Anomaly induced charge dependence of the elliptic flow in heavy ion collisions

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Work done in collaboration with
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Outline

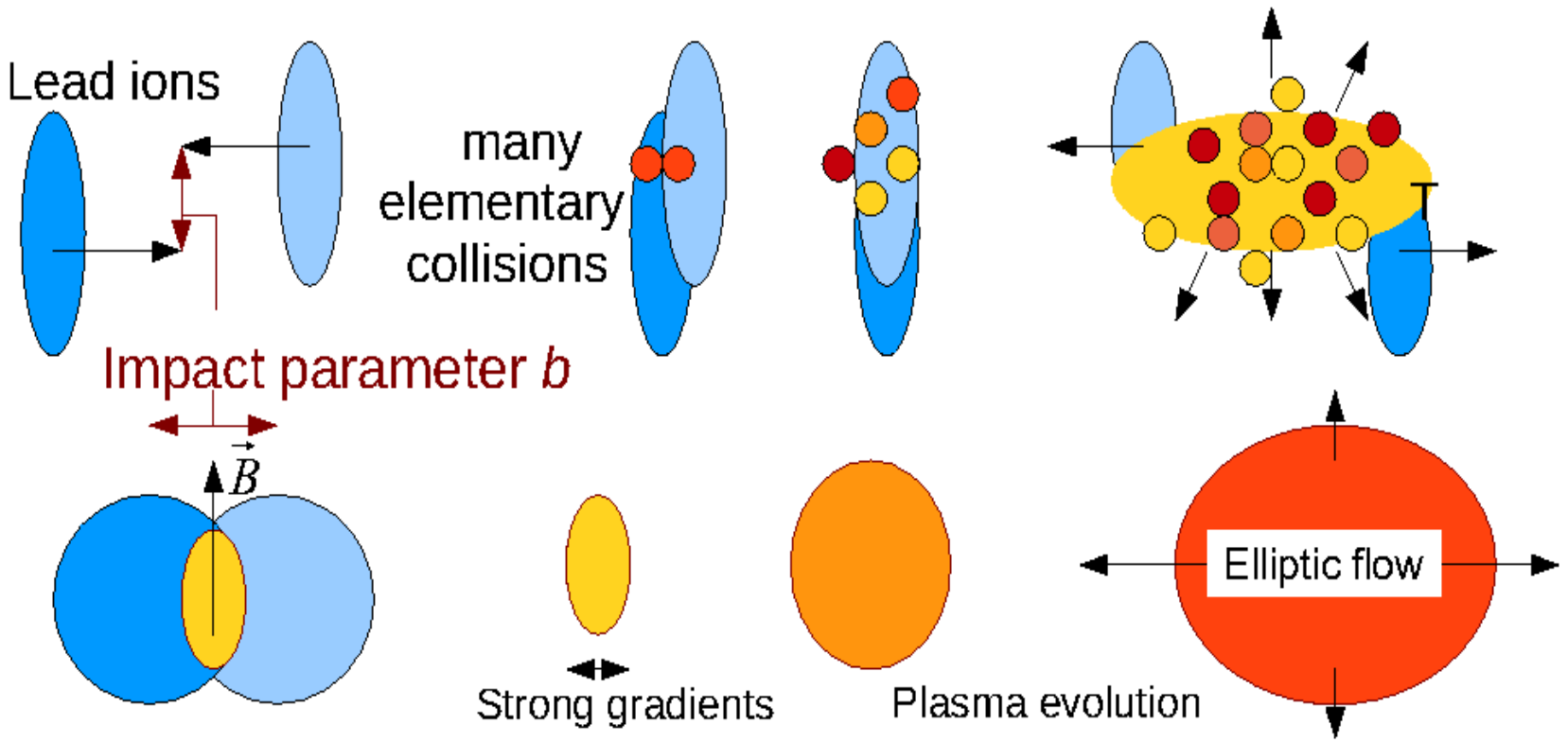
1. Introduction
   - Anomalies in the QCD plasma
   - Chiral magnetic effect
   - Chiral separation effect
2. Charge dependence of the elliptic flow
   - Chiral magnetic wave
   - Evolution of the wave
   - Estimate and comparison with experiment
3. Outlook

