



第二届旋转与磁场下的QCD物质研讨会

The evolution of the electromagnetic field in the quark-gluon plasma

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Outline

1. Introduction

2. Physics induced by EB

A. Magnetic squeeze

B. photon's v_2

C. Charge-Dependent v_1

3. EB evolution

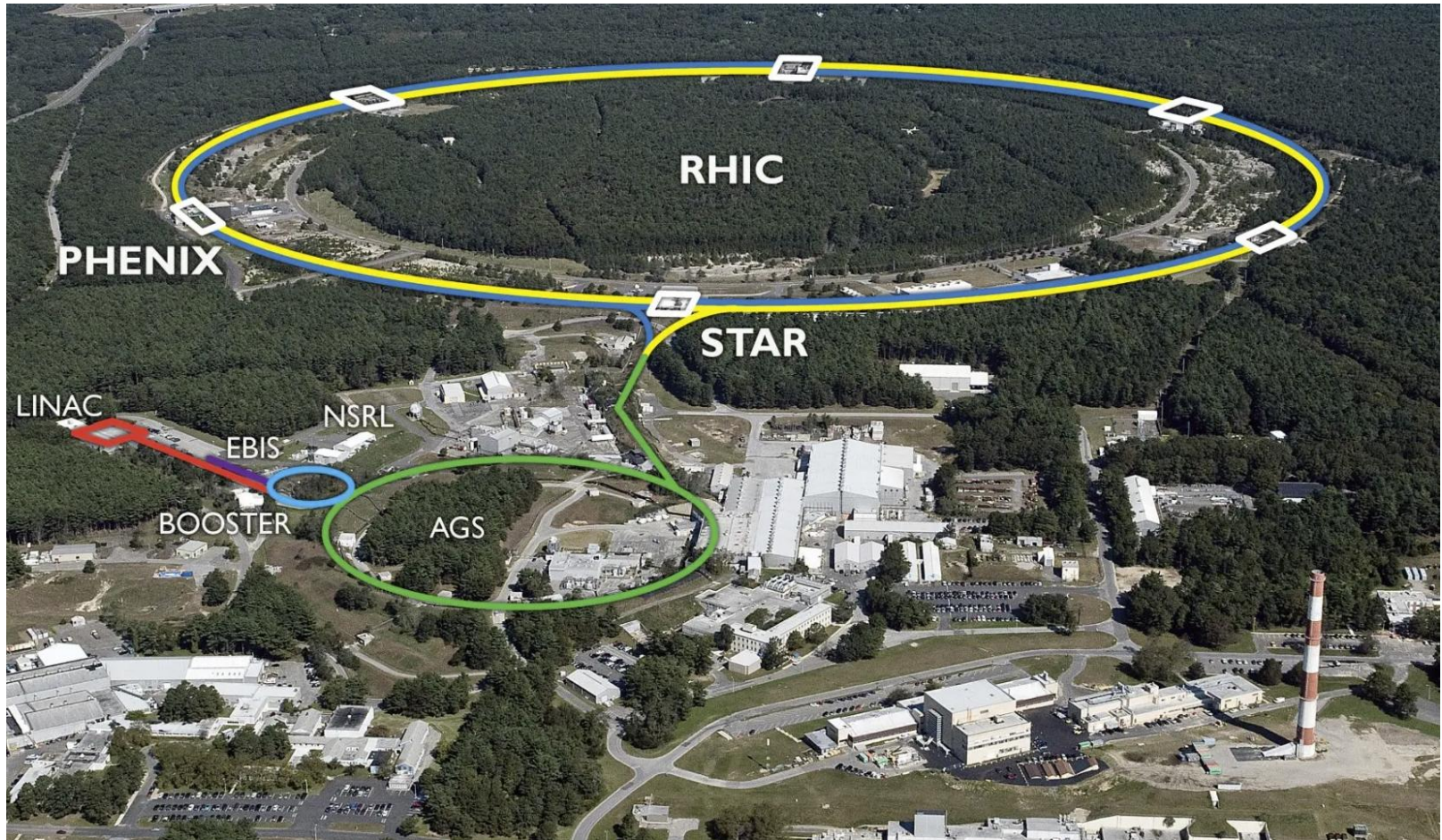
A. Conductivity on EB

B. Fluid vorticity on EB

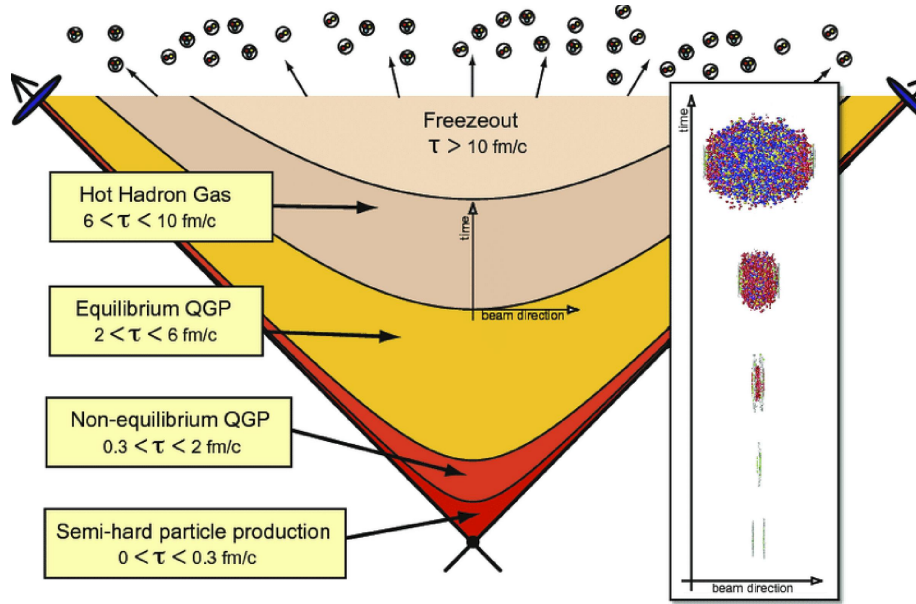
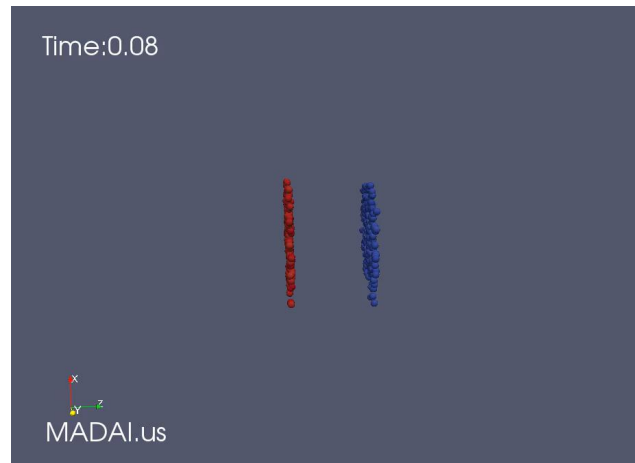
C. Chiral conductivity on EB

