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

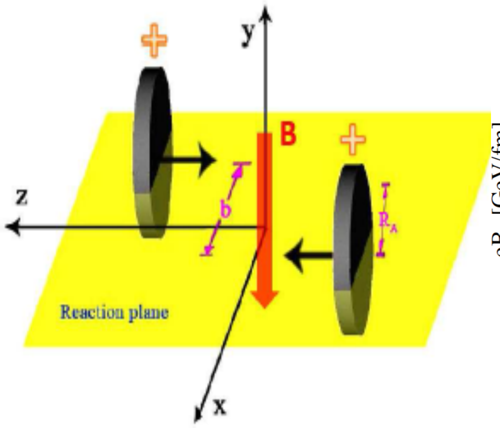
-Find the relation between the time evolution of magnetic field and $\frac{dV_1}{d\eta}(c^+)$- $\frac{dV_1}{d\eta}(c^-)$

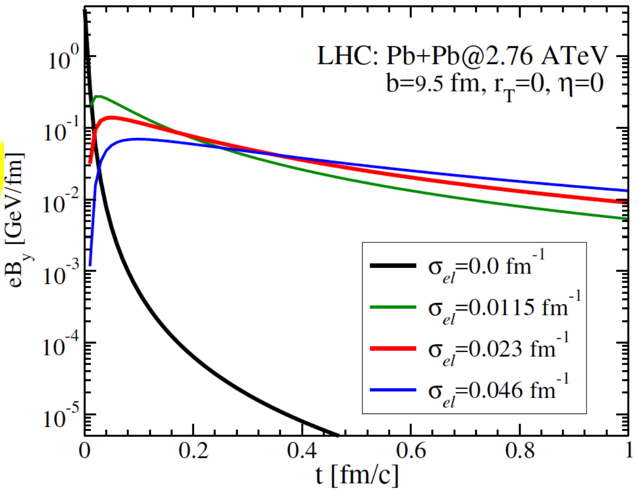
and the feature of EM field inducing v_1 splitting

✧ Impact of glasma field on HF dynamics

v_1 splitting of charmed mesons and leptons from Z^0 decay under the EM field

EM field in uRHICs

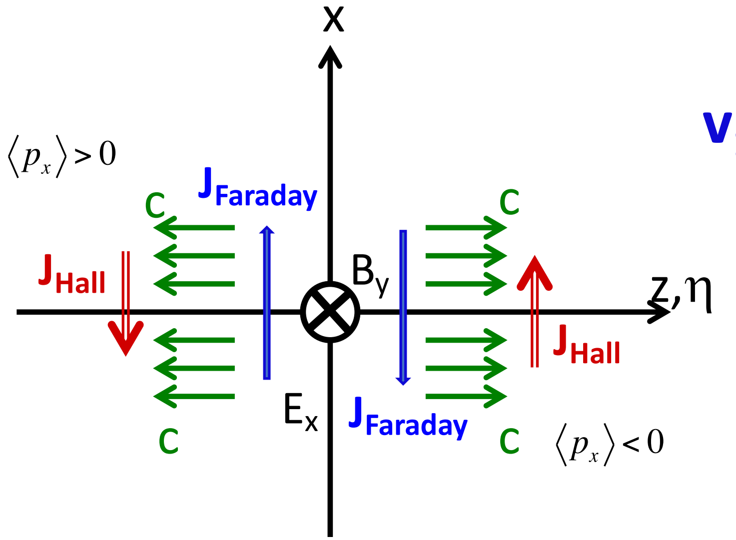




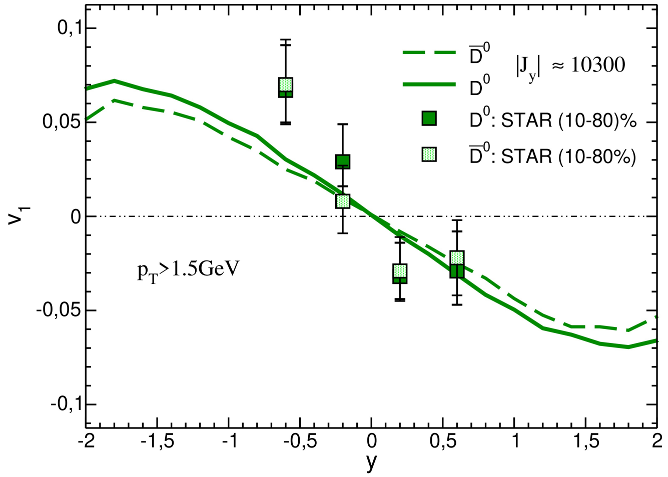
V. Voronyuk et al., PRC **83** (2011), 054911
W.T. Deng et al., PRC **85** (2012), 044907
K. Tuchin, PRC **88** (2013), 024911
U. Gursoy et al., PRC **89** (2014), 054905
H. Li et al., PRC **94** (2016), 044903