1. Introduction
Heavy ion collisions

The ions are 'large' objects and the collision is not always head on:

⇒ Elliptic flow

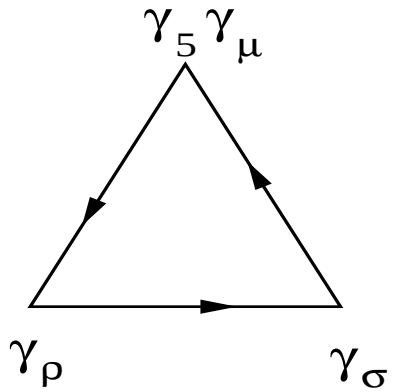
⇒ Magnetic field



QED axial anomaly in plasma

In HIC, we have

- Large magnetic field
- Charge background
- Chirality fluctuations



Anomalies lead to

- Chiral Separation Effect: At finite vector (electric, baryon number) chemical potential μ_V the chiral charge is separated along the axis of external magnetic field:

$$\vec{j}_A = \frac{N_c\ e}{2\pi^2}\mu_V \vec{B}, \tag{1}$$

- Chiral Magnetic Effect: At finite axial chemical potential μ_A, an external magnetic field induces the vector (electric) current:

$$\vec{j}_V = \frac{N_c\ e}{2\pi^2}\mu_A \vec{B}; \tag{2}$$

[Son, Zhitnitsky, 0405216; Zhitnitsky, Metlitski, 0505072;...]

Chiral Magnetic Effect: Electric dipole in heavy ion collisions:

The chiral asymmetry from (QCD) sphalerons is transferred by the chiral (QED) anomaly in an electric charge separation along the magnetic field. [Kharzeev, McLerran, Warringa 0711.0950]

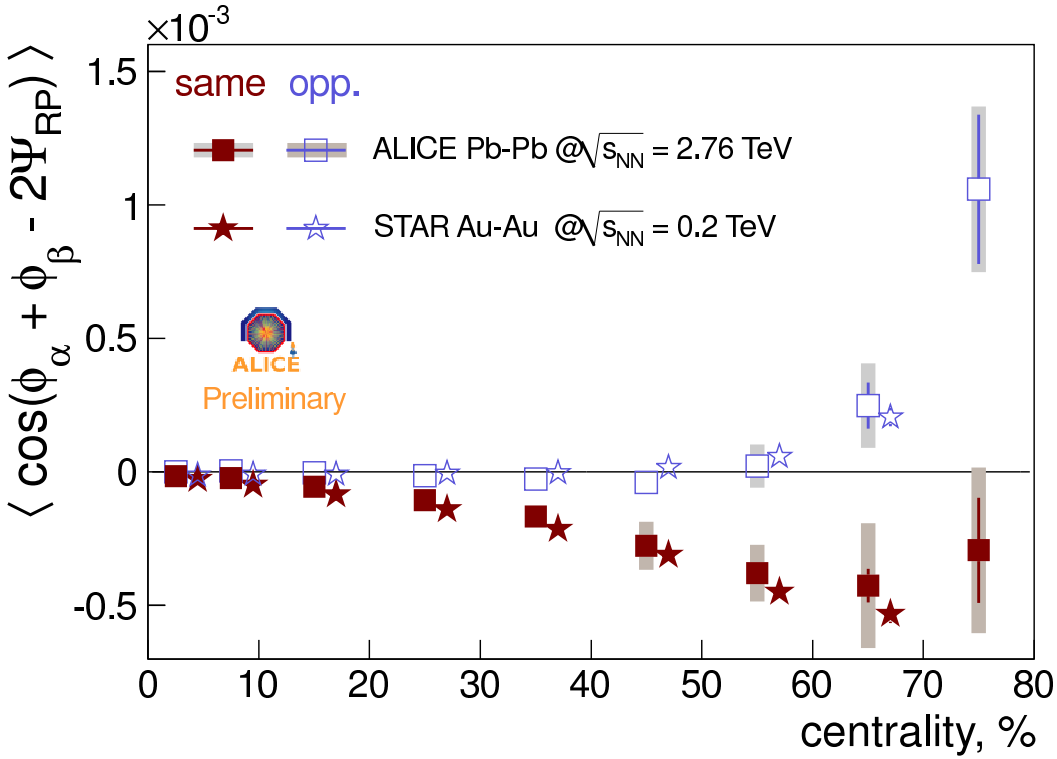
- Need both anomalies
- Formation of an electric dipole in the collision
- Event by event $\mathcal{P}$ violation

Can we see $\mathcal{P}$ violation in HIC?

