安徽理工大學
ANHUI UNIVERSITY OF SCIENCE & TECHNOLOGY

Photoproduction in Relativistic Heavy-Ion Collisions

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Outline

➢ Introduction

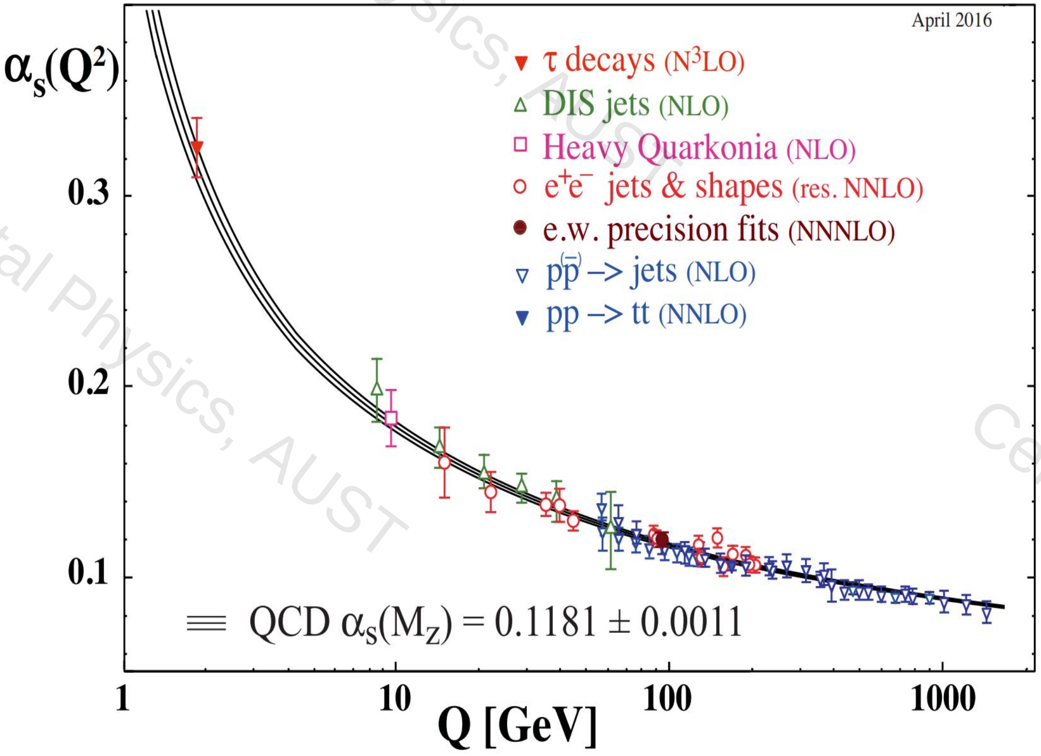
Relativistic heavy-ion collisions and quark-gluon plasma
Strong electromagnetic fields in relativistic heavy-ion collisions

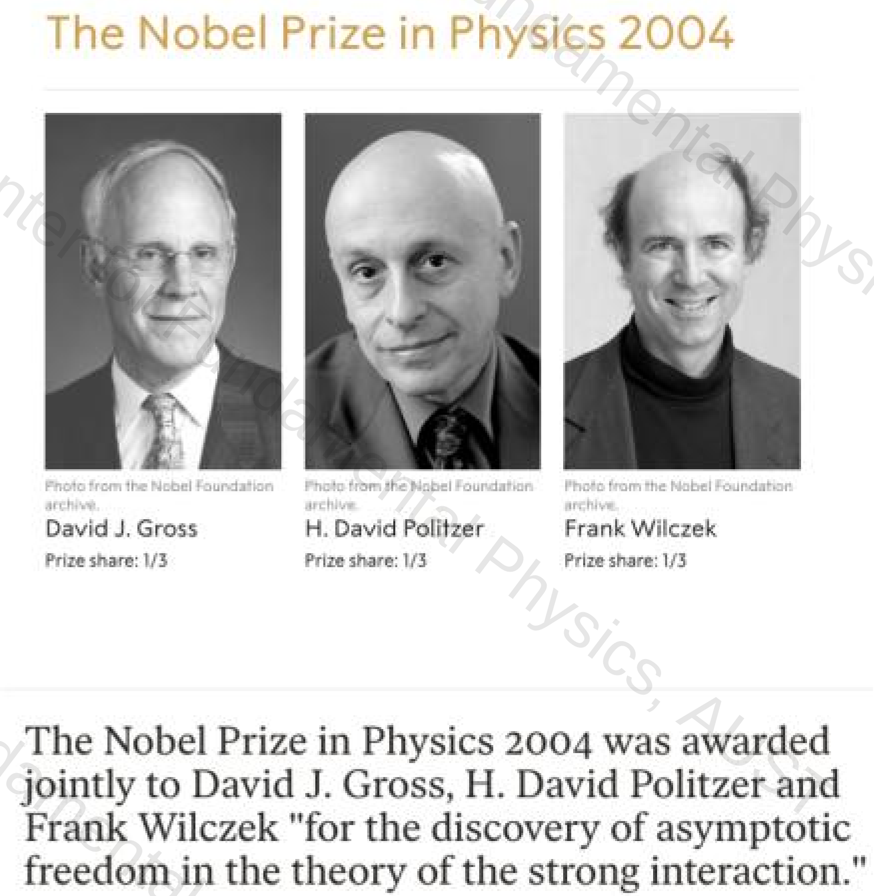
➢ Researches

- **Lepton pair photoproduction in relativistic heavy-ion collisions**
  - Experimental and theoretical progress on photoproduction
  - Photoproduction based on wave packet approximation
  - Numerical results
- **Anomalous magnetohydrodynamics**
  - Analytical solution in the case of Bjorken flow and transverse EM fields
  - Numerical results

➢ Summary

Asymptotic freedom of QCD





The Nobel Prize in Physics 2004

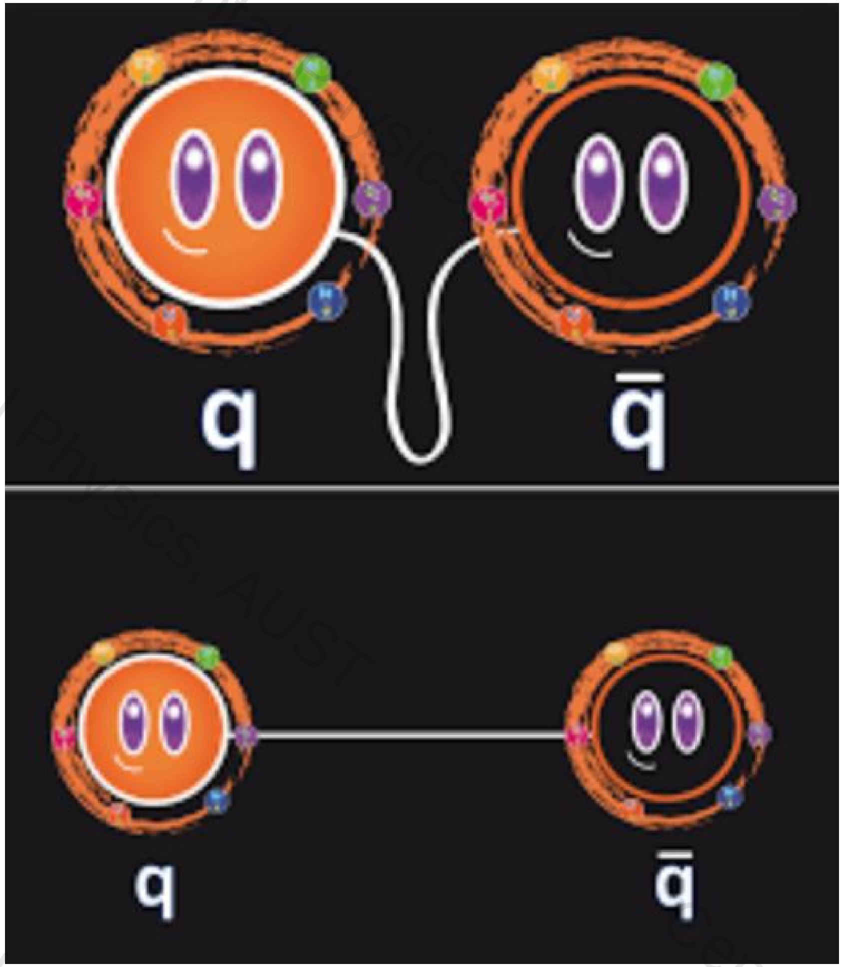
Photo from the Nobel Foundation archive.
David J. Gross
Prize share: 1/3

