中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

Lepton pair photoproduction in peripheral relativistic heavy-ion collisions

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RJW, Shi Pu, Qun Wang, PRD 2021
RJW, Shuo Lin, Shi Pu, Yifei Zhang, Qun Wang, Received by PRD

Outline

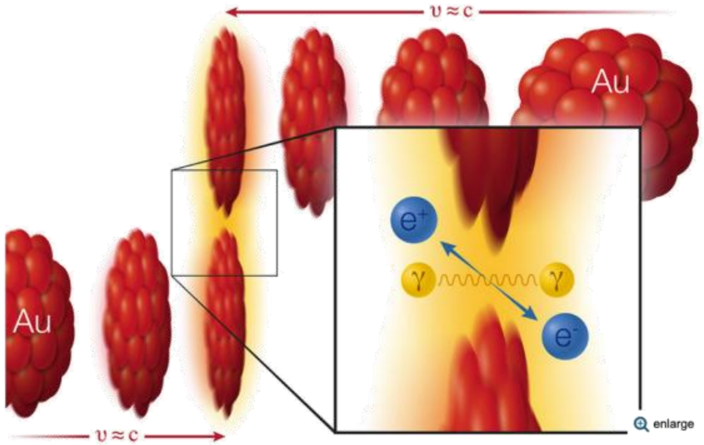
- Introduction
- Theoretical framework
- Numerical results
- Summary

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 PRL 127, 052302 (2021)

THE
PHYSICAL REVIEW

SCATTERING OF HARD γ-RAYS

BY C. Y. CHAO*

NORMAN BRIDGE LABORATORY OF PHYSICS, CALIFORNIA INSTITUTE OF TECHNOLOGY

(Received October 13, 1930)

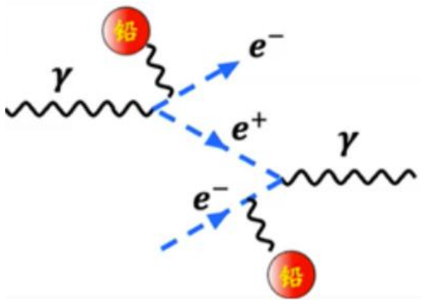
VOL. 16, 1930 PHYSICS: C. Y. CHAO

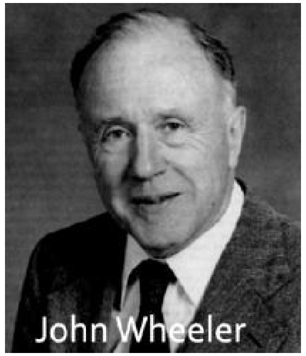
THE ABSORPTION COEFFICIENT OF HARD γ-RAYS

