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Beam energy and system size dependence of heavy flavor production at STAR

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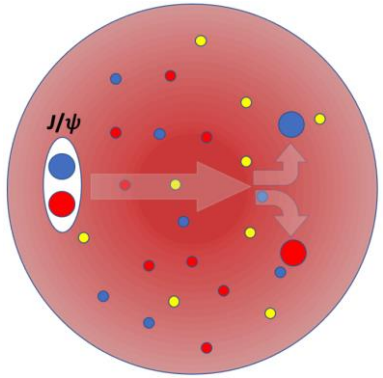
Quark Matter, Sep. 3 – 9, 2023, Houston, USA

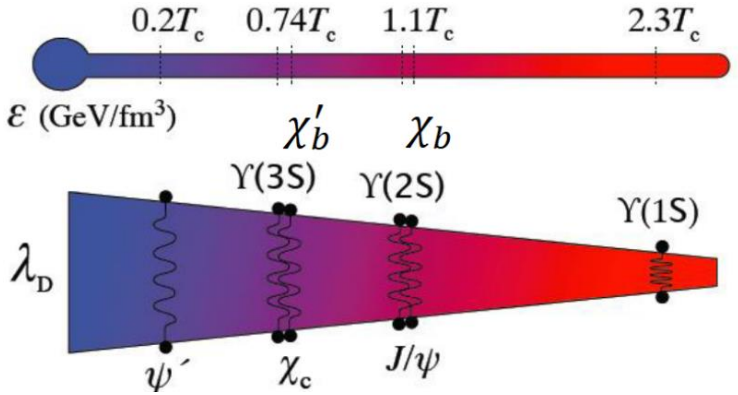
Introduction

- Quarkonium provides a good probe of the Quark-Gluon Plasma (QGP)

Dissociation → sequential suppression



Credit: Q. Yang

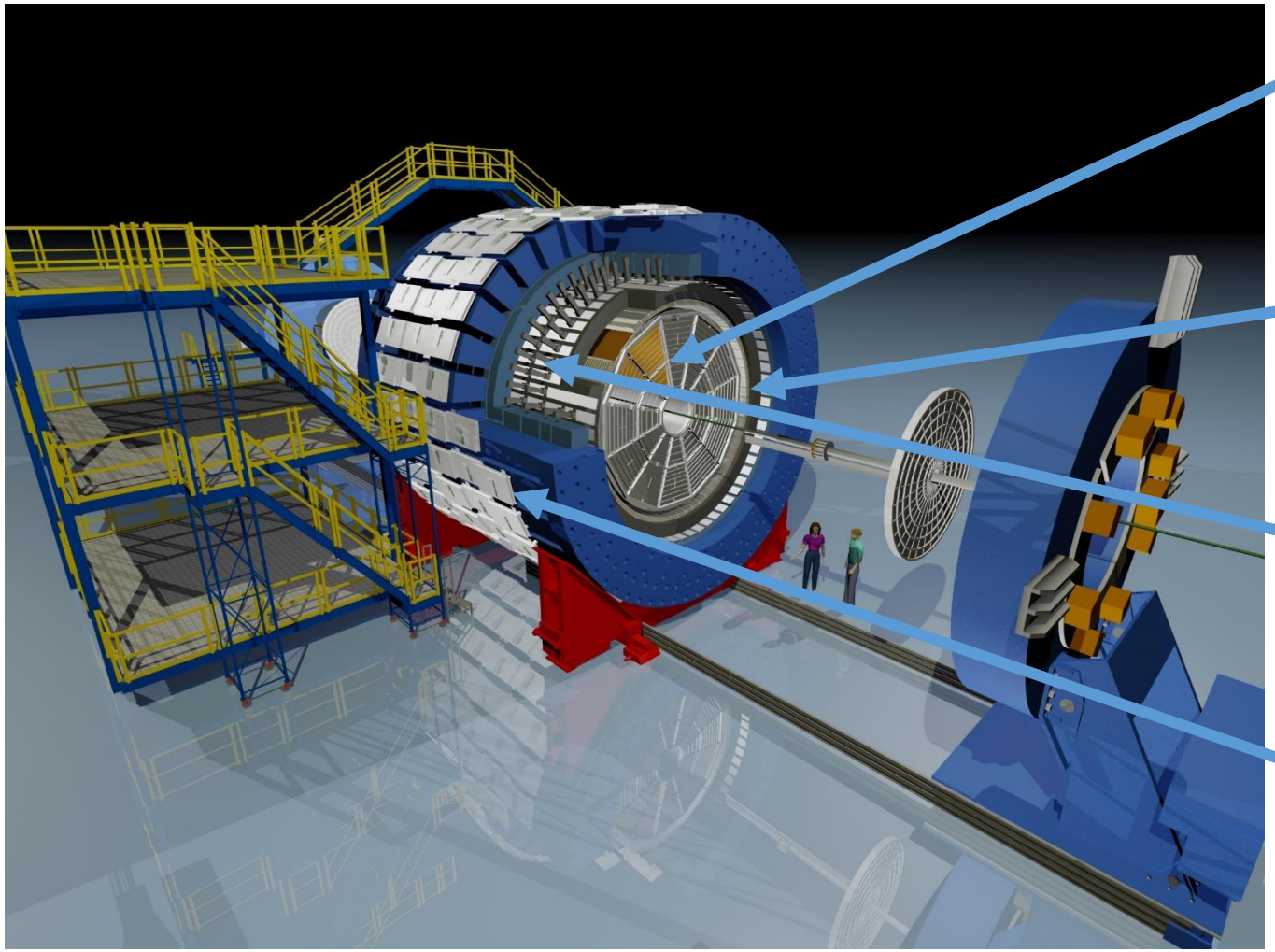


S. Diagl, P. Petreczky and H. Satz, PLB514, 57 (2001)

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

- Systematically analyze
  - Energy dependence
  - System size dependence
  - Different quarkonia
  - Polarization

The Solenoidal Tracker At RHIC



✓ **TPC**

Tracking, momentum and energy loss

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

✓ **TOF**

Time of flight, particle identification

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

✓ **BEMC**

$e^{\pm}$ trigger and identification

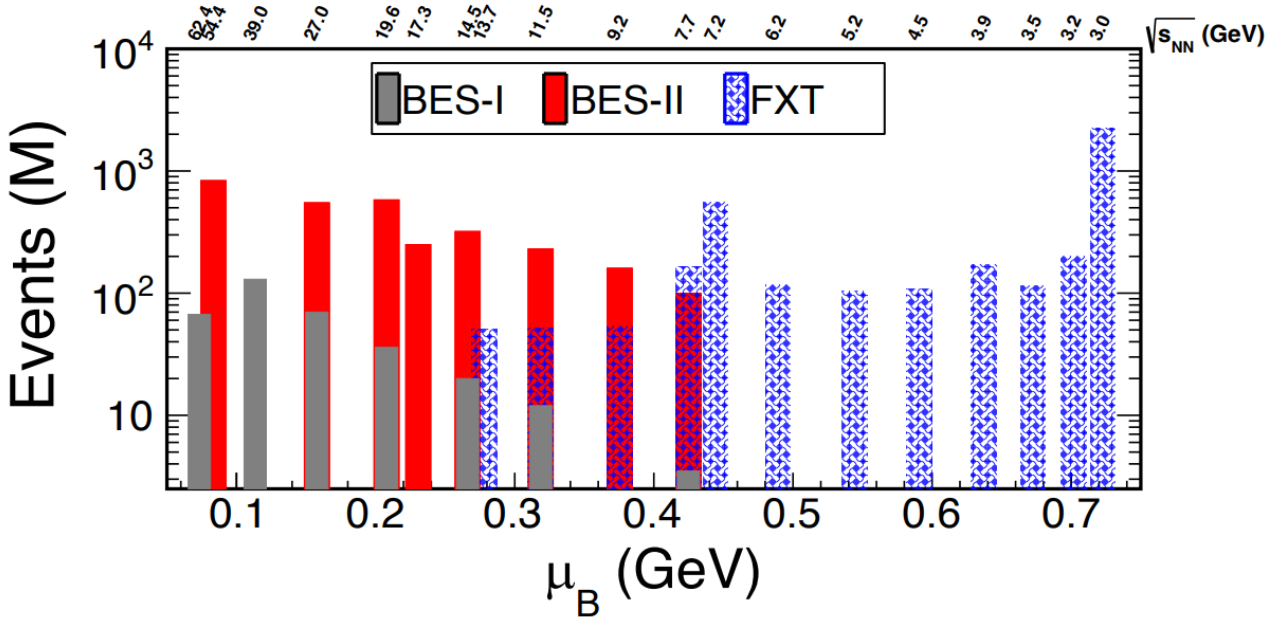
Acceptance: $|\eta| < 1$; $0 \leq \varphi < 2\pi$

