第八届全国重味物理与量子色动力学研讨会，重庆，2026年4月24-28日

Heavy Quarkonium in Heavy Ion Collisions

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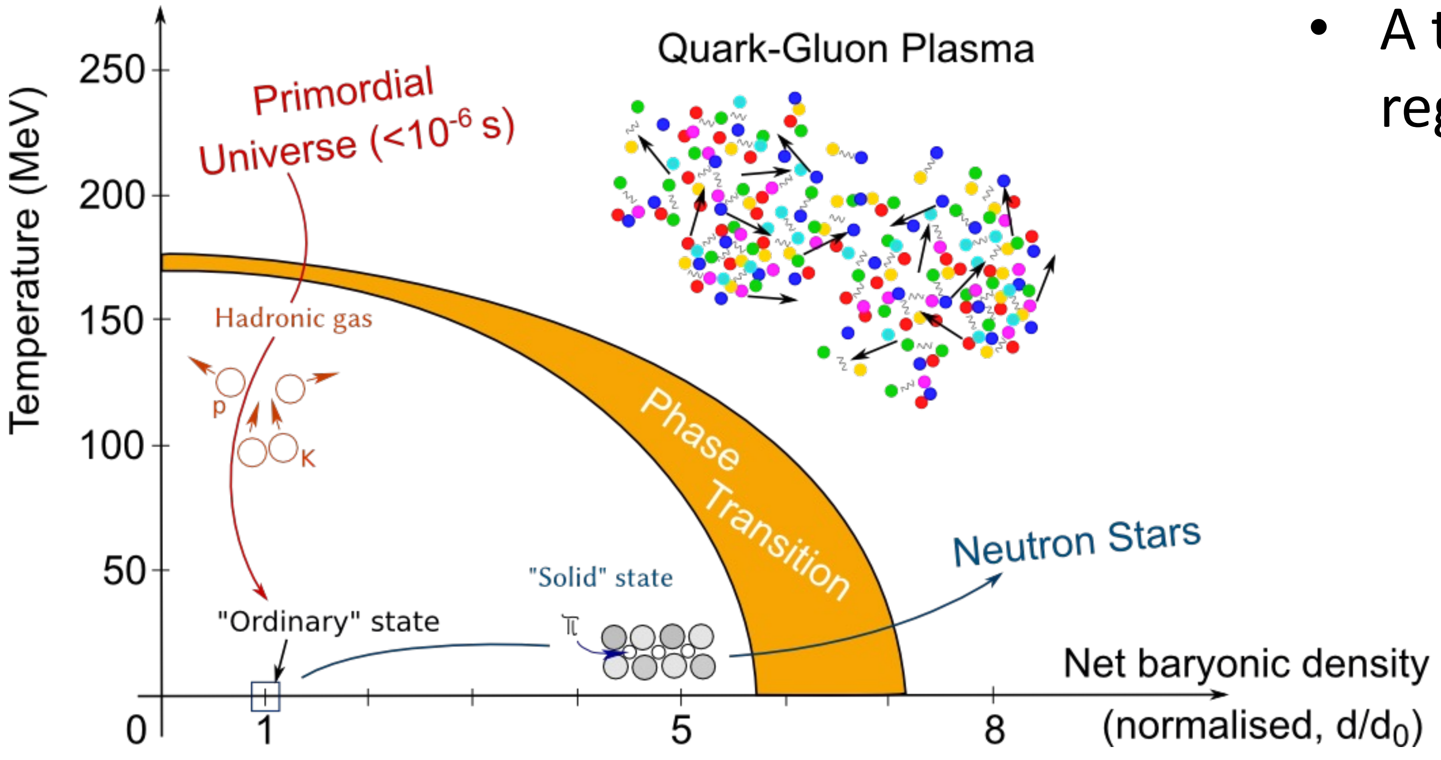
中国科学技术大学物理学院

Quark Gluon Plasma

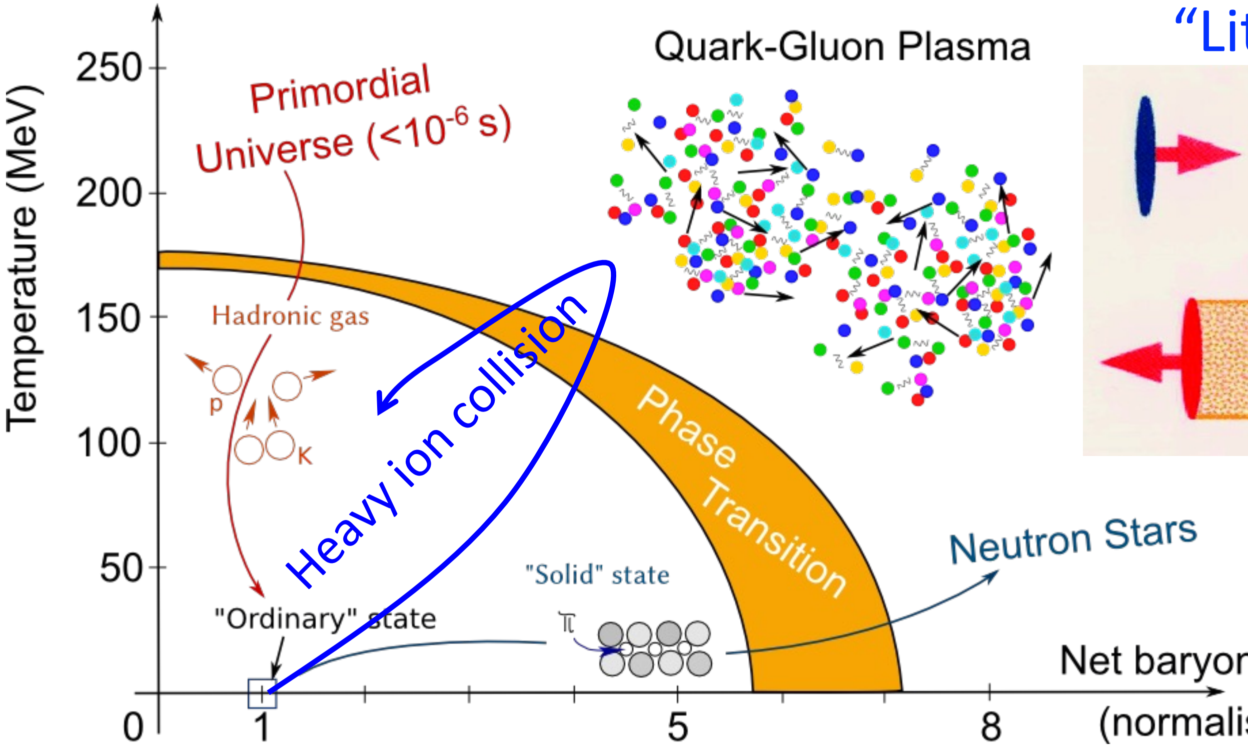


- A test ground of QCD at non-perturbative region and its emergent property

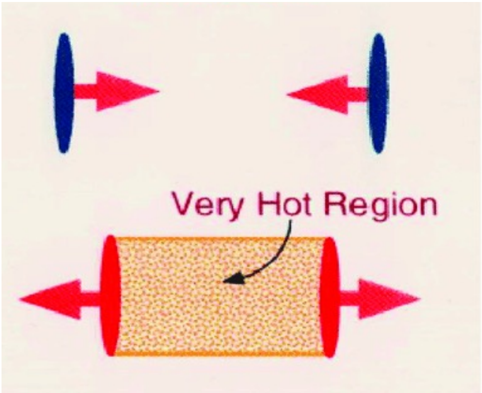
What are the new states of matter at exceedingly high density and temperature?

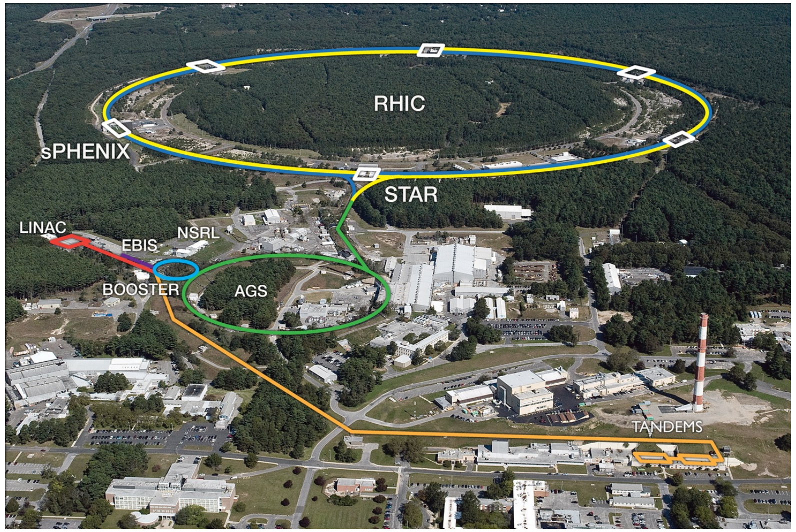
- Quarks are freed from nuclei/hadrons and can move freely in relatively large volume
- New form of matter with partonic (quarks and gluons) degrees of freedom
- It is believed that our Universe was in the form of QGP ~μs after the Big Bang

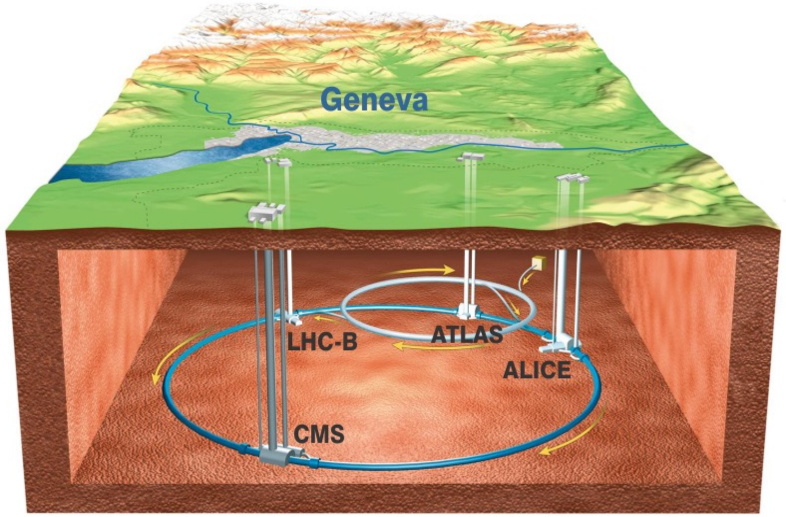
Heavy Ion Collisions



“Little Bang”



