Dilepton and charmonium production in isobaric collisions at STAR

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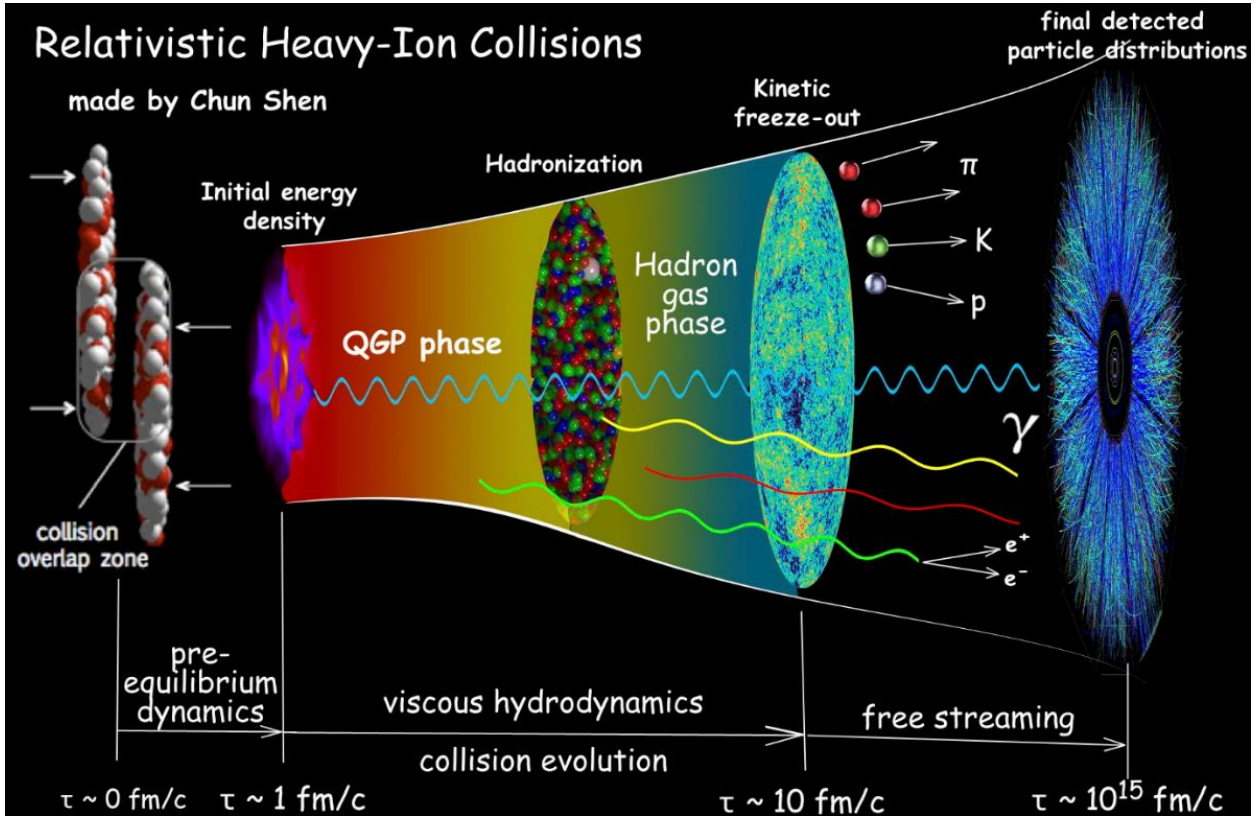
Relativistic Heavy Ion Collision

A new state of de-confined matter, QGP, can be created in high energy heavy-ion collisions



Probes of QGP:

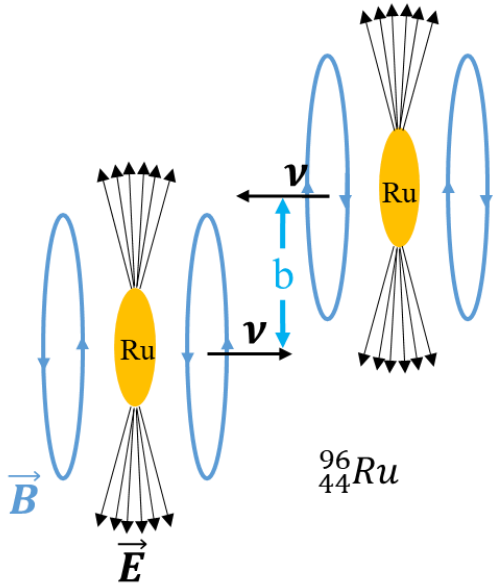
- Electromagnetic radiation (di-lepton)
- Heavy flavor quarkonia (J/ψ,ψ(2s),…)
- …

Outline

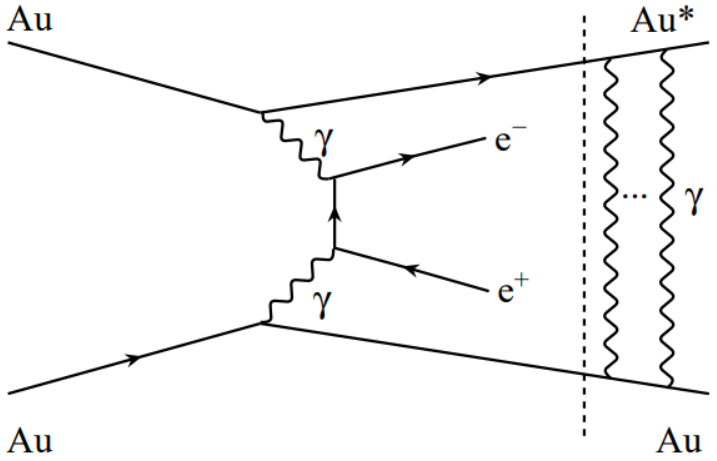
- Initial electromagnetic field induced e^+e^- production
- Coherent J/ψ photon-nuclear production
- Charmonium sequential suppression at RHIC
- Summary

e^+e^- pairs From Photon-Induced Interactions

- Transverse EM fields can be equal to a flux of quasi-real photon ($\propto Z^2$, and $q^2 < (\hbar/R_A)$)

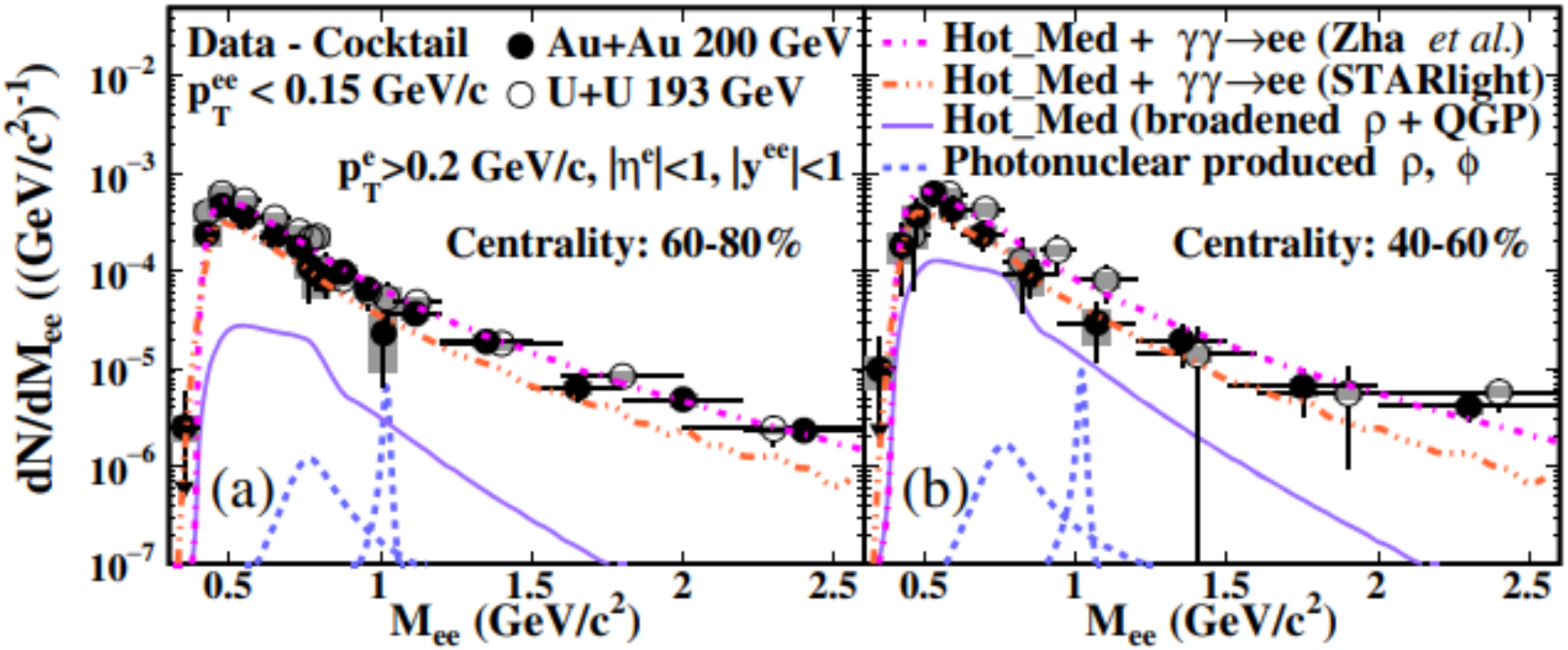


$\vec{E} \perp \vec{B} \perp \vec{k}, |\vec{E}| \approx |\vec{B}|$



- The cross section $\propto Z^4$, sensitive to initial EM field
- The e^+e^- pairs don't participate in the strong interaction

Photon-Induced Production In Peripheral Collisions



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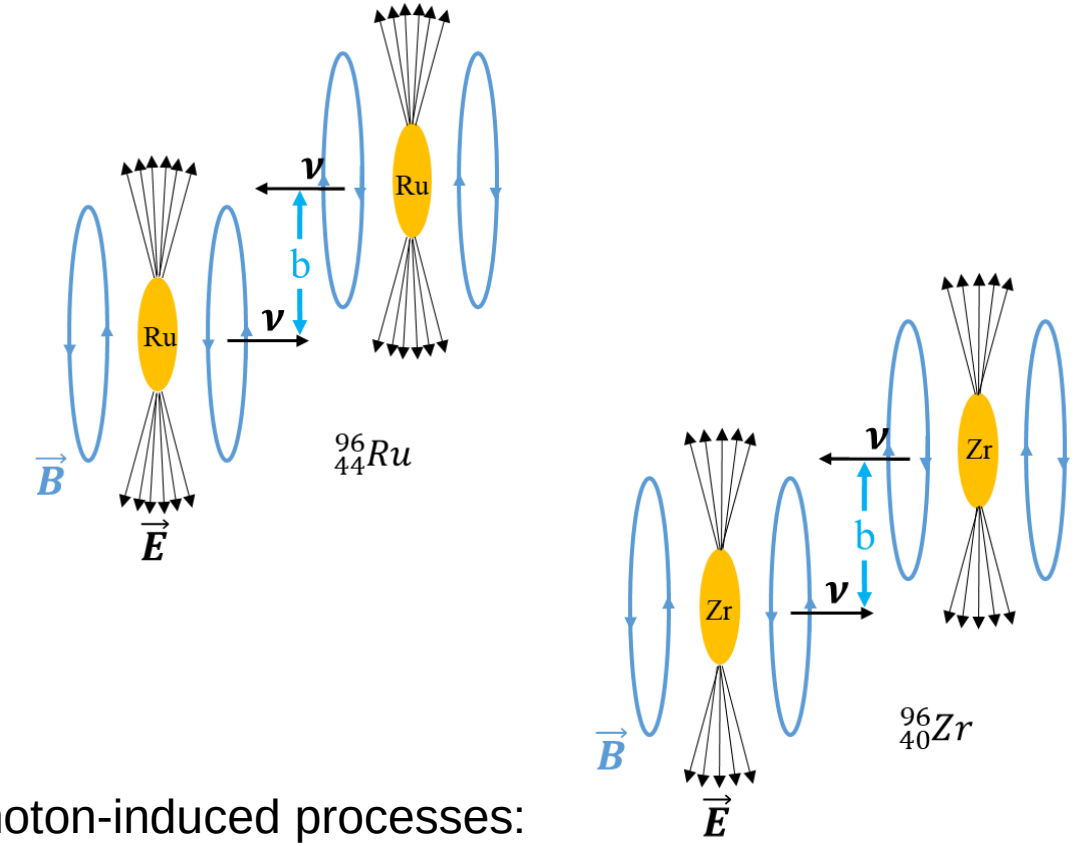
- The enhancements of e^+e^- production at very low p_T have been observed in peripheral collisions
- Photon-induced interactions could explain the observed enhancements

