Anomalous transport model study of chiral magnetic effects in heavy ion collisions

Yifeng Sun, Cheming Ko and Feng Li
Cyclotron Institute and Physics Department
Texas A&M University

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Outline

1) Background and motivation

- CME, CSE, CMW
- Quadrupole moment and v_2 splitting

2) Anomalous transport model

3) Results

- Eccentricity splitting and v_2 splitting
- Lorentz force effect
- Slope parameter

4) Summary and discussion

Chiral magnetic wave and v_2 splitting

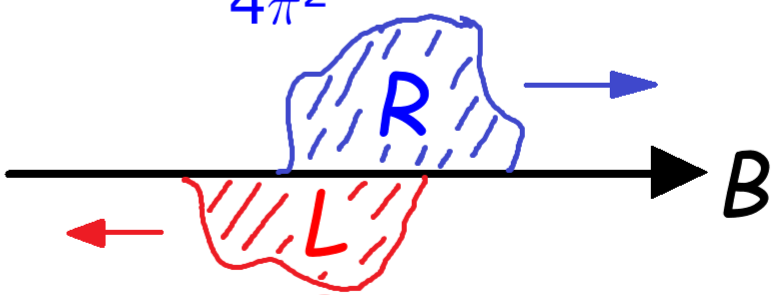
- ❖Chiral magnetic effect (CME)
- ❖Chiral separation effect (CSE)

$$\mathbf{j}_V = \mathbf{j}_R + \mathbf{j}_L = \frac{Q}{2\pi^2}\mu_5 \mathbf{B} = \frac{Q}{2\pi^2}\frac{\mu_R - \mu_L}{2}\mathbf{B}$$
$$\mathbf{j}_A = \mathbf{j}_R - \mathbf{j}_L = \frac{Q}{2\pi^2}\mu \mathbf{B} = \frac{Q}{2\pi^2}\frac{\mu_R + \mu_L}{2}\mathbf{B}$$

$$\mathbf{j}_{R,L} = \pm\frac{Q}{4\pi^2}\mu_{R,L}\mathbf{B}$$

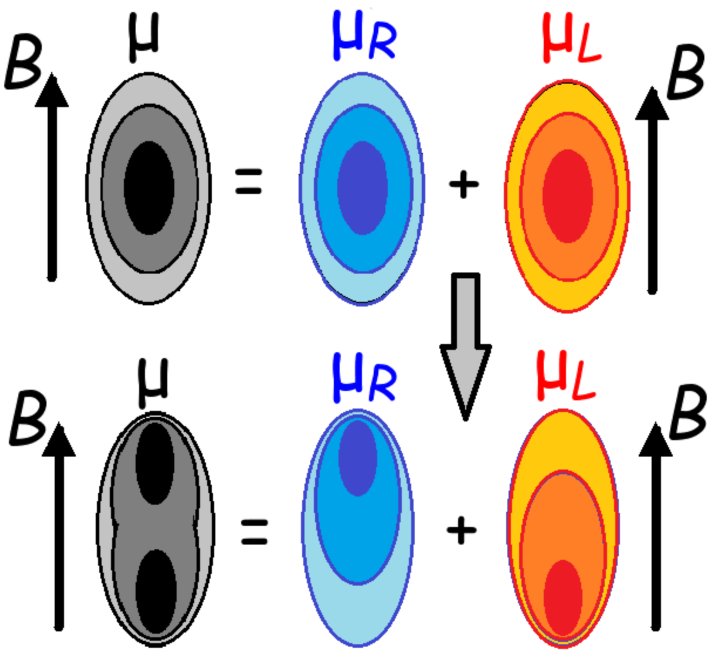
[Fukushima et al., PRD 78 (2008)]
[Y. Burnier et al., PRL 107 (2011)]

