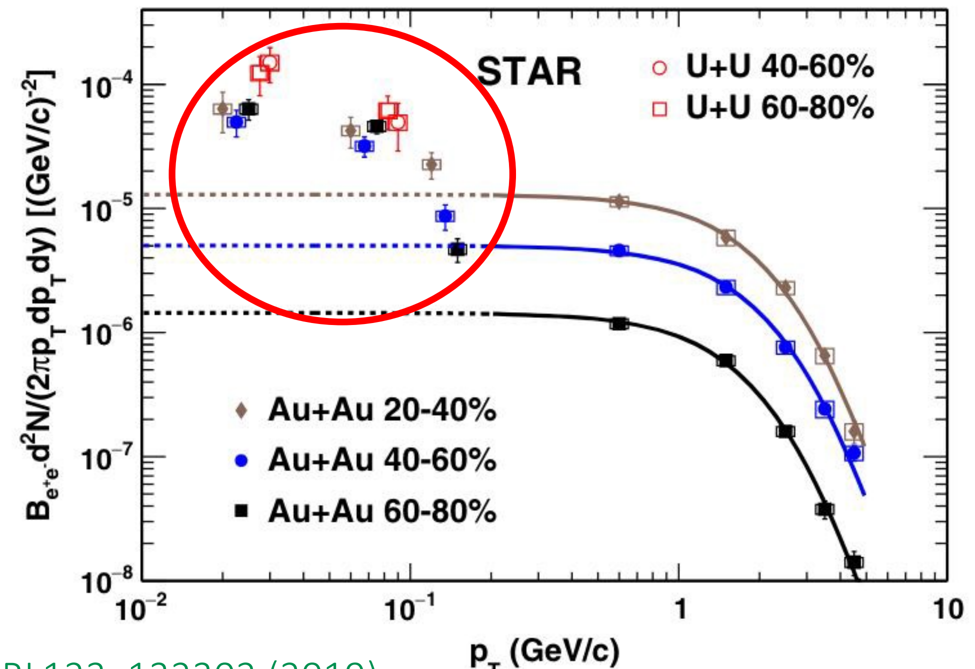
C. Weizsacker, ZP88, 612, E. Williams, PR45, 729 (1934)

- The photons induce particle production



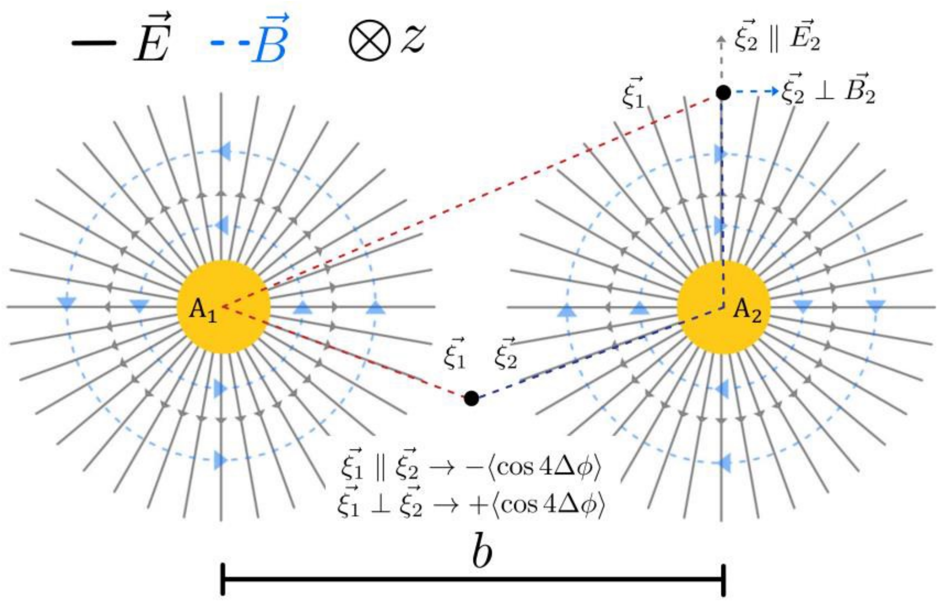


Ann. Rev. Nucl. Part. Sci.55:271 (2005)



