Supported in part by

Quarkonia Physics at STAR

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(For the STAR Collaboration)
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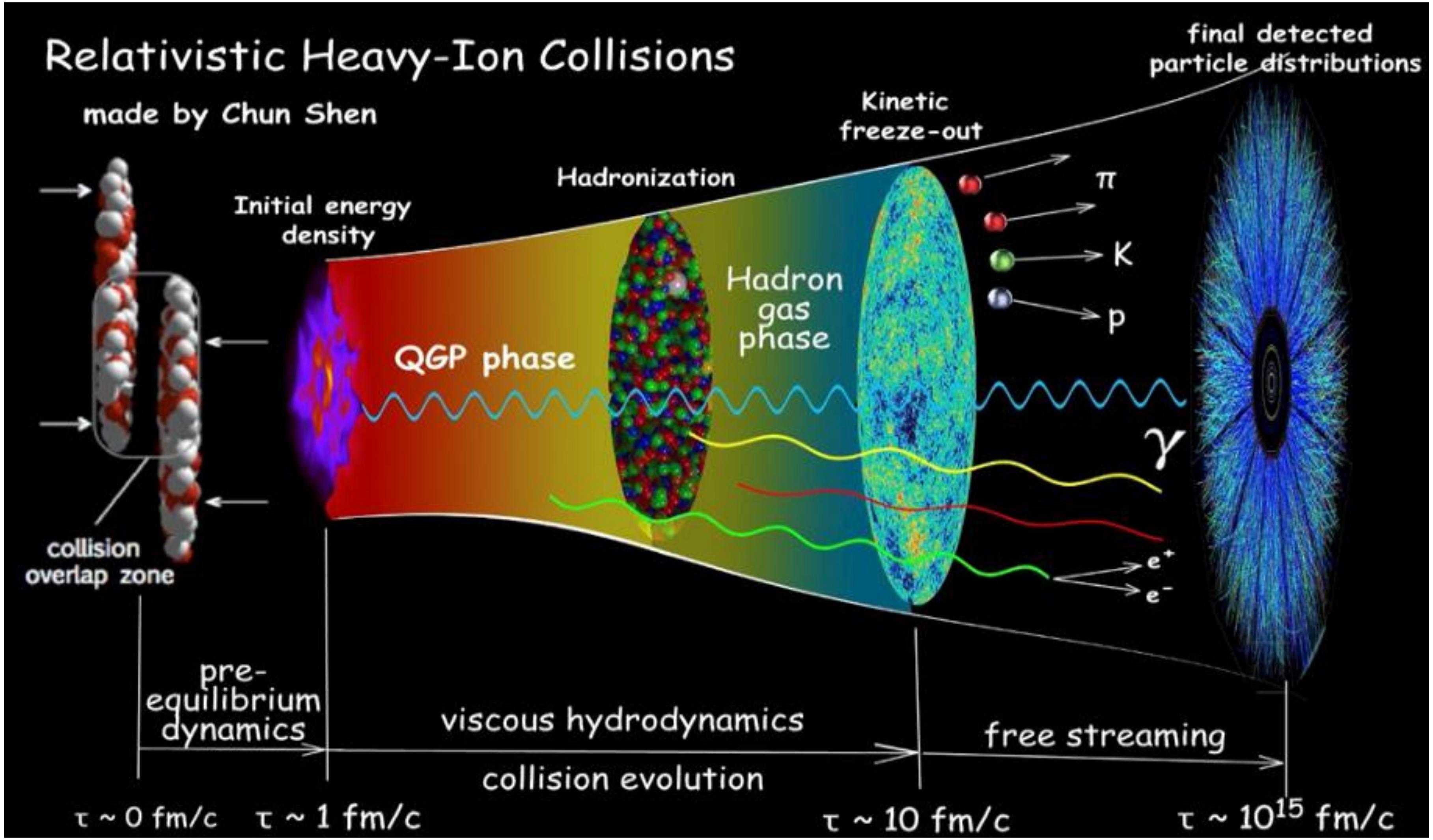
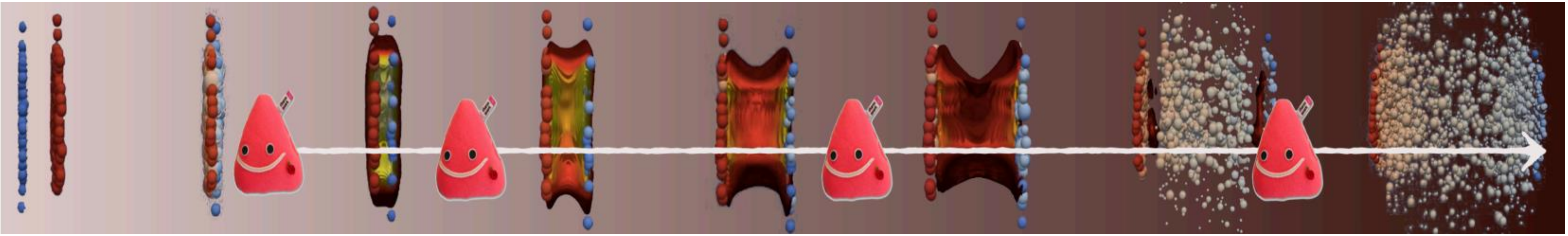
Relativistic Heavy Ion Collisions



Good Probe of the Quark-Gluon Plasma (QGP)

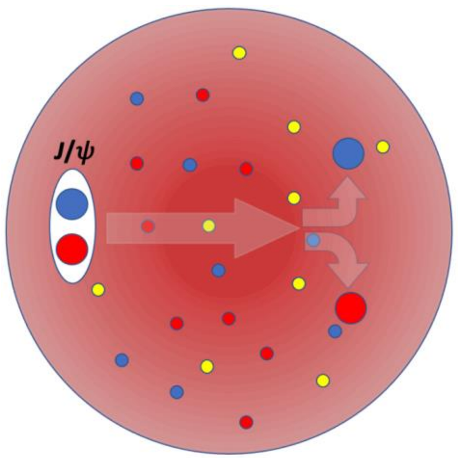


Heavy Quarkonia

- Produced in initial hard scatterings (<0.1fm/c)
- m_c, $m_b >> T_{QGP}$
- Experiences the entire evolution of QGP

Nuclear Modification Factor

Dissociation → Results in a decrease in quarkonia yield



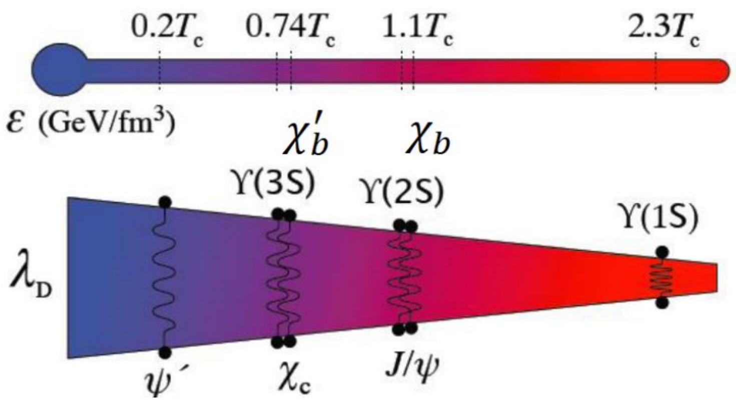
Credit: Q. Yang

$$R_{AA} = \frac{\sigma_{\mathrm{inel}}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dydp_T}{d^2\sigma_{pp}/dydp_T} = \frac{1}{\langle T_{AA} \rangle} \frac{d^2 N_{AA}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

$R_{AA} < 1$ suppression
$R_{AA} = 1$ no net medium effects
$R_{AA} > 1$ enhancement

Sequential Suppression

sequential suppression pattern

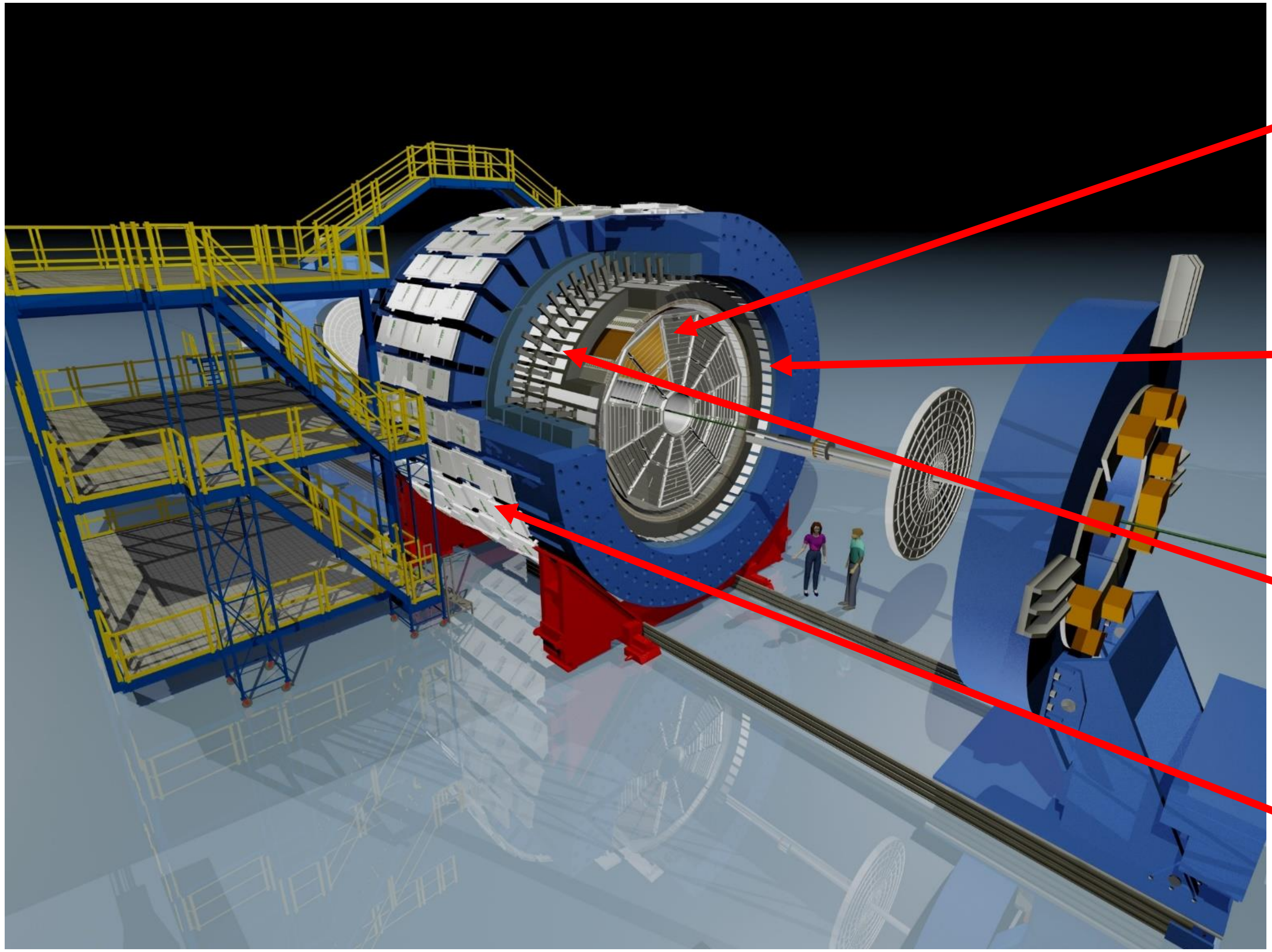


S. Diagl, P. Petreczky and H. Satz, PLB514, 57 (2001)

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

- Systematically analyze
  - Energy dependence
  - P_T, centrality dependence
  - System size dependence
  - Binding energy dependence
  - Polarization