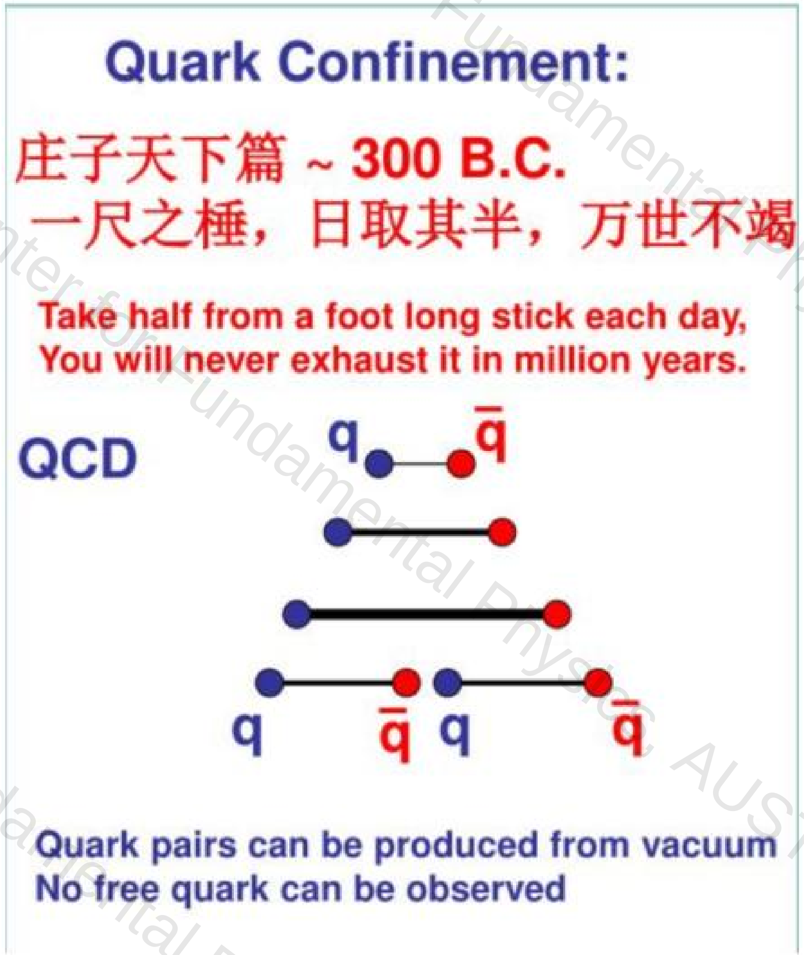
Photo from the Nobel Foundation archive.
H. David Politzer
Prize share: 1/3

Photo from the Nobel Foundation archive.
Frank Wilczek
Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction."

Quark Confinement





Quark Confinement:

庄子天下篇 ~ 300 B.C.

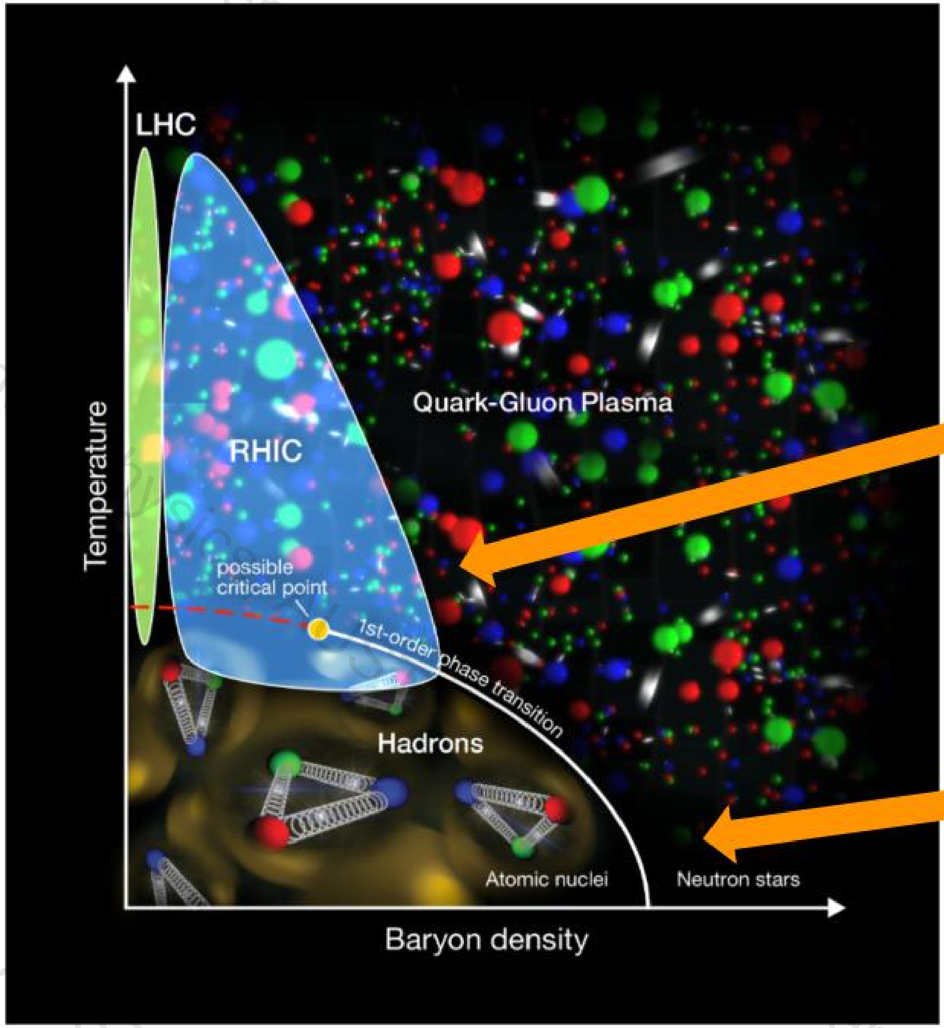
一尺之棰，日取其半，万世不竭

Take half from a foot long stick each day,
You will never exhaust it in million years.

