

Magnetohydrodynamics and charged flow in non-central heavy ion collisions

Umut Gürsoy

Utrecht University

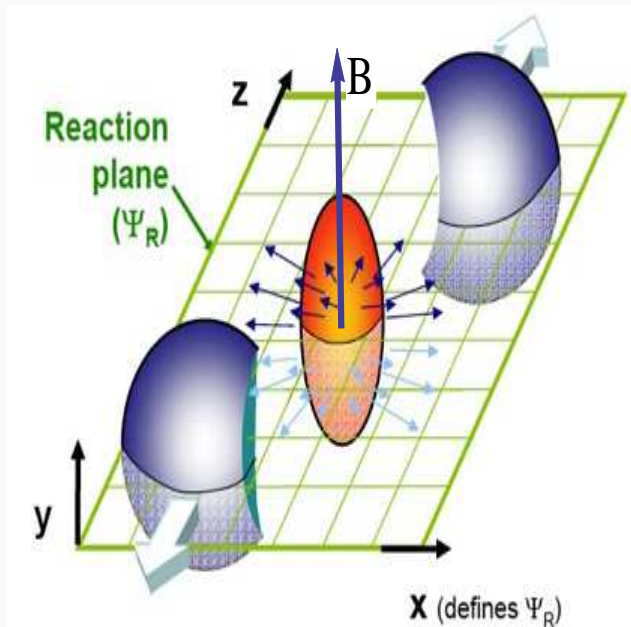
Quark Matter 2015, Kobe 29.09.2015

D. Kharzeev and K. Rajagopal

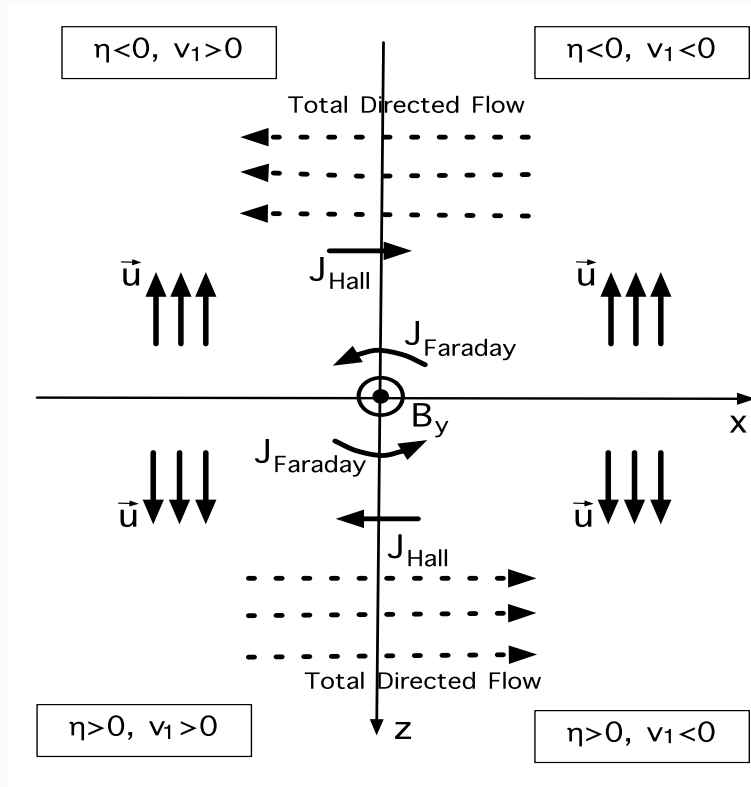
Phys. Rev. C, 089 (2014), arXiv:1401.3805

