Status of Chiral Magnetic Wave in Heavy Ion Collisions

Ho-Ung Yee

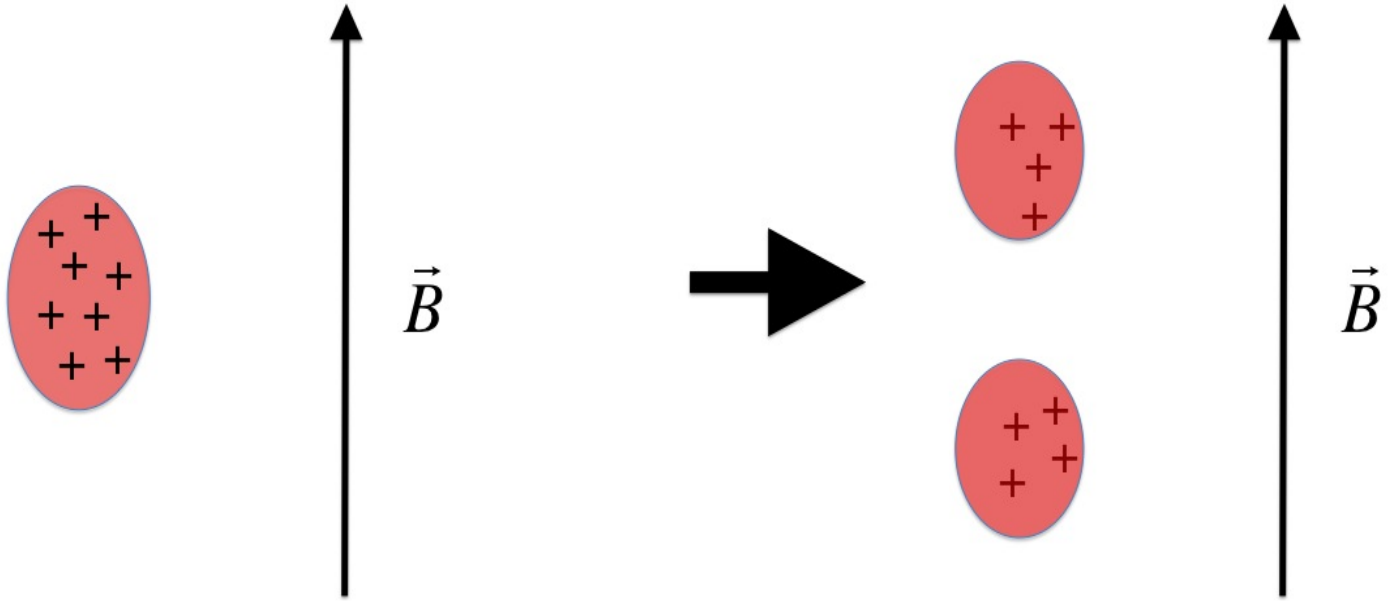
University of Illinois at Chicago and RIKEN-BNL Research Center

June 17, 2014

RHIC & AGS Users Meeting
Brookhaven National Laboratory, June 17-20, 2014

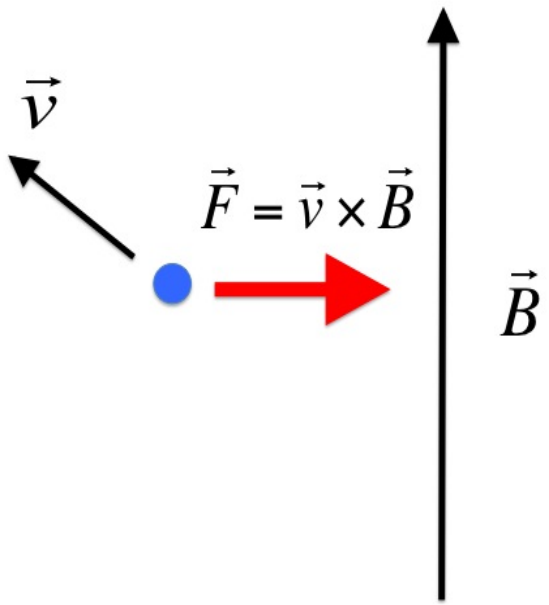
The Chiral Magnetic Wave (CMW) on the Initial (Electric) Charges

(Burnier-Kharzeev-Liao-HUY)



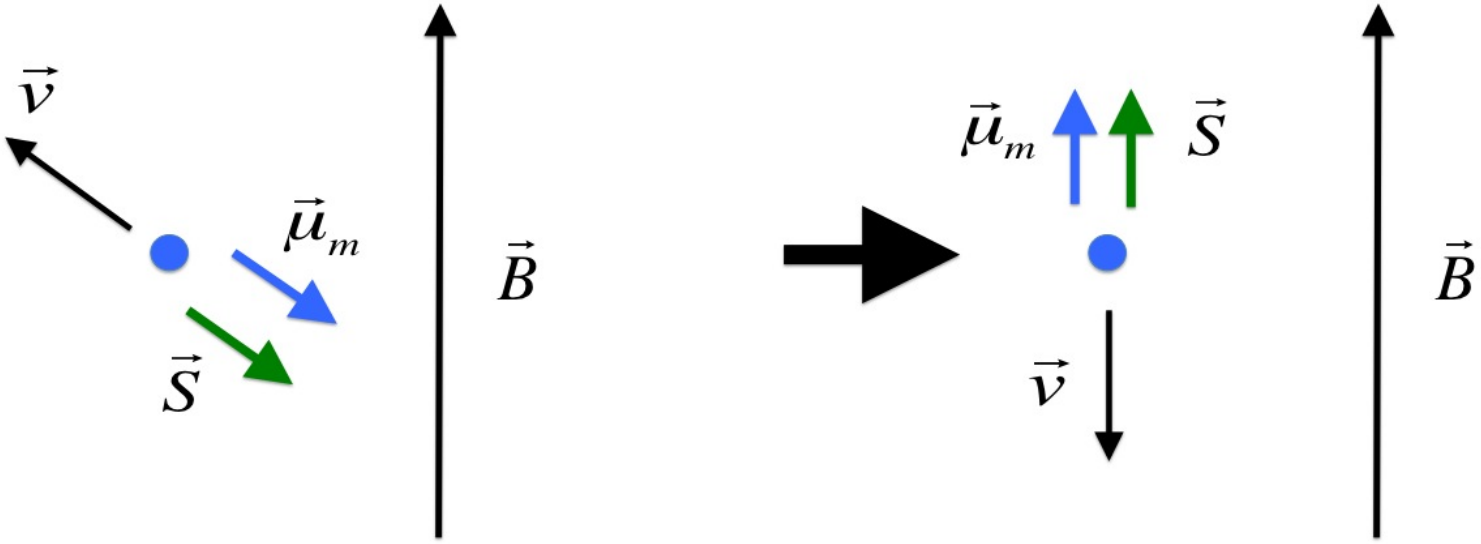
A peculiar motion of electric charges under a magnetic field !!!

Classical Picture of Charged Particles in a Magnetic Field



The force, and hence the induced current, would have been perpendicular to the magnetic field direction

