Impact of the Electromagnetic and glasma fields on HFs

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Outline

✧ $v_1$ splitting of charged particles under the EM field

- charmed mesons

- leptons from $Z^0$ boson decay

- Find the relation between the time evolution of magnetic field and $\frac{dv_1}{d\eta}(c^+)$ - $\frac{dv_1}{d\eta}(c^-)$

and the feature of EM field inducing $v_1$ splitting

✧ Impact of glasma field on HF dynamics
$\nu_1$ splitting of charmed mesons and leptons from $Z^0$ decay under the EM field
EM field in uRHICs

- Novel effects related to magnetic field: CME, CMW, $\Lambda$ polarization splitting.
- Medium prolong magnetic field; Larger conductivity leads to longer lifetime.
\( v_1 \) splitting of charged particles to probe EM field

For \( \Delta v_1 \) between positively and negatively charged particles, \( d\Delta v_1/dy \) is positive from magnetic field, and negative from electric field induced by B field: the balance between these two effects determines the overall sign.

\( D^0(cu) \) is charge neutral, constitute charm is positively charged; Measuring \( \frac{d\Delta v_1}{dy}(D^0) - \frac{d\Delta v_1}{dy}(\bar{D}^0) \) can probe EM fields and also deconfinement.

STAR data does not determine if such splitting exists.
ALICE Results


- ALICE found a clear positive $\Delta v_1/\Delta y$ and huge for charmed mesons than STAR.
- Not predicted by theoretical studies: wrong sign and 2 order smaller magnitude.
- Larger conductivity leads to a less negative $\Delta v_1/\Delta y$.

U. Gursoy et al., PRC 98 (2018), 055201
S. Chatterjee et al., PLB 798 (2019), 134955
Why negative $d\Delta v_1/dy$

\[ \langle p_x \rangle = \int dt \ F_x = \int dt \ (qE_x - qv_yB_y) \Rightarrow \text{sign of } d\Delta v_1/\text{dy} \text{ same as sign of } \int dt \ (E_x - v_yB_y) \text{ at } y>0. \]

- Good correspondence between evolution of $\Delta v_1$ and $F_x$ at center of fireball only.
- Solid and dashed lines show $E_x$ relates to the time derivate of $-v_yB_y$. Using only $B_y$ to determine the sign of $d\Delta v_1/\text{dy}$?
Simplified EM configurations

\[ eB_y(x, y, \tau) = -B(\tau)\rho_B(x, y) \]

\[ \nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t \]

\[ eE_x(t, x, y, \eta_S) = \rho_B(x, y) \int_{\eta_S}^{\eta_S} d\eta B'(t, \eta) \frac{t}{\cosh \eta} \]

\[ x_T=0, \eta_S=0.5 \]

Adopted by studies of CME and Magnetohydrodynamics

Y. Jiang et al., CPC 42 (2018), 011001
S. Shi et al., Anna. Phys. 394 (2018), 50
V. Roy et al., PRC 96 (2017), 054909

Good agreement between the simple relation and the full Maxwell equations solution.
From time evolution of $B_y$ to $d\Delta v_1/dy$

$p_x, p_y, y \rightarrow p_x + \Delta p_x(p_x, p_y, y), p_y + \Delta p_y(p_x, p_y, y), y + \Delta y(p_x, p_y, y)$

\[ V_1 = \left[ \frac{p_x}{p_T} \right] \Rightarrow V_1(p_T, y) \text{ determined by } \Delta p_x(p_T, y) \]

Assumptions
1. no interaction with QGP;
2. $q B_y \tau_B \ll E_p \Rightarrow \text{perturbation}$

\[ \overline{\Delta p_x(p_T, y_z)} = \int_{t_0}^{\infty} dt \int dx_0 dy_0 \rho^2(x_0, y_0) \int \frac{d\phi}{2\pi} \]
\[ q \left[ \text{tanh}_y B(t, y) + \int_0^{y_z} d\eta B'(t, \eta) \frac{t}{\cosh \eta} \right] \Rightarrow \Delta p_x(p_T, y_z) \propto q \int_{0}^{y_z} \frac{d\eta}{\cosh \eta} [\tau_2 B(\tau_2) - \tau_1 B(\tau_1)] \]

\[ \tau_1 = \frac{\tau_0 \cosh y_z}{\cosh \eta} \text{ and } \tau_2 = \frac{\left(\tau_0 + \frac{R m_T}{p_T}\right) \cosh y_z}{\cosh \eta} \]

Production time Typical time of leaving EM or freezeout

- Depend on only initial and final $\tau B$.
- Slowly decaying $B$ lead to positive slope, can constrain $B$ time evolution.
- Turning on interaction decreases only the magnitude of $\Delta p_x$. 

Comparisons

Left is $v_1$ splitting with full $c$ quark evolution in QGP and EM solved from full Maxwell equation; Right is the $\tau B$ starting from $c$ quark production.

