

利用轻味和重味强子直接流研究 QGP的纵向倾斜与电磁场

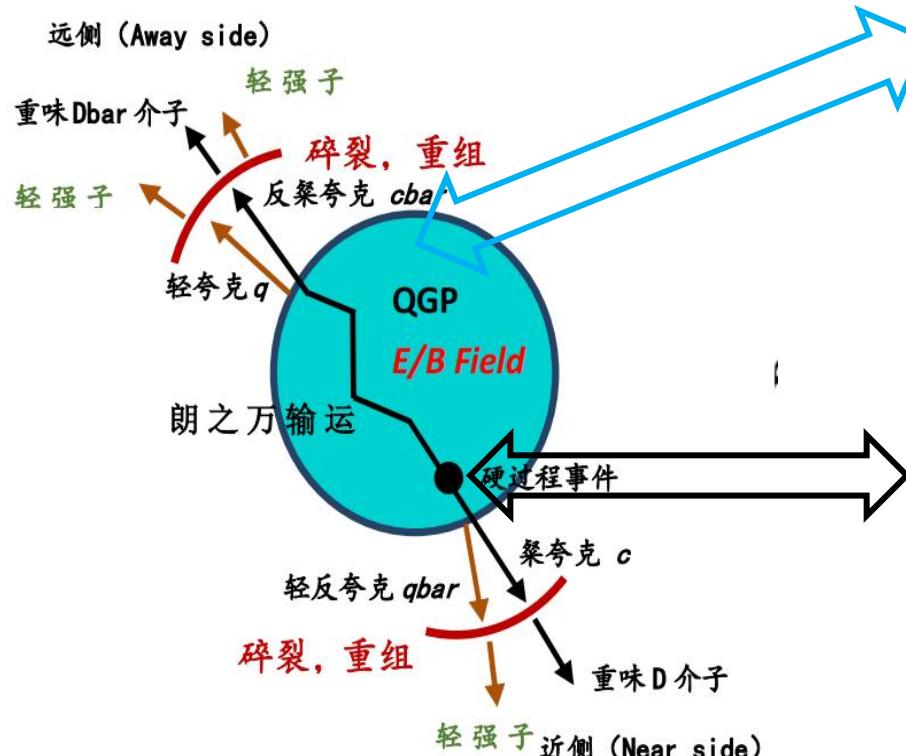
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中国物理学会高能物理分会第十一届会员代表大会暨学术年会
2022年 8月 9 日

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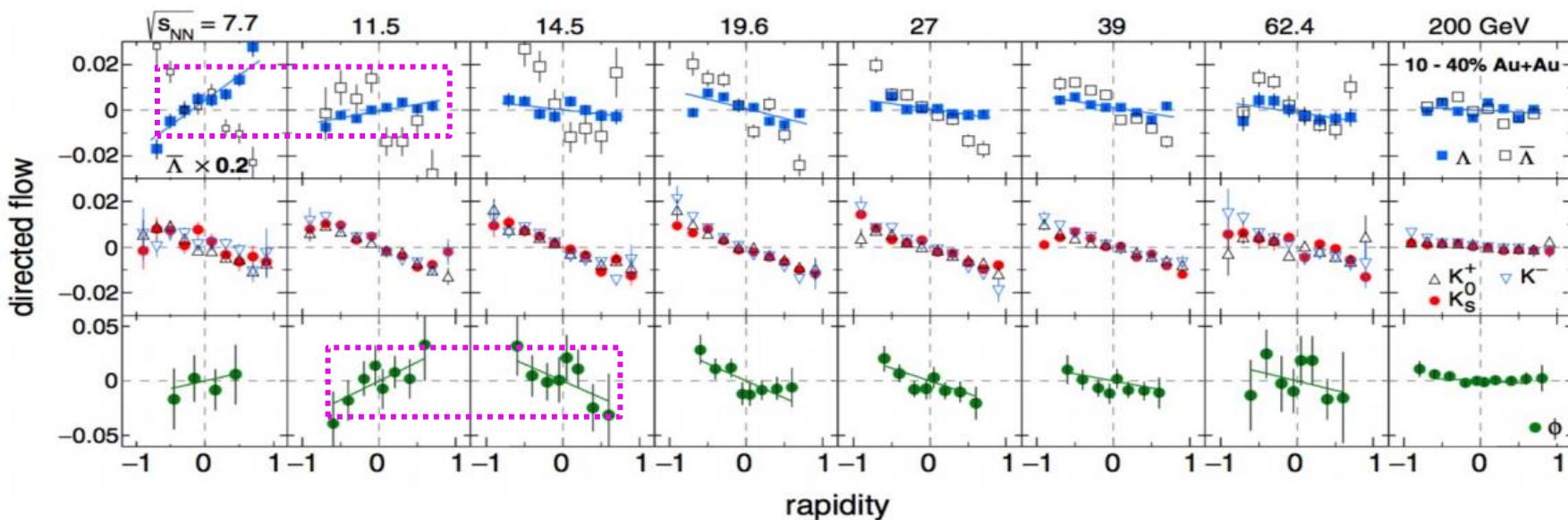
Phys. Rev. C 104, 064903 (2021), Phys. Rev. C 105, 034901 (2022),
Phys. Rev. C 105, 054907 (2022).

1. 直接流简介 @ BES

直接流(Directed flow, 定向流)描述粒子沿 $\textcolor{red}{x}$ 方向的集体偏转:

$$v_1 = \langle p_x / p_T \rangle$$

轻强子直接流 v_1



- Mesons and all anti-baryons show negative slope except ϕ mesons when collisions energy < 14.5 GeV

Change of medium property? High precision data needed: BESII

1. 直流简介@Isobar collisions

直流(Directed flow, 定向流)描述粒子沿 x 方向的集体偏转:

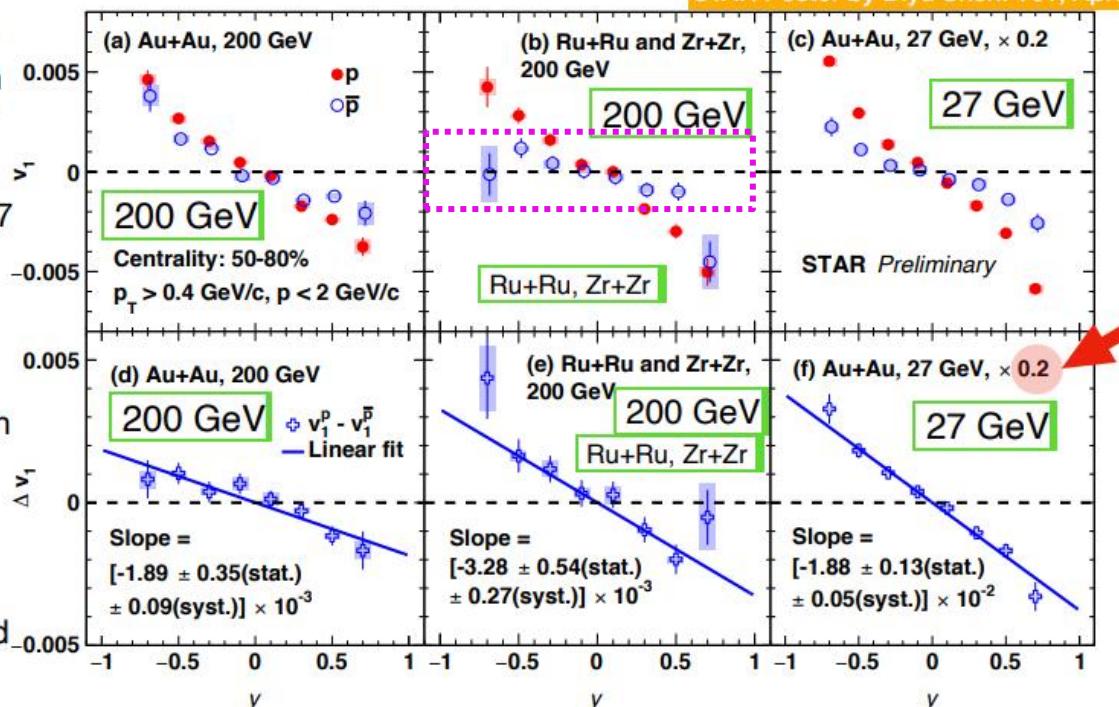
$$v_1 = \langle p_x / p_T \rangle$$

轻强子直流 v_1

Splitting between proton and anti-proton in 50-80% centrality

STAR Poster by Diyu Shen: T01, Apr7

- Splitting shown so far based on species with produced quarks only
- v_1 and Δv_1 for p and \bar{p} are shown in Au+Au 27 GeV, 200 GeV and Ru+Ru, Zr+Zr at 200 GeV collisions
- $\Delta v_1/dy$ between p and \bar{p} is negative, with $>5\sigma$ significance
- $\Delta v_1/dy$ is much (~factor 5) stronger at 27 GeV - Longer persistence of EM field at lower energy?



