Simulating chiral anomalous effects with AMPT model

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References:
[1] Guo-Liang Ma, Bin Zhang, Phys. Lett. B 700, 39 (2011).
[2] Guo-Liang Ma, Phys. Lett. B 735, 383 (2014).
[3] Xin-Li Zhao, Guo-Liang Ma, Yu-Gang Ma, Phys. Lett. B 729, 413 (2019).

Outline

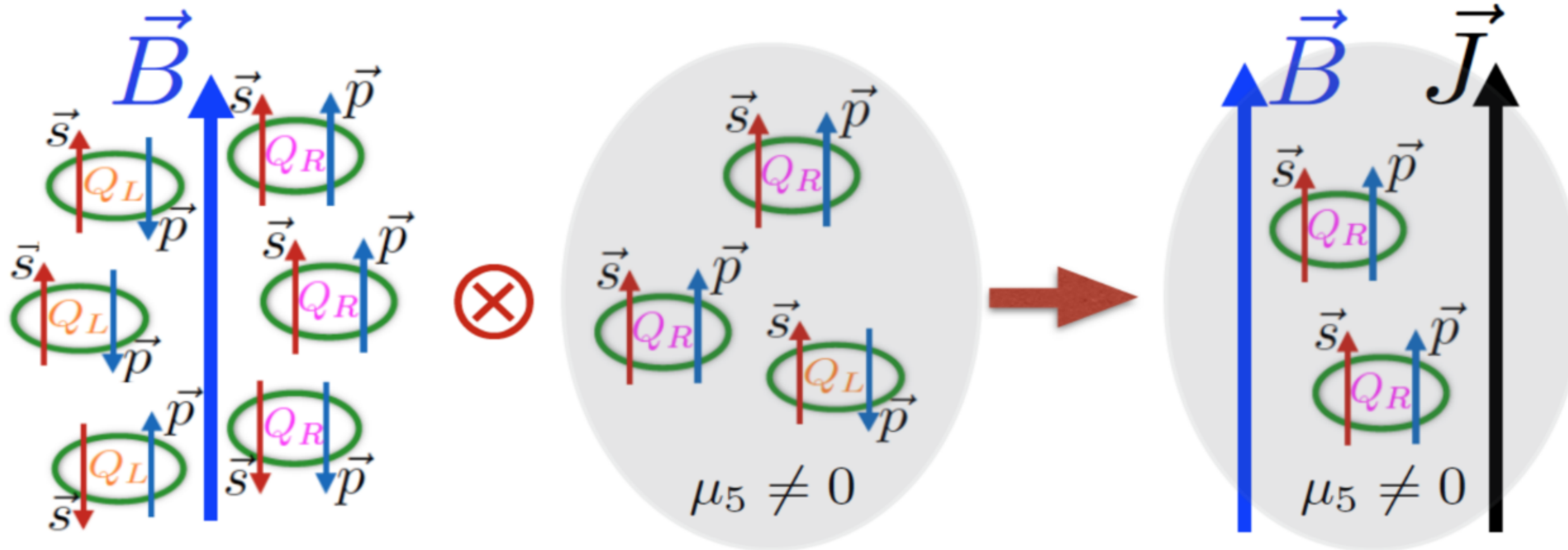
- ➢ Introduction
- ➢ Results and Discussions

(a) Simulating CMW in Au+Au

(b) E·B or CMW?

- ➢ Summary

Chiral Magnetic Effect (CME)

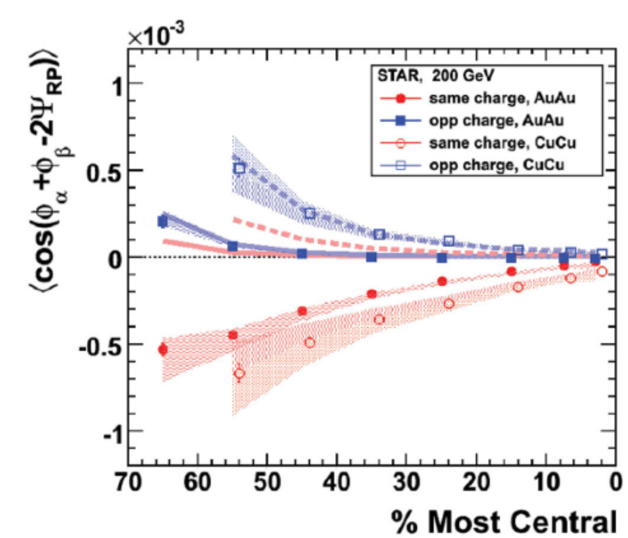


D.E. Kharzeev, J. Liao *et al* , PROG. PART. NUCL. PHYS. 88,1(2016)

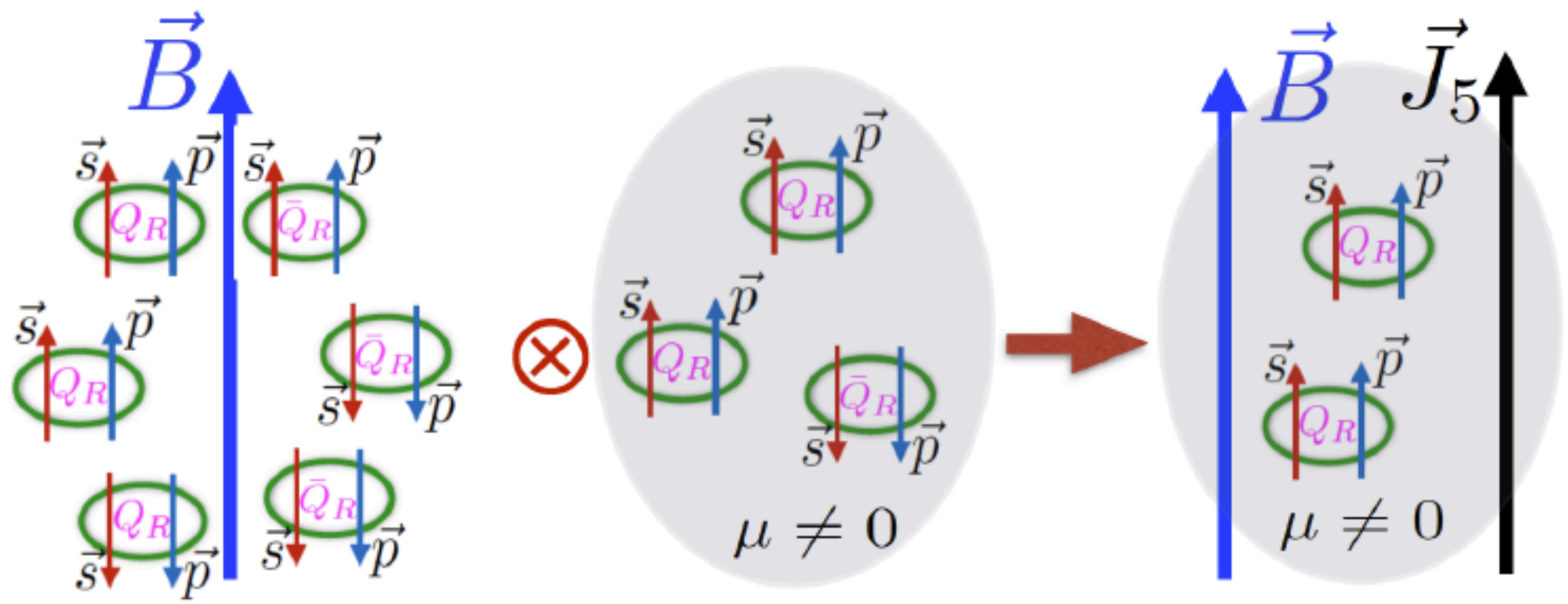
The chiral anomaly creates differences in the number of left and right handed quarks. An excess of right or left handed quarks $\boldsymbol{\mu}_5$ leads to a current flow along the magnetic field.

$$\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5 \mathbf{B}$$

Charge separation observable: γ=<cos(ϕ_a+ϕ_β-2Ψ_{RP})>



Chiral Separation Effect (CSE)



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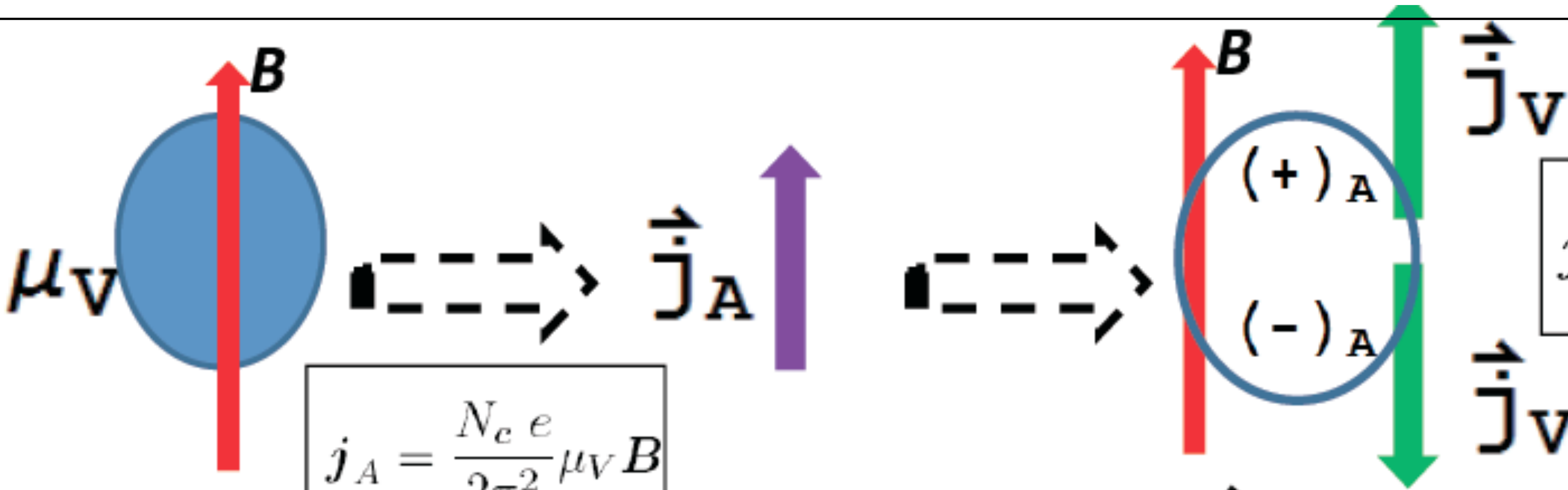
An axial current is generated along an external magnetic field, with its magnitude in proportion to the system's (nonzero) vector chemical potential as well as the magnetic field magnitude.

$$\mathbf{J}_5 = \frac{Qe}{2\pi^2}\mu \ \mathbf{B}$$

CSE observable: ???