- **Novel effects related to magnetic field: CME, CMW, Λ polarization splitting.**
- **Medium prolong magnetic field; Larger conductivity leads to longer lifetime.**

v_1 splitting of charged particles to probe EM field



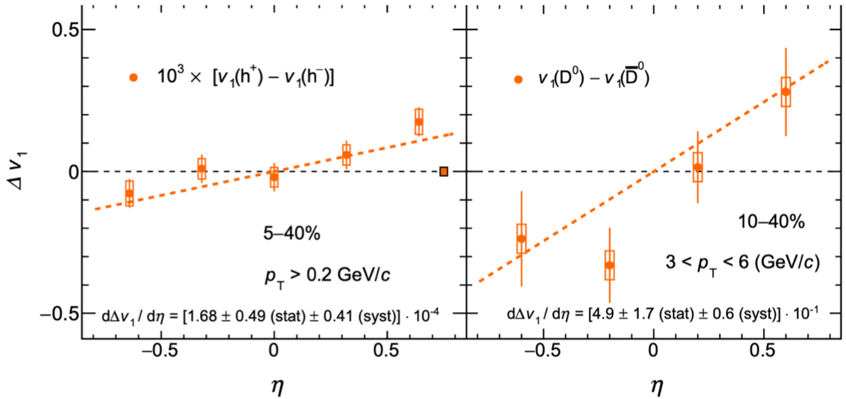
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

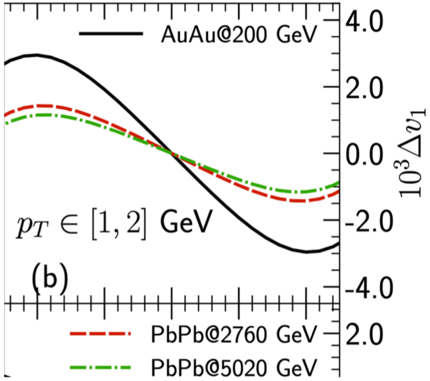


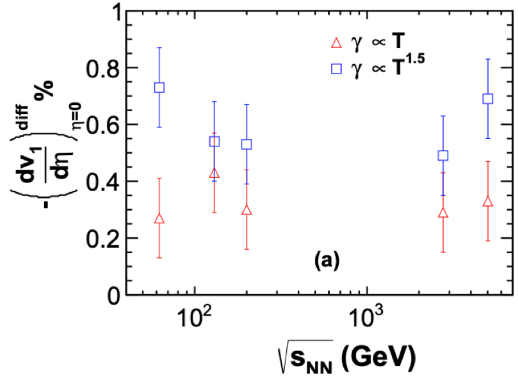
STAR, PRL **123** (2019), 162301

- For Δv_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.
- $D^0(c\bar{u})$ is charge neutral, constitute charm is positively charged; Measuring $\frac{dV_1}{dy}(D^0)$- $\frac{dV_1}{dy}(\overline{D^0})$ can probe EM fields and also deconfinement.
- STAR data does not determine if such splitting exists.