$$\vec{j}_R = \frac{Q}{4\pi^2}\mu_R \vec{B}, \quad \mu_R = \mu + \mu_5$$

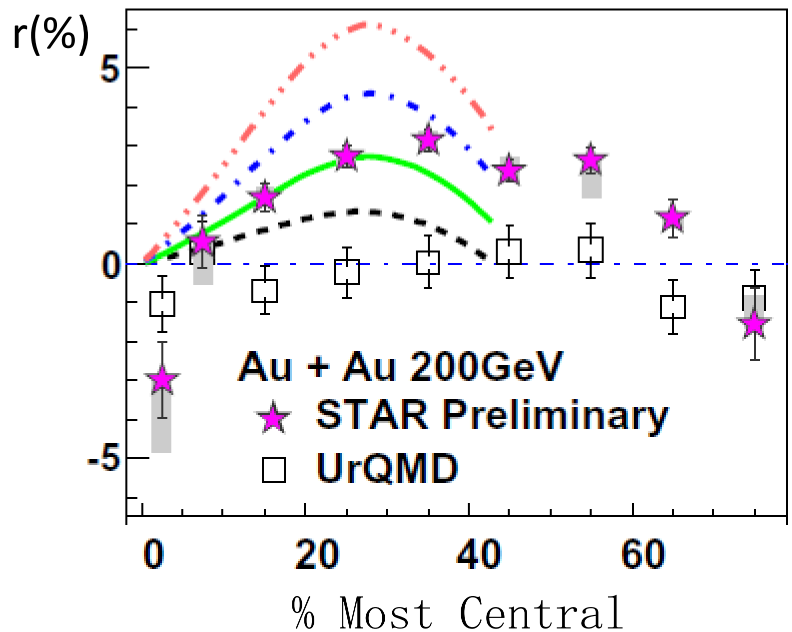


$$\vec{j}_L = -\frac{Q}{4\pi^2}\mu_L \vec{B}, \quad \mu_L = \mu - \mu_5$$

Chiral magnetic wave and v_2 splitting



$$\Delta v_2 = v_2(-) - v_2(+)$$
$$A_\pm = \frac{N_+ - N_-}{N_+ + N_-} \propto \frac{\mu}{T}$$
$$r = \frac{\Delta v_2}{A_\pm}$$



Assumptions:

- Static Background

[Y. Burnier et al., PRL 107 (2011)]

[G. Wang et al., NPA 904-905 (2013)]

Chiral kinetic motion (CKM)

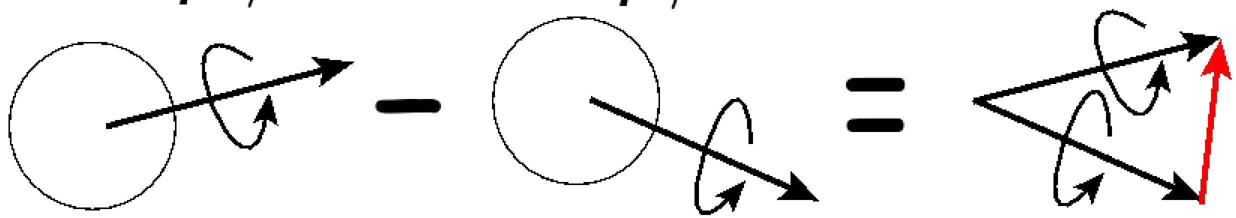
❖The anomalous equations of motion of the massless particles were obtained in both the path integral and Wigner function method. Here, an illustration is given from the point of view of the angular momentum conservation:

$$\dot{\mathbf{r}} = \hat{\mathbf{p}} + h\dot{\mathbf{p}} \times \mathbf{b} \quad \mathrm{b} = \frac{\mathbf{p}}{2p^3}$$

h is the helicity

[Son+Yamamoto, PRL 109 (2012)]
[Stephanov+Yin, PRL 109 (2012)]
[J.W. Gao et al., PRL 109 (2012)]

$$\vec{\sigma}' = \hat{p}'/2 \qquad \vec{\sigma} = \hat{p}/2 \qquad \Delta\vec{\sigma} = \Delta\hat{p}/2$$



Compensated by an anomalous displacement, so that:

$$\Delta\vec{r} \times \vec{p} + \Delta\vec{\sigma} = 0, \; \Delta\vec{r} \perp \Delta\hat{p}$$

Chiral kinetic equation(CKE)

❖Rate of change of angular momentum

$$\mathbf{r} \times \mathbf{F} = \frac{d\mathbf{J}}{dt} = \frac{d(\mathbf{r} \times \mathbf{p} + h\frac{\hat{\mathbf{p}}}{2})}{dt}$$

$$= (\dot{\mathbf{r}} - h\dot{\mathbf{p}} \times \frac{\mathbf{p}}{2p^3}) \times \mathbf{p} + \mathbf{r} \times \mathbf{F}$$

$$\Rightarrow \boxed{\dot{\mathbf{r}} = \hat{\mathbf{p}} + h\dot{\mathbf{p}} \times \mathbf{b}} \qquad \mathbf{b} = \frac{\mathbf{p}}{2p^3}$$

$$+$$

$$\boxed{\dot{\mathbf{p}} = Q\dot{\mathbf{x}} \times \mathbf{B}}$$

$$\Downarrow$$

$$\dot{\mathbf{r}} = \frac{\hat{\mathbf{p}} + Qh(\hat{\mathbf{p}} \cdot \mathbf{b})\mathbf{B}}{1 + Qh\mathbf{B} \cdot \mathbf{b}} \Rightarrow \text{CKM}$$

$$\dot{\mathbf{p}} = \frac{Q\mathbf{p} \times \mathbf{B}}{1 + Qh\mathbf{B} \cdot \mathbf{b}} \Rightarrow \text{LF}$$

❖CME and CSE

$$\mathbf{j}_V = \frac{Q}{2\pi^2}\mu_5\mathbf{B}$$

$$\mathbf{j}_A = \frac{Q}{2\pi^2}\mu\mathbf{B}$$

[Fukushima et al., PRD 78 (2008)]
[Y. Burnier et al., PRL 107 (2011)]

According to CKM, the additional displacement of the right-chiral particle is along B, while that of the left-chiral particle is in the direction opposite to B. And CKM itself is charge blind.