E. Marcus, D. Kharzeev, K. Rajagopal and C. Shen, ongoing

Heavy ion collisions and magnetic fields



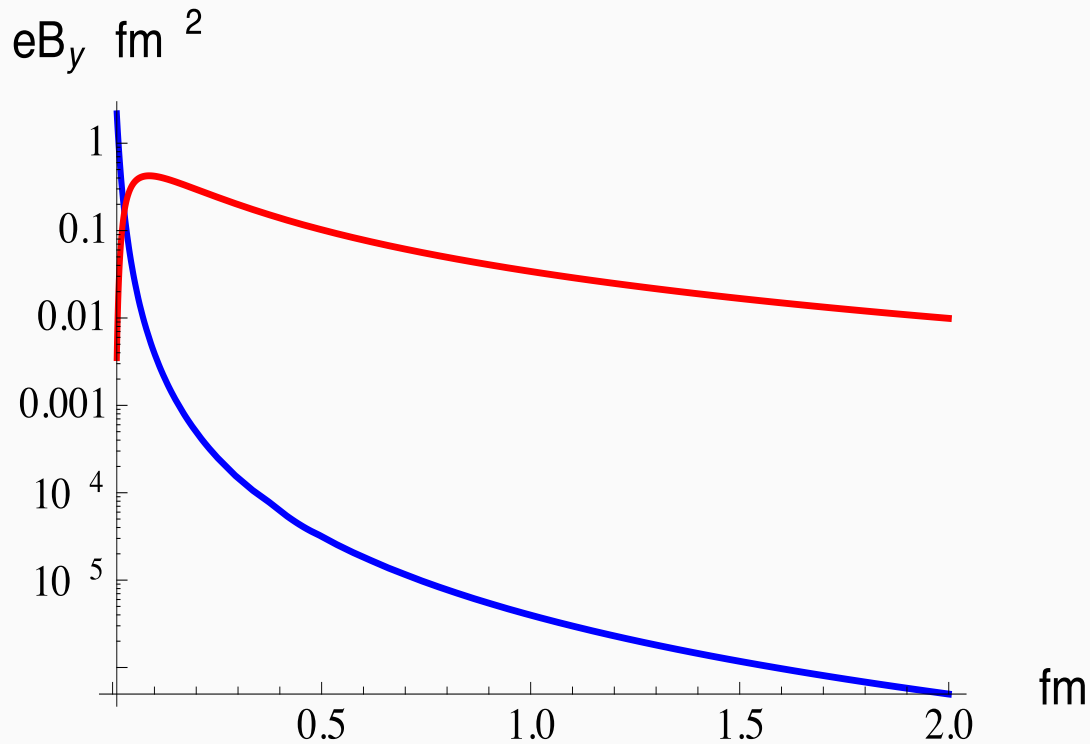
- Initial magnitude of B
- Bio-Savart: $B_0 \sim \gamma Z e \frac{b}{R^3} \Rightarrow eB \approx 5 - 15 \times m_\pi^2$ at RHIC (LHC).
- In this talk $b = 7\text{fm}$ and $R = 7\text{fm}$.
- Motivation: find observables that are directly tied to the presence of B



“Classical” currents in charged and expanding medium:

- Faraday currents $\vec{J}_F \sim \sigma \vec{E}_F$ with $\nabla \times \vec{E}_F = -\frac{\partial \vec{B}}{\partial t}$
- Hall currents $\vec{J}_H \sim \sigma \vec{E}_H$ with $\vec{E}_H = \vec{u} \times \vec{B}$
- Also a “quantum” current $\vec{J}_{CME} \sim \mu_5 \vec{B}$, not considered here.

