Lepton pair photoproduction in peripheral, ultra-peripheral and isobar heavy-ion collisions

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2023.05.28

UPC Physics 2023, Fudan Uni., 2023.05.26 – 05.28

Ref:

R.J. Wang, SP, Q. Wang, PRD 104 (2021) 5, 056011

R.J. Wang, SP, Y.F. Zhang, Q. Wang, PRD 106 (2022) 3, 034025

L. Shuo, R.J. Wang, J.F. Wang, H.J. Xu, SP, Q. Wang, PRD 107 (2023) 5, 054004

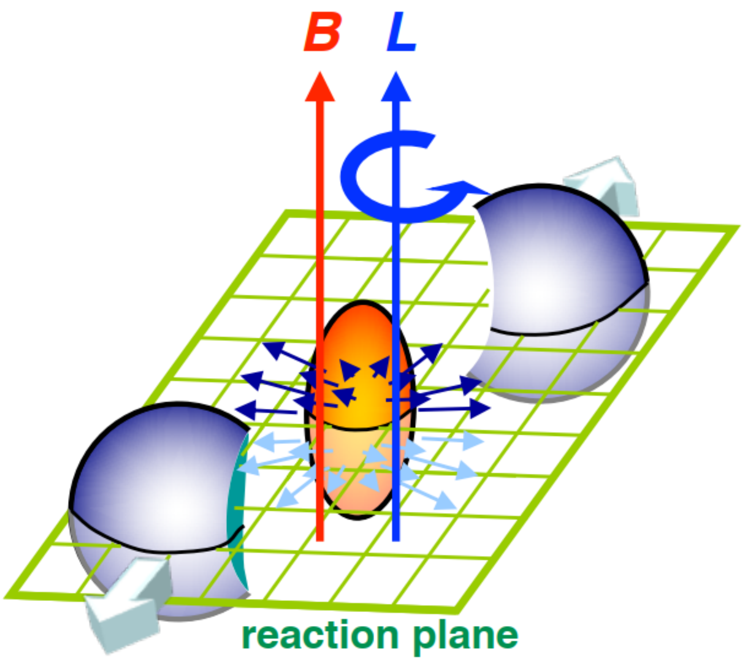
Outline

- **Strong electromagnetic fields and lepton pair photoproduction in heavy ion collisions**
- **QED in classical field approximation with wave packet description of nuclei**
- **Numerical results in peripheral, ultra-peripheral collisions**
- **Lepton pair photoproduction in isobar collisions**

  (Also see Talk by 林硕，2023.05.27，15：00)
- **Summary, discussion and puzzles**

Strong electromagnetic fields and lepton pair photoproduction in heavy ion collisions

Strong EB fields in HIC (I)



- Two charged nuclei moving alone z direction generate the EB fields.

- EB fields can be computed by Lienard-Wiechert potential.

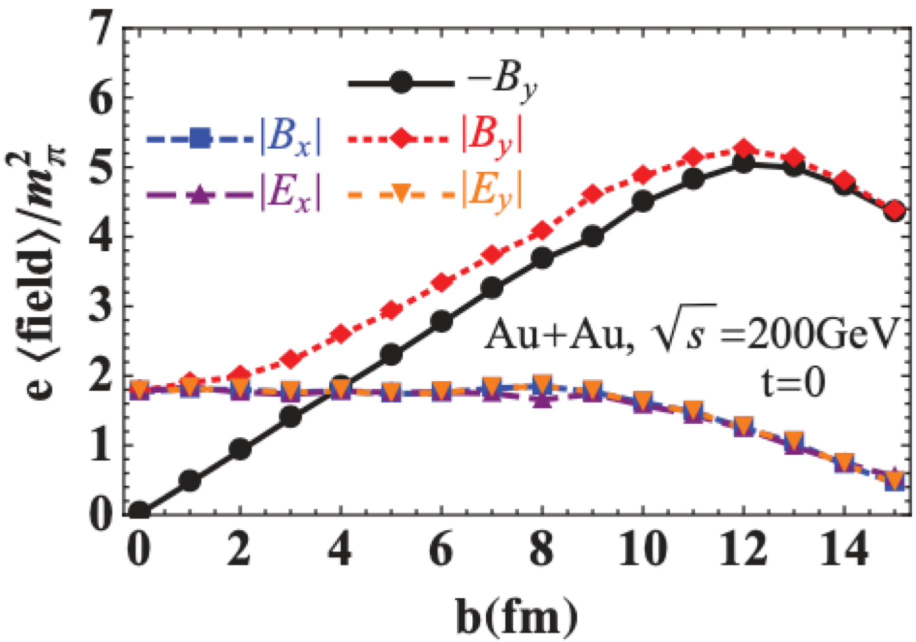
$$\vec{E}(\vec{r},t) = \frac{e}{4\pi} \sum_{i=1}^{N_{\text{proton}}} Z_i \frac{\vec{R}_i - R_i \vec{v}_i}{(R_i - \vec{R}_i \cdot \vec{v}_i)^3} (1 - v_i^2),$$

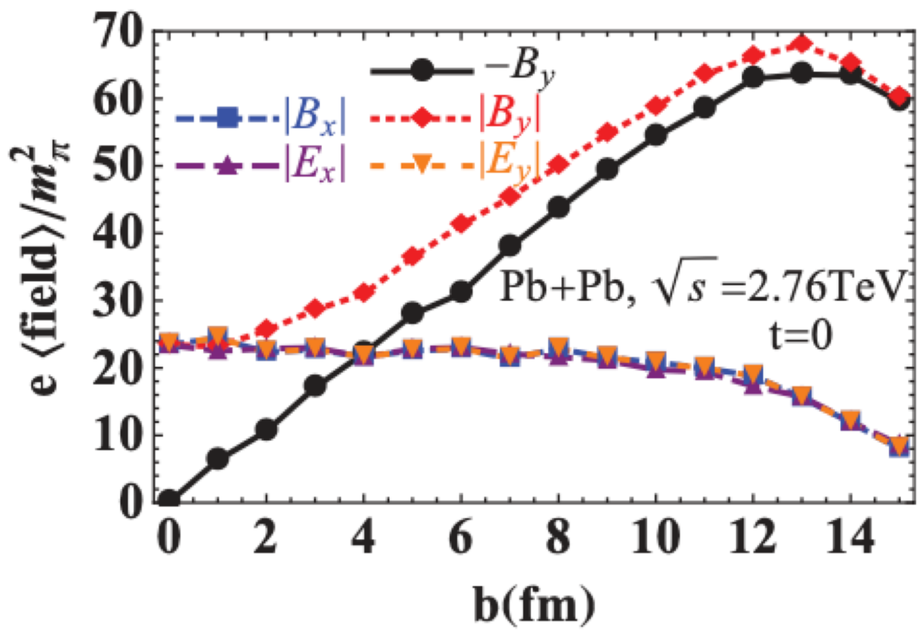
$$\vec{B}(\vec{r},t) = \frac{e}{4\pi} \sum_{i=1}^{N_{\text{proton}}} Z_i \frac{\vec{v}_i \times \vec{R}_i}{(R_i - \vec{R}_i \cdot \vec{v}_i)^3} (1 - v_i^2),$$

Strong EB fields in HIC (II)

- **Theoretical estimation:**

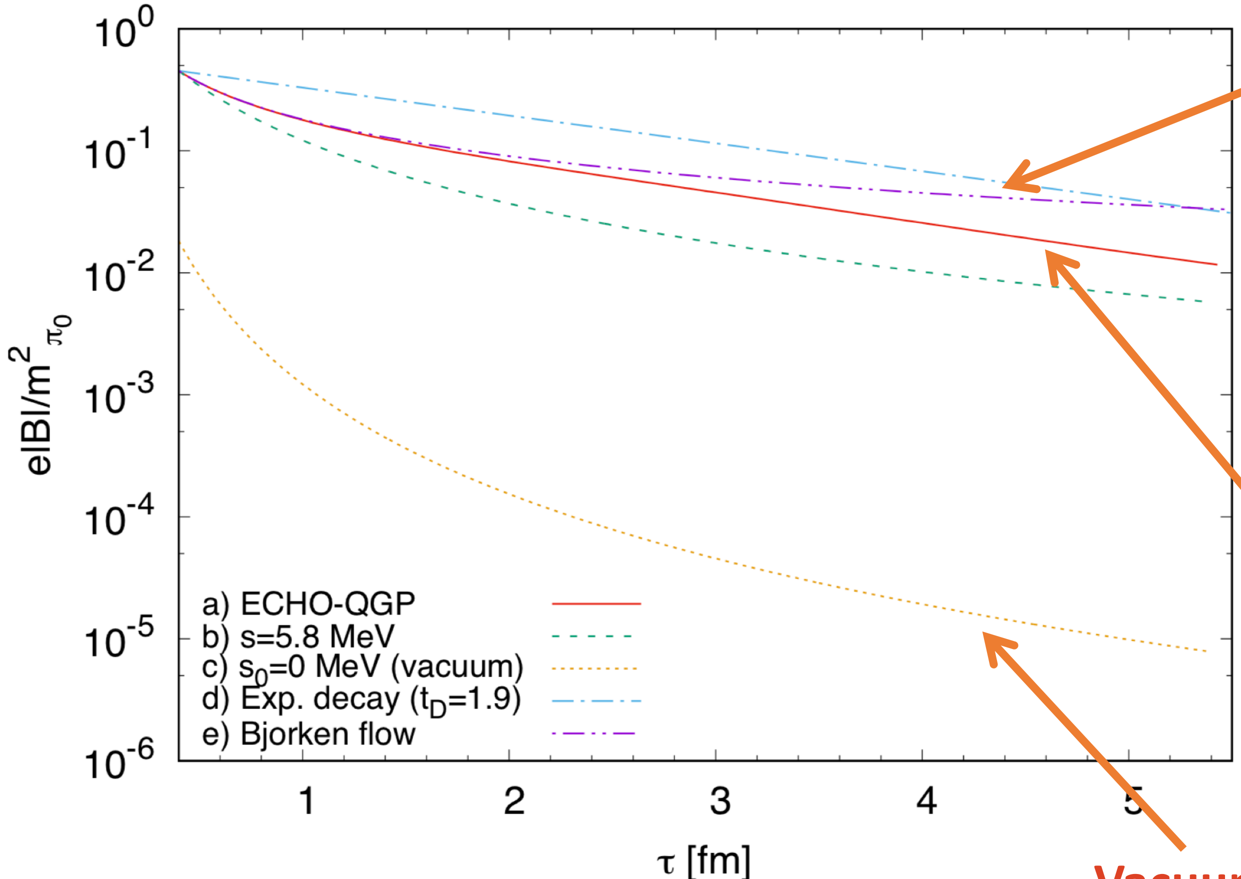
Lienard-Wiechert potential + Event-by-event





A. Bzdak, V. Skokov PRC 2012 ;W.T. Deng, X.G. Huang PRC 2012;V.Roy, SP, PRC 2015; H. Li, X.l. Sheng, Q.Wang, 2016; etc. / review: K. Tuchin 2013

Evolution of EB fields



Ideal Bjorken MHD

SP, V. Roy, L. Rezzolla, D.H. Rischke, PRD(2015)

MHD + CME + Chiral anomaly

Siddique, Wang, SP, Wang, PRD (2019)

ECHO-QGP

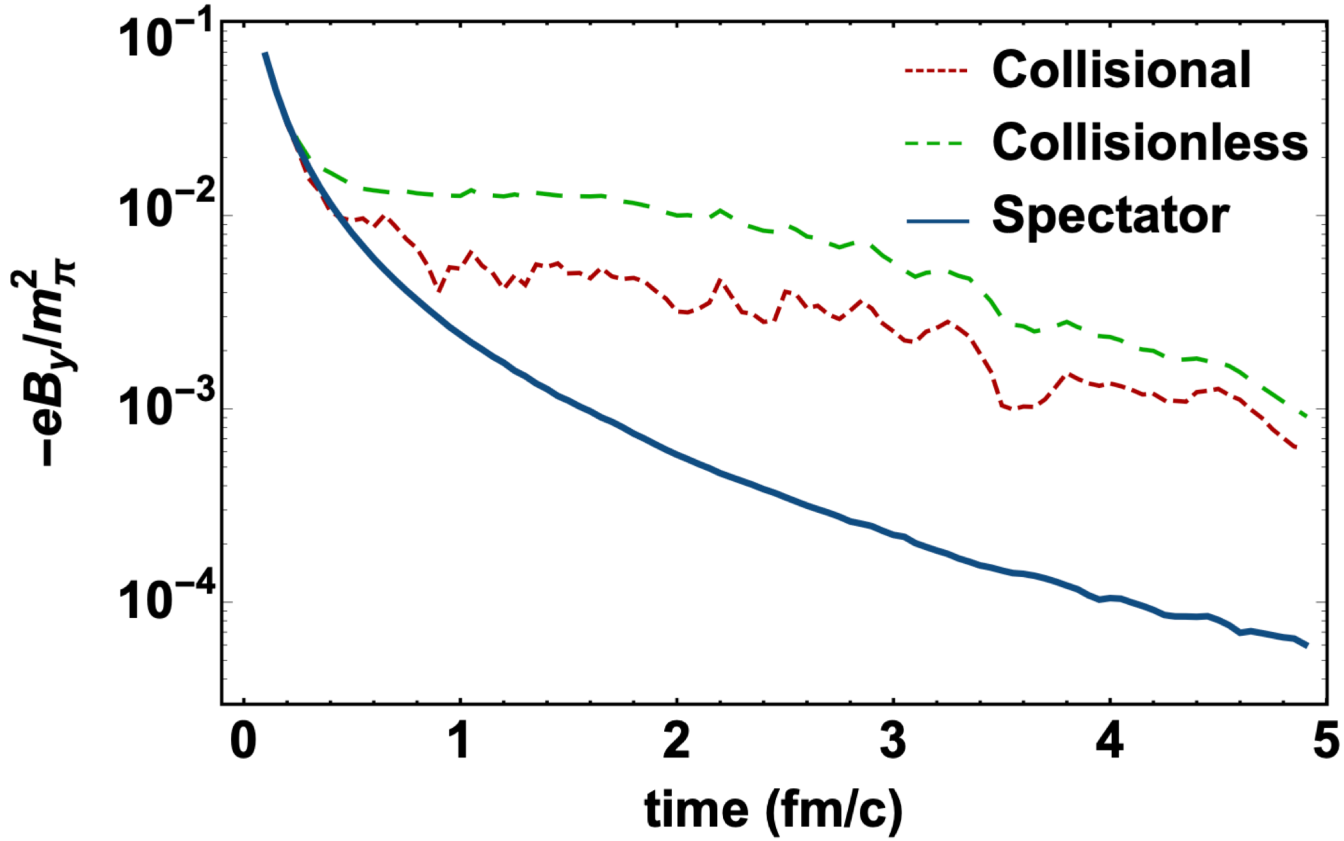
Inghirami, Zanna, Moghaddam, Becattini, Bleicher, EPJC(2016)

