



华南师范大学
SOUTH CHINA NORMAL UNIVERSITY



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Measurements of charmonium production in heavy-ion collisions by STAR

Wei Zhang (South China Normal University)
(for the STAR Collaboration)



Introduction



➤ Quarkonia suppression was proposed as a sensitive probe to QGP properties

- Produced before QGP formation

➤ **Hot medium effects**

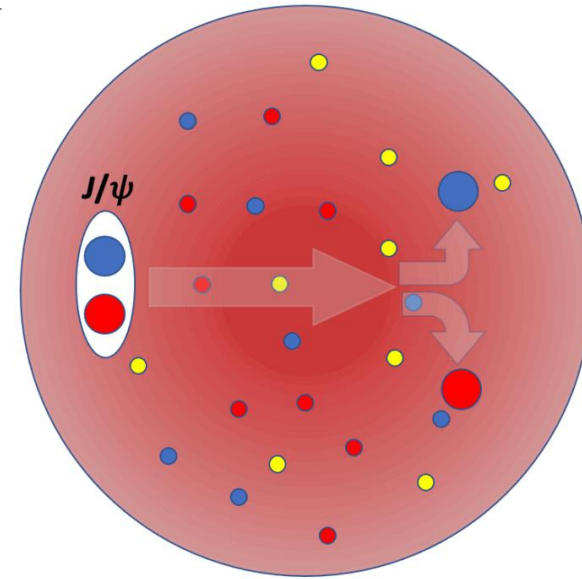
- Dissociation(color screening and dynamic interaction)
- Regeneration

➤ **Cold nuclear matter effects**

- nPDF
- Nuclear absorption

➤ **Other effects**

- Comover interactions
- Feed-down contribution

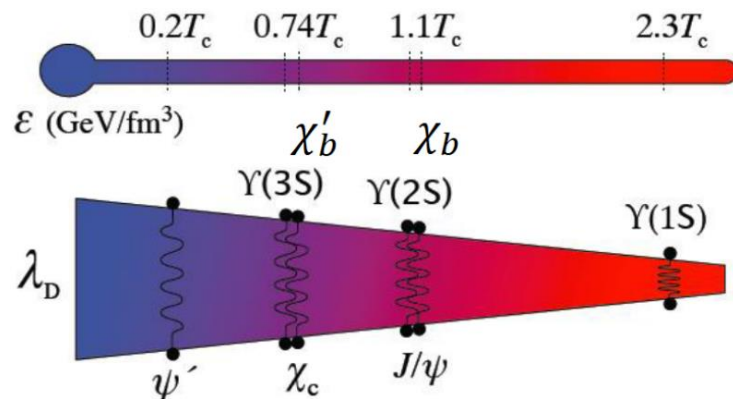


Credit: Q. Yang

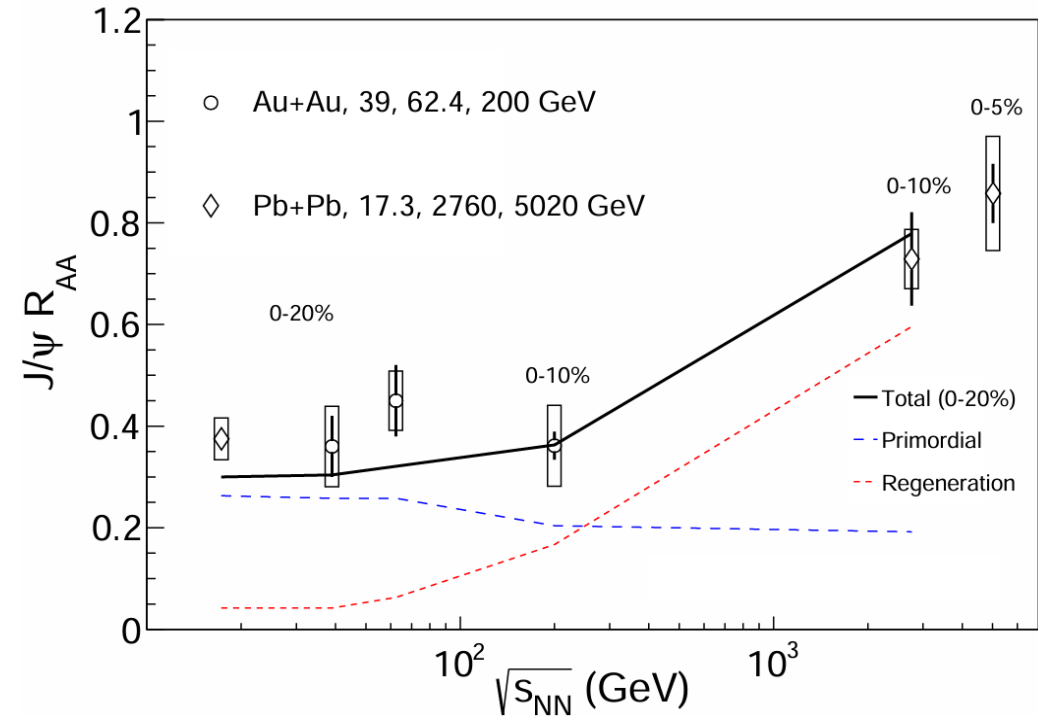
$$R_{AA} = \frac{\sigma_{\text{inel}}}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{AA} / dy dp_T}{d^2 \sigma_{pp} / dy dp_T}$$