Photon-Induced Production In Isobaric Collisions

- The isobaric collisions ($^{96}_{44}Ru$+$^{96}_{44}Ru$, $^{96}_{40}Zr$+$^{96}_{40}Zr$) provide a unique opportunity to test the electromagnetic field dependence



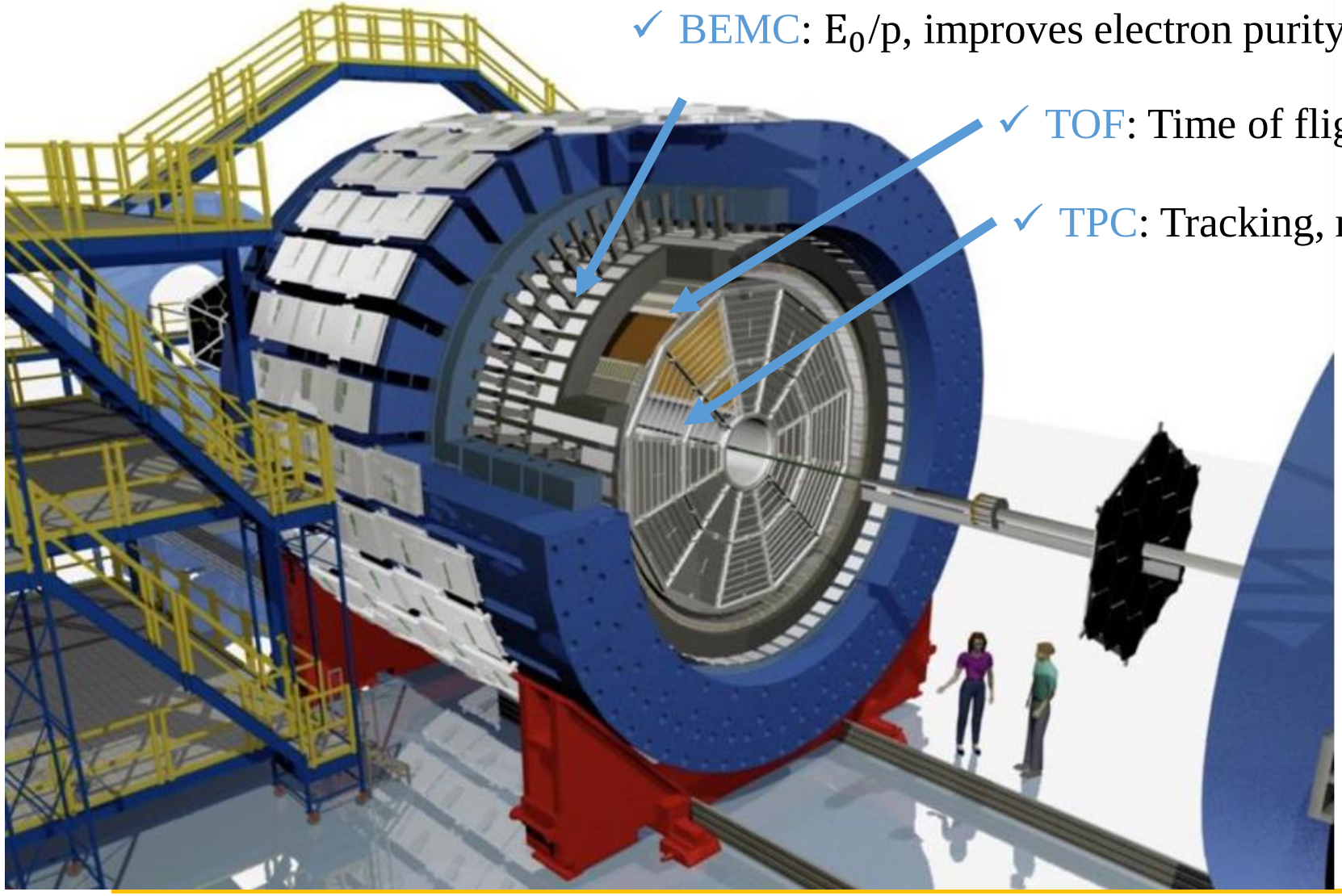
Photon-induced processes:

- $\gamma + \gamma \rightarrow e^+e^-$ ($\propto Z^4$)

- Comparison between Ru+Ru and Zr+Zr:
  - Charge (Z) dependence and verify the difference of initial EM field in isobaric collisions

- Comparison between Au+Au/U+U and Isobaric collisions:
  - Charge (Z)
  - Impact parameter
  - …

The Solenoid Tracker At RHIC



- ✓ BEMC: E_0/p, improves electron purity at high p_T
- ✓ TOF: Time of flight, particle identification
- ✓ TPC: Tracking, momentum and energy loss

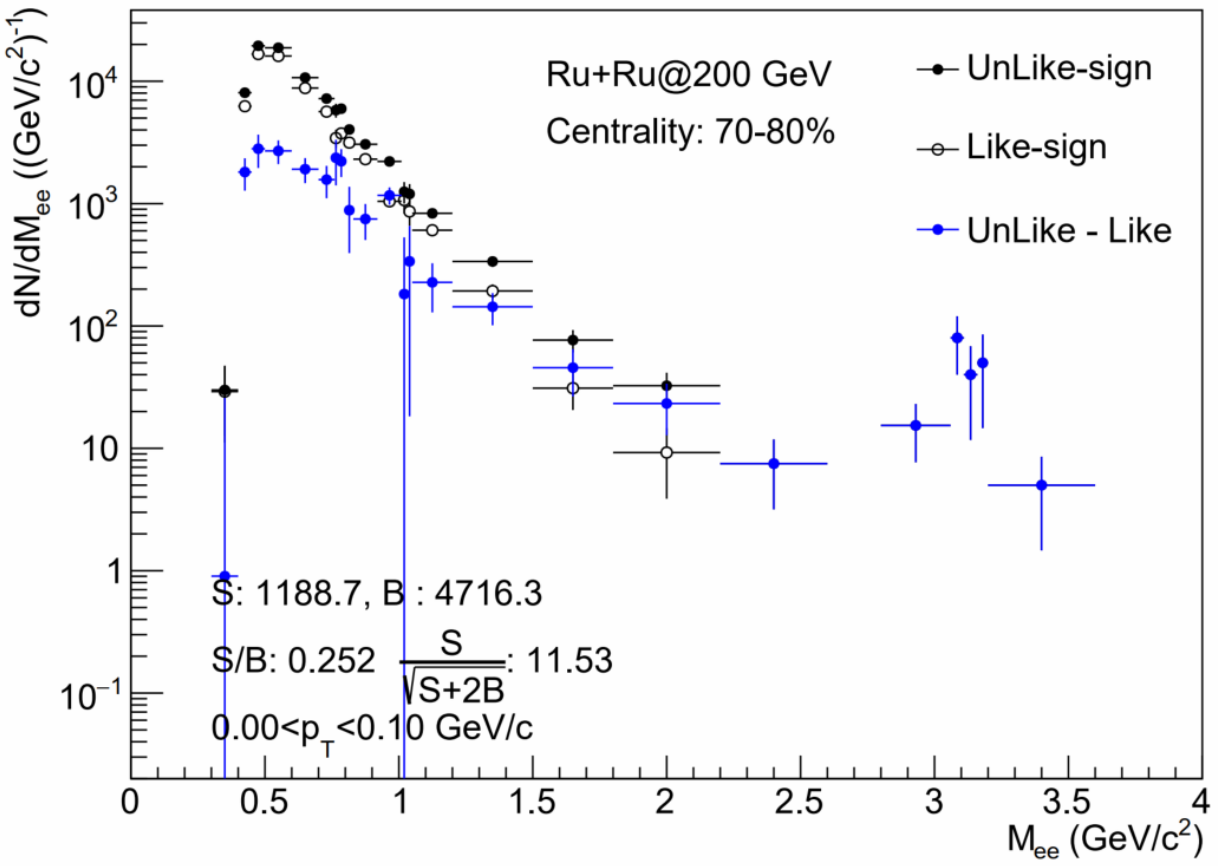
Collision species (taken in 2018)

- ${}^{96}_{44}Ru+{}^{96}_{44}Ru$ (~2B events)
- ${}^{96}_{40}Zr+{}^{96}_{40}Zr$ (~2B events)

Acceptance cuts:

- $p_T^e > 0.2$ GeV/c
- $|\eta^e| < 1$
- $|y^{ee}| < 1$

Di-electron Raw Signal



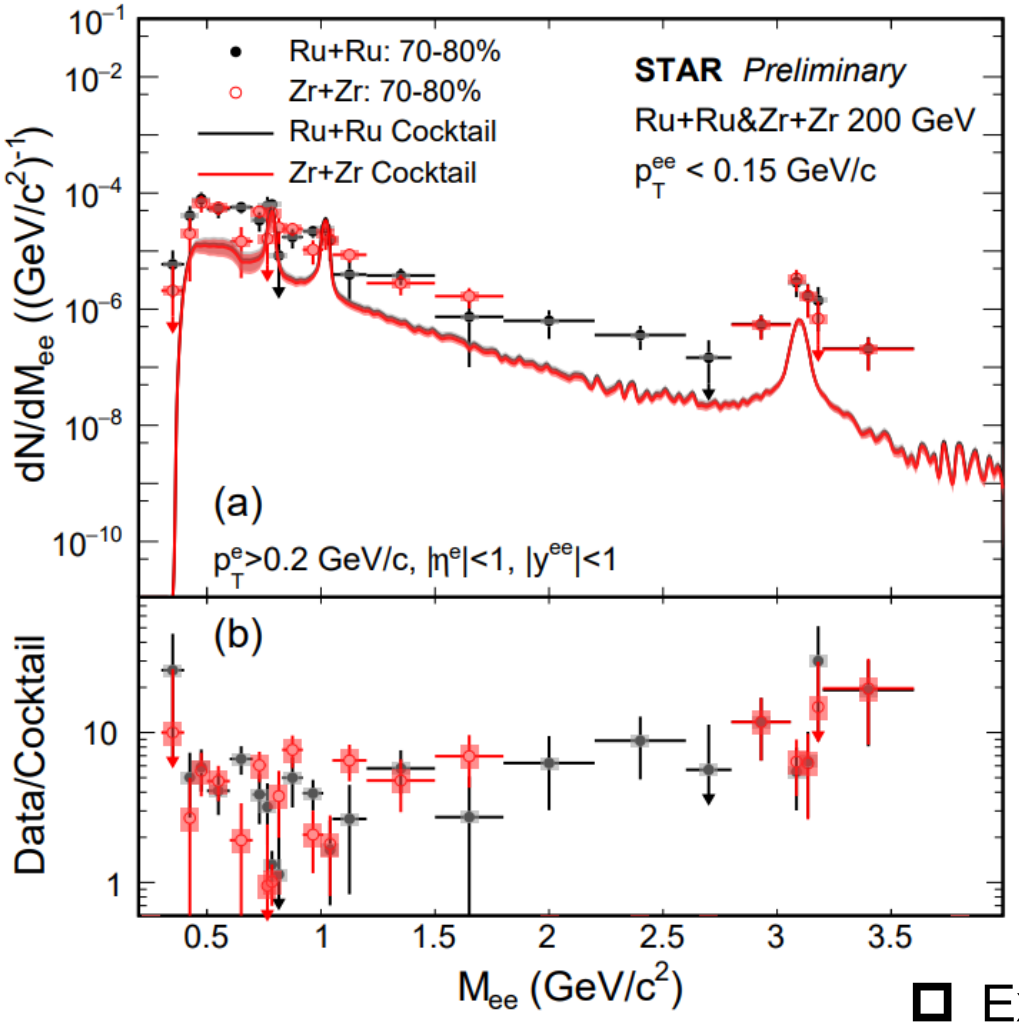
The same-event like-sign background used is calculated by this formula:

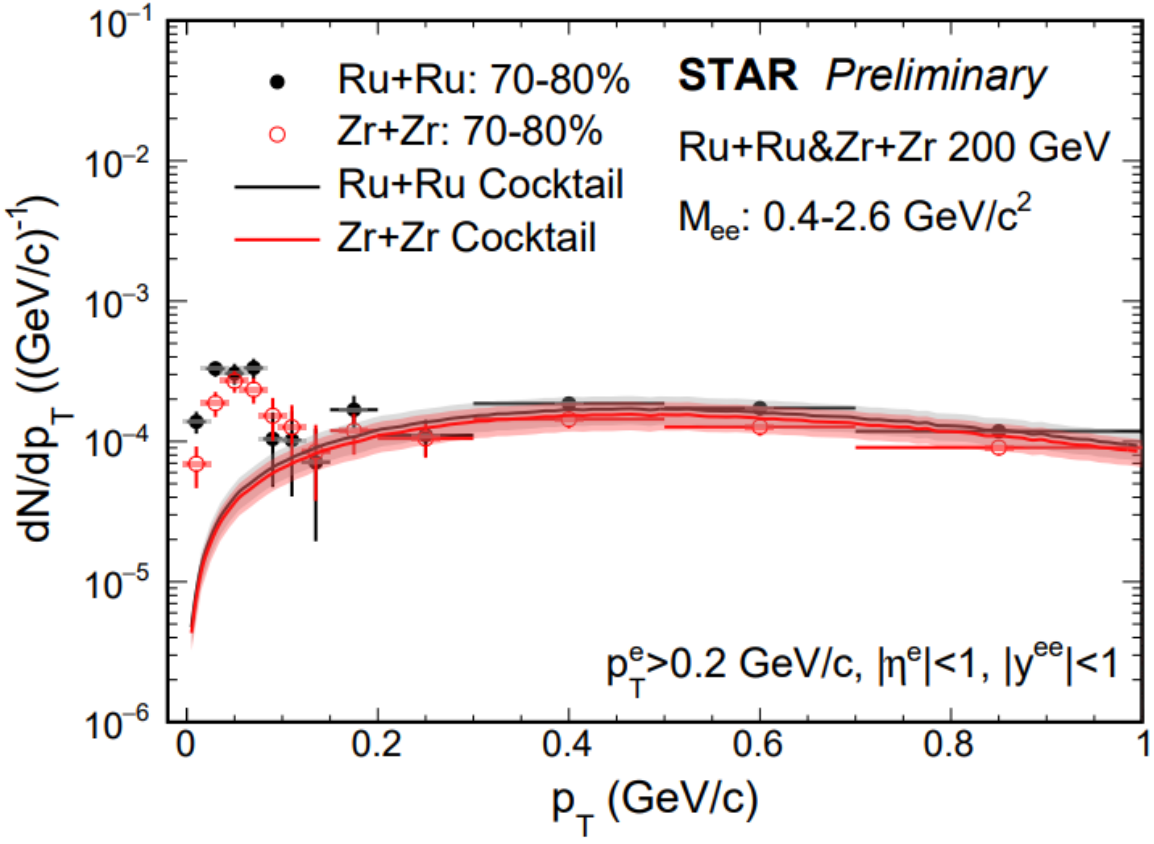
$$N^{corr}_{++\&--} = 2\sqrt{N_{++}(M,p_T) \times N_{--}(M,p_T)} \times \frac{B_{+-}(M,p_T)}{B_{++}(M,p_T) + B_{--}(M,p_T)}$$

Then raw signal is calculated by:

$$N_{raw\ signal} = N_{+-} - N^{corr}_{++\&--}$$

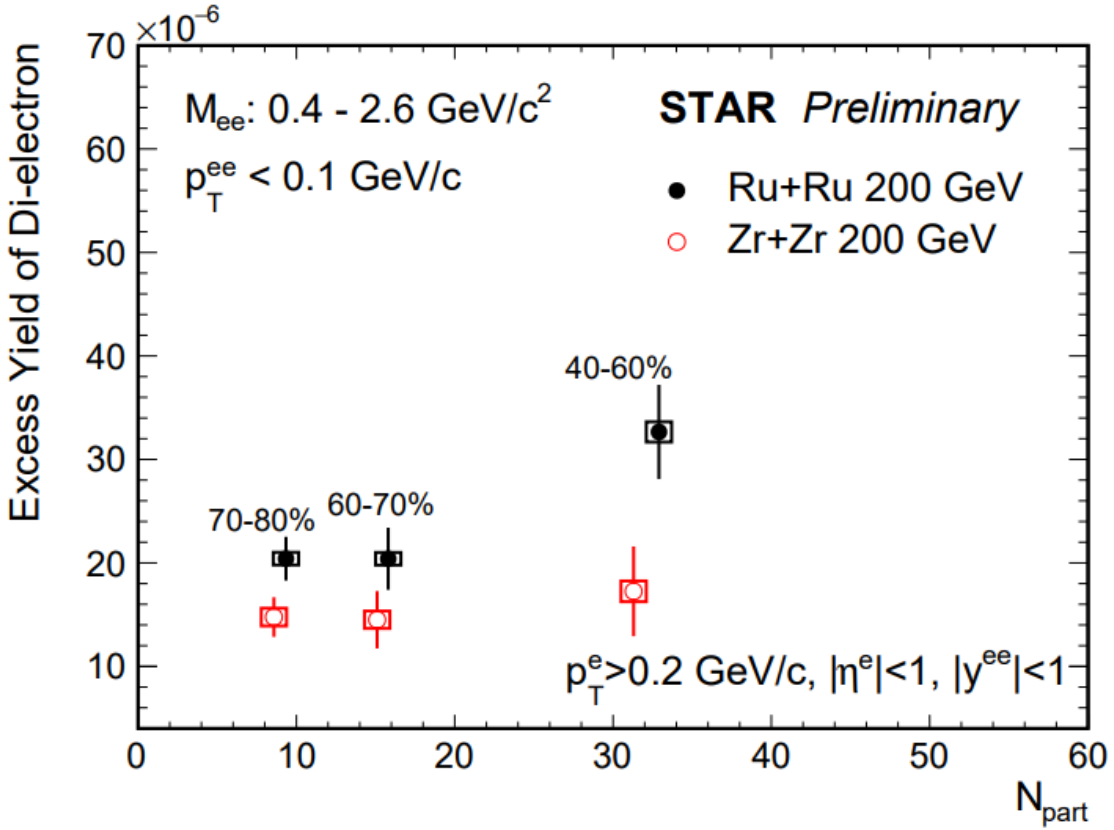
Invariant Mass and Transverse Momentum Distributions of e^+e^-

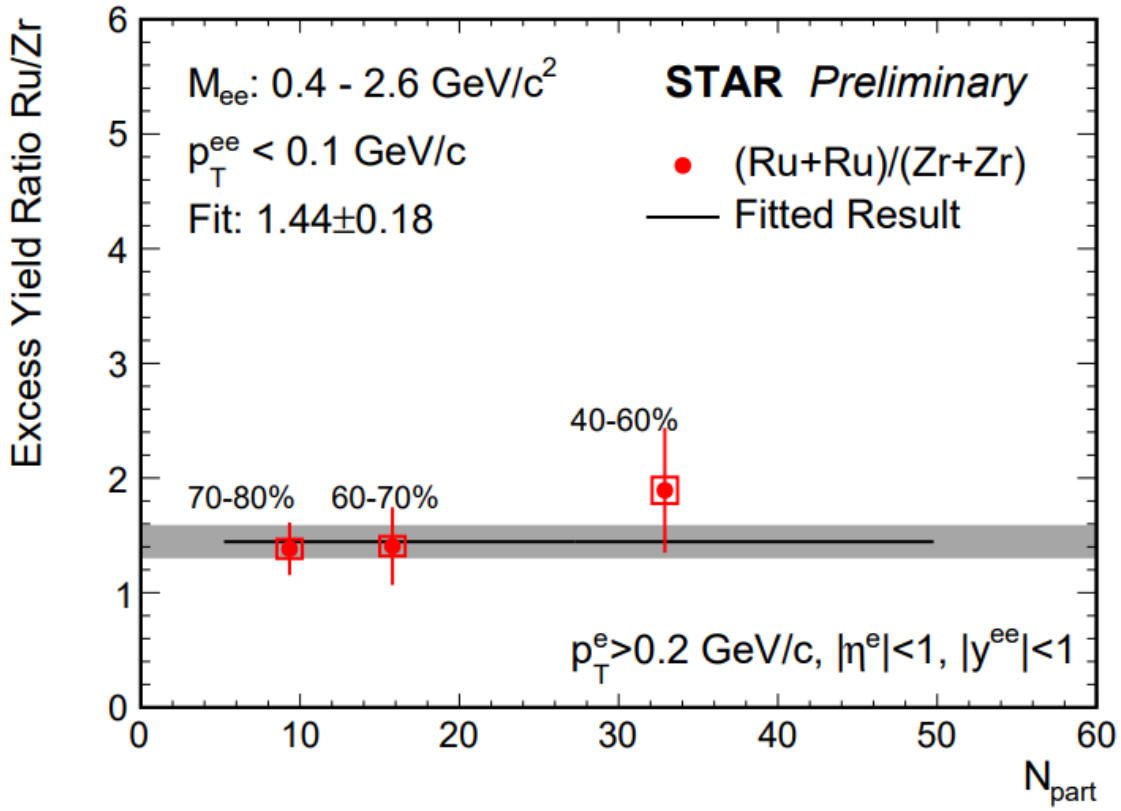




- Excesses above hadronic production are observed at low-p_T

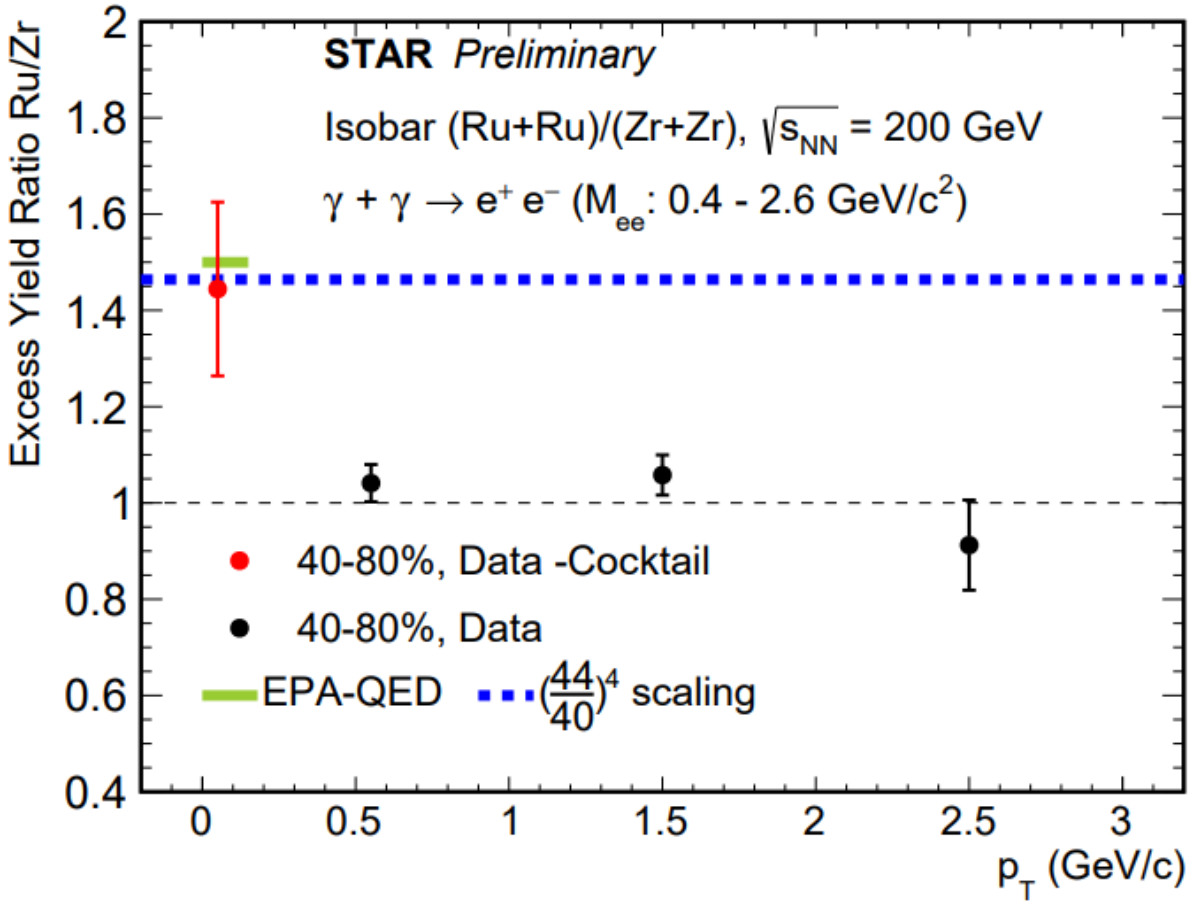
Centrality Dependence of Excess Yield





- The excess yields in Ru+Ru collisions are systematically higher than in Zr+Zr collisions
- A constant function is used to fit the ratio and is about 2.4σ higher than unity