- No $\mathcal{P}$ odd observable can be constructed
  - Sign of B not known.
  - Random sphaleron transitions
- Only charge correlations can be observed

Electric dipole: Experimental evidence?

Two particles correlations with respect to the reaction plane:



[Alice,1111.1875]

Correct order of magnitude and centrality dependence for CME

Chiral Separation Effect: Electric quadrupole in heavy ion collisions

The excess of positive charges (vector chemical potential) induce an axial current

- Left-handed particles move along the magnetic field, Right-handed ones move opposite
- Additional + charges move towards the pole of the fireball
- Distribution of + charges is more elliptic

$\Rightarrow$ After hydro, elliptic flow of + charges is smaller

New physical effect!

- Need chiral anomaly in QED
- But no sphalerons
- No $\mathcal{P}$ violation

$\Rightarrow$ Definite sign

$\Rightarrow$ Present in all events

2. Charge dependence of the elliptic flow

The charges evolution can be represented by the Chiral Magnetic Wave:

Rewrite the anomaly formulas: [Kharzeev, Yee, 1012.6026]

$$\begin{pmatrix} \vec{j}_V \\ \vec{j}_A \end{pmatrix} = \frac{N_c\ e\vec{B}}{2\pi^2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \mu_V \\ \mu_A \end{pmatrix} \tag{3}$$

Dependencies of the chemical potential on the currents:

$$\begin{pmatrix} \mu_V \\ \mu_A \end{pmatrix} = \begin{pmatrix} \frac{\partial \mu_V}{\partial j_V^0} & \frac{\partial \mu_V}{\partial j_A^0} \\ \frac{\partial \mu_A}{\partial j_V^0} & \frac{\partial \mu_A}{\partial j_A^0} \end{pmatrix} \begin{pmatrix} j_V^0 \\ j_A^0 \end{pmatrix} + \mathcal{O}\left((j^0)^2\right) \sim \begin{pmatrix} \alpha & 0 \\ 0 & \alpha \end{pmatrix} \begin{pmatrix} j_V^0 \\ j_A^0 \end{pmatrix} + \mathcal{O}\left((j^0)^2\right) \tag{4}$$

We get:

$$\begin{pmatrix} \vec{j}_V \\ \vec{j}_A \end{pmatrix} = \frac{N_c\ e\vec{B}\alpha}{2\pi^2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} j_V^0 \\ j_A^0 \end{pmatrix} \tag{5}$$

Chiral magnetic wave

In the L,R basis:

$$\vec{j}_{L,R} = \mp \left(\frac{N_c \; e\vec{B}\alpha}{2\pi^2} \right) j^0_{L,R} \tag{6}$$

Combine with the conservation law $\partial_\mu j^\mu_{L,R} = 0$, add diffusion

For $\vec{B} = B\hat{x}^1$ we get:

$$\left(\partial_0 \mp v\partial_1 - D_L\partial_1^2 - D_T\partial_T^2\right) j^0_{L,R} = 0 \tag{7}$$

- With $v = \frac{N_c eB\alpha}{2\pi^2}$ the velocity of the wave
- α, D_L, D_T are B and T dependent and $v < c$
- Calculated in holographic QCD from the Sakai-Sugimoto modell [Kharzeev, Yee, 1012.6026; Sakai, Sugimoto, 0412141]

Evolution in the plasma: approximations

In principle: $\rightarrow$ The wave evolve in an expanding background

- Would require a full hydro simulation
- Require to write the CMW in an evolving metric