Disentangle Different Effects

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

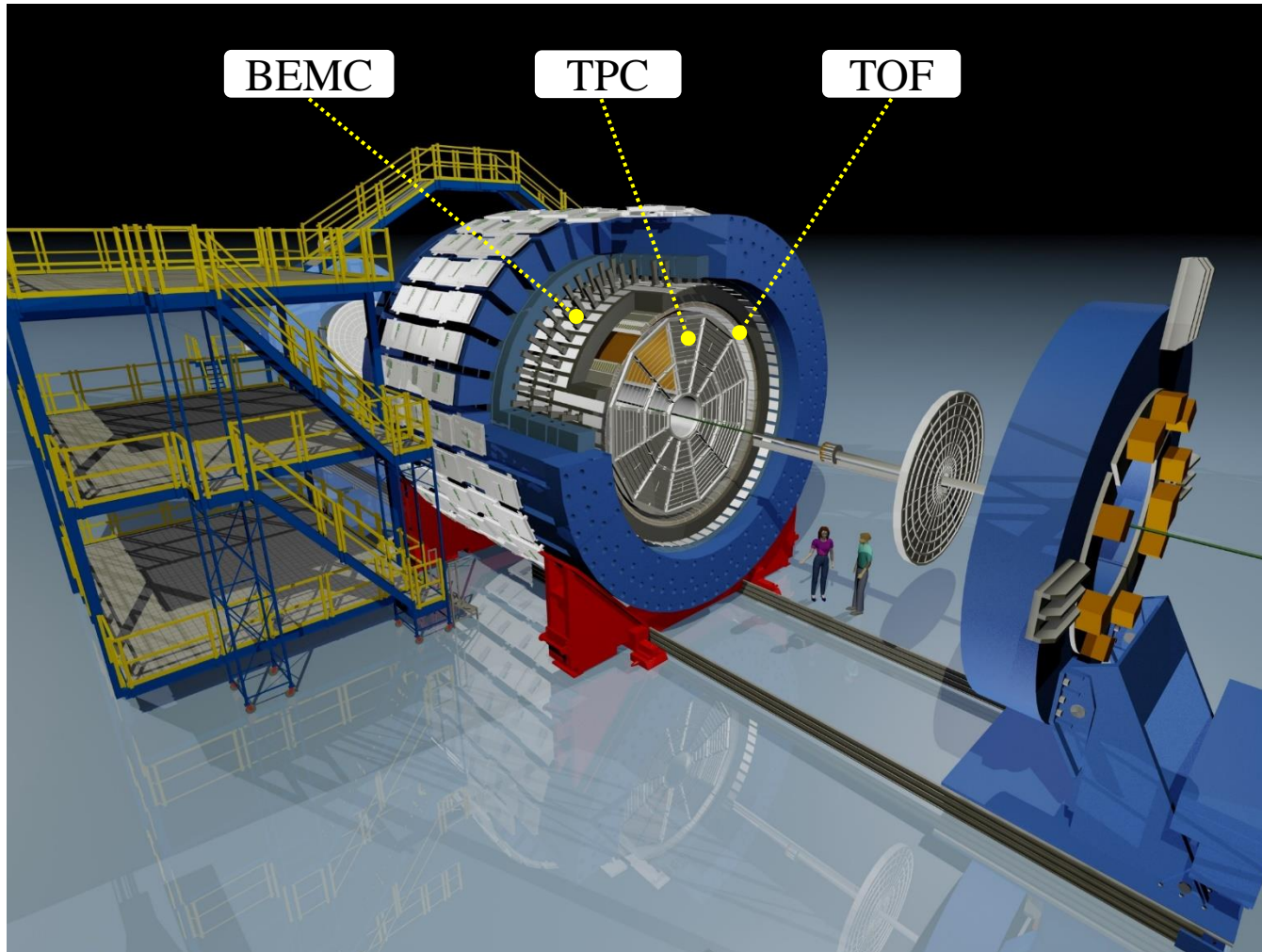


S. Diagl, P. Petreczky and H. Satz, PLB514, 57 (2001)



X. Zhao, R. Rapp, *Phys. Rev. C* 82 (2010) 064905 (private communication).
 L. Kluberg, *Eur. Phys. J. C* 43 (2005) 145.
 NA50 Collaboration, *Phys. Lett. B* 477 (2000) 28.
 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: $|\eta| < 1.5$; $0 \leq \varphi < 2\pi$

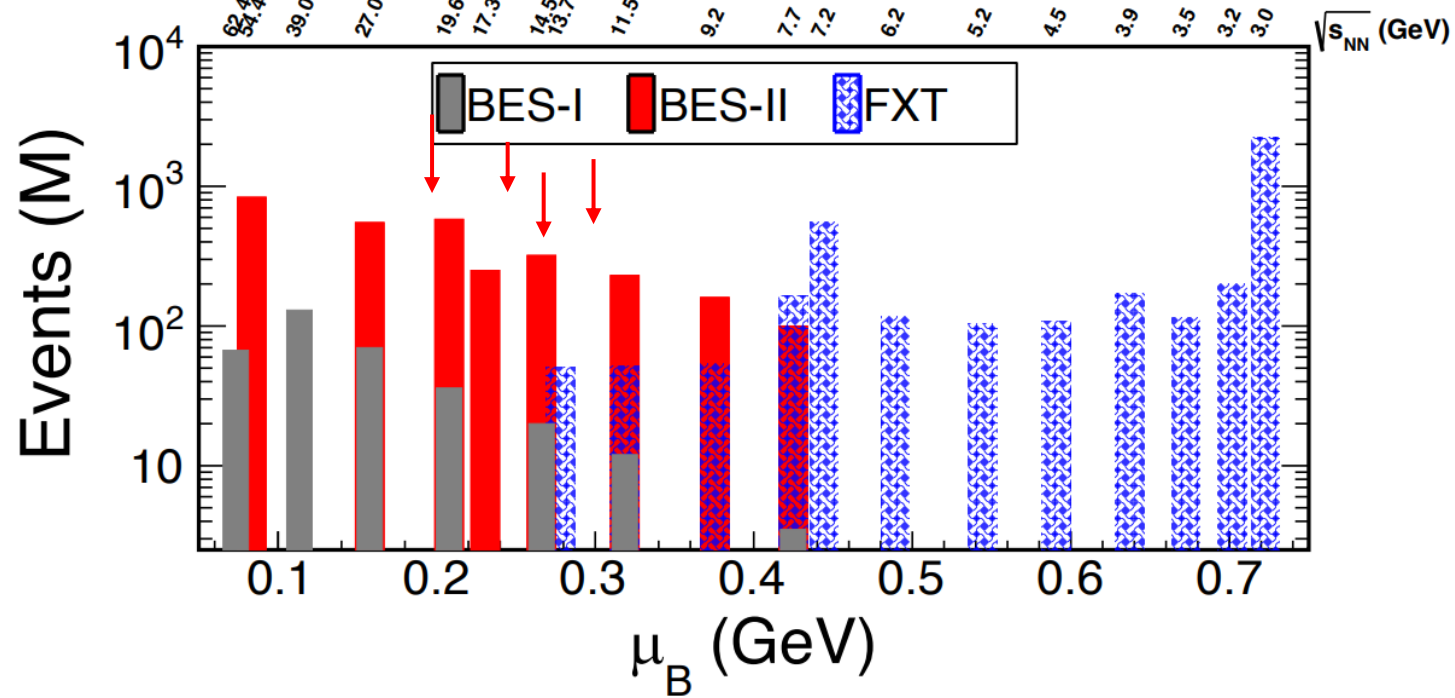
➤ Time Of Flight Detector

- 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: $|\eta| < 1$; $0 \leq \varphi < 2\pi$

