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U.S. DEPARTMENT OF ENERGY

Probe the Quark Gluon Plasma with Quarkonia at RHIC

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Brookhaven National Laboratory

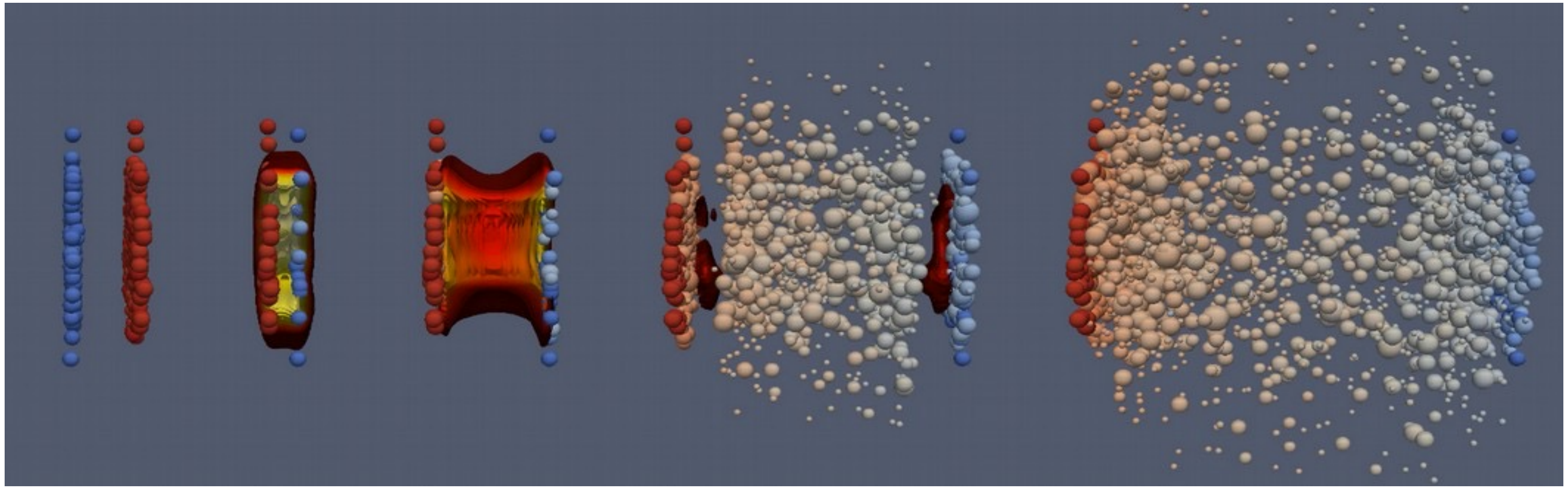
Online Heavy Flavor Seminar

November 12th, 2025

@BrookhavenLab

Quark-Gluon Plasma (QGP)

- QCD matter made of deconfined quarks and gluons
  - Re-created in high-energy high-ion collisions



Credit: MADAI collaboration, Hannah Petersen and Jonah Bernhard

- A central goal of HI physics: characterize and understand QGP properties

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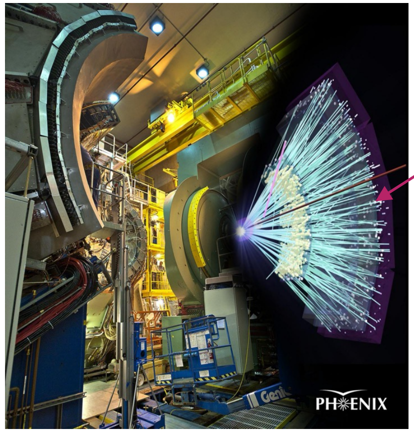
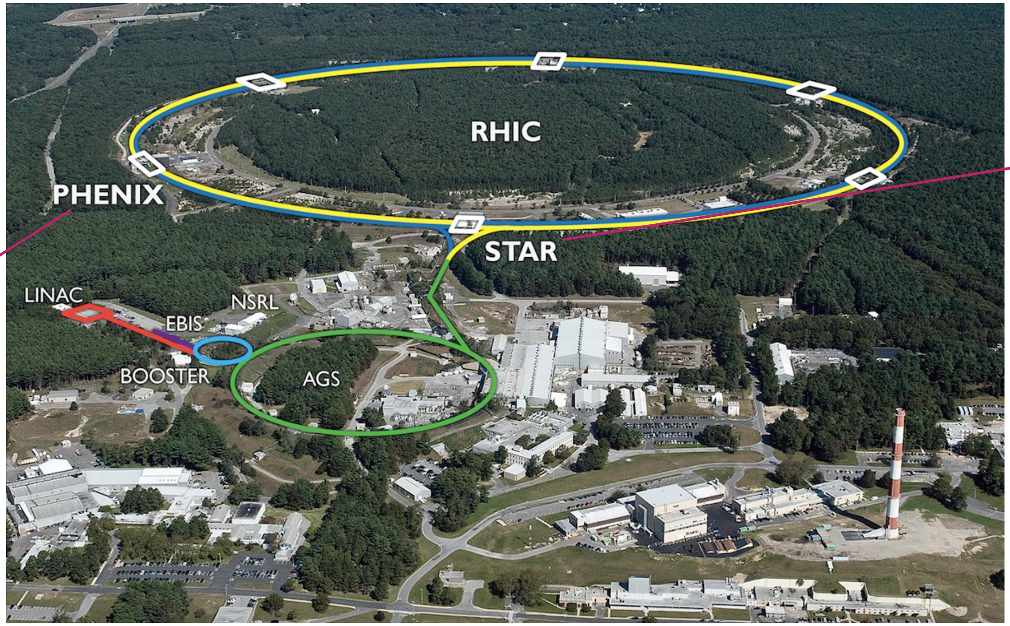
Relativistic Heavy Ion Collider (RHIC)





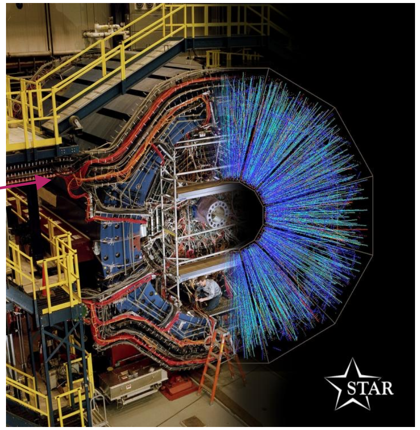
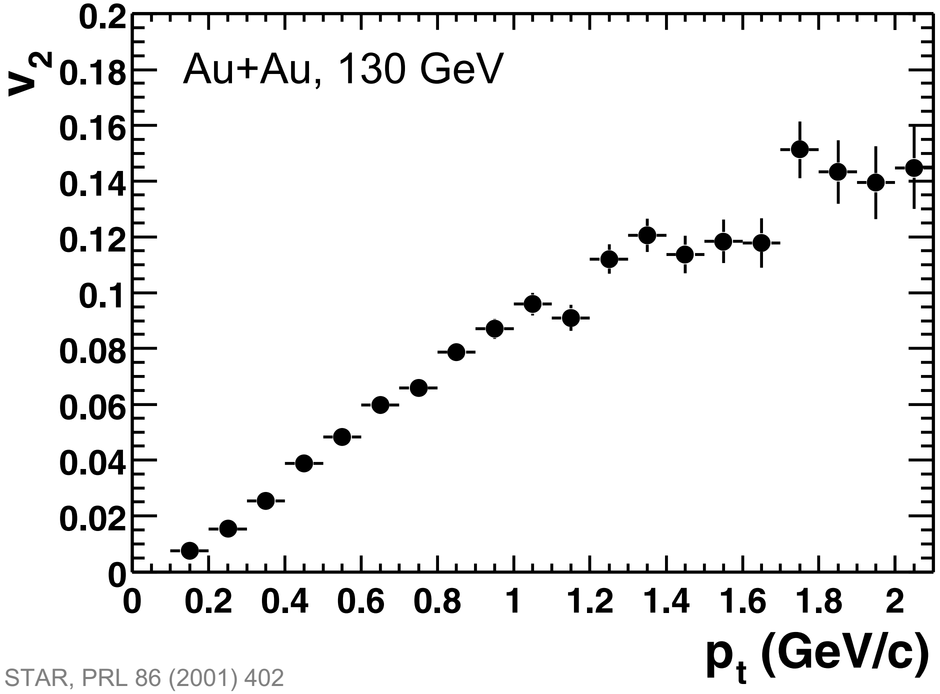


Image credit: BNL

- ➢ Dedicated heavy-ion machine. Start operation in year 2000
- ➢ Versatile machine to collide different systems at different energies

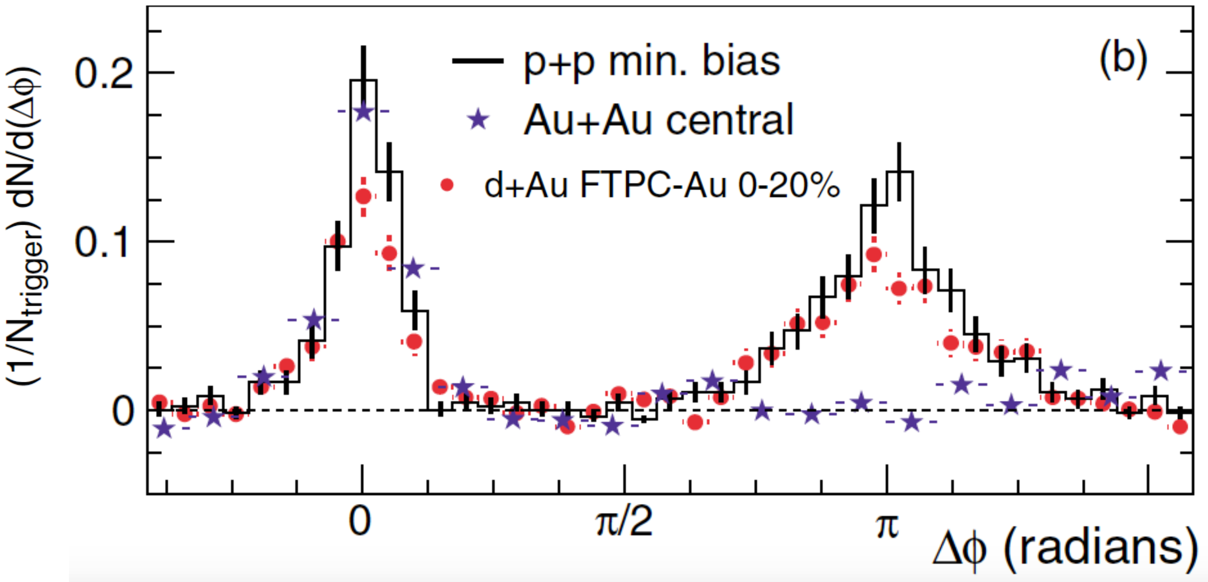
Evidence of QGP Formation

Almost "perfect" fluid



STAR, PRL 86 (2001) 402

Opaque to color objects



STAR, PRL 91 (2003) 72304

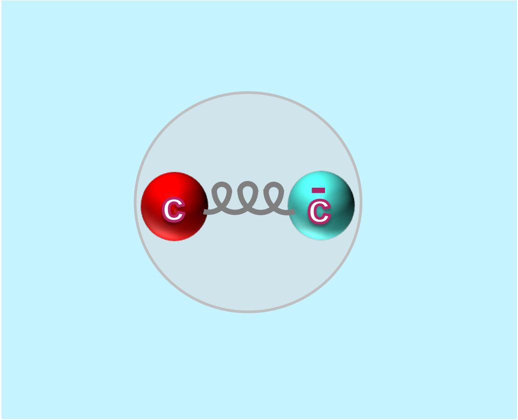
Quarkonia as QGP Probe

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

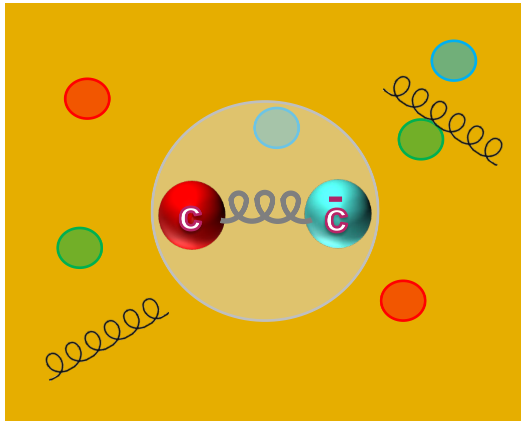
T. Matsui and H. Satz , PLB 178 (1986) 416