Approximation here: $\rightarrow$ The wave evolve in a fixed background, which is expanded afterwards

- Fine if the magnetic field has a short lifetime

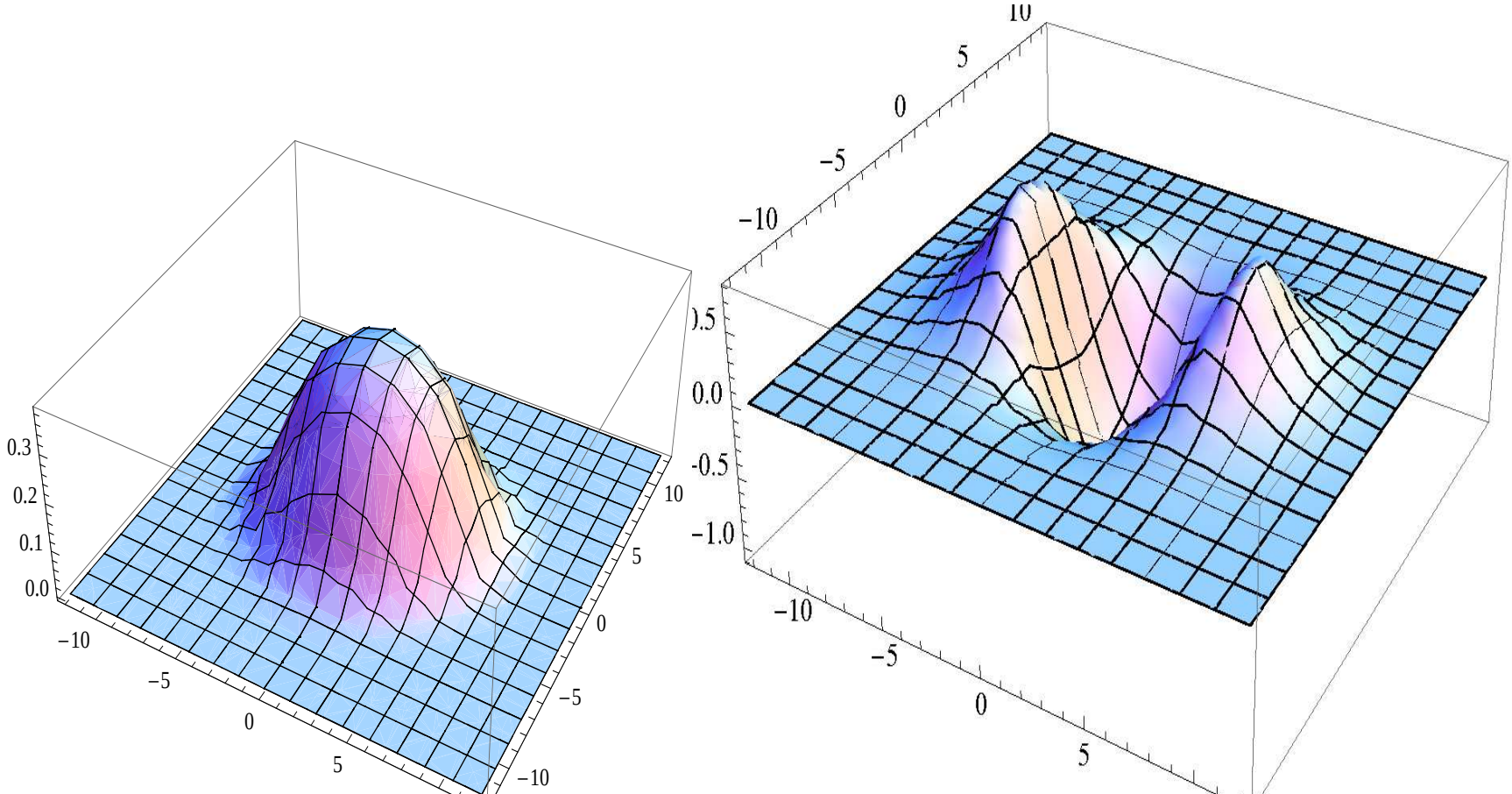
We solve the CMW starting from the almond shaped region with density given by the KLN model [Kharzeev, Levin, Nardi, 0111315].

