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Measurements of charmonium production in heavy-ion collisions by STAR

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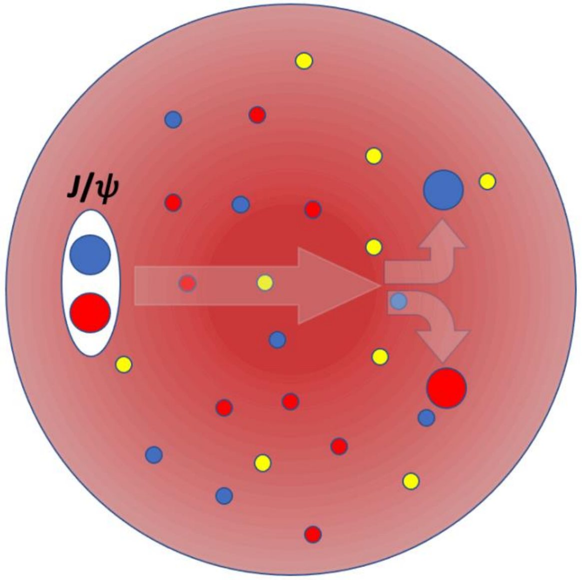
(for the STAR Collaboration)

Introduction

- Quarkonia suppression was proposed as a sensitive probe to QGP properties
  - Dominantly produced before QGP formation
- Hot medium effects
  - Dissociation(color screening and dynamic interaction)
  - Regeneration
- Cold nuclear matter effects
  - nPDF
  - Nuclear absorption
- Other effects
  - Comover interactions
  - Feed-down contribution

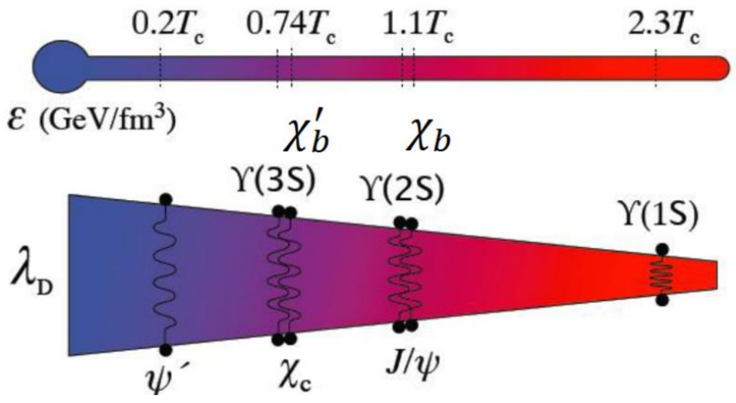


Credit: Q. Yang

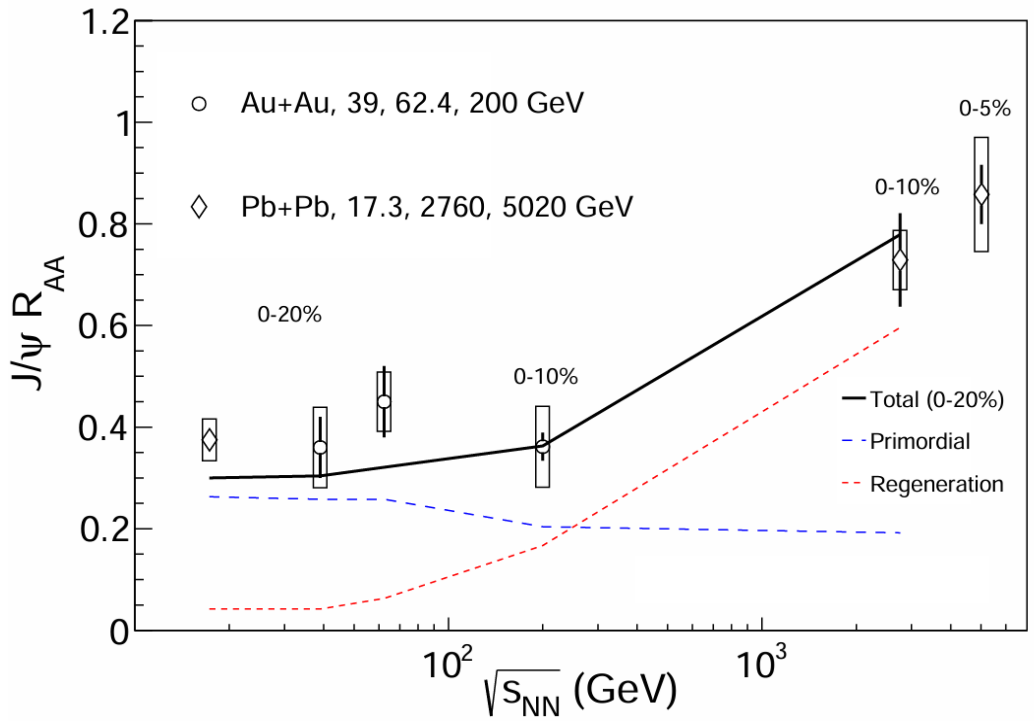
$$R_{AA} = \frac{\sigma_{\text{inel}}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dydp_T}{d^2 \sigma_{pp}/dydp_T}$$

Disentangle Different Effects

- Systematically analyze
  - Collision energy dependence
  - p_T and centrality dependence
  - Binding energy dependence



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



X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
L. Kluberg, Eur. Phys. J. C 43 (2005) 145.
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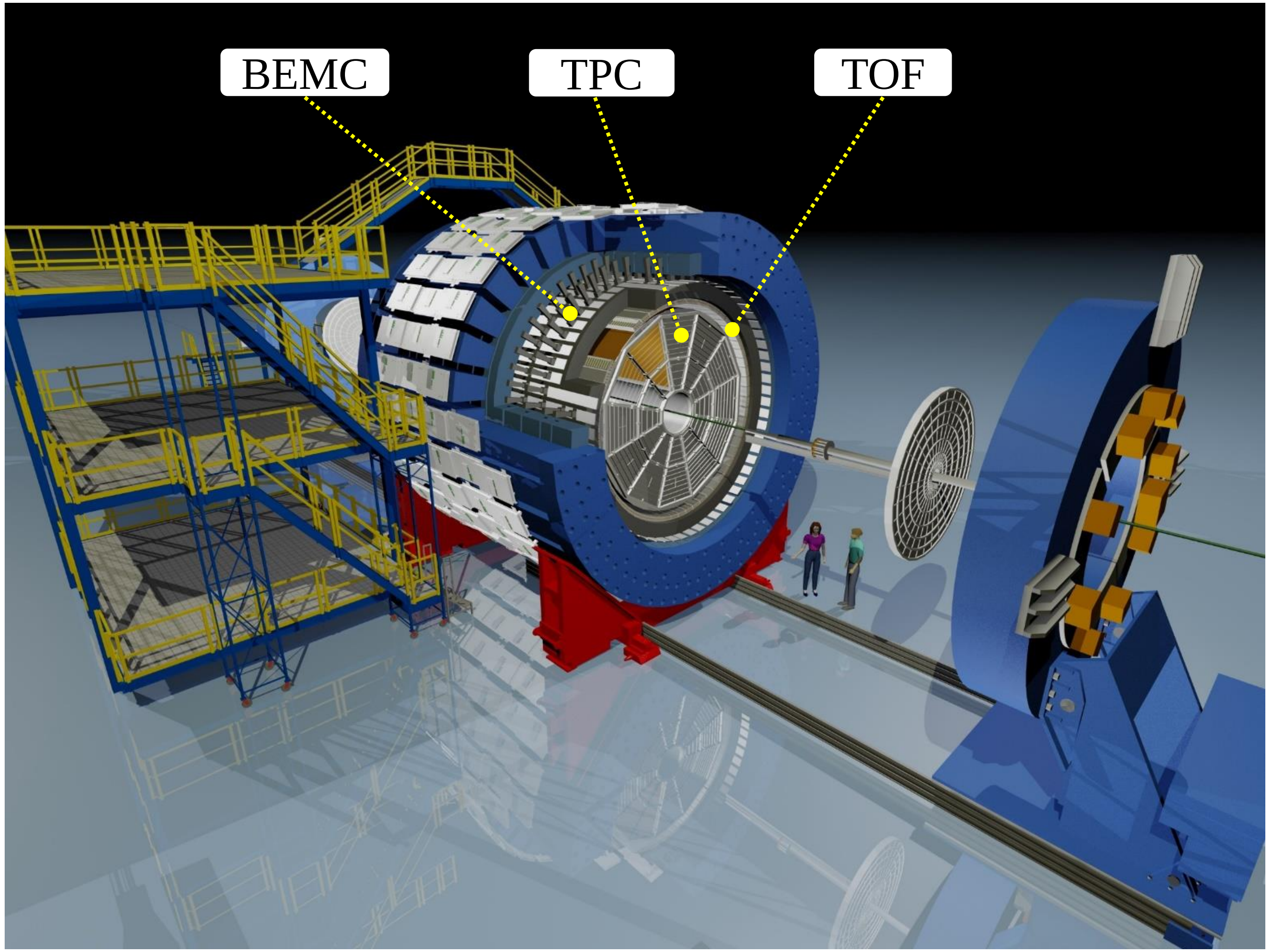
ALICE Collaboration, Phys. Lett. B 734 (2014) 314
STAR Collaboration, Phys. Lett. B 771 (2017) 13-20
STAR Collaboration, Phys. Lett. B 797 (2019) 134917
ALICE Collaboration, Nucl. Phys. A 1005 (2021) 121769