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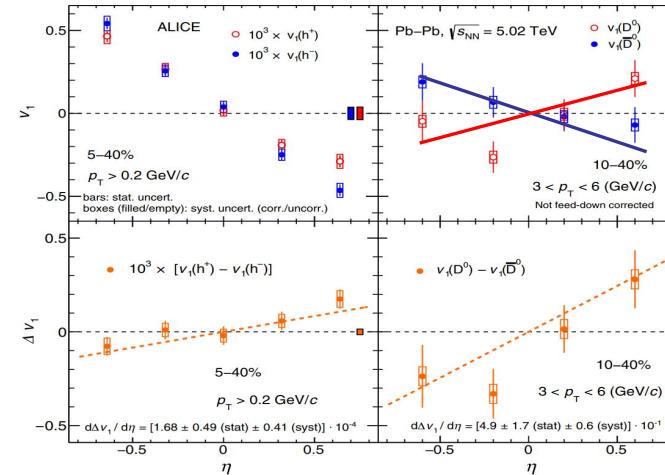
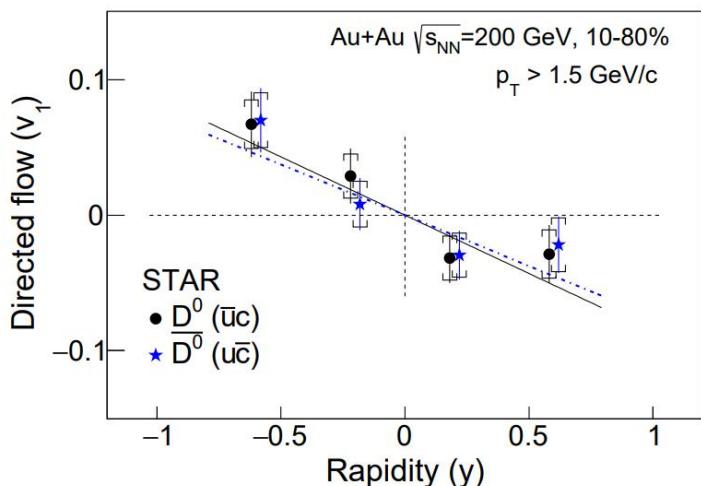
Quark Matter 2022 4

1. 直接流简介: D介子 v_1 反常劈裂

直接流(Directed flow, 定向流)描述粒子沿 $\textcolor{red}{x}$ 方向的集体偏转:

$$v_1 = \langle p_x / p_T \rangle$$

实验上的重味强子直接流 v_1



D^0 和 \bar{D}^0 直接流分布的斜率 dv_1/dy 符号相同

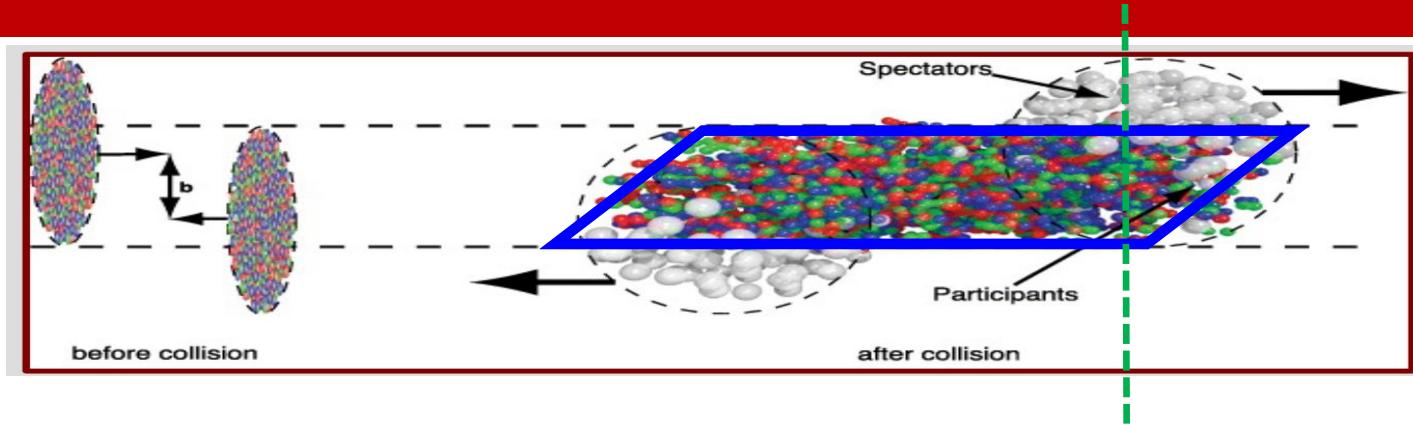
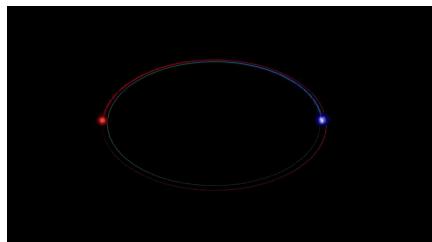
D^0 和 \bar{D}^0 直接流分布的斜率 dv_1/dy 符号相反

STAR Collaboration,
Phys. Rev. Lett. 123, 162301 (2019)

ALICE Collaboration,
Phys. Rev. Lett., 125(2):022301, (2020).

2. 介质纵向倾斜与轻强子直接流

2. 构建QGP的纵向倾斜结构



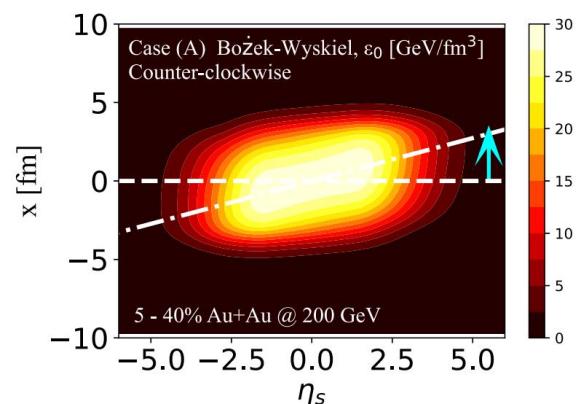
倾斜来源: 1. 向前核(射弹)和向后核(靶核)的参与子密度不对称; 2. 核阻止效应;
3. 其它可能的物理贡献。

为了研究介质纵向倾斜对轻强子直接流的影响, 我们在Optical Glauber模型基础上, 构建了 **P. Bozek et al., CCNU and Shen & Sahr** 三种因子化的纵向倾斜结构。

Case A. Bozek-Wyskiel parametrization:

$$W_N(x, y, \eta_s) = 2(T_1(x, y)f_-(\eta_s) + T_2(x, y)f_+(\eta_s))$$

$$f_-(\eta_s) = \begin{cases} 1 & \eta_s < -\eta_m \\ \frac{-\eta_s + \eta_m}{2\eta_m} & -\eta_m \leq \eta_s \leq \eta_m \\ 0 & \eta_s > \eta_m, \end{cases} \quad f_+(\eta_s) = \begin{cases} 0 & \eta_s < -\eta_m \\ \frac{\eta_s + \eta_m}{2\eta_m} & -\eta_m \leq \eta_s \leq \eta_m \\ 1 & \eta_s > \eta_m, \end{cases}$$



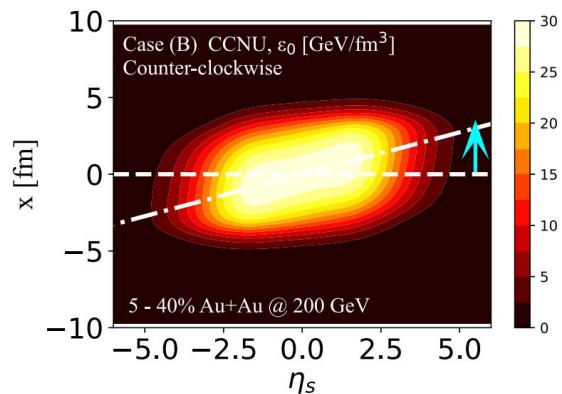
P. Bozek and I. Wyskiel,
Phys. Rev. C, 81:054902, 2010.

2. 构建QGP的纵向倾斜结构

Case (B). CCNU parametrization:

构建一种单调函数来描述介质的倾斜:

$$W_N(x, y, \eta) = [T_1(x, y) + T_2(x, y)] + H_t [T_2(x, y) - T_1(x, y)] \tan\left(\frac{\eta}{\eta_t}\right)$$



Case C. Shen -Alzhrani parametrization:

从纵向能动量守恒及重子密度守恒出发构建介质的倾斜:

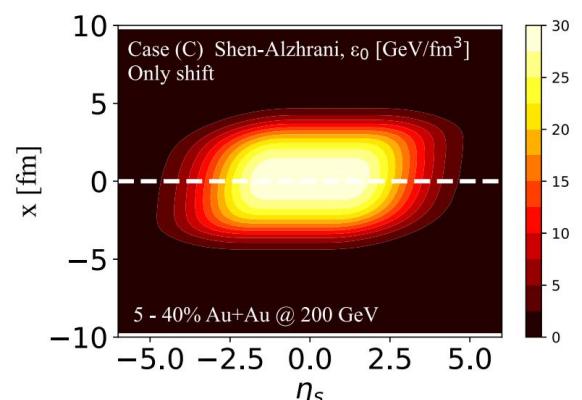
$$y_{CM}(x, y) = \operatorname{arctanh} \left[\frac{T_A - T_B}{T_A + T_B} \tanh(y_{beam}) \right]$$

$$M(x, y) = m_N \sqrt{T_A^2 + T_B^2 + 2T_A T_B \cosh(2y_{beam})}$$

$$\begin{aligned} \varepsilon(x, y, \eta_s; y_{CM}) = & \mathcal{N}_e \times \exp \left[-\frac{(|\eta_s - (y_{CM} - y_L)| - \eta_w)^2}{2\sigma_\eta^2} \right. \\ & \times \theta(|\eta_s - (y_{CM} - y_L)| - \eta_w)], \end{aligned}$$

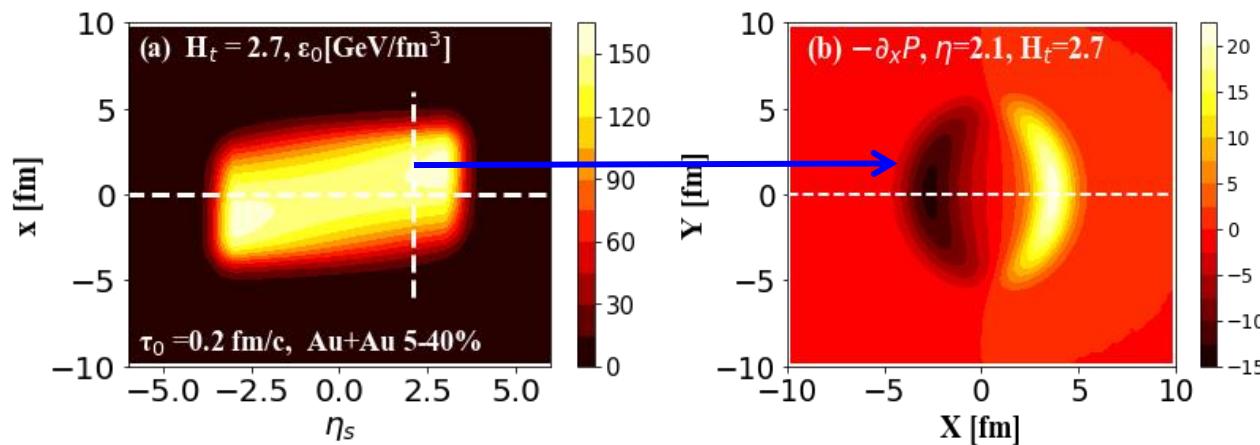
$y_L \equiv f y_{CM}$

Ze-Fang Jiang, C. B. Yang and Qi Peng,
Phys. Rev. C 104, 064903 (2021)