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Vacuum

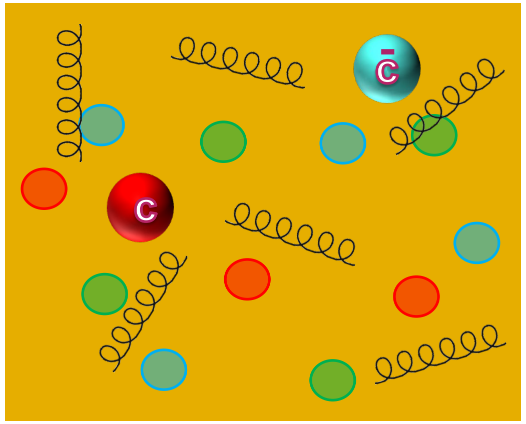


Low temperature
Low density



1/T > r

High temperature
High density

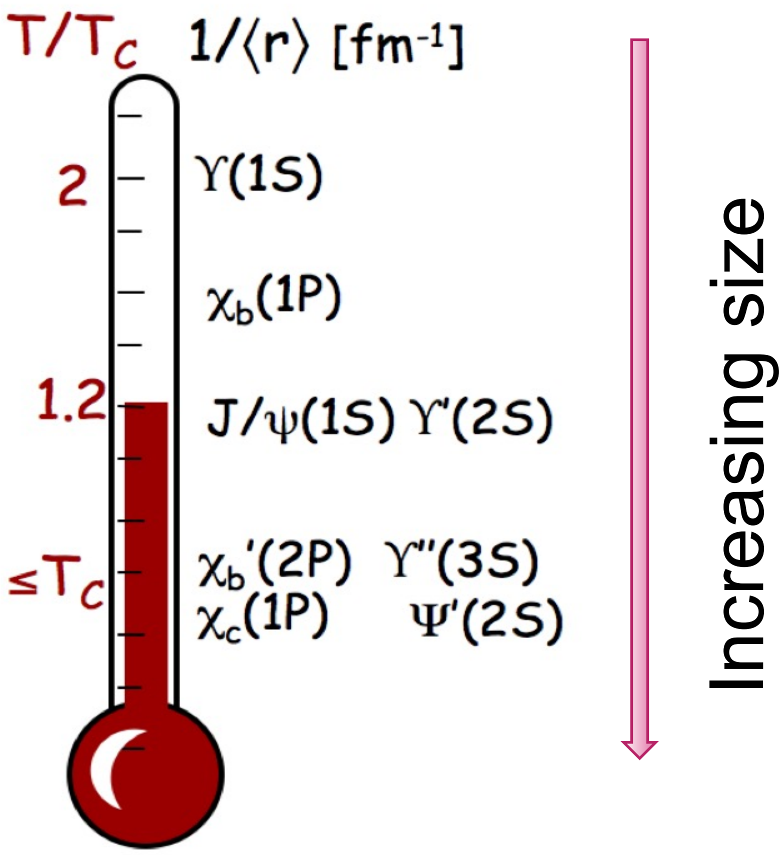


1/T < r

QGP "thermometer"

- For QGP of a given temperature profile, quarkonia of larger sizes melt more easily
- For a given quarkonium, it melts more easily with increasing temperature

"Melting" temperature



A. Mocsy, EPJC 61 (2009) 705

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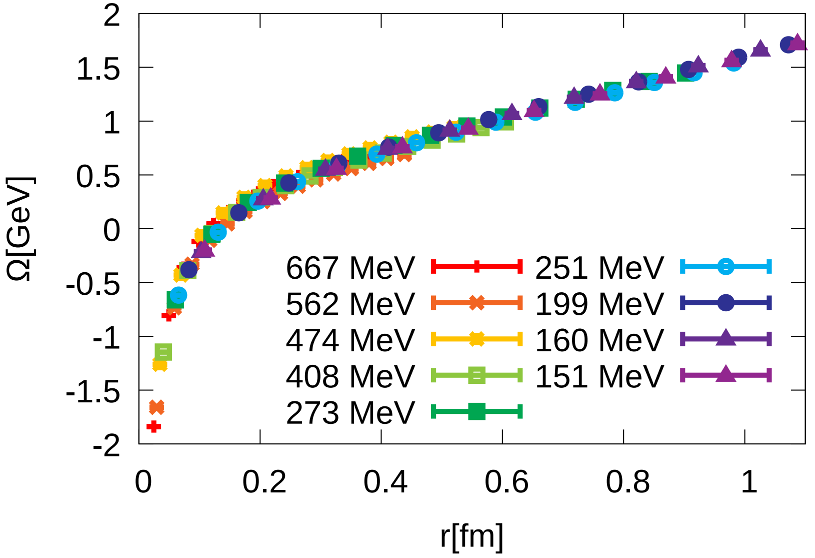
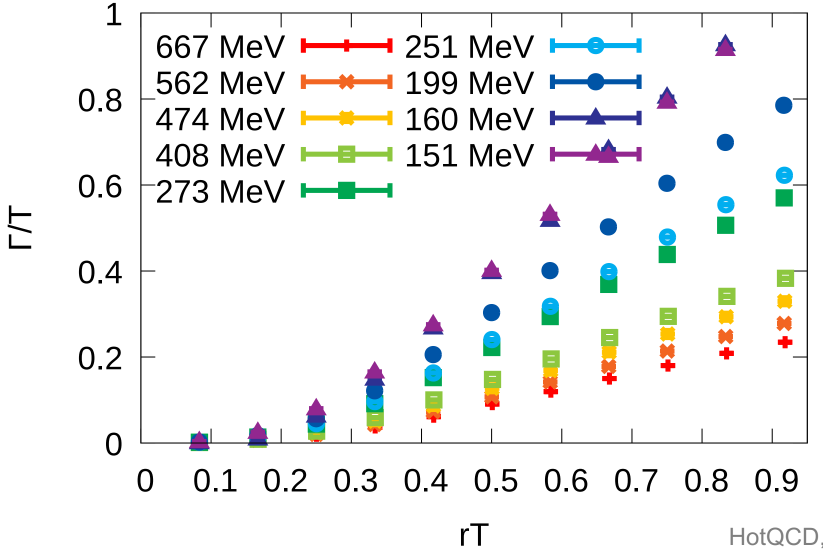
Modern View

- Screening effect very small; dynamical dissociation dominates





HotQCD, PRD 105 (2022) 054513

- Can be used to study QCD force in hot medium, and constrain QGP transport coefficients

B. Scheihing-Hitschfeld and X. Yao, PRD 108 (2023) 054024

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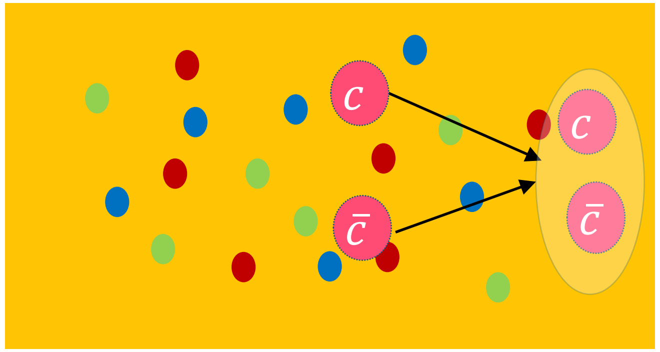
Reality Check

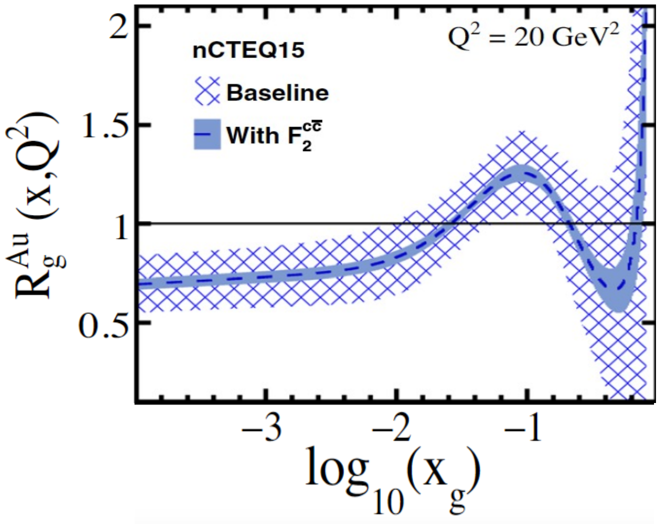
- Besides dissociation, many other effects also influence quarkonia production in HI collisions
  - Hot medium effect: regeneration

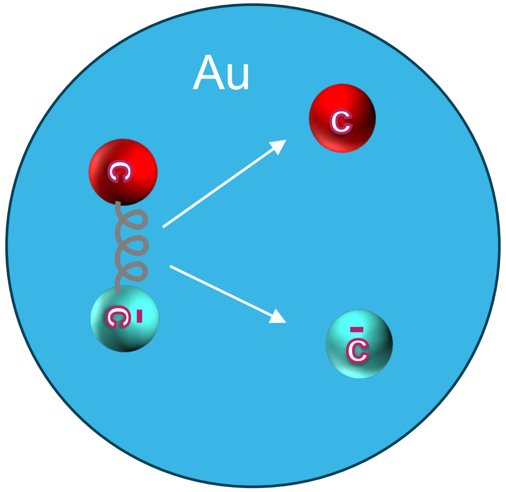


Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 5 TeV
N_{ccbar}/event	~0.2	~10	~115

Reality Check

- Besides dissociation, many other effects also influence quarkonia production in HI collisions
  - Hot medium effect: regeneration
  - Cold nuclear matter effect
    - nPDF; energy loss; nuclear absorption …





M. Kelsey, et. al., PRD 104 (2021) 054002
K. Kovarik, et al., PRD 93 (2016) 085037

Reality Check

- Besides dissociation, many other effects also influence quarkonia production in HI collisions
  - Hot medium effect: regeneration
  - Cold nuclear matter effect
    - nPDF; energy loss; nuclear absorption …
  - Feed-down structure

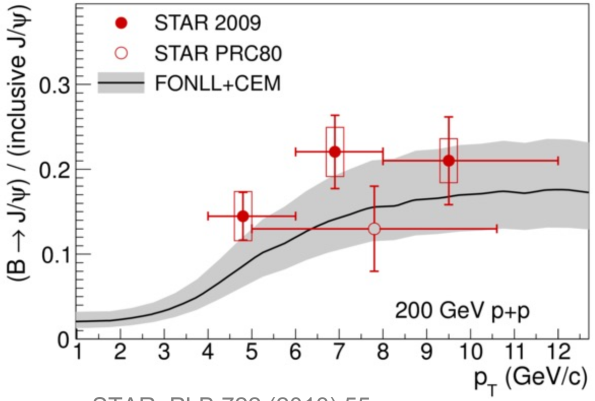
Prompt J/ψ

TABLE I. Cross sections for direct charmonium production in $\pi^- N$ and pN collisions, normalized to the overall J/ψ production cross section in the corresponding reaction [8]; feed-down fractions and mass gap to the open charm threshold.

