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BROOKHAVEN NATIONAL LABORATORY

Measurements of quarkonium suppression in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR experiment

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DNP2020

Fall Meeting of the Division of Nuclear Physics of the American Physical Society

Oct. 29 – Nov. 1, 2020 *Now Virtual Meeting!*

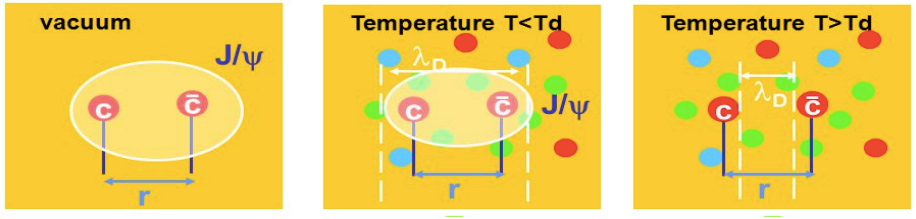
~~Hyatt Regency Hotel, New Orleans, LA~~

APS physics

Why Quarkonia?

- **Early creation:** experience entire evolution of quark-gluon plasma
- **Evidence of deconfinement**: quark-antiquark potential color-screened by surrounding partons → *(static) dissociation*

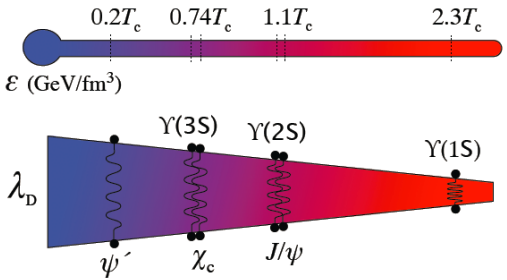
T. Matsui and H. Satz
PLB 178 (1986) 416



$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

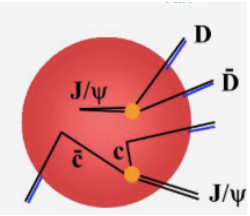
- **"Thermometer"**: different states dissociate at different temperatures → *sequential suppression*

	J/ψ	ψ(2S)	ϒ(1S)	ϒ(2S)	ϒ(3S)
E_b (MeV)	~ 640	~ 60	~ 1100	~ 500	~ 200



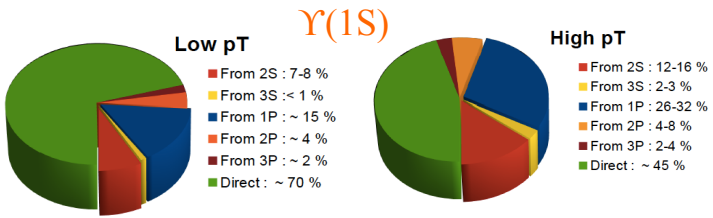
Other Effects

- **(Re)generation of deconfined quarks**
  - Reverse process of deconfinement
  - *Deconfinement is a prerequisite*



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

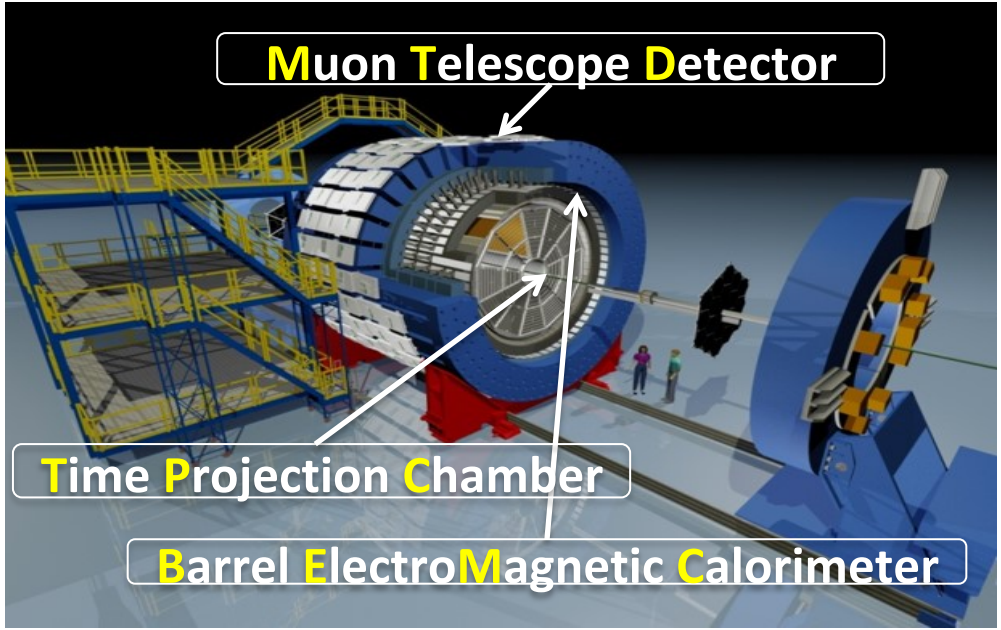
- Medium-induced energy loss
  - Color-octet states; parton fragmentation
- **Feed-down contributions**
  - Depend on species, $\sqrt{s}$, p_T, etc
- Cold Nuclear Matter (CNM) effects
- And more …



