Lepton pair photoproduction in relativistic heavy-ion collisions

Ren-jie Wang (王仁杰)

- RJW, Shi Pu, Qun Wang, PRD (2021)
- RJW, Shuo Lin, Shi Pu, Yi-fei Zhang, Qun Wang, PRD (2022)
- Shuo Lin, RJW, Jian-fei Wang, Hao-jie Xu, Shi Pu, Qun Wang, PRD (2023)

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Outline

➢ Introduction

- Photobiomass and the Breit-Wheeler process
- Equivalent photon approximation (EPA)
- Experimental and theoretical progress on lepton pair photoproduction

➢ Researches

- Lepton pair photoproduction based on wave packet approximation
- Phenomenology in high-energy ion collisions

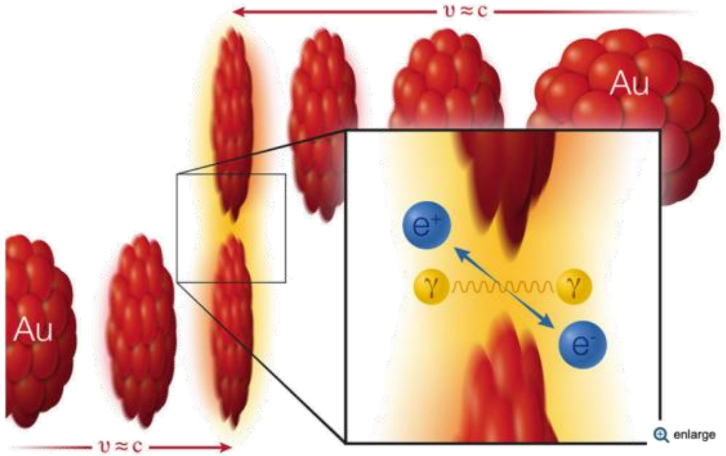
➢ Summary and Outlook

Photobiomass and the Breit-Wheeler process

Collisions of Light Produce Matter/Antimatter from Pure Energy

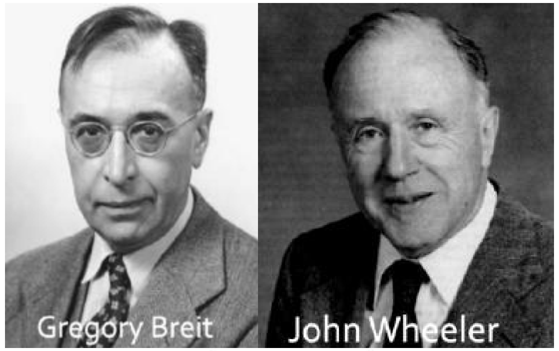
Study demonstrates a long-predicted process for generating matter directly from light — plus evidence that magnetism can bend polarized photons along different paths in a vacuum

July 28, 2021



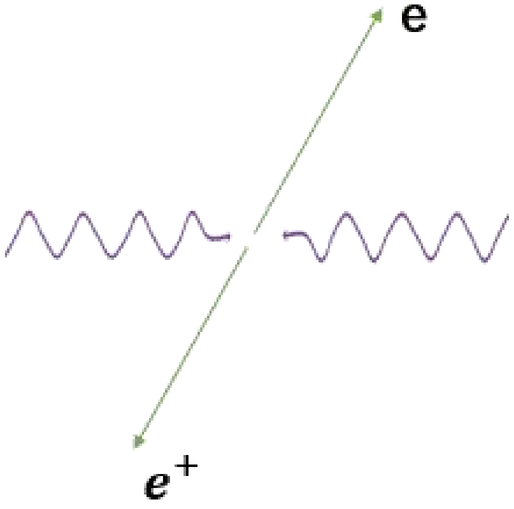
Making matter from light: Two gold (Au) ions (red) move in opposite direction at 99.995% of the speed of light (v, for velocity, = approximately c, the speed of light). As the ions pass one another without colliding, two photons (γ) from the electromagnetic cloud surrounding the ions can interact with each other to create a matter-antimatter pair: an electron (e^-) and positron (e^+).

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



Collision of Two Light Quanta

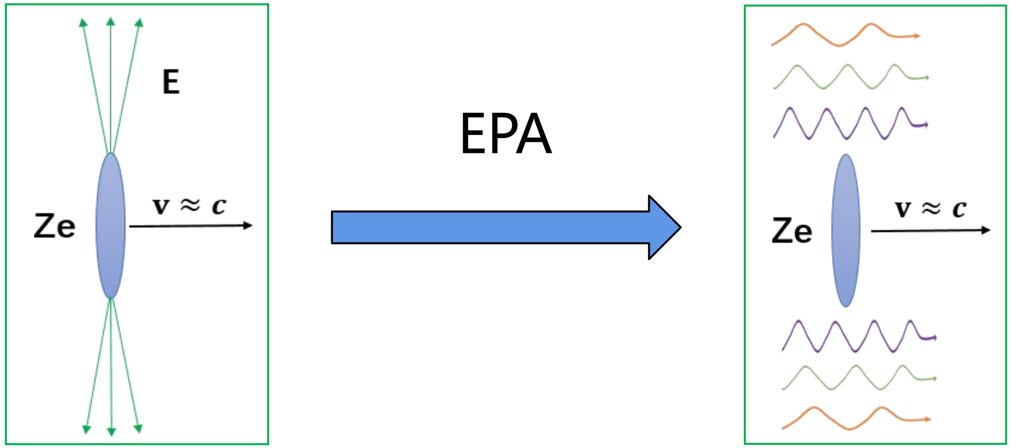
G. Breit* and John A. Wheeler,** *Department of Physics, New York University*
(Received October 23, 1934)



- Breit-Wheeler process: Lepton pair production through the collision of two real photons
- Center of mass energy should large than $2m_e$

(Need high-energy photons!)