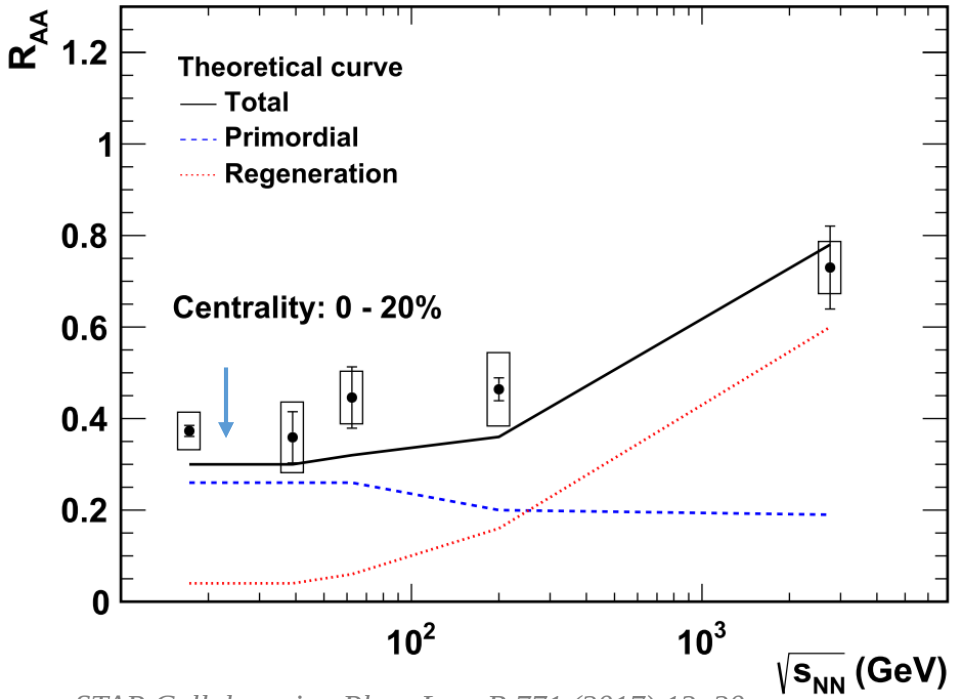
✓ **MTD**

$\mu^{\pm}$ trigger and identification

Acceptance: $|\eta| < 0.5$, ~ 45% in φ

Beam Energy Scan II



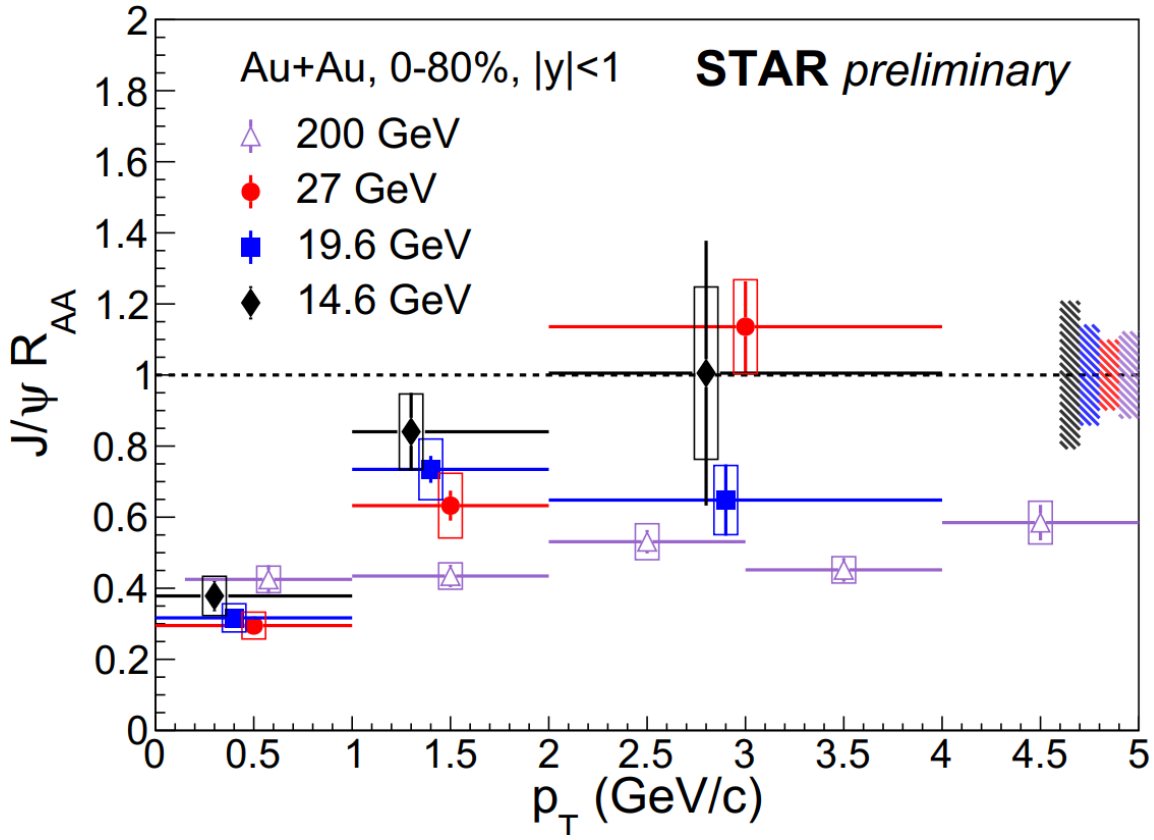


STAR Collaboration Phys. Lett. B 771 (2017) 13–20

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

- Collision energy dependence
  - Au+Au collision at 14.6, 19.6, 27 GeV
  - Smaller regeneration effect

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



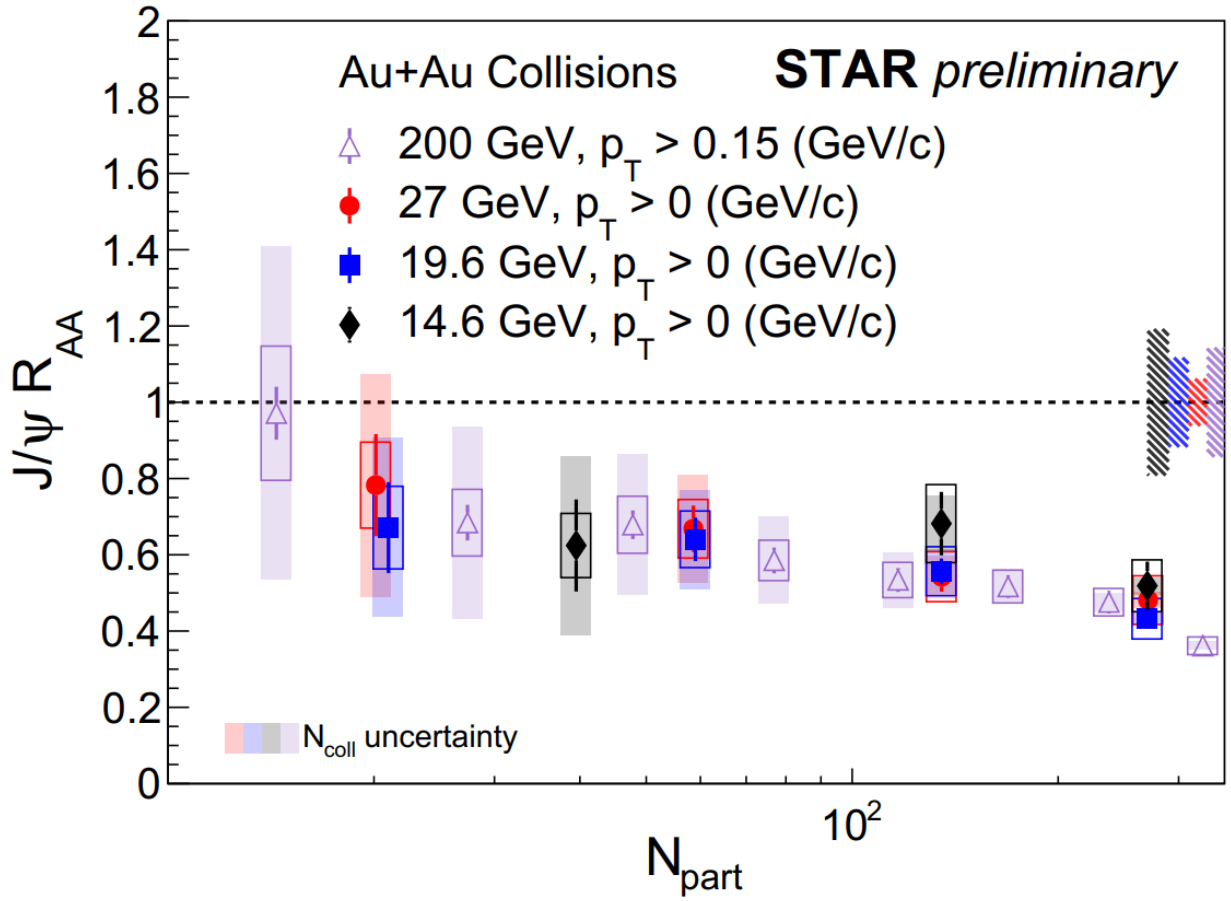
For p+p baselines at 14.6, 19.6, and 27 GeV, they are extracted from phenomenological interpolations

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

Wei Zhang
Poster ID 431

- Low p_T suppression, R_{AA} increases with p_T for 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



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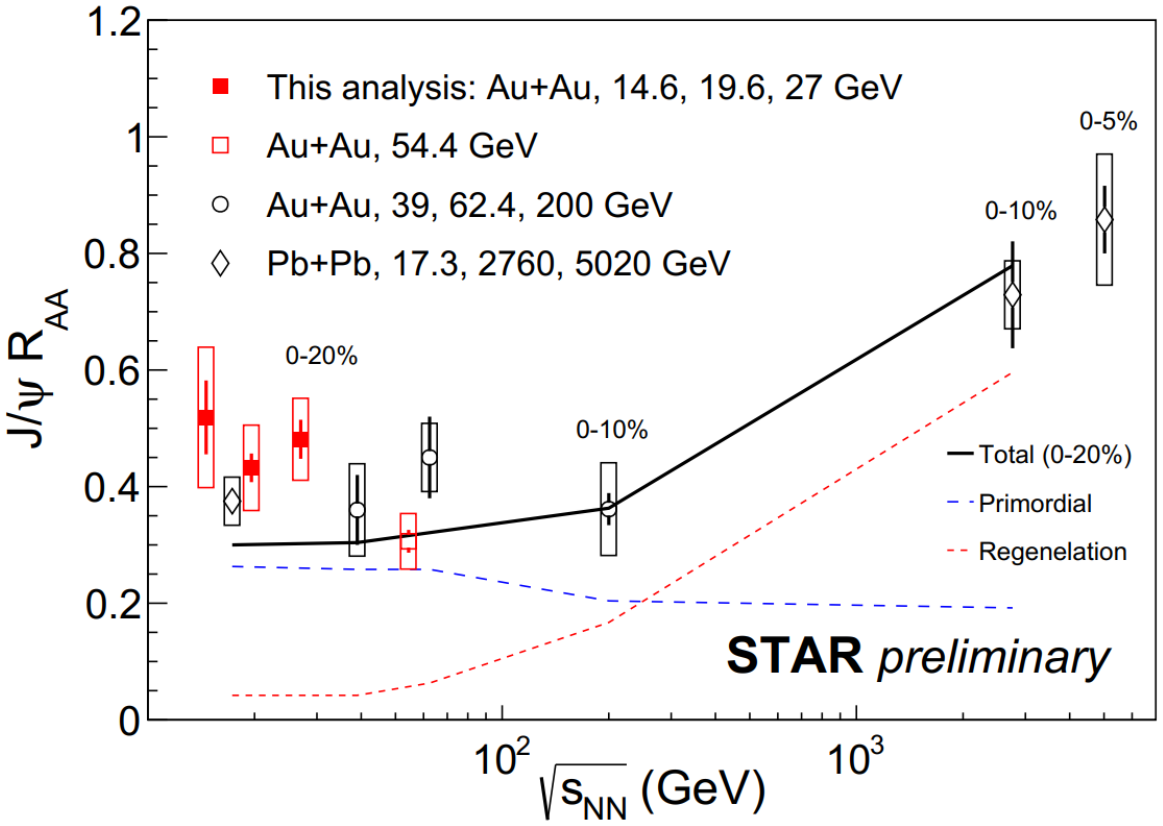
- Hint of similar decreasing trend as function of centrality

Energy dependence of J/ψ R_{AA}



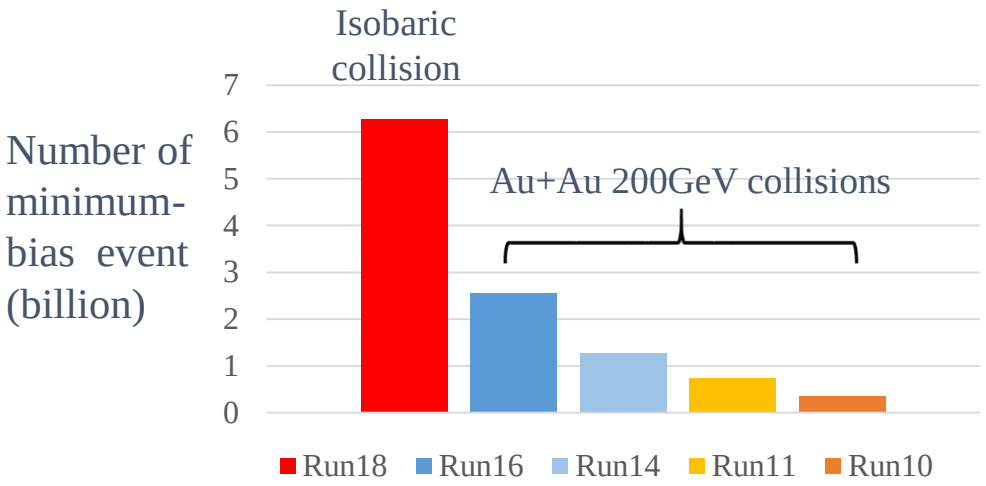
X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
L. Kluberg, Eur. Phys. J. C 43 (2005) 145.
NA50 Collaboration, Phys. Lett. B 477 (2000) 28.

