The 2nd Workshop on Ultra-Peripheral Collision Physics

Strong Electromagnetic Fields in Heavy ion Collisions

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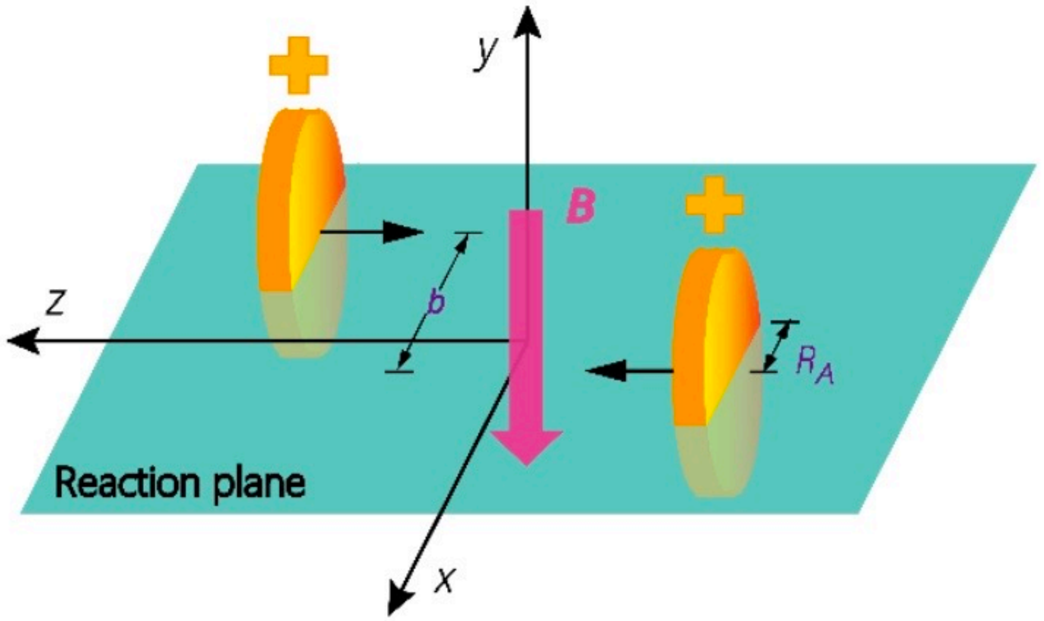
<u>Introduction</u>

Magnetic fields in HICs

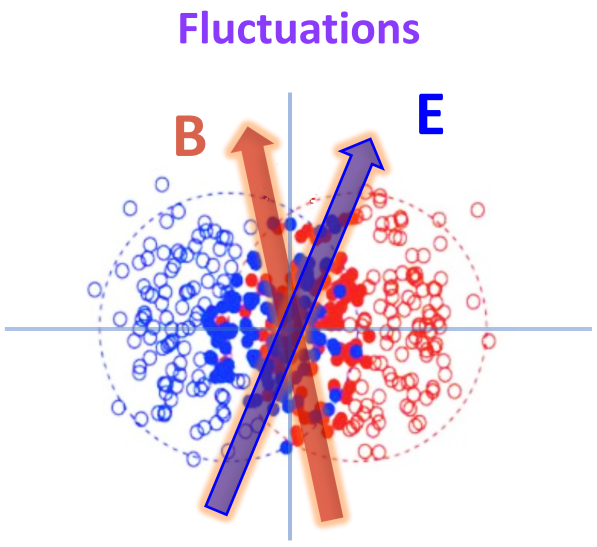


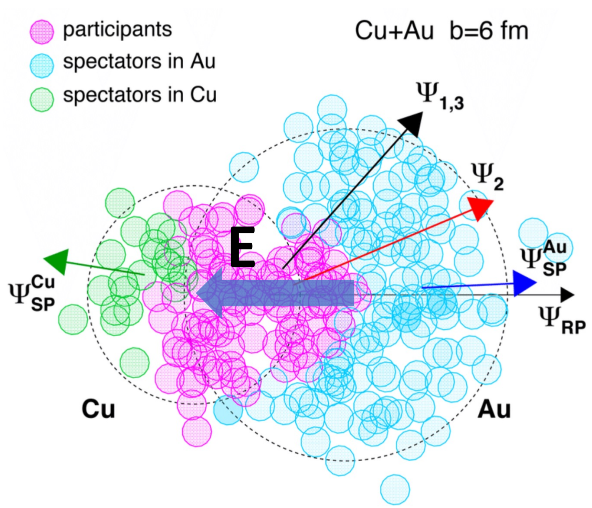
Smallness (fm level) + relativistic enhancement = very strong B field

$$eB \sim \gamma \alpha_{\mathrm{EM}} \frac{Z}{b^2} \sim 10^{18}\ \mathrm{G}$$

(RHIC Au+Au 200 GeV, b=10 fm)

Electric fields in HICs





Nucleon distribution fluctuations or asymmetric collisions (e.g., Cu + Au) or Faraday induction by B-field decay or ……
= very strong E fields (comparable to B fields)

EM effects in heavy-ion collisions

- EM effects in matter (off-central collisions)
    - Chiral magnetic/separation effect
    - Chiral electric separation effect
    - (Inverse) Magnetic catalysis of chiral symmetry breaking
    - Anisotropic pressure and viscosities
    - de Haas – van Alphen effect
    - Einstein – de Haas effect
    - … …
- EM effects in vacuum (UPCs)
    - Schwinger pair production
    - Vacuum birefringence
    - Breit – Wheeler process
    - Photon scattering
    - Vacuum instability
    - … …

EM effects in heavy-ion collisions

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EM fields + matter coupled evolution and distribution?