Evolution of the wave

For all the different quark flavour/helicities we solve the corresponding CMW

The charges reaching the boundary of the plasma stops

Initial KLN density: Evolution of the excess of charges:



Evolution after the plasma phase
How do the charges fly to the detector?

We consider a rapidity slice

Qualitatively:

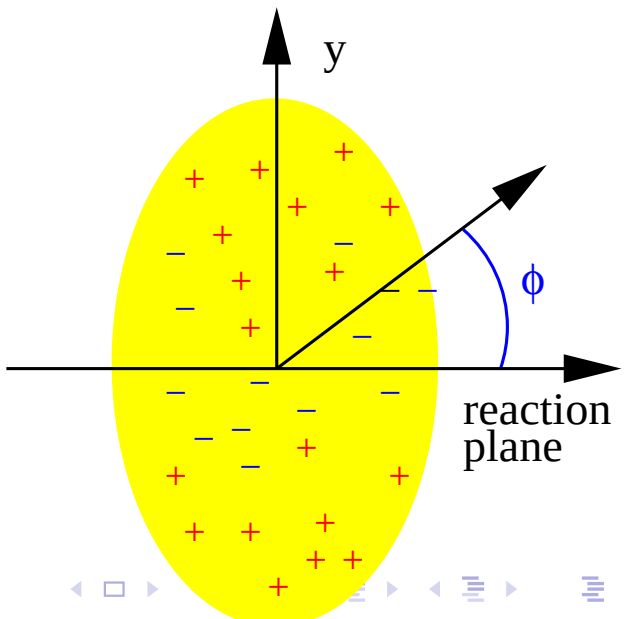
- The distribution of $+$ charges is more elliptic
- The relative - charges boosted more by the hydro flow

$\Rightarrow v_2^+ < v_2^-$.

For the charge asymmetry we approximate the flow to be radial

- Ellipticity is small except for large impact parameter
- We are not interested in v_2 but in the difference $v_2^- - v_2^+$

The strong flow aligns the particles momenta:
i.e. only their position matter



Charge dependent elliptic flow 1

The number of additional charges that will be measured at an angle ϕ are

$$\frac{d(N_+ - N_-)}{d\phi} = \int r\, dr\, j_e^0(r, \phi)$$

In the approximation of an elliptic distribution

$$\frac{d(N_+ - N_-)}{d\phi} = (\bar{N}_+ - \bar{N}_-)[1 - r_e \cos(2\phi)]$$

with

- $\bar{N}_\pm$ the total number of $\pm$ charged particles
- r_e is the ratio between the 2nd harmonic of the charge difference distribution to the total charge difference

$$r_e = 2\frac{q_e}{\rho_e}, \quad q_e = -\int r\, dr\, d\phi \cos(2\phi) \left(j_e^0(r, \phi) - j_{e,B=0}^0(r, \phi)\right)$$

$$\rho_e = \int r\, dr\, d\phi\, j_e^0(r, \phi)$$

$\longleftarrow$ Obtained from the simulation of the CMW

Charge dependent elliptic flow 2

Supposing that the normal elliptic flow is not perturbed by the additional charges,

$$N_+ + N_- = (\bar{N}_+ + \bar{N}_-)[1 + 2v_2 \cos(2\phi)]$$

So that (to $\mathcal{O}(v_2 \times r\, A)$)

$$\frac{dN_\pm}{d\phi} = \bar{N}_\pm \langle [1 + (2v_2 \mp r_e\, A)\cos(2\phi)\rangle]$$

Result: The elliptic flow is charge dependent! $v_2^- - v_2^+ = r_e\, A$

The difference is proportional to

- The second harmonic of the charge distribution r_e
- Charge difference $A = \frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}$ in the rapidity slice

  $\longleftarrow$ At best: obtained from experiment, collision dependent
  - $\langle A \rangle$ small at high energy
  - A can be large in single events

What is the magnetic field in heavy ion collisions?

In a non-central collisions, the moving ions induce a magnetic field

- Perpendicular to the reaction plane
- Time dependent and impact parameter dependent

What happens to the magnetic field inside the plasma?