A. Andronic, EPJC 76 (2016) 107

The Solenoid Tracker At RHIC

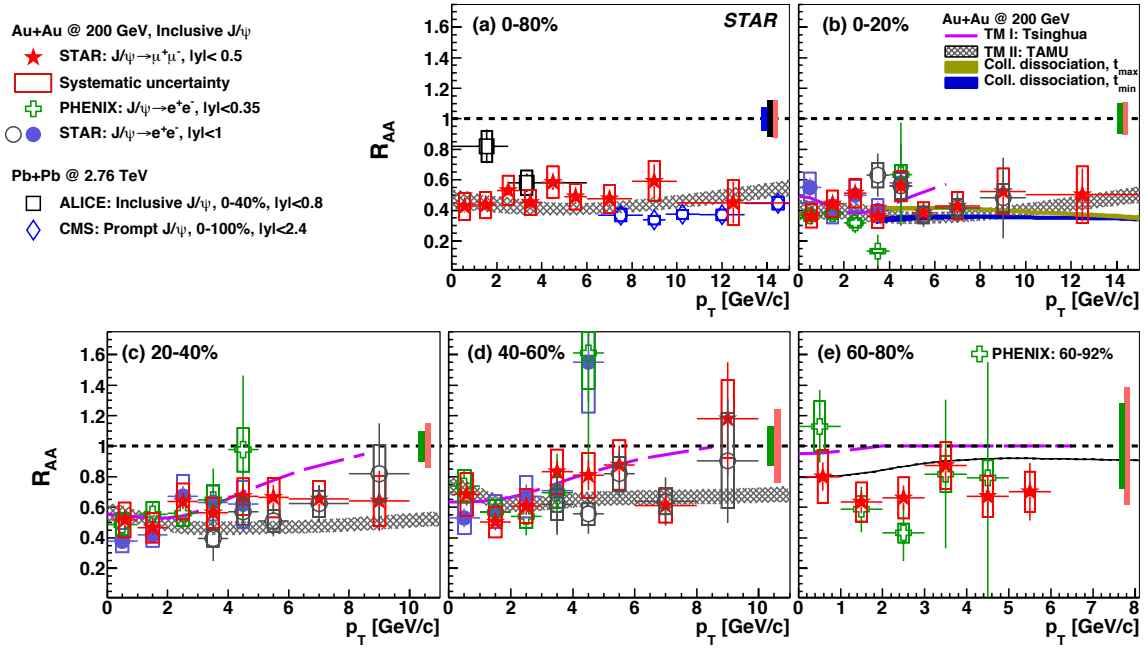
- Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$



- **TPC**: measure momentum and energy loss
- **BEMC**: trigger on and identify high-p_T electrons
- **MTD**: trigger on and identify muons
  - $p_T > 1.3$ GeV/c

