Rapidity physics of the fireball with heavy probes

Sandeep Chatterjee

With: Piotr Bożek

1712.01189, 1804.04893, ...

AGH-UST, Krakow
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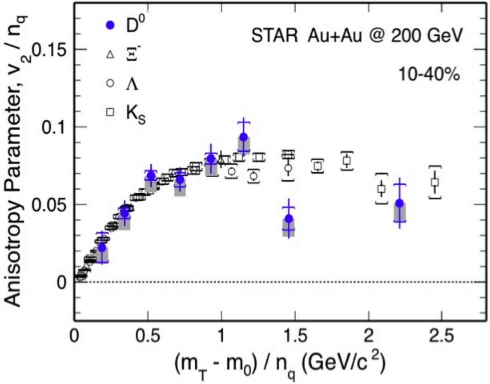
Heavy quarks: Standard viewpoint

G. Arts et. al., 1612.08032
"...They are centered around the following broader questions: Which of the proposed energy-loss mechanisms are compatible with the present lattice results? What are the next steps for the comparison of the different models for the heavy-quark energy loss in the QGP? What are the current crucial experimental issues and limitations? Can we identify key observables.."

however,..

at mid-rapidity

heavy quark (HQ) flows as strong as bulk !

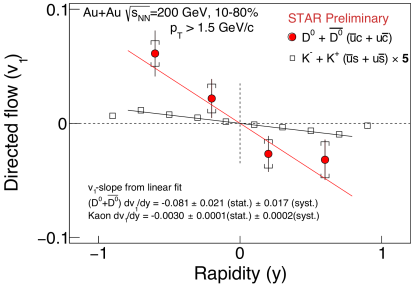


STAR collab.: PRL, 118, 212301 (2017)

away from mid-rapidity, fresh from QM 2018

HQ is pushed 30 times more than bulk !!

v_1 comparison: D^0 vs. kaon



- First observation of non-zero D^0 v_1
- D^0 v_1-slope much larger than that of kaons

Charm v_1-slope > light flavor v_1-slope

So far the largest v_1-slope measured at mid-rapidity at 200 GeV

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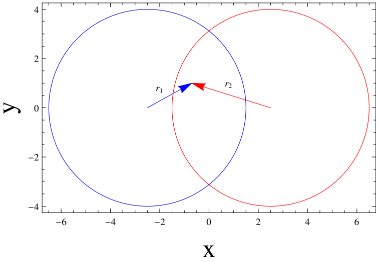
possibly a good time to look at HQ as serious probes of the bulk itself !

- At $\eta = 0$, v_2 of HQ similar to the bulk
- At $\eta \neq 0$, v_1 one order of magnitude larger than the bulk
- Can we learn directly about the bulk with HQ probes, as we use light hadron probes ?

HQs as rapidity probes

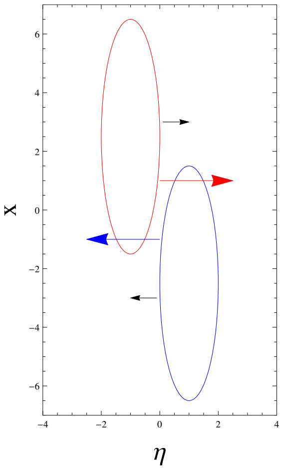
- small formation time $\sim 1/\text{mass} \sim 0.1$ fm
- large thermalization time $\sim 1/\text{drag} \sim 2 - 5$ fm
- large mass/T ensures no late stage thermal production
- witness to the entire evolution of the fireball with possibility of memory of early time dynamics
- rapidity correlations are essentially initial state physics
- hence HQs can serve as good probes of fireball dynamics in rapidity

entropy deposition in non-central collision



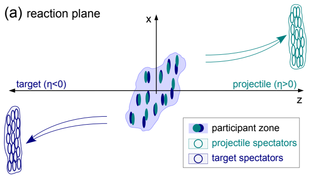
$$r_1 < r_2 \rightarrow \rho(r_1) > \rho(r_2)$$

