
# Initial electromagnetic field dependence of photon-induced production in isobaric collisions at STAR

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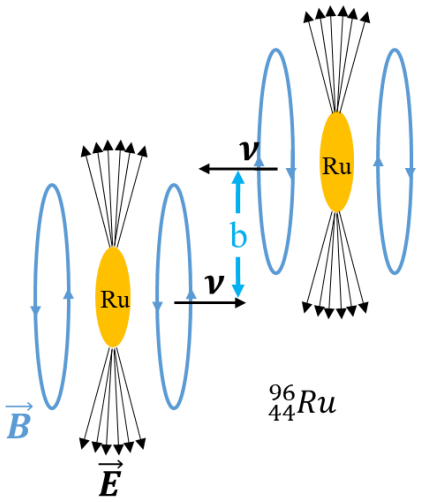
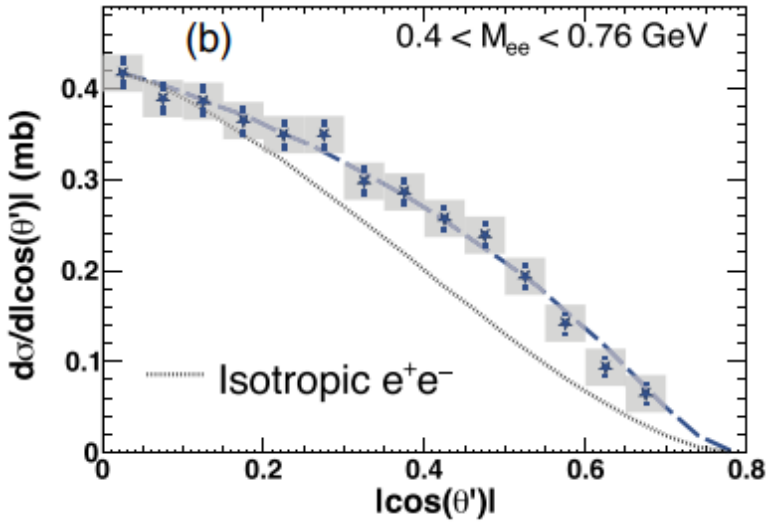
# Outline

- Motivation and  the STAR experiment
- $e^+e^-$ pair production in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV at very low $p_T$
- J/$\psi$ production in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV at very low $p_T$
- Angular distribution of $e^+e^-$ in isobaric collisions
- Summary

# Initial Electromagnetic Field in Heavy Ion Collisions

- Transverse EM fields is equivalent to a flux of quasi-real photons ($\propto Z^2$, and $q^2 \to 0$)




- Photons are transverse and linearly polarized
- High photon density only possible in high-energy heavy ion collisions ($|\vec{B}| \approx 10^{14}$-$10^{16}$T) – test QED under extreme conditions

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

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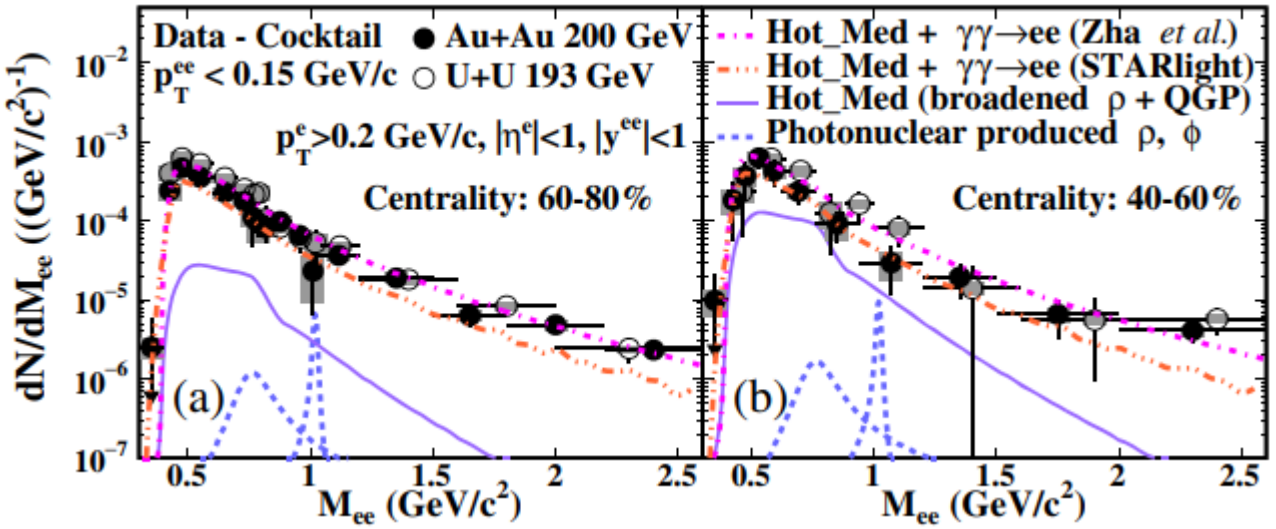
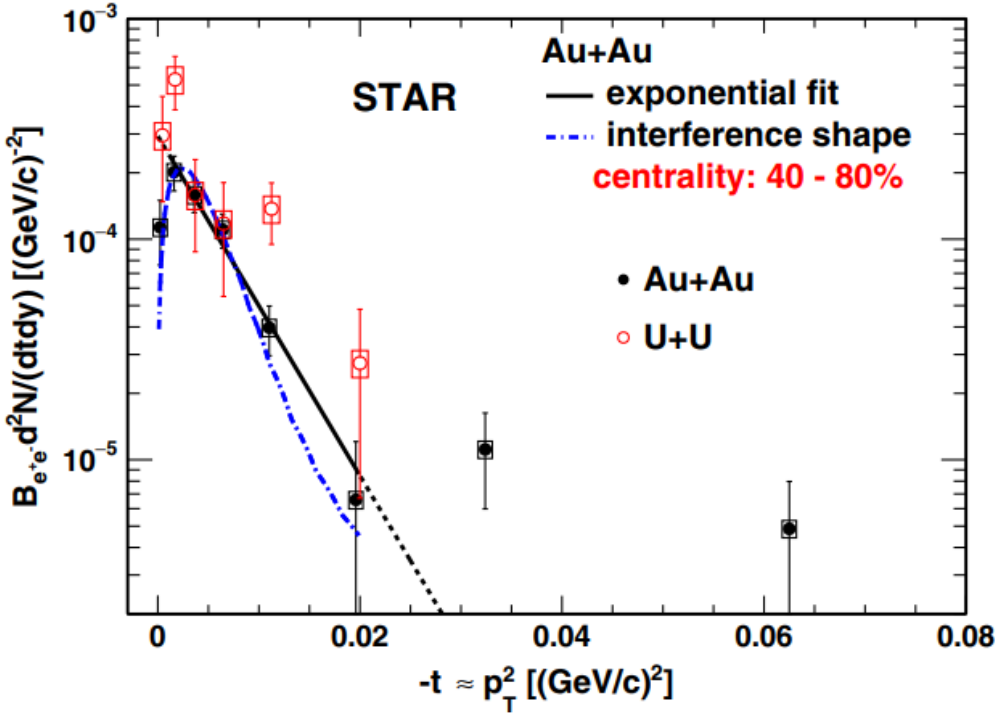
# Photon-induced Production in Peripheral Collisions

- Conventionally, photon-induced process only studied in ultra-peripheral collisions (b>2$R_A$,UPCs) to keep coherence condition

