高能重离子碰撞中的光致双轻子产生

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)

中国科学技术大学核物理研讨会　2024-1-13

概要

➢ 背景介绍

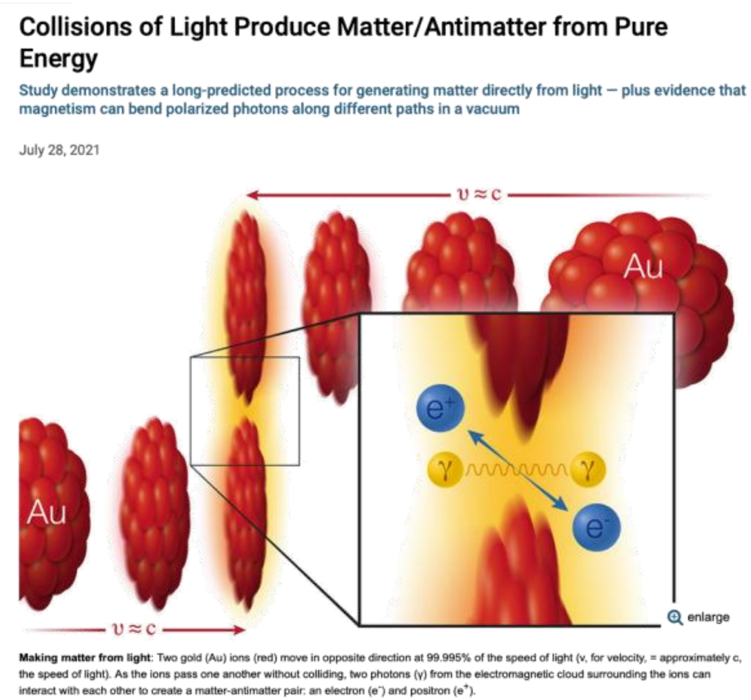
- 光生物质与 Breit-Wheeler 过程
- 等效光子近似 (EPA)
- 光致双轻子产生实验及理论进展

➢ 工作内容

- 基于波包假设的量子电动力学光致双轻子产生框架
- 高能离子碰撞唯象学应用

➢ 总结与展望

光生物质与 Breit-Wheeler 过程

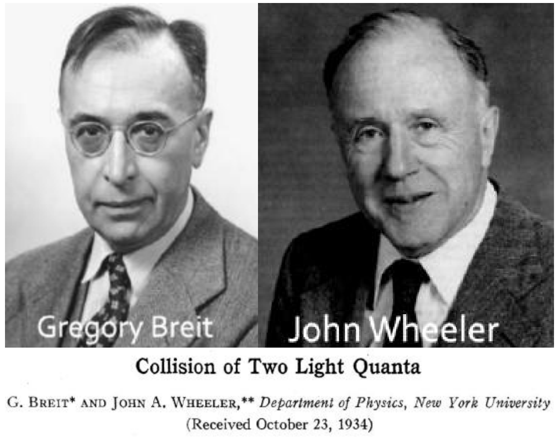


Collisions of Light Produce Matter/Antimatter from Pure Energy

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

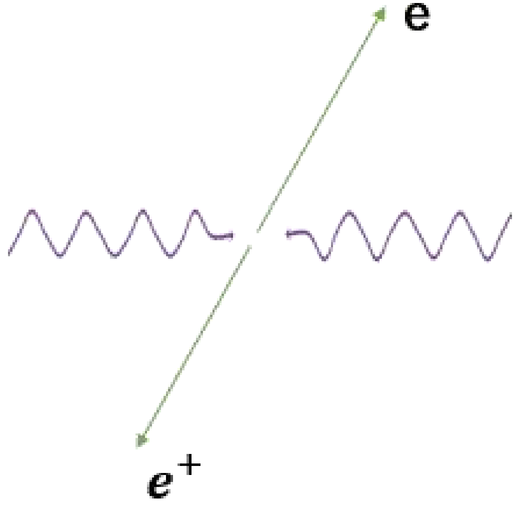
July 28, 2021

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^+).