BY C. Y. CHAO*

NORMAN BRIDGE LABORATORY OF PHYSICS, CALIFORNIA INSTITUTE OF TECHNOLOGY

Communicated May 15, 1930

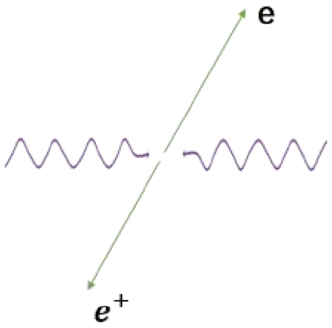




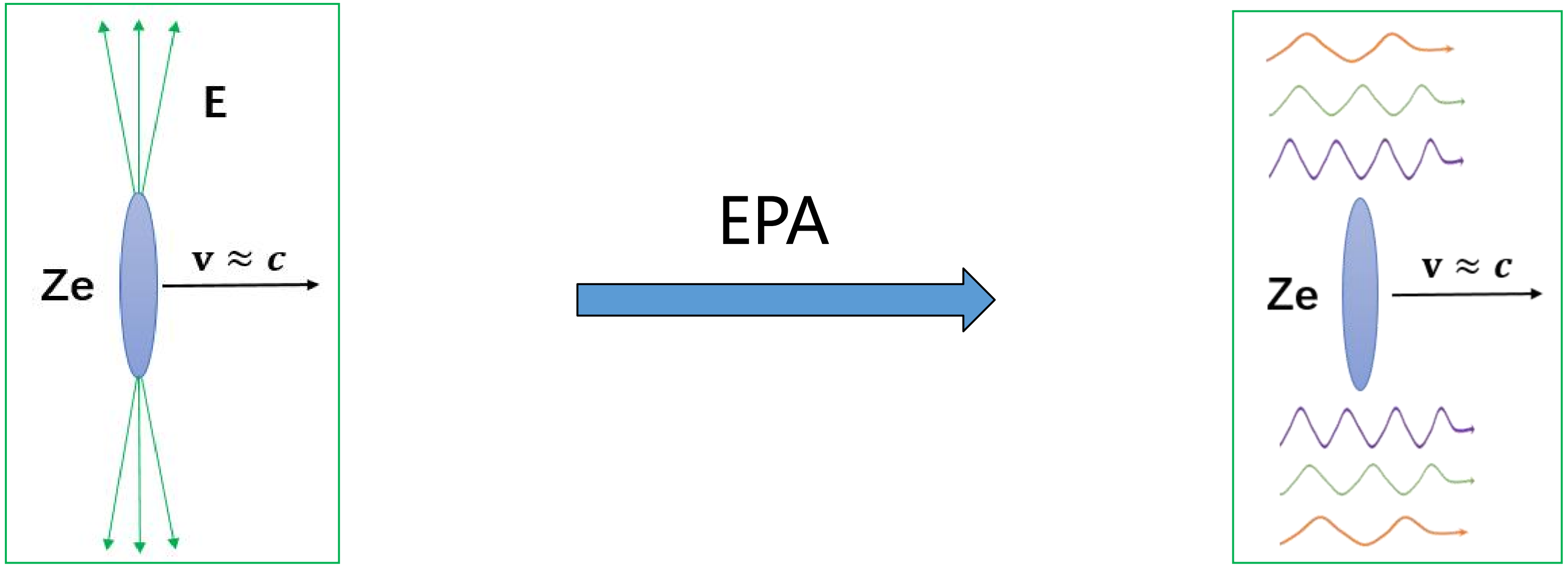
Collision of Two Light Quanta

G. BREIT* AND JOHN A. WHEELER,** Department of Physics, New York University

(Received October 23, 1934)



Equivalent Photon Approximation



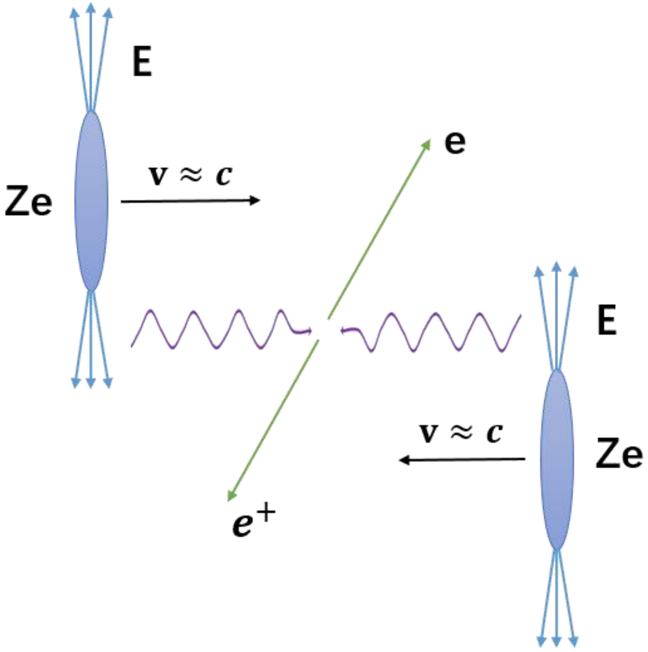
Highly Lorentz-contracted electromagnetic fields

The flux of linearly polarized quasi-real photons

The photon flux are proportional to the F.T. of the Poynting vector.

Weizsacker- Williams,1934

Strong EM fields in RHIC



- $eB \sim 10^{18} G$ in Au+Au collisions at $\sqrt{s_{NN}} = 200\mathrm{GeV}$

  Quasi-real energetic photons

- Hadronic processes are suppressed in Ultra-peripheral collision $(b > 2R_A)$

- UPC provides an opportunity to study the QED under extreme conditions.

Lepton pair photoproduction in UPC

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

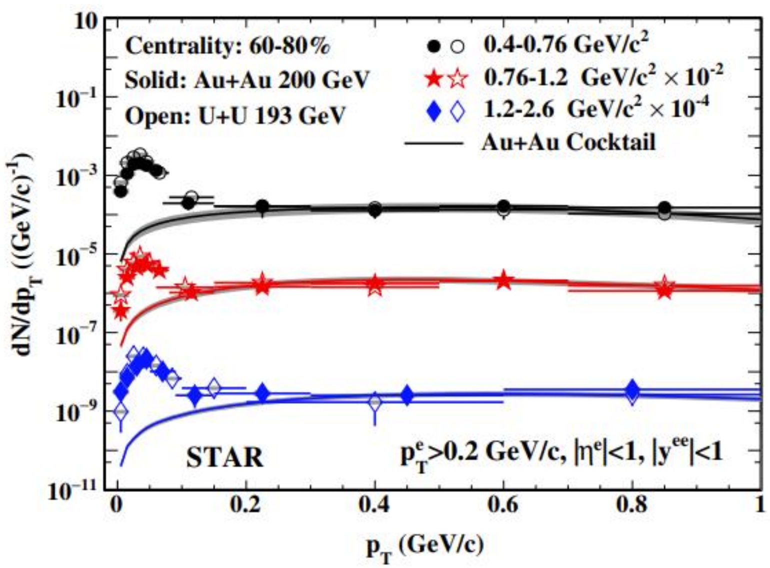
STAR, J. Adam et al., Phys. Rev. Lett. 127, 052302 (2021), 1910.12400.
ATLAS, G. Aad et al., Phys. Rev. C 104, 024906 (2021), 2011.12211.
CMS, A. M. Sirunyan et al., Phys. Rev. Lett. 127, 122001 (2021), 2011.05239.
ALICE, Abbas, E et al., Eur.Phys.J.C 73 (2013)11, 2617, 1305.1467.