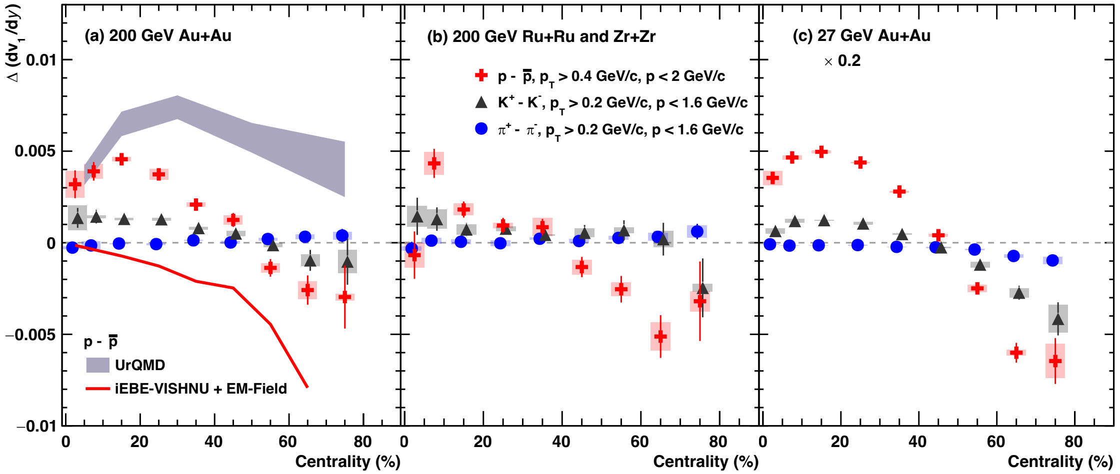
- EM effects in vacuum (UPCs)
    - Schwinger pair production
    - Vacuum birefringence
    - Breit – Wheeler process
    - Photon scattering
    - Vacuum instability
    - … …

Non-perturbative strong-field physics?

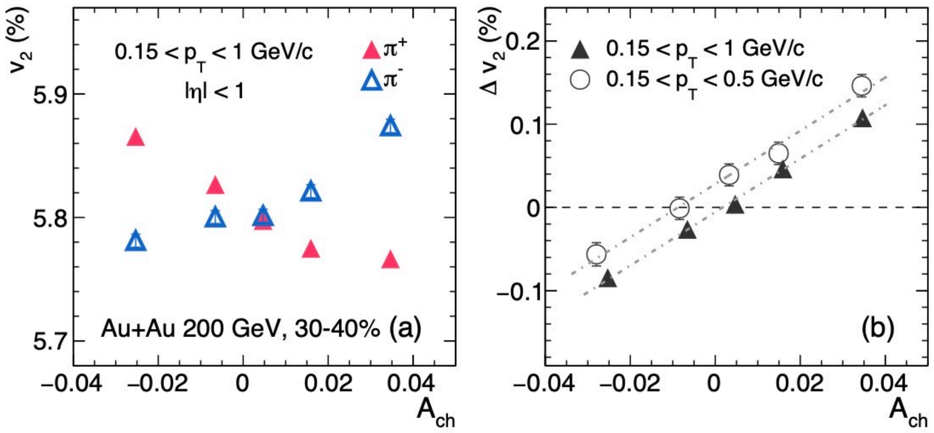
EM fields in matter: 1. Anisotropic viscosities

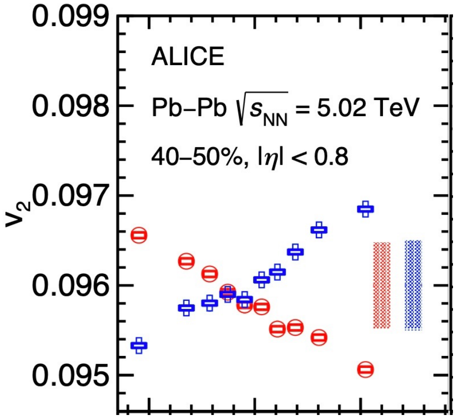
Strong indication of EM fields in HICs

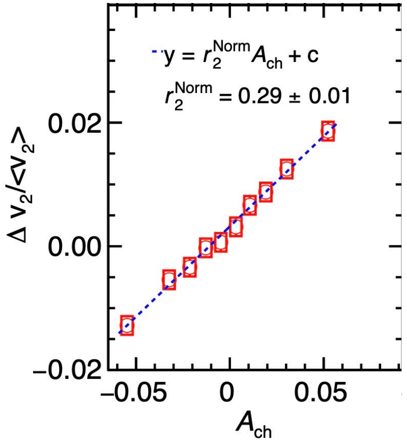
- v1 splitting of charged light flavors measurement by STAR (STAR 2023)



- v2 splitting of charged light flavors measurement by STAR and ALICE (STAR 2022, ALICE 2023)