Chiral Magnetic Wave (CMW)

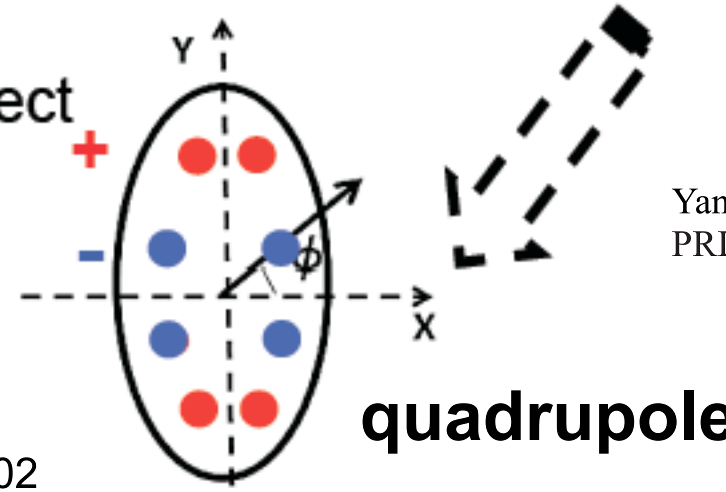


$$j_A = \frac{N_c\, e}{2\pi^2}\mu_V B$$

Chiral Separation Effect

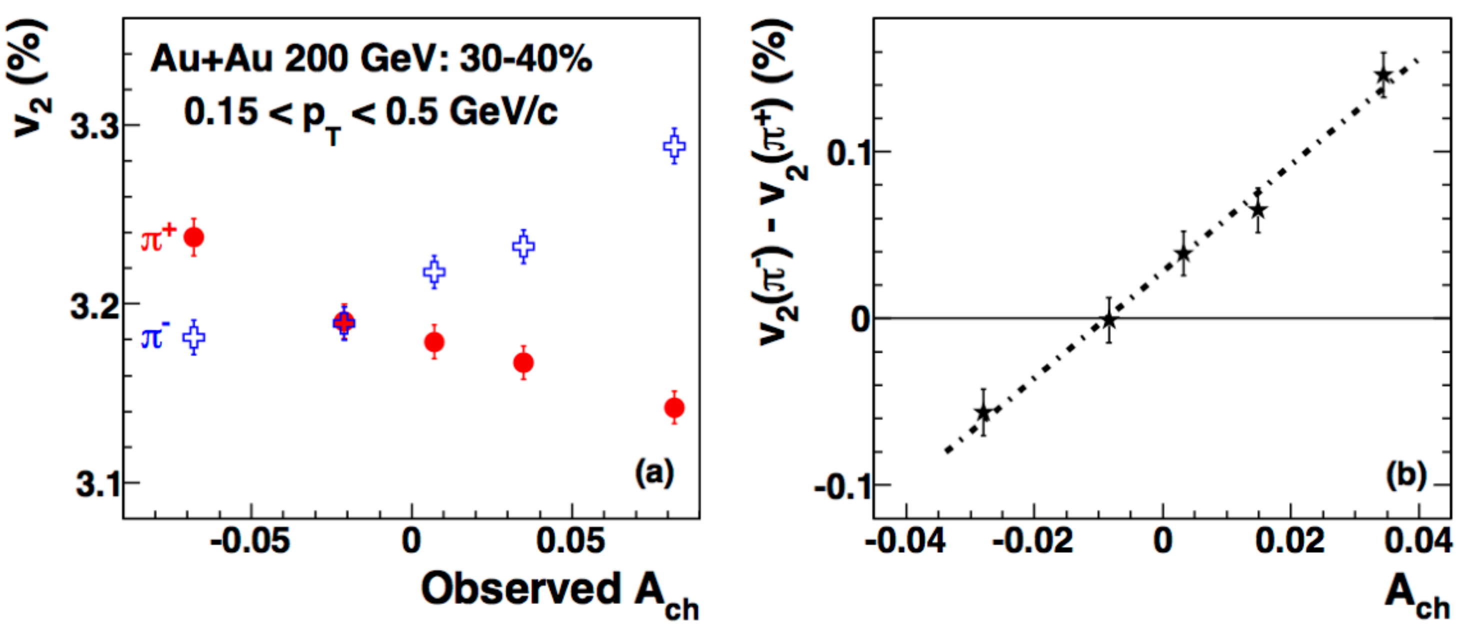
$$j_V = \frac{N_c\, e}{2\pi^2}\mu_A B$$

Chiral Magnetic Effect



Yannis Burnier, Dmitri Kharzeev, Jinfeng Liao, Ho-Ung Yee, PRL 107, 052303 (2011)

STAR, Phys. Rev. Lett. 114 (2015) 252302

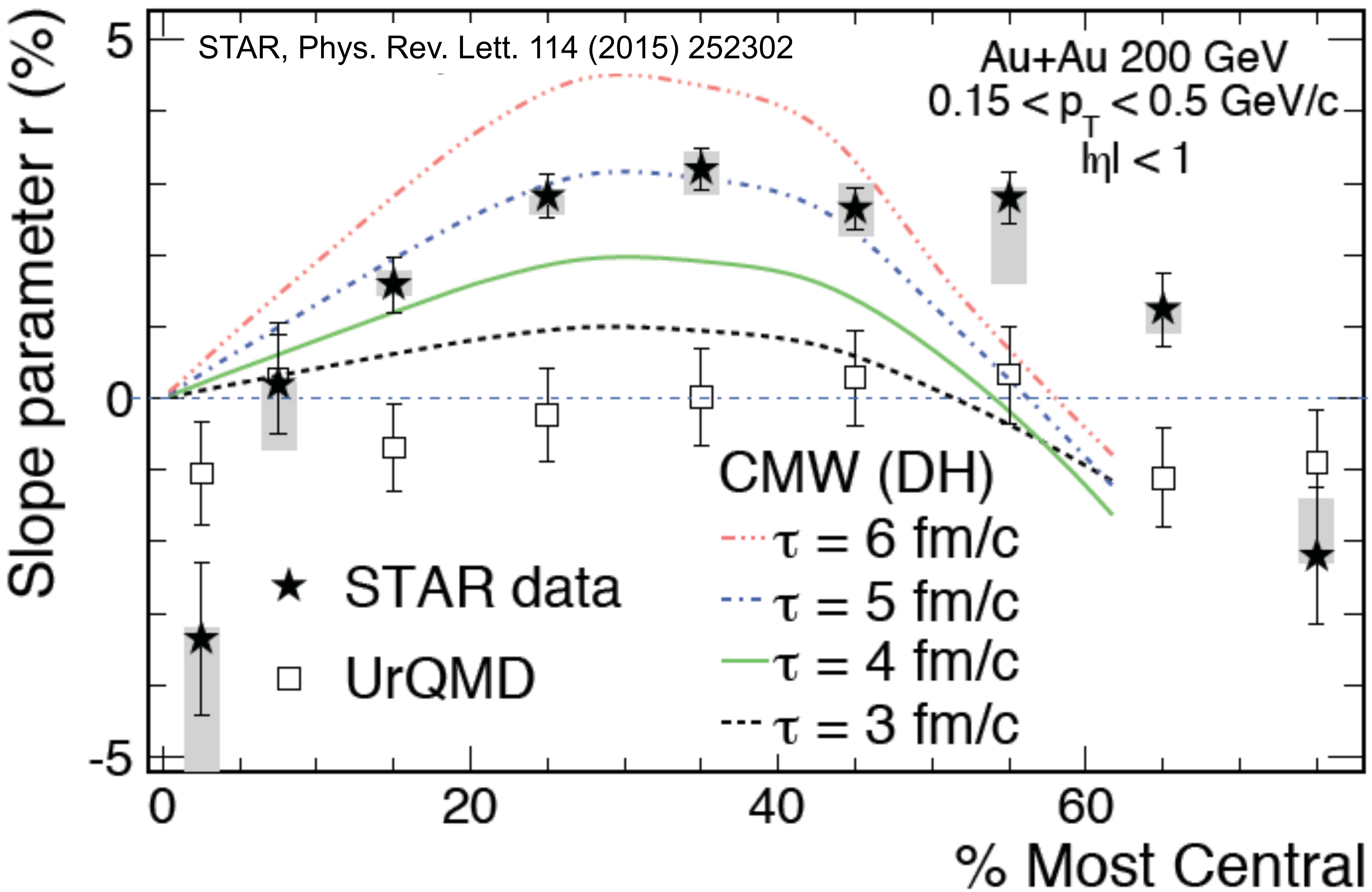


$$v_2^{\pm} = v_2 \mp \frac{r}{2} A_{ch}$$

$$v_2^{-} - v_2^{+} = r A_{ch}$$

- CMW (CME+CSE) signal: v2 splitting of positive and negative charged particles (slope para. *r*)