Missing part: chirality changing scattering (CCS)

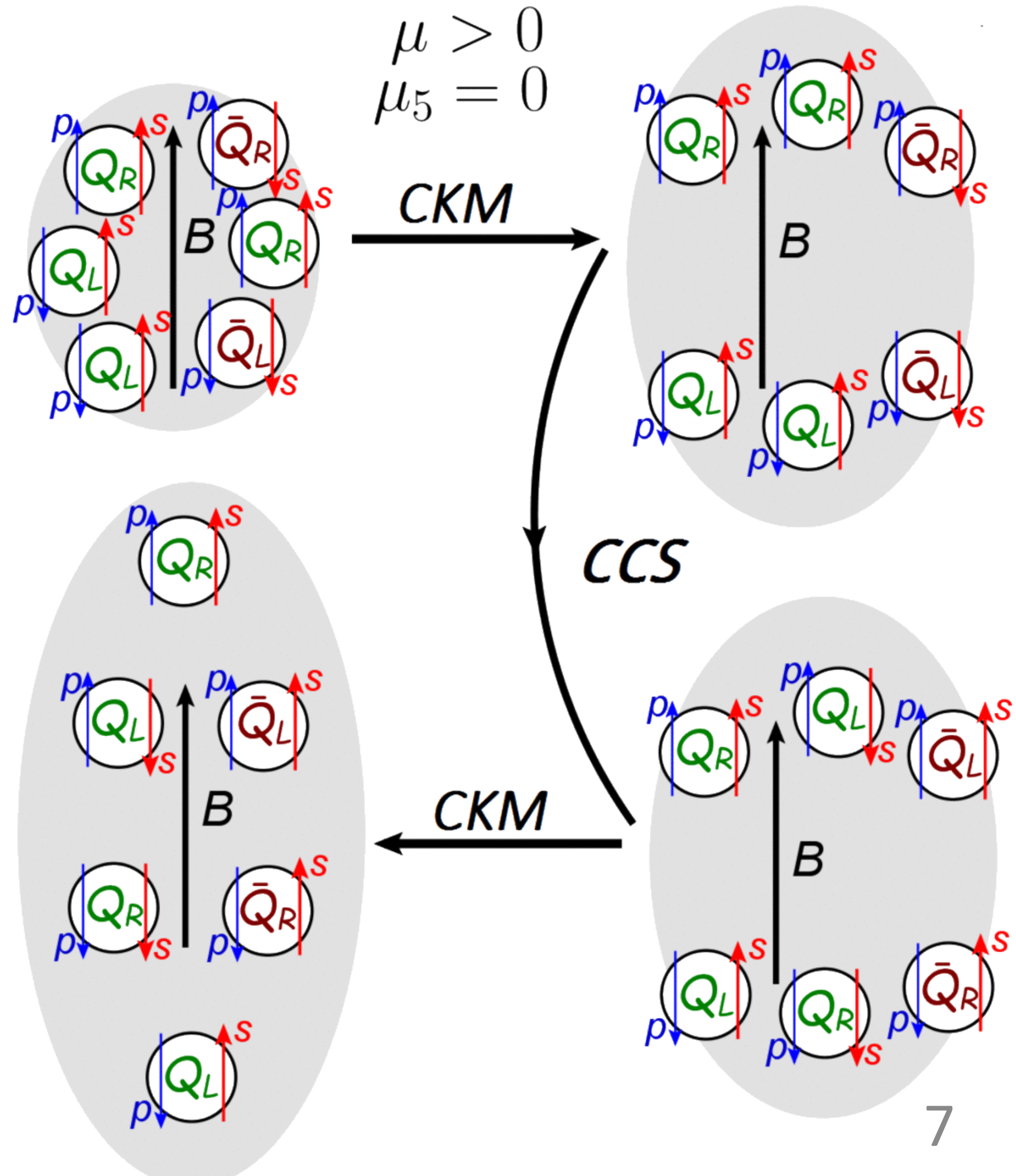
❖CKE leads to the separation of particles of right chirality and left chirality

❖CCS $R\overline{R} \leftrightharpoons L\overline{L}$

❖More positively charged particles move to y direction

$$\dot{\mathbf{r}} = \frac{\hat{\mathbf{p}} + Qh(\hat{\mathbf{p}}\cdot\mathbf{b})\mathbf{B}}{1 + Qh\mathbf{B}\cdot\mathbf{b}}$$

$$\mathbf{b} = \frac{\mathbf{p}}{2p^3}$$



Initial conditions of fireball

❖Initial fireball $T(x,y) = \dfrac{T_0}{(1+e^{\frac{\sqrt{x^2+y^2/c^2}-R}{a}})^{\frac{1}{3}}}$