Equivalent photon approximation (EPA)



Highly Lorentz contracted EM fields

The flux of linearly polarized quasi-real photons

Weizsacker- Williams,1934

Photon flux:

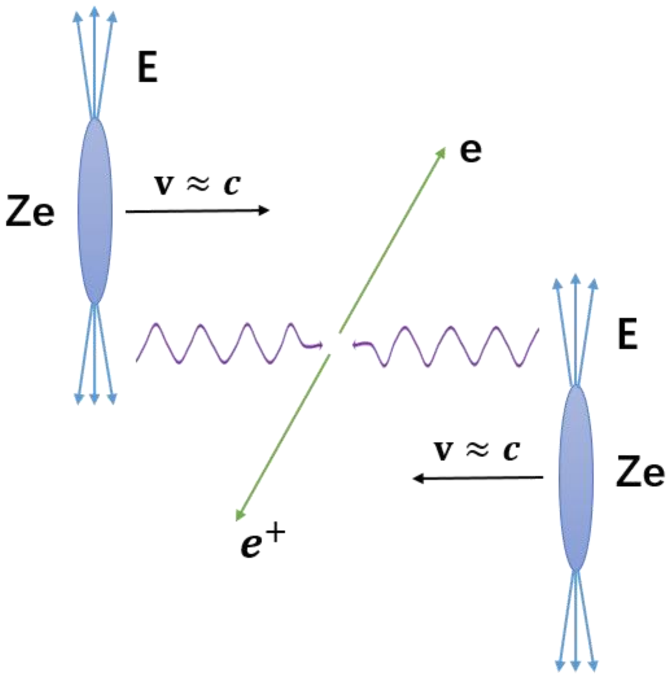
$$n_{A1}(\omega_1, \boldsymbol{b}_{1T}) \cong \frac{1}{\pi\omega_1}|\boldsymbol{E}_T(\omega_1, \boldsymbol{b}_{1T})|^2$$

$$= \frac{4Z^2\alpha}{\omega_1}\left|\int \frac{d^2\boldsymbol{p}_{1T}}{(2\pi)^2} e^{i\boldsymbol{b}_{1T}\cdot\boldsymbol{p}_{1T}} \boldsymbol{p}_{1T} \frac{F(-p_1^2)}{-p_1^2}\right|^2,$$

Point case:

$$n_{A1}(\omega_1, b_{1T}) = \frac{Z^2\alpha}{\pi^2}\frac{\omega_1}{\gamma^2}\left[K_1\left(\frac{\omega_1 b_{1T}}{\gamma}\right)\right]^2,$$

Ultra-peripheral collisions (UPC)



- RHIC can provide high-energy quasi-real photon beams, which can be regarded as a photon-photon or photon-nucleus collider.

- UPC $(b > 2R_A)$ provides a platform for studying QED under extreme EM field conditions.

- Lepton pair photoproduction

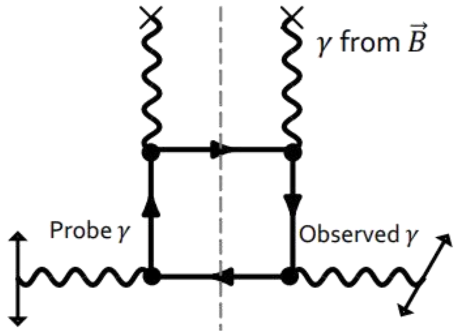
  G. Breit and J. A. Wheeler 1934

- Light-by-light scattering

  H. Euler and B. Kockel 1935

- Vacuum birefringence

  W. Heisenberg and H. Euler 1936



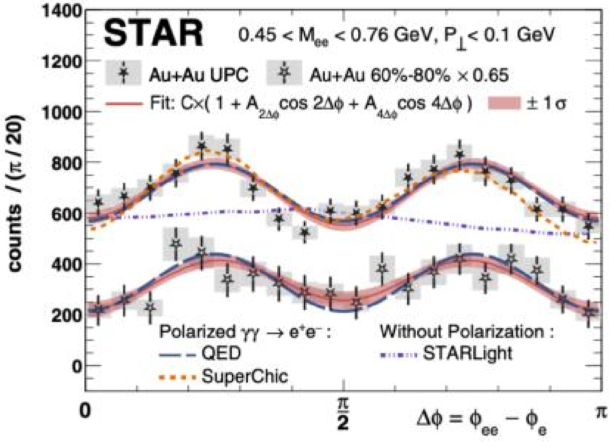
Observations on lepton pair photoproduction