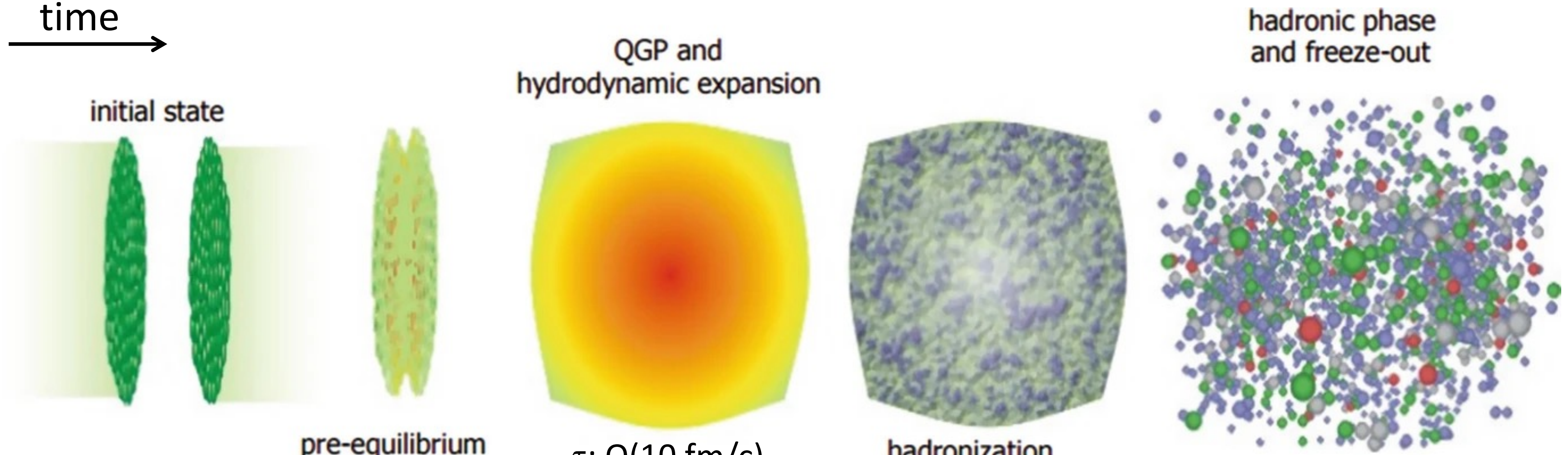




- A large amount of energy is deposited, the vacuum is excited, the QGP could be formed
- QGP (hot and dense) expands and cools down, transits back to ordinary matters

Evolution of Heavy Ion Collision

time →

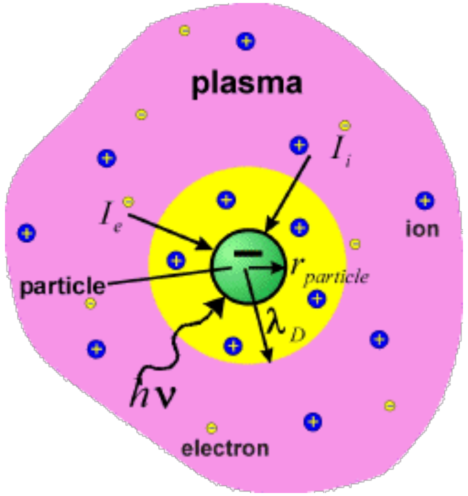


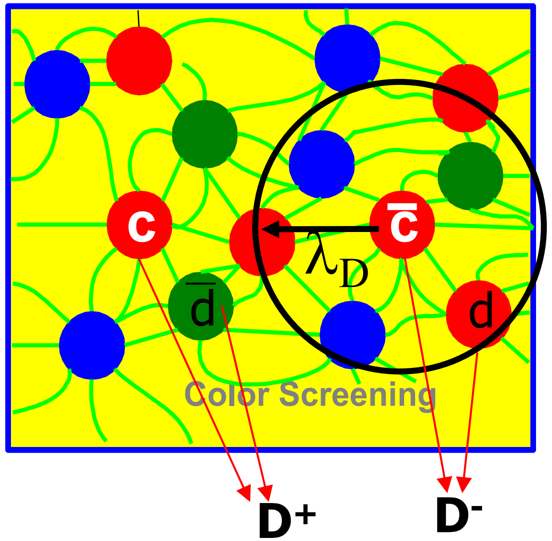
τ: O(10 fm/c)

Chemical freezeout
Kinetic freezeout

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

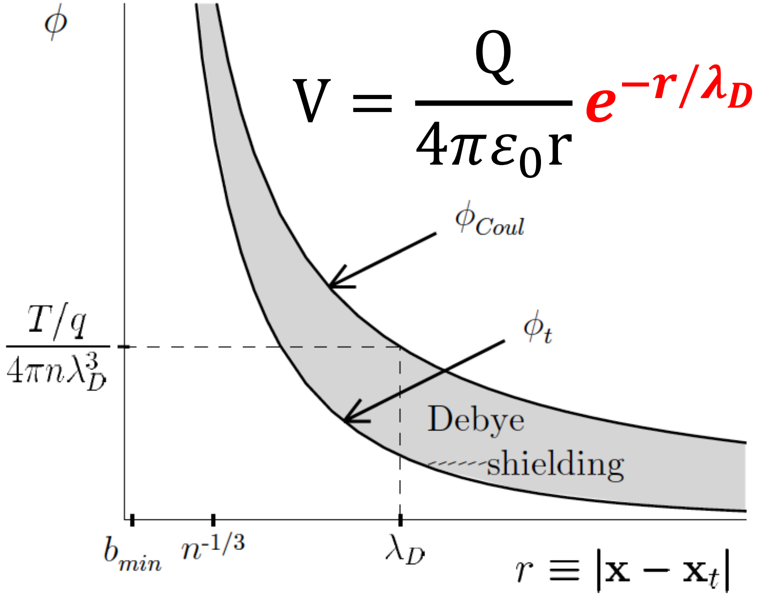
Debye Screening in Plasma and QGP



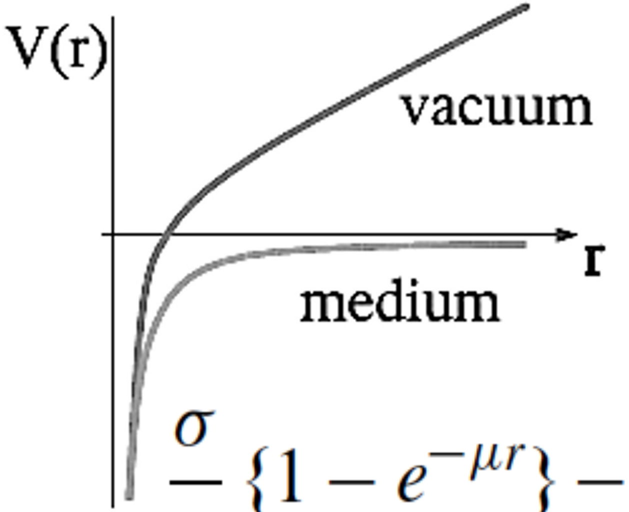


Suppression of quarkonium in heavy ion collision should provide a “smoking-gun” signature of QGP formation

Dissociation rate depends on quarkonium size and Debye length



$$V = \frac{Q}{4\pi\varepsilon_0 r}e^{-r/\lambda_D}$$

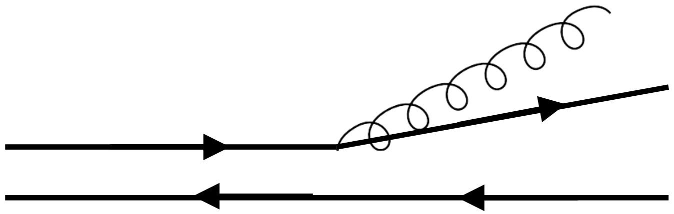


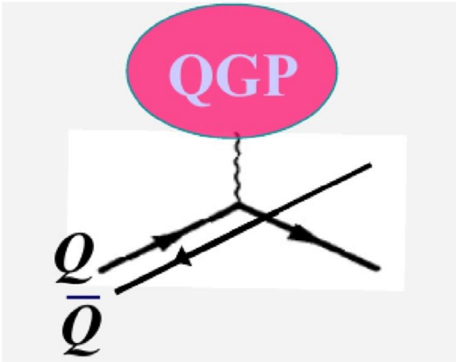
T. Matsui, H. Satz, PLB174, 416 (1986)

