Photoproduction of e^+e^- in peripheral isobar collisions

林硕

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Based on:
R.J. Wang, S. Lin, S.Pu,Y.F. Zhang, Q. Wang, Phys.Rev.D 106 (2022) 3, 034025;
S. Lin,R.J. Wang, J.F. Wang, H.J. Xu, S. Pu and Q. Wang, Phys.Rev.D 107 (2023), 054004

UPC物理研讨会(UPCP2023)

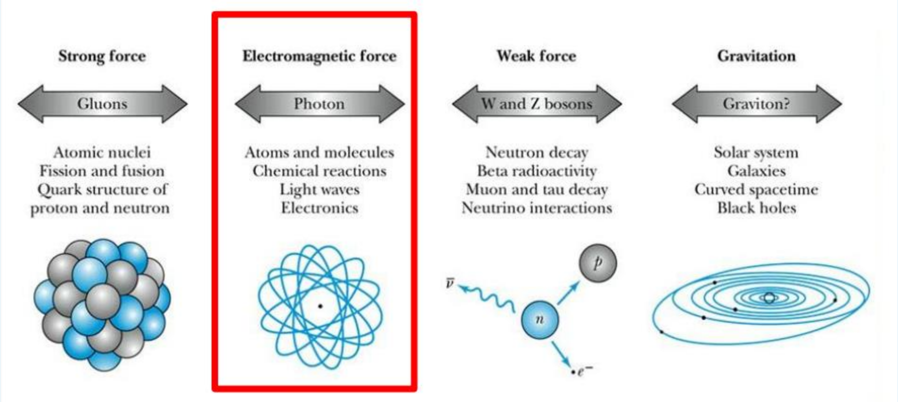
Outline

- **Introduction & Motivation**
- **Theoretical framework**
- **Numerical results**
- **Summary**

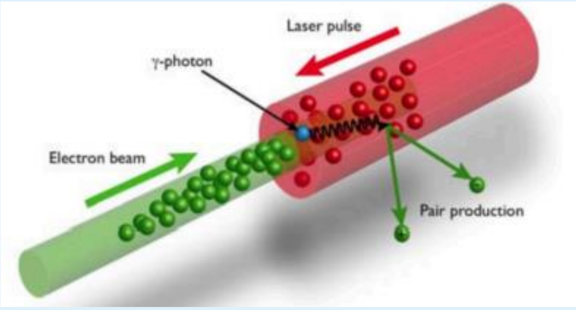
Introduction & Motivation

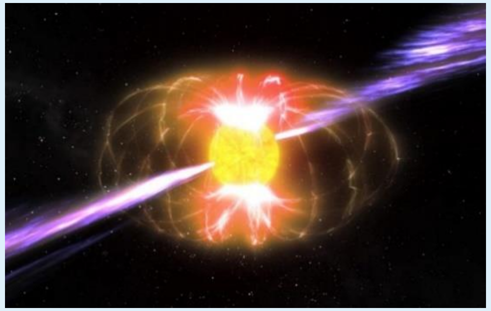
QED under extreme conditions

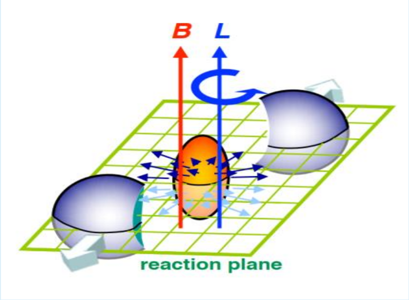
The electromagnetic interaction is one of the four fundamental interactions in Nature



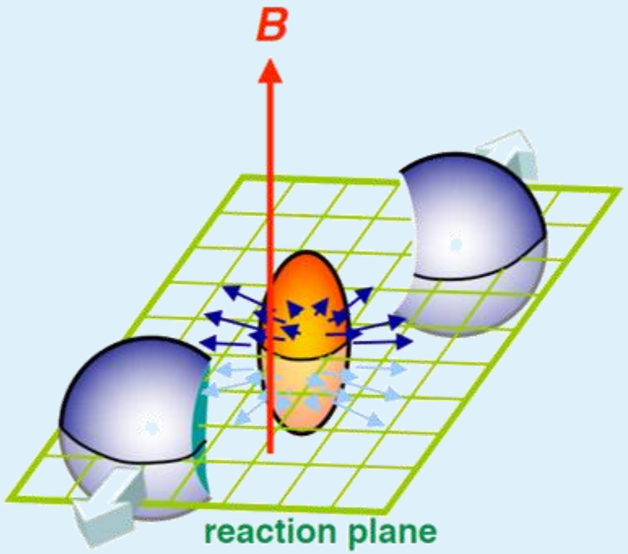
The phenomenon of QED under extreme conditions has received attention from research fields

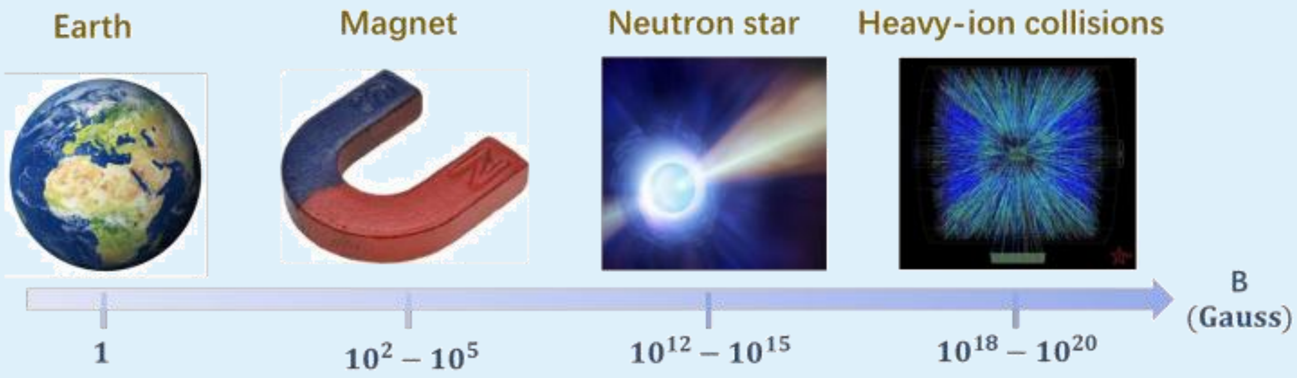






Strong EB fields in HIC





- $eB \sim \gamma Z \alpha v / b_T^2 \sim 10^{18}\mathrm{Gauss}$

  $\sqrt{s_{NN}} = 200\mathrm{GeV}$ Au+Au

D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys. A 803, 227 (2008)
L. McLerran and V. Skokov, Nucl. Phys. A 929, 184 (2014)
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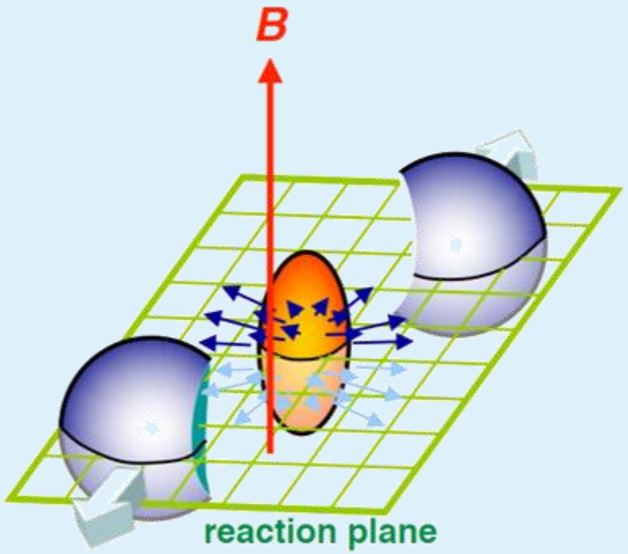
Strong EB fields in HIC



