SOUTH CHINA NORMAL UNIVERSITY

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Recent STAR quarkonium study highlights

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(For the STAR Collaboration)

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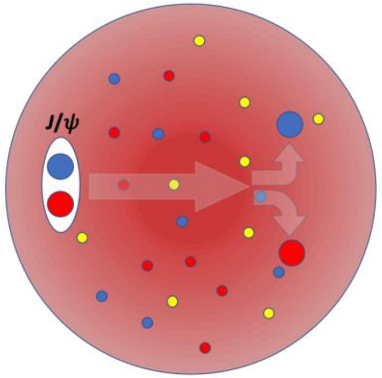
2nd workshop on advancing the understanding of non-perturbative QCD using energy flow

Stony Brook University - November 6-9, 2023

Introduction

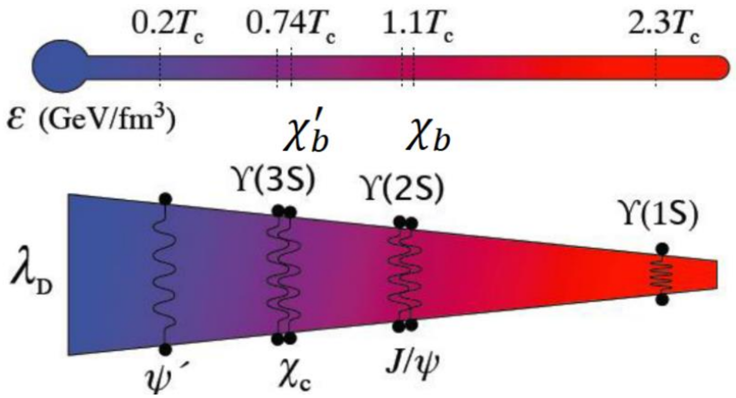
- Quarkonia provide good probes of the Quark-Gluon Plasma (QGP)

Dissociation



Credit: Q. Yang

Sequential suppression

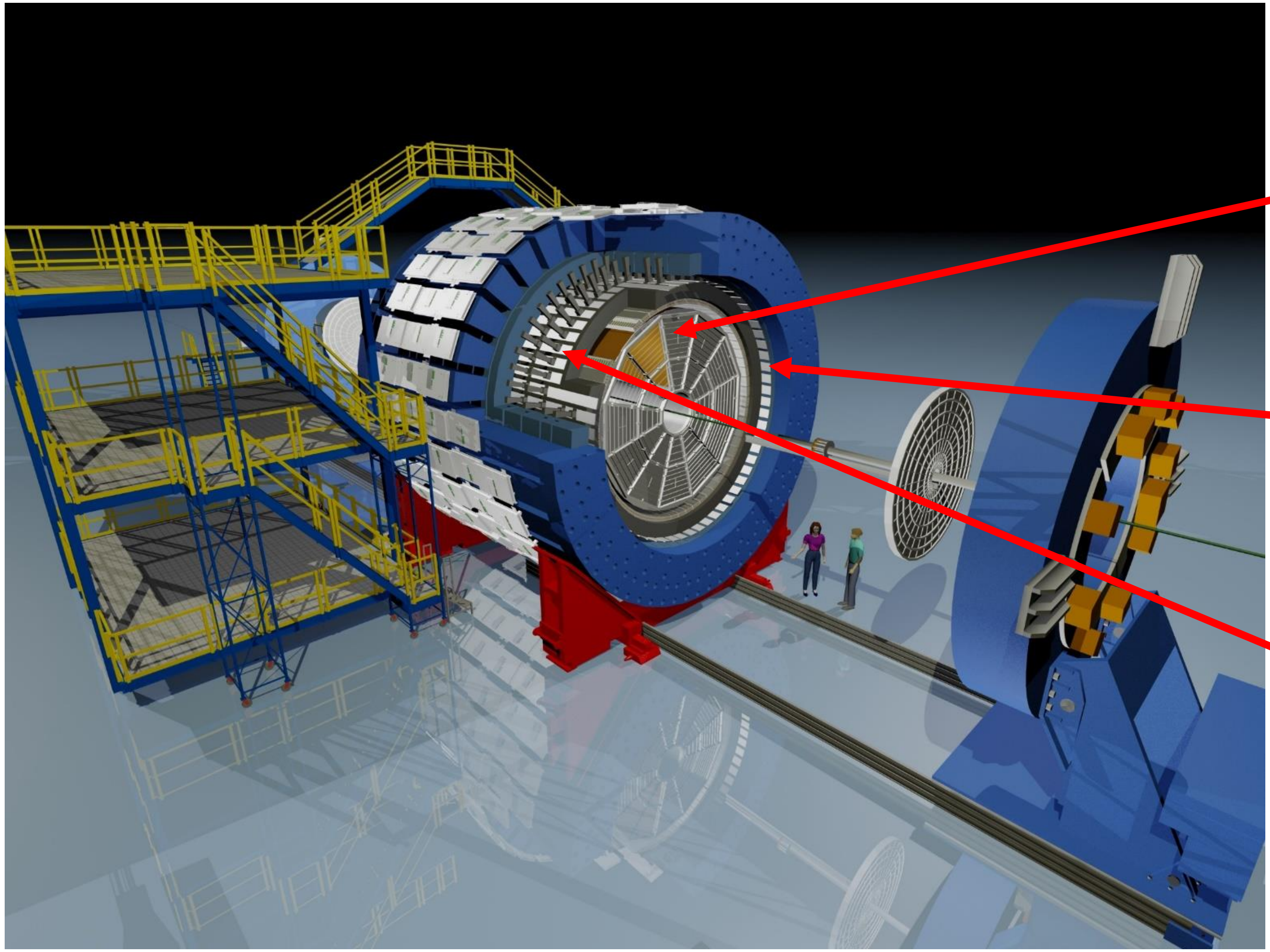


S. Diagl, P. Petreczky and H. Satz, PLB514, 57 (2001)

- Other effects:
  - Regeneration
  - Cold nuclear matter effects
  - Feed down

- Systematically analyze the J/ψ R_{AA}
  - p_T, centrality dependence
  - Collision energy and system dependence
  - Binding energy dependence