- It existed before the plasma was created
- Its evolution depends on the electrical properties of the plasma
- Electric conductivity σ not well known
- If $\sigma t,\ \sigma L \gg 1,\ \Rightarrow$ the system is described by magnetohydro:
  $\Rightarrow$ Magnetic flux conserved

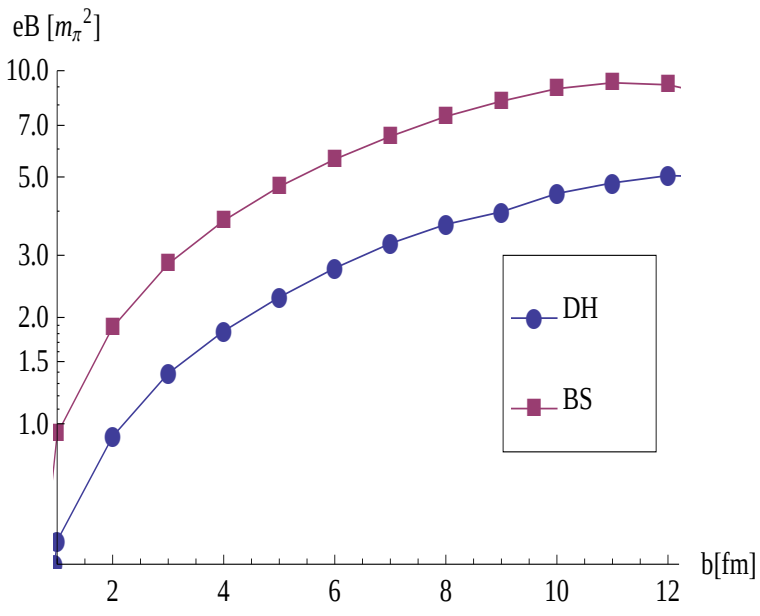
Done for this estimate:

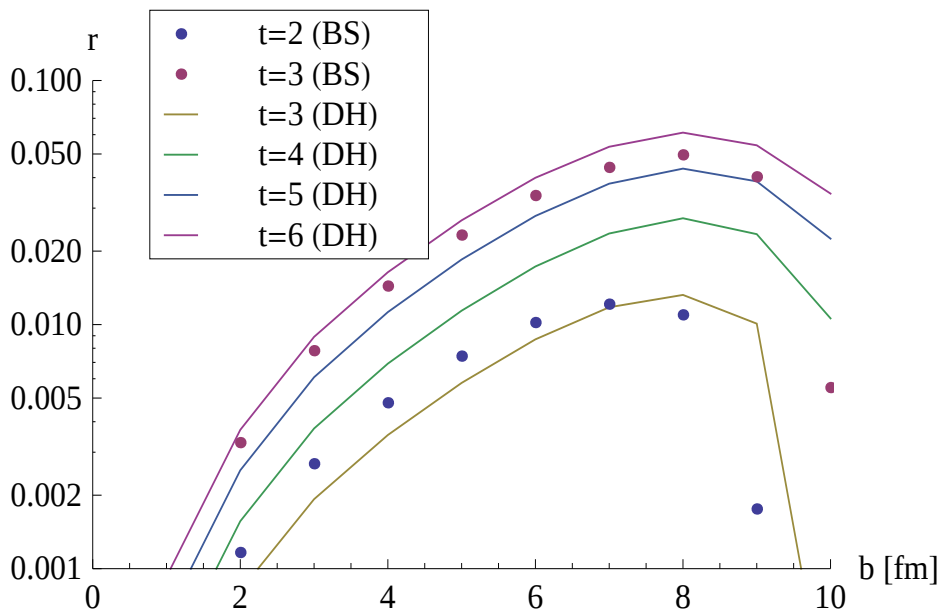
- Use a constant magnetic field
- Evolution of CMW as function of its lifetime

Charge quadurpole as function of the magnetic field lifetime

- Originally [YB, Kharzeev, Liao, Yee, 1103.1307] we used $B_y(b)$ from [Kharzeev, McLerran, Warringa 0711.0950]
- Recently there were more precise calculation of the magnetic field [Bzdak, Skokov 1111.1949 (BS); Deng, Huang 1201.5108 (DH)]