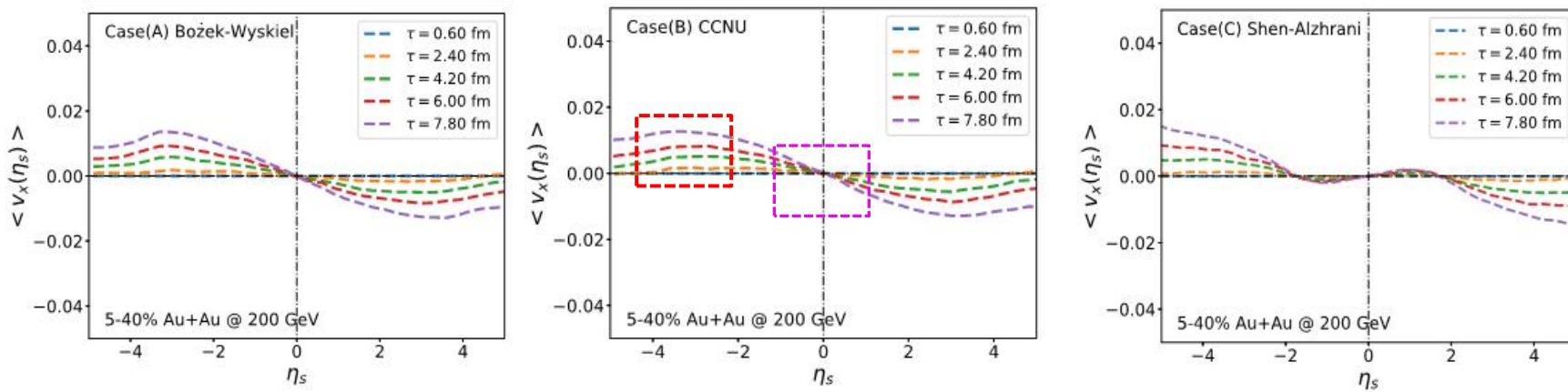


Shen -Alzhrani et al.:
Phys. Rev. C 102 (2020) 1, 014909
Phys. Rev. C 104 (2021) 5, 054908

2. 带电粒子直接流的形成过程



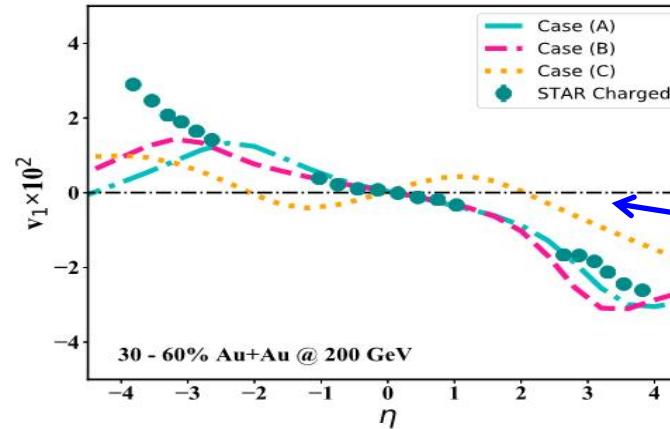
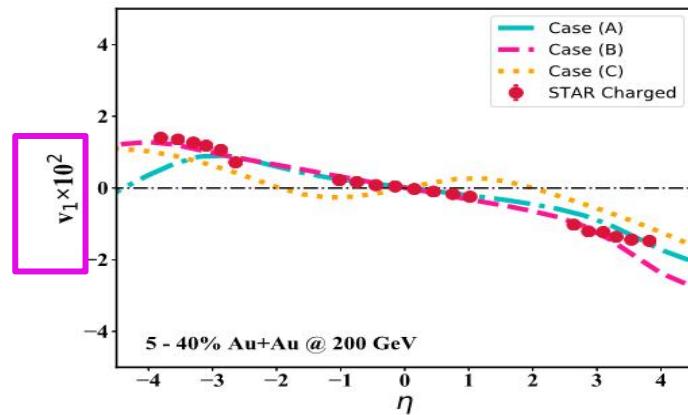
沿着 x 方向压强梯度的不对称 $\Rightarrow x$ 方向平均速度不同 $\langle v_x \rangle \Rightarrow$ Light hadron v_1



结论：1. x 方向平均压强梯度不对称产生的力，促使介质非对称膨胀；
2. 介质倾斜逆时针偏转使中心快度区域平均速度斜率 $d\langle v_x \rangle / d\eta_s$ 为负值。

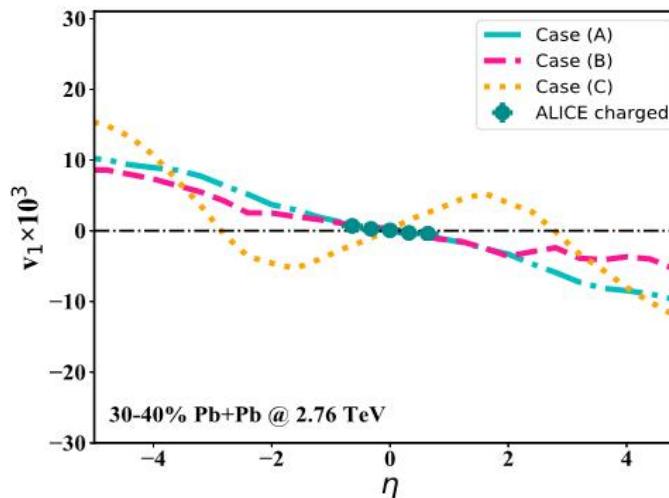
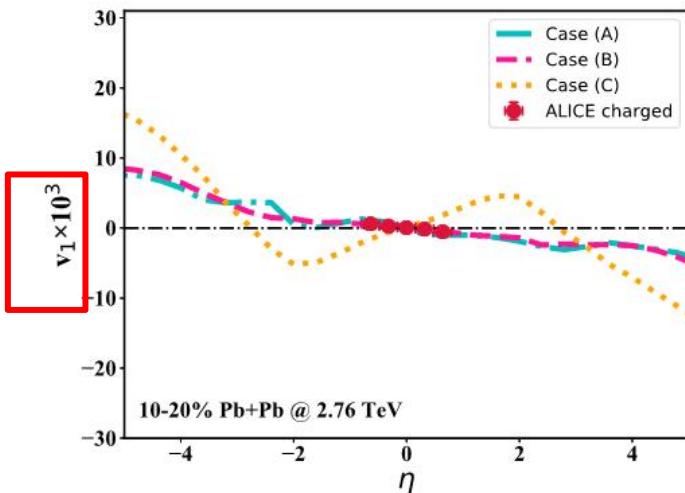
2.RHIC以及LHC能区带电粒子直接流

RHIC Au+Au @ 200 GeV



如果火球既不倾斜，又不偏转，则
 $v_1 = 0$.

LHC Pb+Pb @ 2.76 TeV

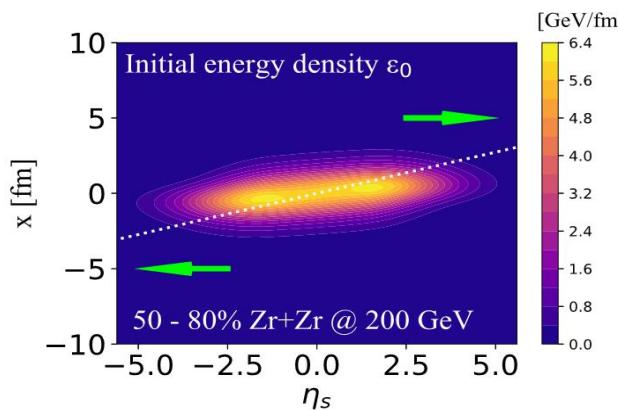
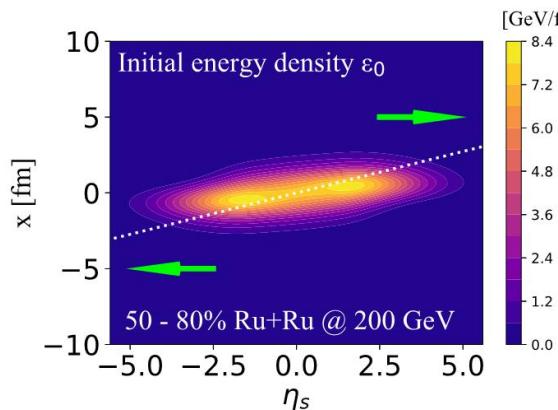


LHC能区轻强子的 v_1 比RHIC能区小?
高能量下洛伦兹收缩效应强，核阻止效应弱，介质更不倾斜。

结论：QGP初态纵向的倾斜与逆时针偏转是形成轻强子直接流的主要原因之一。

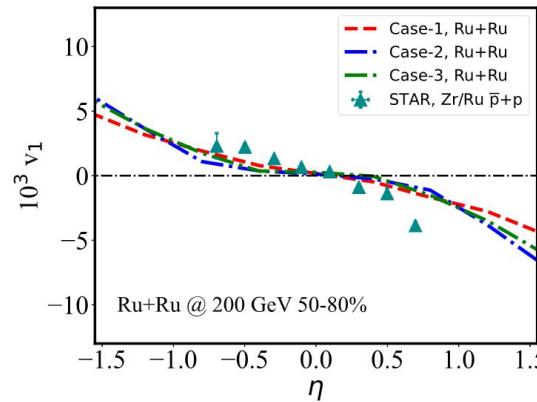
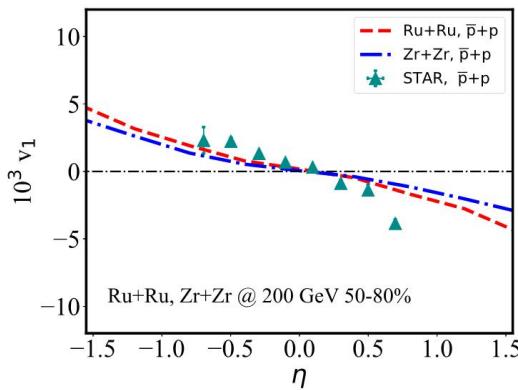
2. 200 GeV Isobar collisions 带电粒子直接流

Isobar collisions @ 200 GeV 初态能量密度分布



利用CCNU模型，
构建 Ru+Ru and
Zr+Zr 碰撞初始倾斜介质。

Isobar collisions @ 200 GeV 直接流



Parameters	Case-1		Case-2		Case-3	
	Ru+Ru	Zr+Zr	Ru+Ru	Zr+Zr	Ru+Ru	Zr+Zr
R (fm)	5.067	4.965	5.085	5.02	5.085	5.02
d (fm)	0.500	0.556	0.46	0.46	0.46	0.46
β_2	0.0	0.0	0.158	0.08	0.053	0.217

STAR Phys. Rev. C, 105(1):014901, 2022.