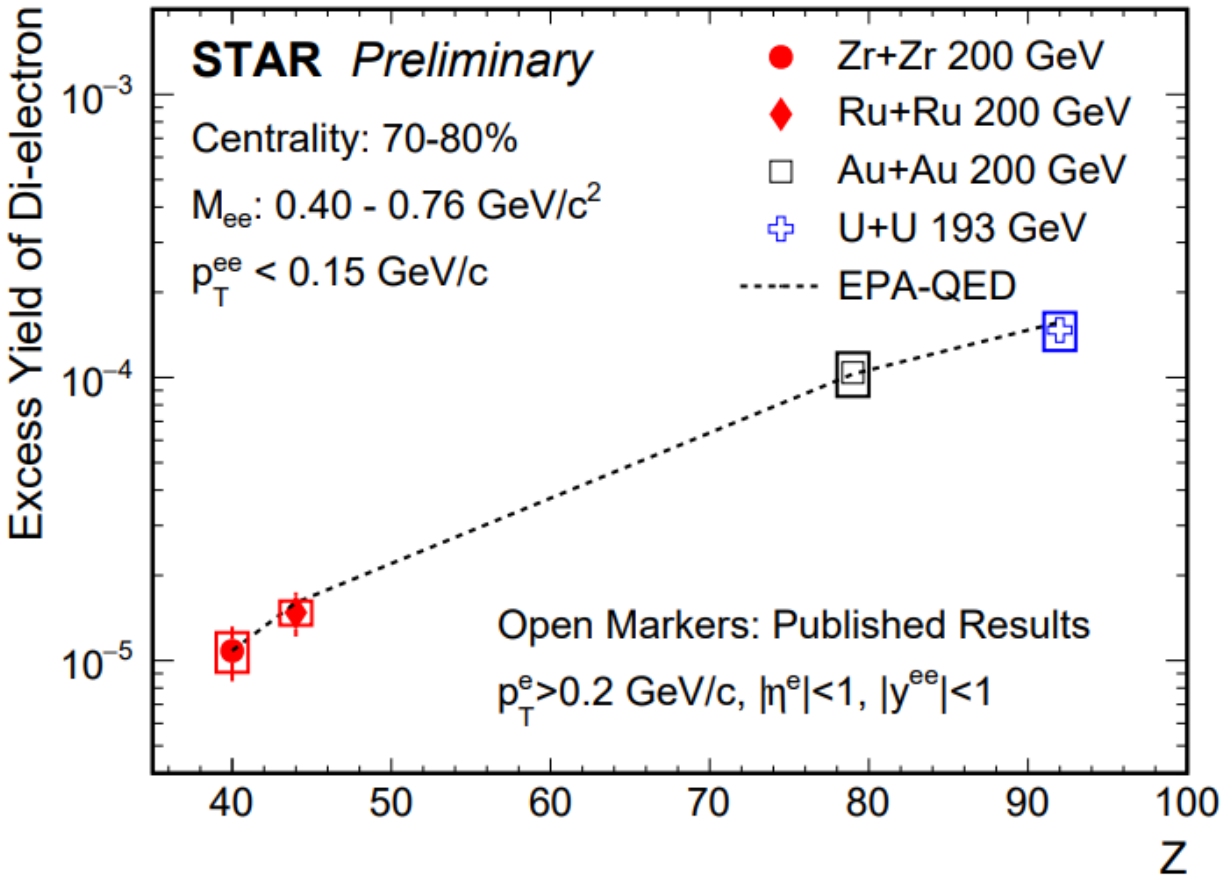
Excess Yield Ratio Between Isobaric Collisions

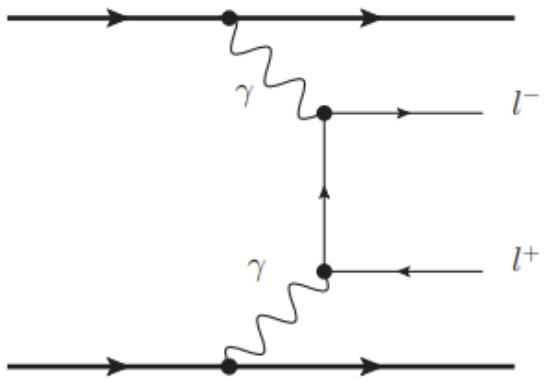


W. Zha et al, Phys. Lett. B 789 (2019) 238-242

- With cocktail subtracted, the yields at low-p_T are mainly from photon-induced production while the hadronic contributions dominate in intermediate p_T range
- The ratio of excess e^+e^- yield at low-p_T (< 0.1 GeV/c) in the 40-80% centrality is consistent with EPA-QED calculation and Z^4 scaling
- The initial EM fields seem to be different

Charge Dependence of Excess Yield





$\gamma + \gamma \rightarrow e^+e^-$

- The excess yields in isobaric collisions are significantly smaller compared to those in Au+Au and U+U collisions
- An interplay of the differences in charge, impact parameter and form factor

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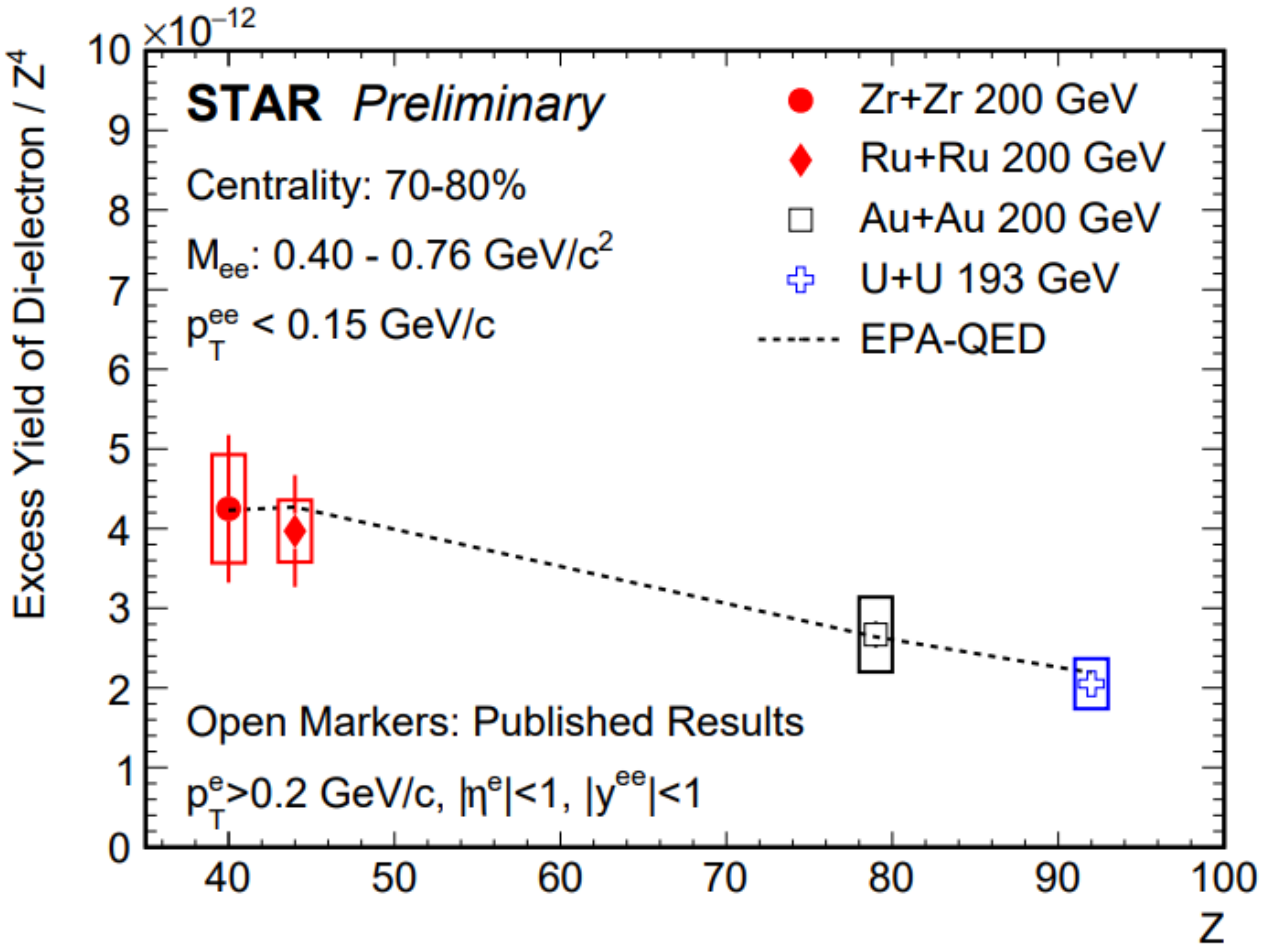
Charge Dependence of Scaled Excess Yield



J.Adam et al. (STAR) Phys. Rev. Lett. 121 (2018) 132301

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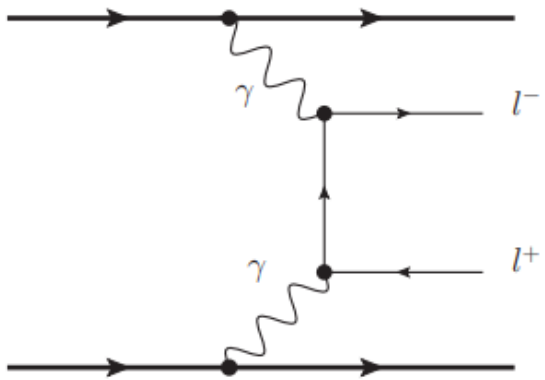


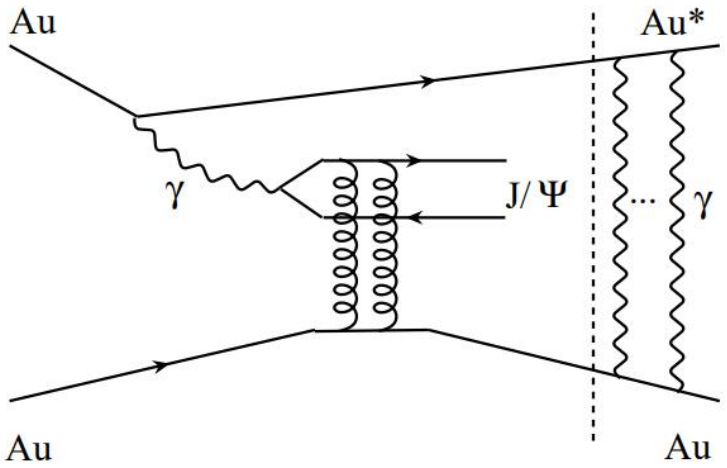
$\gamma + \gamma \rightarrow e^+e^-$

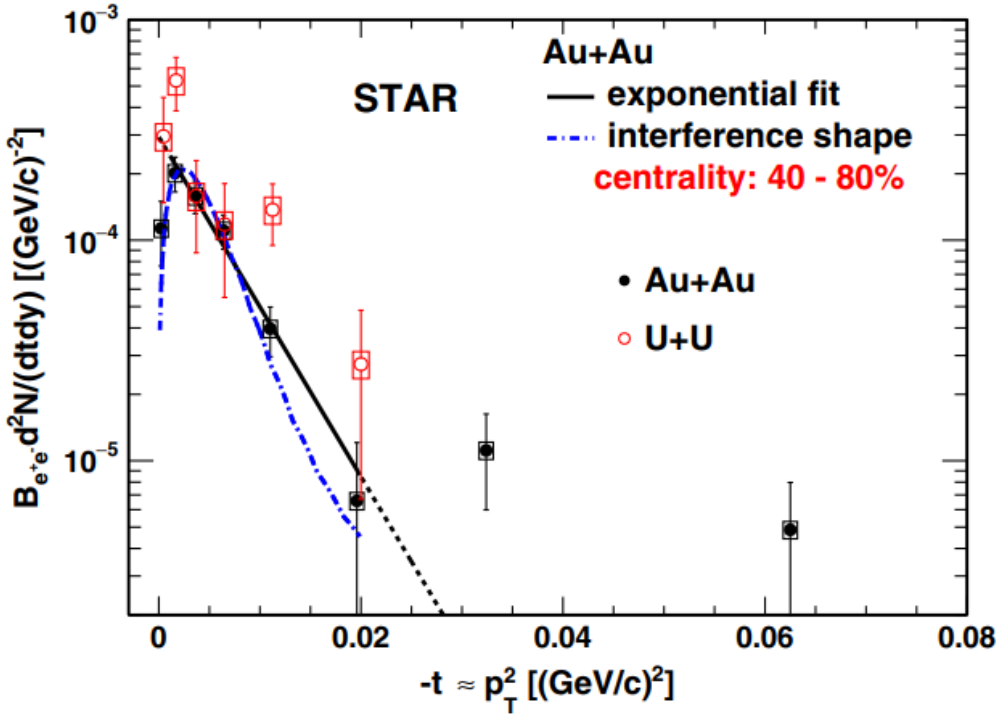
- Z^4 scaled yield shows clear collision system dependence, likely originating from impact parameter dependence
- Decreasing trend described the EPA-QED calculation