the Solenoidal Tracker at RHIC



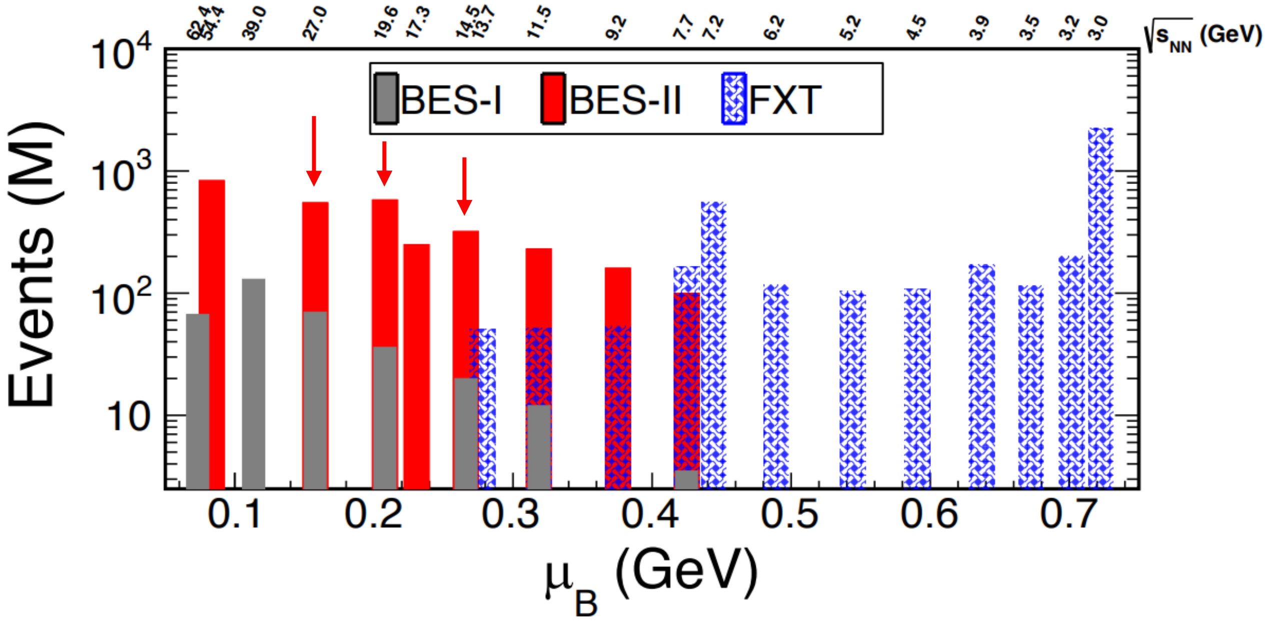
Time Projection Chamber
Tracking, momentum and energy loss
Acceptance: $|\eta| < 1$; $0 \leq \varphi < 2\pi$

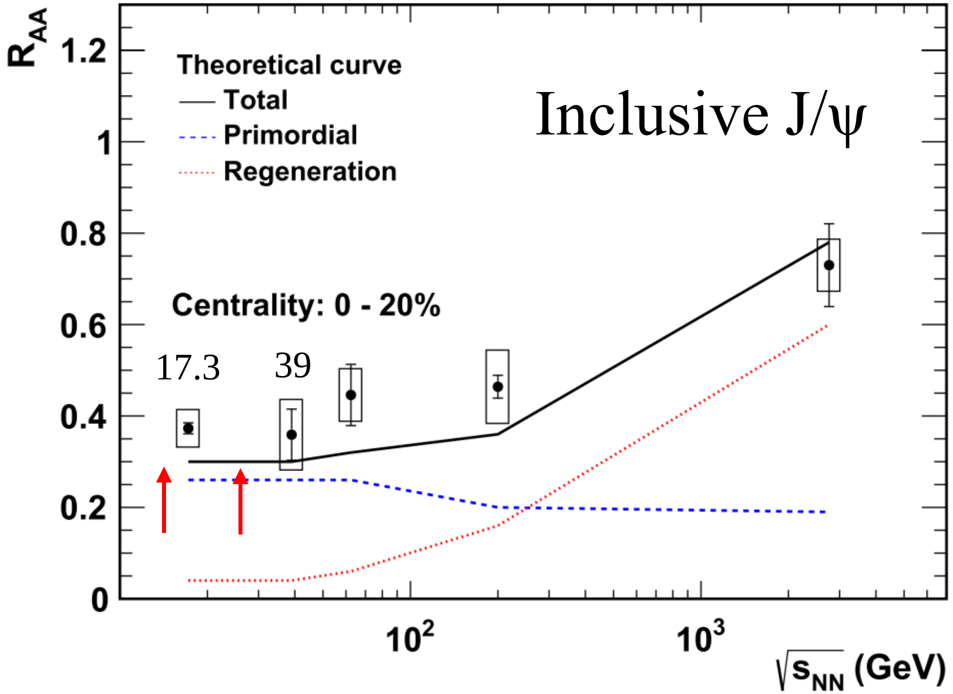
Time Of Flight Detector
Time of flight, particle identification
Acceptance: $|\eta| < 1$; $0 \leq \varphi < 2\pi$

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

Muon Telescope Detector
$\mu^{\pm}$ trigger and identification
Acceptance: $|\eta| < 0.5$, ~ 45% in φ

Au+Au Collisions at STAR



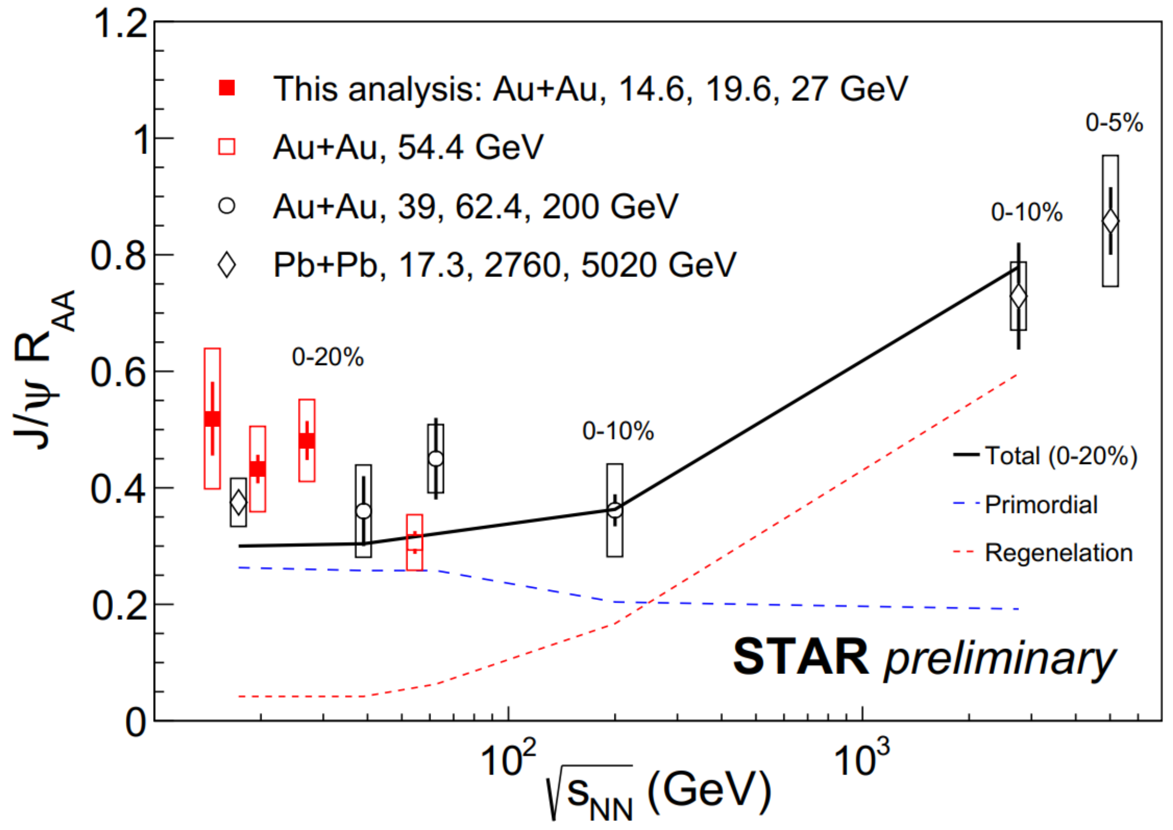


STAR Collaboration Phys. Lett. B 771 (2017) 13–20

- 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

Energy Dependence of J/ψ R_{AA}

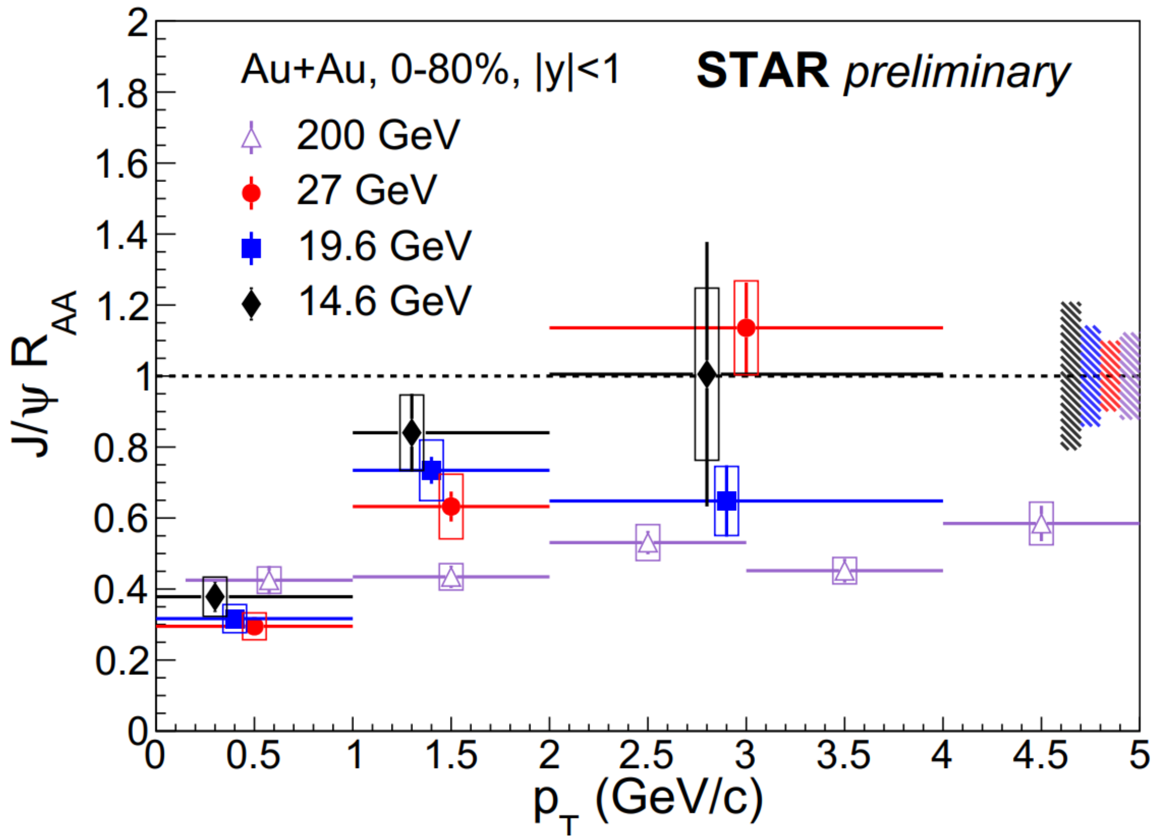


X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
L. Kluberg, Eur. Phys. J. C 43 (2005) 145.
NA50 Collaboration, Phys. Lett. B 477 (2000) 28.

