Probing initial condition of heavy ion collisions with heavy flavor

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which specific initial conditions?

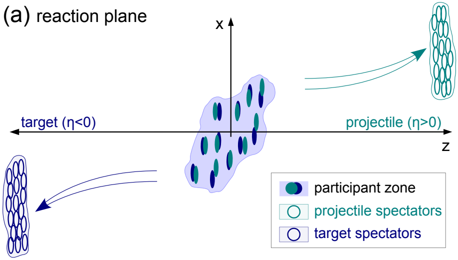
- rapidity profile of the fireball: the longitudinal (along the beam) deposition of entropy in the initial state
- the produced electromagnetic fields: mainly by the proton spectators

advantages of heavy flavor as a probe of this early time physics

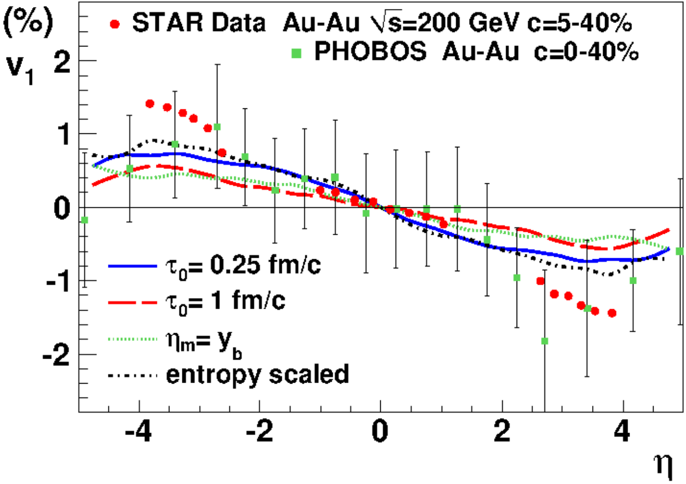
- already discussed several times
- distinct production mechanism: mainly produced in the initial state by hard binary collisions
- longer time to thermalize with the medium

the sign convention of directed flow v_1

- the directed 'flow/motion' of the spectators flying along positive rapidity is positive; which also sets the direction of the B field along negative y and a clockwise charged current (response of the medium with conductivity), i.e. E field along negative x at $\eta > 0$

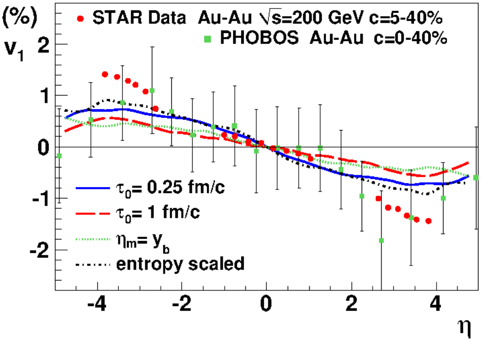


charged particle v_1



Tilted bulk → directed fluid velocity → charged particle v_1

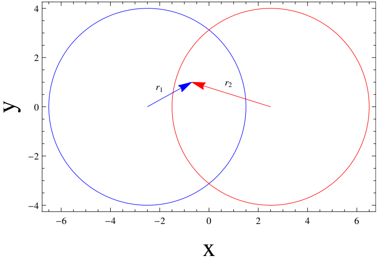
Tilted bulk: Brodsky et. al. 1977; Adil, Gyulassy 2005; Bialas, Czyz 2005



Bożek, Wyskiel 2010

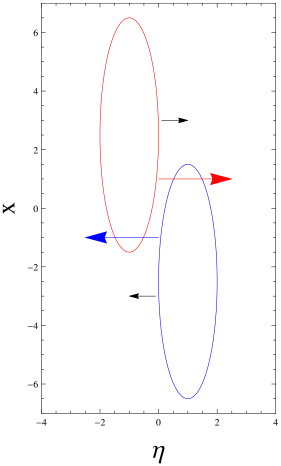
- Tilted IC captures the charged particle v_1
- small v_1

entropy deposition in non-central collision



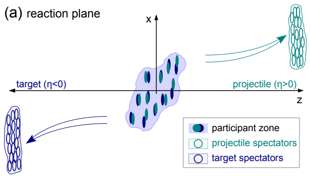
$r_1 < r_2 \rightarrow \rho(r_1) > \rho(r_2)$