4. Conclusion and Future

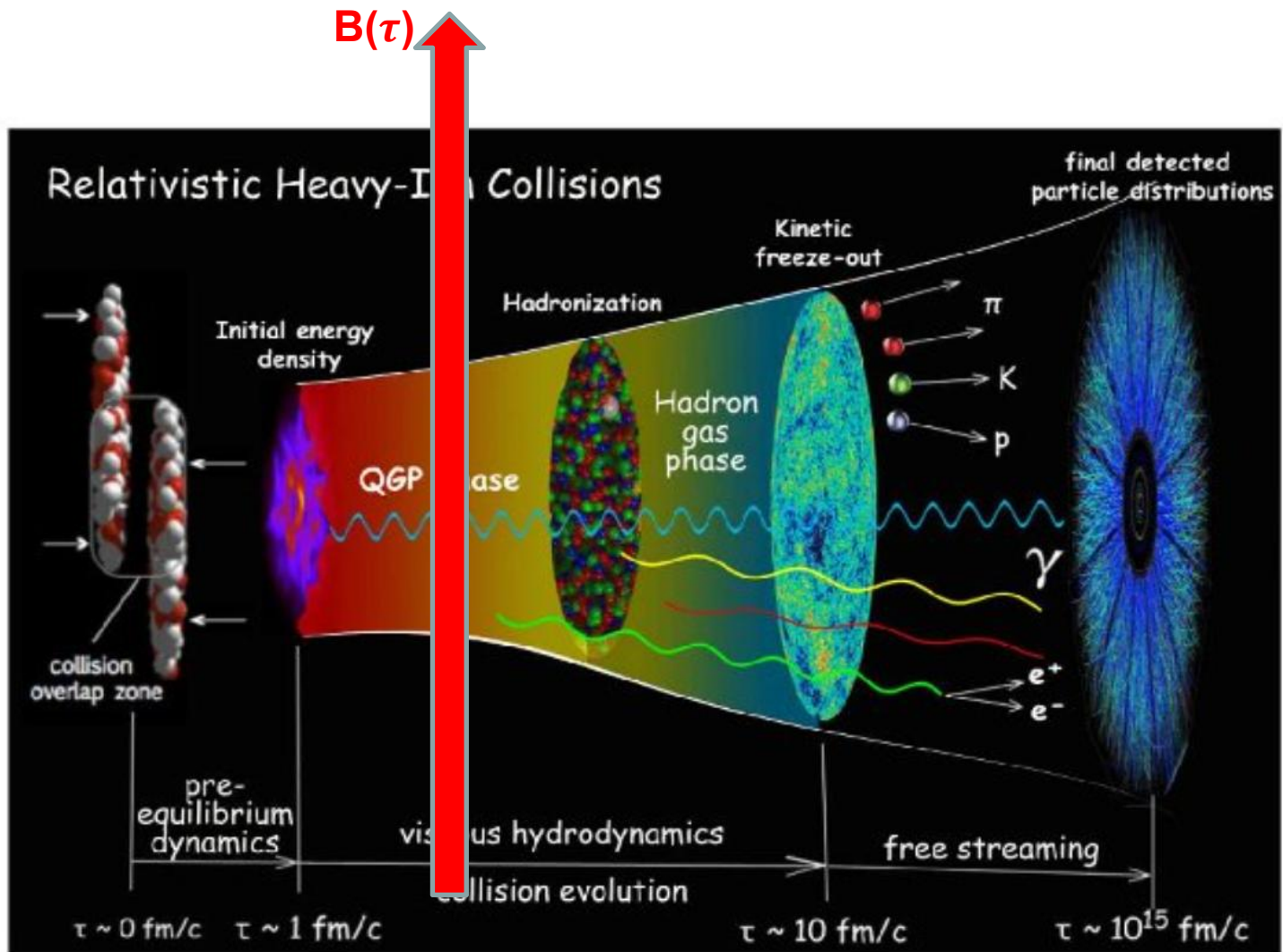
Introduction



Introduction



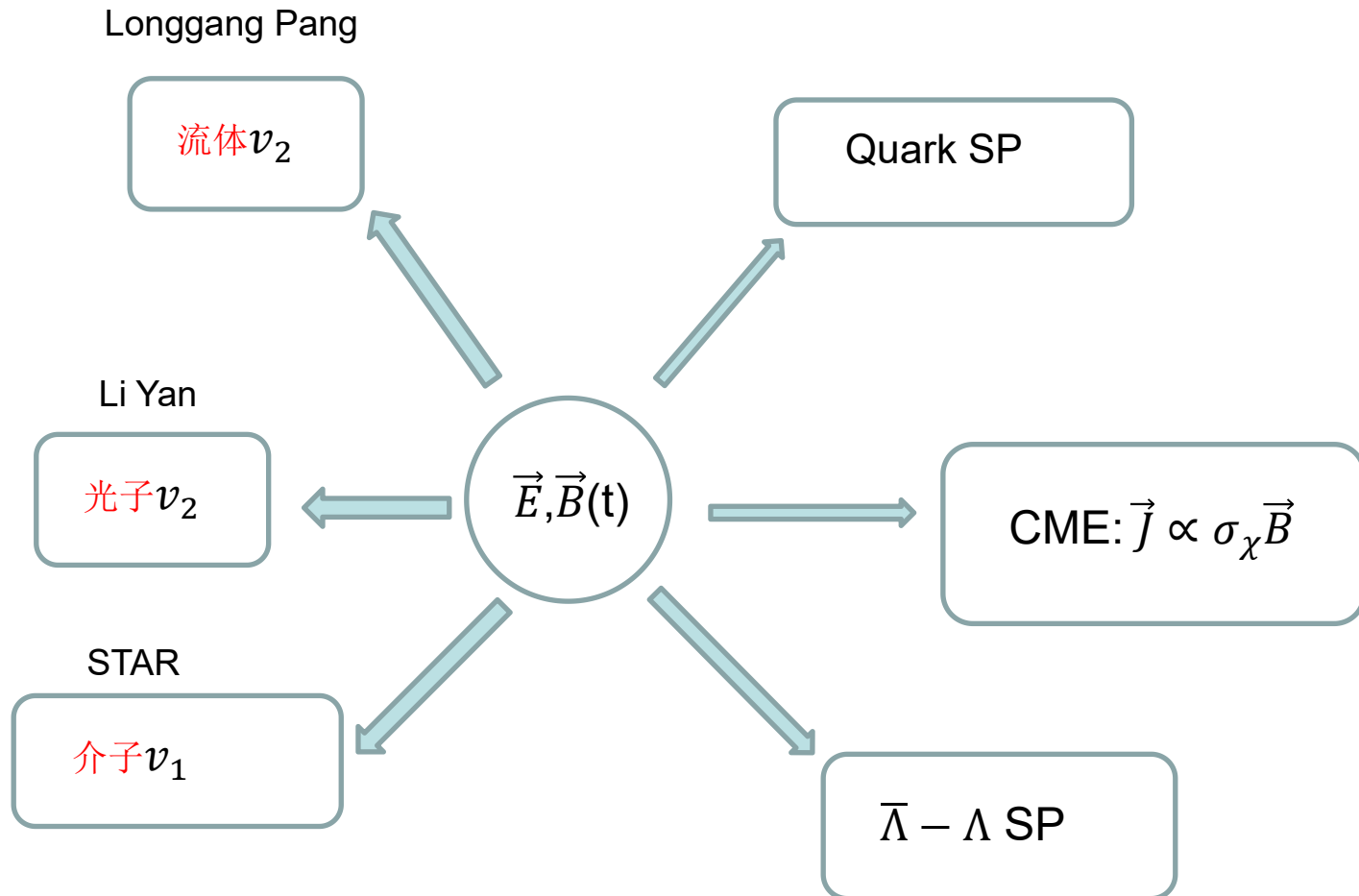
Introduction



made by Chun Shen

2. Physics induced by EB

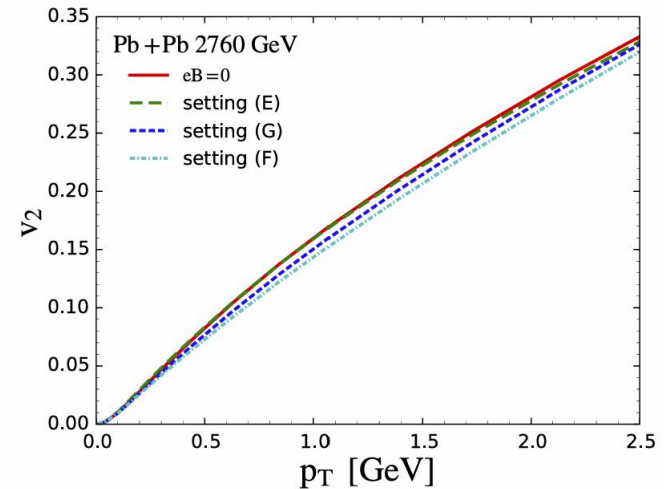
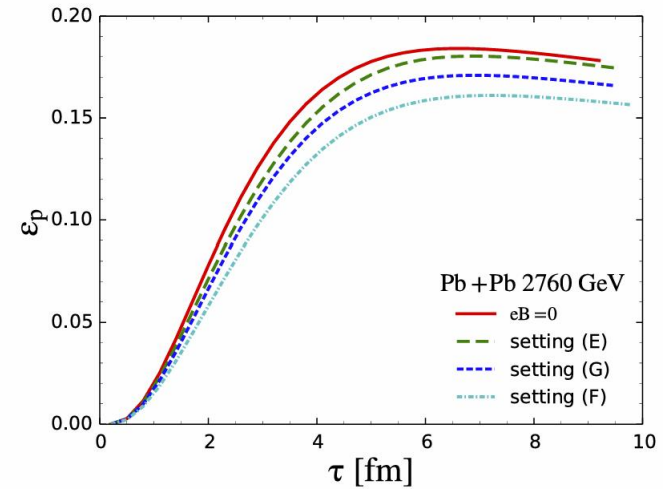
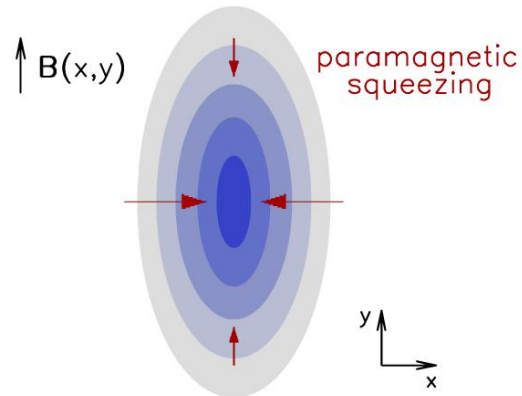
The electromagnetic fields in HIC are related to many physical phenomena.



2. Physics induced by EB

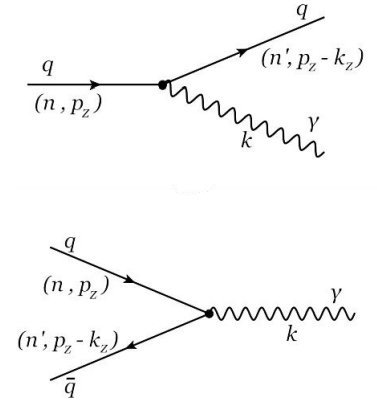
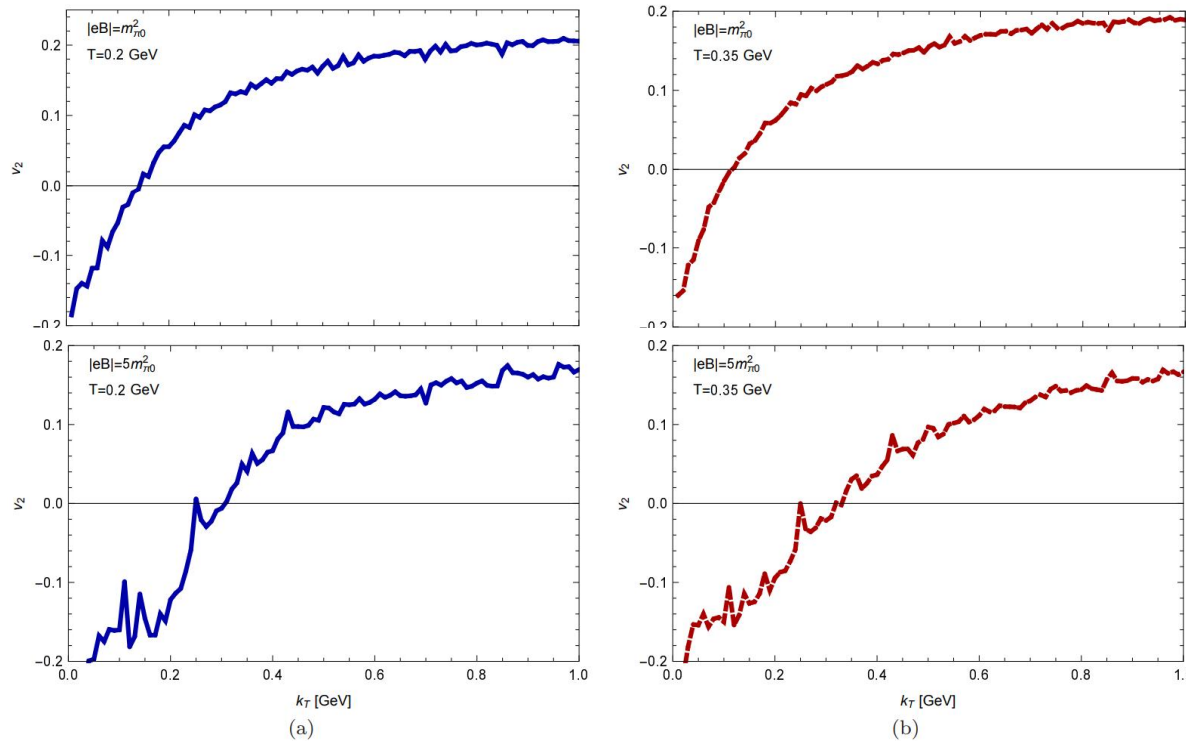
EB fields suppress the fluid v_2

$$F^x = \frac{\chi}{2} \partial_x |\mathbf{B}|^2, \quad F^y = \frac{\chi}{2} \partial_y |\mathbf{B}|^2,$$



2. Physics induced by EB

Nontrivial momentum dependence of the photon v_2

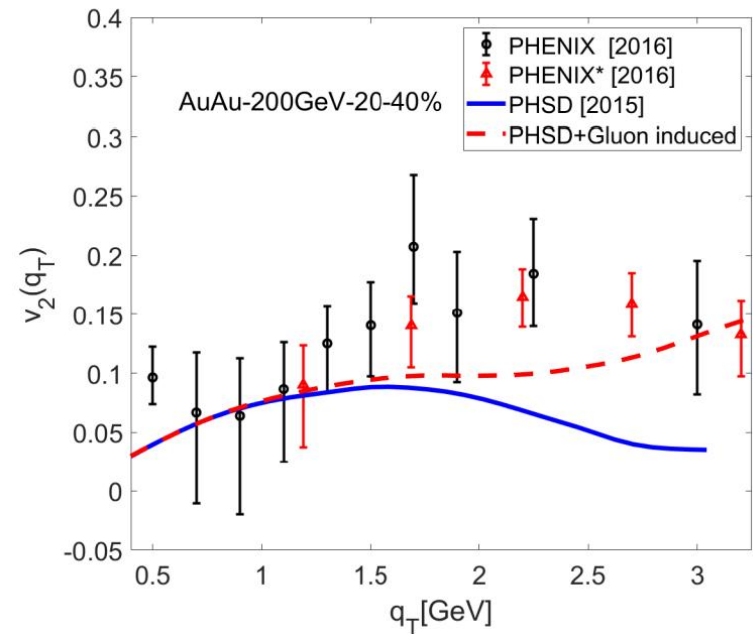
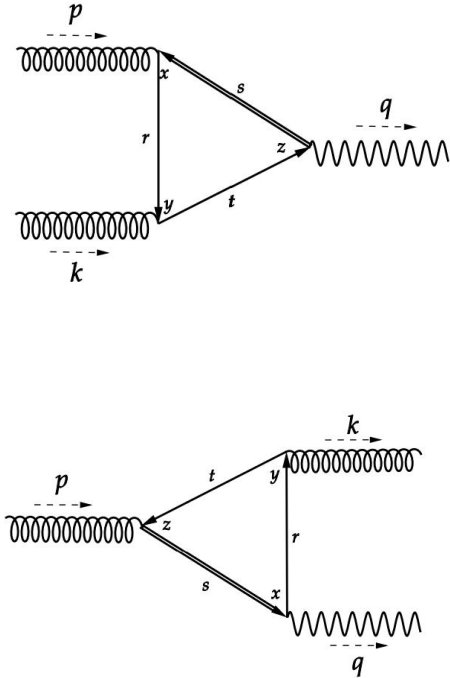


$$v_n(k_T) = -\frac{1}{(2\pi)^3 \mathcal{R}} \int_0^{2\pi} \frac{\text{Im} [\Pi_\mu^\mu(k)]}{\exp\left(\frac{k_0}{T}\right) - 1} \cos(n\phi) d\phi,$$

Xinyang Wang, Igor Shovkovy, Lang Yu, Mei Huang **Phys. Rev. D** **102**, 076010 (2020). Xinyang Wang, Igor A. Shovkovy, *Phys. Rev. D* (2024).