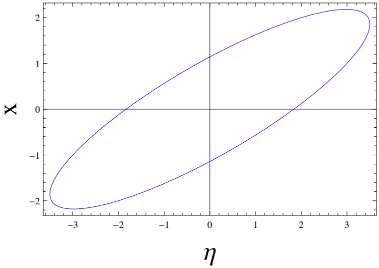
entropy deposition in non-central collision



entropy deposition from participant sources

Tilted bulk: Brodsky et. al. 1977; Adil, Gyulassy 2005; Bialas, Czyz 2005



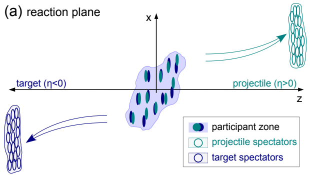


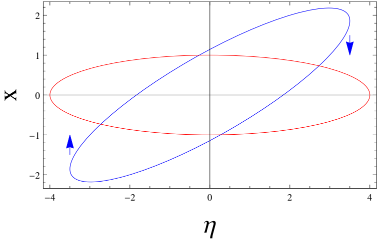
from 1306.4145

Bulk profile

entropy depositing sources: participant vs binary collision sources

HQ from hard processes → FB-symmetric
Rapidity-even HQ dragged by Rapidity-odd bulk





from 1306.4145

Bulk vs heavy flavor

Initial condition for a tilted fireball

$$s\left(\tau_0, x, y, \eta_{||}\right) = s_0\left[\alpha N_{coll} + (1-\alpha)\left(N^{+}_{part} f_{+}\left(\eta_{||}\right) + N^{-}_{part} f_{-}\left(\eta_{||}\right)\right)\right] f\left(\eta_{||}\right)$$

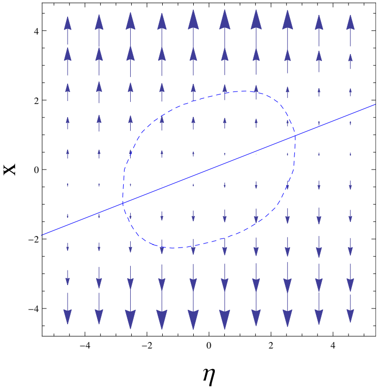
$$f\left(\eta_{||}\right) = \exp\left(-\theta\left(|\eta_{||}| - \eta^0_{||}\right)\frac{\left(|\eta_{||}| - \eta^0_{||}\right)^2}{2\sigma^2}\right)$$

$$f_{+}\left(\eta_{||}\right) = \begin{cases} 0, & \eta_{||} < -\eta_T \\ \frac{\eta_T + \eta_{||}}{2\eta_T}, & -\eta_T \le \eta_{||} \le \eta_T \\ 1, & \eta_{||} > \eta_T \end{cases}$$

with $f_{-}\left(\eta_{||}\right) = f_{+}\left(-\eta_{||}\right)$ (rapidity-odd component)

Bożek, Wyskiel 2010

Tilted bulk → directed fluid velocity



Tilted bulk → directed fluid velocity

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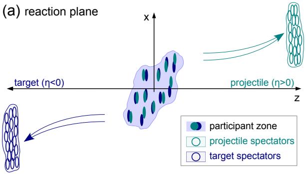
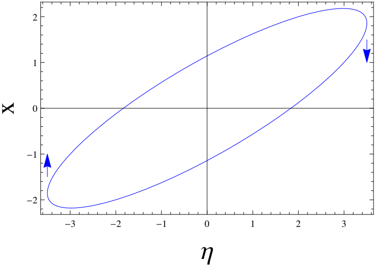
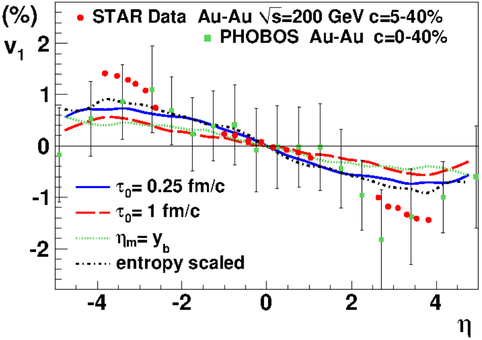




from 1306.4145

Bulk directed flow

Tilted bulk → directed fluid velocity → charged particle v_1

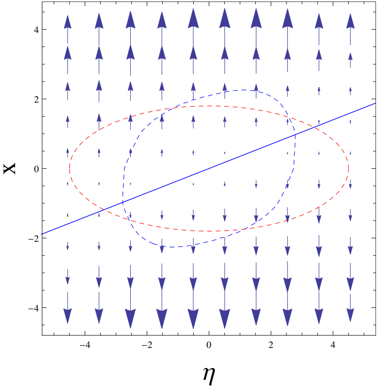


Bożek, Wyskiel 2010

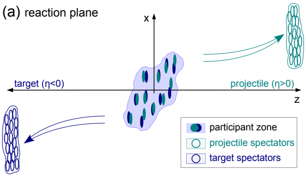
- Tilted IC captures the charged particle v_1
- small v_1