Time profile of B at LHC

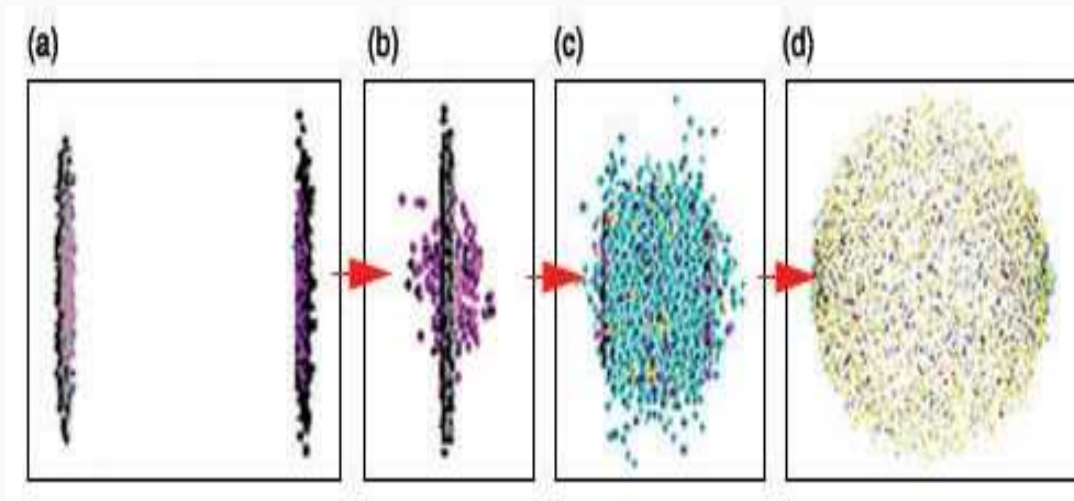


with $\sigma = 0.023\text{fm}^{-1}$ and with $\sigma = 0$

- Simplifying assumption **hard-sphere distribution** for **spectators** and **participants**
- For participants **empirical distribution** over Y : [Kharzeev et al. 2007](#)

$$f(Y_b) = (4 \sinh(Y_0/2))^{-1} e^{Y_b/2}, \quad -Y_0 \leq Y_b \leq Y_0$$

Strategy



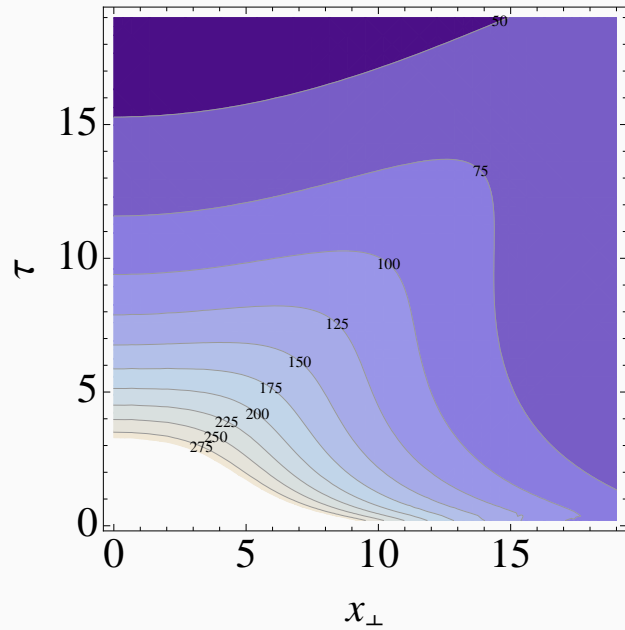
- Suppose $u^\mu(x)$ for expanding QGP is given.
- Calculate stationary velocity v_B :
$$m \frac{d\langle v_B^\vec{i} \rangle}{dt} = q \langle v_B^\vec{i} \rangle \times \vec{B}' + q \vec{E}' - \mu m \langle v_B^\vec{i} \rangle = 0, \text{ with}$$
$$\mu m = \frac{\pi \sqrt{\lambda}}{2} T^2 \text{ from AdS/CFT.}$$
- Add the induced velocity v_B to $u^\mu(x)$, assuming $|\vec{v}_B| \ll |\vec{u}|$
- Total 4-velocity $V^\mu \sim u^\mu + v_B^\mu$: contains induced currents.
- Apply Cooper-Frye to obtain flow coefficients v_i .

Analytic Hydro solution for u^μ

- Gubser-Bjorken flow Bjorken '83, Gubser '10
 1. Boost invariance along z: $\xi = z\partial_t + t\partial_x$
 2. Rotation around z: $\xi = x\partial_y - y\partial_x$
 3. Translations + special conformal transformations in transverse plane:
 $\xi = \partial_x, \partial_y$ with $\xi_i = \partial_i + q^2 [2x^i x^\mu \partial_\mu - x^\mu x_\mu \partial_i]$
- Solution to $[\xi, u] = 0$ on $ds^2 = -d\tau^2 + \tau^2 d\eta^2 + dx_\perp^2 + x_\perp^2 d\phi^2$
- $(u^\tau, u^\eta, u^\perp, u^\phi) = (\cosh \kappa, 0, \sinh \kappa, 0)$ with
$$\kappa = \frac{2q^2 \tau x_\perp}{1 + q^2 \tau^2 + q^2 x_\perp^2}$$
- Energy density: $\epsilon = \frac{\hat{\epsilon}_0}{\tau^{4/3}} \frac{(2q)^{8/3}}{[1 + 2q^2(\tau^2 + x_\perp^2) + q^4(\tau^2 - x_\perp^2)^2]^{4/3}}$