- 14.6, 19.6 and 27 GeV data follow the trend
- No significant energy dependence is observed within uncertainties up to 200 GeV
  - Interplay of dissociation, regeneration and cold nuclear matter effects
- Model qualitatively describes the observed energy dependence

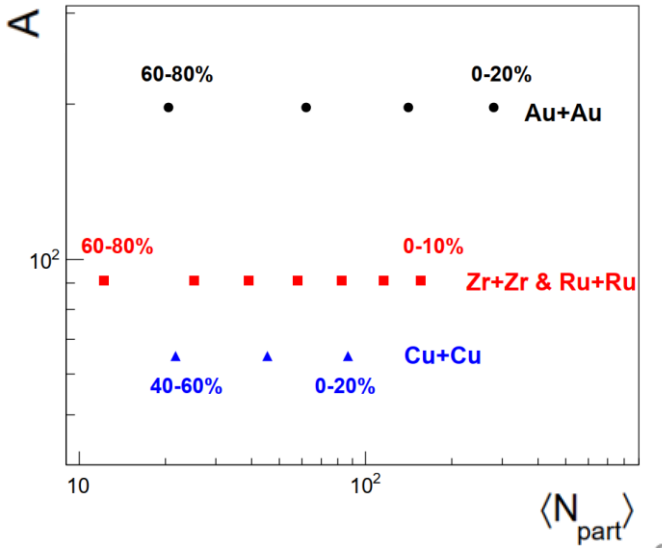
ALICE Collaboration, Phys. Lett. B 734 (2014) 314
STAR Collaboration, Phys. Lett. B 771 (2017) 13-20
STAR Collaboration, Phys. Lett. B 797 (2019) 134917
ALICE Collaboration, Nucl. Phys. A 1005 (2021) 121769

Wei Zhang
Poster Session 431

Zr+Zr & Ru+Ru collisions

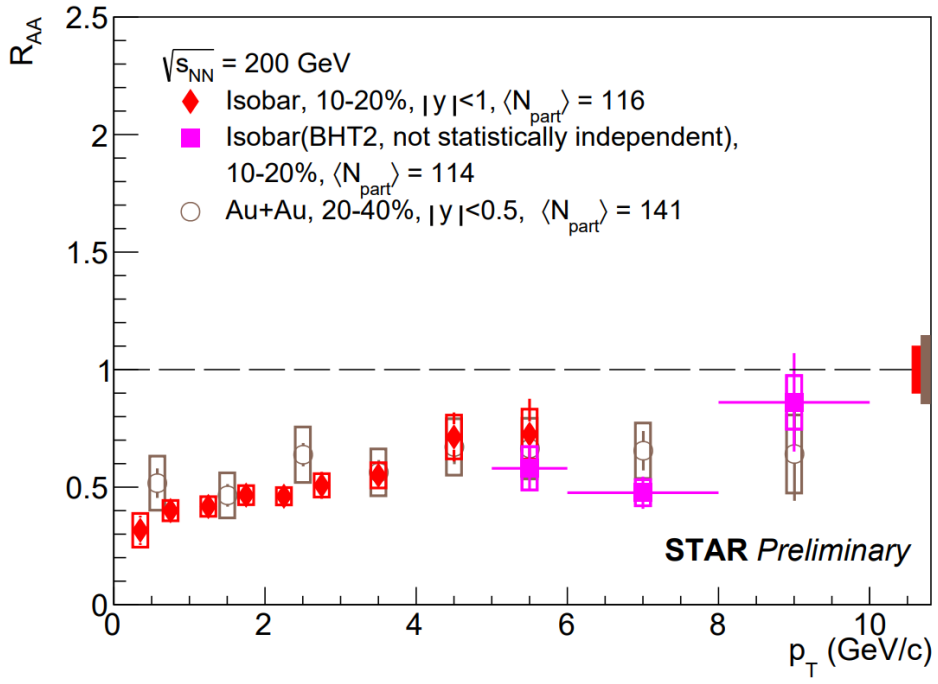


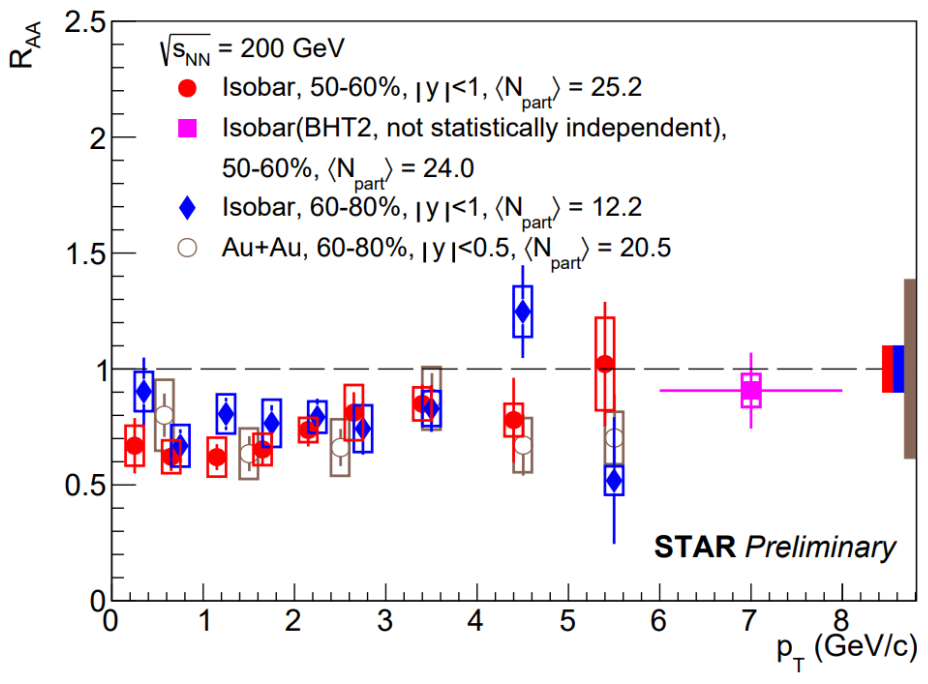
- High statistics enables measurements of:
  - J/ψ production with high precision
  - Sequential suppression of J/ψ, ψ(2S), Υ(1S), Υ(2S)
  - J/ψ polarization