STAR Detector

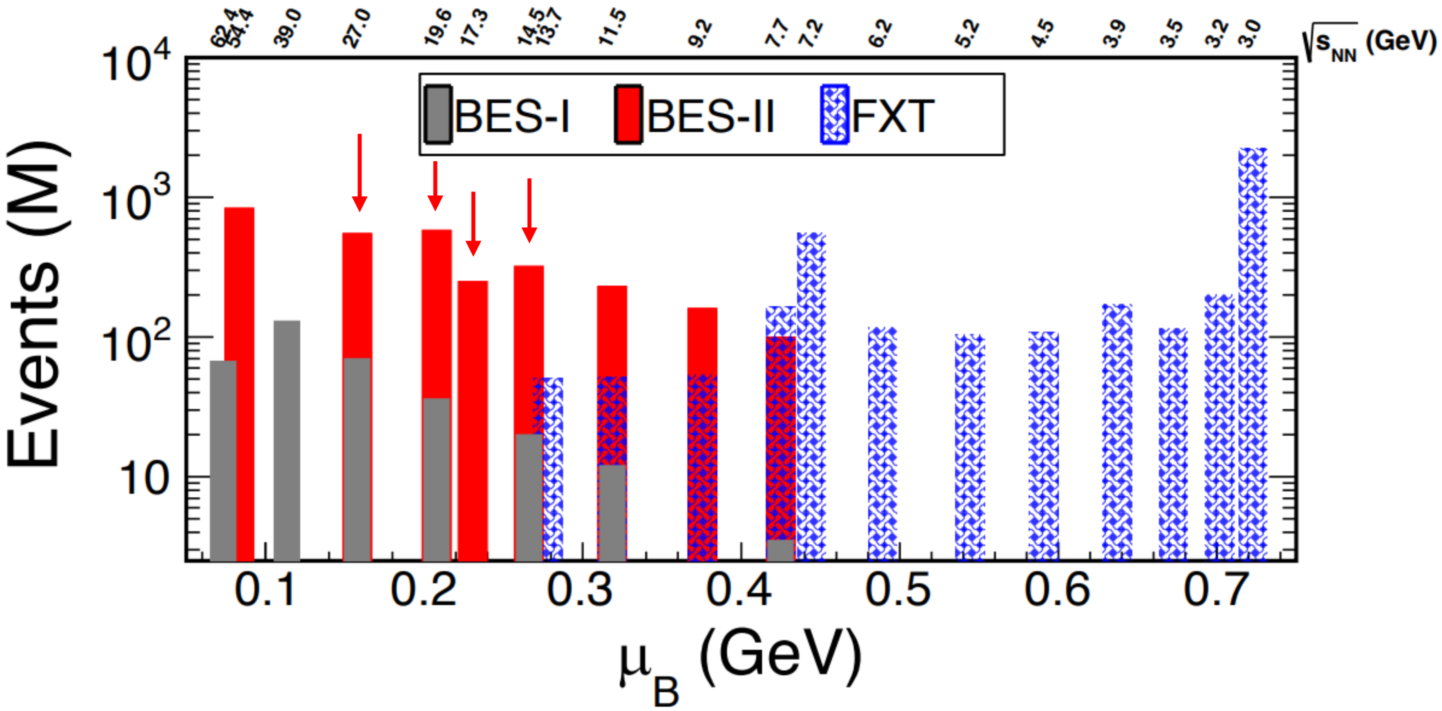


- **Time Projection Chamber**
  - Tracking
  - Momentum and energy loss
  - Acceptance: $|\eta| < 1.5; 0 \leq \varphi < 2\pi$

- **Time Of Flight Detector**
  - Time of flight
  - Particle identification
  - Acceptance: $|\eta| < 1; 0 \leq \varphi < 2\pi$