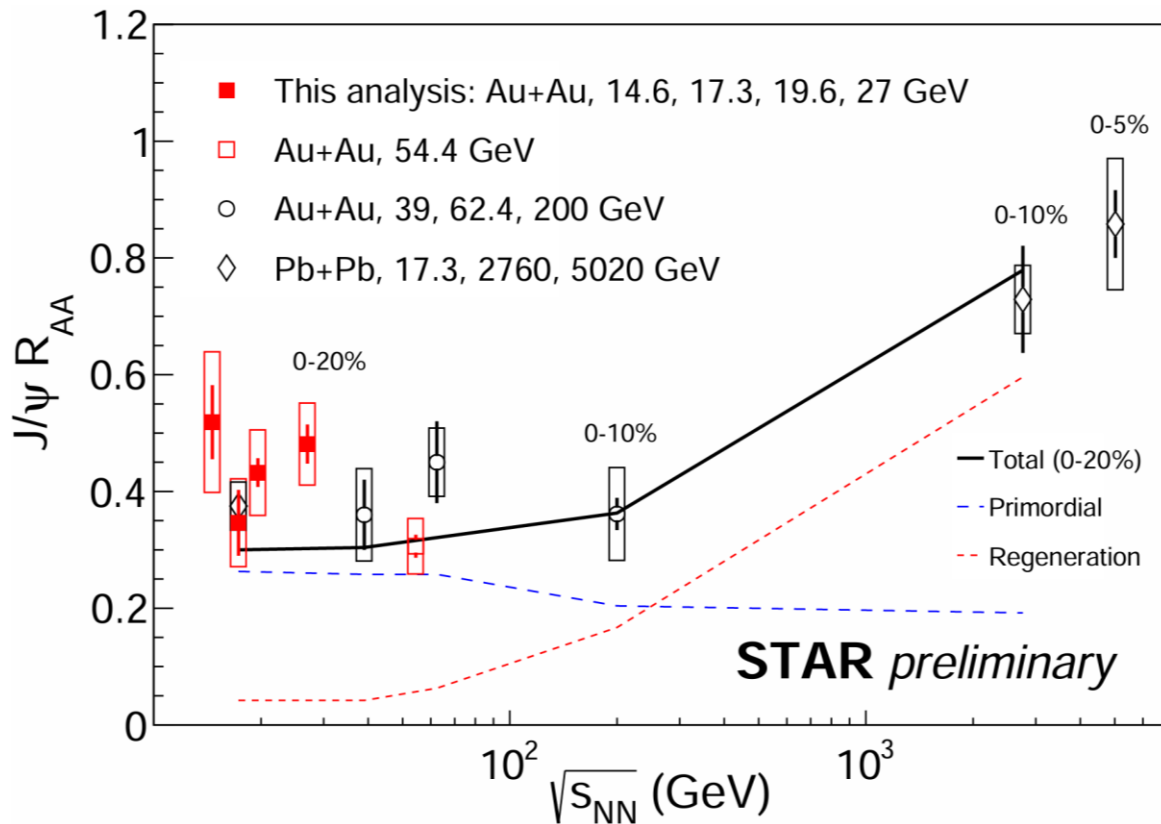
Collision Energy Dependence: BES-I \rightarrow BES-II



➤ BES-I \rightarrow BES-II

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

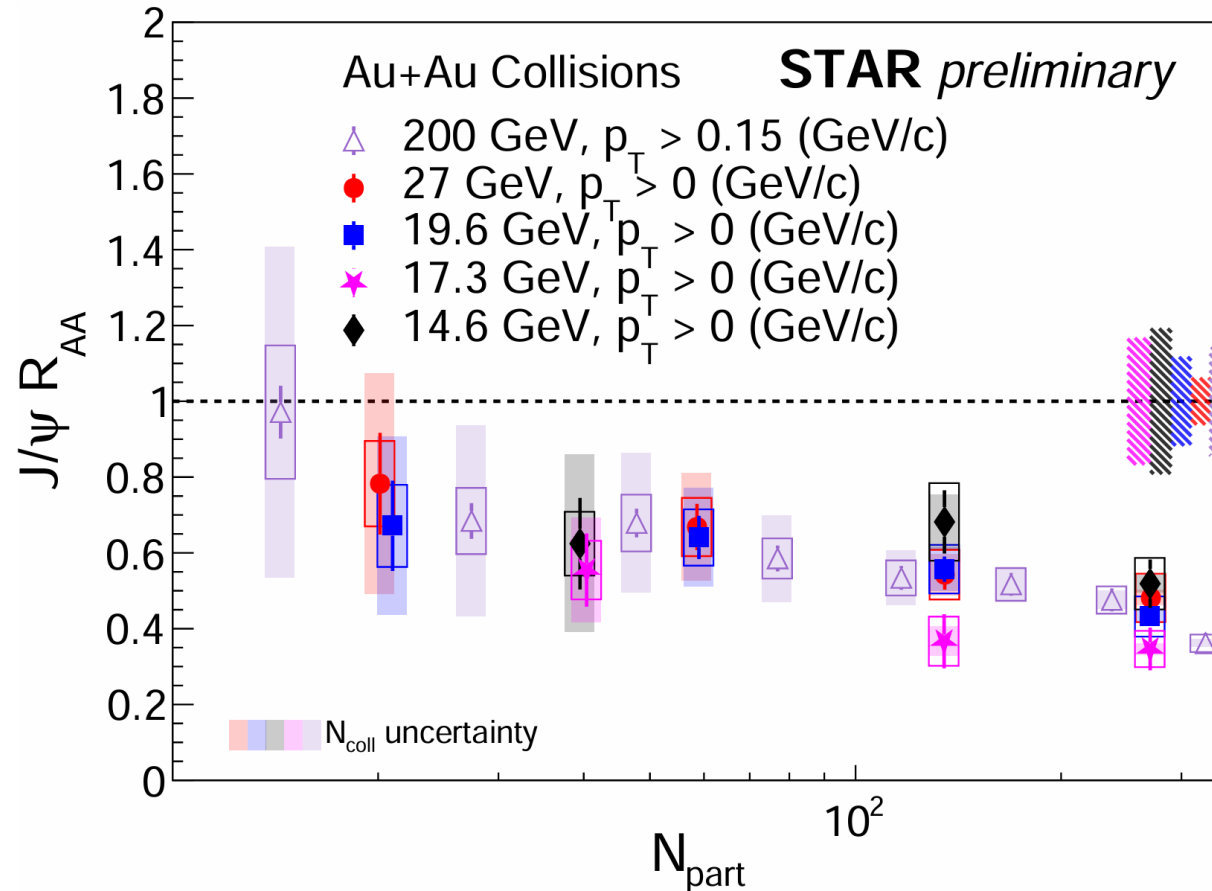
Energy Dependence of Inclusive J/ψ R_{AA}