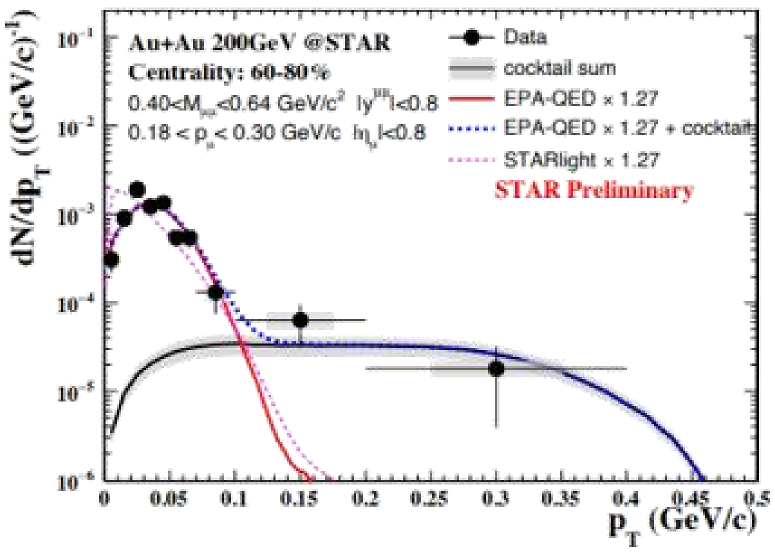
Lepton pair photoproduction in PC

- $\gamma\gamma \rightarrow l^+l^-$ 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.

