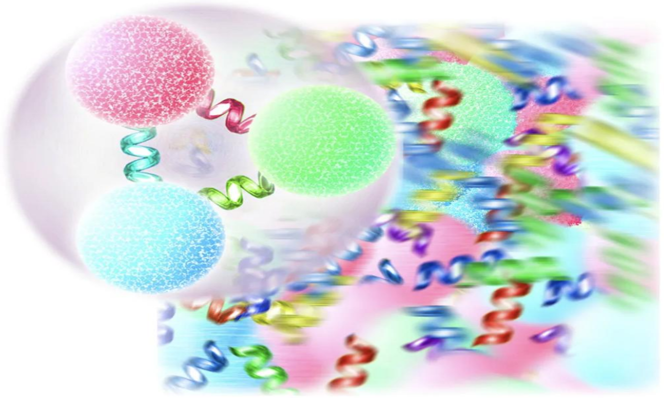
上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

INPAC INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

The Strong Fields in Relativistic Heavy Ion Collisions

Yifeng Sun, SJTU

USTC Hefei, 2024/04/14



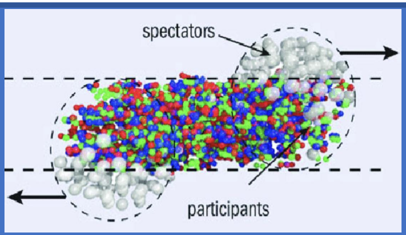
The 2nd Workshop on Ultra-Peripheral Collision Physics

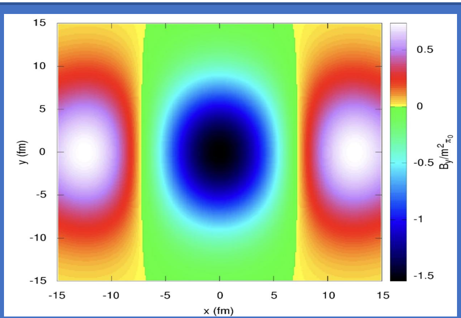
Outline

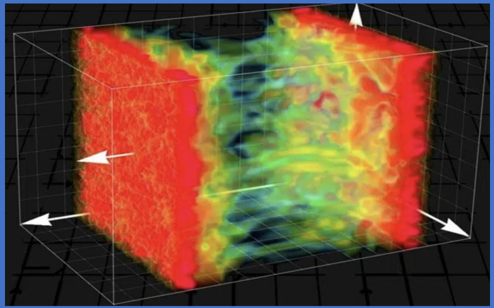
I. Strong fields in RHICs

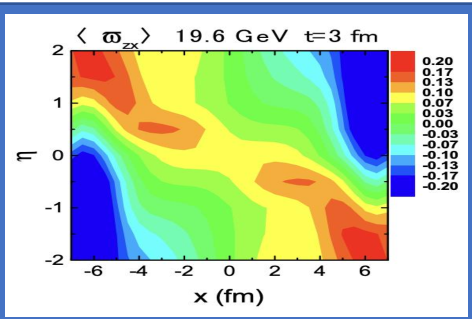
1. Strong magnetic, chromo-electromagnetic and vorticity fields are (may be) generated in RHICs

Deng, Huang, PRC 85 (2012), 044907
Mclerran, Venugopalan, PRD 49 (1994), 2233
Jiang, Lin, Liao, PRC 94 (2016), 044910





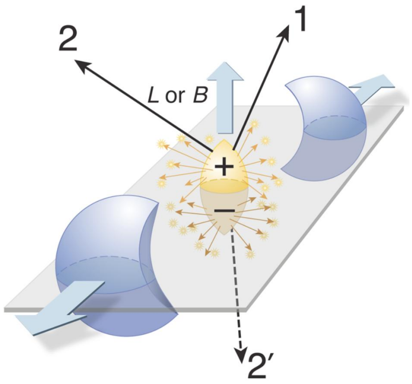




$$\partial_\mu F^{\mu\nu} = \mu_0 J^\nu \qquad \partial^\mu F^a_{\mu\nu} + g\, f^{abc}\, A^{b\mu}\, F^c_{\mu\nu} = -J^a_\nu \qquad \boldsymbol{\omega} = (1/2)\boldsymbol{\nabla} \times \boldsymbol{v}$$

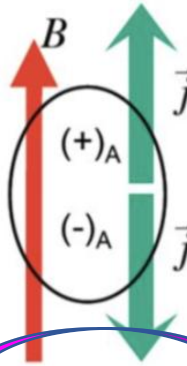
II. CME and CMW

Chiral Magnetic Effect



$$\vec{j}_V = \frac{N_c\, e}{2\pi^2}\mu_A \vec{B}$$

Chiral Magnetic Wave



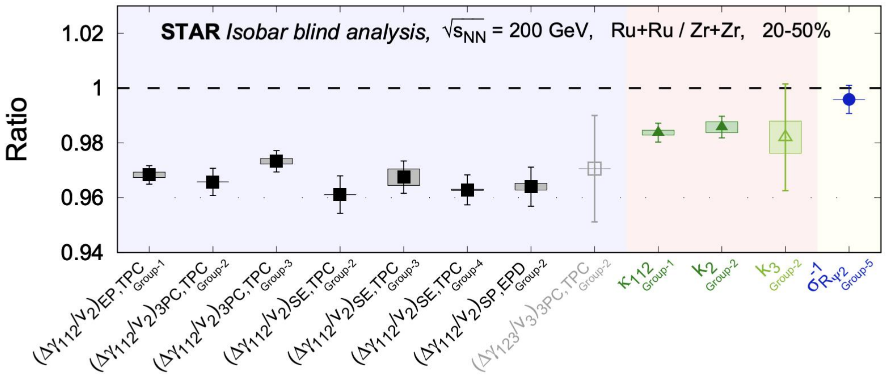
$$\vec{j}_A = \frac{N_c\, e}{2\pi^2}\mu_V \vec{B} \quad \vec{j}_V = \frac{N_c\, e}{2\pi^2}\mu_A \vec{B}$$