State	$R_i(\pi^- N)$	$R_i(pN)$	$f_i(\pi^- N)$ (%)	$f_i(pN)$ (%)	E_{dis} (MeV)
$J/\psi(1S)$	0.57 ± 0.03	0.62 ± 0.04	57 ± 3	62 ± 4	0.642
$\chi_1(1P)$	0.72 ± 0.18	0.60 ± 0.15	20 ± 5	16 ± 4	0.229
$\chi_2(1P)$	1.04 ± 0.29	0.99 ± 0.29	15 ± 4	14 ± 4	0.183
$\psi(2S)$	0.14 ± 0.04	0.14 ± 0.04	8 ± 2	8 ± 2	0.054
J/ψ	1	1	100	100	

S. Digal, P. Petreczky, H. Satz, PRD 64 (2001) 094015

Non-prompt J/ψ



STAR, PLB 722 (2013) 55

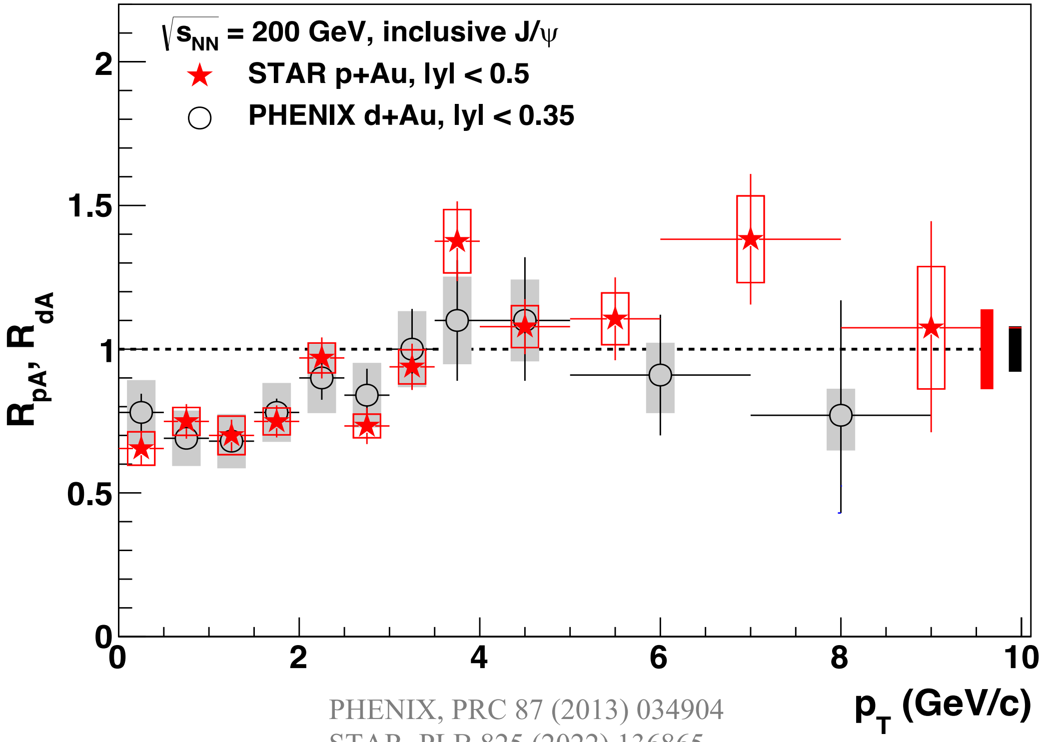
Reality Check

- Besides dissociation, many other effects also influence quarkonia production in HI collisions
  - Hot medium effect: regeneration
  - Cold nuclear matter effect
    - nPDF; energy loss; nuclear absorption …
  - Feed-down structure

- Multi-differential measurements, in concert with theoretical developments, to disentangle different effects

Characterize CNM Effects for J/ψ

- Modifications due to the presence of ions in the collisions, but not related to QGP formation



PHENIX, PRC 87 (2013) 034904
STAR, PLB 825 (2022) 136865

- ~25% suppression at low p_T
- Consistent with no suppression above ~ 3 GeV/c

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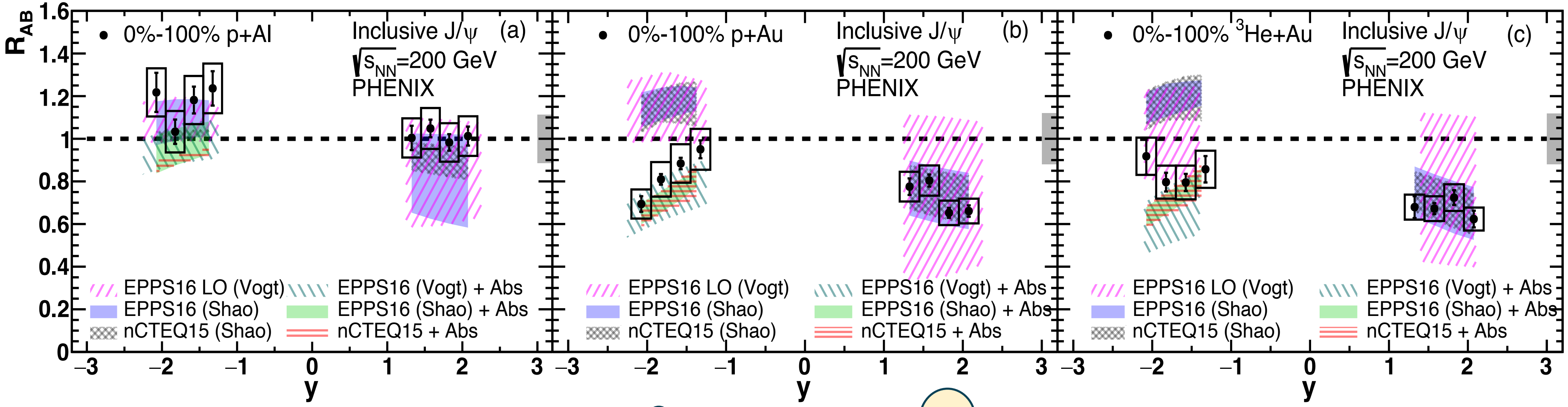
Understand CNM Effects for J/ψ

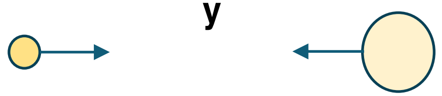
p+Al

p+Au

PHENIX, PRC 102 (2020), 014902

^{3}He+Au





- Forward rapidity: ~30% suppression in Au; consistent with nPDF effects
- Backward rapidity: additional suppression beyond nPDF; can be described by nuclear absorption

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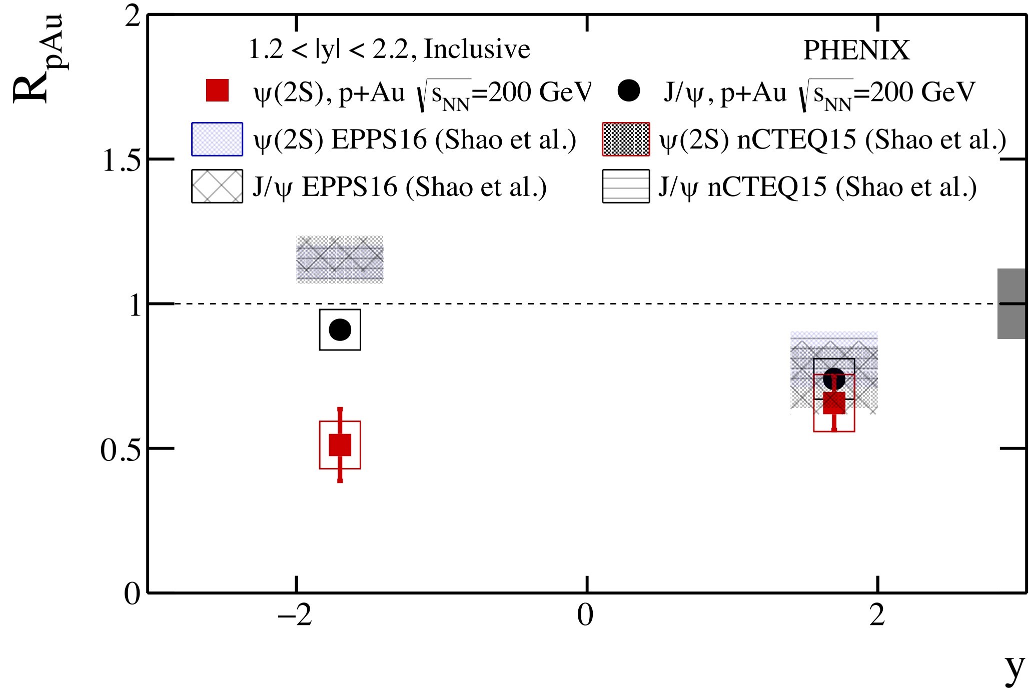
CNM effects for ψ(2S)

p+Au



PHENIX, PRC 105 (2022), 064912

- Forward rapidity: similar suppression for J/ψ and ψ(2S), consistent with nPDF
- Backward rapidity: stronger suppression for ψ(2S) than J/ψ → final-state effects

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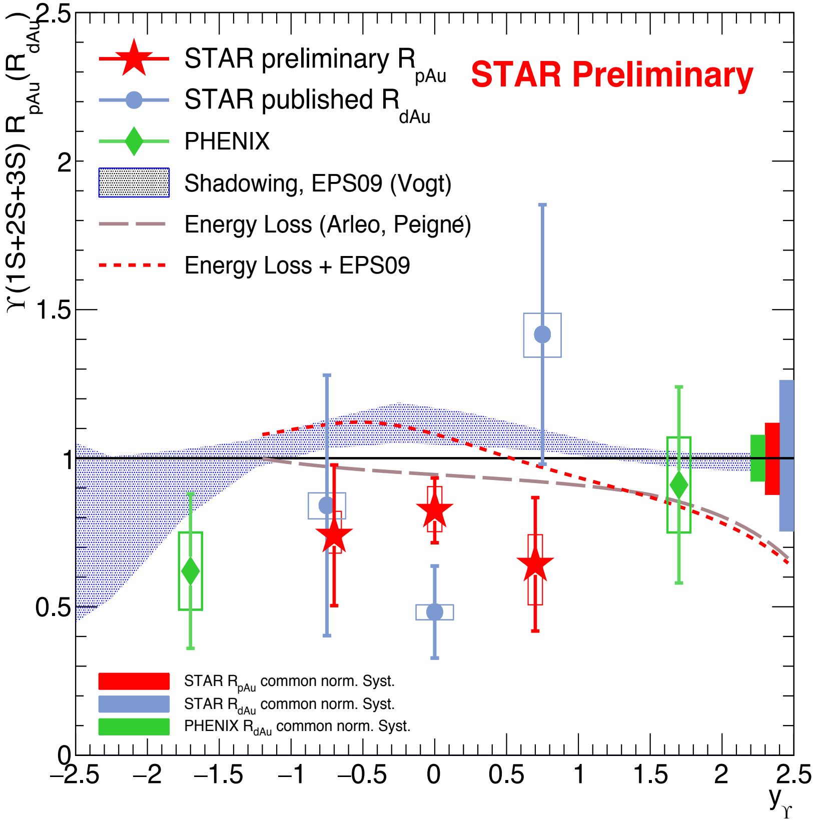
CNM effects for ϒ

p+Au



STAR: PLB 735 (2014) 127, PHENIX: PRC 87 (2013) 044909
R. Vogt, et. al, PoS ConfinementX 203 (2012)
F. Arleo, S. Peigne, JHEP 1303 (2013) 122
K. J. Eskola, et. al, JHEP 0904 (2009) 065

- R_{pAu} ~ 0.8 within |y| < 1.0
  → Indicates sizable CNM effects
- nPDF effects alone not able to describe data. Other effects needed.