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

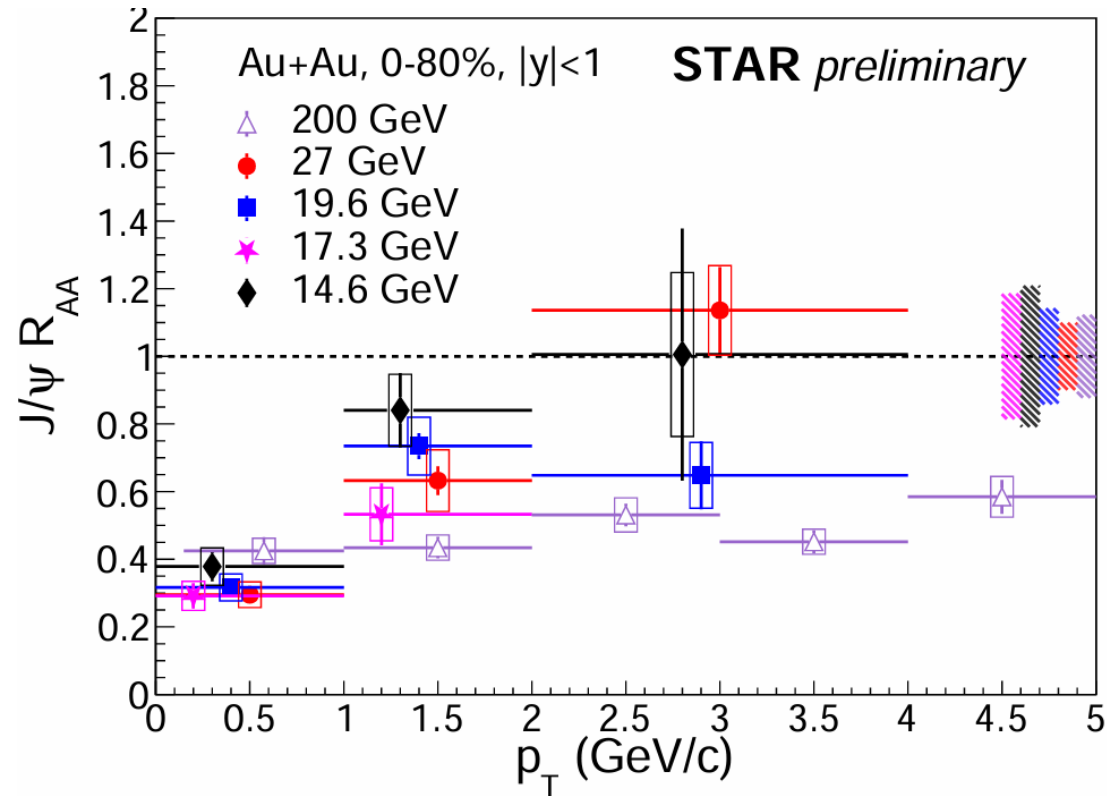
X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
L. Kluberg, Eur. Phys. J. C 43 (2005) 145.

Centrality Dependence of Inclusive J/ψ R_{AA}



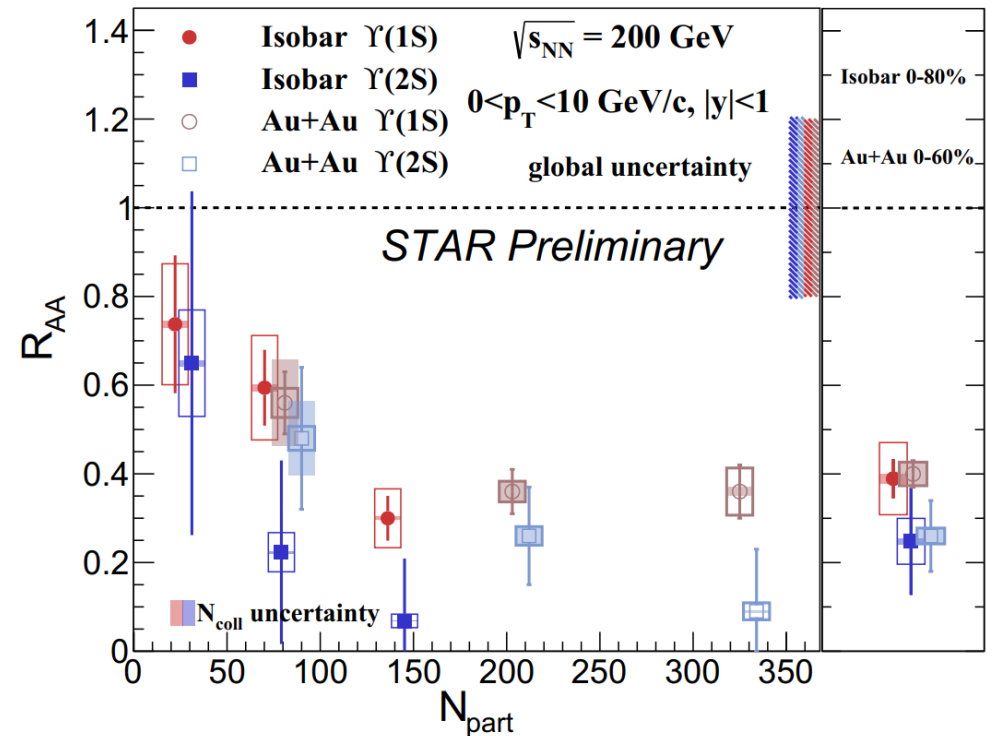
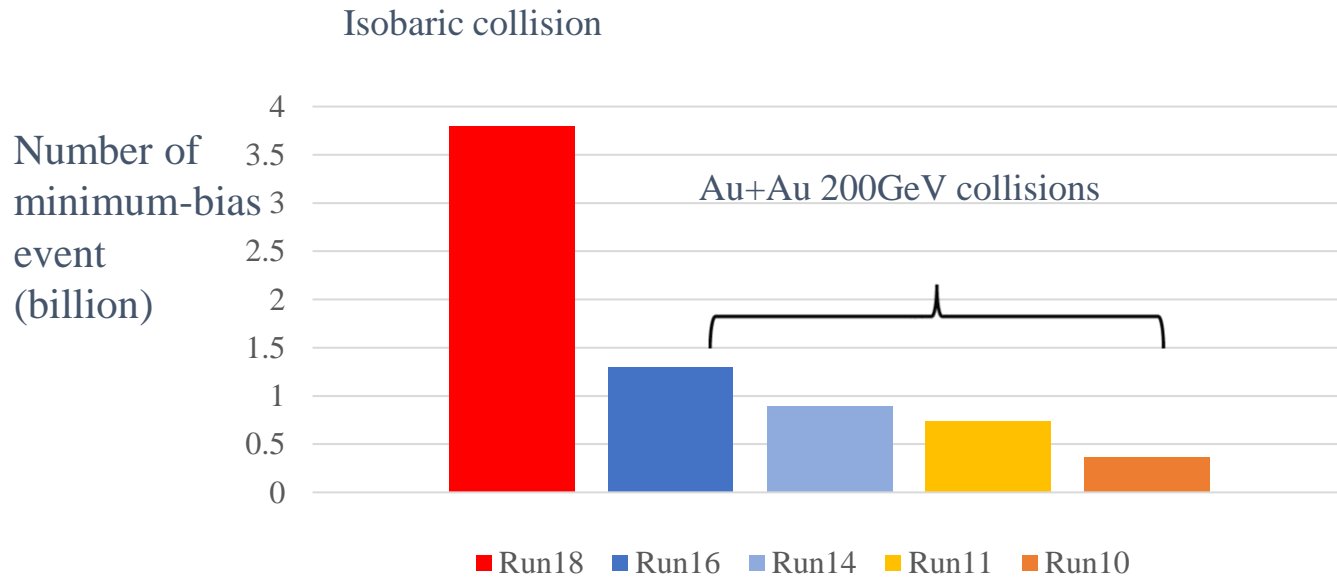
- Hint of decreasing trend as a function of centrality
- R_{AA} shows no significant energy dependence at RHIC for similar $\langle N_{part} \rangle$