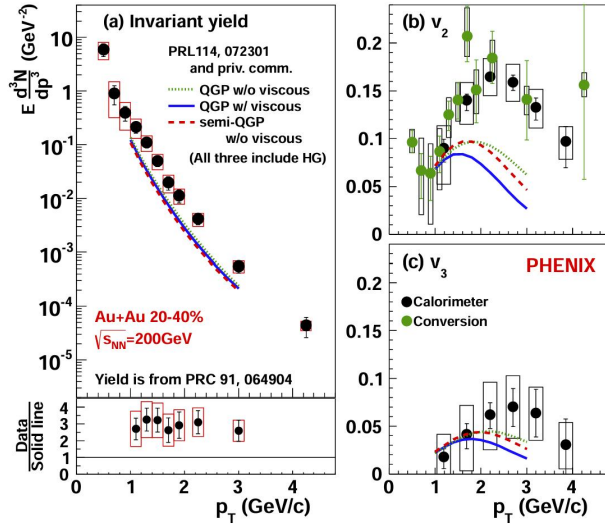
2. Physics induced by EB

gluon induced the photon v_2



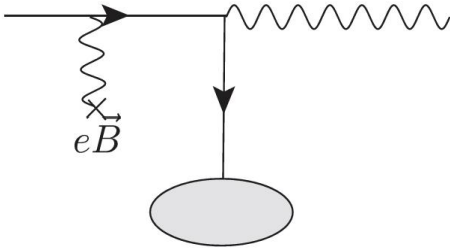
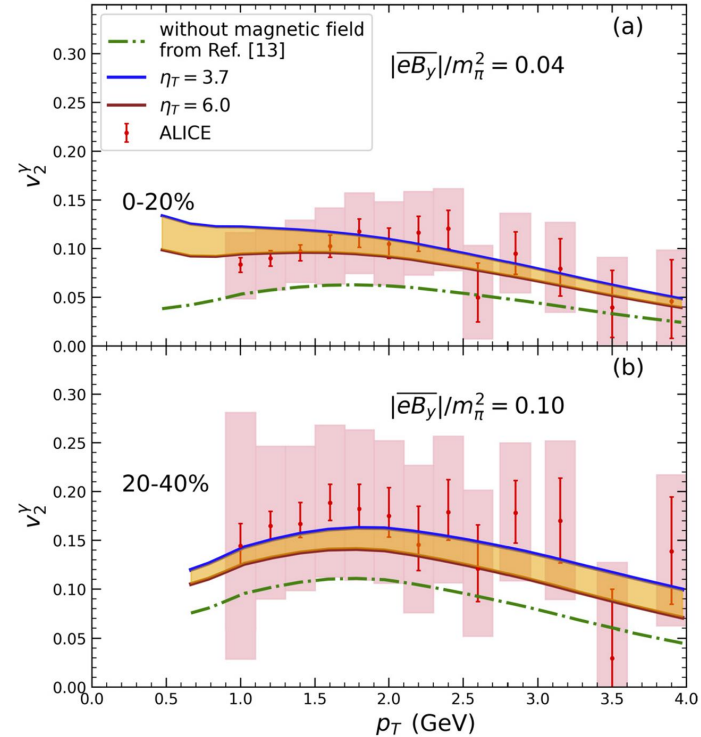
2. Physics induced by EB

EB fields contribute to the photon's v_2



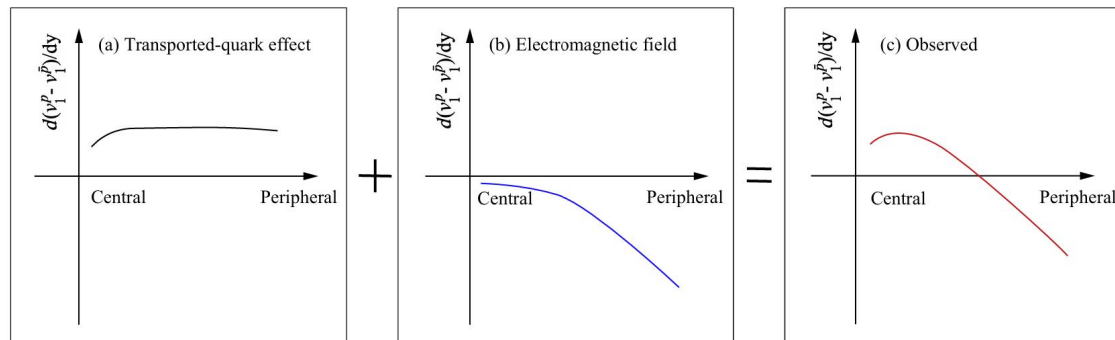
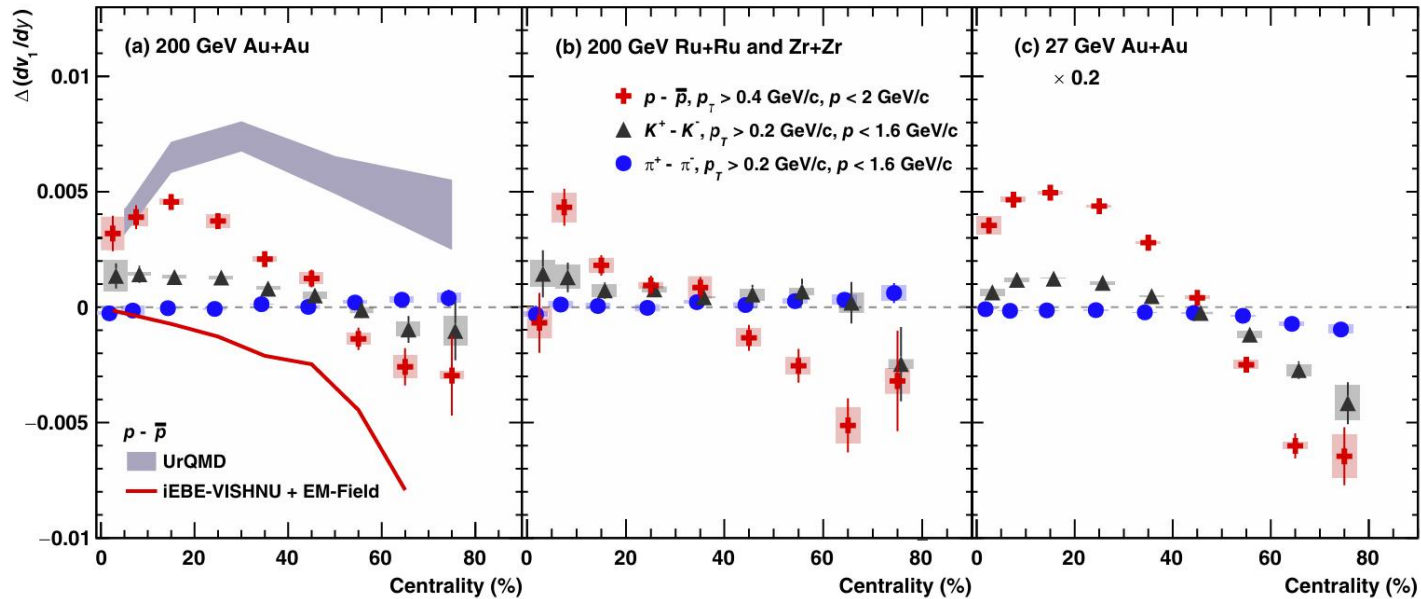
$$f_{EM} = \frac{c}{8\alpha_{EM}} \frac{\sigma_{el} n_{eq} (1 - n_{eq})}{T^3 p \cdot u} e Q_f F^{\mu\nu} p_\mu u_\nu$$

$$v_0^\gamma = \bar{v}_0 + v_0^{EM}, \quad v_2^\gamma = \frac{\bar{v}_2 \bar{v}_0 + v_2^{EM} v_0^{EM}}{\bar{v}_0 + v_0^{EM}}$$

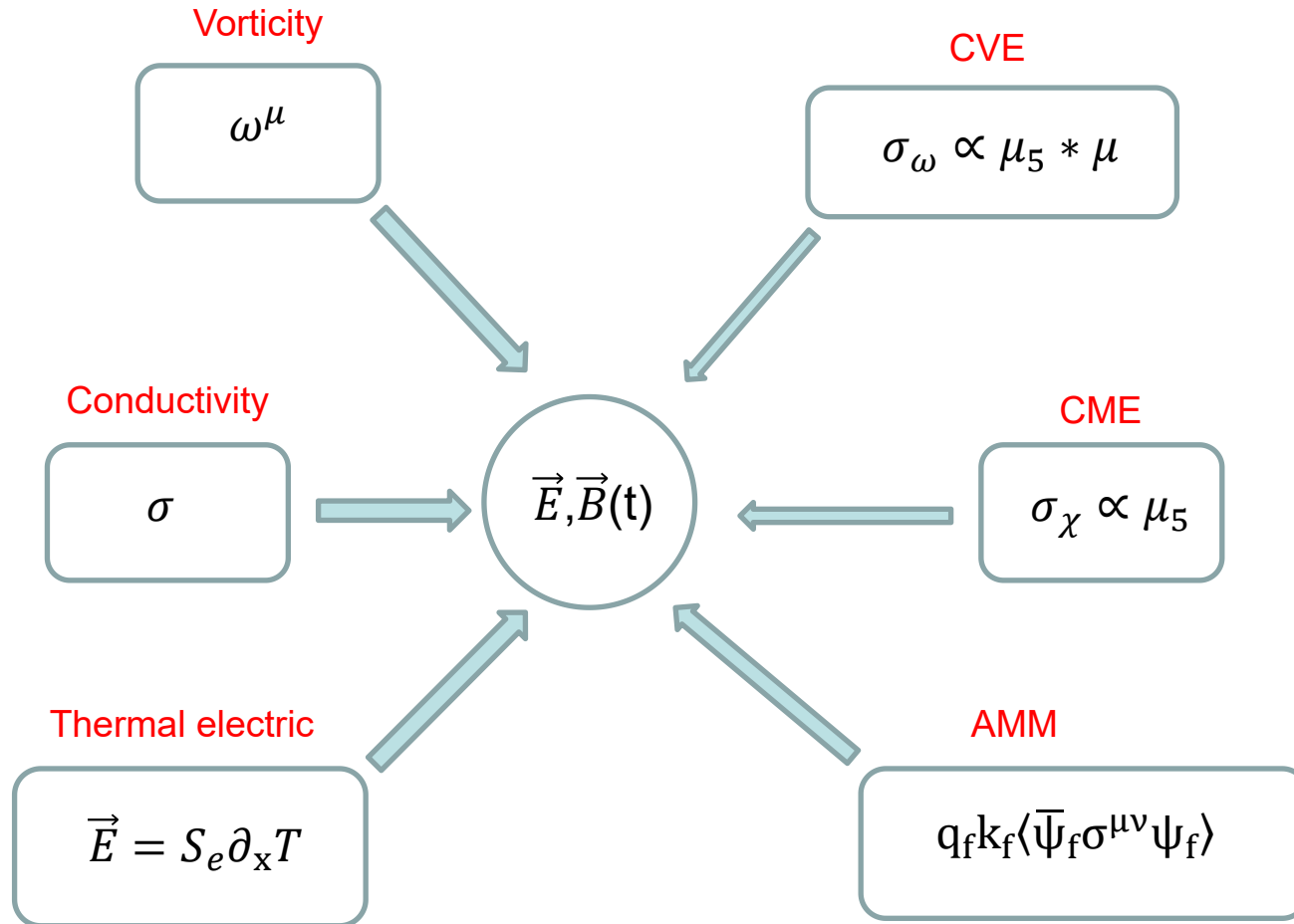


2. Physics induced by EB

EB Effect on v_1



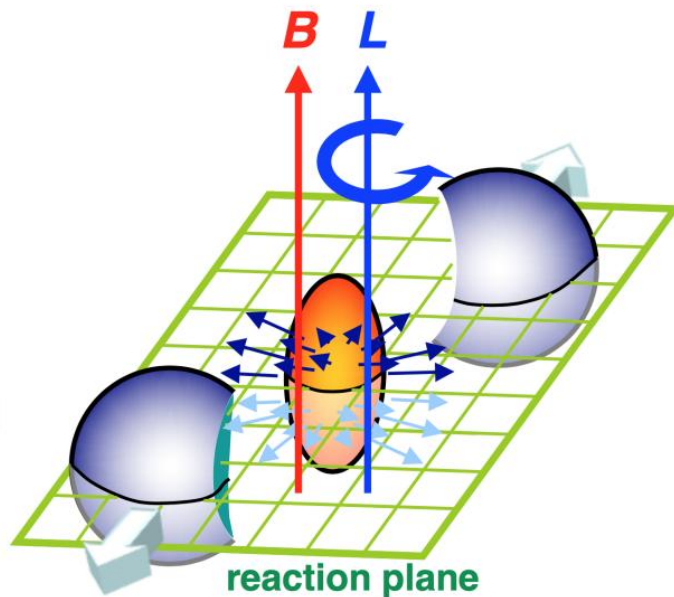
3. EB evolution



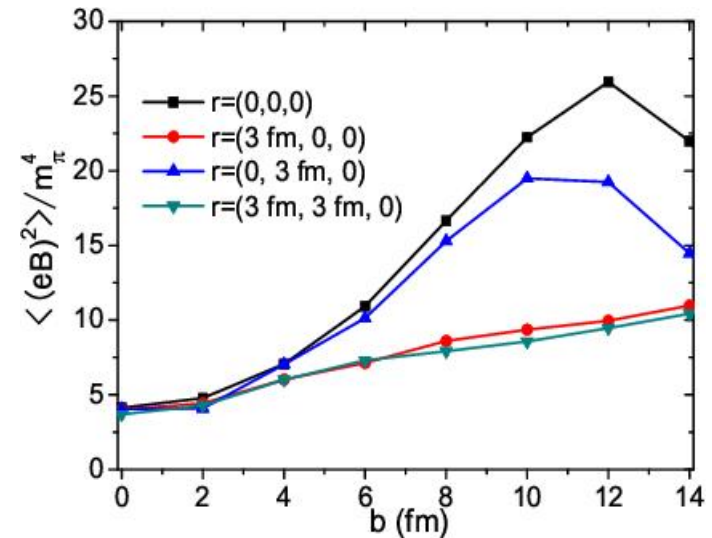
The evolution of the electromagnetic field is affected by various factors, such as classical effects: electric conductivity, vortical field, thermoelectric effect, etc.; and quantum effects: the chiral magnetic effect, the chiral vortical effect, the anomalous magnetic moment effect, etc.