The Solenoidal Tracker at RHIC

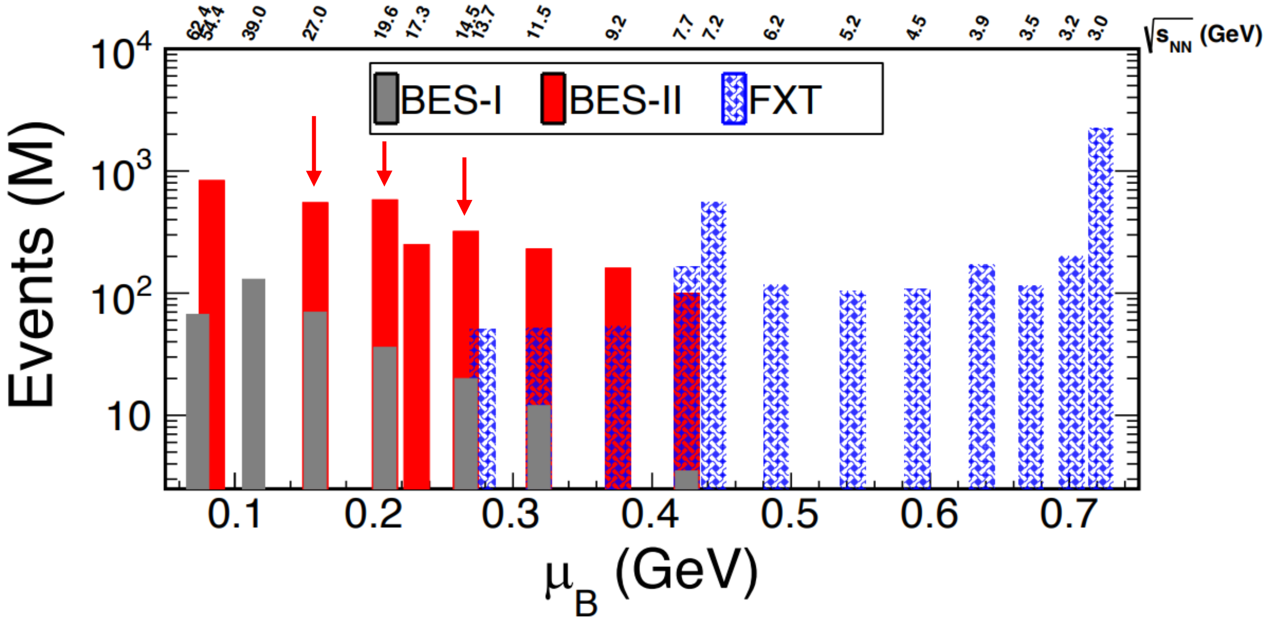


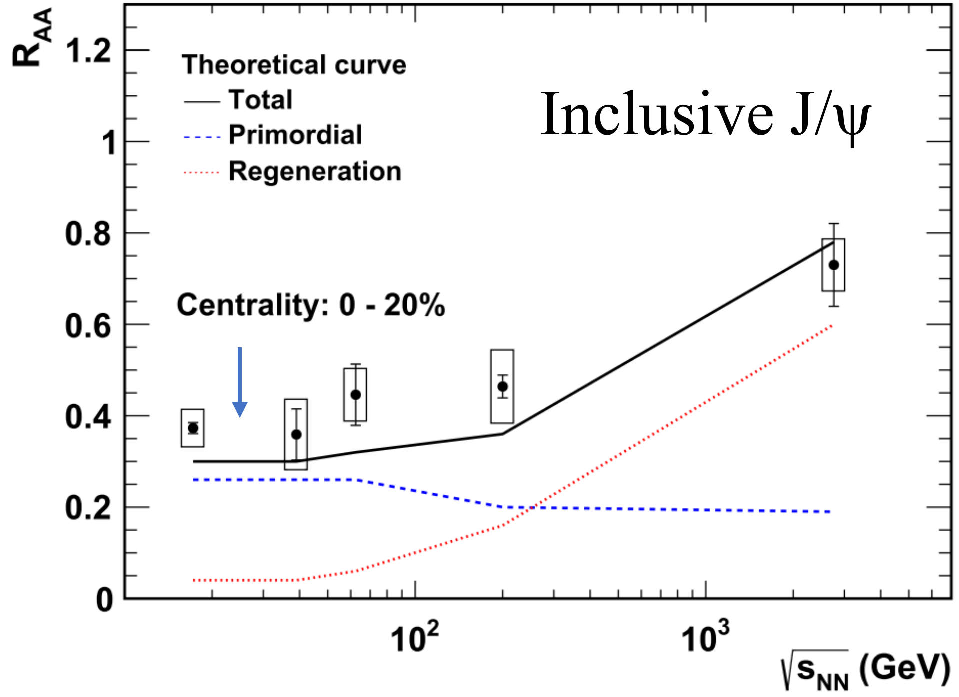
Time Projection Chamber
Tracking, momentum and energy loss
Acceptance: $|\eta| < 1$; $0 \leq \varphi < 2\pi$

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

Barrel ElectroMagnetic Calorimeter
$e^{\pm}$ trigger and identification
Acceptance: $|\eta| < 1$; $0 \leq \varphi < 2\pi$

Au+Au Collisions at STAR





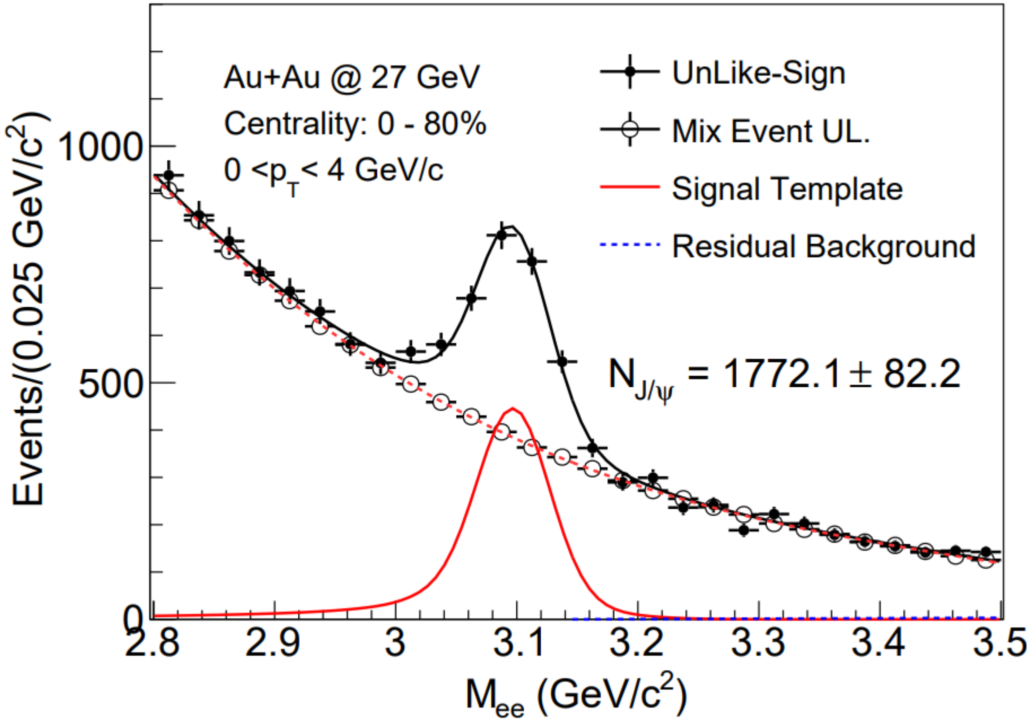
STAR Collaboration Phys. Lett. B 771 (2017) 13–20

- Beam Energy Scan II
  - 10-20 times higher statistics than BES-I
  - Unique opportunity to study the collision energy dependence

- Collision energy dependence of J/ψ production
  - Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6, 19.6, 27 GeV
  - Smaller regeneration effect

Raw J/ψ Signal

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

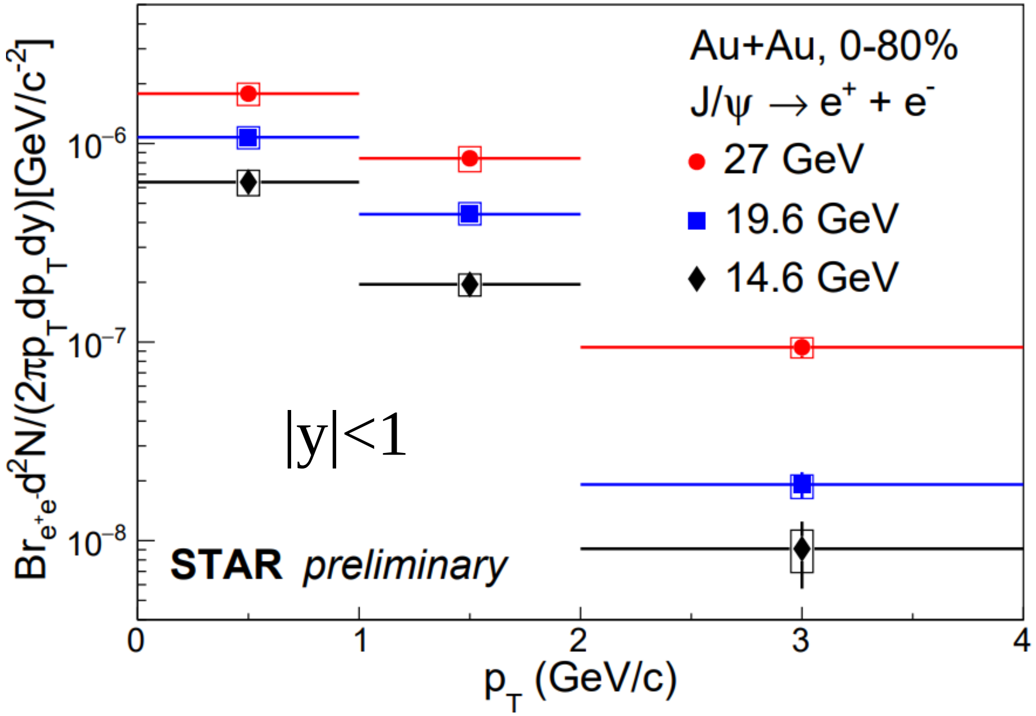


$\sqrt{s_{NN}} = 27$ GeV

- 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

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



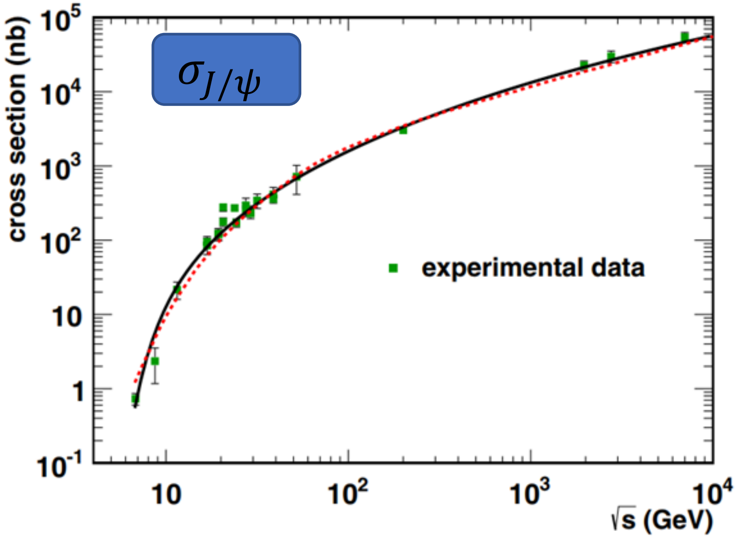
Inclusive J/ψ invariant yields as a function of p_T at mid-rapidity ($|y| < 1$) in Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6, 19.6, 27 GeV.