Vacuum

Kharzeev, McLerran, Warringa, NPA(2008)

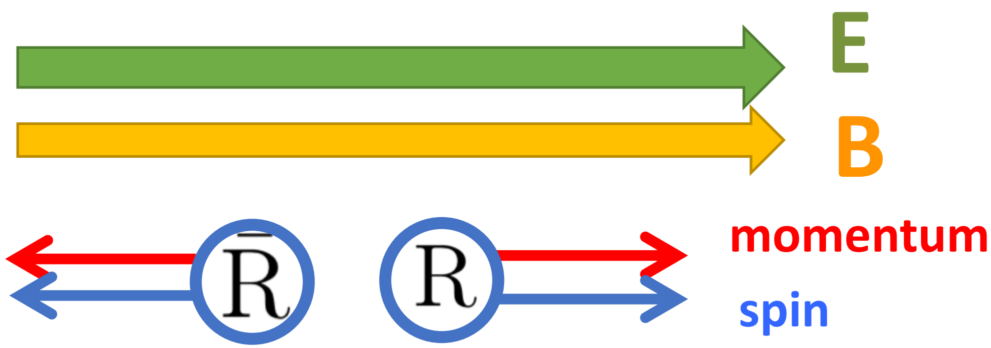
Evolution of EB from Maxwell-Boltzmann Eqs.

Relativistic kinetic theory with leading-log order 2->2 QCD + Maxwell's equations



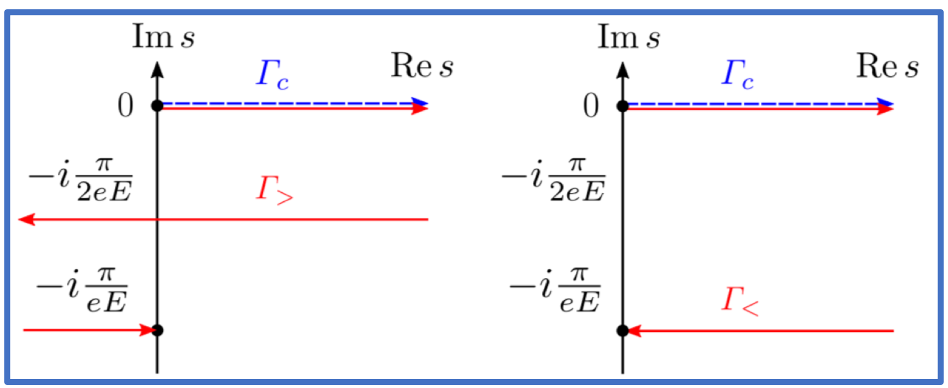
J.J Zhang, X.L. Sheng, SP , J.N. Chen, G.L. Peng, J.G. Wang, Q. Wang, Phys.Rev.Res. 4 (2022) 3, 033138

Connection to the Schwinger pair production



$$\frac{1}{2}\partial_t n_5 = \text{Schwinger Pair Production rate}$$

Fukushima, Kharzeev, Warringa, PRL(2010)



- We rediscover a **non-perturbative** method to compute **real-time** dynamical quantities in strong EB fields.
  - ➢Axial Ward identity, correct mass correction!

$$\partial_\mu j_5^\mu = \frac{e^2 EB}{2\pi^2} \exp\left(-\frac{\pi m^2}{eE}\right)$$

  - ➢Mass correction to CME

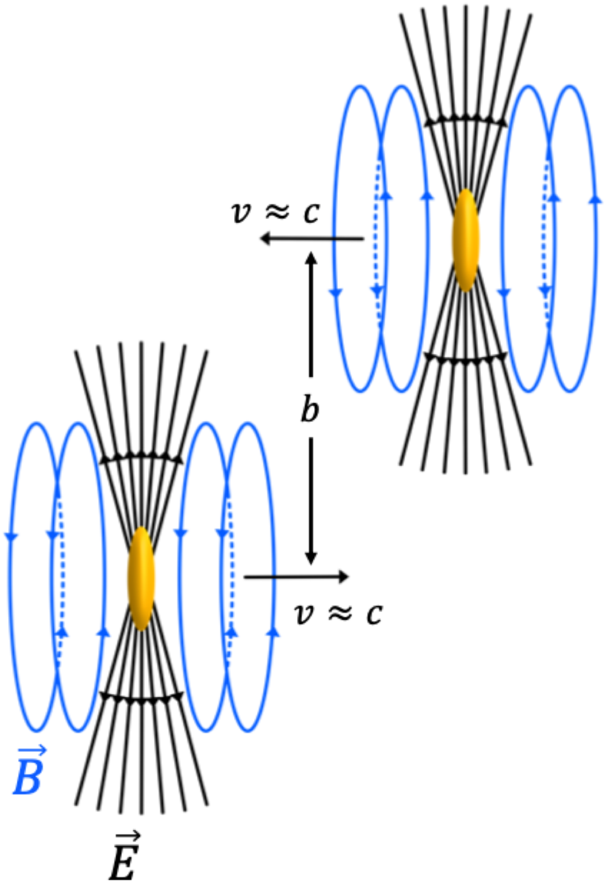
$$j^3 = \frac{e^2 EB}{2\pi^2} \coth\left(\frac{B}{E}\pi\right) \exp\left(-\frac{\pi m^2}{eE}\right) t$$

  - ➢Dynamical chiral condensate

Copinger, Fukushima, SP, PRL(2018)

Also see recent review: Copinger, SP, IJMPA (2020)

Ultra-Peripheral Collisions



- Ultra-Peripheral Collisions (UPC): the impact parameter is larger than 2 times the radius of a nucleus
- Since the QCD effects are higher orders and QED effects are enhanced by the Ze, UPC provides a nice platform to study the strong EB effects.

  $Z\alpha \approx 1$ → High photon density

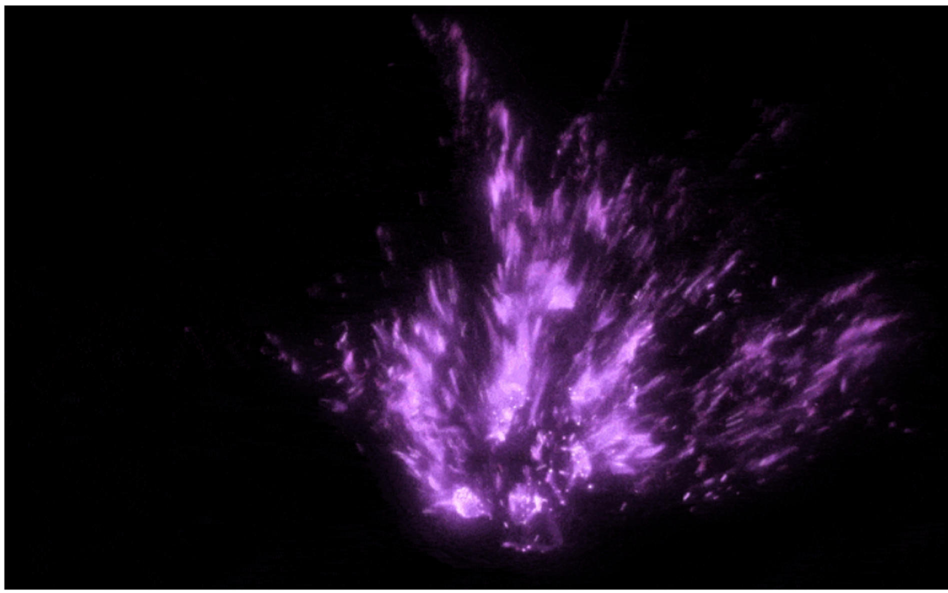
  Magnetic field strength B ≈ $10^{12} - 10^{14}$ T
- Because the relativity, the photon (EB fields) are almost real.
- Photon-photon, photon-nuclear interactions

Generation matter directly from lights

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

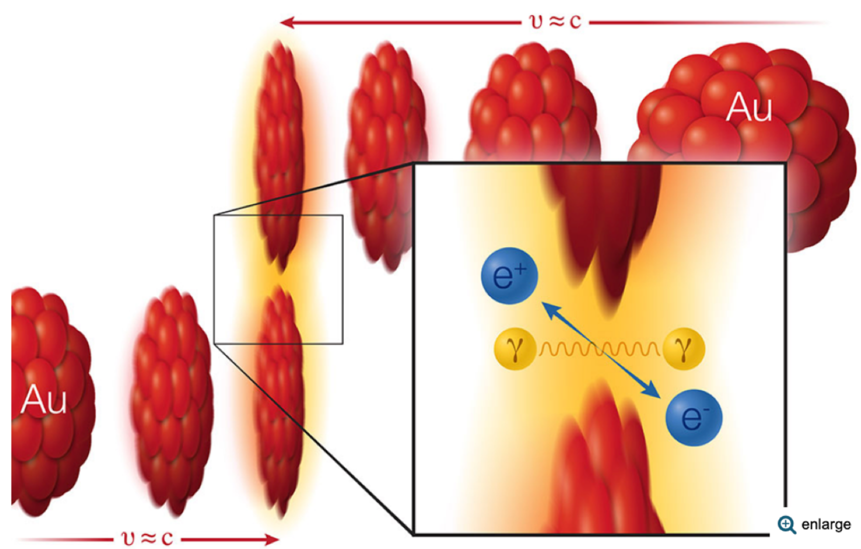


Abstract energy concept illustration.

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

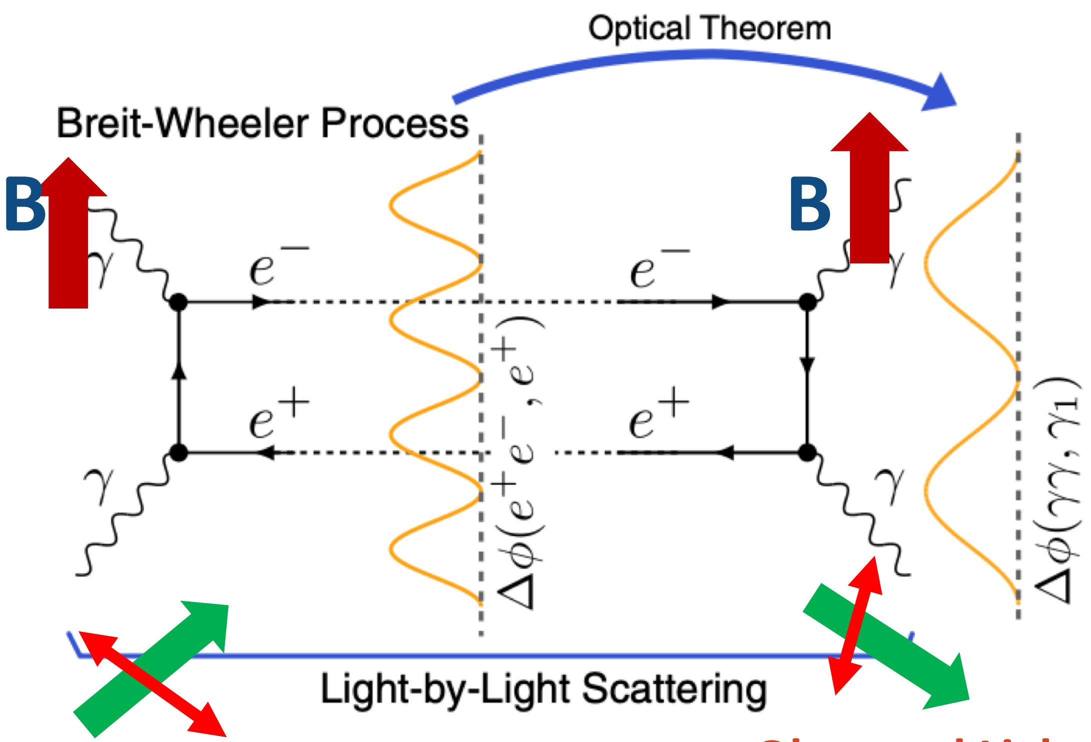


Making matter from light: Two gold (Au) ions (red) move in opposite direction at 99.995% of the speed of light (v, for velocity, = approximately c, the speed of light). As the ions pass one another without colliding, two photons (γ) from the electromagnetic cloud surrounding the ions can interact with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