Collision of Two Light Quanta

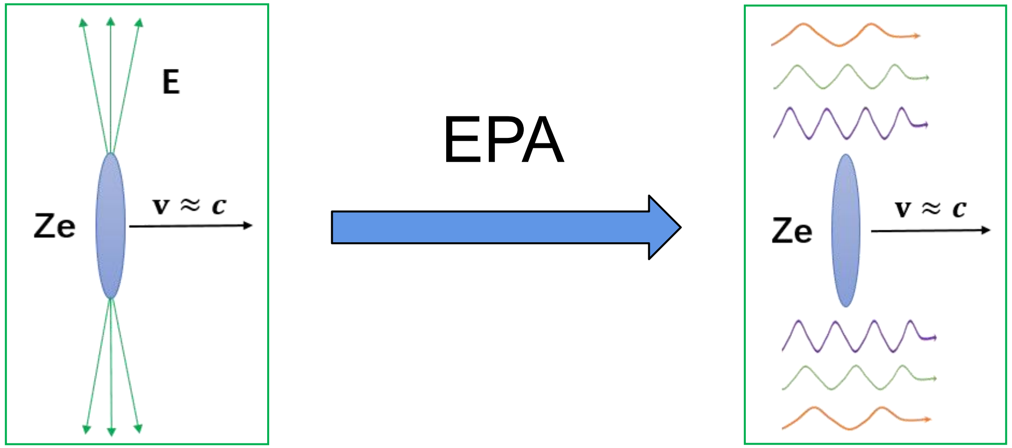
G. Breit* and John A. Wheeler,** *Department of Physics, New York University*
(Received October 23, 1934)



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

- Breit-Wheeler 过程：两个实光子碰撞产生轻子对
- 质心系能量需要大于$2m_e$　(高能量光子!)

等效光子近似 (EPA)



高度洛伦兹收缩的电磁场

线偏振的近实光子流

Weizsacker- Williams,1934

光子流：

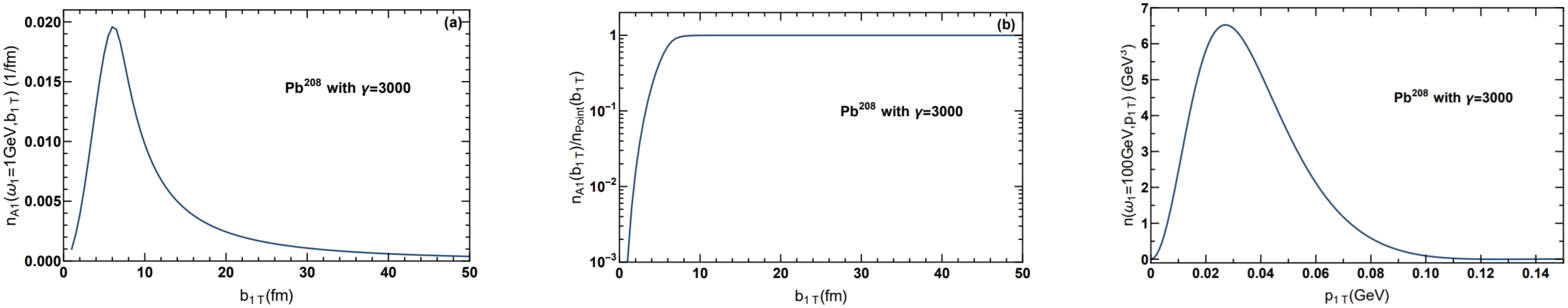
$$n_{A1}(\omega_1, \boldsymbol{b}_{1T}) \cong \frac{1}{\pi\omega_1}|\boldsymbol{E}_T(\omega_1, \boldsymbol{b}_{1T})|^2$$

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

点粒子情况：

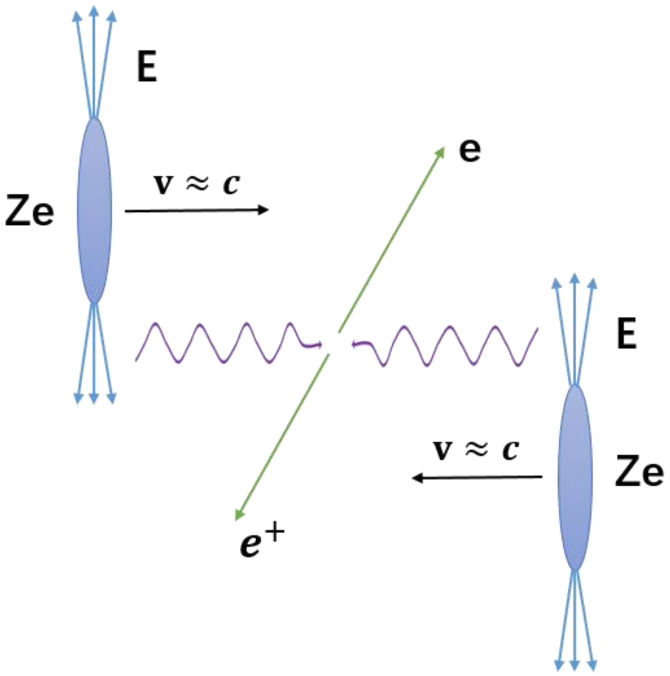
$$n_{A1}(\omega_1, b_{1T}) = \frac{Z^2\alpha}{\pi^2}\frac{\omega_1}{\gamma^2}\left[K_1\left(\frac{\omega_1 b_{1T}}{\gamma}\right)\right]^2,$$