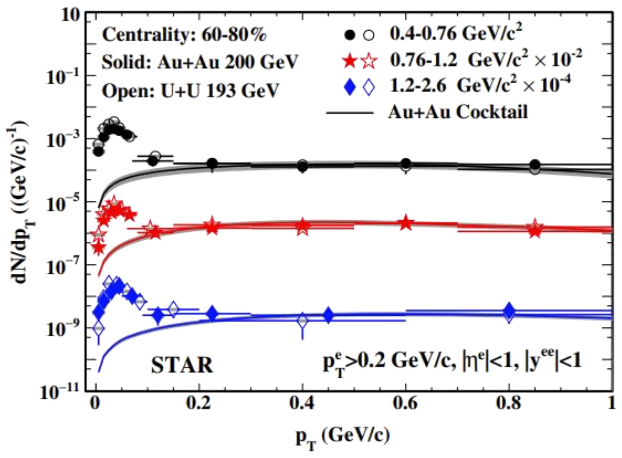
- Observations in UPC

STAR, J. Adam et al., Phys. Rev. Lett. 127, 052302 (2021).
ATLAS, G. Aad et al., Phys. Rev. C 104, 024906 (2021).
CMS, A. M. Sirunyan et al., Phys. Rev. Lett. 127, 122001 (2021).

- Observations in PC

STAR, J. Adam et al., Phys. Rev. Lett. 121, 132301 (2018).
ATLAS, M. Aaboud et al., Phys. Rev. Lett. 121, 212301 (2018).
ALICE, S. Lehner et al., PoS LHCP2019 (2019) 164.





Theoretical methods

- EPA

A. J. Baltz, Y. Gorbunov, S. R. Klein, and J. Nystrand, 0907.1214
S. R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, and J. Butterworth, 1607.03838
W. Zha, L. Ruan, Z. Tang, Z. Xu, and S. Yang, 1804.01813

- QED in background field approach and generalized EPA

M. Vidovic, M. Greiner, C. Best, and G. Soff, 1993
K. Hencken, G. Baur, and D. Trautmann, 0402061
W. Zha, J. D. Brandenburg, Z. Tang, and Z. Xu, Phys. Lett. B800, 135089 (2020)

- Transverse momentum dependent parton distribution functions (TMDPDF) and Wigner functions factorization formalism

C. Li, J. Zhou, and Y.-J. Zhou, Phys. Lett. B795, (2019), Phys. Rev. D 101, 034015 (2020).
B.-W. Xiao, F. Yuan, and J. Zhou Phys. Rev. Lett. 125, 232301
S. Klein, A. H. Mueller, B.-W. Xiao, and F. Yuan, Phys. Rev. D102, 094013 (2020).

How to connect these methods?

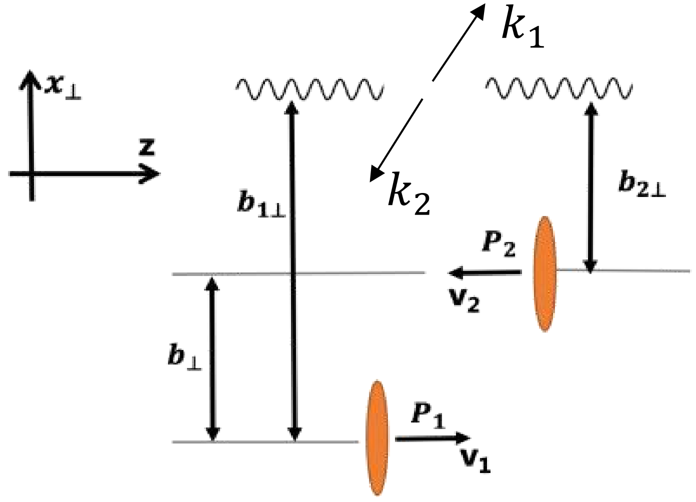
QED method based on wave packet method

Starting point:

Wave packets form of the nuclear state

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

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



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

- $q(p_1) + \bar{q}(p_2) \rightarrow l(k_1) + \bar{l}(k_2)$
- $\gamma(p_1) + \gamma(p_2) \rightarrow l(k_1) + \bar{l}(k_2)$

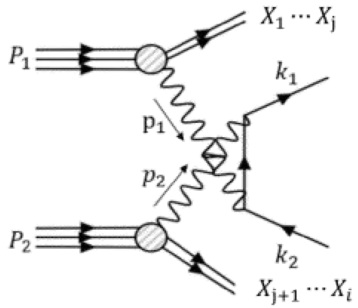
RJW, Shi Pu and Qun Wang, PRD 2021

QED method based on wave packet method

$$\frac{d\sigma}{d^3k_1d^3k_2} = \frac{1}{32(2\pi)^6}\frac{1}{E_{k1}E_{k2}}\int d^2\boldsymbol{b}_T d^2\boldsymbol{b}_{1T} d^2\boldsymbol{b}_{2T}\int d^4p_1 d^4p_2\, \delta^2(\boldsymbol{b}_T - \boldsymbol{b}_{1T} + \boldsymbol{b}_{2T})(2\pi)^4\delta^4(p_1+p_2-k_1-k_2)$$

$$\times\int \frac{d^2\boldsymbol{P}_{(1+1')T}}{(2\pi)^2}\frac{d^2\boldsymbol{P}_{(2+2')T}}{(2\pi)^2}\frac{1}{v\sqrt{E_{P1}E_{P2}E_{P1'}E_{P2'}}}G^2[(P_1'^Z - P_{A1}^Z)^2]\phi_T(\boldsymbol{P}_{1T})\phi_T(\boldsymbol{P}_{2T})\phi_T^*(\boldsymbol{P}'_{1T})\phi_T^*(\boldsymbol{P}'_{2T})$$