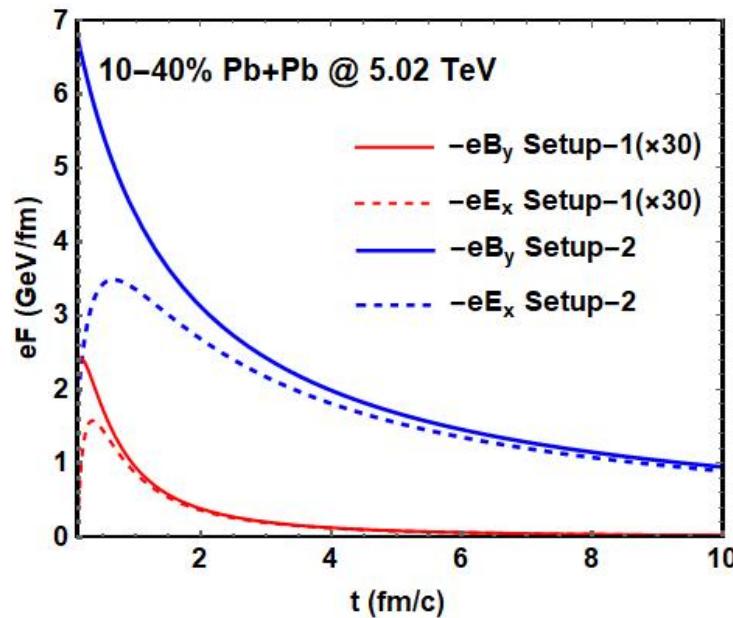
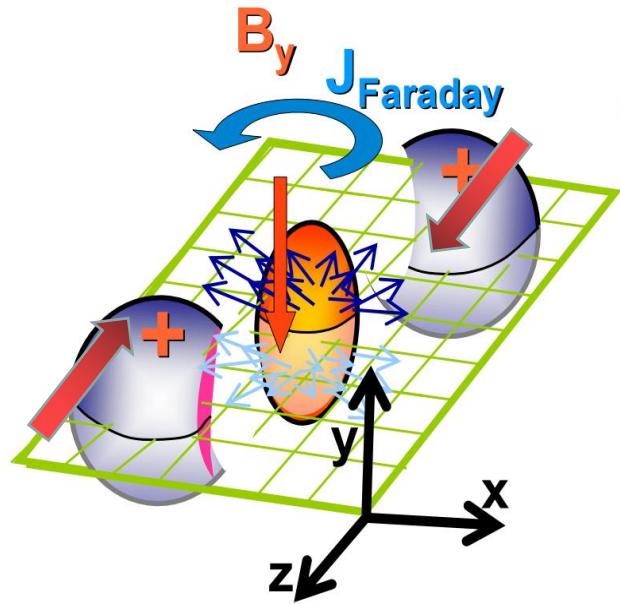
原子核结构 (effect of nuclear structure) 影响也有部分贡献, 但贡献较小。

结论: 同重异位素碰撞中, 轻强子的直接流主要来源于介质纵向倾斜。

3. 倾斜介质、电磁场与重味夸克直接流

3. v_1 and Δv_1 of heavy quark in E/B field

大量研究均表明，LHC能区重离子对撞产生的初始磁场强度比RHIC能区的更大，因此重味介子直接流可以用来探测强电磁场的信号。



- **Setup 1:** Direct solution of Maxwell equation with constant electric conductivity $\sigma = 0.023 \text{ fm}^{-1}$
- **Setup 2:** Model $B_y(\tau) \sim B_y^{\text{vac}}(0)/(1 + \tau/\tau_B)$, then solve E_x from B_y with Maxwell equation

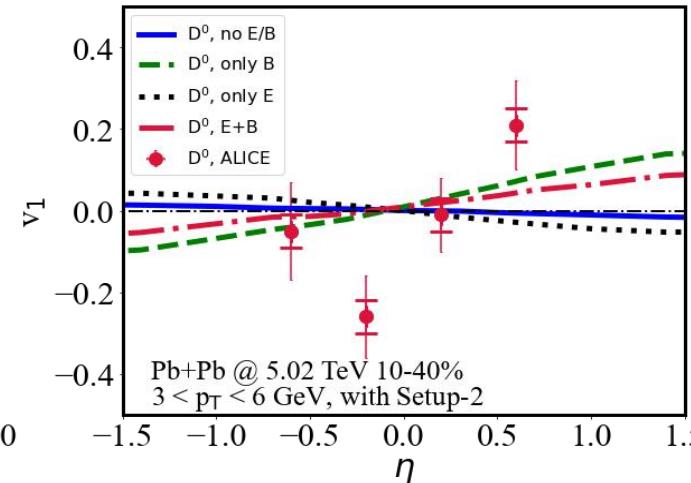
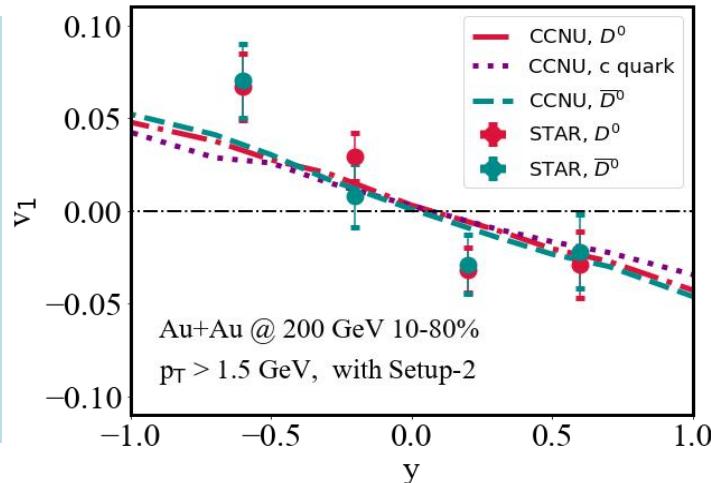
RHIC能区和LHC能区重味介子直接流 v_1 和 Δv_1 的形成机制是否相同？

3. v_1 and Δv_1 of D meson in E/B field

$$\frac{d\vec{p}}{dt} = -\eta_D(\vec{p})\vec{p} + \vec{\xi} + \vec{f}_g + [q(\vec{E} + \vec{v} \times \vec{B})],$$

Shanshan Cao et al., Phys. Rev. C 92 (2015) 2, 024907
 Ze-Fang Jiang et al., Phys. Rev. C 105, 054907 (2022)

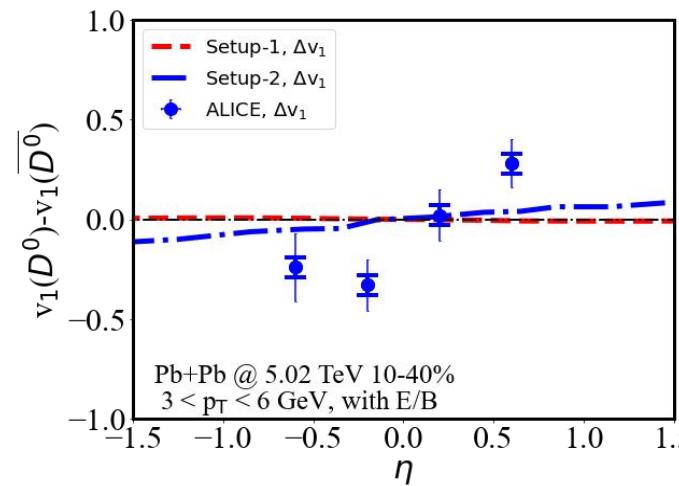
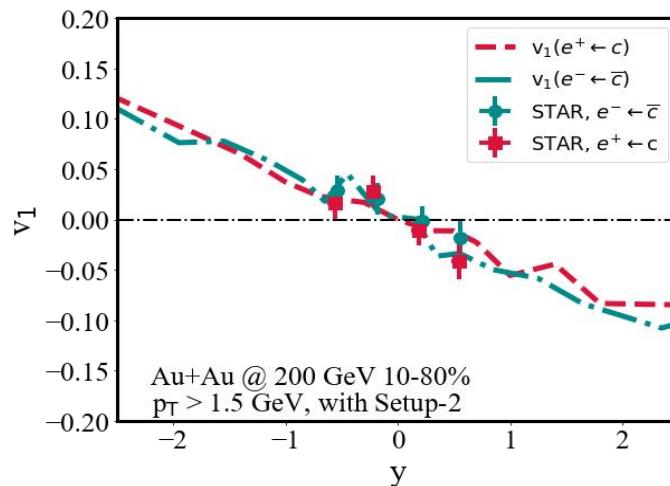
RHIC能区介质更倾斜(主要效应)
 弱电磁场(次要效应)
 解释STAR数据



LHC能区介质弱倾斜(次要贡献)

强电磁场(主要贡献)
 解释ALICE数据

结论1.
 强电磁场可诱导出一个D介子大的直接流的劈裂行为。



结论2.
 v_1 和 Δv_1 可以用来研究电磁场的演化.