- T_0=300 MeV, R=3.5 fm, a=0.5 fm, c=1.5 so that the initial eccentricity is equal to 0.2
- Q=e/2 and -e/2
- μ/T is uniform and μ_5/T is zero

❖Magnetic field
$$eB = \frac{eB_0}{1+(t/\tau)^2}$$
$$eB_0 = 7m_\pi^2$$
[G. Basar et al., PRL 109 (2012)]

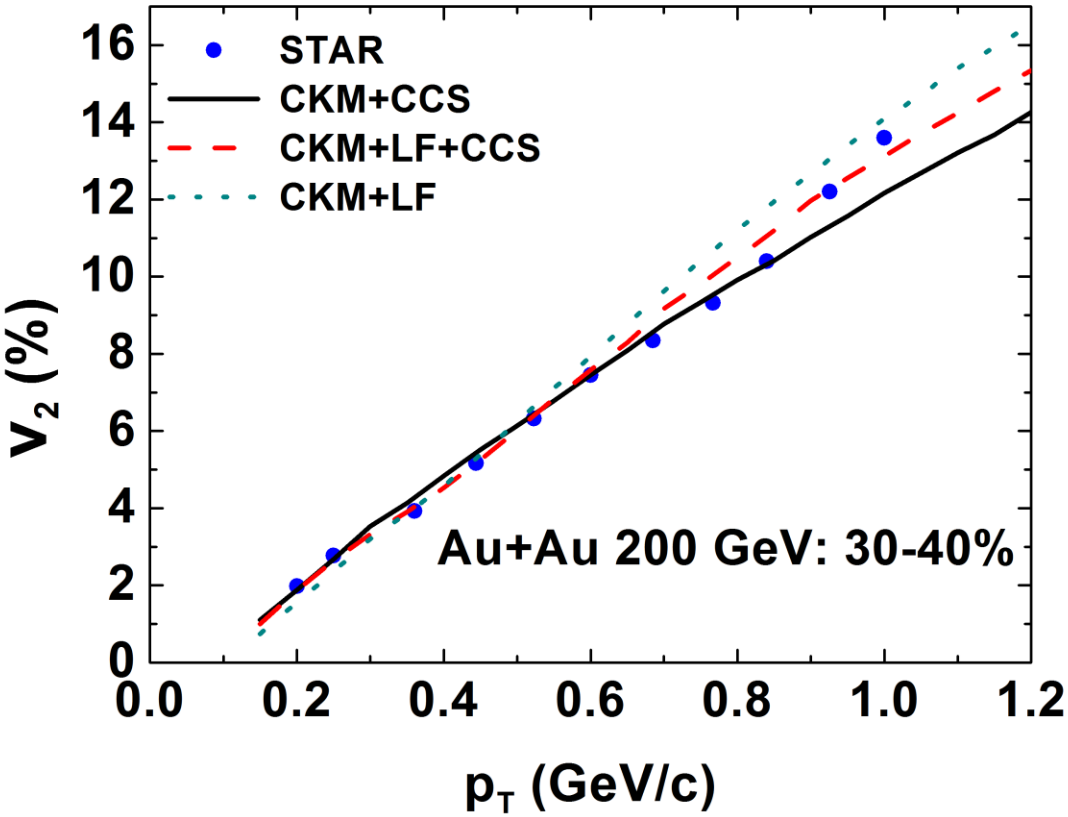
❖Collision and equation of motion T_χ=150 MeV, T_f =120 MeV

$$T > T_\chi, \sigma = \sigma_0 (T_0/T)^3$$
$$T_f < T < T_\chi, \sigma = \sigma_{\pi\pi}$$
[Li+Ko, PRC 52 (1995)]
$$T < T_f, \sigma = 0$$

$T > T_\chi$, CKM

$T < T_\chi$, normal

Elliptic flow as a function of transverse momentum



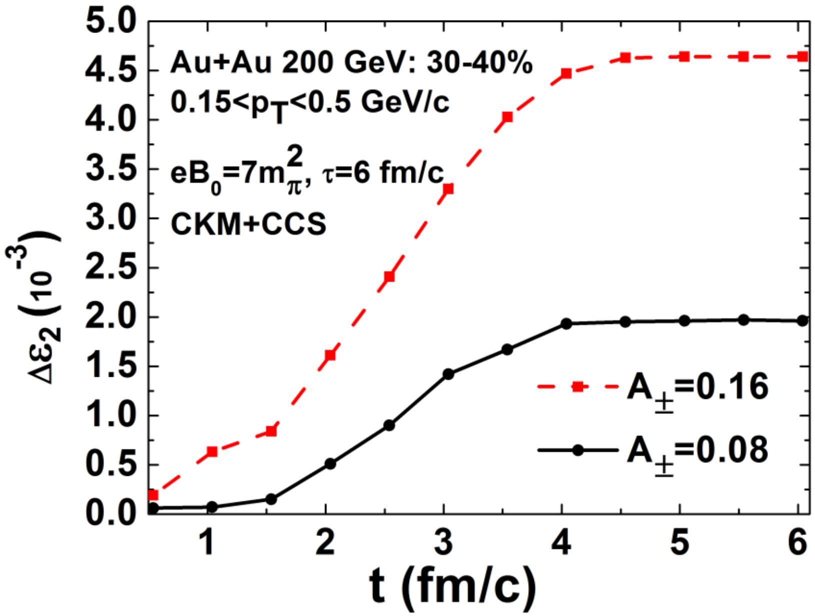
[J. Adams et al., PRC 72 (2005)]