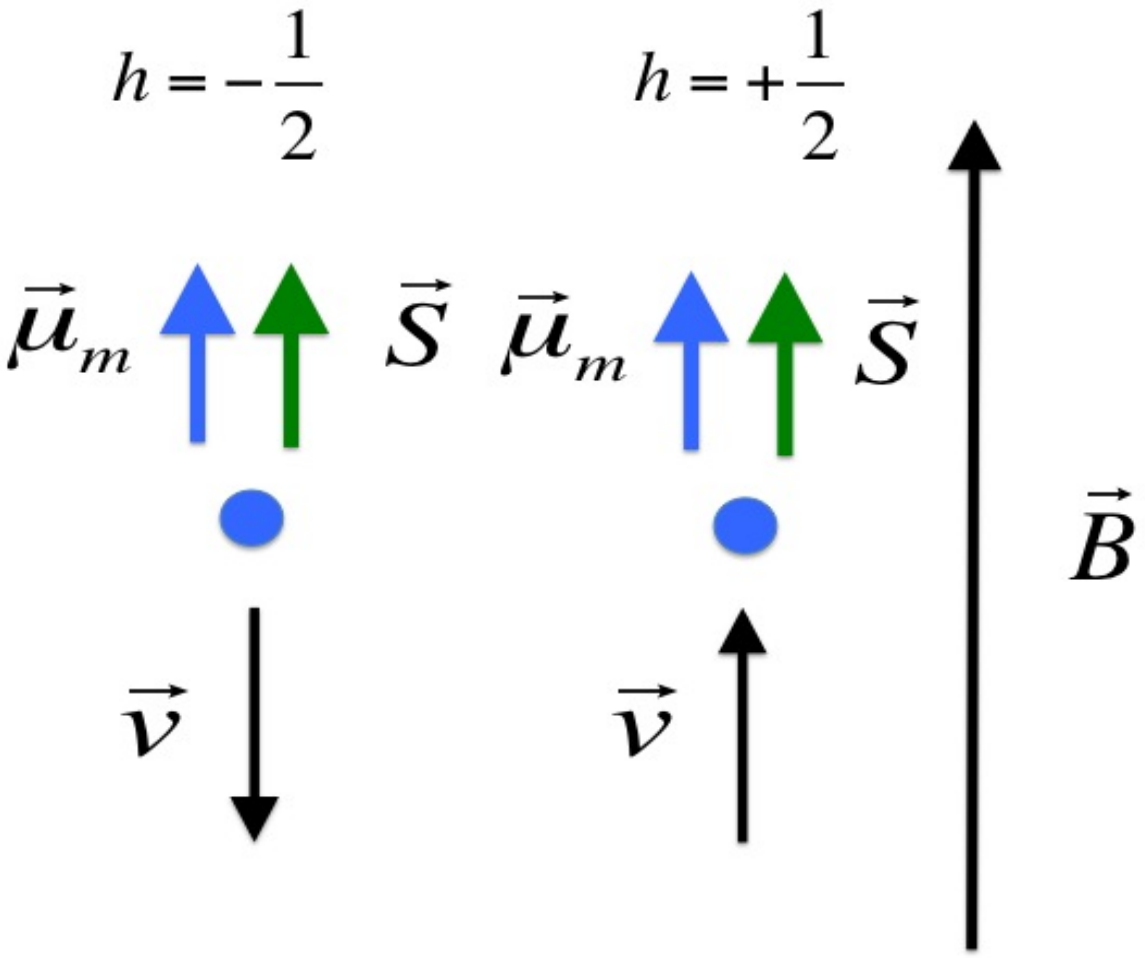
Quantum Picture of Fermionic Charge Carriers in a Magnetic Field (Kharzeev-Warringa)



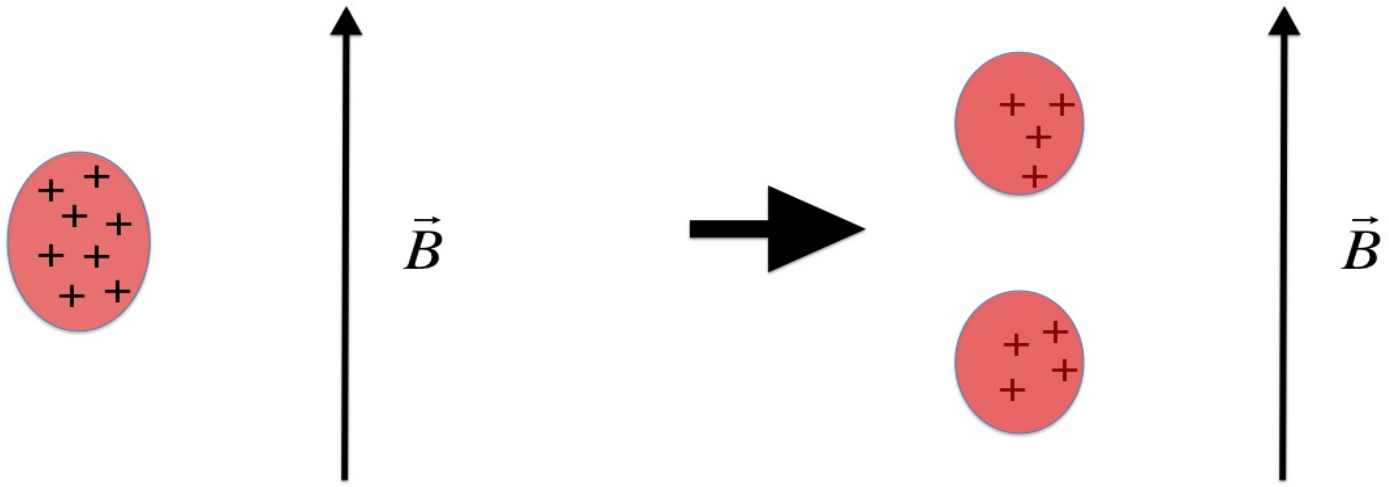
Helicity : $\vec{S} = h\frac{\vec{v}}{|\vec{v}|}, \quad h = \pm\frac{1}{2}$

Wigner-Eckart Theorem : $\vec{\mu}_m \propto q\vec{S}, \quad q =$ **charge**

Spin Magnetic Moment Interaction : $H = -\vec{\mu}_m \cdot \vec{B}$



A motion along the direction of the magnetic field is induced. Some go up, others go down, depending on their helicity



An intricate interplay of

- **Quantum Spin**
- **Charge and Magnetic Moment**
- **Helicity (Chirality)**

Theoretical Description of CMW
(Kharzeev-HUY)

CMW arises from the interplay of

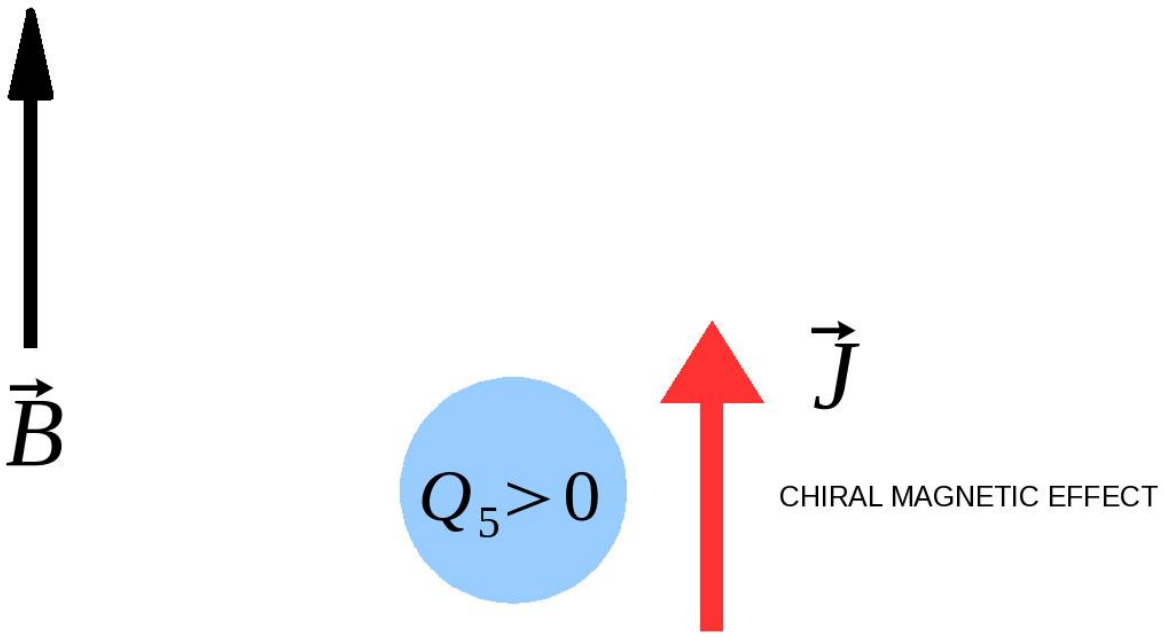
- **Chiral Magnetic Effect :** $\vec{J}_V = \frac{e\mu_A}{2\pi^2}\vec{B}$
  (Fukushima-McLerran-Kharzeev-Warringa)
- **Chiral Separation Effect :** $\vec{J}_A = \frac{e\mu_V}{2\pi^2}\vec{B}$
  (Son-Zhitnitsky)