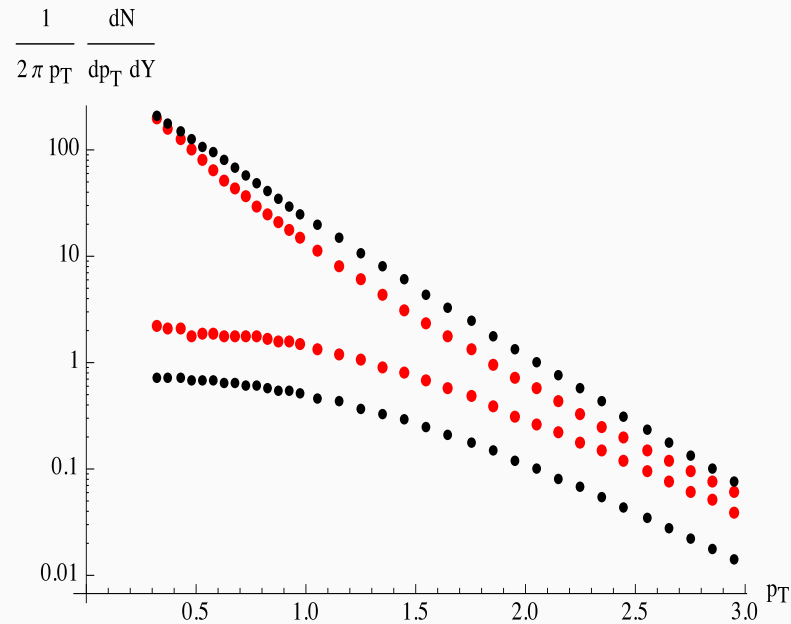
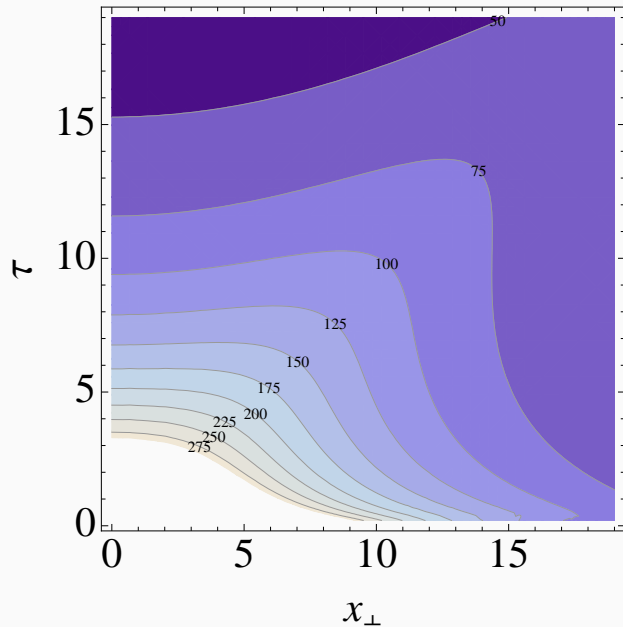
Cooper-Frye and parameter fixing