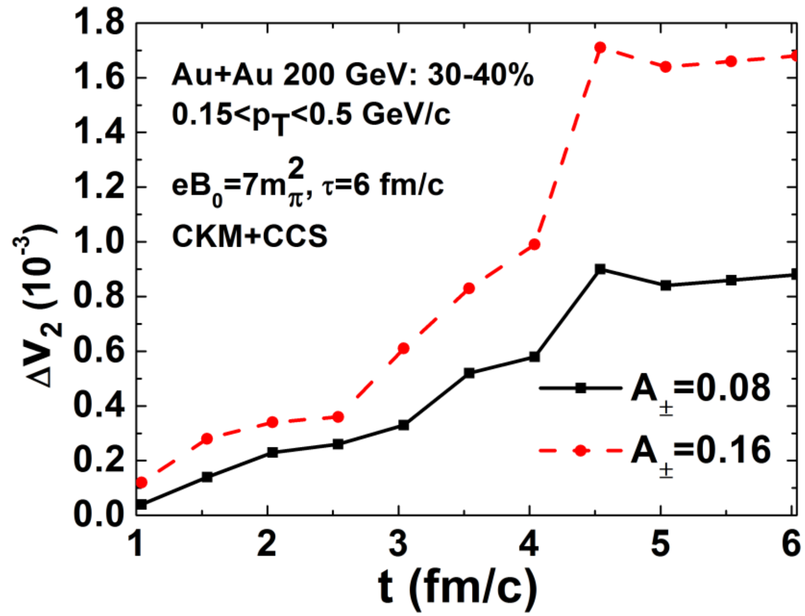
CKM ⇒ $$\dot{\mathbf{r}} = \frac{\hat{\mathbf{p}} + Qh(\hat{\mathbf{p}}\cdot\mathbf{b})\mathbf{B}}{1 + Qh\mathbf{B}\cdot\mathbf{b}}$$

LF ⇒ $$\dot{\mathbf{p}} = \frac{Q\mathbf{p}\times\mathbf{B}}{1 + Qh\mathbf{B}\cdot\mathbf{b}}$$

CCS ⇒ $$R\overline{R} \leftrightharpoons L\overline{L}$$

Time evolution of eccentricity splitting and v_2 splitting



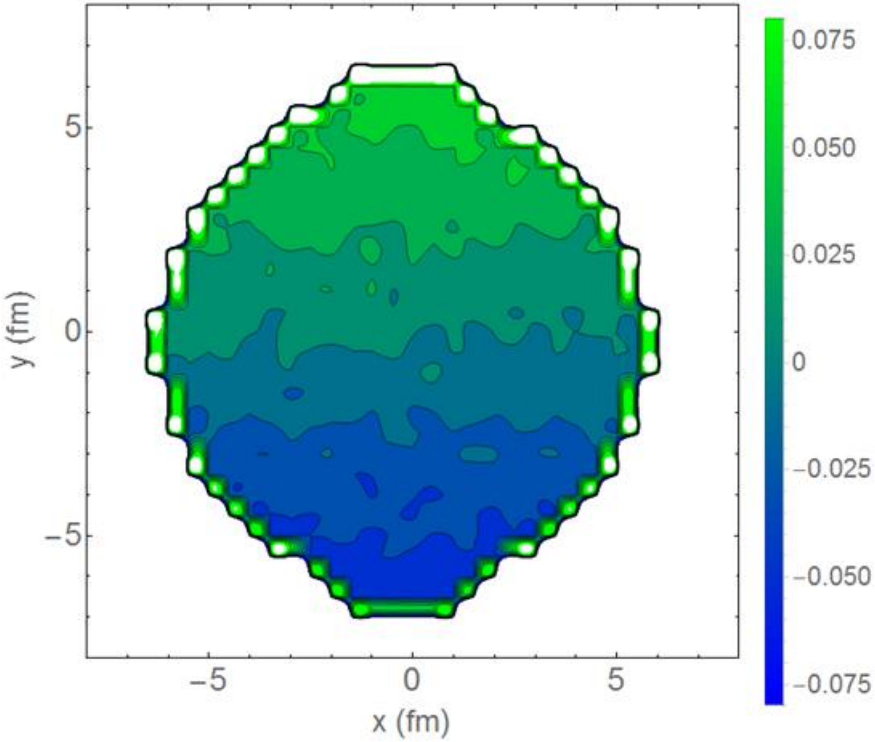


$$\Delta\epsilon_2 = \epsilon_2(-) - \epsilon_2(+)$$
$$\epsilon_2 = \left\langle \frac{x^2 - y^2}{x^2 + y^2} \right\rangle$$

$$\Delta v_2 = v_2(-) - v_2(+)$$
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