The velocity is

$$v_\chi = \frac{eB}{4\pi^2}\frac{1}{\chi}, \quad \chi = \text{susceptibility}$$

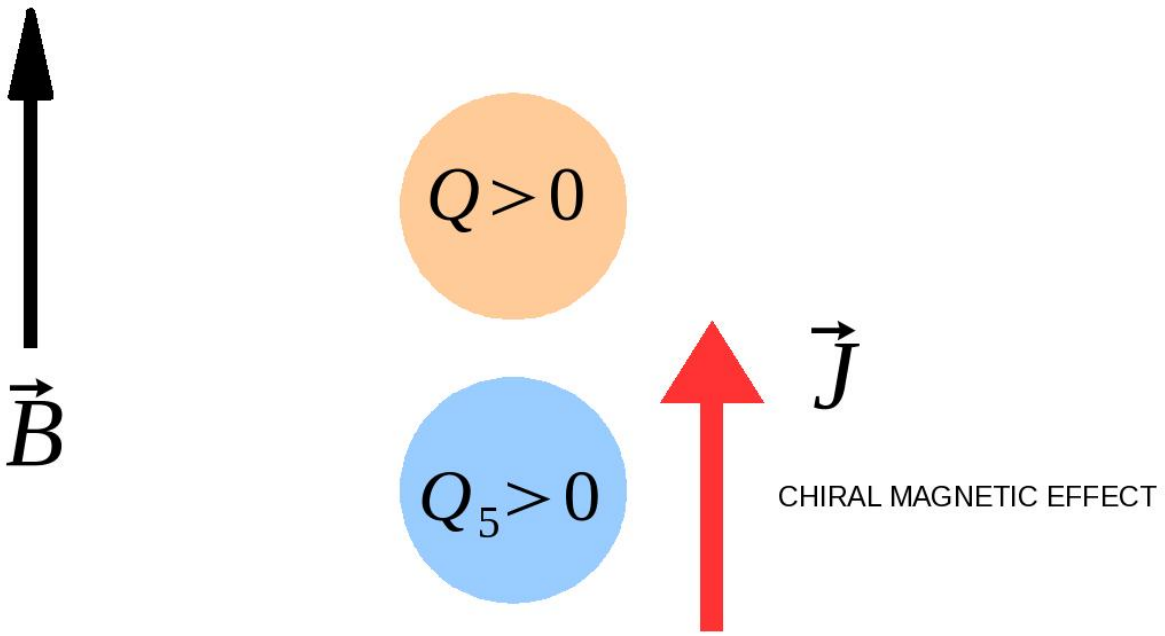
It is quite computable!

Why do we have waves ?



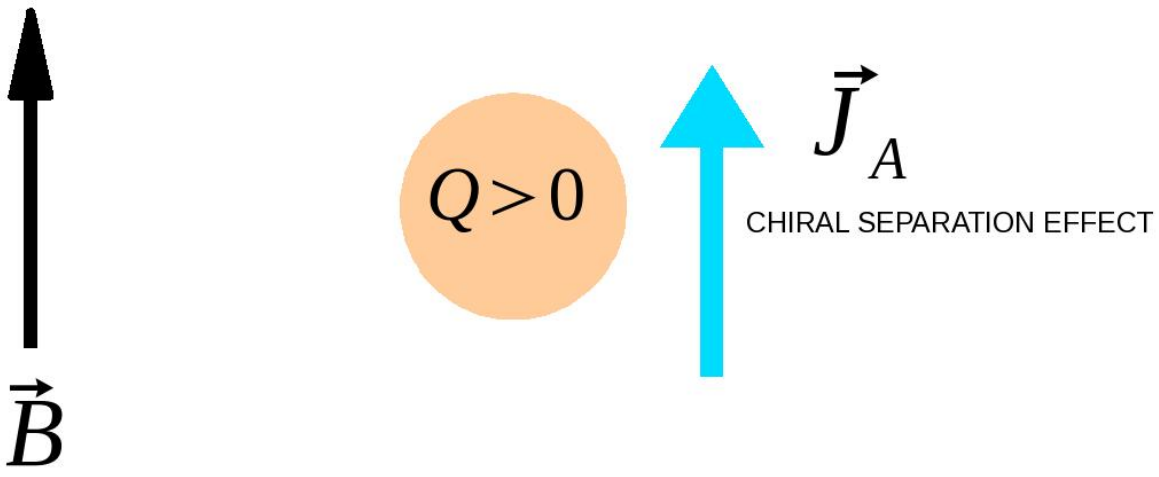
$$\vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2}\mu_A \quad , \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2}\mu_V$$

Why do we have waves ?



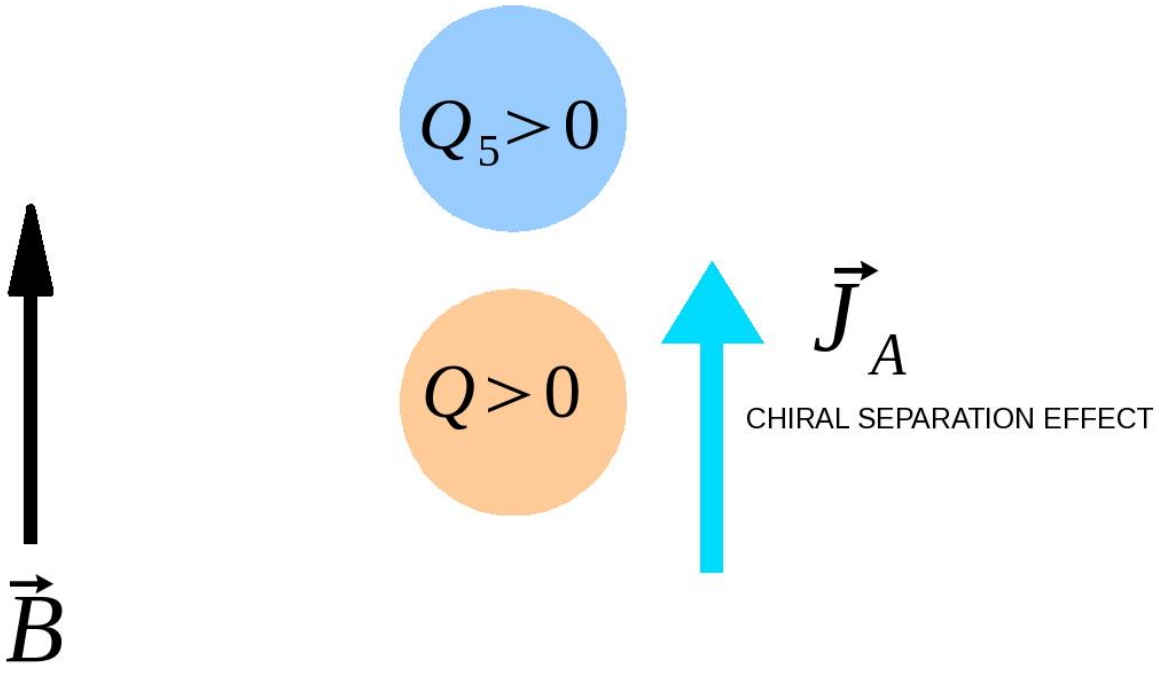
$$\vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2}\mu_A \quad , \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2}\mu_V$$

Why do we have waves ?