p_T Dependence of Inclusive J/ψ R_{AA}



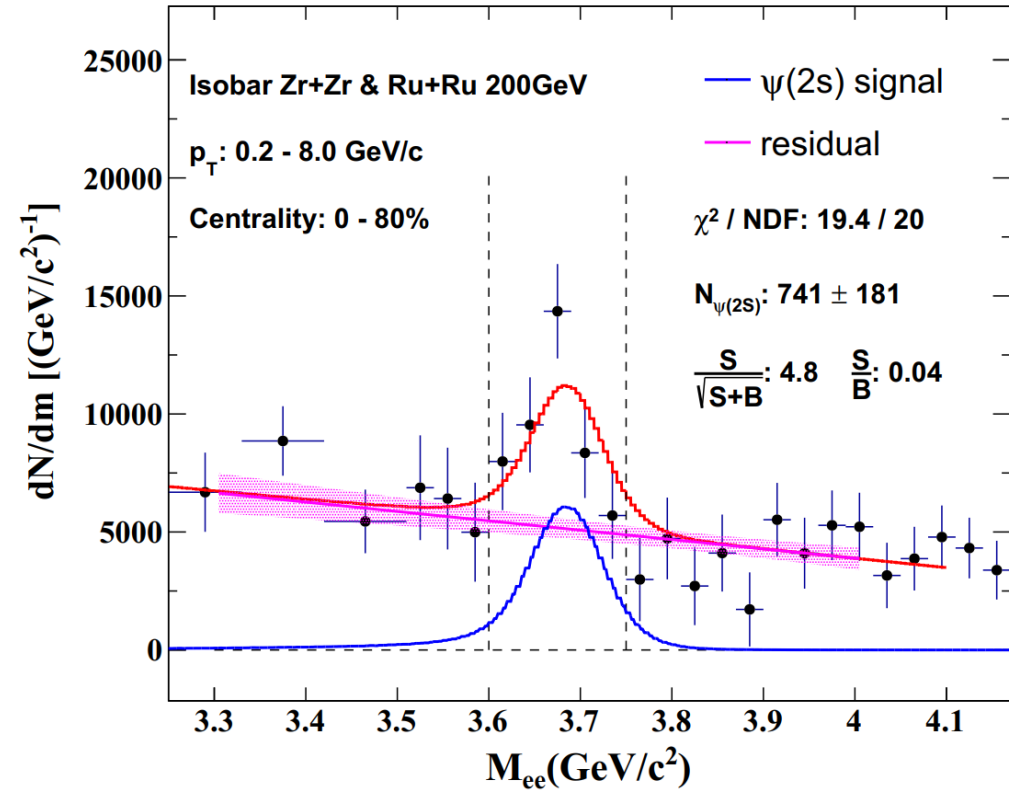
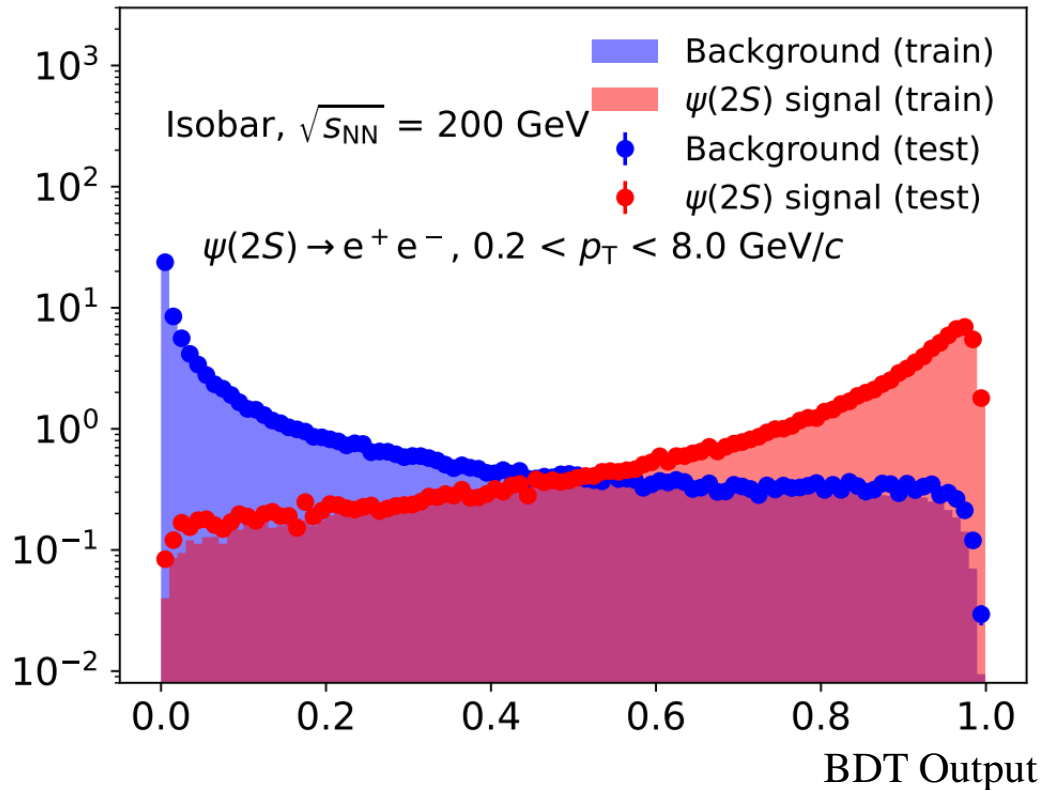
- R_{AA} increases with p_T for $\sqrt{s_{NN}} = 14.6, 17.3, 19.6$ and 27 GeV
- No significant p_T dependence at 200 GeV