QCD

Quark pairs can be produced from vacuum
No free quark can be observed

Deconfinement phase transition

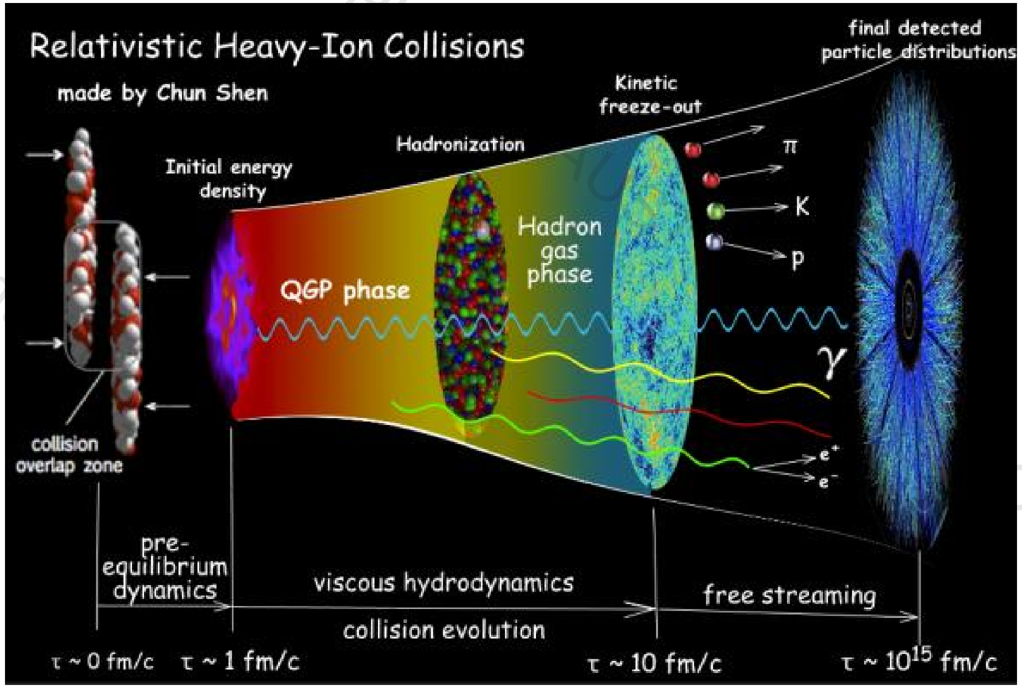


High temperature

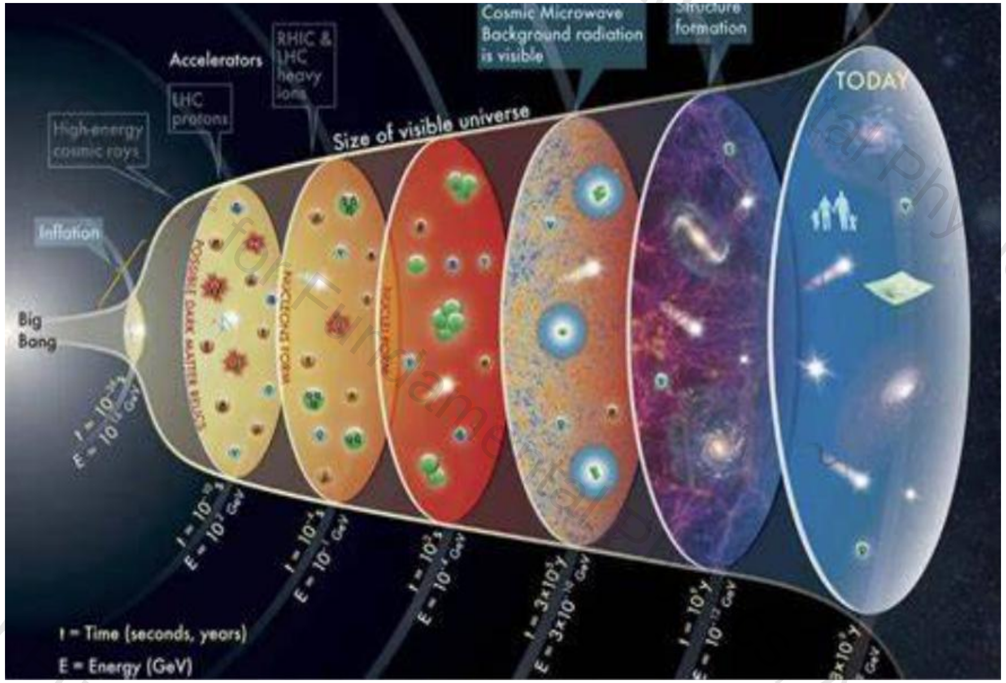
High pressure

T.D. Lee (1974) and Collins (1975): Heavy ion collision to create a new form of matter!

Relativistic heavy-ion collisions (RHIC)

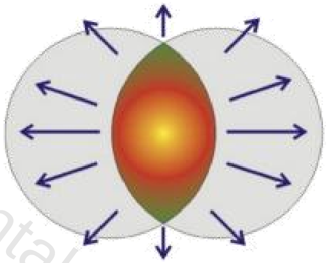


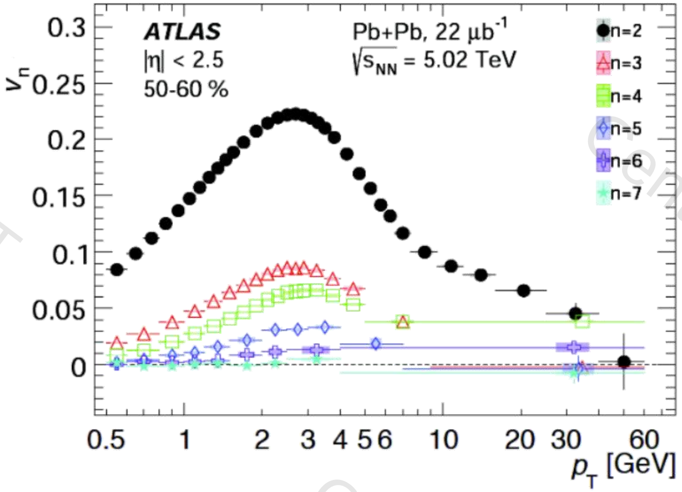
Little Bang

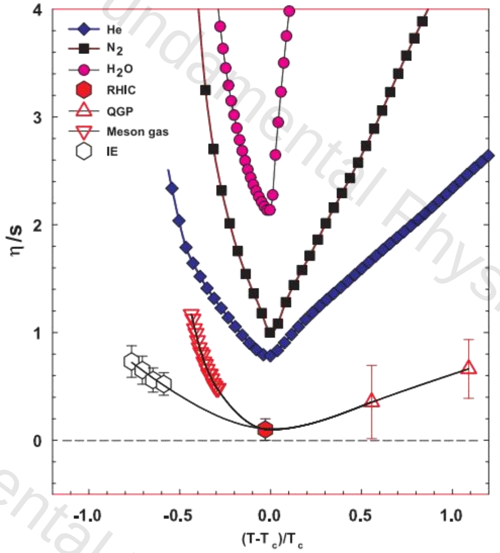


Big Bang

Quark-gluon plasma (QGP)





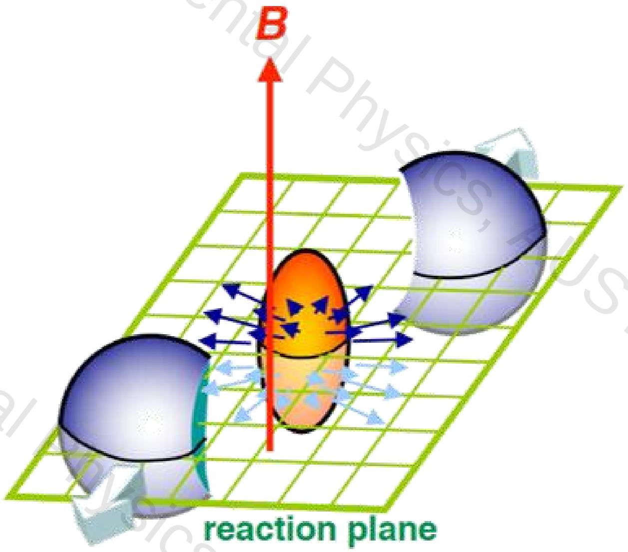


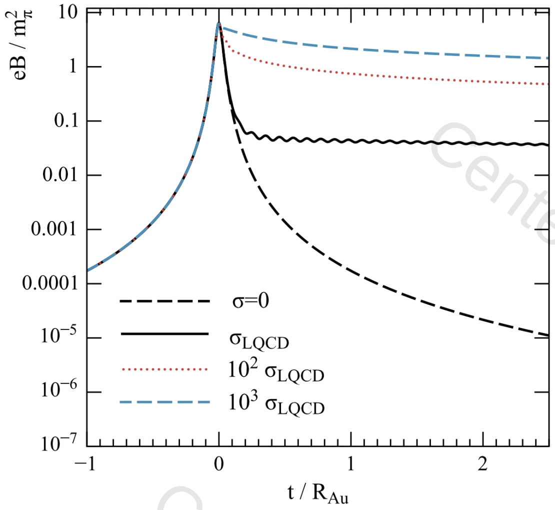
$$\frac{dN}{d\phi} = N_0\left\{1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\phi - \Phi_r)\right]\right\}$$