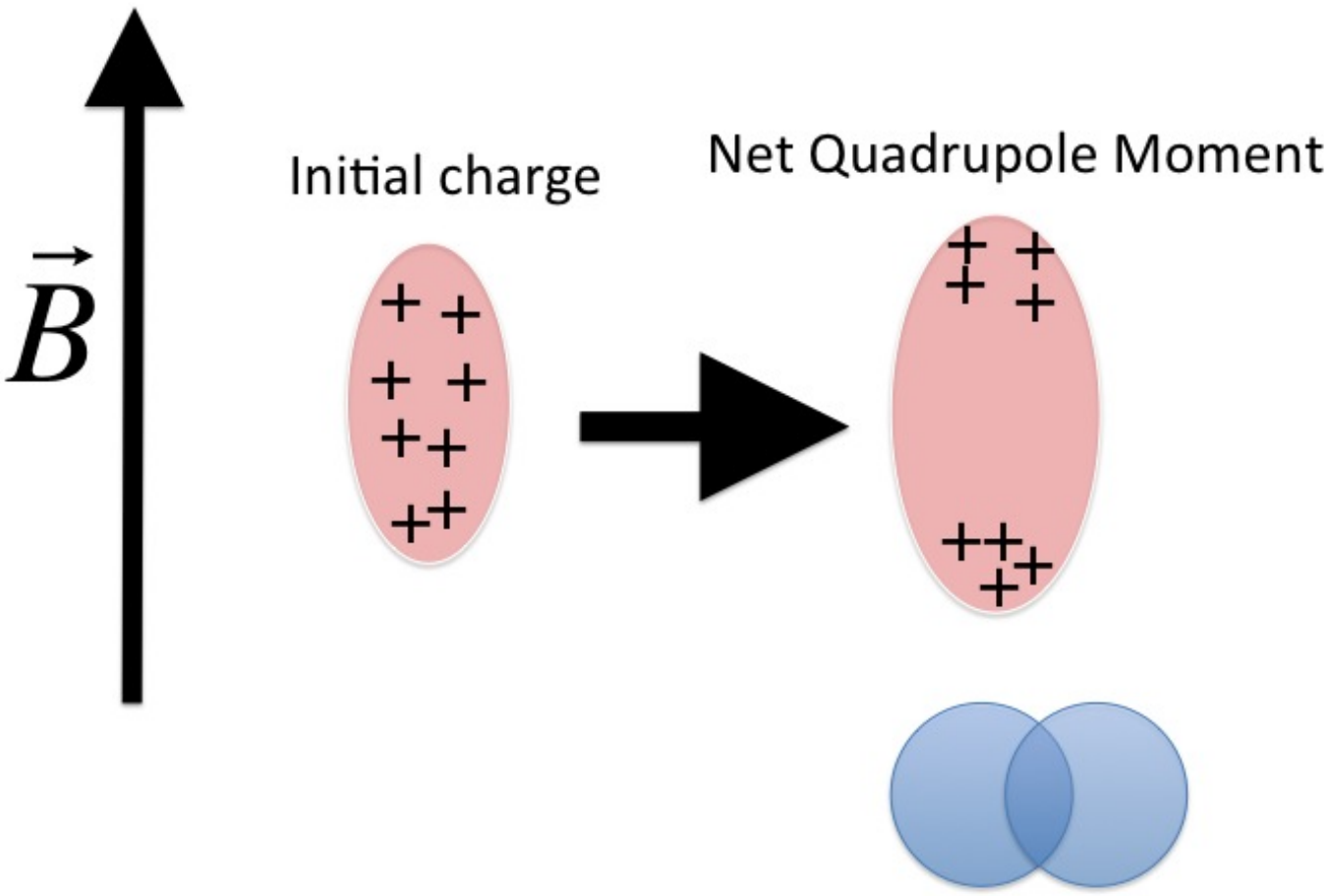
$$\vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2}\mu_A \quad , \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2}\mu_V$$

Why do we have waves ?

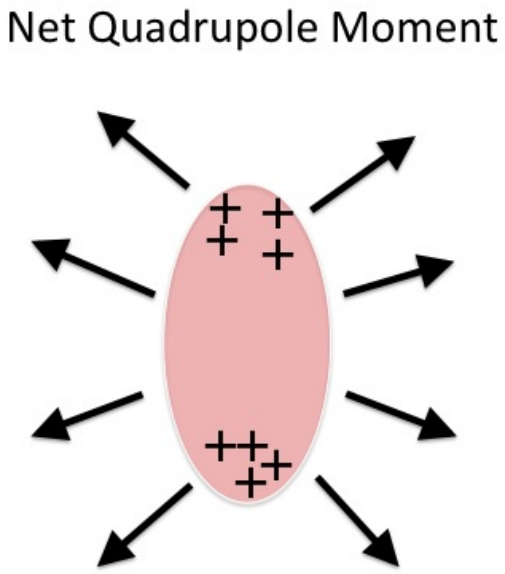


$$\vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2}\mu_A \quad , \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2}\mu_V$$

CMW in Heavy Ion Collisions
(Burnier-Kharzeev-Liao-HUY)

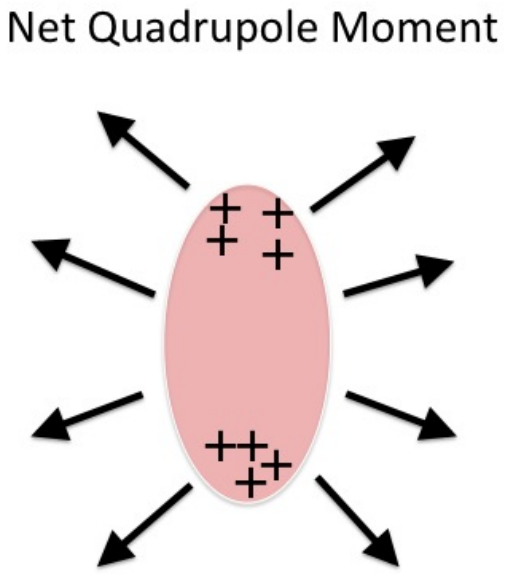


CMW in Heavy Ion Collisions



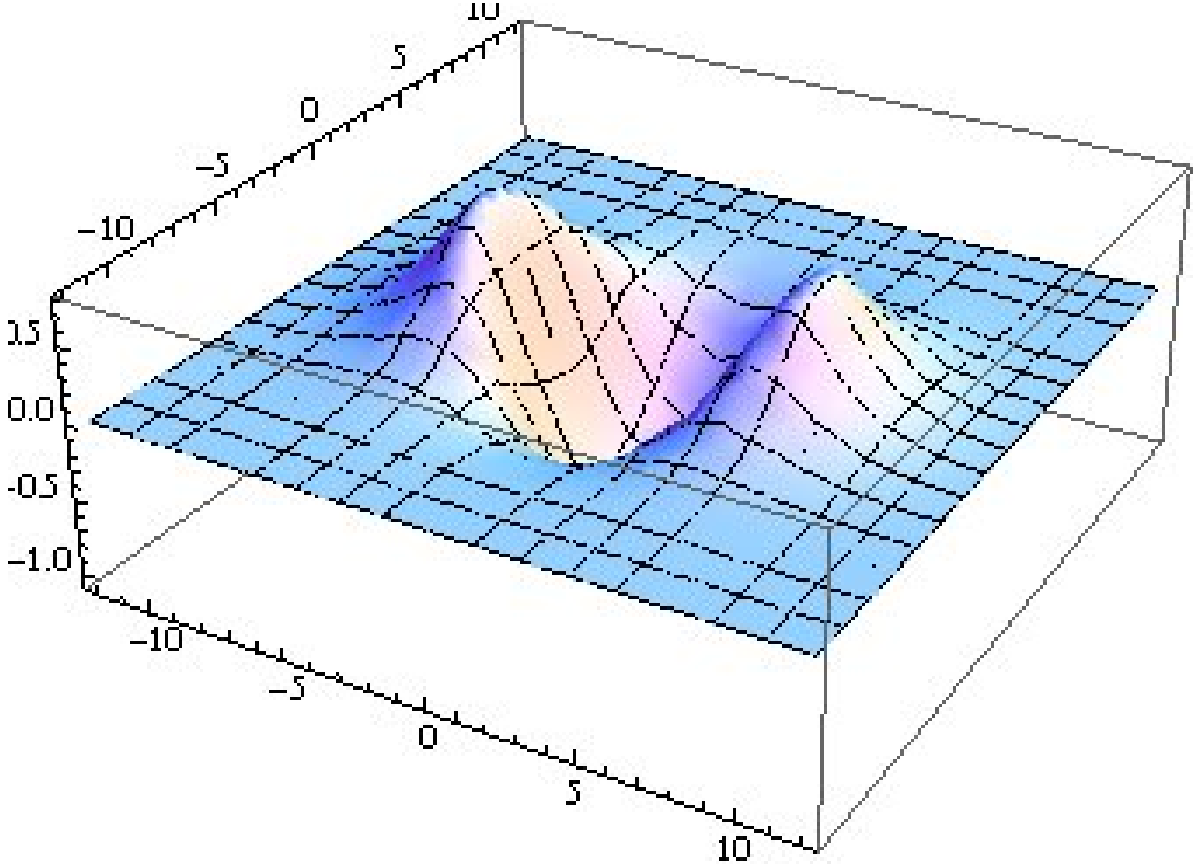
This leads to charge dependent elliptic flows of pions
$v_2(\pi^+) < v_2(\pi^-)$ **if the initial charge is positive** $A_\pm > 0$