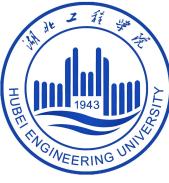
4. 总结与展望

总结

- ✓ 轻强子直接流主要来源于介质纵向倾斜结构；
- ✓ RHIC能区 D^0 /HF-electron直接流主要来源于介质纵向倾斜；
- ✓ LHC能区 D^0 和 \bar{D}^0 介子的 v_L 和 Δv_L 主要来源于强电磁场。

展望

- *CLVisc 3.0.* proton- antiproton v_L -slope @ BES III.
- LBT + EM field for heavy productions @ Isobar collisions.
- Magnetic field induced squeezing effect.



谢谢大家！

backup

1. 直接流简介-轻味： QGP倾斜

直接流(Directed flow, 定向流)描述粒子沿 $\textcolor{red}{x}$ 方向的集体偏转：

$$v_1 = \langle p_x / p_T \rangle$$

研究**轻强子**直接流 v_1

1. 研究早期火球初始纵向倾斜及横平面压强梯度不对称；

A. Adil and M. Gyulassy. Phys. Rev. C, 72:034907, 2005.

P. Bozek and I. Wyskiel. Phys. Rev. C, 81:054902, 2010.

U. Heinz and R. Snellings. Ann. Rev. Nucl. Part. Sci., 63:123–151, 2013.

Chun Shen and S. Alzhrani. Phys. Rev. C, 102(1):014909, 2020.

Jun-Jie Zhang, Xin-Li Sheng, Shi Pu et al., arXiv: 2201.06171.

Ze-Fang Jiang, Shanshan Cao et al., Phys.Rev.C 105 (2022) 3, 034901...

2. 研究高能核核对撞早期电磁场（磁流体）；

D. E. Kharzeev et al., Phys. Rev. C, 89(5):054905, 2014.

U. Gürsoy et al., Phys. Rev. C, 98(5):055201, 2018.

A. Dubla, U. Gürsoy, and R. Snellings. Mod. Phys. Lett. A, 35(39):2050324, 2020.

G. Inghirami et al., Eur. Phys. J. C, 80(3):293, 2020...

3. 作为研究整体极化的约束条件。

Chun Shen et al., arXiv:2106.08125.

Xu-Guang Huang et al., arXiv: 1108.5649.

Xiao-Liang Xia et al., arXiv:1803.00867.

Xiaowen Li, Ze-Fang Jiang, Shanshan Cao et al., arXiv:2205.02409..

1. 直交流简介-重味：倾斜+电磁场

直接流(Directed flow, 定向流)描述粒子沿 $\textcolor{red}{x}$ 方向的集体偏转：

$$\nu_1 = \langle p_x/p_T \rangle$$

研究重味介子直接流 ν_1

1. 探测火球早期纵向倾斜；

P. Bozek et al., Phys. Rev. Lett., 120(19):192301, 2018.

P. Bozek et al., Phys. Lett. B, 798:134955, 2019.

A. Beraudo et al., JHEP, 05:279, 2021.

Baoyi Chen et al., Phys. Lett. B802 (2020) 135271...

2. 探测高能核对撞早期电磁场演化。

Santosh K. Das et al., Phys. Lett. B, 768:260–264, 2017.

Yifeng Sun and V. Greco, Phys. Lett. B, 816:136271, 2021.

L. Oliva et al., JHEP, 05:034, 2021.

Ze-Fang Jiang, Shanshan Cao et al., Phys. Rev. C 105, 054907 (2022) ...

我们的研究方法及目标：

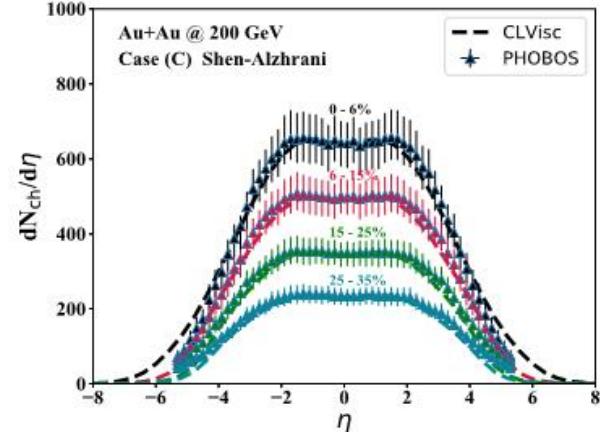
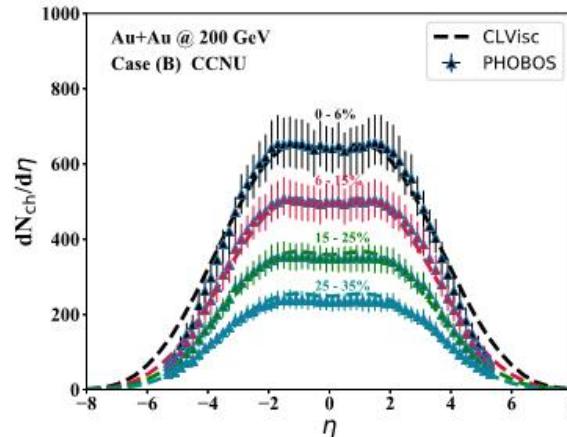
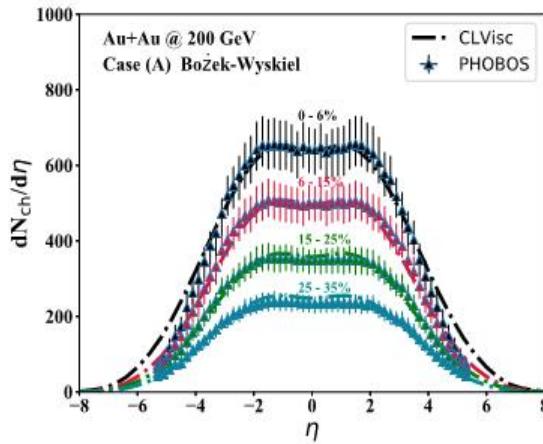
1. 构建纵向倾斜初始条件，结合流体力学模型，描述 STAR, ALICE 等大型国际合作组轻强子直接流 ν_1 结果，目标在“研究高能核碰撞产生的QGP早期3维结构及 ν_1 形成的过程”。

2. 通过**CLVisc + Duke-Langevin+EM Field**混合构架，研究 D 介子直接流，目标在“利用 D 介子为探针研究高能核碰撞早期火球3D结构及电磁场演化”。

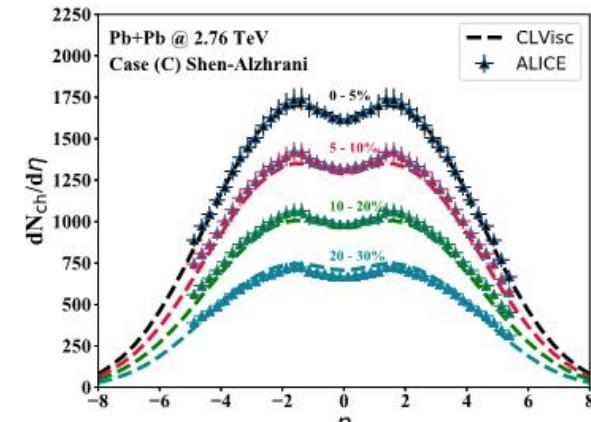
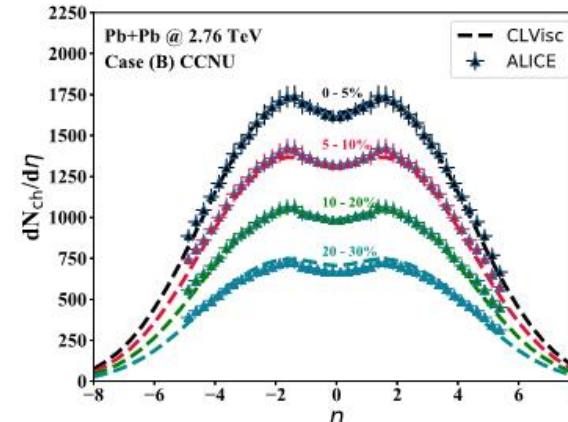
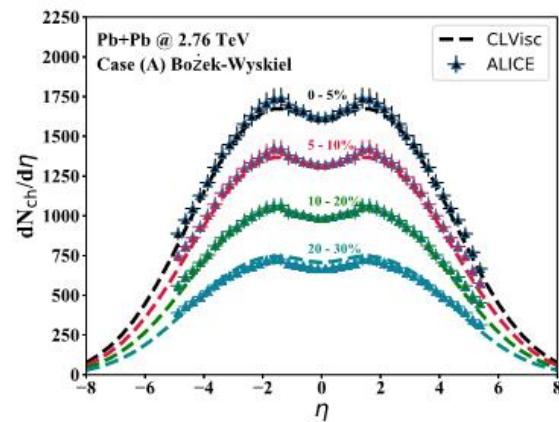
2. $dN/d\eta$ from 3 tilted fireballs