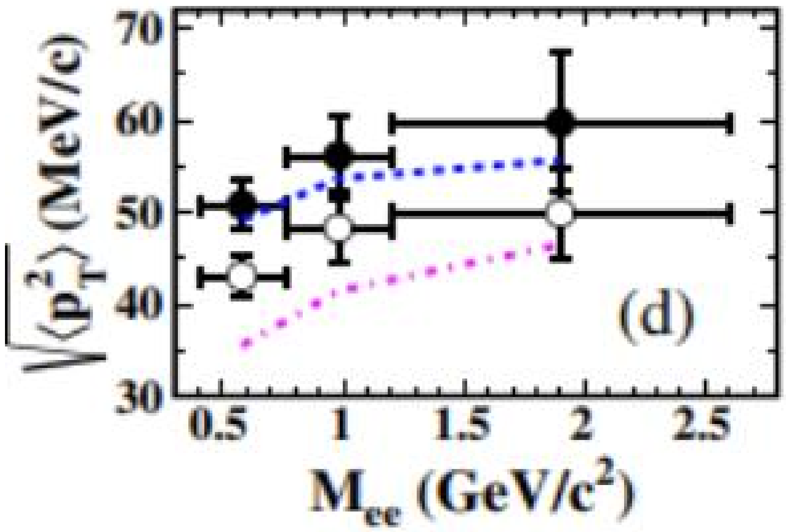
Lepton pair photoproduction in PC





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

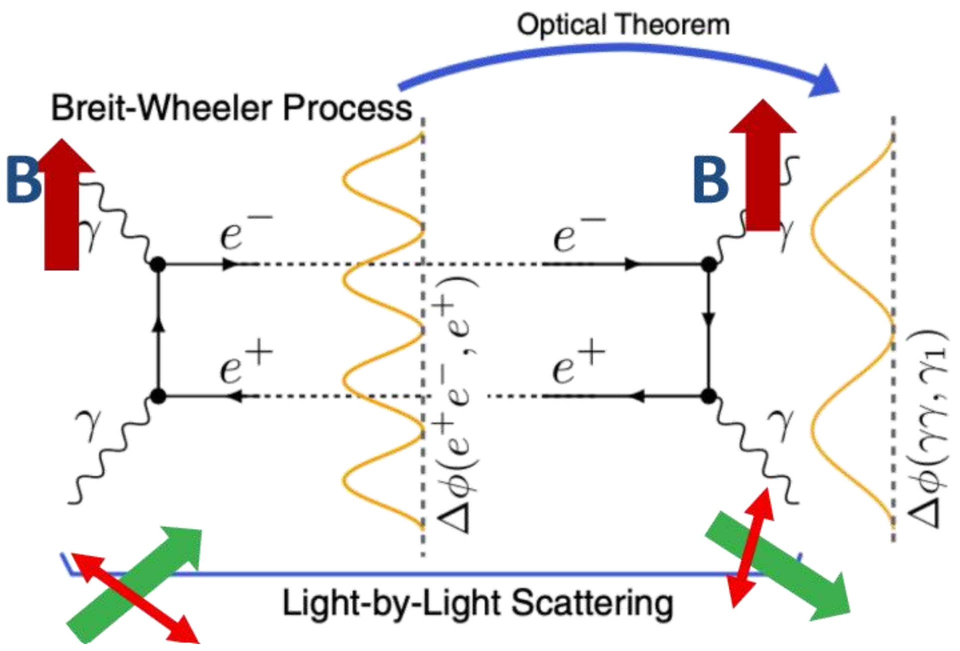
P_T^{ee} broadening in PC



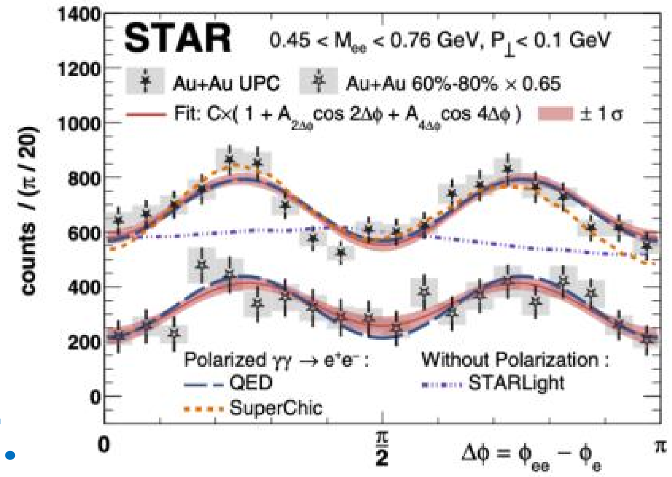
STAR PRL 121, 132301 (2018)

- Higher $\sqrt{(P_T^{ee})^2}$ seen in PC than UPC
- STARlight do not have such impact parameter dependence
- Final state interaction of lepton with medium? Lorentz force effects?
- Initial photon transverse momentum distribution and Sudakov factor can lead to P_T^{ee} broadening effect, which provide a baseline for the medium effect.

Azimuthal asymmetry & vacuum birefringence



The vacuum birefringence are thought to be related to the azimuthal asymmetry of lepton pairs in the Breit-Wheeler process.



$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+]$$

STAR PRL 127, 052302 (2021)
C. Li, J. Zhou, and Y.-J. Zhou, 1903.10084, 1911.00237.

Main theoretical methods

- EPA

  A. J. Baltz, Y. Gorbunov, S. R. Klein, and J. Nystrand, 0907.1214

  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, 1812.02820

- Transverse momentum dependent distribution (TMD) and Wigner function factorization formalism

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

  B.-W. Xiao, F. Yuan, and J. Zhou PRL, 125, 232301

  S. Klein, A. H. Mueller, B.-W. Xiao, and F. Yuan, 2003.02947

  What is the connection between these methods?

  RJW, Shi Pu, Qun Wang, PRD 2021

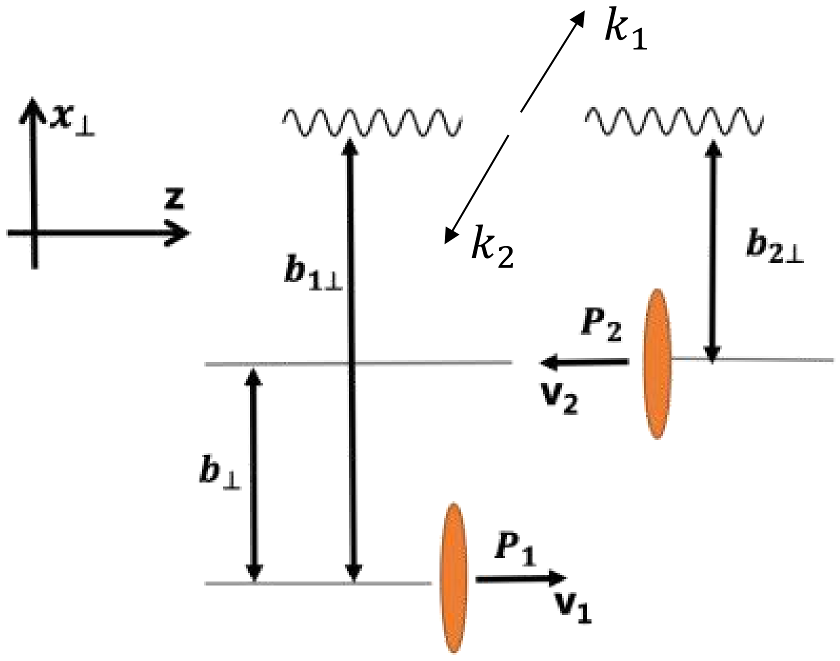
Cross section for photoproduction

Starting point:

Wave packets form of nuclear state

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

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



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

Cross section for photoproduction

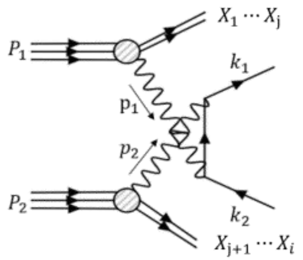
$$\frac{d\sigma}{d^3k_1 d^3k_2} = \frac{1}{32(2\pi)^6}\frac{1}{E_{k1}E_{k2}}\int d^2\boldsymbol{b}_T d^2\boldsymbol{b}_{1T} d^2\boldsymbol{b}_{2T}\int d^4p_1 d^4p_2$$
$$\times\,\delta^2(\boldsymbol{b}_T - \boldsymbol{b}_{1T} + \boldsymbol{b}_{2T})(2\pi)^4\delta^4(p_1 + p_2 - k_1 - k_2)$$
$$\times\int\frac{d^2\boldsymbol{P}_{(1+1')T}}{(2\pi)^2}\frac{d^2\boldsymbol{P}_{(2+2')T}}{(2\pi)^2}\frac{1}{v\sqrt{E_{P1}E_{P2}E_{P1'}E_{P2'}}}$$
$$\times\,G^2\left[(P_1'^Z - P_{A1}^Z)^2\right]\phi_T(\boldsymbol{P}_{1T})\phi_T(\boldsymbol{P}_{2T})\phi_T^*(\boldsymbol{P}_{1T}')\phi_T^*(\boldsymbol{P}_{2T}')$$
$$\times\,S_{\sigma\mu}(p_1, \boldsymbol{b}_{1T})S_{\rho\nu}(p_2, \boldsymbol{b}_{2T})$$
$$\times\sum_{\text{spin of } l\bar{l}} L^{\mu\nu}(p_1, p_2, k_1, k_2)L^{*\sigma\rho}(p_1', p_2', k_1, k_2)$$

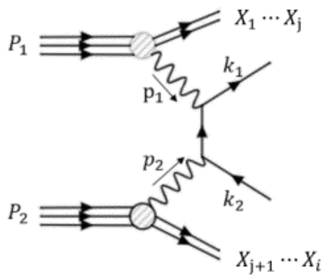
Information of initial Wave packets

Lepton part

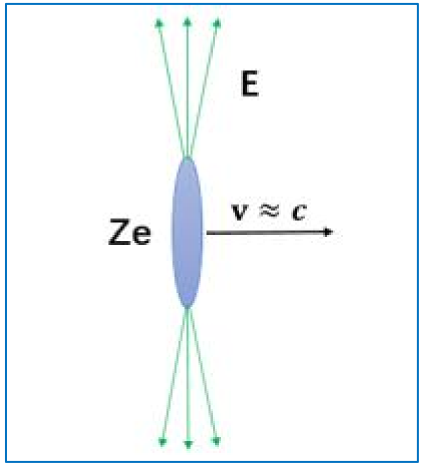
Wigner functions for photons in Born level:

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





Classical field approximation



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

Maxwell's Eq in Lorentz gauge:

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

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

Nuclear charge form factor

RJW, Shi Pu, Qun Wang, PRD 2021

High energy expansion

Ward identity:

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

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

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

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

M. Greiner, et al.,1993

- It implies that the photons are almost on-shell at Ultra-relativistic limit

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

Equivalent Photon Approximation

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

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:

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

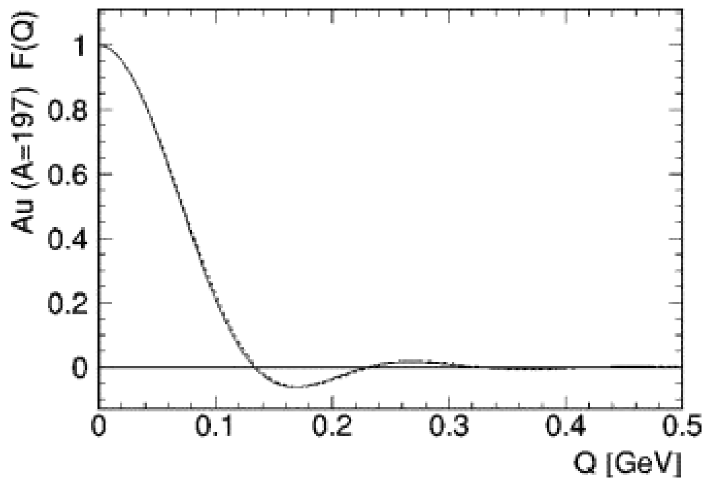
$$n_{A1}(\omega_1, \boldsymbol{b}_{1T}) = \int \mathrm{d}^2\boldsymbol{p}_{1T} \, n_{A1}(\omega_1, \boldsymbol{p}_{1T}, \boldsymbol{b}_{1T}) = \frac{4Z^2\alpha}{\omega_1} \left| \int \frac{\mathrm{d}^2\boldsymbol{p}_{1T}}{(2\pi)^2} e^{i\boldsymbol{b}_{1T}\cdot\boldsymbol{p}_{1T}} \frac{F(-p_1^2)}{-p_1^2}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

$$\sigma_{\text{twist 2}} = \sigma_0$$

- Ultra-relativistic limit lead to the results of gEPA

Numeral calculations

Nuclear charge form factor:



$$F(q) = \frac{4\pi\rho^0}{q^3 A}\left[\sin(qR_A) - qR_A\cos(qR_A)\right]\frac{1}{a^2q^2+1}$$

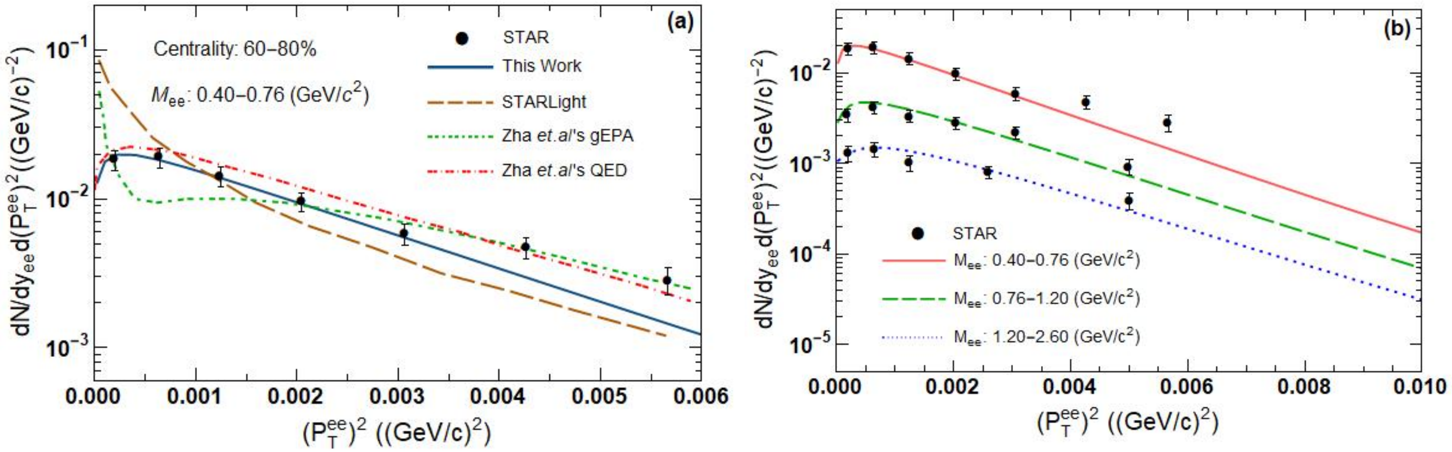
$a = 0.7\ \mathrm{fm}$ $\quad F(q\to 0) = 1$