- Data at $\sqrt{s_{NN}}$ = 14.6, 19.6 and 27 GeV follow global 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

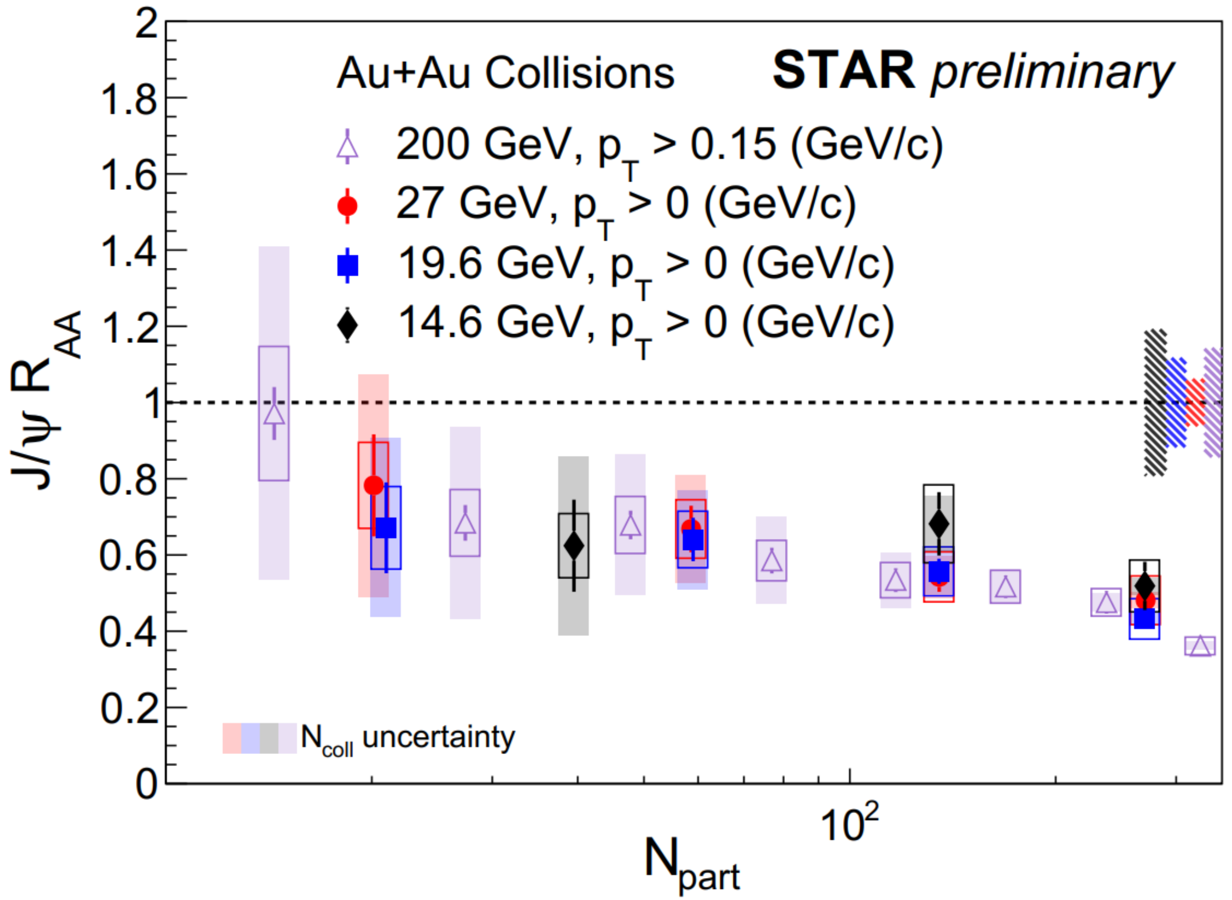
ALICE Collaboration, Phys. Lett. B 734 (2014) 314
STAR Collaboration, Phys. Lett. B 771 (2017) 13-20
STAR Collaboration, Phys. Lett. B 797 (2019) 134917
ALICE Collaboration, Nucl. Phys. A 1005 (2021) 121769

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



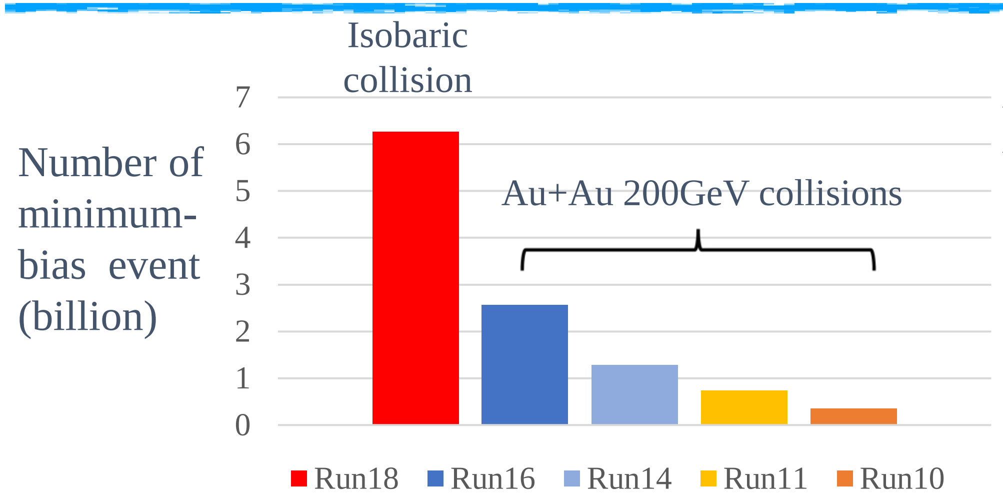
- Low p_T suppression, R_{AA} increases with p_T for $\sqrt{s_{NN}}$ = 14.6, 19.6 and 27 GeV
- No significant p_T dependence at 200 GeV

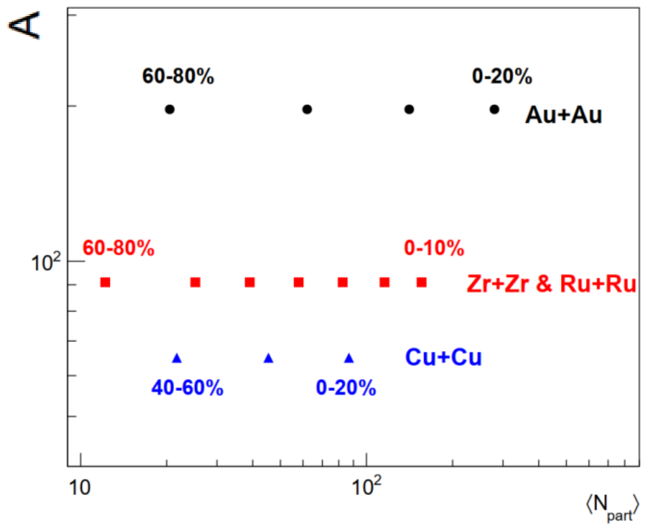
J/ψ R_{AA} vs. $\langle N_{part} \rangle$ in Au+Au Collisions



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

Zr+Zr & Ru+Ru Collisions at STAR

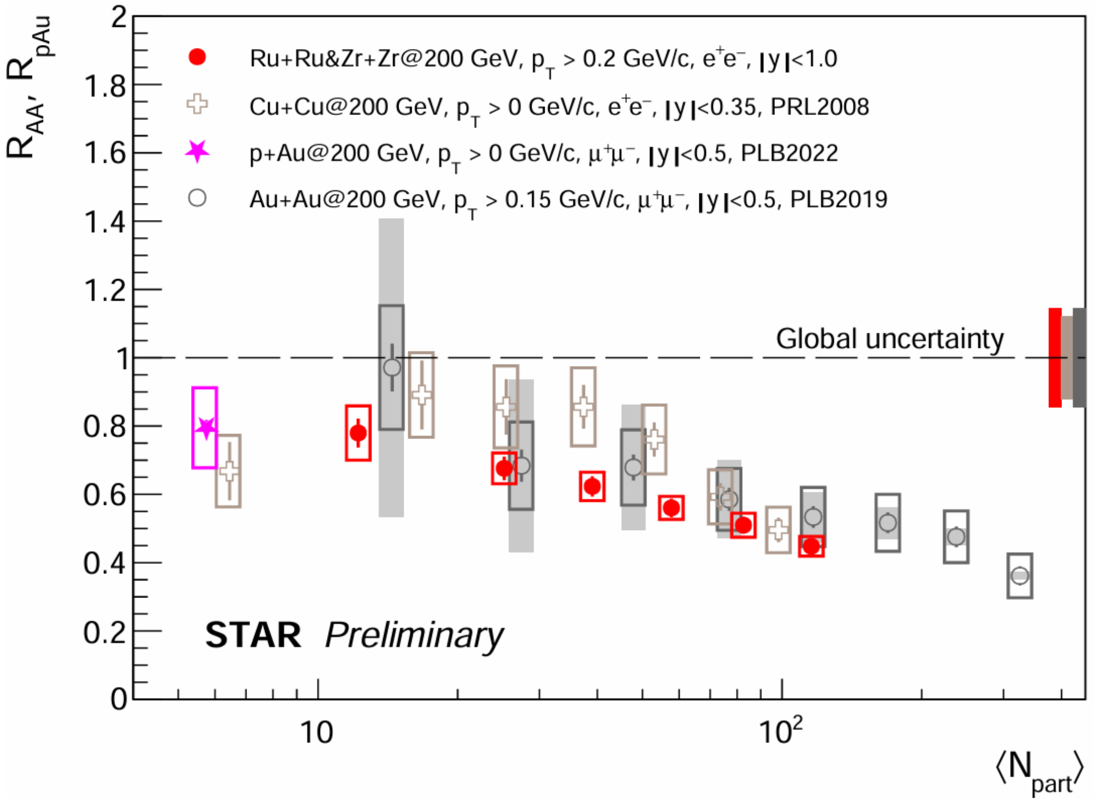




- High statistics enables measurements of：
  - J/ψ production with high precision
  - Sequential suppression of J/ψ, ψ(2S), ϒ(1S), ϒ(2S)
  - J/ψ polarization

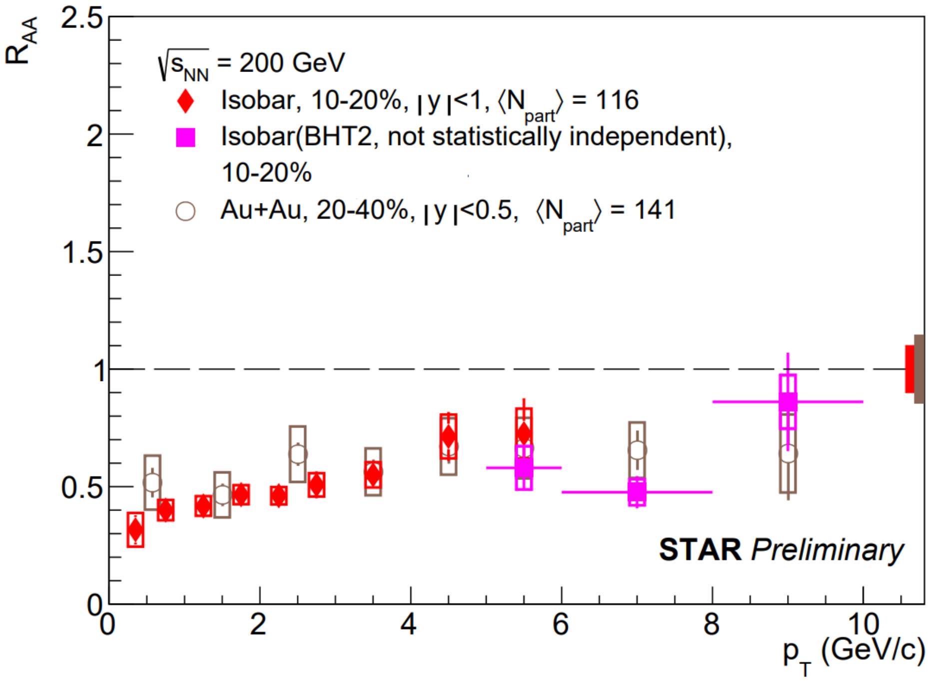
- A moderate size collision system
  - Unique opportunity to study the system size dependence