RHIC Au+Au @ 200 GeV

almost same

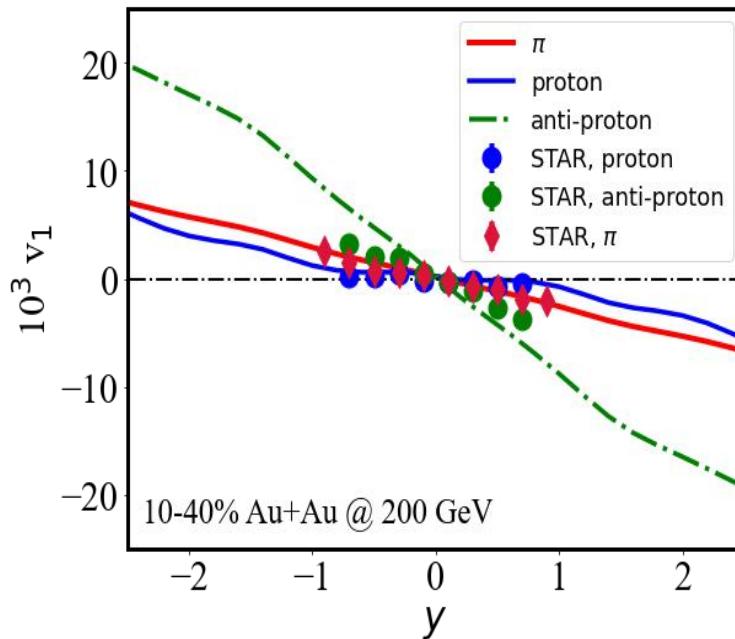


LHC Pb+Pb @ 2.76 TeV



Our calculation provides reasonable descriptions of the PHOBOS data on the $dN/d\eta$ distributions in other centralities at RHIC and the ALICE data at LHC

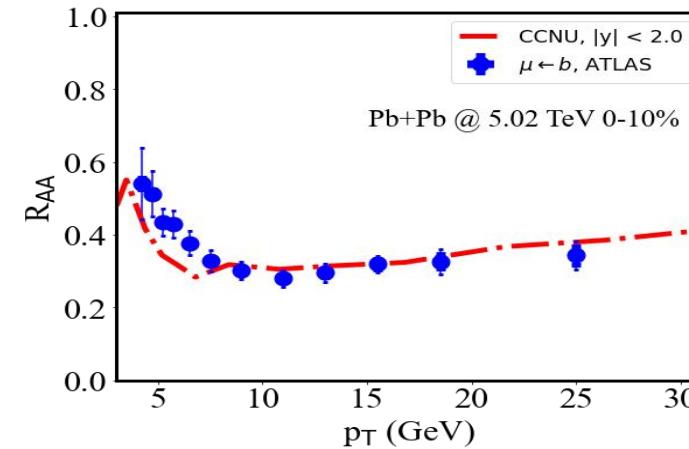
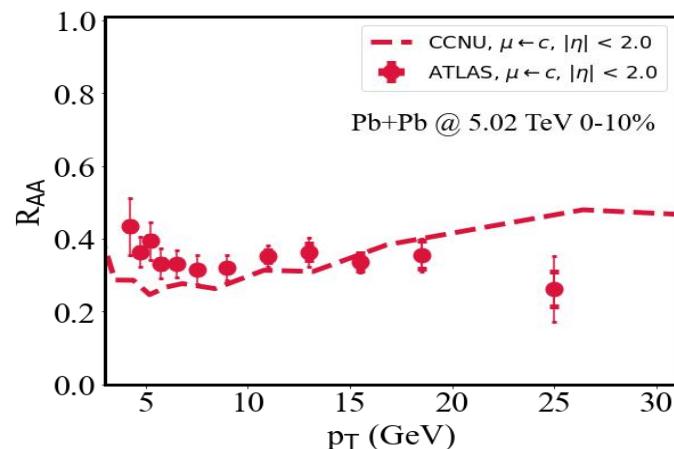
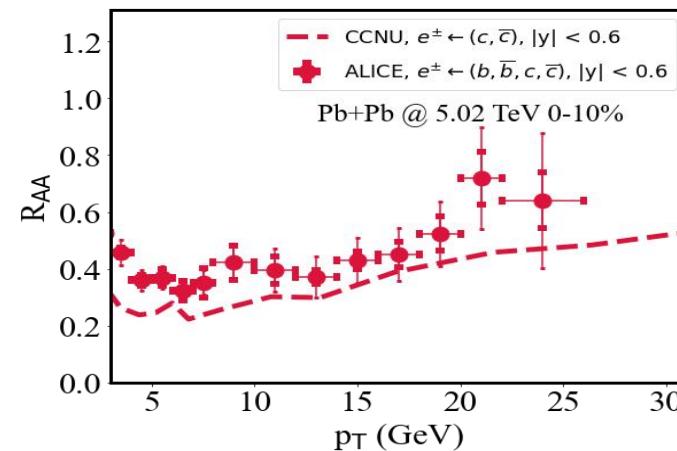
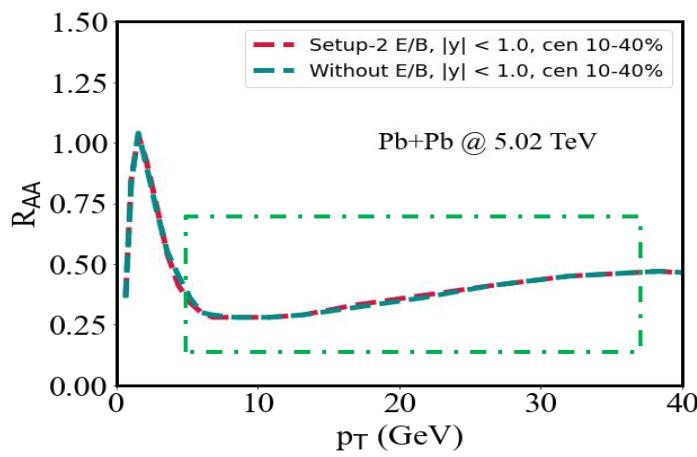
2. proton-antiproton splitting from CLVisc



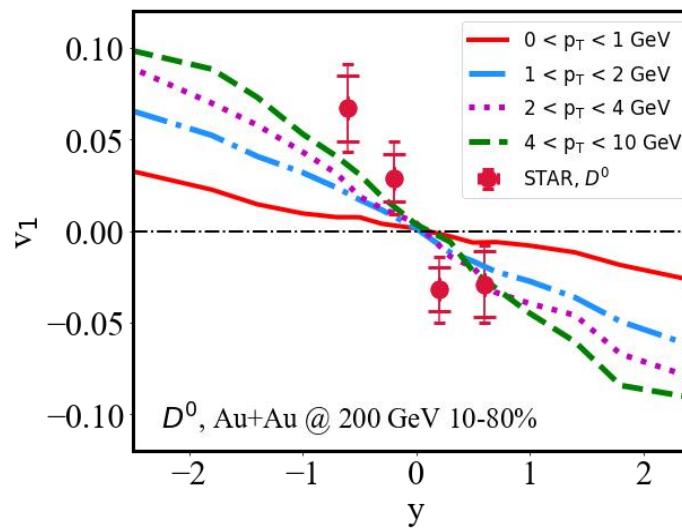
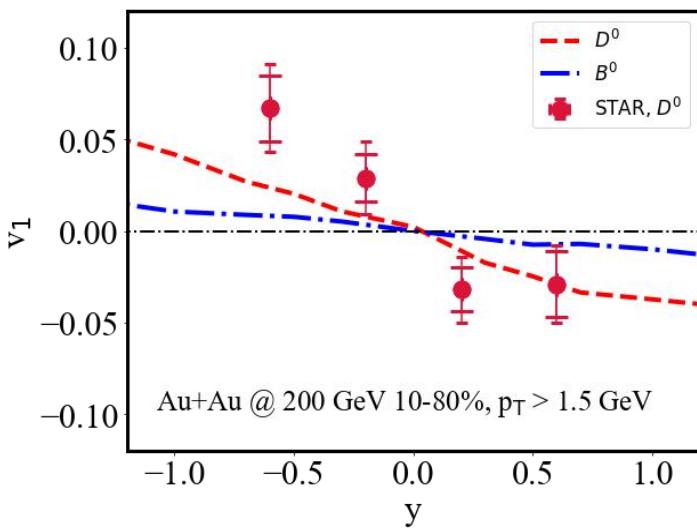
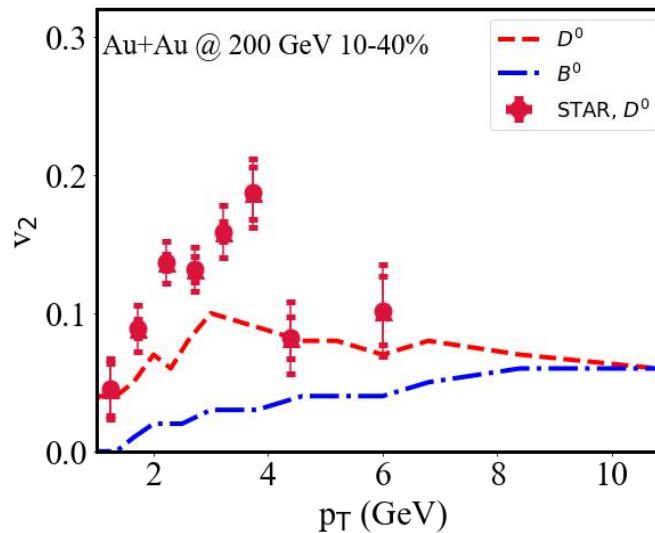
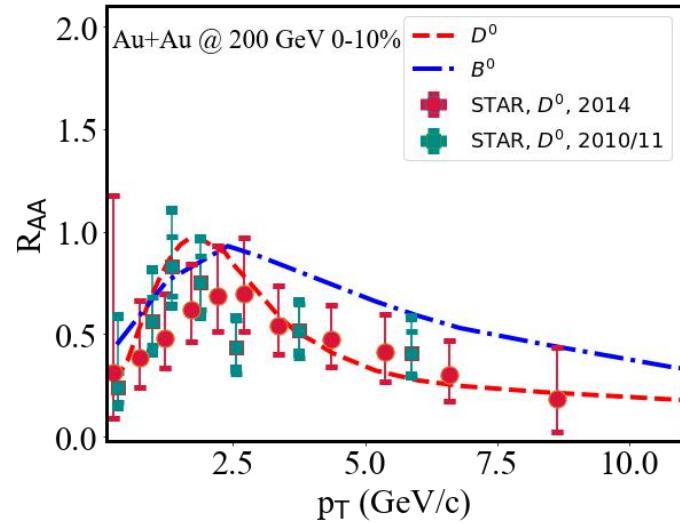
3. v_L and Δv_L of D meson in E/B field

$$\frac{d\vec{p}}{dt} = -\eta_D(\vec{p})\vec{p} + \vec{\xi} + \vec{f}_g + q(\vec{E} + \vec{v} \times \vec{B}),$$