$$\frac{\sigma}{\mu}\{1-e^{-\mu r}\}-\frac{\alpha}{r}e^{-\mu r}$$

$$\mu = 1/\lambda_D$$

Dynamic Dissociation in QGP



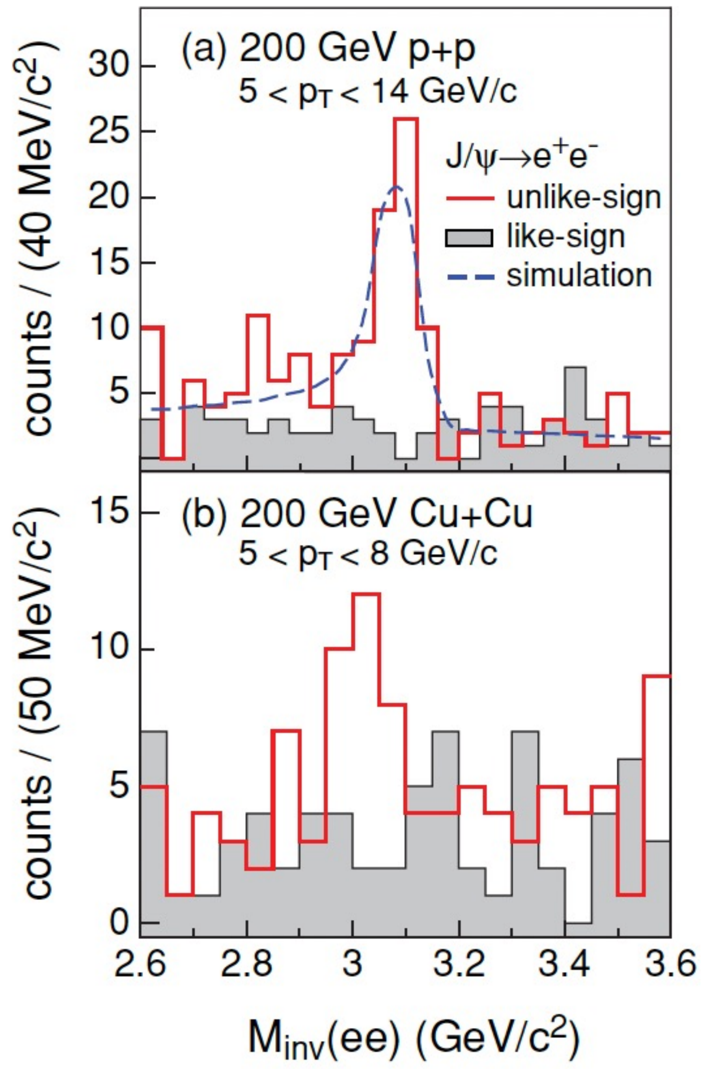


M. He, H. van Hees and R. Rapp, PPNP130, 104020 (2023)

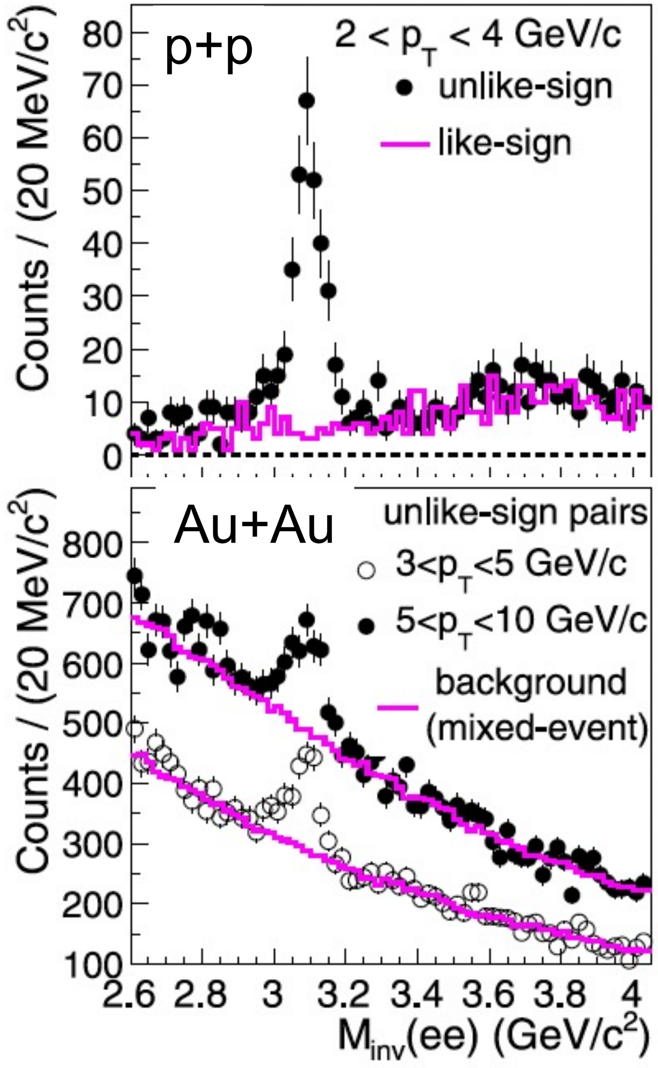
Quarkonium may absorb a gluon or interact with partons in QGP and be dissociated

Dissociation rate depends also on quarkonium size and QGP temperature etc

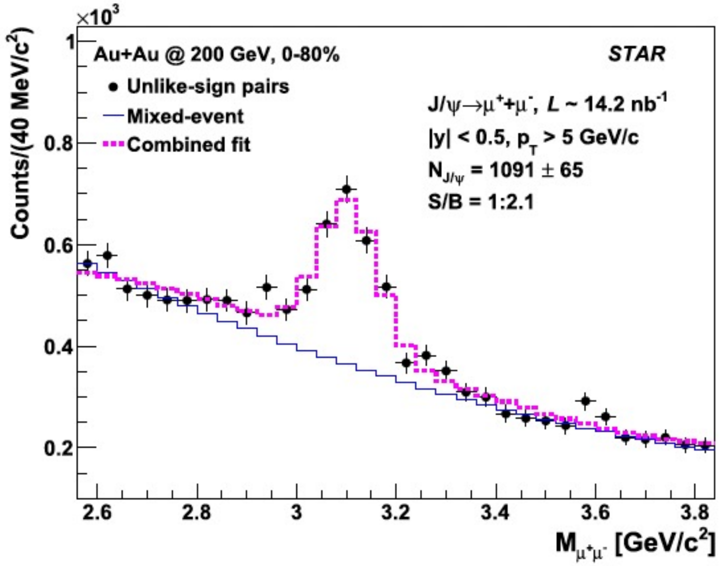
J/ψ Signals in Heavy Ion Collisions



STAR, PRC(R) 80, 014902 (2010)

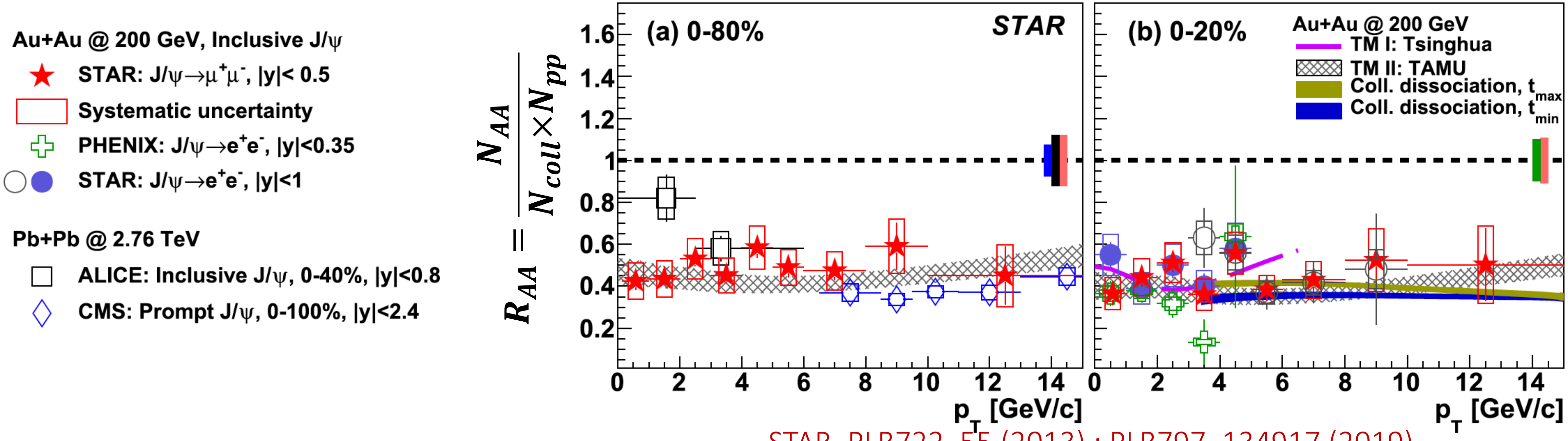


STAR, PLB722, 55 (2013)



STAR, PLB797, 134917 (2019)

J/ψ Yield Suppression in Au+Au at 200 GeV



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

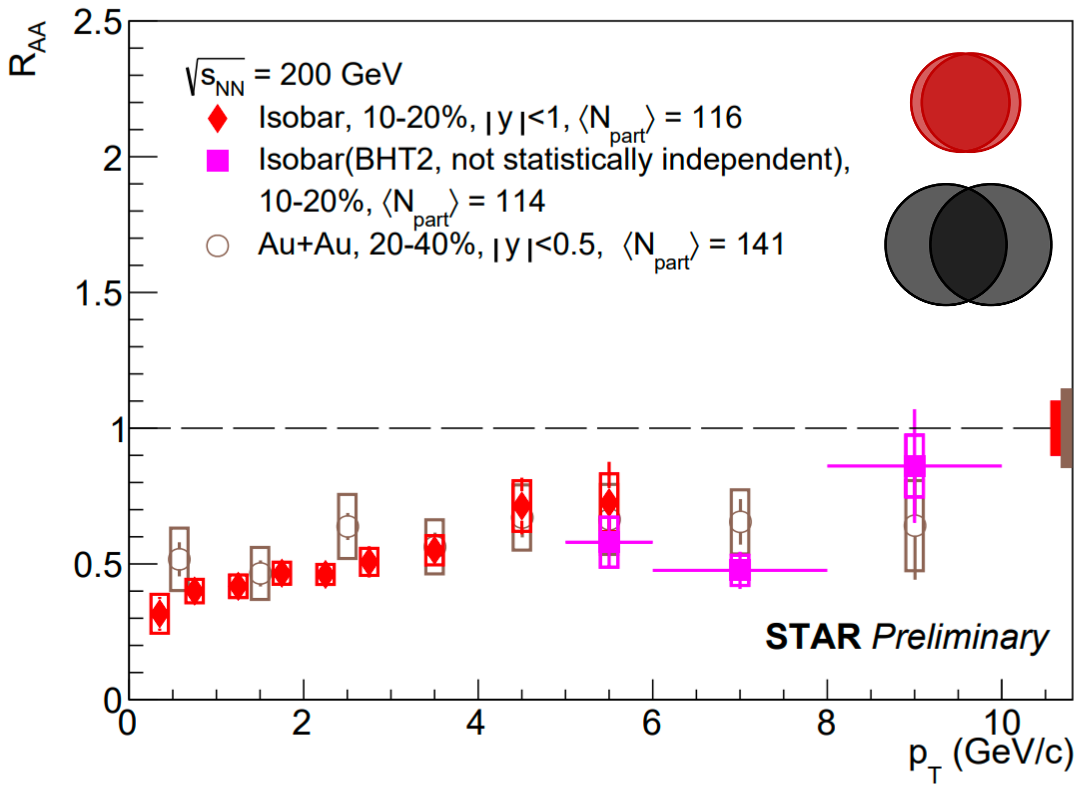
- Yield suppression quantified with nuclear modification factor R_{AA}