Schwinger Effect

J.S. Schwinger,Phys. Rev. 82 (1951) 664P. Copinger, K. Fukushima, and S. Pu, Phys. Rev. Lett. 121, 261602 (2018)

P. Copinger and S. Pu, Int. J. Mod. Phys. A 35, 2030015 (2020)

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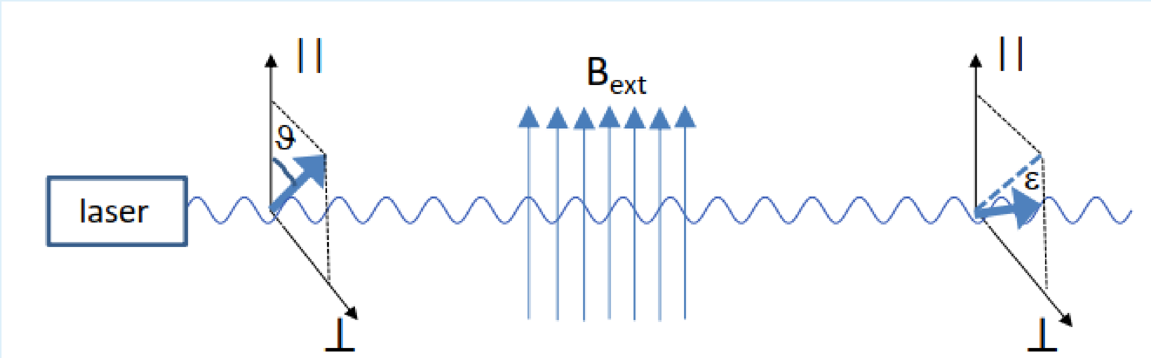
Vacuum birefringence



S. L. Adler, Annals Phys. 67, 599 (1971).

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Breit-Wheeler Process

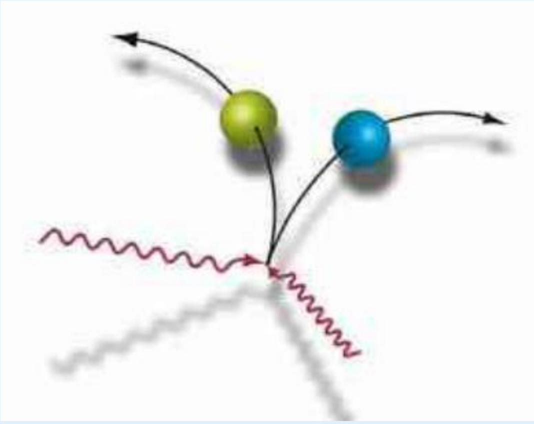
In 1934 Breit and Wheeler

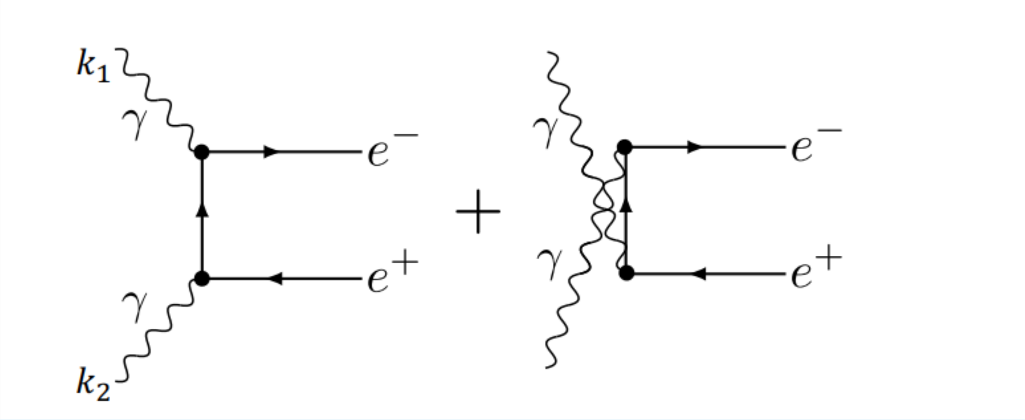
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME 46

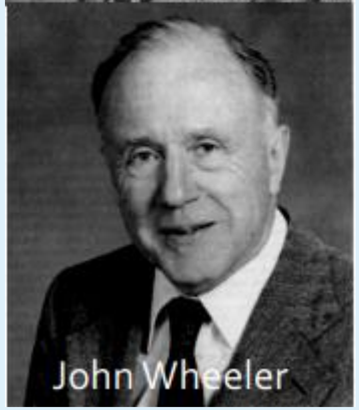
Collision of Two Light Quanta

G. Breit* and John A. Wheeler,** *Department of Physics, New York University*

(Received October 23, 1934)

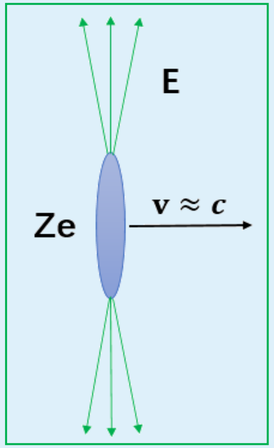






Equivalent Photon Approximation

Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field



Equivalent Photon Approximation

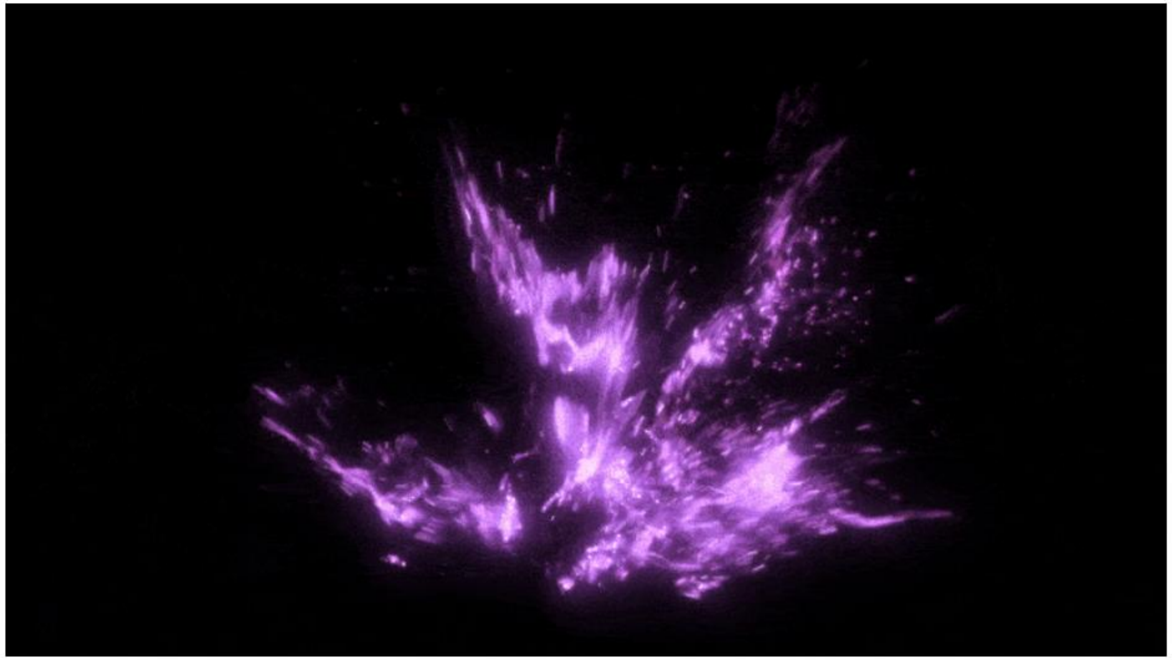
Classical EM ⇔ Quasi-real photons

Ultraperipheral Collisions(UPC)

Scientists Generate Matter Directly From Light – Physics Phenomena Predicted More Than 80 Years Ago