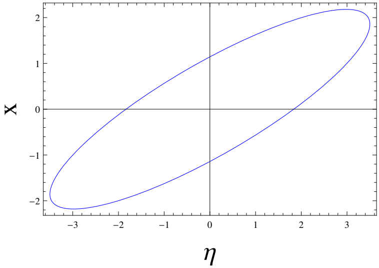
entropy deposition in non-central collision



entropy deposition from participant sources

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





Bulk profile

Initial condition for a tilted fireball

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

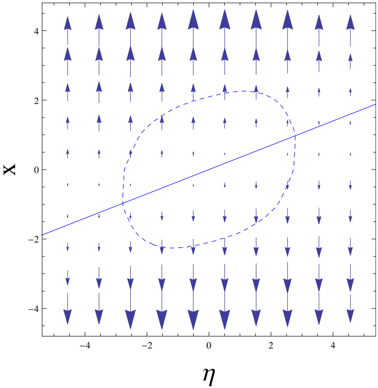
$$f\left(\eta_{||}\right) = \exp\left(-\theta\left(|\eta_{||}| - \eta^0_{||}\right)\frac{\left(|\eta_{||}| - \eta^0_{||}\right)^2}{2\sigma^2}\right)$$

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

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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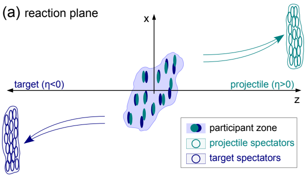
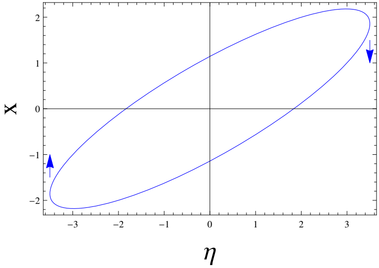
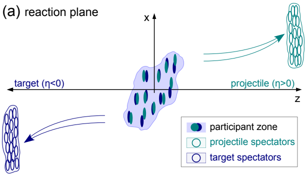


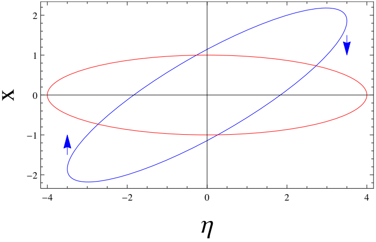


Bulk directed flow

entropy depositing sources: participant vs binary collision sources

HQ from hard processes $\rightarrow$ FB-symmetric
Rapidity-even HQ dragged by Rapidity-odd bulk