p+p Baseline

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

- **For p+p baselines at $\sqrt{s_{NN}}$ = 14.6, 19.6, and 27 GeV are extracted from phenomenological interpolations**

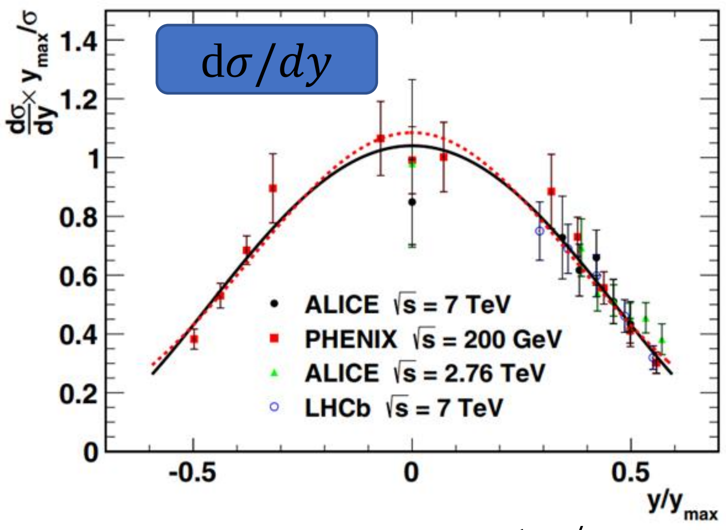
W. Zha, et al., Phys. Rev. C 93 (2016) 024919.



$\sigma = \alpha \times \sigma_{CEM}$

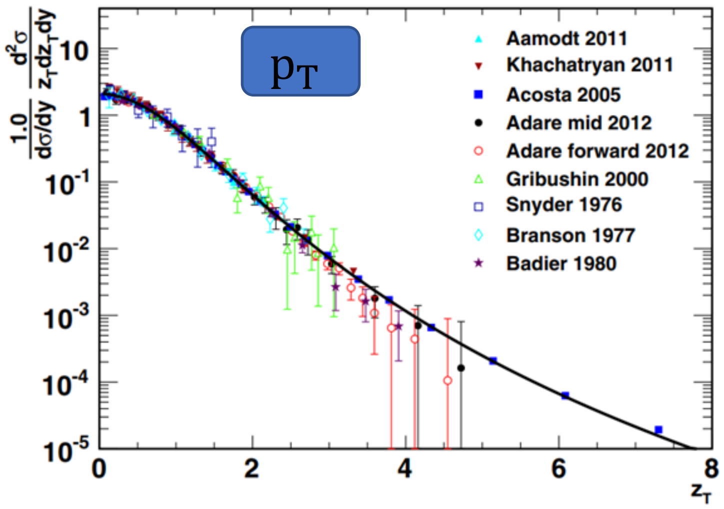
α: scale factor

σ_{CEM}: σ from color evaporation model



$$\frac{1}{\sigma}\frac{d\sigma}{d(y/y_{max})} = a e^{-\frac{1}{2}\left(\frac{y/y_{max}}{b}\right)^2}$$

where $y_{max} = ln\left(\frac{\sqrt{s}}{m_{J/\psi}}\right)$

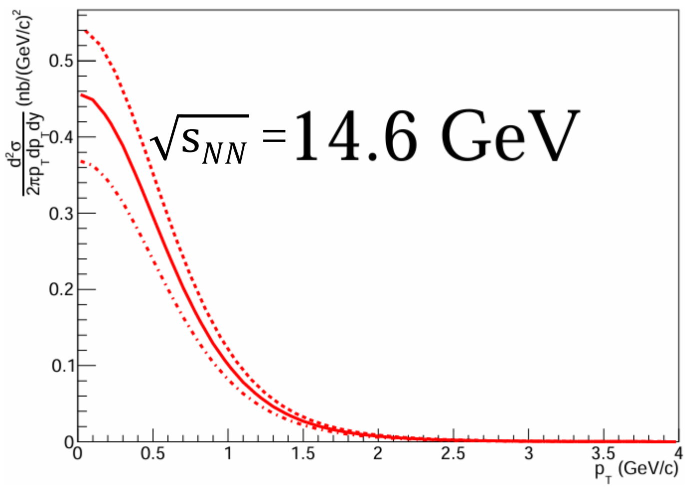


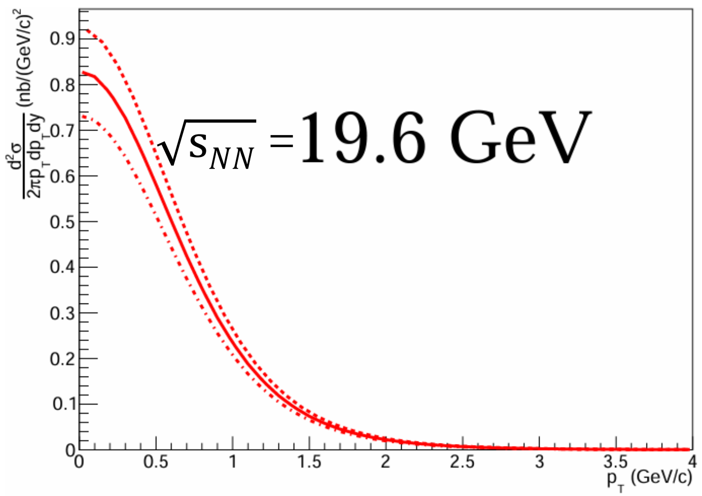
$$\frac{1}{d\sigma/dy}\frac{d^2\sigma}{z_T dz_T dy} = a \times \frac{1}{(1+b^2 z_T^2)^n}$$

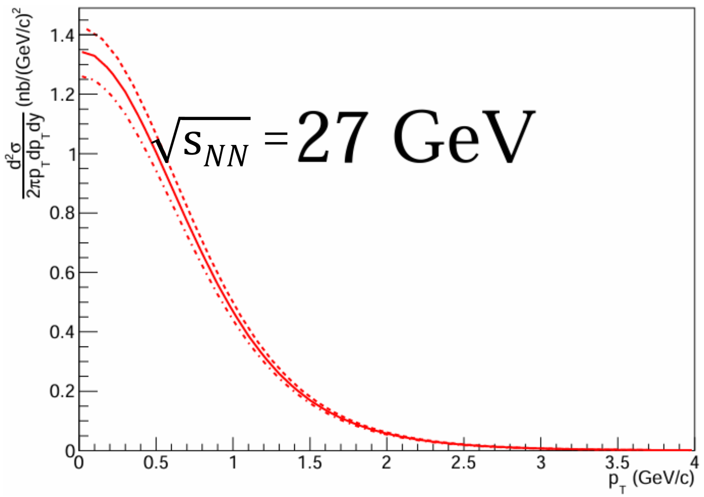
where $z_T = p_T/\langle p_T\rangle$

p+p Baseline

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





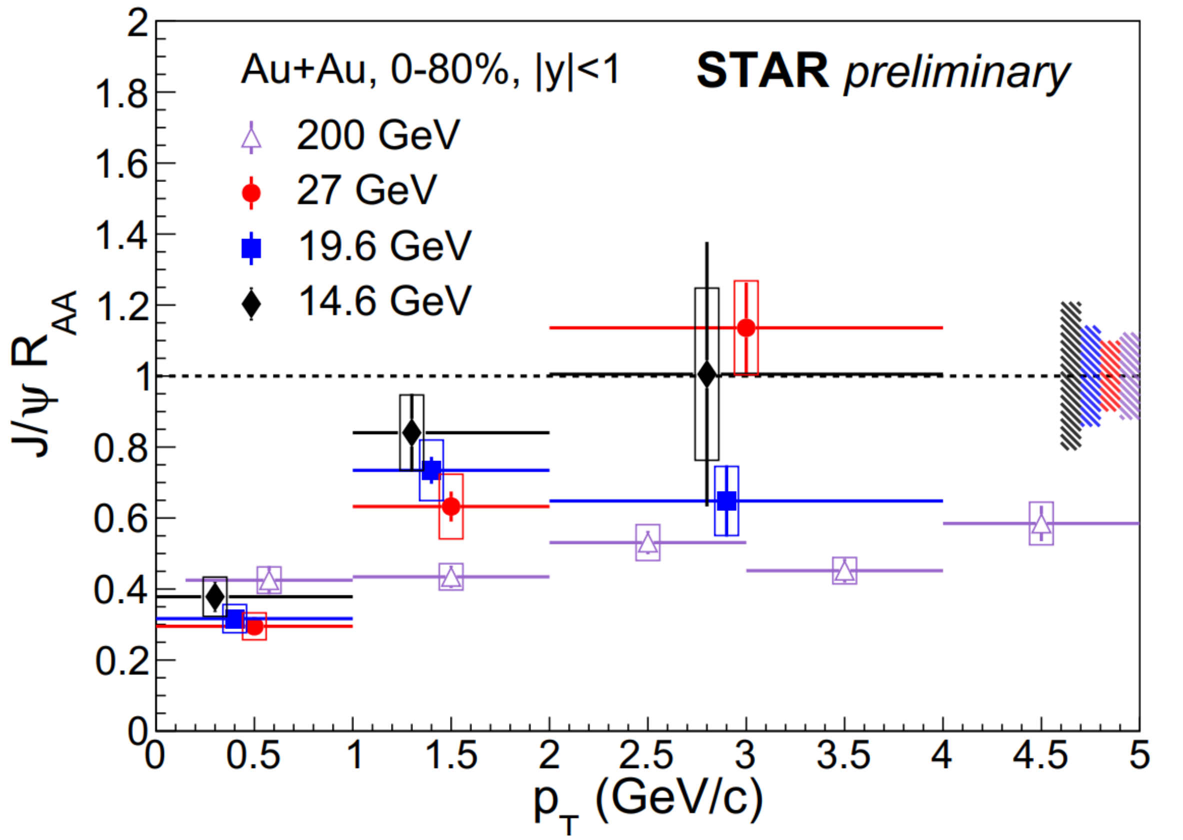


- The p_T dependence of deduced J/ψ differential cross section at midrapidity in p+p collisions at $\sqrt{s_{NN}}$ = 14.6, 19.6, 27 GeV