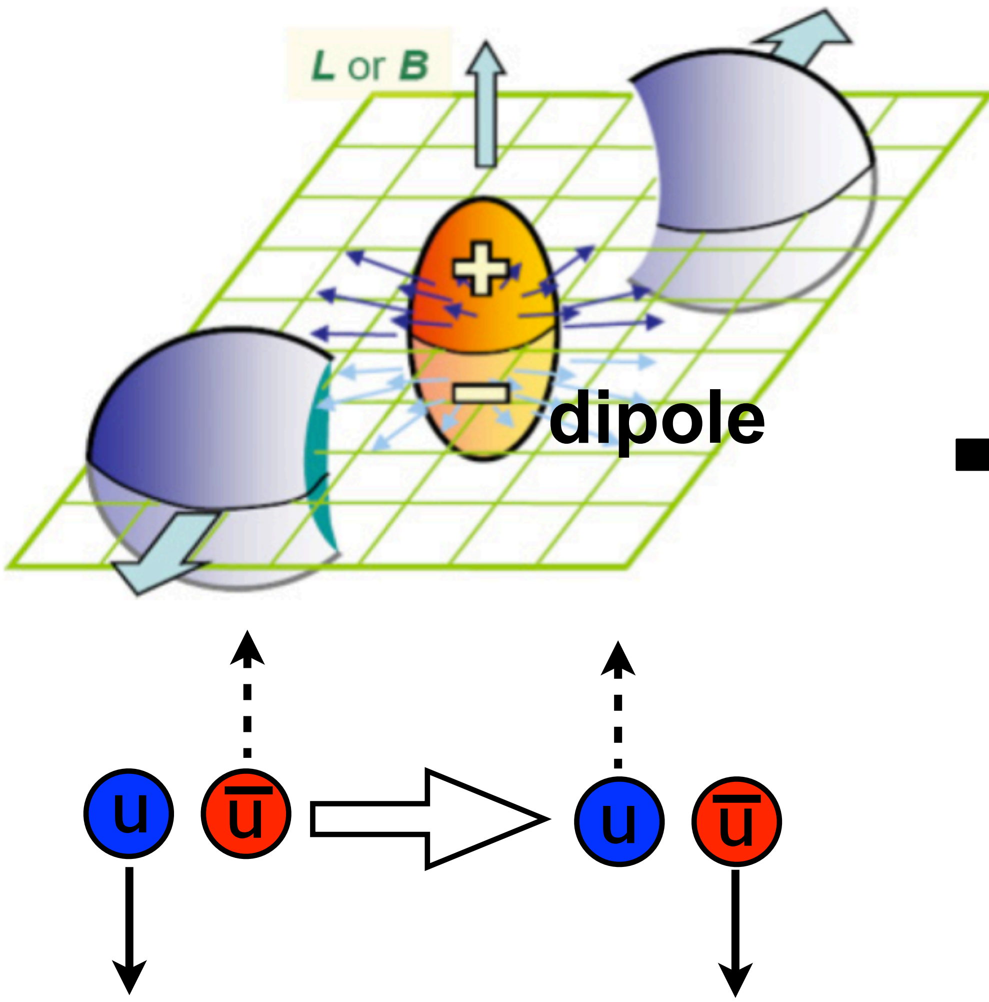
Charge asymmetry slope r of pion v2

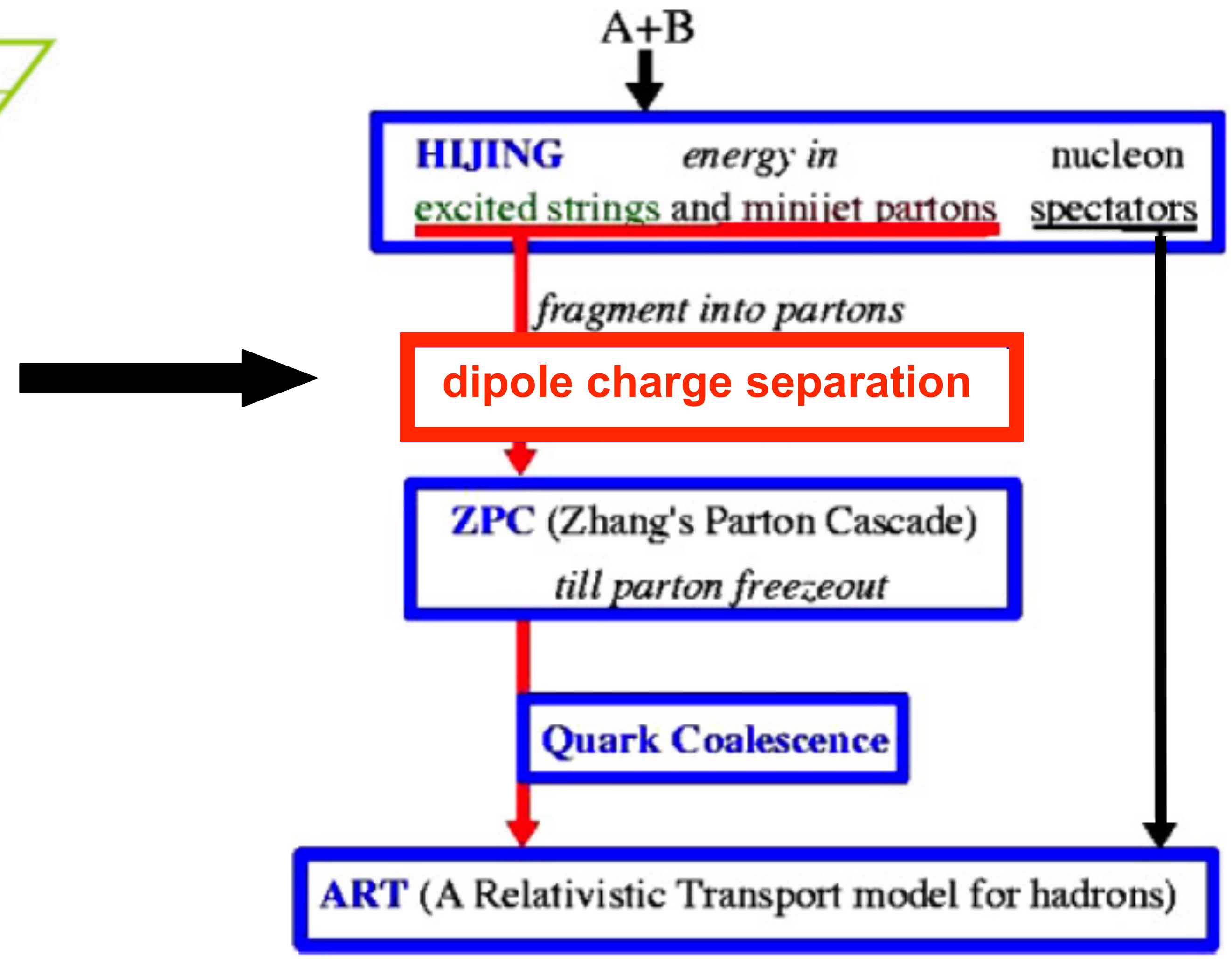


- RHIC-STAR data can be described by the CMW expectation with different CMW duration times.
- UrQMD can not reproduce the slopes r.

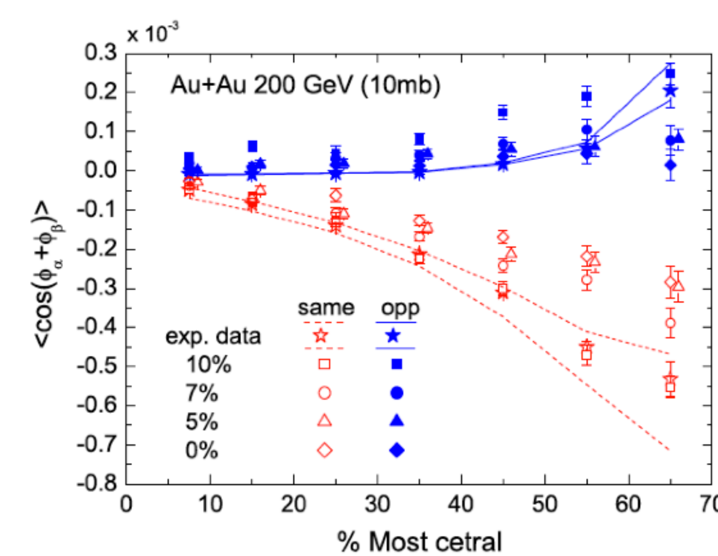
AMPT with dipole charge separation

Guo-Liang Ma, Bin Zhang, Phys. Lett. B 700, 39 (2011)



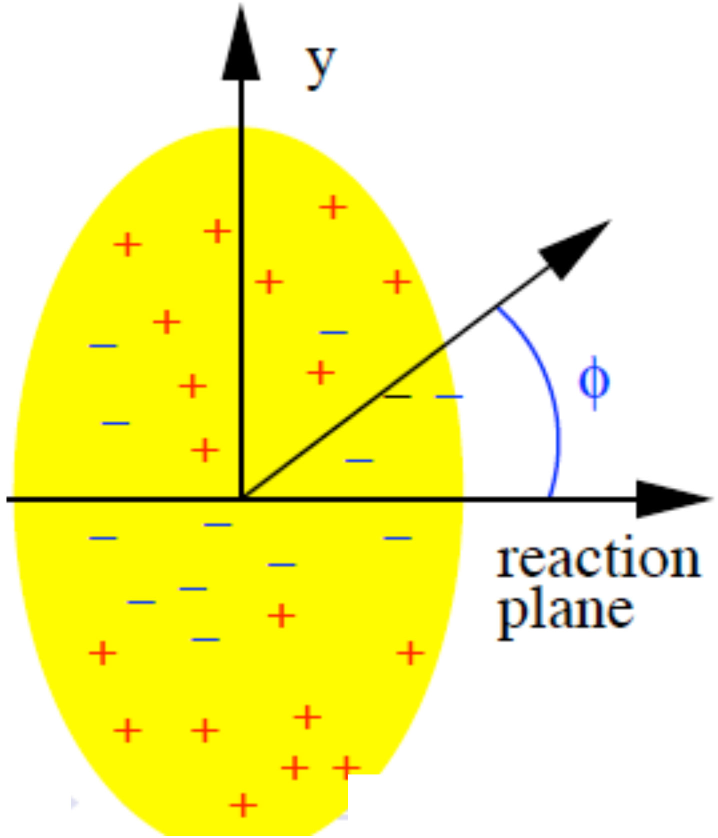


$$f\% = (N^{+}_{upward} - N^{+}_{downward}) / (N^{+}_{upward} + N^{+}_{downward})$$

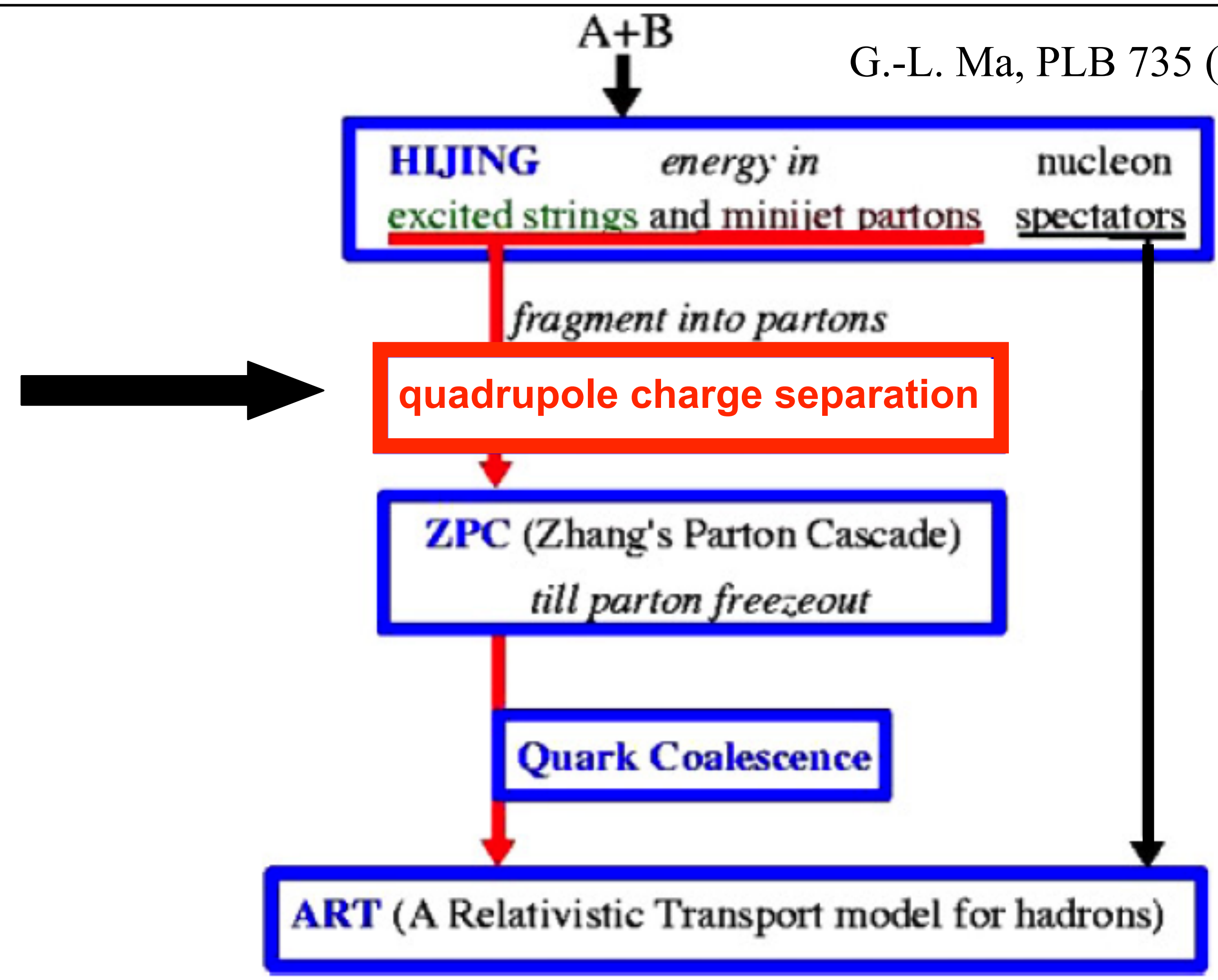


- We included an initial dipole charge separation mechanism into AMPT model.
- **Final state interaction effect on CME:** From a percentage of charge separation of 10% in the beginning →1-2% percentage in the end.

AMPT with quadrupole charge separation



G.-L. Ma, PLB 735 (2014) 383



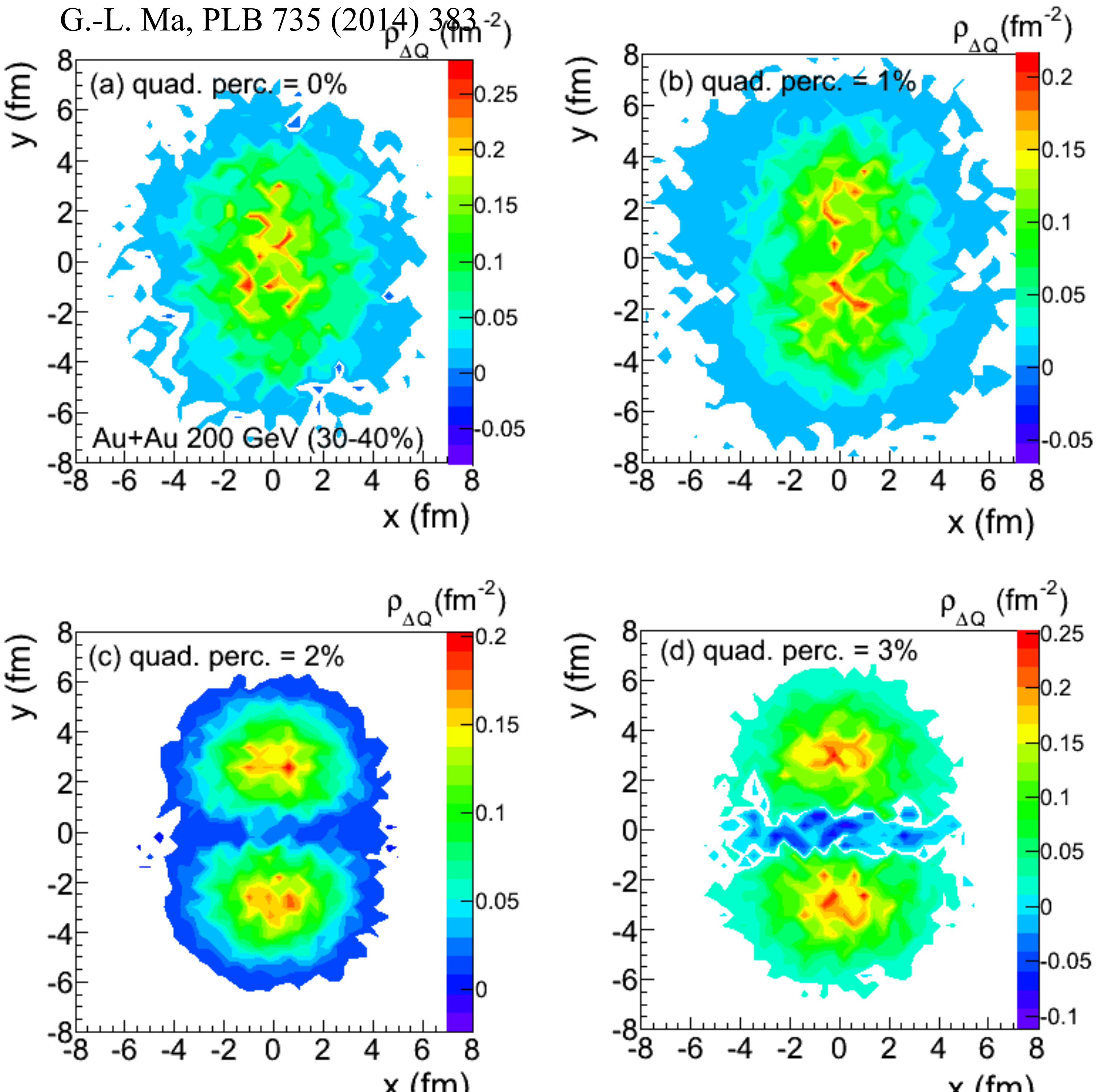
- **How to include initial quadrupole charge separation into the AMPT model:**

switch the positions (x,y,z) of a percentage of the small-|y| u quarks with those of large-|y| u-bar quarks, and likewise for d-bar and d quarks for Ach>-0.01 events; A contrary manner for A_{ch}<-0.01 events.