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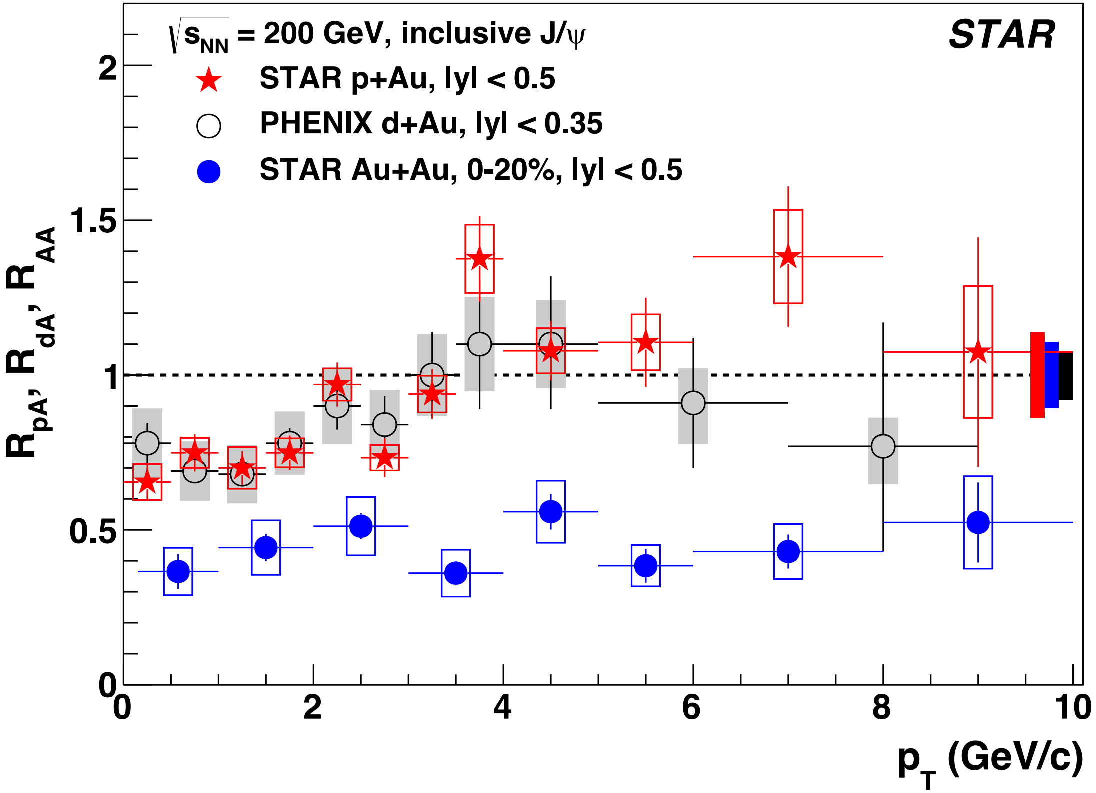
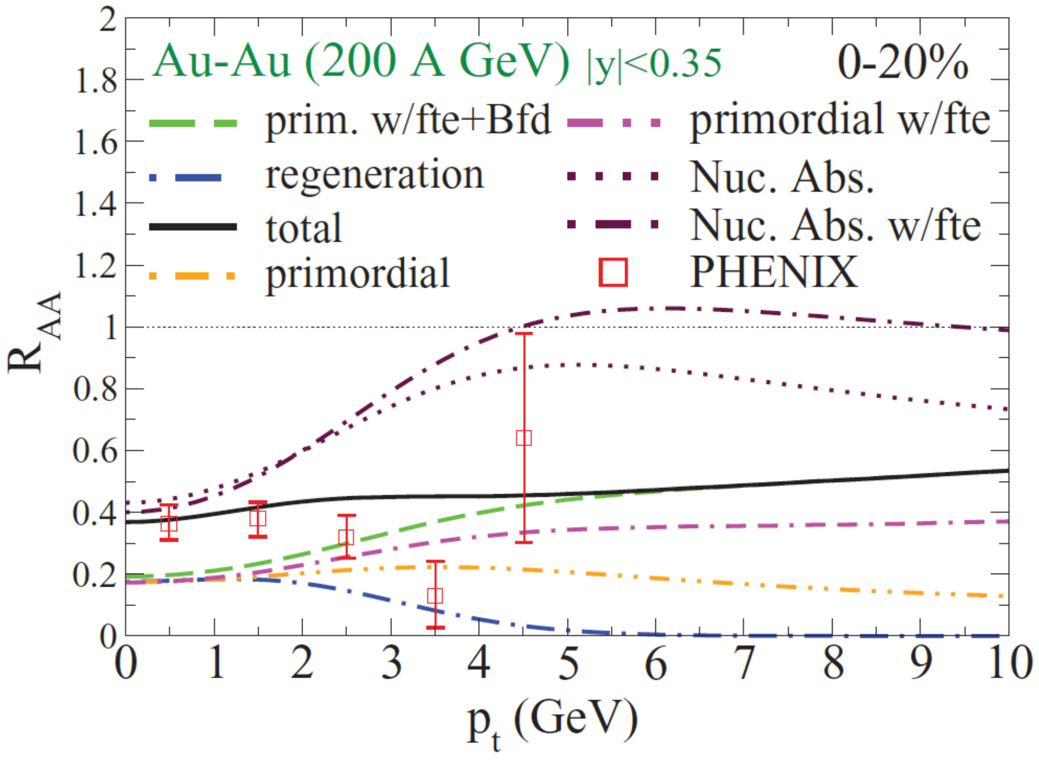
J/ψ: p_T Dependence



PHENIX, PRC 87 (2013) 034904
STAR, PLB 825 (2022) 136865
STAR, PLB 797 (2019) 134917

- A factor ~2 suppression of J/ψ production in Au+Au collisions beyond CNM effects → evidence of QGP formation

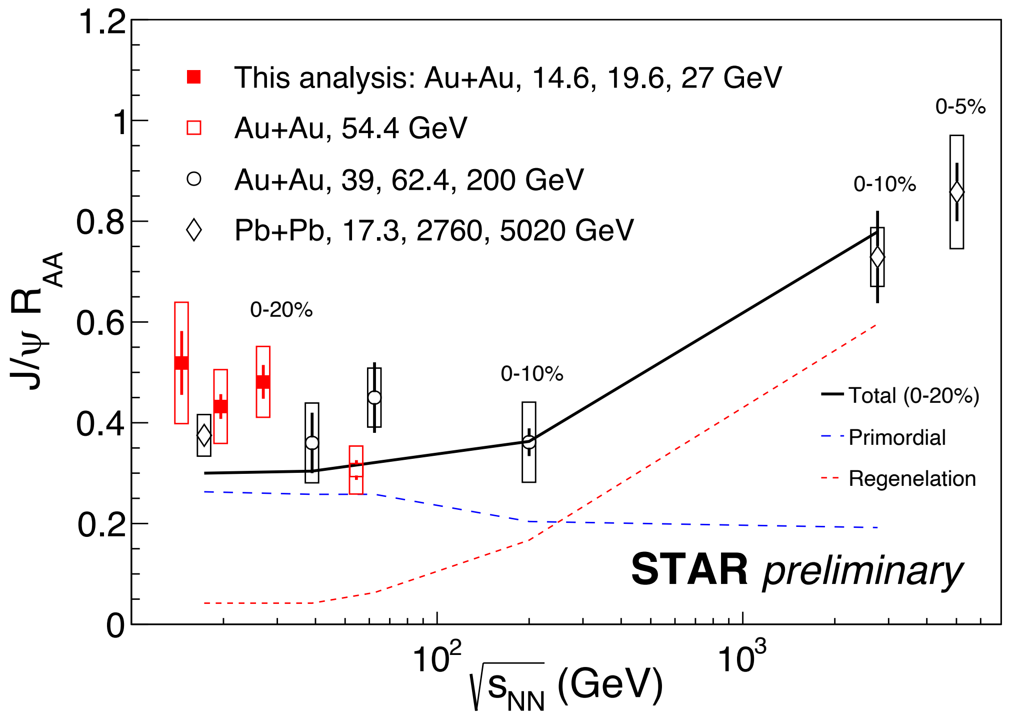
J/ψ: p_T Dependence



X. Zhao, R. Rapp, RPC 82 (2010) 064905

- Mild p_T dependence; interplay of different effects
  - Dissociation
  - Regeneration
  - CNM
  - b-hadron feeddown
  - Flight time effect

J/ψ: Energy Dependence



- No strong energy dependence up to 200 GeV → interplay of CNM, regeneration and dissociation
  - Can be well described by transport model calculation
- **Regeneration dominates at the LHC**

X. Zhao, R. Rapp, PRC 82 (2010) 064905
NA50, PLB 477 (2000) 28, STAR, PLB 771 (2017) 13, STAR, PLB 797 (2019) 134917
ALICE, PLB 734 (2014) 314, ALICE, NPA 1005 (2021) 121769

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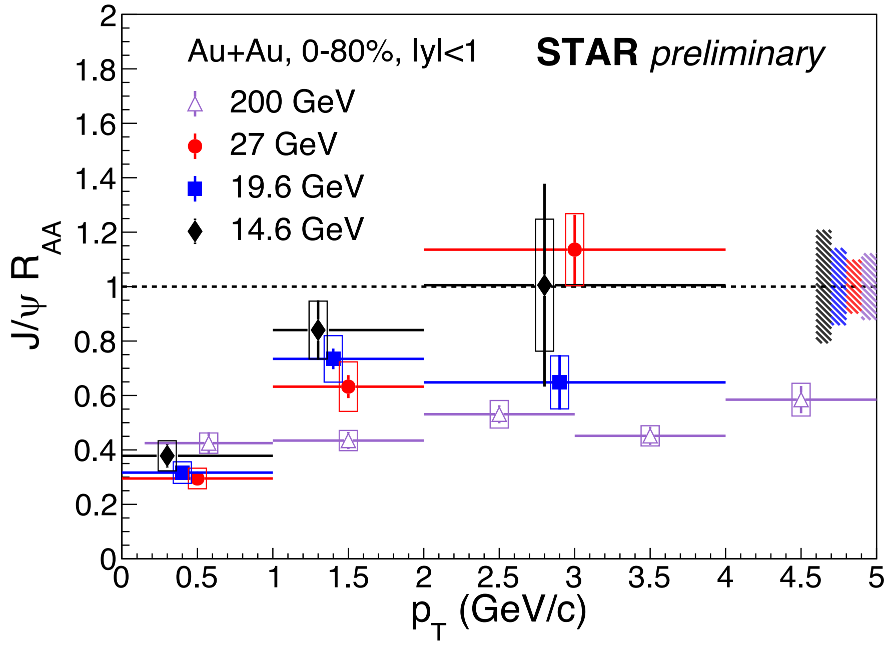
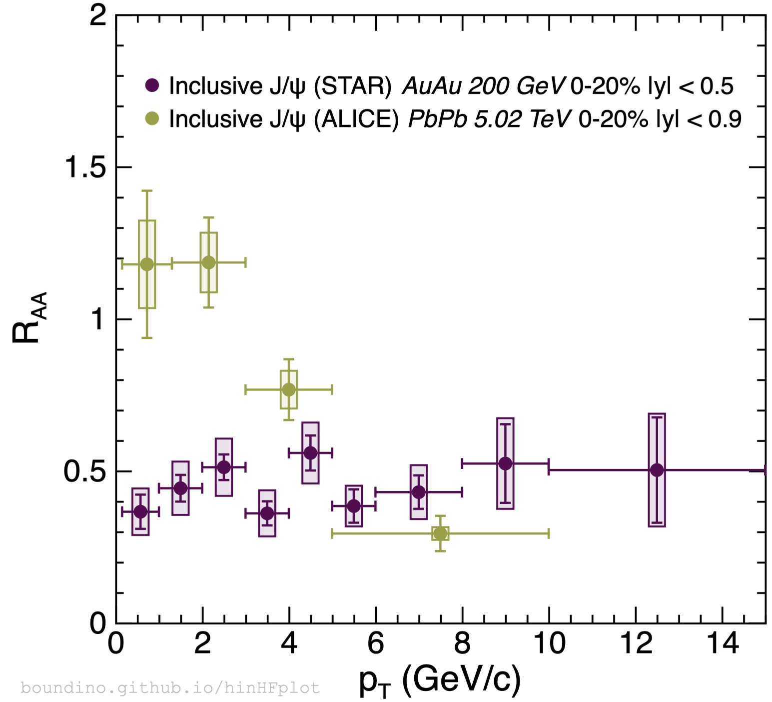
J/ψ: Energy & p_T Dependence

STAR, PLB 797 (2019) 134917
ALICE, PLB 805 (2020) 135434





- ➢ Different p_T dependence at low and high energies
- ➢ CNM effects & regeneration vary with collision energy