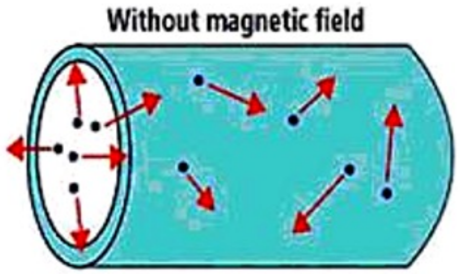


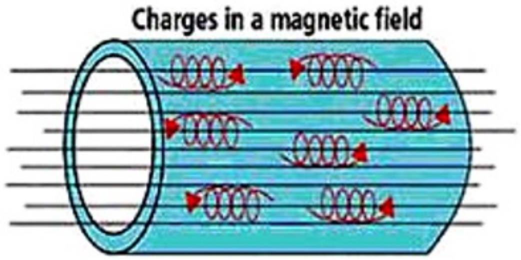




Strong-field magnetohydrodynamics

- Though there may be non-hydro contribution, MHD may provide a benchmark for understanding v1, v2 splitting of light flavors
- What are special for strong-field MHD? Anisotropic pressure and viscosities





Ideal fluid

$$P_\perp = P - MB \qquad P_\parallel = P$$

$$T^{\mu\nu}_{F0} = \mathrm{diag}(\varepsilon, P_\perp, P_\perp, P_\parallel) \Leftarrow \text{In rest frame}$$

Lorentz boost $\Rightarrow$

$$T^{\mu\nu}_{F0} = \varepsilon u^\mu u^\nu - P_\perp \Xi^{\mu\nu} + P_\parallel b^\mu b^\nu$$

$$\Xi^{\mu\nu} \equiv \Delta^{\mu\nu} + b^\mu b^\nu$$

Direction of B ($b^\mu b^\nu$)

$$\Delta^{\mu\nu} \equiv g^{\mu\nu} - u^\mu u^\nu$$

$$1/T \ll \text{Larmor radius } R_T = T/eB \leq \lambda_{\rm mfp}$$

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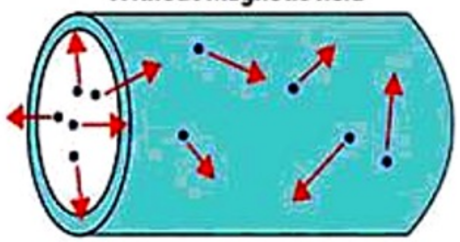

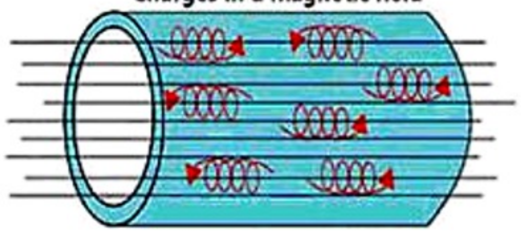

$$1/T \ll \text{Larmor radius } R_T = T/eB \leq \lambda_{\rm mfp}$$

Viscous fluid: seven viscosities

$$\theta \equiv \partial_\mu u^\mu$$

$$\begin{aligned}\tau^{\mu\nu} &= 2\eta_0\left(w^{\mu\nu} - \Delta^{\mu\nu}\theta/3\right) + \eta_1\left(\Delta^{\mu\nu} - \frac{3}{2}\Xi^{\mu\nu}\right)\left(\theta - \frac{3}{2}\phi\right) - 2\eta_2\left(b^\mu\Xi^{\nu\alpha}b^\beta + b^\nu\Xi^{\mu\alpha}b^\beta\right)w_{\alpha\beta} \\ &- 2\eta_3\left(\Xi^{\mu\alpha}b^{\nu\beta} + \Xi^{\nu\alpha}b^{\mu\beta}\right)w_{\alpha\beta} + 2\eta_4\left(b^{\mu\alpha}b^\nu b^\beta + b^{\nu\alpha}b^\mu b^\beta\right)w_{\alpha\beta} + \frac{3}{2}\zeta_\perp\Xi^{\mu\nu}\phi + 3\zeta_\parallel b^\mu b^\nu\varphi,\end{aligned}$$

$$w^{\mu\nu} \equiv \frac{1}{2}\left(\nabla^\mu u^\nu + \nabla^\nu u^\mu\right).$$

$$\phi \equiv \Xi^{\mu\nu}w_{\mu\nu}; \qquad \varphi \equiv b^\mu b^\nu w_{\mu\nu}$$

(XGH, Sedrakian, Rischke 2011; Hernandez, Kovtun 2017; Grozdanov, Hofman, Iqbal 2017; Hattori-Hongo-XGH 2022)

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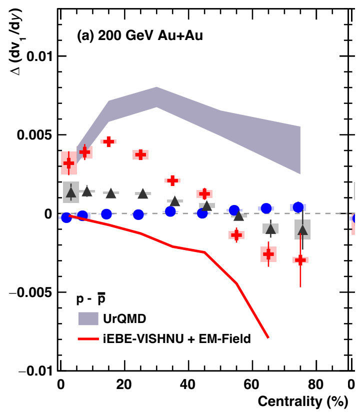

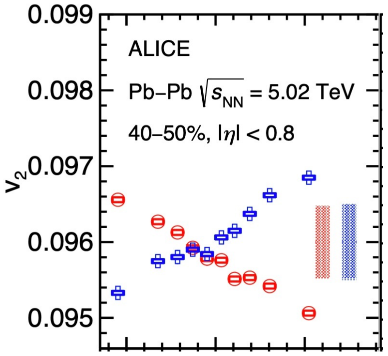

Viscous fluid: seven viscosities

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$$\tau^{\mu\nu} = 2\eta_0\left(w^{\mu\nu} - \Delta^{\mu\nu}\theta/3\right) + \eta_1\left(\Delta^{\mu\nu} - \frac{3}{2}\Xi^{\mu\nu}\right)\left(\theta - \frac{3}{2}\phi\right) - 2\eta_2\left(b^\mu \Xi^{\nu\alpha} b^\beta + b^\nu \Xi^{\mu\alpha} b^\beta\right) w_{\alpha\beta}$$
$$- 2\eta_3\left(\Xi^{\mu\alpha} b^{\nu\beta} + \Xi^{\nu\alpha} b^{\mu\beta}\right) w_{\alpha\beta} + 2\eta_4\left(b^{\mu\alpha} b^\nu b^\beta + b^{\nu\alpha} b^\mu b^\beta\right) w_{\alpha\beta} + \frac{3}{2}\zeta_\perp \Xi^{\mu\nu}\phi + 3\zeta_\parallel b^\mu b^\nu \varphi,$$