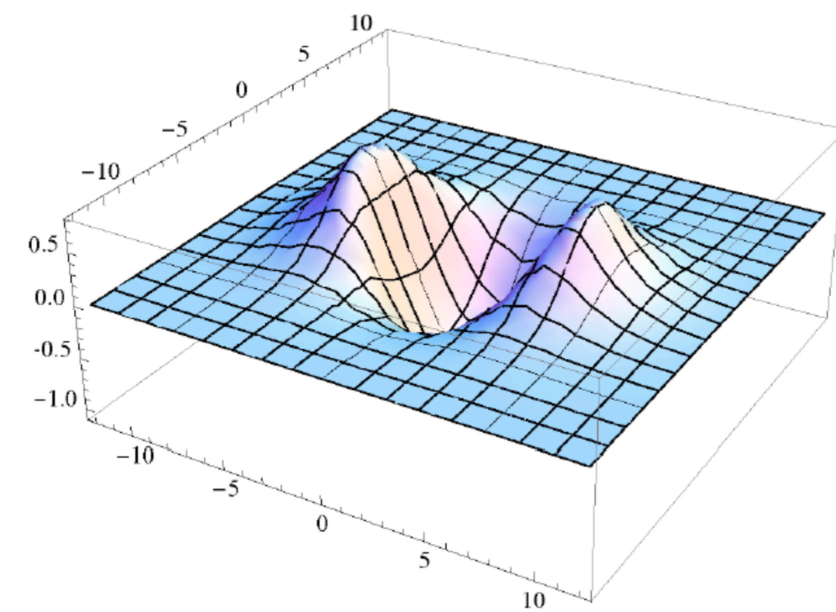
- **The goal is to learn some properties of chiral magnetic wave through how final charge asymmetry of pion v_2 depends on the quadrupole fraction after $\vec{B}$ and $\vec{E}$ vanish.**

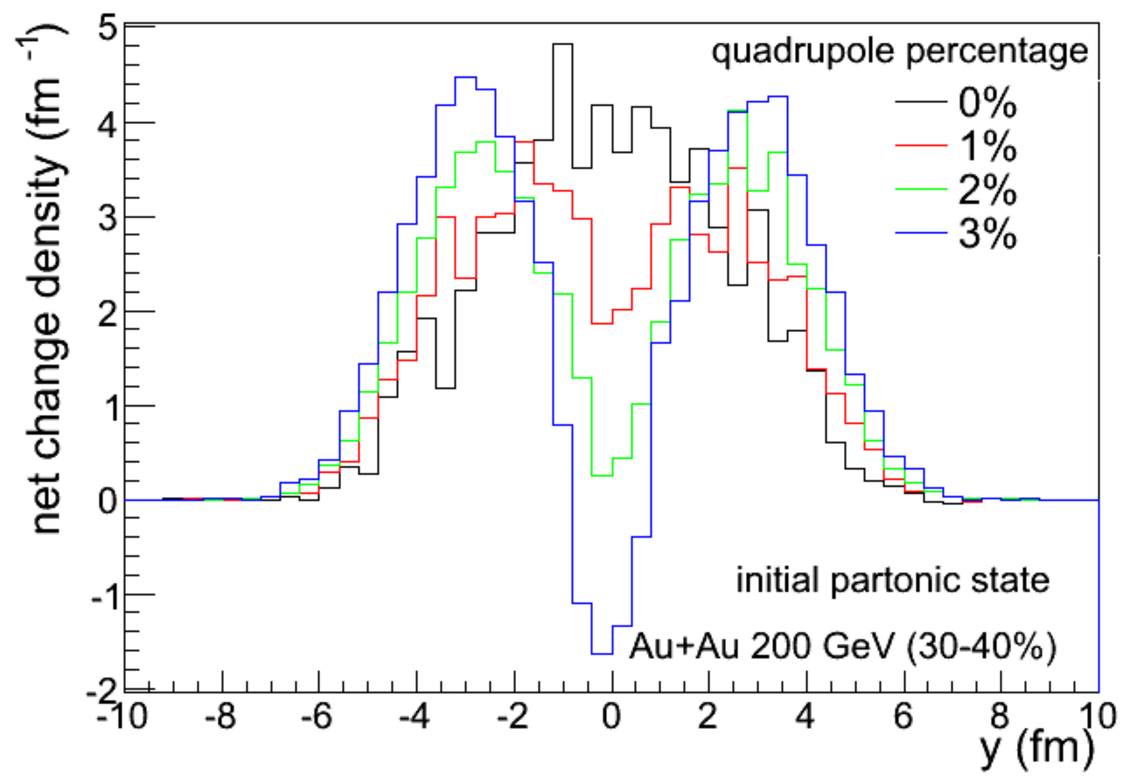
Initial charge quadrupole distribution

G.-L. Ma, PLB 735 (2014) 383



Yannis Burnier, Dmitri Kharzeev, Jinfeng Liao, Ho-Ung Yee,PRL 107, 052303 (2011)

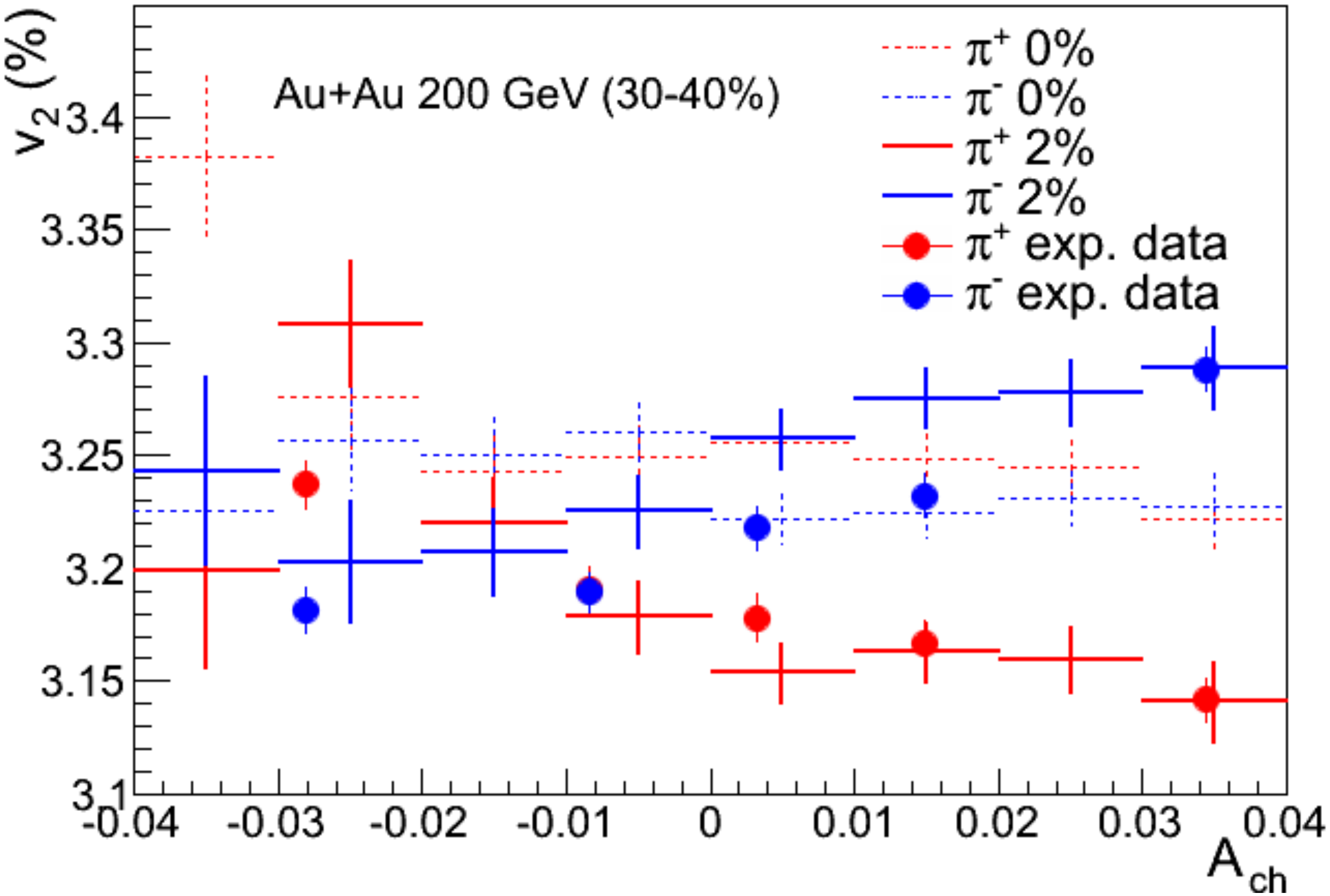




- Initial partonic net charge distribution (~2 fm/c) changes with quadrupole percentage.