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

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

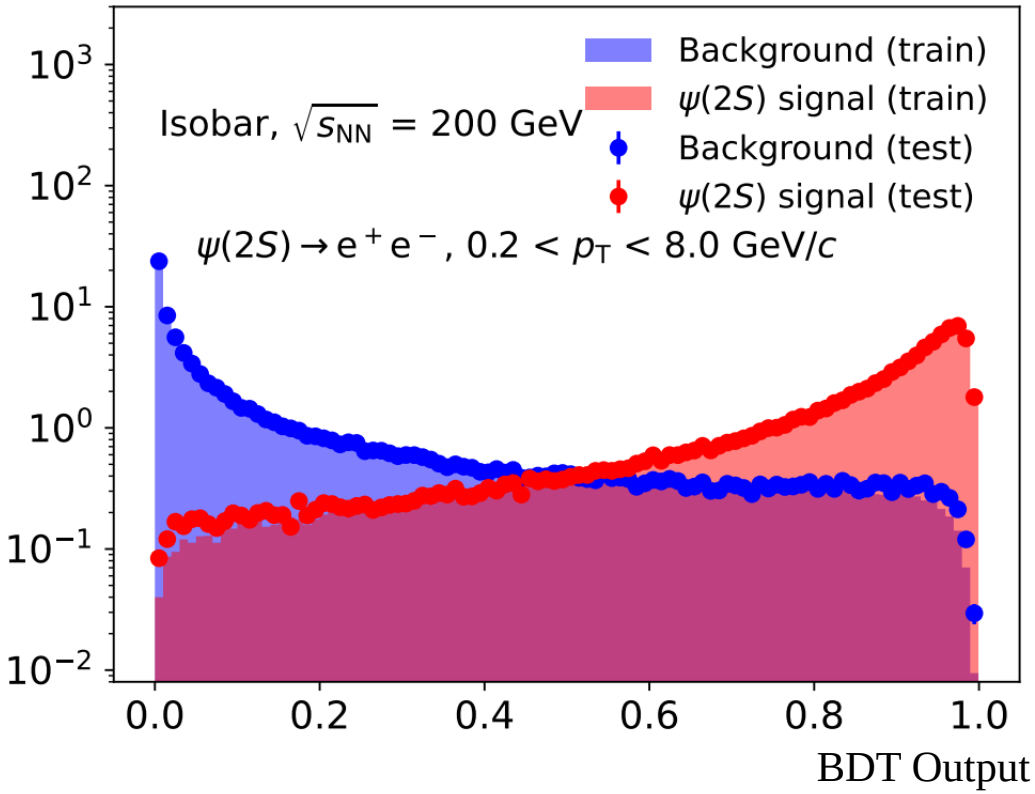


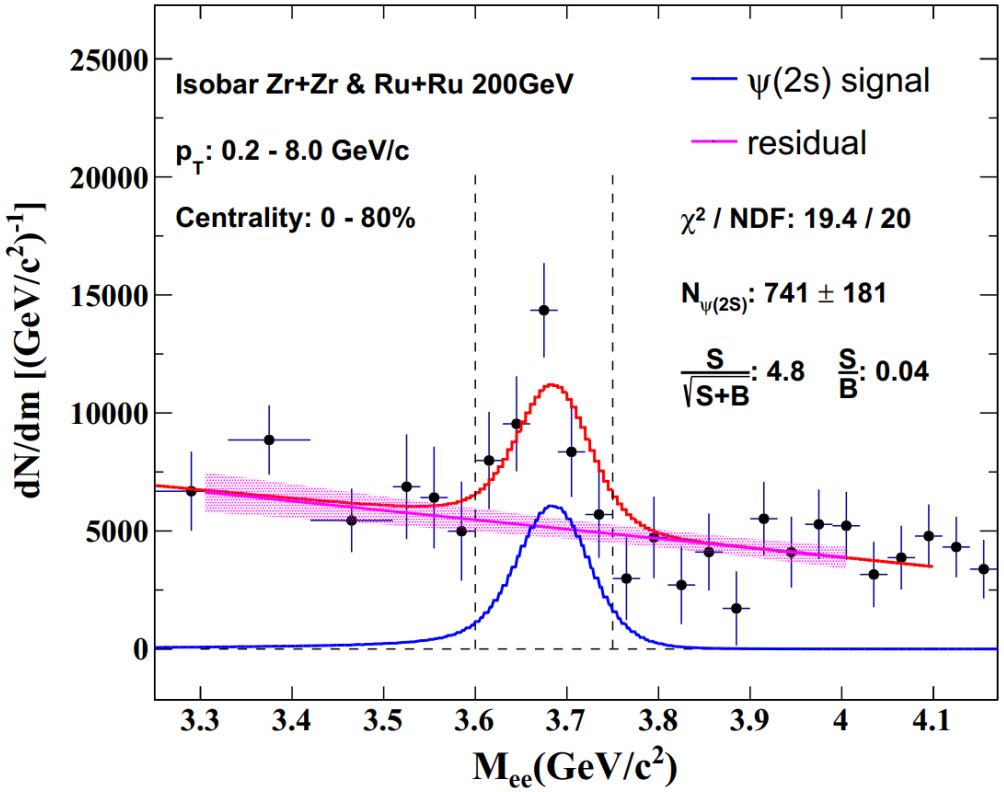


STAR Collaboration, Phys. Lett. B 797 (2019) 134917

- 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

ψ(2S) signal in Zr+Zr & Ru+Ru collisions



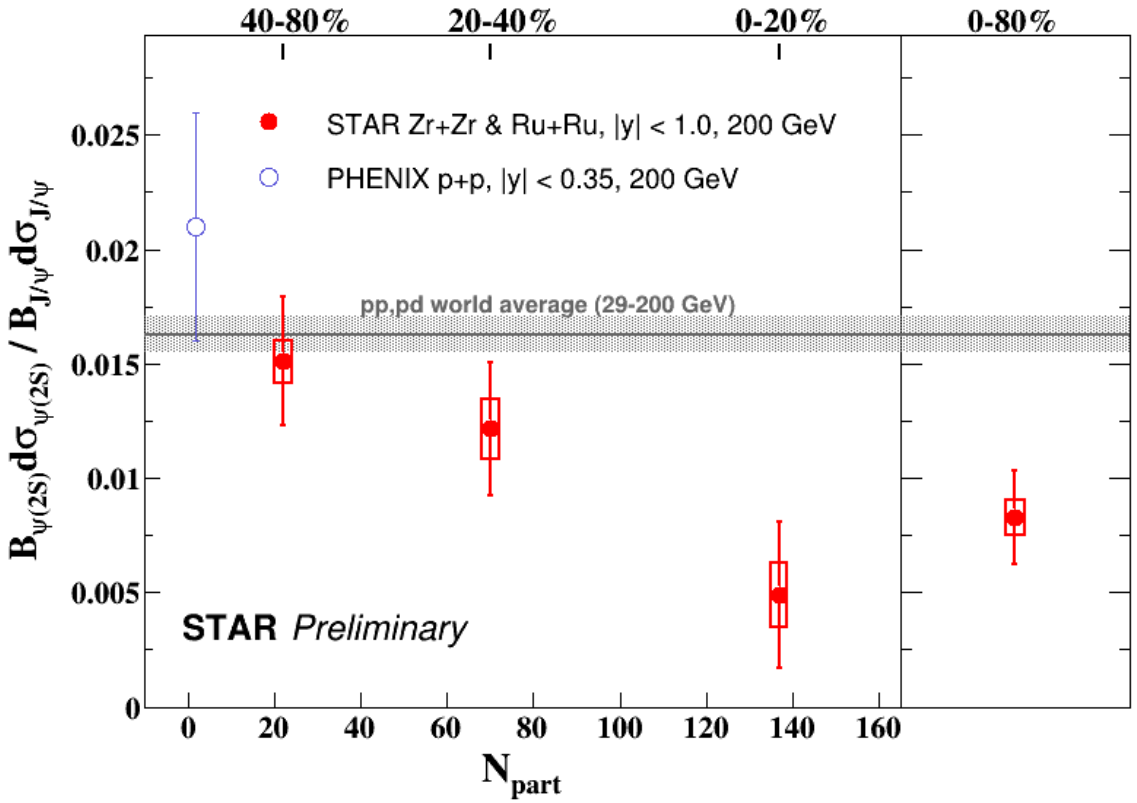


- A machine learning method is employed to reconstruct the ψ(2S) signal
- XGBoost (Extreme Gradient Boosting) as core

hipe4ml

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

ψ(2S) to J/ψ ratio in Zr+Zr & Ru+Ru collisions

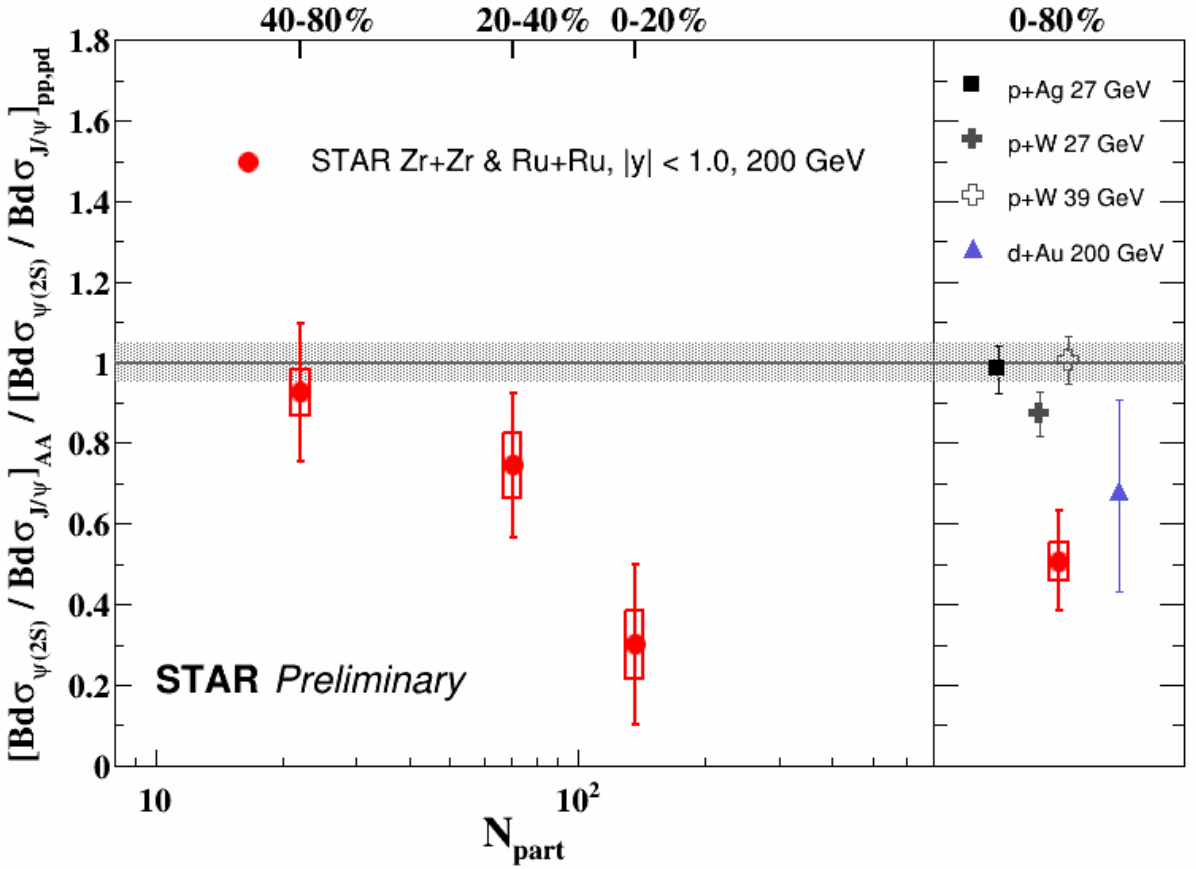


pp reference is the average of measurements in p+p(d) by NA51, ISR and PHENIX

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%)
- Ratio decreases towards central collisions

Double ratio



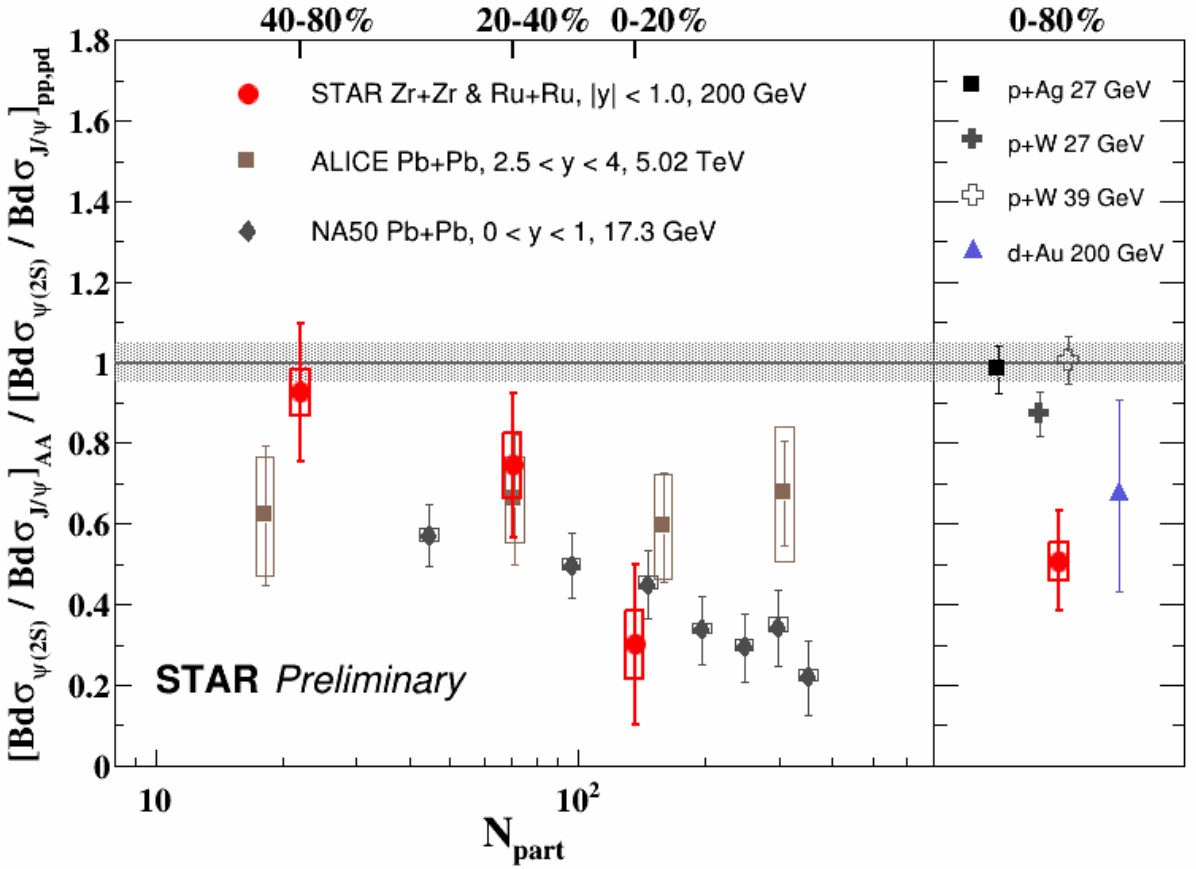
$$\frac{[(Bd\sigma_{\psi(2s)})/(Bd\sigma_{J/\psi})]_{AA}}{[(Bd\sigma_{\psi(2s)})/(Bd\sigma_{J/\psi})]_{pp,pd}}$$

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



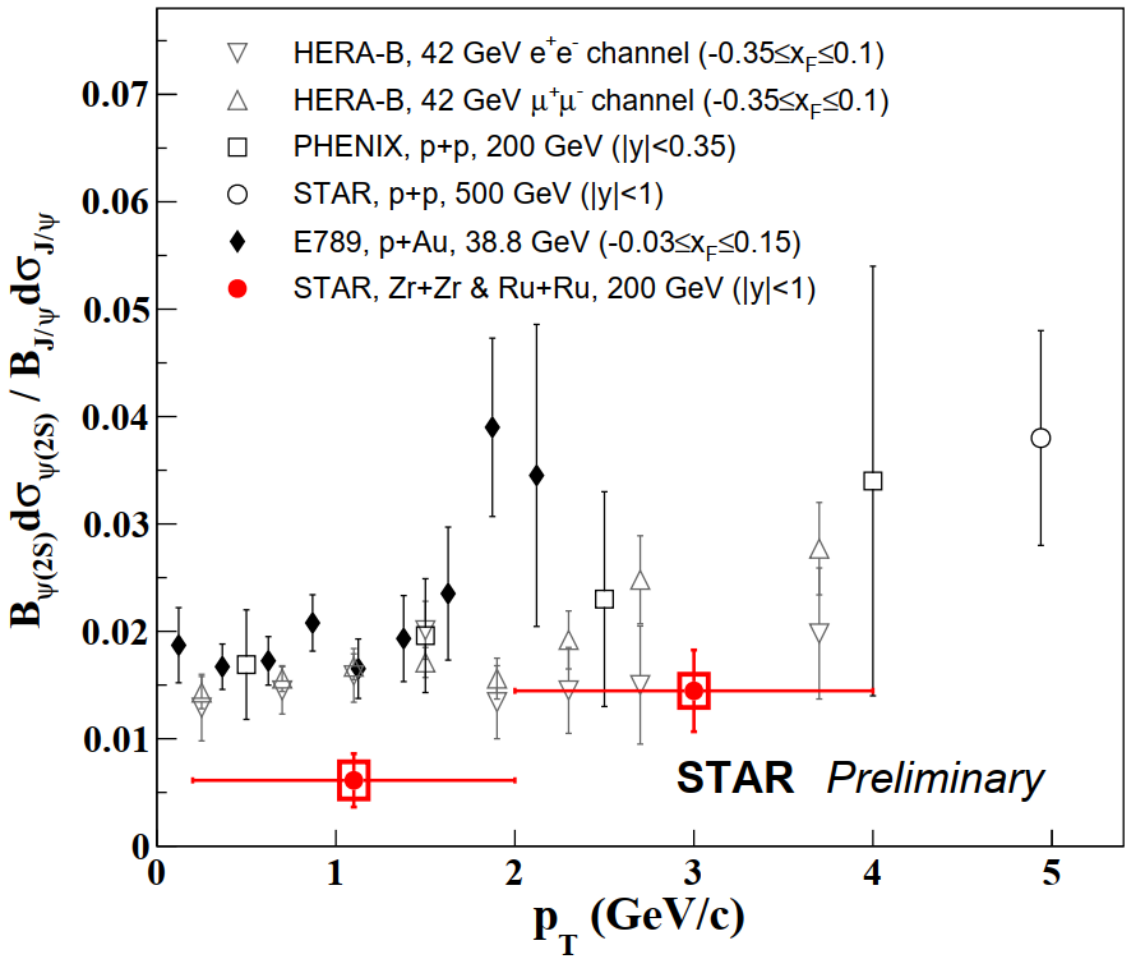
$$\frac{[(\mathrm{Bd}\sigma_{\psi(2s)})/(\mathrm{Bd}\sigma_{\mathrm{J}/\psi})]_{AA}}{[(\mathrm{Bd}\sigma_{\psi(2s)})/(\mathrm{Bd}\sigma_{\mathrm{J}/\psi})]_{pp,pd}}$$