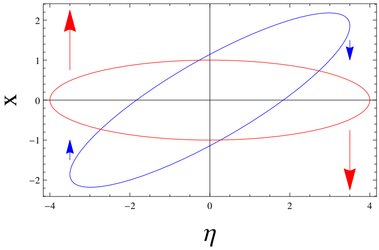
Heavy Quark Tomography

charm, anti-charm stronger probes of the tilt than the light flavor



Heavy Quark Tomography





from 1306.4145

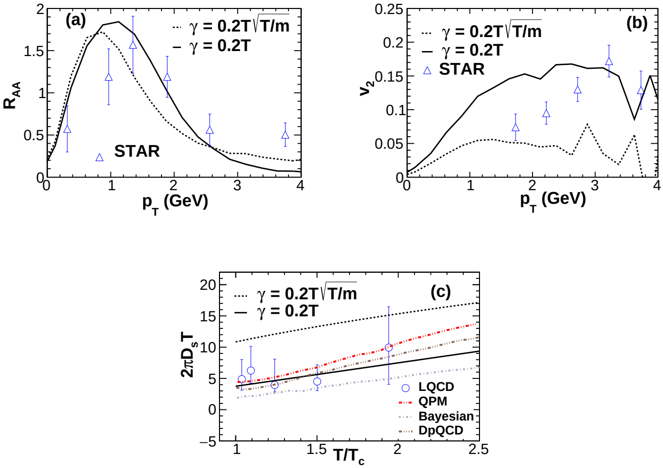
$v_1(HQ) > v_1(Bulk)$

to quantify the heavy flavor v_1

need to calibrate

- the tilt of the bulk: constrained by charged particle v_1, Bożek, Wyskiel 2010
- drag between the bulk and heavy flavor: constrained by heavy flavor R_{AA} and v_2 at mid-rapidity, we use an ansatz $\gamma = \gamma_0 T \left(\frac{T}{m}\right)^x$

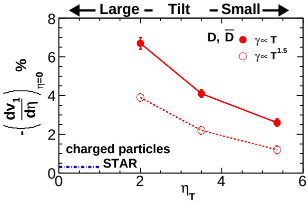
Calibrating the drag on HQs

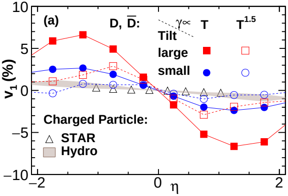


SC, Bożek 1712.01189)

HQ v_1 $\mathcal{O}(10)$ larger !

predicted to be 5 - 20 times larger than charged particle v_1 slope !





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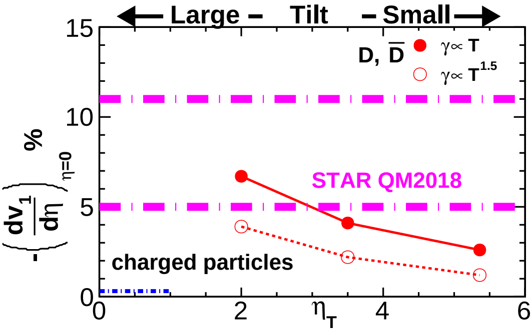
comparison to data

largest measured v_1: order of magnitude larger than that of charged particle



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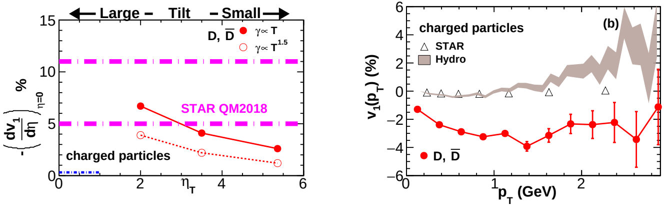

NOTE: data with $p_T > 1.5$ GeV, similar cut in model will result in larger v_1

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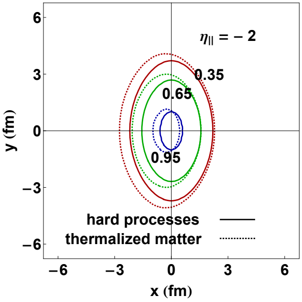
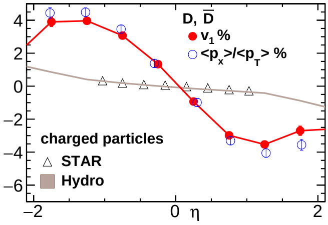
HQ acquires non-zero $\langle p_X \rangle$ - a clear signal of the initial shift between HQ and bulk