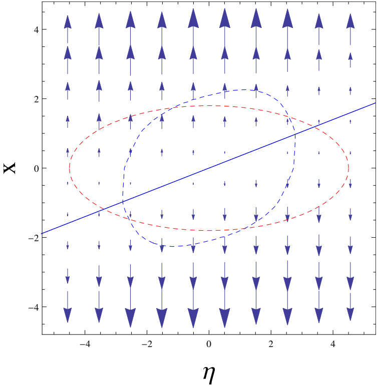




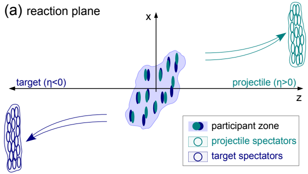
Bulk vs heavy flavor

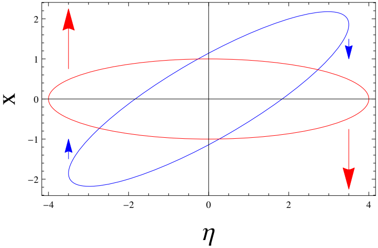
Heavy Quark Tomography

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



entropy depositing sources: participant vs binary collision sources





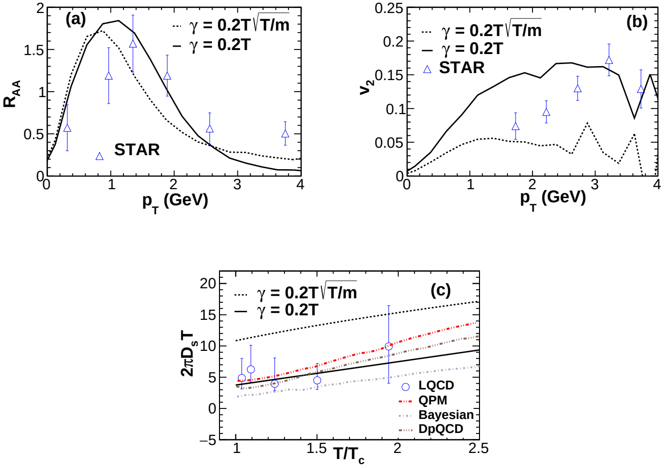
$v_1(HQ) > v_1(Bulk)$

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 $\gamma = \gamma_0 T \left(\frac{T}{m}\right)^x$

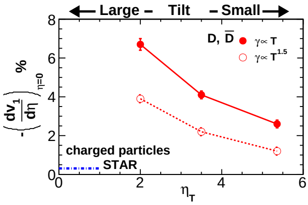
Calibrating the drag on HQs

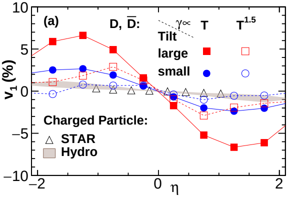


SC, Bożek 2018

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

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

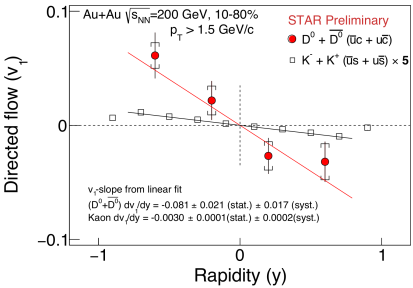




SC, Bożek 2018

QM 2018: heavy flavor is pushed 30 times more than bulk !!

v_1 comparison: D^0 vs. kaon



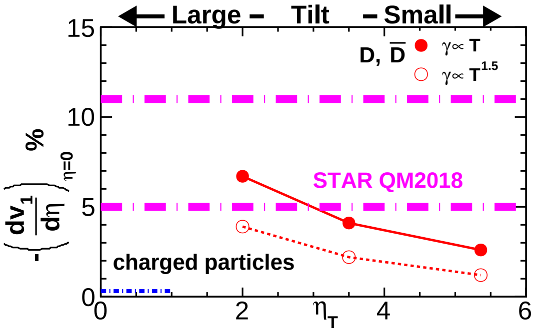
- First observation of non-zero D^0 v_1
- D^0 v_1-slope much larger than that of kaons

Charm v_1-slope > light flavor v_1-slope

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

comparison to data

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

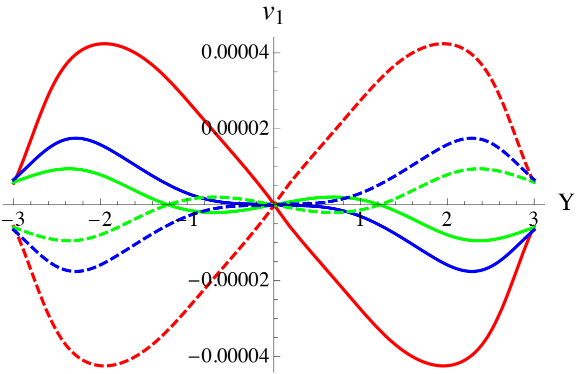


SC, Bożek 2018

which specific initial conditions?