1. CME can probe P and CP violations in QCD
2. CMW can explore chiral symmetry restoration and deconfinement phase transition in "Little Bang"

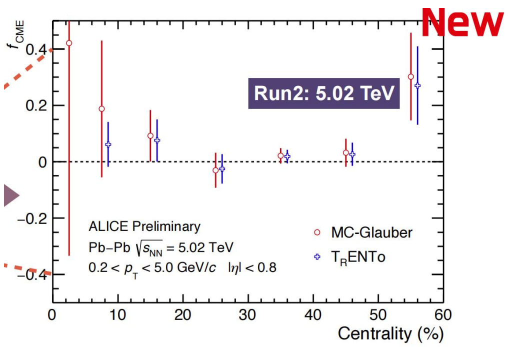
Kharzeev, PLB 633 (2006), 260
Fukushima, Kharzeev, Warringa, PRD 78 (2008), 074033
Kharzeev, Yee, PRD 83 (2011), 085007

II. Challenges in detection

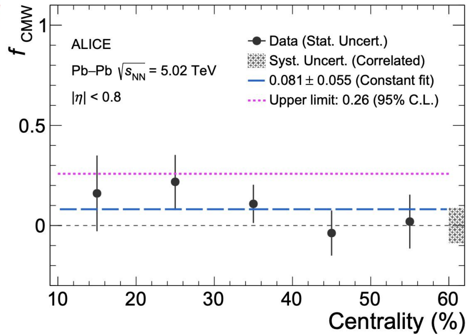
STAR, PRC 105 (2022), 014901



Wang, QM2023

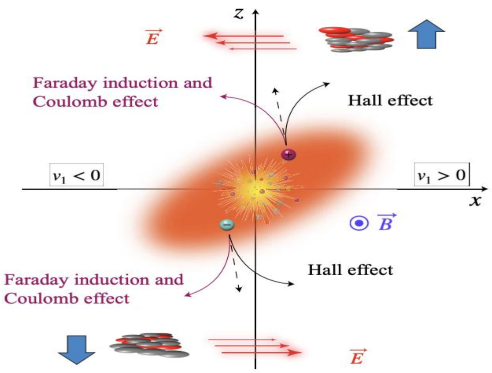


ALICE, arXiv:2308.16123



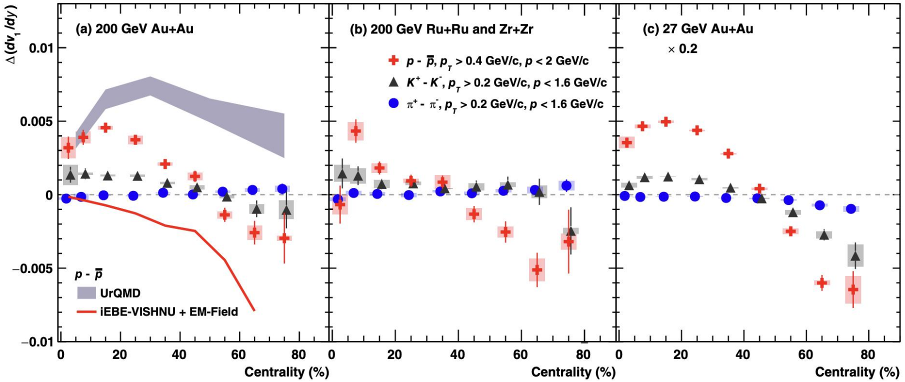
1. No definitive signs of CME and CMW detected by RHIC and LHC; Background dominates
2. Or may be **CP violation probability low** or **magnetic field weak**
3. Signal depends on CP violation and B quadratically

II. Possible signals of B

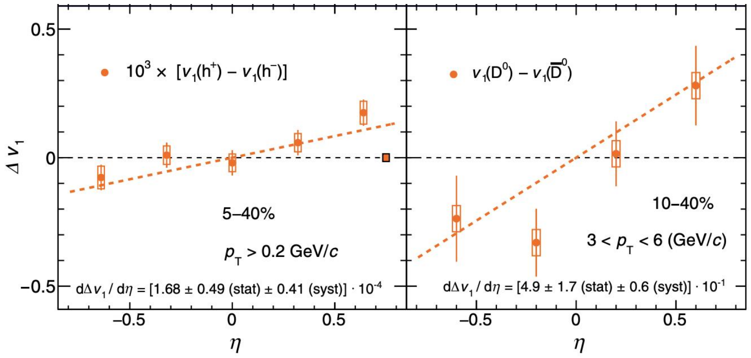


$$\boldsymbol{F}_{ext} = qE + \frac{q}{E_p}(\boldsymbol{p} \times \boldsymbol{B})$$