3. EB evolution

The initial magnetic field



Maxim Chernodub



Bloczynski-Huang-Deng-Zhang-Liao

$$eB \sim m_\pi^2 \sim 10^{18} G$$

地表磁场: $eB \sim 0.25 - 0.65 G$

医用核磁共振设备的磁场强度: $1.5 \times 10^4 \sim 3 \times 10^4 G$

人造最强磁场（脉冲磁场）: $1.2 \times 10^7 G$

人造最强磁场（稳定磁场）: $4.5 \times 10^5 G$

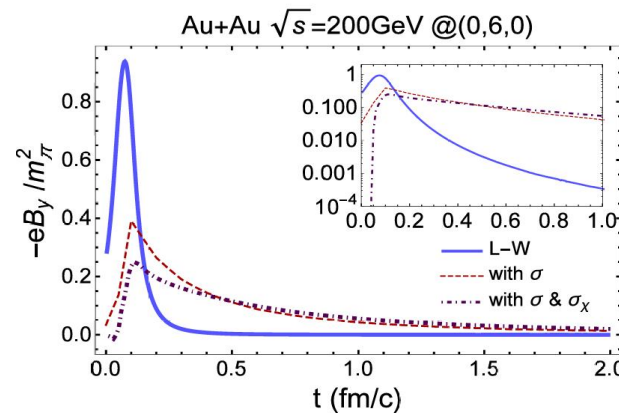
3. EB evolution

The analytical method to EB

1. Umut Gursoy, Dmitri Kharzeev, and Krishna Rajagopal. Phys. Rev., C89(5):054905, 2014.
2. Umut G'ursoy, Dmitri Kharzeev, Eric Marcus, Krishna Rajagopal, and Chun Shen. Phys. Rev., C98(5):055201, 2018.
3. Hui Li, Xin-li Sheng, and Qun Wang. *Physical Review C*, 94(4), 044903.
4. K Tuchin. PhysRevC.91.064902.
5.

$$\begin{aligned}(\nabla^2 - \partial_t^2 - \sigma \partial_t) \mathbf{E} + \sigma_\chi \nabla \times \mathbf{E} &= \partial_t \mathbf{J}_s + \nabla J_s^0, \\(\nabla^2 - \partial_t^2 - \sigma \partial_t) \mathbf{B} + \sigma_\chi \nabla \times \mathbf{B} &= -\nabla \times \mathbf{J}_s.\end{aligned}$$

$$\begin{aligned}B_\phi &= \frac{Q}{4\pi} \frac{v\gamma x_T}{\Delta^{3/2}} \left(1 + \frac{\sigma v\gamma}{2} \sqrt{\Delta}\right) e^A, \\B_r &= -\sigma_\chi \frac{Q}{8\pi} \frac{v\gamma^2 x_T}{\Delta^{3/2}} \left[\gamma(vt - z) + A\sqrt{\Delta}\right] e^A, \\B_z &= \sigma_\chi \frac{Q}{8\pi} \frac{v\gamma}{\Delta^{3/2}} \left[\gamma^2(vt - z)^2 \left(1 + \frac{\sigma v\gamma}{2} \sqrt{\Delta}\right) \right. \\&\quad \left. + \Delta \left(1 - \frac{\sigma v\gamma}{2} \sqrt{\Delta}\right)\right] e^A,\end{aligned}$$



3. EB evolution

The numerical method to EB

The Maxwell equation

$$\partial_{\mu} F^{\mu\nu} = J^{\nu}, \partial_{\mu} \tilde{F}^{\mu\nu} = 0$$

$$J^{\mu} = n_e u^{\mu} + v^{\mu} + \sigma E^{\mu} + \sigma_{\chi} B^{\mu}$$

1. L. McLerran and V. Skokov. Nucl. Phys., A929:184–190, 2014.
2. Kirill Tuchin. Phys. Rev. C, 93(1):014905, 2016.
3. B. G. Zakharov. Phys. Lett., B737:262–266, 2014.
4. Huang A, She D, Shi S, Huang M, Liao J 2023 Phys. Rev. C 107 034901
5. Huang A, Wu X Y, Huang M 2024 Phys. Rev. D 110 094032

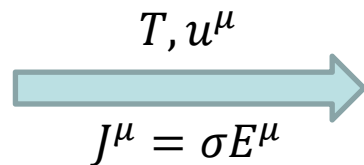
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3. EB evolution

Conductivity σ on EB

Hydro background

$$D_\mu T^{\mu\nu} = 0,$$

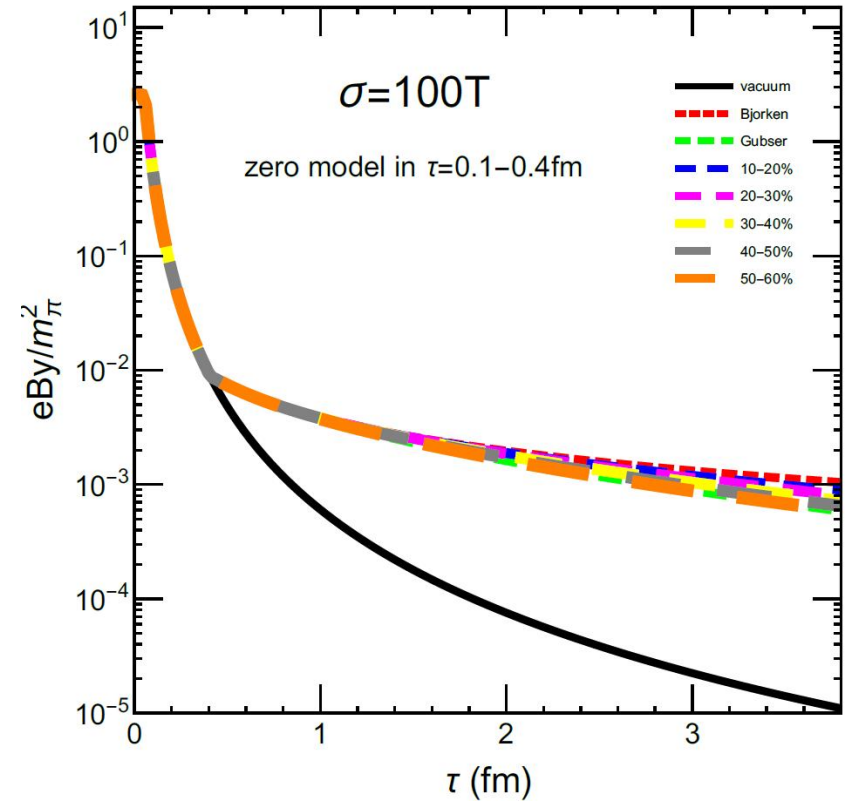
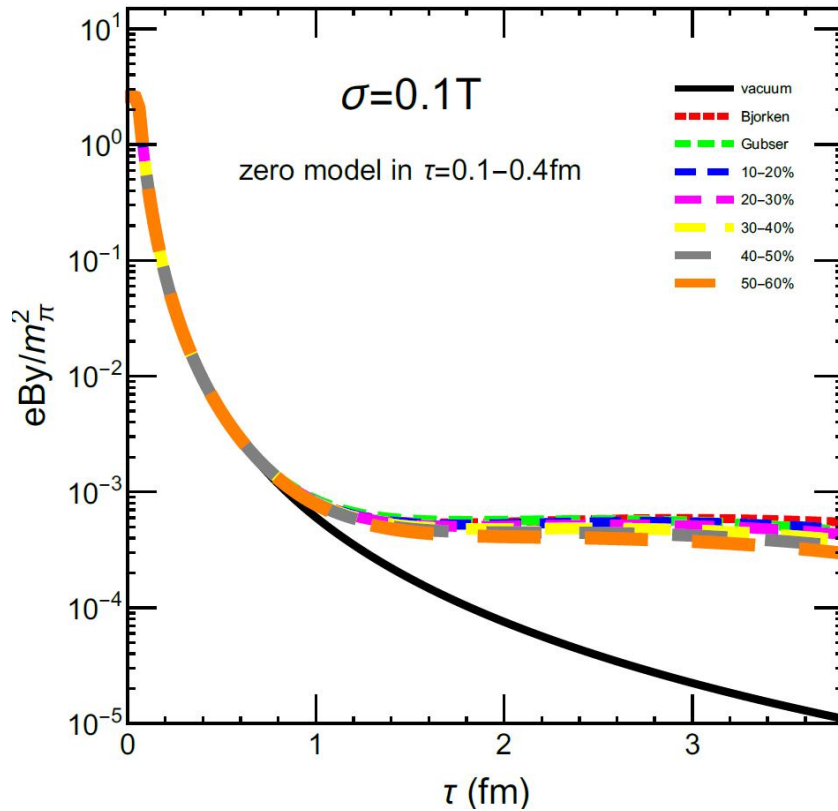


EB evolution

$$\begin{aligned} D_\mu F^{\mu\nu} &= J^\nu, \\ D_\mu \tilde{F}^{\mu\nu} &= 0 \end{aligned}$$

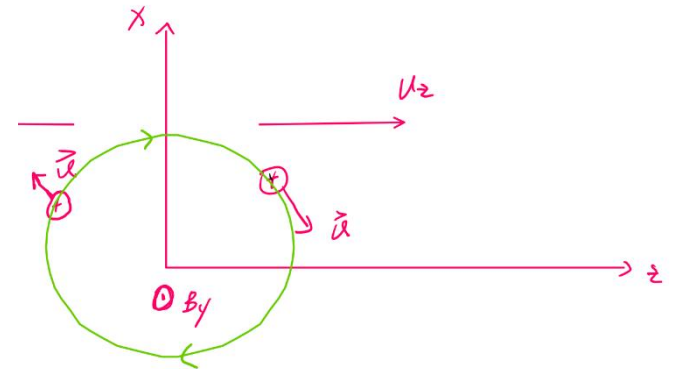
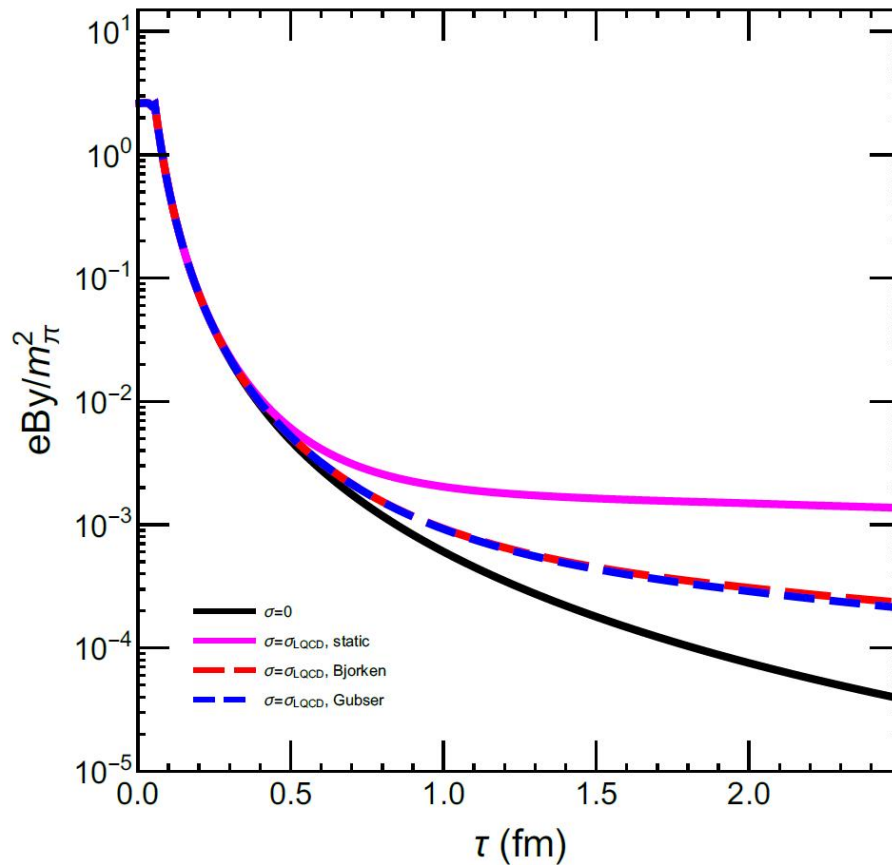
3. EB evolution

Conductivity σ on EB



3. EB evolution

Conductivity σ on EB



The Lorentz force induced by the longitudinal expansion depress the magnetic field.