R_{AA}<1 means suppression compared to p+p collisions at the same energy

- Significant suppression observed at high p_T

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

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

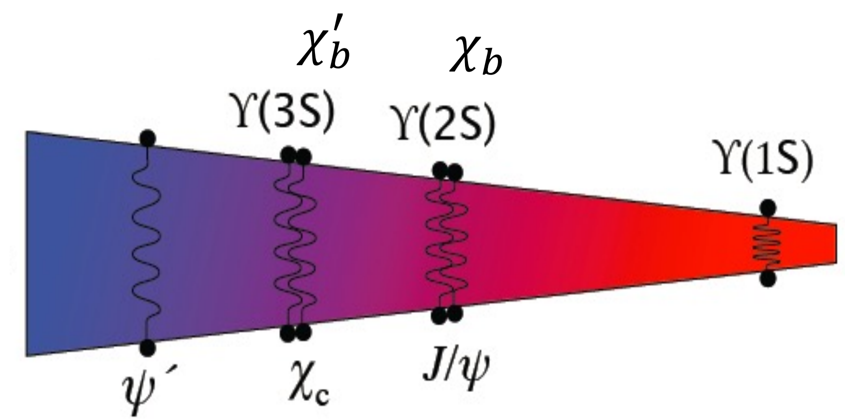


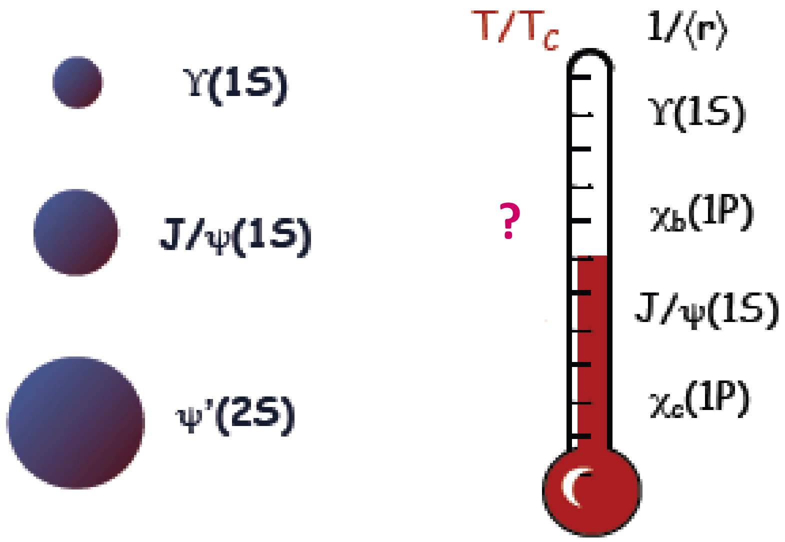
STAR, paper in preparation

- Highest precision measurement at RHIC to date
- Significant suppression observed with improved precision
- Consistent with Au+Au results at similar system size
- Provide strong constraints to the inner-working of QGP

Sequential Melting

Plasma thermometer



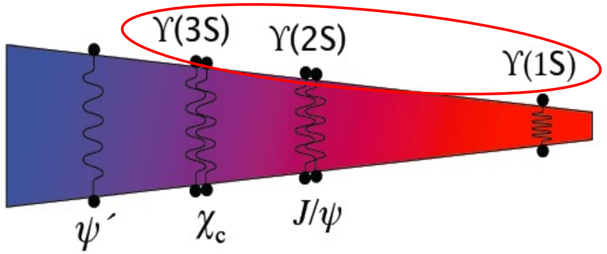


Debye radius is inversely proportional to the temperature of QGP

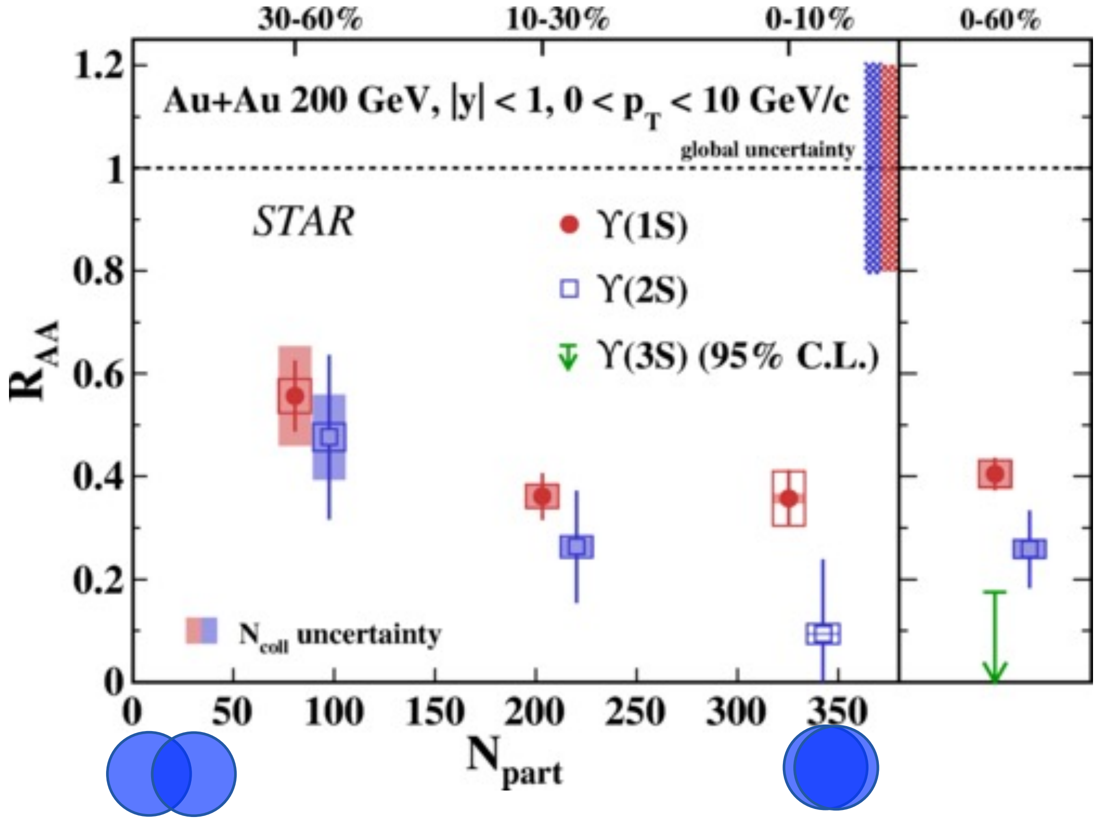
Different quarkonium states dissociate at different temperatures
→ Sequential melting

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

Sequential Melting in Bottom Sector

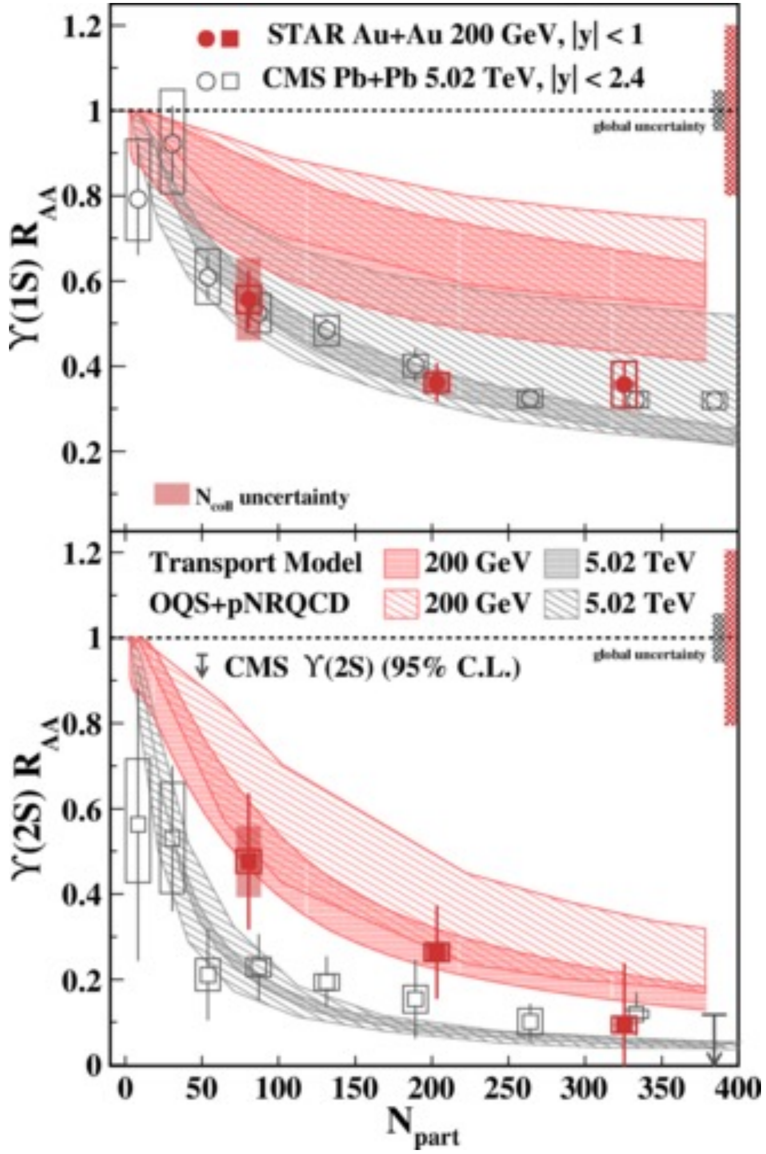


STAR, PRL 130, 112301 (2023)



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)

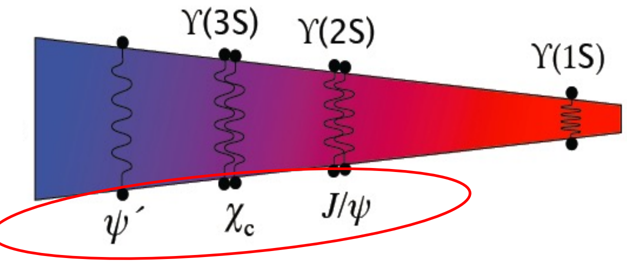
→ Primordial Upsilon(1S) not significantly suppressed

Upsilon(2S):