STAR, PRX 14 (2024), 011028



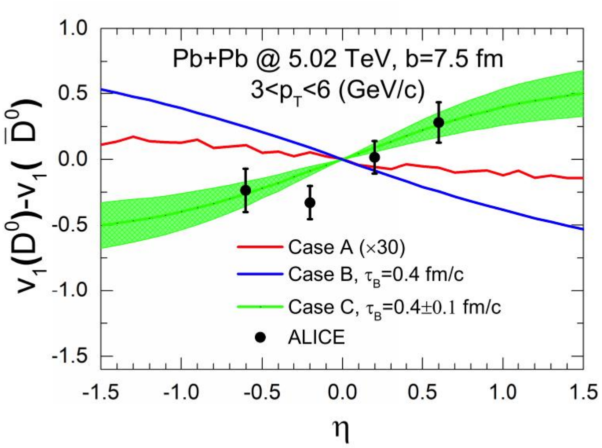
ALICE, PRL 125 (2020), 022301

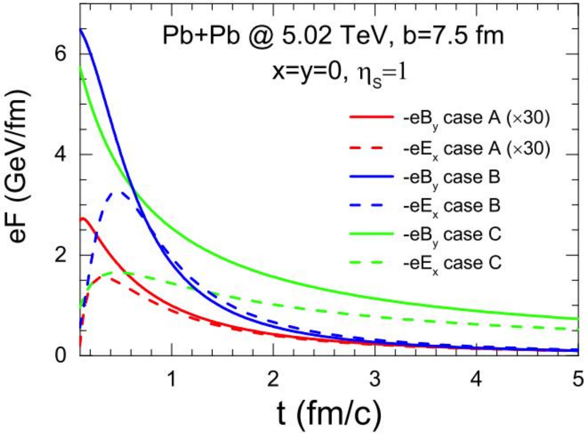


1. The effect of B may be seen by RHIC and LHC by **directed flow measurement, though different in sign**

II. Implication by D meson v_1 measurement

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





Case B and C

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

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

- ✓ eB_0 fixed by the value t=0 in vaccum; a and τ_B can be tuned
- ✓ E_x is evaluated by the Faraday's Law

1. If charge neutral D^0 meson v_1 splitting is due to e.m. field, it is the **first direct evidence of free quarks in QGP**
2. ALICE data can only be reproduced by **a very slowly decaying B**
3. **The form matters**

II. General study

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

$$
\begin{aligned}
f'(\mathbf{p}_T, y_z) &= \int d^2\Delta p_T d\Delta y_z f(\mathbf{p}_T - \Delta\mathbf{p}_T, y_z - \Delta y_z) \\
&\times T(\Delta\mathbf{p}_T, \Delta y_z, \mathbf{p}_T - \Delta\mathbf{p}_T, y_z - \Delta y_z) \\
&\approx \int d^2\Delta p_T d\Delta y_z [f(\mathbf{p}_T, y_z) T(\Delta\mathbf{p}_T, \Delta y_z, \mathbf{p}_T, y_z) \\
&- \frac{\partial fT}{\partial p_x}\Delta p_x - \frac{\partial fT}{\partial p_y}\Delta p_y - \frac{\partial fT}{\partial y_z}\Delta y_z] \\
&= f - (\frac{\partial f\overline{\Delta p_x}}{\partial p_x} + \frac{\partial f\overline{\Delta p_y}}{\partial p_y} + f\frac{\partial \overline{\Delta y_z}}{\partial y_z}), \qquad (1)
\end{aligned}
$$

$$
\begin{aligned}
\overline{\Delta y_z} &= -\frac{p_T \tanh y_z}{m_T^2}(\cos\phi\overline{\Delta p_x} + \sin\phi\overline{\Delta p_y}) \\
&+ \frac{\overline{\Delta p_z}}{m_T \cosh y_z},
\end{aligned}
$$

$$
\begin{aligned}
\overline{\Delta p_x} &= q\int dt(E_x - v_z B_y), \\
\overline{\Delta p_y} &= q\int dt(E_y + v_z B_x), \\
\overline{\Delta p_z} &= q\int dt(E_z + v_x B_y - v_y B_x)
\end{aligned}
$$

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

$$
\begin{aligned}
f' &= f - \{\frac{\partial f(a_1+b_1)}{\partial p_T} + f(-\frac{p_T}{m_T^2}\frac{\partial(a_1+b_1)\tanh y_z}{\partial y_z} \\
&+ \frac{a_1+b_1}{p_T} + \frac{2}{m_T}\frac{\partial c_0/\cosh y_z}{\partial y_z})\} \\
&- \{-f\frac{p_T}{m_T^2}\frac{\partial(a_0+b_0)\tanh y_z}{\partial y_z} + \frac{\partial(a_0+b_0)f}{\partial p_T}\}\cos\phi \\
&- \sum_{n=1}\{\frac{\partial f(a_{n+1}+b_{n+1}+a_{n-1}-b_{n-1})}{\partial p_T} \\
&+ f[\frac{(n+1)(a_{n+1}+b_{n+1})-(n-1)(a_{n-1}-b_{n-1})}{p_T} \\
&- \frac{p_T}{m_T^2}\frac{\partial\tanh y_z(a_{n+1}+b_{n+1}+a_{n-1}-b_{n-1})}{\partial y_z} \\
&+ \frac{2}{m_T}\frac{\partial c_n/\cosh y_z}{\partial y_z}]\}\cos n\phi. \qquad (7)
\end{aligned}
$$