J. Adams et al, Phys. Rev. Lett., 92:062301, 2004.
Roy A. Lacey et al, Phys. Rev. Lett., 98:092301, 2007
……

QGP is a high temperature, high density, strongly coupled system composed of quark and gluon degrees of freedom. Its behavior is similar to a ideal fluid.

Strong electromagnetic fields in HIC

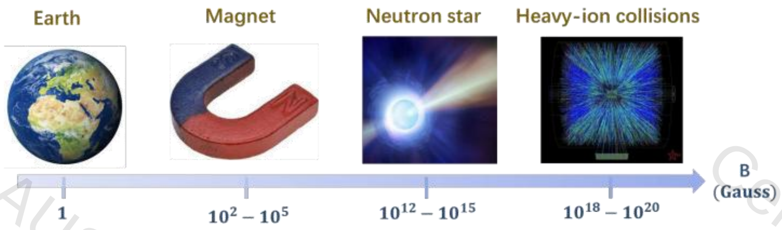




- $eB\sim\gamma Z\alpha v/b_T^2\sim10^{18}\text{Gauss}$

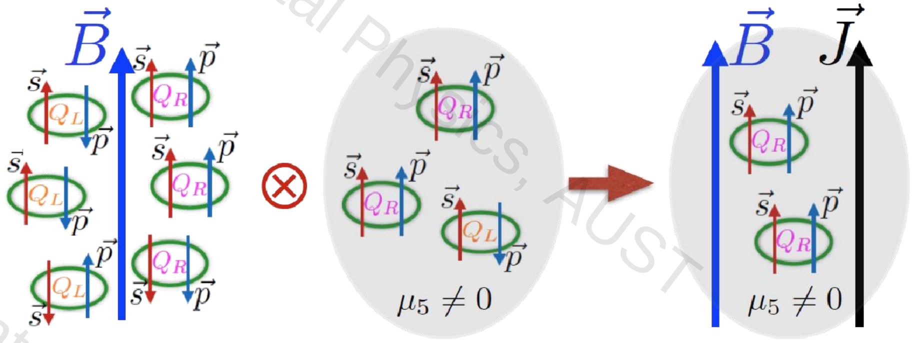
  $\sqrt{s_{NN}} = 200\text{GeV}$ Au+Au

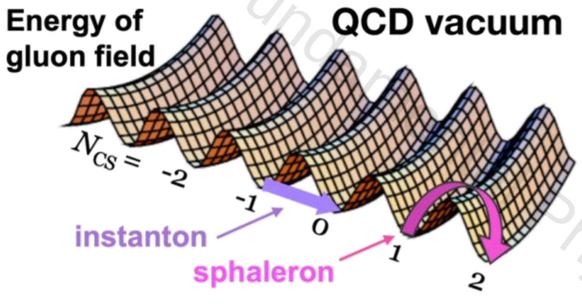
- The evolution of the electromagnetic field is always self-consistently coupled with the evolution of the QGP, and one needs to solve or simulate the magneto-hydrodynamics (MHD) equations



D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys. A 803, 227 (2008)
L. McLerran and V. Skokov, Nucl. Phys. A 929, 184 (2014)
……

Chiral magnetic effect (CME)





$$\boxed{\boldsymbol{j}_{CME} = \frac{e^2}{2\pi^2}\mu_5 \boldsymbol{B}}$$

$$\Delta N_{CS} = \frac{g^2}{4\pi^2}\int dx^4\, \boldsymbol{E}_g \cdot \boldsymbol{B}_g$$

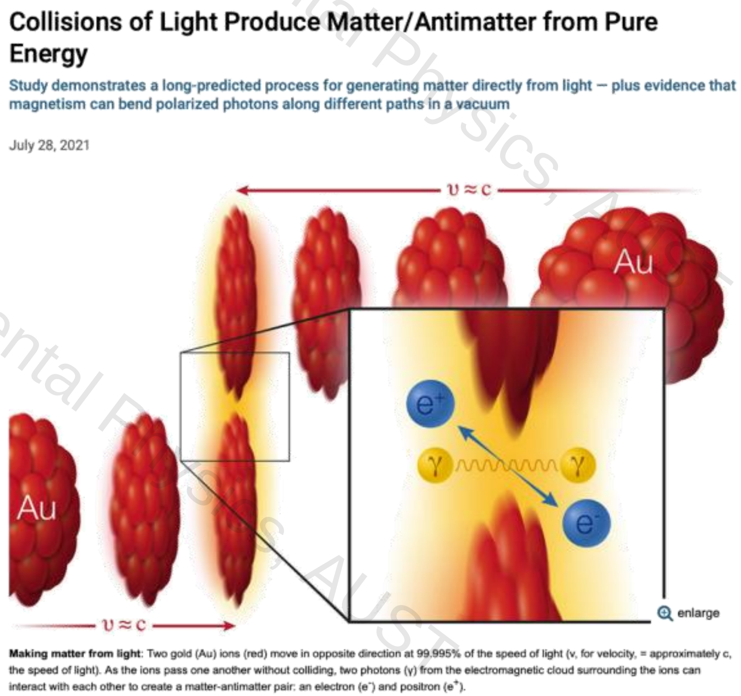
$$N_5(t=\infty) - N_5(t=-\infty) = 2\Delta N_{CS}$$

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

……

CME: When there is a chiral imbalance in a chiral fermion system, an external magnetic field will induce an electric current.

Photobiomass and the Breit-Wheeler process

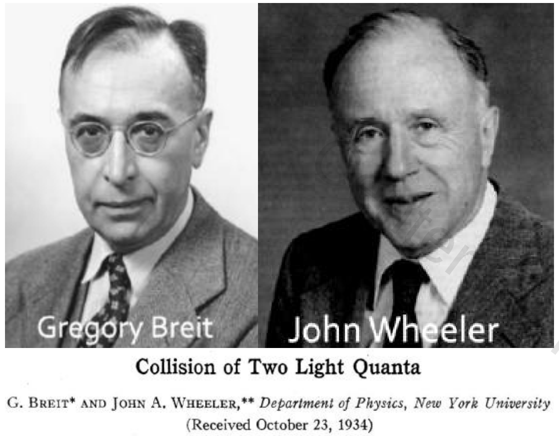


Collisions of Light Produce Matter/Antimatter from Pure Energy

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

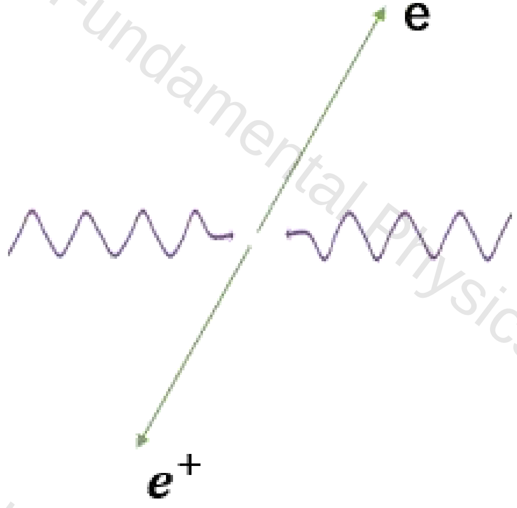
July 28, 2021

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^+).