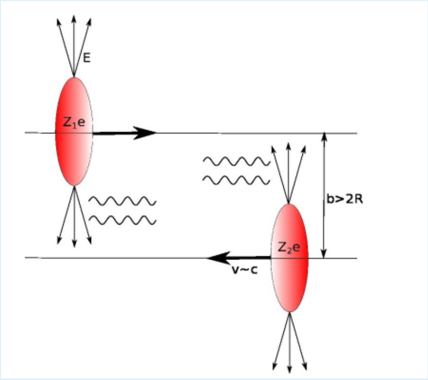
TOPICS: Antimatter Atomic Physics Brookhaven National Laboratory DOE Popular

By BROOKHAVEN NATIONAL LABORATORY JULY 30, 2021



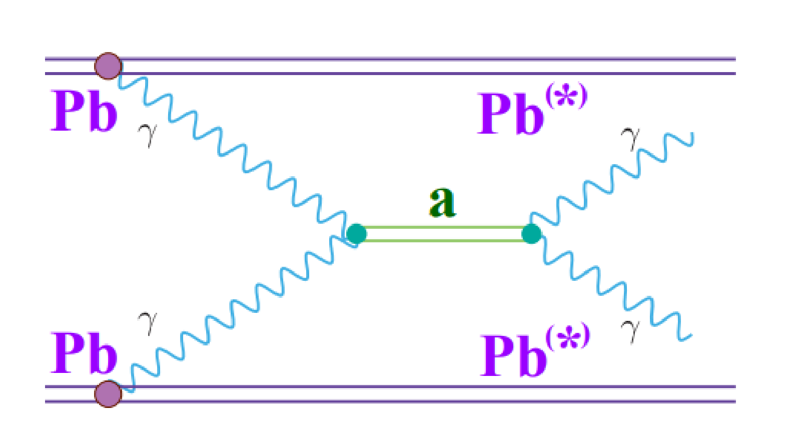
UPC: the impact parameter is larger than 2 times the radius of a nucleus

Clean background



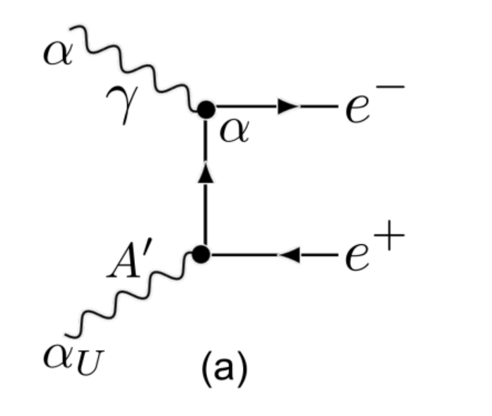
Ultraperipheral Collisions(UPC)

constrain axion-photon coupling



S. Knapen, T. Lin, H. K. Lou, and T. Melia, Phys. Rev. Lett. 118 (2017) 171801

search for dark photons



I. Xu, N. Lewis, X. Wang, J. D. Brandenburg, and L. Ruan, (2022)

UPC: the impact parameter is larger than 2 times the radius of a nucleus

QED effects are enhanced by the Ze

Breit-Wheeler Process

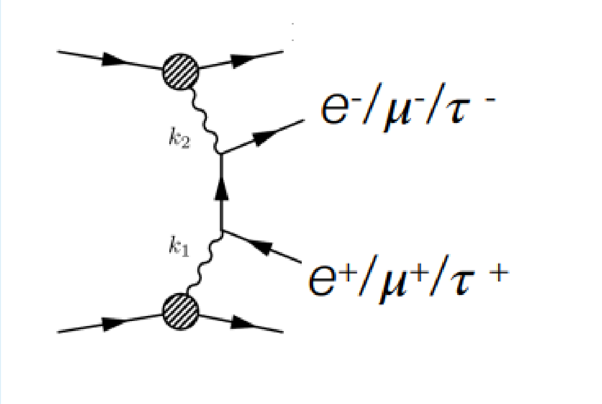
- $\gamma\gamma \rightarrow l^{+}l^{-}$ **processes has been measured in UPC**

  STAR, J. Adam et al., Phys. Rev. Lett. 127, 052302 (2021), 1910.12400.

  ATLAS, G. Aad et al., Phys. Rev. C 104, 024906 (2021), 2011.12211.

  CMS, A. M. Sirunyan et al., Phys. Rev. Lett. 127, 122001 (2021), 2011.05239.

  ALICE, Abbas, E et al., Eur.Phys.J.C 73 (2013)11, 2617, 1305.1467.



Breit-Wheeler Process

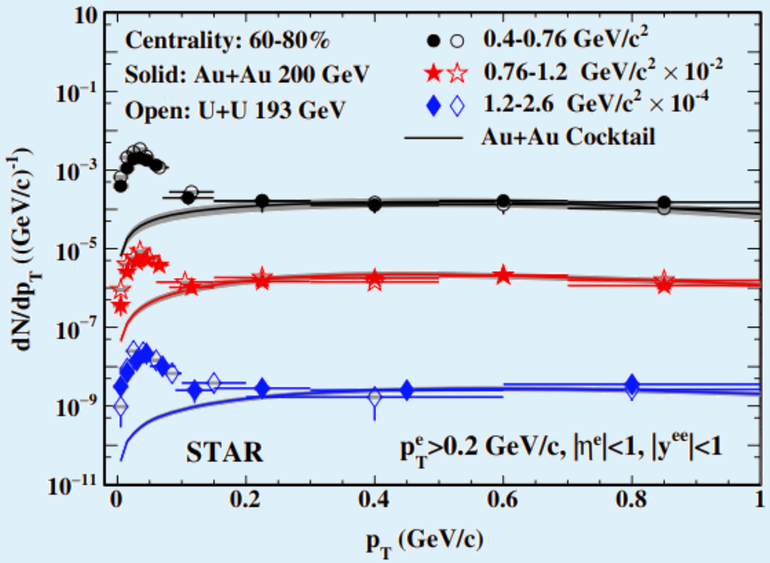
- $\gamma\gamma \rightarrow l^{+}l^{-}$ **processes has also been measured in peripheral collisions (**$b < 2R_A$ **PC)**

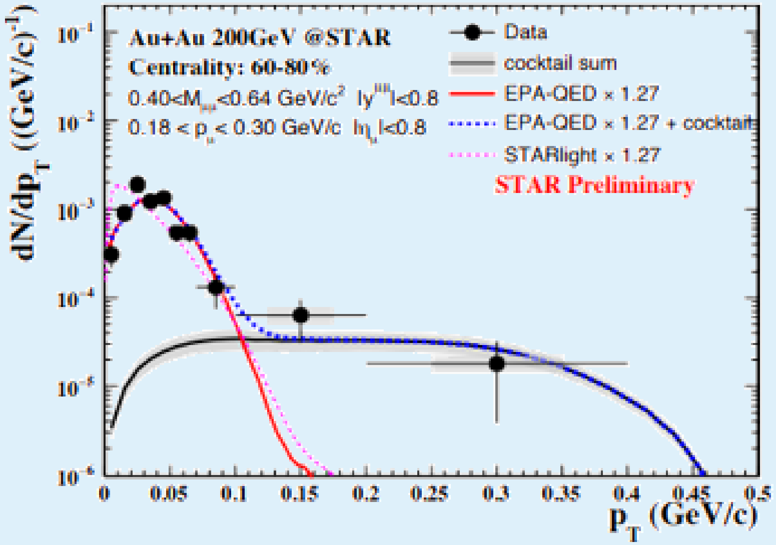
STAR, J. Adam et al., Phys. Rev. Lett. 121, 132301 (2018), 1806.02295.

ATLAS, M. Aaboud et al., Phys. Rev. Lett. 121, 212301 (2018), 1806.08708.

ALICE, Sebastian Lehner et al., PoS LHCP2019 (2019) 164, 1909.02508.