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 Ze-Fang Jiang et al., Phys. Rev. C 105, 054907 (2022)



3. R_{AA} , v_1 and v_2 of D^0/B^0 mesons



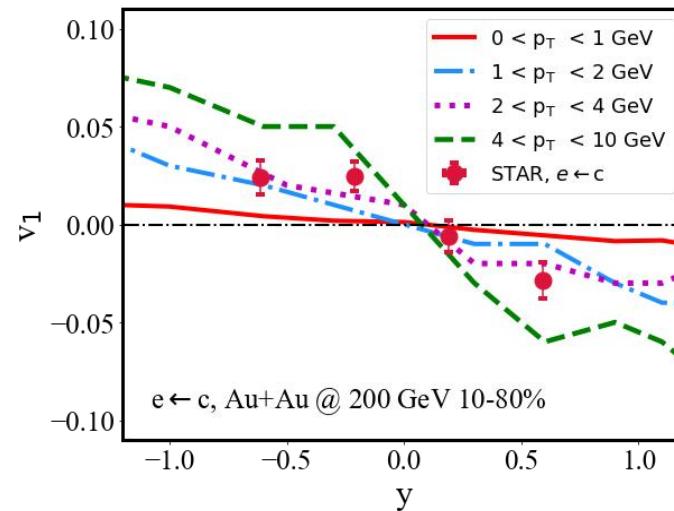
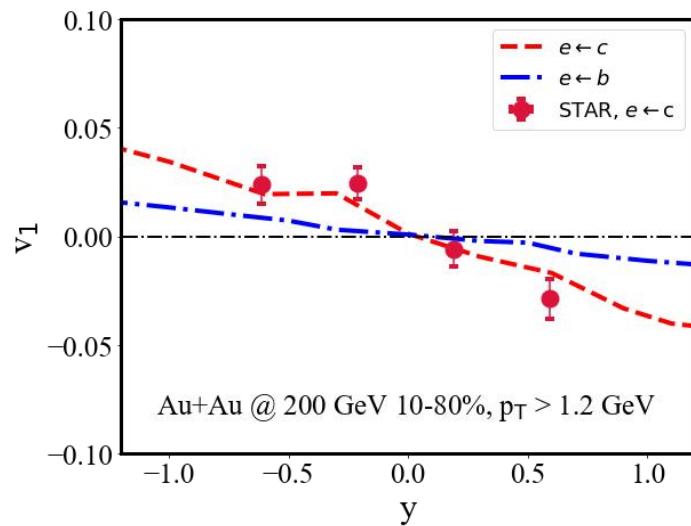
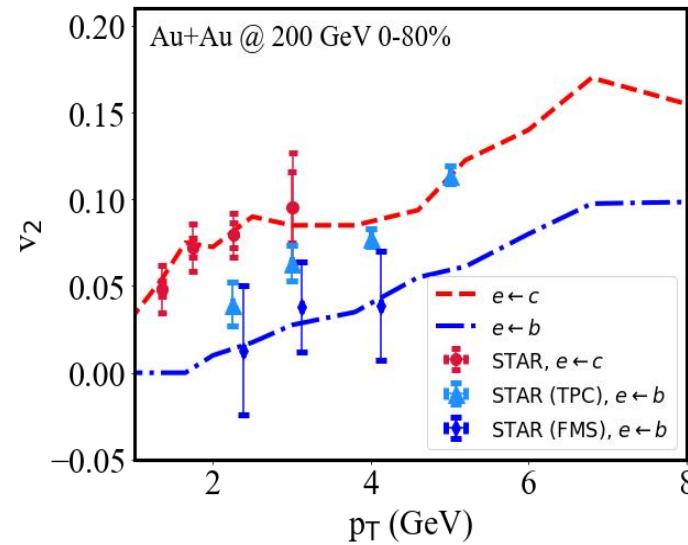
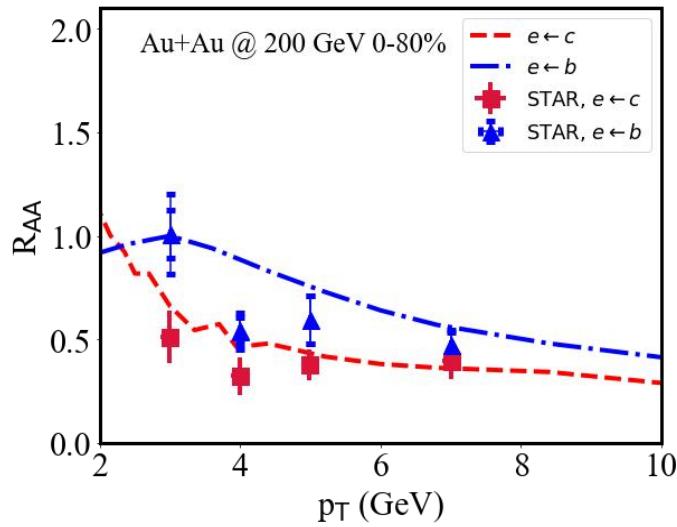
D mesons:
 $D2\pi T = 4.0$

B mesons:
 $D2\pi T = 3.0$

R_{AA} , v_1 and v_2 of D^0 meson. ✓

The B mesons results are predicted.

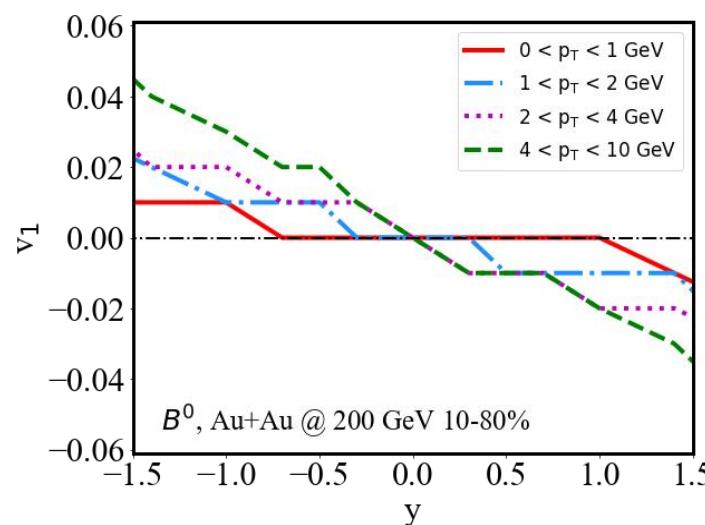
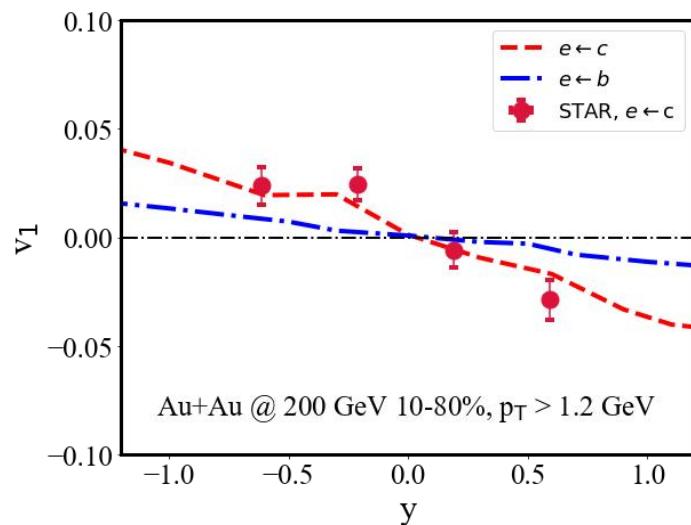
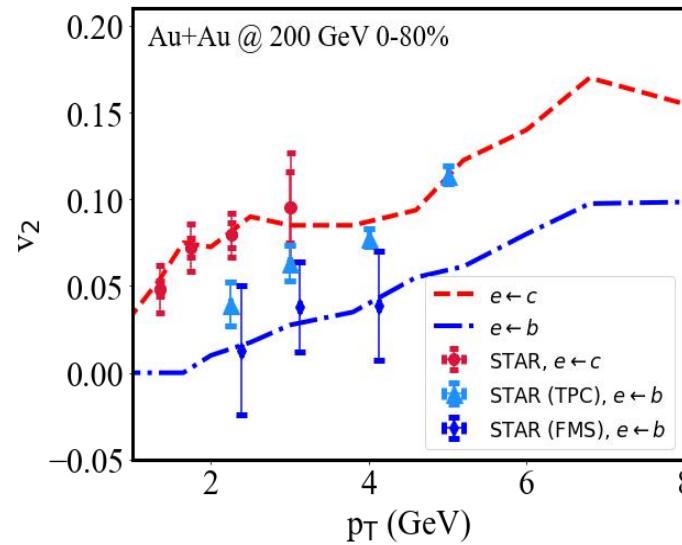
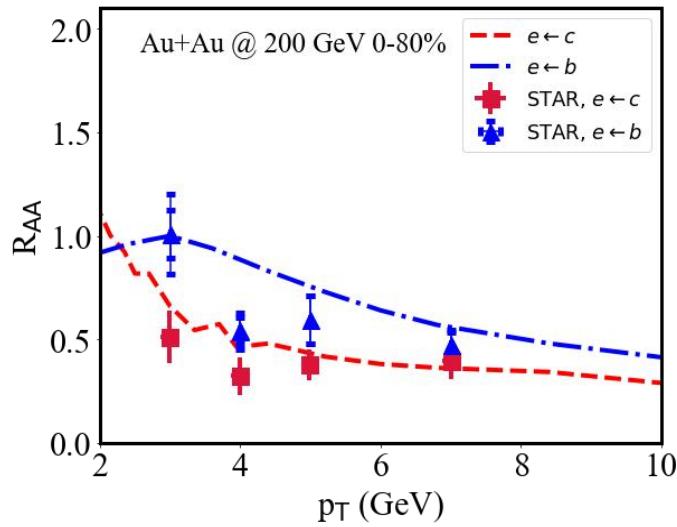
3. R_{AA} , v_1 and v_2 of HF electron