Au+Au @ 200 GeV: J/ψ R_{AA} vs. p_T

STAR: PLB 797 (2019) 134917



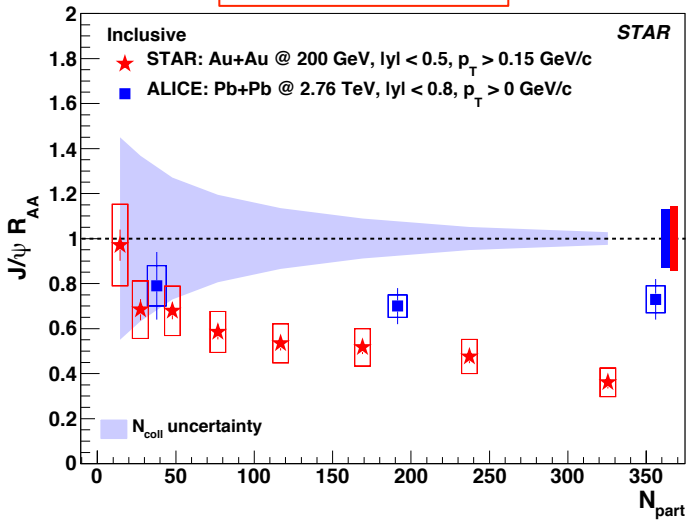
- *J/ψ* is suppressed up to 15 GeV/c
- No strong p_T dependence; interplay of different effects
  - Dissociation: decrease with p_T due to formation time effects
  - Regeneration: mostly at low p_T
  - CNM: more profound at low p_T
  - b-hadron feed-down at higher p_T
- Transport and energy loss models can qualitatively describe data

Central: $R_{AA} \sim 0.4$ for $p_T > 5$ GeV/c → **dissociation in effect**

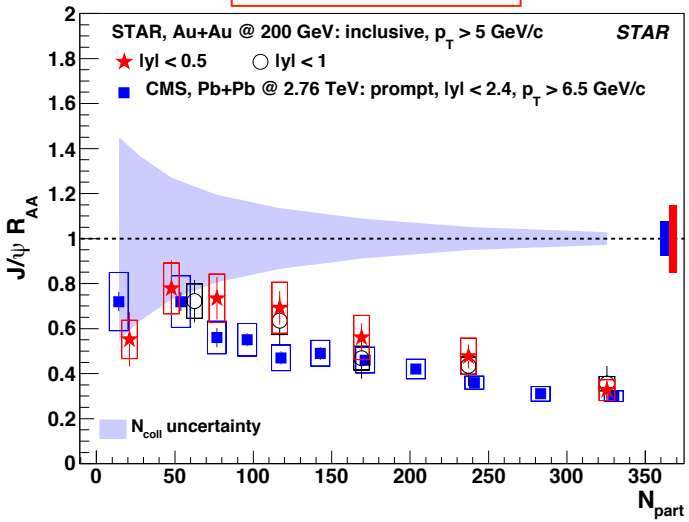
J/ψ R_{AA}: RHIC vs. LHC

STAR: PLB 797 (2019) 134917
ALICE: JHEP 07 (2015) 051
CMS: EPJC 77 (017) 052

$p_T > 0$ GeV/c

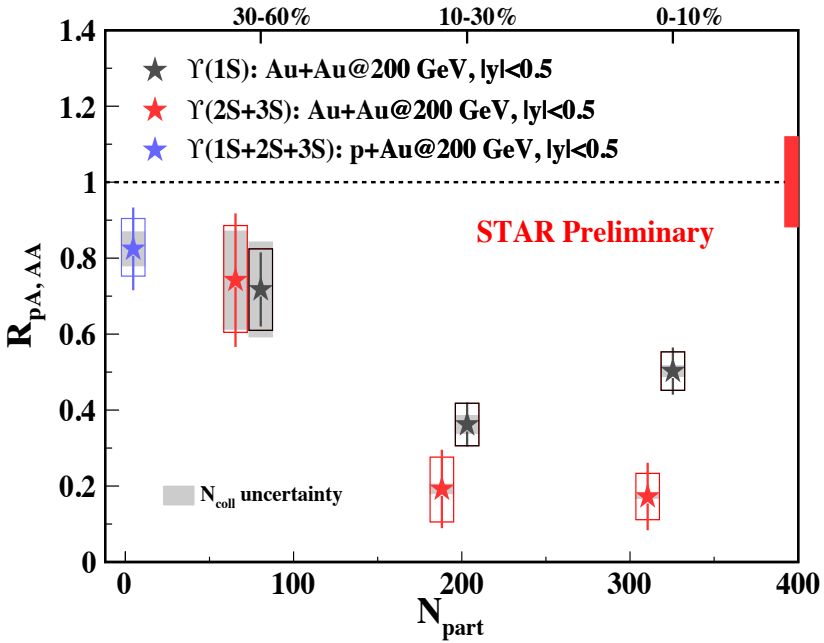


$p_T > 5$ GeV/c



- $p_T > 0$ GeV/c: more suppressed at RHIC in central events → smaller regeneration contribution due to lower charm cross-section
- $p_T > 5$ GeV/c: indication of less suppression at RHIC in semi-central events → smaller dissociation rate due to lower temperature