Large correlation between $d\Delta v_1/dy$ and the difference of final and initial $\tau B$. 
Simulations

\[ eB_y(x, y, \tau) = -B(\tau)\rho_B(x, y) \]

- \( B_y(\tau = 0) = B_y(t = 0) \) in vacuum

\[ \rho_B(x, y) = \exp\left[ -\frac{x^2}{2\sigma^2_x} - \frac{y^2}{2\sigma^2_y} \right] \]

Case B: \( B(\tau) = eB_0/(1 + \tau^2/\tau^2_B) \)
Case C: \( B(\tau) = eB_0/(1 + \tau/\tau_B) \)

\[ \Delta p_x(p_T; y_z) \propto q \int_{y_z}^{y} \frac{d\eta}{\cosh\eta} [\tau_2 B(\tau_2) - \tau_1 B(\tau_1)] \]

- eB_0 \sim 70 m^2 for 5 TeV

W.T. Deng et al., PRC 85 (2012), 044907

- case B opposite to Case C and experiments.
- If originated from EM fields only, By decreases like case C and \( \tau_B \sim 0.3-0.5 \) fm/c. Strong and decay slowly??

Y.F. Sun et al., arXiv: 2004.09880
Correlated measurement of leptons from $Z^0$ boson decay

- Leptons feels the e.m. field and not the strong one.
- Leptons from $Z^0$ decay are separable by other sources.
- $\tau_{\text{decay}}(Z^0)=\tau_{\text{form}}(\text{charm})=0.08\text{fm/c}$: go through the e.m. fields at the same time → meaningful look at the correlation $\Delta v_1(D^0, \bar{D}^0)$ and $\Delta v_1(l^+, l^-)$.

- Surprising behavior: with case C, $d\Delta V_1/d\eta$ is positive above 45 GeV, but negative at 30 or 40 GeV; Largest at 50 GeV.
- Peculiar spectra of leptons from $Z^0$ decay

Leptons from Z decay increases with $p_T$ at low $p_T$ and decreases with $p_T$ at high $p_T$

Y.F. Sun et al., arXiv: 2004.09880
A feature of EM inducing $v_1$ splitting

Left: decreases with $p_T$, Right: increases with $p_T$

- $d\Delta V_1/d\eta(p_T)$ depends on both $\Delta p_X$ and the spectra of charged particles.

$$v_1(p_T, y) \approx \frac{\Delta p_x(p_T, y)}{2f_a} \frac{-\partial f_a}{\partial p_T} = \frac{\Delta p_x(p_T, y) - \partial f_a}{2} \frac{-\partial \ln f_a}{\partial p_T}.$$ 

**Unique feature**

\[
\frac{dN}{dp_x dp_y} = \int d\Delta_x f_a \left( \sqrt{p_x^2 + p_y^2} \right) \rho(\Delta_x) \delta(p_x - p_{x_0} + \Delta_x)
\approx \int d\Delta_x \left( f_a(p_T) - \frac{\partial f_a}{\partial p_T} \frac{\Delta p_x}{p_T} \right) \rho(\Delta_x)
= f_a(p_T) - \Delta p_x(p_T, y) \frac{\partial f_a}{\partial p_T} \frac{p_x}{p_T},
\]

- $p_T$ dependence of $d\Delta V_1/d\eta$ is better to probe the effect of EM field.

A shift in positive $p_x$ due to EM field

Y.F. Sun et al., arXiv: 2004.09880

$\Delta p_x \sim 0.3$ GeV for charms, $0.7$ GeV for leptons
HF dynamics in Glasma
HF dynamics in Glasma

\[
\frac{dA^a_i(x)}{dt} = E^a_i(x), \\
\frac{dE^a_i(x)}{dt} = \sum_j \partial_j F^a_{ji}(x) + \sum_{b,c,j} f^{abc} A^b_j(x) F^c_{ji}(x), \\
\frac{dx_i}{dt} = \frac{p_i}{E}, \\
E \frac{dp_i}{dt} = Q_a F^a_{i\nu} p^\nu, \\
E \frac{dQ_a}{dt} = -Q_c \varepsilon^{cba} A_b \cdot p,
\]

M. Ruggieri et al., PRD 98 (2018), 094024
Y. Sun et al., PLB 798 (2019) 134933

✧ Enhancement of \( R_{AA}(p_T) \) due to initial glasma.

✧ The effect is similar to Fokker-Planck EOM with large diffusion and small drag.
Charmed mesons observables

\[ R_{AA}(p_T; b) = \frac{dN_{Q}^{AA}(b)/dp_t}{N_{\text{coll}}(b) \frac{dN_{Q}^{pp}}{dp_t}} \]

\[ v_2(p_T; b) = \frac{\int d\phi \frac{dN_{Q}^{AA}(b)}{dp_t dy d\phi} \cos(2\phi)}{\int d\phi \frac{dN_{Q}^{AA}(b)}{dp_t dy d\phi}} \]

Y. Sun et al., PLB 798 (2019) 134933

افتراض می‌شود که بهبود \( R_{AA}(p_T) \) با همین توان تداخلی می‌باشد.

امتیاز 

\( \diamond \) Alter the relation between \( R_{AA} \) and \( V_2 \).
Summary & Outlook

- The correlated measurements of $v_1$ splitting of charmed mesons and leptons from $Z^0$ decay can prove the existence of EM fields and also constrain the time evolution of it; Deconfinement

- The unique feature that at large $p_T$ $d\Delta V_1/d\eta$ depends on $\Delta p_x$ and the spectra of charged particles.

- Glasma field leads to a diffusion like effect on HF spectra, and can alter the relation between $R_{AA}$ and $v_2$.

There are more things to do and to learn than expected!