Breit-Wheeler Process





- **Excesses above hadronic production has been observed at low transverse momenta of dileptons (P_T^{ee})**

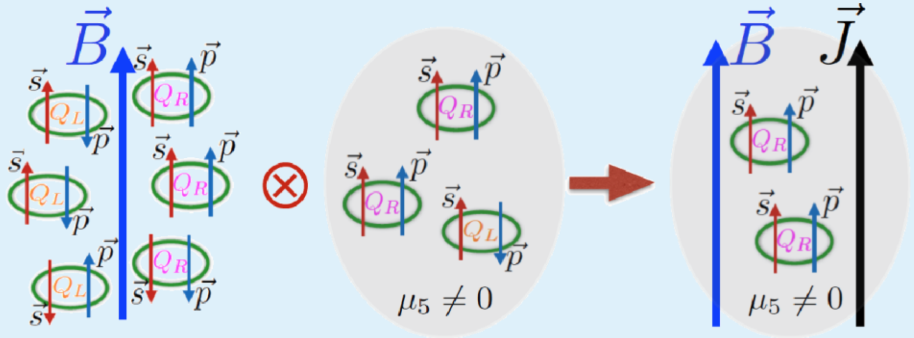
Isobar collisions

- **The isobar collisions was proposed to measure the chiral magnetic effect.**

- **Same background**
- **Different magnetic field => different CME signal**

$$
j_{CME} = \frac{e^2}{2\pi^2}\mu_5 \boldsymbol{B}
$$

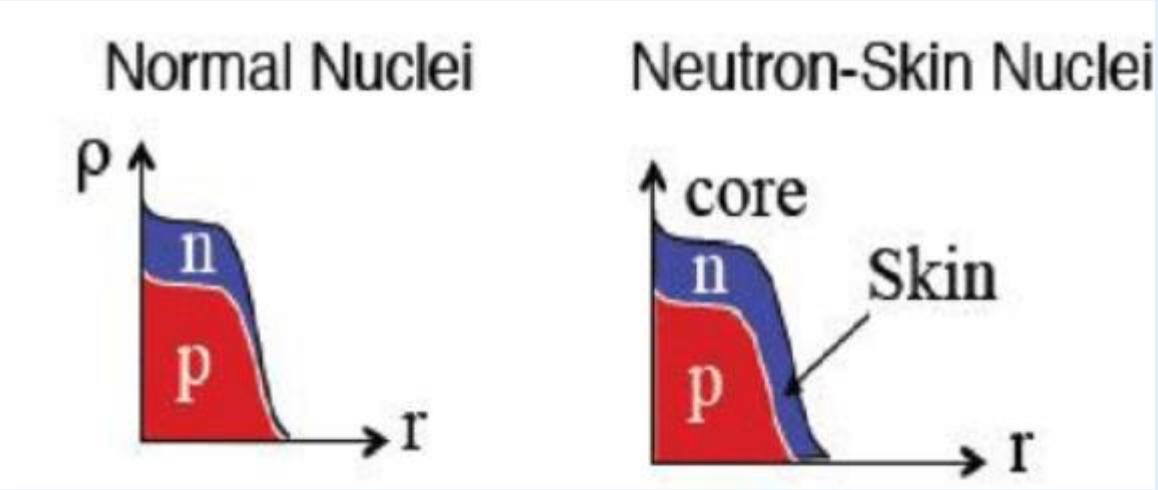
D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys. A 803, 227 (2008)
……



Isobar collisions

- **Precision isobar data can be used to probe neutron skin thickness ,nuclear symmetry energy and nuclear deformation**

Backgrounds are not identical!



H.J. Xu, et.al., PRL121, 022301 (2018)

H. Li, H.J. Xu et.al., PRC98, 054907(2018)

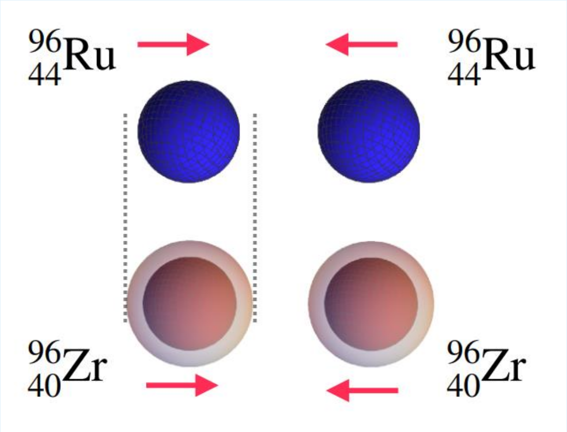
C. Zhang, J. Jia, PRL128, 022301(2022)

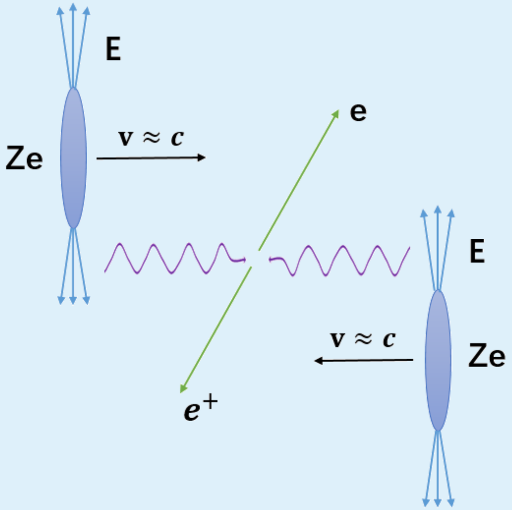
S. Zhao, H.J. Xu, et.al, PLB839, 137838 (2023)

……

Isobar collisions

➢ **Can nuclear structure information be reflected in the photoproduction of lepton pairs ?**





Theoretical framework

Theoretical framework

- **Equivalent photon approximation (EPA)**
  - A. J. Baltz, Y. Gorbunov, S. R. Klein and J. Nystrand, PRC 80, 044902 (2009)
  - W. Zha, L. Ruan, Z. Tang, Z. Xu and S. Yang, PLB 781, 182 (2018)
- **kt＆bt dependent**
  - C. Li, J. Zhou and Y. J. Zhou, PLB 795, 576 (2019) ;PRD 101 (2020) 3, 034015
  - Klein, Muller, Xiao, Yuan, PRL 122 (2019) 13, 132301; PRD 102 (2020) 9,094013
  - W. Zha, J. D. Brandenburg, Z. Tang and Z. Xu, PLB 800 (2020) 13508
  - Xiao, Yuan, Zhou, PRL 125 (2020) 23, 232301
  - R.J. Wang, S.Pu, Q. Wang, PRD 104 (2021) 5, 056011
  - X. Wang, J. D. Brandenburg, L. Ruan, F. Shao, Z. Xu, C. Yang, and W. Zha,PRC 107 (2023) 4, 044906
  - D. Y. Shao, C. Zhang, J. Zhou and Y. Zhou, PRD 107 (2023) 3, 036020