- The systematic uncertainty arises from fitting world-wide data:

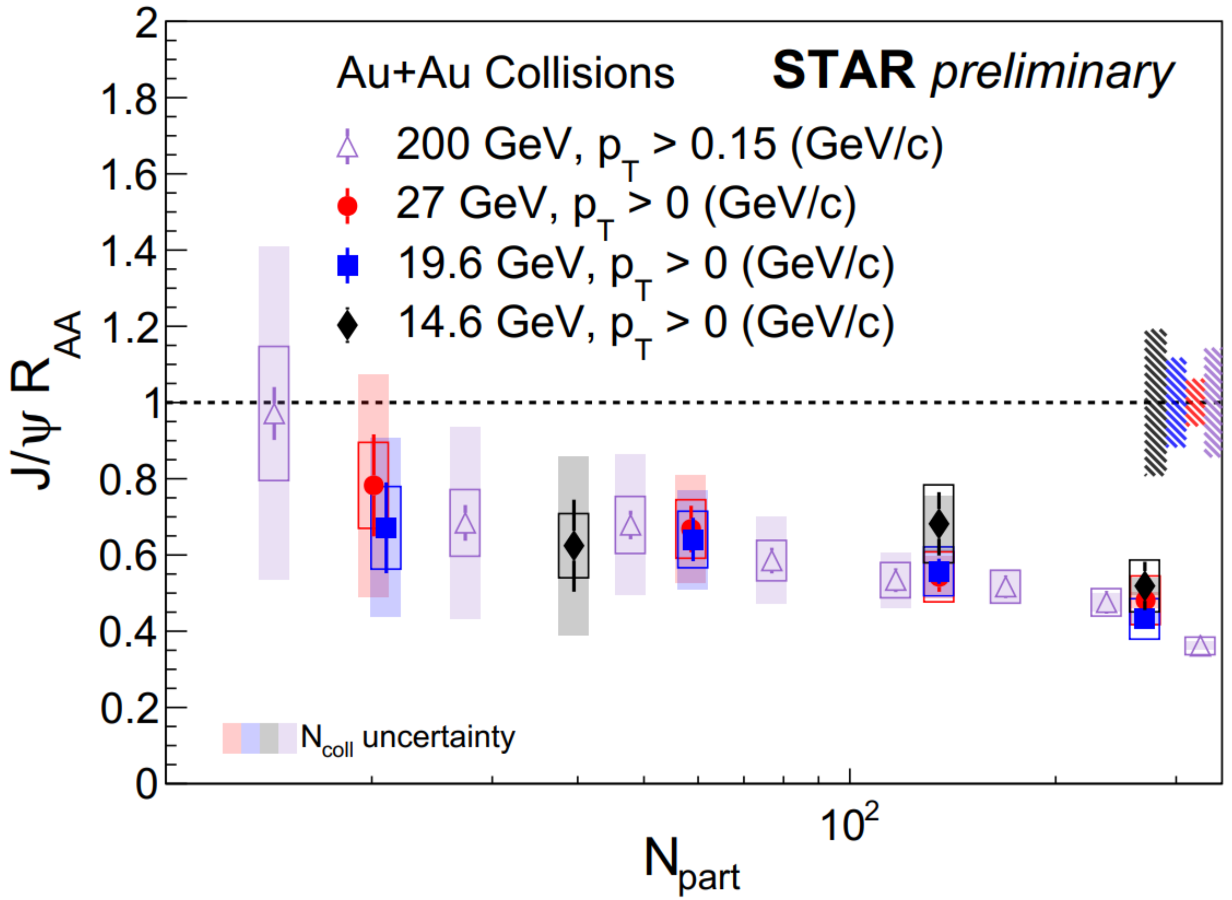
$\sqrt{s_{NN}}$ = 14.6 GeV	19.2 %
$\sqrt{s_{NN}}$ = 19.6 GeV	11.7 %
$\sqrt{s_{NN}}$ = 27 GeV	6.1 %

J/ψ R_{AA} vs. p_T in Au+Au Collisions



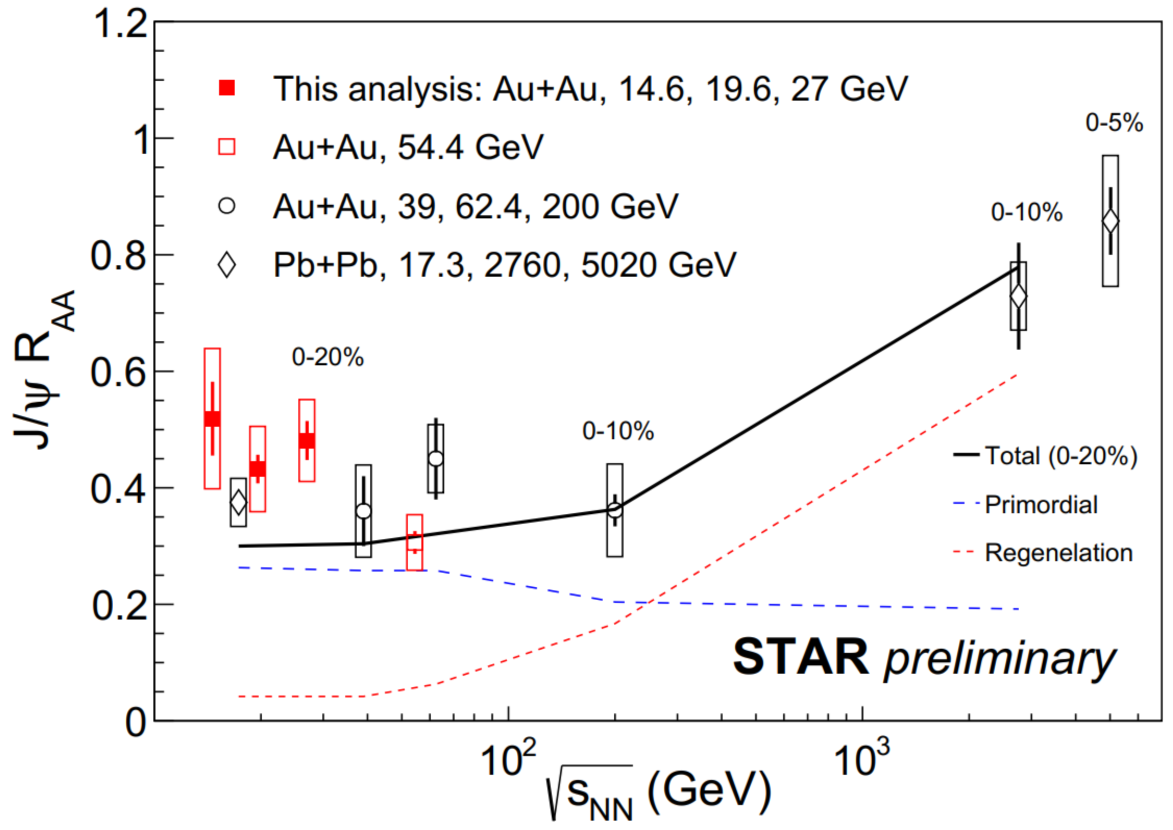
- Low p_T suppression, R_{AA} increases with p_T for $\sqrt{s_{NN}}$ = 14.6, 19.6 and 27 GeV
- No significance p_T dependence at 200 GeV