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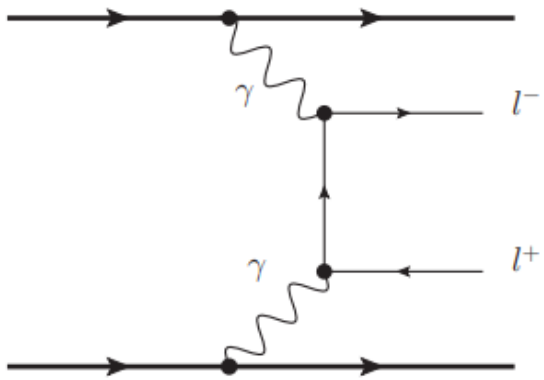
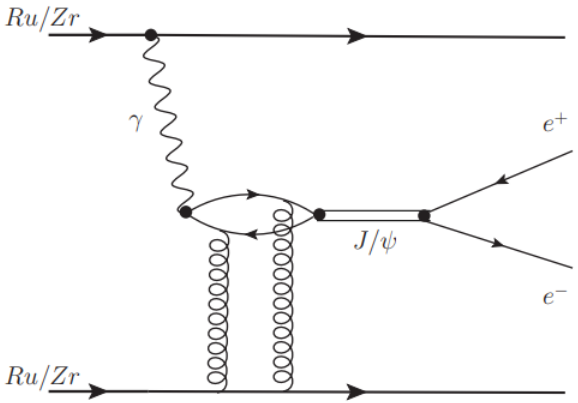
- The enhancements of J/$\psi$ and $e^+e^-$ production at very low $p_T$ have been observed in peripheral collisions
- Photon-induced interactions could explain the observed enhancements

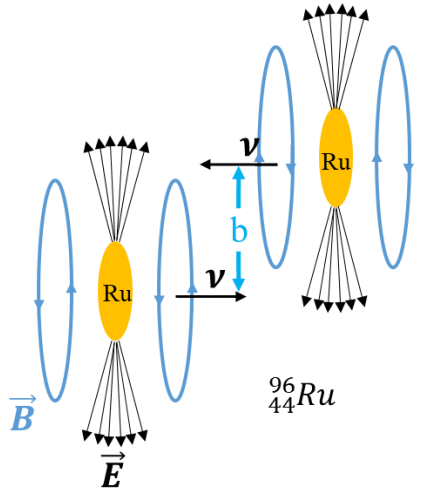
# Photon-induced Production in Peripheral Collisions

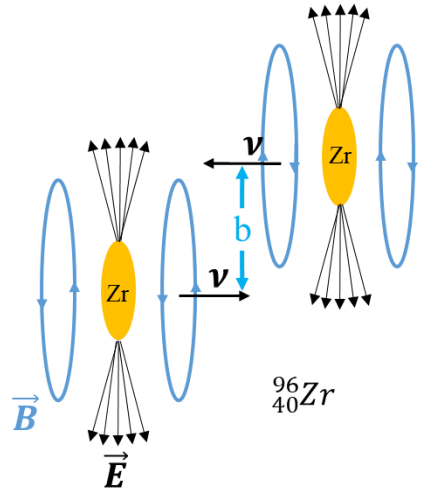
- The isobaric collisions provide a unique opportunity to test the electromagnetic field dependence




- Charge (Z)
- Impact parameter
- …

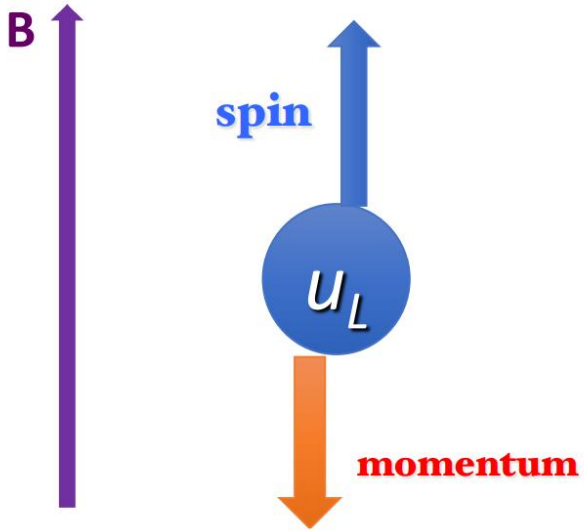


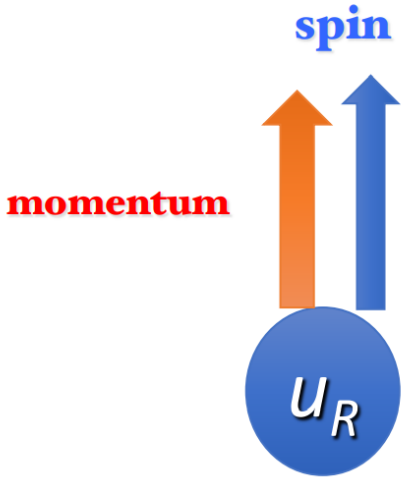




- The photon-induced production is sensitive to initial EM field:
  - ➢Charge (Z) of the colliding nuclei
  - ➢Collision system

# Implication for Searching Chiral Magnetic Effect

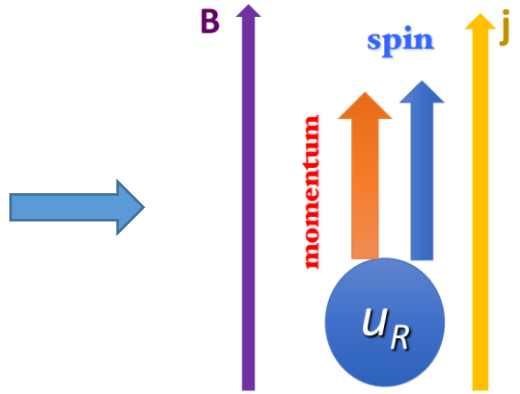
- The photon-induced production is sensitive to initial EM field




Heavy ion collisions:

- Strong magnetic fields
- Imbalance of left-handed & right-handed quarks

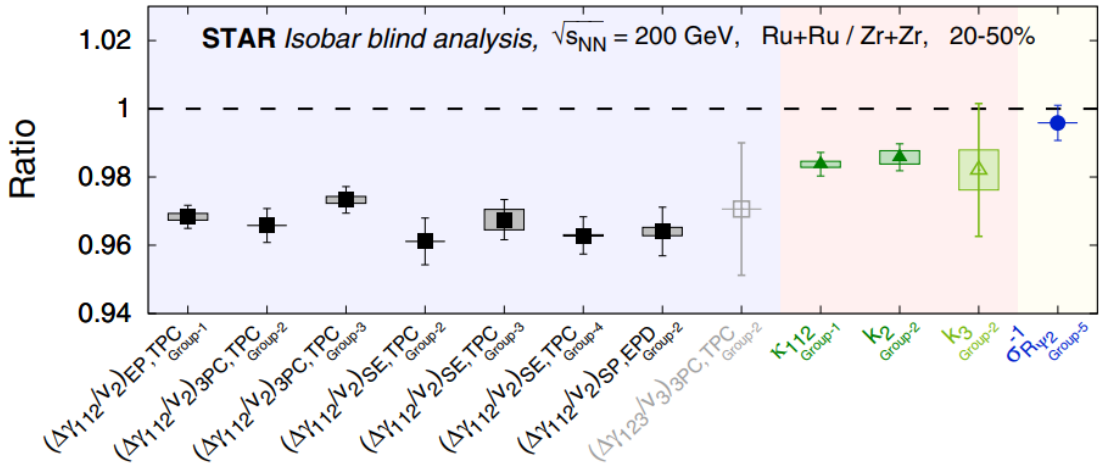



Charge current, called Chiral Magnetic Effect

Results from blind analysis of isobaric collisions:

- No pre-defined CME signatures observed

Need to confirm the EM field difference in isobaric collisions for further CME study