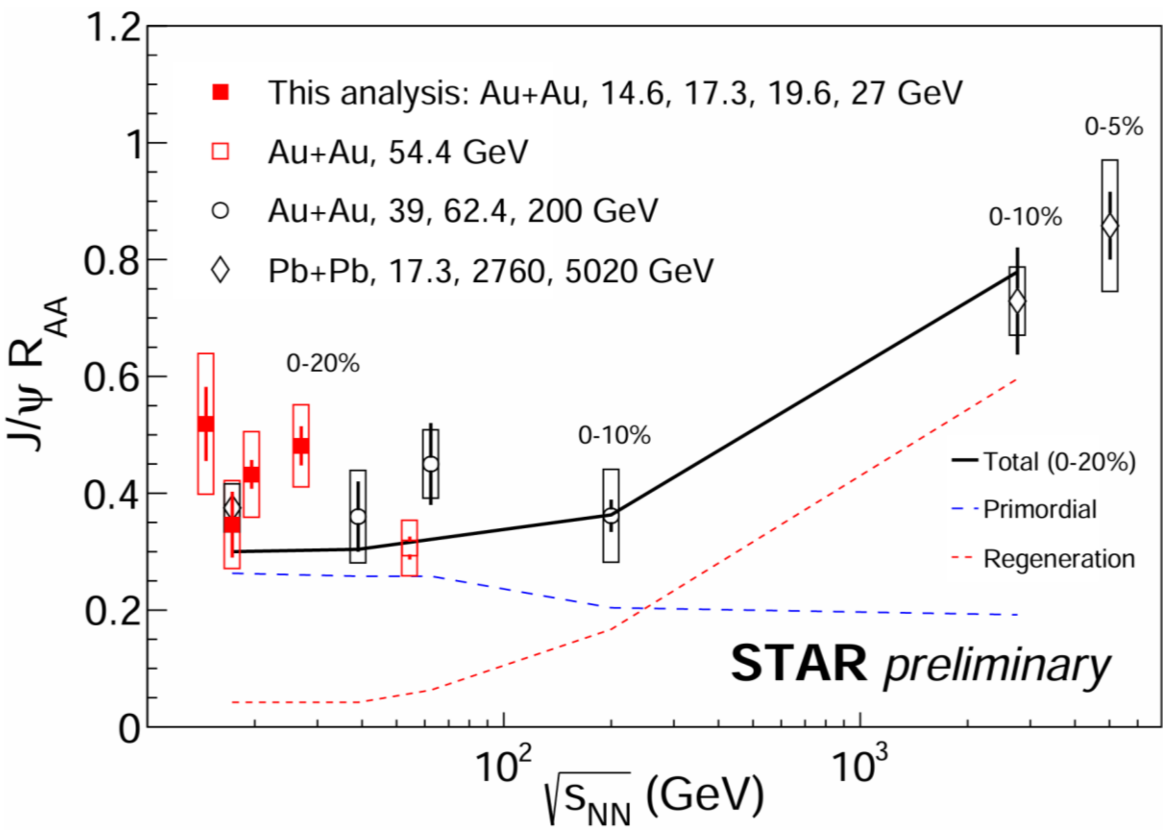
- **Barrel ElectroMagnetic Calorimeter**
  - $e^{\pm}$ trigger
  - Particle identification with deposited energy
  - Acceptance: $|\eta| < 1; 0 \leq \varphi < 2\pi$

Collision Energy Dependence: BES-I → BES-II



- BES-I → BES-II
  - 10-20 times higher statistics than BES-I
  - Enables differential measurements at low collision energies

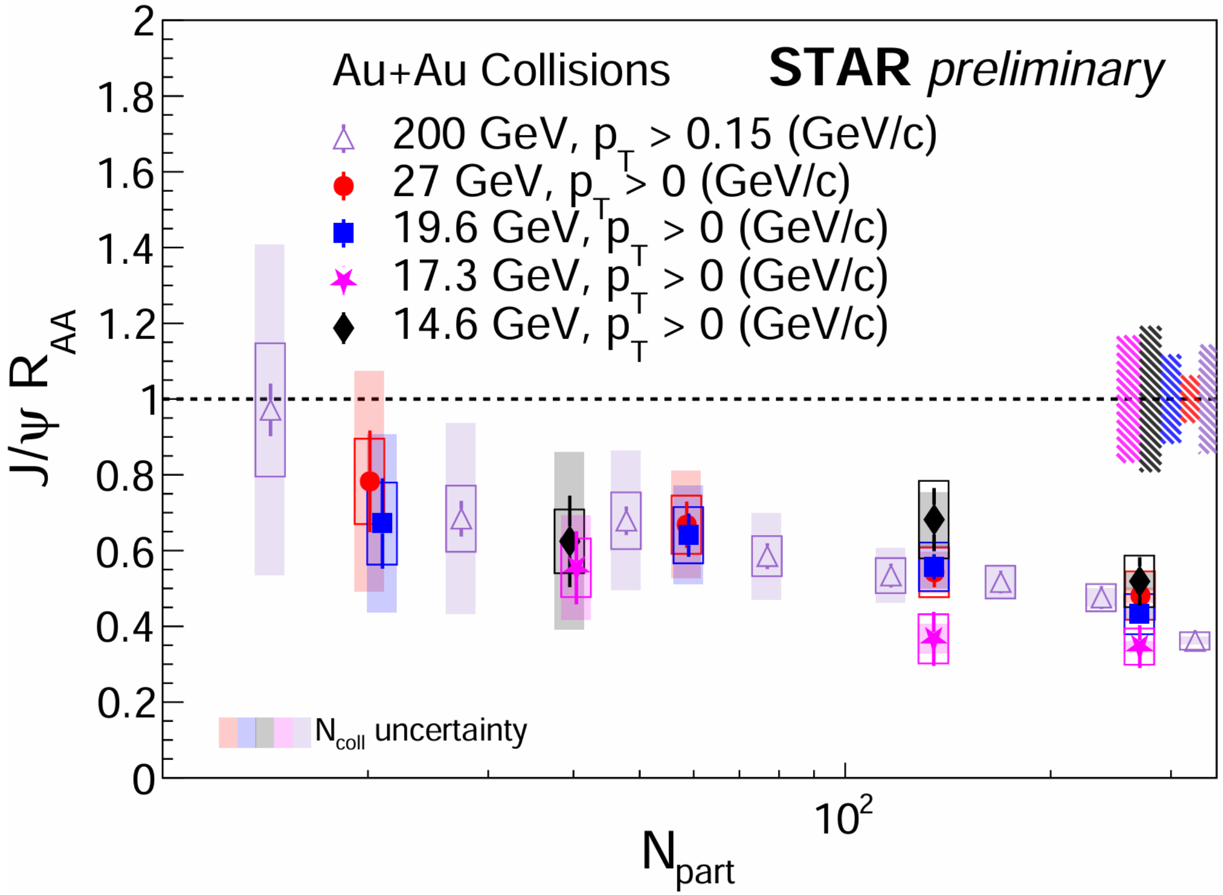
Energy Dependence of Inclusive J/ψ R_{AA}



X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
L. Kluberg, Eur. Phys. J. C 43 (2005) 145.

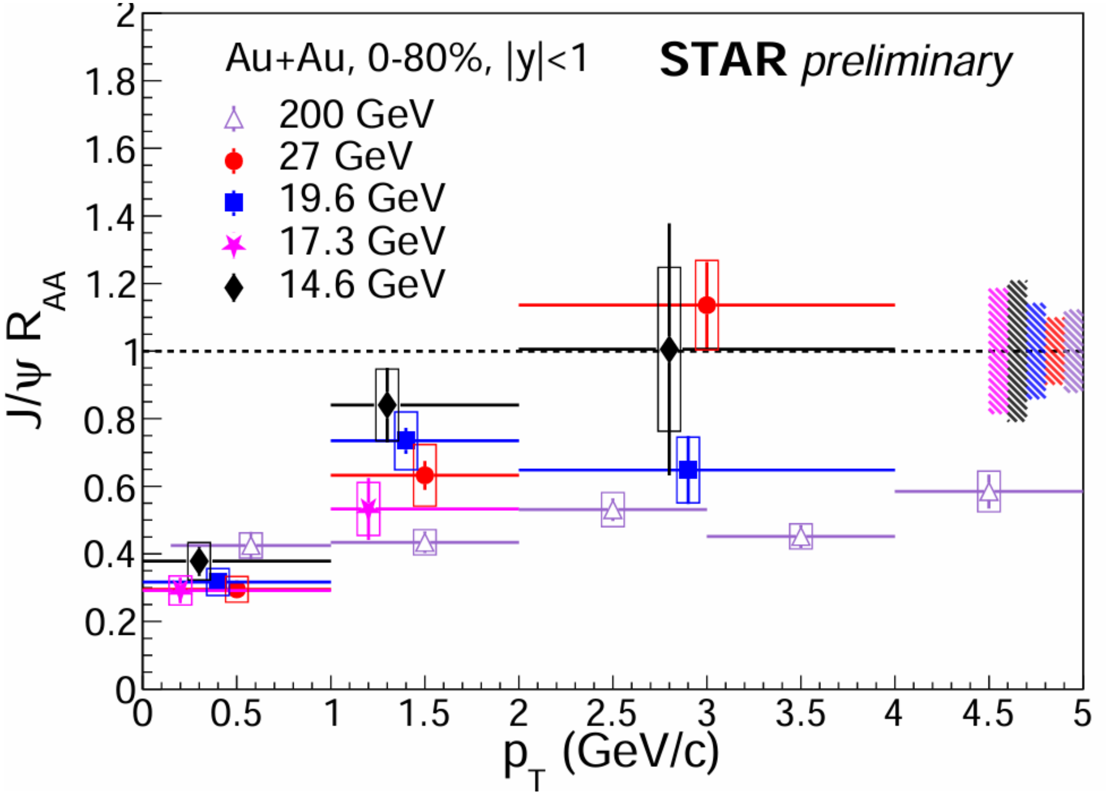
- J/ψ R_{AA} at $\sqrt{s_{NN}}$ = 14.6, 17.3, 19.6 and 27 GeV follow global trend
- No significant energy dependence of J/ψ R_{AA} in central collisions is observed within uncertainties up to 200 GeV
- The observed energy dependence is qualitatively described by the transport model