J/ψ R_{AA} vs. $\langle N_{part} \rangle$ in Au+Au Collisions



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

Energy Dependence of J/ψ R_{AA}

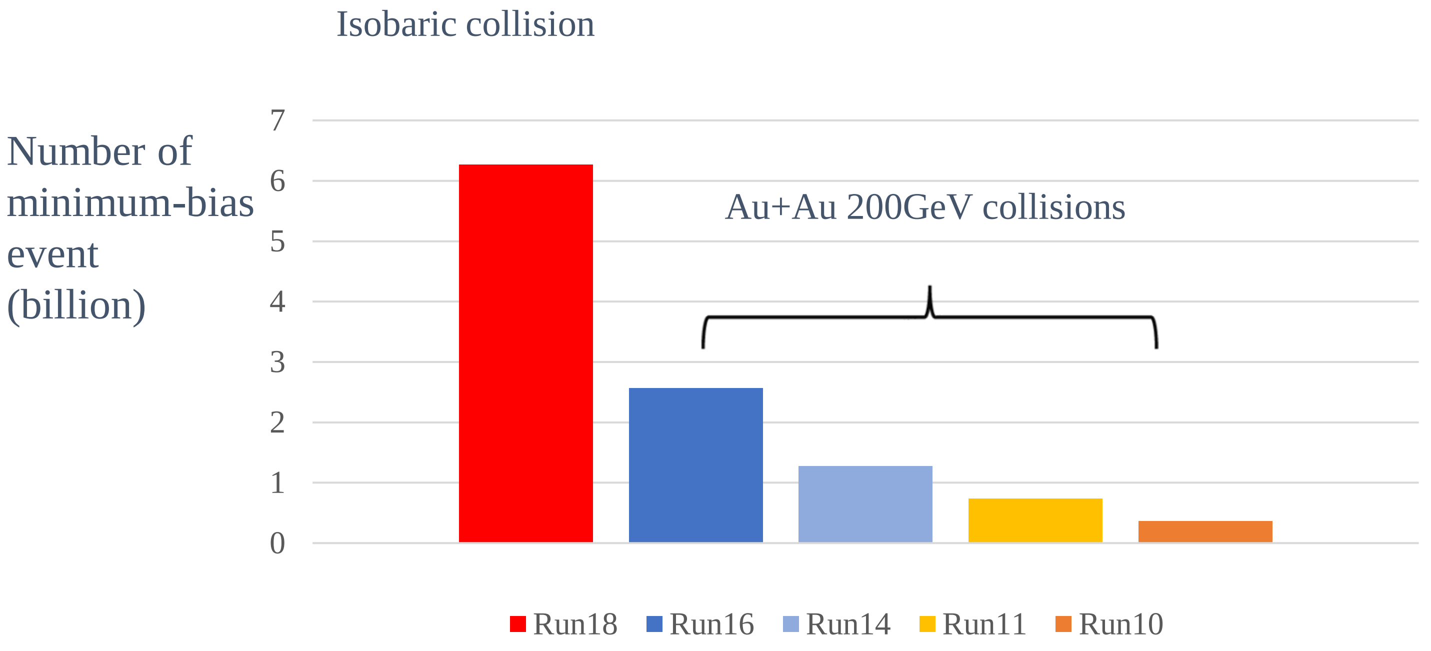


X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
L. Kluberg, Eur. Phys. J. C 43 (2005) 145.
NA50 Collaboration, Phys. Lett. B 477 (2000) 28.

- Data at $\sqrt{s_{NN}}$ = 14.6, 19.6 and 27 GeV follow the trend
- No significant energy dependence of J/ψ R_{AA} in central collisions is observed within uncertainties up to 200 GeV
- Regeneration dominates at LHC energies
- Model qualitatively describes the observed energy dependence

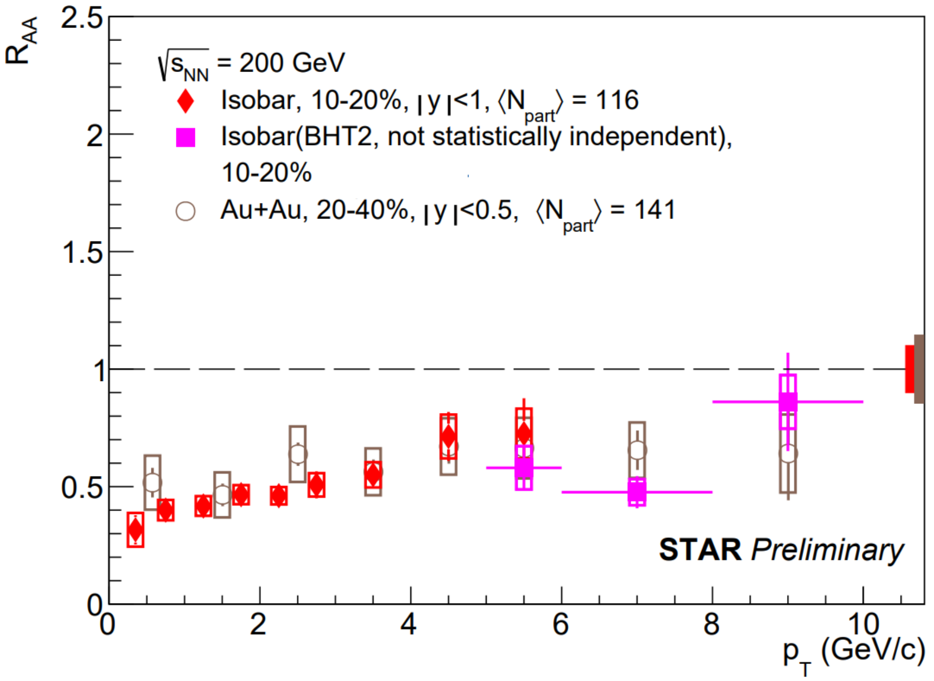
ALICE Collaboration, Phys. Lett. B 734 (2014) 314
STAR Collaboration, Phys. Lett. B 771 (2017) 13-20
STAR Collaboration, Phys. Lett. B 797 (2019) 134917
ALICE Collaboration, Nucl. Phys. A 1005 (2021) 121769

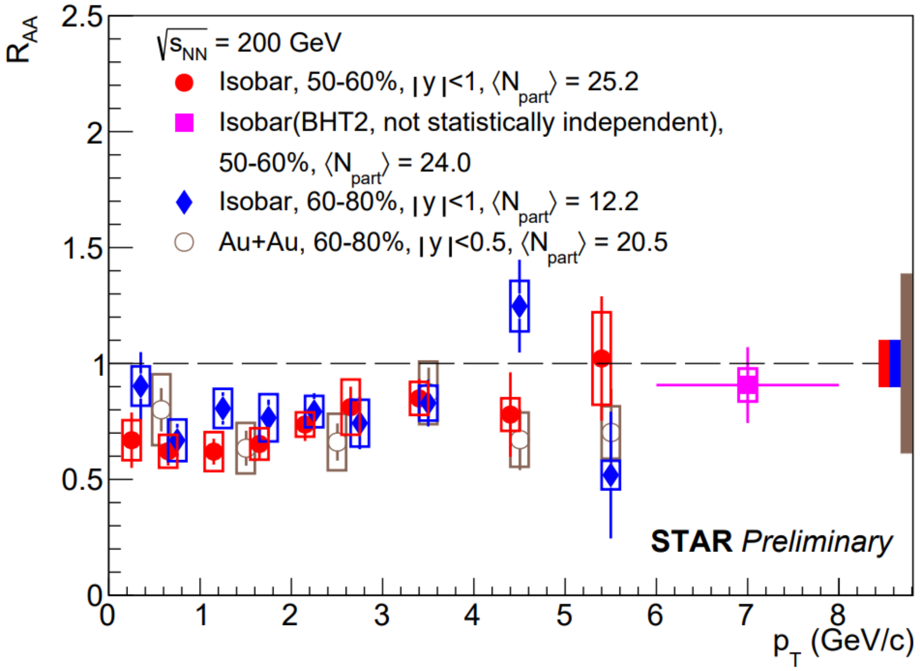
Zr+Zr & Ru+Ru Collisions



- High statistics enables measurements of：
  - J/ψ production with high precision
  - Sequential suppression of J/ψ, ψ(2S)