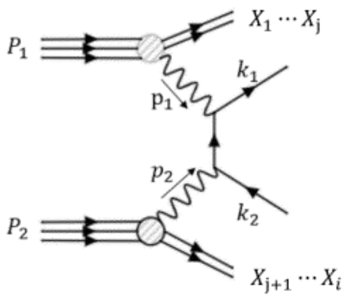
$$\times S_{\sigma\mu}(p_1,\boldsymbol{b}_{1T})S_{\rho\nu}(p_2,\boldsymbol{b}_{2T}) \times e^4 \sum_{\text{spin of } l\bar{l}} L^{\mu\nu}(p_1,p_2,k_1,k_2)L^{*\sigma\rho}(p_1',p_2',k_1,k_2)\,,$$



→ Lepton part

Wigner functions for photons in the Born approximation:

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



→ Classical field approximation

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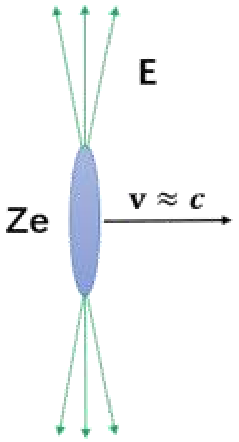
Classical field approximation

$$\langle P' | A_\sigma^\dagger(p') A_\mu(p) | P \rangle \cong 2\sqrt{E_P E_{P'}}\, A_\sigma^*(p') A_\mu(p) \times (2\pi)^3 \delta^2(\boldsymbol{P}' - \boldsymbol{p}' - \boldsymbol{P} + \boldsymbol{p}),$$

A^μ of a fast-moving nucleus in the Lorentz gauge:



$$\partial^2 A^\mu(x) = j^\mu(x)$$

$$A^\mu(p) = 2\pi Z e \delta(p \cdot u) \frac{F(p)}{-p^2} u^\mu$$

$$\sigma = \frac{Z^4 e^4}{2\gamma^4 v^3} \int d^2\boldsymbol{b}_T d^2\boldsymbol{b}_{1T} d^2\boldsymbol{b}_{2T} \int \frac{d\omega_1 d^2\boldsymbol{p}_{1T}}{(2\pi)^3} \frac{d\omega_2 d^2\boldsymbol{p}_{2T}}{(2\pi)^3}$$
$$\times \int \frac{d^2\boldsymbol{p}'_{1T}}{(2\pi)^2} e^{-i\boldsymbol{b}_{1T}\cdot(\boldsymbol{p}'_{1T} - \boldsymbol{p}_{1T})} \frac{F^*(-\bar{p}_1'^2)}{-\bar{p}_1'^2} \frac{F(-\bar{p}_1^2)}{-\bar{p}_1^2}$$
$$\times \int \frac{d^2\boldsymbol{p}'_{2T}}{(2\pi)^2} e^{-i\boldsymbol{b}_{2T}\cdot(\boldsymbol{p}'_{2T} - \boldsymbol{p}_{2T})} \frac{F^*(-\bar{p}_2'^2)}{-\bar{p}_2'^2} \frac{F(-\bar{p}_2^2)}{-\bar{p}_2^2}$$
$$\times \int \frac{d^3k_1}{(2\pi)^3 2E_{k1}} \frac{d^3k_2}{(2\pi)^3 2E_{k2}} (2\pi)^4 \delta^4(\bar{p}_1 + \bar{p}_2 - k_1 - k_2)$$
$$\times \sum_{\text{spin of } l\bar{l}} [u_{1\mu} u_{2\nu} L^{\mu\nu}][u_{1\sigma} u_{2\rho} L^{*\sigma\rho}]\, \delta^2(\boldsymbol{b}_T - \boldsymbol{b}_{1T} + \boldsymbol{b}_{2T}).$$

The cross section incorporates the information on the transverse, momentum, position and polarization of photons and the impact parameters.

RJW, Shi Pu and Qun Wang, PRD 2021

Relativistic limit and gEPA

Ward identity:

$$p_{1\mu}L^{\mu\nu} = p_{2\nu}L^{\mu\nu} = 0$$

$$\frac{p_1^+}{\omega_1}, \frac{p_2^-}{\omega_2} \sim \mathcal{O}(1) \qquad \frac{p_1^i}{\omega_1}, \frac{p_2^i}{\omega_2} \sim \mathcal{O}(\gamma^{-1})$$

$$\frac{p_1^-}{\omega_1}, \frac{p_2^+}{\omega_2} \sim \mathcal{O}(\gamma^{-2}) \qquad \frac{p^2}{\omega^2} \sim \mathcal{O}(\gamma^{-2})$$

$$u_{1\mu}u_{2\nu}L^{\mu\nu} = \gamma^2 v^2 \frac{p_1^i}{\omega_1}\frac{p_2^j}{\omega_2}L^{ij} - 2\gamma^2 v^2 \left(\frac{p_1^i}{\omega_1}\frac{p_2^+}{\omega_2}L^{i-} + \frac{p_1^-}{\omega_1}\frac{p_2^j}{\omega_2}L^{+j}\right) + 4\gamma^2 v^2 \frac{p_1^-}{\omega_1}\frac{p_2^+}{\omega_2}L^{+-}$$