J. Adam *et al*. (STAR Collaboration), Measurement of e+e− Momentum and Angular Distributions from Linearly Polarized Photon Collisions, *Phys. Rev. Lett* 127, 052302

Vacuum birefringence

- **Vacuum birefringence: Index of refraction for photon interaction with B field depends on relative polarization angle**



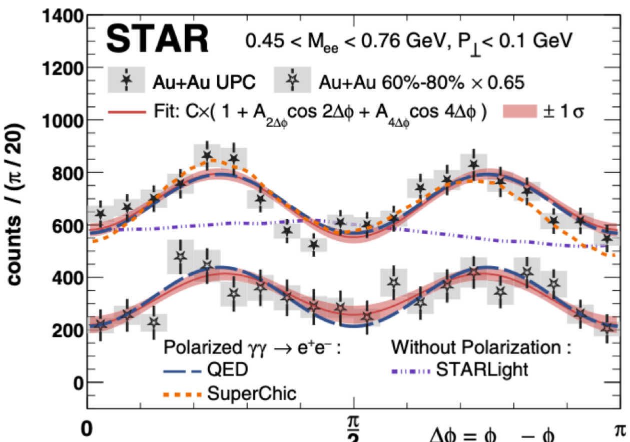
Linear Polarized Probe Light

Observed Light polarization direction is modified

- **The difference of linear polarization between probe and observed lights leads to $\sim \cos(n\phi)$ type correction to differential cross section.**

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

Li, Zhou, Zhou, PLB 795, 576 (2019)

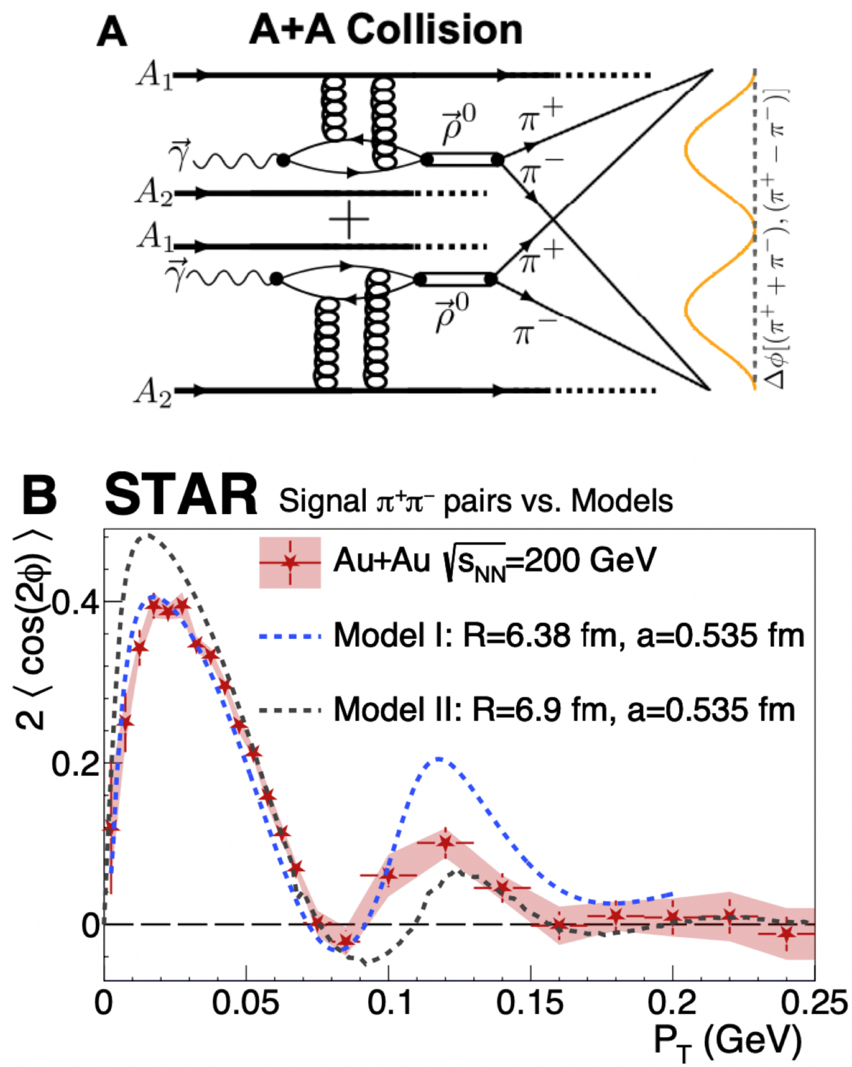


STAR, PRL 127, 052302

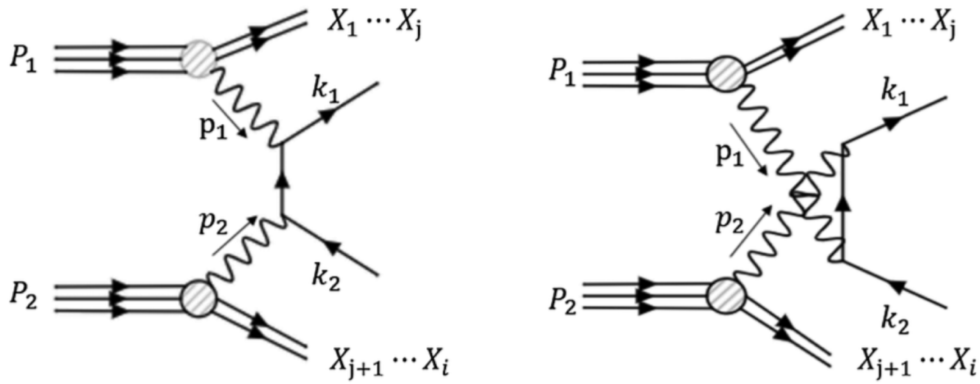
Strong QED fields studies: Hattori, Itakura, Annals.Phys. (2013)

Polarization dependent vector meson production

- **Azimuthal asymmetries $\cos(2\phi)$ in diffractive vector meson production in UPC**
- $\rho^0 \to \pi^+\pi^-$
  - ➢ **STAR: Sci. Adv. 9 (2023) 1, eabq3903**
  - ➢ **Theory:**
    - ○ **Model I: Zha, Brandenburg, Ruan, Tang, Xu, PRD 2021**
    - ○ **Model II: Xing, Zhang, Zhou, Zhou, JHEP 2020**
  - ➢ **For $\cos(\phi)$ and $\cos(3\phi)$ related to ρ^0, see Hagiwara, Zhang, Zhou, Zhou, PRD 2021**
- **Also see studies for J/ψ : Brandenburg, Xu, Zha, Zhang, Zhou, Zhou, PRD 2022**



Dilepton photoproduction



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)
- W. Zha, J. D. Brandenburg, Z. Tang and Z. Xu, PLB 800 (2020) 135089

Based on QED calculations

- **Transverse momentum dependent (TMD) formulism**
  - C. Li, J. Zhou and Y. J. Zhou, Phys. Lett. B 795, 576 (2019) ; arXiv:1911.00237 [hep-ph]].
  - Klein, Muller, Xiao, Yuan, PRL 122 (2019) 13, 132301; PRD 102 (2020) 9, 094013
  - Xiao, Yuan, Zhou, PRL 125 (2020) 23, 232301
- **QED in classical field approximation**
  - Vidovic, Greiner, Best, Soff, PRC (1993)
  - W. Zha, J. D. Brandenburg, Z. Tang and Z. Xu, PLB 800 (2020) 135089
- R.J. Wang, SP, Q. Wang, PRD (2021)

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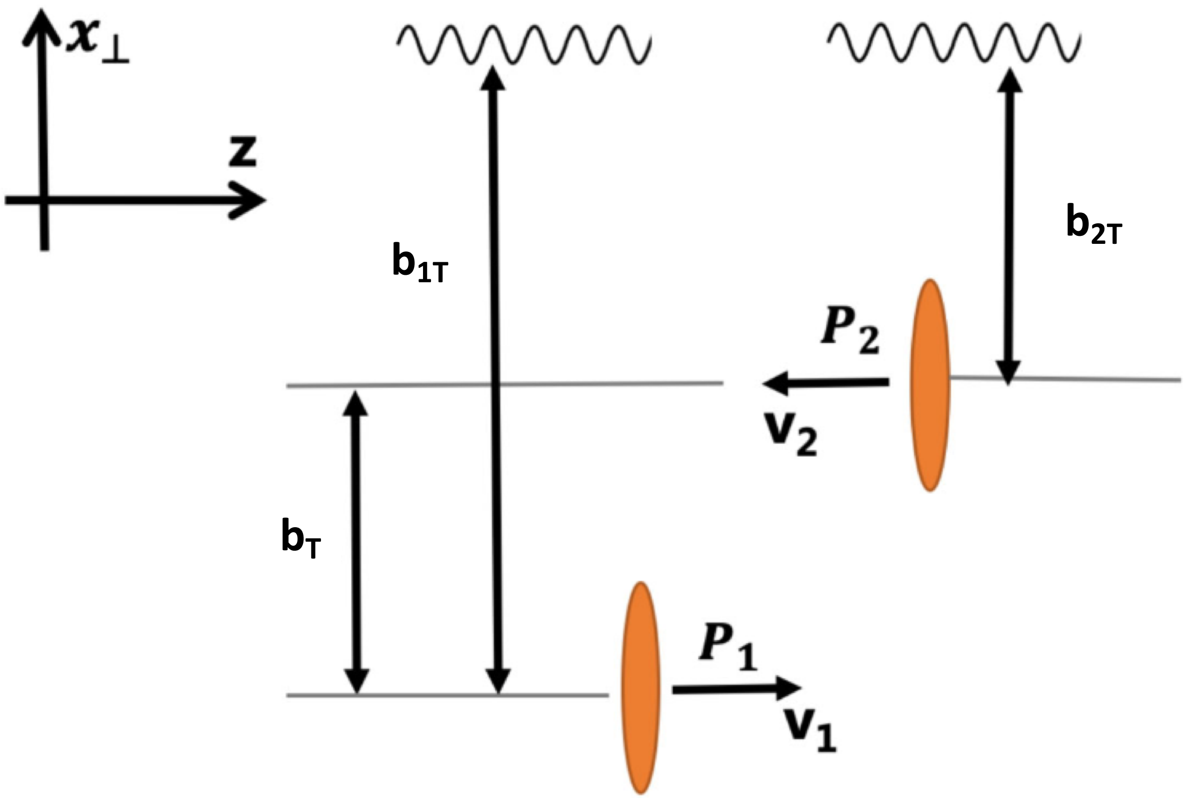
QED in classical field approximation with wave packet description of nuclei

Our theoretical framework

- How to consider the space and momentum dependence for photons?

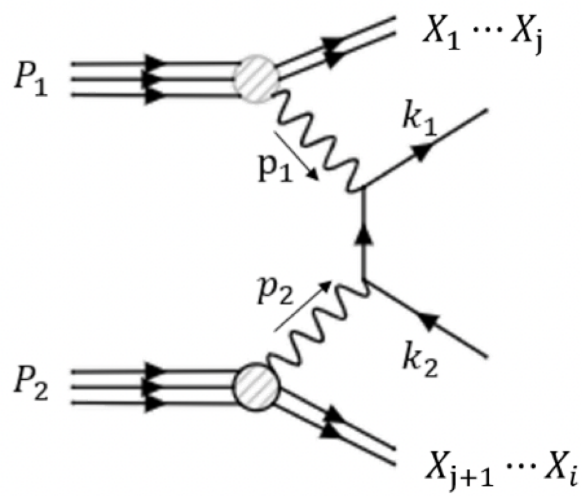


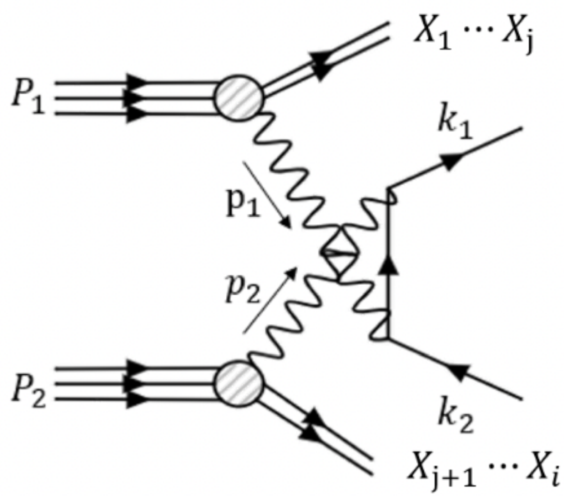
- Three related impact parameters: b_T, b_{1T}, b_{2T}

Wave packet description of nuclei

- We start from the wave- packet description of nuclei.

$$A_1(P_{A1}) + A_2(P_{A2}) \to l(k_1) + \bar{l}(k_2) + \sum_f X_f(K_f),$$





$$|A_1\rangle = \int \frac{d^3 P_1}{(2\pi)^3\sqrt{2E_{P1}}} \phi(P_1) e^{ib\cdot P_1} |P_1\rangle ,$$

$$|A_2\rangle = \int \frac{d^3 P_2}{(2\pi)^3\sqrt{2E_{P2}}} \phi(P_2) |P_2\rangle ,$$