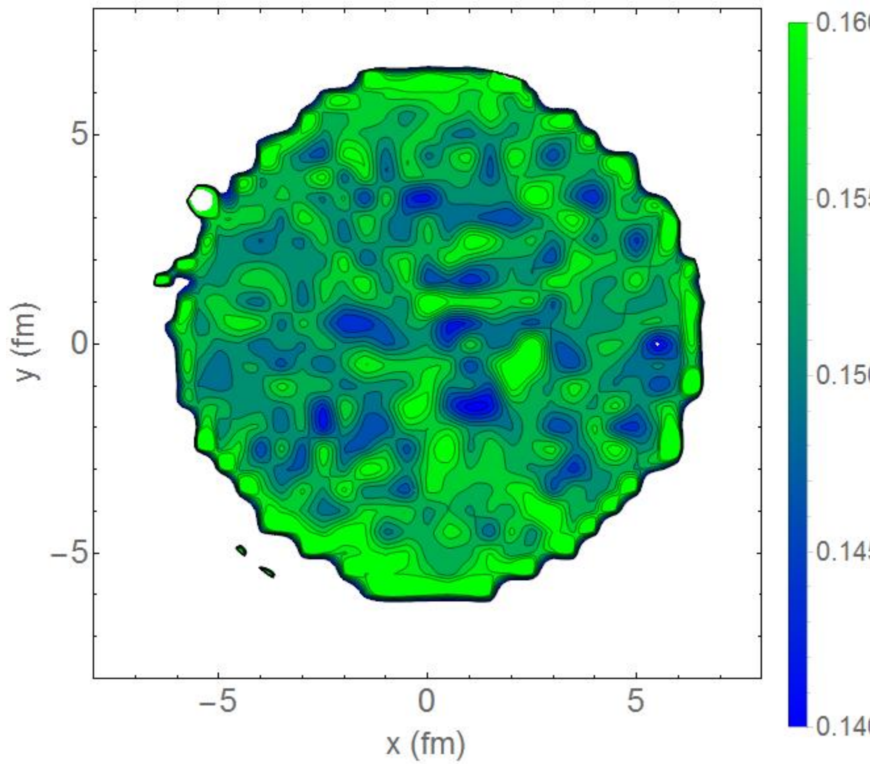
- No Lorentz force
- Enhance negatively charged particles' eccentricity and v_2
- Proportional to charge asymmetry

μ_5/T and μ/T at t=5 fm/c and in the z=0 plane



$$\mu_5/T(\frac{N_R - N_{\overline{R}} - N_L + N_{\overline{L}}}{N_R + N_{\overline{R}} + N_L + N_{\overline{L}}})$$