$\Rightarrow$ New simulations for r_e: [YB, Kharzeev, Liao, Yee in perparation]





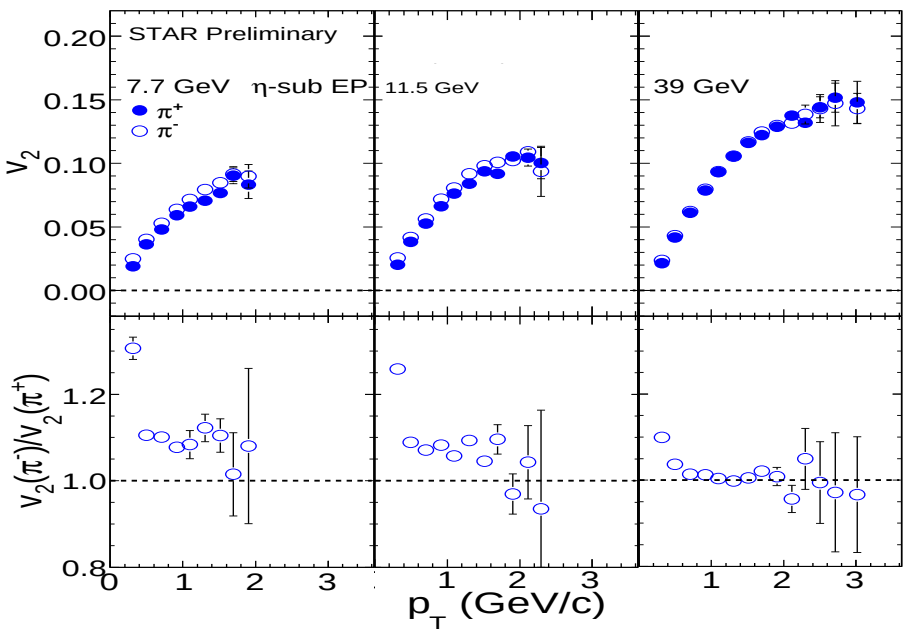
Comparison with experiment

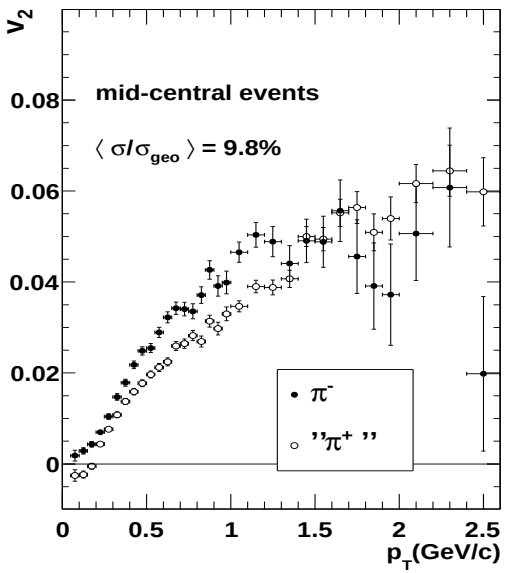
Positive and negative pions have similar absorption/scattering in the hadronic phase $\Rightarrow$ so they represent the best channel

- Compare $v_2^- - v_2^+ = r_e A$

[STAR, 1106.5902] $v_2(p_T)$ for minimum bias (0-80% most central collisions)

Similar results at CERN NA-45 at $17.3 GeV$ in [CERES 1205.3692]