ALICE Results

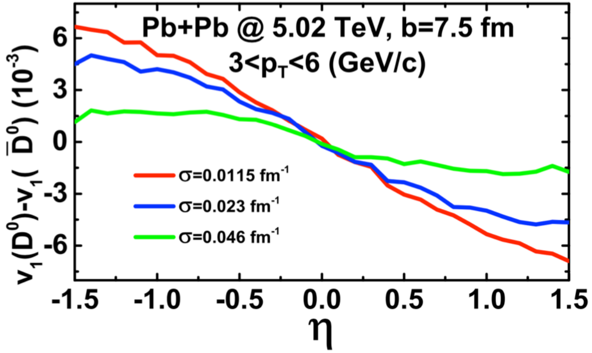






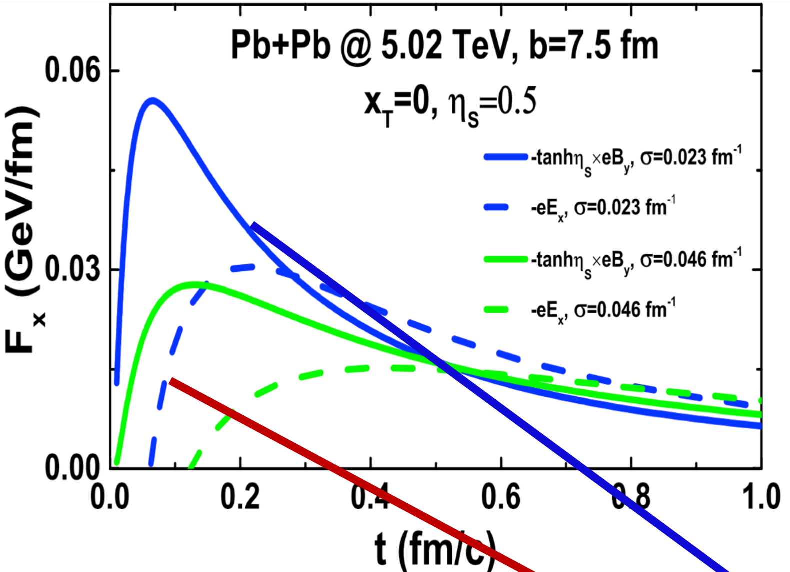
ALICE, arXiv:1910.14406

- **ALICE found a clear positive $d\Delta v_1/dy$ 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 $d\Delta v_1/dy$.**

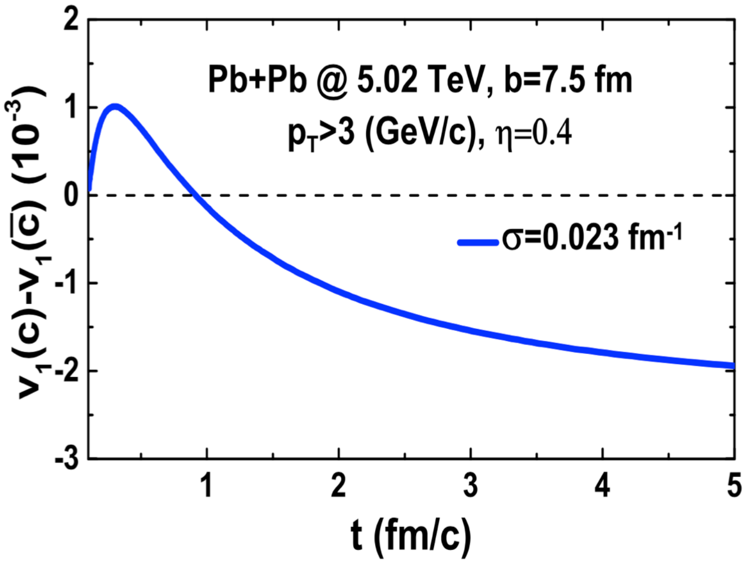


U. Gursoy et al., PRC **98** (2018), 055201
S. Chatterjee et al., PLB **798** (2019), 134955

Why negative $d\Delta v_1/dy$



$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$



- $\langle p_x \rangle = \int dt\, F_x = \int dt\, (qE_x - qv_zB_y) \Rightarrow$ **sign of $d\,\Delta\, v_1/dy$ same as sign of $\int dt\, (E_x - v_zB_y)$ at y>0.**
- **Good correspondence between evolution of Δv_1 and F_x at center of fireball only.**
- **Solid and dashed lines show E_x relates to the time derivate of -v_zB_y. Using only B_y to determine the sign of $d\Delta v_1/dy$?**

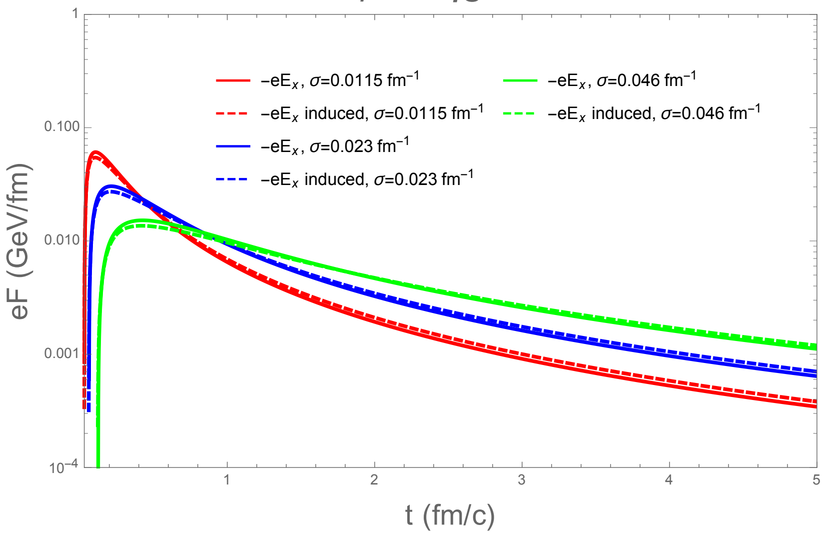
Simplified EM configurations

$$eB_y(x,y,\tau) = -B(\tau)\rho_B(x,y)$$
$$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$$
$$eE_x(t,x,y,\eta_S) = \rho_B(x,y)\int_0^{\eta_S} d\eta B'(t,\eta)\frac{t}{\cosh\eta}$$