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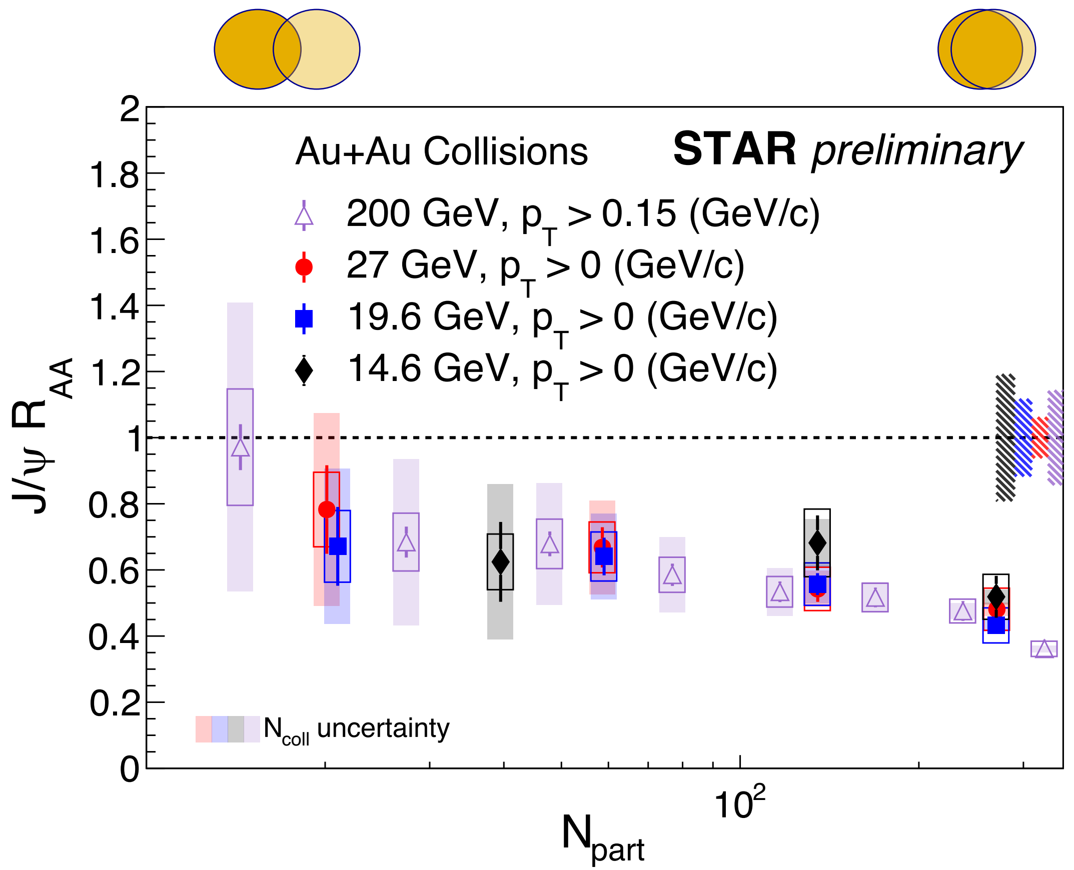
J/ψ: Centrality Dependence

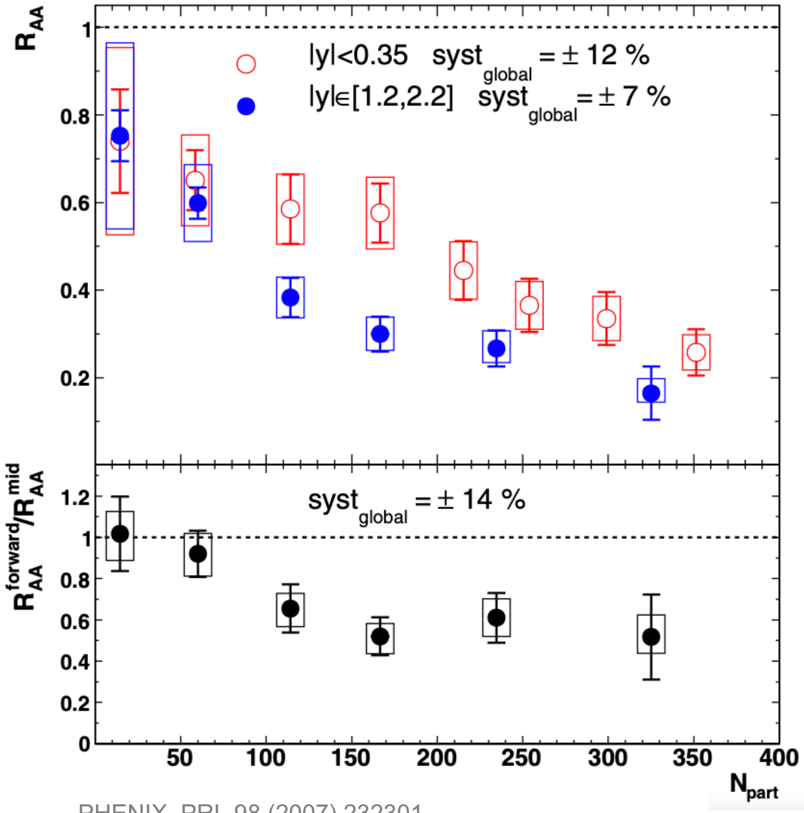


- Hint of decreasing R_{AA} from peripheral to central collisions

  → dissociation/CNM grows slightly faster than regeneration at RHIC

J/ψ: Rapidity Dependence

Au+Au @ 200 GeV

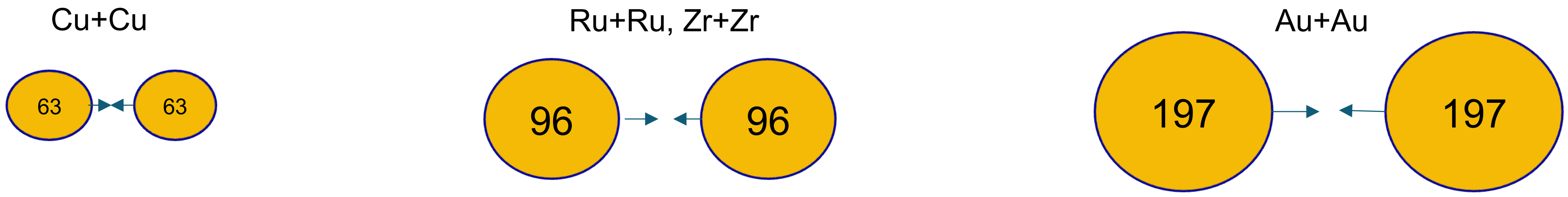


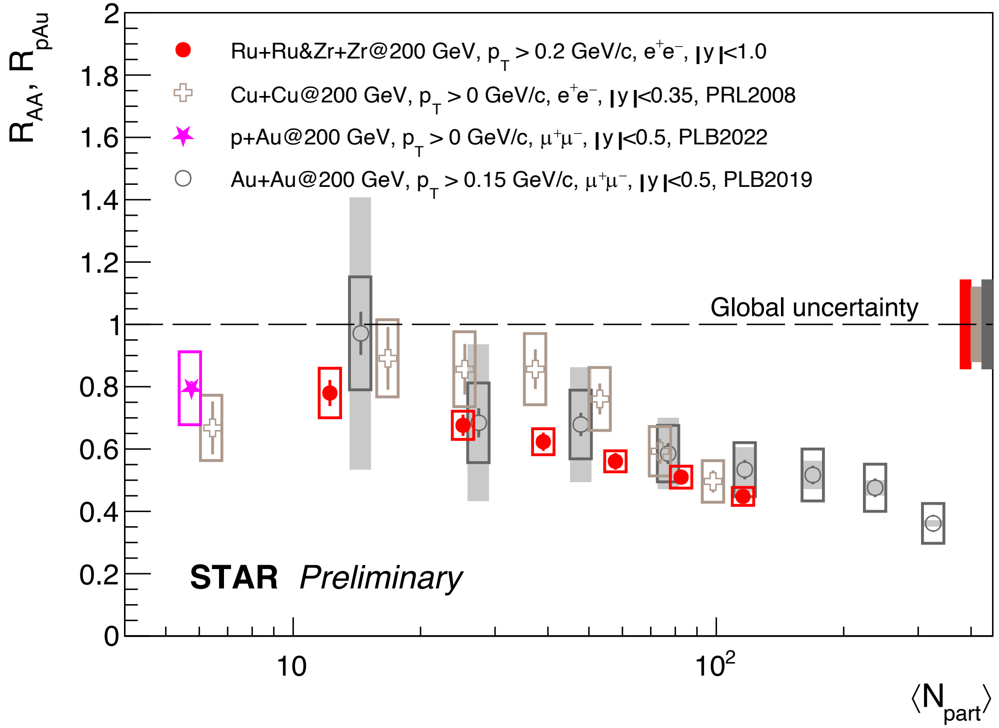
PHENIX, PRL 98 (2007) 232301

- Stronger suppression at forward rapidity compared to midrapidity

  → Larger regeneration effect than dissociation

J/ψ: System Size Dependence

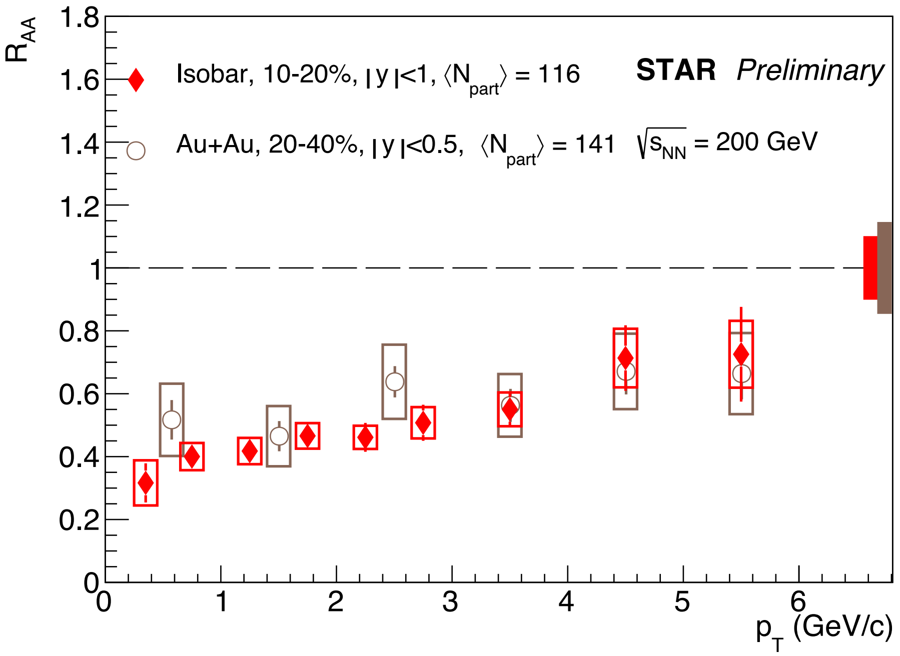


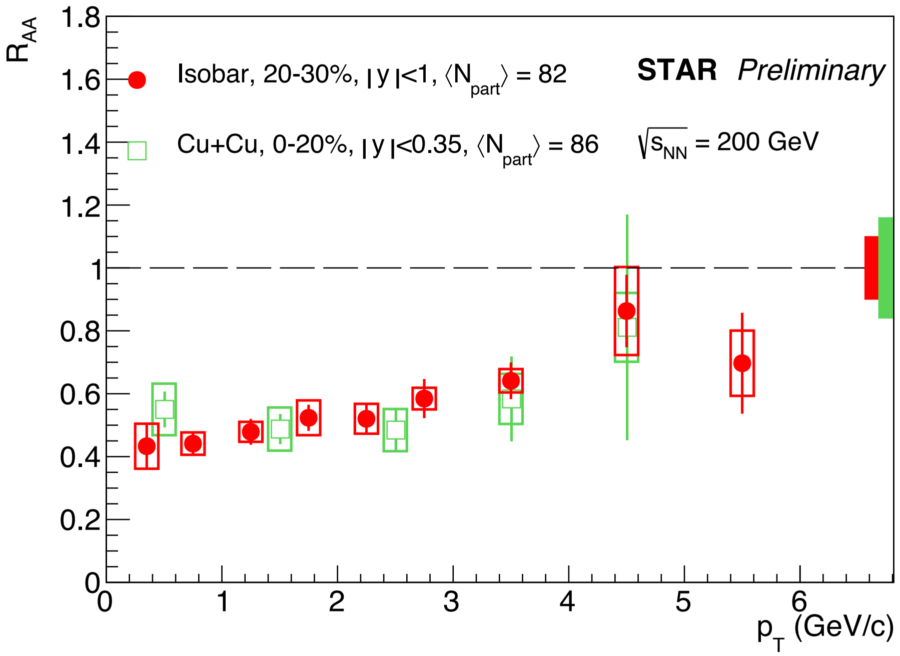


- Indication of a global trend of R_{AA} vs. N_{part} for different colliding systems