CMW in Heavy Ion Collisions

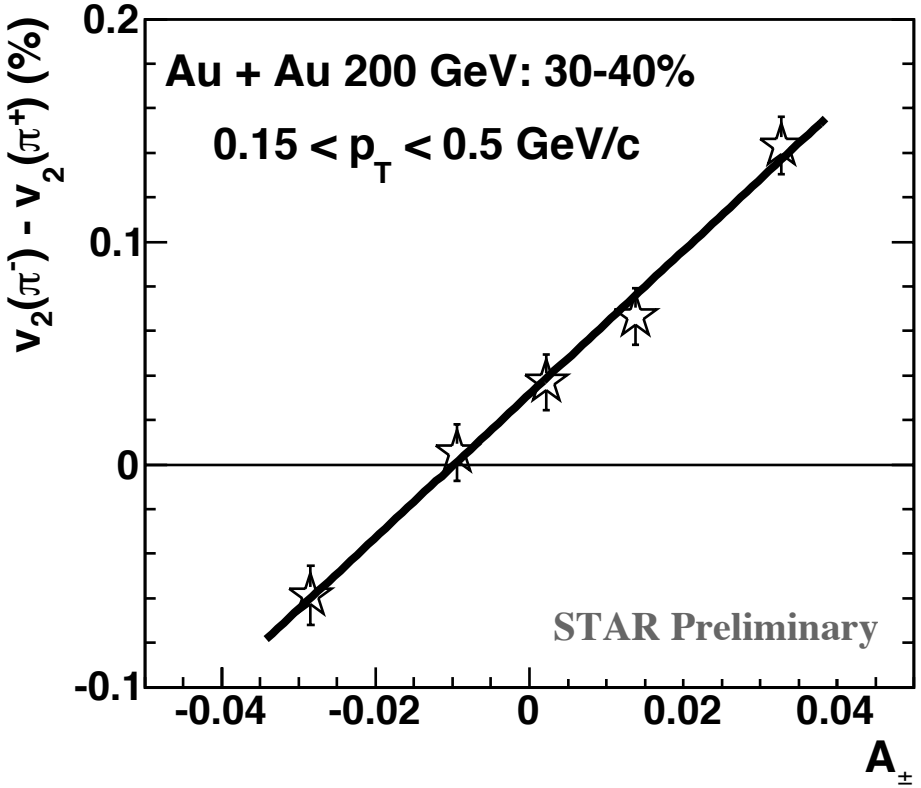


Prediction $\Delta v_2 \equiv v_2(\pi^-) - v_2(\pi^+) = r\ A_\pm\,, \quad A_\pm \equiv \frac{N_+ - N_-}{N_+ + N_-}$

Initial Simulation
(Burnier-Kharzeev-Liao-HUY)

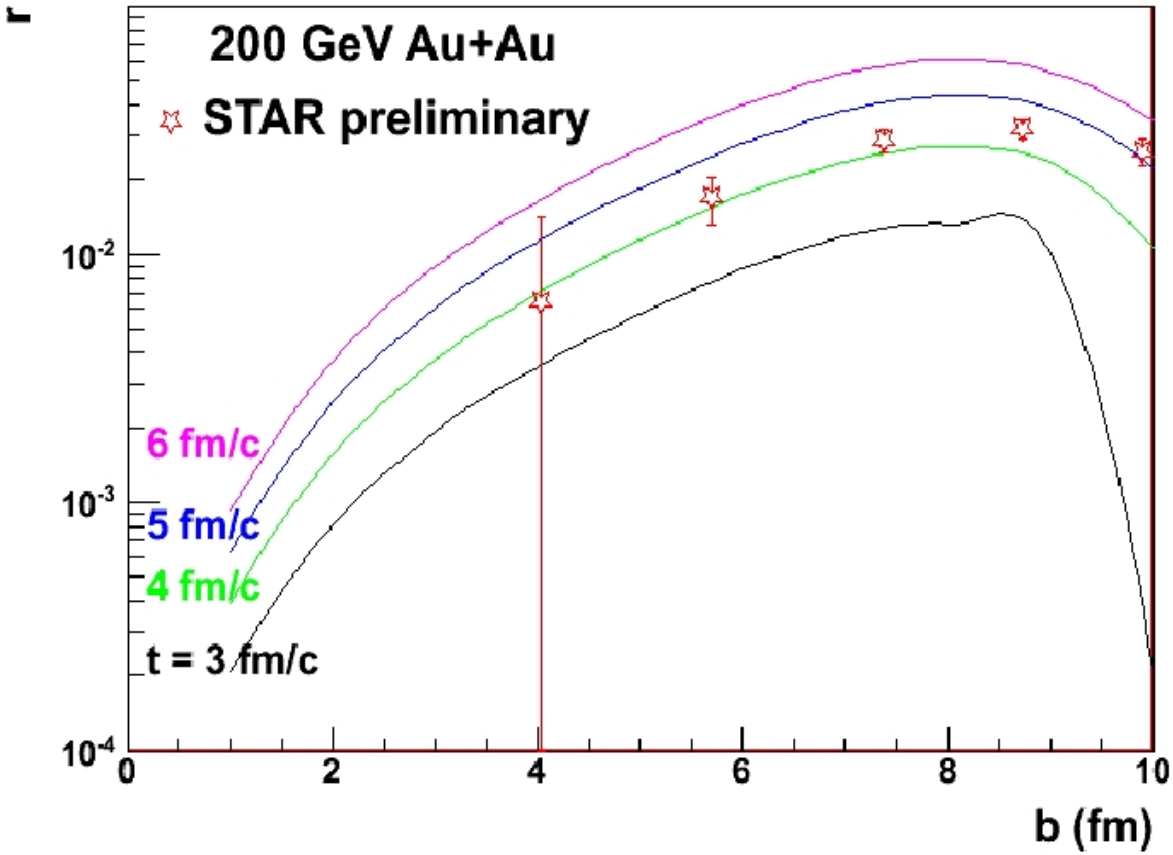


Confirmation of linear dependency by RHIC (more details in Aihong's talk)



$\Delta v_2 = r\ A_\pm + \Delta v_2^0$: **Note the intercept** Δv_2^0

Centrality Dependence



The colored curves are from the simulations by Burnier-Kharzeev-Liao-HUY

Other Sources for The Slope r?

In the equation

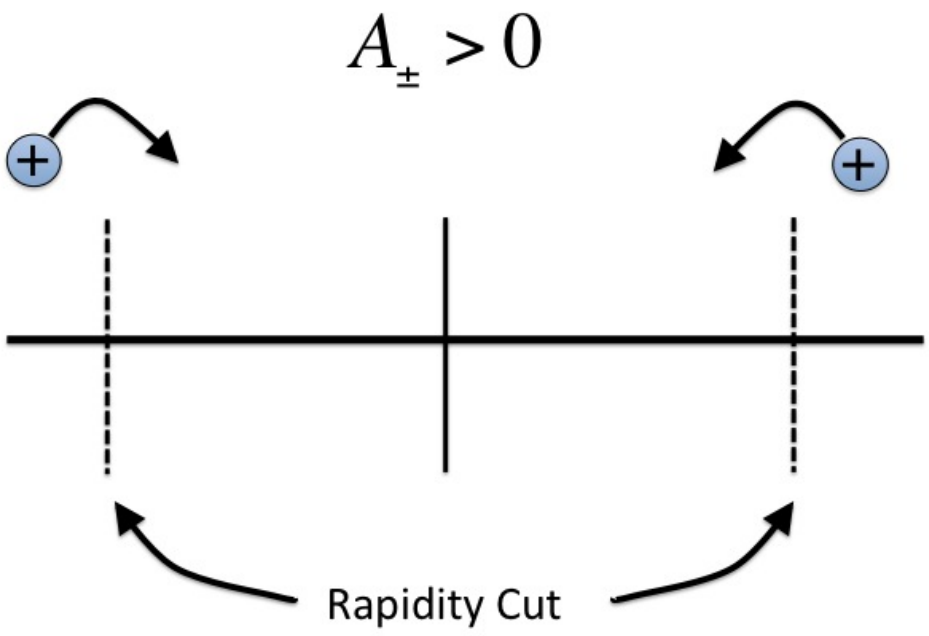
$$\Delta v_2 = r\ A_\pm + \Delta v_2^0$$

both Δv_2 and $A_\pm$ are charge conjugation (C) odd, so that the slope r is C even.