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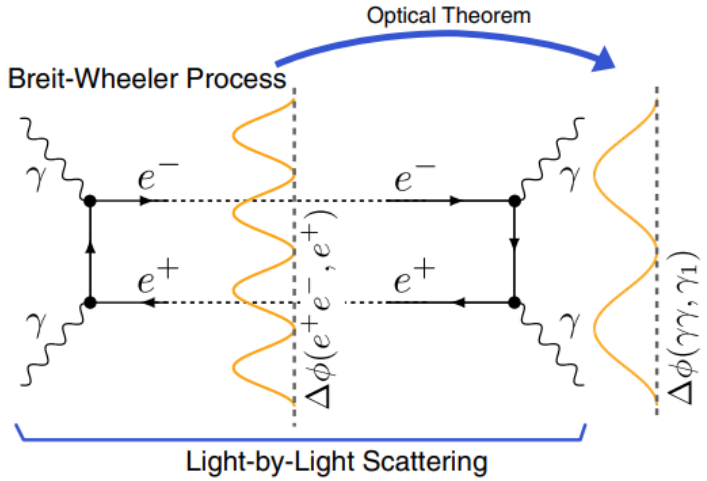
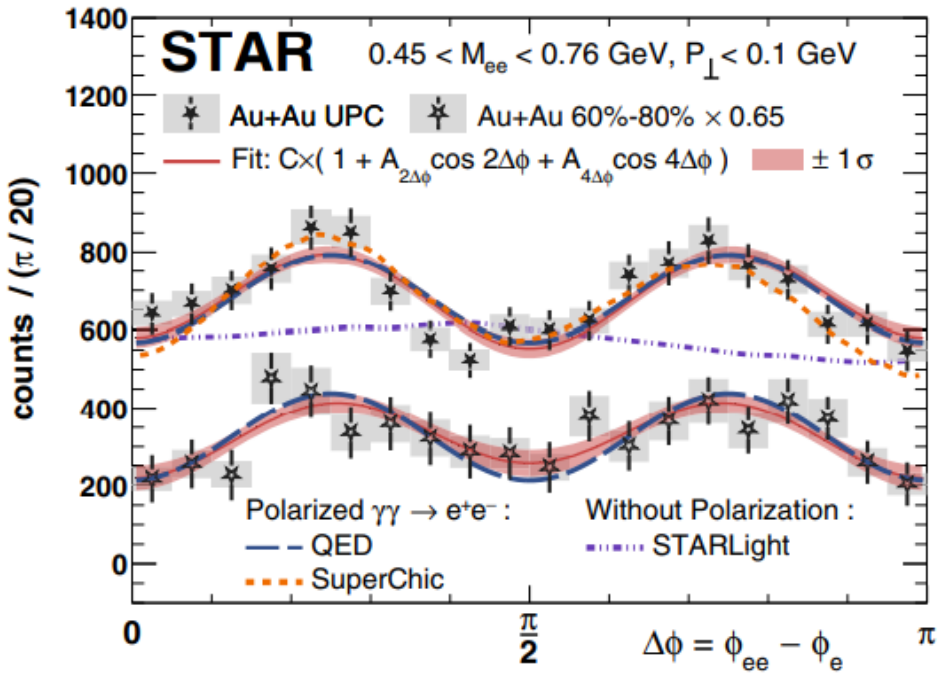
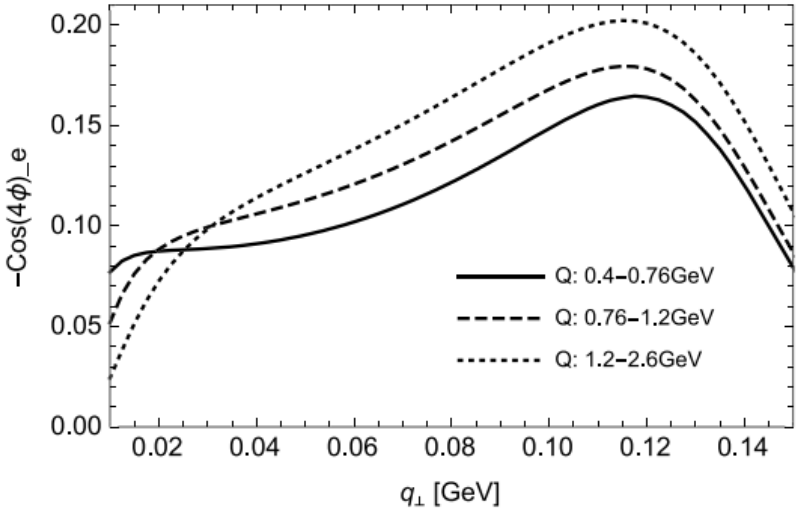
# Birefringence of the QED Vacuum




- The Breit-Wheeler process has been investigated in peripheral and ultraperipheral Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV through $\gamma + \gamma \rightarrow e^+e^-$ process




$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2} = \frac{2\alpha_e^2}{Q^4}[\mathrm{A+B\times\cos(2\varphi)+C\times\cos(4\varphi)}]$$

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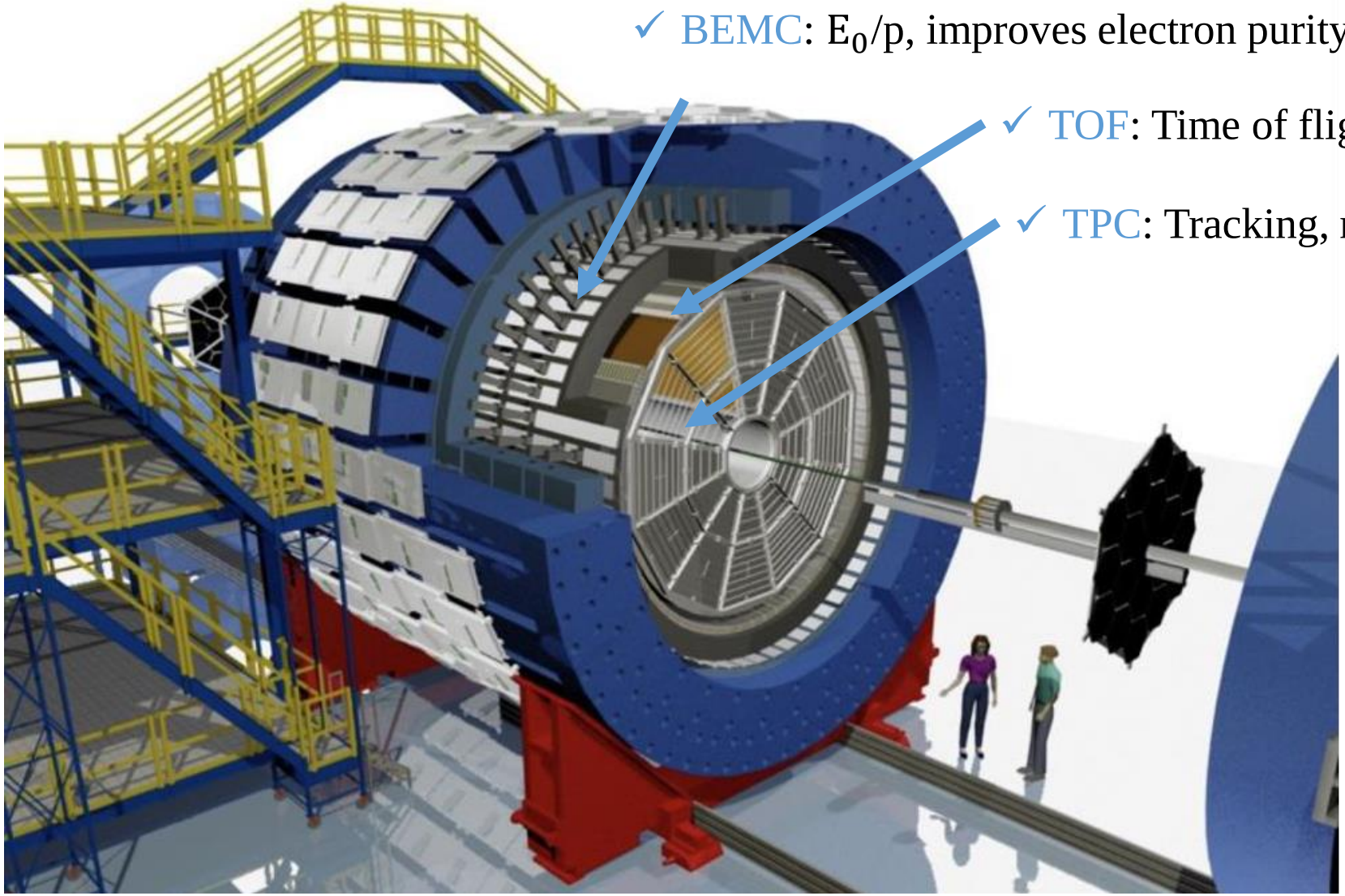
C.Li, J.Zhou, Y.J.Zhou, Phys. Lett. B. 795, 576 (2019)