$w^{\mu\nu} \equiv \frac{1}{2}\left(\nabla^\mu u^\nu + \nabla^\nu u^\mu\right).$

$\phi \equiv \Xi^{\mu\nu} w_{\mu\nu};$

$\varphi \equiv b^\mu b^\nu w_{\mu\nu}$

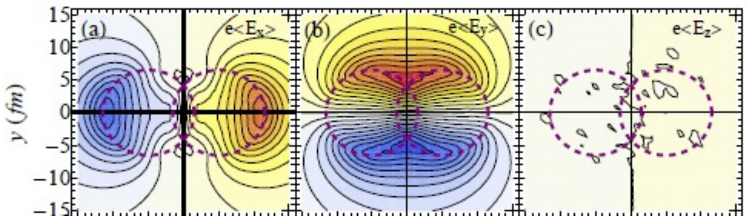
Test strong-field MHD?
Measure anisotropic viscosities?

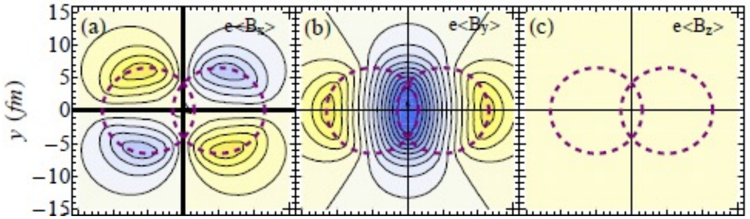
EM fields in matter: 2. Time-varying fields

Spacetime dependence of EM fields

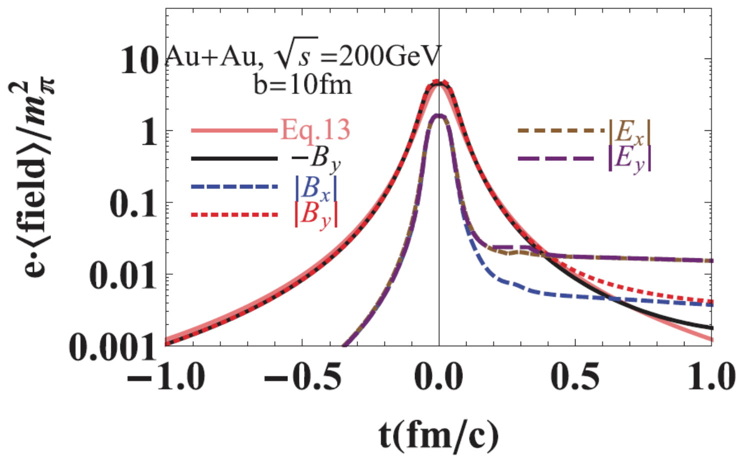
- The EM fields are inhomogeneous

(Deng, XGH 2012; and many others)





- The EM fields are rapidly decaying if the matter is insulating



Well fitted by

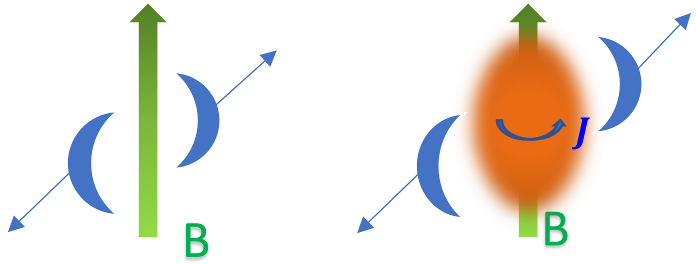
$$\langle eB_y(t)\rangle \approx \frac{\langle eB_y(0)\rangle}{(1+t^2/t_B^2)^{3/2}}$$