Centrality Dependence of Inclusive J/ψ R_{AA}



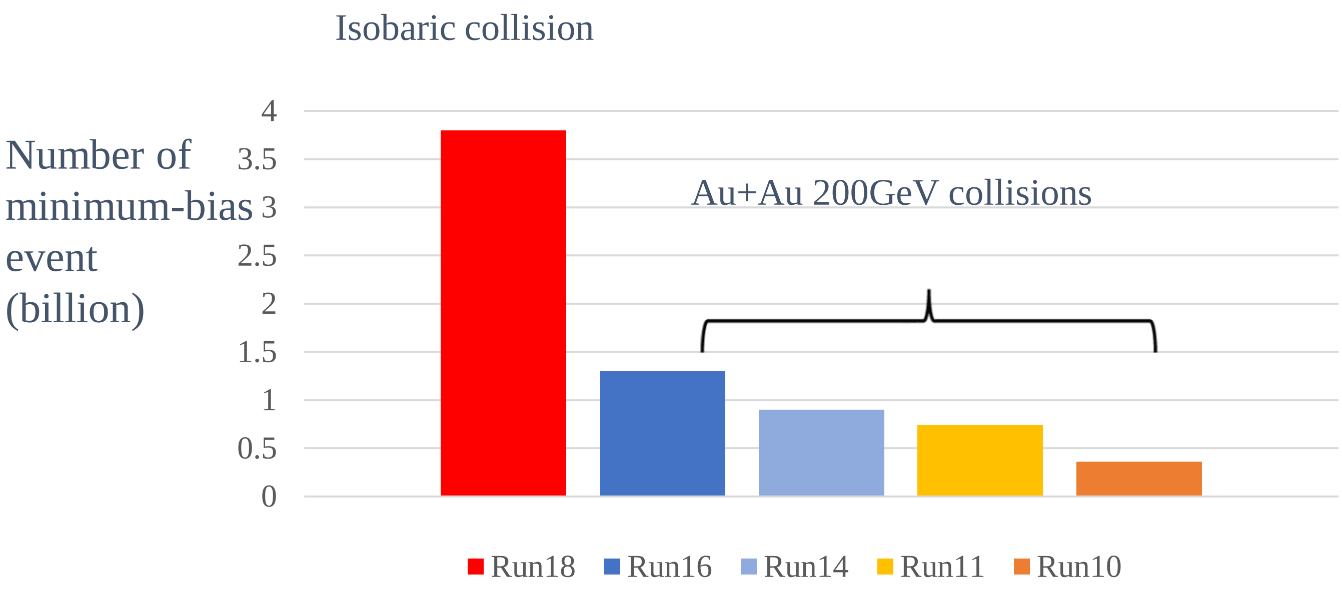
- ➢ Hint of decreasing trend as a function of centrality
- ➢ R_{AA} shows no significant energy dependence at RHIC for similar <N_{part}>

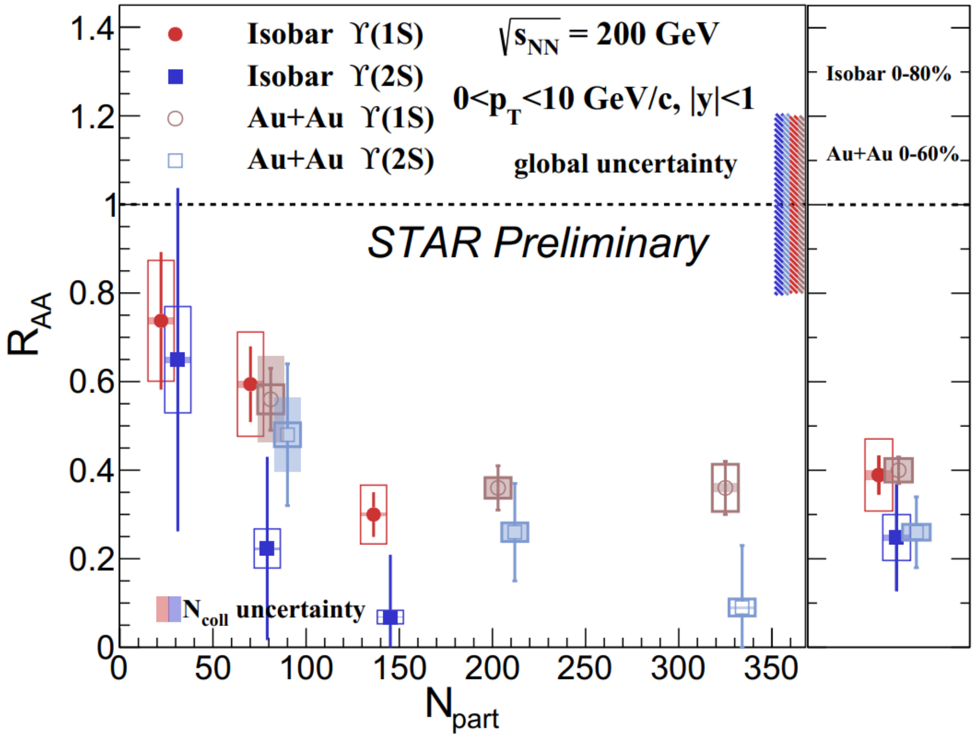
p_T Dependence of Inclusive J/ψ R_{AA}



- R_{AA} increases with p_T for $\sqrt{s_{NN}}$ = 14.6, 17.3, 19.6 and 27 GeV
- No significant p_T dependence at 200 GeV