  → suppression driven by event multiplicity rather than collision geometry

J/ψ: System Size & p_T Dependence





- Similar R_{AA} vs. p_T for different colliding systems of similar N_{part}
- Rising R_{AA} vs. p_T in Isobar collisions

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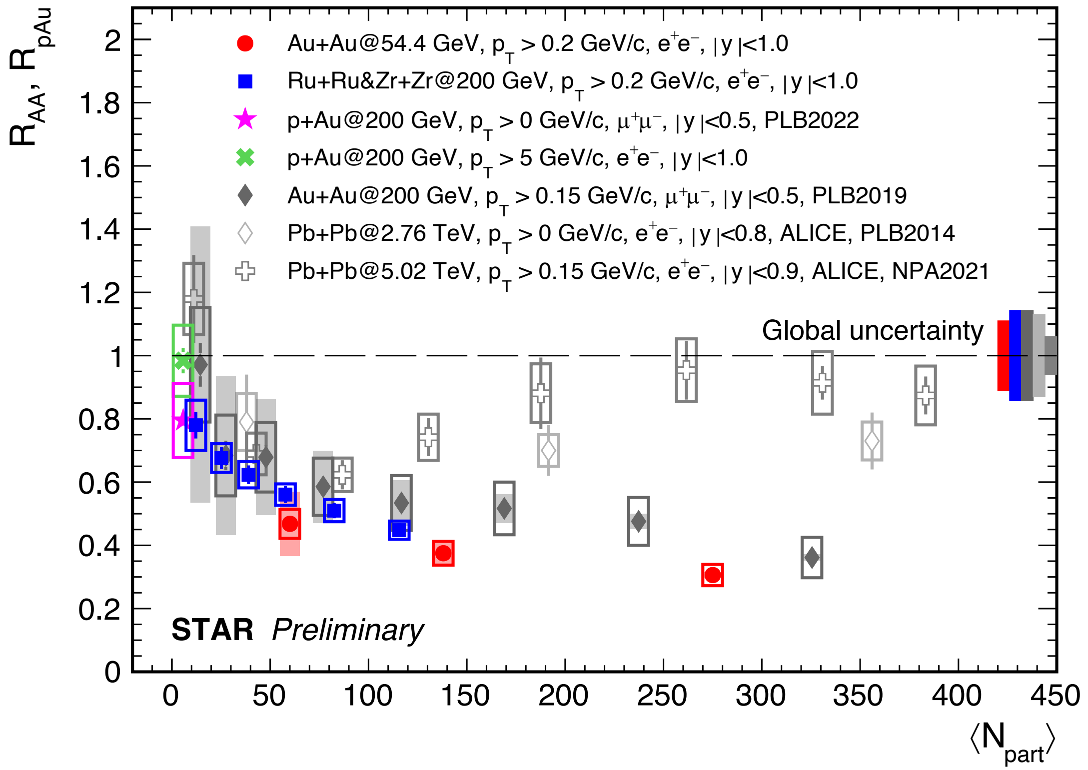
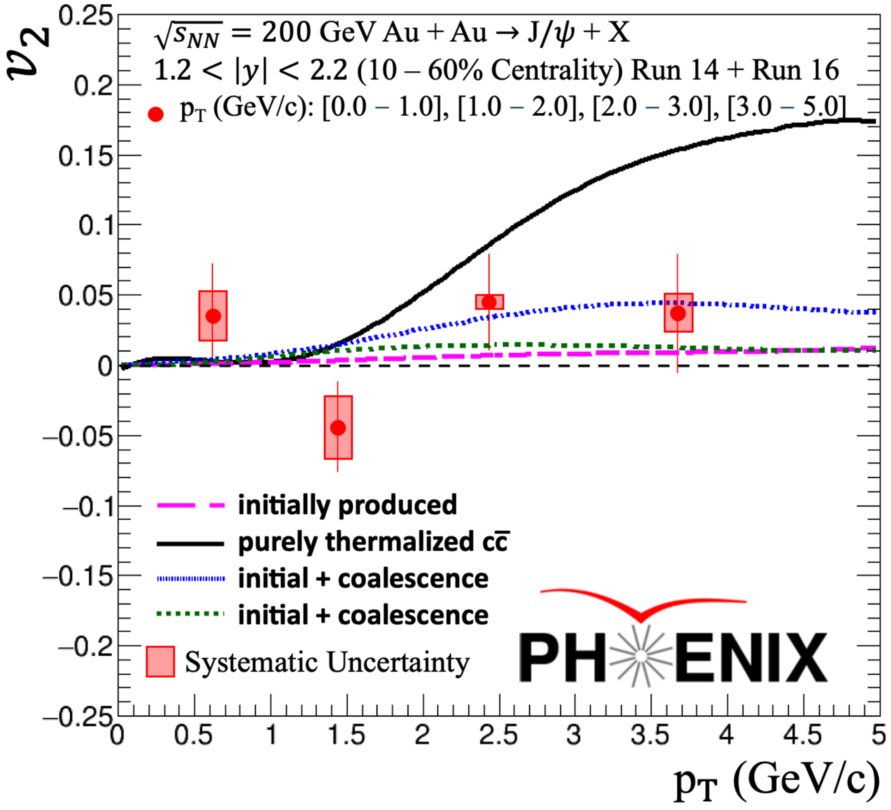
J/ψ: System Size & Energy & Centrality



- Interplay of different effects
- Great constraining power for theoretical calculations

J/ψ: Event Plane Dependence



PHENIX, PRC 112 (2025) 014904
STAR, PRL 111 (2013) 052301

- No significant v_2 at RHIC
  → disfavor the scenario that high-p_T J/ψ is solely from regeneration

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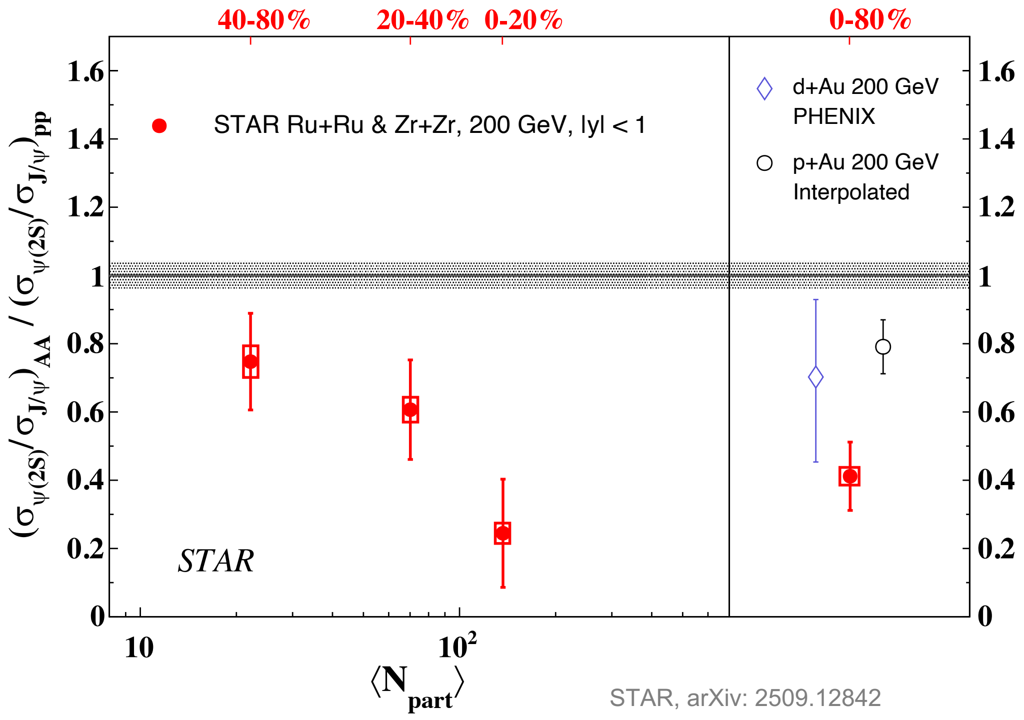
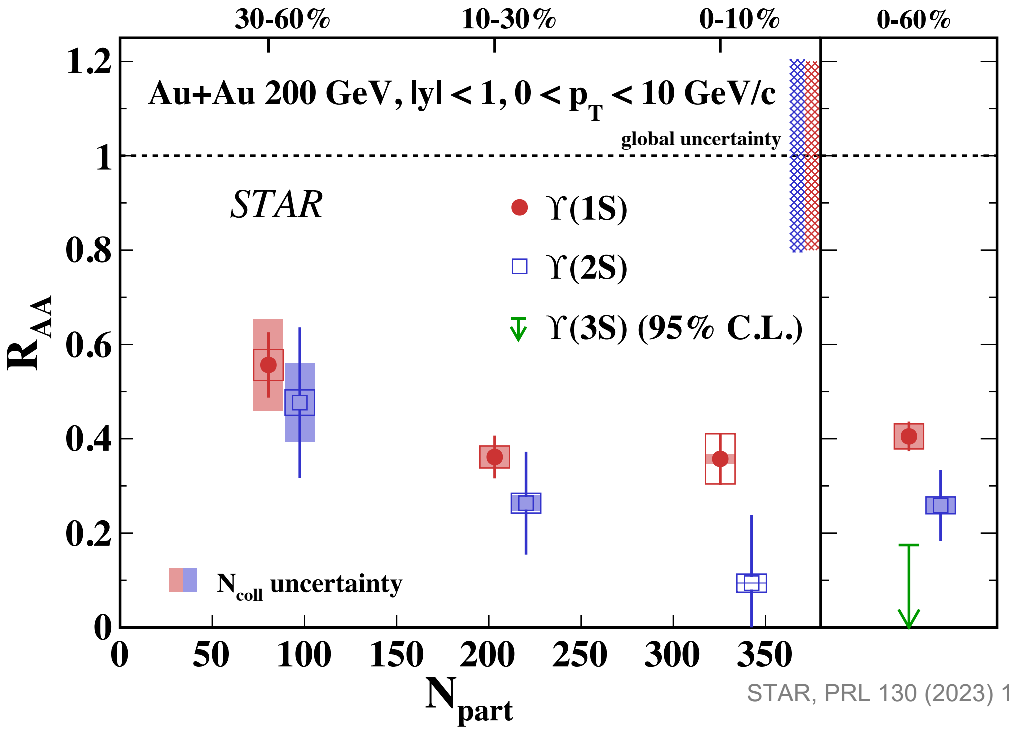
Quarkonia: Binding Energy Dependence