Life time of B field

$$t_B \approx R_A/(\gamma v_z) \approx \frac{2m_N}{\sqrt{s}} R_A$$

Realistic evolution of B fields

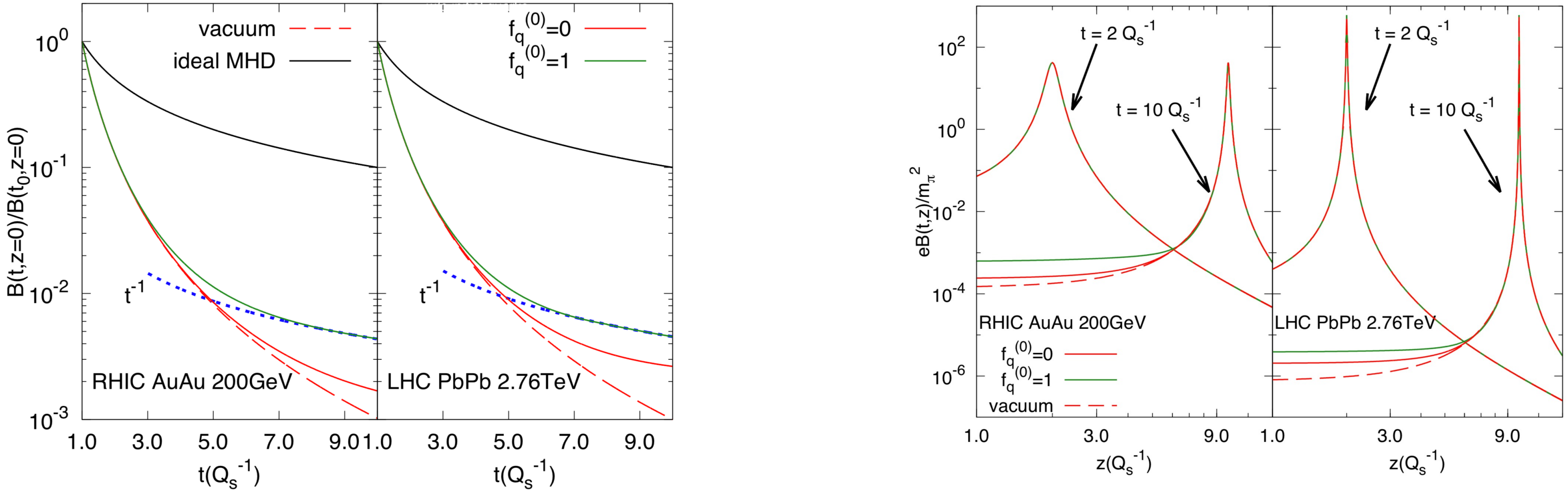
- If the matter is conducting



In vacuum:
moving charges

In conductor:
Faraday effect

- Solve coupled kinetic equation of partons and Maxwell equations:

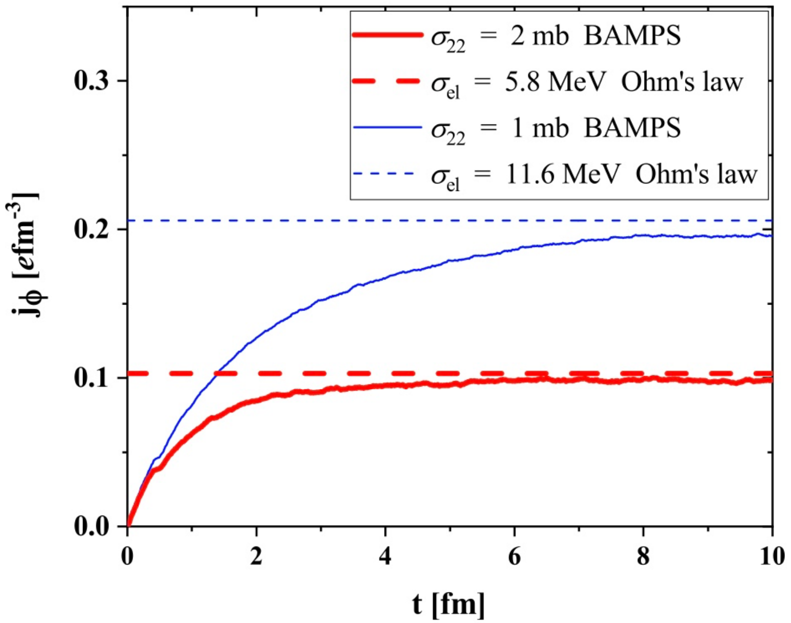


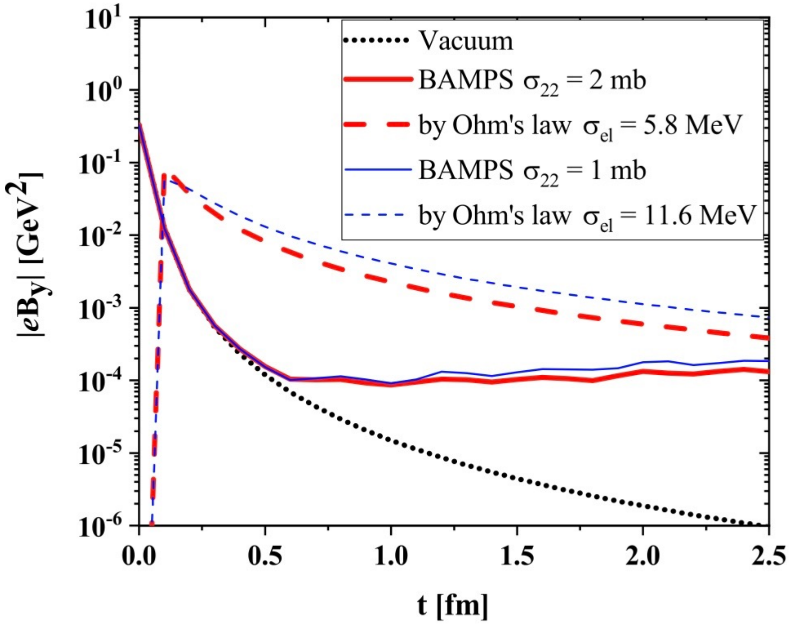
(Yan, XGH 2021)

Realistic evolution of B field

- Similar results from BAMPS with binary collisions (Wang, Zhao, Greiner, Xu, Zhuang 2021)