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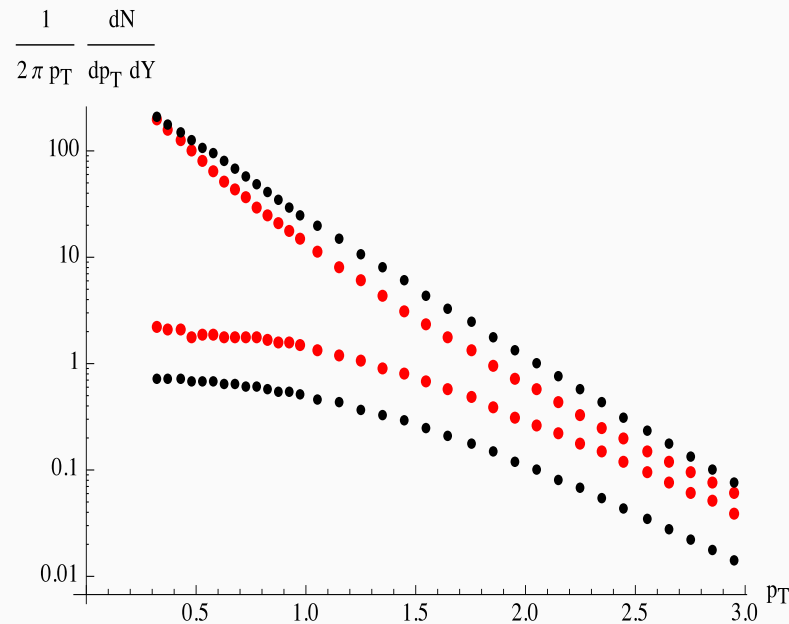
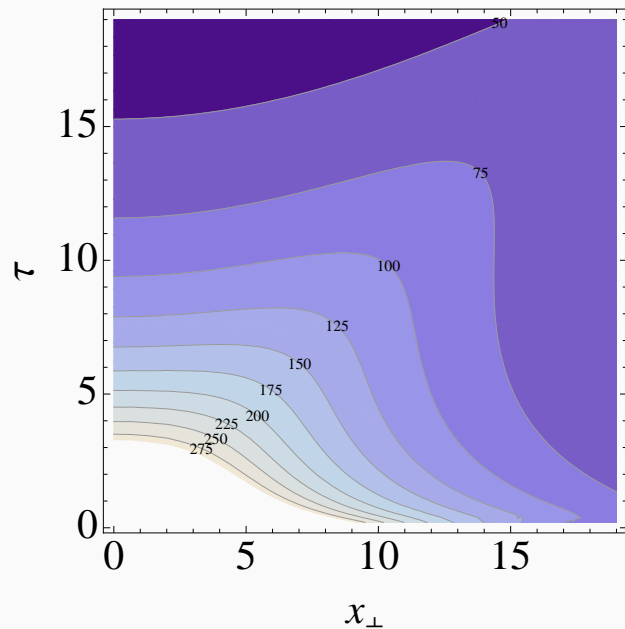
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Cooper-Frye and parameter fixing



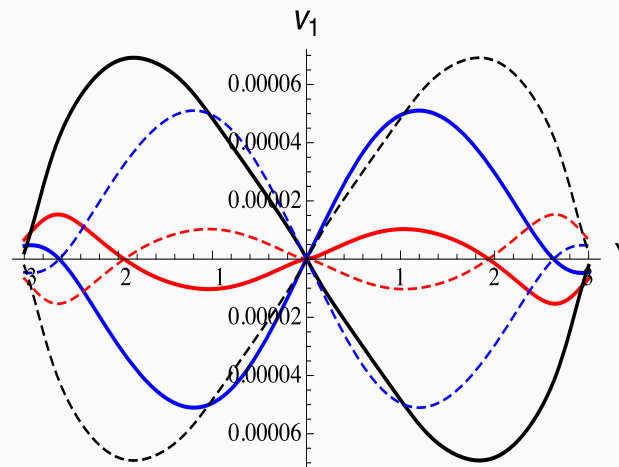
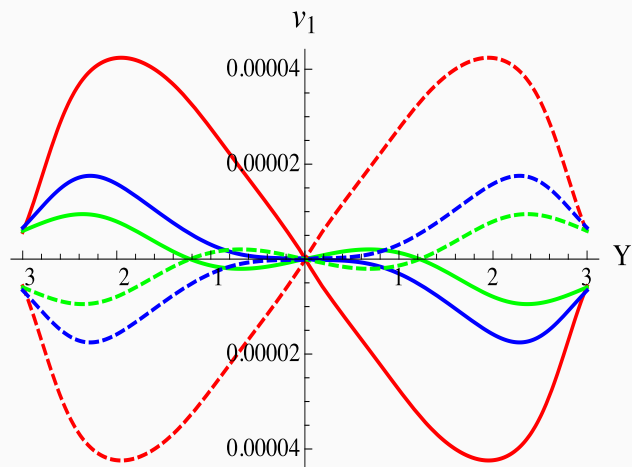
- Cooper-Frye analysis at isothermal surfaces. $T_f \approx 130$ MeV
- Demand realistic comparison with ALICE data for pions and protons and reasonable hadronization temperature $T_h \approx 400 - 550$ MeV
- Optimal solution $q^{-1} = 6.5$ fm and $\hat{\epsilon}_0 = (8.7)^4$.

