# Probing electromagnetic fields with heavy quarks and $Z^0$ decaying leptons in uRHICs

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Refs: PLB 816, 136271 (2021); EPJP 136, 726 (2021)

### □ Impact of e.m. fields in uRHICs

**Probing e.m. fields with v**<sub>1</sub> splitting of heavy quarks and leptons from Z<sup>0</sup> decay

□ The general behavior of charge dependent flows induced by e.m. fields

**G** Summary

# Impact of electromagnetic (e.m.) fields in uRHICs

Many Impacts: Chiral magnetic effect (CME), Chiral magnetic wave (CMW), Hyperons polarization splitting, Chiral condensate, Fluctuation of conserved charge and so on



D.E. Kharzeev et al., NPA 803 (2008) Y. Burnier et al., PRL 107 (2011), 052303 STAR, Nature 548 (2017), 62-65 H.T. Ding et al., PRD 105 (2022), 034514 J.H. Liu, QM 2022







# Probing e.m. fields with $v_1$ splitting of heavy quarks and leptons from Z<sup>0</sup> decay

# Probing e.m. fields with $v_1$ splitting of charged particles



U. Gursoy et al., PRC 89 (2014), 054905 S.K. Das et al., PLB 768 (2017), 260-264

$$F_{ext} = q\mathbf{E} + \frac{q}{E_p} (\mathbf{p} \times \mathbf{B})$$
  
Faraday Hall  
(decaying B)  
$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$$

#### Delicate balance between E and B

- $\checkmark$  E wins -> negative slope  $\varDelta v_1$  vs  $y_z$  between positively and negatively charged particles
- ✓ B wins -> positive slope  $\Delta v_1 v_5 y_z$

# Why heavy Quarks (HQs)?



#### **HQs best probe** for v<sub>1</sub> induced by e.m. fields:

- 1. pQCD hard processes
- 2. negligible thermal production
- 3.  $t_{form} \approx 0.08$  fm/c when  $B_y$  is  $\approx$  its maximum and witness of all the QGP evolution
- 4.  $\tau_{th}(c) \approx \tau_{QGP} \gg \tau_{e.m}$  (keep more memory effects)

# E.M. fields

≈ 50m<sub>π</sub><sup>2</sup>

10

10

0

10

10

10

eB<sub>y</sub> [GeV/fm]

$$\left( \nabla^2 - \partial_t^2 - \sigma_{el} \, \partial_t \right) \boldsymbol{B} = -\nabla \times \boldsymbol{J}_{ext}, \left( \nabla^2 - \partial_t^2 - \sigma_{el} \, \partial_t \right) \boldsymbol{E} = -\nabla \rho_{ext} + \partial_t \boldsymbol{J}_{ext},$$

U. Gursoy et al., PRC 89 (2014), 054905 H. Li et al., PRC 94 (2016), 044903

#### Assuming constant conductivity gives an analytical and simple solution of the Maxwell equations



S. Shi et al., AP 394 (2018), 50-72 L. Mclerran et al., NPA 929 (2014) 184 G. Inghirami et al., EPJC 76 (2016), 659

#### \* Computation of early stage e.m. field is quite an issue:

- ✓ large gap @LHC:  $eB_y(t=0)$  in the vacuum: ≈ 50 m<sub>π</sub><sup>2</sup> but  $eB_y(t=0)=0$  assuming a medium in equilibrium at  $\sigma_{el}$  even before t=0 (need more realistic simulations)
- ✓ IQCD  $\sigma_{el}$ ? Early time what is  $\sigma_{el}$  in the Glasma?

# Parametrized E.M. field



#### Sun&Plumari&Greco, PLB 816 (2021), 136271

#### Case A

 ✓ E-B fields like U. Gursoy et al., PRC 89 (2014), 054905
 ✓ Medium at t<0 + eq. medium  $σ_{el}$ =0.023 fm<sup>-1</sup>

F

#### Case B and C

 $eB_{y}(x, y, \tau) = -B(\tau)\rho_B(x, y) \quad B(\tau) = eB_0/(1 + (\tau/\tau_B)^a)$ 

 $B(\tau) = eB_0/(1 + \tau^2/\tau_B^2)$   $B(\tau) = eB_0/(1 + \tau/\tau_B)$ 

- $\checkmark$  ~~  $E_x$  is evaluated by the Faraday's Law
- \* <u>Case C</u> reproduces experimental data:
  - ✓ Case B and Case C have the same  $\tau_B$  and  $eB_0$  but very different  $v_1$  splitting
  - Constrain strongly the decay form of B<sub>y</sub>(t): A slowly decay
     B leads to a relative smaller E, and B (Hall effect) wins over

# Leptons from Z<sup>0</sup> decay



- ✓ Clearer observables
- ✓ Separable from other sources
- ✓  $\tau_{decay}(Z^0) = \tau_{form}(charm) = 0.08 \text{ fm/c} \rightarrow \text{ Strong}$ correlation between  $\Delta v_1(D^0, \overline{D}^0)$  and  $\Delta v_1(I^+, I^-)$







- v<sub>1</sub> splitting of Z<sup>0</sup> decaying leptons **are quite different from** that of charm quarks:
  - ✓ Sign change?
  - Smaller magnitude (1e > 2/3e)?

$$\frac{d\Delta v_1^c}{dy_z}|_{y_z=0} \propto -\alpha \frac{\partial \ln f_c}{\partial p_T}$$

# The relation between $v_1$ and charged particle's spectra



# The general behavior of charge dependent flows induced by e.m. fields

# General behavior of charge dependent flows by e.m. fields

□ What happens to **all** charge dependent flows by e.m. fields? Is there a general behavior? Does it depend on the details of e.m. fields?