J/ψ R_{AA} vs. p_T in Zr+Zr & Ru+Ru Collisions

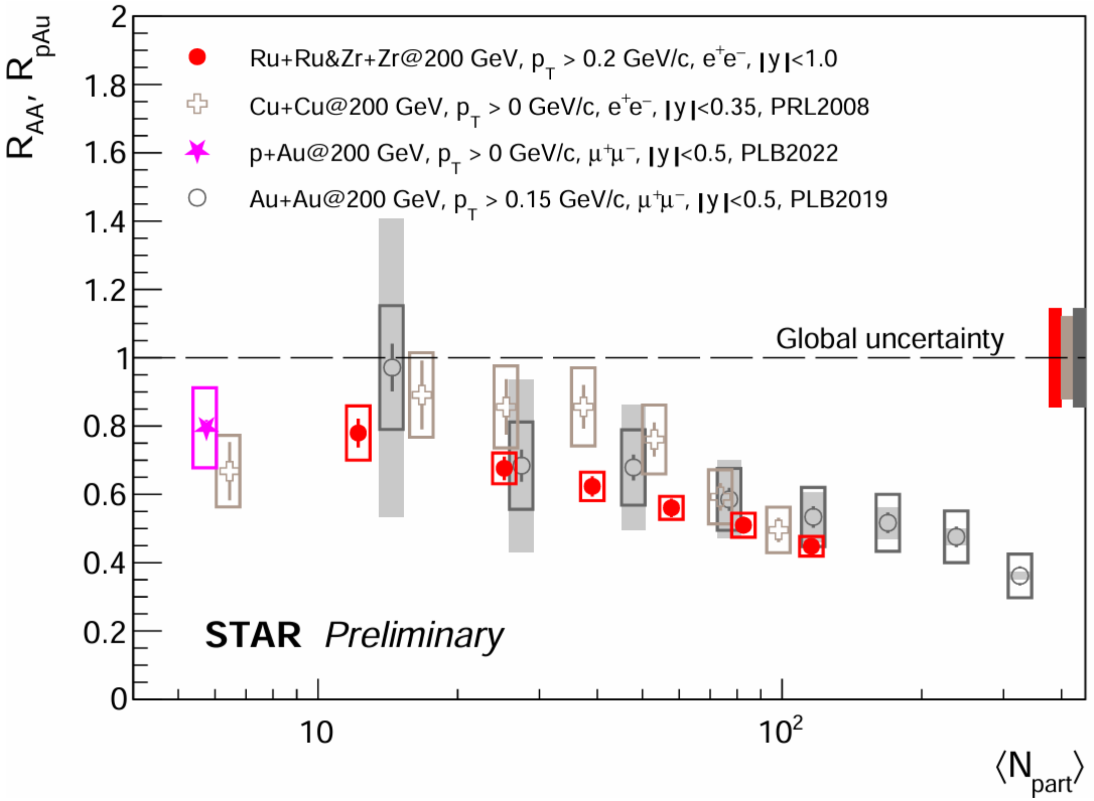




STAR Collaboration, Phys. Lett. B 797 (2019) 134917

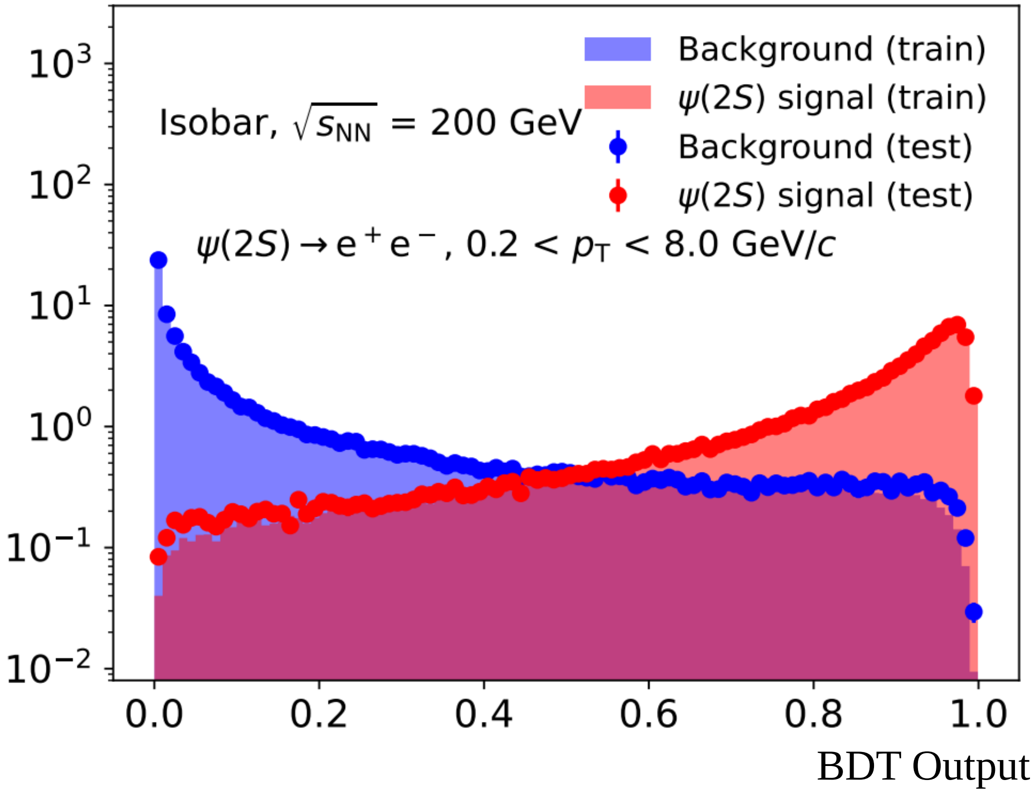
- Highest precision measurement at RHIC to date
- Significant suppression observed in central collisions
- Consistent with Au+Au results at similar $\langle N_{\mathrm{part}} \rangle$ range

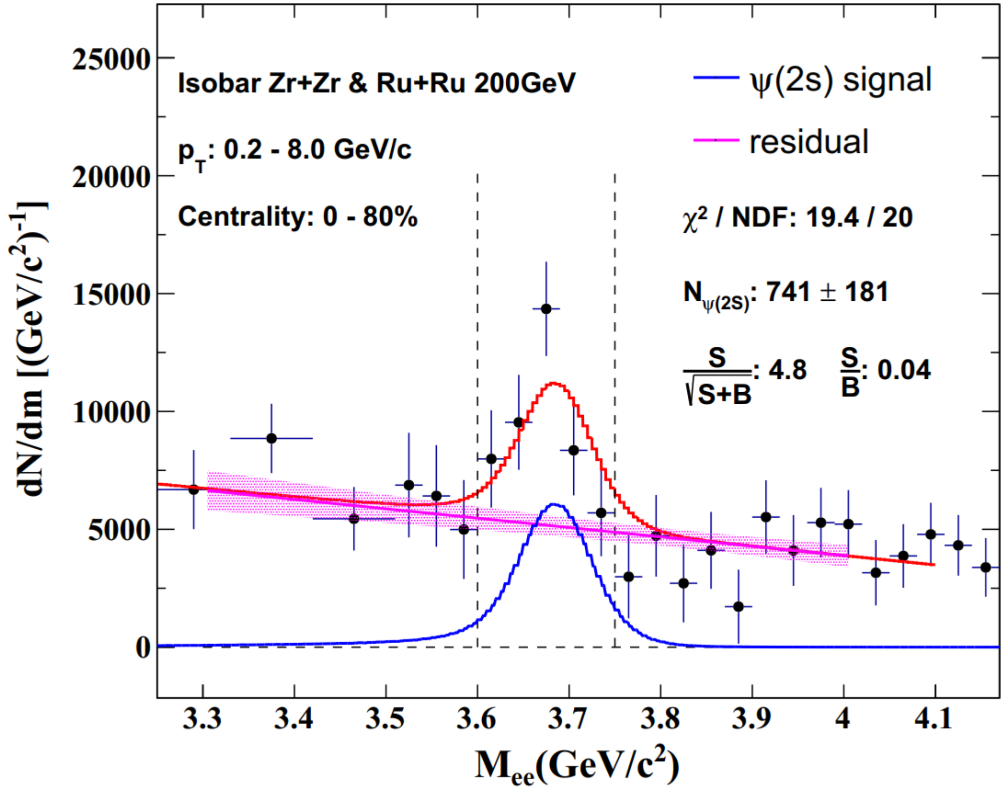
J/ψ R_{AA} vs. $\langle N_{part} \rangle$ at RHIC