- Electric current: incomplete Ohm's law
- B field



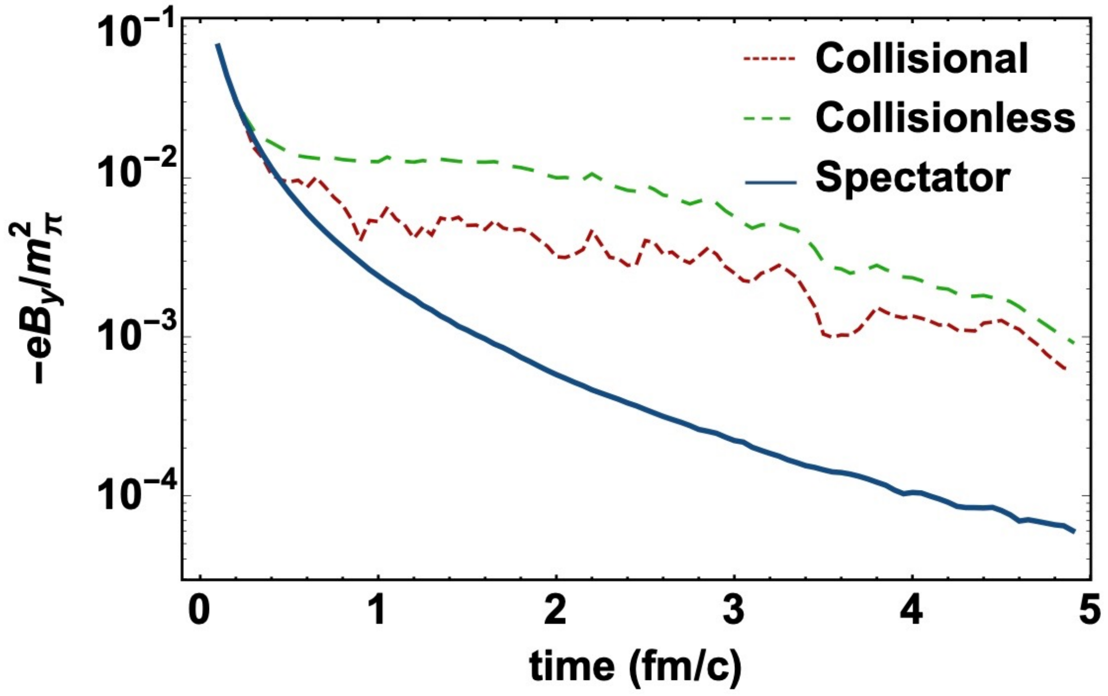


"The relaxation time is larger than the lifetime of the external magnetic field for the QCD matter in relativistic heavy-ion collisions"
"Our results show a strong suppression by two orders of magnitude in the magnetic field, relatively to calculations assuming the validity of Ohm's law. "

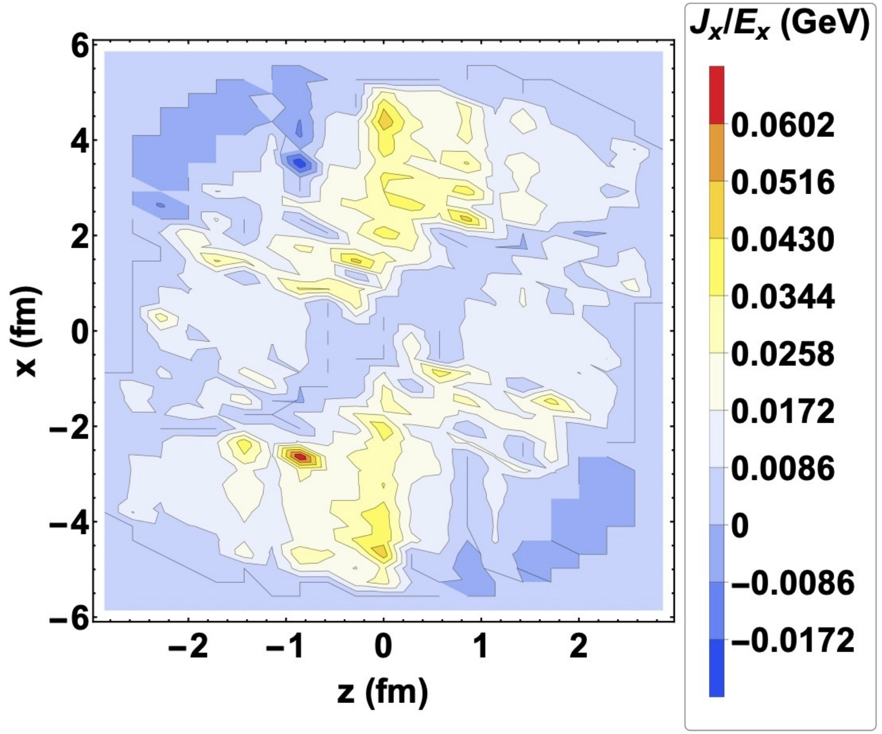
Realistic evolution of B field

- Similar results from USTC group (Zhang-Sheng-Pu-Wang etal 2022)

- B fields:



- Effective conductivity



Note that the effective conductivity can be negative

CME under time-varying B field

- All these simulations show strong time-dependence of B field, and thus indicating incomplete chiral magnetic response

$$\boldsymbol{J}_V(t) \neq \frac{e^2\mu_A}{2\pi^2}\boldsymbol{B}(\mathrm{t})$$

- In momentum space (Son-Yamamoto 2012; Satow 2014)

$$J_V^i(\omega,\boldsymbol{k}) = G_R^{ij,-}(\omega,\boldsymbol{k})A^j(\omega,\boldsymbol{k})$$

$$G_R^{ij,-} = ie^2\frac{\mu}{4\pi^2}\epsilon^{ijk}k^k - e^2\frac{\mu\omega}{4\pi^2}\int\frac{d\Omega_{\hat{\mathbf{p}}}}{(4\pi)}\frac{\epsilon^{ilk}\hat{p}^j - \epsilon^{jlk}\hat{p}^i}{-i\omega + i\hat{\mathbf{p}}\cdot\mathbf{k} + \tau^{-1}}\hat{p}^l k^k$$