Cooper-Frye and parameter fixing

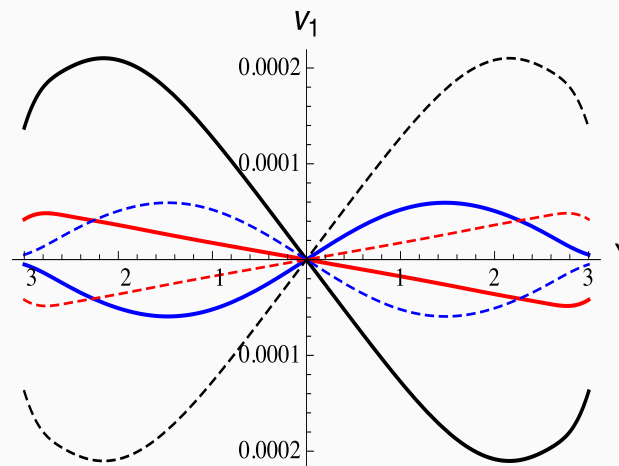
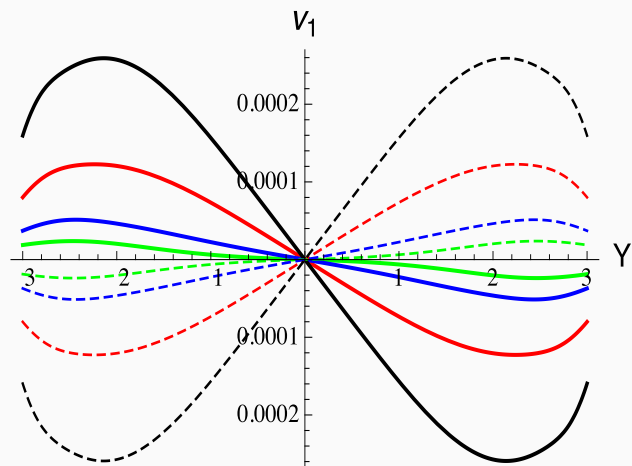


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- Spectra from Gubser flow independent of Φ_p and Y