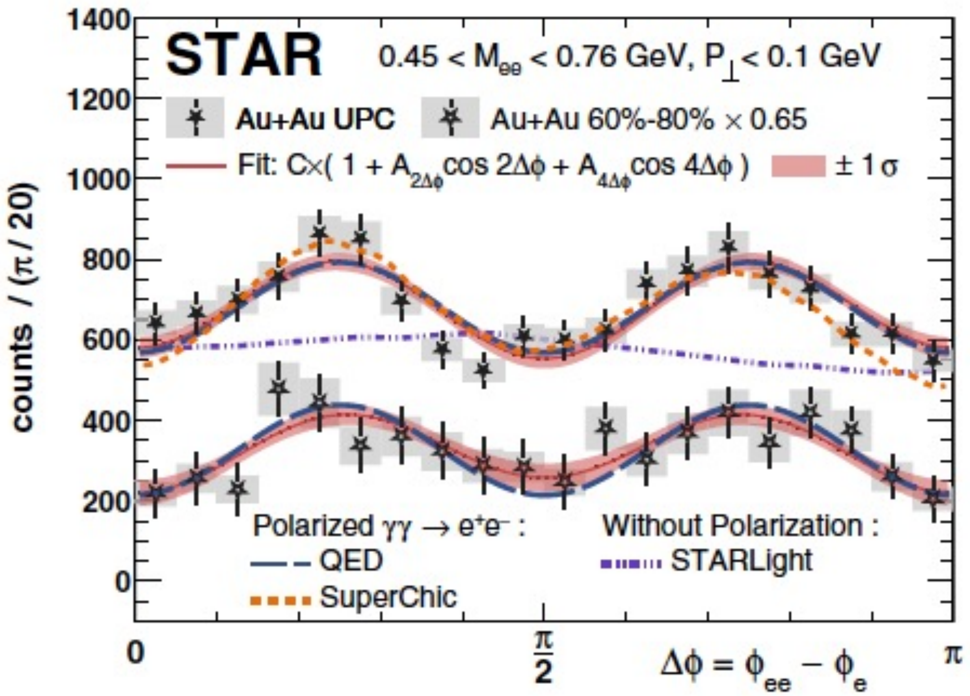
STAR, PRL123, 132302 (2019)

Linearly Polarized Photons



C. Li, Y. Zhou, J. Zhou, PLB795, 576 (2019)

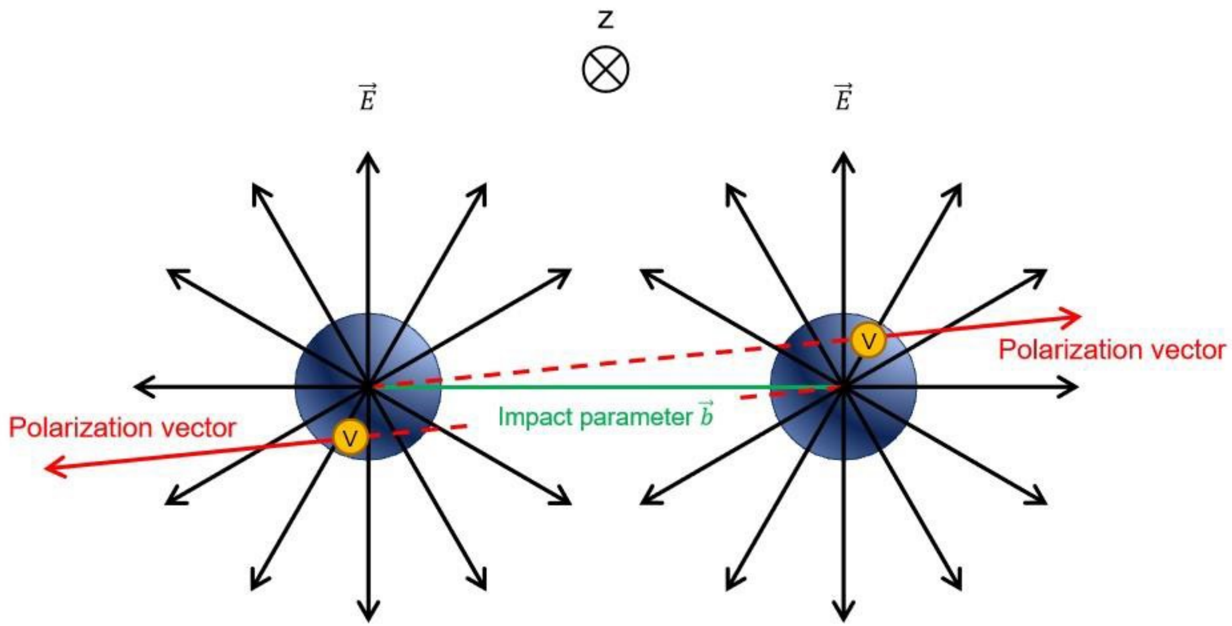
STAR, PRL127, 052302 (2021)