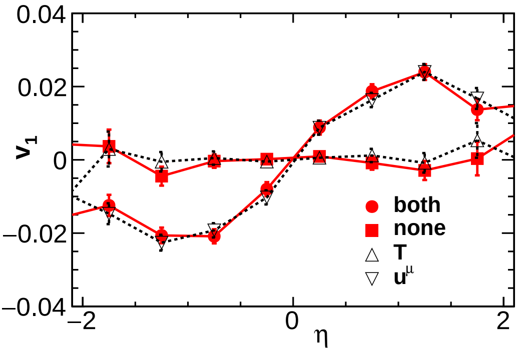




$\langle p_x \rangle \sim 40$ MeV at $\eta = 1$

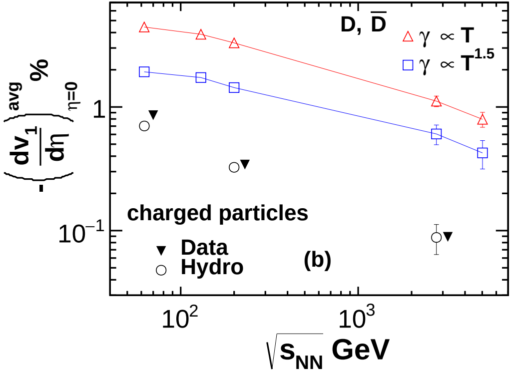
SC, Bożek 1712.01189

What causes the large v_1: T or u^μ ?



- FB asymmtery of which hydro field causes the large HQ v_1 ?
- By selectively choosing profiles with broken boost invarinace, we find the HQ v_1 is mainly caused by the FB asymmetric drag by the flow field u^μ

Beam energy dependence



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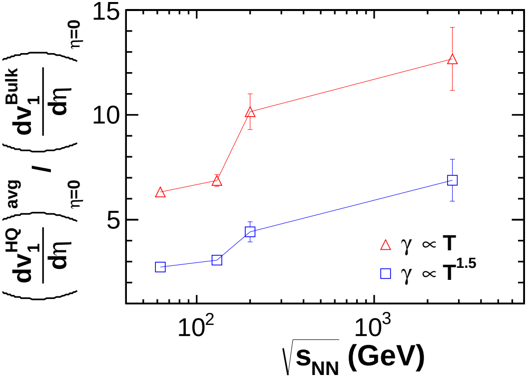
Ratio of HQ to bulk v_1



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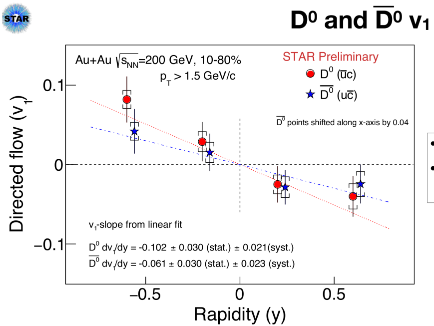
fresh from QM 2018: hint of split in v_1 of D^0 and $\overline{D^0}$



- First observation of non-zero D^0 v_1
- Both D^0 and $\overline{D^0}$ v_1 show a negative slope at mid-rapidity

$$D^0 \; dv_1/dy = -0.102 \pm 0.030 \pm 0.021$$
$$\overline{D^0} \; dv_1/dy = -0.061 \pm 0.030 \pm 0.023$$

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EM field in the initial state

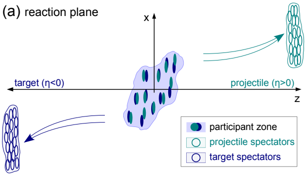
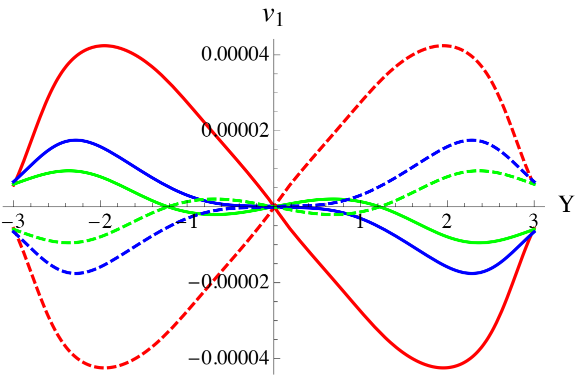