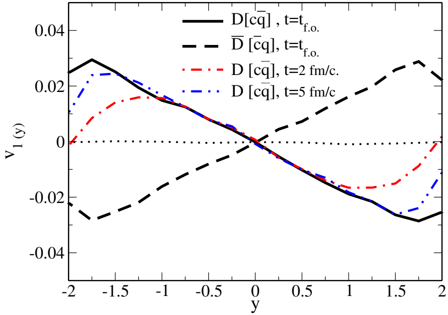
- rapidity profile of the fireball: the longitudinal (along the beam) deposition of entropy in the initial state
- the produced electromagnetic fields: mainly by the proton spectators

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



Gursoy, Kharzeev, Rajagopal 2014

1000 times stronger split in D^0 - $\overline{D^0}$



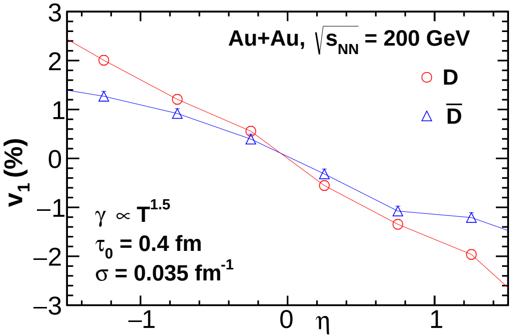
Das, Plumari, SC, Alam, Scardina, Greco 2016

-

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

- Tilt: $v_1^{\text{avg}} \neq 0$, $v_1^{\text{diff}} = 0$; EM: $v_1^{\text{avg}} = 0$, $v_1^{\text{diff}} \neq 0$;

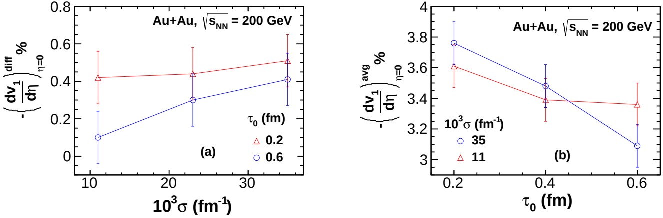
HQ v_1 with Tilt+EM field



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

SC, Bożek 2018

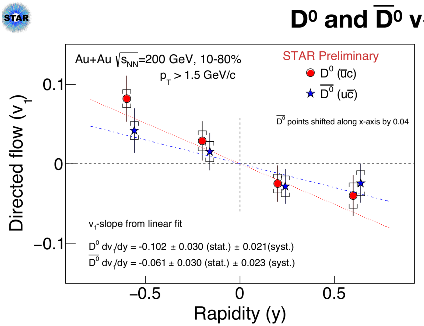
Dependence on conductivity and initialization time



SC, Bożek 2018

- note: Δv_1 is predicted due to EM; however, sign of Δv_1 is a matter of details in the parameter space (τ_0, σ)

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

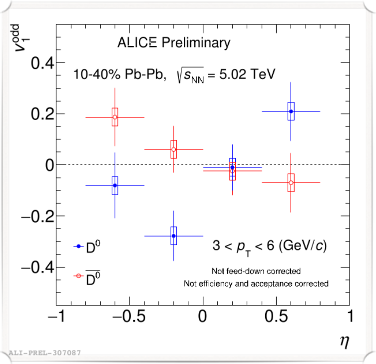


- First observation of non-zero D^0 v_1
- Both D^0 and $\overline{D^0}$ v_1 show a negative slope at mid-rapidity

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

Subhash Singha, 11

Hard Probes 2018: hint of split (opp. sign) in v_1 of D^0 and $\overline{D^0}$ at ALICE



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 average v_1 was predicted for heavy flavor compared to bulk: hints from STAR data as well
- 1000 times stronger split in v_1 of D and $\overline{D}$ than in light flavor sector predicted due to EM field: hint of split seen at STAR and ALICE; however they seem to be of opposite sign
- Detailed model study of the parameter space like τ_0, σ etc needed; also to be noted that ALICE has $p_T > 3$ GeV while STAR $p_T > 1.5$ GeV
- Opens door to study of the longitudinal geometry; extraction of the electric conductivity of hot and dense QCD; measuring the strongest EM fields $\rightarrow$ crucial input to search and modelling of the chiral magnetic effect

THANK YOU