- Investigate collision system dependence of cos(4Δ$\phi$) modulation

# 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

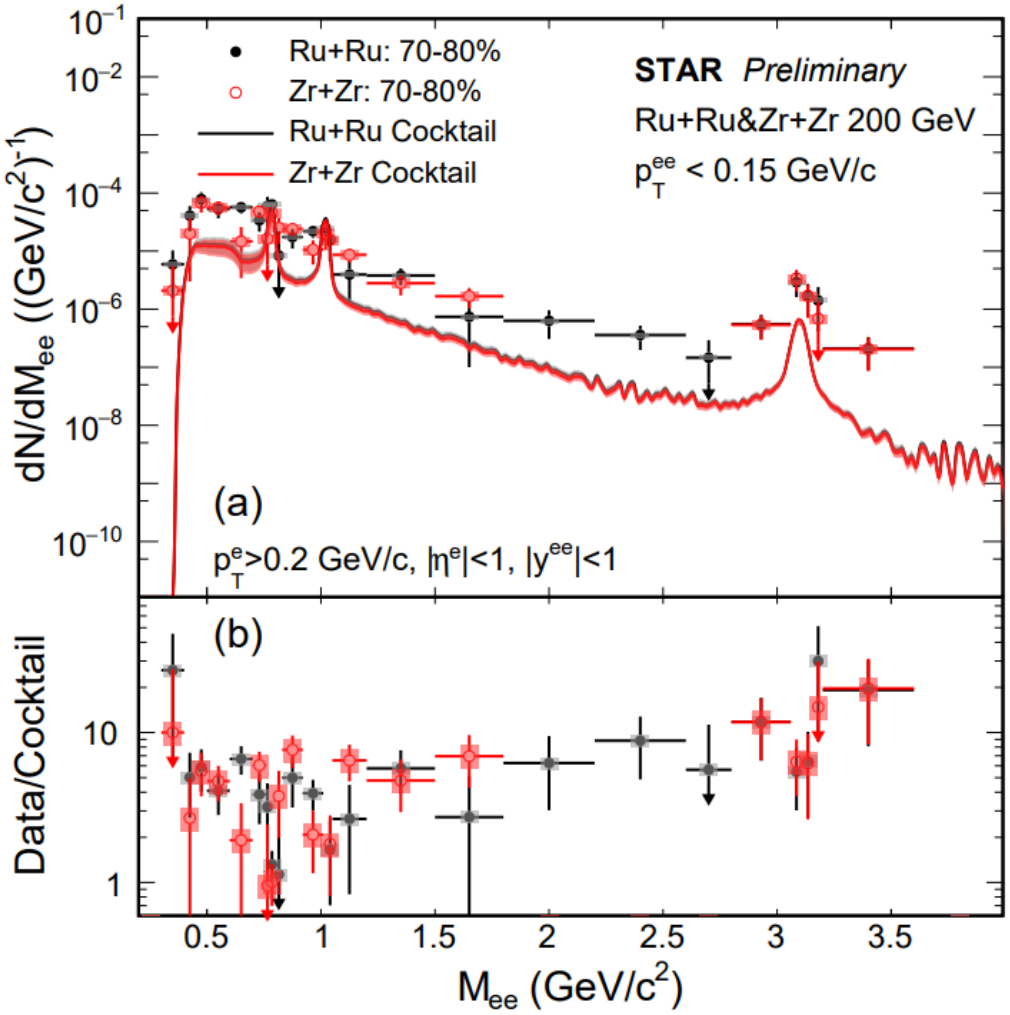
Collision species (taken in 2018)

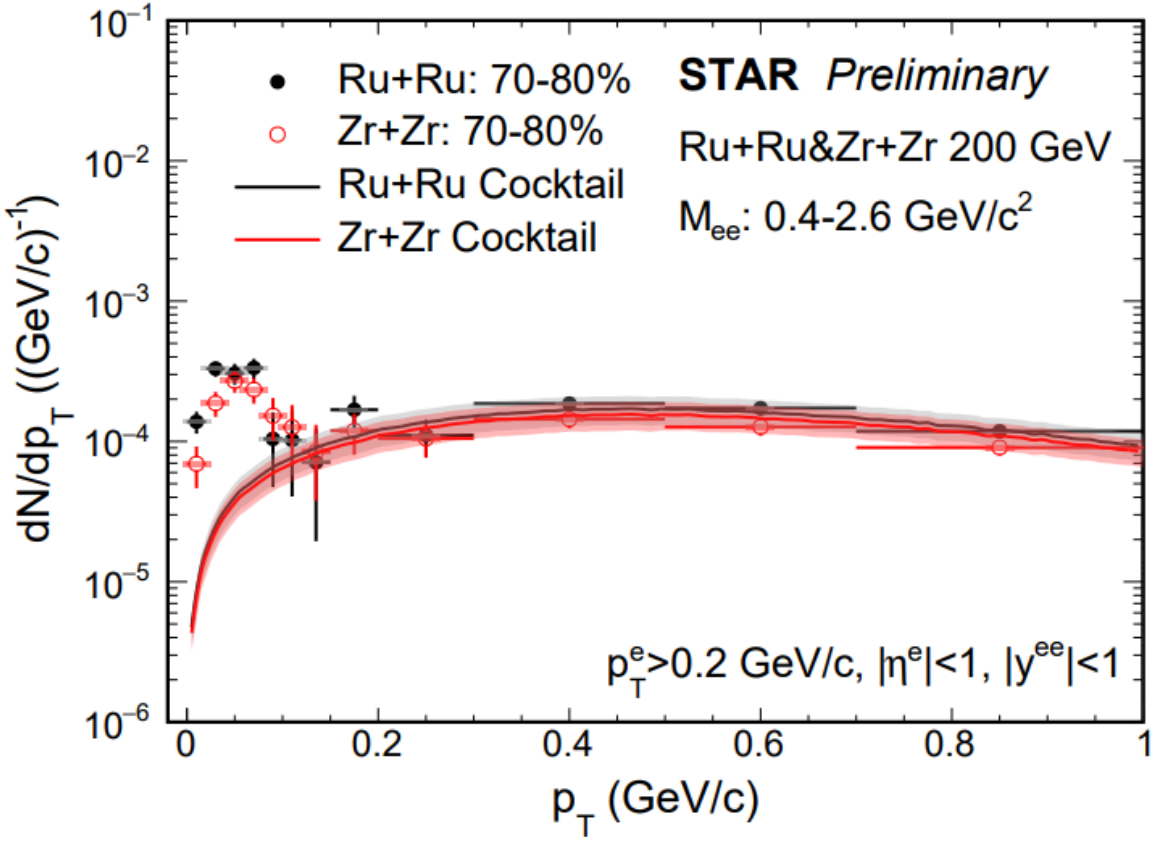
- $^{96}_{44}Ru+^{96}_{44}Ru$ (~2B)
- $^{96}_{40}Zr+^{96}_{40}Zr$ (~2B)

Acceptance cuts:

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

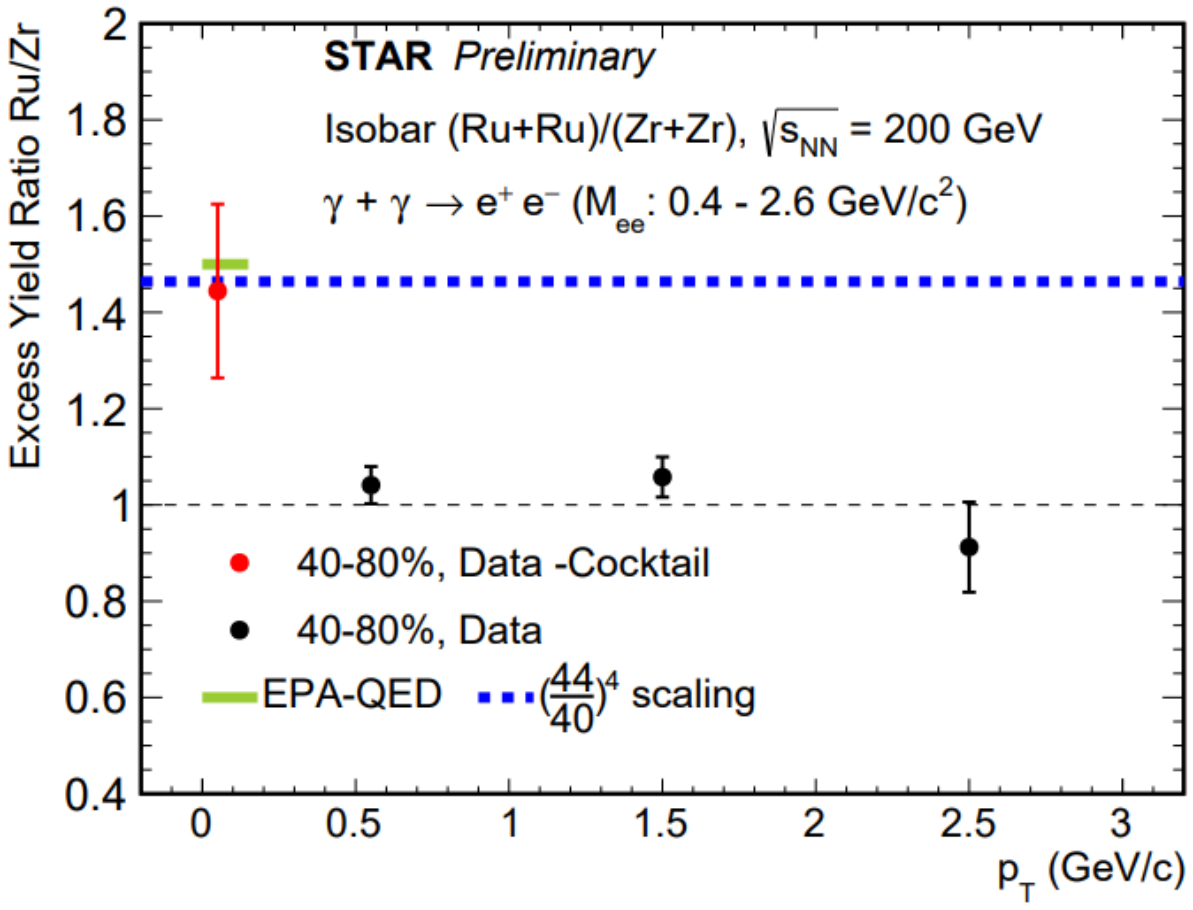
# Invariant Mass and Transverse Momentum Distributions of $e^+e^-$




- Excesses above known hadronic production are observed at low-$p_T$

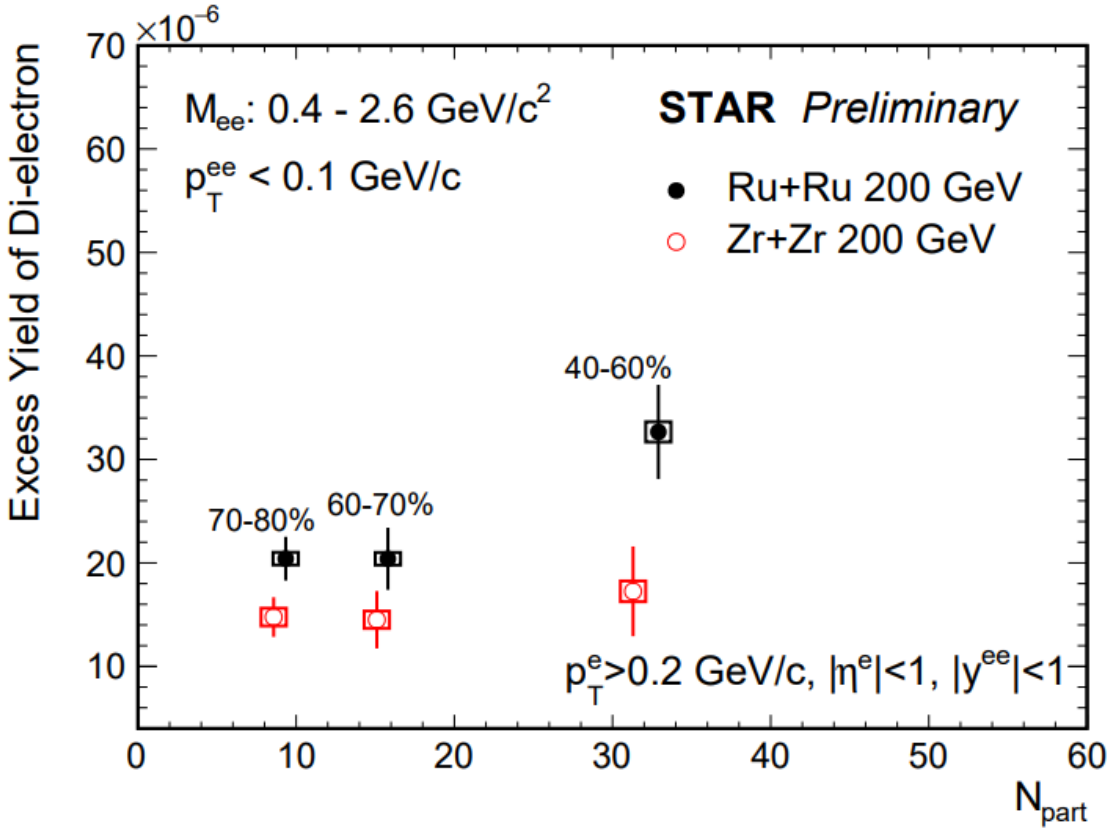
# $p_T$ Dependence of Excess Yield Ratio

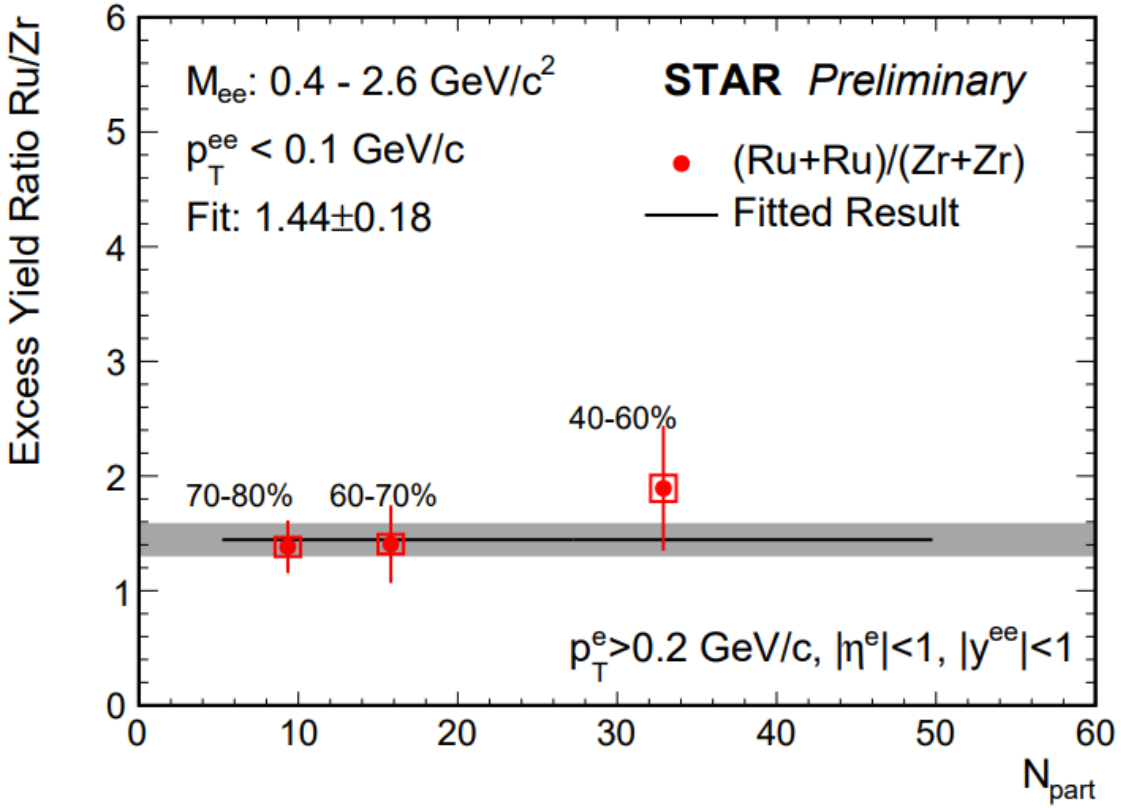



W. Zha et al, Phys. Lett. B 789 (2019) 238-242

- 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, which is significantly above unity
- The initial EM fields seem to be different