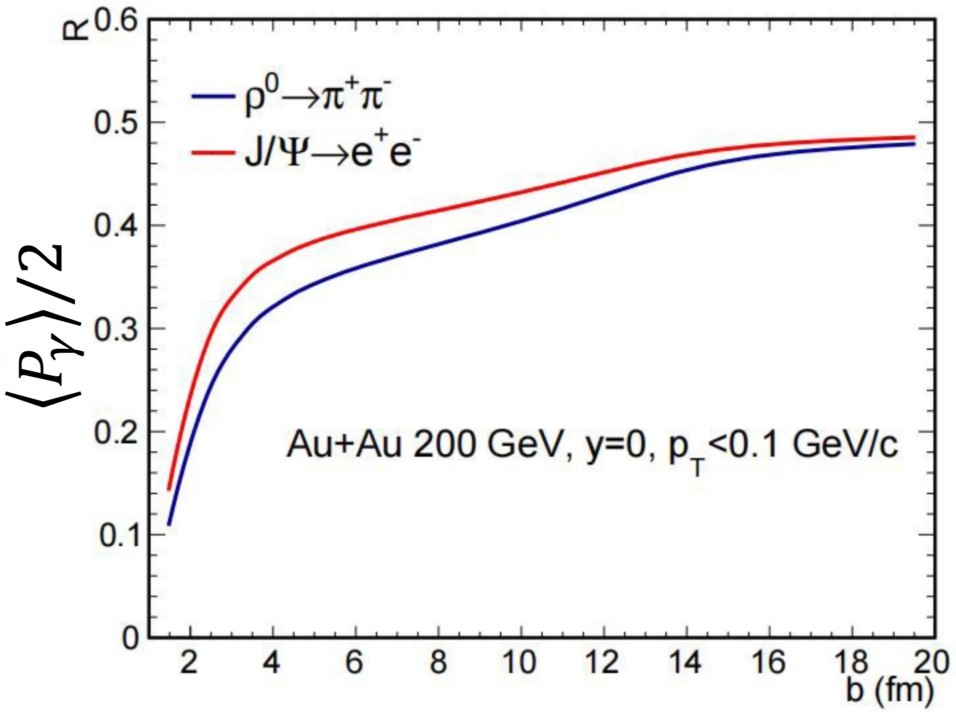


- Photons from the highly Lorentz contracted EM filed are linearly polarized in the transverse plane
- Polarization vectors coincide with the positions and thus p_T
- QED predicts cos4ϕ modulation and confirmed by data

Align the Reaction Plane in Heavy Ion Collisions

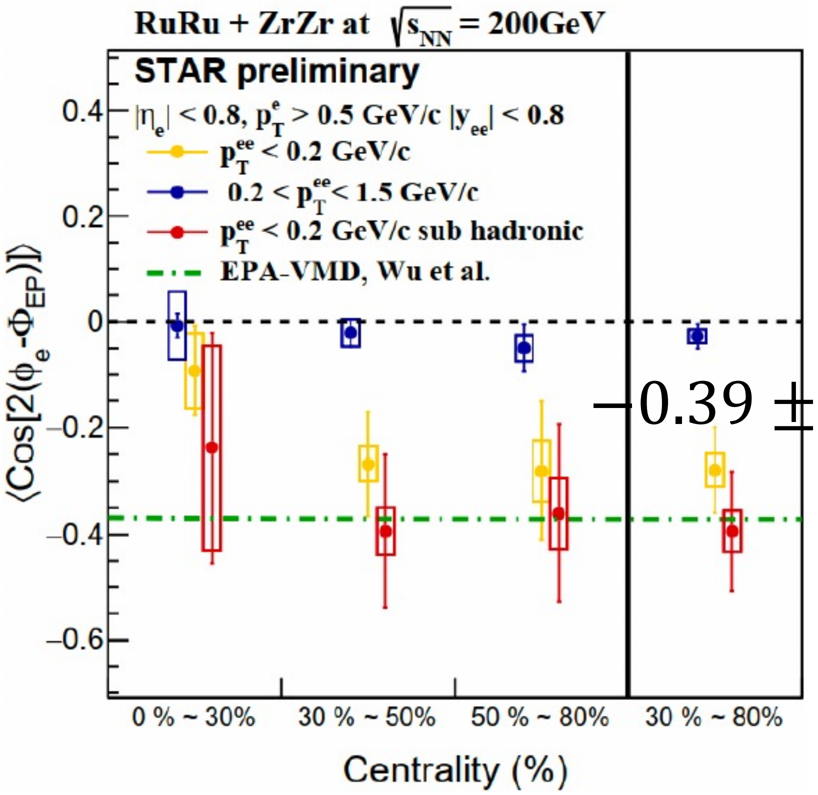
X. Wu et al., Phys. Rev. Res. 4, L042048 (2022)