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 be more similar to that at SPS than at LHC

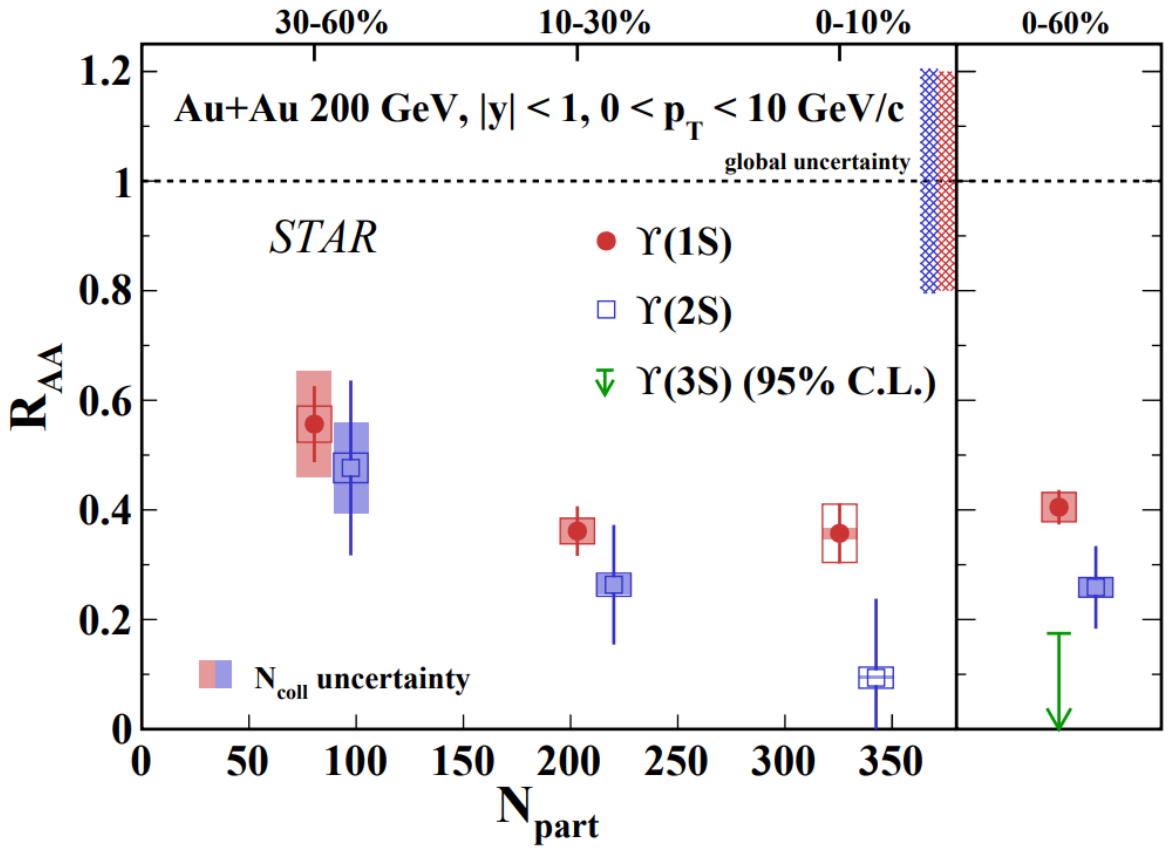
ψ(2S) to J/ψ ratio vs p_T



- 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.

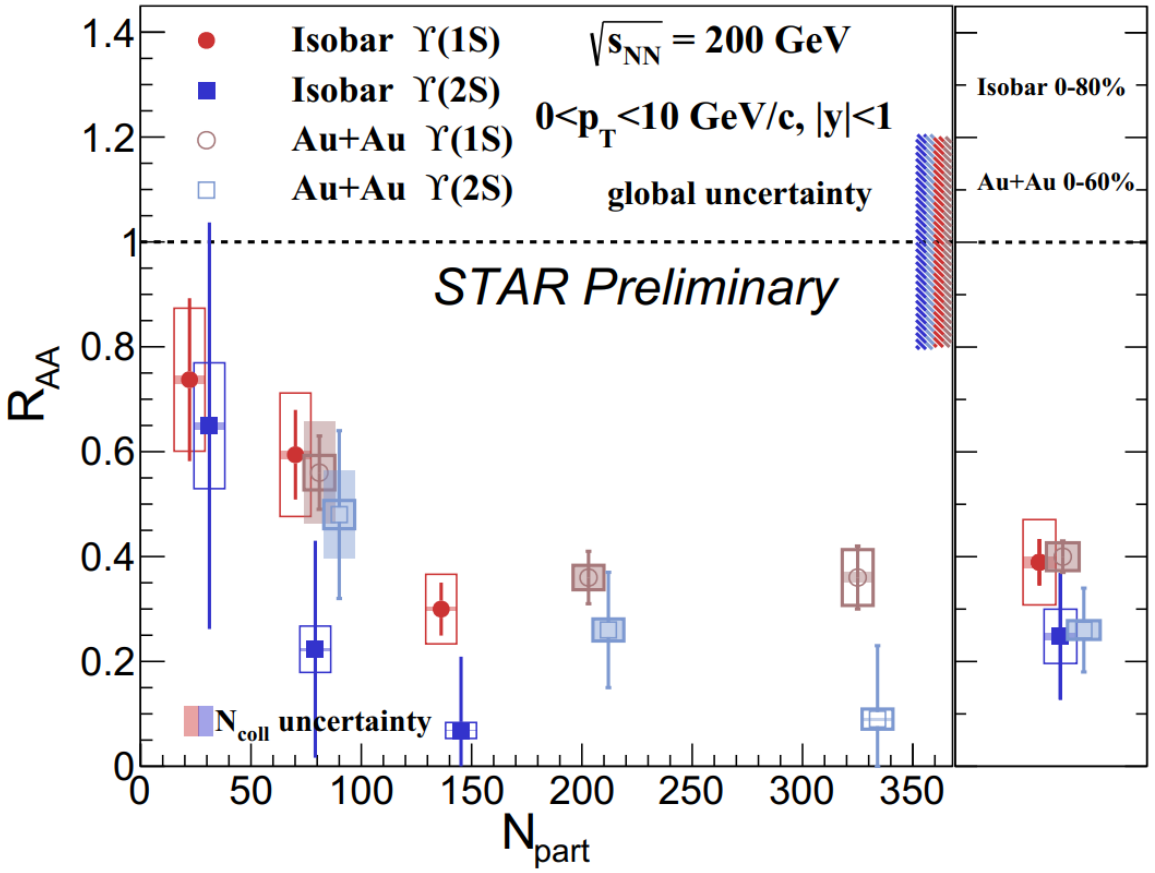
Υ R_{AA} vs. $\langle N_{part} \rangle$ in Au+Au collisions



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

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

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

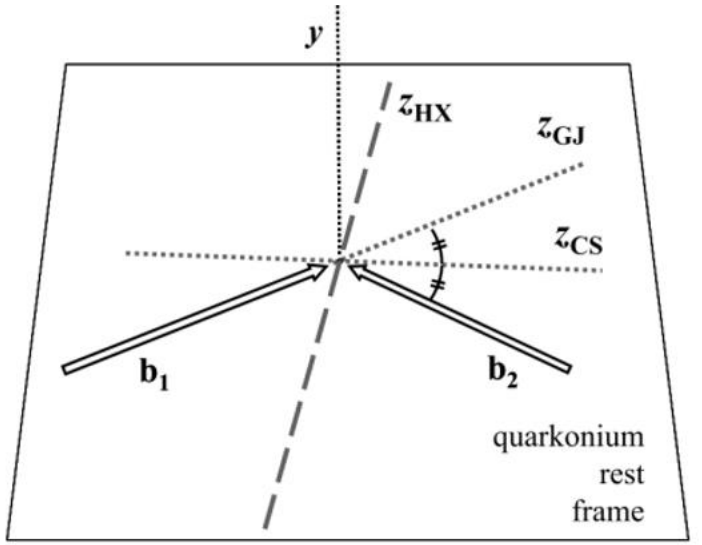


STAR, Phys. Rev. Lett. 130 (2023) 112301

- Hint of sequential suppression pattern
- Isobar covers lower $\langle N_{part} \rangle$ range than Au+Au
- 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

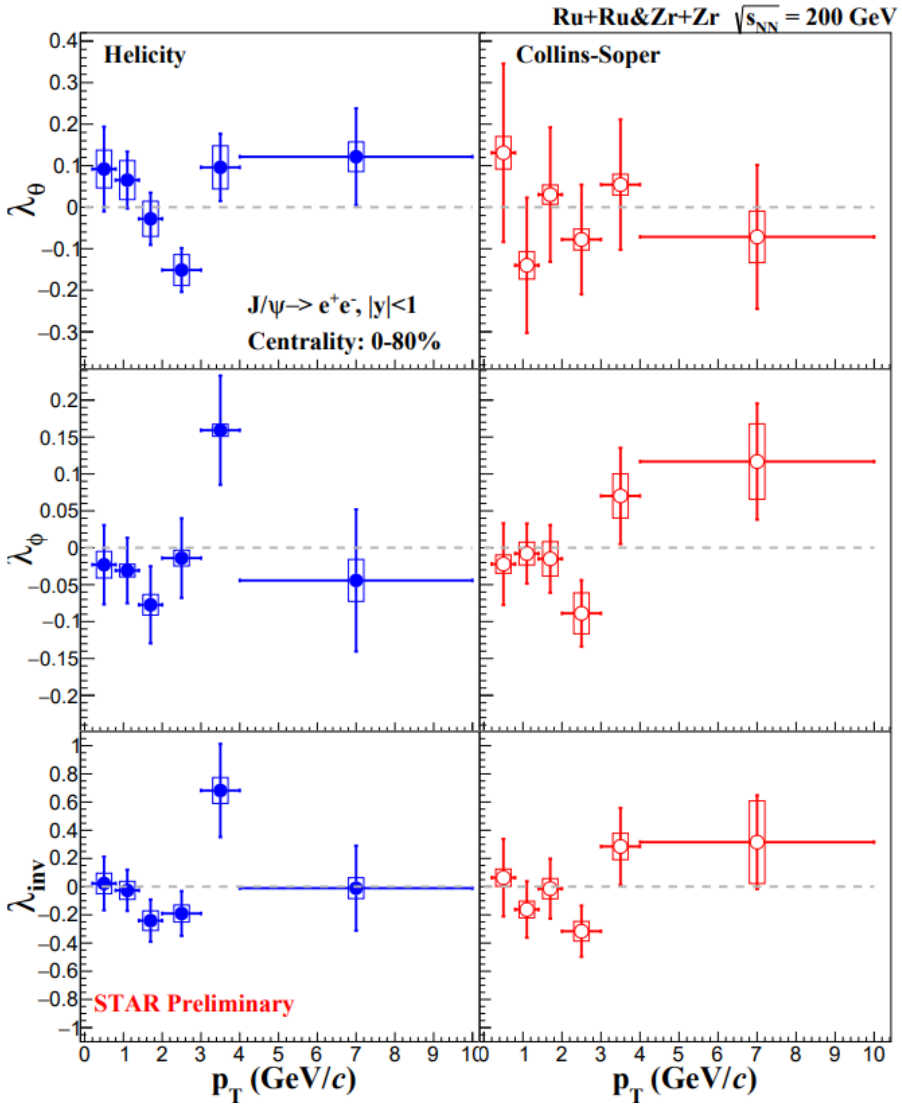
Helicity frame (HX) and Collins-Soper frame (CS)