This means that r can receive contributions from other sources unrelated to the magnetic field

Main issue of the CMW explanation for the slope r

Example: Bzdak-Bozek Scenario



Since v_2 drops sharply for a larger rapidity, the $v_2(\pi^+)$ will be relatively smaller than $v_2(\pi^-)$

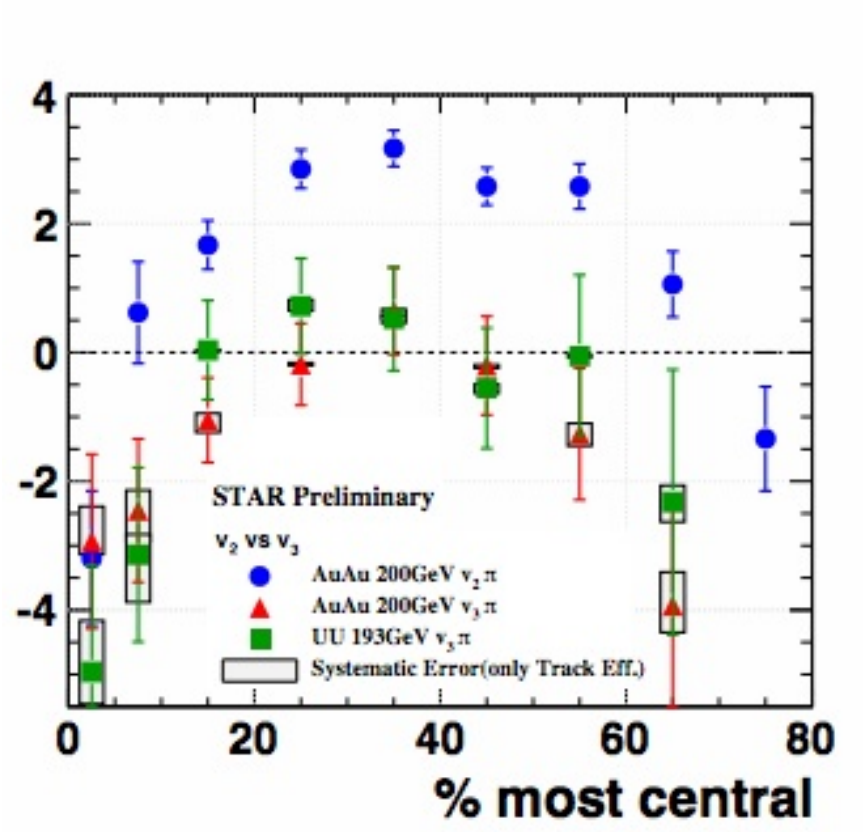
Can explain the 1/3 of the slope

Distinction in Δv_3?

The slope in $\Delta v_3 \equiv v_3(\pi^-) - v_3(\pi^+) = r_3\ A_\pm$

CMW: $r_3 \approx 0$

Bzdak-Bozek: $r_3 \approx r \times \frac{v_3}{v_2} \approx r \times \frac{1}{3}$



See Aihong's plot for more detail

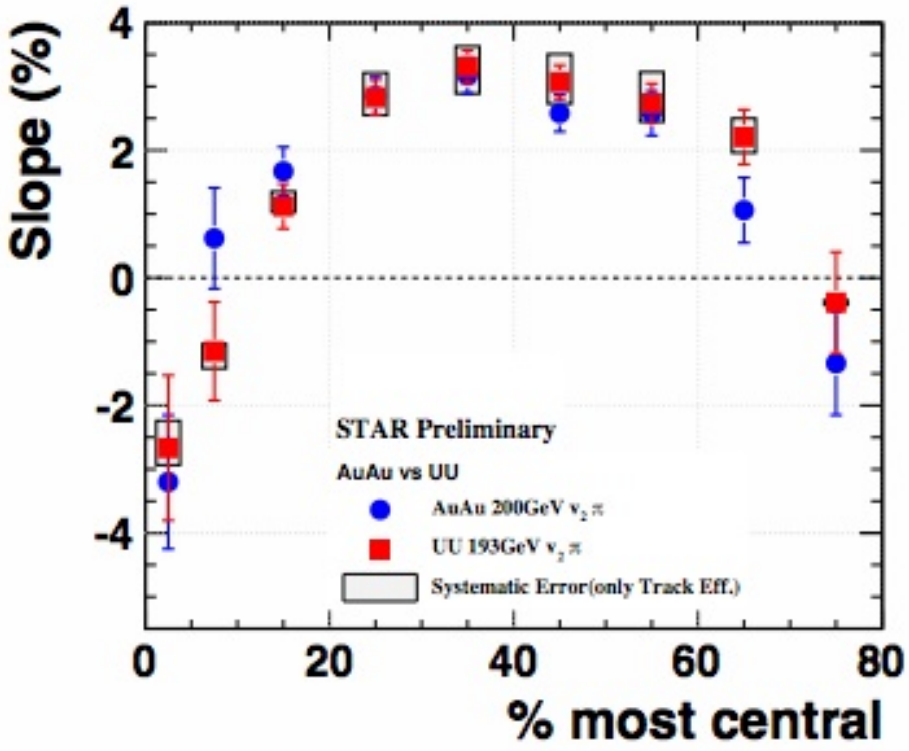
Distinction in U-U Collisions?

What should be most interesting is near zero centrality

CMW: No magnetic field, so $r \approx 0$

(Note: there are non-zero fluctuations uncorrelated to the event plane (Bloczynski-Huang-Zhang-Liao))

Bzdak-Bozek: v_2 is finite even at zero centrality, so r should be non-zero



The slope *r* becomes negative near zero centrality:
no current theoretical understanding

Toward More Realistic Simulation

Hongo-Hirono-Hirano:

- Full ideal hydrodynamics simulation with anomalous transport (O)
- Cooper-Frye freeze-out at constant time (X)
- Initial charge distribution is peculiar (?)

Taghavi-Wiedmann:

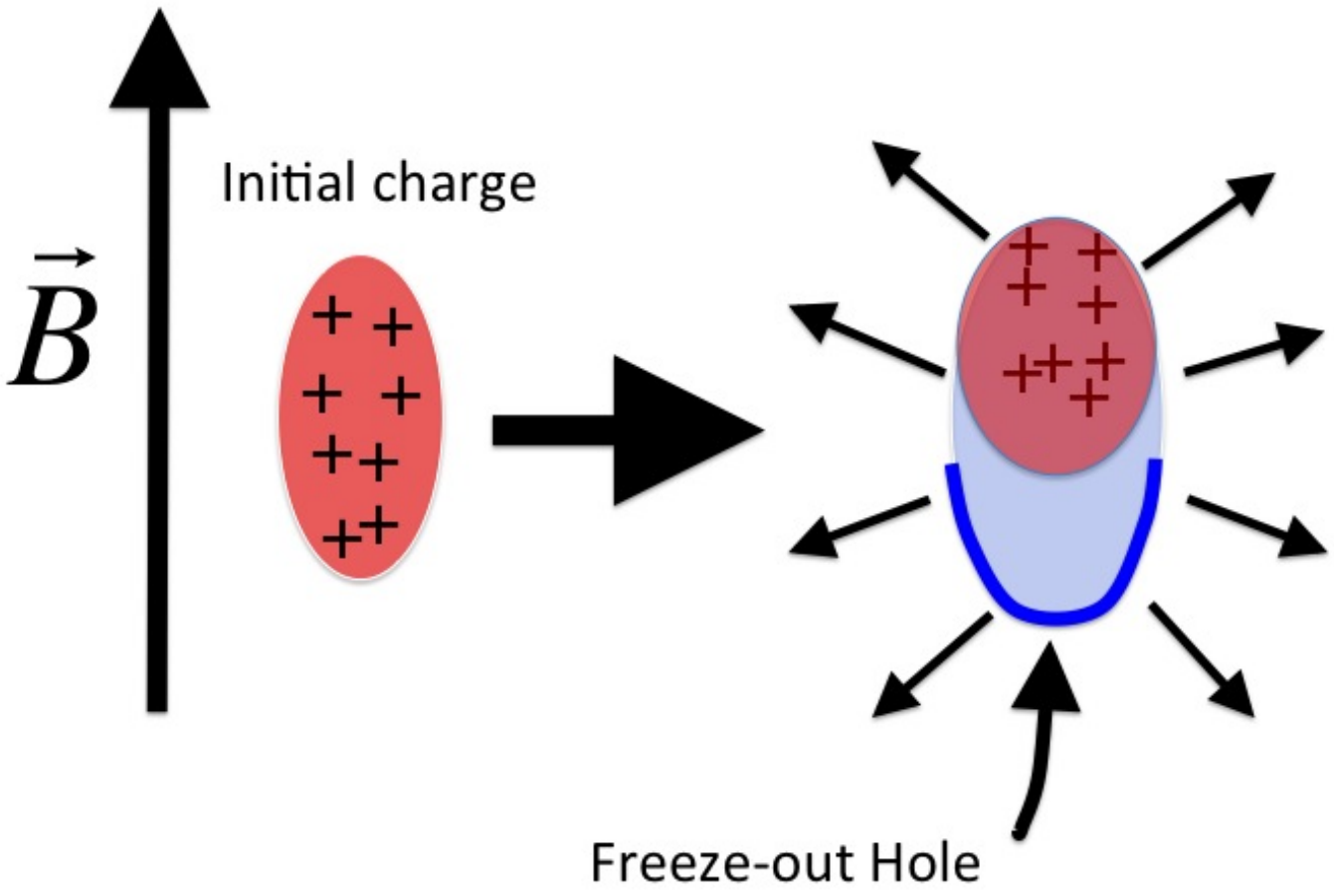
- Boost invariant plasma (O)
- Small life-time of magnetic field (?)
- Small values of instantaneous quadrupole moment predicted (?)