Adopted by studies of CME and Magnetohydrodynamics

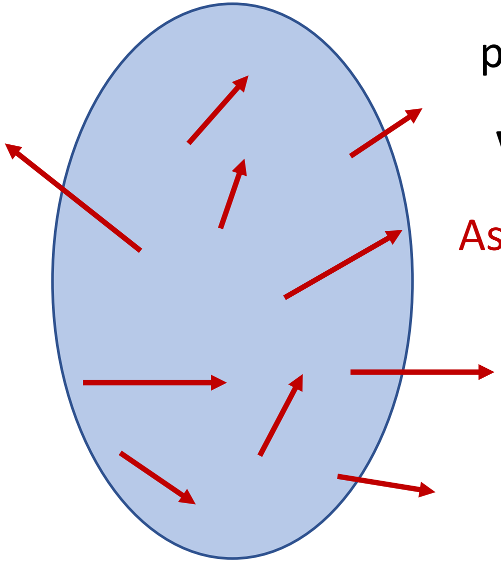
Y. Jiang et al., CPC **42** (2018), 011001
S. Shi et al., Anna. Phys. **394** (2018), 50
V. Roy et al., PRC **96** (2017), 054909

x_T=0,η_S=0.5



- **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, $y \to p_x+\Delta p_x(p_x,p_y,y)$, $p_y+\Delta p_y(p_x,p_y,y)$, $y+\Delta y(p_x,p_y,y)$

$\mathbf{V_1}=\left\langle \frac{p_x}{p_T} \right\rangle \Rightarrow V_1(p_T,y)$ determined by $\overline{\Delta p_x}(p_T,y)$

Assumptions 1 no interaction with QGP; 2 $qB_y\tau_B \ll E_p \Rightarrow$pertubation

$$\overline{\Delta p}_x(p_T,y_z) = \int_{t_0}^{\infty} dt \int dx_0 dy_0\, \rho^a(x_0,y_0) \int \frac{d\phi}{2\pi}$$
$$q\left[\tanh y_z\, B(t,y_z) + \int_0^{y_z} d\eta\, B'(t,\eta)\frac{t}{\cosh\eta}\right]$$
$$\rho_B\left[x_0 + \frac{p_T\cos\phi}{m_T\cosh y_z}(t-t_0), y_0 + \frac{p_T\sin\phi}{m_T\cosh y_z}(t-t_0)\right]$$

$$\Rightarrow \overline{\Delta p}_x(p_T,y_z) \propto q\int_0^{y_z}\frac{d\eta}{\cosh\eta}\left[\tau_2 B(\tau_2)-\tau_1 B(\tau_1)\right]$$

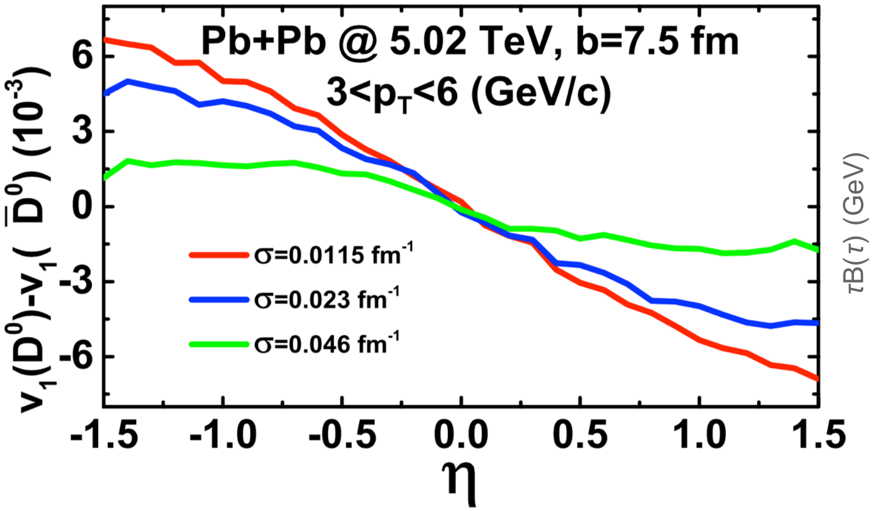
$$\tau_1 = \frac{\tau_0\cosh y_z}{\cosh\eta} \text{ and } \tau_2 = \frac{(\tau_0+Rm_T/p_T)\cosh y_z}{\cosh\eta}$$