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
- Hint of non-trivial p_T dependence in HX frame, but overall no significant p_T dependence in either HX or CS

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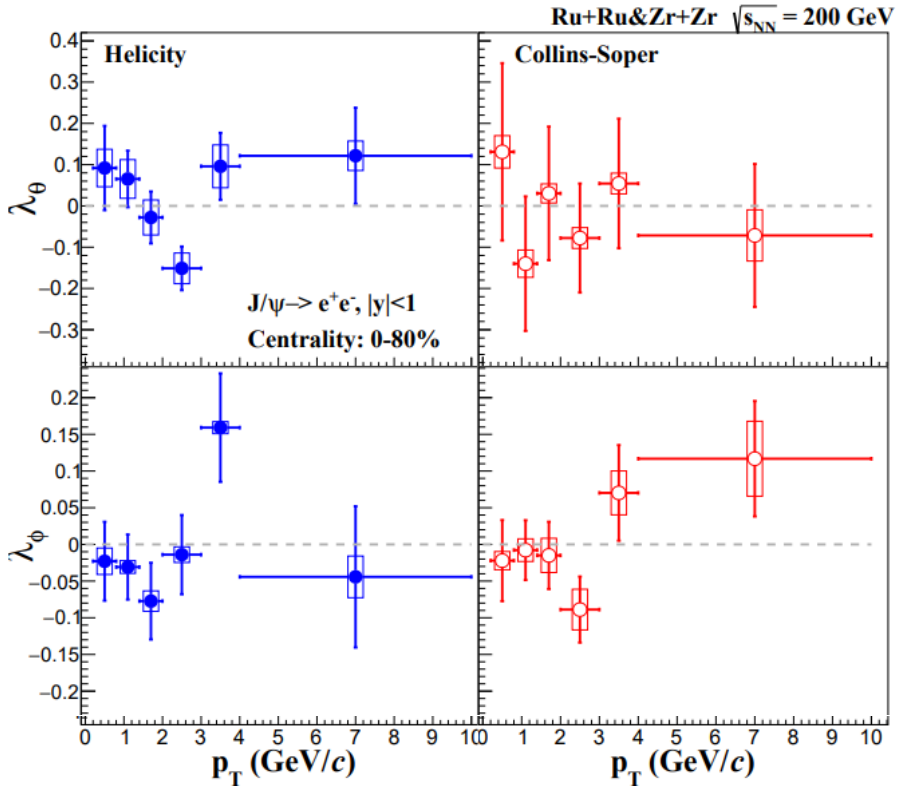
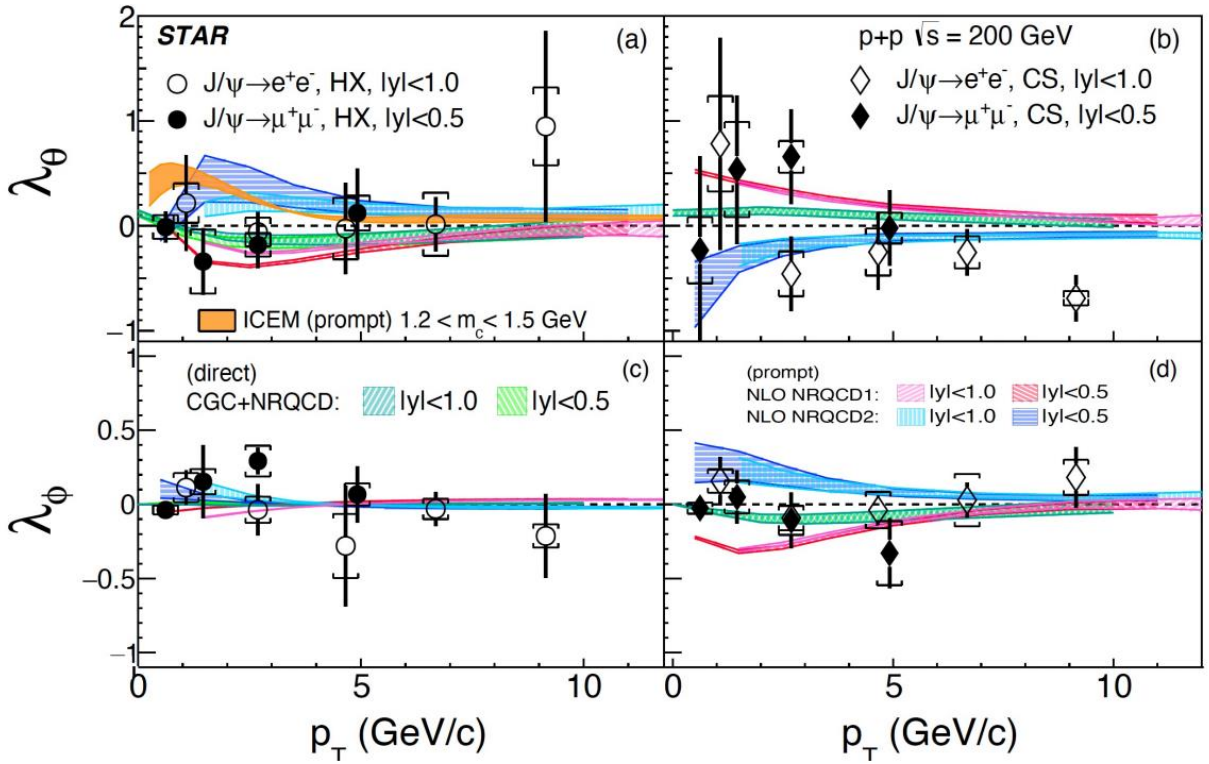
Poster ID: 225

J/ψ polarization parameters vs. p_T





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

- λ_θ,λ_ϕ consistent with pp results within uncertainties

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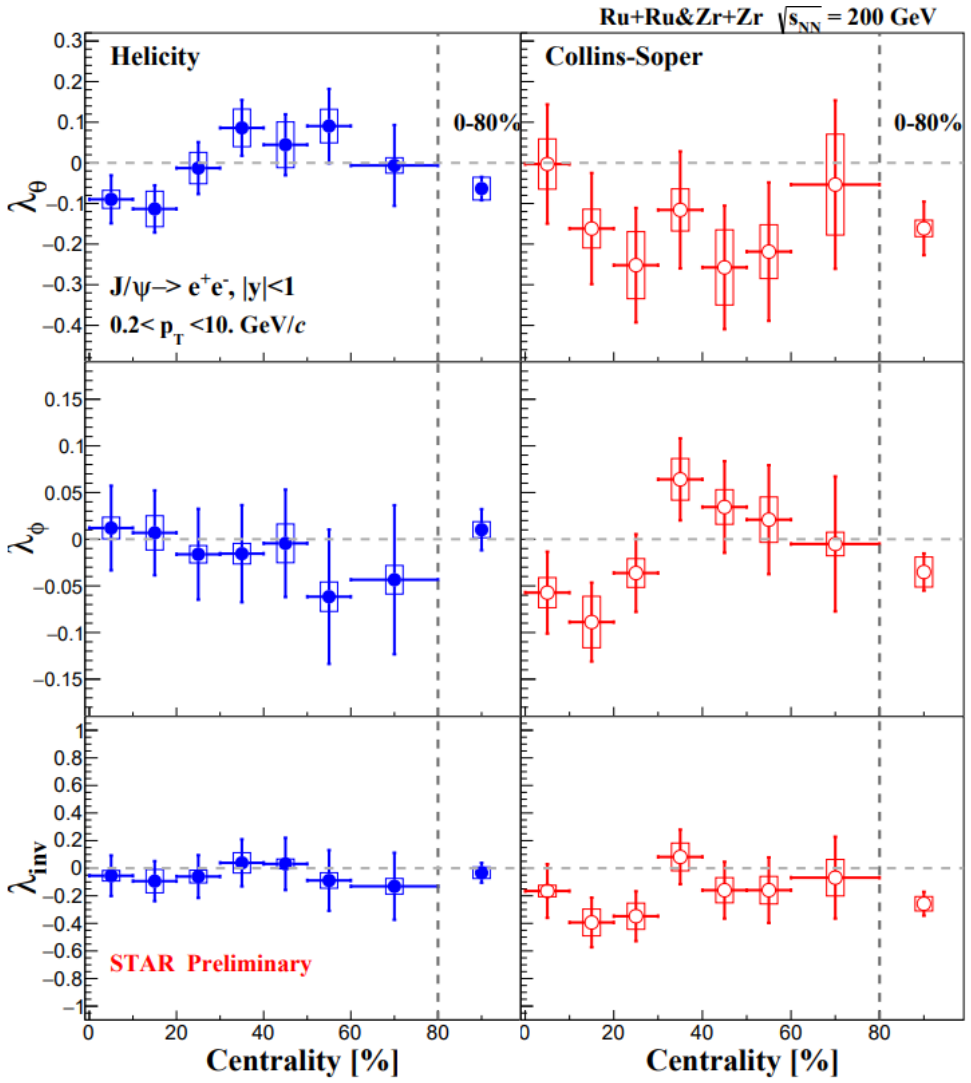
J/ψ polarization parameters vs. centrality



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

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Poster ID: 225

Summary

- Significant suppression of charmonium and bottomonium in central heavy-ion collisions

- No significant collision energy dependence of J/ψ R_{AA} with BES-II data

→ Interplay of dissociation, regeneration and cold nuclear matter effects

- First observation of sequential suppression for charmonium at RHIC; similar for bottomonium

→ Constrain QGP properties

- First measurement of J/ψ polarization in heavy-ion collisions at RHIC, consistent with zero and pp results

Outlook

✓ Run 23-25, ~18B minimum bias Au+Au events; high statistics p+p, p+A samples

➢ Au+Au 200 GeV

- Sequential suppression studies for J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S)
- J/ψ v_1, v_2, spin alignment studies

➢ J/ψ R_{AA} in Au+Au collisions at 17.3 GeV

➢ New p+p reference for J/ψ, ψ(2S), Υ(nS)