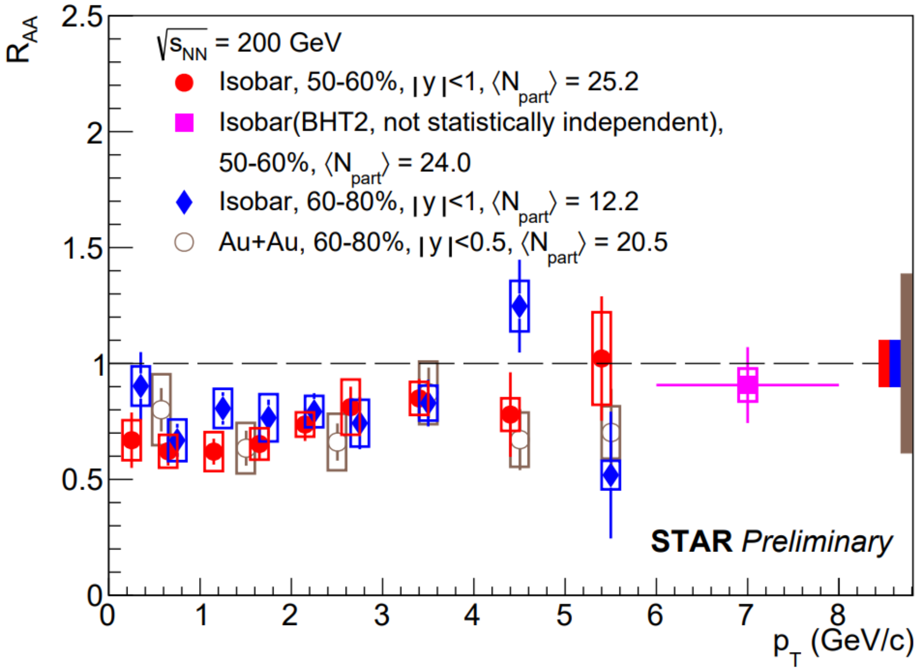
J/ψ R_{AA} vs. $\langle N_{part} \rangle$ at RHIC



- No significant collision system dependence observed at RHIC
- Driven by overlap size rather than collision geometry