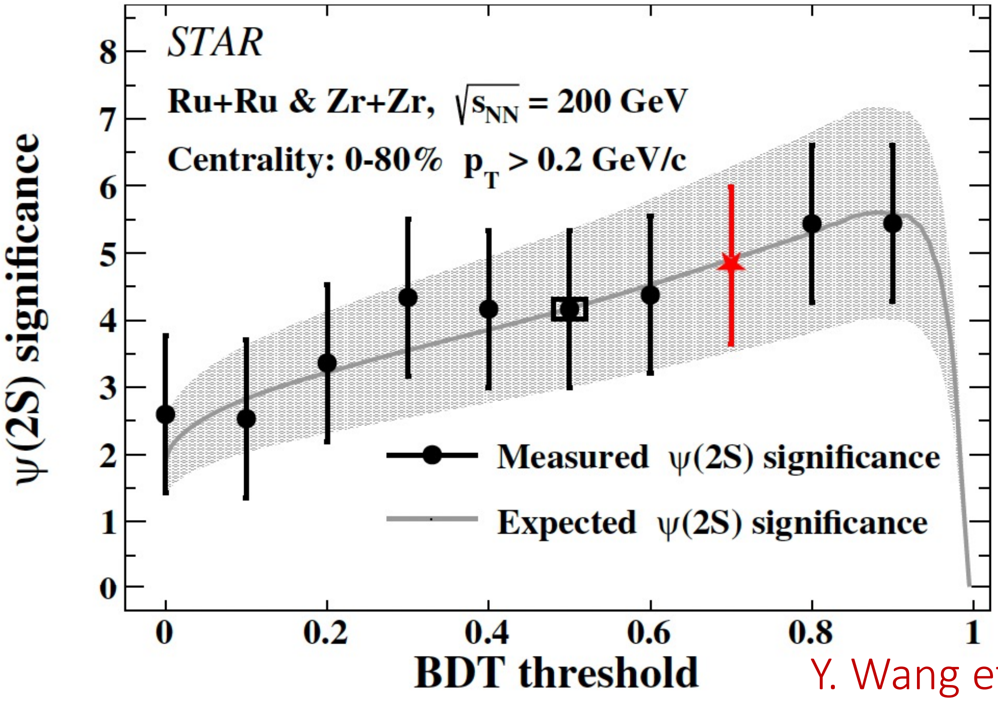
- Stronger suppression than 1S state
- Hints of less suppression at RHIC in peripheral collisions

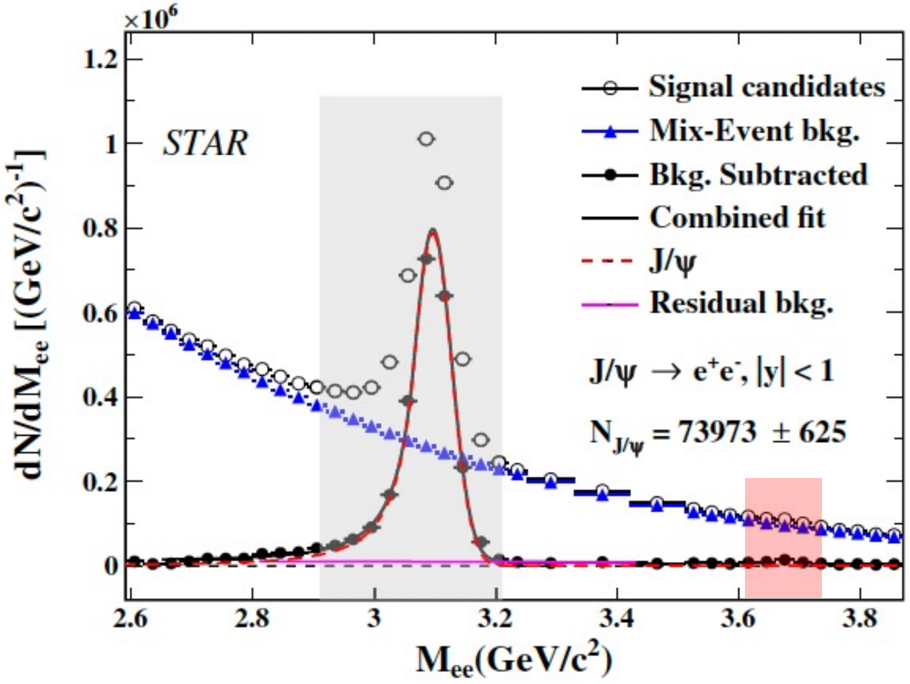
QGP is formed, and its temperature is high enough to melt excited bottomonium states!!!

STAR, PRL130, 112301 (2023)



- ψ(2S) is a very loosely bounded heavy quarkonium state
- Very sensitive to QGP properties

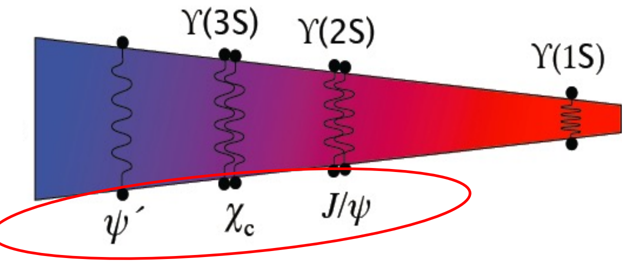


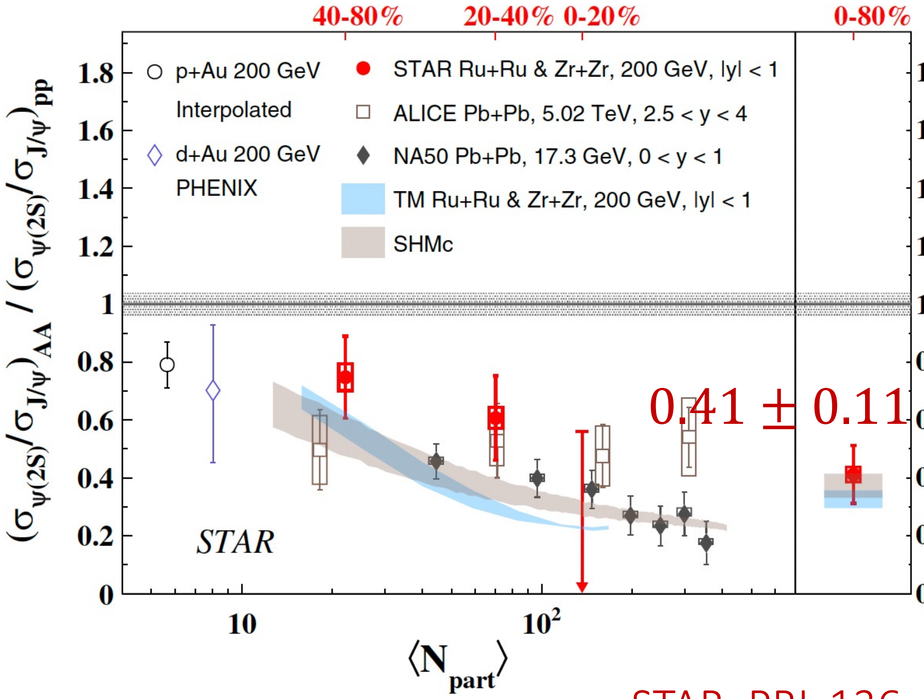


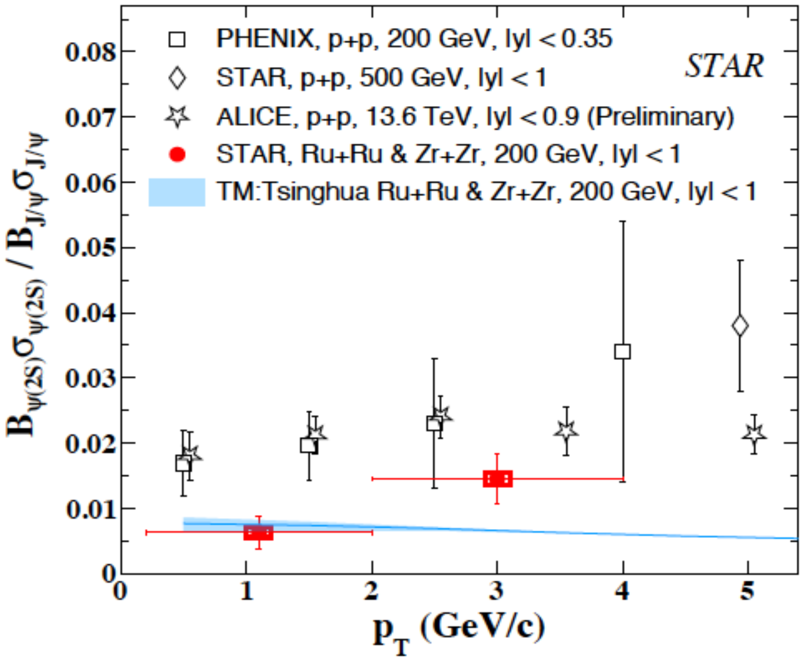
Y. Wang et al., arXiv:2511.10028
NST in press

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

Sequential Melting in Charm Sector





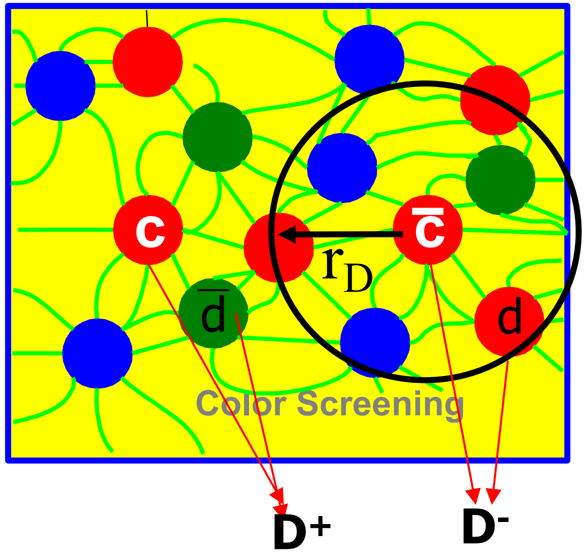


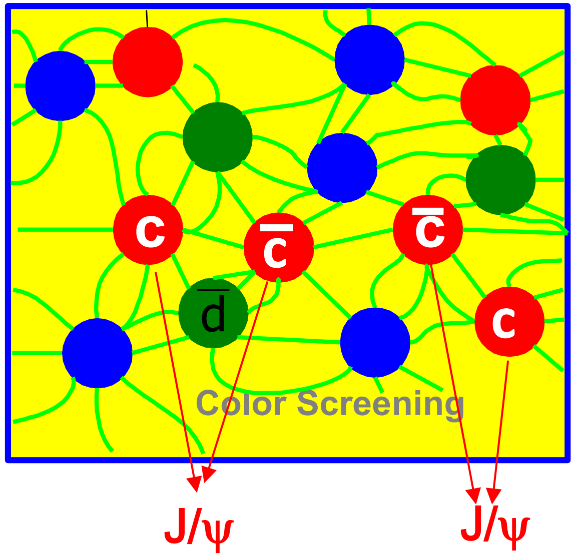
STAR, PRL 136, 122302 (2026)