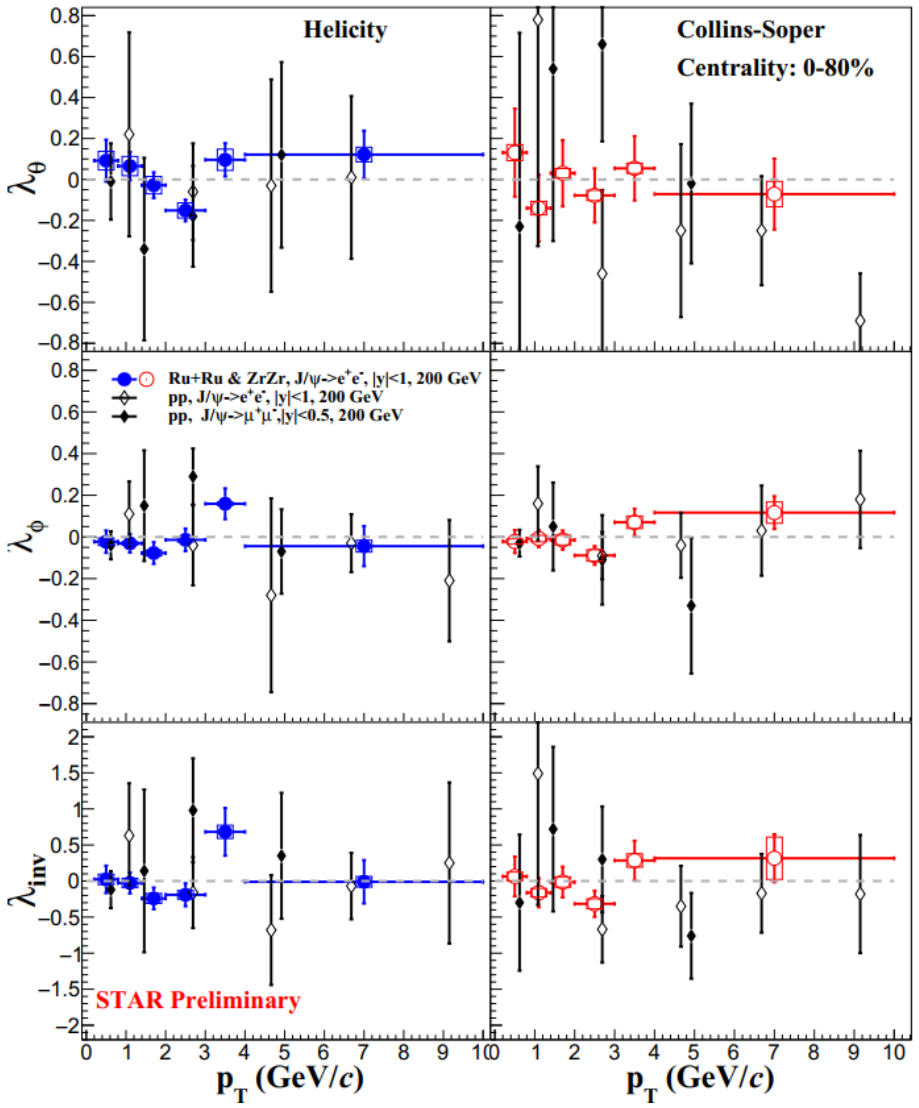
$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	p+p	142 pb^{-1}/12w	2024
200	p+Au	0.69 pb^{-1}/10.5w	2024
200	Au+Au	18B / 32.7 nb^{-1}/40w	2023+2025

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

Thank you!

Back up

J/ψ polarization parameters vs. p_T



- λ_θ,λ_ϕ consistent with zero in HX and CS frames
- Hint of non-trivial p_T dependence in HX frame, but overall no significant p_T dependence in either HX or CS
- Consistent with pp results

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

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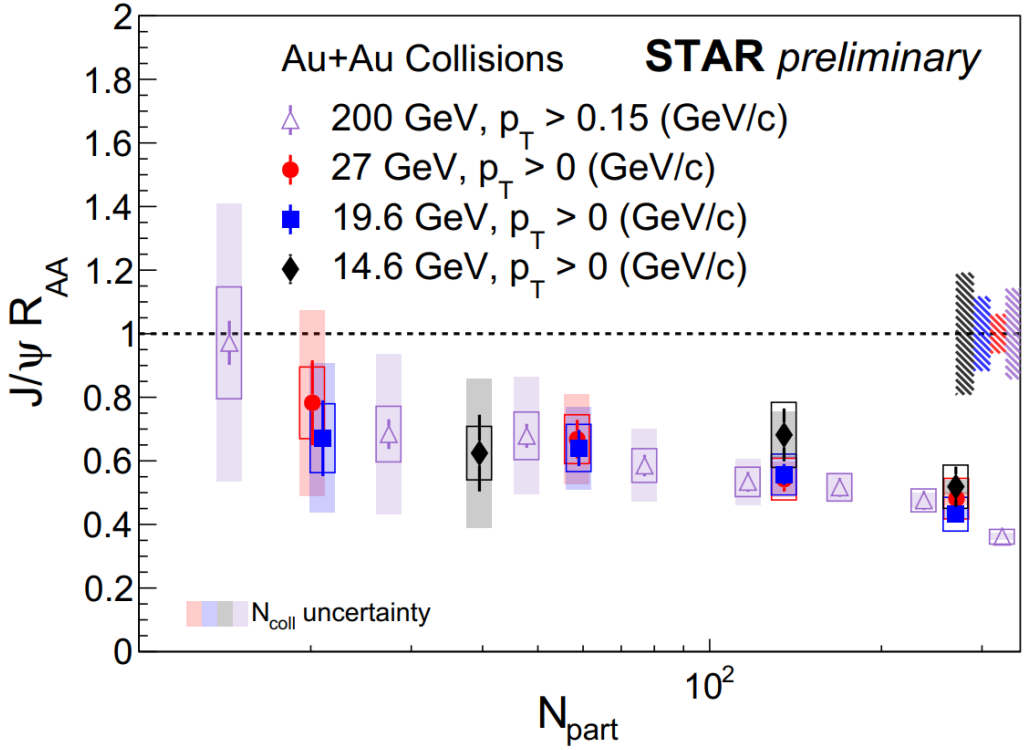
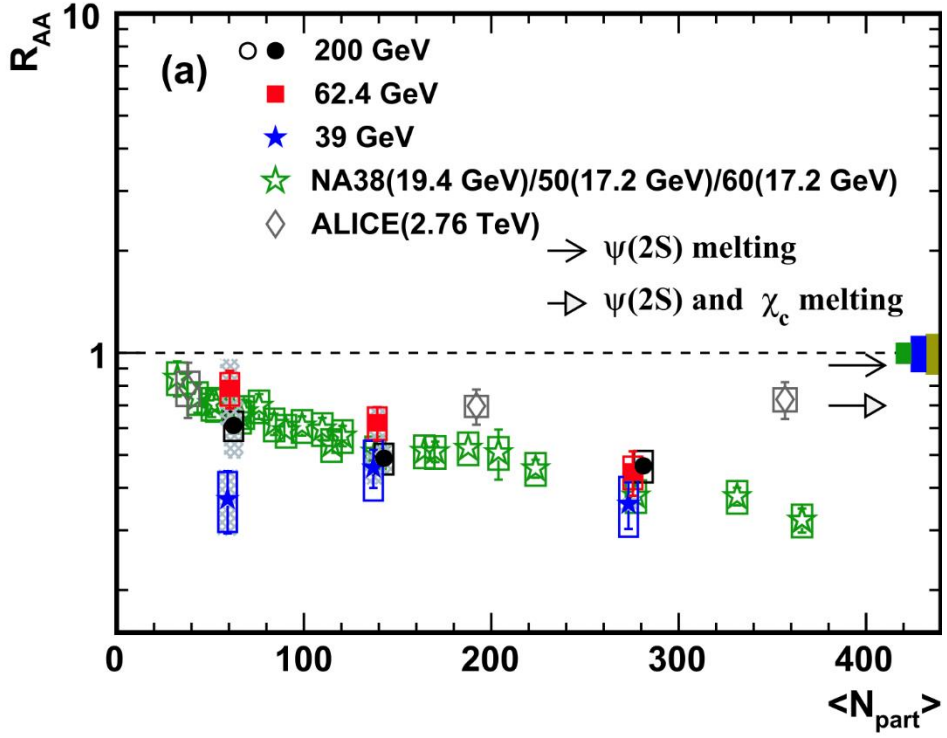
J/ψ R_{AA} vs. $\langle N_{part} \rangle$

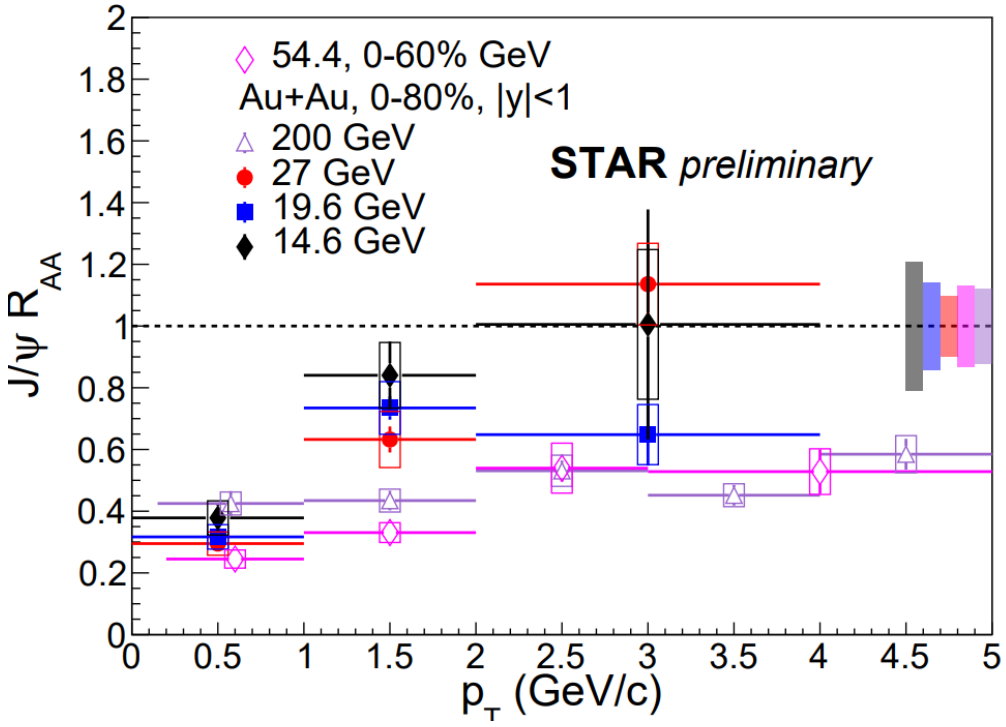


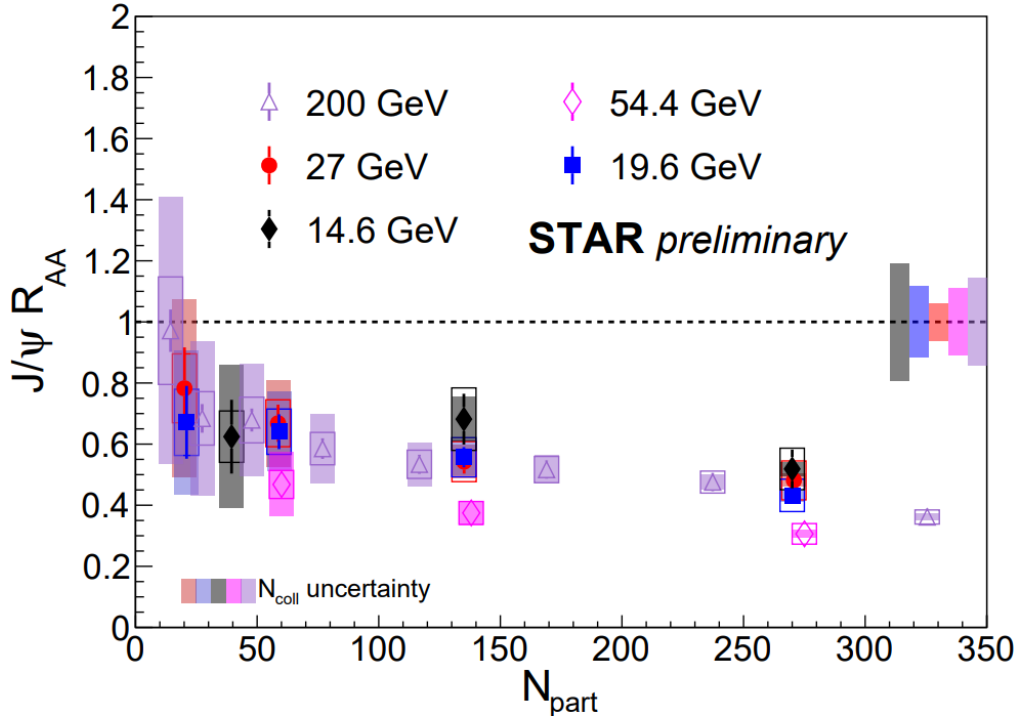
W. Zha, et al., Phys. Rev. C 93 (2016) 024919