1. Charge-dependent f and v_n can qualify the 3D distribution of e.m. field
2. Lorentz force in z direction can generate v_n
3. At high p_T $\quad f' = f - \sum_{n=0}(d_n\frac{\partial f}{\partial p_T} + e_n\frac{f}{p_T})\cos n\phi \quad (p_T \gg m)$

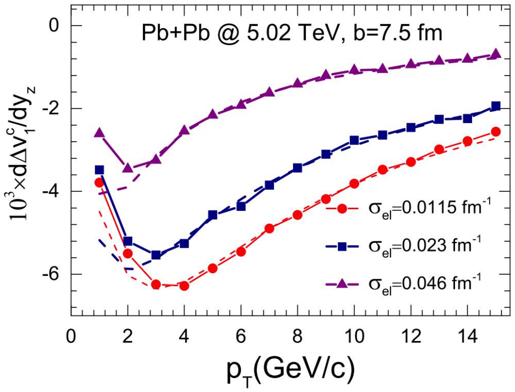
II. Directed flow

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

$$v_1 = \frac{p_T}{m_T^2}\frac{\partial}{\partial y_z}[(a_0+\frac{1}{2}(a_2+b_2))\tanh y_z] - \frac{1}{m_T}\frac{\partial c_1/\cosh y_z}{\partial y_z} - [a_0+\frac{1}{2}(a_2+b_2)]\frac{\partial \ln f}{\partial p_T} - \frac{(a_2+b_2)}{p_T} \quad (10)$$

$$\frac{d\Delta v_1^c}{dy_z}|_{y_z=0} = \frac{d\Delta a_0}{dy_z}|_{y_z=0}\left(-\frac{\partial \ln f_c}{\partial p_T}+\frac{2p_T}{m_T^2}\right)-\frac{1}{m_T}(\frac{d^2c_1}{dy_z^2}-c_1) = -\alpha\frac{\partial \ln f_c}{\partial p_T}+(2\alpha-\beta)\frac{p_T}{m_T^2}$$

$$\alpha \simeq -|q|K\ [\tau_1 B_y(\tau_1,0)-\tau_0 B_y(\tau_0,0)]$$



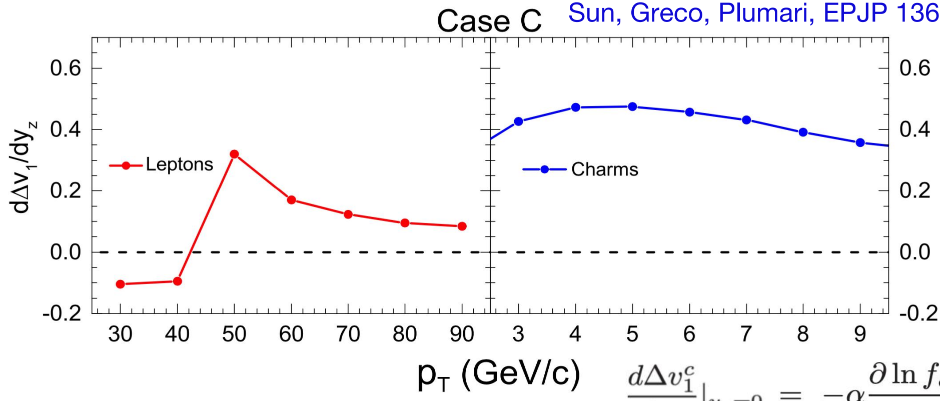
1. Confirmed by **c, b quarks** with **different e.m. fields**
2. Whole behavior mainly determined by B_y at two times, which are distinct by quark flavors

II. Leptons from Z^0 decay

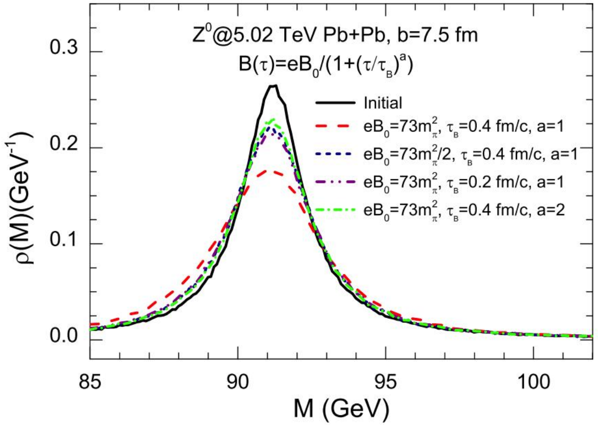
Leptons from Z^0 decay as **a more ideal probe**

1. Clearer observables
2. Separable from other sources

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



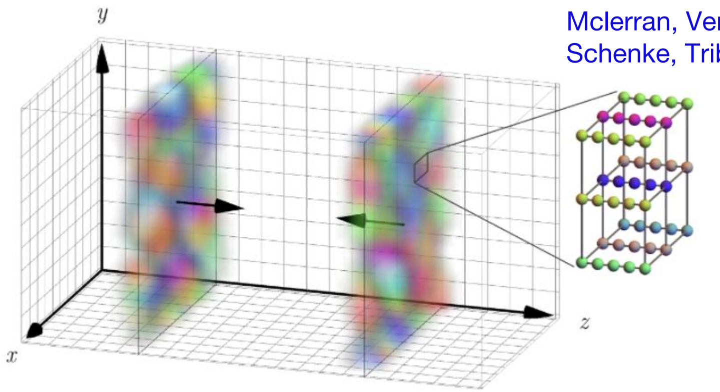
Sun, Greco, Wang, PLB 827 (2022), 136962