Initial state: wave packet

$$\left| l, \bar{l}, \sum_f X_f \right\rangle \equiv \left| k_1, k_2, \sum_f K_f \right\rangle_{\text{out}} ,$$

Final state

See Appendix A in R.J. Wang, SP, Q. Wang, PRD 2021

Introducing another two impact parameters

- By definition, the cross section is given by

$$\sigma = \int d^2\mathbf{b}_T \sum_{\{f\}} \int \frac{d^3k_1}{(2\pi)^3 2E_{k_1}} \frac{d^3k_2}{(2\pi)^3 2E_{k_2}} \prod_f \frac{d^3K_f}{(2\pi)^3 2E_f} \times \left| {}_{\text{out}}\langle k_1, k_2, \sum_f K_f \,|A_1 A_2\rangle_{\text{in}} \right|^2$$

- Inserting the expressions of wave packet, we must have the energy momentum conservation in a delta function,

$$\delta^{(2)}\left(\mathbf{P}_{1T} + \mathbf{P}_{2T} - \mathbf{P}'_{1T} - \mathbf{P}'_{2T}\right) = \int \frac{d^2\mathbf{b}_{2T}}{(2\pi)^2} \exp\left[i\mathbf{b}_{2T} \cdot \left(\mathbf{P}_{1T} + \mathbf{P}_{2T} - \mathbf{P}'_{1T} - \mathbf{P}'_{2T}\right)\right],$$

- Considering the geometry, we can use the following identity to introduce another impact parameter,

$$\int d^2\mathbf{b}_{1T}\, \delta^{(2)}\left(\mathbf{b}_T - \mathbf{b}_{1T} + \mathbf{b}_{2T}\right) = 1,$$

See Appendix A in R.J. Wang, SP, Q. Wang, PRD 2021

Differential cross section

- **Our general expression for differential cross section is as follows.**

R.J. Wang, SP, Q. Wang, PRD 2021

$$\frac{d\sigma}{d^3k_1 d^3k_2} \approx \frac{1}{32(2\pi)^6}\frac{1}{E_{k1}E_{k2}}\int d^2\mathbf{b}_T d^2\mathbf{b}_{1T} d^2\mathbf{b}_{2T}\int d^4p_1 d^4p_2$$
$$\times\delta^{(2)}\left(\mathbf{b}_T-\mathbf{b}_{1T}+\mathbf{b}_{2T}\right)(2\pi)^4\delta^{(4)}\left(p_1+p_2-k_1-k_2\right)$$
$$\times\int\frac{d^2\mathbf{P}_{(1+1')T}}{(2\pi)^2}\frac{d^2\mathbf{P}_{(2+2')T}}{(2\pi)^2}\frac{1}{v\sqrt{E_{P1}E_{P2}E_{P1'}E_{P2'}}}$$
$$\times G^2\left[(P_1'^z-P_{A1}^z)^2\right]\phi_T(\mathbf{P}_{1T})\phi_T(\mathbf{P}_{2T})\phi_T^*(\mathbf{P}'_{1T})\phi_T^*(\mathbf{P}'_{2T})$$
$$\times S_{\sigma\mu}(p_1,\mathbf{b}_{1T})S_{\rho\nu}(p_2,\mathbf{b}_{2T})$$
$$\times L^{\mu\nu;\sigma\rho}\left(p_1,p_2;p_1-P_1+P_1',p_2-P_2+P_2';k_1,k_2\right),$$

Fluctuations from wave package: we neglect this part contributions so far.

Photon Wigner function: provides information of space and momentum for photons

Lepton tensor: Can be computed by perturbative theories

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

Transverse Momentum Dependent (TMD) Photon Distribution

Klein, Muller, Xiao, Yuan, PRL (2019)

Connection to other theories

- If we consider A as background fields and take the virtuality expansion, we can reproduce the equivalent photon approximation (EPA) at LO.

$$\sigma_0(A_1A_2 \to l\bar{l}) = \int d\omega_1 d\omega_2 n_{A1}(\omega_1) n_{A2}(\omega_2) \sigma_{\gamma\gamma\to l\bar{l}}(\omega_1, \omega_2),$$

- If we integrate over the space dependence of photon Wigner function, we will reduce to the formulism introduced by Greiner etc. [Vidovic, Greiner, Best, Soff, PRC (1993)] and used by W. Zha, D. Brandenburg, Z.B. Tang, X.B. Xu's group.

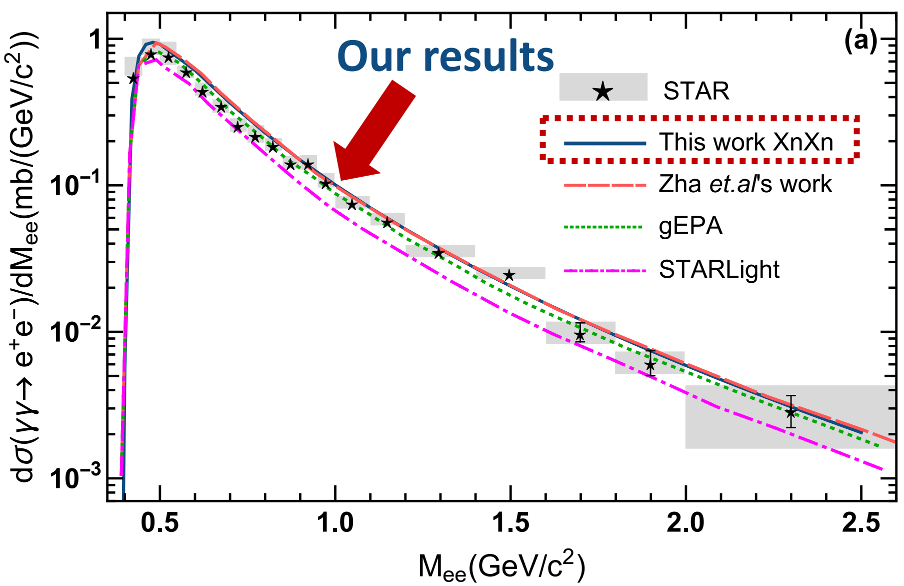
- If we use the light-cone coordinates and take a twist expansion, then we can reproduce the formulism from transverse momentum dependent (TMD) parton distribution function (PDF) community (J. Zhou's and B.W. Xiao's group).

$$\frac{d\sigma_{\text{twist}\,2}}{d^3k_1 d^3k_2} = \frac{1}{2(2\pi)^{10}} Z^4\alpha^2 v \int d\omega_1 d^2\mathbf{p}_{1T} d\omega_2 d^2\mathbf{p}_{2T} \frac{1}{E_{k1}E_{k2}} \frac{p^\sigma_{1T} p^\mu_{1T} p^\rho_{2T} p^\nu_{2T}}{\omega_1^2\omega_2^2} \left|\frac{F(-p_1^2)}{-p_1^2}\right|^2 \left|\frac{F(-p_2^2)}{-p_2^2}\right|^2 \times L_{\mu\nu;\sigma\rho}(p_1, p_2; p_1, p_2; k_1, k_2)(2\pi)^4\delta^4(p_1 + p_2 - k_1 - k_2).$$

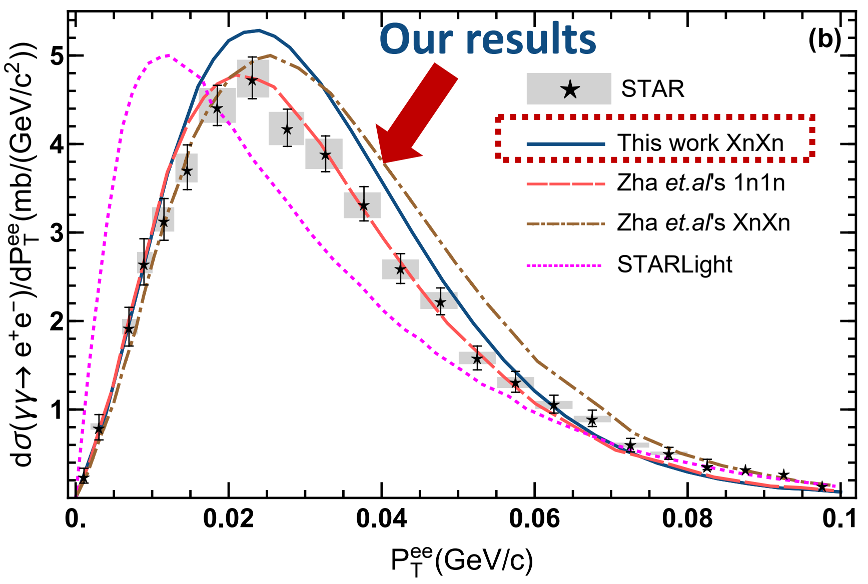
$$\sigma_{\text{twist}\,n} = \frac{Z^4\alpha^2 v}{8\pi^4} \int \frac{d^3k_1}{(2\pi)^3 2E_{k1}} \frac{d^3k_2}{(2\pi)^3 2E_{k2}} \frac{d\omega_1}{\omega_1^2} \frac{d\omega_2}{\omega_2^2} d^2p_{1T} d^2p_{2T} \left|\frac{F(-p_1^2)}{-p_1^2}\right|^2 \left|\frac{F(-p_2^2)}{-p_2^2}\right|^2 (2\pi)^4\delta^4(p_1 + p_2 - k_1 - k_2)\mathcal{I},$$

Numerical results in peripheral, ultra-peripheral collisions

Differential cross section in UPCs



Invariant mass of dilepton



Total transverse momentum of dilepton

- Our results for UPC agree with experimental data.
- Differences between our results and data may come from the higher order corrections.

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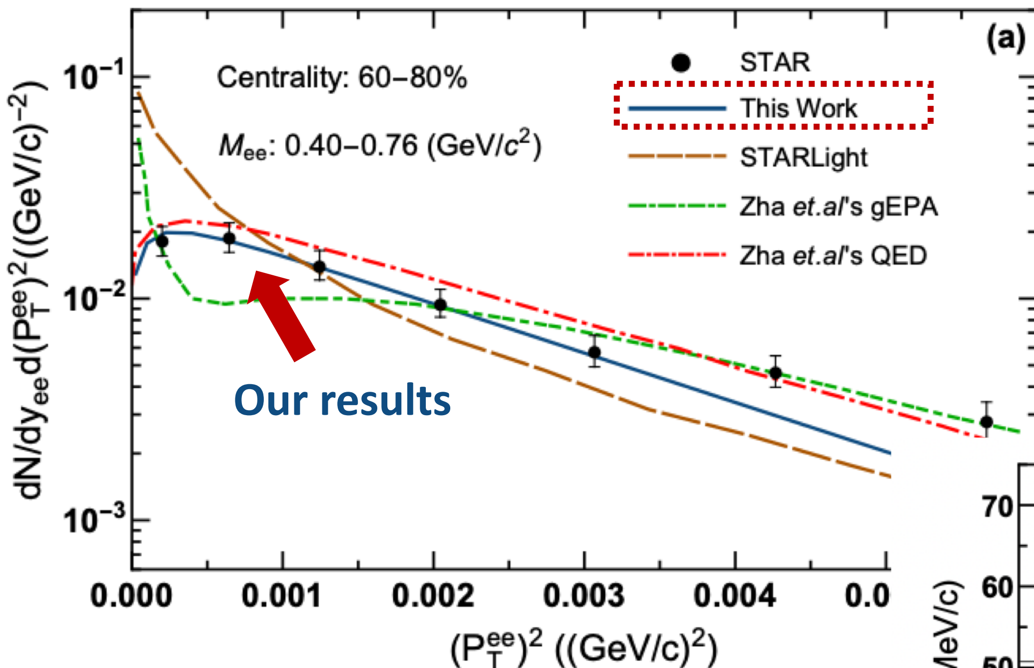
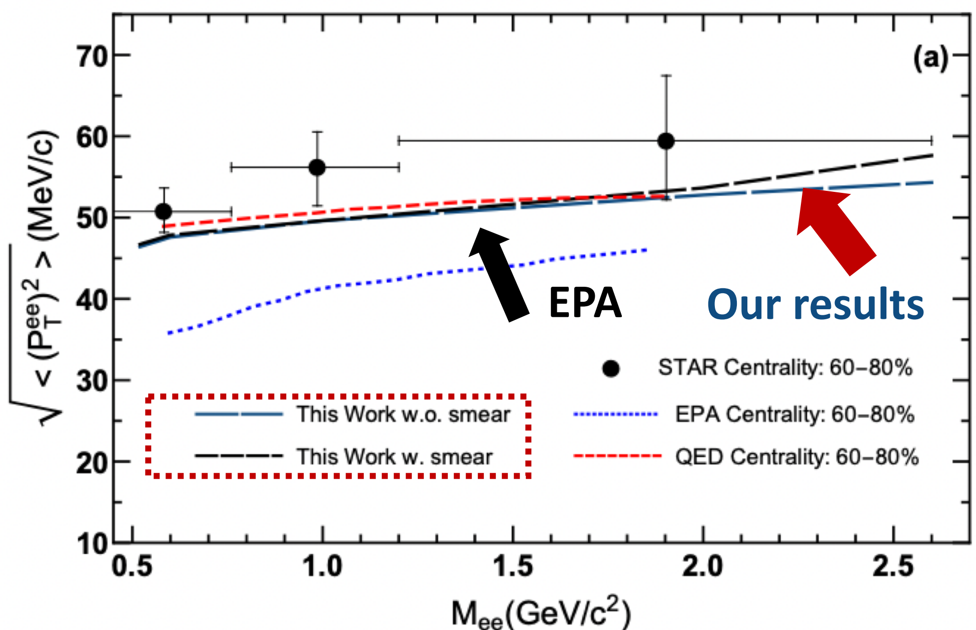
Spectra of transverse momentum in PCs



Square of Total transverse momentum of dilepton

- The calculation based on QED can explain the curve at low P^2_T .