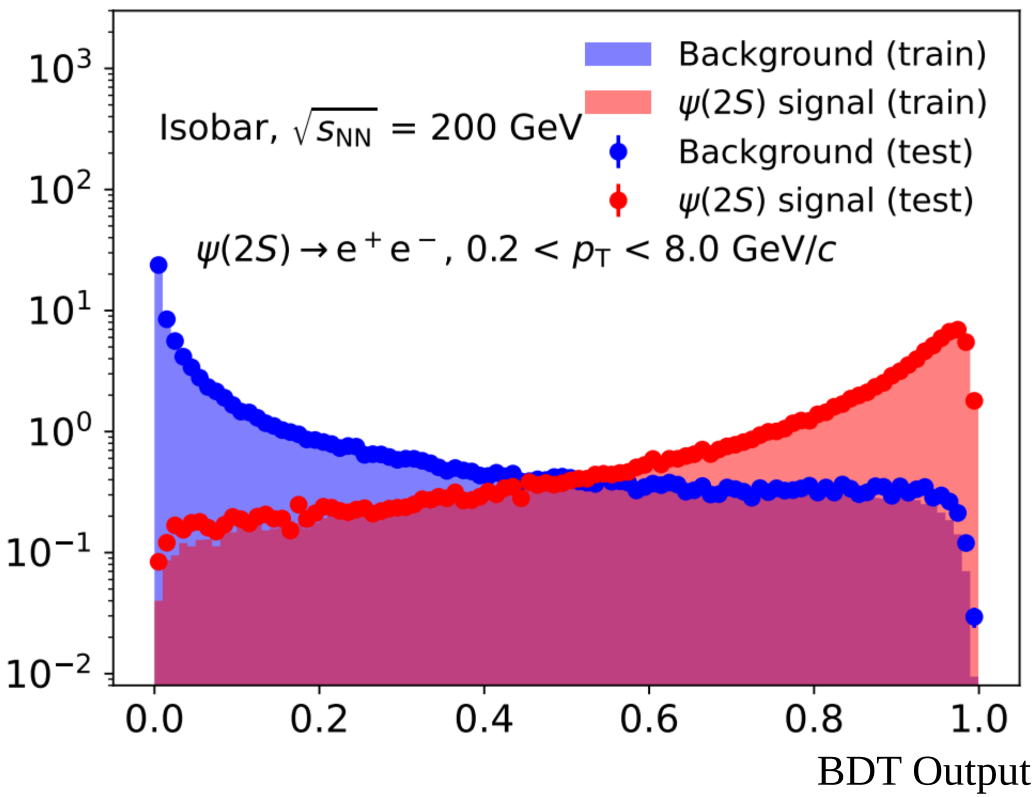
Binding Energy Dependence in Isobar Collisions

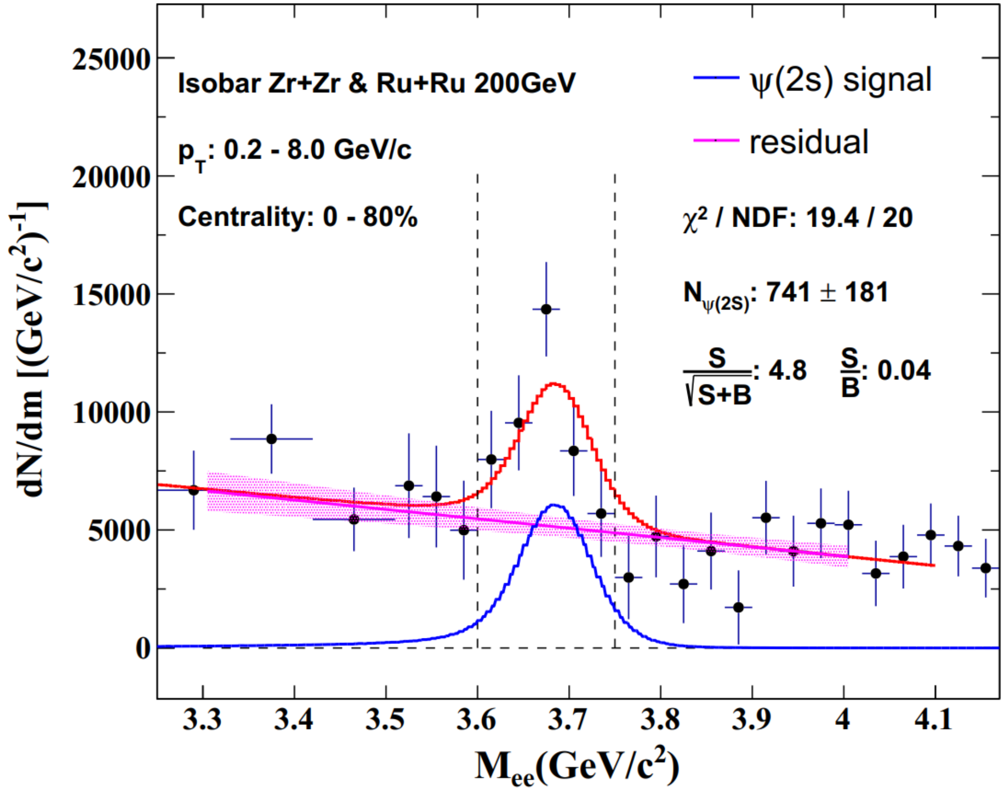




- High statistics enables measurements of:
  - Sequential suppression of J/ψ, ψ(2S), ϒ (1S), ϒ(2S)
- Hint of sequential suppression for ϒ(1S) and ϒ(2S) in Isobar and Au+Au collisions

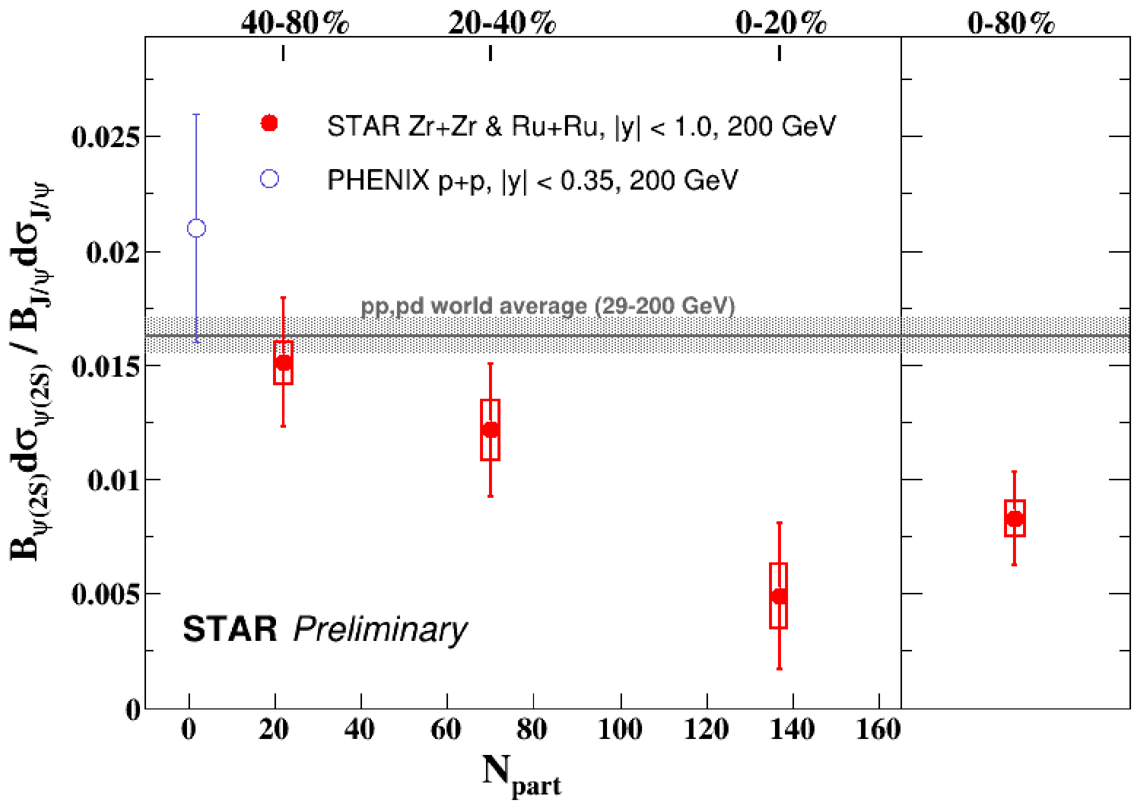
ψ(2S) Signal in Zr+Zr & Ru+Ru Collisions