等效光子流



- 光子流在 $b_{1T} \approx R_A$，$p_{1T} \approx 1/R_A$ 处取最大值
- 最大光子能量 $\omega_{1max} \approx \gamma/R_A \gg p_{1T}$
- $-\frac{p_1^2}{\omega_1^2} \sim \mathcal{O}(\gamma^{-2})$ 说明高能情况下等效光子是近实的

超偏心碰撞 (UPC)

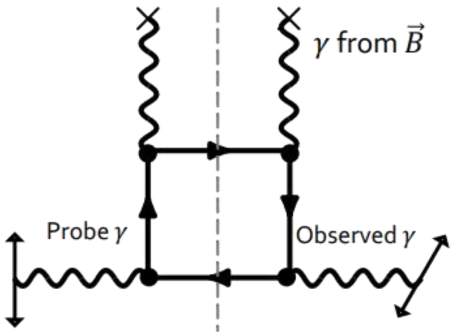


- RHIC 能够提供高能量近实光子流，可视作光子光子或光子原子核对撞机
- UPC $(b > 2R_A)$ 中强过程被压低，为研究极端强电磁场条件下的 QED 提供了平台
- 光致双轻子产生

  G. Breit and J. A. Wheeler 1934
- 光子光子散射

  H. Euler and B. Kockel 1935
- 真空双折射

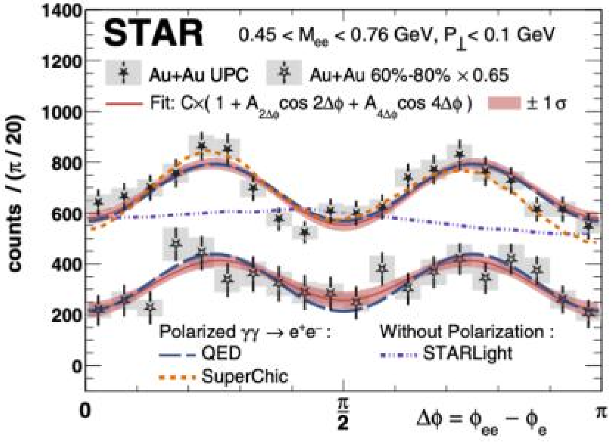
  W. Heisenberg and H. Euler 1936



HIC 中光致双轻子产生的实验观测

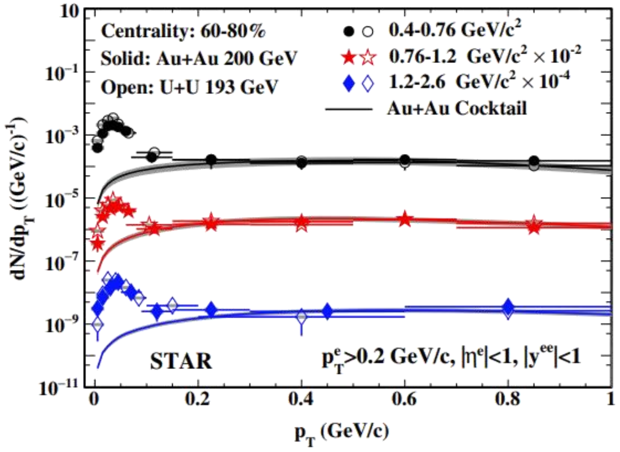
- UPC 中 $\gamma\gamma \rightarrow l^+l^-$ 实验观测

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



- PC $(b_T < 2R_A)$ 中 $\gamma\gamma \rightarrow l^+l^-$ 实验观测

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



HIC 中光致双轻子产生的理论进展

- 等效光子近似 (EPA) (不包含光子横向动量分布及光子极化信息)

  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

- 背景场近似下的 QED 方法及推广的等效光子近似 (gEPA 包含光子横向动量信息)

  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

- 横向动量依赖的部分子分布函数 (TMDPDF) 及 Wigner 函数因子化框架

  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

如何将这些方法联系起来?