Charmonia in Isobar



STAR, arXiv: 2509.12842

Bottomonia in Au+Au



STAR, PRL 130 (2023) 112301

➢ Sequential suppression at RHIC

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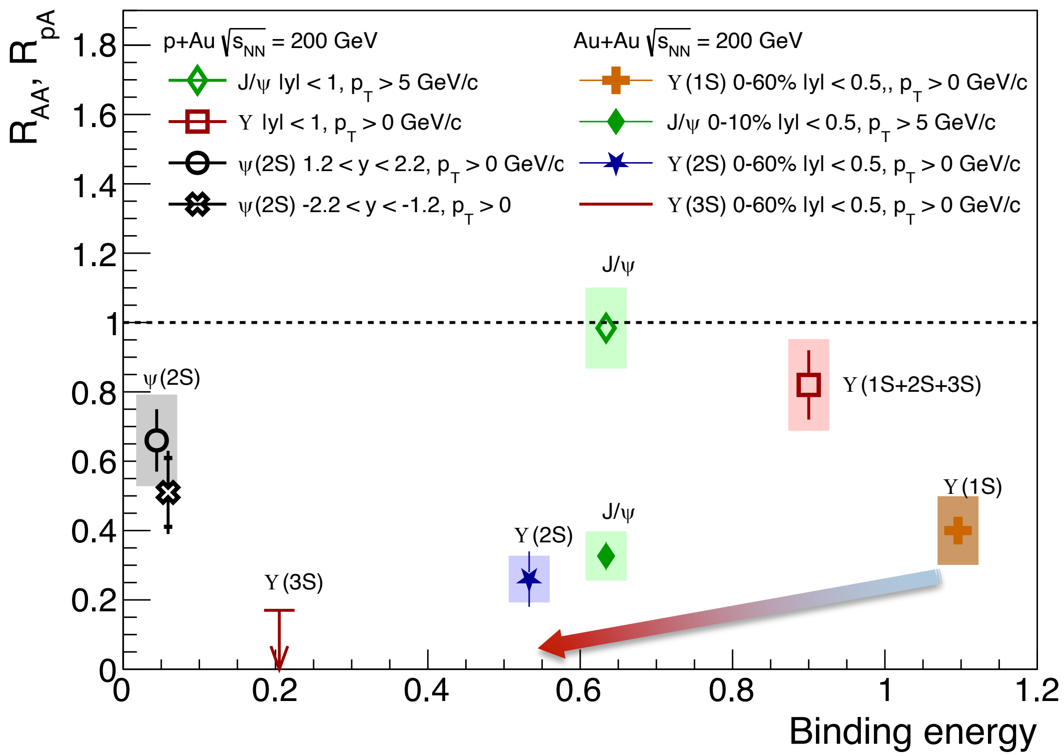
Where Are We at RHIC?



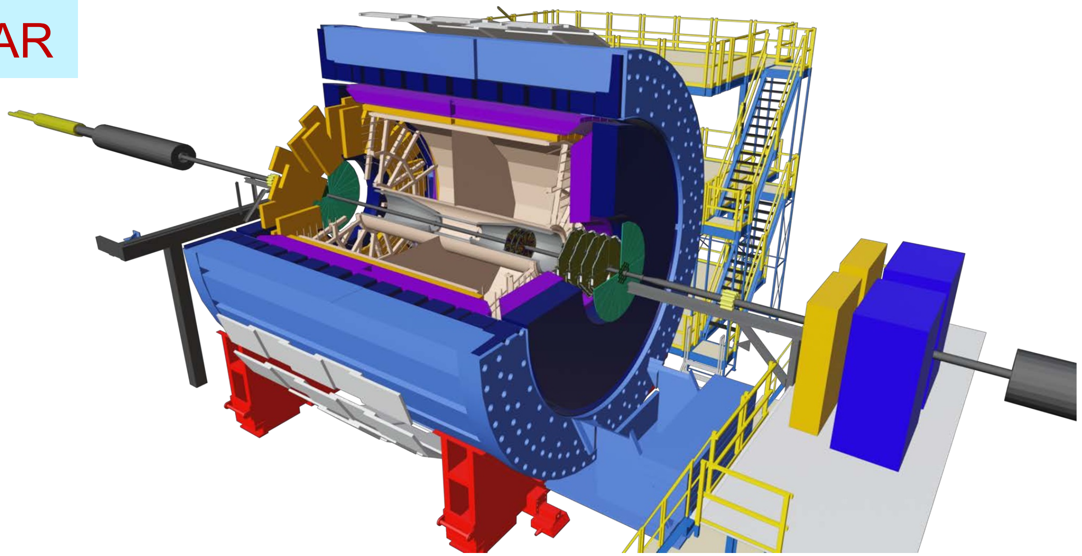
Hot QCD White Paper, arXiv:2303.17254

- Hint of stronger suppression with decreasing binding energy beyond CNM
- **Areas for improvement**
  - Only an upper limit for ϒ(3S)
  - No measurement of ψ(2S) in Au+Au
  - No separate measurement of CNM for different ϒ states
  - Limited precision

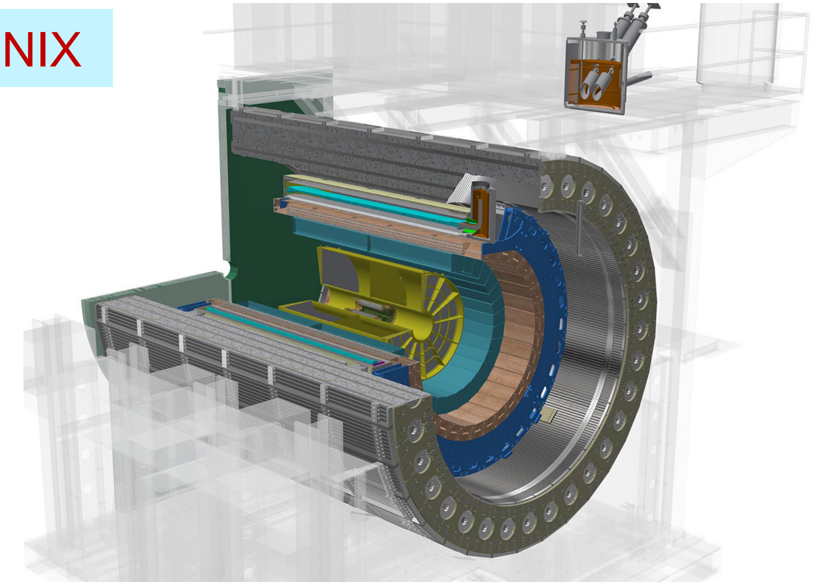
RHIC: Moving Forward

- Unprecedented statistics to be collected in 2023-2025 with new detector capabilities
  - p+p, p+Au (possibly), Au+Au @ 200 GeV

STAR

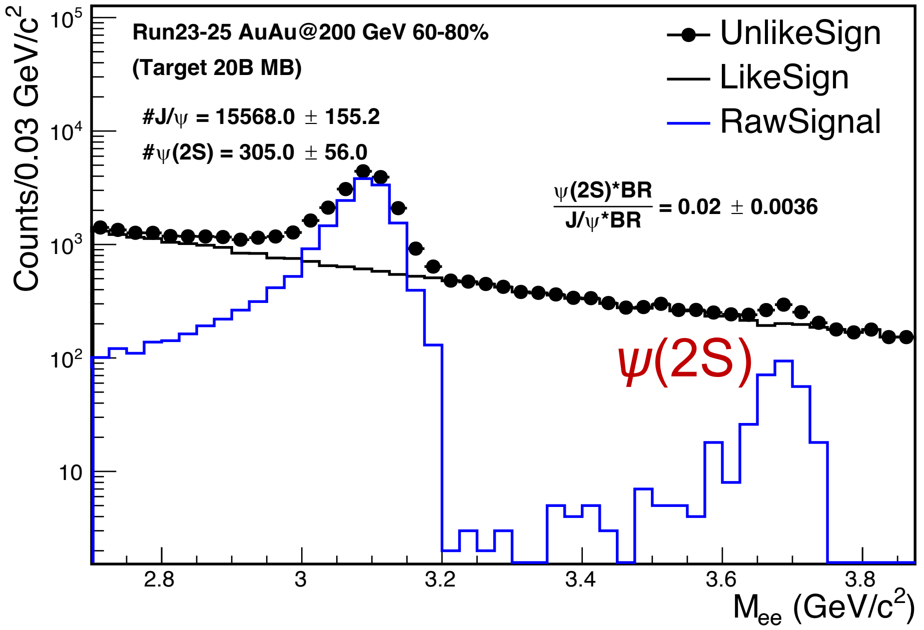


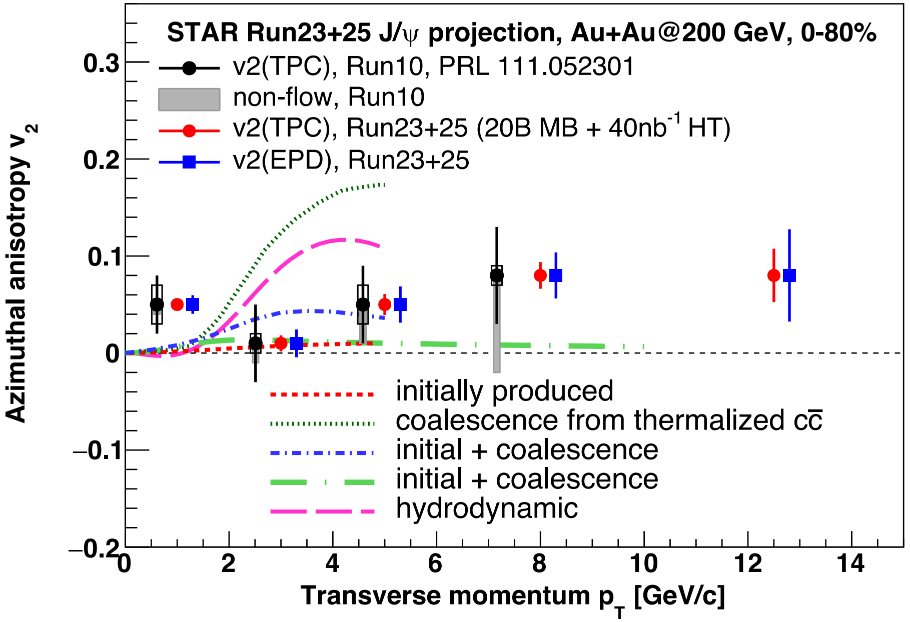
sPHENIX



RHIC: Moving Forward

[STAR Beam Use Request]