- A machine learning method is employed to reconstruct the ψ(2S) signal
- First observation of ψ(2S) in heavy-ion collisions at RHIC

ψ(2S) to J/ψ Ratio in Zr+Zr & Ru+Ru Collisions



pp reference is the average of measurements in p+p(d) by NA51, ISR and PHENIX

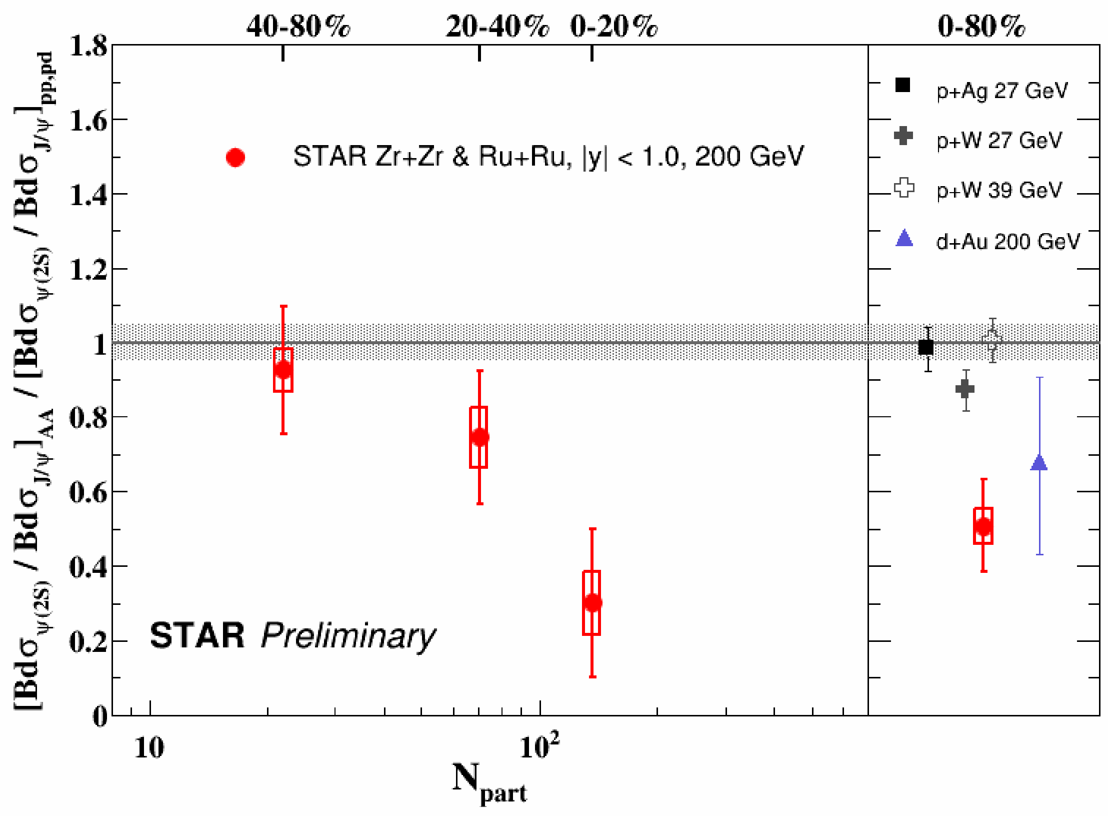
PHENIX, Phys.Rev.D, 85,092004 (2012)
NA51, Phys.Lett.B 438 (1998) 35-40
ISR, Nucl.Phys.B 142 (1978) 29

- First observation of charmonium sequential suppression in heavy-ion collisions at RHIC (3.5σ, 0-80%)

Double Ratio

Double Ratio:

$$\frac{[(Bd\sigma_{\psi(2s)})/(Bd\sigma_{J/\psi})]_{AA}}{[(Bd\sigma_{\psi(2s)})/(Bd\sigma_{J/\psi})]_{pp,pd}}$$



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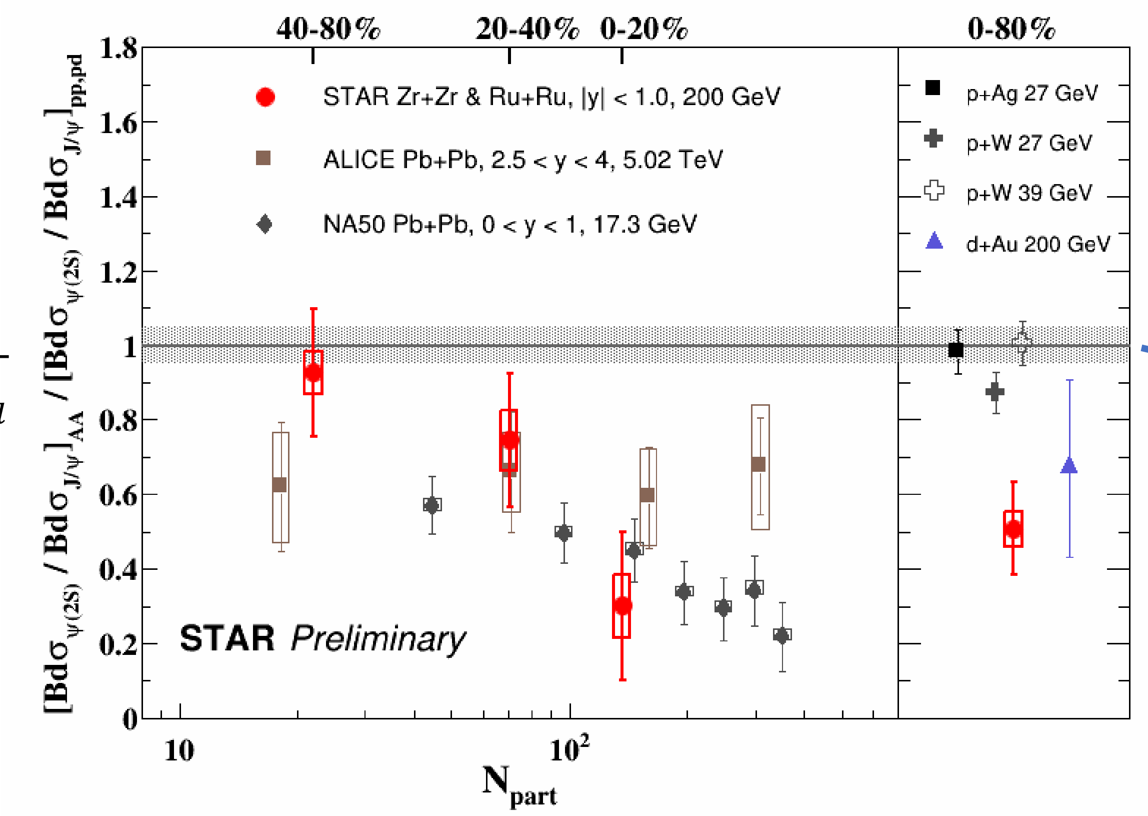
- ψ(2S) over J/ψ double ratio is smaller than that in p+A collisions
- Hint of ratio decreasing towards central collisions