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

Melting vs. Regeneration

Two competing effects for quarkonium production in heavy ion collisions



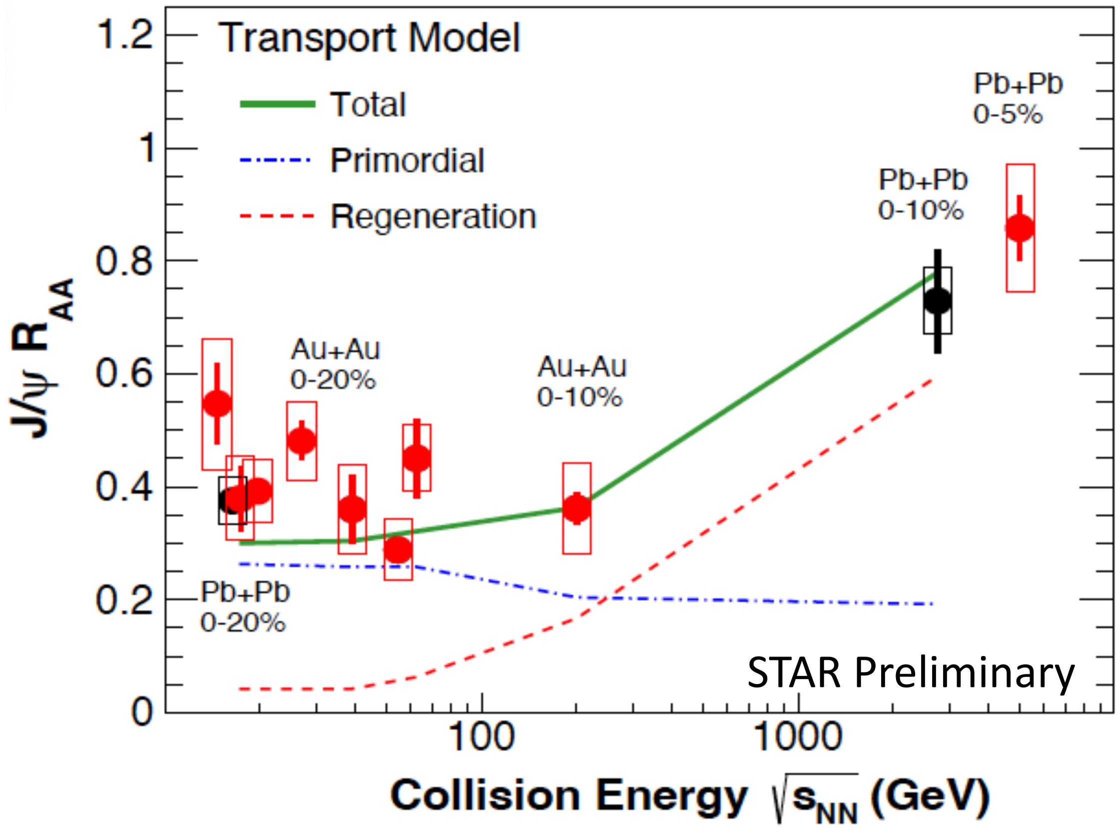


Quarkonium melting in QGP

Quarkonium regeneration in QGP

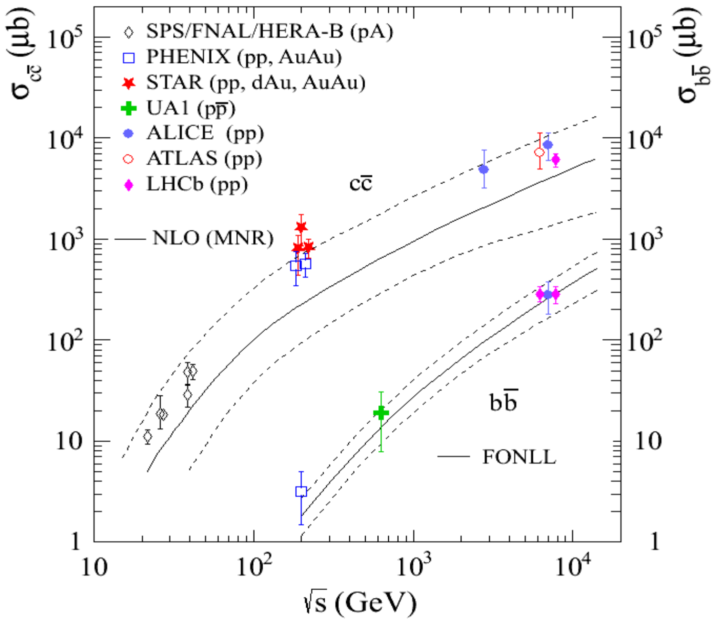
QGP formation is the prerequisite of both effects

Energy Dependence of J/ψ Suppression



NA50, PLB 477, 28 (2000)
Wei Zhang, QM 2023
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)

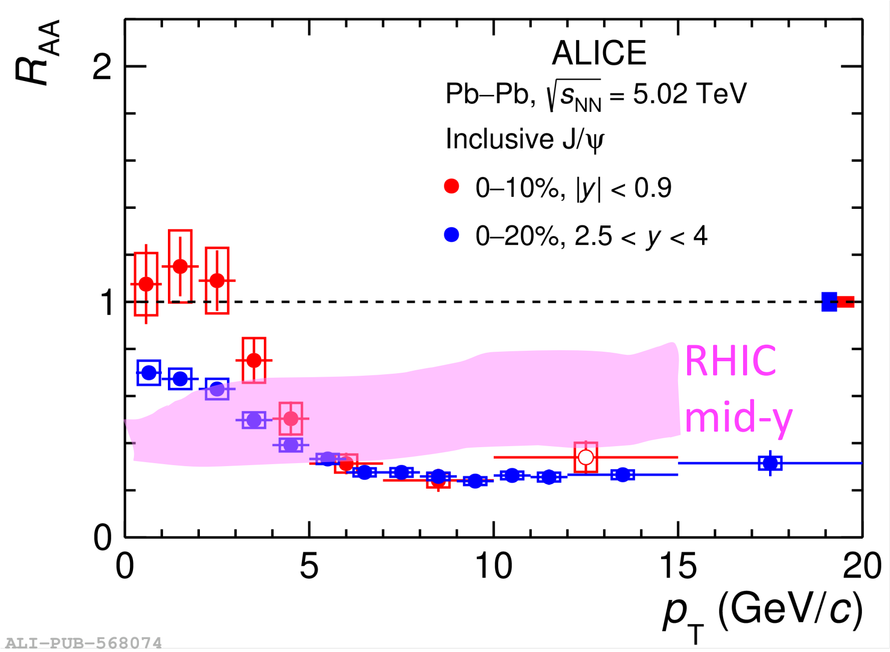
20 years efforts at STAR and the LHC

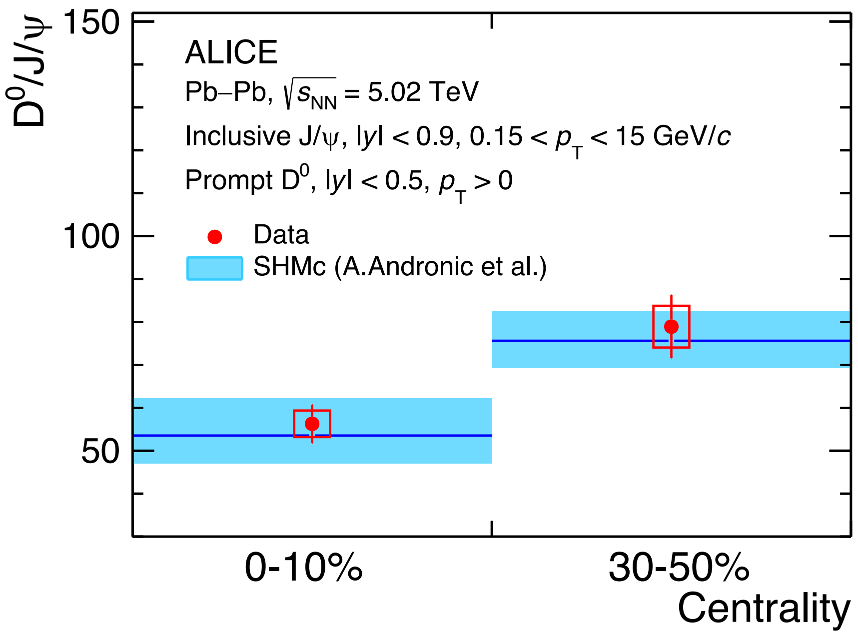


SPS	→	RHIC	→	LHC
Melting		Melting + regeneration		Regeneration domain

J/ψ Measurements at ALICE

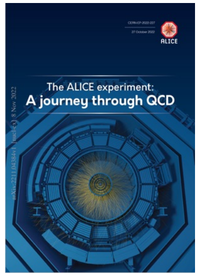
ALICE, PLB 849, 138451 (2024)





- 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

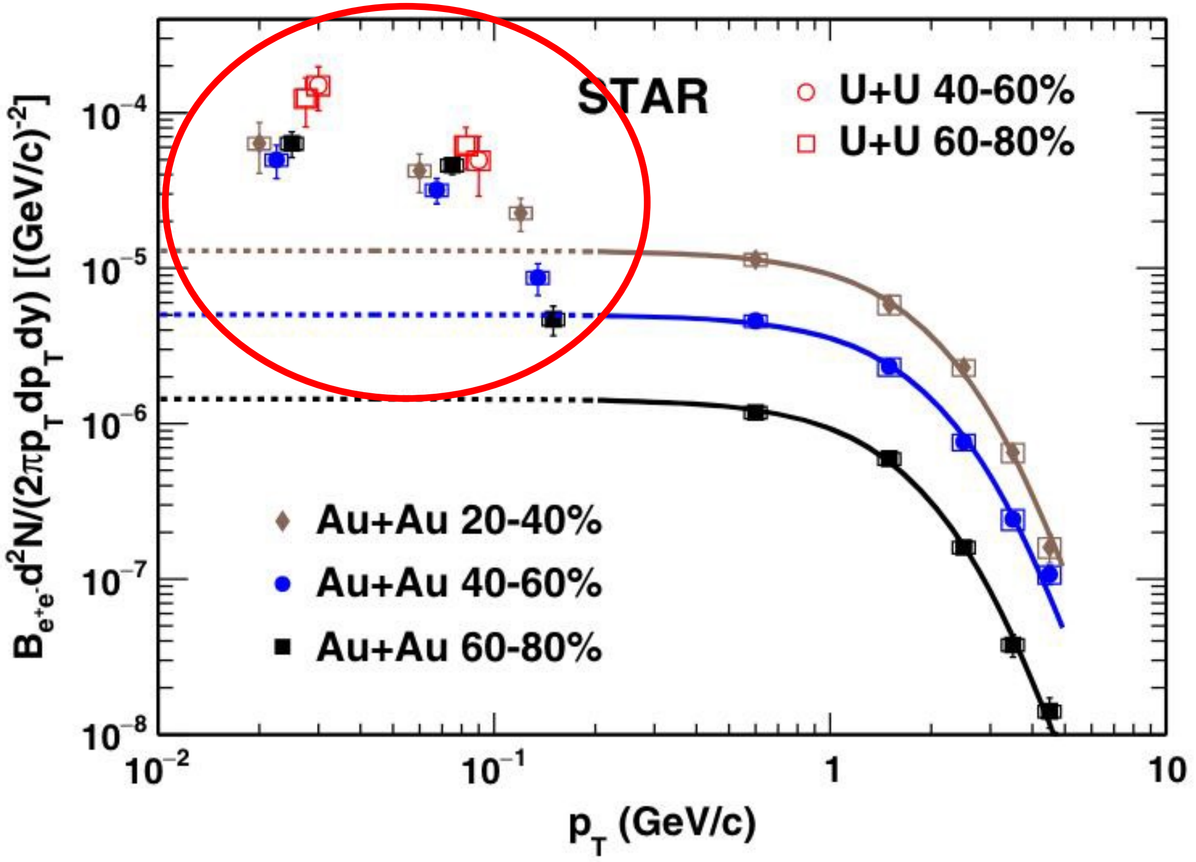


2.5.1 *Study of the charmonium ground state: evidence for the (re)generation and demonstration of deconfinement at LHC energies*