R_{AA} , v_1 and v_2 of HF electron. ✓

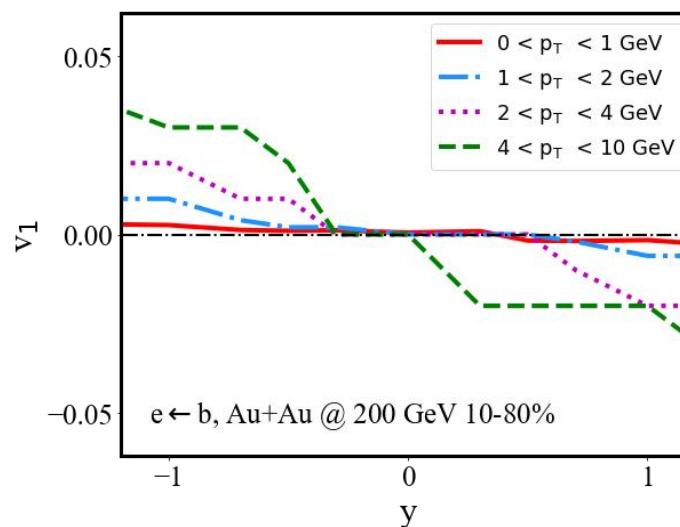
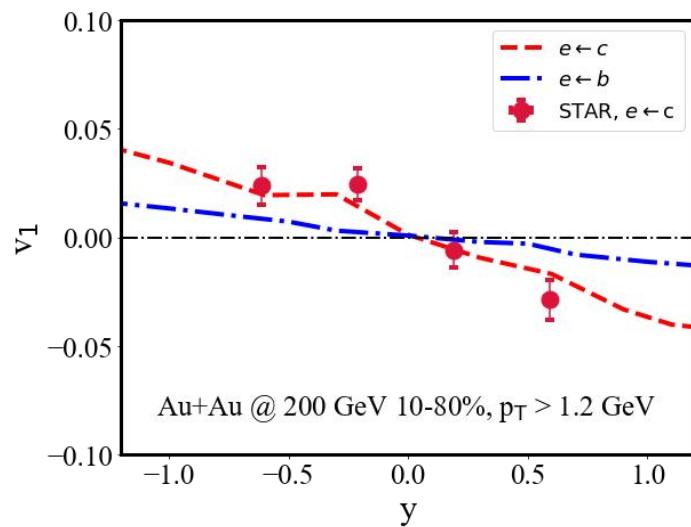
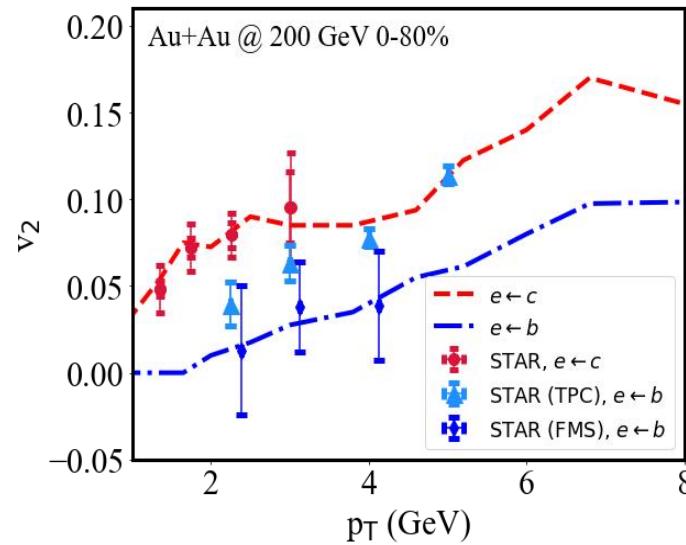
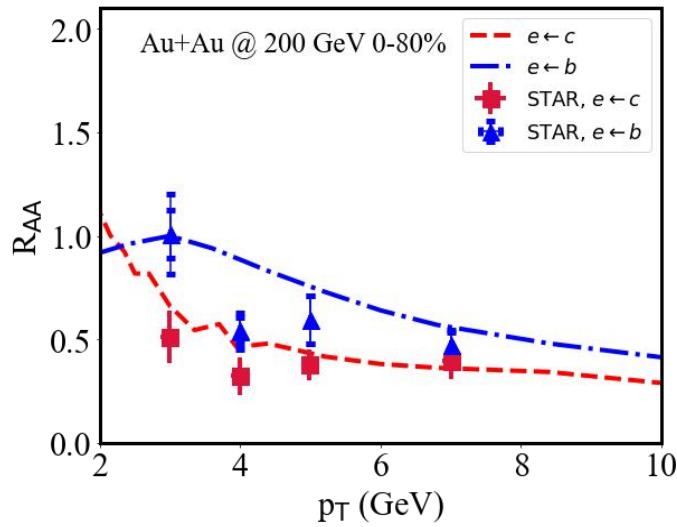
v_1 vs. p_T for D^0 meson

3. v_1 of D^0 , B^0 and HF-e for different p_T classes



v_1 .vs. p_T for B^0 meson.

3. v_1 of D^0 , B^0 and HF-e for different p_T classes



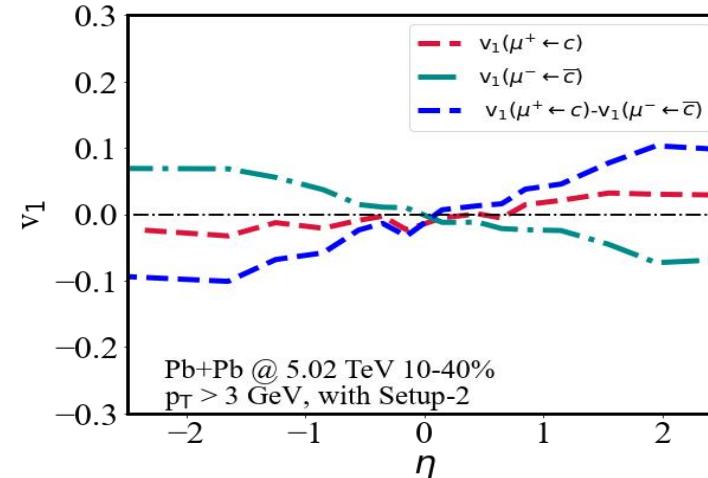
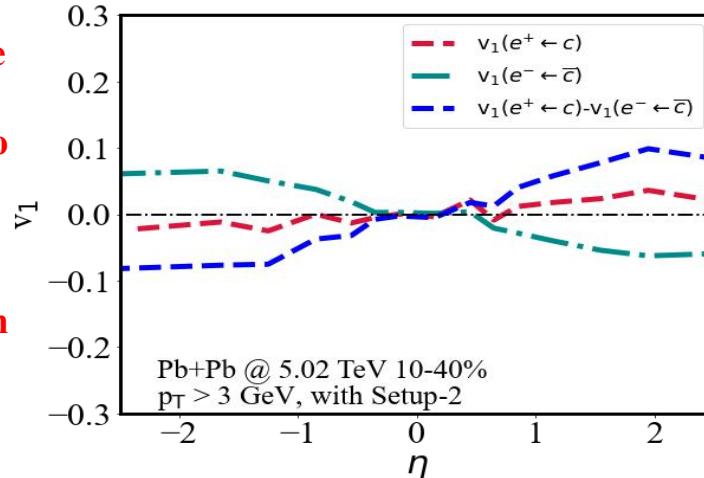
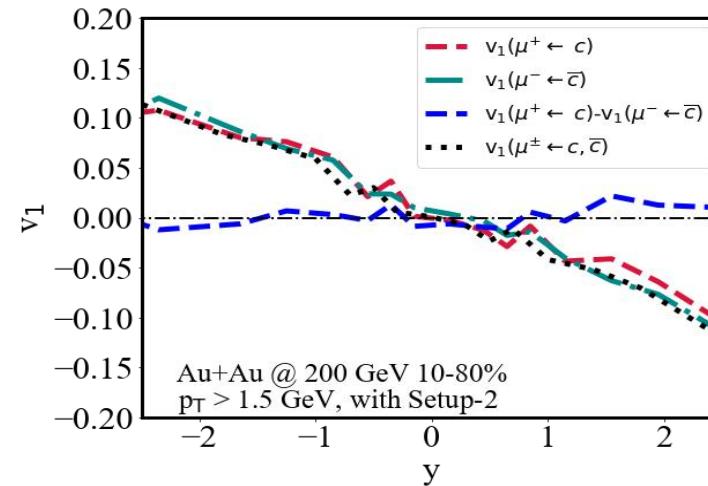
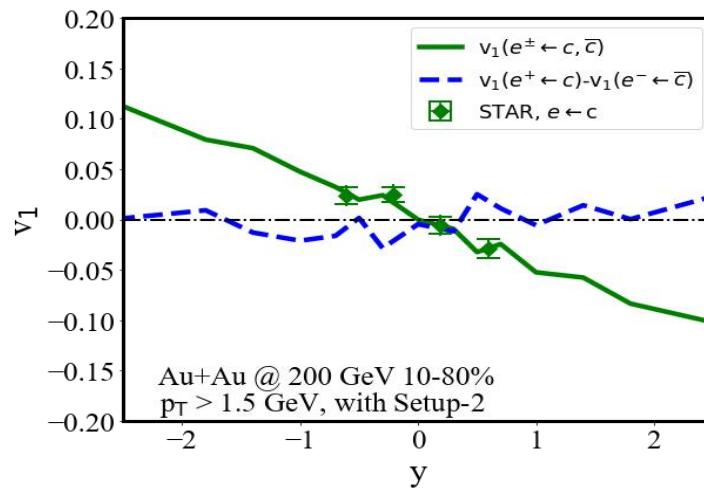
R_{AA} , v_1 and v_2 of HF electron. ✓

v_1 .vs. p_T for B^0 meson.

4. v_1 and Δv_1 of D meson in E/B field

$$\frac{d\vec{p}}{dt} = -\eta_D(\vec{p})\vec{p} + \vec{\xi} + \vec{f}_g + [q(\vec{E} + \vec{v} \times \vec{B})],$$

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charm
quarks are
more
sensitive to
the EMF
due to the
early
production