- The study of $<P^2_T>$ as a function of Mee is an nice example to show that the information of transverse momentum of photons is essential.



Invariant mass of dilepton

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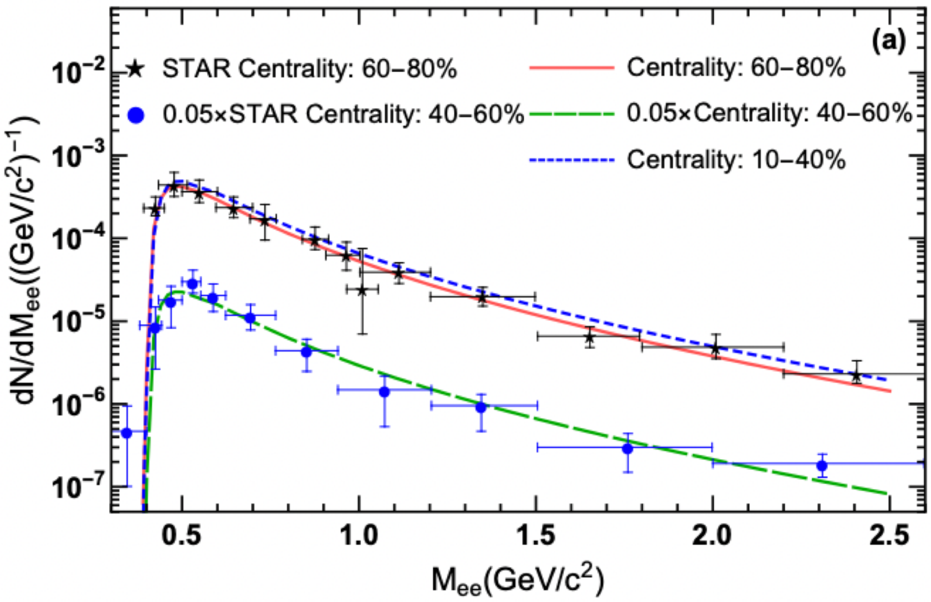
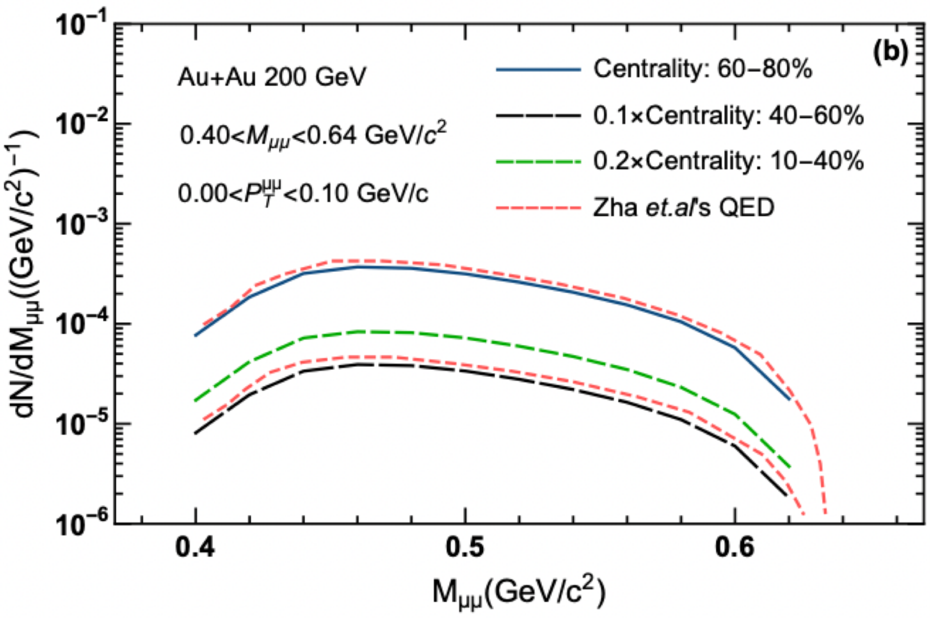
Invariant mass distributions in PCs

e+ e-



μ+ μ-



- Invariant mass distributions for both e+e- and μ+μ- pairs agree with the data.

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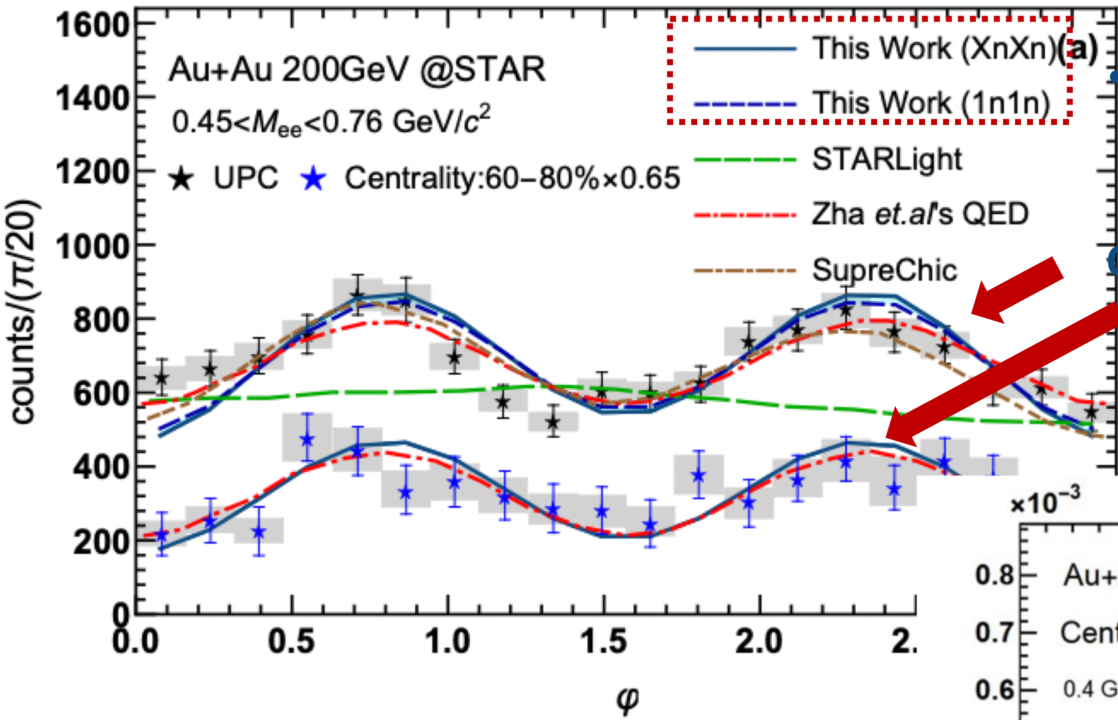
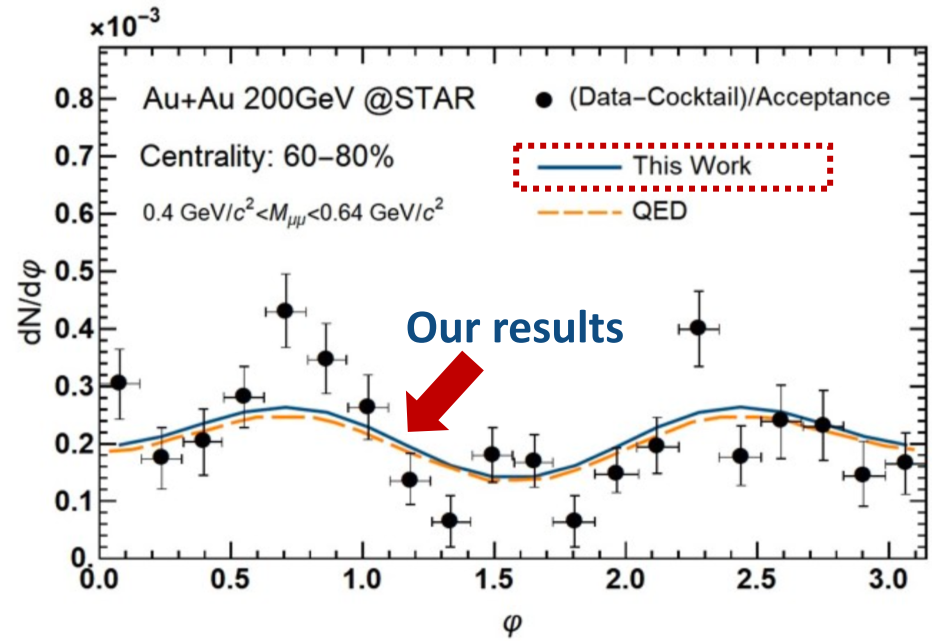
Angle distribution related to vacuum birefringence



- Our results agree with the experimental data for $e+e-$.

Our results



- So far, we do not know the source for the difference between our results and data for $\mu+\mu-$.

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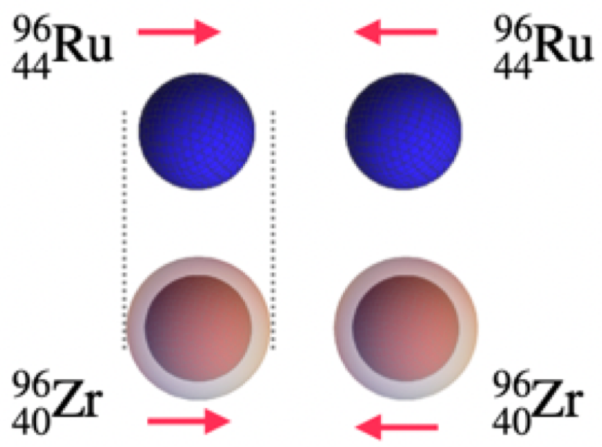
Lepton pair photoproduction in isobar collisions: a possible way to study the nuclear structure

(Also see Talk by 林硕，2023.05.27，15：00)

Isobar collisions and photoproduction



- **One lesson that we have learnt from isobar collisions is the mass and charge distributions for Zr and Ru are different.**

Charge distribution ⟷ **Nuclear charge form factor**

Mass distribution ⟷ **Impact parameters (centrality)**

e.g. see Xu, et al., PRL 2018; Li, et al, PRC 2018; Zhang, Jia, PRL 2022; Deng, Huang, Ma, Wang PRC 2016

Woods-Saxon distributions for charge and mass

- One can parameterize the charge and mass distribution as

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

by matching the <r> and <r²>.

- The centrality and impact parameters are computed by optical Glauber model .

(a) Parameters given by energy density functional theory (DFT) ✓

(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

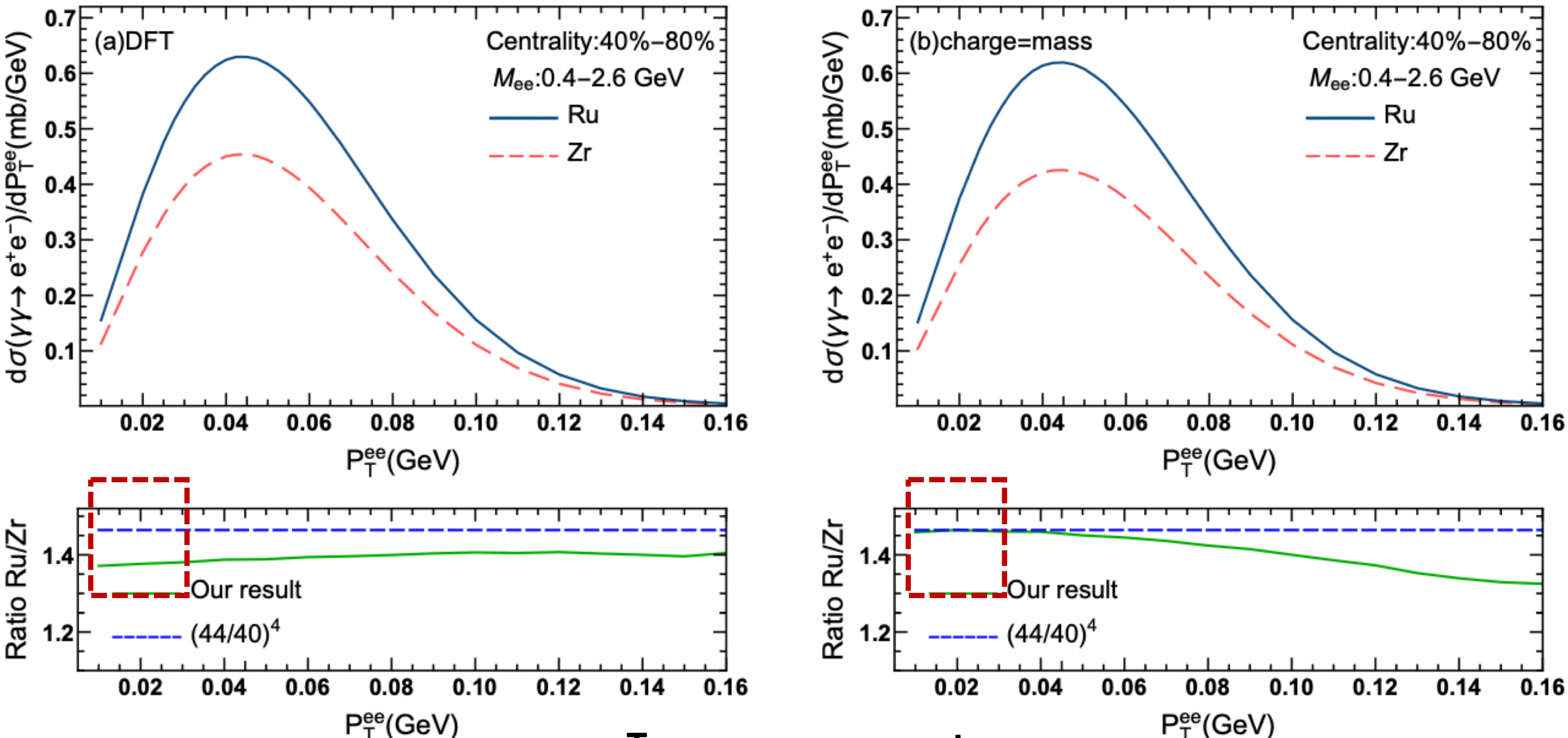
Centrality	40%	60%	70%	80%
Impact parameter	7.464 fm	9.143 fm	9.874 fm	10.563 fm
Impact parameter	7.615 fm	9.326 fm	10.073fm	10.780 fm