- ➢ No significant collision system dependence at RHIC

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

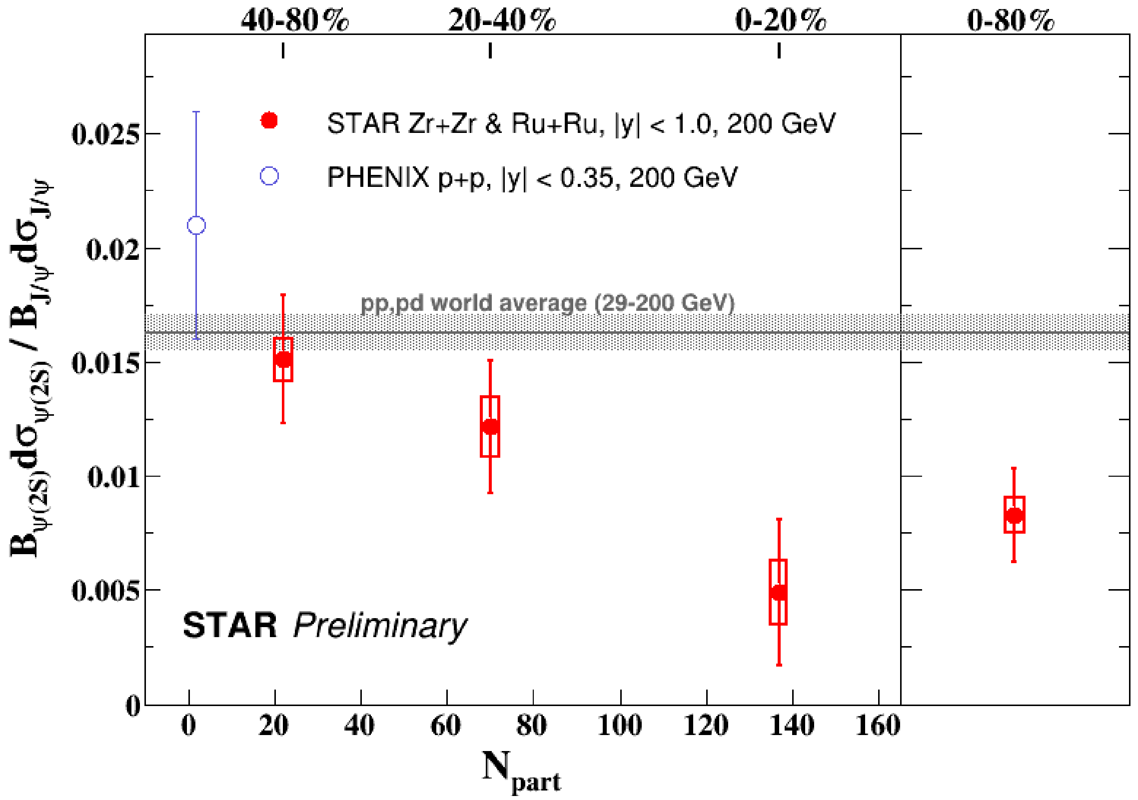




- A machine learning method is employed to reconstruct the ψ(2S) signal

- Combinatorial background subtracted (mixed event)
- Fit with ψ(2S) signal lineshape (simulation) and residual background (linear function)

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

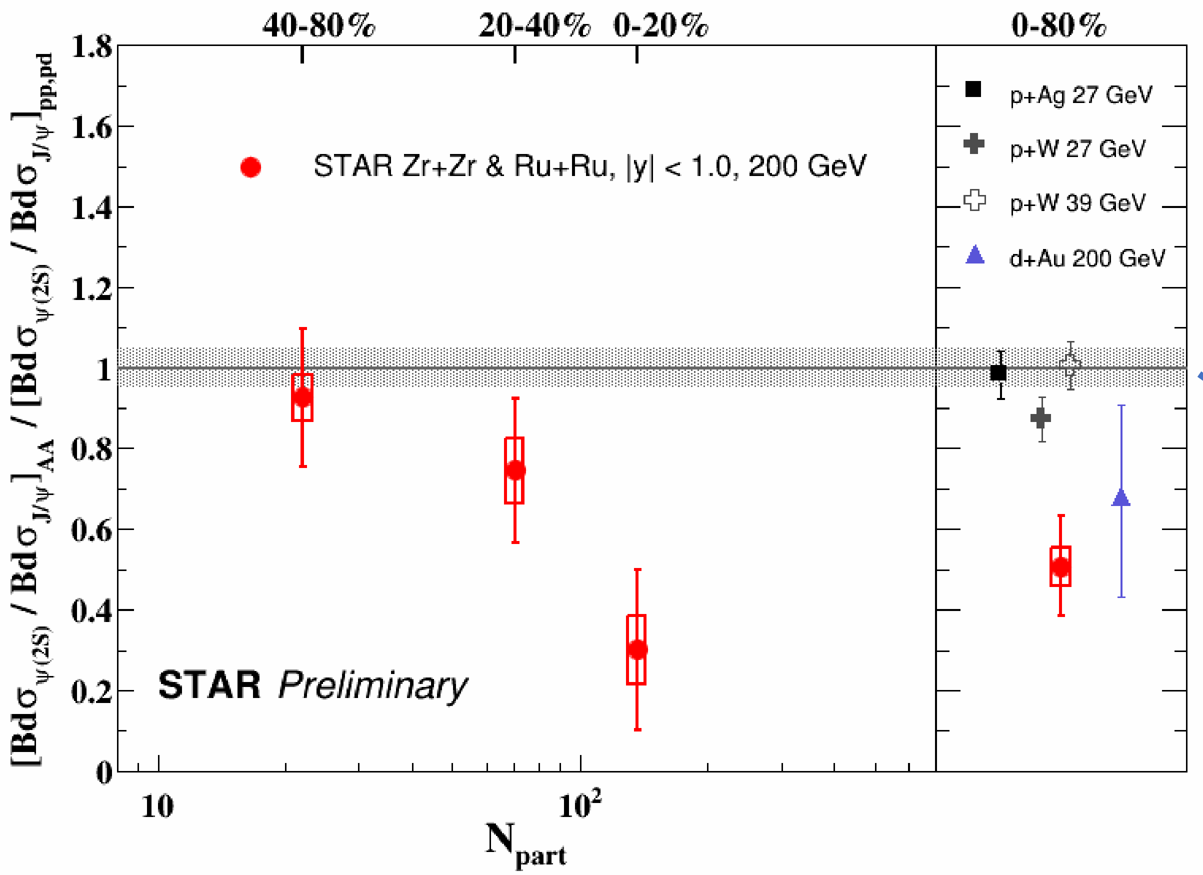


pp reference is the average of measurements in p+p(d) by NA51, ISR and PHENIX

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%)
- Ratio decreases towards central collisions

Double Ratio



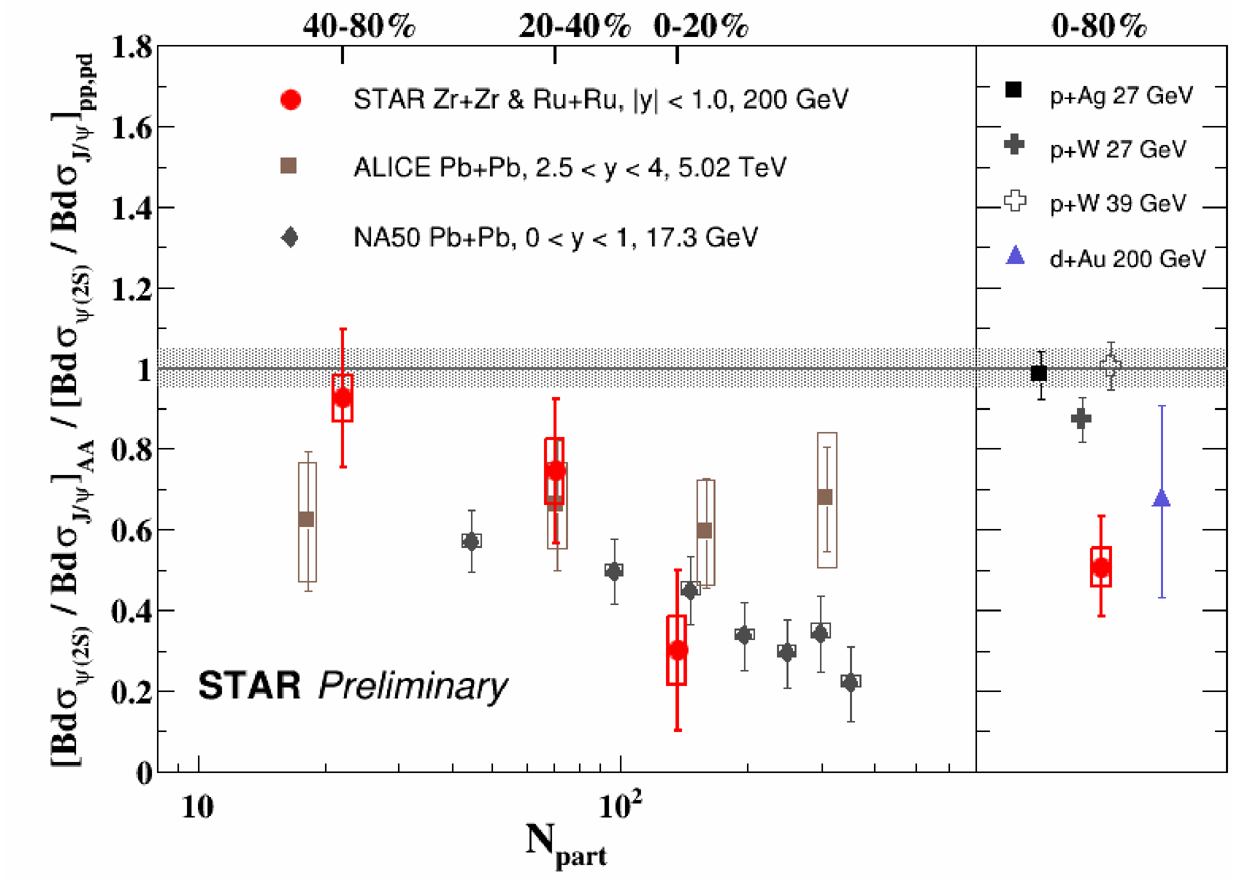
$$\frac{[(Bd\sigma_{\psi(2s)})/(Bd\sigma_{J/\psi})]_{AA}}{[(Bd\sigma_{\psi(2s)})/(Bd\sigma_{J/\psi})]_{pp,pd}}$$