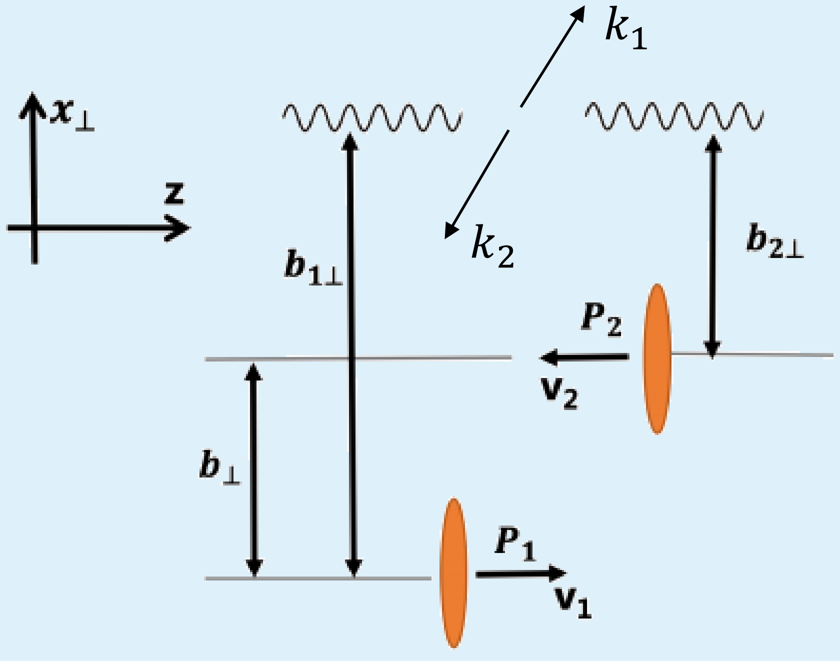
Theoretical framework

Starting point:

Wave packets form of nuclear state

$$|A_1A_2\rangle_{in} = \int \frac{d^3P_1}{(2\pi)^3}\frac{d^3P_2}{(2\pi)^3}\frac{\phi(P_1)\phi(P_2)e^{ib_T\cdot P_1}}{\sqrt{2E_{P1}}\sqrt{2E_{P2}}}|P_1P_2\rangle_{in}$$

$$\sigma = \int d^2\boldsymbol{b}_T \sum_{\{f\}} \int \frac{d^3k_1}{(2\pi)^3 2E_{k1}}\frac{d^3k_2}{(2\pi)^3 2E_{k2}}\prod_f \frac{d^3K_f}{(2\pi)^3 2E_{Kf}} \times \left|{}_{out}\langle k_1, k_2, \textstyle\sum_f K_f | A_1A_2\rangle_{in}\right|^2$$



$$\boldsymbol{b}_T = \boldsymbol{b}_{1T} - \boldsymbol{b}_{2T}$$

Theoretical framework

R.J. Wang, S.Pu, Q. Wang, PRD (2021)

$$\frac{d\sigma}{d^3k_1 d^3k_2} = \frac{1}{32(2\pi)^6}\frac{1}{E_{k1}E_{k2}}\int d^2\boldsymbol{b}_T d^2\boldsymbol{b}_{1T} d^2\boldsymbol{b}_{2T}\int d^4p_1 d^4p_2$$

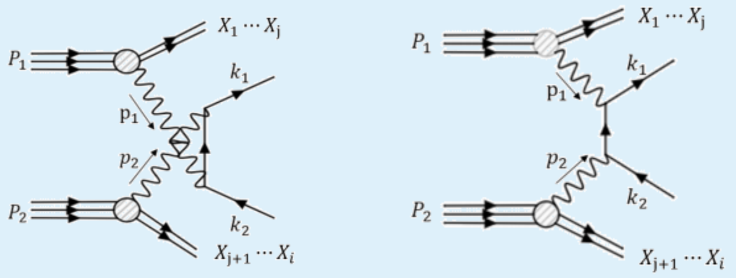
$$\times\, \delta^2(\boldsymbol{b}_T - \boldsymbol{b}_{1T} + \boldsymbol{b}_{2T})(2\pi)^4\delta^4(p_1+p_2-k_1-k_2)$$

$$\times \int \frac{d^2\boldsymbol{P}_{(1+1')T}}{(2\pi)^2}\frac{d^2\boldsymbol{P}_{(2+2')T}}{(2\pi)^2}\frac{1}{v\sqrt{E_{P1}E_{P2}E_{P1'}E_{P2'}}}$$

$$\times\, G^2[(P_1'^Z - P_{A1}^Z)^2]\phi_T(\boldsymbol{P}_{1T})\phi_T(\boldsymbol{P}_{2T})\phi_T^*(\boldsymbol{P}'_{1T})\phi_T^*(\boldsymbol{P}'_{2T})$$

$$\times\, S_{\sigma\mu}(p_1,\boldsymbol{b}_{1T})S_{\rho\nu}(p_2,\boldsymbol{b}_{2T})$$

$$\times\, e^4 \sum_{\text{spin of } l\bar{l}} L^{\mu\nu}(p_1,p_2,k_1,k_2)L^{*\sigma\rho}(p_1',p_2',k_1,k_2)$$



Lepton tensor:

Can be computed by perturbative theories

Photon Wigner function

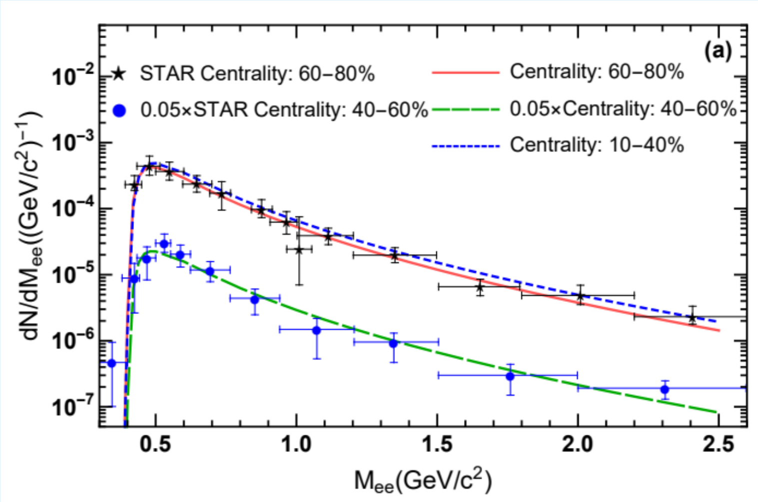
$$S_{\sigma\mu}(p_1,\boldsymbol{b}_{1T}) = \int \frac{d^2\Delta_{1T}}{(2\pi)^2}\frac{d^4y_1}{(2\pi)^4} e^{ip_1\cdot y_1}\langle P_1'|A_\sigma^\dagger(0)A_\mu(y_1)|P_1\rangle e^{-i\boldsymbol{b}_{1T}\cdot\Delta_{1T}}$$

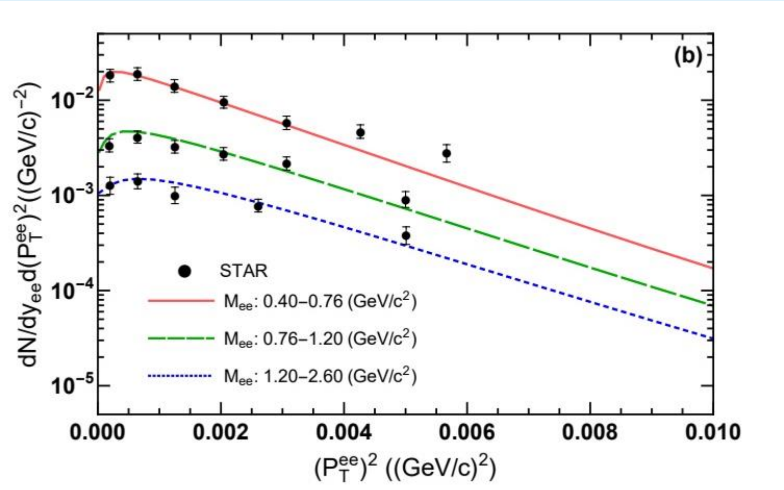
B.-W. Xiao, F. Yuan, and J. Zhou PRL, 125 (2020) 23, 232301