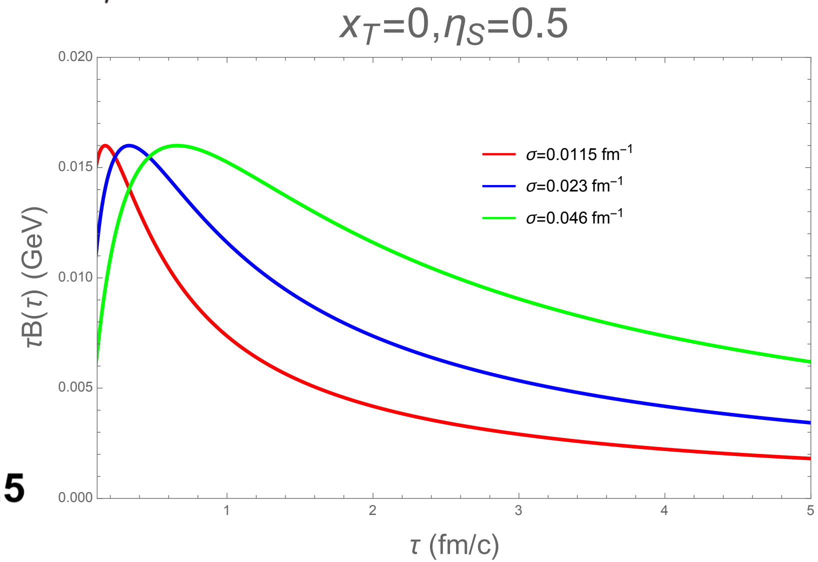
Production time Typical time of leaving EM or freezeout

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

Comparisons

$$\overline{\Delta p}_x(p_T, y_z) \propto q \int_0^{y_z} \frac{d\eta}{\cosh\eta} \left[\tau_2 B(\tau_2) - \tau_1 B(\tau_1)\right]$$





- **Left is v_1 splitting with full c quark evolution in QGP and EM solved from full Maxwell equation; Right is the τB starting from c quark production.**
- **Large correlation between $d\Delta v_1/dy$ and the difference of final and initial τB.**

Simulations

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

- $\boldsymbol{B_y(\tau=0) = B_y(t=0)}$ **in vacuum**

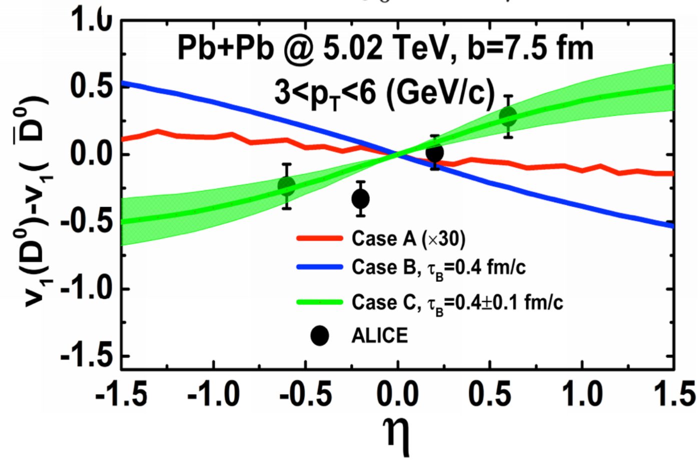
$$\rho_B(x,y) = \exp[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}]$$

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

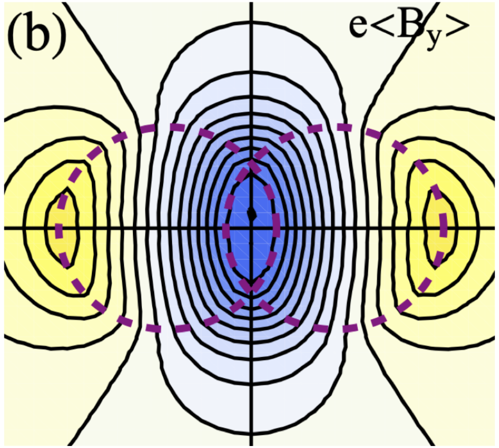
Case C: $B(\tau) = eB_0/(1+\tau/\tau_B)$

eB$_0$~70m_π^2 at 5 TeV

$$\overline{\Delta p}_x(p_T, y_z) \propto q \int_0^{y_z} \frac{d\eta}{\cosh\eta} [\tau_2 B(\tau_2) - \tau_1 B(\tau_1)]$$