$$\sigma = \sigma_0 + \delta\sigma$$

RJW, Shi Pu and Qun Wang, PRD 2021

Relativistic limit and gEPA

$$\sigma = \sigma_0 + \delta\sigma$$

Beyond EPA

$$\sigma_0 = \int d^2\boldsymbol{b}_T d^2\boldsymbol{b}_{1T} d^2\boldsymbol{b}_{2T} \int d\omega_1 d^2\boldsymbol{p}_{1T} d\omega_2 d^2\boldsymbol{p}_{2T}$$
$$\times\ n_{A1}(\omega_1, \boldsymbol{p}_{1T}, \boldsymbol{b}_{1T}) n_{A2}(\omega_2, \boldsymbol{p}_{2T}, \boldsymbol{b}_{2T})$$
$$\times\ \delta^2(\boldsymbol{b}_T - \boldsymbol{b}_{1T} + \boldsymbol{b}_{2T}) \sigma_{\gamma\gamma\to l\bar{l}}(\omega_1, \omega_2)$$

Photon flux:

$$n_{A1}(\omega_1, \boldsymbol{p}_{1T}, \boldsymbol{b}_{1T}) = \frac{Z^2\alpha}{\omega_1\pi^2} \int \frac{d^2\boldsymbol{p}'_{1T}}{(2\pi)^2} \frac{F^*(-p_1'^2)}{-p_1'^2} \frac{F(-p_1^2)}{-p_1^2} |\boldsymbol{p}_{1T}||\boldsymbol{p}'_{1T}| e^{-i\boldsymbol{b}_{1T}\cdot(\boldsymbol{p}'_{1T} - \boldsymbol{p}_{1T})},$$

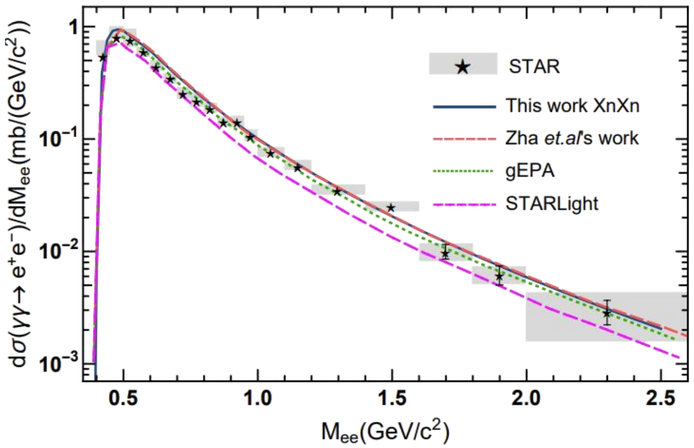
$$n_{A1}(\omega_1, \boldsymbol{b}_{1T}) = \int \mathrm{d}^2\boldsymbol{p}_{1T}\, n_{A1}(\omega_1, \boldsymbol{p}_{1T}, \boldsymbol{b}_{1T})$$
$$= \frac{4Z^2\alpha}{\omega_1} \left| \int \frac{\mathrm{d}^2\boldsymbol{p}_{1T}}{(2\pi)^2} e^{i\boldsymbol{b}_{1T}\cdot\boldsymbol{p}_{1T}} \boldsymbol{p}_{1T} \frac{F(-p_1^2)}{-p_1^2} \right|^2.$$

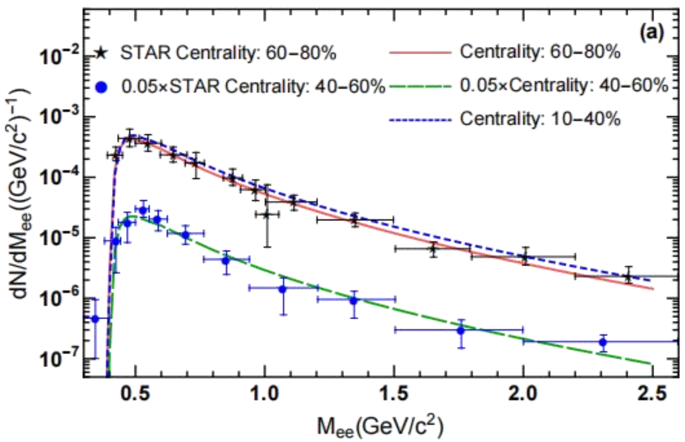
- Ultra-relativistic limit lead to the results of gEPA.

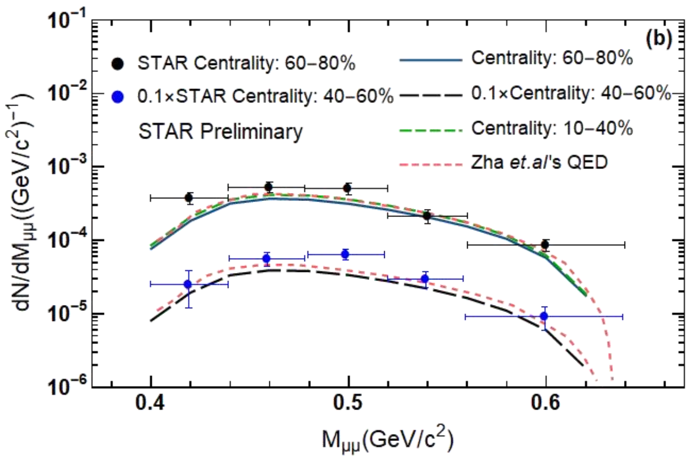
$$\sigma_0 = \sigma_{\mathrm{gEPA}} = \sigma_{\mathrm{twist\ 2}}$$