S. Klein, A. H. Mueller, B.-W. Xiao, and F. Yuan, PRD 102 (2020) 9, 094013

Peripheral Collisions

R.J. Wang, S. Lin, S.Pu,Y.F. Zhang, Q. Wang， Phys.Rev.D 106 (2022) 3, 034025

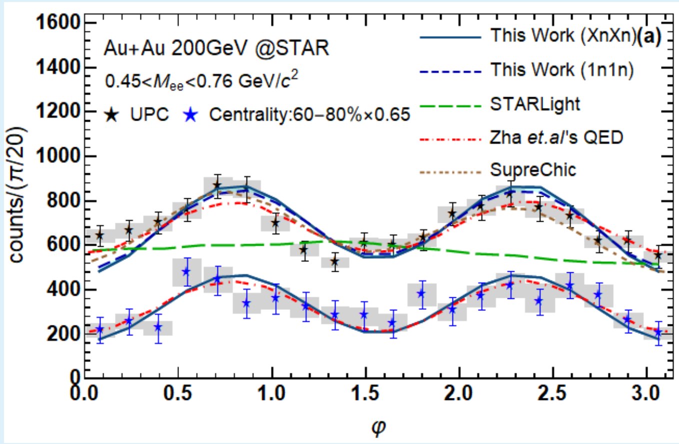


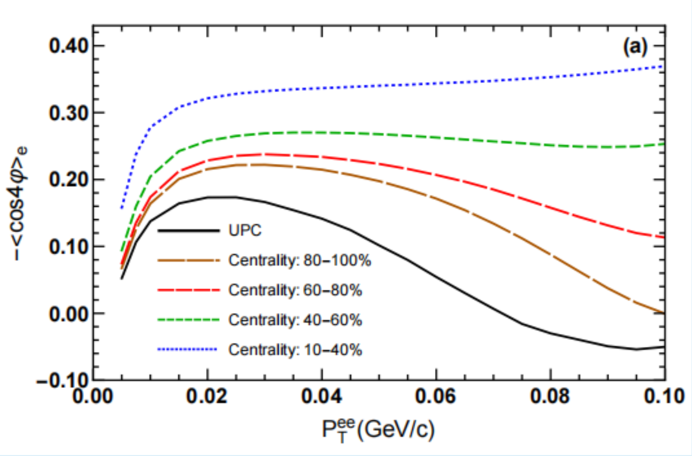


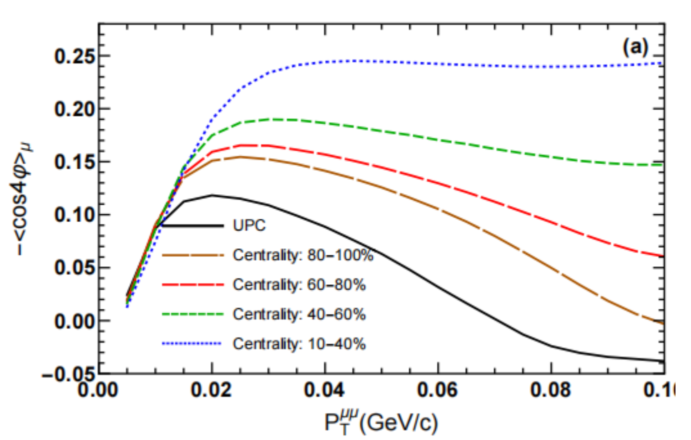
Our results agree with the experimental data

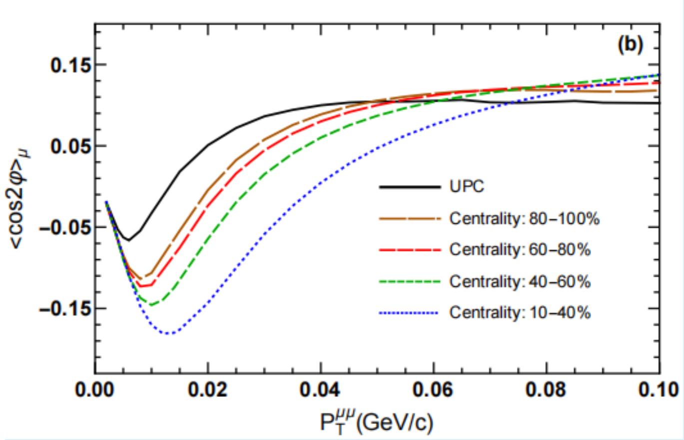
Peripheral Collisions

R.J. Wang, S. Lin, S.Pu,Y.F. Zhang, Q. Wang， Phys.Rev.D 106 (2022) 3, 034025









- **The linear polarization information of photons is important for understanding the azimuthal asymmetry of the lepton pair.**
- **The $\cos 2\varphi$ modulations of $\mu^+\mu^-$ are higher than e^+e^- case.**

C. Li, J. Zhou, and Y.-J. Zhou, 1903.10084, 1911.00237.

Peripheral isobar collisions

$$\sigma = \frac{Z^4 e^4}{2\gamma^4 v^3} \int d^2\mathbf{b}_T d^2\mathbf{b}_{1T} d^2\mathbf{b}_{2T} \int \frac{d\omega_1 d^2\mathbf{p}_{1T}}{(2\pi)^3} \frac{d\omega_2 d^2\mathbf{p}_{2T}}{(2\pi)^3}$$

$$\times \int \frac{d^2\mathbf{p}'_{1T}}{(2\pi)^2} e^{-i\mathbf{b}_{1T}\cdot(\mathbf{p}'_{1T}-\mathbf{p}_{1T})} \frac{F^*(-\bar{p}'^2_1)}{-\bar{p}'^2_1} \frac{F(-\bar{p}^2_1)}{-\bar{p}^2_1}$$

$$\times \int \frac{d^2\mathbf{p}'_{2T}}{(2\pi)^2} e^{-i\mathbf{b}_{2T}\cdot(\mathbf{p}'_{2T}-\mathbf{p}_{2T})} \frac{F^*(-\bar{p}'^2_2)}{-\bar{p}'^2_2} \frac{F(-\bar{p}^2_2)}{-\bar{p}^2_2}$$

$$\times \int \frac{d^3k_1}{(2\pi)^3 2E_{k1}} \frac{d^3k_2}{(2\pi)^3 2E_{k2}} (2\pi)^4 \delta^{(4)}(\bar{p}_1 + \bar{p}_2 - k_1 - k_2)\, \delta^{(2)}(\mathbf{b}_T - \mathbf{b}_{1T} + \mathbf{b}_{2T})$$

$$\times \sum_{\text{spin of } l,\bar{l}} \left[u_{1\mu} u_{2\nu} L^{\mu\nu}(\bar{p}_1, \bar{p}_2; k_1, k_2)\right] \left[u_{1\sigma} u_{2\rho} L^{\sigma\rho *}(\bar{p}'_1, \bar{p}'_2; k_1, k_2)\right],$$

Charge density distribution → F

Mass density distribution → $\int_{b_{min}}^{b_{max}} db_T$

The lepton pair photoproduction is calculated with the charge density distribution, while the centrality is defined from the Glauber model with the nuclear mass density.

Nuclear structure calculation by DFT

➢ **Nuclear charge density ≠ Nuclear mass density**

(a)	R_c	d_c	R_n	d_n
Ru	5.083 fm	0.477 fm	5.093 fm	0.488 fm
Zr	4.977 fm	0.492 fm	5.022 fm	0.538 fm

$$\rho_i(\mathbf{r}) \equiv \frac{C_i}{1+\exp[(|\mathbf{r}|-R_i)/d_i]}$$

c: nuclear charge density
n:nuclear mass density

S. Lin,R.J. Wang, J.F. Wang, H.J. Xu, S. Pu and Q. Wang, Phys.Rev.D 107 (2023), 054004.

Parameter setting

(a)	R_c	d_c	R_n	d_n
Ru	5.083 fm	0.477 fm	5.093 fm	0.488 fm
Zr	4.977 fm	0.492 fm	5.022 fm	0.538 fm

(b)	R_c	d_c	R_n	d_n
Ru	5.083 fm	0.477 fm	R_c^{Ru}	d_c^{Ru}
Zr	4.977 fm	0.492 fm	R_c^{Zr}	d_c^{Zr}