Toward More Realistic Simulation

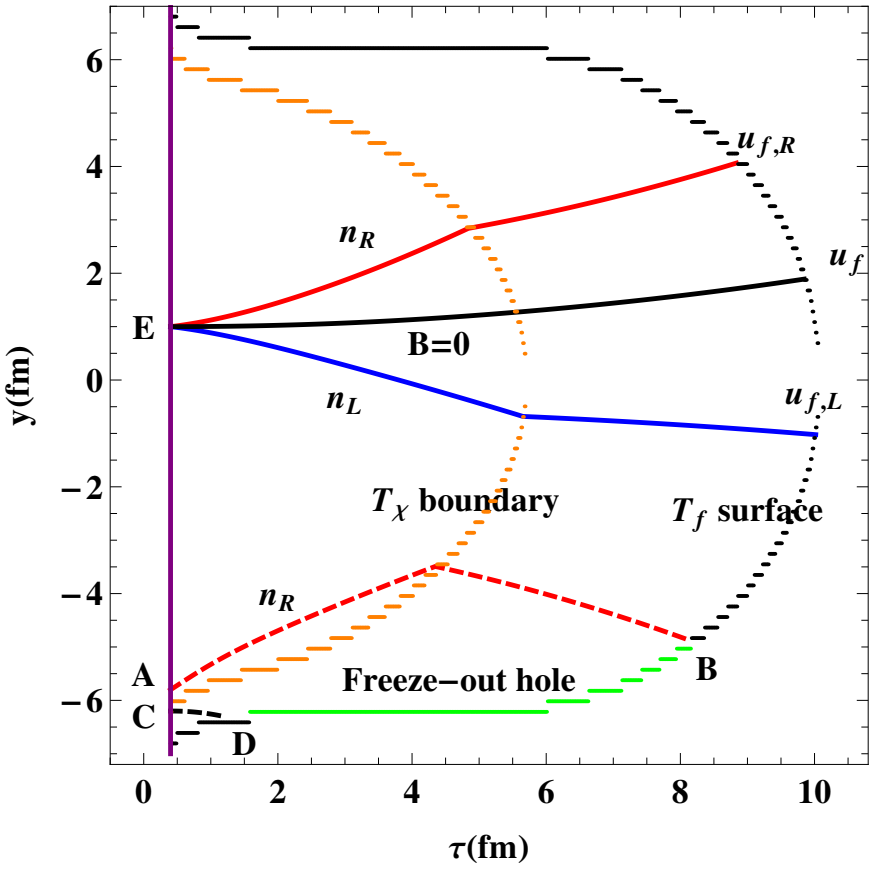
HUY-Yin:

- **Full ideal boost invariant hydrodynamics**
- **Initial charge distribution: $\frac{\delta\mu}{T}$ =constant**
  : No slope *r* without CMW
- **More realistic Cooper-Frye freeze-out at constant temperature and chiral phase transition**
  : Freeze-out Hole Effect is induced!