Outline

- Initial electromagnetic field induced e^+e^- production
- **Coherent J/ψ photon-nuclear production**
- Charmonium sequential suppression at RHIC
- Summary

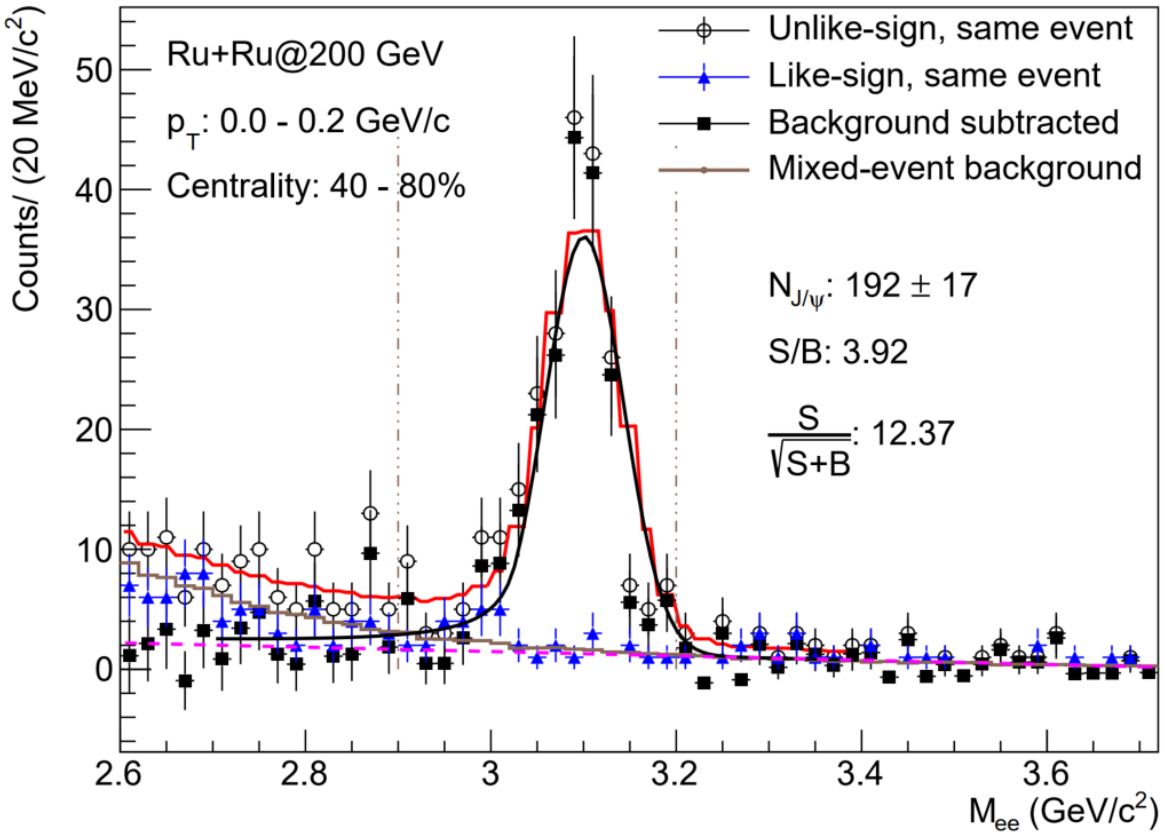
J/ψ Production From Photon-Induced Interactions

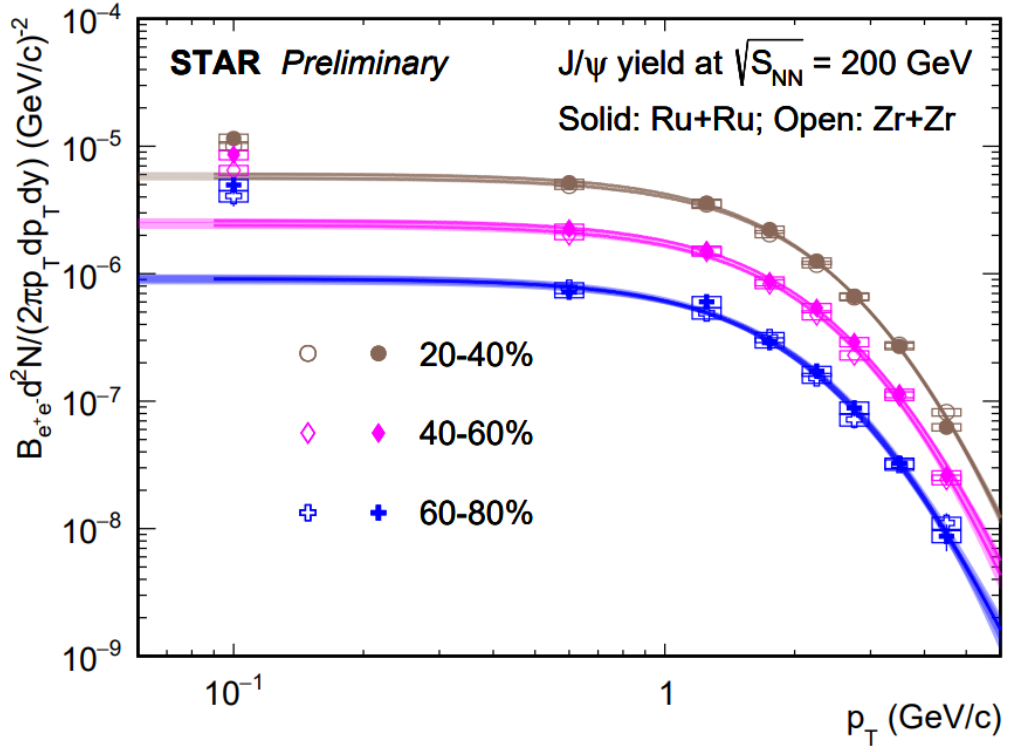




- The photon-induced production is sensitive to initial EM field:
  - Charge (Z) of the colliding nuclei
  - Gluon distribution in the colliding nuclei
- Coherent: J/ψ production at low p_T^2 (≤0.02 (GeV/c)^2), while both nuclei stay intact

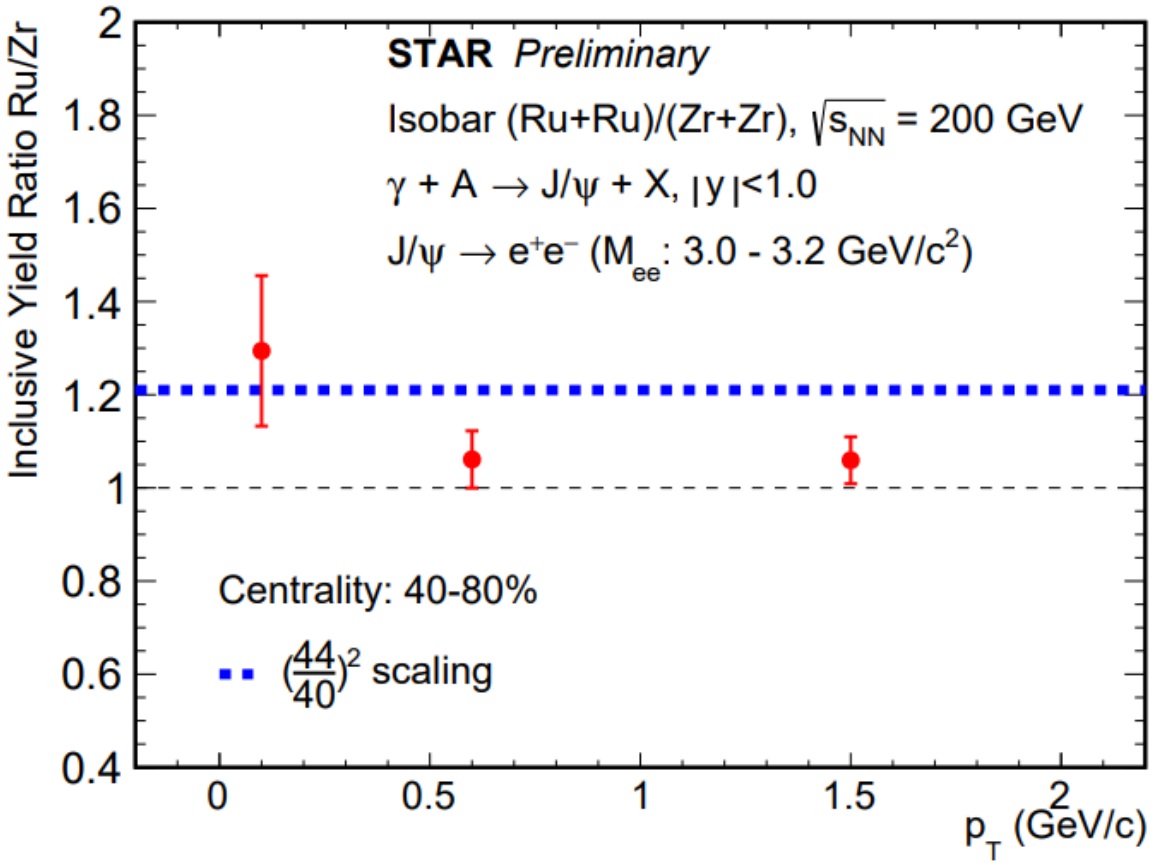
J/ψ Raw Signal





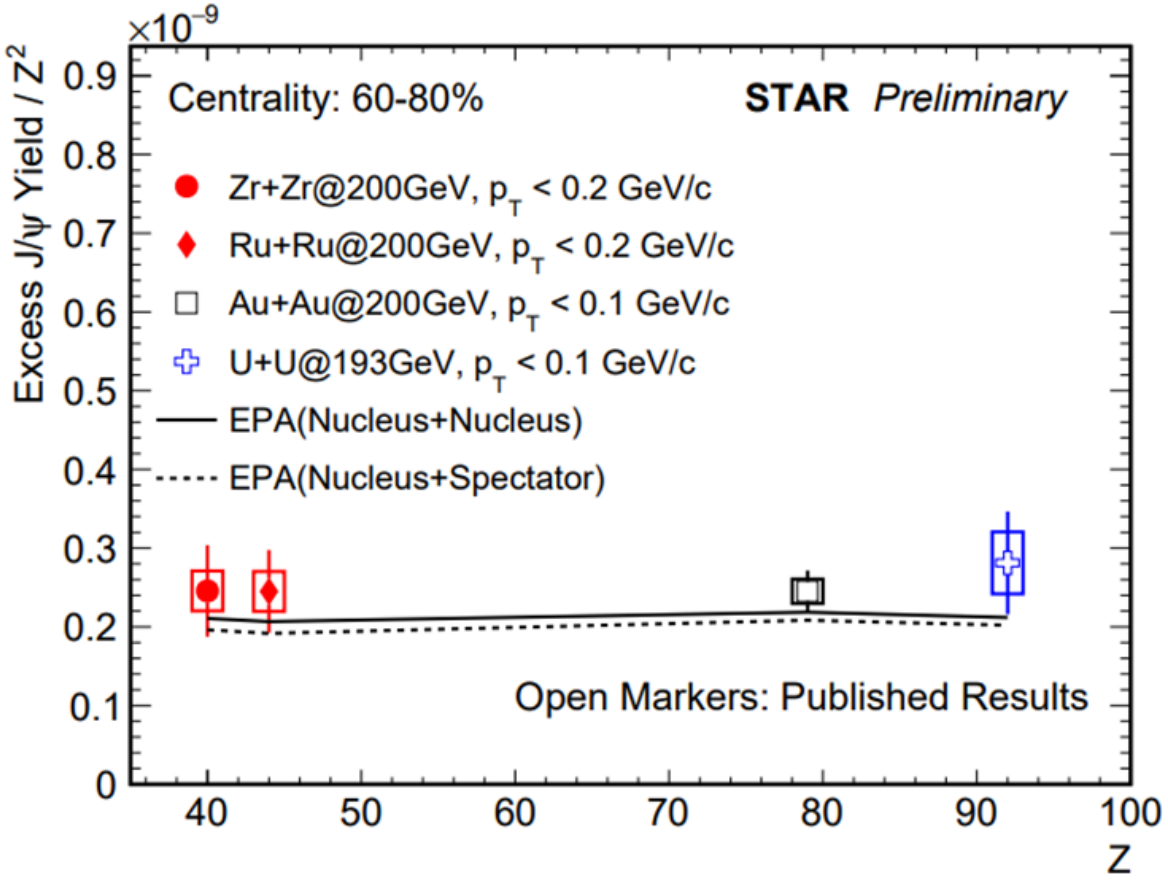
- The yield spectra are fitted by the Tsallis function
- Significant enhancements at low-p_T range