3. EB evolution

Vorticity ω on EB

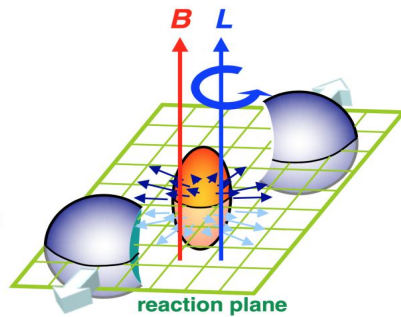
Hydro background

$$\begin{aligned} D_\mu T^{\mu\nu} &= 0, \\ D_\mu N^\mu &= 0 \end{aligned}$$

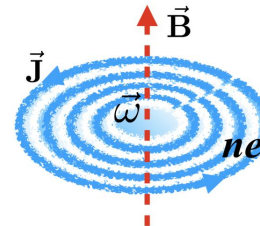
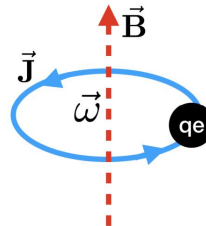
$$\begin{aligned} T, u^\mu, n_B, n_e &= 0.4n_B \\ J^\mu &= n_e u^\mu + v^\mu + \sigma E^\mu \end{aligned}$$

EB evolution

$$\begin{aligned} D_\mu F^{\mu\nu} &= J^\nu, \\ D_\mu \tilde{F}^{\mu\nu} &= 0 \end{aligned}$$



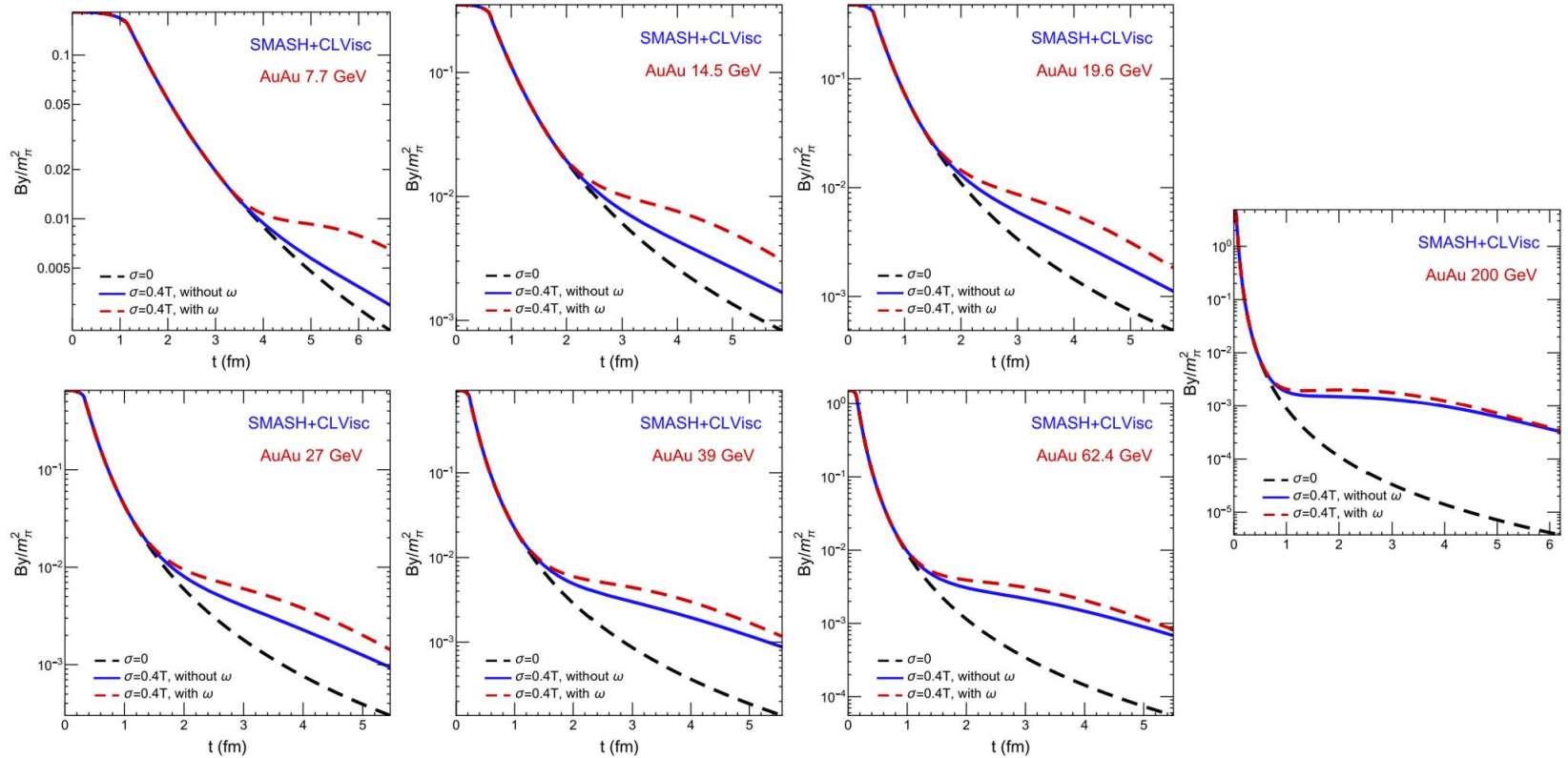
Maxim Chernodub



Guo, Xingyu, et al. *Scientific Reports* 10.1 (2020): 2196.

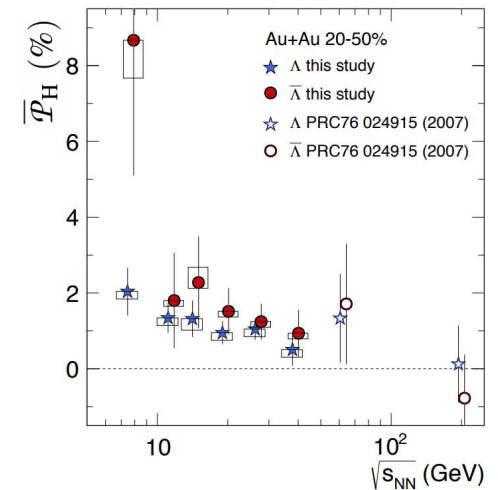
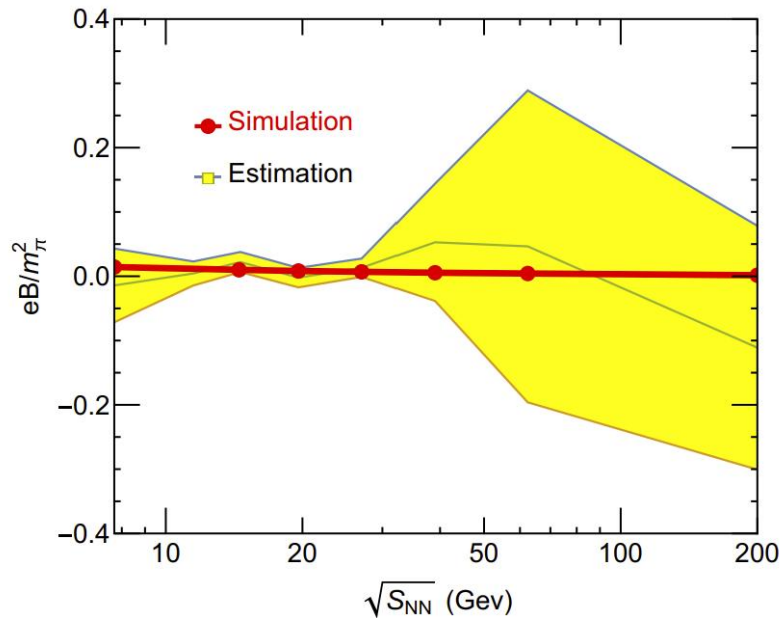
3. EB evolution