Binding Energy Dependence in Isobar Collisions



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

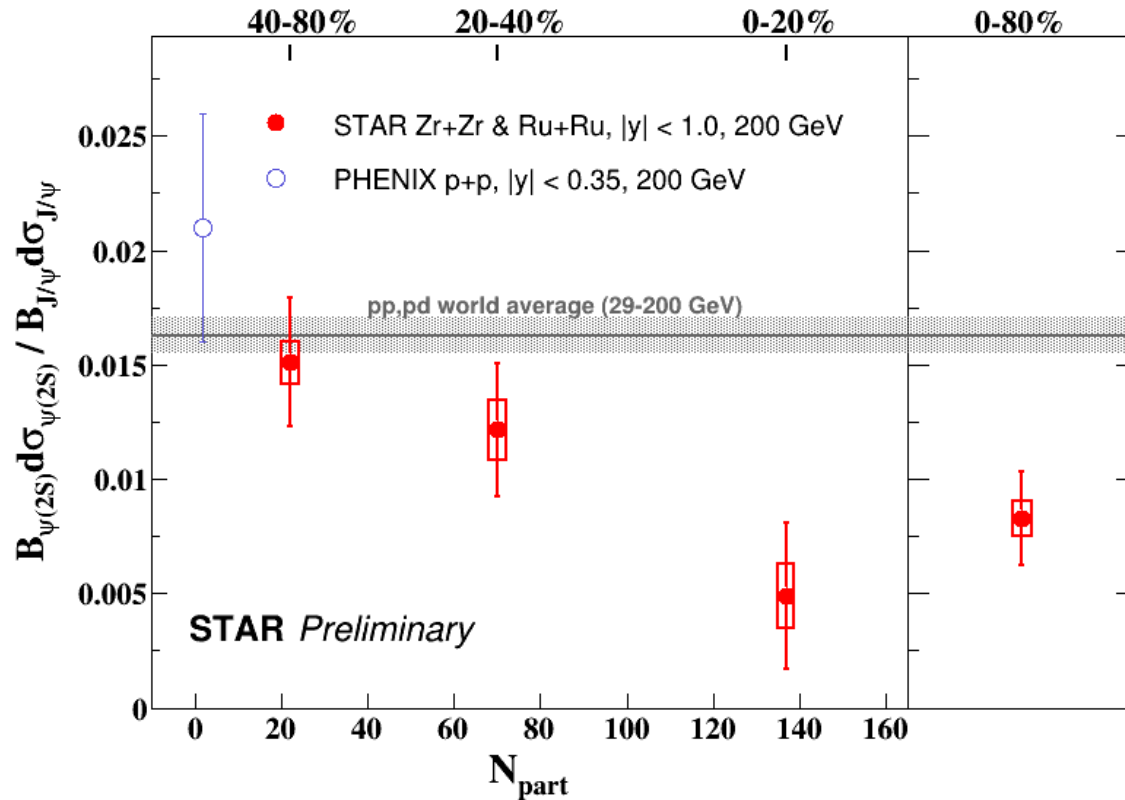
$\psi(2S)$ Signal in Zr+Zr & Ru+Ru Collisions



➤ A machine learning method is employed to reconstruct the $\psi(2S)$ signal

➤ First observation of $\psi(2S)$ in heavy-ion collisions at RHIC

$\psi(2S)$ 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

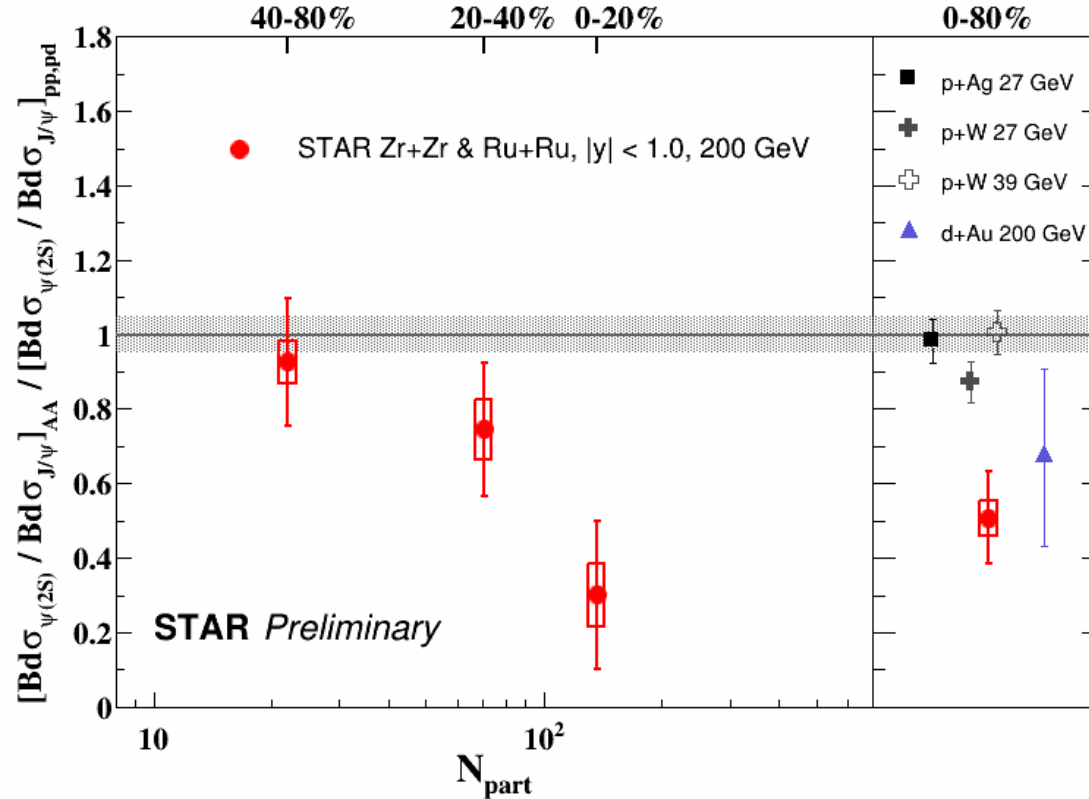
PHENIX, *Phys.Rev.D*, 85,092004 (2012)
NA51, *Phys.Lett.B* 438 (1998) 35-40
ISR, *Nucl.Phys.B* 142 (1978) 29

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

Double Ratio

Double Ratio:

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



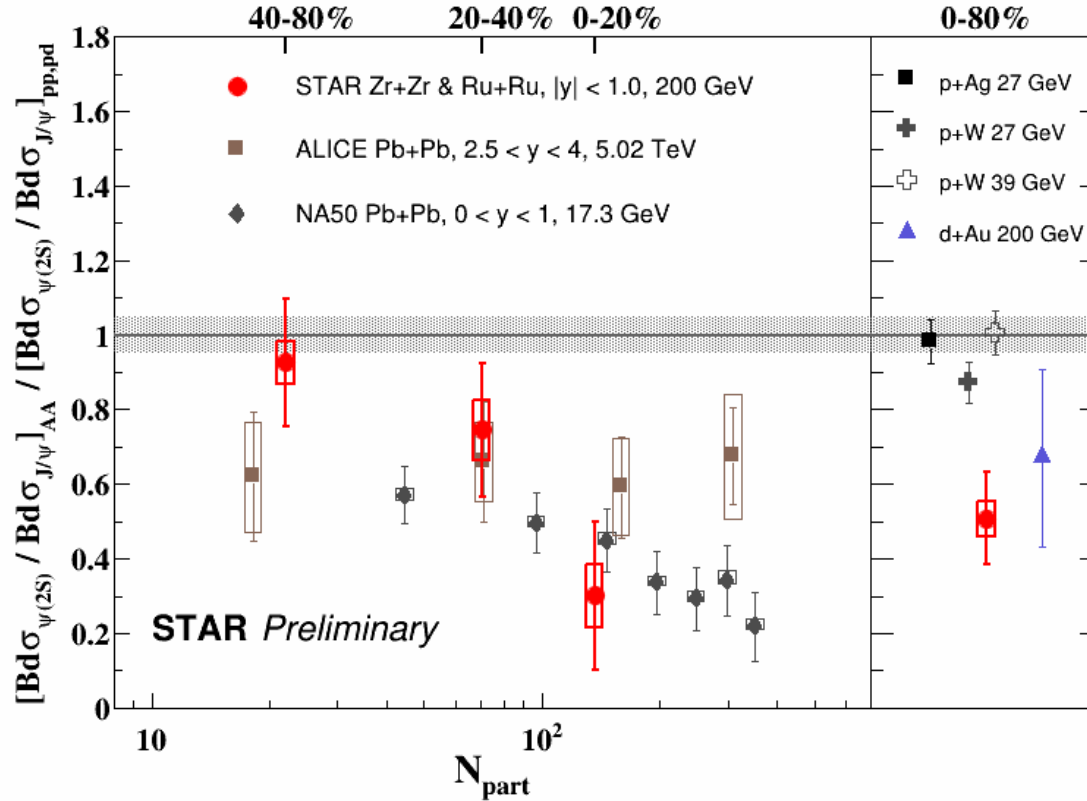
PHENIX, *Phys.Rev.D*, 85,092004 (2012)
 NA51, *Phys.Lett.B* 438 (1998) 35-40
 ISR, *Nucl.Phys.B* 142 (1978) 29

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

Double Ratio

Double Ratio:

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

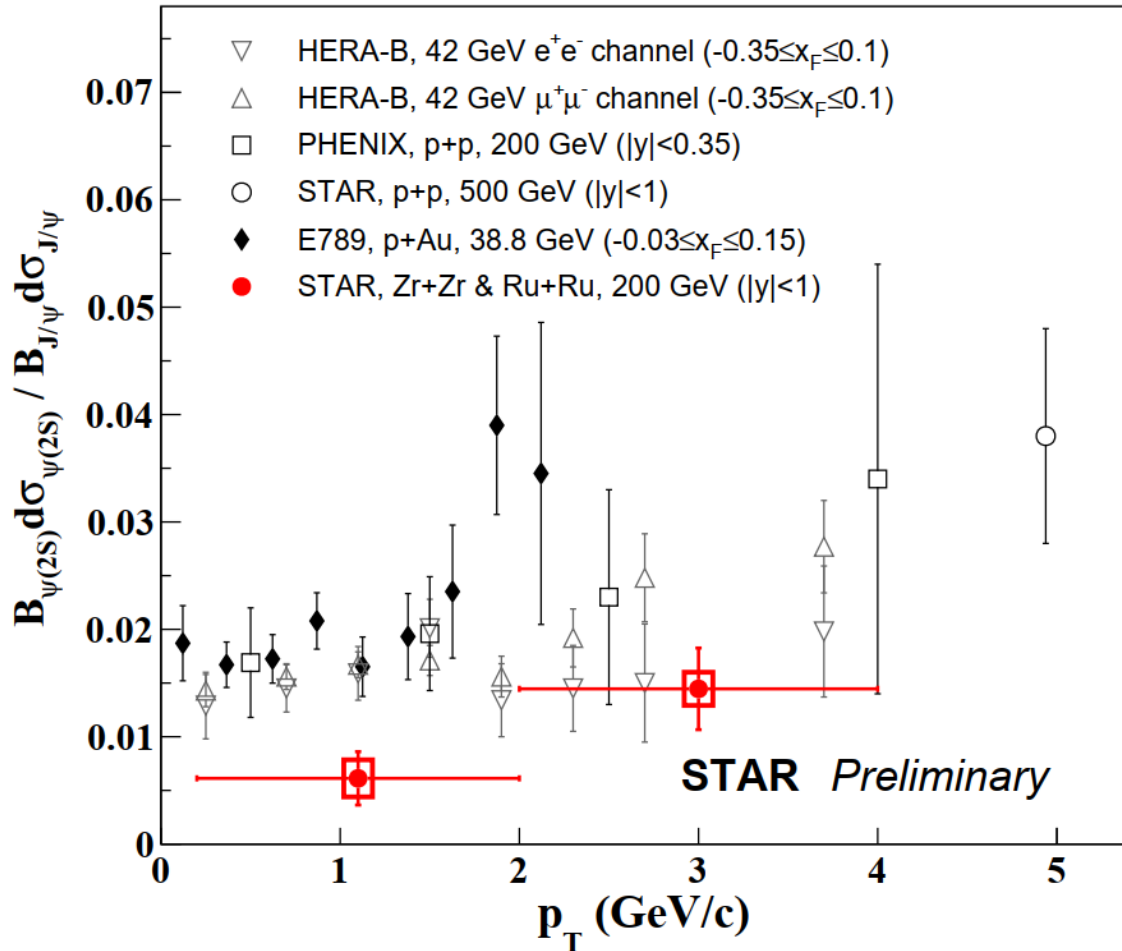


pp reference is the average of measurements in p+p(d) by NA51, ISR and PHENIX

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

➤ 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

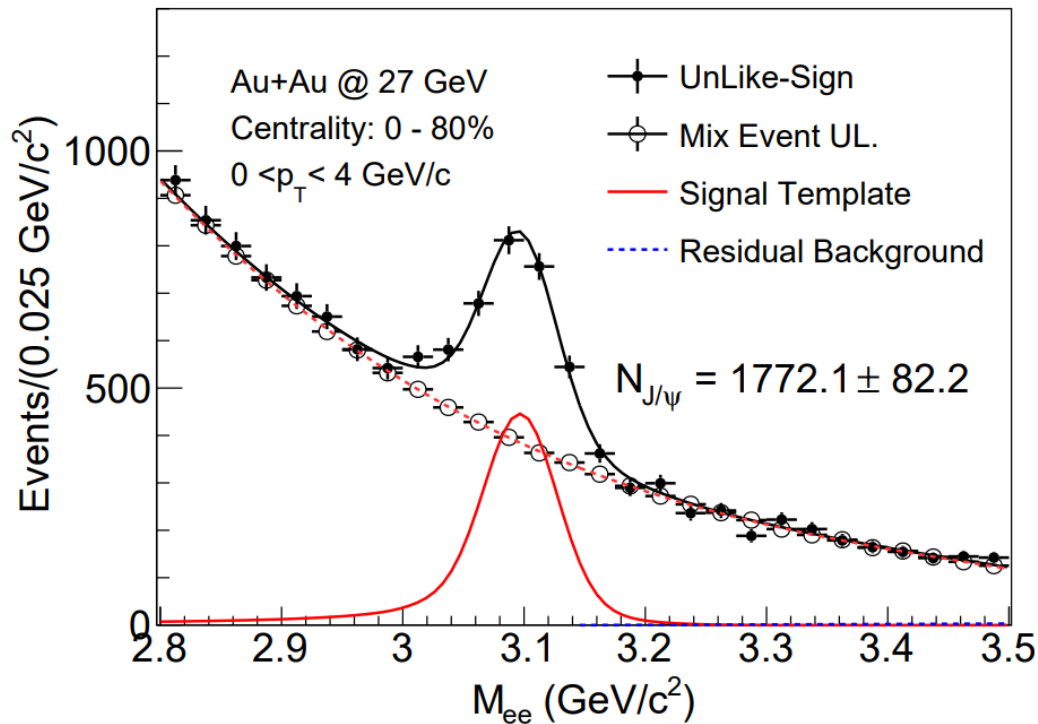


Back up

Raw J/ψ Signal



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



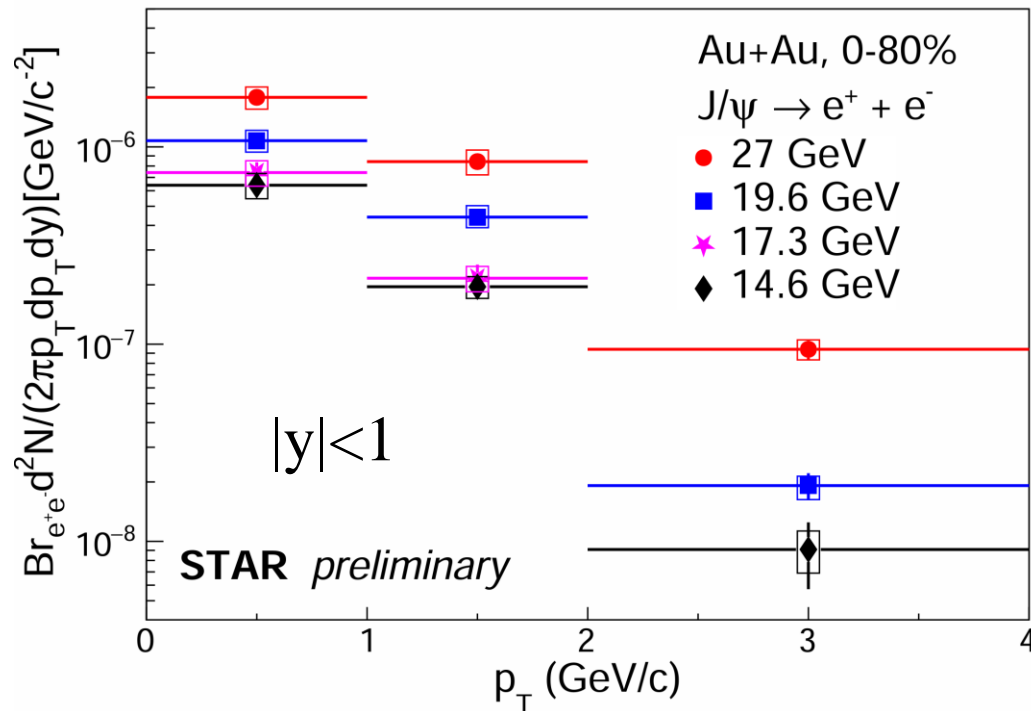
$$\sqrt{s_{NN}} = 27 \text{ GeV}$$

- 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



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



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

- n HitsFit
- n HitsDedx
- 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

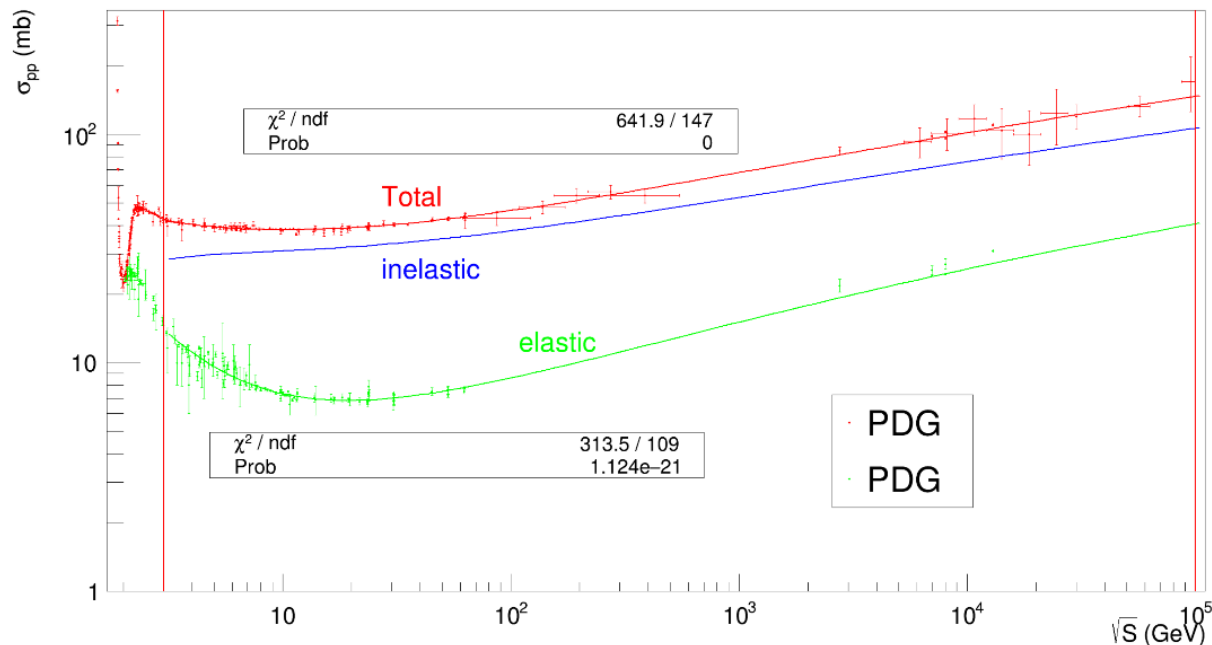
| Analyzed bin | 27 GeV | 19.6 GeV | 14.6 GeV | 17.3GeV |
|--------------|--------|----------|----------|---------|
| 0-80% | 12.4 % | 11.2 % | 13.2 % | 12.8 % |
| 0-20% | 13.2 % | 12.3 % | 13.1 % | 13.8 % |
| 20-40% | 12.1 % | 11.5 % | 15.0 % | 17.7 % |
| 40-60% | 11.5 % | 11.6 % | 13.5 % | 13.9% |
| 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

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

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



| $\sqrt{s_{NN}}$ (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/>