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

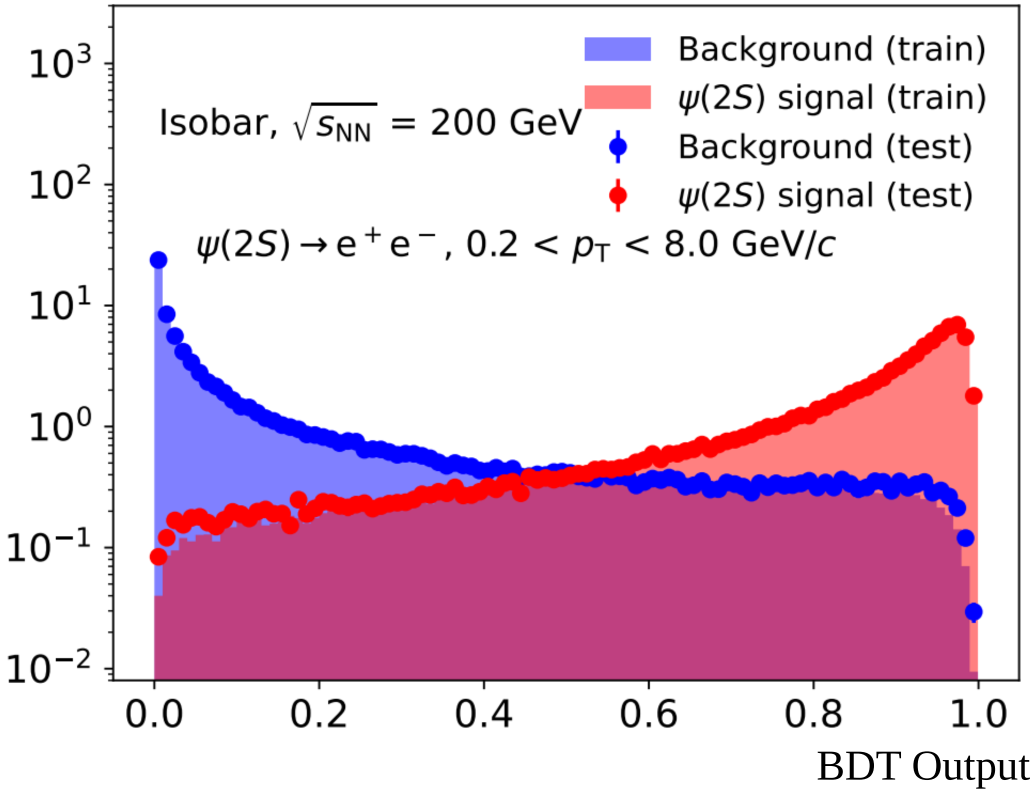


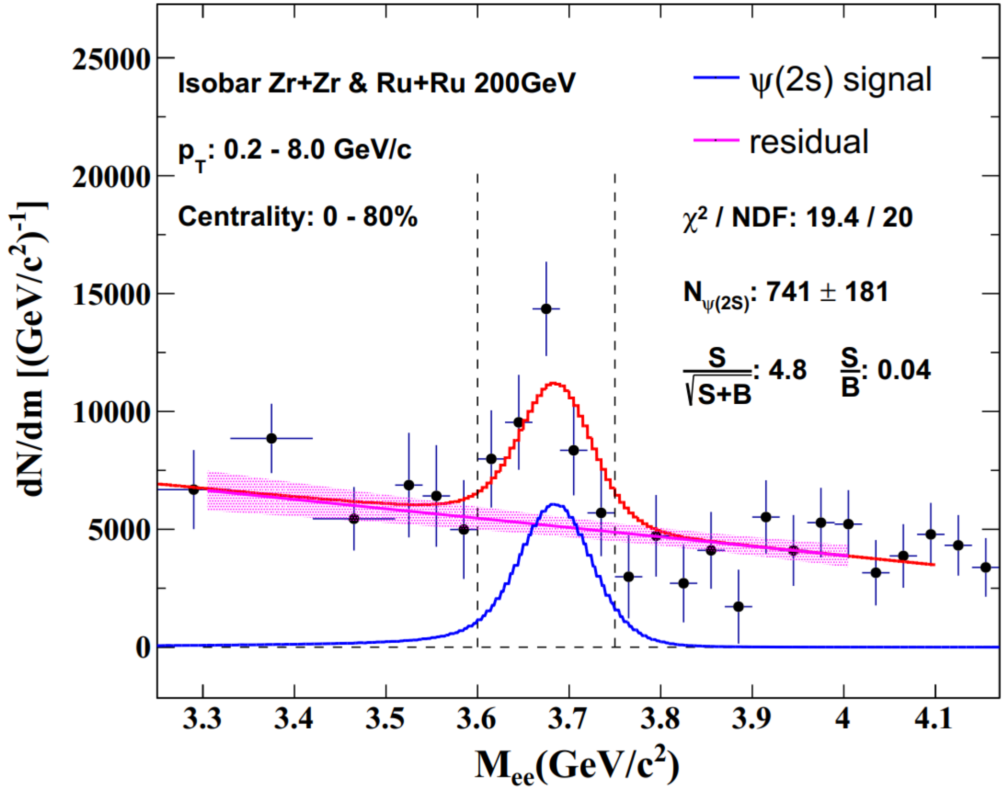


STAR Collaboration, Phys. Lett. B 797 (2019) 134917

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

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

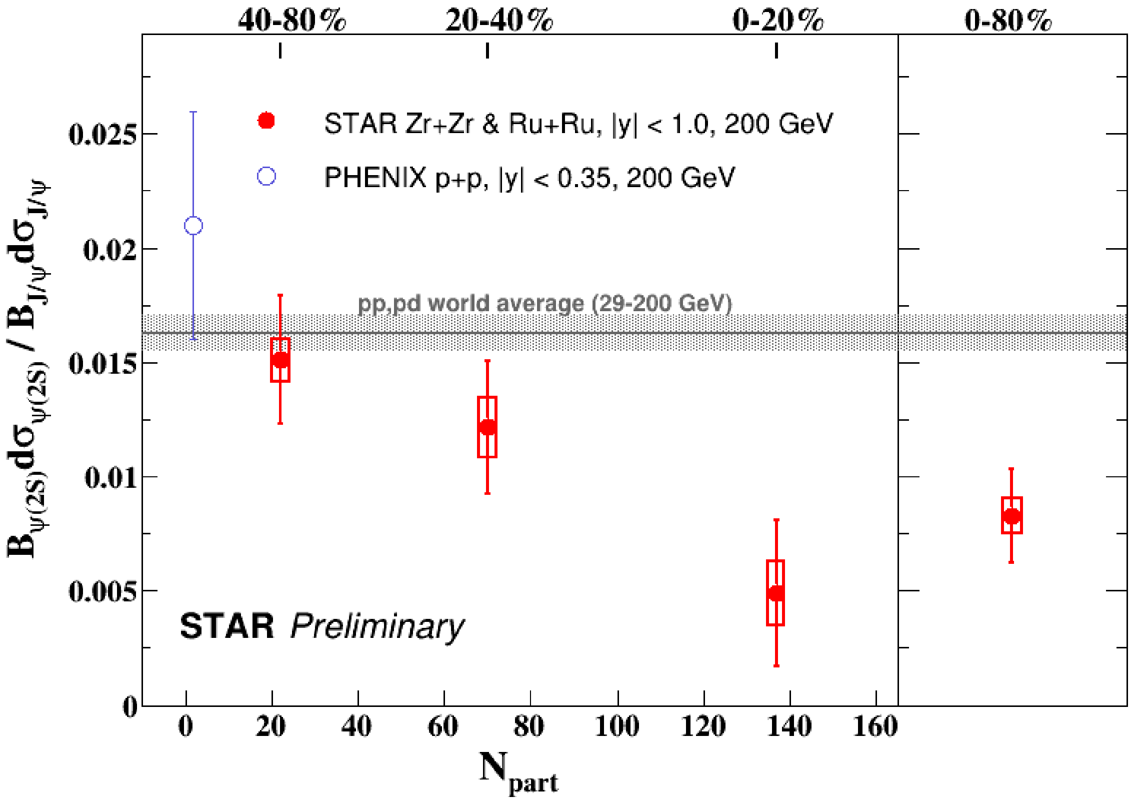




- A machine learning method is employed to reconstruct the ψ(2S) signal

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

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

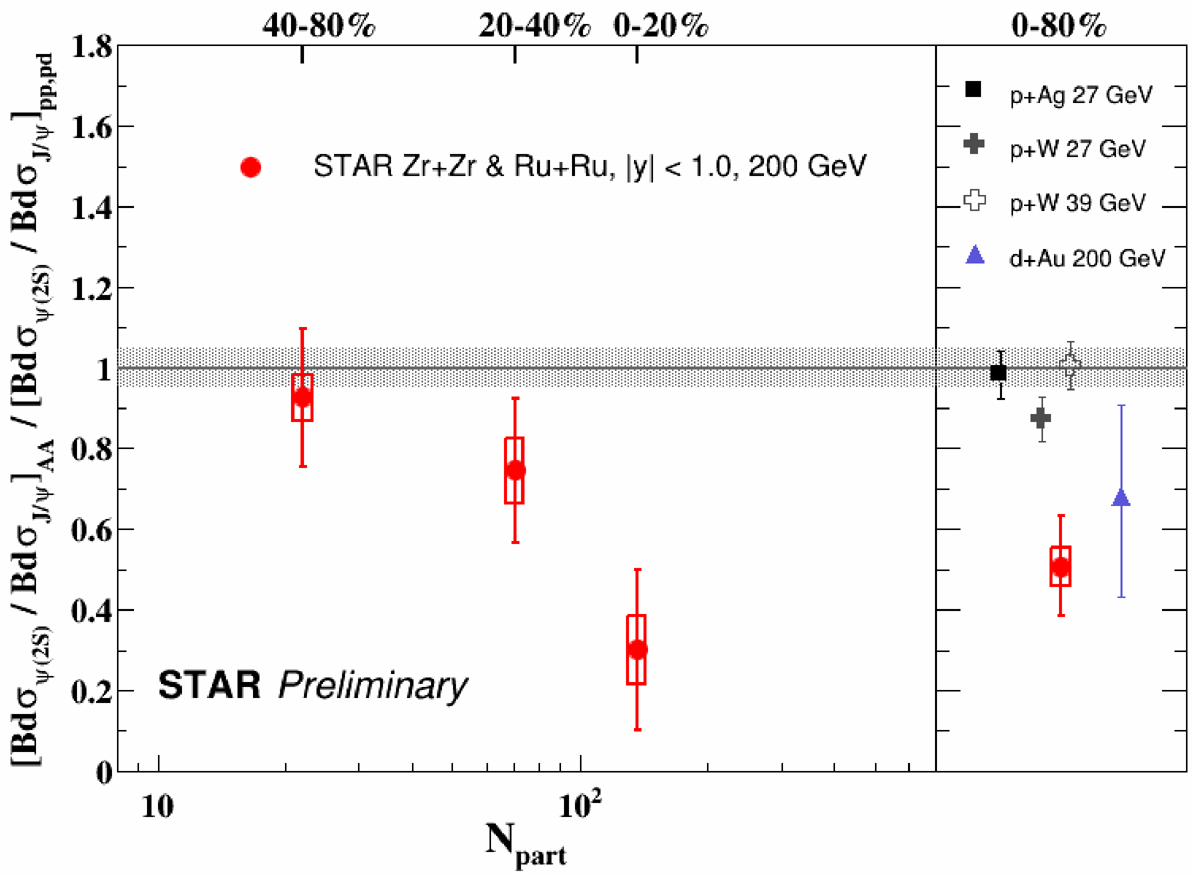


pp reference is the average of measurements in p+p(d) by NA51, ISR and PHENIX

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%)
- Hint of ratio decreases towards central collisions

Double Ratio



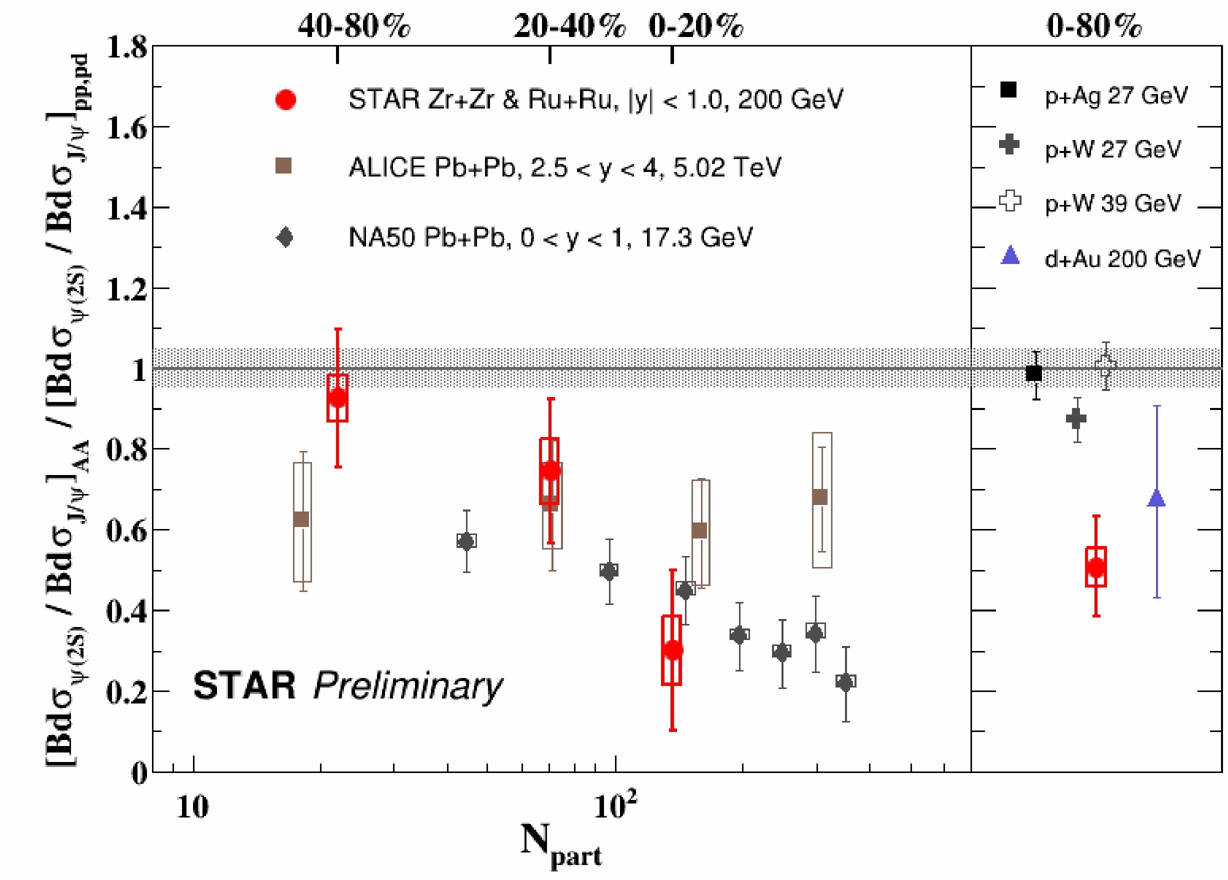
$$\frac{[(Bd\sigma_{\psi(2s)})/(Bd\sigma_{J/\psi})]_{AA}}{[(Bd\sigma_{\psi(2s)})/(Bd\sigma_{J/\psi})]_{pp,pd}}$$

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



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

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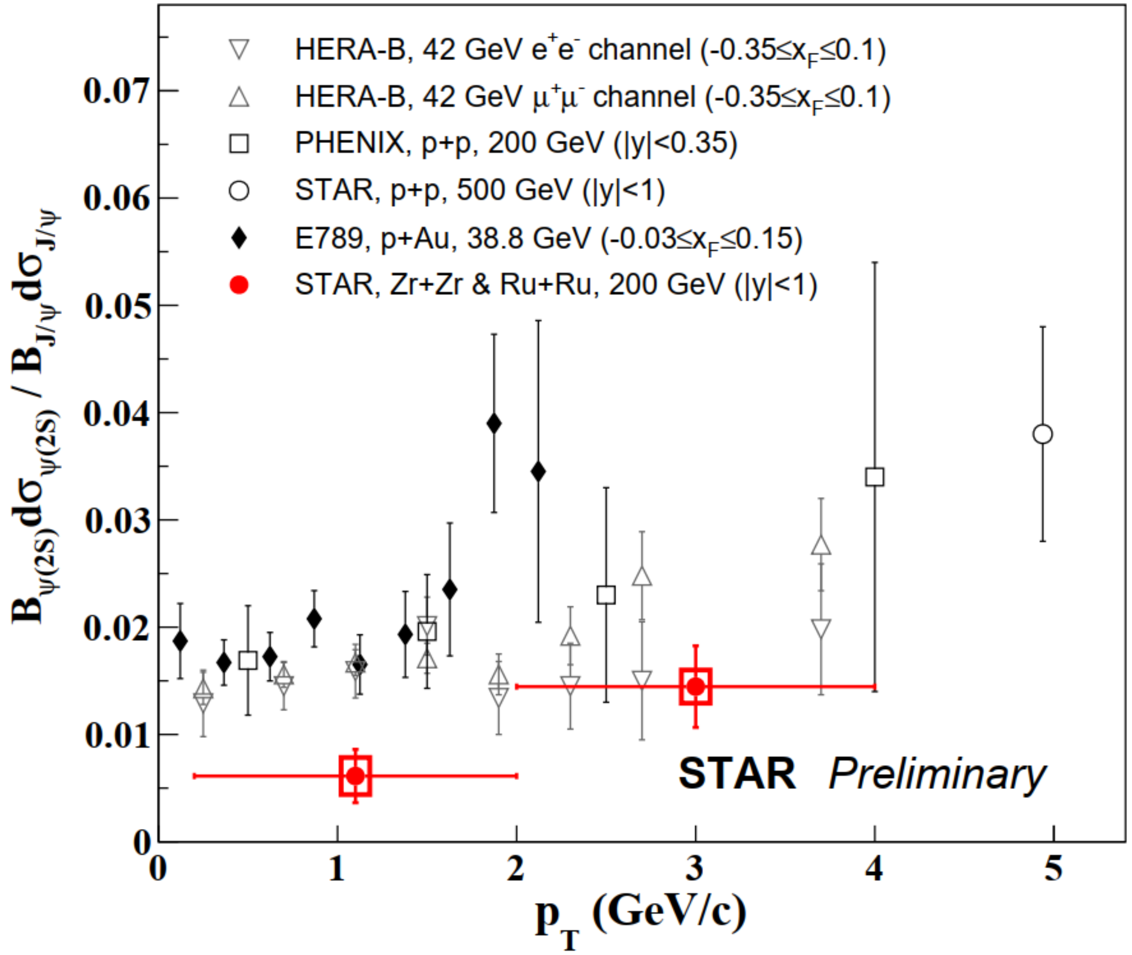
PHENIX, Phys.Rev.Lett. 111 (2013)
PHENIX, Phys.Rev.D, 85,092004 (2012)
NA50, Eur.Phys.J.C 48, (2006)
E772, Phys.Rev.Lett. 66 (1991) 133-136

- 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

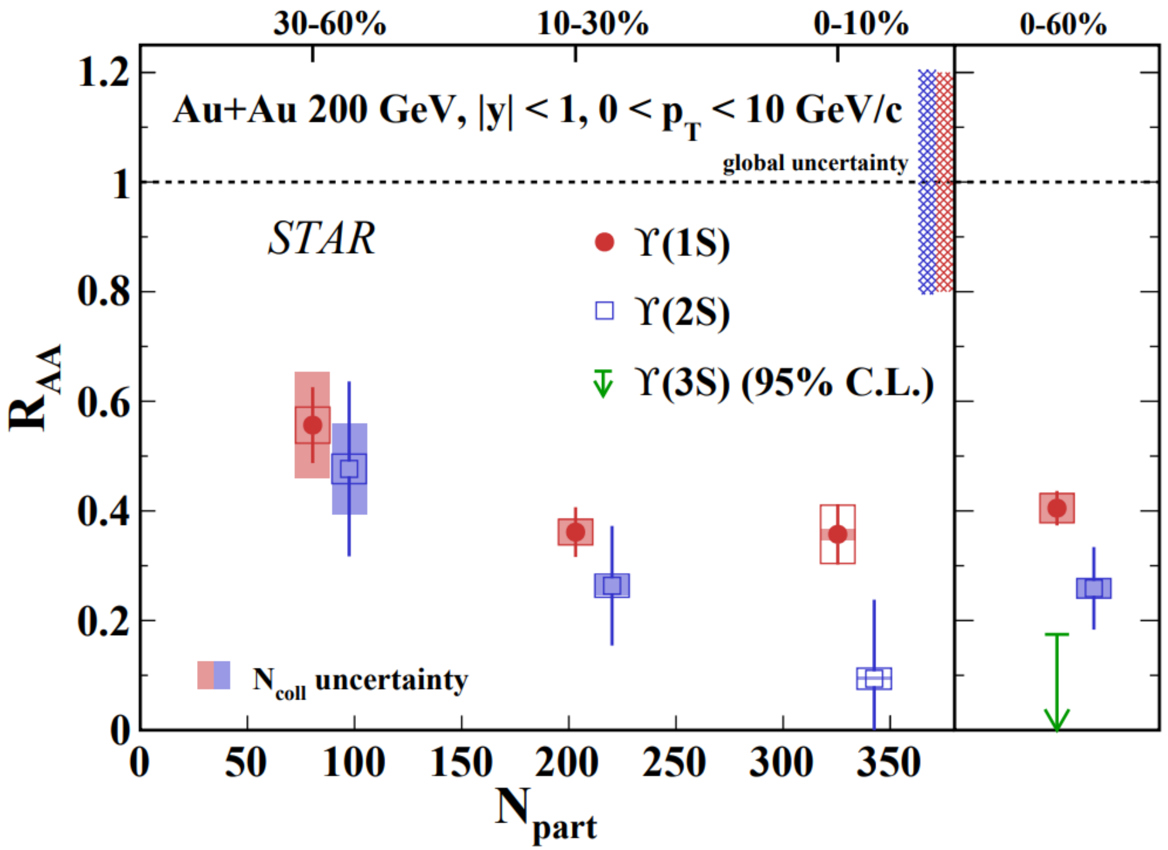
ψ(2S) to J/ψ Ratio vs p_T



- 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

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.