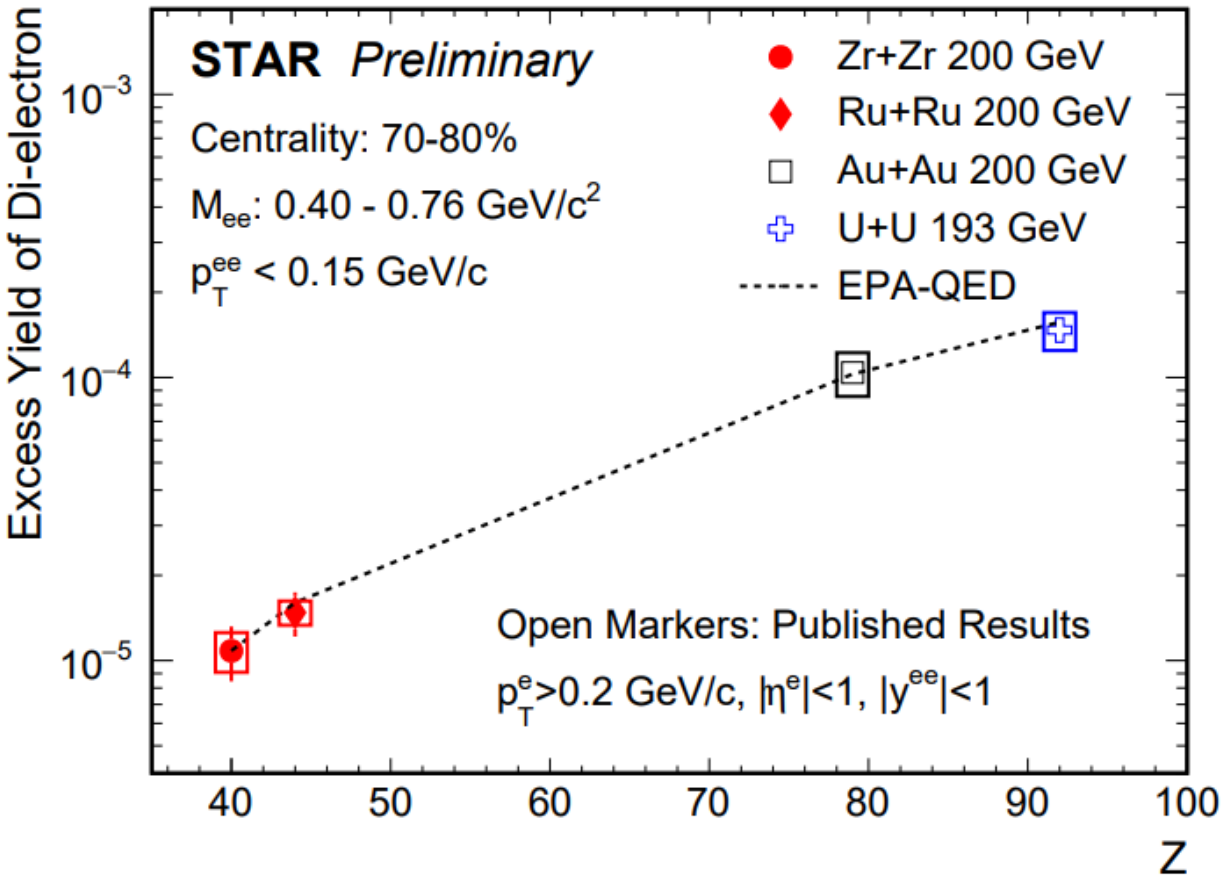
# Centrality Dependence of Excess Yield

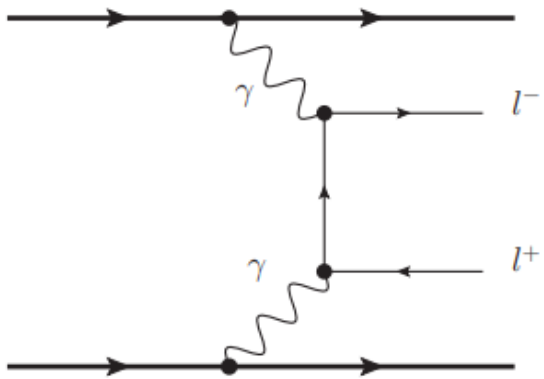



- The low-$p_T$ ($p_T$ < 0.1 GeV/c) $e^+e^-$ excess and the ratio of excess are shown as function of $\mathrm{N_{part}}$
- The excess yields in Ru+Ru collisions are systematically away from in Zr+Zr collisions
- A constant function is used to fit the ratio and is about 2.4$\sigma$ higher than unity

# Charge Dependence of Excess Yield




- The excess yields in isobaric collisions are significantly smaller compared to those in Au+Au and U+U collisions
- The charge difference is dominant and understood both in theory and experiment ($\propto Z^4$)

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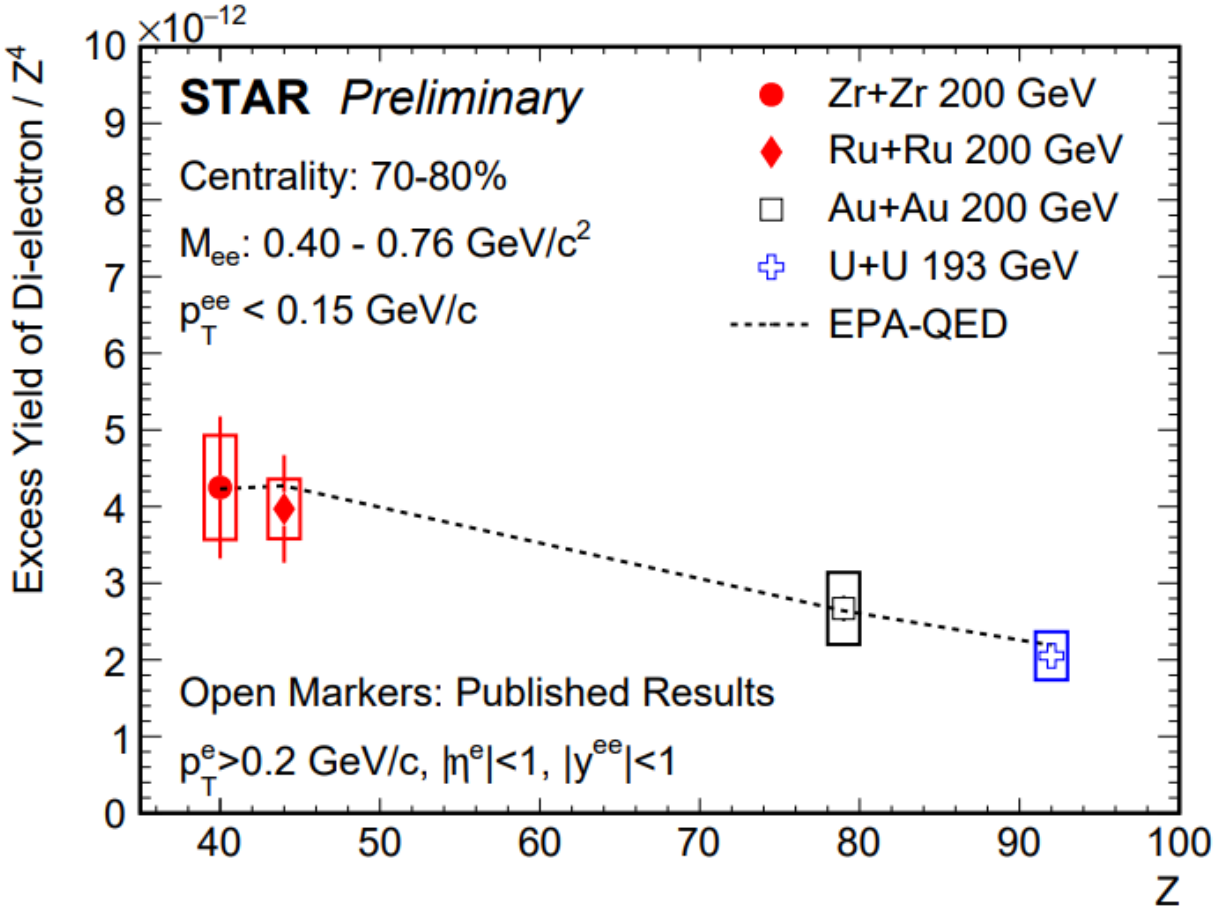
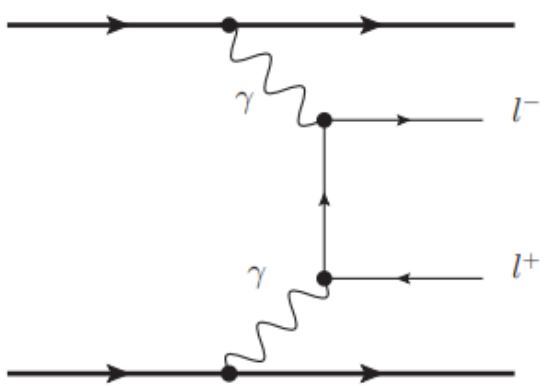
W. Zha et al, Phys. Lett. B 800 (2020) 135089