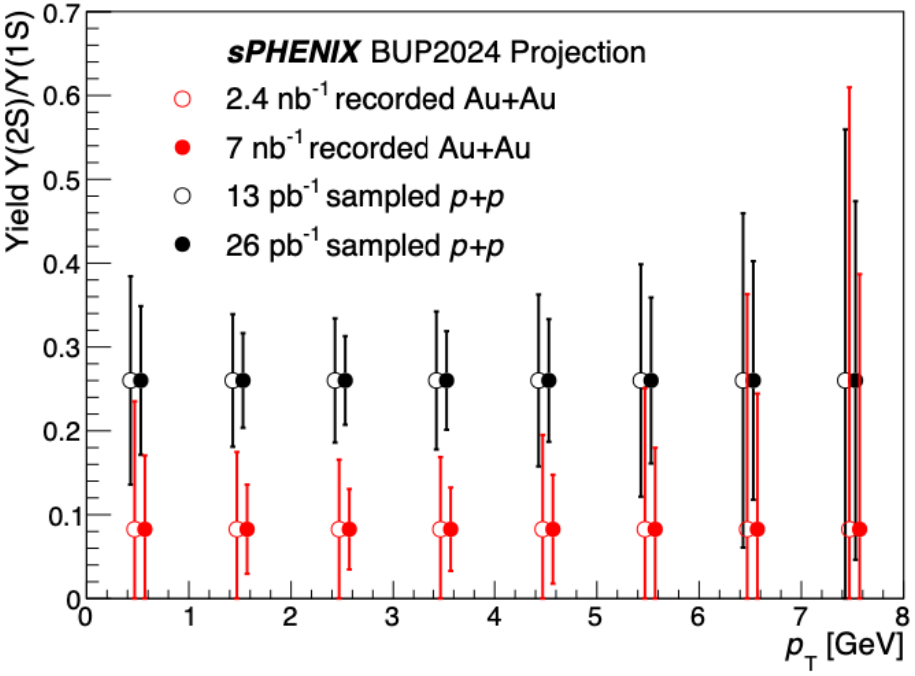




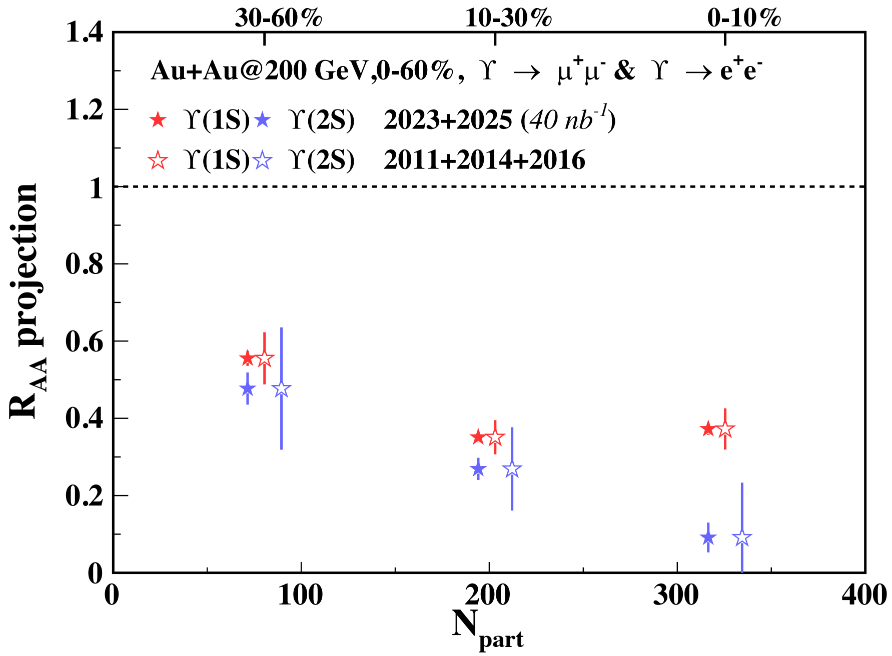
- ➢ First-time access to ψ(2S) in 200 GeV Au+Au collisions
- ➢ J/ψ v_2: more statistics + reduced non-flow with forward detectors

RHIC: Moving Forward

sPHENIX Beam Use Proposal



STAR Beam Use Request



- Precision measurement of different ϒ states by both STAR & sPHENIX
- Possible access to ϒ(3S)

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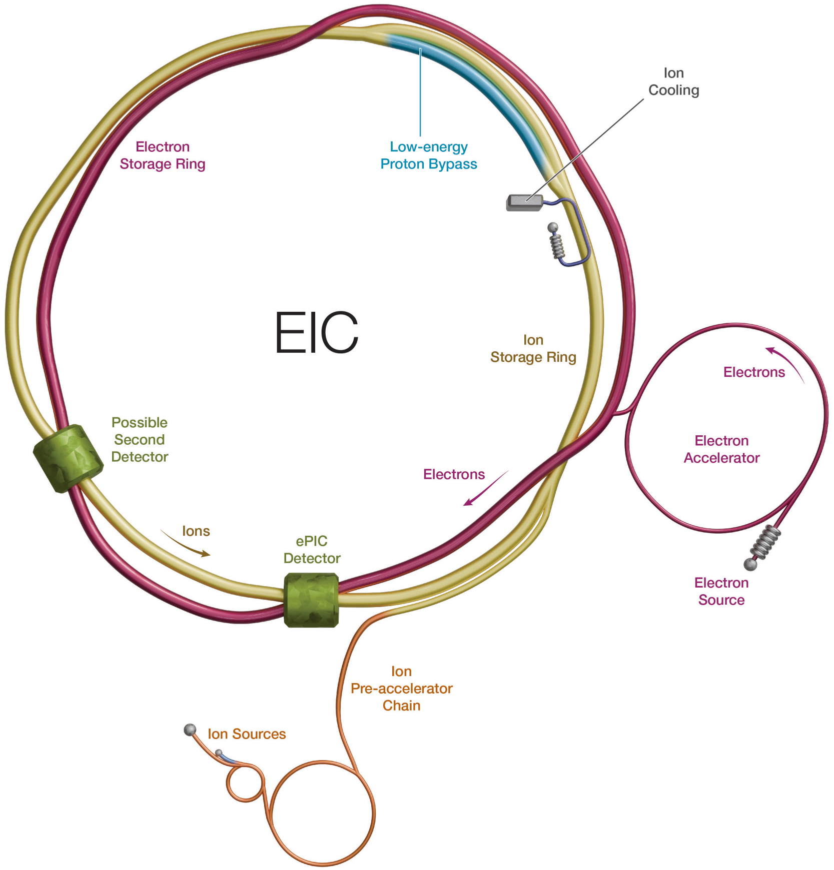
RHIC → Electron Ion Collider (EIC)

- NSAC LRP: **Complete EIC Construction (Recommendation 3):** The expeditious completion of the Electron-Ion Collider (EIC) is the highest priority for facility construction. The EIC will elucidate the origin of visible matter in the universe and significantly advance accelerator technology.

- To be built at BNL



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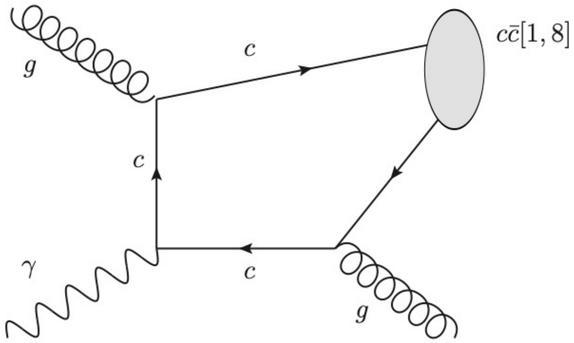
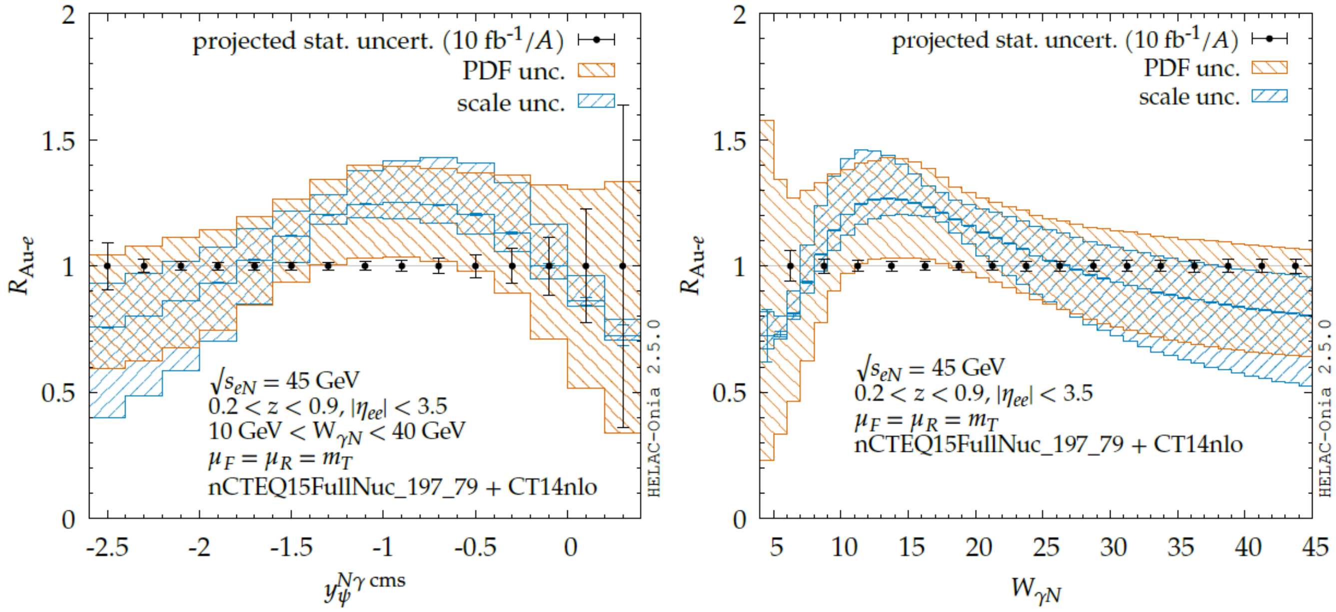
Probe Gluon Momentum Distribution

- Inclusive J/ψ photoproduction
  - Constrain gluon nPDF in shadowing and antishadowing regions

D. Boer, et. al., arXiv:2409.03691

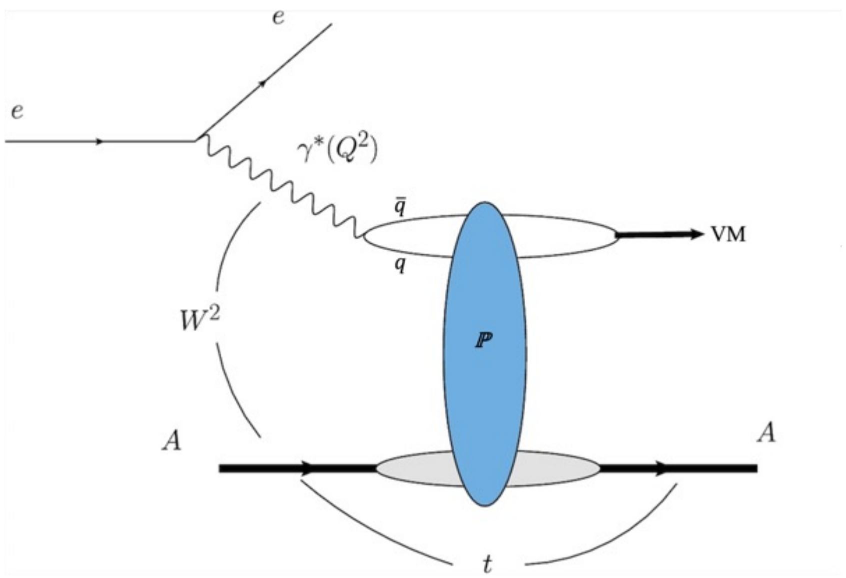


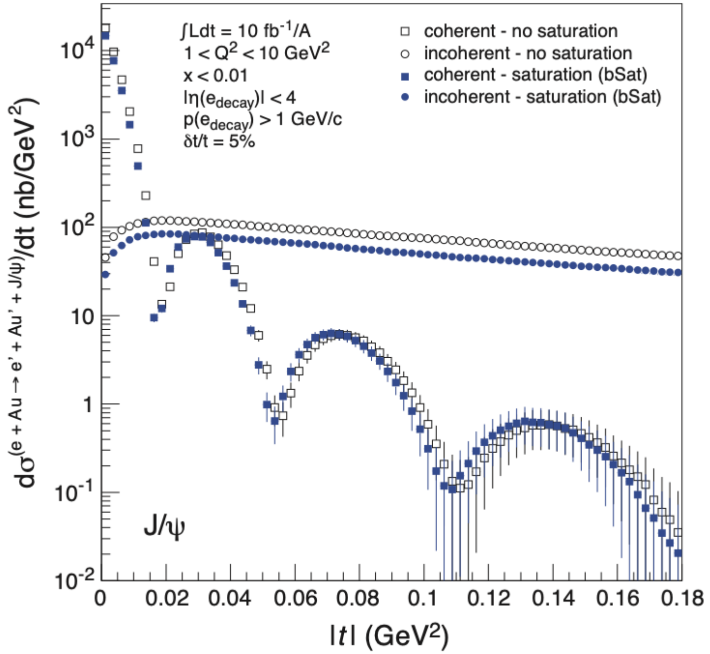
X. Zhan, et. al., JHEP 09 (2022) 050



Probe Gluon Spatial Distribution

- Exclusive J/ψ production
  - Gluon spatial distributions and fluctuations in nuclei encoded in |*t*| distributions for coherent and incoherent production
  - Probe saturation effects





EIC White Paper, arXiv:1212.1701

Summary

- **2007-25: successful quarkonium program at RHIC**
  - Multi-differential measurements of quarkonia suppression → interplay of various cold and hot medium effects
  - Comprehensive/coherent comparisons to theory → QGP properties
- **2025+: new opportunities** brought by high statistics and upgraded detector
  - Better precision; access to excited states. **What else should we measure?**
- **2035+: continue to shine** at the **EIC**
  - Probe gluon distributions