Collision of Two Light Quanta

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

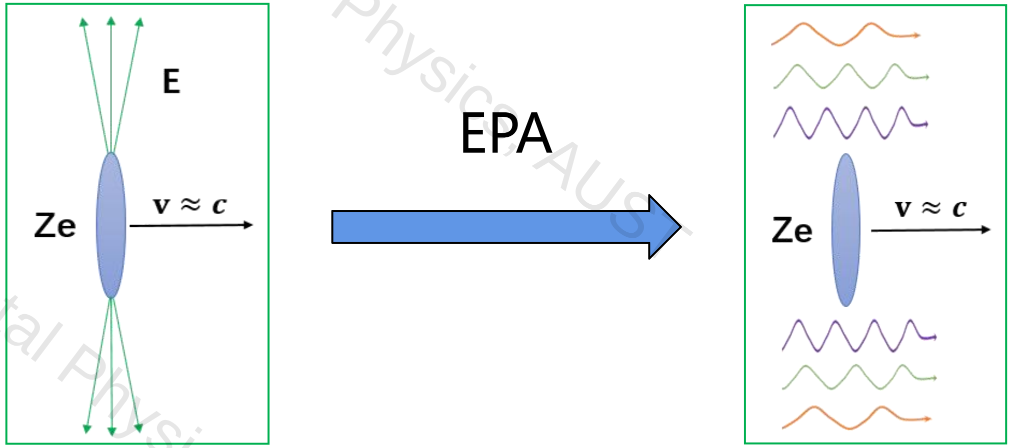


STAR, J. Adam et al. Phys. Rev. Lett. 127, 052302 (2021)

- Breit-Wheeler 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:

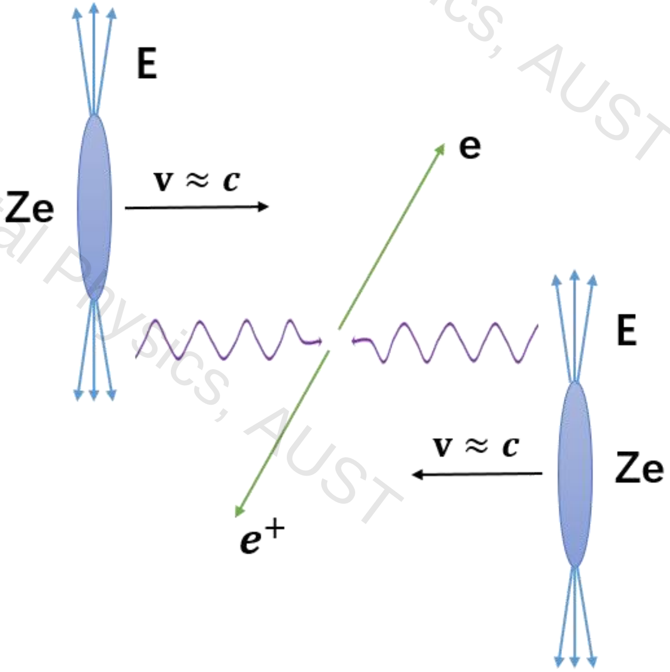
$$n_{A1}(\omega_1, \boldsymbol{b}_{1T}) \cong \frac{1}{\pi\omega_1}|\boldsymbol{E}_T(\omega_1, \boldsymbol{b}_{1T})|^2$$

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

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.

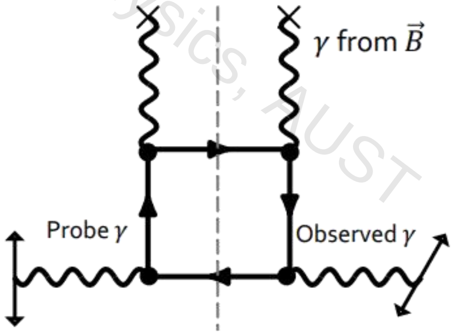
- UPC $(b > 2R_A)$ provides a platform for studying QED under extreme EM field conditions.

- 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



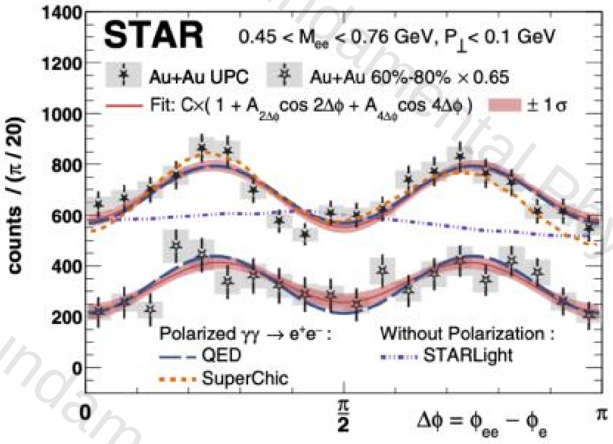
Observations on lepton pair photoproduction

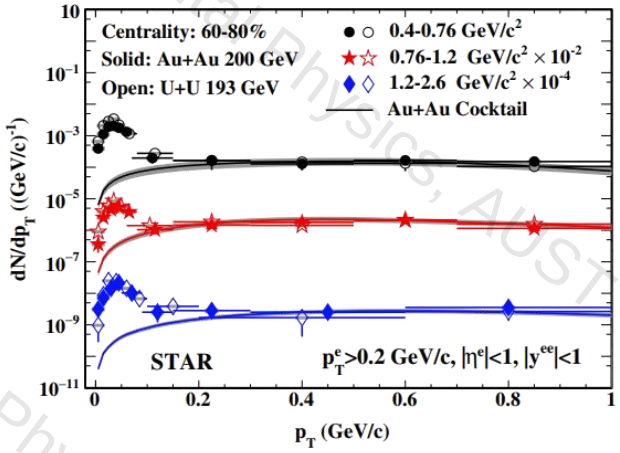
- Observations in UPC

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?

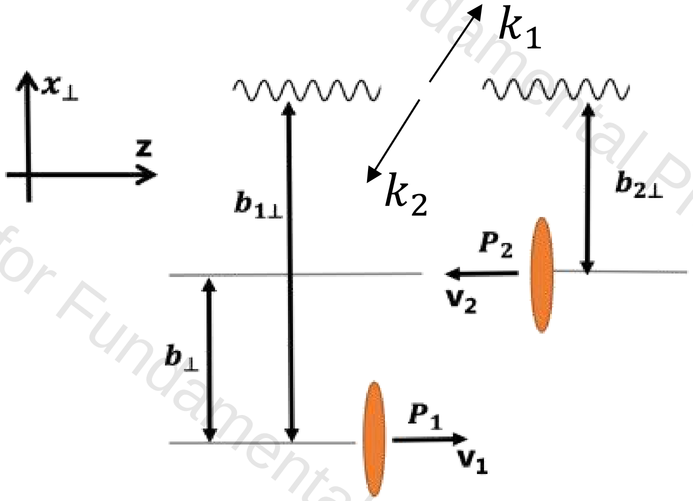
QED method based on wave packet method

Starting point:

Wave packets form of the nuclear state

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

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



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

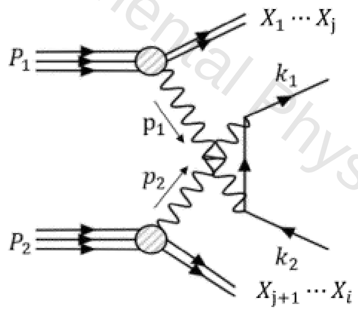
- $q(p_1) + \bar{q}(p_2) \rightarrow l(k_1) + \bar{l}(k_2)$
- $\gamma(p_1) + \gamma(p_2) \rightarrow l(k_1) + \bar{l}(k_2)$

RJW, Shi Pu and Qun Wang, PRD 2021

QED method based on wave packet method

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

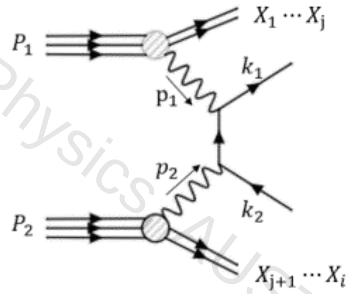
$$\times S_{\sigma\mu}(p_1,\mathbf{b}_{1T})S_{\rho\nu}(p_2,\mathbf{b}_{2T})\times e^4\sum_{\text{spin of } l\bar{l}} L^{\mu\nu}(p_1,p_2,k_1,k_2)L^{*\sigma\rho}(p_1',p_2',k_1,k_2)\,,$$



Lepton part

Wigner functions for photons:

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



Classical field approximation

RJW, Shi Pu and Qun Wang, PRD 2021

Classical field approximation

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

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:

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

$$\Longrightarrow$$

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

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

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

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

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:

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

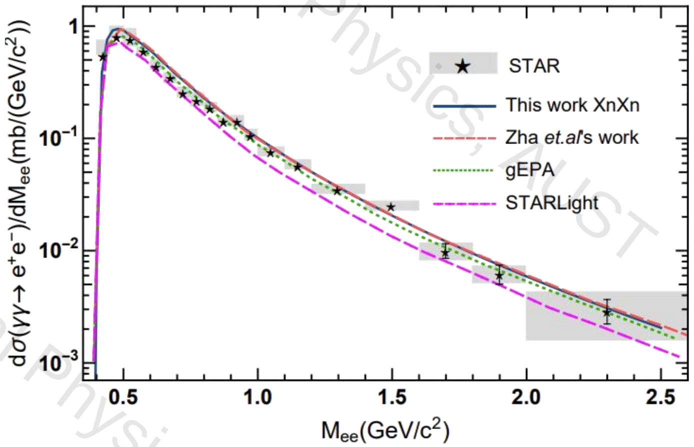
$$n_{A1}(\omega_1, \boldsymbol{b}_{1T}) = \int \mathrm{d}^2\boldsymbol{p}_{1T}\, n_{A1}(\omega_1, \boldsymbol{p}_{1T}, \boldsymbol{b}_{1T})$$
$$= \frac{4Z^2\alpha}{\omega_1} \left| \int \frac{\mathrm{d}^2\boldsymbol{p}_{1T}}{(2\pi)^2} e^{i\boldsymbol{b}_{1T}\cdot\boldsymbol{p}_{1T}} \boldsymbol{p}_{1T}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

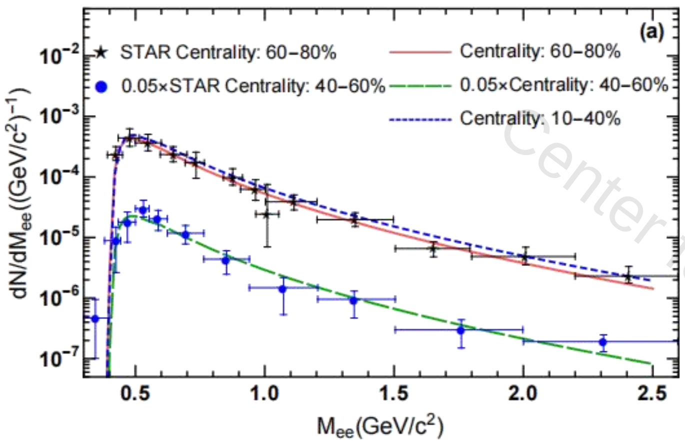
- Ultra-relativistic limit lead to the results of gEPA.

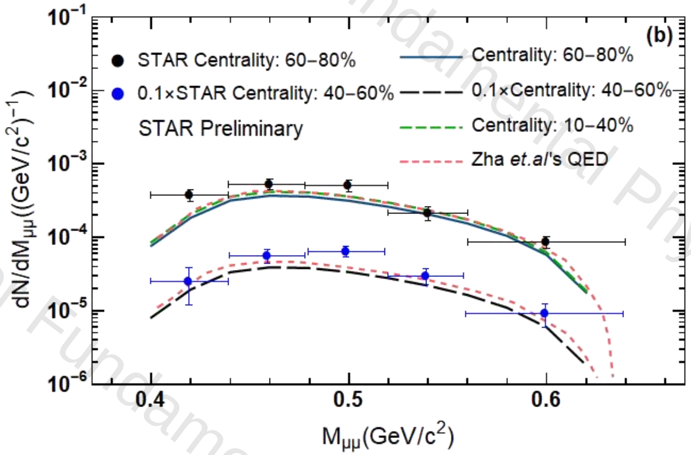
$$\sigma_0 = \sigma_{\mathrm{gEPA}} = \sigma_{\mathrm{twist\ 2}}$$

RJW, Shi Pu and Qun Wang, PRD 2021

Invariant mass spectrum of lepton pairs



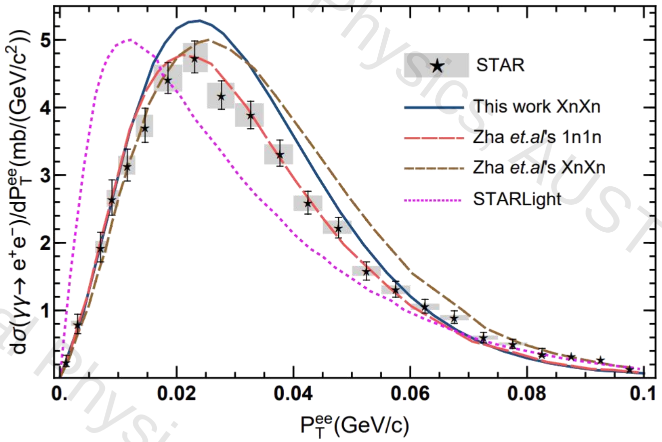


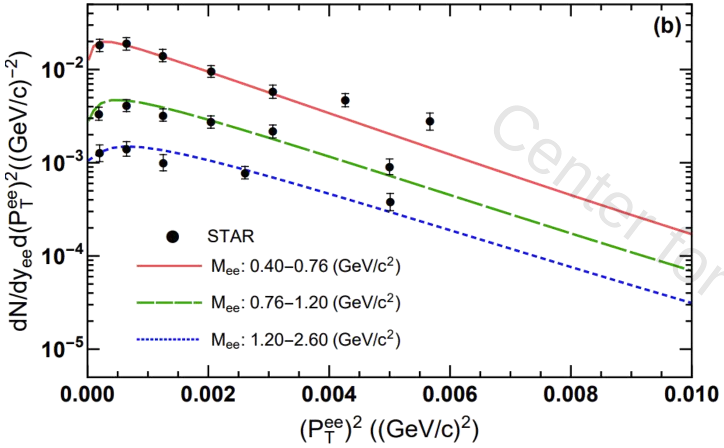


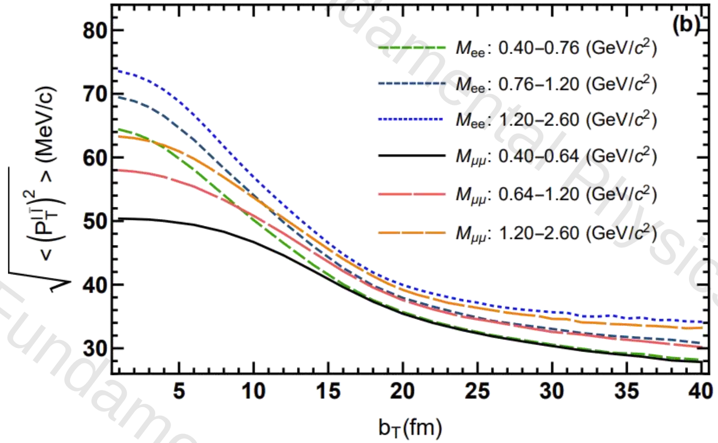
- Different model calculation of invariant mass spectra that are consistent with the experimental data from the STAR experiment.
- The smoothness of the invariant mass spectrum indicates that the equivalent photons in RHIC can be approximated as real photons.