Vorticity ω on EB



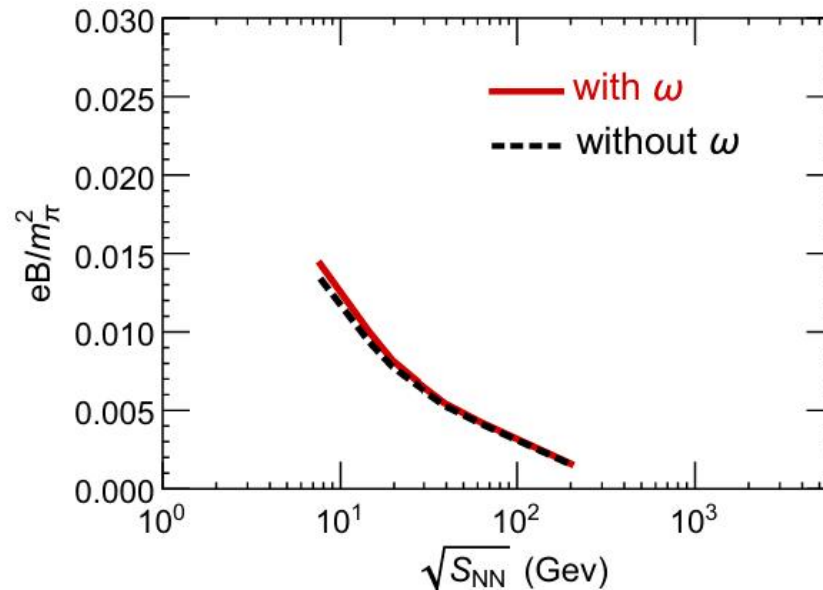
3. EB evolution

Vorticity ω on EB



3. EB evolution

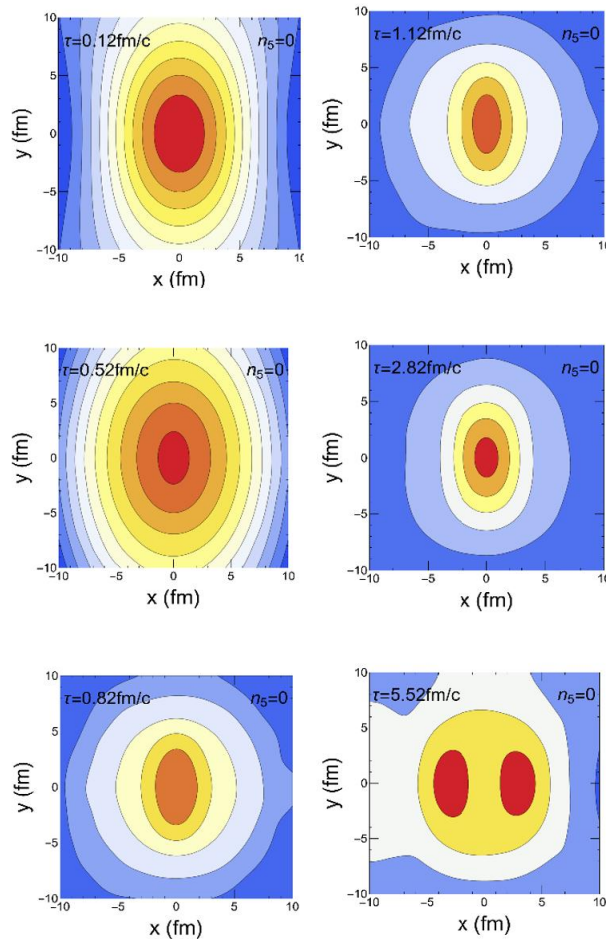
Vorticity ω on EB



The strength of the magnetic field on the freeze-out hypersurface

3. EB evolution

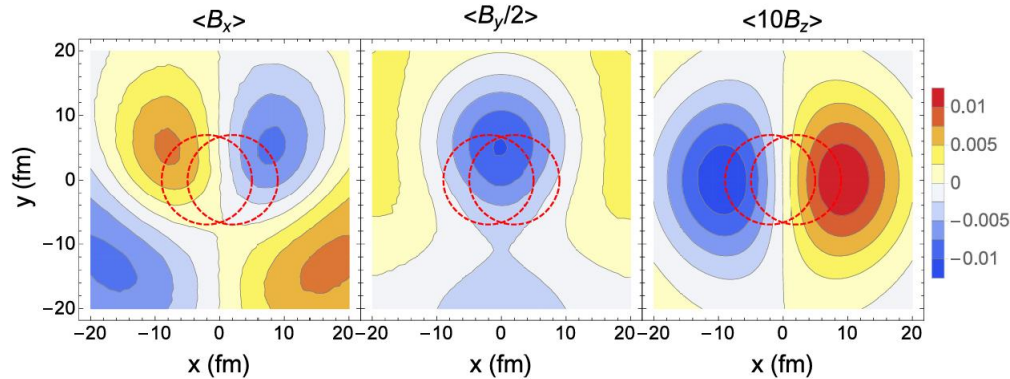
Chiral conductivity σ_χ on EB



Is the spatial distribution of EB clearly defined?

3. EB evolution

Chiral conductivity σ_χ to EB



‘The magnitudes of the axial components of both electric field and magnetic field have the symmetry of flipping the signs of their transverse coordinate arguments x and y .’

Hui Li, Xin-li Sheng, and Qun Wang. *Physical Review C*, 94(4), 044903.

$$\begin{aligned}(\nabla^2 - \partial_t^2 - \sigma \partial_t) \mathbf{E} + \sigma_\chi \nabla \times \mathbf{E} &= \partial_t \mathbf{J}_s + \nabla J_s^0, \\(\nabla^2 - \partial_t^2 - \sigma \partial_t) \mathbf{B} + \sigma_\chi \nabla \times \mathbf{B} &= -\nabla \times \mathbf{J}_s.\end{aligned}$$

3. EB evolution

Chiral conductivity σ_χ on EB

Hydro background

$$\begin{aligned} D_\mu T^{\mu\nu} &= 0, \\ D_\mu N^\mu &= 0 \end{aligned}$$

$$\begin{aligned} &T, u^\mu, n_B, n_e = 0.4n_B \\ &J^\mu = n_e u^\mu + v^\mu + \sigma E^\mu + \sigma_\chi B^\mu \end{aligned}$$

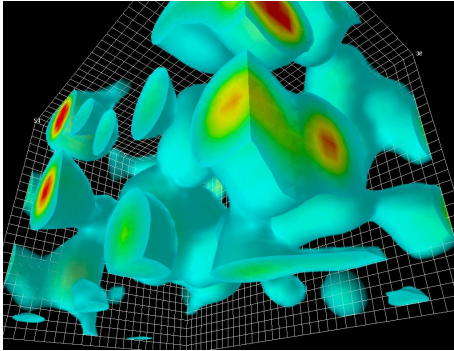
EB evolution

$$\begin{aligned} D_\mu F^{\mu\nu} &= J^\nu, \\ D_\mu \tilde{F}^{\mu\nu} &= 0 \end{aligned}$$

3. EB evolution

Chiral conductivity σ_χ on EB

$$J^\mu = n_e u^\mu + v^\mu + \sigma(T) E^\mu + \sigma_\chi(T) B^\mu$$



[Derek Leinweber](#)

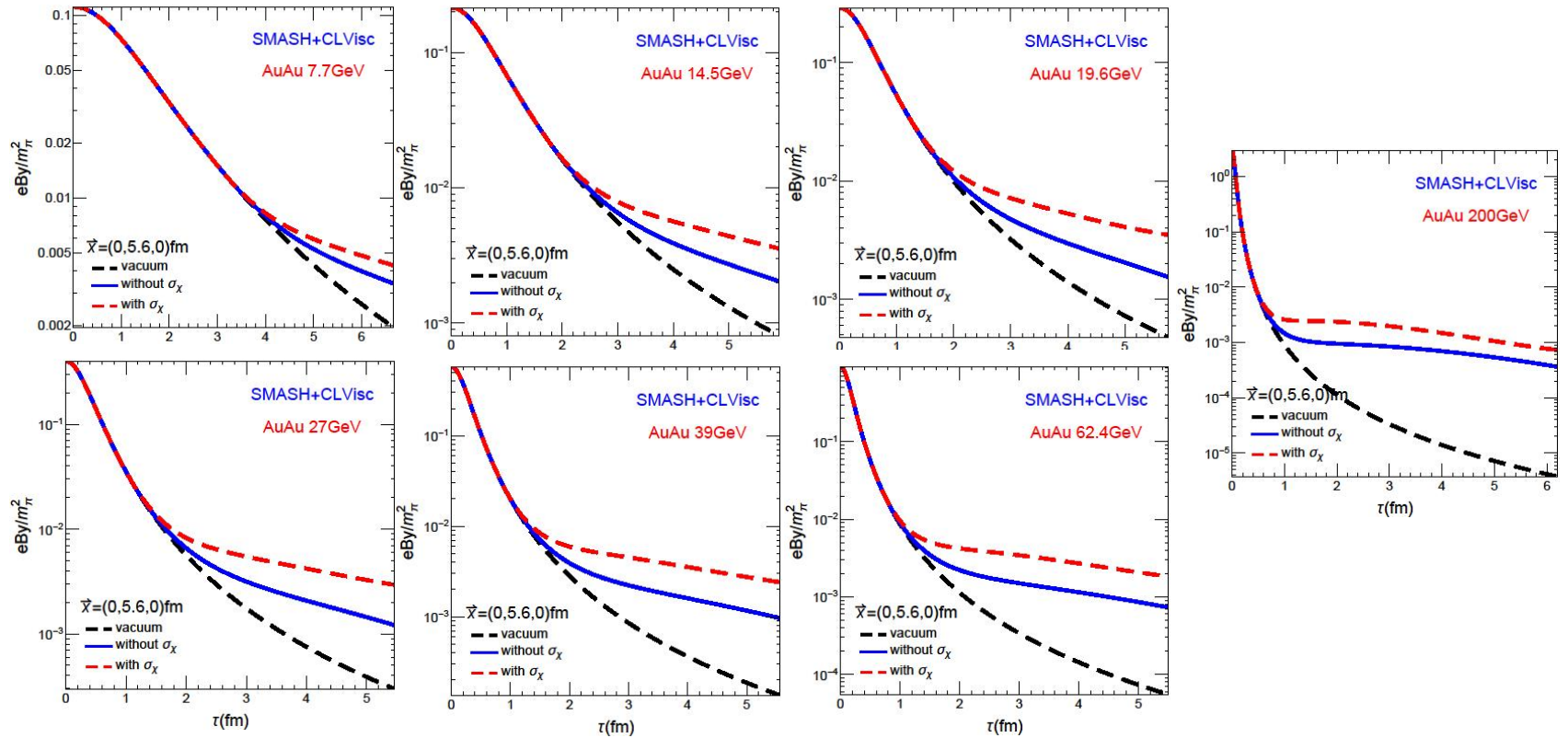
$$\sigma_\chi = \frac{e^2}{2\pi^2} \mu_5$$

$$\mu_5 = \sqrt{3} \pi \left(\frac{320 N_f^2 \Gamma_{ss}}{T^2} - \frac{T^2}{3} \right)^{\frac{1}{2}}$$