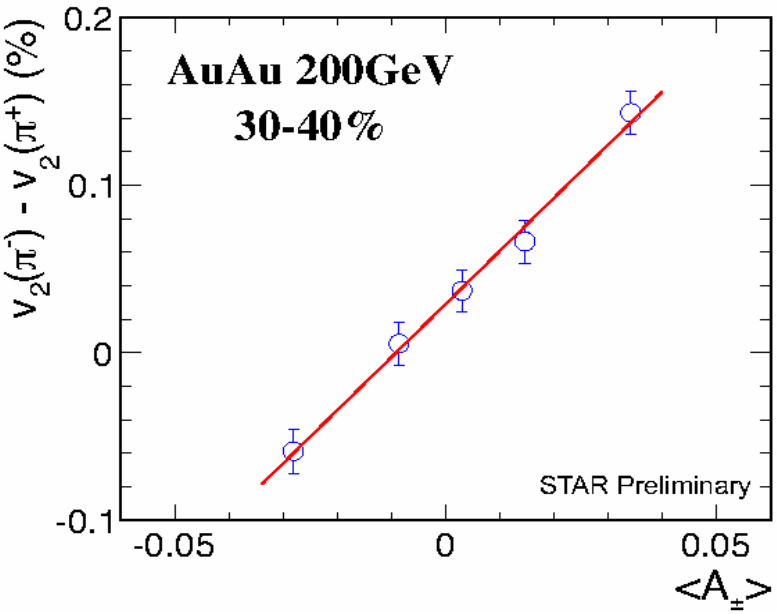


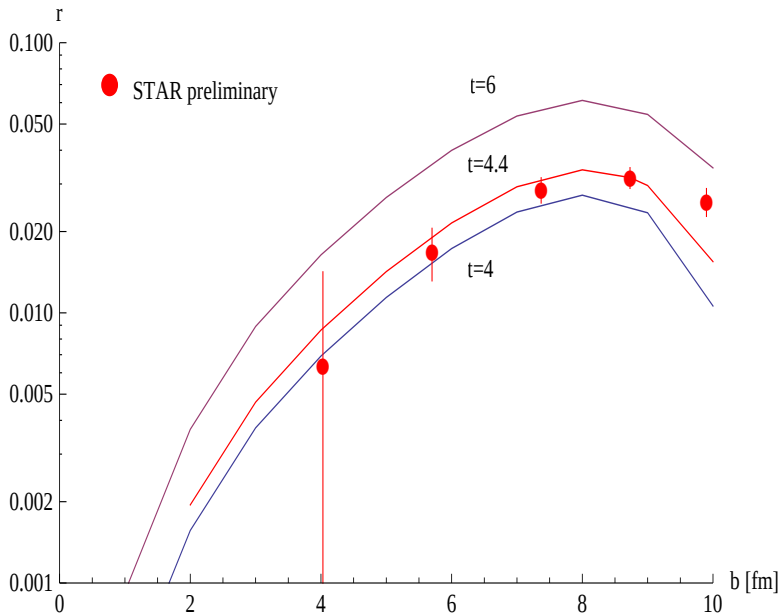


Comparison with experiment

- Compare r_e: measure $v_2^- - v_2^+$ and A and get $r = \frac{v_2^- - v_2^+}{A}$

Preliminary results from the STAR experiment:





[G. Wang, talk at the CPODD workshop]

Gives a good match with our prediction, for t=4-5fm (magnetic field from Deng, Huang or t=2-3 for Bzdak, Skokov)

Summary: CME versus CSE

CSE

- QED anomaly
- Magnetic field
- Initial charge imbalance

$\Rightarrow$ Charge quadrupole

$\Rightarrow$ r_e: same sign in all events

$\Rightarrow$ A is positive in average

- Measure $v_2^- - v_2^+$ or r_e

CME

- QED and QCD anomaly
- Magnetic field
- Initial chiral imbalance

$\Rightarrow$ Charge dipole

$\Rightarrow$ Event by event $\mathcal{P}$ violation

$\Rightarrow$ Vanishes in average

- Measure charge correlations

3. Oulook: Is the effect seen due to the CSE?

Improve the estimate...

- Electric properties of the quark-gluon plasma
- Magnetic field during the collision
- Chiral magnetic wave in expanding medium
- Coefficient v_χ or α from QCD
- Diffusion coefficients from QCD (at least at $B = 0$)
- Full hydrodynamical simulation of the collision

Backgrounds and other effects

- Coulomb repulsion
- Decay of doubly charged particles
- Rescattering of the pions after the plasma phase
- What happens to Kaons, protons?