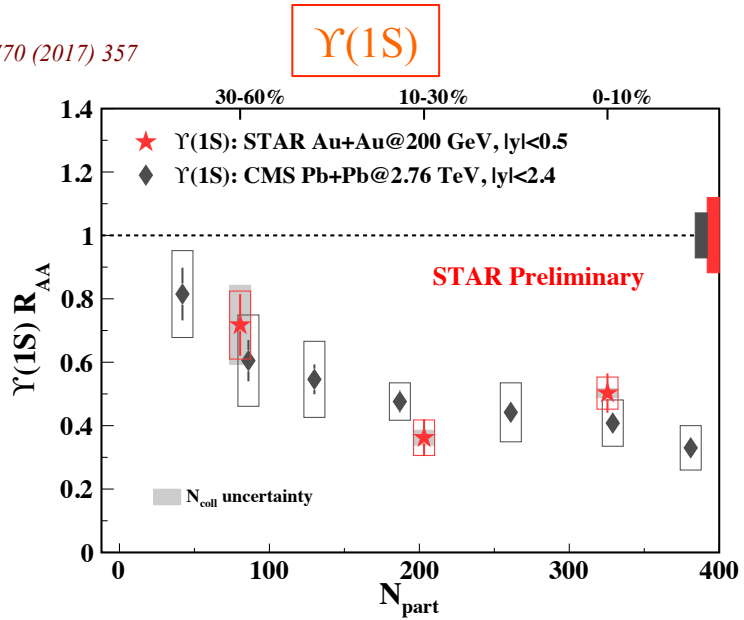
Υ R_{pA} and R_{AA} vs. Centrality @ 200 GeV

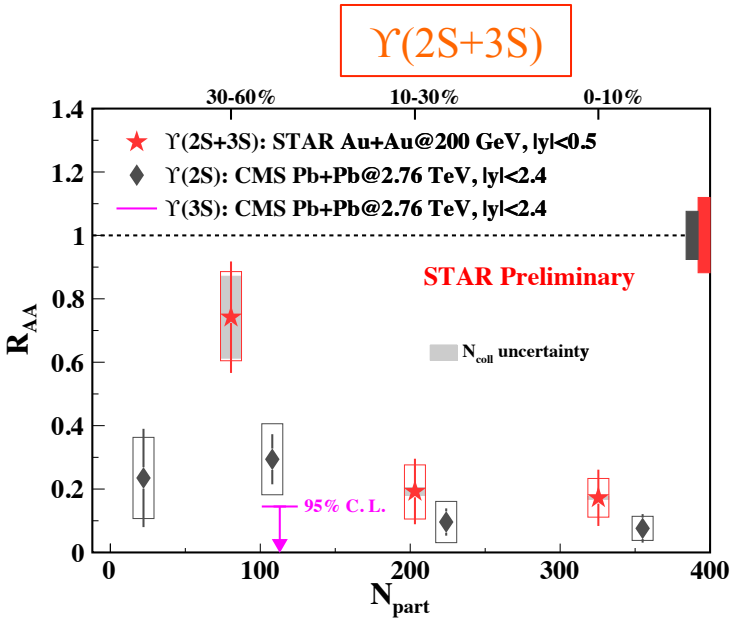


- Improved precision for Υ suppression
  - 2014+2016: dimuon
  - 2011: dielectron
- CNM plays a role
- $R_{AA}^{peri} > R_{AA}^{cent}$: increasing hot medium effects
- 0-10% central: $R_{AA}^{\Upsilon(2S+3S)} < R_{AA}^{\Upsilon(1S)}$
  → sequential suppression
  - Similar to that observed at the LHC