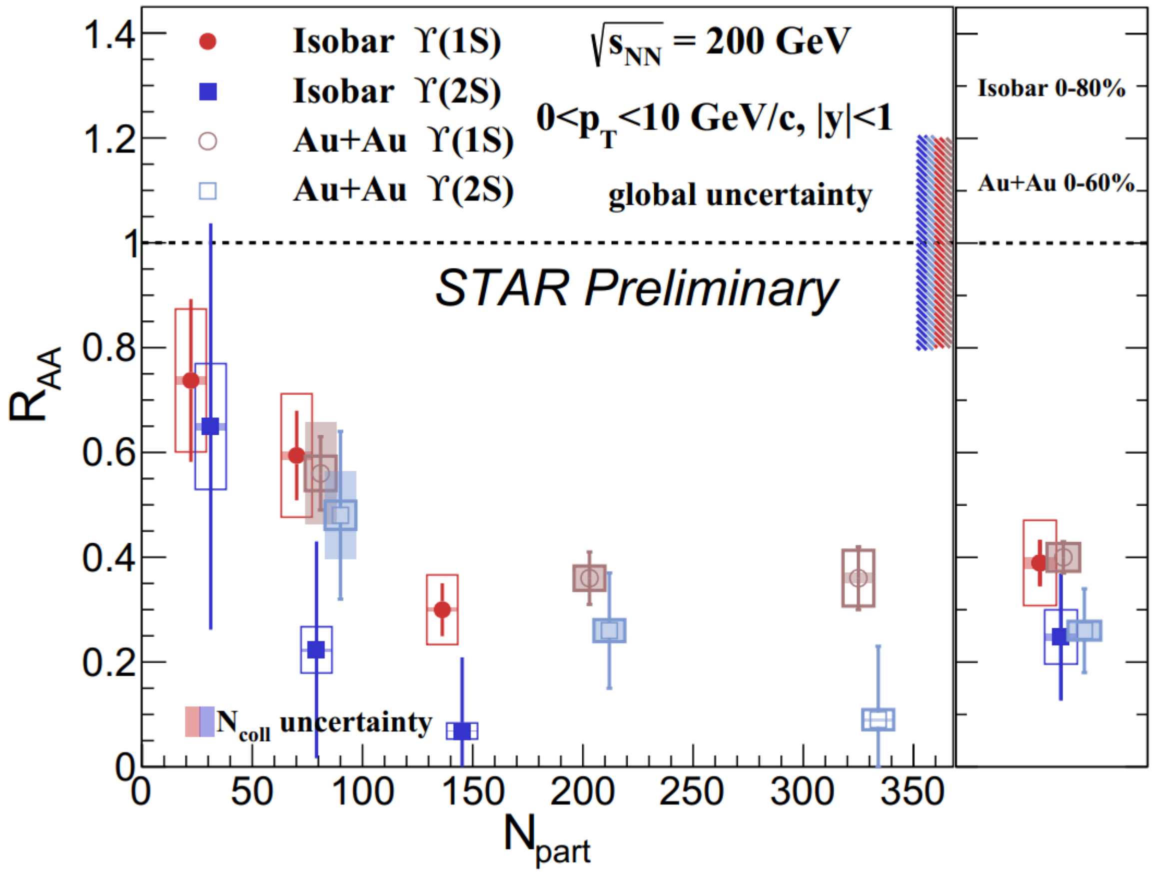
Υ R_{AA} vs. $\langle N_{part} \rangle$ in Au+Au Collisions



STAR, Phys. Rev. Lett. 130 (2023) 112301

- First measurement of suppression of three Υ states separately at RHIC
- $> 3\sigma$ difference for $\Upsilon(1S)$ and $\Upsilon(3S)$

Υ R_{AA} vs. $\langle N_{part} \rangle$ in Zr+Zr & Ru+Ru Collisions

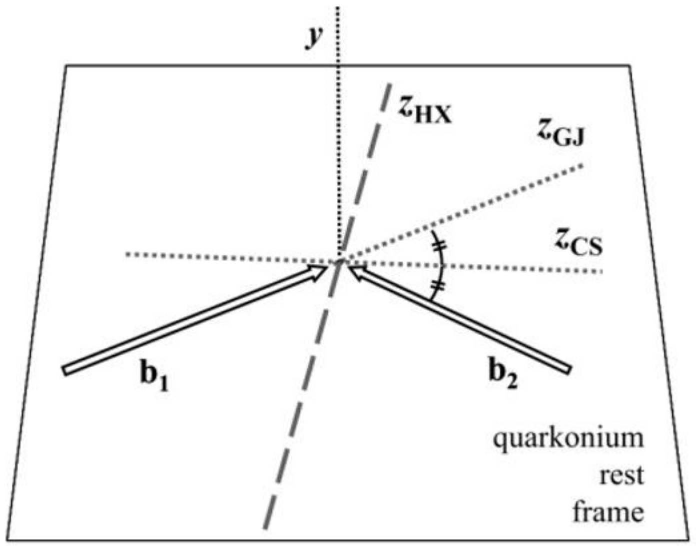


STAR, Phys. Rev. Lett. 130 (2023) 112301

- Hint of sequential suppression pattern
- Isobar covers lower $\langle N_{part} \rangle$ range than Au+Au
- R_{AA} shows a smooth trend from isobar to Au+Au collisions

J/ψ Polarization in Zr+Zr & Ru+Ru Collisions

- Study J/ψ production mechanism in heavy-ion collisions
- J/ψ polarization could be modified by QGP
  - Suppression of feed down
  - Regeneration



Faccioli et al, EPJC 69 (657-673), 2010

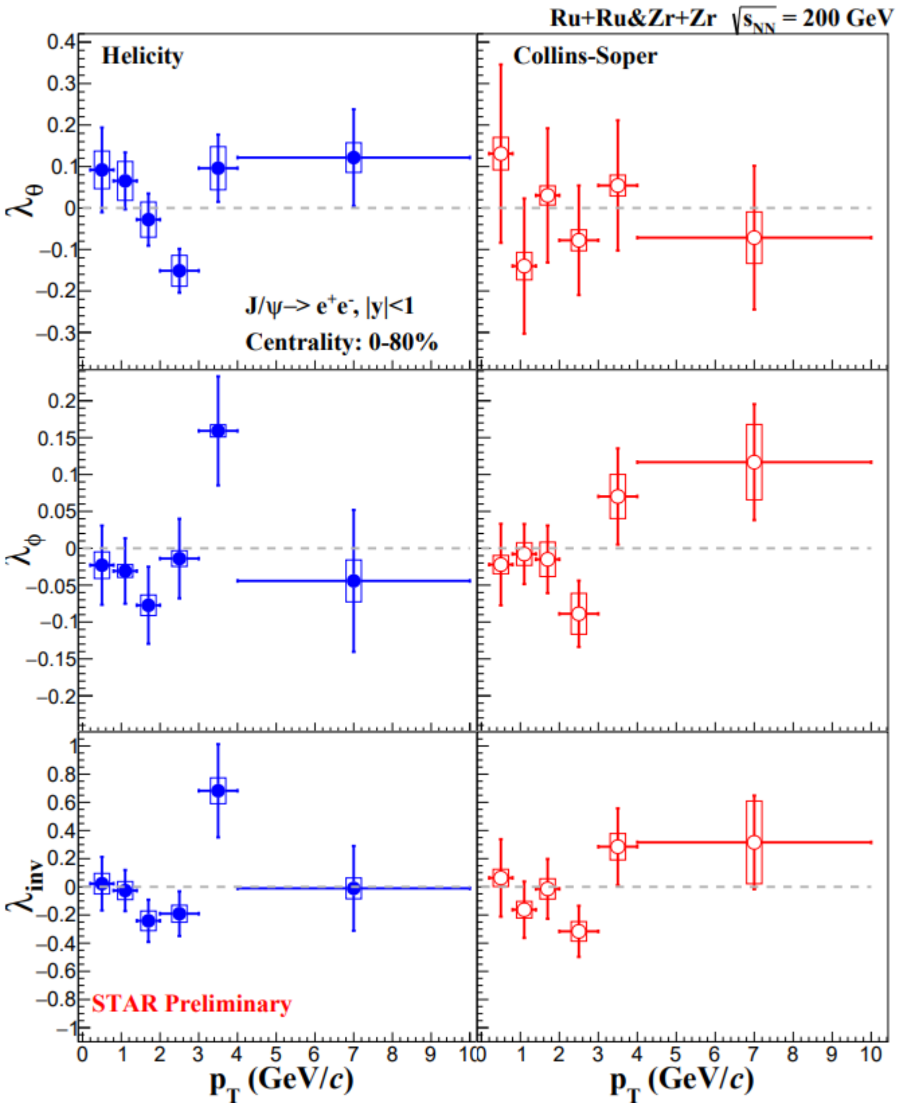
Helicity frame (HX) and Collins-Soper frame (CS)

J/ψ polarization can be extracted via the angular distribution of the decayed positron:

$$W(cos\theta,\phi) \propto 1 + \lambda_\theta cos^2\theta + \lambda_\phi sin^2\theta cos2\phi + \lambda_{\theta\phi} sin2\theta cos\phi$$

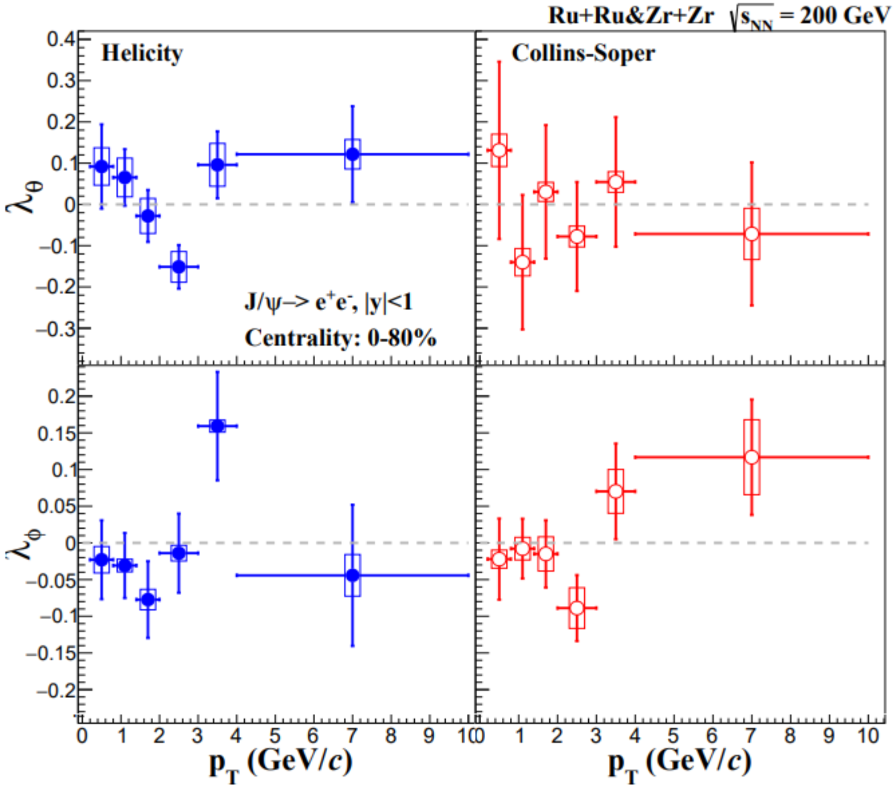
$$\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