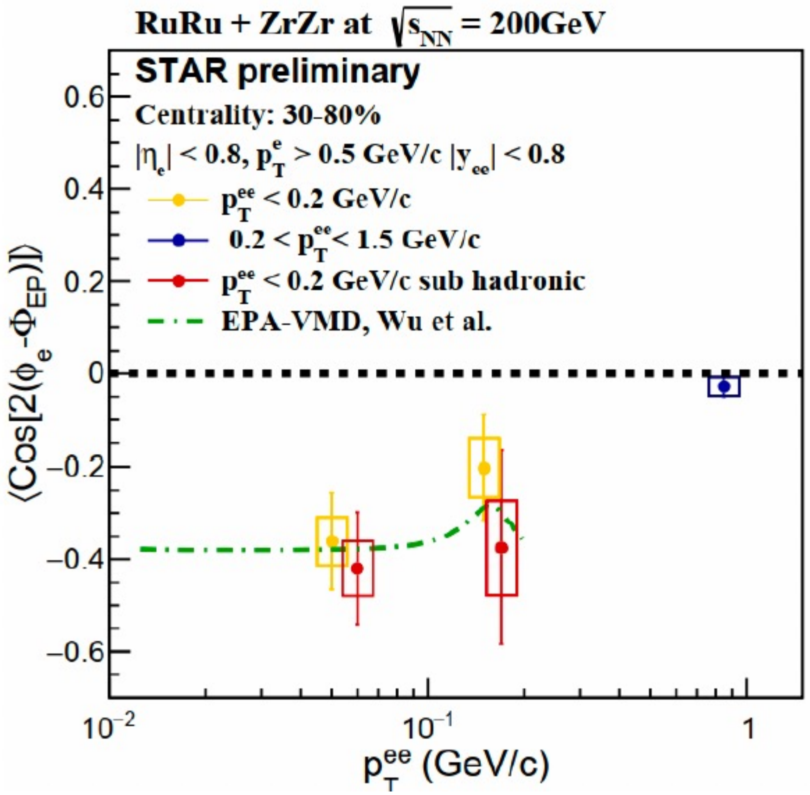


- Photoproduced vector mesons inherit the polarization of photons, which is completely determined by the initial collision geometry
- Vector meson is expected to be polarized with respect to reaction plane