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

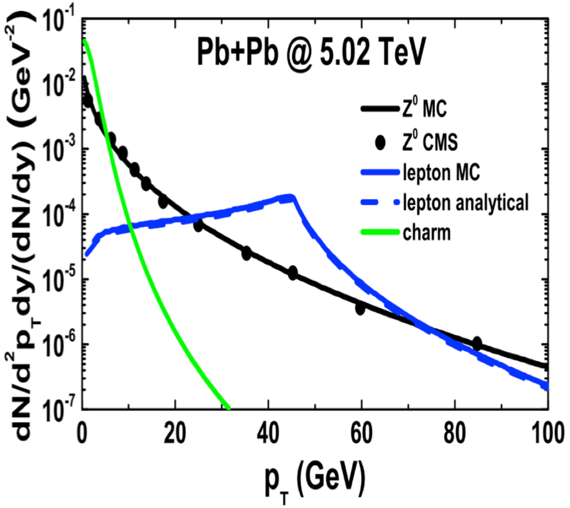


W.T. Deng et al., PRC **85** (2012), 044907

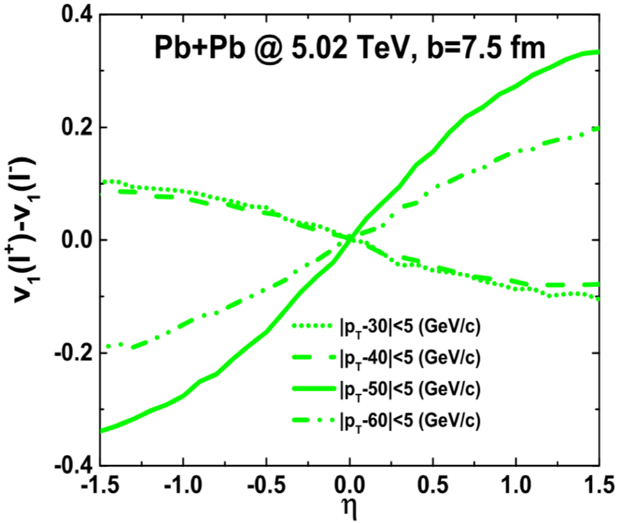
- **case B opposite to Case C and experiments.**
- **If originated from EM fields only, B$_y$ decreases like case C and τ_B~0.3-0.5 fm/c. Strong and decay slowly??**

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.**
- **$\tau_{decay}(Z^0)=\tau_{form}(charm)=0.08fm/c$: go through the e.m. fields at the same time → meaningful look at the correlation $\Delta v_1(D^0, \overline{D^0})$ and $\Delta v_1(l^+,l^-)$.**