ALICE, EPJC 84, 813 (2024)

Move to Very Low p_T

STAR, PRL123, 132302 (2019)



- Significantly enhancement of J/ψ yield at p_T<0.2 GeV/c
- Due to coherent photoproduction?

Electromagnetic Field in Heavy Ion Collisions

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

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

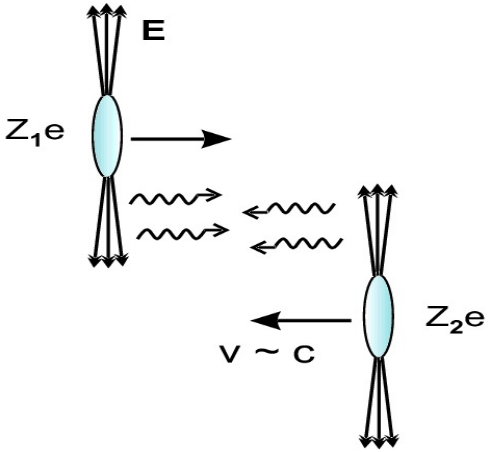
- The Lorentz contracted EM field can be expressed in terms of equivalent photon flux

$$E \perp B \perp \mathrm{z}, E = B$$

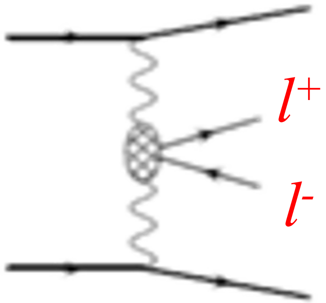
$$\omega_{max} \sim\ 3\ \text{GeV @ RHIC}, \sim 80\ \text{GeV @ LHC}$$

E. Fermi, Z. Phys. 29, 315 (1924)
C. Weizsacker, ZP88, 612 (1934)
E. Williams, PR45, 729 (1934)

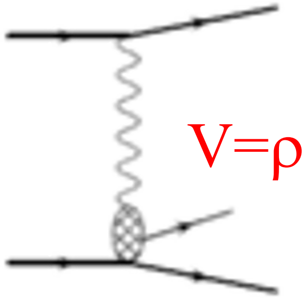
- The photons induce particle production



$\gamma + \gamma$



$\gamma + A$

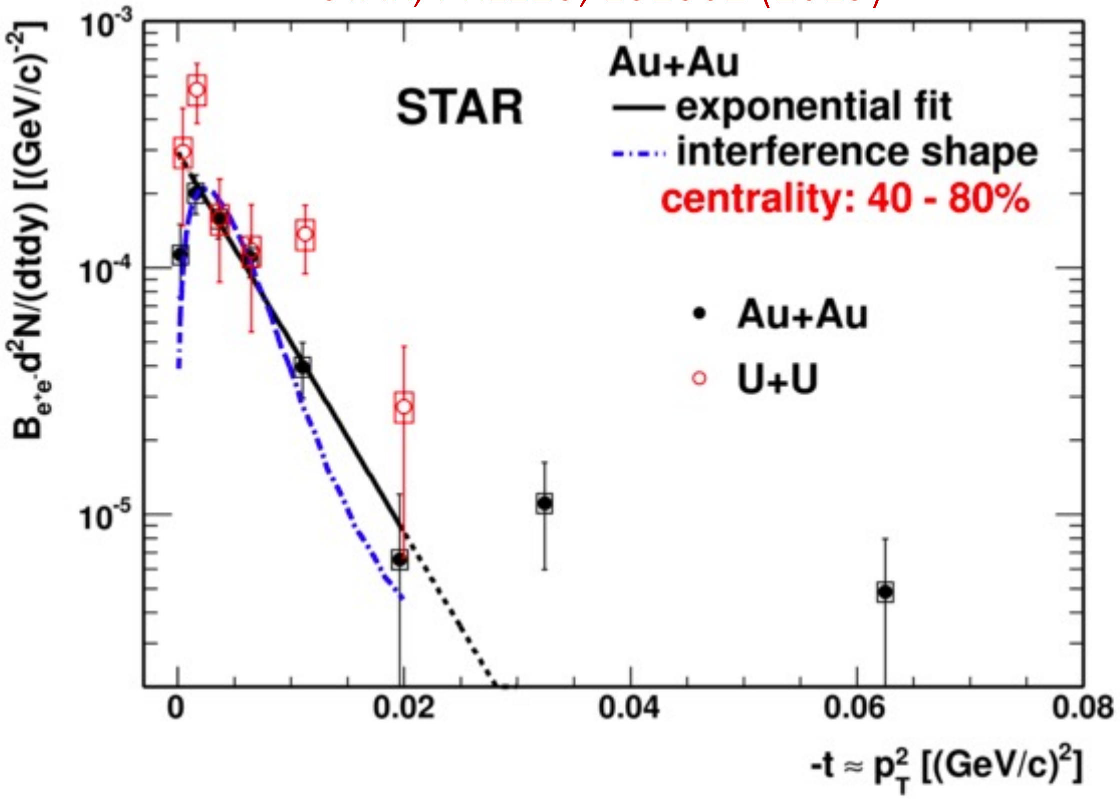


V=ρ, ω, ϕ, J/ψ…

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

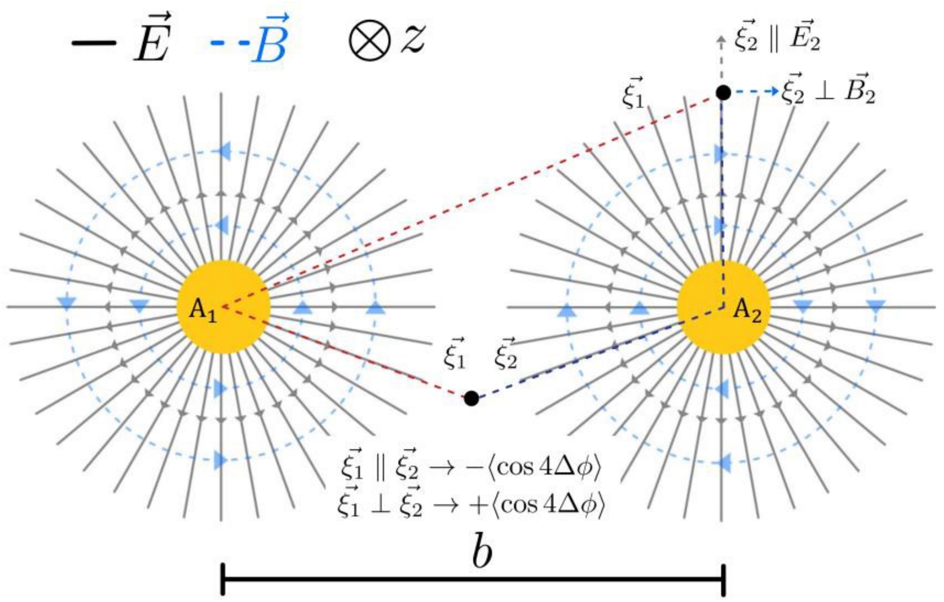
Momentum Transfer Squared Distribution

STAR, PRL123, 132302 (2019)



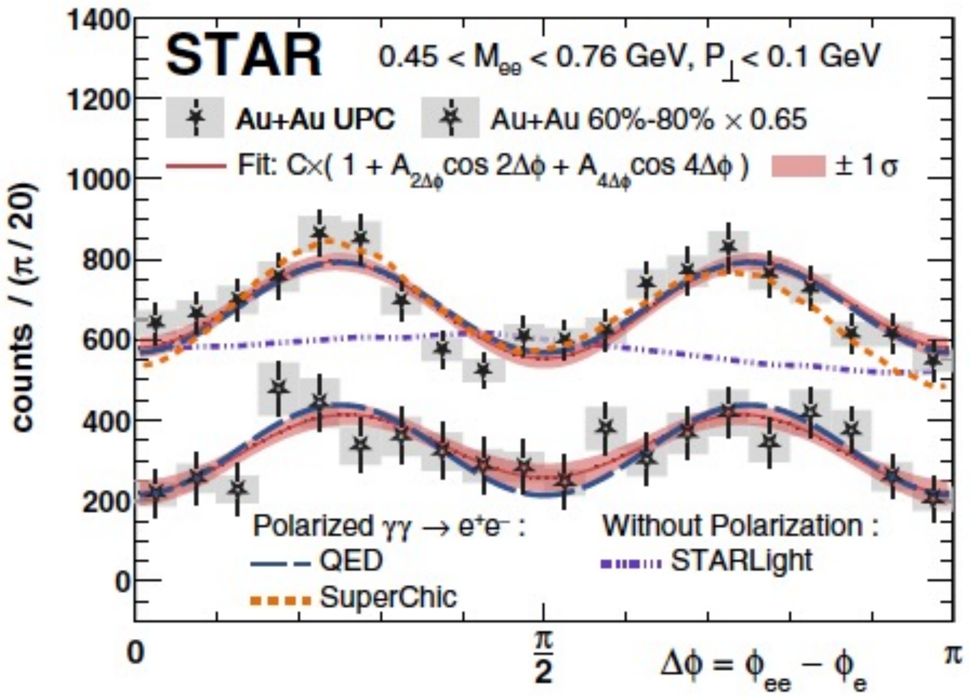
- Slope = 177 ± 22 (GeV/c)$^{-2}$ consistent with expected from coherent photoproduction for an Au nucleus (199 (GeV/c)$^{-2}$)
- The drop at the lowest bin indicates of interference
- The yield of photoproduced heavy quarkonium can constrain gluon distribution in nucleus