# Collision System Dependence of Scaled Excess Yield




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

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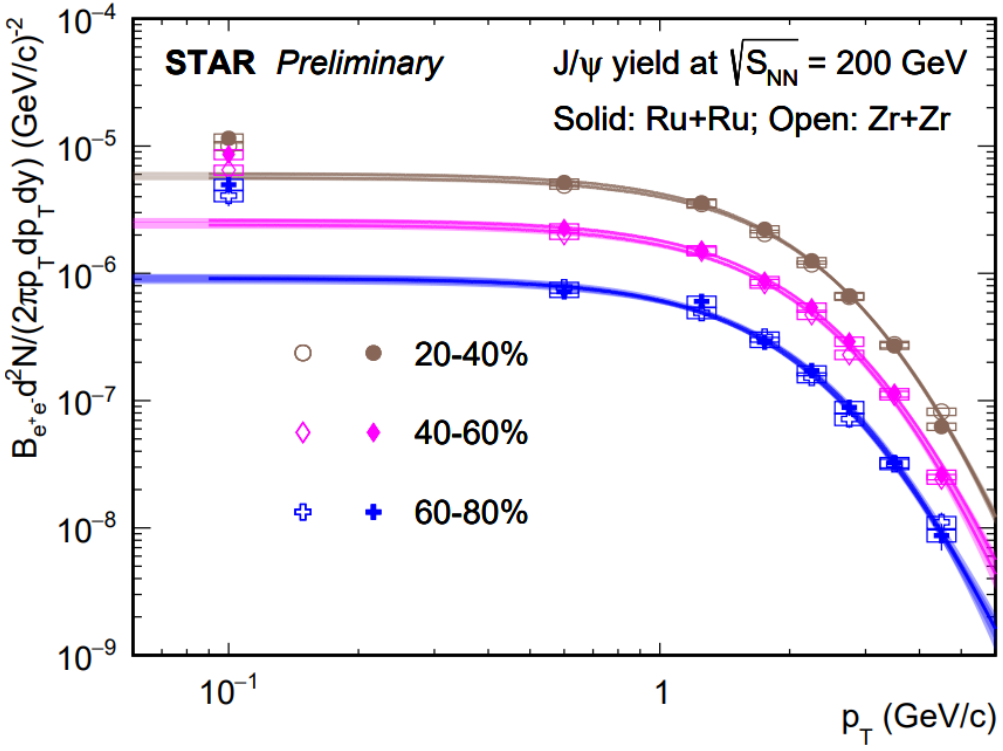
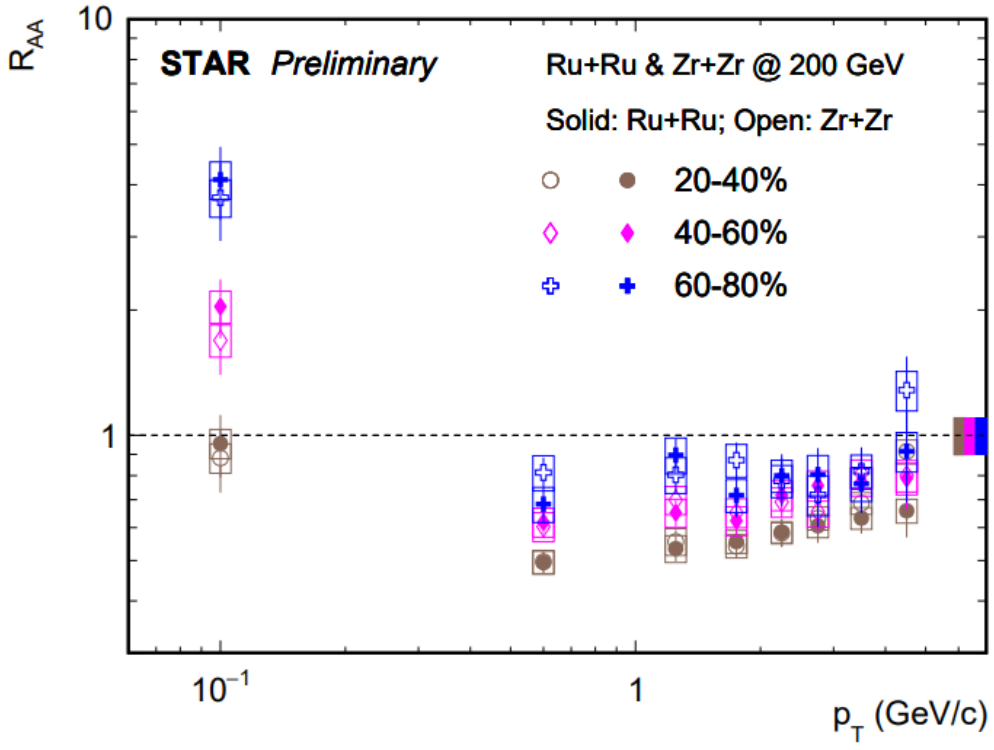
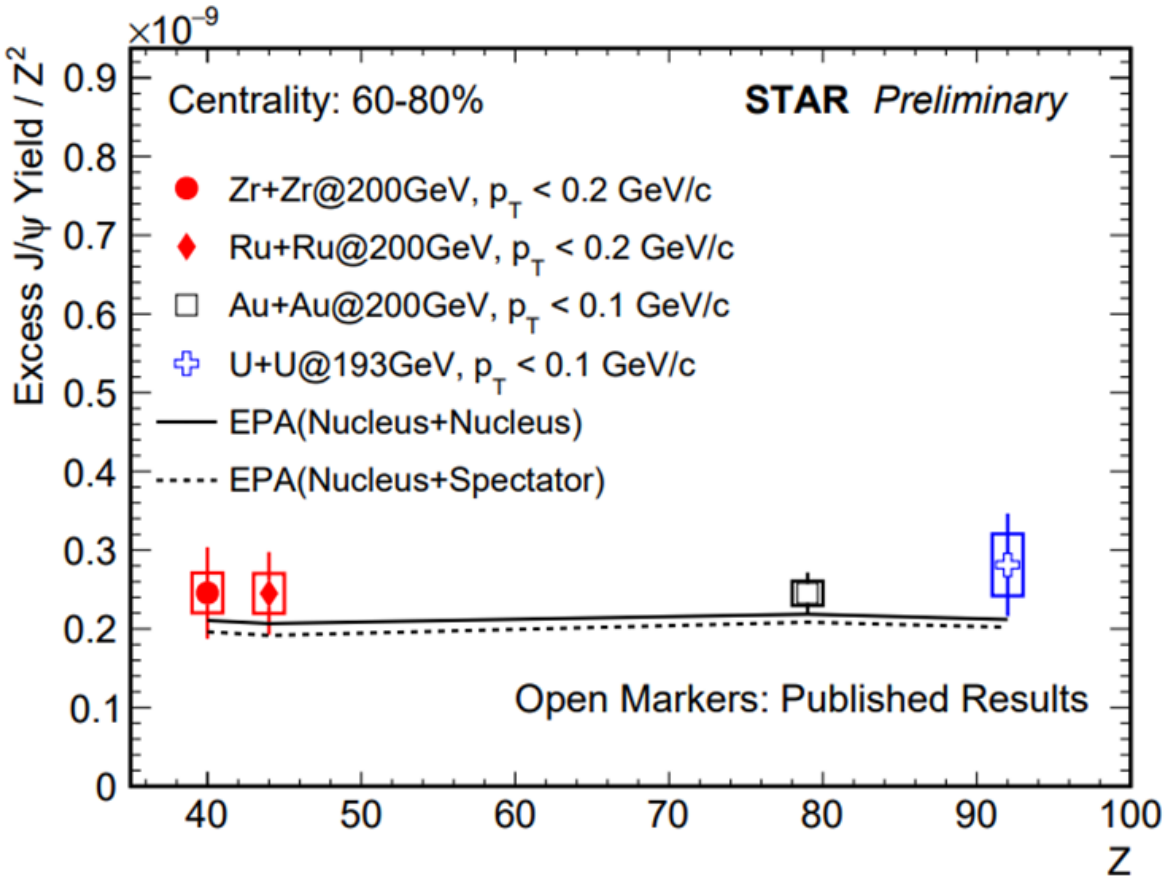
# Invariant Yield and Nuclear Modification Factor of J/$\psi$