(b) Set the mass distribution be the same as charge distribution

(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}

Centrality	40%	60%	70%	80%
Impact parameter	7.406 fm	9.070 fm	9.797 fm	10.479 fm
Impact parameter	7.373 fm	9.030 fm	9.754 fm	10.434 fm

Differential cross sections Ru+Ru and Zr+Zr (I)

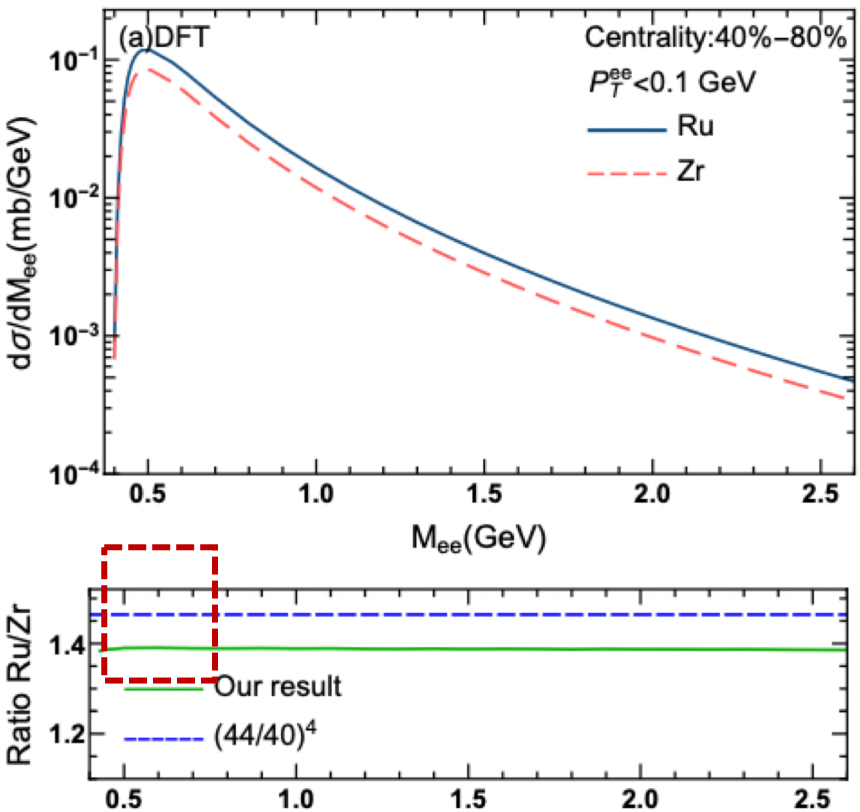


Transverse momentum

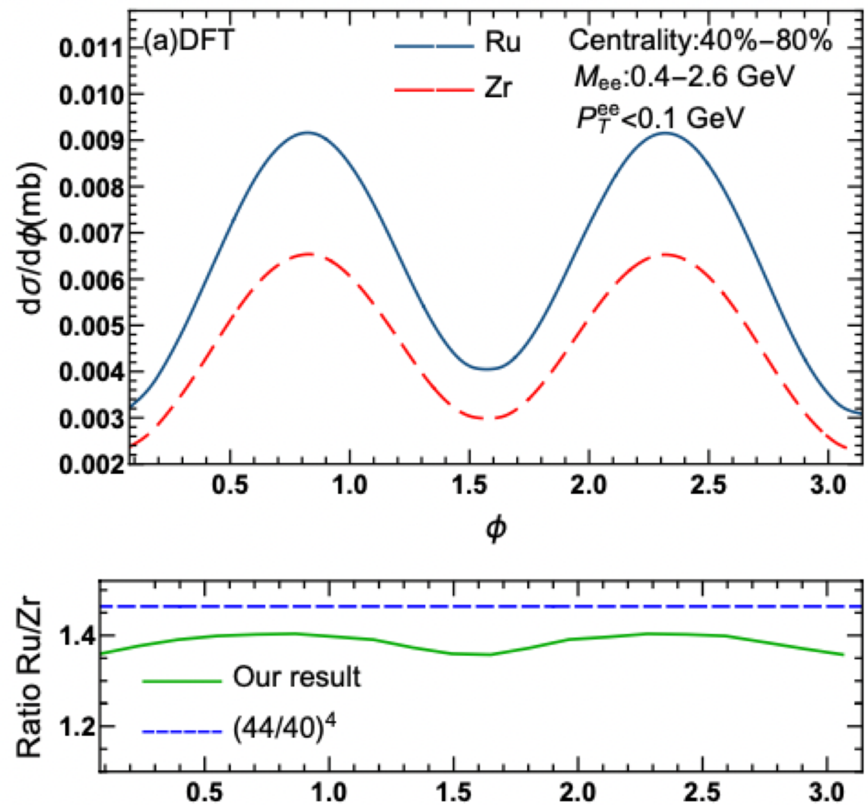
- If there is no difference between Ru and Zr, the ratio should be (44/40)^4.
- By (a) DFT, the ratio is smaller than (44/40)^4, while by (b) it is larger than (44/40)^4.

L. Shuo, R.J. Wang, J.F. Wang, H.J. Xu, SP, Q. Wang, PRD 107 (2023) 5, 054004

Differential cross sections Ru+Ru and Zr+Zr (II)



Invariant mass M_{ee}(GeV)



Azimuthal angle ϕ

- If there is no difference between Ru and Zr, the ratio should be (44/40)^4.
- By both (a) DFT, the ratios are smaller than (44/40)^4.

L. Shuo, R.J. Wang, J.F. Wang, H.J. Xu, SP, Q. Wang, PRD 107 (2023) 5, 054004

Summary, discussions and puzzles

Puzzles and connection to other fields

1) $P(b_\perp)$ dependence: Need input from nuclear physics

2) Pt broadening: medium effect? Need input from QGP

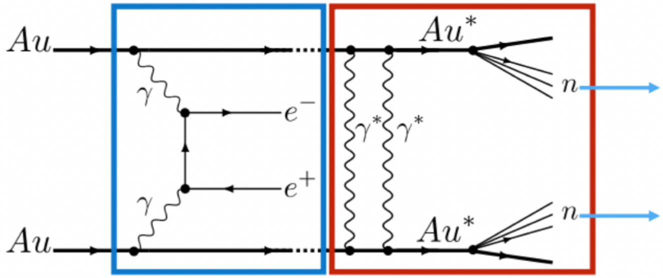
3) Beyond the Born level: laser physics, non-linear QED, Schwinger mechanism

4) <Cos nΦ> photon polarization: EIC, EICC

…

(1) Probability of emitting neutrons - nuclear structure

$\mathcal{P}(b_T)$:



Probability of emitting a single neutron from an excited nucleus

C. A. Bertulani and G. Baur, Phys. Rept. 163, 299 (1988).

The choice of $P(b_\perp)$:

- Based on the Giant dipole resonance (GDR) model

$$\mathcal{P}(b_T) = \sum_{N_\gamma=1}^{\infty} \frac{1}{N_\gamma!} w^{N_\gamma} \exp(-w) = 1 - \exp(-w),$$

$$w = 5.45 \times 10^{-5} \frac{Z^3(A-Z)}{A^{2/3} b_T^2}$$

$$\mathcal{P}(b_T) \simeq w$$

$$\mathcal{P}(b_T) = w \exp(-w)$$

Z: number of charge
A: number of nucleons

GDR does not include the information of nuclear structure.

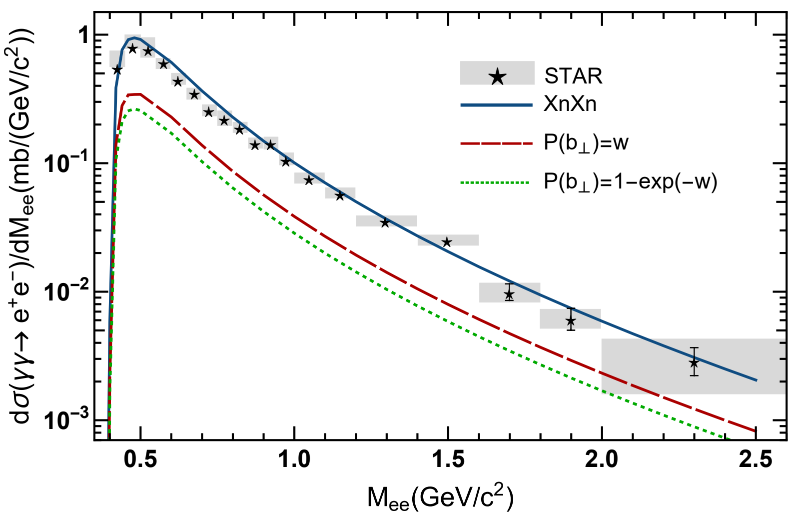
- Based on the fixed-target experimental measurements

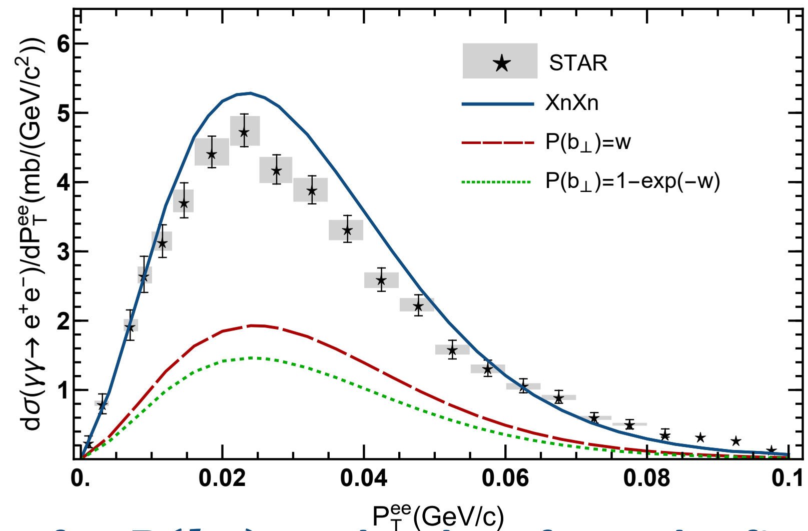
$$w_{Xn}(b_T) = \int d\omega n(\omega, b_T) \sigma_{\gamma+A\to A'+Xn}(\omega)$$

Similar to the EPA, $n(\omega, b_T)$ is photon flux, X is the number of neutrons emitted by a nuclei, $\sigma_{\gamma+A\to A'+Xn}$ is photon-nucleus cross section given by fixed-target experiments.

(1) Probability of emitting neutrons - nuclear structure

- **The differential cross section strongly depends on the choice of $P(b_\perp)$.**

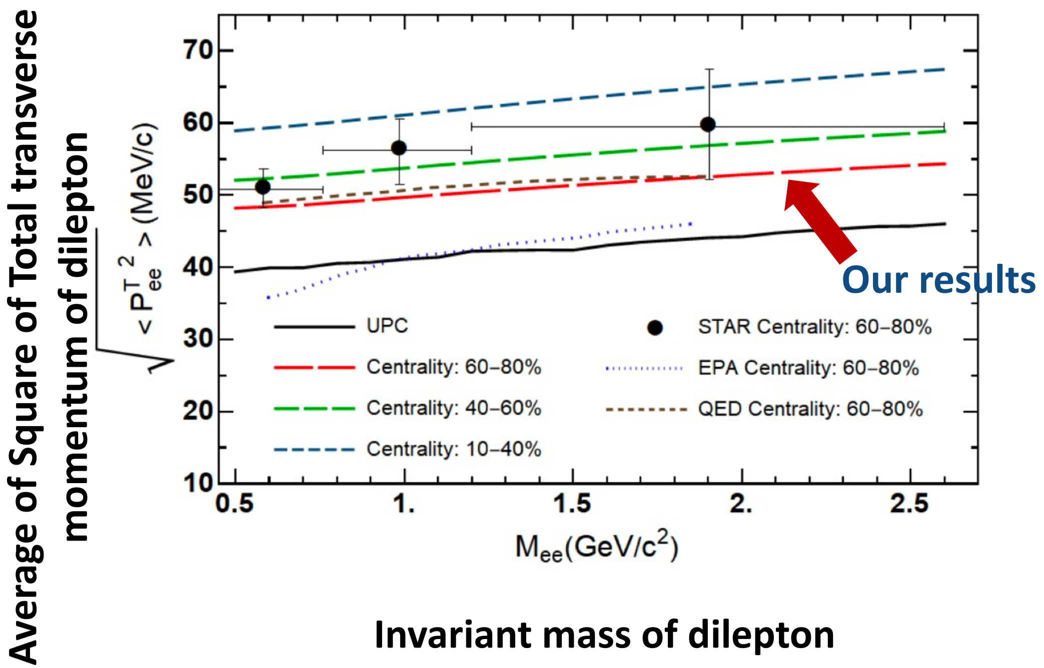




- **We need the first principle calculations for $P(b_\perp)$ or the data from the fixed target nuclear experiments.**

Nuclear	Data from exp.
Au	✓
Pb	✓
Zr	Limited
Ru	✗

(2) PT broadening from medium effects? - QGP



- We need to consider the higher order corrections related to the PT broadening effect.
- One well-known effect comes from the Sudakov factor in TMD community.