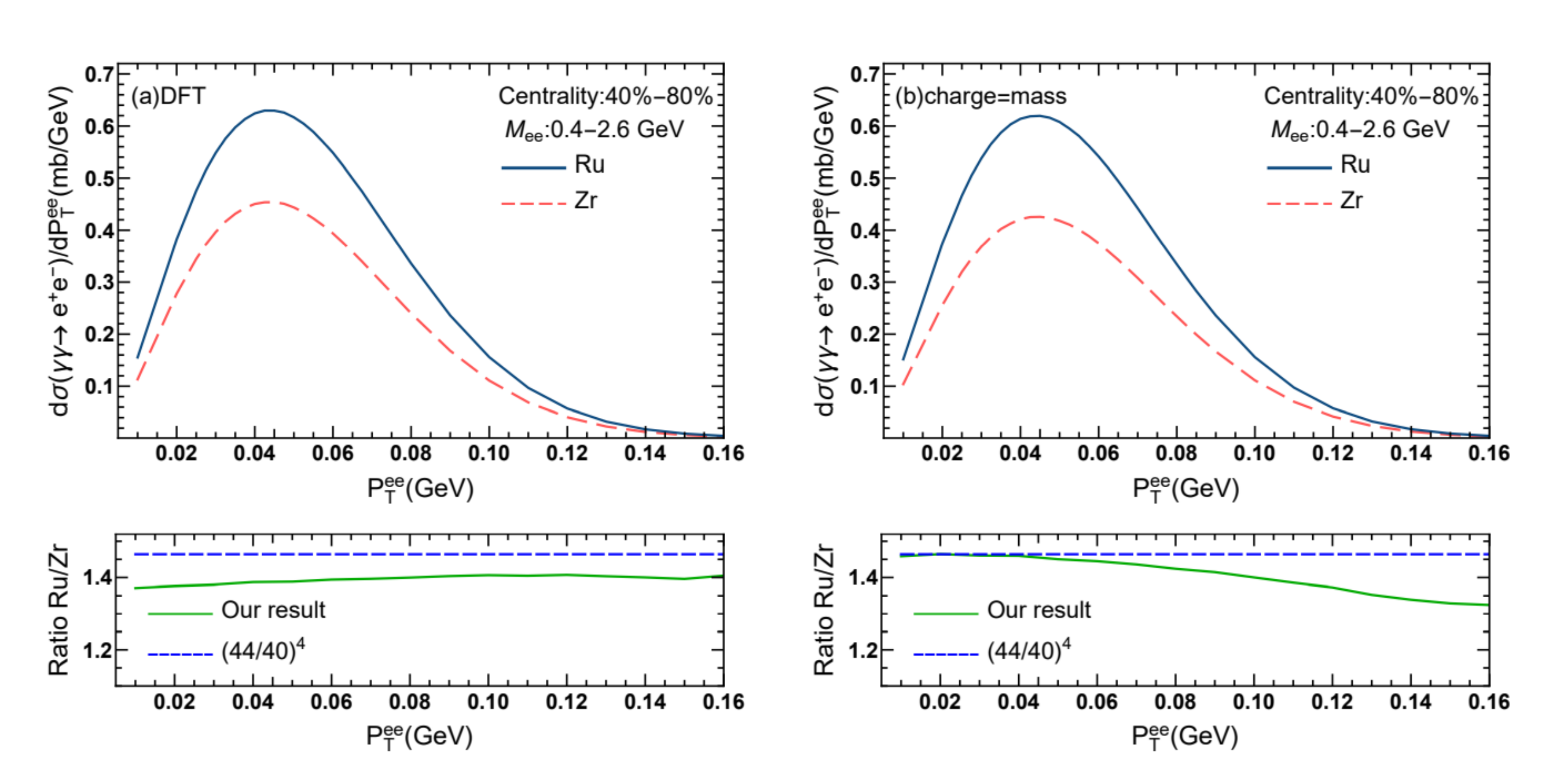
For comparison, we also use the charge density distribution as the mass density distribution to define the centrality

S. Lin,R.J. Wang, J.F. Wang, H.J. Xu, S. Pu and Q. Wang, Phys.Rev.D 107 (2023), 054004.

Numerical results

Numerical results

➢ P_T^{ee} distribution



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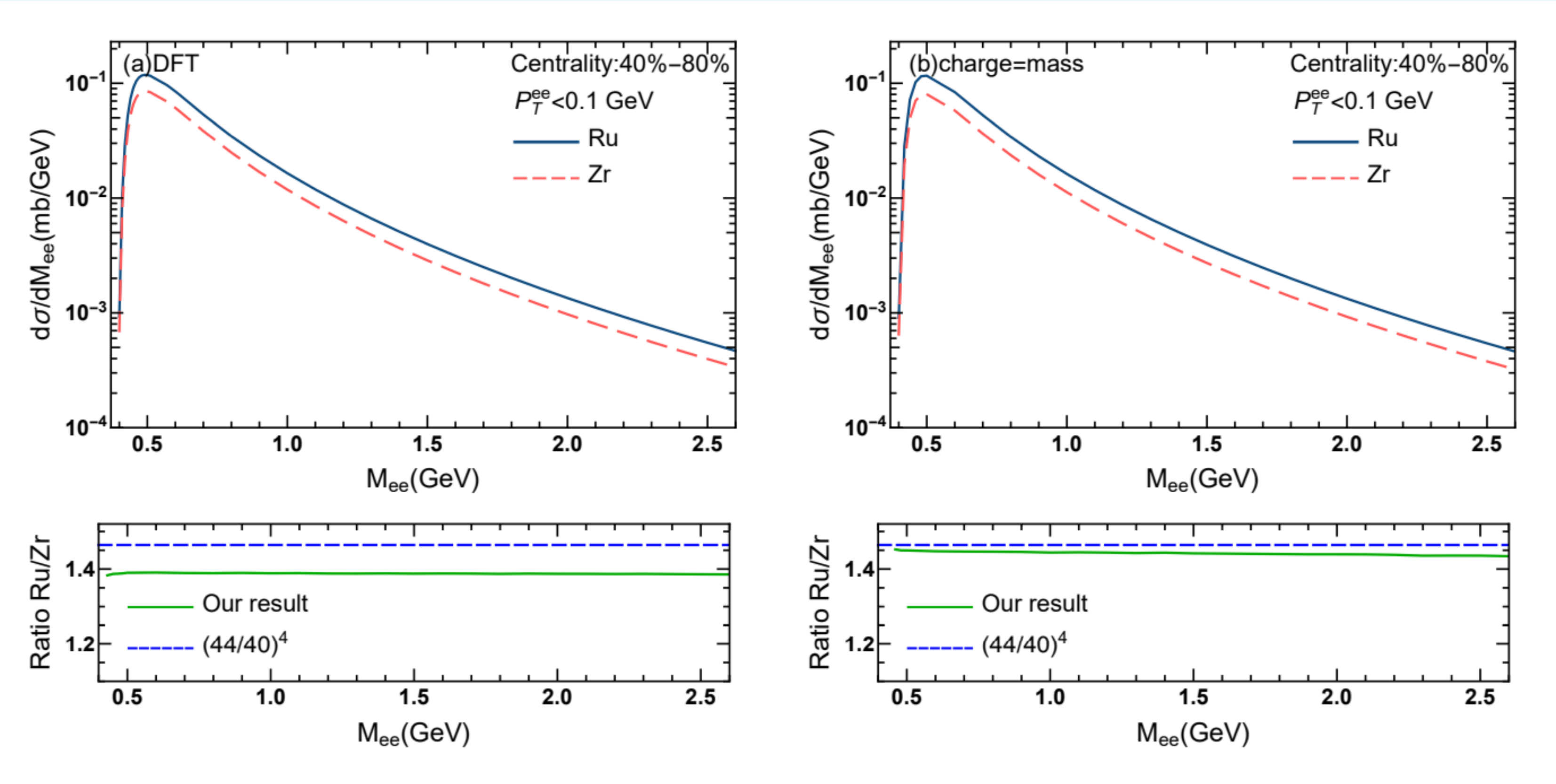
Numerical results