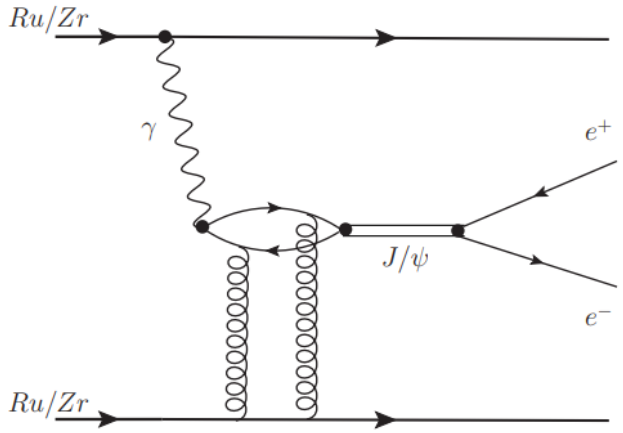




- The yield spectra are fitted by the Tsallis function at $p_T$ larger than 0.2 GeV/c, and extrapolated to low-$p_T$ range
- The data are well described by the fitted curves above 0.2 GeV/c, but show significant enhancements at low-$p_T$ range
- The $R_{AA}$ is significantly higher than unity at the very low-$p_T$ range

# Collision System Dependence of Scaled Excess J/$\psi$ yield

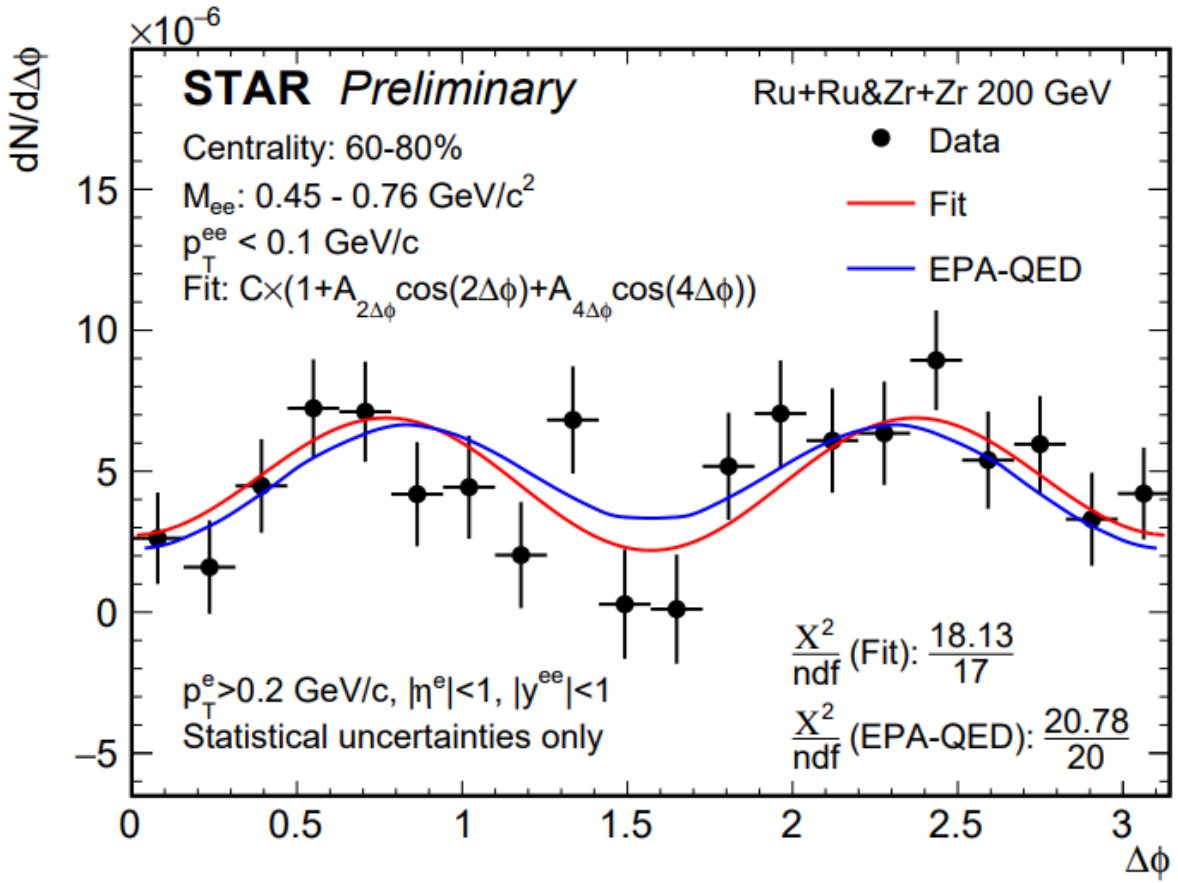



J.Adam et al. (STAR) Phys. Rev. Lett. 123 (2019) 132302.
W. Zha et al. Phys. Rev. C 97, 044910 (2018)




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

# cos(4Δ$\phi$) Modulation in Isobaric Collisions




| | $\lvert A_{4\Delta\phi}\rvert$ (%) | $\lvert A_{2\Delta\phi}\rvert$ (%) |
|---|---|---|
| Isobar(60-80%) | 47±13(stat) | 6±12(stat) |
| Au+Au(60-80%) | 27±6 | 6±6 |

- Clear cos(4Δ$\phi$) signal (~3.6$\sigma$) in isobaric collisions: $\lvert A_{4\Delta\phi}\rvert$ = 0.47±0.13(stat)±0.05(sys)
  - $\lvert A_{4\Delta\phi}\rvert$ predicted by QED-EPA is 0.40

# Summary

- Enhancements of J/$\psi$ and $e^+e^-$ production at very low $p_T$ have been observed in peripheral isobaric collisions
- 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/$\psi$ is mostly independent of collision system, while $e^+e^-$ shows an impact parameter dependence
- The cos(4$\Delta\phi$) signal is prominent (~3.6$\sigma$) in isobaric collisions and no significant difference is observed between isobaric and Au+Au collisions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