RJW, Shi Pu and Qun Wang, PRD 2021

Invariant mass spectrum of lepton pairs



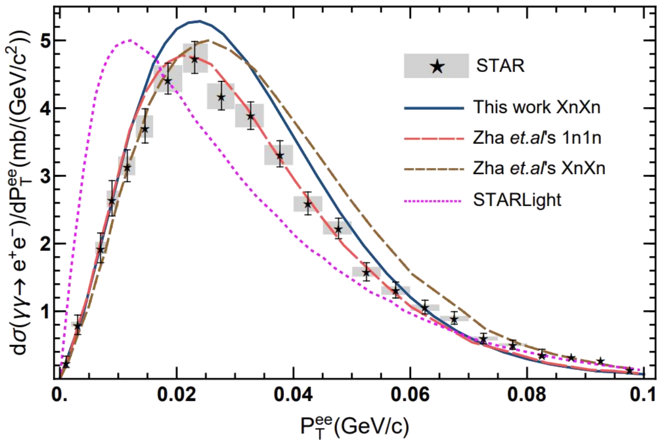


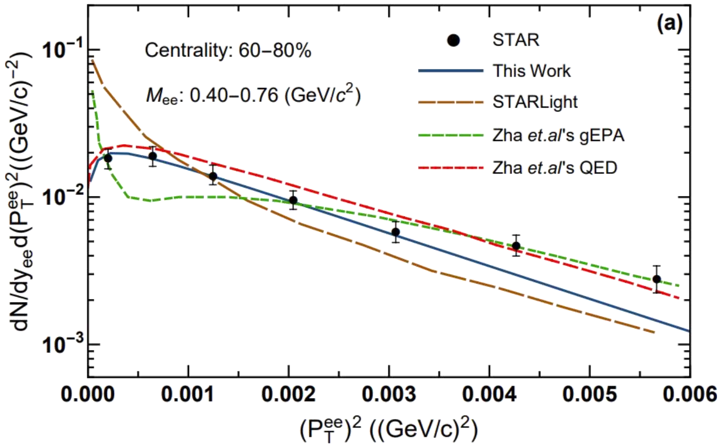


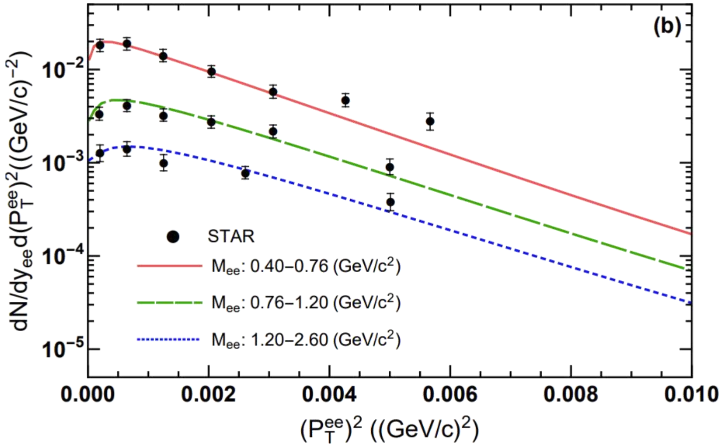
- Different model calculation of invariant mass spectra that are consistent with the experimental data from the STAR experiment.
- The smoothness of the invariant mass spectrum indicates that the equivalent photons in RHIC can be approximated as real photons.