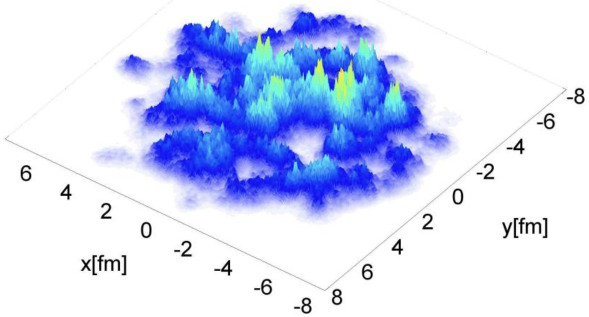
$$\frac{d\Delta v_1^c}{dy_z}|_{y_z=0} = -\alpha\frac{\partial \ln f_c}{\partial p_T} + (2\alpha - \beta)\frac{p_T}{m_T^2}$$

1. The effect on leptons is comparable to charm though significant p_T different
2. Invariant mass measurement can probe e.m. fields, mainly the time accumulation

III. Glasma field



Mclerran, Venugopalan, PRD 49 (1994), 2233
Schenke, Tribedy, Venugopalan, PRC 86 (2012), 034908



Sun et al, PLB 798 (2019), 134933

$$\partial^\mu F^a_{\mu\nu} + g\, f^{abc}\, A^{b\mu}\, F^c_{\mu\nu} = -J^a_\nu$$ Yang-Mills equations

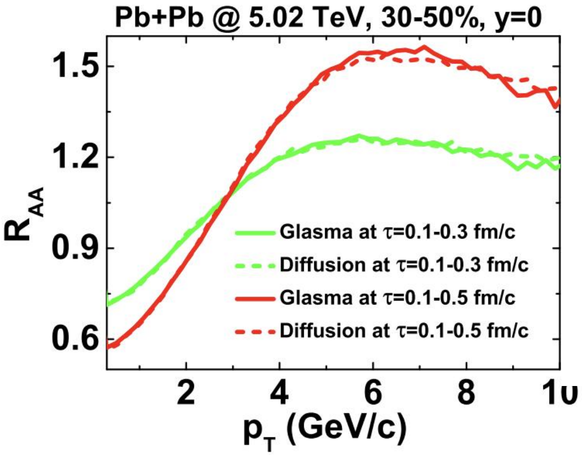
$$\frac{dx_i}{dt} = \frac{p_i}{E},$$
$$E\frac{dp_i}{dt} = Q_a F^a_{i\nu} p^\nu$$
$$E\frac{dQ_a}{dt} = -Q_c \varepsilon^{cba} \boldsymbol{A}_b \cdot \boldsymbol{p}$$

Wong equations

1. CGC is used to generate energy density and n_5
2. We employ the classical equations to model the effect of glasma on charm quarks

III. Momentum broading

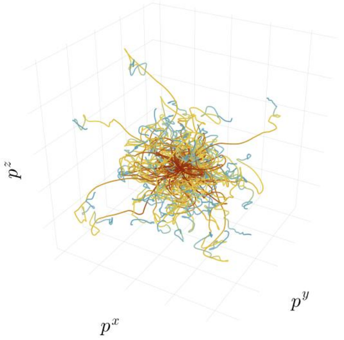
Sun et al, PLB 798 (2019), 134933

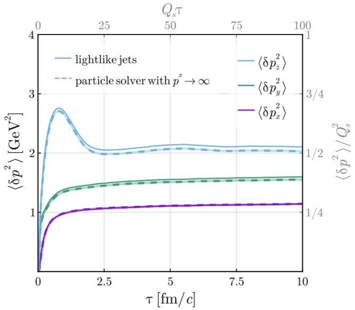


$$dx_i = \frac{p_i}{E} dt,$$

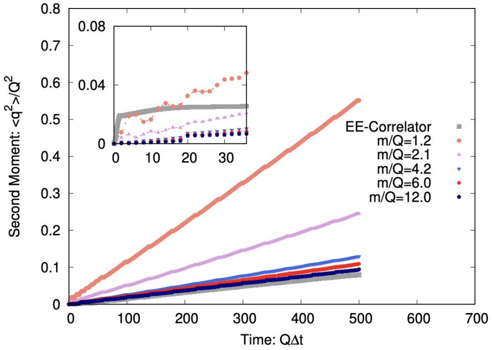
$$dp_i = -\Gamma p_i dt + C_{ij} \rho_j \sqrt{dt},$$

Avramescu et al, PRD 107 (2023), 114021





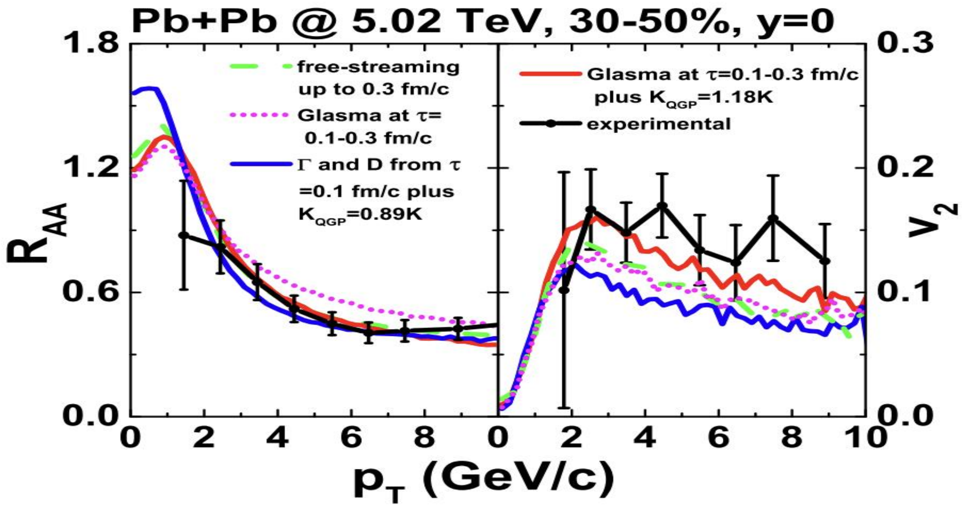
Pandey, Schlichting, Sharma, arXiv:2312.12280



