

Directed flow of heavy flavor dragged by a hot tilted fireball and pushed by electromagnetic field

Sandeep Chatterjee
With: Piotr Bożek
AGH-UST, Krakow

based on:

Phys. Rev. Lett. **120**, 192301 (2018) (arXiv: 1712.01189);
arXiv: 1804.04893



WPCF, Krakow, 24 May, 2018

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

EM field in the initial state

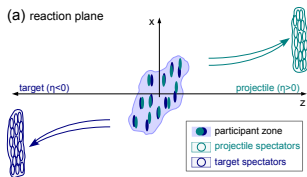


fig. from 1306.4145

- $\mathbf{B} = -B \hat{y}$, 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

Directed flow:
Electromagnetic origin

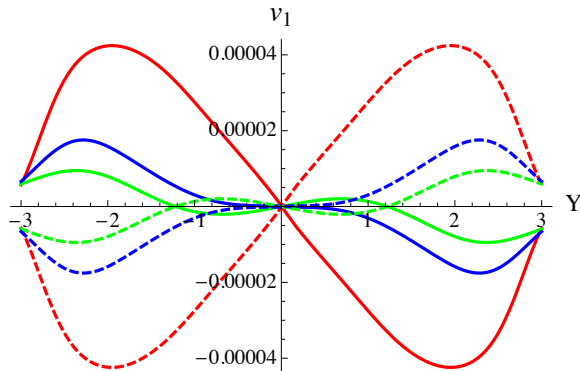
Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

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



Gursoy, Kharzeev, Rajagopal 2014

Directed flow:
Electromagnetic origin

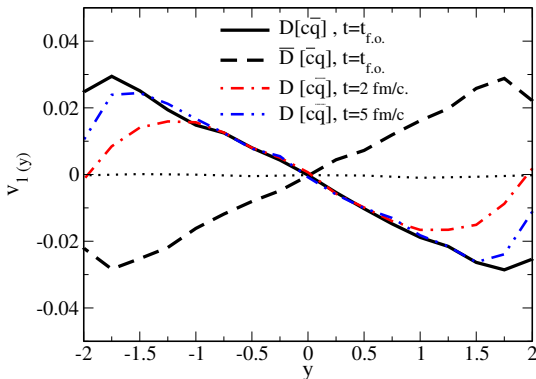
Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

1000 times stronger effect on HQ



Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

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

•

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

$$v_1^{\text{diff}} = v_1(D^0) - v_1(\bar{D}^0)$$

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

Effect of bulk v_1 on HQ ?

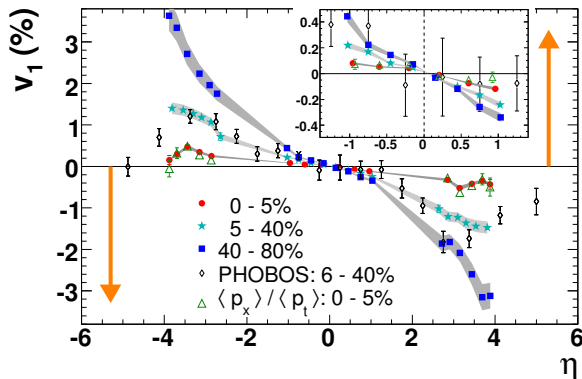


fig. from PRL **101** 252301 (2008)

Directed flow:
Electromagnetic origin

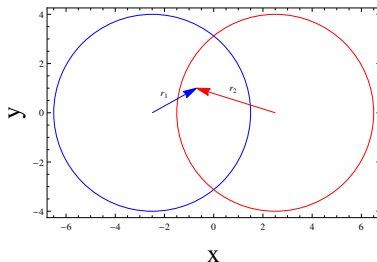
Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

entropy deposition in non-central collision



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

Directed flow:
Electromagnetic origin

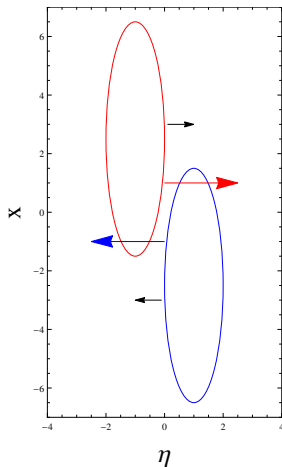
Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

entropy deposition in non-central collision



Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

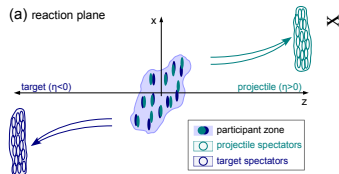
Directed flow:
electromagnetic +
geometric

Summary

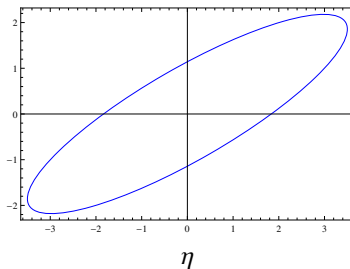
Backup

entropy deposition from participant sources

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



from 1306.4145



Bulk profile

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

Initial condition for a tilted fireball

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

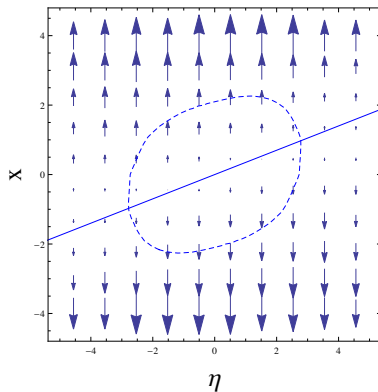
$$s(\tau_0, x, y, \eta_{||}) = s_0 \left[\alpha N_{coll} + (1 - \alpha) (N_{part}^+ f_+(\eta_{||}) + N_{part}^- f_-(\eta_{||})) \right] f(\eta_{||})$$