Ratio of J/ψ Yields Between Isobaric Collisions

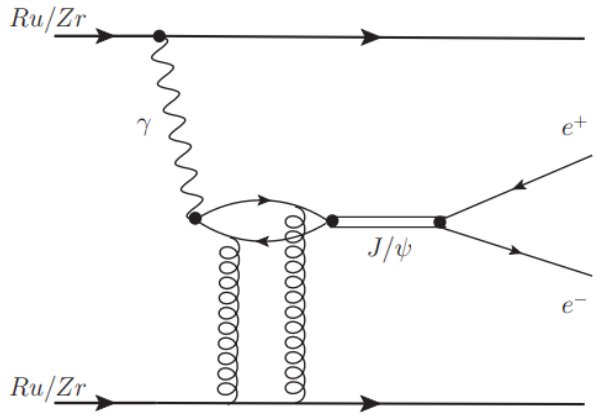


- Inclusive J/ψ production follows Z^2 scaling at very low p_T
- ~1.7σ deviation from unity at p_T < 0.2 GeV/c
- Hint of different initial EM fields

Collision System Dependence Between Isobar and Au+Au / U+U



J.Adam et al. (STAR) Phys. Rev. Lett. 123 (2019) 132302.
W. Zha et al. Phys. Rev. C 97, 044910 (2018)



$\gamma + \mathrm{A} \rightarrow J/\psi + \mathrm{A}$

- Scale J/ψ excess yields at very low p_T with Z^2
- The photo-nuclear production of J/ψ seems to be independent of collision species at a given centrality
- Effects of form factor and impact parameter seem to balance each other

Outline

- Initial electromagnetic field induced e^+e^- production
- Coherent J/ψ photon-nuclear production
- **Charmonium sequential suppression at RHIC**
- Summary

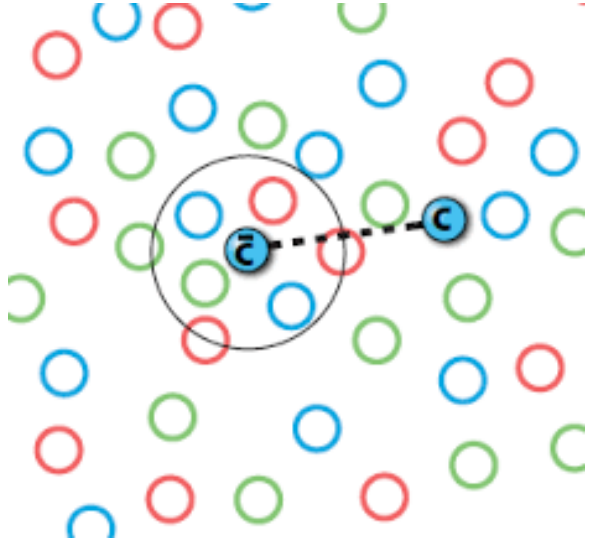
J/ψ Suppression In Heavy Ion Collisions

Heavy quarkonia, for example J/ψ, are ideal probes of the Quark-Gluon Plasma (QGP)

Heavy quarkonia mainly produced from initial hard partonic scattering

Suppressed in QGP due to the color screening, first proposed by T. Matsui and H. Satz in 1986

T. Matsui, H. Satz, Phys. Lett. B, 1986, 178: 416-422

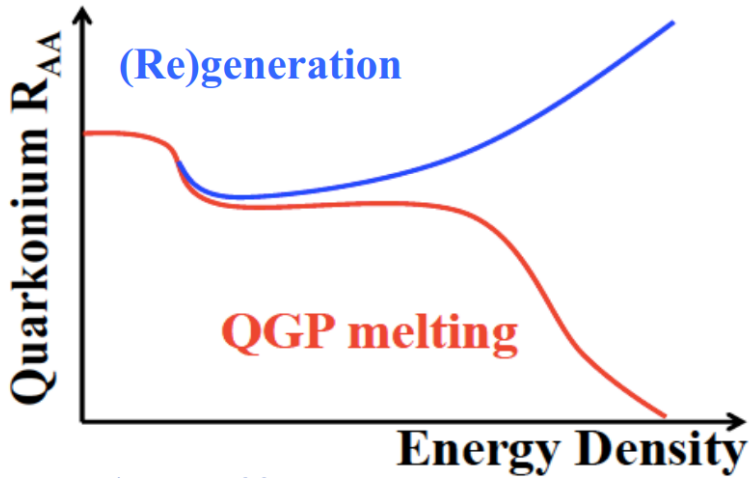


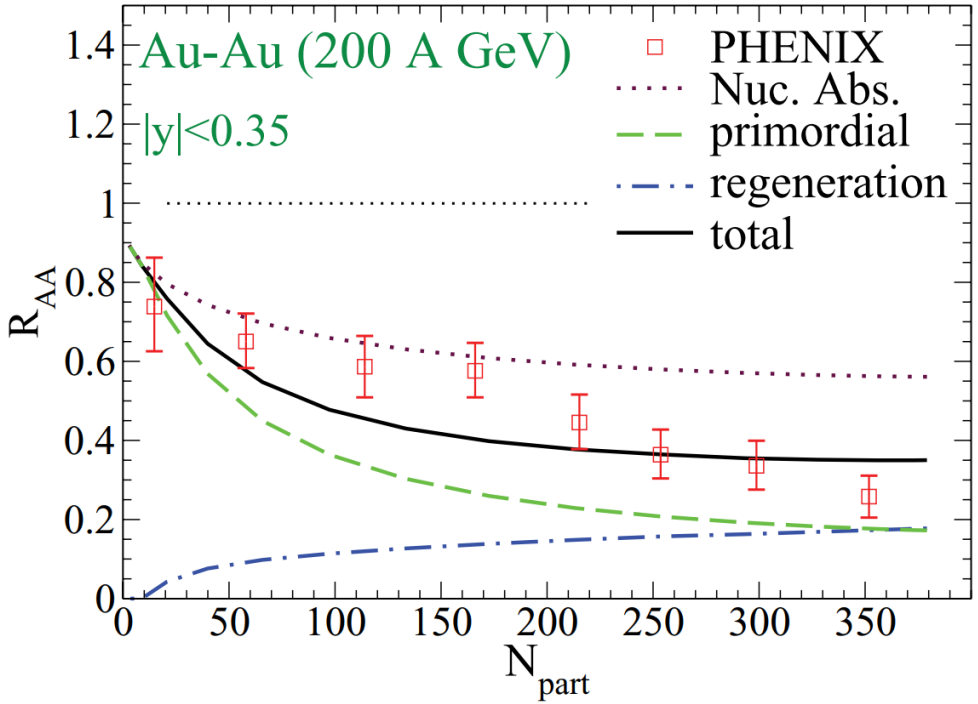
$$V(r) = -\frac{\alpha_{eff}}{r} e^{[-\frac{r}{\lambda_D}]}$$

	$\psi(2s)$	J/ψ
T_D	$1.12T_c$	$2.10T_c$

J/ψ Production In Heavy Ion Collisions

- Dissociation in QGP (static and dynamic screening)





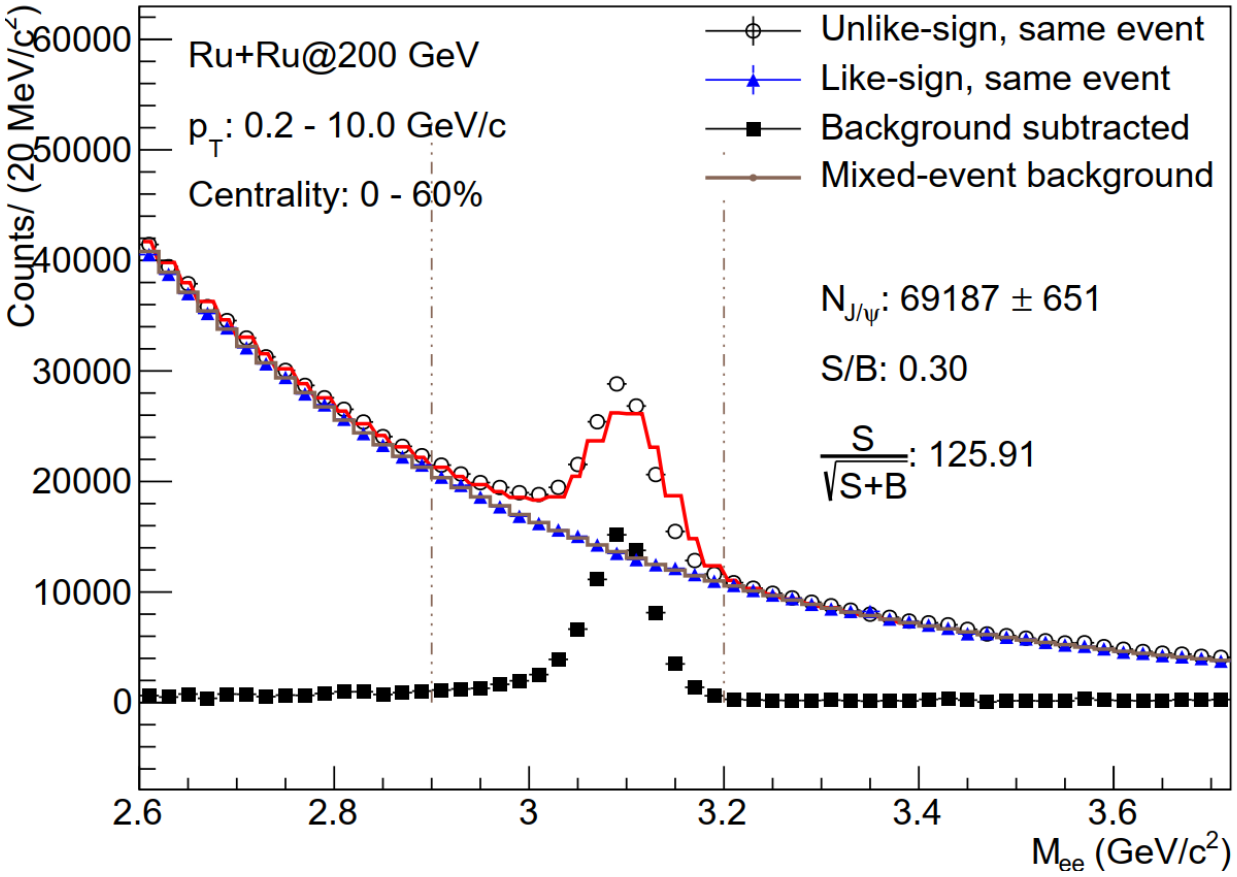
X. Zhao, R. Rapp, et al. Phys. Rev. C 82, 064905 (2010)