Linearly Polarized Photons



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

STAR, PRL127, 052302 (2021)

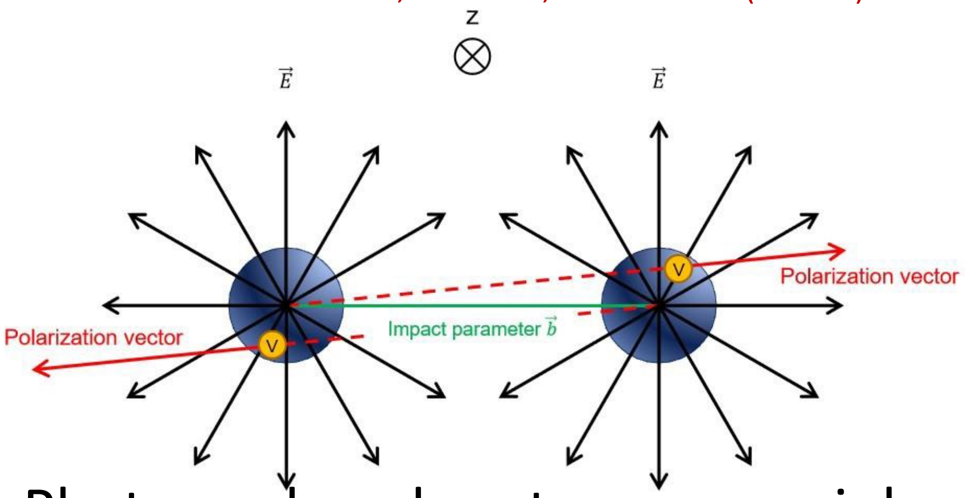


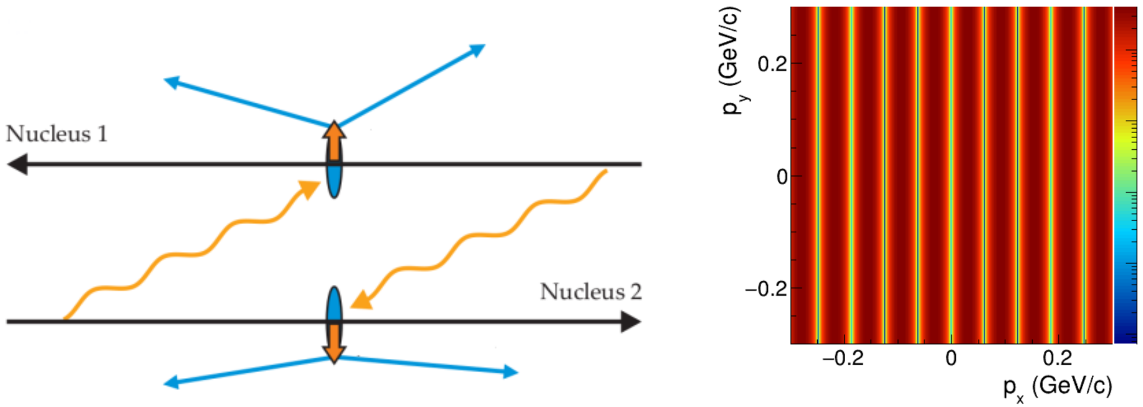
- Photons from the highly Lorentz contracted EM filed are linearly polarized in the transverse plane
- Polarization vectors coincide with the positions and thus p_T
- QED predicts cos4ϕ modulation and confirmed by data

J/ψ Spin–Interference Effect

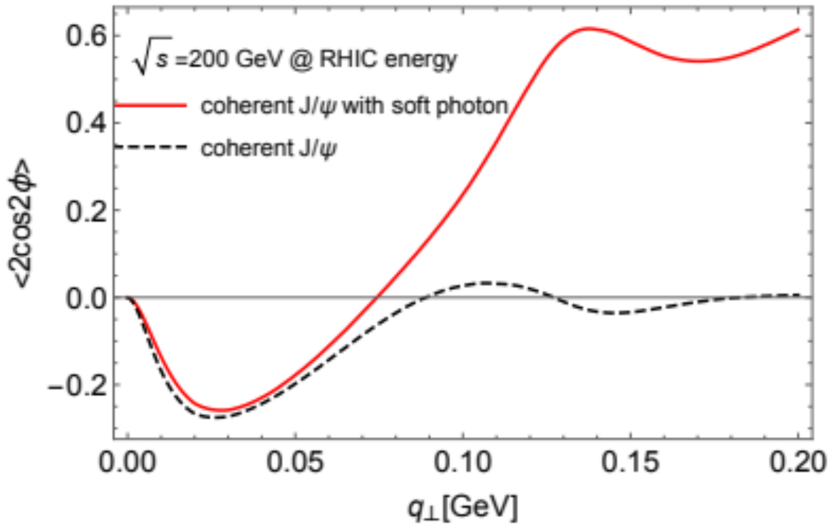
X. Wu et al., PRR. 4, L042048 (2022)

W. Zha et al., PRD103, 033007 (2021)





- Photoproduced vector mesons inherit the polarization of photons
- Interference from the double-slit experiment



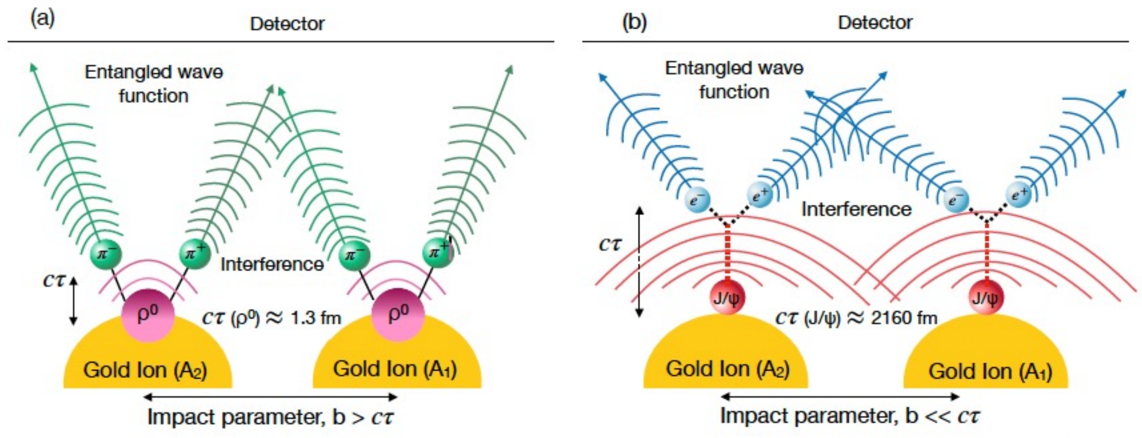
- Azimuthal angle asymmetry of vector meson decay daughters

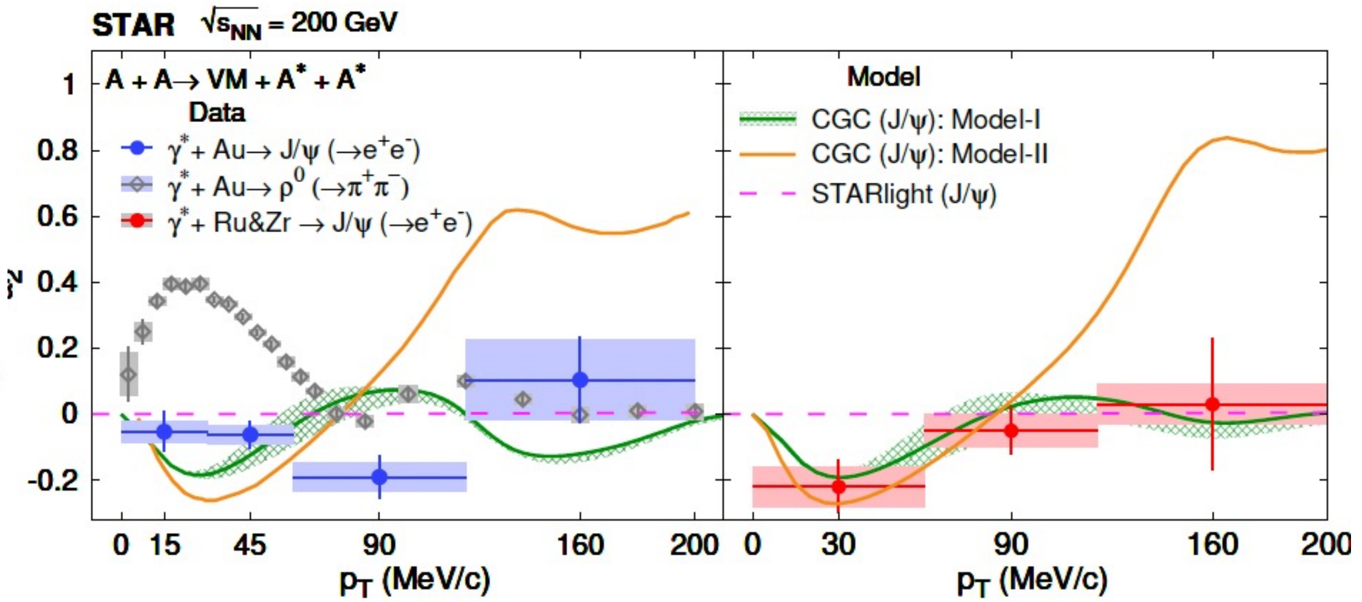
J. Brandenburg et al.,

PRD106, 074008 (2022)

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

Quarkonium is a golden probe of QGP, systematic experimental investigations provide strong evidence for

- Color Debye screening in the deconfined medium
- Sequential melting (binding-energy-dependent suppression)
- Regeneration (coalescence of quarks) in the deconfined medium

➔ **All consistent with the formation of QGP**

Understanding the inner-working of QGP requires further investigations

Quarkonium photoproduction provides a useful tool for the study of

- Properties of the electromagnetic field
- Gluon distribution function in nucleus and nuclear shape
- Quantum effects
- …

Thanks!