Charge asymmetry of pion v2

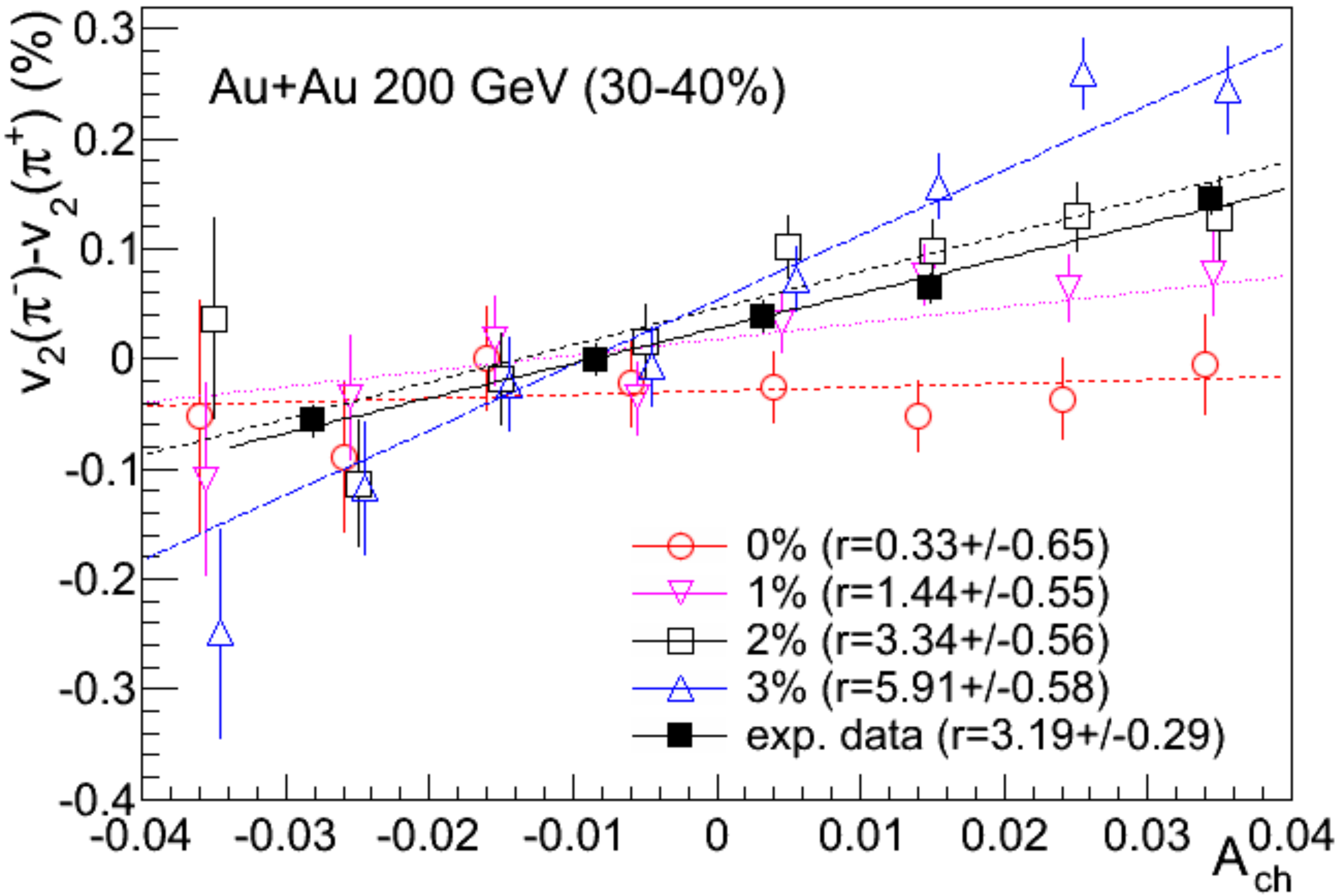
G.-L. Ma, PLB 735 (2014) 383



- The Ach dependences of pion+/- v_2 appear with a non-zero initial charge quadrupole.

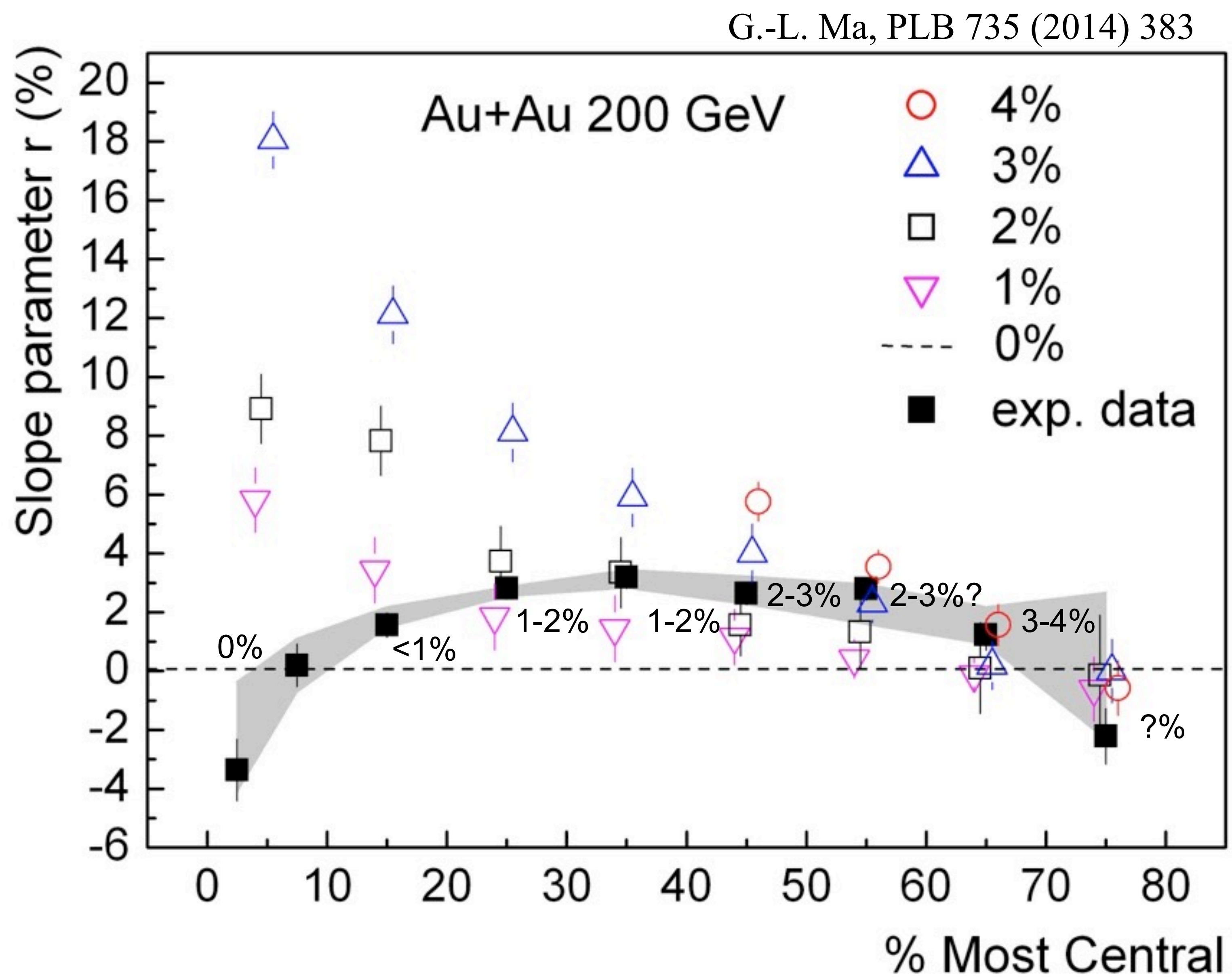
Δv_2 vs A_{ch}

G.-L. Ma, PLB 735 (2014) 383



- No charge asymmetry of pion v_2 for the initial quadrupole percentage of 0%.
- Δv_2 increases with A_{ch} for non-zero initial quadrupole percentages.
- Δv_2 increases faster with larger initial quadrupole percentage.

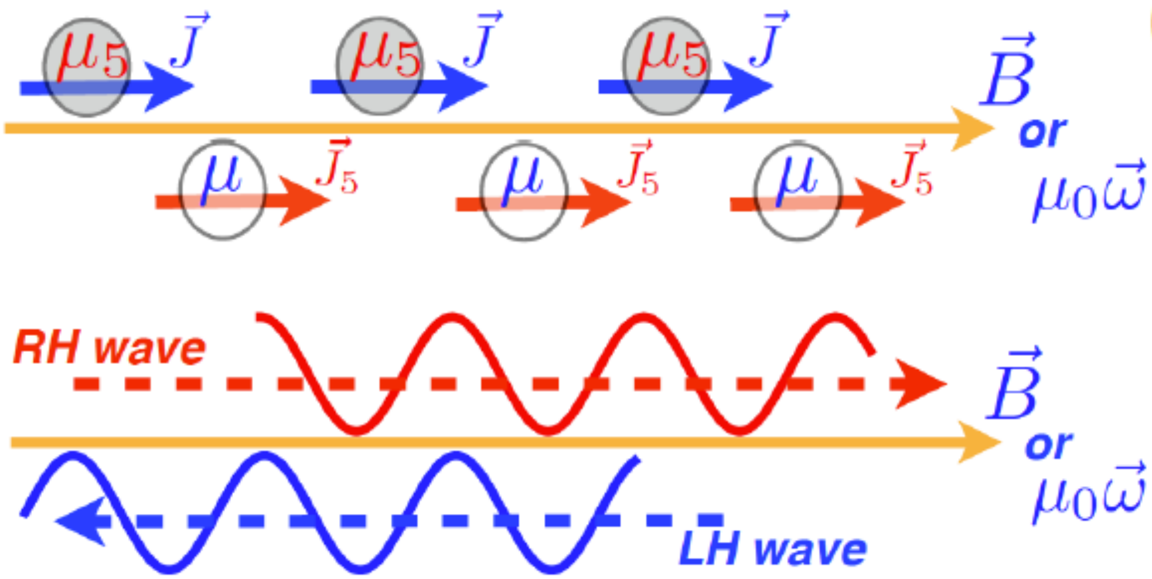
Possible constraint on CMW



centrality bin	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%
initial quad. perc.	0%	<1%	1-2%	1-2%	2-3%	2-3%	3-4%	?%

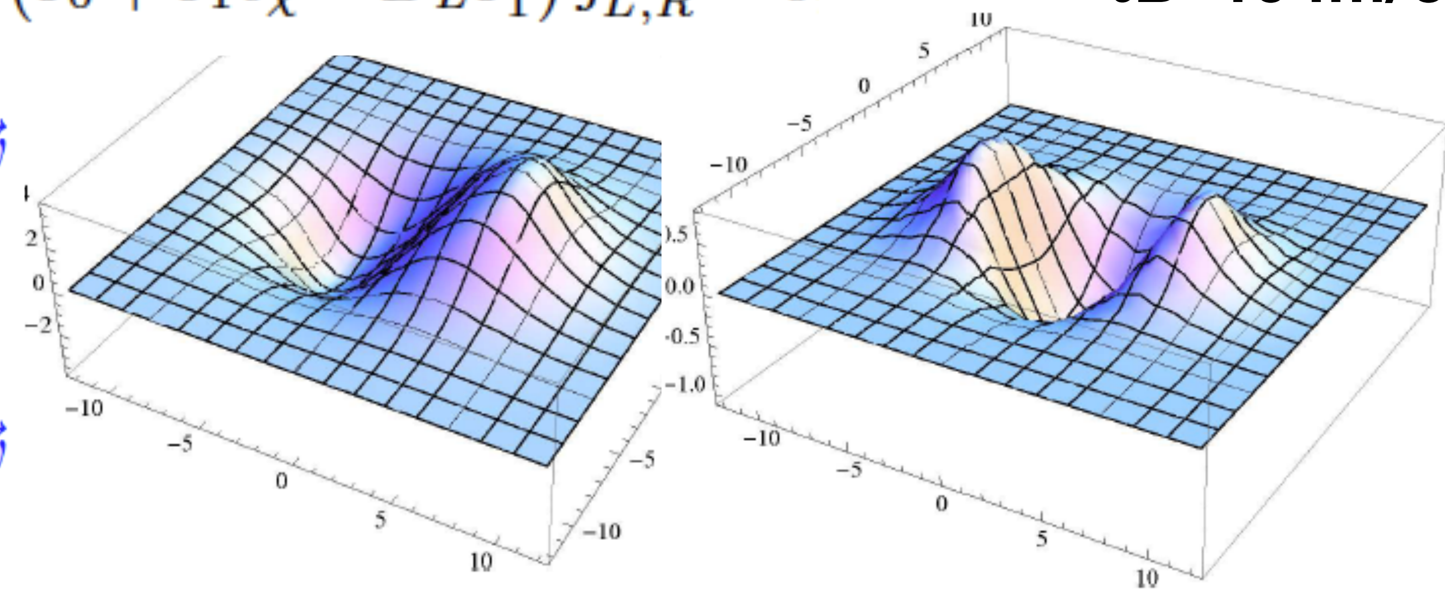
•A constraint (<4%) to the centrality dependence of initial quadrupole percentage.