1. The effect of glasma on HQs/jets is similar to the effect of diffusion
2. Quantum and classical simulations are different

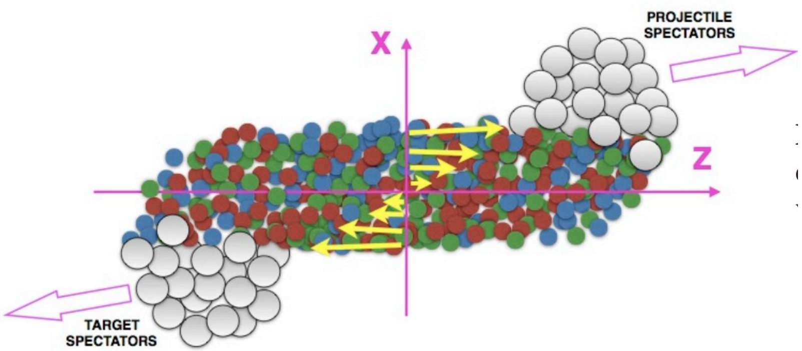
III. Impact in RHICs

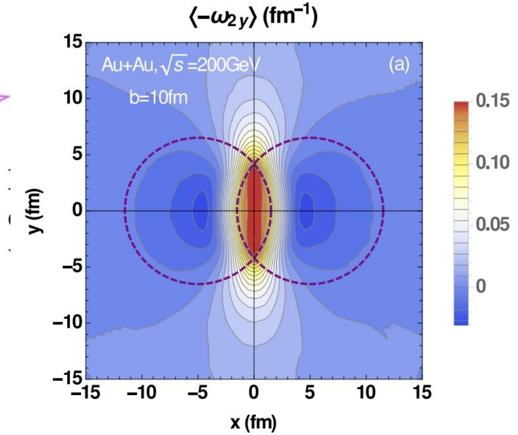
Sun et al, PLB 798 (2019), 134933

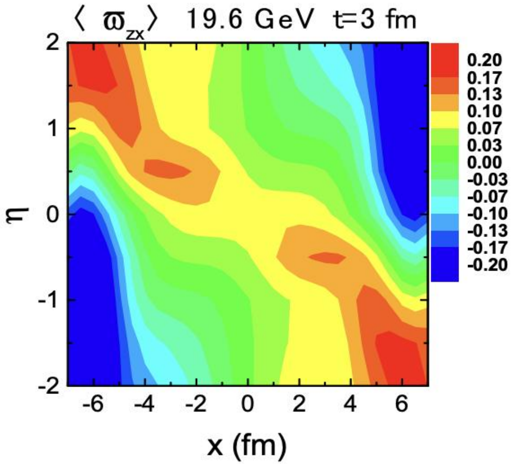


1. Alter the relation between R_{AA} and v_2
2. Should be extended to include jets and pA systems

IV. Vorticity field







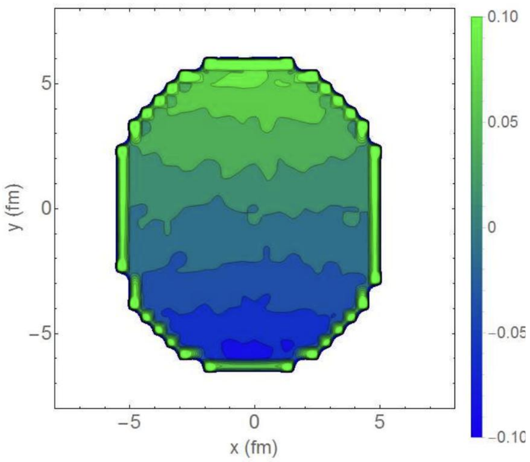
Jiang, Lin, Liao, PRC 94 (2016), 044910
Deng, Huang, PRC 93 (2016), 064907
Wei, Deng, Huang, PRC 99 (2019), 014905