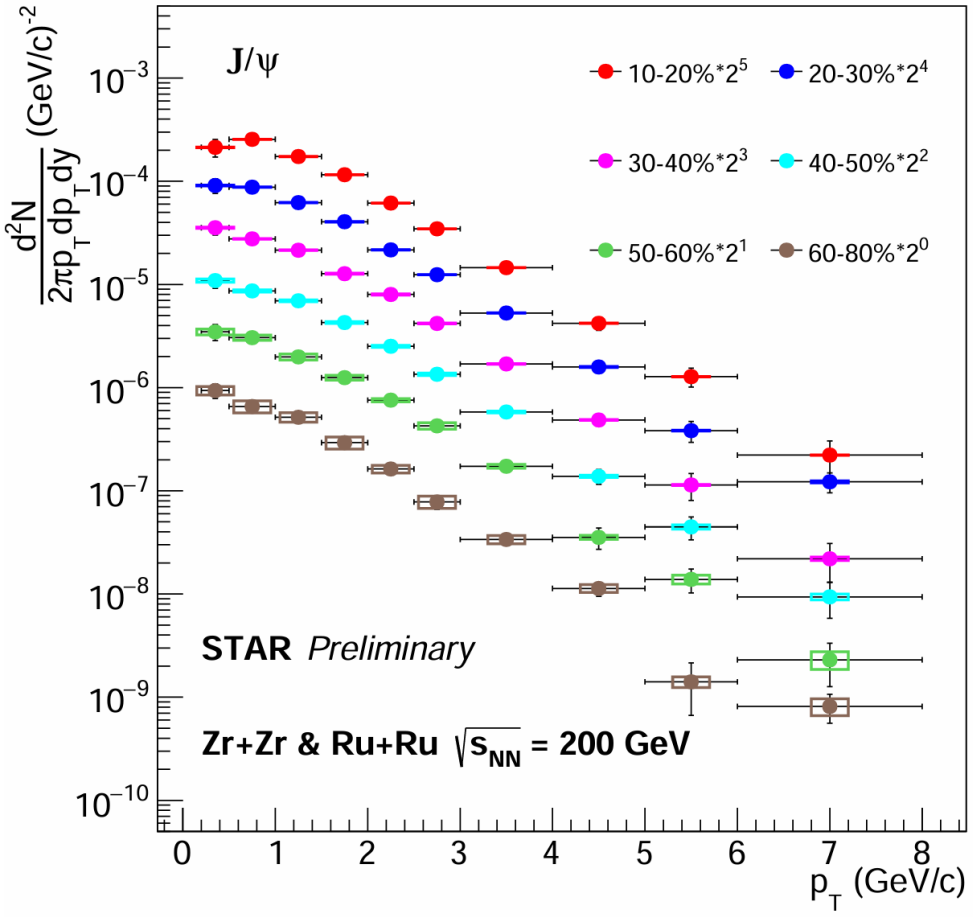
Other effects:

- Regeneration
- Cold nuclear matter effects (e.g. nPDF, nuclear absorption,…)
- Other final state effects (e.g. comovers)

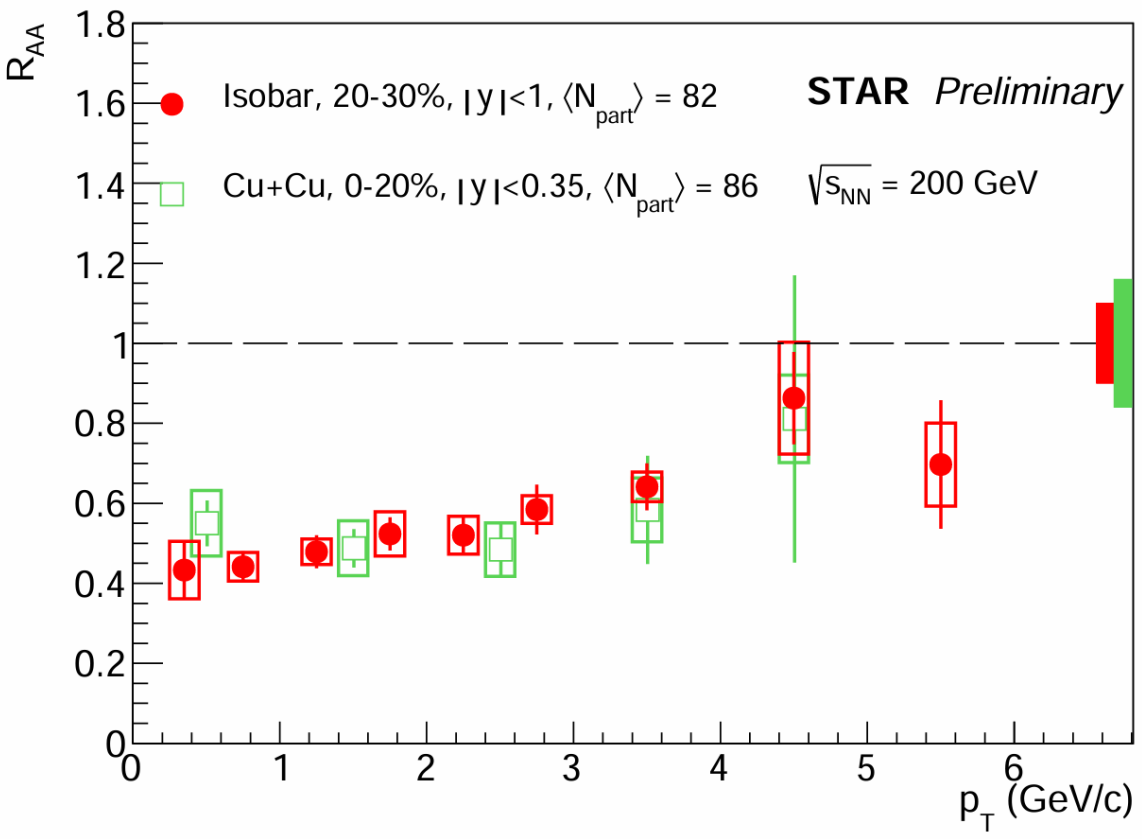
J/ψ Signal

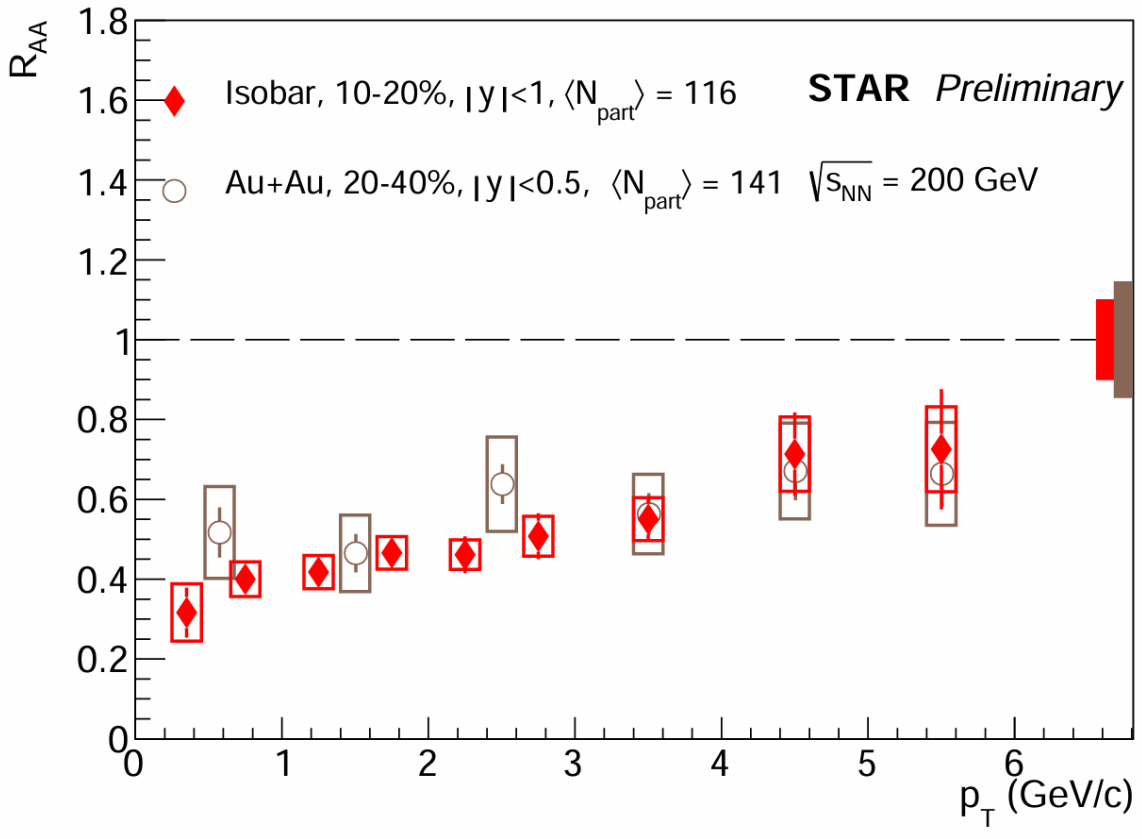
The extremely significant J/ψ production at isobaric collisions





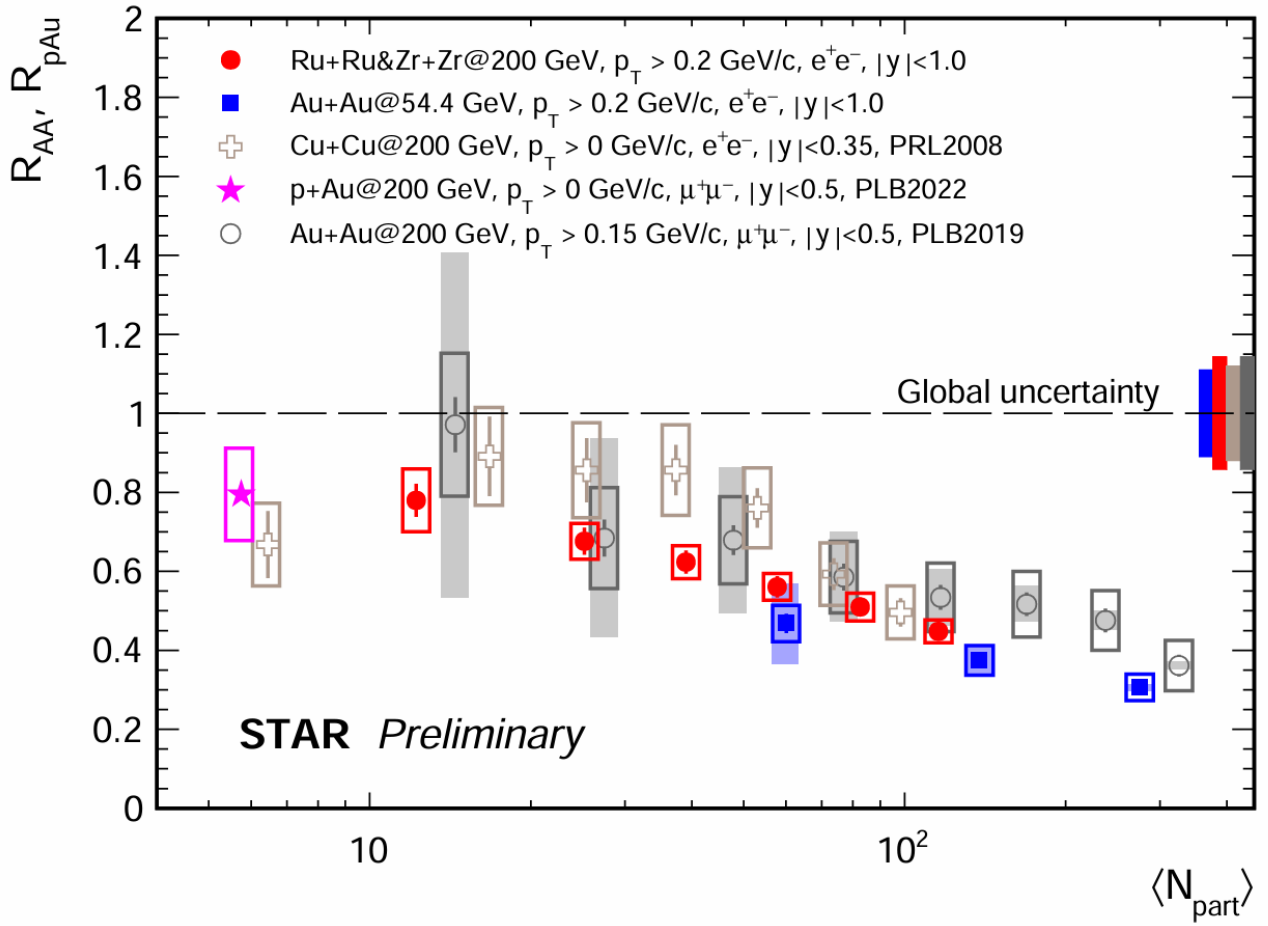
Collision System Dependence Between Isobar and Au+Au/Cu+Cu