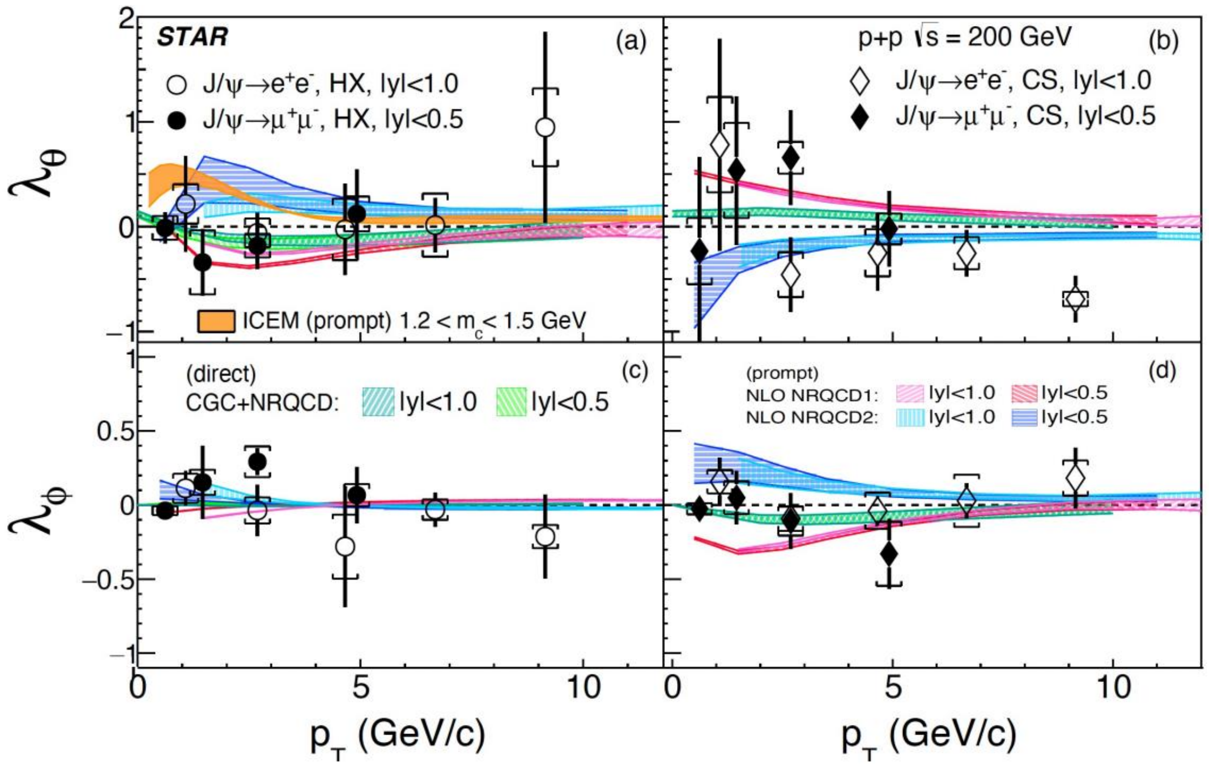
J/ψ Polarization Parameters vs. p_T



- λ_θ,λ_ϕ consistent with zero in HX and CS frames
- overall no significant p_T dependence in either HX or CS

J/ψ Polarization Parameters: HI vs. pp

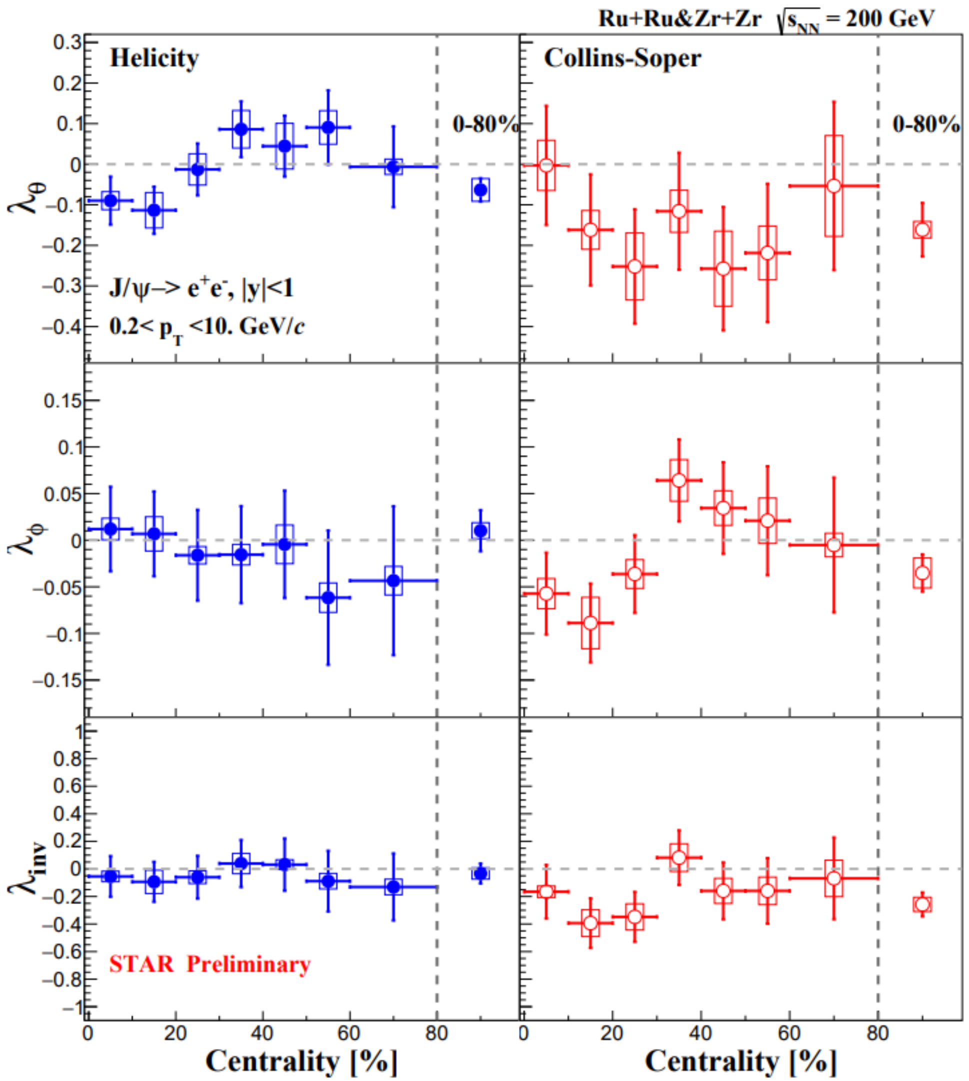




STAR, Phys.Rev.D 102 (2020) 9, 092009

- $\lambda_\theta, \lambda_\phi$ consistent with p+p results within uncertainties

J/ψ Polarization Parameters vs. Centrality



- No significant centrality dependence is observed
- λ_{inv} are consistent between HX and CS frames within uncertainty as expected

Summary

- Significant suppression of charmonia and bottomonia in central heavy-ion collisions
- No significant collision energy dependence of J/ψ R_{AA} with BES-II data
- J/ψ R_{AA} increases with p_T, hint of decreasing with centrality
- No significant dependence of the J/ψ R_{AA} on the collision system size is observed when comparing isobar and Cu+Cu to Au+Au collisions
- First observation of sequential suppression for charmonia and bottomonia at RHIC;
- First measurement of J/ψ polarization in heavy-ion collisions at RHIC, consistent with zero and p+p results

Outlook

✓ Run 23-25, ~18B minimum bias Au+Au events;

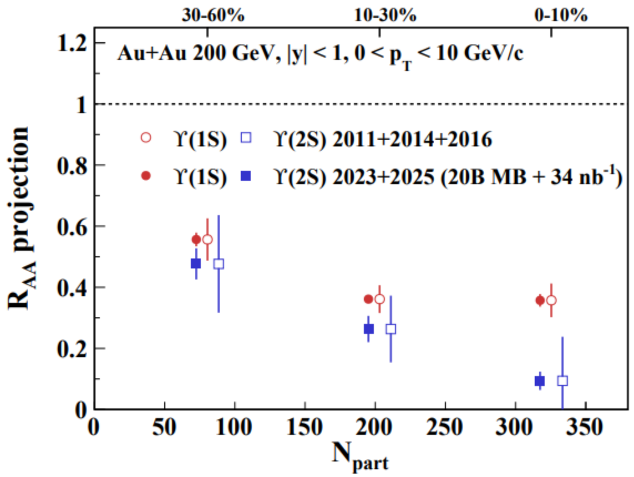
high statistics p+p samples

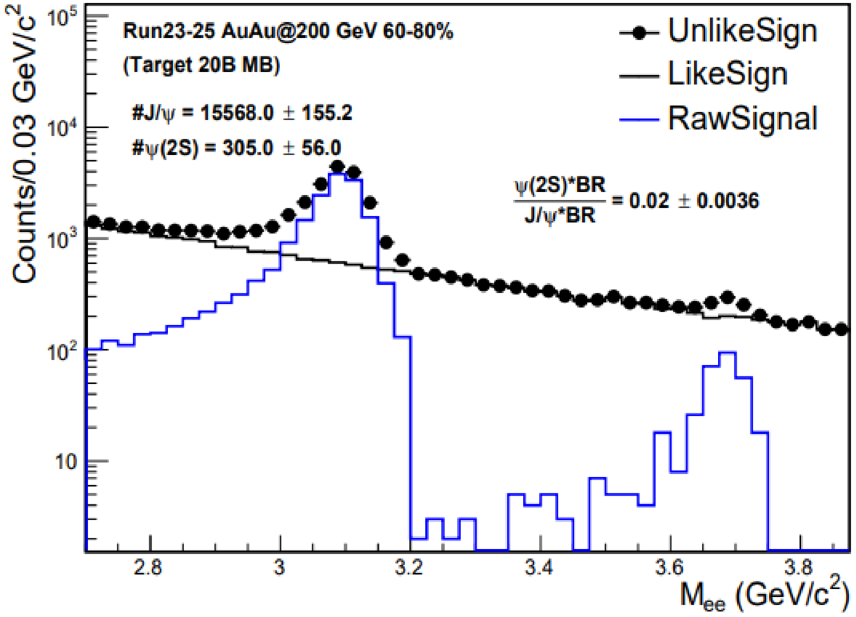
$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	$p+p$	142 pb^{-1}/12w	2024
200	p+Au	0.69 pb^{-1}/10.5w	2024
200	Au+Au	18B / 32.7 nb^{-1}/40w	2023+2025

drupal.star.bnl.gov/STAR/system/files/STAR_BUR_Runs24_25_2023.pdf

➢ Au+Au 200 GeV

- Sequential suppression studies ϒ(1S), ϒ(2S)
- Opportunity to measure ψ (2S) in Au+Au collisions