Double Ratio

Double Ratio:

$$\frac{[(\mathrm{Bd}\sigma_{\psi(2s)})/(\mathrm{Bd}\sigma_{\mathrm{J}/\psi})]_{AA}}{[(\mathrm{Bd}\sigma_{\psi(2s)})/(\mathrm{Bd}\sigma_{\mathrm{J}/\psi})]_{pp,pd}}$$



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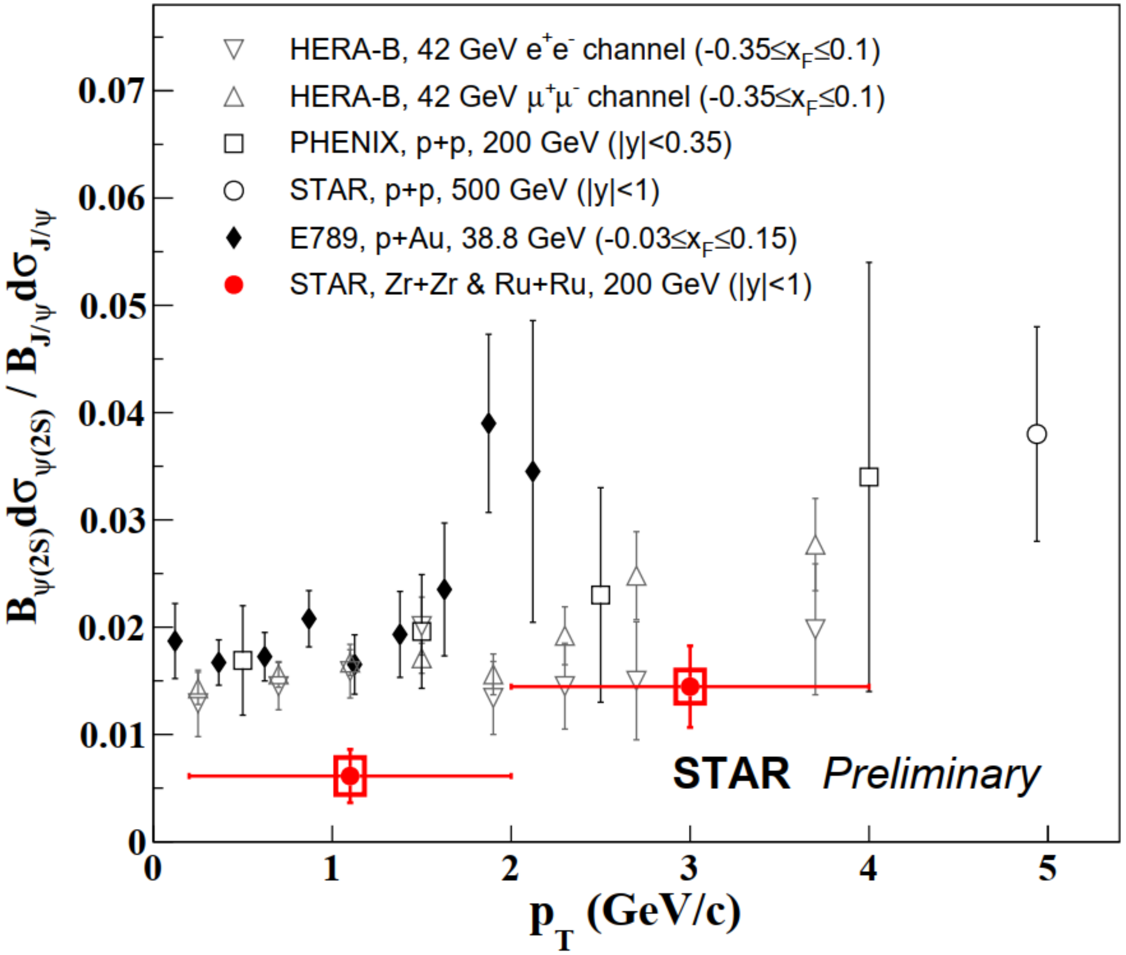
PHENIX, Phys.Rev.D, 85,092004 (2012)
NA51, Phys.Lett.B 438 (1998) 35-40
ISR, Nucl.Phys.B 142 (1978) 29

- Centrality dependence trend seems to be more similar to that at SPS than at LHC

$\psi(2S)$ to J/ψ Ratio vs p_T



- $\psi(2S)$ to J/ψ ratio increases with p_T in isobaric collisions
- Significantly lower than that in p+p and p+A collisions at $p_T < 2$ GeV/c

STAR, Phys.Rev.D 100 (2019)
PHENIX, Phys.Rev.D, 85,092004 (2012)
HERA-B, Eur.Phys.J.C 49 (2007)
E789, Phys.Rev.D 52 (1995) 1307, 1995.

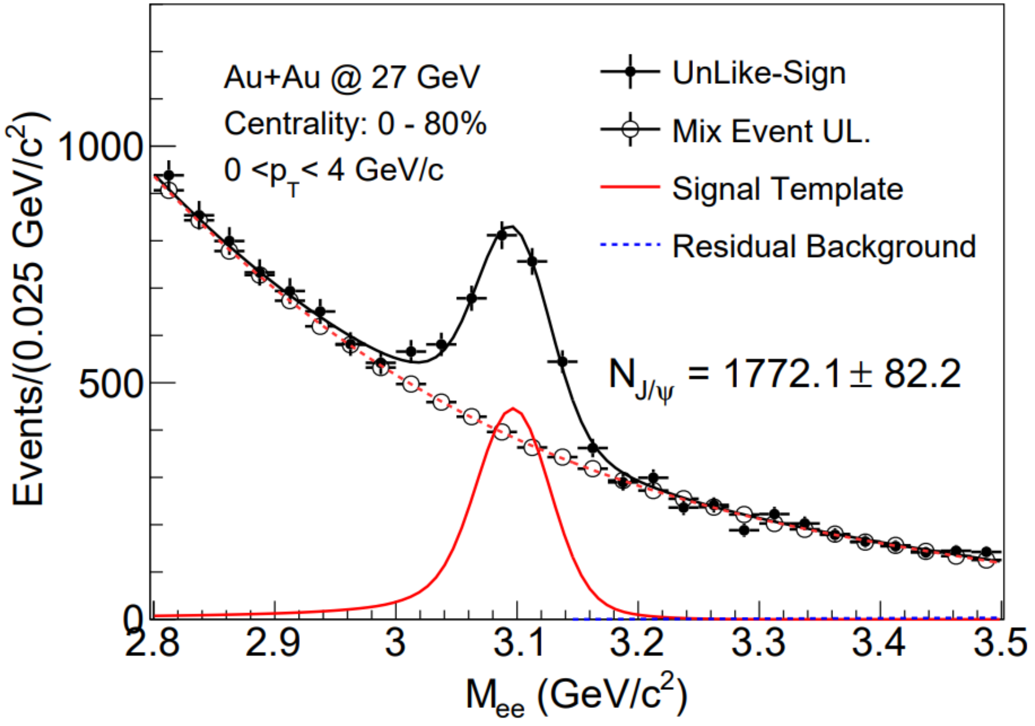
Summary

- Significant suppression of charmonium in central heavy-ion collisions at RHIC
- No significant collision energy dependence of J/ψ R_{AA} at RHIC
- Hint of decreasing with centrality and increasing with p_T for J/ψ R_{AA} at low energies
- First observation of charmonium sequential suppression at RHIC
- Interplay of dissociation, regeneration and cold nuclear matter effects
- Can be used to constrain QGP properties

Back up

Raw J/ψ Signal

$$R_{AA} = \frac{\sigma_{\text{inel}}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