Can CMW produce a quadrupole in HIC ?



$$\left(\partial_0 \mp \partial_1 v_\chi - D_L \partial_1^2\right) j^0_{L,R} = 0$$

τB=10 fm/c



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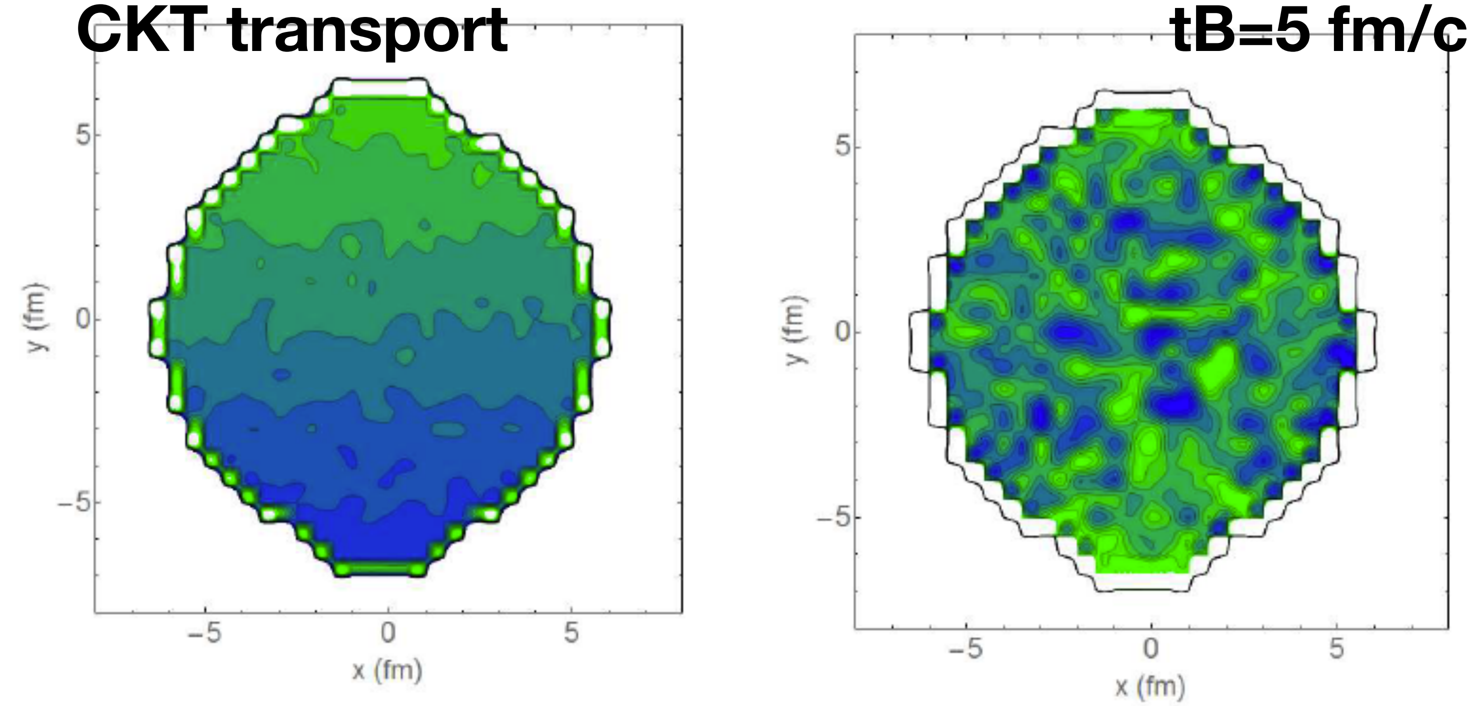
- It has to take a long lifetime of magnetic field for CMW to produce quadrupole.
- **τ**B may be very short.
- Other mechanism to produce quadrupole?

CKT transport

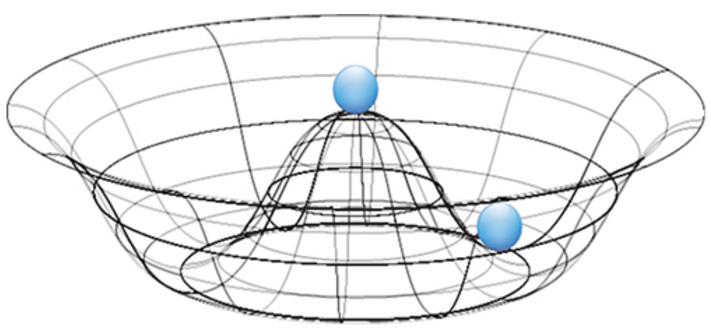
tB=5 fm/c

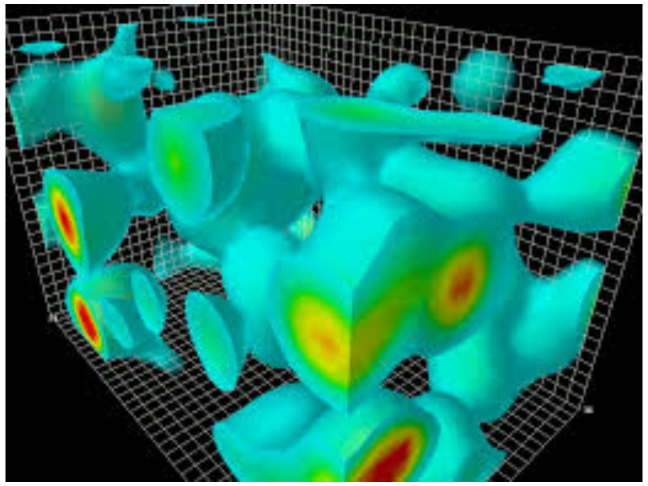


Yifeng Sun, Che Ming Ko, Feng Li, Phys.Rev. C94 (2016), 045204

Chiral anomaly μ_5 sources

$$\partial_\mu J_5^\mu = 2im\bar{\psi}\gamma^5\psi - \frac{e^2}{16\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} - \frac{g^2}{16\pi^2}tr\epsilon^{\mu\nu\rho\sigma}G_{\mu\nu}G_{\rho\sigma}$$





- **QED anomaly effects**: Fermi surface balance in the Dirac sea; neutral pion condensation; Dirac semimetal experiments etc.
- ***QED anomaly in heavy-ion collisions?***

$$\mathbf{E}\cdot\mathbf{B} = E_x B_x + E_y B_y + E_z B_z.$$

Spatial Distributions of magnetic Fields

From Lienard-Wiechert potential:

$$e\mathbf{E}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{R}_n - R_n \mathbf{v}_n}{(R_n - \mathbf{R}_n \cdot \mathbf{v}_n)^3}(1 - v_n^2),$$

$$e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{v}_n \times \mathbf{R}_n}{(R_n - \mathbf{R}_n \cdot \mathbf{v}_n)^3}(1 - v_n^2),$$

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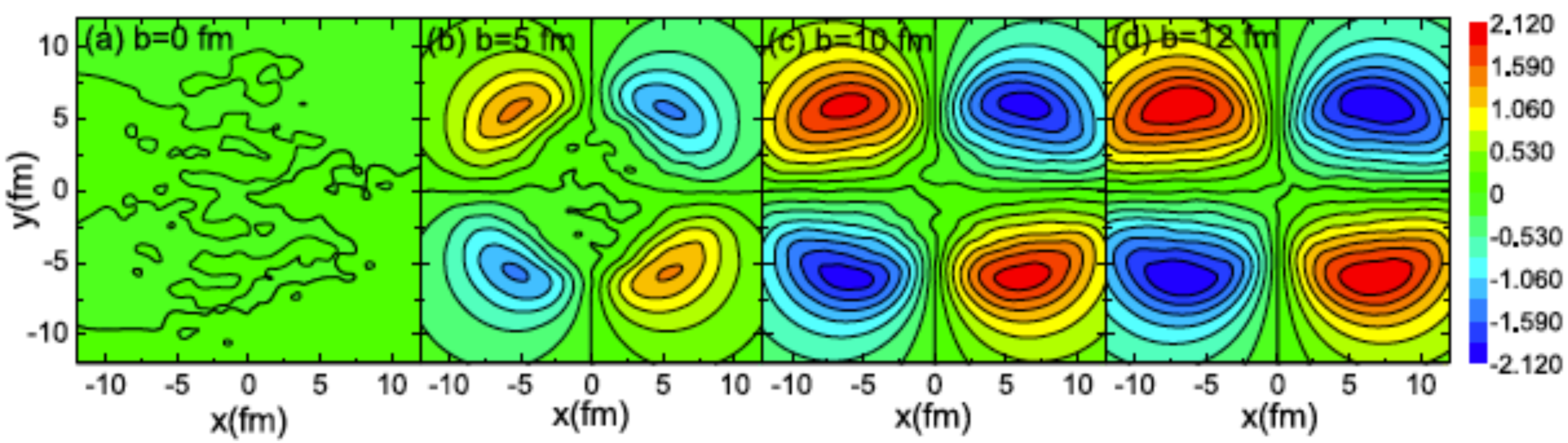

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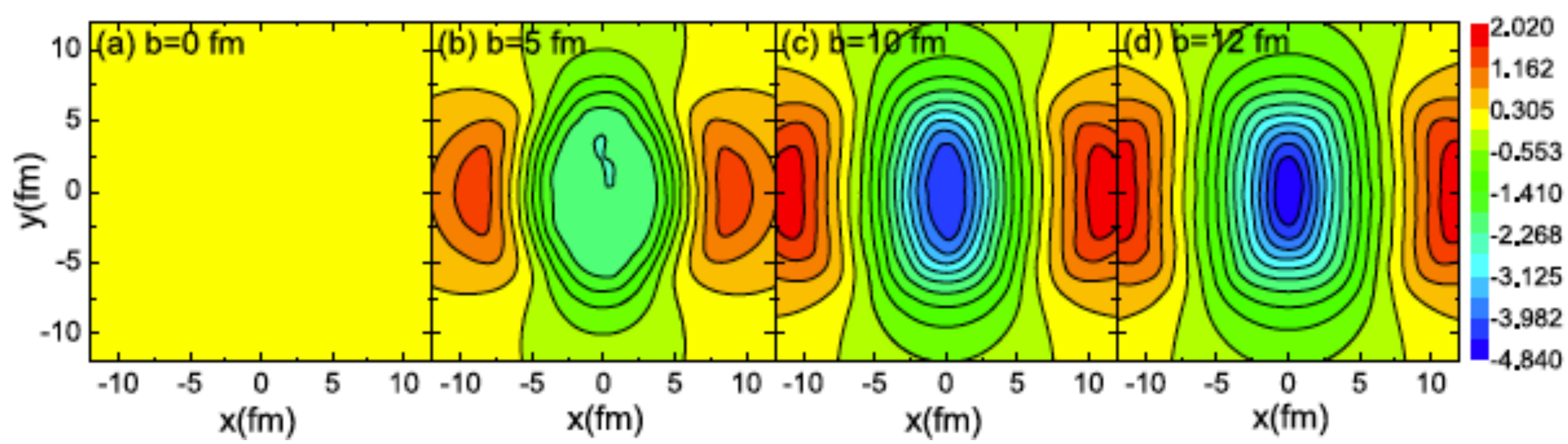


Au+Au 200 GeV

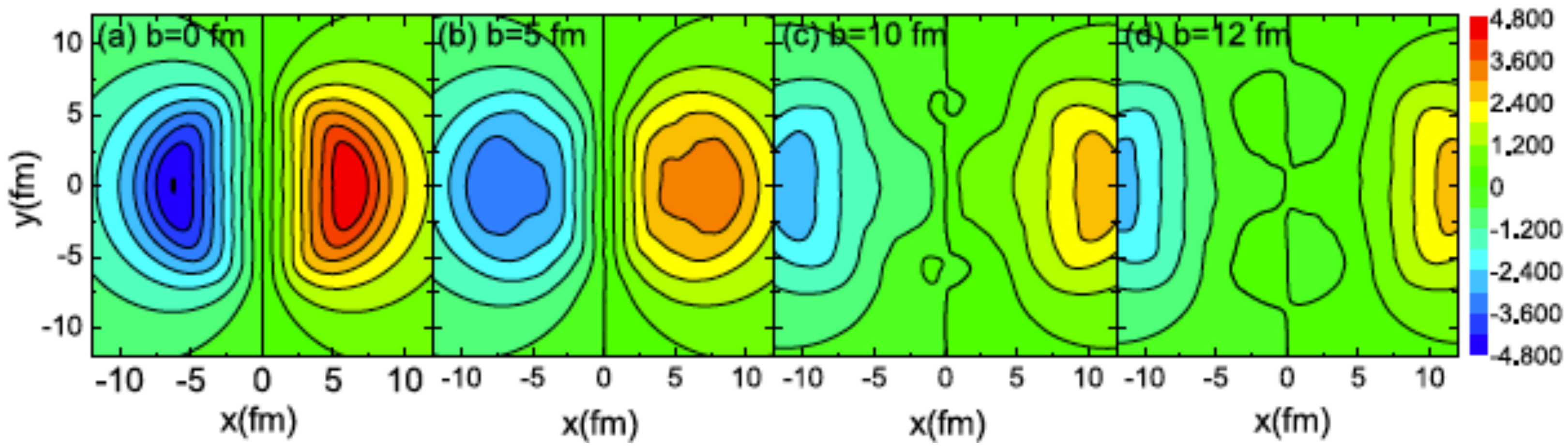
Spatial Distributions of Electric Fields