Υ R_{AA}: RHIC vs. LHC

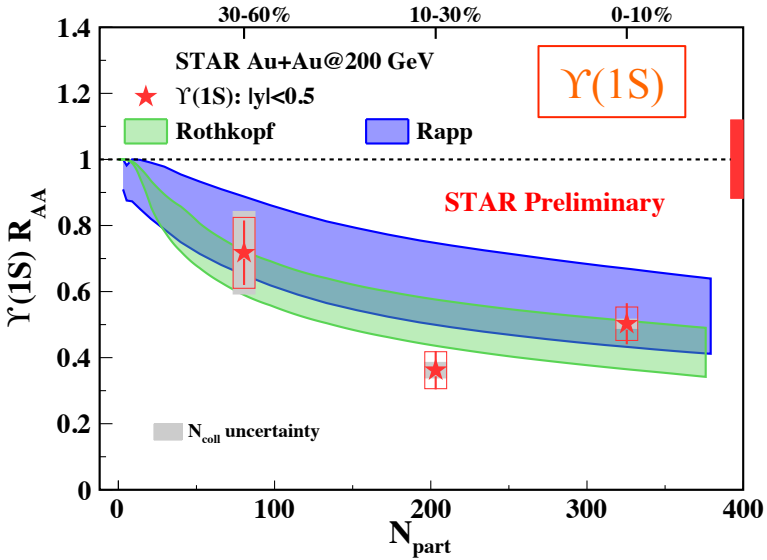
CMS: PLB 770 (2017) 357

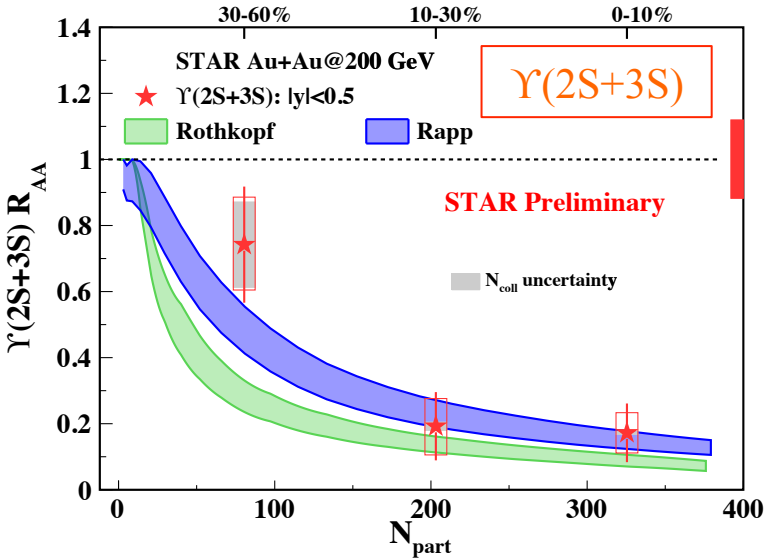




- Υ(1S) $R_{AA}^{0.2\text{TeV}} \sim R_{AA}^{2.76\text{TeV}}$: could be due to similar CNM (~20%) + strong suppression of excited states
- Υ(2S+3S) $R_{AA}^{0.2\text{TeV}} >\sim R_{AA}^{2.76\text{TeV}}$: hint of less melting at RHIC peripheral

Υ R_{AA}: STAR vs. Model





B. Krouppa, A. Rothkopf, M. Stickland, PRD 97 (2018) 016017
X. Du, M. He and R. Rapp, PRC 96 (2017) 054901

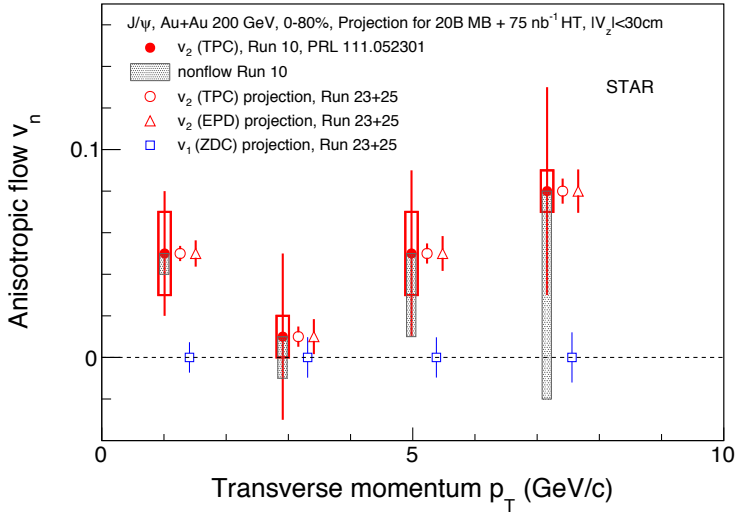
- Model ingredients
  - Rothkopf: Complex potential (lQCD); aHydro medium; No regeneration or CNM
  - Rapp: T-dependent binding energy; Kinetic rate equation; Include CNM and regeneration
- Model calculations can qualitatively describe Υ suppression at RHIC