1. A long-lived vorticity
2. Strong spatial dependence and large variation

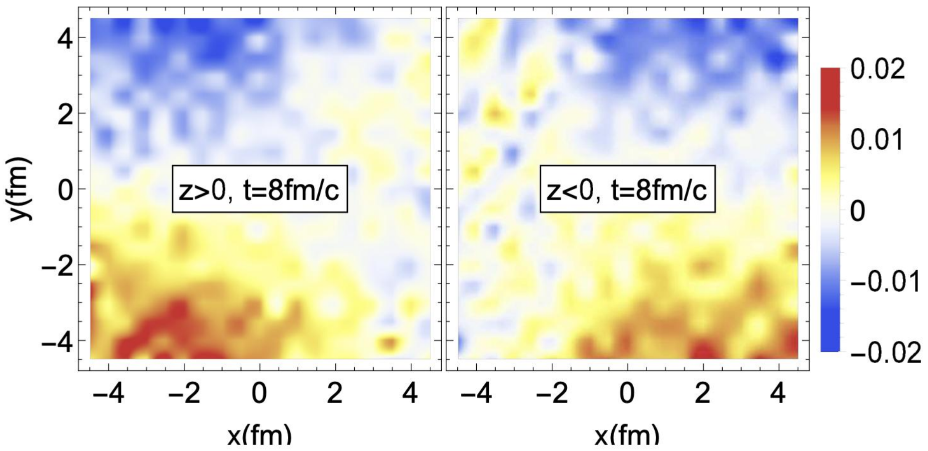
IV. Axial charge of u, d quarks

$$j^5_\mu = \left(\frac{T^2}{6} + \frac{\mu^2}{2\pi^2}\right)\omega_\mu$$

Sun, Ko, PRC 95 (2017), 034909



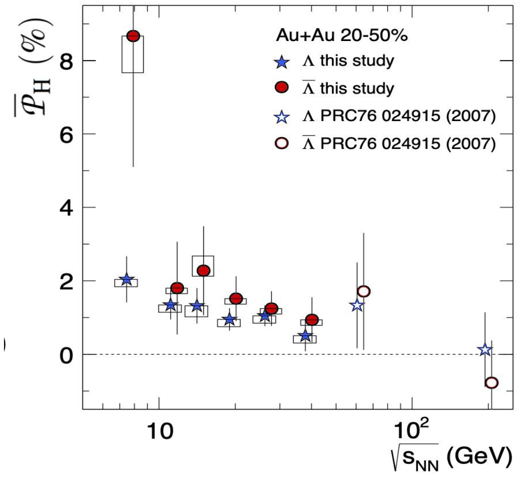
Liu, Sun, Ko, PRL 125 (2020), 062301



1. Chiral kinetic approaches: simulate the evolution
2. The axial charge is redistributed due to axial vorticity effect
3. The detection is crucial to understand chiral symmetry restoration in QGP

IV. Spin polarization

STAR, Nature 548 (2017)



$$S^\mu(x,p) = -\frac{s(s+1)}{6m}(1-n_F)\epsilon^{\mu\nu\rho\sigma}p_\nu\varpi_{\rho\sigma}(x)$$

Becattini et al., AP 338 (2013)

Is spin DOE thermalized?

$$j^5_\mu = \left(\frac{T^2}{6}+\frac{\mu^2}{2\pi^2}\right)\omega_\mu$$

Spin polarization vector

$$\frac{dN_\Lambda}{d^3\mathbf{P}_\Lambda} = g_C g_S \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1) f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3) \times W_\Lambda(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2)\delta^{(3)}(\mathbf{P}_\Lambda-\mathbf{p}_1-\mathbf{p}_2-\mathbf{p}_3)$$

$$g_S = \frac{1}{4}(1-\lambda_1\lambda_2\hat{\mathbf{p}}_1\cdot\hat{\mathbf{p}}_2)$$

Spin Coalescence

Sun, Ko, PRC 96 (2017), 024906

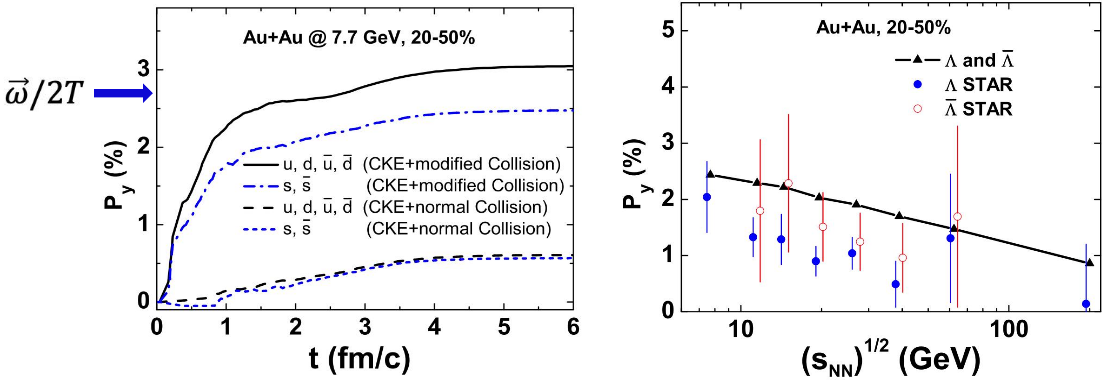
1. Spin relaxation time is longer
2. Spin polarization by chiral kinetic approaches+spin coalescence

IV. Spin polarization by CKT

$$\frac{\partial F_A}{\partial t} + \nabla_x \cdot (\frac{d\mathbf{x}}{dt} F_A) + \nabla_p \cdot (\frac{d\mathbf{p}}{dt} F_A) = -\frac{1}{E_A} \int_{BCD} |\mathcal{M}|^2 (2\pi)^4 \delta(p_A + p_B - p_C - p_D)(F_A F_B \sqrt{G_C G_D} - F_C F_D \sqrt{G_A G_B})$$

$$\frac{d\mathbf{x}}{dt} = \frac{\hat{\mathbf{p}} + \lambda \frac{\boldsymbol{\omega}}{|\mathbf{p}|}}{1 + a\lambda |\mathbf{p}|(\mathbf{b}\cdot\boldsymbol{\omega})}, \quad \frac{d\mathbf{p}}{dt} = 0$$