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

PHENIX, Phys.Rev.Lett. 111 (2013)
PHENIX, Phys.Rev.D, 85,092004 (2012)
NA50, Eur.Phys.J.C 48, (2006)
E772, Phys.Rev.Lett. 66 (1991) 133-136

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

Double Ratio



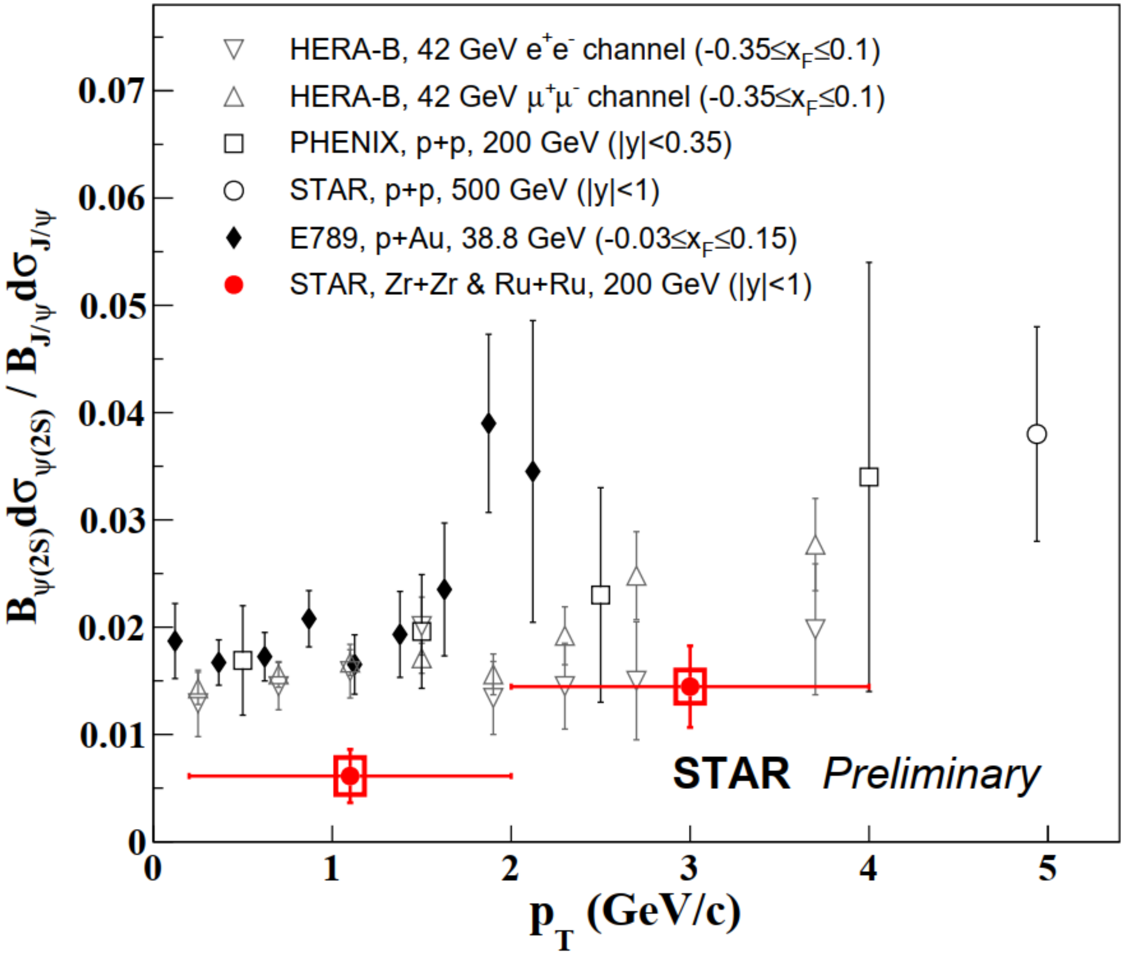
$$\frac{\left[\left(Bd\sigma_{\psi(2s)}\right)/\left(Bd\sigma_{J/\psi}\right)\right]_{AA}}{\left[\left(Bd\sigma_{\psi(2s)}\right)/\left(Bd\sigma_{J/\psi}\right)\right]_{pp,pd}}$$

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

PHENIX, Phys.Rev.Lett. 111 (2013)
PHENIX, Phys.Rev.D, 85,092004 (2012)
NA50, Eur.Phys.J.C 48, (2006)
E772, Phys.Rev.Lett. 66 (1991) 133-136

- ψ(2S) over J/ψ double ratio is smaller than that in p+A collisions
- Centrality dependence trend seems to be more similar to that at SPS than at LHC

ψ(2S) to J/ψ Ratio vs p_T



- ψ(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
- Less conclusive at higher p_T due to large uncertainties in both p+p and A+A

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
- First observation of charmonium sequential suppression at RHIC
- No significant collision energy and system dependence of J/ψ R_{AA}
- J/ψ R_{AA} increases with p_T, hint of decreasing with centrality

→ Interplay of dissociation, regeneration and cold nuclear matter effects

→ Constrain QGP properties

Back up

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

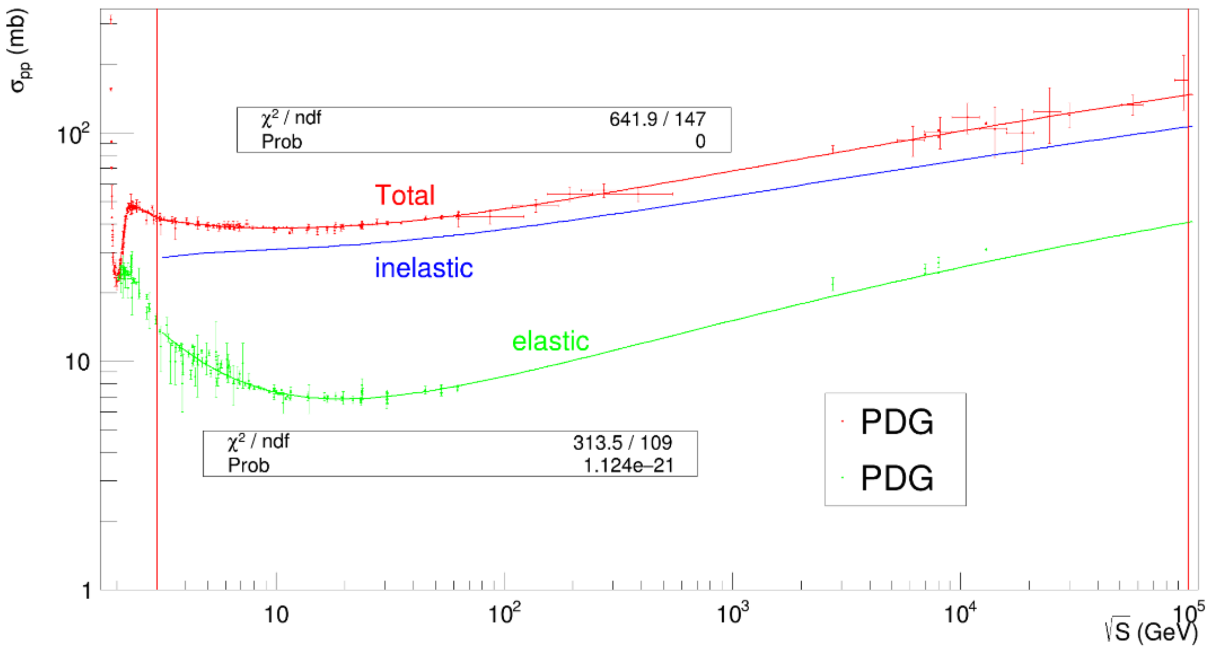
- $n\sigma_e$ efficiency
- 1/β efficiency
- TOF Matching efficiency

<table>
<tr><th>Analyzed bin</th><th>27 GeV</th><th>19.6 GeV</th><th>14.6 GeV</th></tr>
<tr><td>0-80%</td><td>12.4 %</td><td>11.2 %</td><td>13.2 %</td></tr>
<tr><td>0-20%</td><td>13.2 %</td><td>12.3 %</td><td>13.1 %</td></tr>
<tr><td>20-40%</td><td>12.1 %</td><td>11.5 %</td><td>15.0 %</td></tr>
<tr><td>40-60%</td><td>11.5 %</td><td>11.6 %</td><td rowspan="2">13.5 %</td></tr>
<tr><td>60-80%</td><td>14.4 %</td><td>16.1 %</td></tr>
<tr><td>0-1GeV/c</td><td>12.8 %</td><td>12.5 %</td><td>14.6 %</td></tr>
<tr><td>1-2GeV/c</td><td>14.4 %</td><td>11.6 %</td><td>12.7 %</td></tr>
<tr><td>2-4GeV/c</td><td>11.6 %</td><td>15.0 %</td><td>24.1 %</td></tr>
</table>

PP Inelastic Cross Section

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

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



$\sqrt{S_{NN}}$ (GeV)	$\sigma_{inelastic}$ (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/