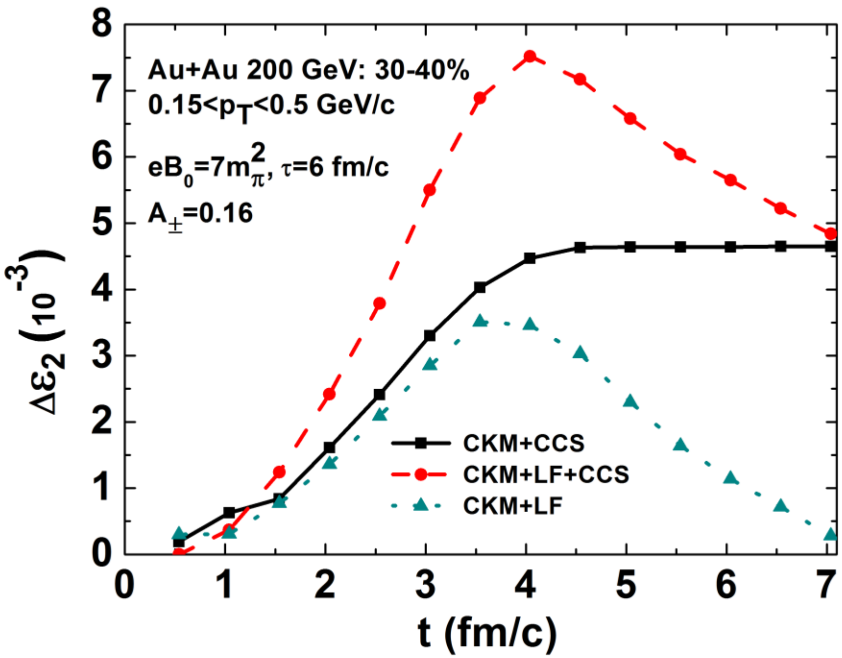
Axial charge dipole

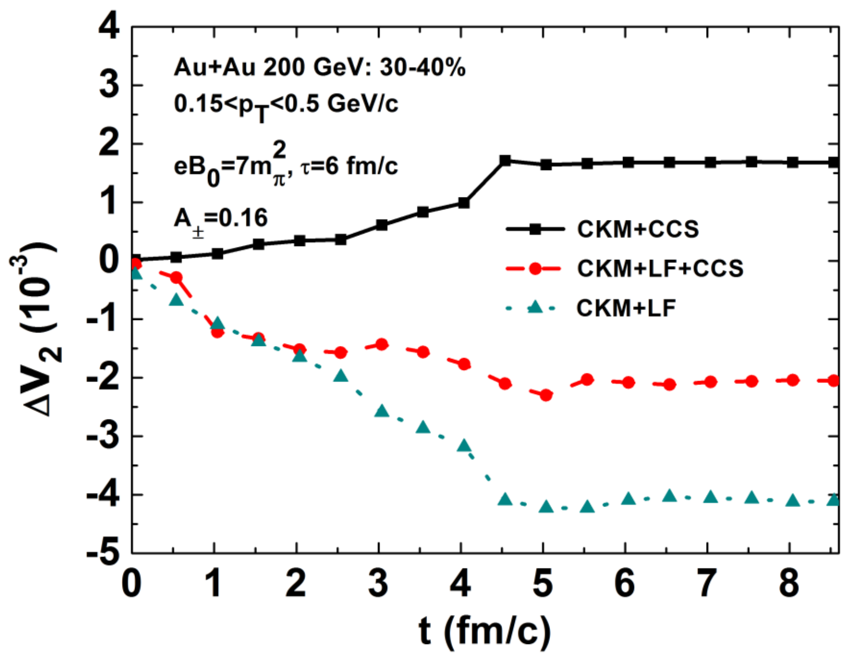


$$\mu/T(\frac{N_R - N_{\overline{R}} + N_L - N_{\overline{L}}}{N_R + N_{\overline{R}} + N_L + N_{\overline{L}}})$$

Charge quadrupole

Lorentz force effect



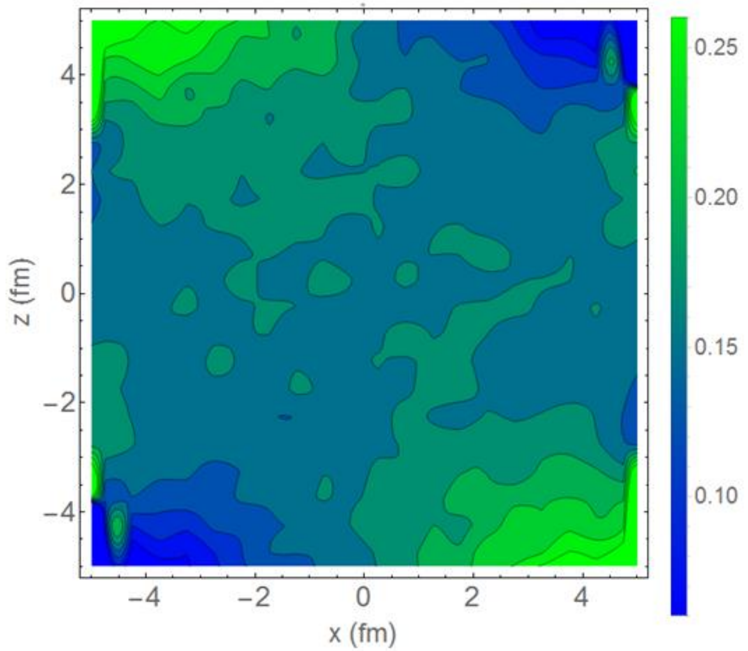


- Not included before

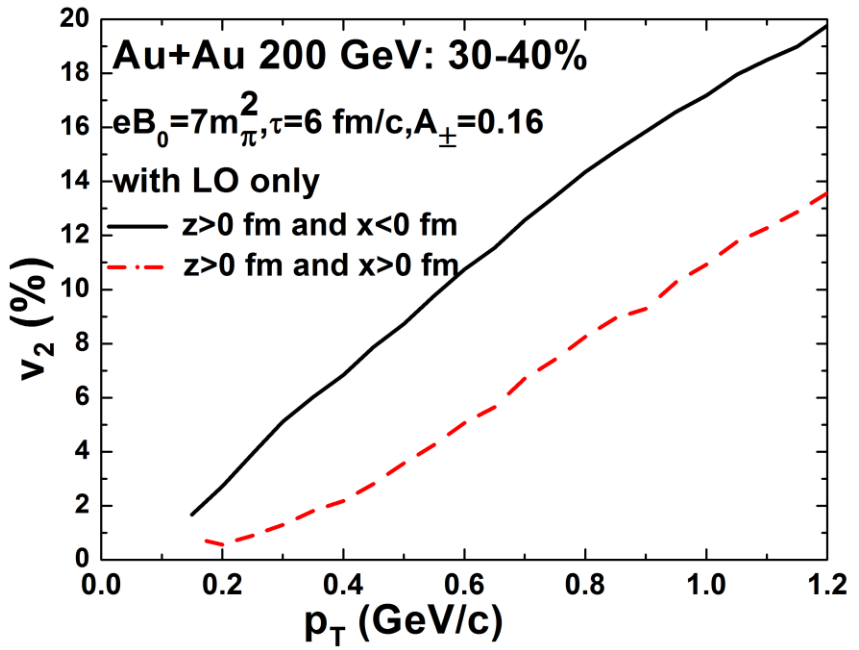
[Y. Burnier et al., PRL 107 (2011)]
[M. Hongo et al., arXiv 1309.2823 (2013)]
[Yee+Yin, PRC 89 (2014)]