RJW, Shuo Lin, Shi Pu, Yi-fei Zhang and Qun Wang, PRD 2022

Transverse momentum spectrum of lepton pairs





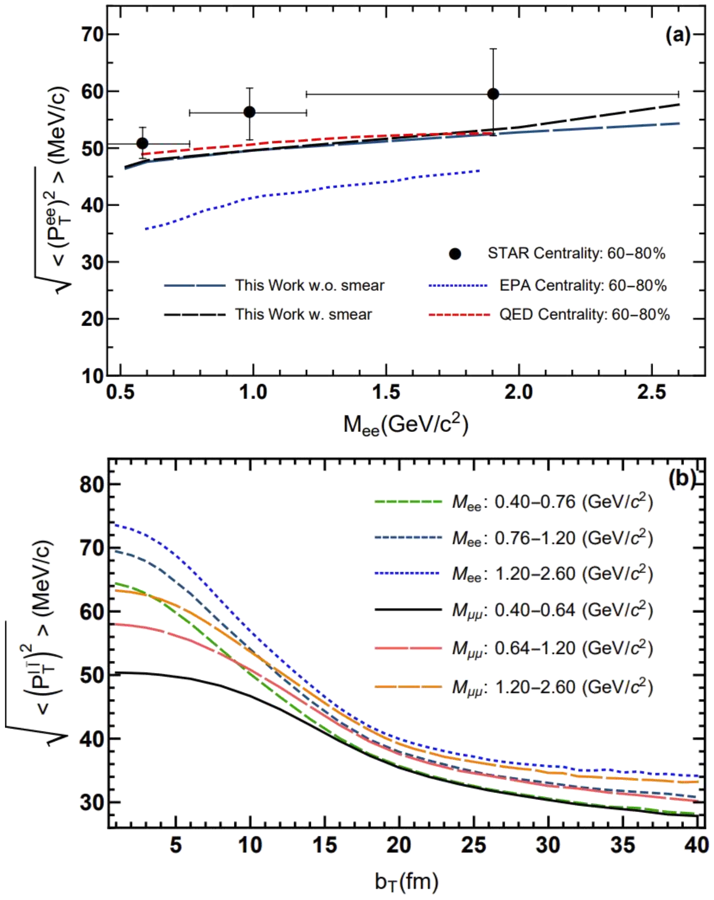


UPC: $\sqrt{\langle (P_T^{ee})^2 \rangle} \approx 38\ \mathrm{MeV}$ 60-80%: $\sqrt{\langle (P_T^{ee})^2 \rangle} \approx 55\ \mathrm{MeV}$

- P_T^{ee} broadening effects: $\sqrt{(P_T^{ee})^2}$ for PC is larger than that for UPC case.

STAR PRL 121, 132301 (2018) RJW, Shuo Lin, Shi Pu, Yi-fei Zhang and Qun Wang, PRD 2022

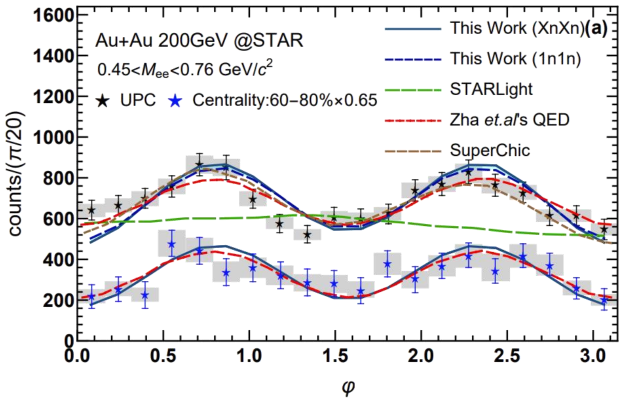
Transverse momentum spectrum of lepton pairs

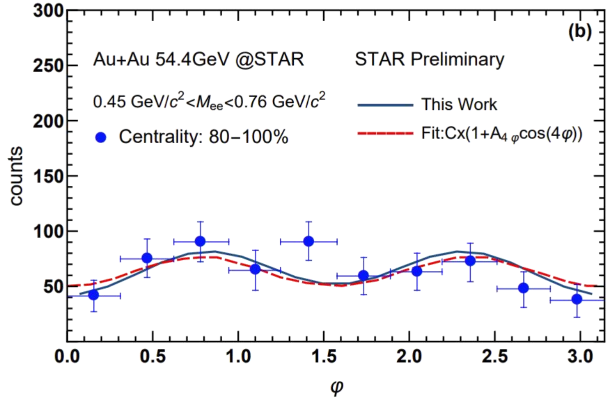


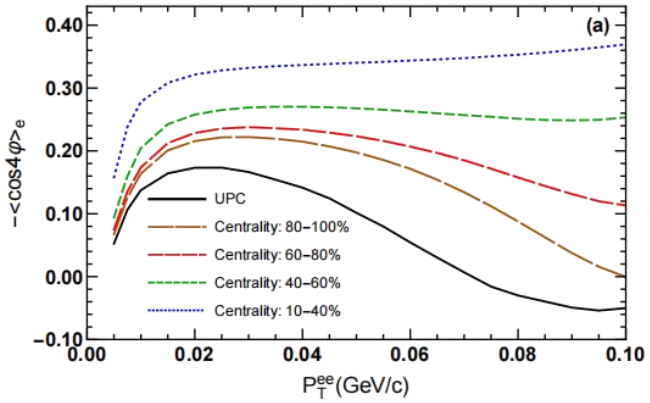
- STARLight (EPA) model cannot successfully describe this impact parameter dependent behavior.
- The transverse momentum information of initial photons is important for understanding the P_T^{ee} broadening effects.
- Need high order correction, such as Sudakov factor, Coulomb correction
- Medium effects: Multiple scattering between final state leptons and the medium produced in PC?

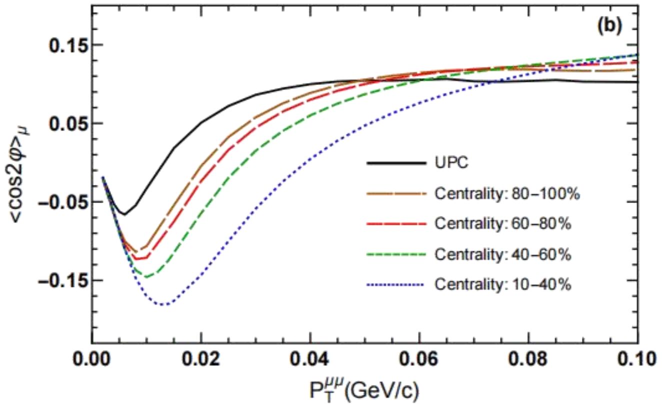
RJW, Shuo Lin, Shi Pu, Yi-fei Zhang and Qun Wang, PRD 2022