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

Transverse momentum spectrum of lepton pairs







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

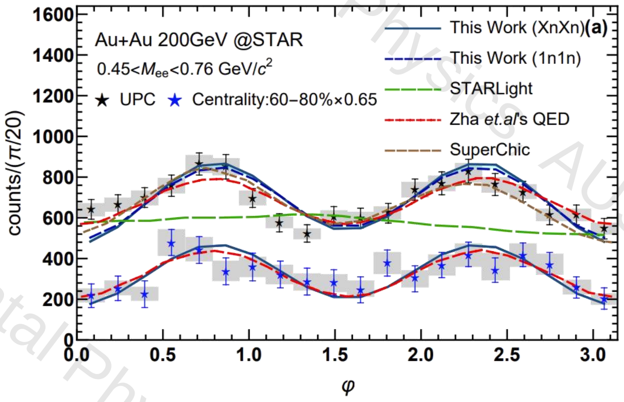
60-80%: $\sqrt{\langle (P_T^{ee})^2 \rangle} \approx 55$ MeV

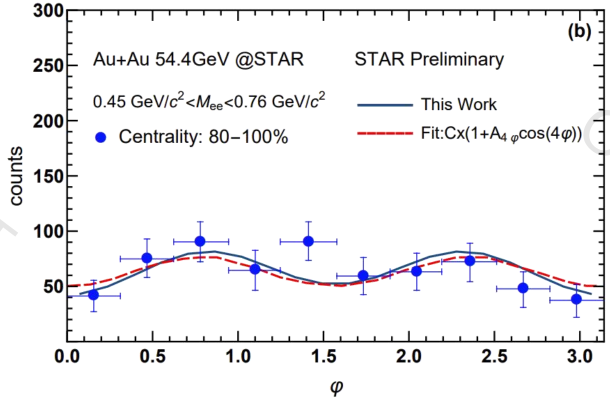
- P_T^{ee} broadening effects: $\sqrt{(P_T^{ee})^2}$ for PC is larger than that for UPC case.

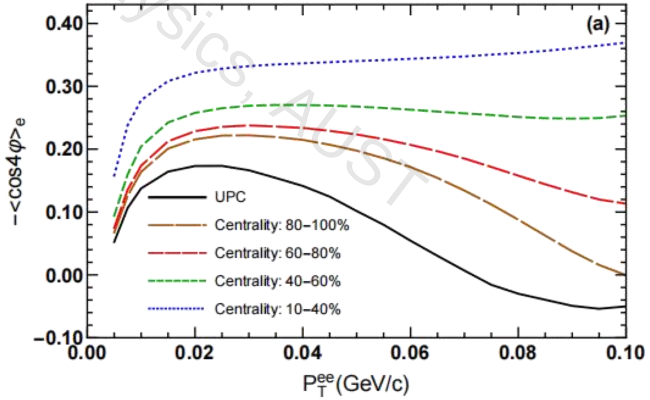
STAR PRL 121, 132301 (2018)

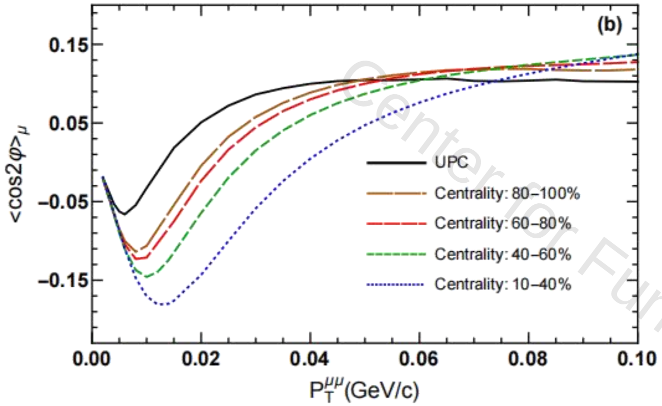
RJW, Shuo Lin, Shi Pu, Yi-fei Zhang and Qun Wang, PRD 2022

Azimuthal angle distribution of lepton pairs







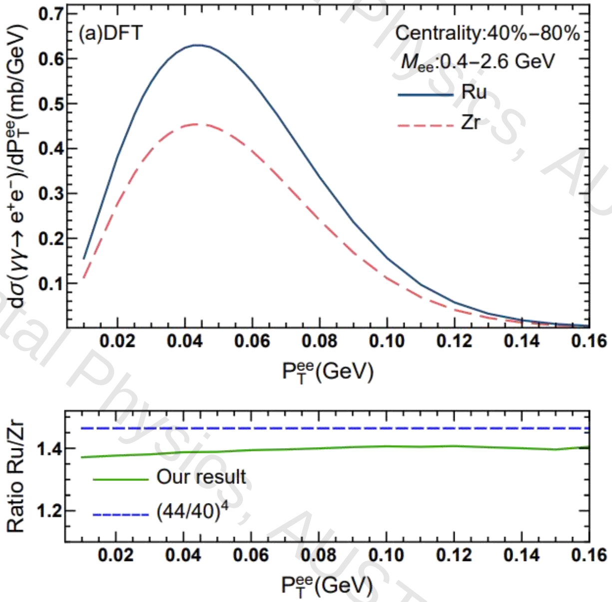


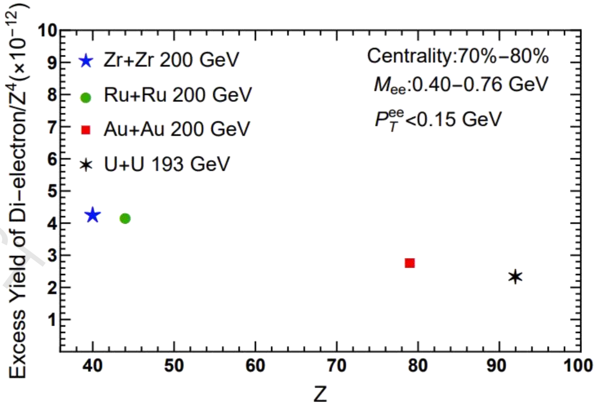
- The polarization information of initial photons is important for describing the azimuthal modulation.
- The azimuthal modulation behavior is believed to be closely related to the vacuum birefringence.
- The cos(2φ) contribution in the muon pairs case is enhanced compared to the case of electron pairs.