- This could modify the chiral anomalous hydrodynamics, e.g., AVFD (Shi, Jiang, Liao 2018)

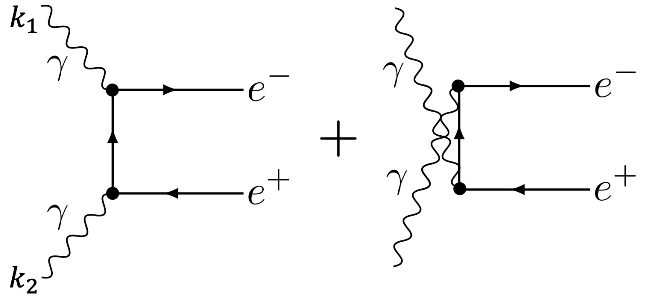
Provide a more reliable theoretical basis for understanding CME-sensitive observables?

<u>EM fields in vacuum: UPC</u>

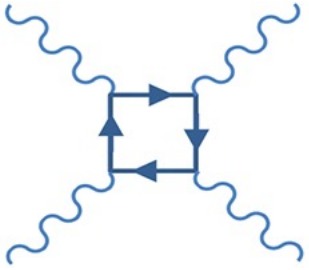
Non-perturbative QED effects in UPC?

- Two typical processes in UPC

(STAR 2019)



Breit-Wheeler process



(ATLAS 2016)

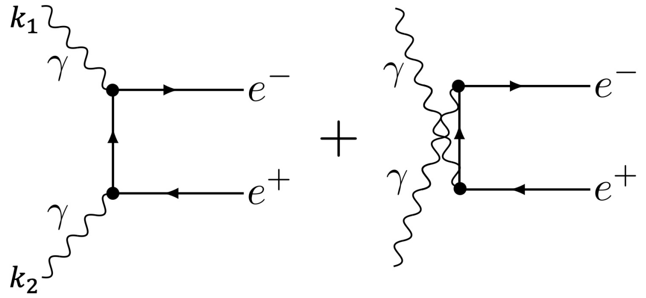
Photon-photon scattering

- Why perturbative treatment is sufficient even when $eE/m^2 \gg 1$?

Non-perturbative QED effects in UPC?

- Two typical processes in UPC

(STAR 2019)



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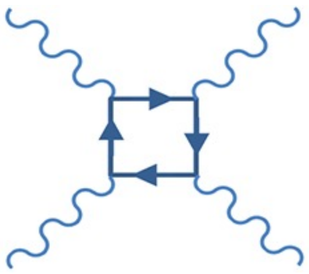

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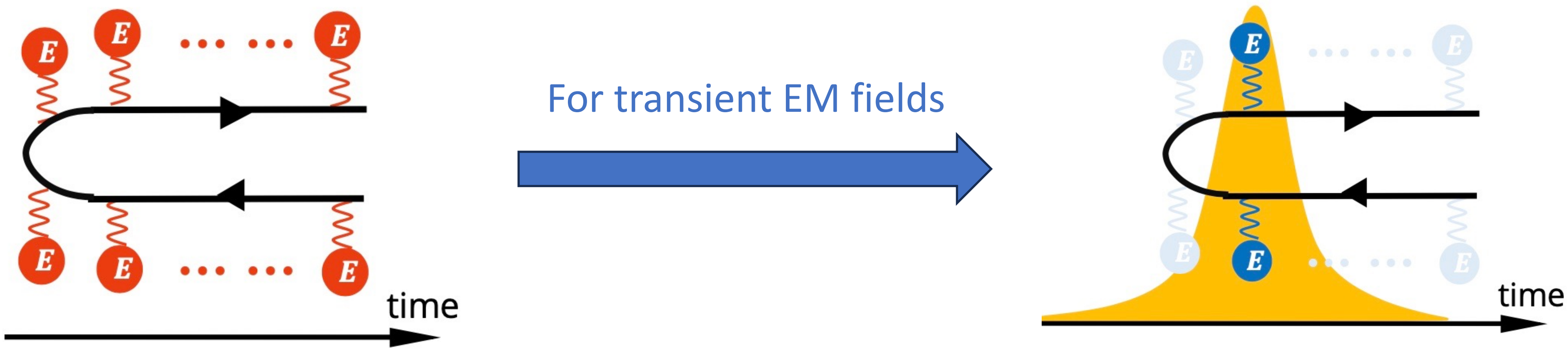
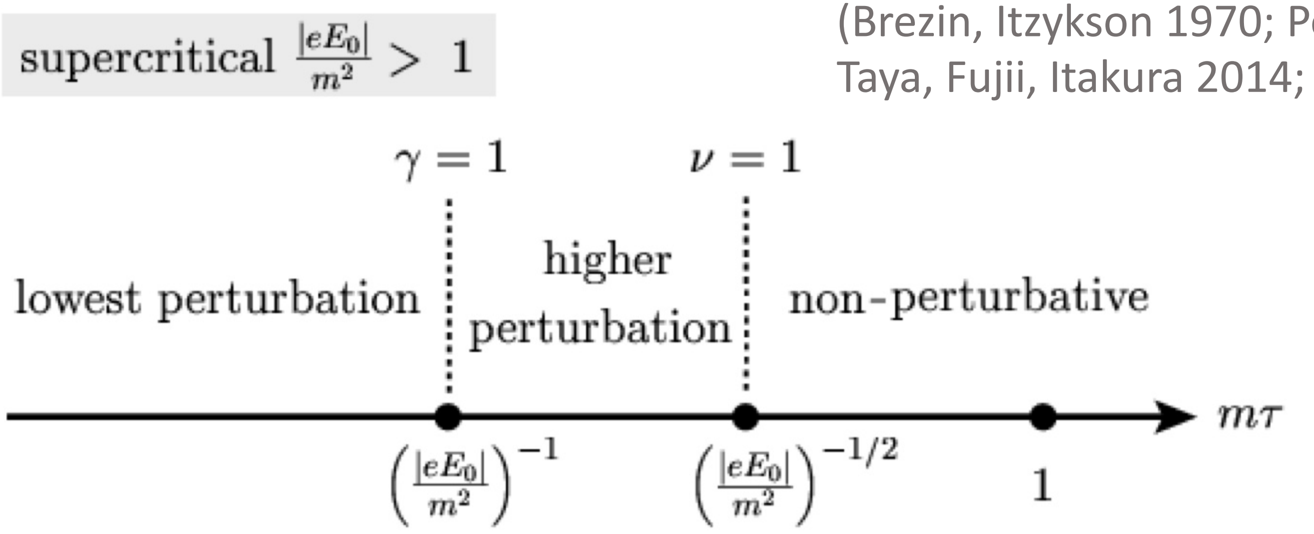