J/ψ Polarization with Respect to Reaction Plane



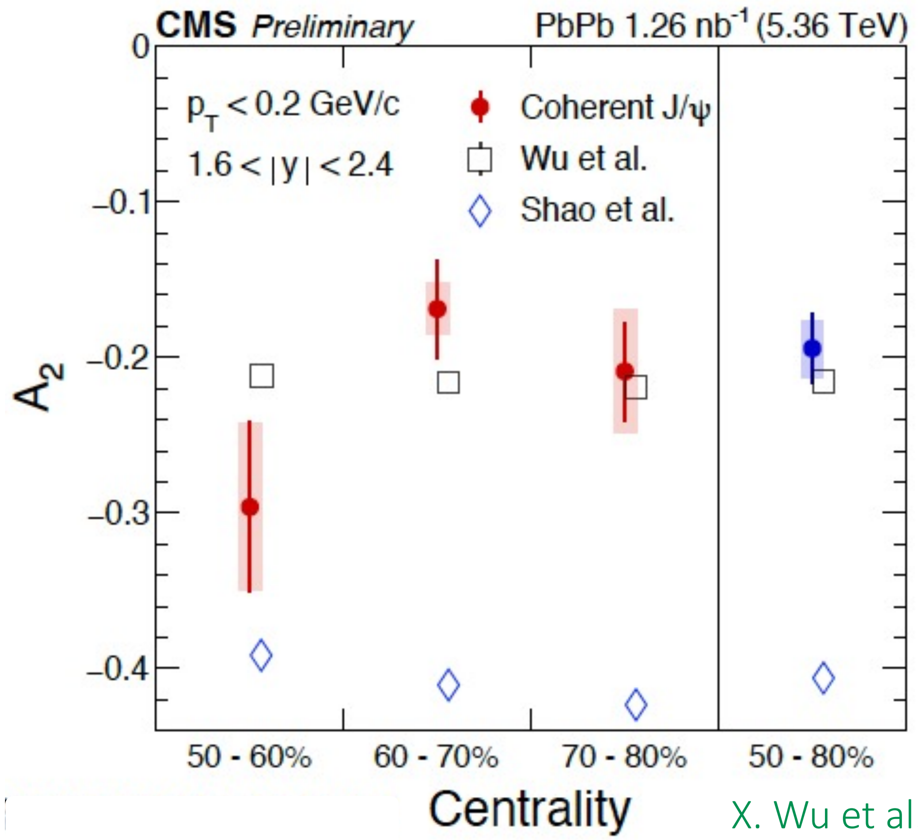
$-0.39 \pm 0.11 \pm 0.04$



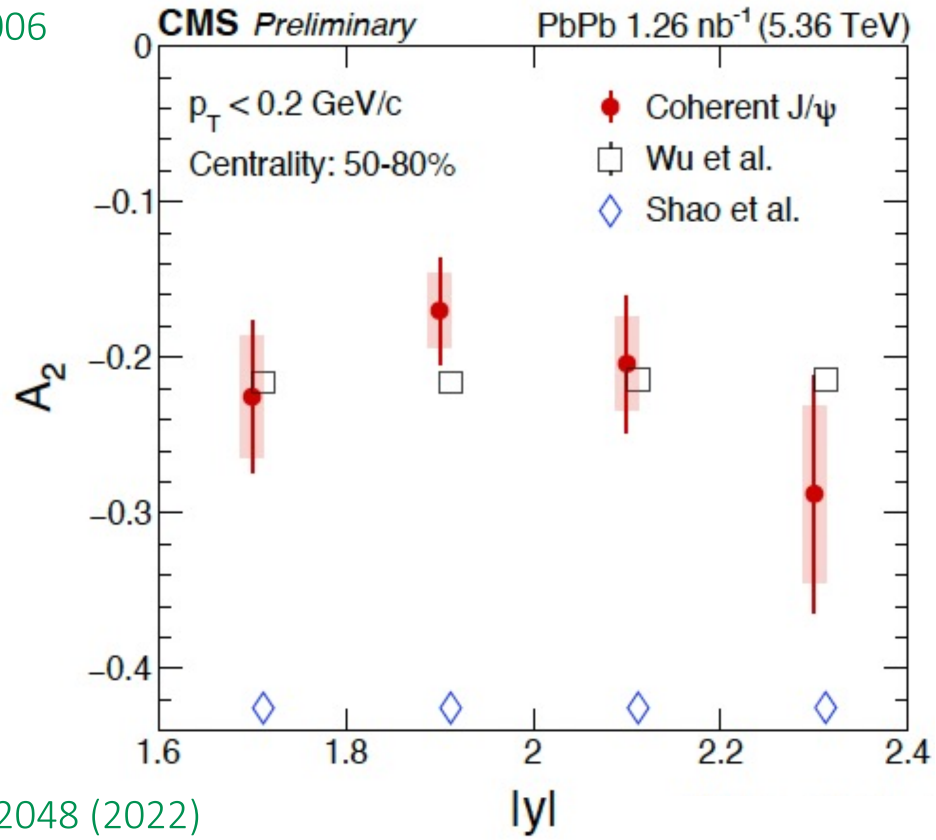
Kaiyang Wang, QM 2025

- Evidence of J/ψ polarization align with impact parameter
- Accessing impact parameter (reaction plane) with photoproduced vector meson