- Enhance positively charged particles' v_2

Why?

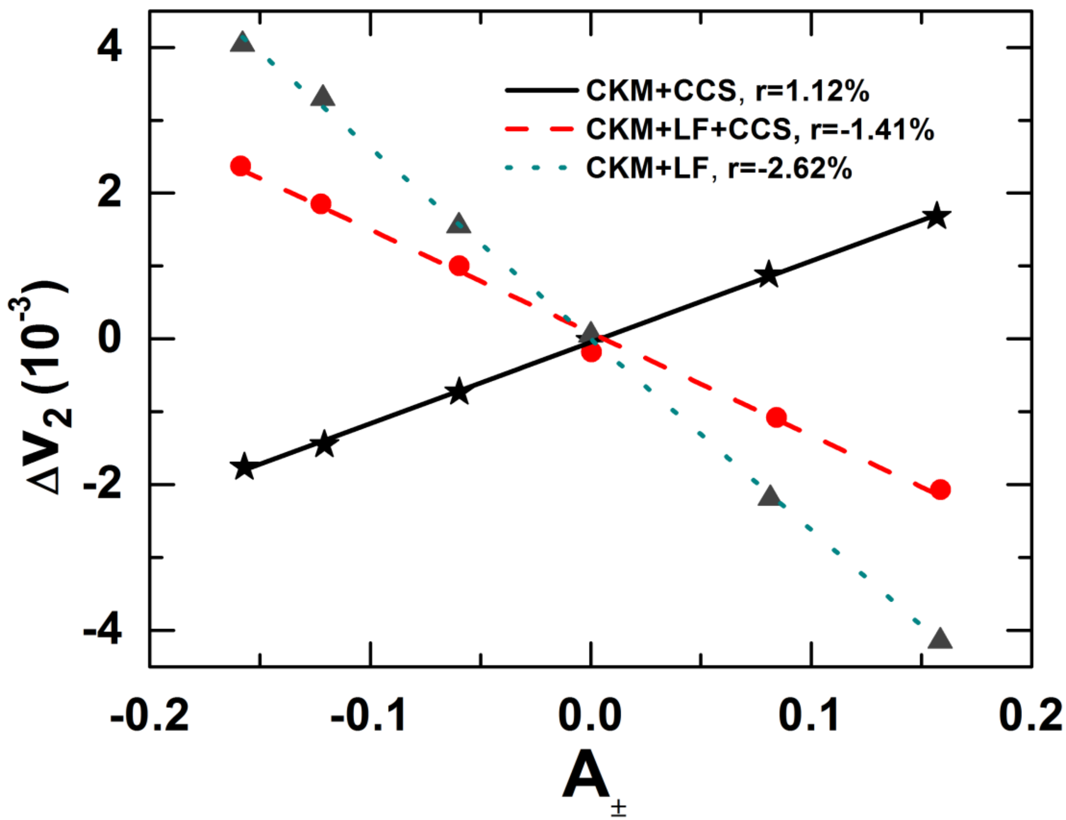


$$\mu/T\left(\frac{N_R - N_{\overline{R}} + N_L - N_{\overline{L}}}{N_R + N_{\overline{R}} + N_L + N_{\overline{L}}}\right)$$



- Flow is larger in z direction because of the initial narrow size in z direction.
- Lorentz force leads to different v_1 for positively and negatively charged particles.
- Elliptic flow is larger in upper left and lower right sections.

V_2 splitting dependence on charge asymmetry



- Lorentz force leads to negative slope parameter
- The positive slope parameter is smaller than experiment result (r=3%)

Summary and discussion

1) **Chirality changing scattering is essential to generate eccentricity and elliptic flow splitting.**
2) **CMW enhances negatively charged particles' v_2 and leads to positive slope parameter.**
3) **Lorentz force enhances positively charged particles' v_2 and leads to negative slope parameter, and it exists even when CKM and CCS are not included.**
4) **Slope parameter is smaller than experimental result which is r=0.03, and other effects need to be included (CVE?).**
5) **It takes time to generate axial charge dipole. To have a large positive slope parameter, we need to generate it more quickly. An initial axial charge dipole can help increase slope parameter.**

Thank You