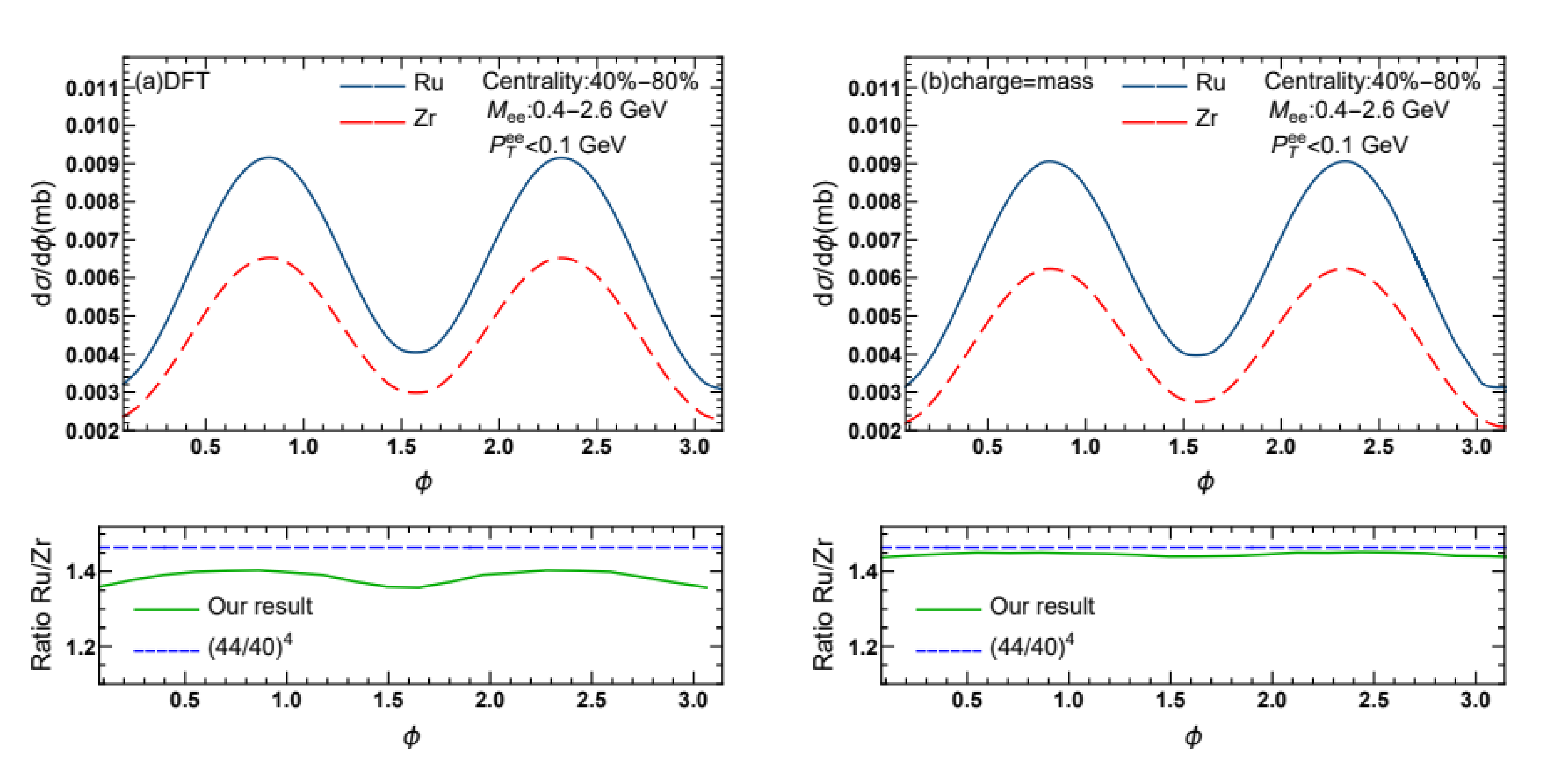
➢ Invariant mass distribution



S. Lin, R.J. Wang, J.F. Wang, H.J. Xu, S. Pu and Q. Wang, Phys.Rev.D 107 (2023), 054004.

Numerical results

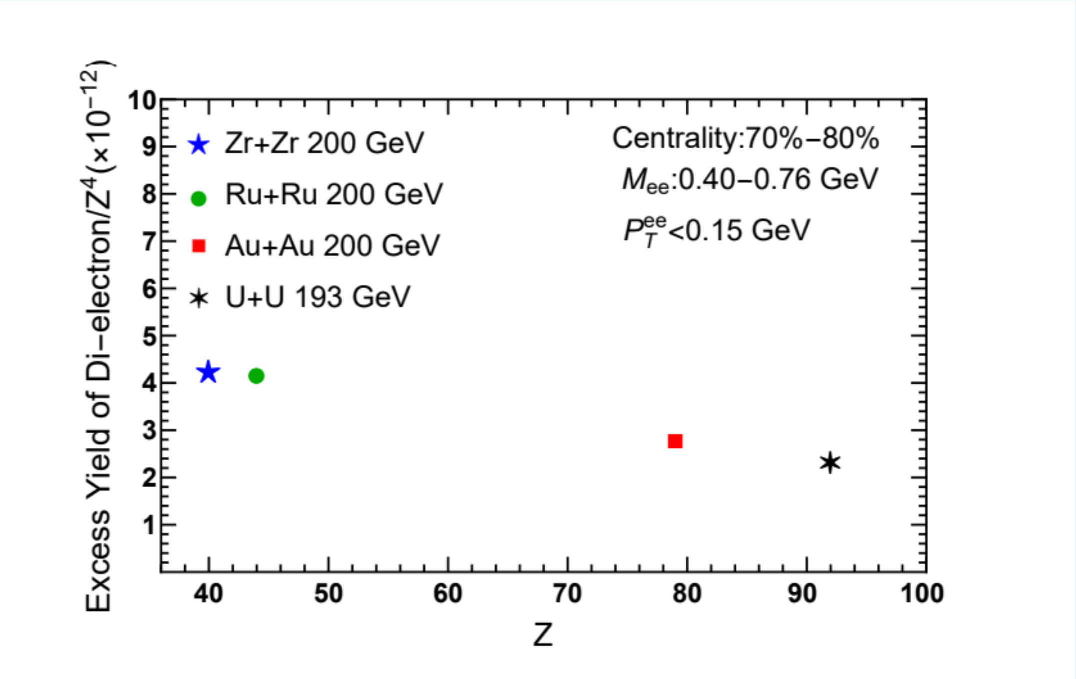
➢ **Azimuthal asymmetry**



S. Lin,R.J. Wang, J.F. Wang, H.J. Xu, S. Pu and Q. Wang, Phys.Rev.D 107 (2023), 054004.

Numerical results

➢ **Charge and centrality dependence**



	Ru	Zr	ratio Ru/Zr
40-60%	2.328×10^{-5}	1.615×10^{-5}	1.441
60-70%	2.245×10^{-5}	1.549×10^{-5}	1.449
70-80%	2.178×10^{-5}	1.495×10^{-5}	1.457

S. Lin, R.J. Wang, J.F. Wang, H.J. Xu, S. Pu and Q. Wang, Phys.Rev.D 107 (2023), 054004.

Summary

- We calculated the spectra of transverse momentum, invariant mass and azimuthal angle for di-electrons at 40-80% centrality in Ru+Ru and Zr+Zr collisions at 200 GeV.

- We take the ratio of these spectra in Ru+Ru collisions to Zr+Zr collisions and show the effect arising from the difference between the mass and charge density distributions.

- The photoproduction of lepton pairs in isobar collisions may provide a new way to probe the nuclear structure.

Thanks for your attention!