From Lienard-Wiechert potential:

$$e\mathbf{E}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{R}_n - R_n\mathbf{v}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2),$$

$$e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{v}_n \times \mathbf{R}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2),$$

<Ex>



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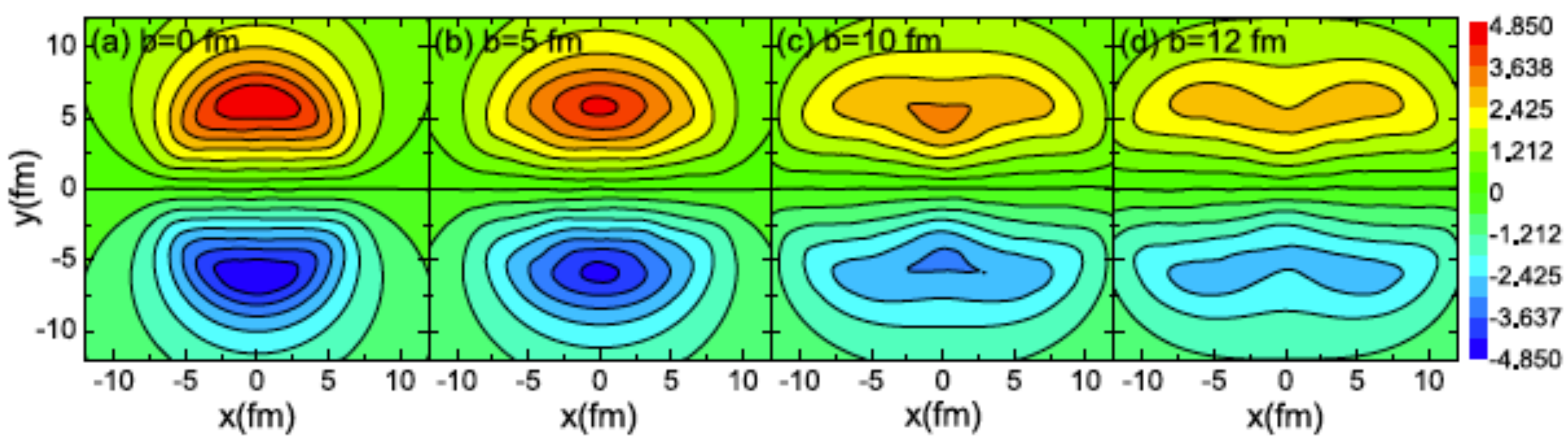
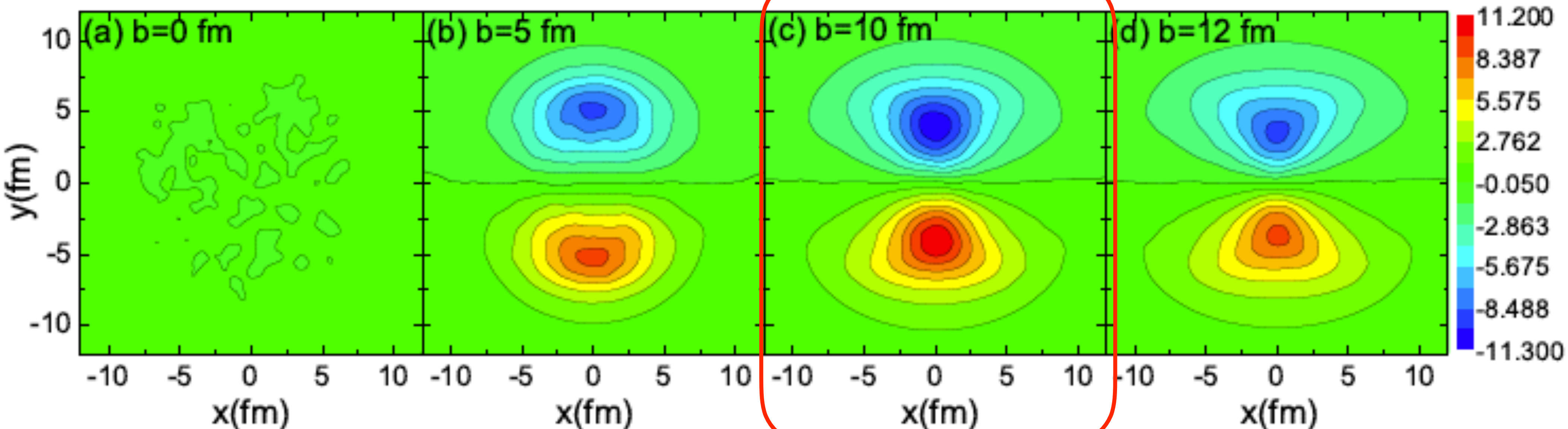


Au+Au 200 GeV

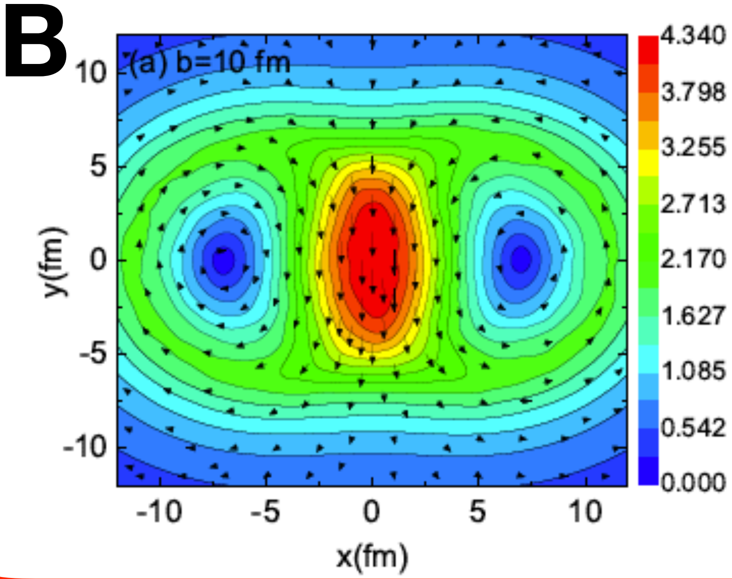
E·B in Au+Au 200GeV

E·B

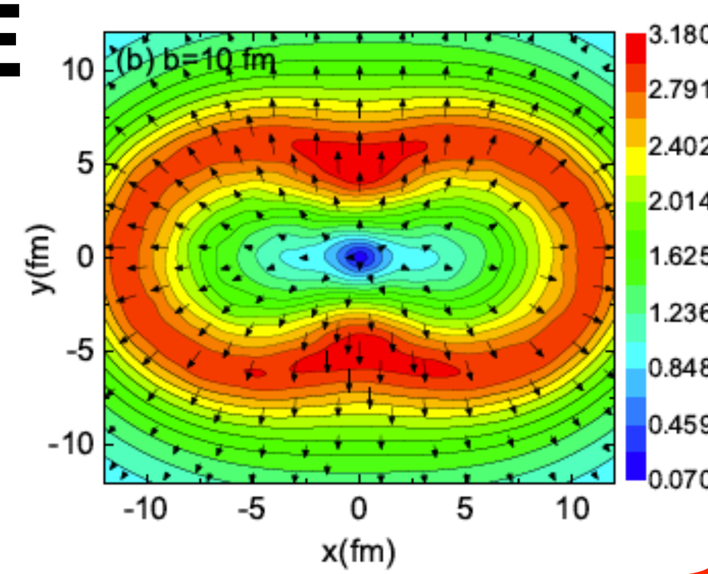


b=10 fm

B



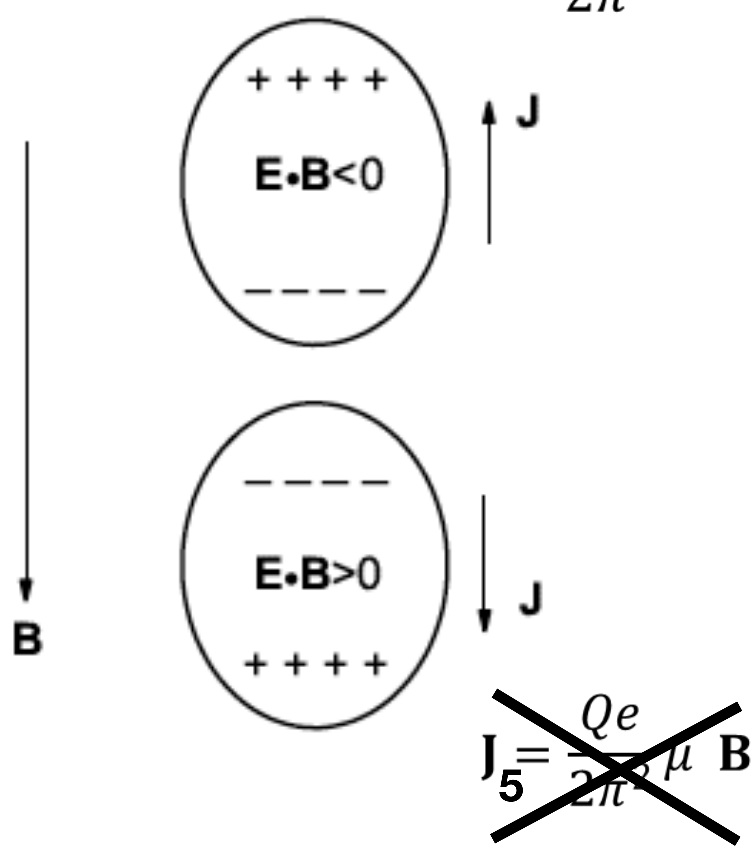
E

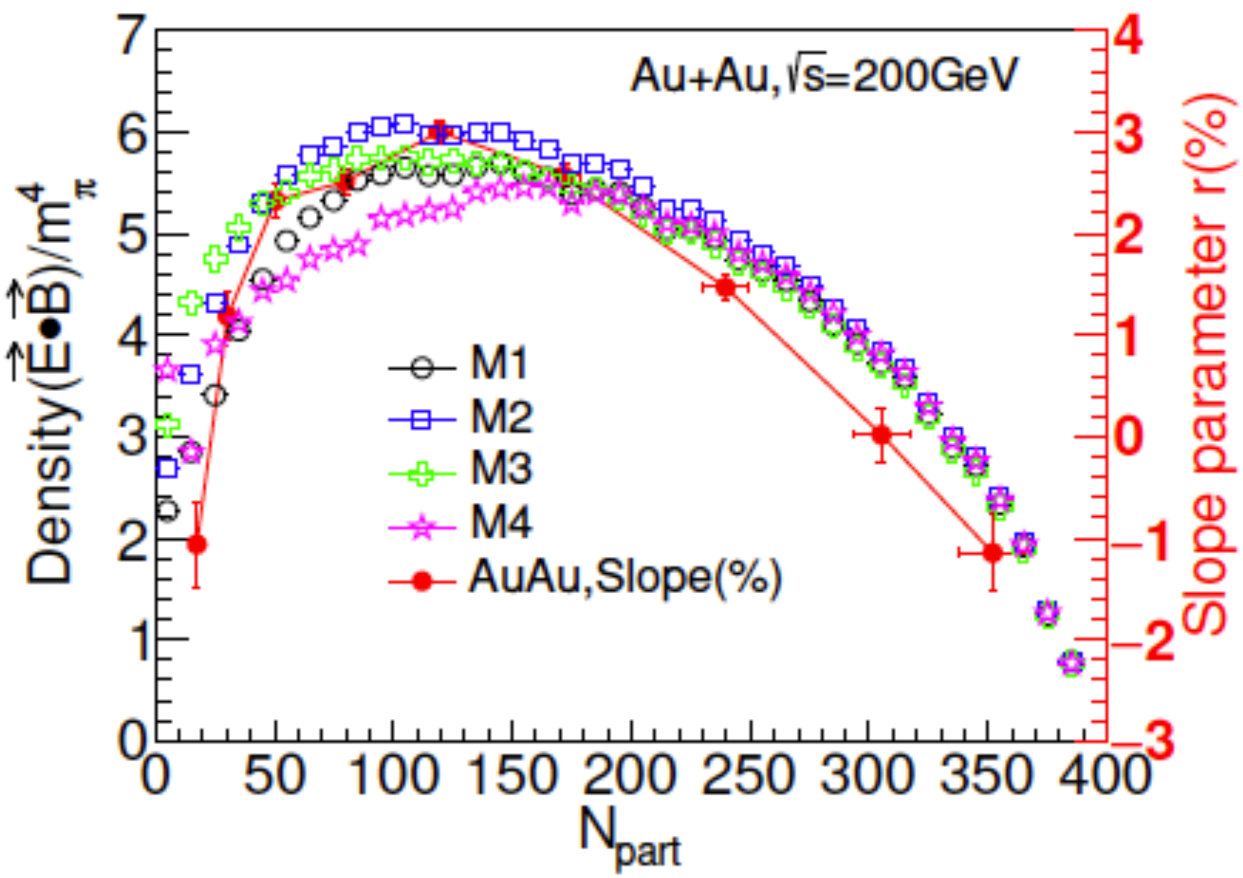


- **A dipolar distribution of E·B is observed at t=0 in noncentral Au+Au collisions.**