Future Perspective

- **Better detector with enhanced statistics**
  - Low material budget, EPD, iTPC, forward upgrade
  - Complementary electron and muon channels

See D. Brandenburg, Sunday 8:30am CT

Year	System	Measurements
2017+2022	p+p @ 500 GeV	✓ J/ψ polarization ✓ J/ψ in jets ✓ J/ψ vs. event activity …
2024	p+p @ 200 GeV	
2024	p+Au @ 200 GeV	✓ J/ψ & Υ CNM …
2023+2025	Au+Au @ 200 GeV	✓ **low p_T J/ψ v_1 & v_2** ✓ $\psi(2S)$ suppression ✓ Υ suppression (sample full L) …



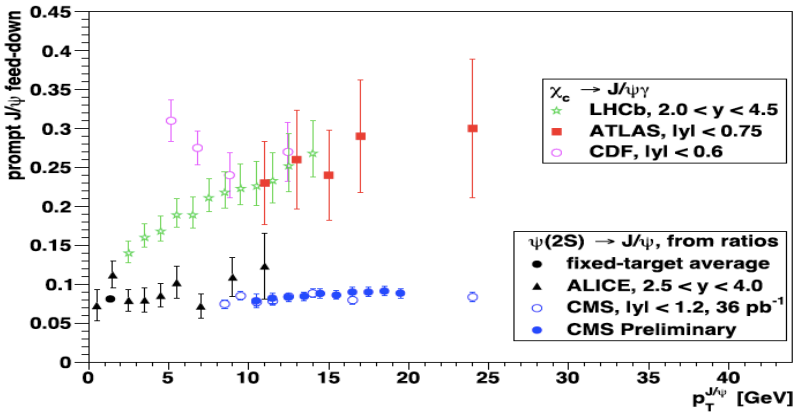
Summary

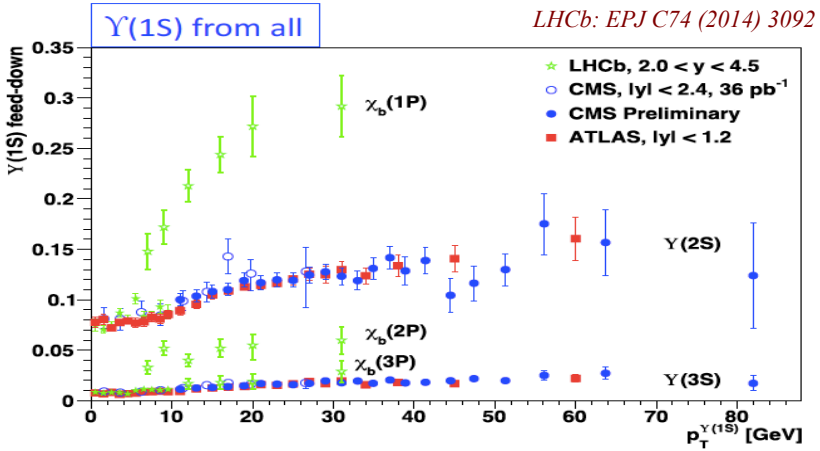
- J/ψ and Υ suppression in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR experiment
- High-p_T J/ψ strongly suppressed in central collisions
  → **dissociation**
- Ground and excited Υ states exhibit different suppression
  → **sequential suppression**
- Model calculations can qualitatively describe quarkonium suppression at RHIC
- ***Outlook***: comprehensive and high-precision measurements of quarkonium production in p+p, p+Au and Au+Au collisions through both dielectron and dimuon channels in 2022+