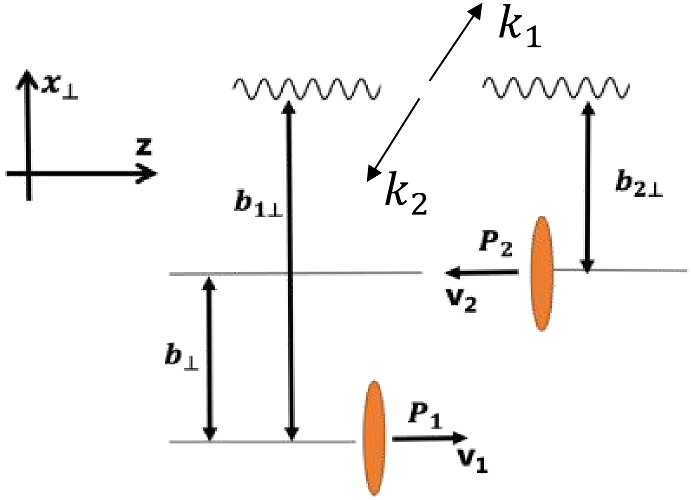
基于波包假设QED光致双轻子产生框架

出发点:

波包形式的原子核初态

$$|A_1A_2\rangle_{\text{in}} = \int \frac{d^3P_1}{(2\pi)^3}\frac{d^3P_2}{(2\pi)^3}\frac{\phi(P_1)\phi(P_2)e^{i\boldsymbol{b}_T\cdot\boldsymbol{P}_1}}{\sqrt{2E_{P1}}\sqrt{2E_{P2}}}|P_1P_2\rangle_{\text{in}}$$

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



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

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

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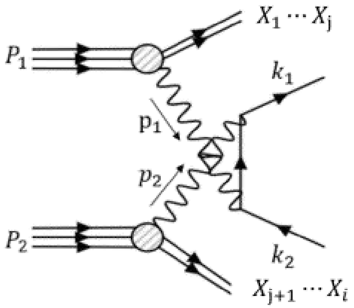
基于波包假设QED光致双轻子产生框架

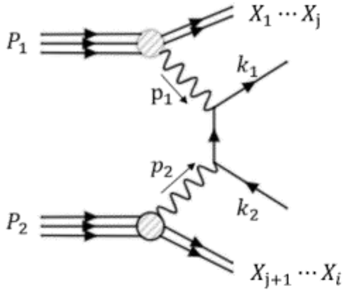
$$\frac{d\sigma}{d^3k_1 d^3k_2} = \frac{1}{32(2\pi)^6}\frac{1}{E_{k1}E_{k2}}\int d^2\boldsymbol{b}_T d^2\boldsymbol{b}_{1T} d^2\boldsymbol{b}_{2T}\int d^4p_1 d^4p_2\, \delta^2(\boldsymbol{b}_T - \boldsymbol{b}_{1T} + \boldsymbol{b}_{2T})(2\pi)^4\delta^4(p_1+p_2-k_1-k_2)$$

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

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



轻子部分



波恩近似下原子核的光子 Wigner 函数:

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

经典场近似

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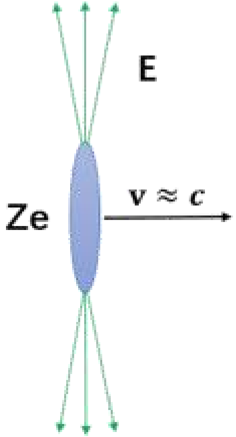
经典场近似

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

Lorentz 规范下快速运动原子核产生的经典电磁矢势:



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

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

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

该截面不仅包含有碰撞参数依赖，也包含了初态光子的动量，横向位置及线偏振等信息。

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极端相对论极限与gEPA

Ward 恒等式:

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

$$\Longrightarrow$$

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

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

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

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

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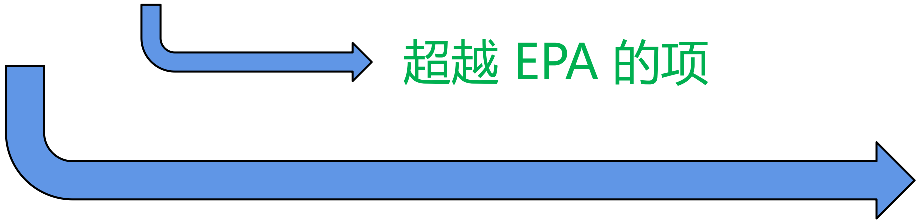
极端相对论极限与gEPA

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



超越 EPA 的项

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

单光子分布函数：

$$n_{A1}(\omega_1, \boldsymbol{p}_{1T}, \boldsymbol{b}_{1T}) = \frac{Z^2\alpha}{\omega_1 \pi^2} \int \frac{d^2\boldsymbol{p}'_{1T}}{(2\pi)^2} \frac{F^*(-p'^2_1)}{-p'^2_1} \frac{F(-p^2_1)}{-p^2_1} |\boldsymbol{p}_{1T}||\boldsymbol{p}'_{1T}| e^{-i\boldsymbol{b}_{1T}\cdot(\boldsymbol{p}'_{1T} - \boldsymbol{p}_{1T})},$$

$$n_{A1}(\omega_1, \boldsymbol{b}_{1T}) = \int \mathrm{d}^2\boldsymbol{p}_{1T}\, n_{A1}(\omega_1, \boldsymbol{p}_{1T}, \boldsymbol{b}_{1T})$$
$$= \frac{4Z^2\alpha}{\omega_1} \left| \int \frac{\mathrm{d}^2\boldsymbol{p}_{1T}}{(2\pi)^2} e^{i\boldsymbol{b}_{1T}\cdot\boldsymbol{p}_{1T}} \boldsymbol{p}_{1T} \frac{F(-p^2_1)}{-p^2_1} \right|^2.$$

极端相对论极限下
可以给出 gEPA

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

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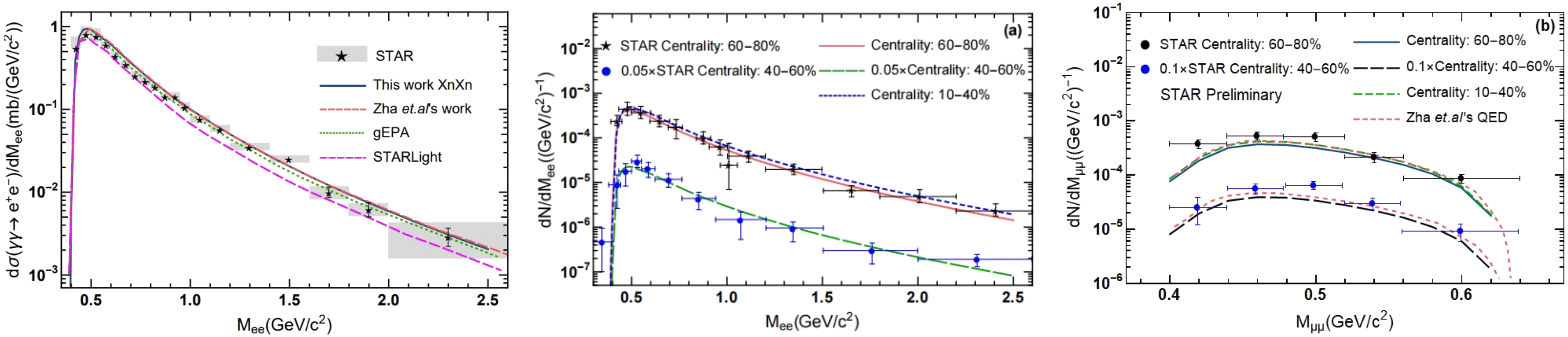
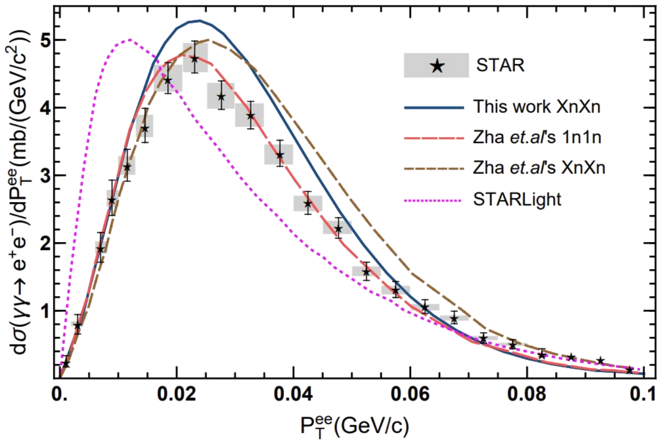
高能重离子碰撞唯象学应用（不变质量谱）