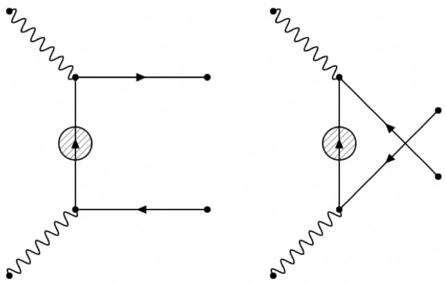
Klein, Mueller, Xiao, Yuan, PRL(2019); PRD (2020)
Li, Zhou, Zhou, PLB (2019); PRD(2020)
Hatta, Xiao, Yuan, Zhou, PRD (2021)

- Do we need to consider the medium effects?

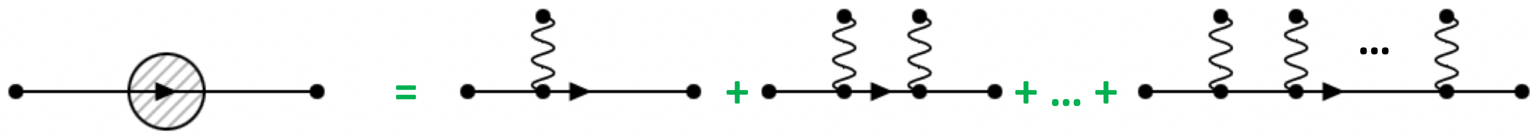
Review: Brandenburg, Zha, Xu, EPJA 2021

(3) Beyond Born level – laser physics, Schwinger mechanism

- In principle, there are higher order corrections to the fermionic propagators in strong EM fields.



Baur, Hencken, Trautmann, Phys. Rep. 453, 1 (2007)

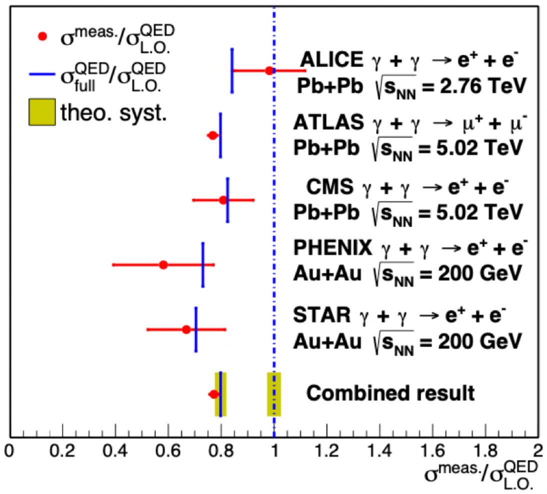


(e.g. Schwinger full propagator in 1+1 dim)

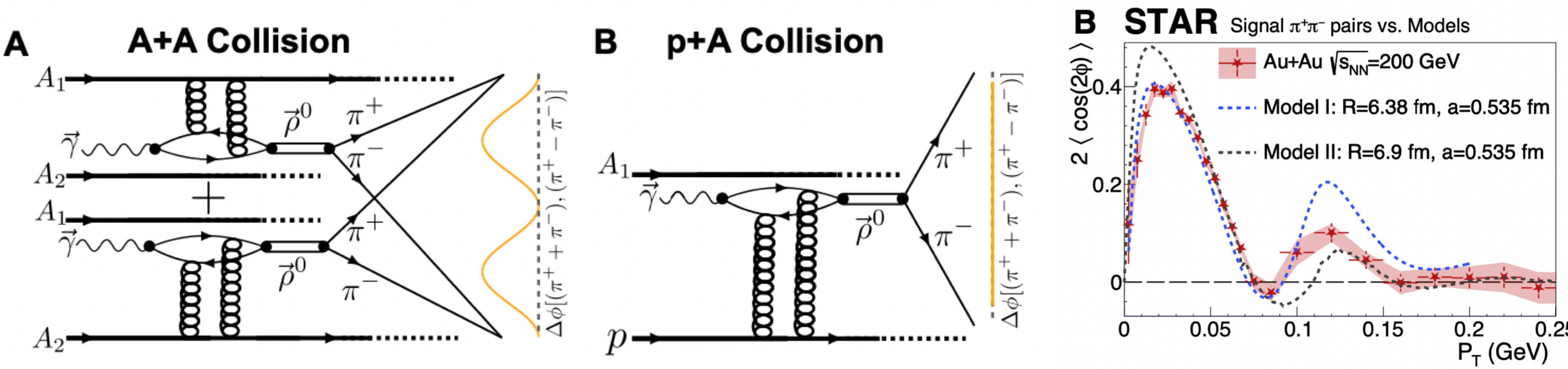
- Could we observe higher order corrections in HIC? If not, why?

Zha, Tang, JHEP 2021

Sun, Zhang, Zhou, Zhou, PLB (2020)



(4) Exploring gluon tomography – EIC, EICC

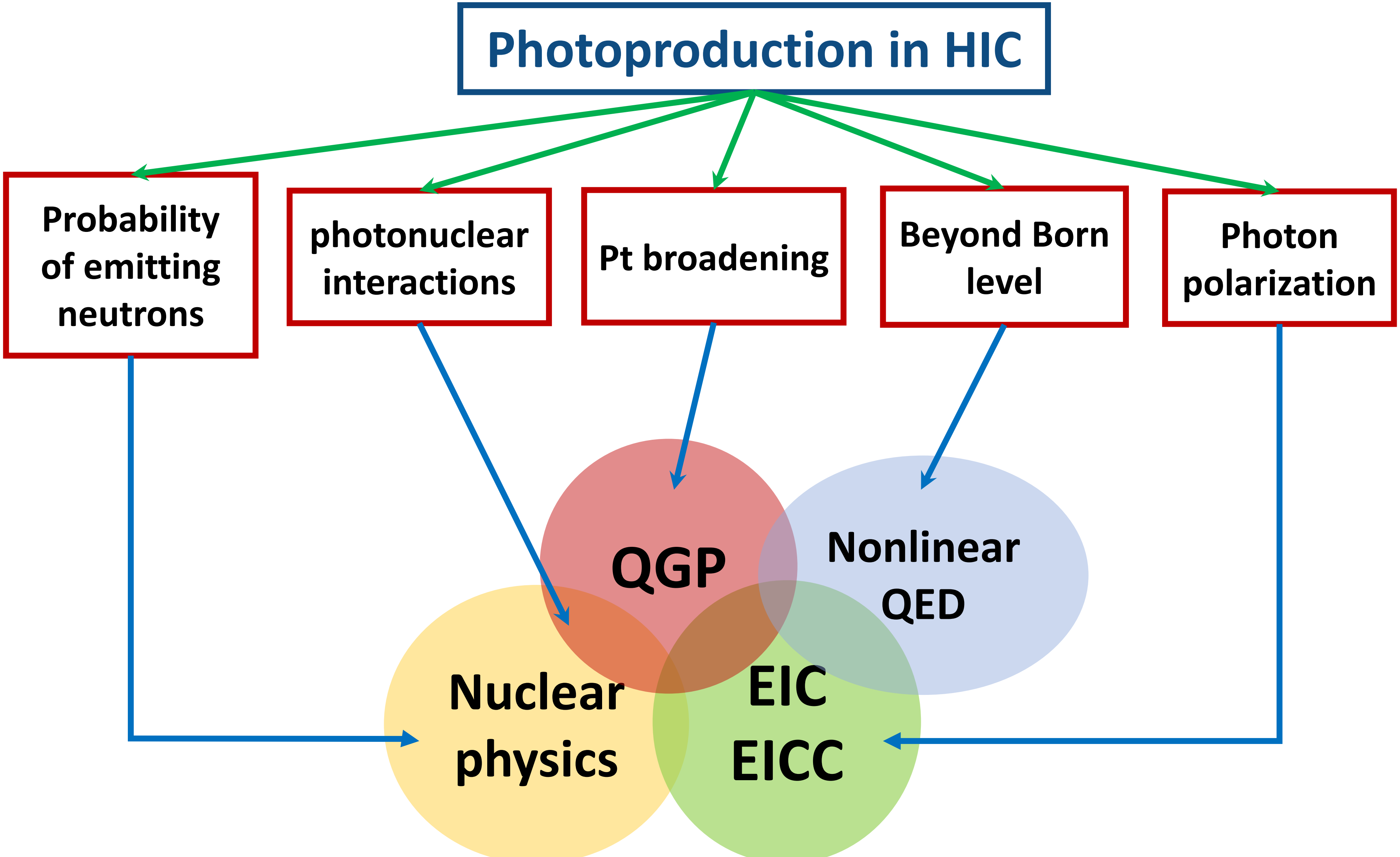


- **The final results are very sensitive to the nuclear geometry and provide a new way to extract transverse spatial gluon distribution.**

STAR: Sci. Adv. 9 (2023) 1, eabq3903 .

Xing, Zhang, Zhou, Zhou, JHEP 2020; Zha, Brandenburg, Ruan, Tang, Xu, PRD 2021; Hagiwara, Zhang, Zhou, Zhou, PRD 2021; Brandenburg, Xu, Zha, Zhang, Zhou, Zhou, PRD 2022

Summary



Photoproduction in HIC
Probability of emitting neutrons
photonuclear interactions
Pt broadening
Beyond Born level
Photon polarization
QGP
Nonlinear QED
Nuclear physics
EIC
EICC

Summary

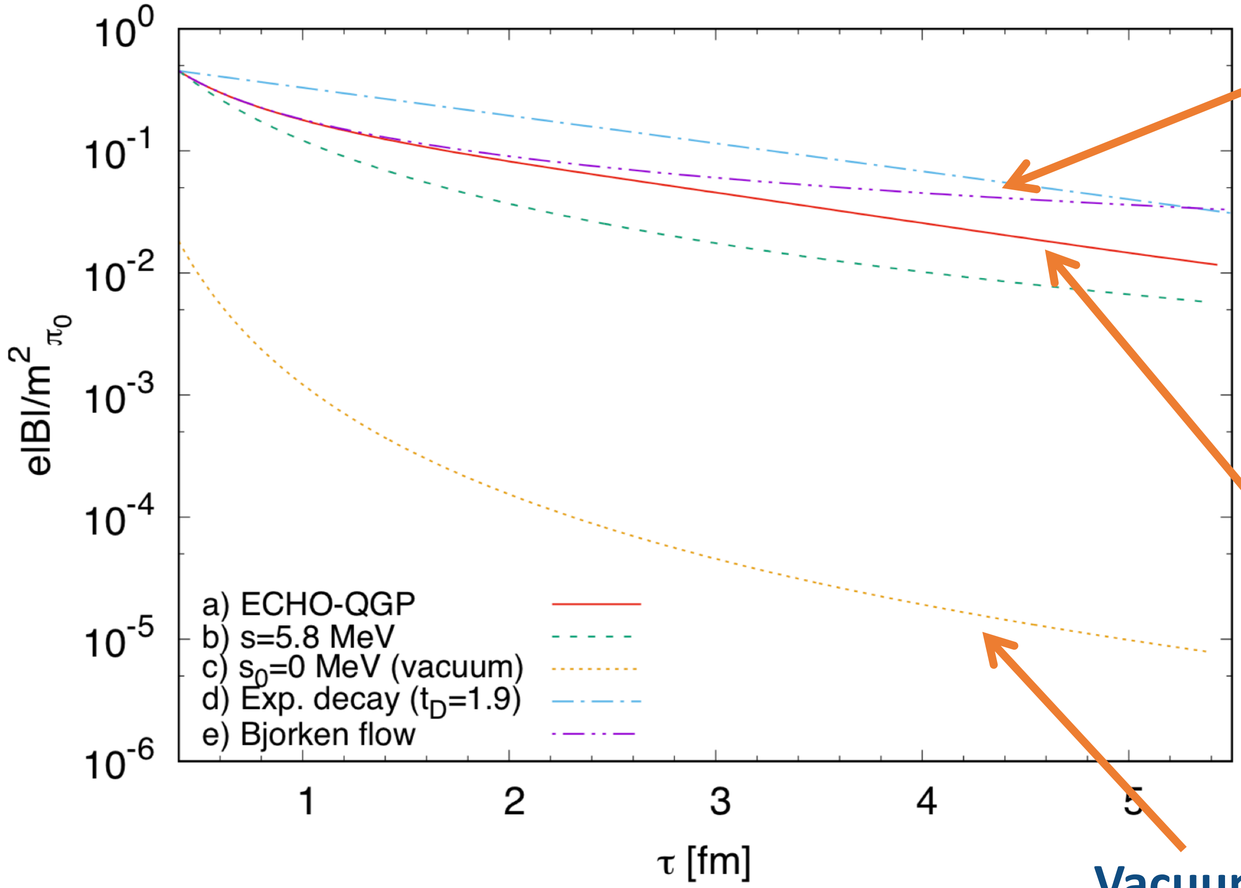
- **The quantum matter under strong QED fields is a still rapid developing area.**

- **Ultra-peripheral collisions with excellent measurements from STAR, etc. provide us a nice platform to study the strong QED effects. Many famous but never been discovered effects, e.g. the generation matter directly from lights and vacuum birefringence etc, may be measured from experiments.**

Thank you for your time!