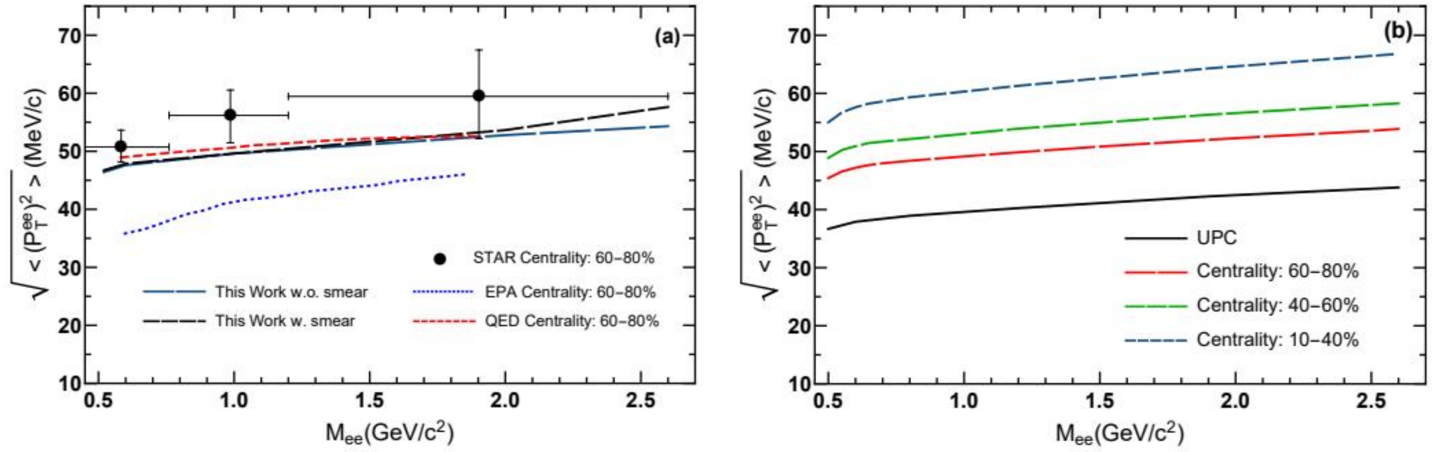
$R_A = 1.2A^{\frac{1}{3}}\ \mathrm{fm}$ $\quad \rho^0 = \frac{3A}{4\pi R_A^3}$

S. Klein and J. Nystrand, 9902259

High-dimensional integrals： ZMCintegral **J.-J. Zhang, H.-Z. Wu, S. Pu, G.-Y. Qin, and Q. Wang，1912.04457**

Numerical results （P_T^{ee} distribution）





- The transverse momentum of initial photons has an b_T dependence, which plays an important role in understanding the $P_T^{l\bar{l}}$ broadening effects.
- Need high order correction: Sudakov factor.

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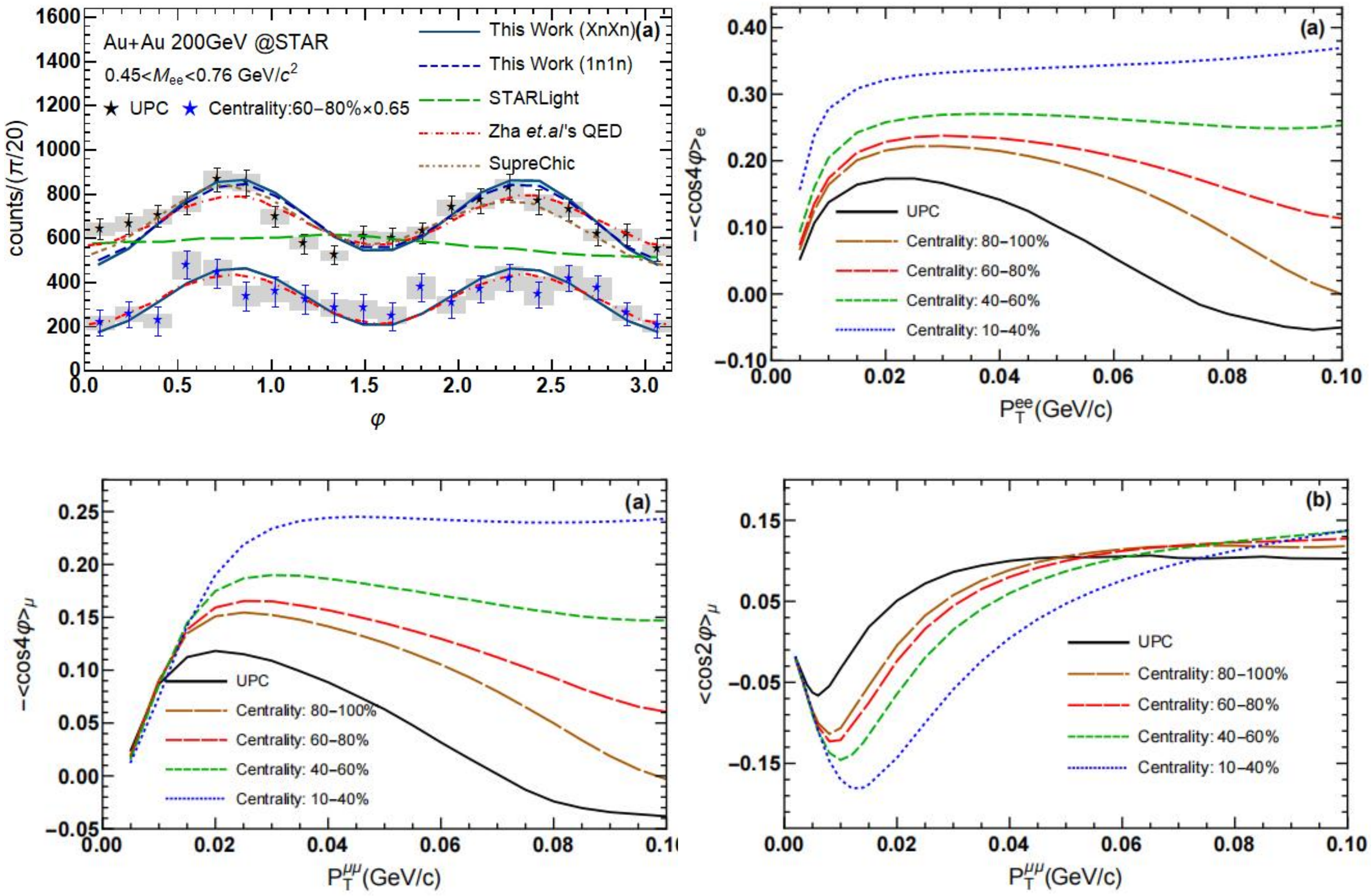
Numerical results（Azimuthal asymmetry)