- Pions and protons at LHC

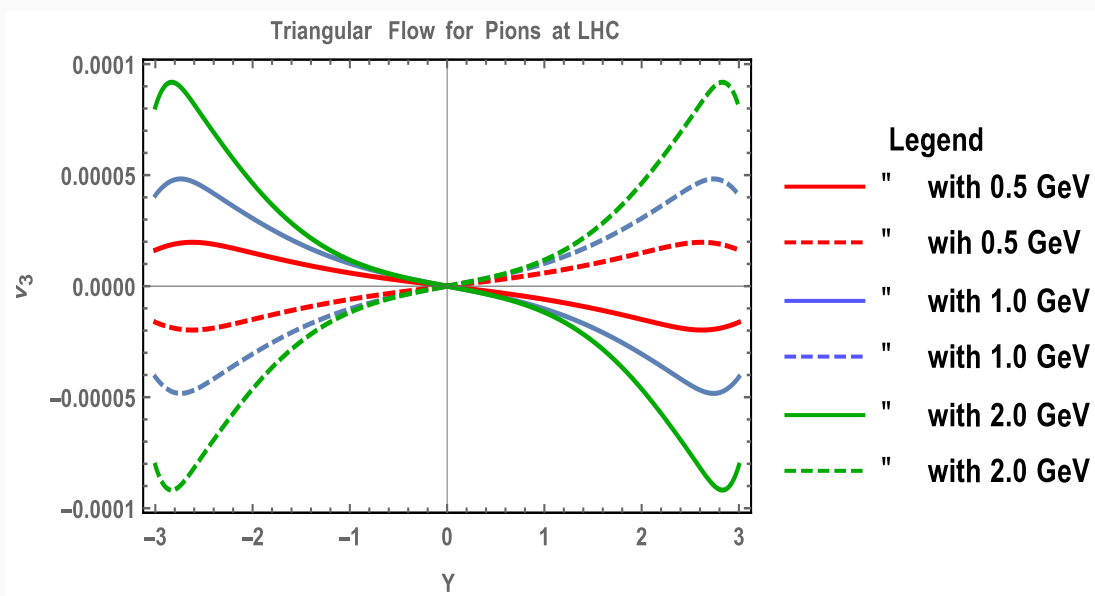
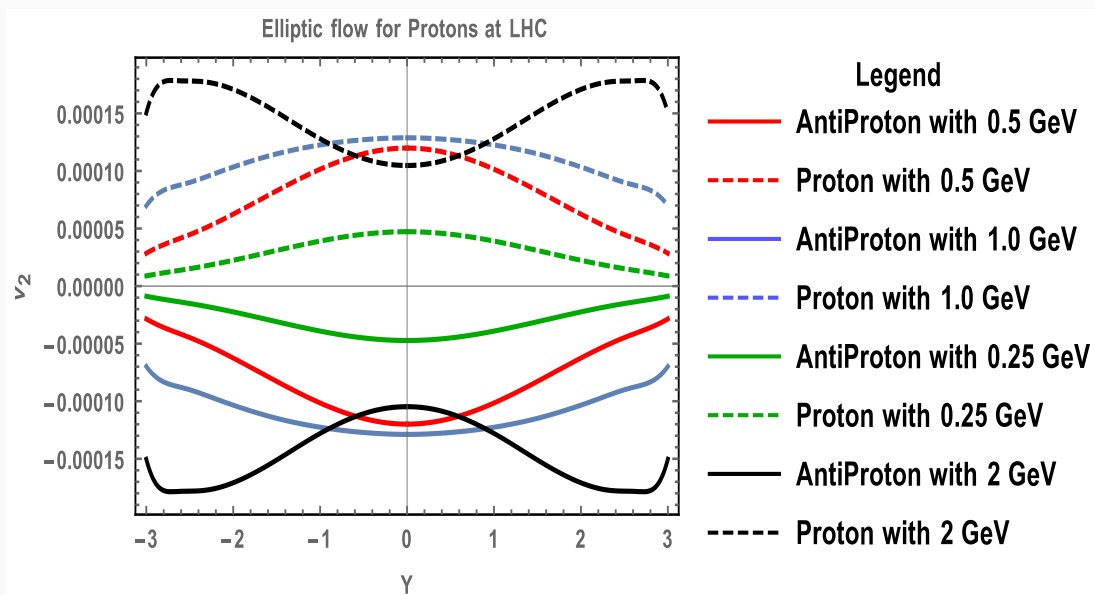


- Pions and protons at RHIC



Color coding: $p_T = 0.25$ (green), 0.5 (blue), 1 (red), 2 (black) GeV

Charge identified v_2 and v_3 : D. Kharzeev, E. Marcus and K. Rajagopal



Proposal for observables

- Define $A_1^{+-}(Y_1, Y_2) = v_1^+(Y_1) - v_1^-(Y_2)$,
 $A_1^{++}(Y_1, Y_2) = v_1^+(Y_1) - v_1^+(Y_2)$, etc.
to eliminate **charge independent contributions** to v_1 produced in event-by-event fluctuations
- Look at **quadratic observables**
 $C_1^{+-,+-}(Y, Y) = \langle A_1^{+-}(Y, Y) A_1^{+-}(Y, Y) \rangle = 4 \langle v_1^+(Y) v_1^+(Y) \rangle$
to eliminate event-by-event fluctuations in **direction of B**.
- To be compared with data ...

- **Summary:**
 - Calculated the contribution of the **time-varying B** in an **expanding plasma**, using a **perturbative approach to magnetohydrodynamics**.
 - Effect has definite signature **under charge and rapidity**.
 - Competition between **“Faraday”** and **“Hall”** effects.
 - However **the magnitude is small**.

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 - Calculated the contribution of the **time-varying B** in an **expanding plasma**, using a **perturbative approach to magnetohydrodynamics**.
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 - However **the magnitude is small**.
- **Outlook:**
 - Time dependence of σ, μ, T etc.
 - More realistic hydrodynamics **ongoing with C. Shen**
 - Backreaction of EM on hydro \Rightarrow full magnetohydrodynamics
 - More realistic distributions for the sources

THANK YOU !