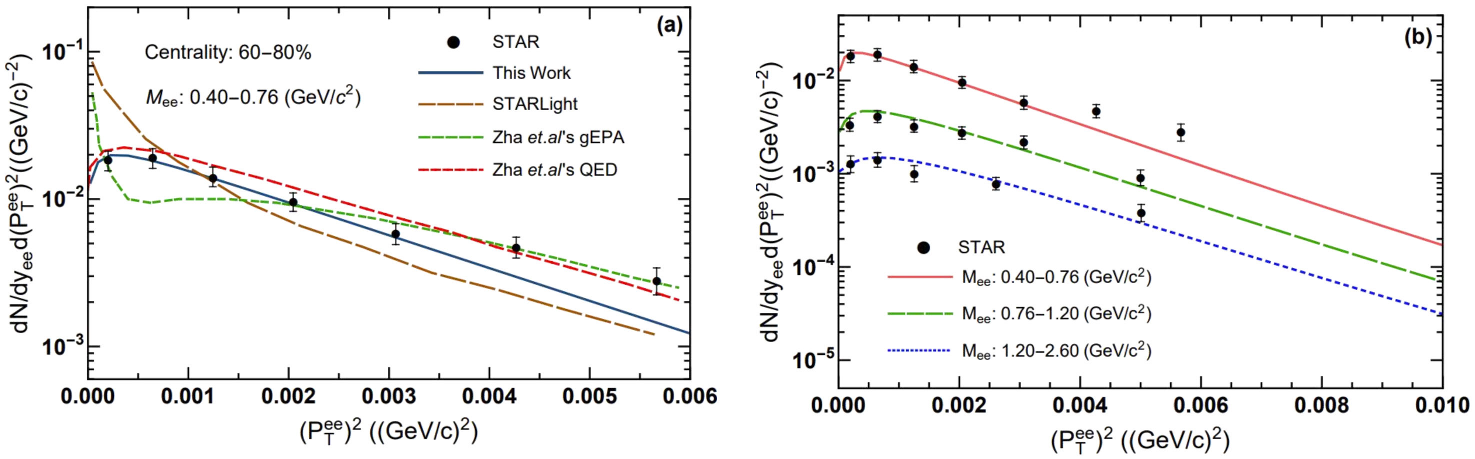


- 不同模型在波恩近似阶计算的光致轻子对不变质量谱均与 STAR 实验数据相符合。
- 光致轻子对不变质量谱比较光滑没有出现矢量介子峰说明 RHIC 中等效光子可近似为实光子。

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

高能重离子碰撞唯象学应用（横动量谱）





UPC: $\sqrt{\langle (P_T^{ee})^2 \rangle} \approx 38$ MeV

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

- 光致轻子对 P_T^{ee} 谱展宽：PC 光致双轻子的 $\sqrt{(P_T^{ee})^2}$ 比 UPC 情况的大。

STAR PRL 121, 132301 (2018)