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

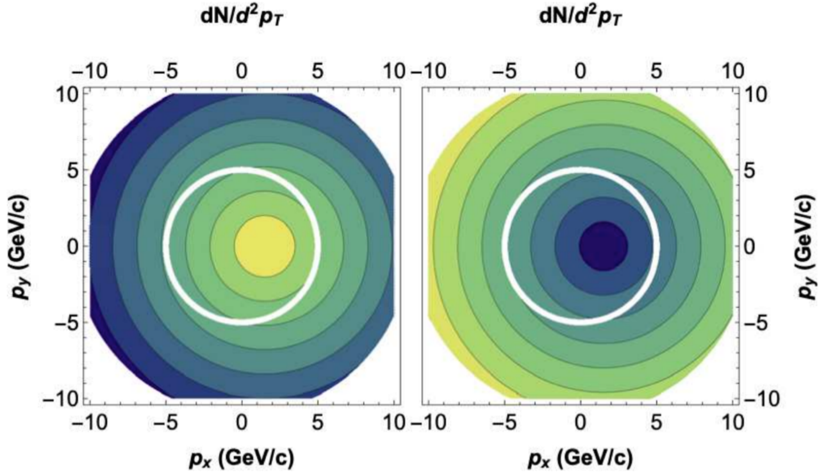


Y.F. Sun et al., arXiv: 2004.09880

- **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**

A feature of EM inducing v_1 splitting

Left: decreases with p_T; Right: increases with p_T



A shift in positive p_x due to EM field

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

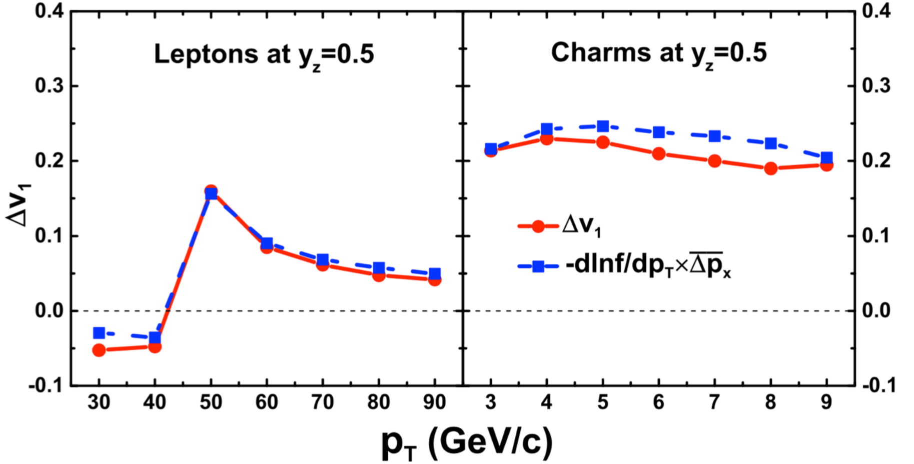
Y.F. Sun et al., arXiv: 2004.09880

- **$d\Delta V_1/d\eta(p_T)$ depends on both $\overline{\Delta p_x}$ and the spectra of charged particles.**

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

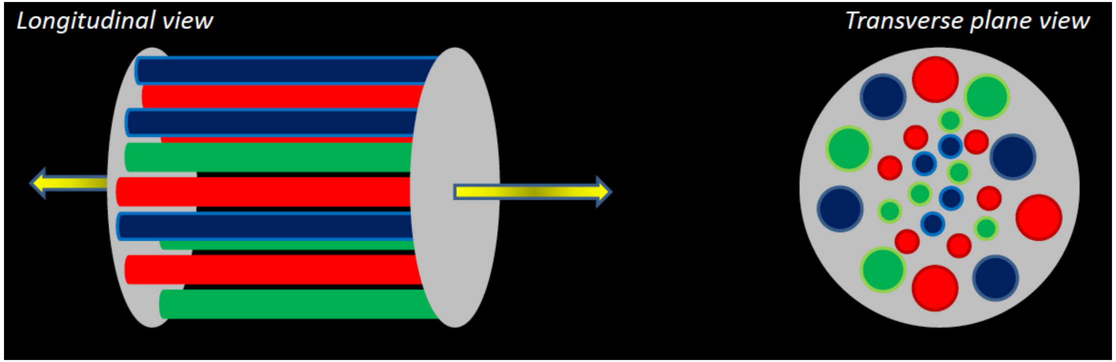
Unique feature

$$\begin{aligned}\frac{dN}{dp_x dp_y} &= \int dp_{xi} d\Delta_x f_a\left(\sqrt{p_{xi}^2+p_y^2}\right)\rho(\Delta_x)\delta\left(p_x - p_{xi}+\Delta_x\right)\\ &\approx \int d\Delta_x \left(f_a(p_T) - \frac{\partial f_a}{\partial p_T}\frac{\Delta_x p_x}{p_T}\right)\rho(\Delta_x)\\ &= f_a(p_T) - \overline{\Delta p}_x(p_T,y)\frac{\partial f_a}{\partial p_T}\frac{p_x}{p_T}, \qquad (10)\end{aligned}$$