- The interaction with QGP just dampens the effect at p<sub>T</sub><3 GeV/c</p>
  - One can study the charge dependent flows with pure e.m. fields for heavy quarks and jets and leptons

# General behavior of charge dependent flows by e.m. fields

$$\begin{aligned} f' &= f - \left\{ \frac{\partial f(a_1 + b_1)}{\partial p_T} + f(-\frac{p_T}{m_T^2} \frac{\partial (a_1 + b_1) \tanh y_z}{\partial y_z} \right. \\ &+ \frac{a_1 + b_1}{p_T} + \frac{2}{m_T} \frac{\partial c_0 / \cosh y_z}{\partial y_z} \right) \right\} \\ &- \left\{ -f \frac{p_T}{m_T^2} \frac{\partial (a_0 + b_0) \tanh y_z}{\partial y_z} + \frac{\partial (a_0 + b_0) f}{\partial p_T} \right\} \cos \phi \\ &- \sum_{n=1} \left\{ \frac{\partial f(a_{n+1} + b_{n+1} + a_{n-1} - b_{n-1})}{\partial p_T} \right. \\ &+ f\left[ \frac{(n+1)(a_{n+1} + b_{n+1}) - (n-1)(a_{n-1} - b_{n-1})}{p_T} \right. \\ &- \frac{p_T}{m_T^2} \frac{\partial \tanh y_z(a_{n+1} + b_{n+1} + a_{n-1} - b_{n-1})}{\partial y_z} \\ &+ \frac{2}{m_T} \frac{\partial c_n / \cosh y_z}{\partial y_z} \right] \right\} \cos n\phi. \end{aligned}$$

$$(7)$$

$$\overline{\Delta p_x} = \sum 2a_n(p_T, y_z) \cos n\phi, \\ \overline{\Delta p_y} = \sum 2b_n(p_T, y_z) \sin n\phi, \\ \overline{\Delta p_y} = \sum 2c_n(p_T, y_z) \cos n\phi. \end{aligned}$$

- E.M. fields modify spectra and charge dependent flow
- ✓ The Lorentz force in z direction also modifies charge dependent flows as a azimuthal angle of transverse momentum
  - The trajectory and the Lorentz force are same for quarks with p<sub>T</sub>>>m
    - $\checkmark$  p<sub>T</sub> dependence is general and simple

$$\frac{\partial a_n}{\partial p_T} \simeq 0, \frac{\partial b_n}{\partial p_T} \simeq 0, \frac{\partial c_n}{\partial p_T} \simeq 0 (p_T \gg m)$$
$$f^{'} = f - \sum_{n=0} (d_n \frac{\partial f}{\partial p_T} + e_n \frac{f}{p_T}) \cos n\phi \quad (p_T \gg m)$$

*nφ*. Sun&Greco &Plumari, EPJP 136 (2021), 726

## Spectra modification by e.m. fields



# v<sub>1</sub> splitting by e.m. fields



✓ The v₁ splitting by e.m. fields for charm, bottom and Z<sup>0</sup> decaying leptons has a general p<sub>T</sub> dependence

✓ low p<sub>T</sub> derivation for charm quarks due to QGP interaction

v<sub>1</sub> splitting by e.m. fields



✓  $p_T$  dependence of  $d\Delta v_1$ /dy applies to **different e.m. fields (Case A and Case C)** 

## Relation between $\alpha$ and $B_v$



# Correlation between $v_1$ splitting of $D^0-\overline{D}{}^0$ and $I^+-I^-$ from $Z^0$ decay



Sun&Greco & Plumari, EPJP 136 (2021), 726

- ✓ α ratio for Case A with conductivity 0.0115, 0.023 fm<sup>-1</sup> ~1.3-1.4, for Case C ~ 2, close to their charge ratio 1.5 for very different e.m. fields: 100 times
- ✓ Does not depend on the details of e.m. fields due to same e.m. fields + similar formation time 0.08 fm/c + same space of charm and these leptons
- ✓ Should apply to all charge dependent flows + spectra ratio  $(a_n, b_n, c_n)$

- $\Box$  v<sub>1</sub> splitting can only probe tB<sub>y</sub> varation at two times
- $\Box$  Charge dependent flows and spectra modification induced by e.m. fields has a general  $p_T$  dependence
- □ The correlation between charge dependent flow of charmed mesons and leptons from Z<sup>0</sup> decay applies to all e.m. fields; strong indication of e.m. field origin

# Thank you for your attention!