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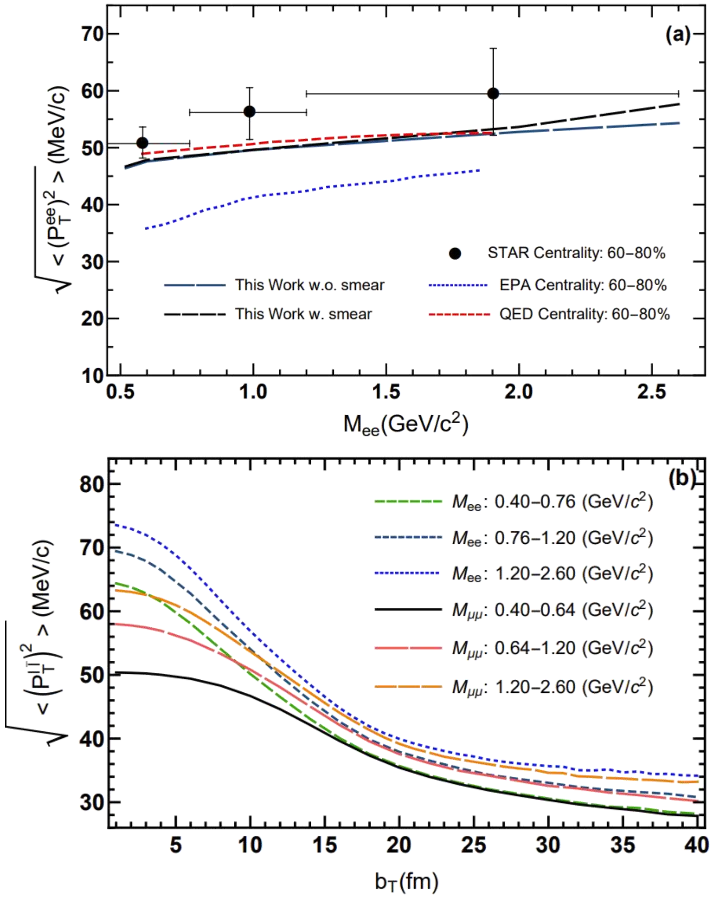
高能重离子碰撞唯象学应用 (横动量谱)



- STARLight (EPA) 模型不能成功描述这种碰撞参数依赖行为。
- 初态光子横动量信息对于理解轻子对横动量谱展宽现象是重要的。
- 需要考虑高阶修正，如 Sudakov 因子，库伦修正等。
- 介质效应: 末态轻子与 PC 中产生介质间的多重散射？磁场对末态轻子的偏转效应？

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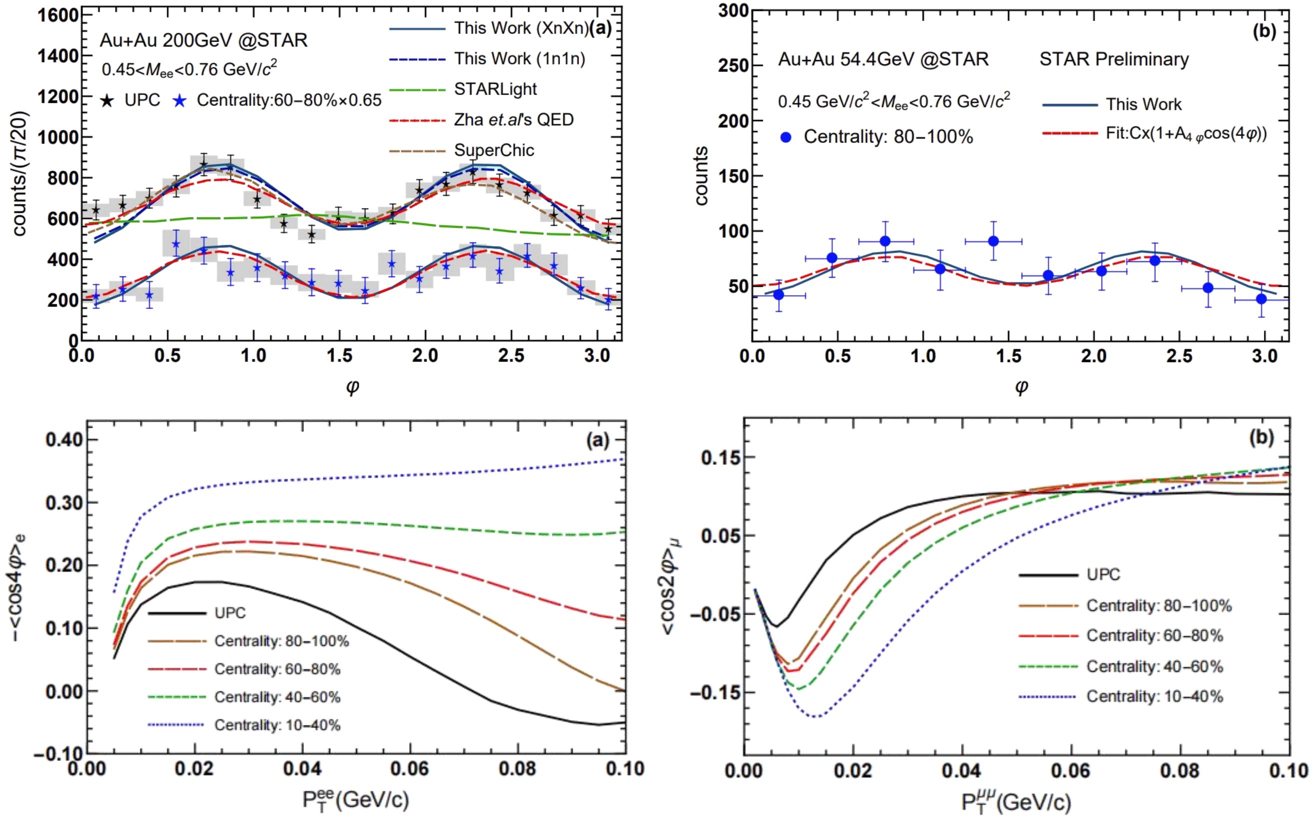
高能重离子碰撞唯象学应用 (辐角分布)