Non-perturbative QED effects in UPC?

- For time varying fields, not only the Schwinger parameter $\theta = eF/m^2$ but also $\gamma = m/(eF\, t_B)$ and $\nu = eFt_B^2$ important

(Brezin, Itzykson 1970; Popov 1971; Taya, Fujii, Itakura 2014; Taya, Nishimura, Ohnishi 2024)



- The life-time of EM field

$$t_B \approx R_A/(\gamma v_z) \approx \frac{2m_N}{\sqrt{s}} R_A$$

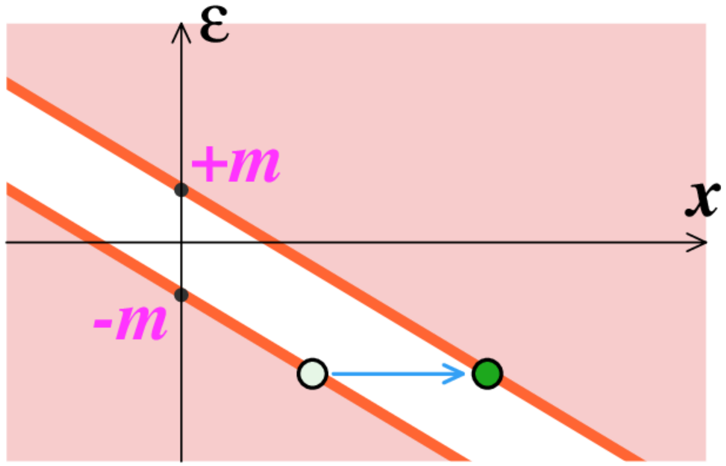
Non-perturbativeness →

$$\sqrt{s} \leq \alpha_{EM} \frac{2Zm_N}{b^2} R_A^2 \sim O(\mathrm{GeV})$$

Lower-energy UPC makes non-perturbativeness more favored

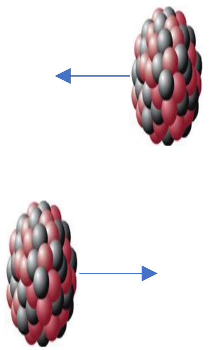
Non-perturbative QED effects in UPC?

- Schwinger pair production

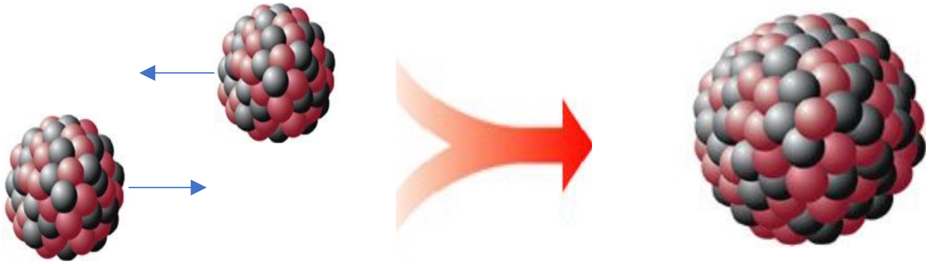


$$N_{e^{\pm}} = \frac{(eE)^2 VT}{(2\pi)^3} \times \exp\left[-\pi \frac{m^2}{eE}\right]$$

- Is UPC (or non-UPC) at lower and lower energies good place for Schwinger pair?



Or



HIAF, NICA, FAIR, BES@RHIC?

Summary

Summary

- Strong EM fields in HICs
- Can charge-dependent v1, v2, v3 be used to extract anisotropic viscosities?
- Time-varying EM fields lead to new contribution to CME, CMW, etc?
- Low-energy UPC to detect non-perturbative QED phenomena?

Thank you