Measurement from CMS



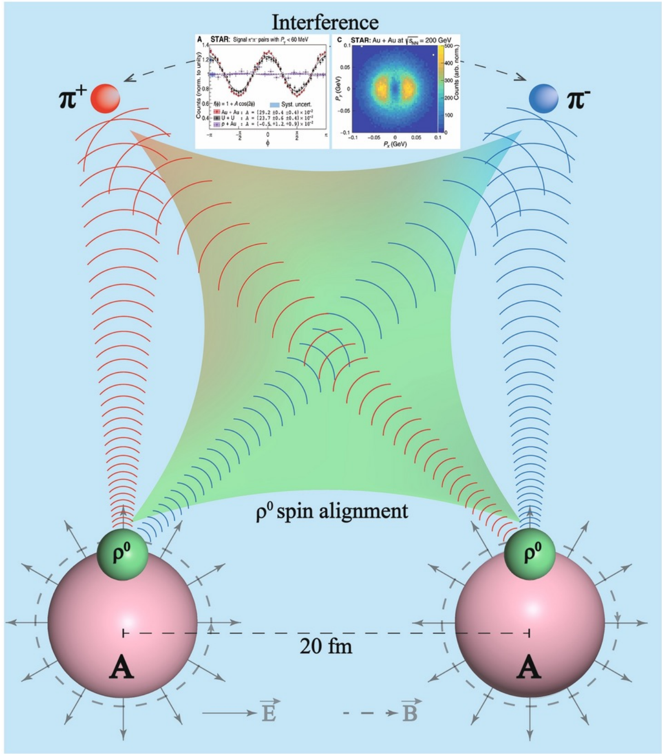
CMS-PAS-HIN-25-006



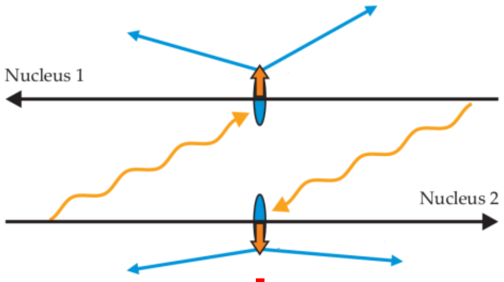
X. Wu et al., Phys. Rev. Res. 4, L042048 (2022)
D. Y. Shao et al., PRD 113, 034902 (2026)

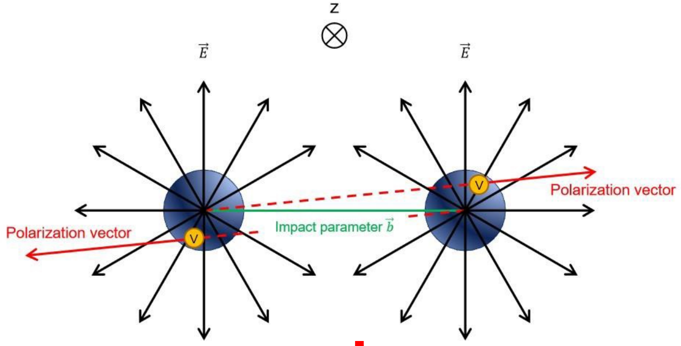
- Similar observation at CMS
- Described by VMD+QED calculation, disagrees with dipole model calculation

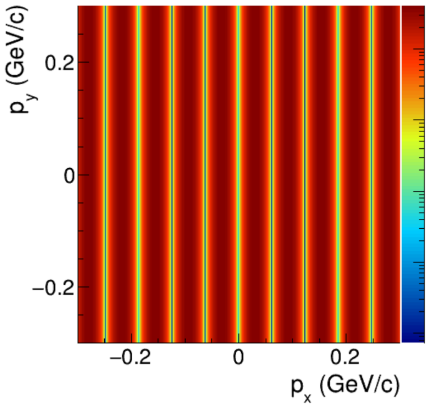
Spin-Interference Effect of Vector Meason Production

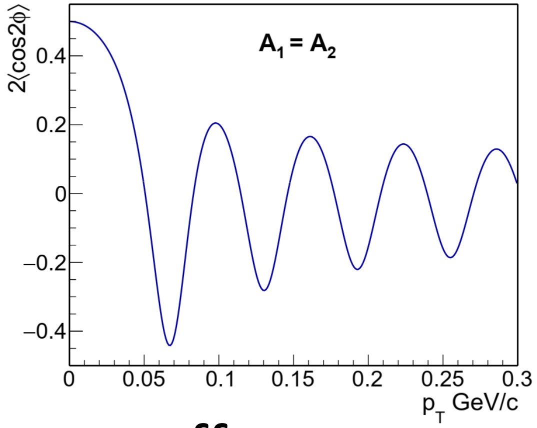


STAR, Sci. Adv. 9, eabq3903 (2023)
Y. Ma, Nucl. Sci. Tech. 34, 16 (2023)