$\overline{\Delta p_x}$~0.3 GeV for charms, 0.7 GeV for leptons

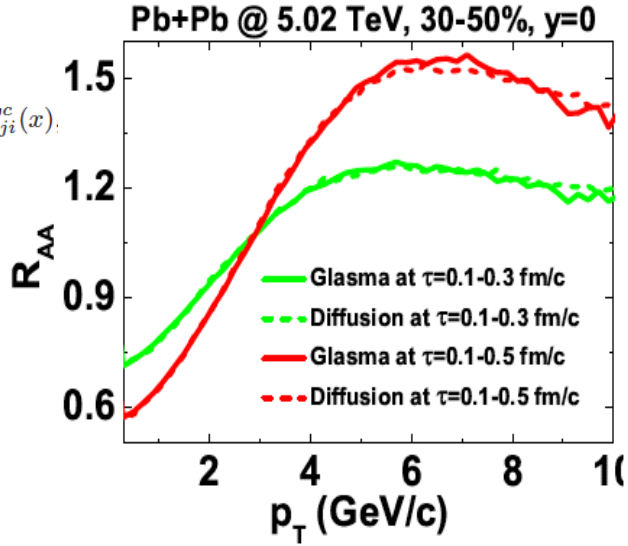
HF dynamics in Glasma

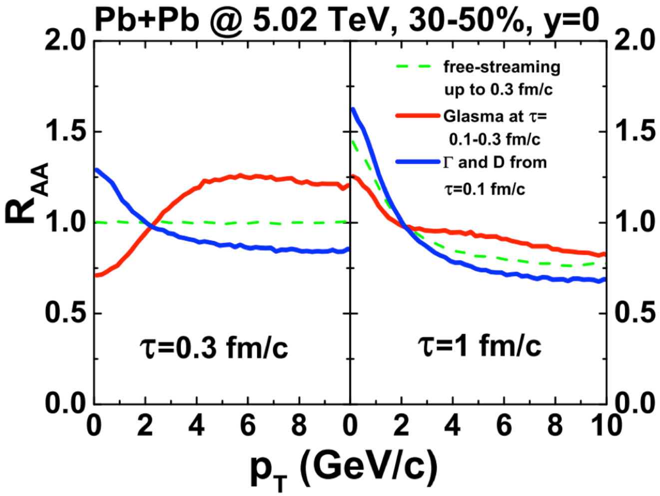


HF dynamics in Glasma

$$\frac{dA_i^a(x)}{dt} = E_i^a(x),$$
$$\frac{dE_i^a(x)}{dt} = \sum_j \partial_j F_{ji}^a(x) + \sum_{b,c,j} f^{abc} A_j^b(x) F_{ji}^c(x),$$

$$\frac{dx_i}{dt} = \frac{p_i}{E},$$
$$E\frac{dp_i}{dt} = Q_a F_{i\nu}^a p^\nu,$$
$$E\frac{dQ_a}{dt} = -Q_c \varepsilon^{cba} A_b \cdot p,$$





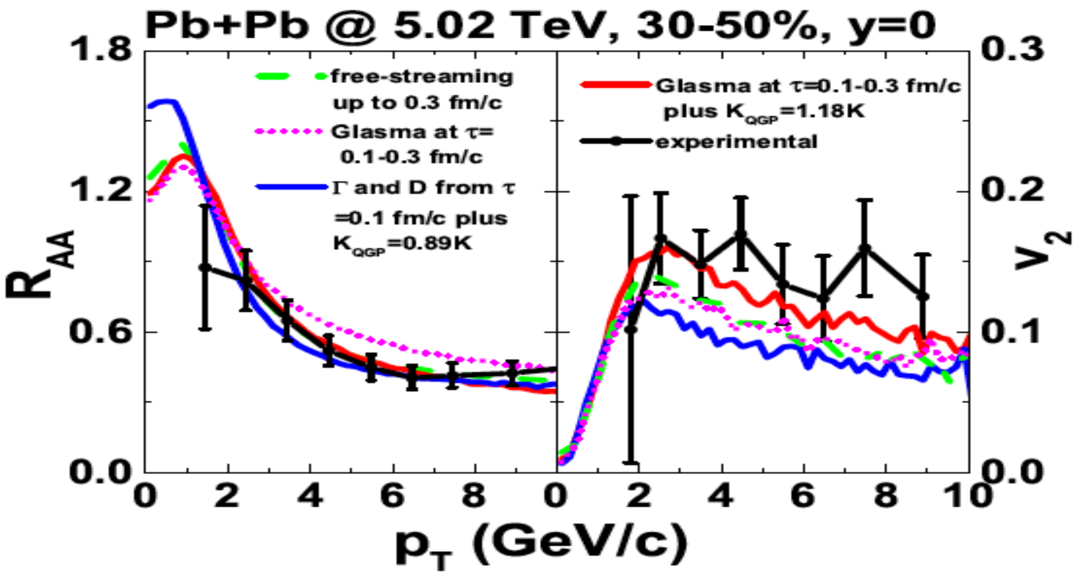
M. Ruggieri et al., PRD **98** (2018), 094024
Y. Sun et al., PLB **798** (2019) 134933

- ✧ **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

$$R_{AA}(p_t;b) = \frac{\mathrm{d}N_{\mathrm{Q}}^{AA}(b)/\mathrm{d}p_t}{N_{\mathrm{coll}}(b)\ \mathrm{d}N_{Q}^{pp}/\mathrm{d}p_t}$$

$$v_2(p_t;b) = \frac{\int \mathrm{d}\phi \frac{\mathrm{d}N_{\mathrm{Q}}^{AA}(b)}{\mathrm{d}p_t \mathrm{d}y \mathrm{d}\phi} \cos(2\phi)}{\int \mathrm{d}\phi \frac{\mathrm{d}N_{\mathrm{Q}}^{AA}(b)}{\mathrm{d}p_t \mathrm{d}y \mathrm{d}\phi}}$$



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

✧ **Enhancement of $R_{AA}(p_T)$ with same interaction strength.**

✧ **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 $\overline{\Delta p_x}$ 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!