Backup

Feed-down Contribution

Woehri@Quarkonia'14

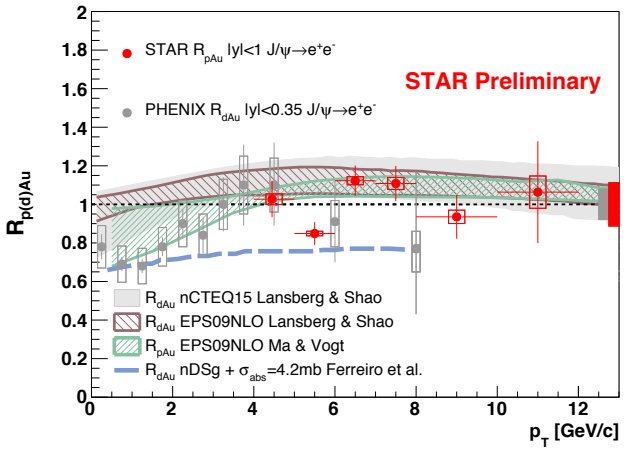


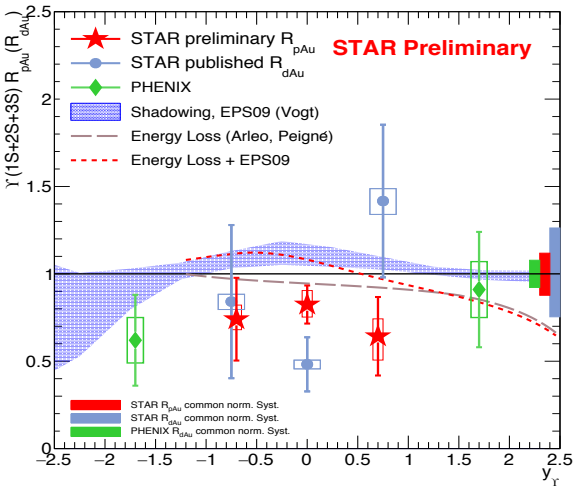


J/ψ feed-down	
χ_c	10-30% (vs. p_T)
ψ(2S)	~ 8%
B-hadron	0-50% (vs. p_T, $\sqrt{s}$)

Υ(1S) feed-down	
χ_b(1P)	10-30% (vs. p_T)
χ_b(2P+3P)	~5%+1-2%
Υ(2S+3S)	8-13%+1-2%

Cold Nuclear Matter Effects 200 GeV

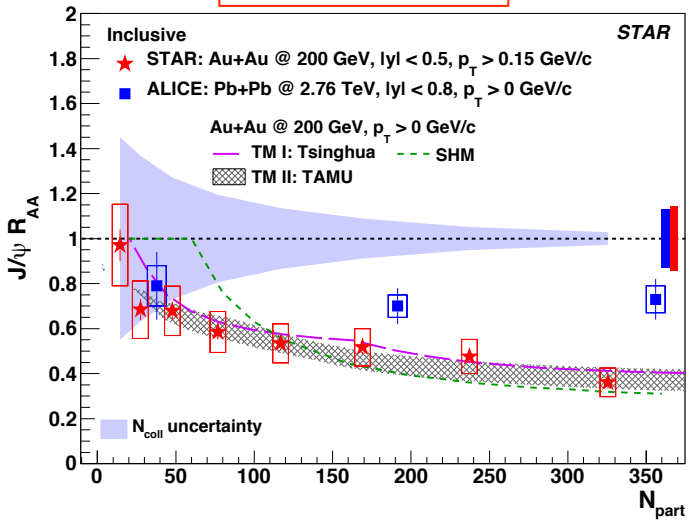




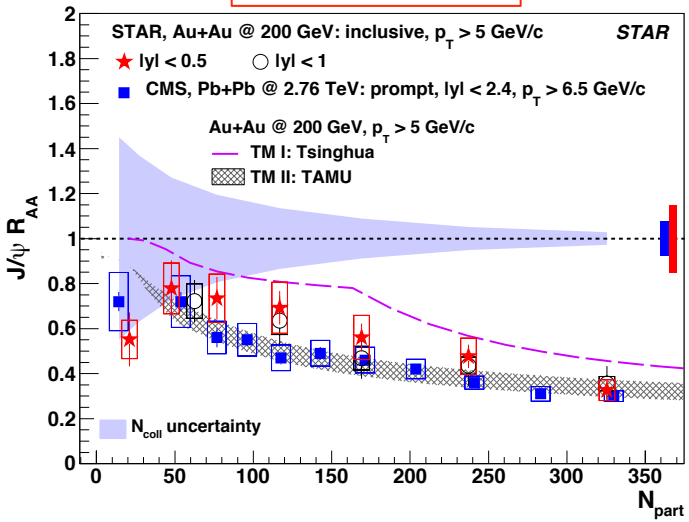
- $R_{pAu}^{J/\psi} \sim 0.65$ at 1 GeV/c and rises to 1 at high p_T
- $R_{pAu}^{\Upsilon} = 0.82 \pm 0.10(\text{stat}) + 0.08(\text{syst}) - 0.07(\text{syst}) \pm 0.10(\text{global})$