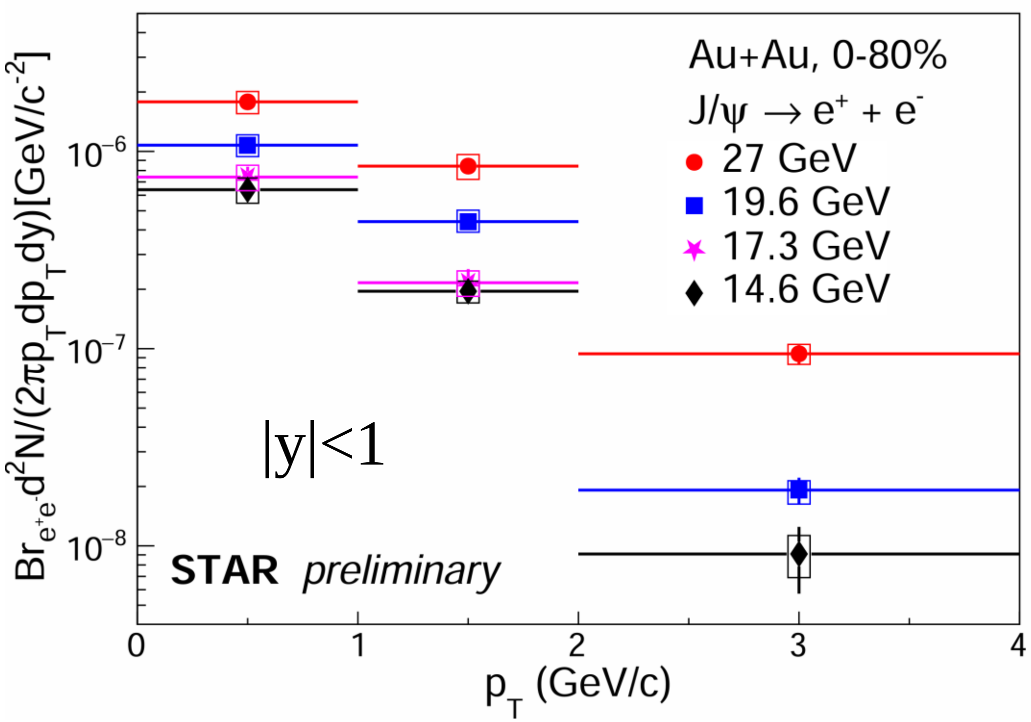


$\sqrt{s_{NN}} = 27$ GeV

- The function used to fit UL-Sign (UL) consists of
  - J/ψ template
  - combinatorial background
  - residual background
- Extracted combinatorial background shape from mixed-event UL-Sign.
- Residual background parameterized using a first-order polynomial.

Inclusive J/ψ Invariant Yields

$$R_{AA} = \frac{\sigma_{\text{inel}}}{\langle N_{coll}\rangle} \frac{d^2N_{AA}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$



Inclusive J/ψ invariant yields as a function of p_T at mid-rapidity (|y| < 1) in Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6, 17.3, 19.6, 27 GeV.

Systematic Uncertainty

➢ Systematic uncertainty from J/ψ yield measurements

Source：

Track quality cuts

- nHitsFit
- nHitsDedx
- Dca (cm)

Signal extraction

- J/ψ templates
- Fitting range
- Residual background function form
- Combinatorial background function form
- Bin Width

Electron identification cuts

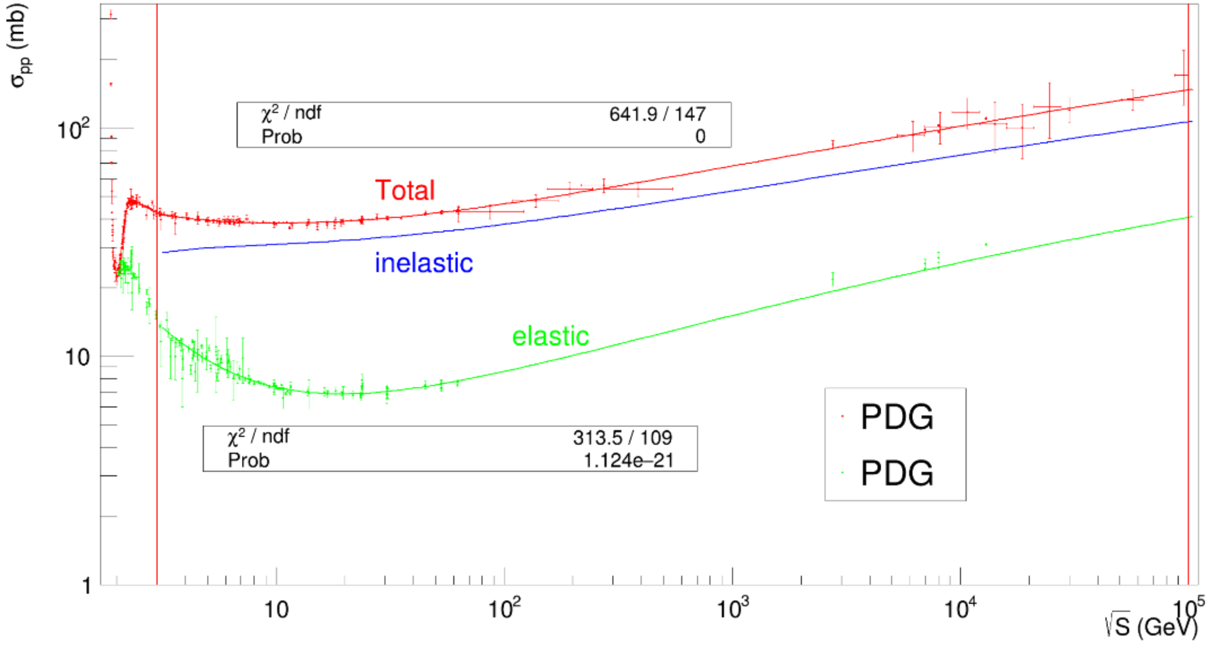
- $n\sigma_e$ efficiency
- $1/\beta$ efficiency
- TOF Matching efficiency

Analyzed bin	27 GeV	19.6 GeV	14.6 GeV	17.3GeV
0-80%	12.4 %	11.2 %	13.2 %	12.8 %
0-20%	13.2 %	12.3 %	13.1 %	13.8 %
20-40%	12.1 %	11.5 %	15.0 %	17.7 %
40-60%	11.5 %	11.6 %	13.5 %	13.9%
60-80%	14.4 %	16.1 %		
0-1GeV/c	12.8 %	12.5 %	14.6 %	14.7 %
1-2GeV/c	14.4 %	11.6 %	12.7 %	14.7 %
2-4GeV/c	11.6 %	15.0 %	24.1 %	-

PP Inelastic Cross Section

$$R_{AA} = \frac{\boxed{\sigma_{\text{inel}}}}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

$$\sigma_{\text{inelastic}} = \sigma_{\text{total}} - \sigma_{\text{elastic}}$$



$\sqrt{S_{NN}}$ (GeV)	$\sigma_{\text{inelastic}}$ (mb)	Error
200	43.3960	0.766915
27	32.9876	0.163660
19.6	32.0776	0.137064
17.3	31.7791	0.131443
14.6	31.4194	0.125273
11.5	30.9905	0.124518
9.2	30.6478	0.130914

Data from PDG（Particle Data Group）：
https://pdg.lbl.gov/2022/hadronic-xsections/