From E·B dipole to electric quadrupole

$$\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5 \mathbf{B}$$

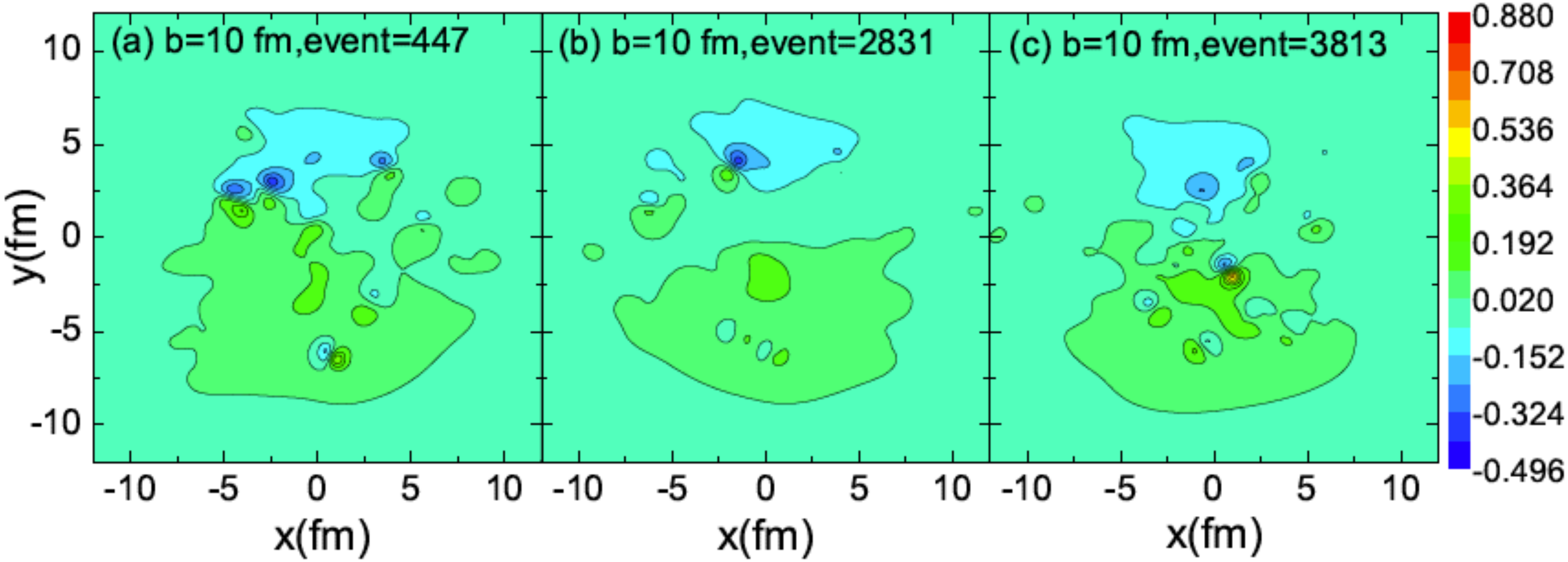




- **A dipolar E·B in a magnetic field can lead to a electric quadrupole with the help of CME.**
- **No formation of CMW here**

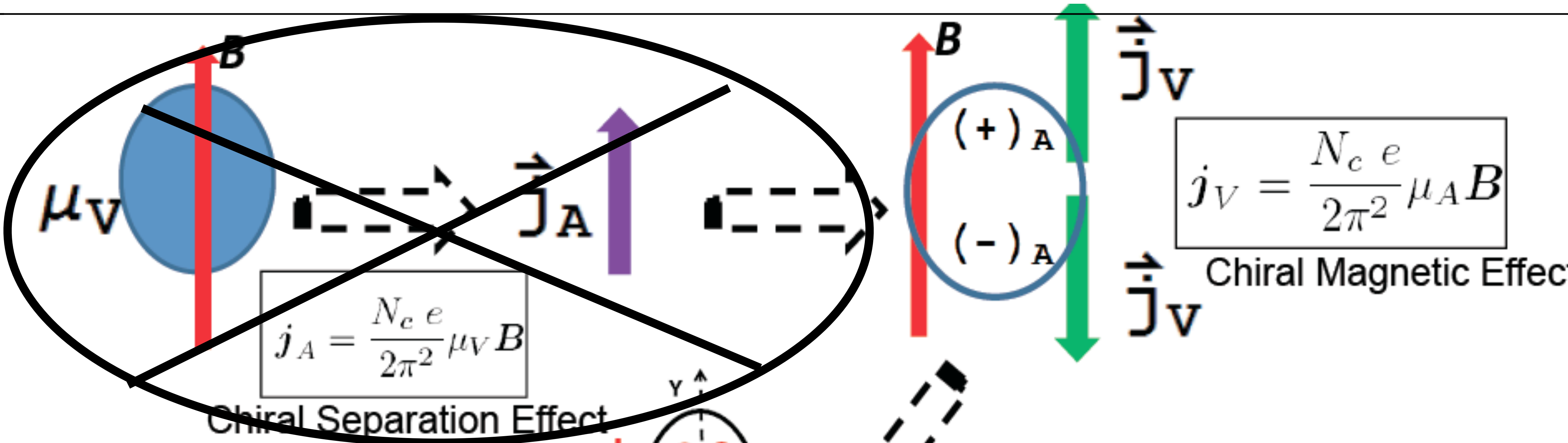
- **The density of E·B is consistent with the centrality dependence of the slope para. r by STAR**

Event-by-event E·B in Au+Au

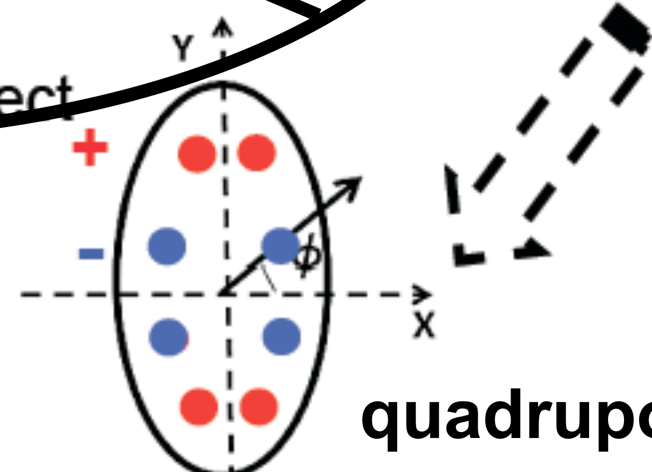


- **A dipolar E·B holds on event-by-event basis.**
- **Our new mechanism does not need the CSE (μ-dependent) ➠different energy dependence from the CMW-driven one**

Impact on CMW researches



$$\left(\partial_0 \mp \partial_1 v_\chi - D_L \partial_1^2\right) j^0_{L,R} = 0$$

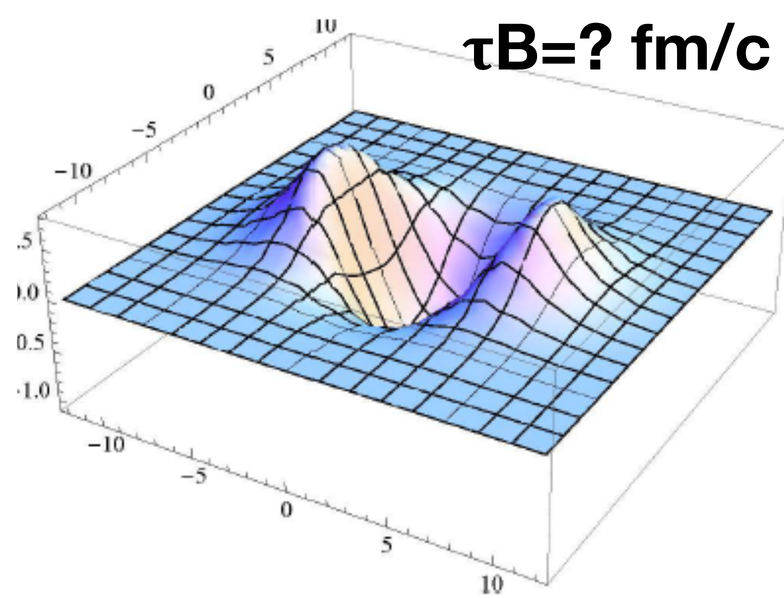


Yannis Burnier, Dmitri Kharzeev, Jinfeng Liao, Ho-Ung Yee, PRL 107, 052303 (2011)

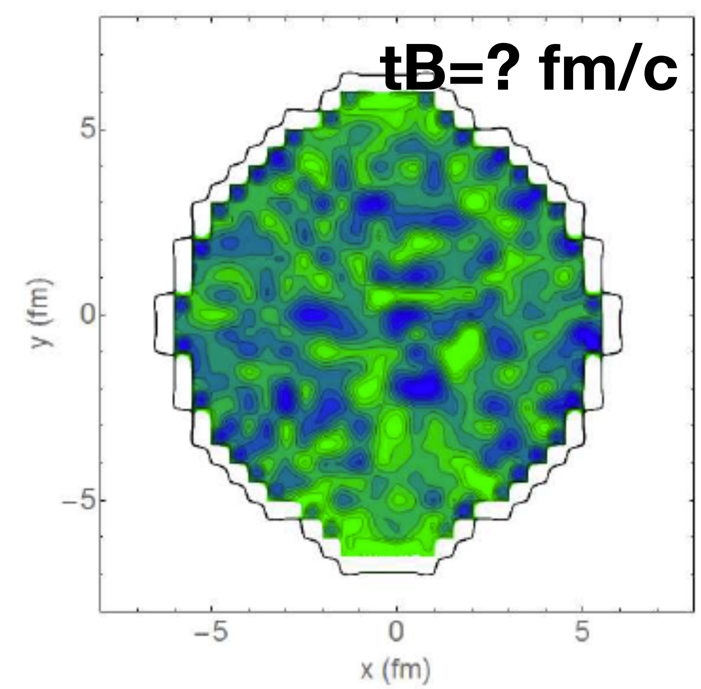
quadrupole

- CMW requires a long lifetime of magnetic field to produce quadrupole **based on a zero-μ5 initial condition.**
- **If there is an initial dipolar E·B**, how long lifetime of B is needed to generate quadrupole???

τB=? fm/c



tB=? fm/c



Summary

- The electric quadrupole can be transferred into charge asymmetry of pion v2 through final interactions.
- A dipolar E·B is observed in noncentral Au+Au collisions, which also lead to a electric quadrupole without CMW.
  => a new interpretation to the slope r measured in Au+Au by STAR.
- The dipolar E·B may provide a source/chiral anomalous initial condition to other chiral effects?

Congratulations to Prof. Che-Ming Ko's 50-year scientific research career!