J/ψ R_{AA}: Data vs. Transport Model

$p_T > 0$ GeV/c



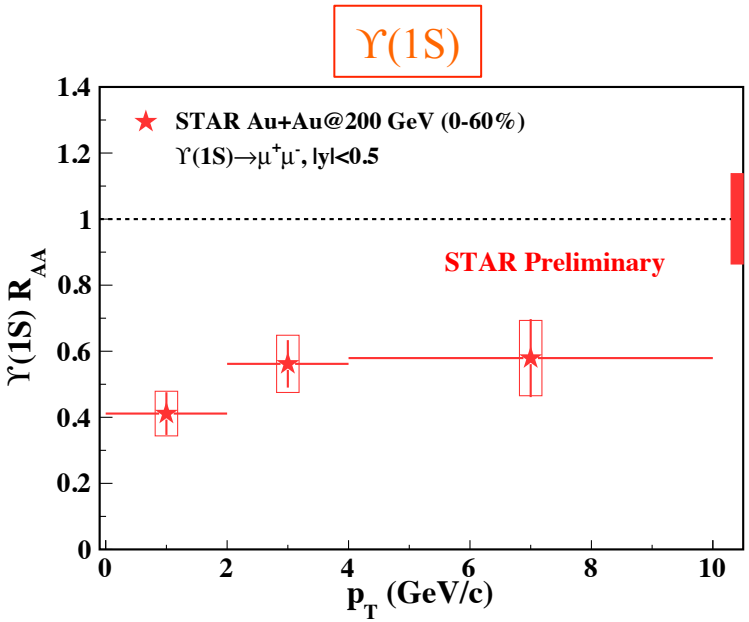
$p_T > 5$ GeV/c

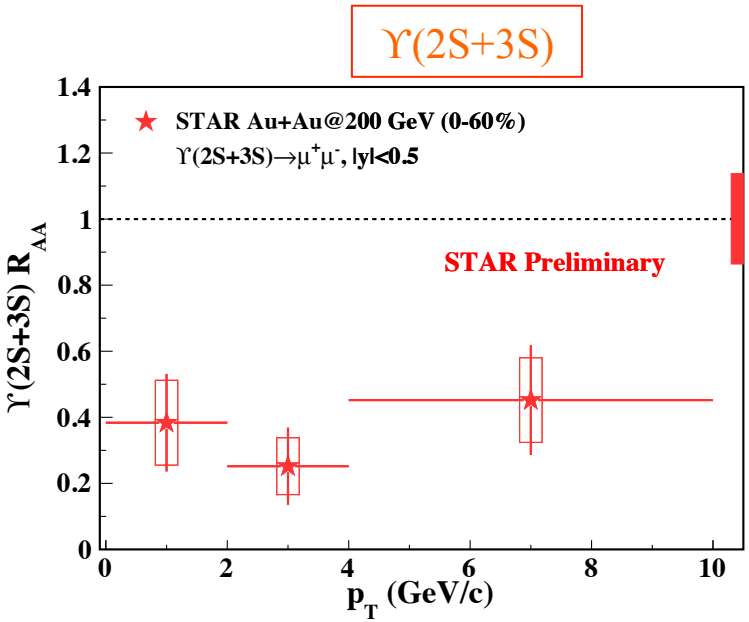


- $p_T > 0$ GeV/c: describe centrality dependence quite well
  - SHM: no CNM
- $p_T > 5$ GeV/c: Tsinghua model overshoots data while TMAU model is below data in semi-central collisions

L. Yan, et al, PRL 97 (2006) 232301
K. Zhou, et al, PRC 89 (2014) 054911
X. Zhao, et al, PRCC 82 (2010) 064905

Au+Au @ 200 GeV: Υ R_{AA} vs. p_T





- No significant p_T dependence
  - Similar to the *J/ψ* case
  - Possible explanation: CNM + correlated regeneration

Future Perspective

- **STAR detector configuration**
  - 2017+: Heavy Flavor Tracker removed → low material budget for electrons
  - 2018+: Event Plane Detector at forward-y → improve EP resolution; reduce non-flow
  - 2019+: iTPC upgrade → improved resolution; increased efficiency; extended acceptance
  - 2022+: forward tracking + calorimetry → event activity