Azimuthal angle distribution of lepton pairs







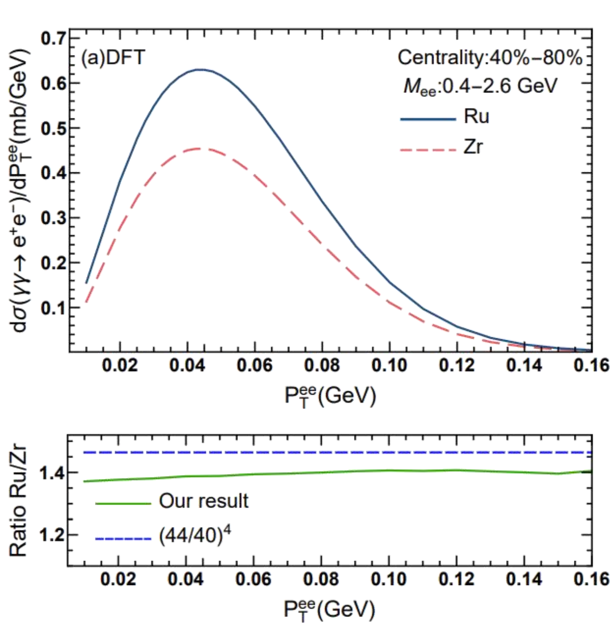


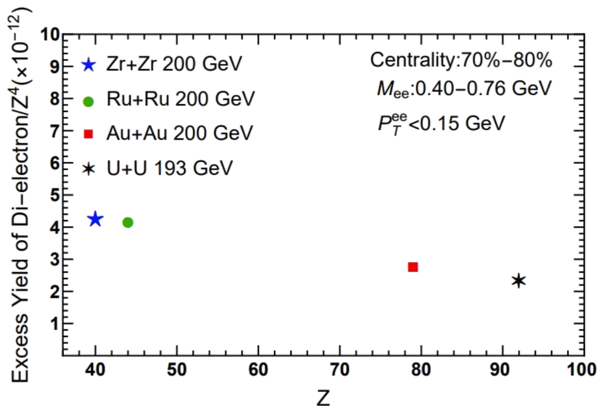
- The polarization information of initial photons is important for describing the azimuthal modulation.
- The azimuthal modulation behavior is believed to be closely related to the vacuum birefringence.
- The cos(2φ) contribution in the muon pairs case is enhanced compared to the case of electron pairs.

C. Li, J. Zhou, and Y.-J. Zhou, PLB 2019, PRD 2020.

RJW, Shuo Lin, Shi Pu, Yi-fei Zhang and Qun Wang, PRD 2022

Lepton pair photoproduction in isobar collisions





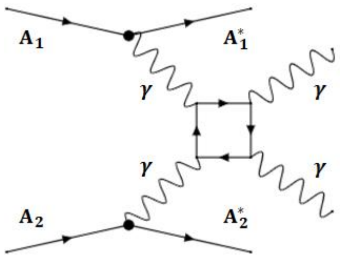
- If the nucleus is treated as a point charge, the cross section is proportional to Z^4.
- The nuclear charge distribution and mass distribution will affect the cross section of the lepton pair photoproduction.

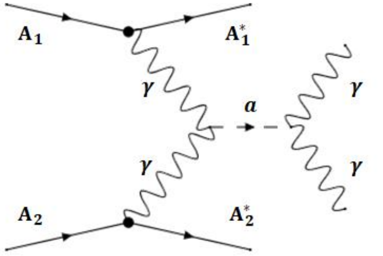
- It provides assistance for future research on isotopic collisions and related studies of nuclear distribution.

Shuo Lin, RJW, Jian-fei Wang, Hao-jie Xu, Shi Pu and Qun Wang, PRD 2023

Apply to other photo-induced processes

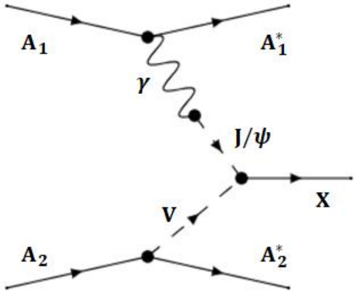
- Light-by-light scattering

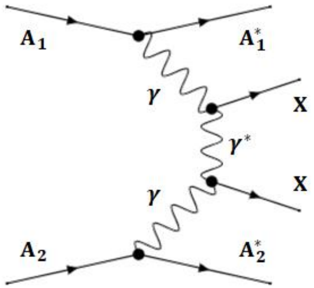




A. M. Sirunyan et al, PLB 2019.
G. Aad et al, JHEP 2021.

- Photoproduction of X(3872)





M. Albaladejo, A. N. Hiller Blin, A. Pilloni , D. Winney, C. Fernández- Ramírez, V. Mathieu, and A. Szczepaniak, PRD 2020

Summary and Outlook

➢ Relativistic heavy-ion collision provide a platform for studying quantum matter under extremely strong electromagnetic fields.

- Anomalous chiral transport，strong fields QED，nuclear structure，new physics……

➢ A general form of the lepton pair photoproduction cross section was derived based on the wave packet form of nuclear wave functions.

- The information on transverse momentum, position, and polarization of initial photon fields are consistently included in the photon effective Wigner function, and these information are crucial for accurately describing the experiment.
- Our theoretical method also provides a correlation between different theoretical models.

➢ In the future, we will further consider the higher-order corrections, nuclear deformation effects etc. We will also explore additional photo-induced processes.

Thanks for your attention!