Phys.Lett.B 771 (2017) 13-20

J/ψ R_{AA} at 14.6, 19.6 and 27 GeV





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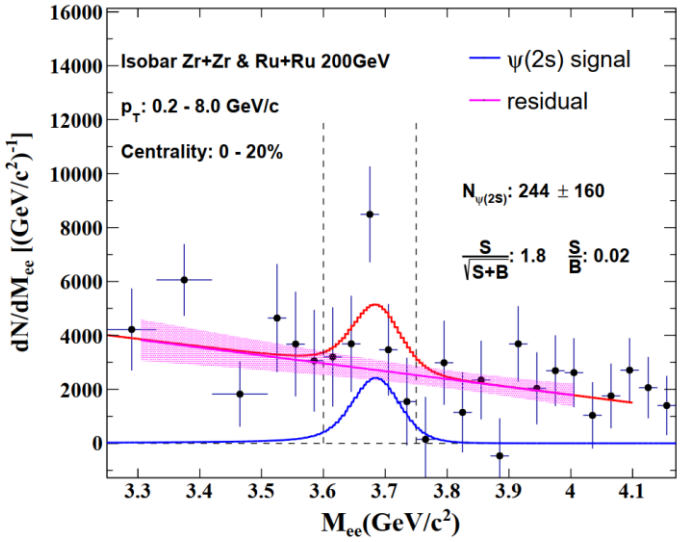
05/09/2023, 17:30
Poster Session 431

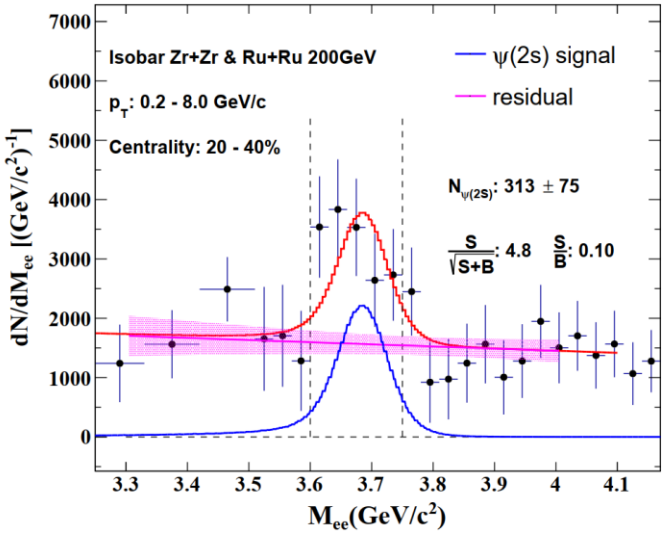
STAR Collaboration, Phys. Lett. B 797 (2019) 134917

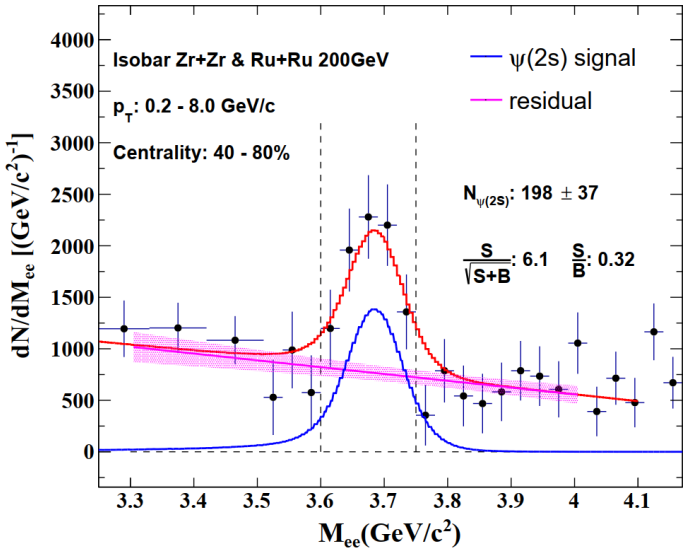
- R_{AA} increases with increasing p_T for 14.6, 19.6, 27 and 54.4 GeV

No clear energy dependence is observed among 14.6, 19.6, 27, 54.4 and 200 GeV

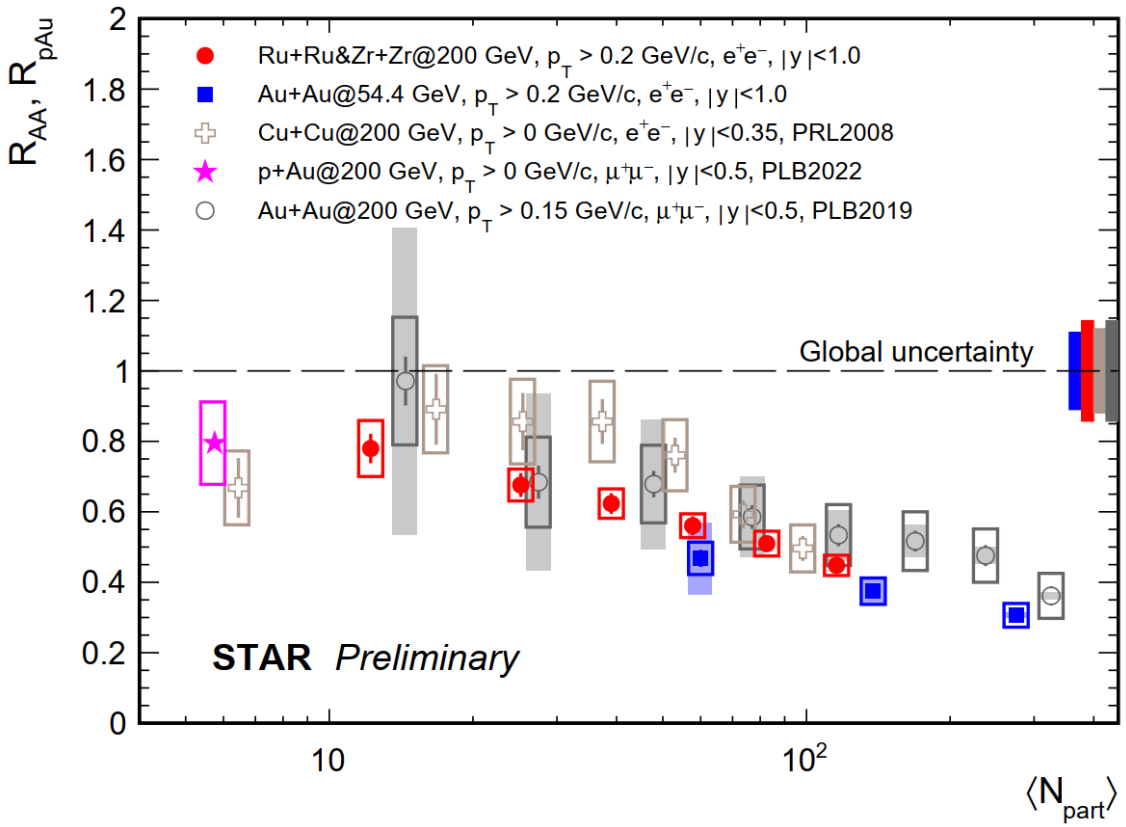
ψ(2S) signal







J/ψ R_{AA} vs. $\langle N_{part} \rangle$ in isobaric collisions

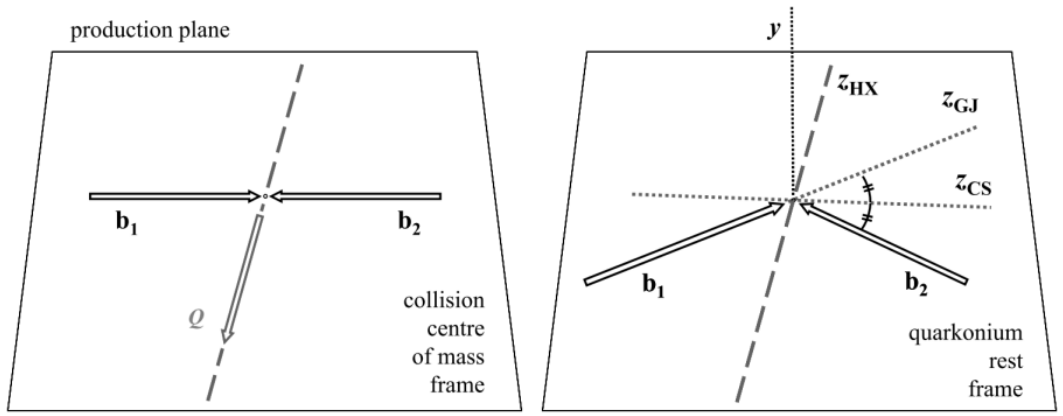


- All of these results demonstrate a similar trend
- Significant suppression is observed at large N_{part} range
- No significant collision system size and energy dependence at RHIC at similar $\langle N_{\mathrm{part}} \rangle$

J/ψ polarization in isobaric collisions

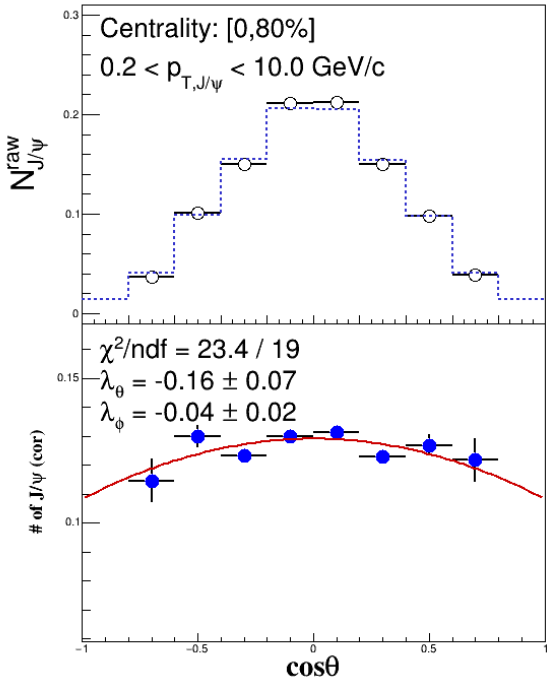
Angular distribution of the decayed leptons:

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

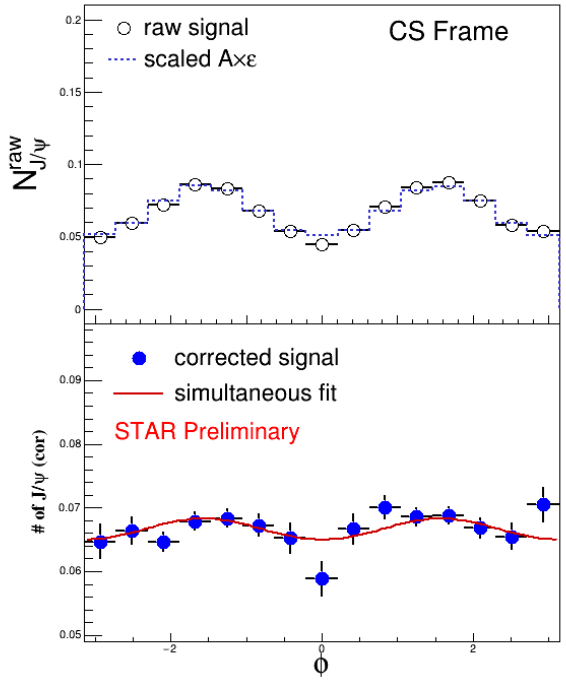


Helicity frame(HX)

Collins-Soper frame(CS)



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



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

pp reference