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





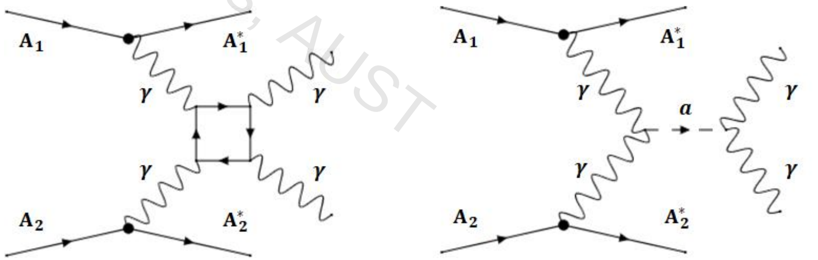
- If the nucleus is treated as a point charge, the cross section is proportional to Z^4.
- The nuclear charge distribution and mass distribution will affect the cross section of the lepton pair photoproduction.

- 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

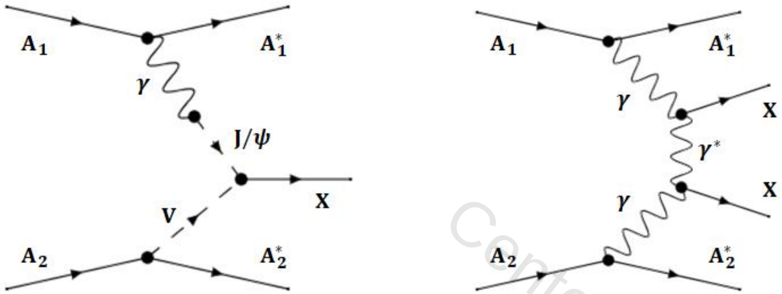
Apply to other photo-induced processes

- 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

Anomalous magnetohydrodynamics (AMHD)

$\partial_\mu T^{\mu\nu} = 0$ ⟷ Energy momentum conservation

$\partial_\mu j_{\mathrm{e}}^\mu = 0$ ⟷ Conservation of charge

$\partial_\mu j_5^\mu = -e^2 C E \cdot B$ ⟷ Chiral anomaly

$\partial_\mu F^{\mu\nu} = j_{\mathrm{e}}^\mu$

$\partial_\mu\left(\epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}\right) = 0$ ⟷ Maxwell's equations

$j_{\mathrm{e}}^\mu = n_e u^\mu + \sigma E^\mu + \underbrace{\xi B^\mu}_{\text{CME}}$ $\quad j_5^\mu = n_5 u^\mu$ + Equation of state

AMHD for Bjorken flow, transverse EM fields

Simplify:

Transverse EM fields:

$$E^\mu = (0, E\cos(\varphi)\,, E\sin(\varphi), 0)$$
$$B^\mu = (0, B\cos(\phi)\,, B\sin(\phi), 0)$$

Bjorken flow:

$$u^\mu = (\cosh(\eta), 0,0, \sinh(\eta))$$

$$\tau = \sqrt{t^2 - z^2}$$
$$\eta = \frac{1}{2}\ln\frac{t+z}{t-z}$$

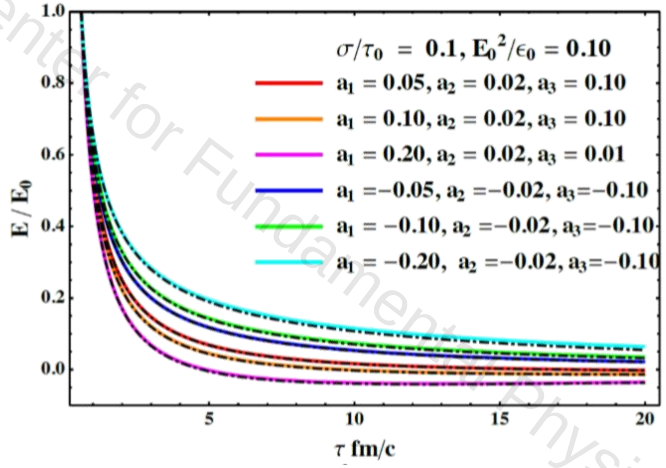
$$\boxed{\begin{aligned} &\frac{d}{d\tau}\varepsilon + (\varepsilon + p)\frac{1}{\tau} - \sigma E^2 - \chi\xi EB = 0, \\ &\frac{d}{d\tau}E + \frac{E}{\tau} + \sigma E + \chi\xi B = 0, \\ &\frac{d}{d\tau}B + \frac{B}{\tau} = 0, \\ &\frac{d}{d\tau}n_5 + \frac{n_5}{\tau} - e^2 C\chi EB = 0, \quad \chi = \pm 1. \end{aligned}}$$

Irfan Siddique, RJW, Shi Pu, Qun Wang, PRD 2019

Analytical and numerical results

$$\frac{d}{d\tau}f(\tau)+m\frac{f(\tau)}{\tau}=f(\tau)\frac{d}{d\tau}\lambda(\tau) \quad \Longrightarrow \quad f(\tau)=f(\tau_0)\exp[\lambda(\tau)-\lambda(\tau_0)]\left(\frac{\tau_0}{\tau}\right)^m$$

$$\boxed{\begin{aligned} B(\tau) &= B(\tau_0)\frac{\tau_0}{\tau}, \\ E(\tau) &= E(\tau_0)\frac{\tau_0}{\tau}e^{-\sigma(\tau-\tau_0)}+\mathcal{O}(a_i), \\ \varepsilon(\tau) &= \varepsilon(\tau_0)\left(\frac{\tau_0}{\tau}\right)^{1+c_s^2}+\mathcal{O}(a_i), \\ n_5(\tau) &= n_5(\tau_0)\frac{\tau_0}{\tau}+\mathcal{O}(a_i), \quad a_i \propto \hbar \end{aligned}}$$



Anisotropic conductivity:

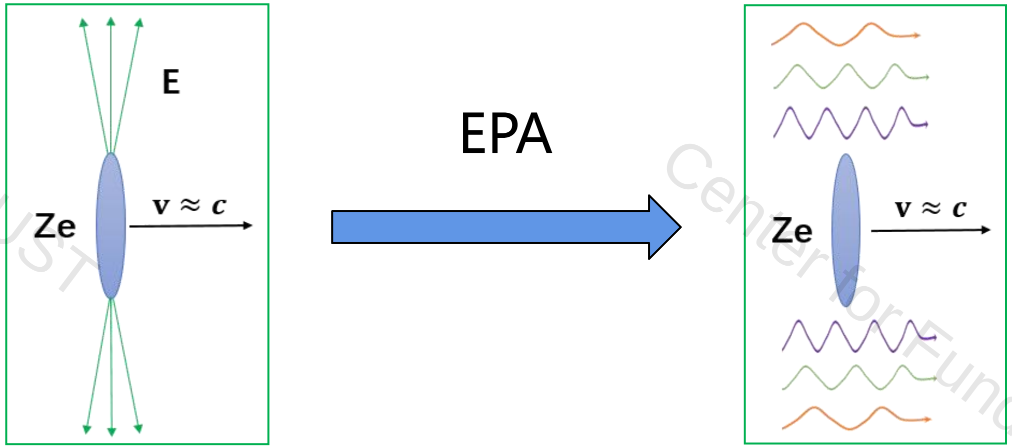
$$\sigma^{\mu\nu}=\sigma_H\epsilon^{\mu\nu\alpha\beta}u_\alpha\frac{B_\beta}{B}-\sigma_\parallel\frac{B^\mu B^\nu}{B^2}+\sigma_\perp\left(g^{\mu\nu}+\frac{B^\mu B^\nu}{B^2}\right)$$

$$\boxed{\sigma \to \sigma_\parallel}$$

Irfan Siddique, RJW, Shi Pu, Qun Wang, PRD 2019

RJW, Patrick Copinger, Shi Pu, NPA 2021

Summary



Highly Lorentz contracted EM fields

The flux of linearly polarized quasi-real photons

HIC provides a platform for studying quantum matter under extremely strong electromagnetic fields.

Thanks for your attention!