Sun, Ko, PRC 96 (2017), 024906



1. CKT can describe global spin polarization

IV. Covariant CKT

How to incorporate vorticity self-consistently?

$$J^{\mu\nu}_A + J^{\mu\nu}_B = J^{\mu\nu}_C + J^{\mu\nu}_D$$
$$J^{\mu\nu} \equiv x^\mu p^\nu - x^\nu p^\mu + S^{\mu\nu}$$
$$S^{\mu\nu} \equiv \lambda \frac{\epsilon^{\mu\nu\rho\sigma} p_\rho n_\sigma}{np}$$
$$n \equiv (1, \mathbf{0})$$
$$\lambda = \pm \frac{1}{2}$$

$$\dot{\boldsymbol{x}} = \hat{\boldsymbol{p}} + \dot{\boldsymbol{p}} \times \boldsymbol{b};$$
$$\dot{\boldsymbol{p}} = \boldsymbol{E} + \dot{\boldsymbol{x}} \times \boldsymbol{B}.$$
$$\boldsymbol{b} = \frac{\hat{\boldsymbol{p}}}{2|\boldsymbol{p}|^2}$$

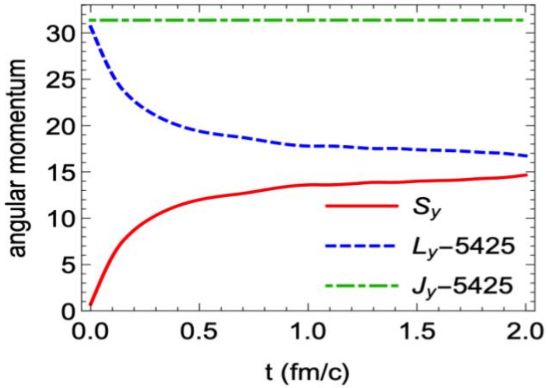
Stephanov, Yin, PRL 109 (2012), 162001

$$\frac{d\mathbf{J}}{dt} = \frac{d\left(\mathbf{r}\times\mathbf{p} \pm \frac{\hat{\mathbf{p}}}{2}\right)}{dt} = \frac{d\mathbf{r}}{dt}\times\mathbf{p} + \mathbf{r}\times\frac{d\mathbf{p}}{dt} \pm \left[\frac{\dot{\mathbf{p}}}{2p} - \mathbf{p}\left(\frac{\mathbf{p}}{2p^3}\cdot\dot{\mathbf{p}}\right)\right] = \left(\dot{\mathbf{r}} \mp \dot{\mathbf{p}}\times\frac{\mathbf{p}}{2p^3}\right)\times\mathbf{p} + \mathbf{r}\times\mathbf{F},$$

Sun, Ko, Li, PRC 94 (2016), 045204

Liu, Sun, Ko, PRL 125 (2020), 062301

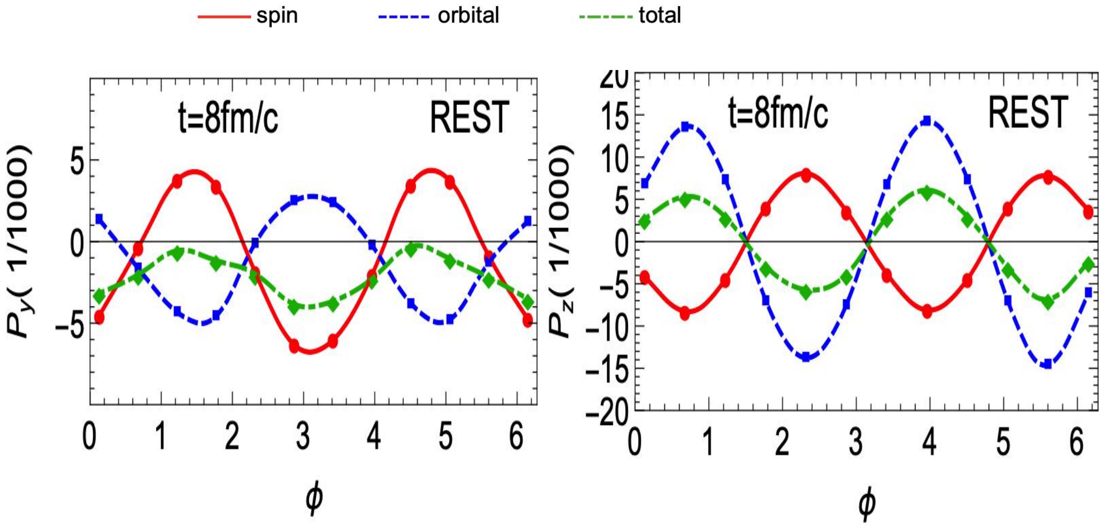
For massless particle, one can not conserve spin and orbital angular momentum separately; introduce nonlocal collision



IV. Covariant CKT

$$j_5^\mu(x,p) \;=\; \lambda(p^\mu + S^{\mu\nu}\partial_\nu)f(x,p)$$

Liu, Sun, Ko, PRL 125 (2020), 062301



1. Covariant CKT describes local polarization

Summary

1. The strong fields in RHICs generate many interesting phenomena, and help to understand QCD; Need experimental work
2. Remaining questions
   1. Quantatively explain experiment data on v_1
   2. Spin transport of massive particles in QGP and hadron gas phase
   3. Pusedogauge transformation
   4. Spin alignment of J/Psi

Thanks!