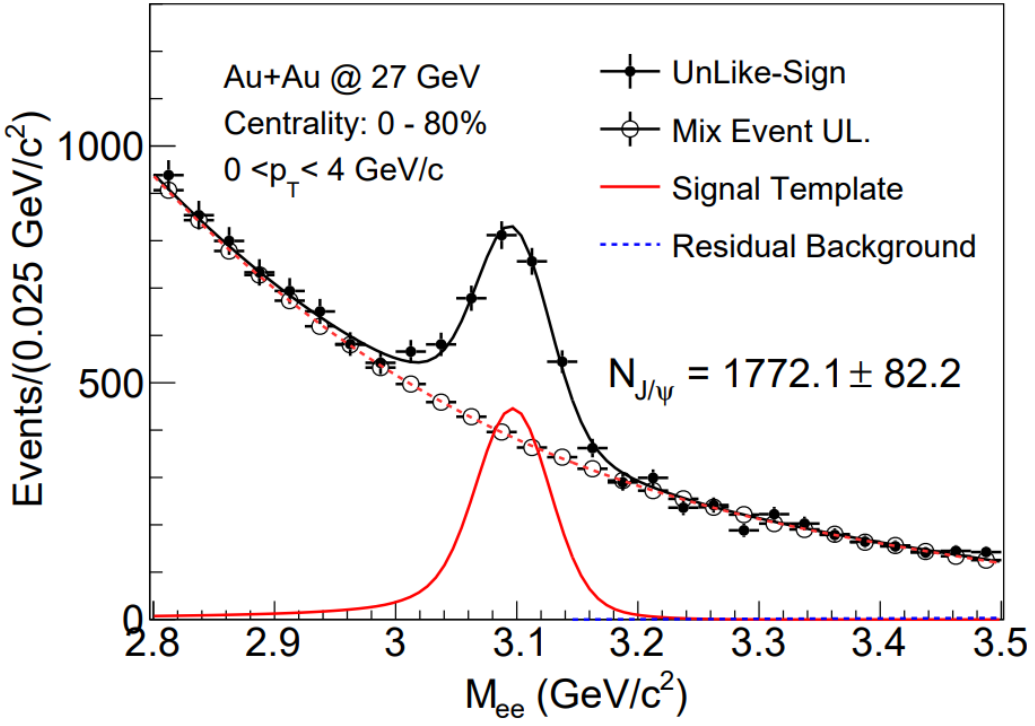




Back up

Raw J/ψ Signal

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

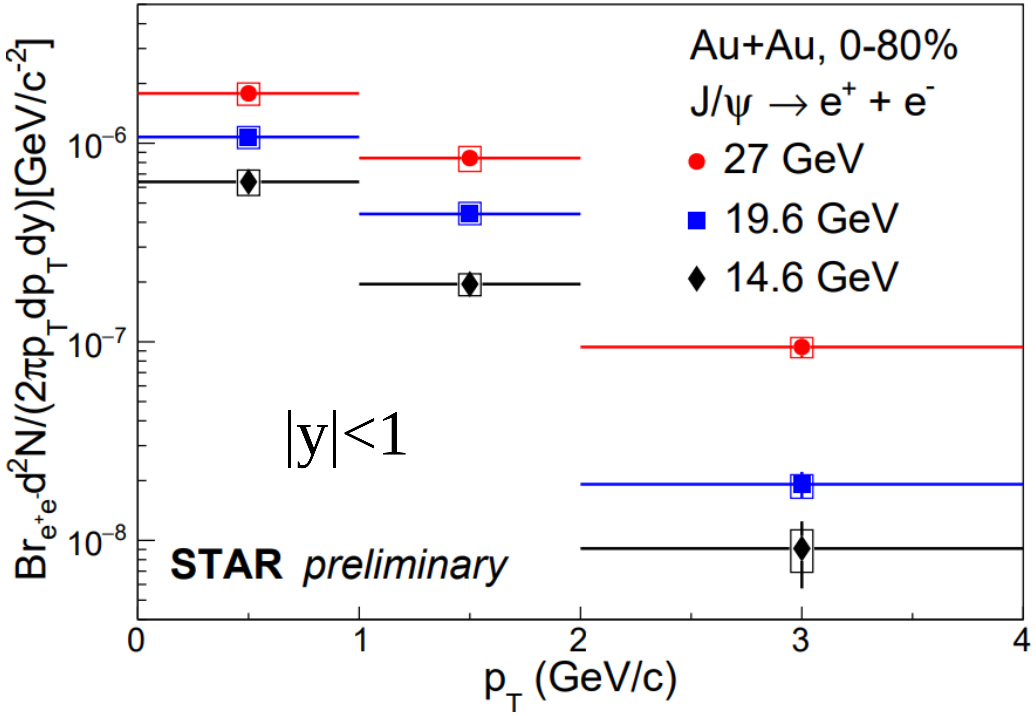


$\sqrt{s_{NN}} = 27$ GeV

- 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, 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

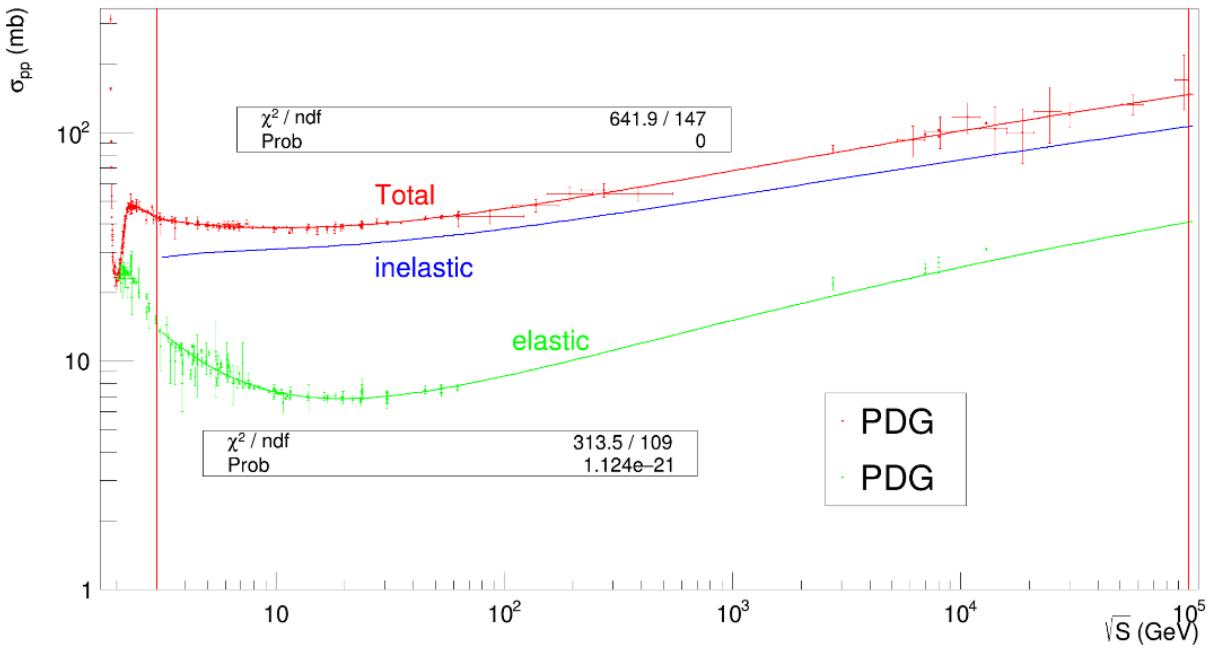
- $n\sigma_e$ efficiency
- $1/\beta$ efficiency
- TOF Matching efficiency

<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

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

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



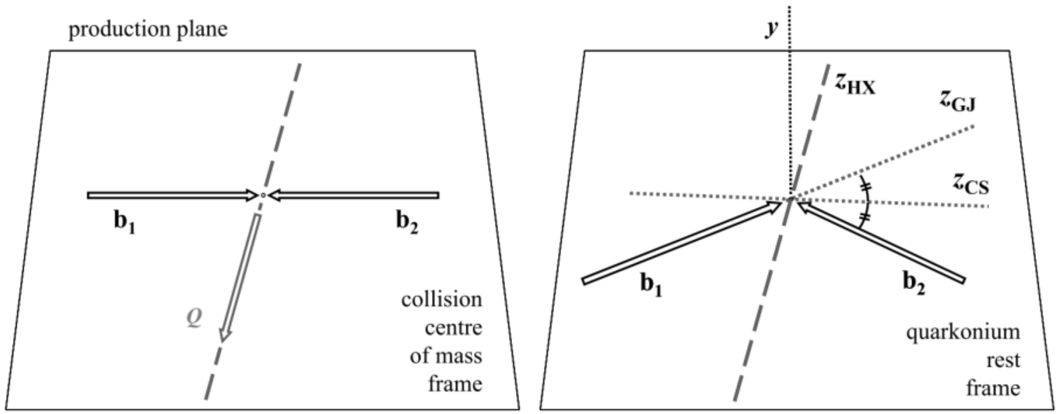
$\sqrt{S_{NN}}$ (GeV)	$\sigma_{inelastic}$ (mb)	Error
200	43.3960	0.766915
27	32.9876	0.163660
19.6	32.0776	0.137064
17.3	31.7791	0.131443
14.6	31.4194	0.125273
11.5	30.9905	0.124518
9.2	30.6478	0.130914

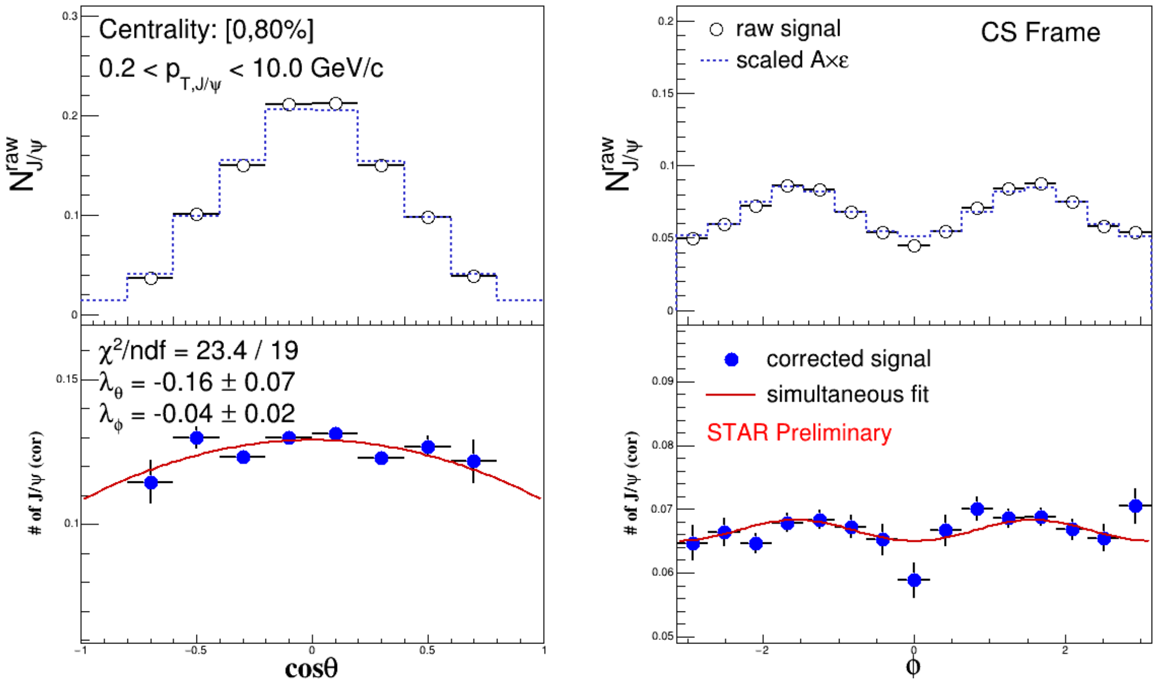
Data from PDG（Particle Data Group）：
https://pdg.lbl.gov/2022/hadronic-xsections/

J/ψ polarization in isobaric collisions

Angular distribution of the decayed leptons:

$$W(cos\theta,\phi) \propto 1 + \lambda_\theta cos^2\theta + \lambda_\phi sin^2\theta cos2\phi + \lambda_{\theta\phi} sin2\theta cos\phi$$





$$F(\theta) = 3 \times \frac{1 + \lambda_\theta cos^2\theta}{2 \times (3 + \lambda_\theta)}$$

$$F(\phi) = \frac{2 \times \lambda_\phi}{2\pi \times (3 + \lambda_\theta)} cos2\phi$$

Helicity frame(HX)

Collins-Soper frame(CS)