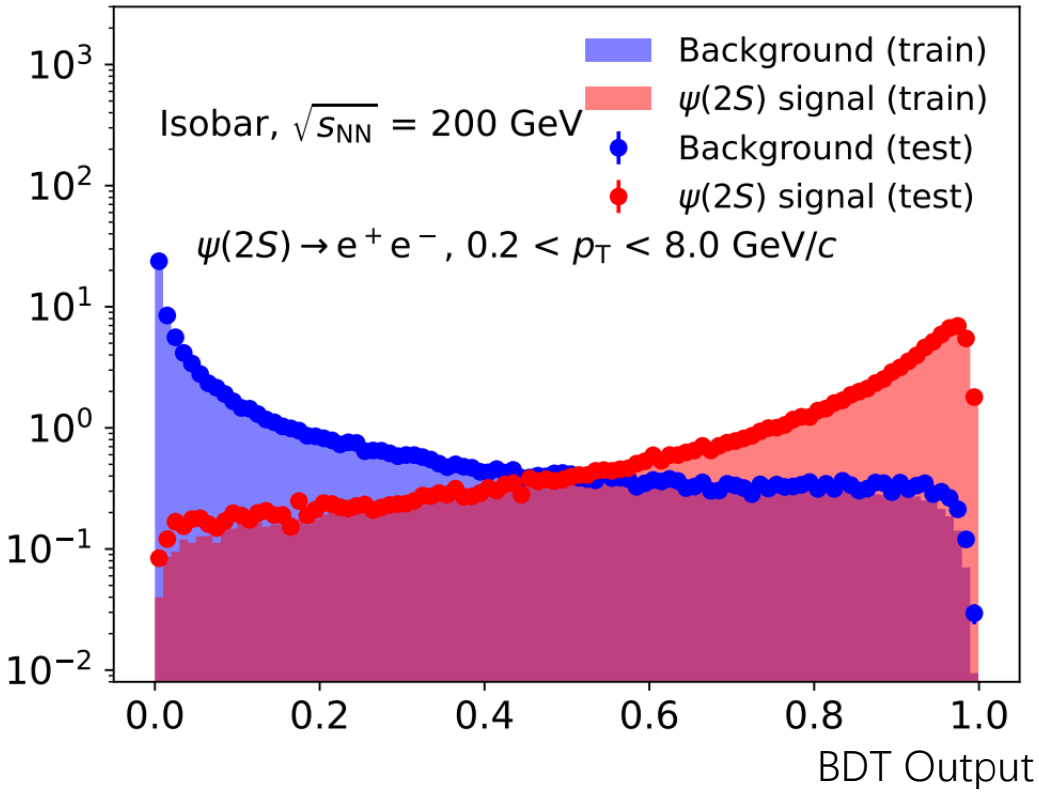
- The nuclear modification factor of J/ψ in isobaric collision has been measured
- No significant p_T dependence of J/ψ suppression has been observed

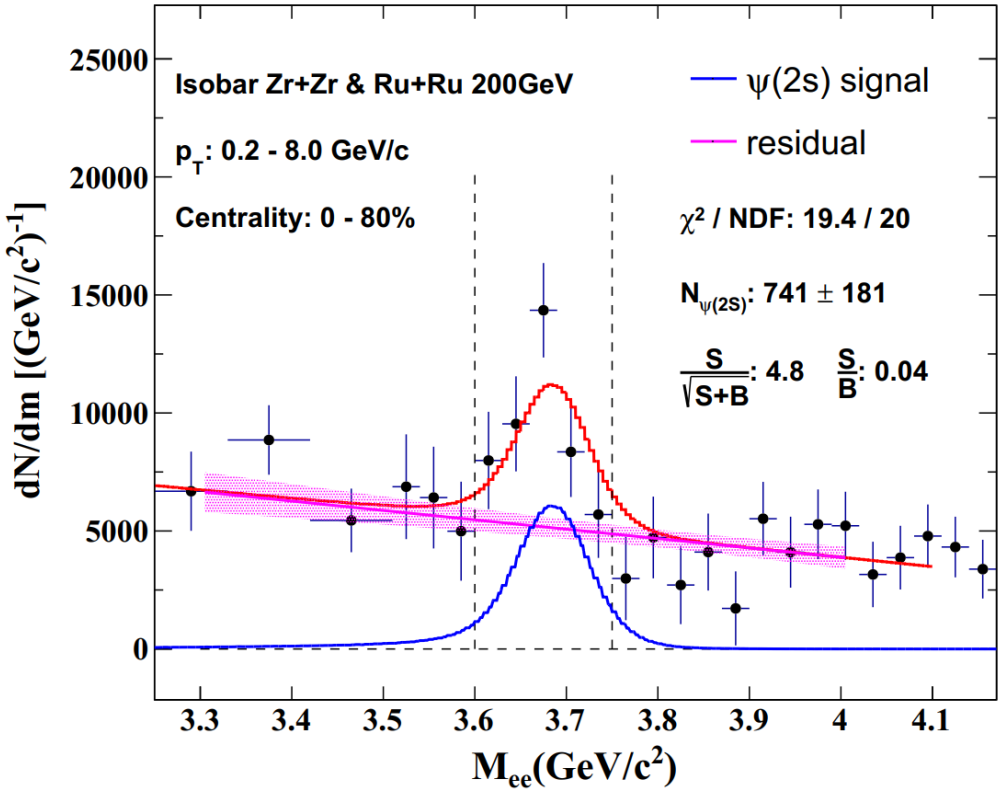
N_{Part} Scaling of J/ψ Nuclear Modification Factor



- After N_{part} scaled, no significant collision system dependence

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



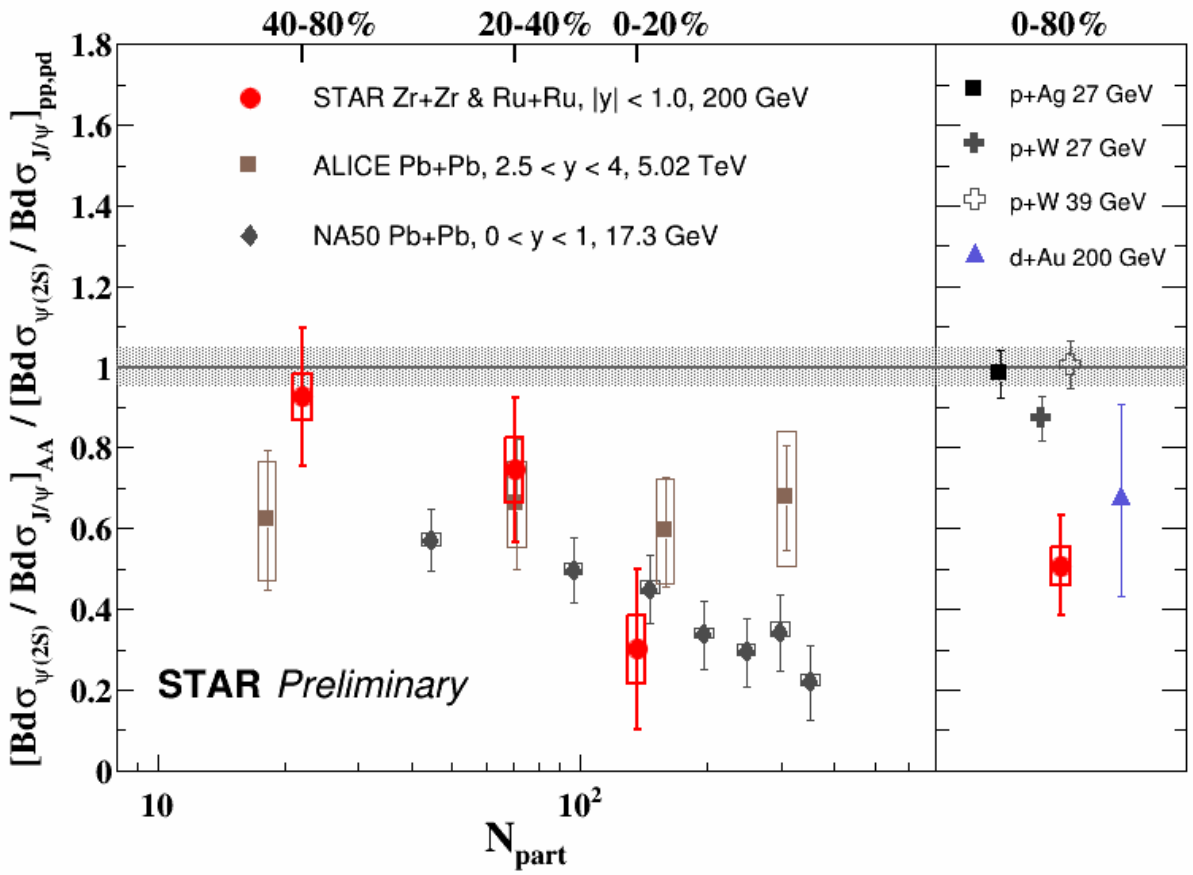


- A machine learning method is employed to reconstruct the ψ(2S) signal
- XGBoost (Extreme Gradient Boosting) as core

hipe4ml

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

Double ratio



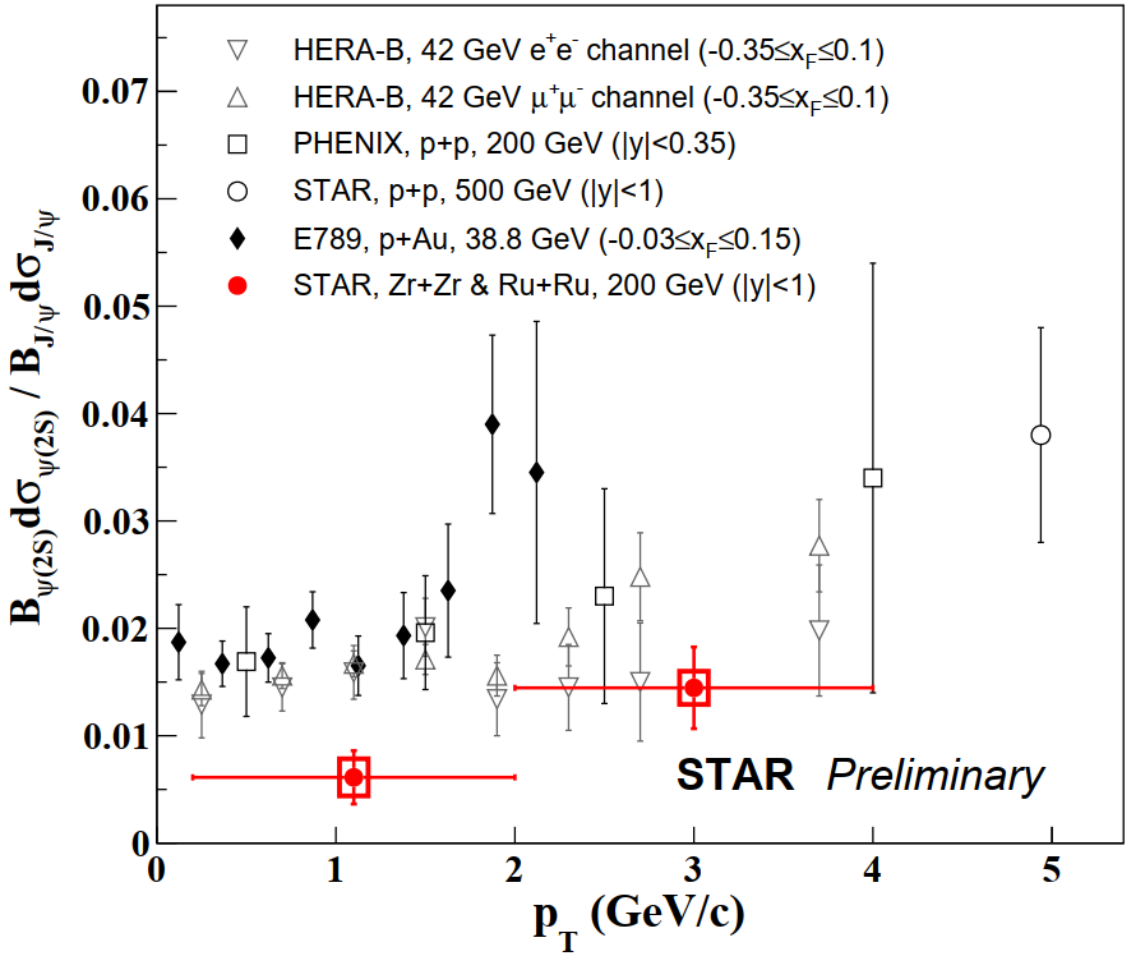
- First observation of charmonium sequential suppression in heavy ion collisions at RHIC (3.5σ, 0-80%)
- ψ(2S) over J/ψ double ratio is smaller than that in p+A collisions
- Centrality dependence trend seems be more similar to that at SPS than at LHC

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

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) 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.

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- Initial electromagnetic field induced e^+e^- production
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- Charmonium sequential suppression at RHIC
- **Summary**

Summary

- The collision species dependence of photon-induced production have been measured at STAR
  - ➢The initial EM field seems to be different in peripheral Ru+Ru and Zr+Zr collisions
  - ➢After taking out the charge difference, the excess yield of J/ψ is mostly independent of collision system, while e^+e^- shows an impact parameter dependence

- No significant collision system dependence of inclusive J/ψ production has been observed at RHIC energies

- A Clear charmonium sequential suppression (3.5σ, 0-80%) has been measured firstly at RHIC energy

Thanks!

Back up