$$N_R^f - N_L^f = N_5 = V \chi \mu_5$$

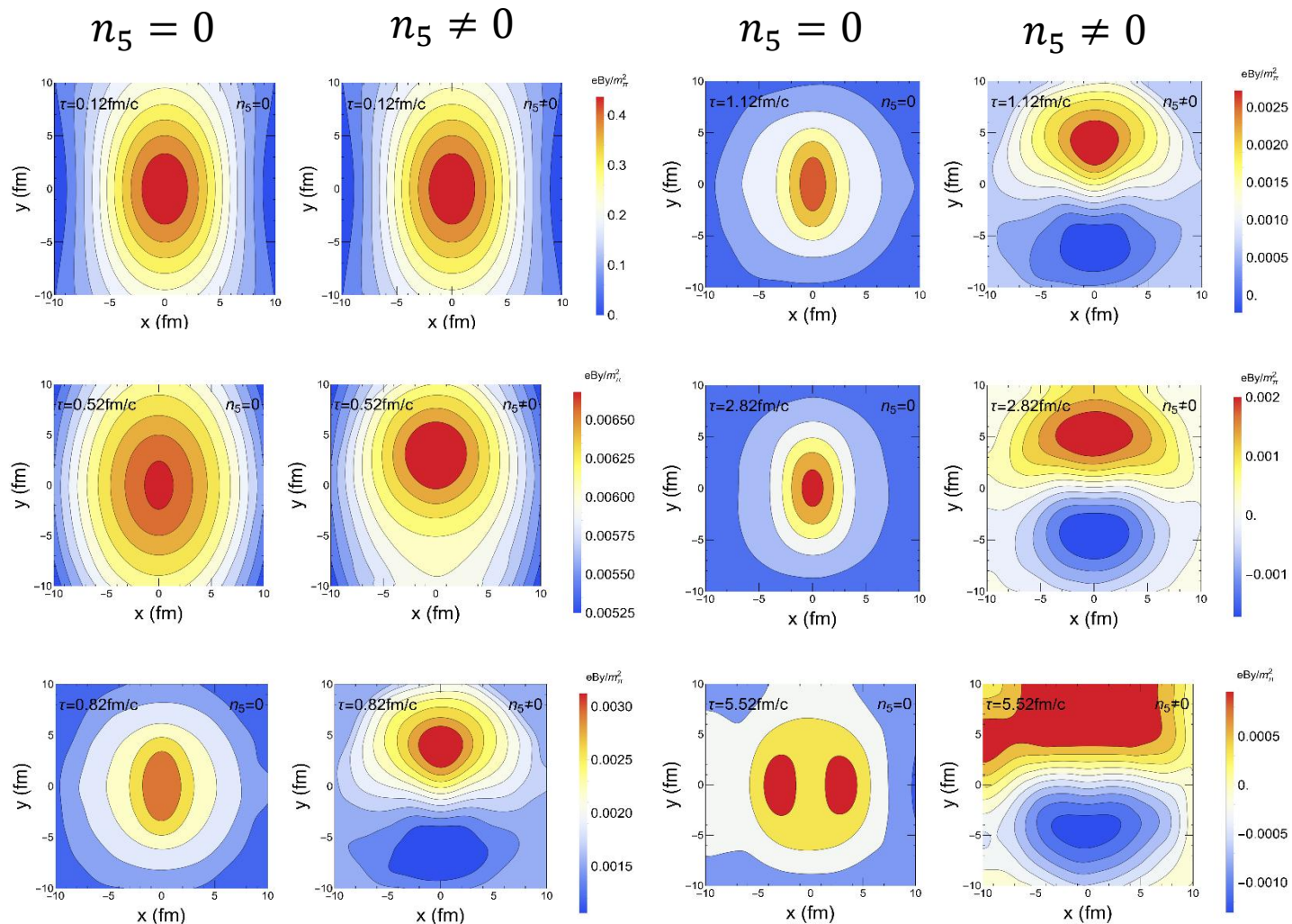
3. EB evolution

Chiral conductivity σ_χ on EB



3. EB evolution

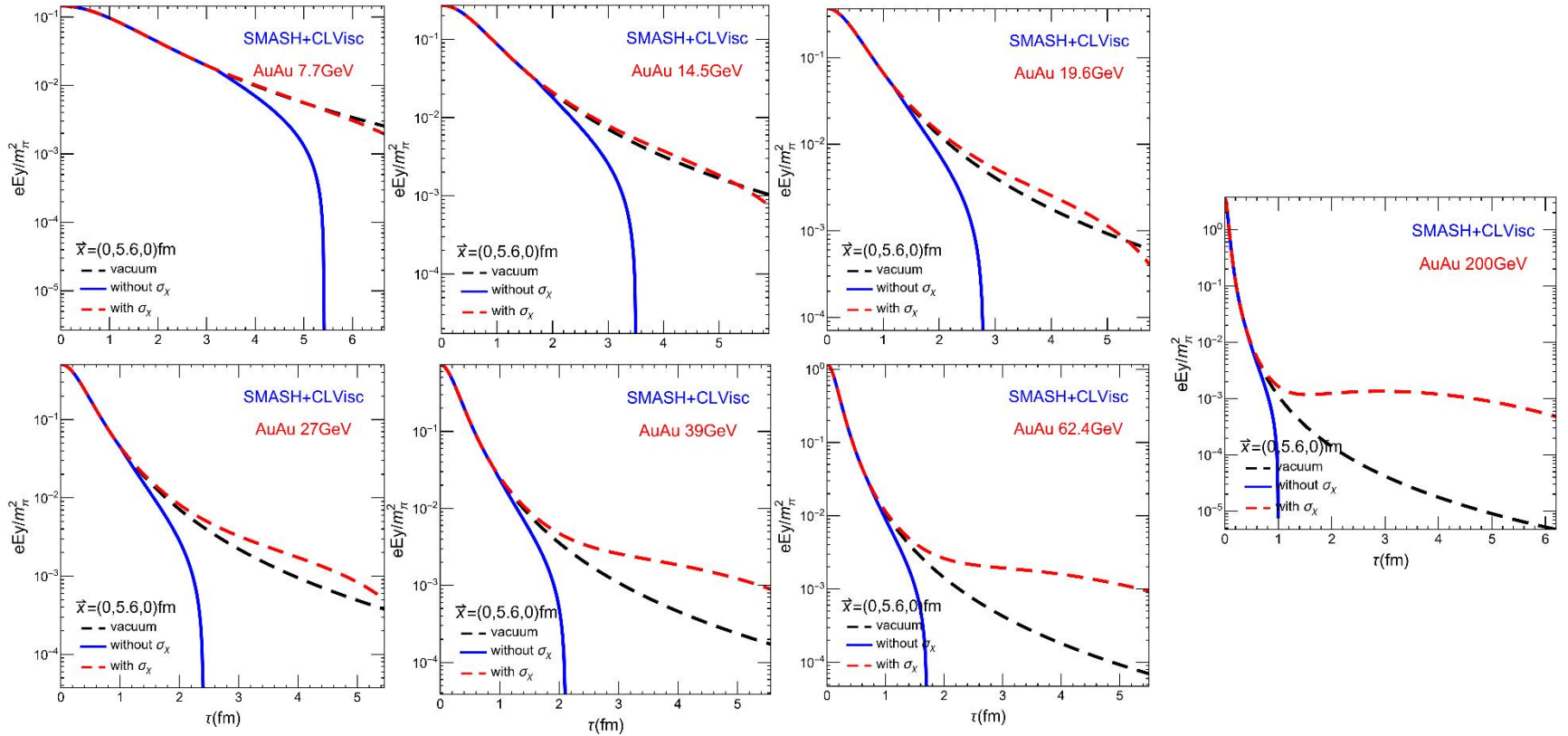
Chiral conductivity σ_χ on EB



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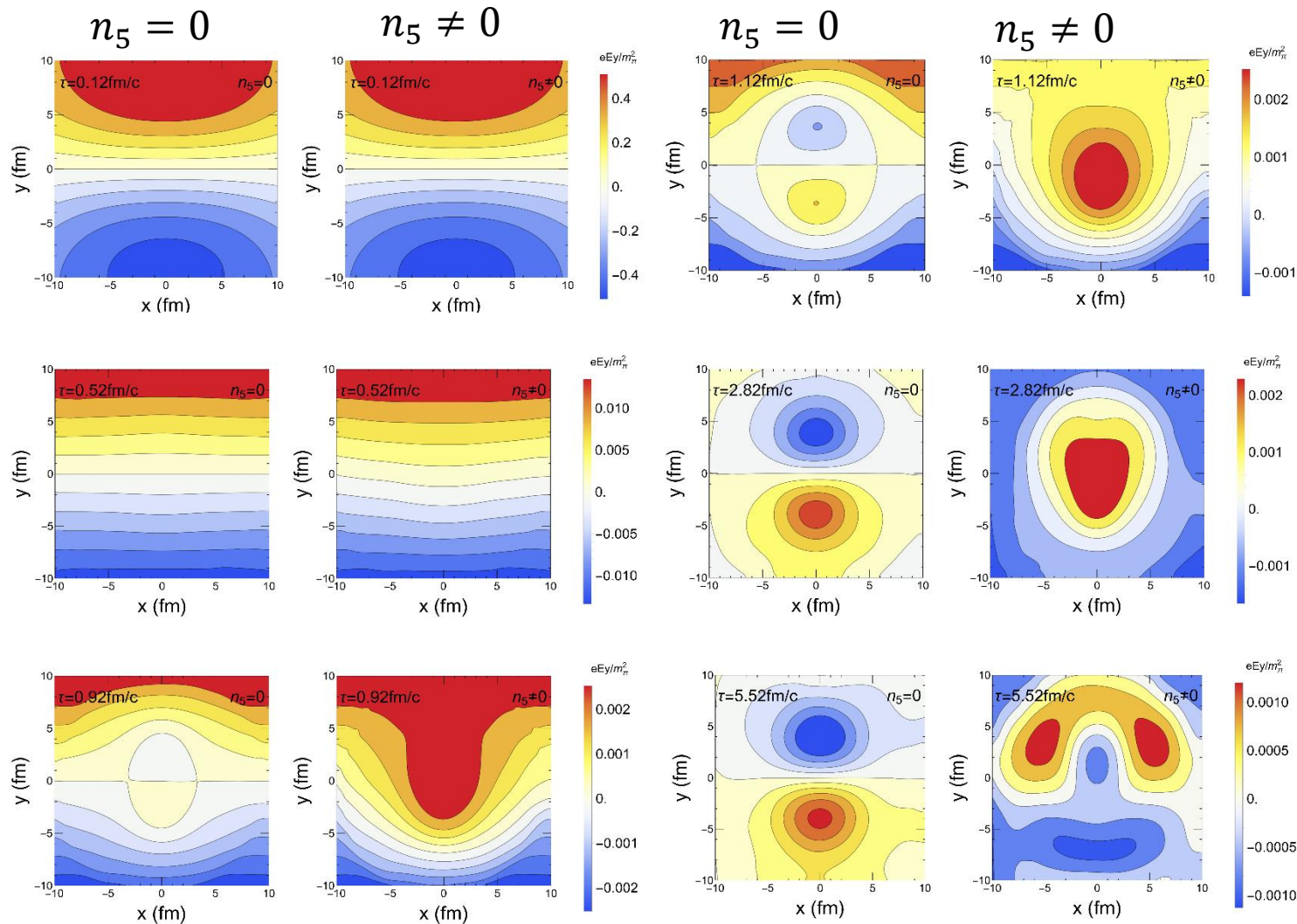
3. EB evolution