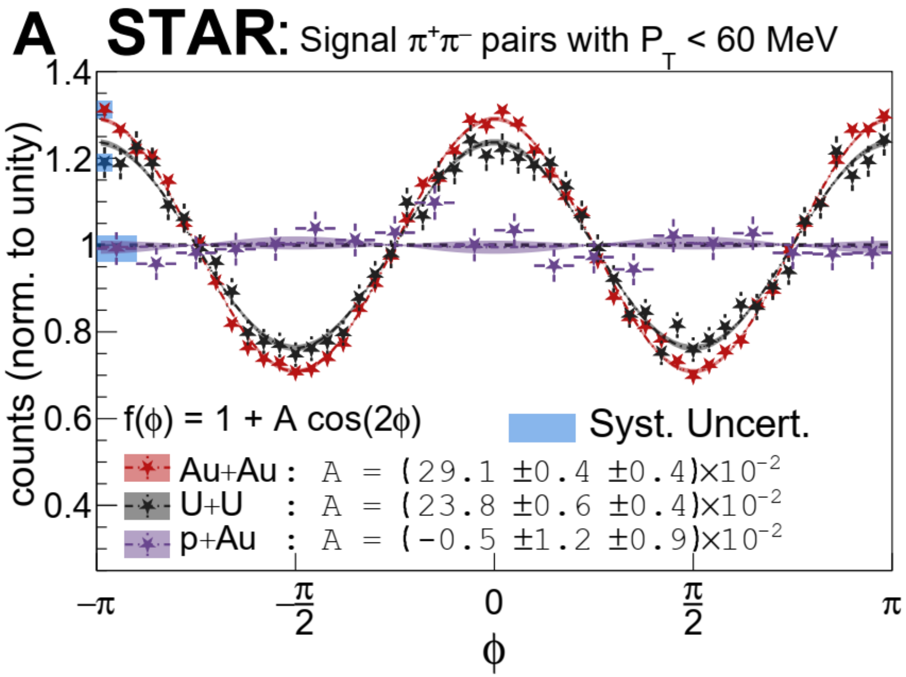


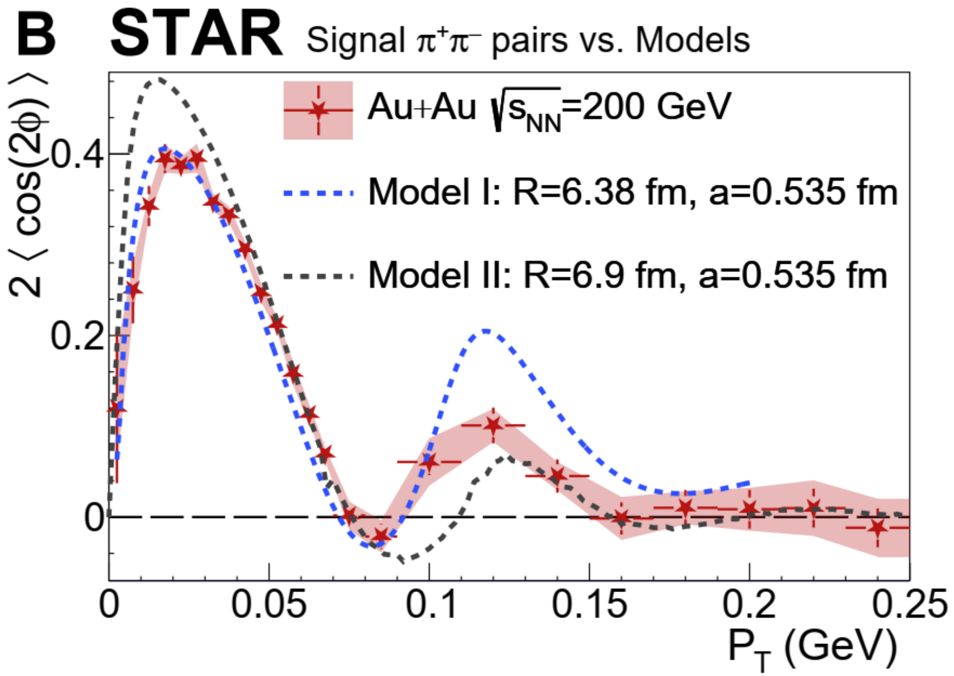
- The vector meson momentum distribution has destructive interference effect
- Vector meson inherit the polarization of photon

➔ Spin-interference effect, can be accessed via angular distribution of decay daughters

Spin–Interference of ρ in Au+Au

STAR, Sci. Adv. 9, eabq3903 (2023)





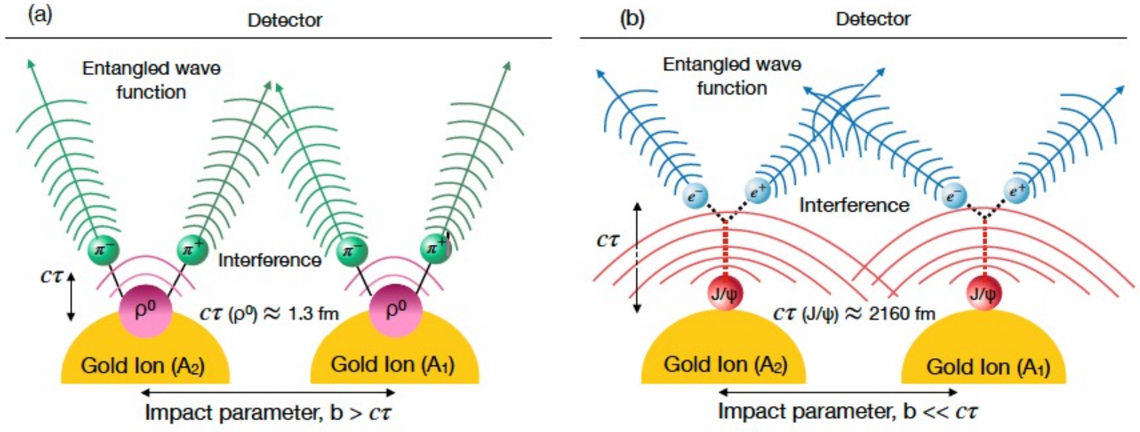
Significant second order modulation of $\Delta\phi$ observed in A+A but not in p+A