fig. from 1306.4145

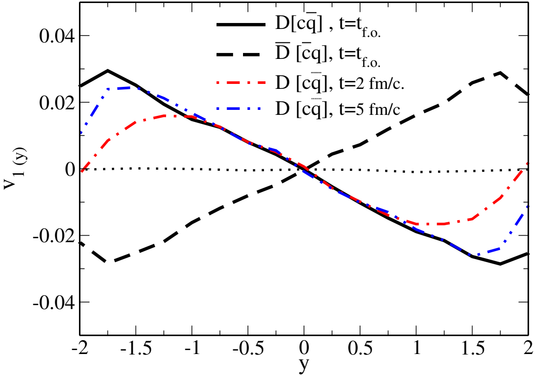
- $\mathbf{B} = -B\ \hat{y}$, B decreases as the spectators recede. For non-zero conductivity σ of the medium, this gives rise to a clock-wise $\mathbf{E}$ in the above reaction plane
- A positive charge at $\eta > 0$ experiences $\mathbf{B}$ force along $\hat{x}$ while $\mathbf{E}$ force along $-\hat{x}$, the net force resulting in a directed flow v_1

v_1 split between positive and negative charged particles due to EM field



Gursoy, Kharzeev, Rajagopal 2014

1000 times stronger effect on HQ

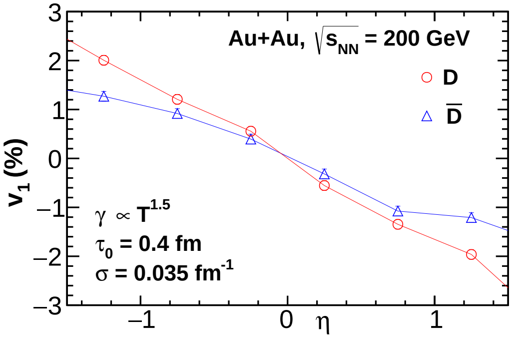


Das, Plumari, SC, Alam, Scardina, Greco 2016

- $$v_1^{\text{avg}} = \frac{1}{2}\left(v_1\left(D^0\right) + v_1\left(\overline{D^0}\right)\right)$$
  $$v_1^{\text{diff}} = v_1\left(D^0\right) - v_1\left(\bar{D}^0\right)$$

$v_1^{\text{avg}} = 0,\ v_1^{\text{diff}} \neq 0;$

HQ v_1 with Tilt+EM field



- $v_1^{avg} \neq 0$, $v_1^{diff} \neq 0$

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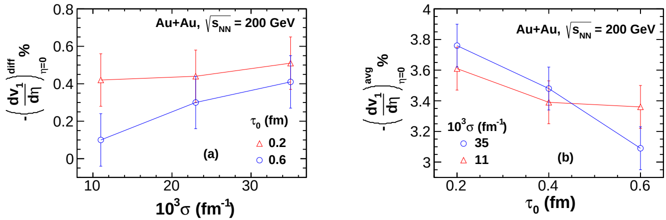
Dependence on conductivity and initialization time



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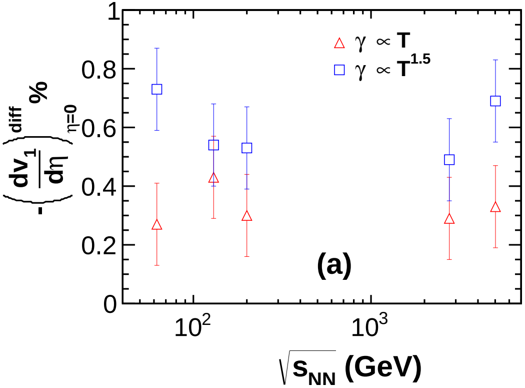
Beam energy dependence



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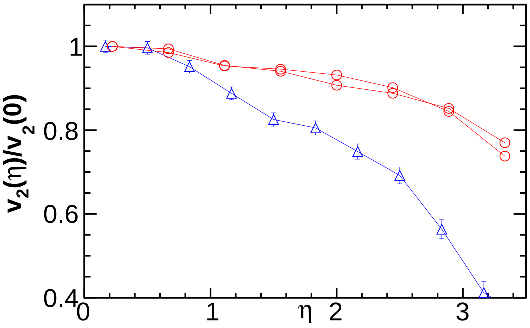
Strong v_2 decorrelation



SC, Bożek in preparation

Summarising

- Heavy flavor directed flow as a probe of 2 initial state physics was discussed: longitudinal profile of matter distribution and the electromagnetic field and medium conductivity
- Order of magnitude larger directed flow was predicted for heavy flavor compared to bulk. Split due to EM field is smaller compared to the average directed flow due to tilted bulk, resulting in same sign flow of both D^0 and $\overline{D^0}$
- Comparison to STAR QM2018 data suggests preference for large tilt (effect of p_T cut is expected to allow for smaller tilt)
- Ratio of HQ to bulk v_1 is predicted to be larger at LHC than at RHIC- stronger drag due to higher temperature
- HQ v_1 adds to the existing list of HQ R_{AA} and v_2 to provide information on the drag coefficient between the bulk matter and HQ