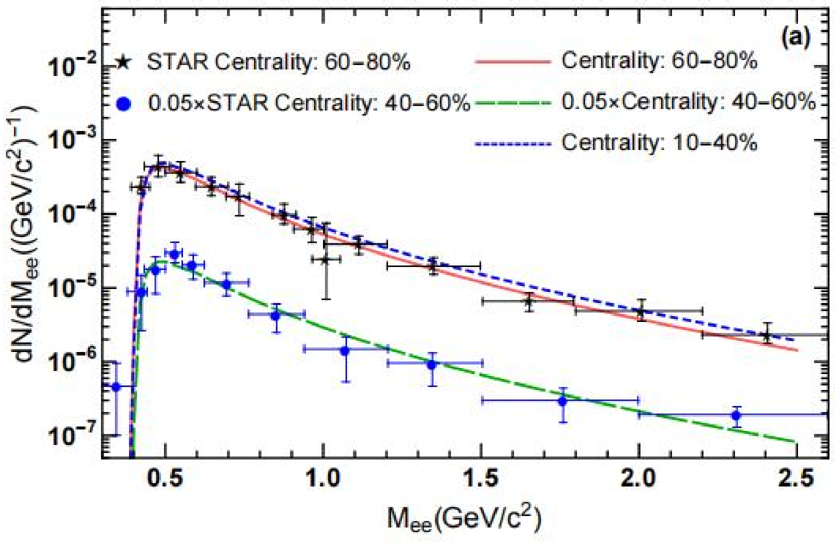


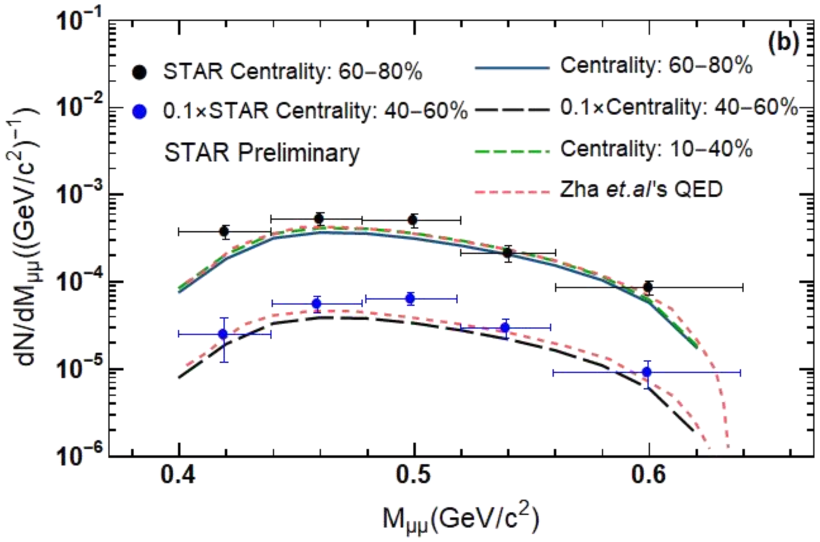
- The linear polarization information of photons is important for understanding the azimuthal asymmetry of the lepton pair.
- The $\cos 2\varphi$ modulations of $\mu^+\mu^-$ are higher than e^+e^- case.

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

RJW, Shuo Lin, Shi Pu, Yifei Zhang, Qun Wang, Received by PRD

Numerical results（Invariant mass distribution)





RJW, Shuo Lin, Shi Pu, Yifei Zhang, Qun Wang, Received by PRD

Summary

- A general form of the lepton pair photoproduction cross section was derived in terms of photon distributions which depend on the transverse momentum and coordinate based on the wave packet form of nuclear wave functions.

- $\gamma\gamma$ processes: test QED under extreme conditions, may provide a baseline for the medium effect in PC.

- The information on the transverse momentum and polarization for photons are essential to describe the experimental data.

- High order corrections need to be considered.

Thanks for your attention!