Backup

Evolution of EB fields



Ideal Bjorken MHD

SP, V. Roy, L. Rezzolla, D.H. Rischke, PRD(2015)

MHD + CME + Chiral anomaly

Siddique, Wang, SP, Wang, PRD (2019)

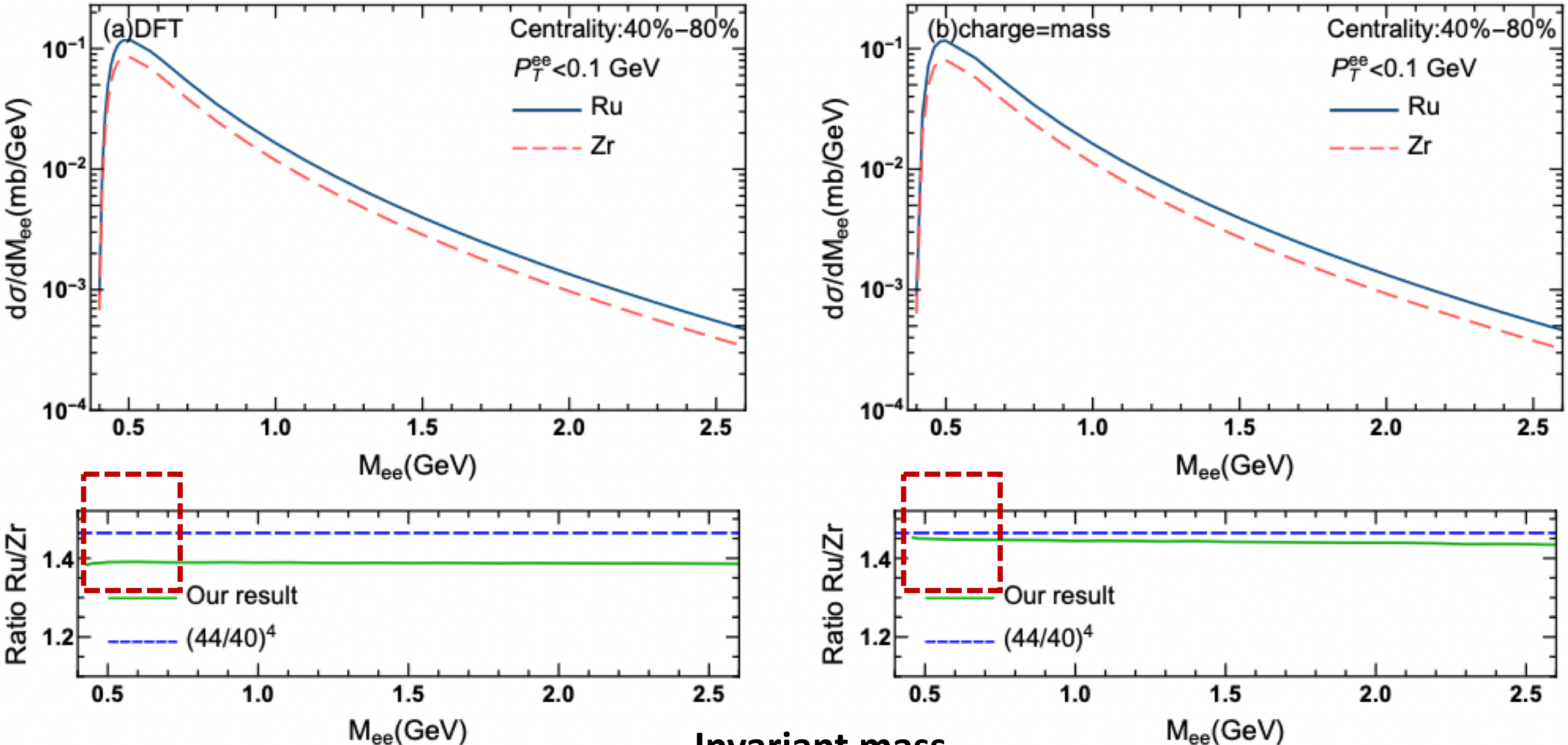
ECHO-QGP

Inghirami, Zanna, Moghaddam, Becattini, Bleicher, EPJC(2016)

Vacuum

Kharzeev, McLerran, Warringa, NPA(2008)

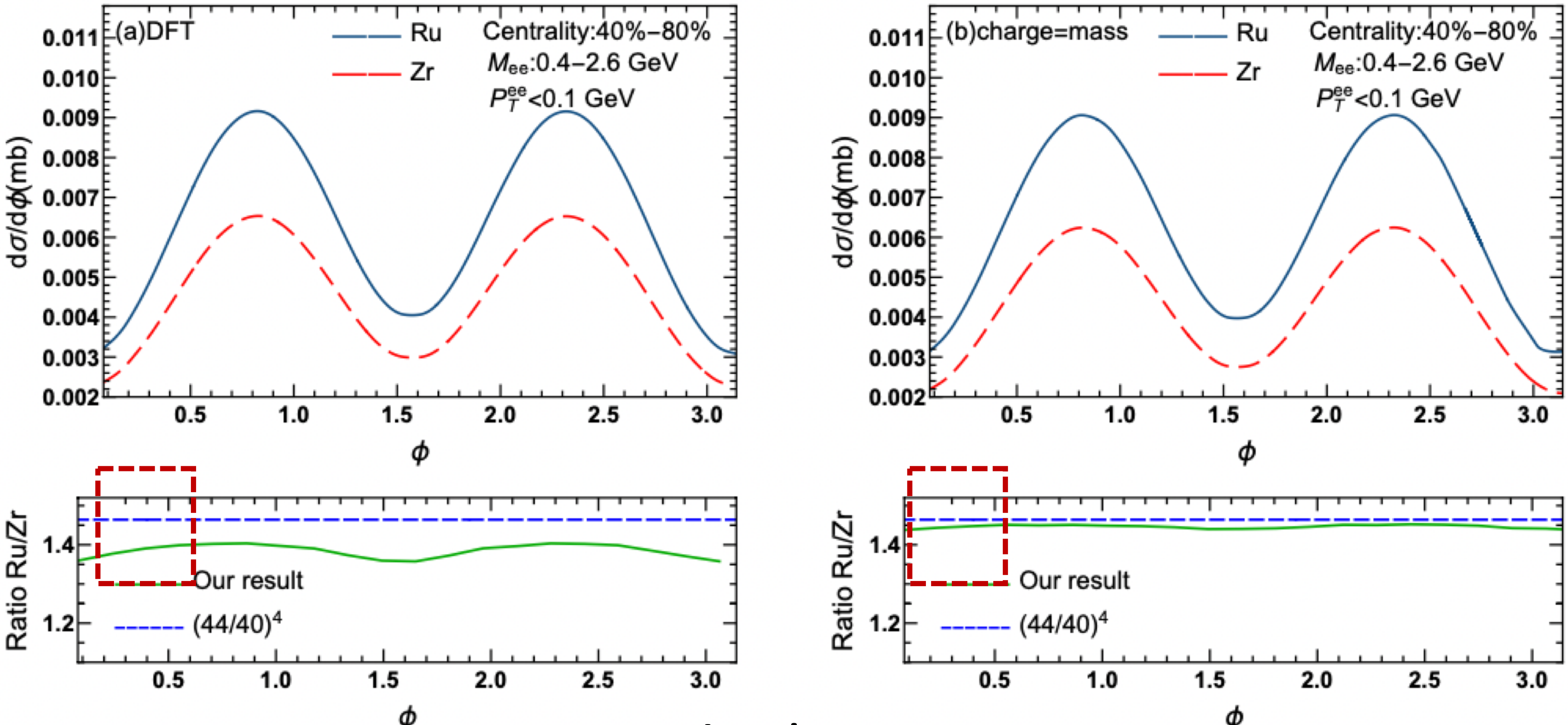
Differential cross sections Ru+Ru and Zr+Zr (II)



Invariant mass

- **If there is no difference between Ru and Zr, the ratio should be (44/40)^4.**
- **By both (a) DFT and (b), the ratios are smaller than (44/40)^4.**
  L. Shuo, R.J. Wang, J.F. Wang, H.J. Xu, SP, Q. Wang, 2210.05106

Differential cross sections Ru+Ru and Zr+Zr (III)



Invariant mass

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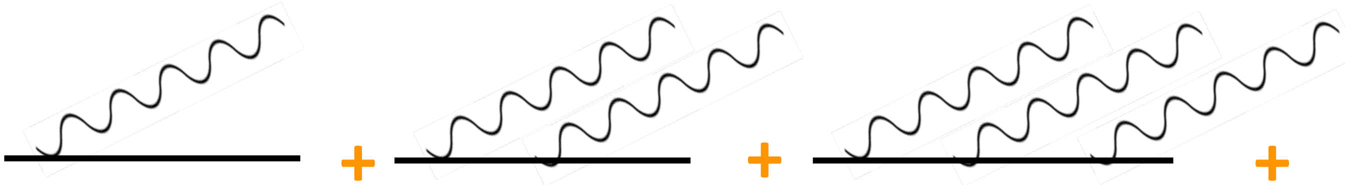
  L. Shuo, R.J. Wang, J.F. Wang, H.J. Xu, SP, Q. Wang, 2210.05106

Sudakov factor



- We learn how to resum the soft photon radiation and derive

$$\frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} = \int \frac{d^2 r_\perp}{(2\pi)^2} e^{i r_\perp \cdot q_\perp} e^{S(r_\perp)} \int d^2 q'_\perp e^{-i r_\perp \cdot q'_\perp} \frac{d\sigma(q'_\perp)}{d\mathcal{P}.\mathcal{S}.}$$

Leading order differential cross section

$$d\mathcal{P}.\mathcal{S}. = dp_{1\perp} dp_{2\perp} dy_1 dy_2 d^2 b_\perp$$

Hatta, Xiao, Yuan, Zhou, PRD (2021)

- Note that S(r) is different with the ordinary double-log type Sudakov factor.

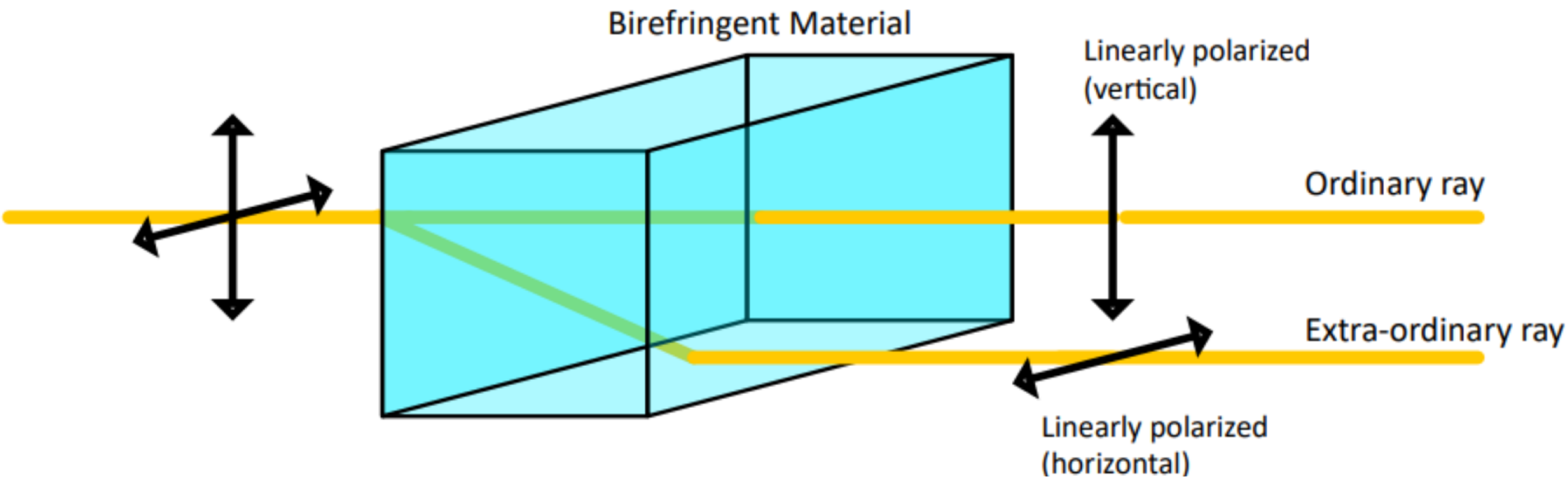
$$S(r_\perp) = -\frac{\alpha}{\pi^2} \ln \frac{Q^2}{m^2} \left(\ln \frac{r_\perp^2 Q^2}{c_0^2} \right)$$

No colinear divergence due to the mass of leptons.

In collaboration with S. Lin, R.J. Wang, Q. Wang, etc. in preparation

Optical birefringence

- **Optical birefringence:**
  Different index of refraction for light polarized parallel vs. perpendicular to material's ordinary axis



Figures from the talks given by Daniel Brandenburg and Zhangbu Xu

Our primary result (IV)