Chiral conductivity σ_χ on EB



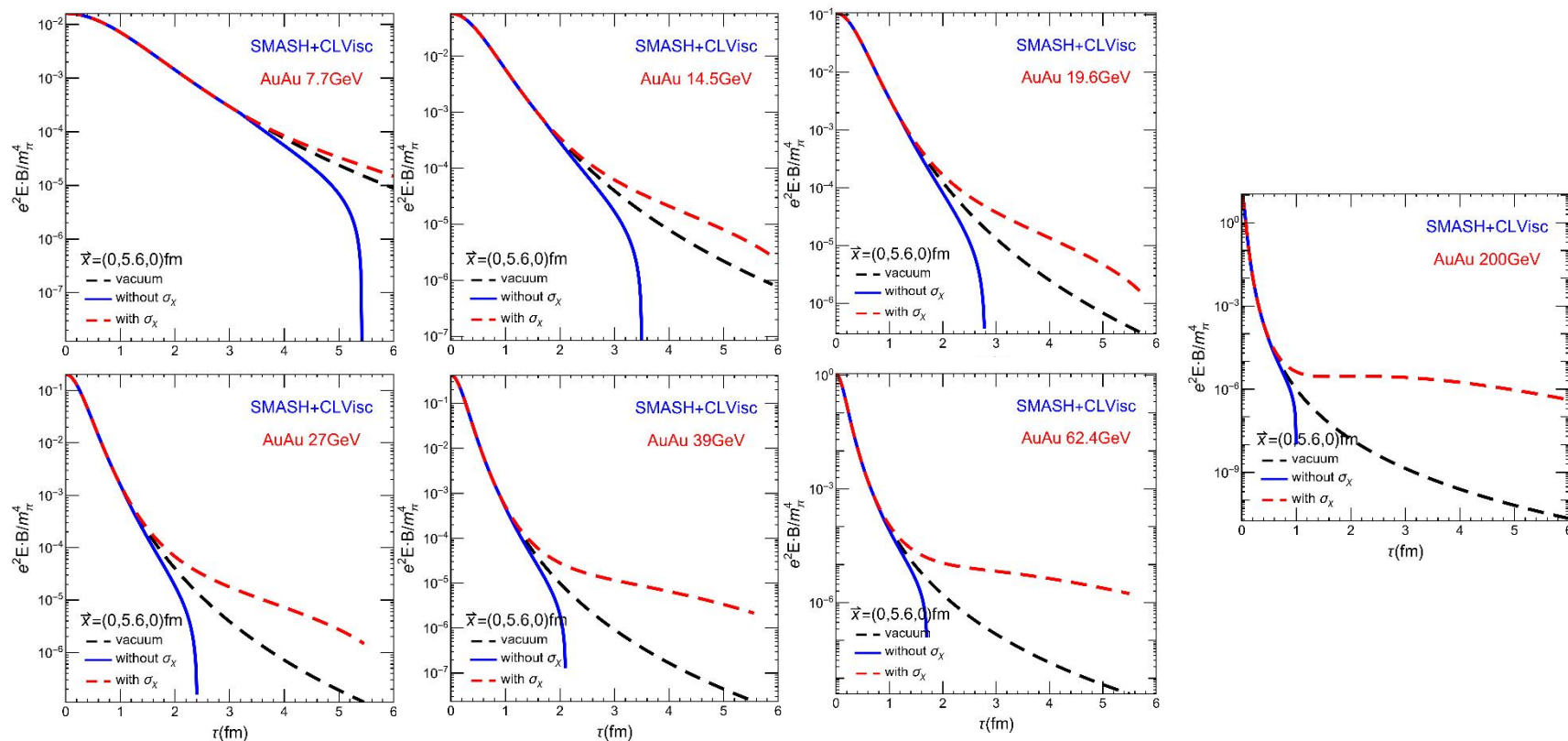
3. EB evolution

Chiral conductivity σ_χ on EB



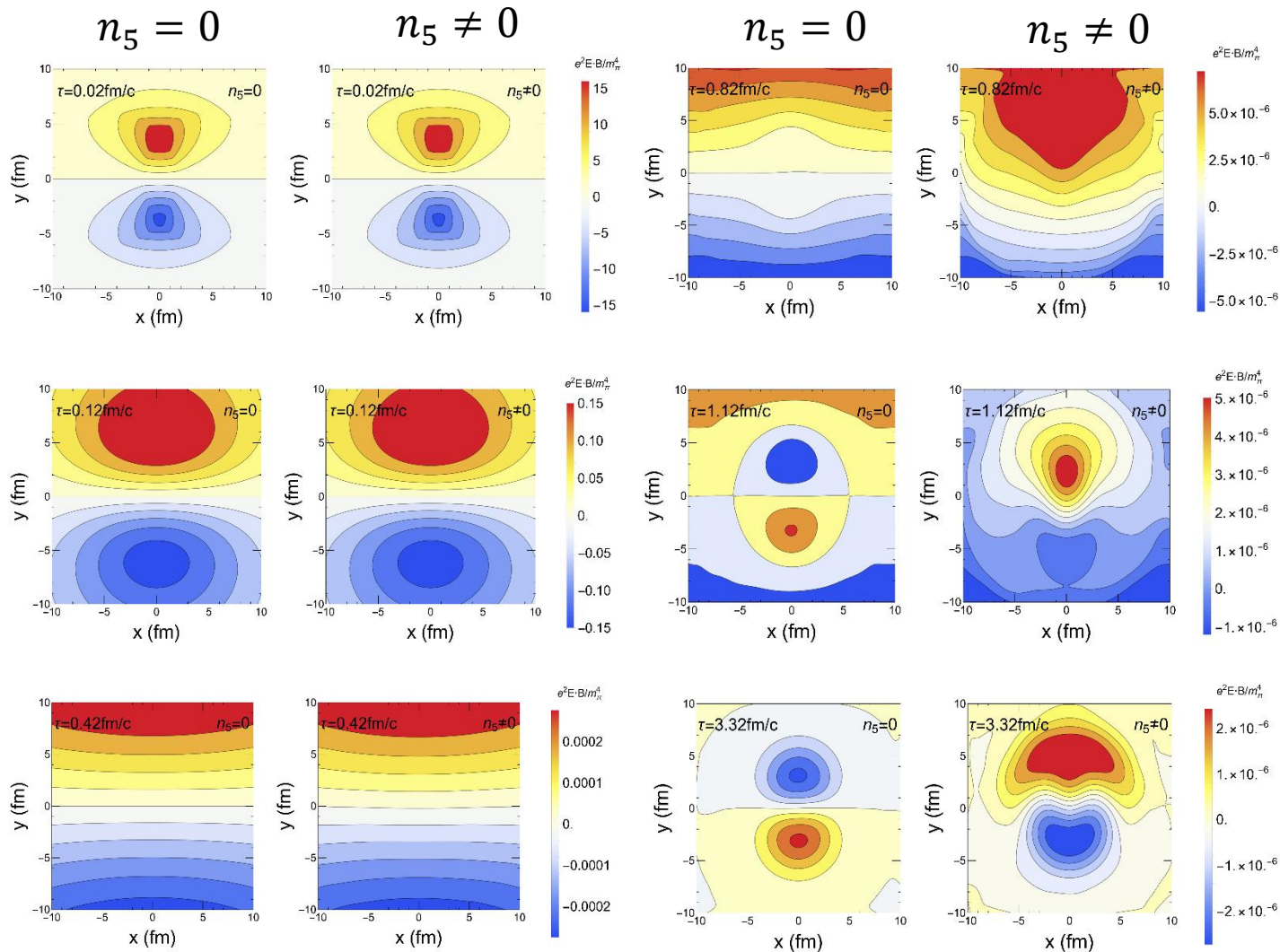
3. EB evolution

Chiral conductivity σ_χ on EB



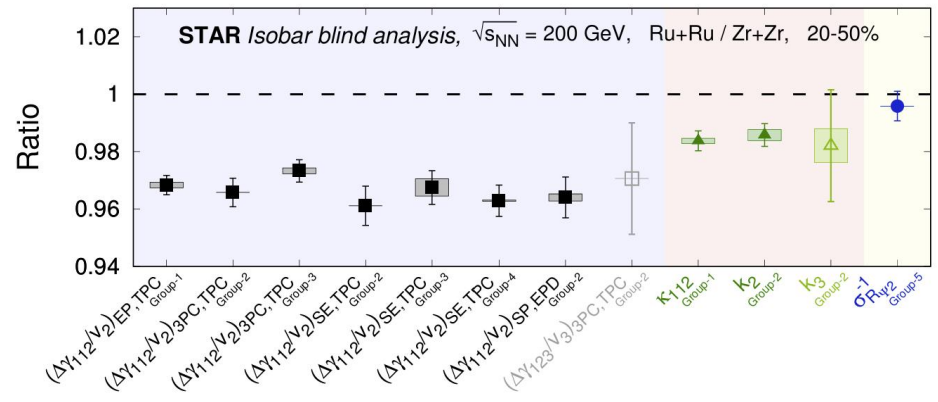
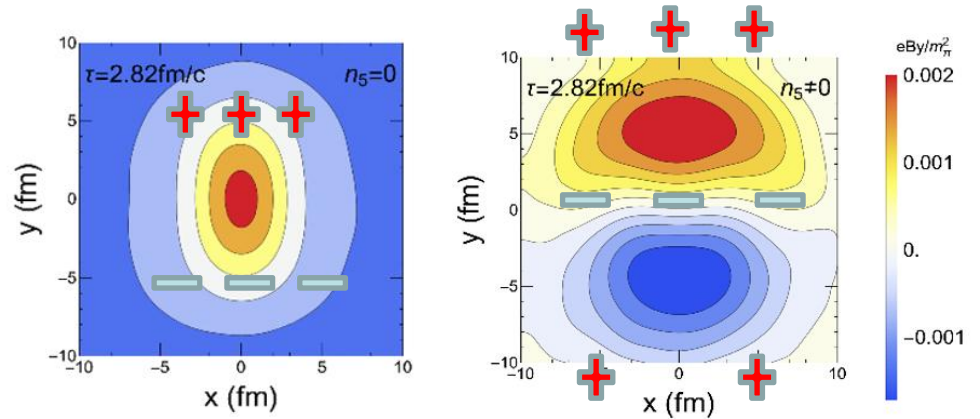
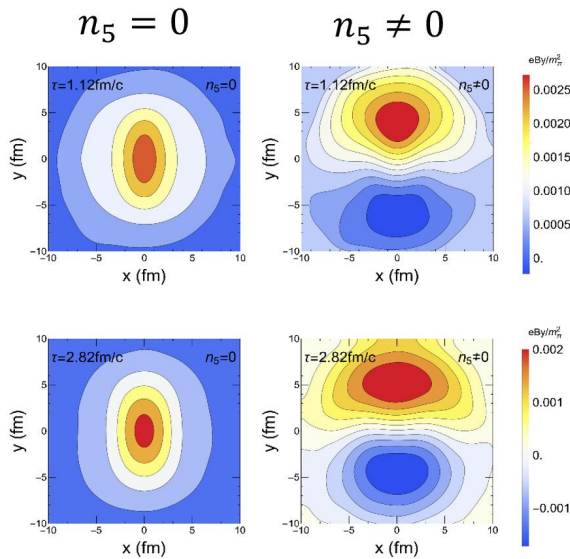
3. EB evolution

Chiral conductivity σ_χ on EB



3. EB evolution

Chiral conductivity σ_χ on EB



4. Outlook

Hydro background

$$\begin{aligned} D_\mu T^{\mu\nu} &= 0, \\ D_\mu N^\mu &= 0 \end{aligned}$$

T, u^μ

$$J^\mu = n_e u^\mu + v^\mu + \sigma E^\mu + \sigma_\chi B^\mu$$

EB evolution

$$\begin{aligned} D_\mu F^{\mu\nu} &= J^\nu, \\ D_\mu \tilde{F}^{\mu\nu} &= 0 \end{aligned}$$

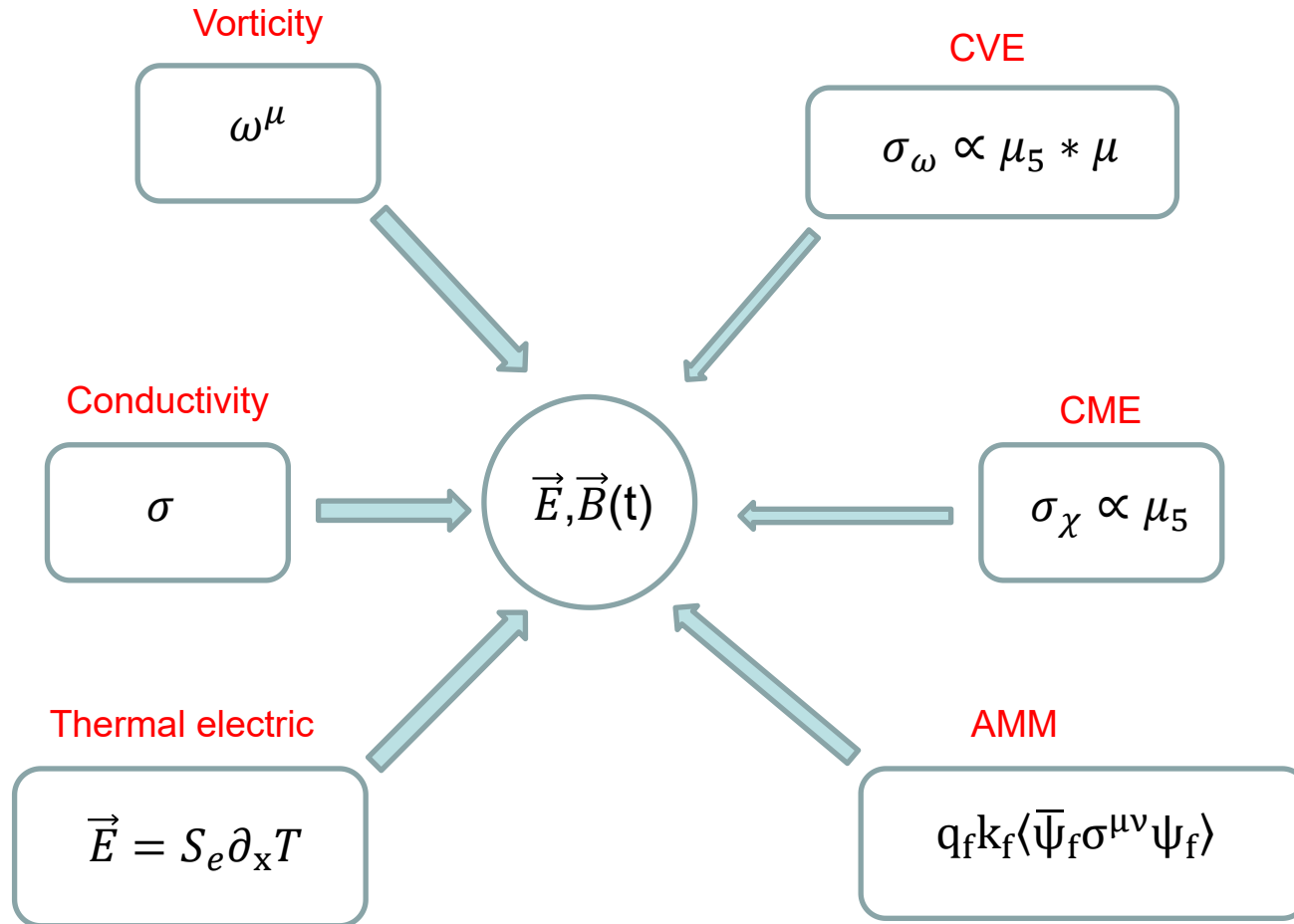
+

$$\begin{aligned} D_\mu J^\mu &= 0, \\ D_\mu J_5^\mu &= C_5 E \cdot B \end{aligned}$$

$$\begin{aligned} \sigma_\chi &= \frac{e^2}{2\pi^2} \mu_5 & \mu_5 &= \sqrt{3} \pi \left(\frac{320 N_f^2 \Gamma_{ss}}{T^2} - \frac{T^2}{3} \right)^{\frac{1}{2}} \\ n_e &= 0.4 n_B \end{aligned}$$

This work is in progress!

4. Outlook



The evolution of the electromagnetic field is affected by various factors, such as classical effects: electric conductivity, vortical field, thermoelectric effect, etc.; and quantum effects: the chiral magnetic effect, the chiral vortical effect, the anomalous magnetic moment effect, etc.

4. Outlook

Chiral conductivity σ_χ on EB

The Maxwell equation

$$\partial_\mu F^{\mu\nu} = J^\nu, \partial_\mu \tilde{F}^{\mu\nu} = 0$$

$$J^\mu = n_e u^\mu + v^\mu + \sigma E^\mu - \sigma_e S_e \nabla_\mu T + \sigma_\chi B^\mu + \sigma_\omega \omega^\mu + \partial_\mu G^{\mu\nu}$$

经典部分

量子部分

It is difficult to analytically solve the Maxwell equations due to the complexity of the current. Therefore, our study is based on numerical methods.

Thank You!