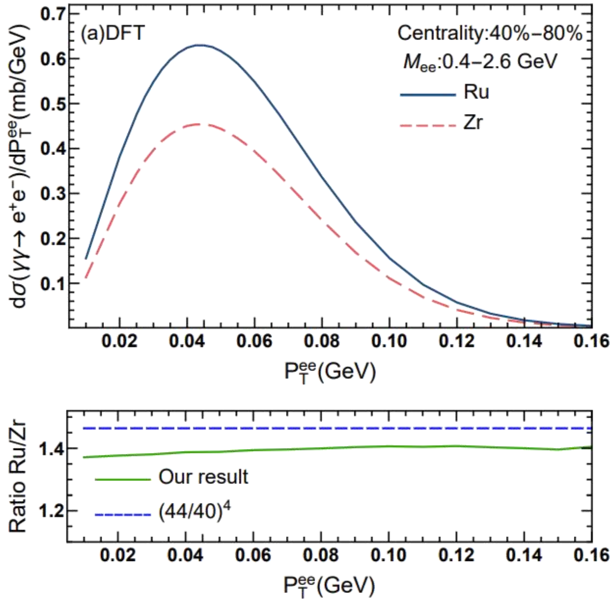


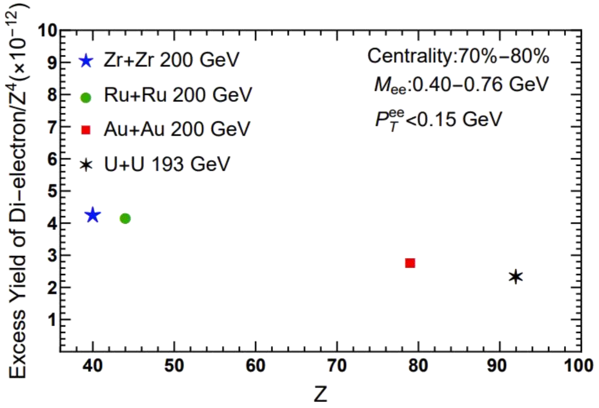
- 初态光子线偏振信息对描述光致轻子对辐角分布是重要的。
- 光致轻子对辐角调制行为被认为与真空双折射现象密切相关。
- 光致缪子对辐角分布中 $\cos(2\varphi)$ 的贡献比电子对的情况有所增强。

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

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

高能重离子碰撞唯象学应用 (不同碰撞核系统)





- 如将原子核视作点电荷，光致双轻子截面正比于 Z^4
- 相同中心度下核电荷分布与质量分布可分别影响电形状因子和碰撞参数来影响光致双轻子截面。

- 为未来同量异位素碰撞及核分布等相关研究提供了帮助。

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

总结与展望

- 相对论重离子碰撞实验为人们提供了研究极强电磁场下量子物质的平台
- QCD 相结构，QGP，反常手征输运，强场 QED，核结构，新物理……

- 基于原子核波包假设推导出了 QED 光致双轻子产生截面。

- 初态光子场横动量、位置和极化等信息，都自洽地包含在光子有效 Wigner 函数中，这些初态光子信息是准确描述实验的关键。

- 同时我们的理论框架也提供了不同理论模型之间的关联。

- 未来，我们将进一步考虑高阶修正，原子核形变等对光致双轻子产生截面带来的影响，也将考虑更多光致产生过程。

Thanks for your attention!