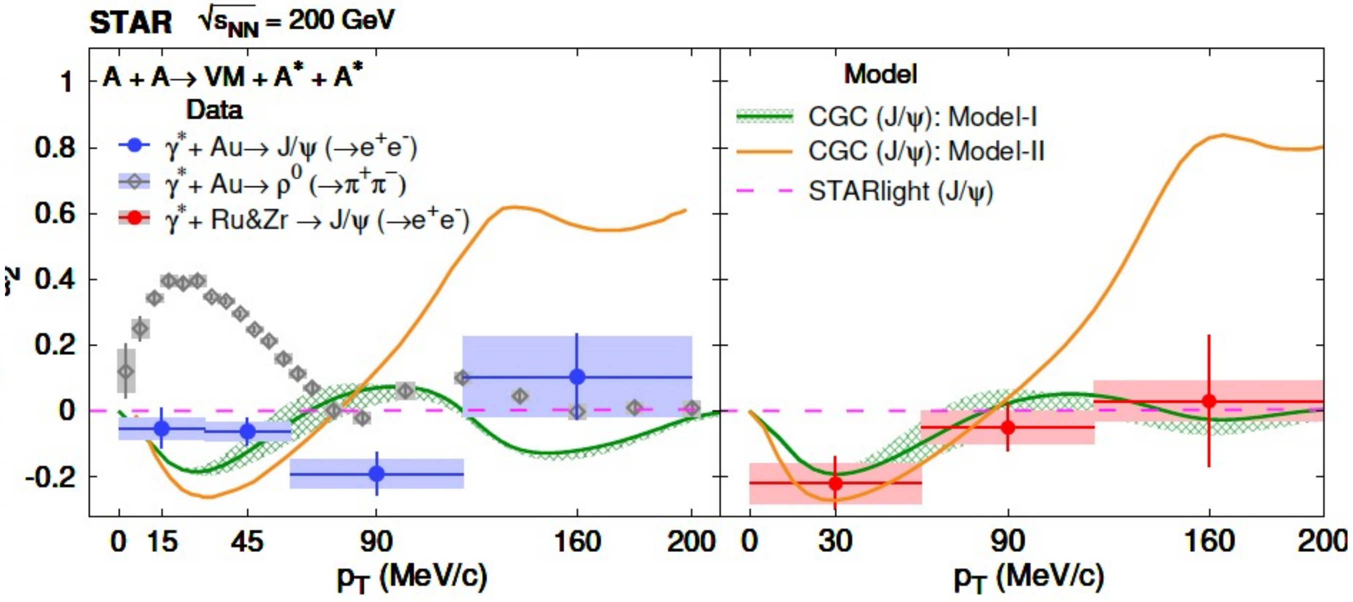
Clear difference between Au+Au and U+U

- Sensitive to nuclear geometry / gluon distribution

Evidence of Spin-Interference Effect

ρ: STAR, Sci. Adv. 9, eabq3903 (2023)
J/ψ: STAR, arXiv:2512.02865, accepted by PRL





- 2^{nd} azimuthal angle modulation observed for both ρ and J/ψ mesons
- Different sign due to the different spin of the daughters
- Different lifetime results in the amplitudes overlapping before or after the decay

Summary and Outlook

- High-p_T J/ψ suppression and quarkonium sequential suppression provide strong evidence of quarkonium melting in QGP → static and dynamic color screening in QGP
- Energy dependence measurements provide strong evidence of deconfinement via regeneration
- J/ψ suppression in O+O suggesting QGP formation in small system
- J/ψ spin alignment call for precision measurements
- J/ψ photoproduction provides novel probe of nuclear matter and quantum effects
- Statistics hungry measurements → Stay tuned with high statistics 2023-2025 data

Thanks!