Freeze-out Hole Effect: A significant effect on the slope *r*

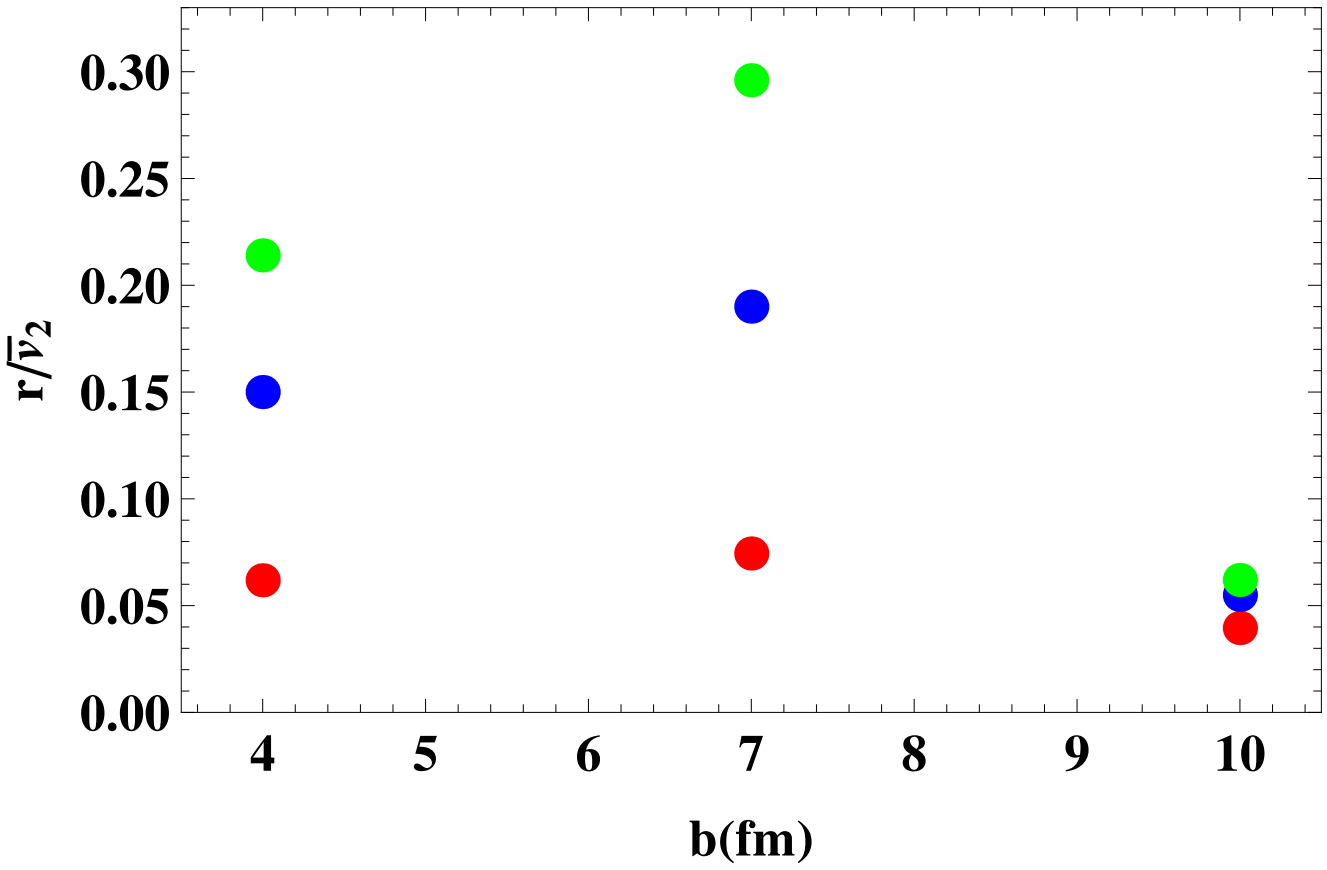


Freeze-out Hole Effect: A significant effect on the slope *r*



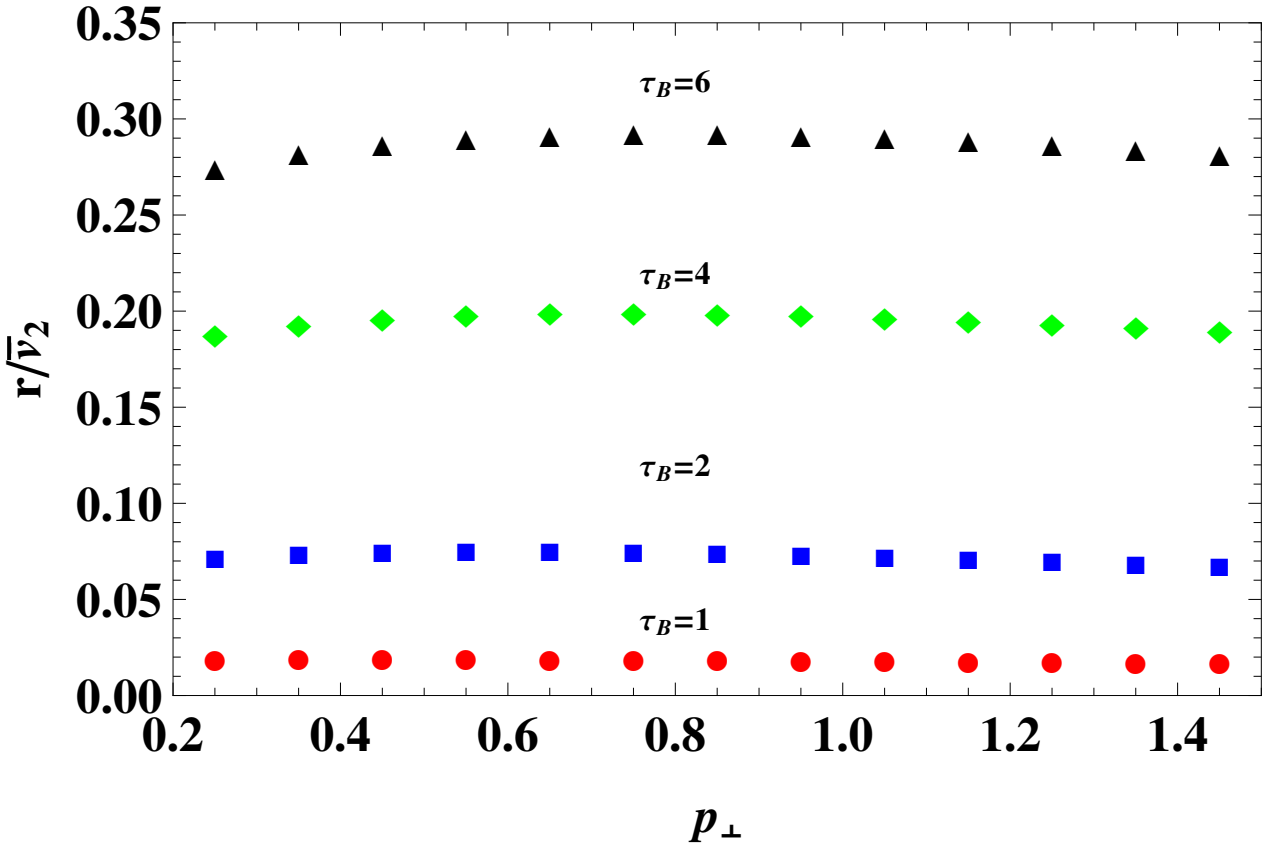
What it looks like in realistic simulations

Results



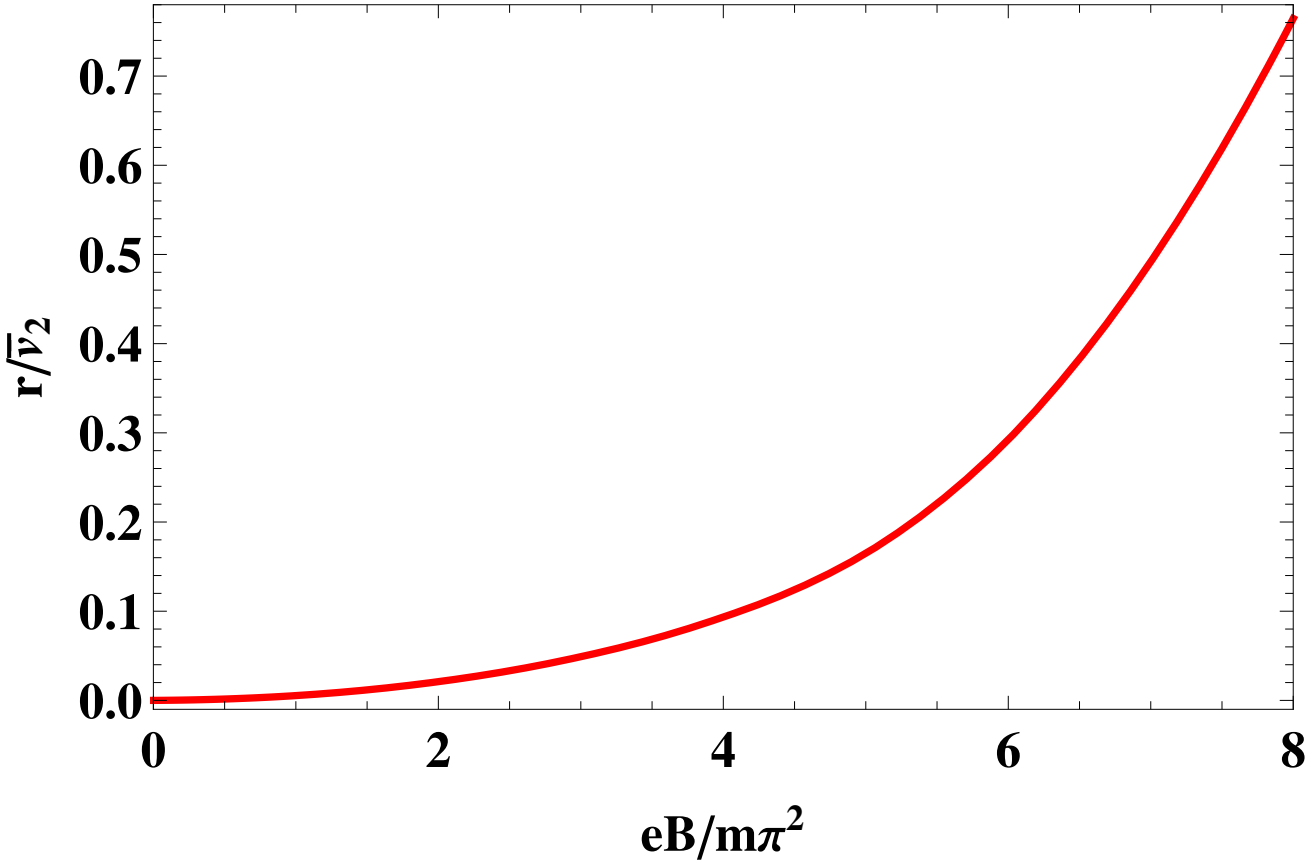
Centrality dependence
for three lifetimes of the magnetic field:
6 **fm (green),** 4 **fm (blue),** 2 **fm (red)** ($eB = 6m_\pi^2$)

Main Uncertainty
: Lifetime and Strength of Magnetic Field



Dependence on the lifetime (τ_B) of the magnetic field ($eB = 6m_\pi^2$)

Main Uncertainty
: Lifetime and Strength of Magnetic Field



Dependence on the strength of the magnetic field
($\tau_B = 6$ fm, $p_T = 0.8$ GeV)

Summary

About the same order, but somewhat small ($50\% - 30\%$) compared to the experimental values, in the optimal scenario of $\tau_B = 4 - 6$ fm and $eB = 4 - 6\ m_\pi^2$

We don't claim that CMW explains all portion of the data, since the slope is subject to other possible sources

Our point: CMW needs to be included since it may give order one contributions

Future Directions

- **Full magnetohydrodynamics needs to be considered**
  (Tuchin, McLerran-Skokov, Gursoy-Kharzeev-Rajagopal)
- **Magnetic field is time dependent: time-dependent responses (Kharzeev-Warringa, HUY)**
- **Fluctuations of magnetic fields**
  (Bloczynski-Huang-Zhang-Liao)
- **Out-of equilibrium may enhance the charge transports (Lin-HUY)**

Thank you very much for listening