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

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

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

Tilted bulk \rightarrow directed fluid velocity



Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

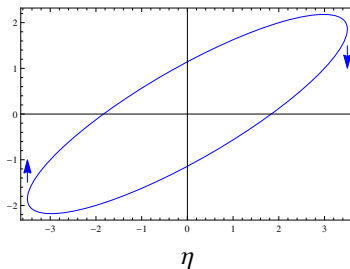
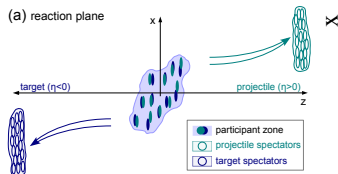
Directed flow:
electromagnetic +
geometric

Summary

Backup

Tilted bulk \rightarrow directed fluid velocity

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



from 1306.4145

Bulk directed flow

Directed flow:
Electromagnetic origin

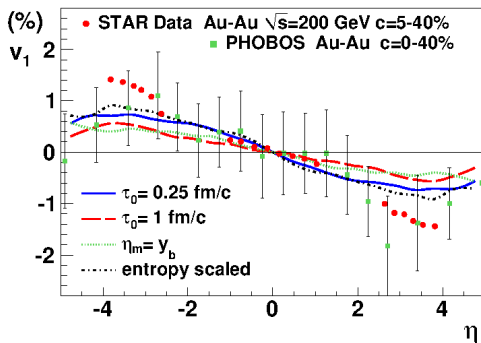
Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

Tilted bulk \rightarrow directed fluid velocity \rightarrow charged particle v_1



Bożek, Wyskiel 2010

- Tilted IC captures the charged particle v_1
- small v_1

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

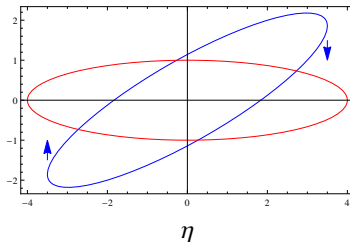
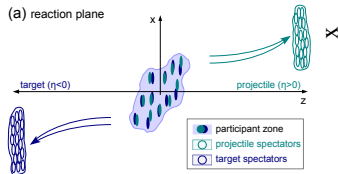
Summary

Backup

entropy depositing sources: participant vs binary collision sources

HQ from hard processes \rightarrow FB-symmetric

Rapidity-even HQ dragged by Rapidity-odd bulk



from 1306.4145

Bulk vs heavy flavor

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

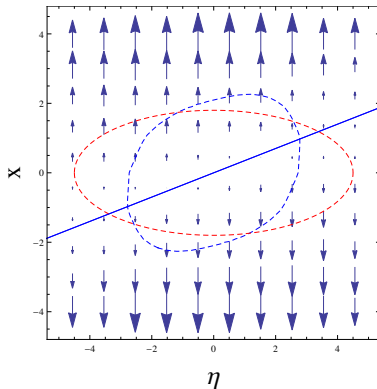
Directed flow:
electromagnetic +
geometric

Summary

Backup

Heavy Quark Tomography

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



Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

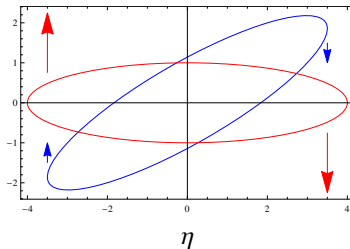
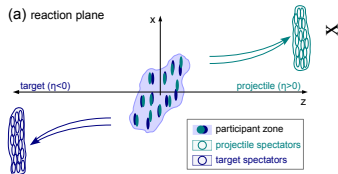
Directed flow:
electromagnetic +
geometric

Summary

Backup

entropy depositing sources: participant vs binary collision sources

(a) reaction plane



from 1306.4145

$$v_1(HQ) > v_1(Bulk)$$

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

to quantify the heavy flavor v_1

need to calibrate

- the tilt of the bulk: constrained by charged particle v_1 , Božek, 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
$$\gamma = \gamma_0 T \left(\frac{T}{m} \right)^x$$

Directed flow:
Electromagnetic origin

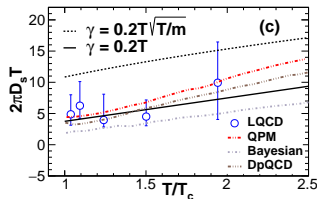
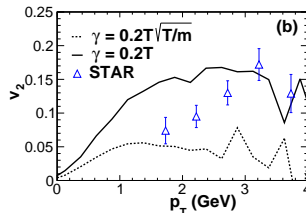
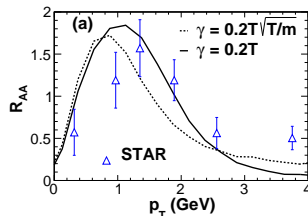
Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

Calibrating the drag on HQs



Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

SC, Bożek PRL, **120**, 192301 (2017)

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

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

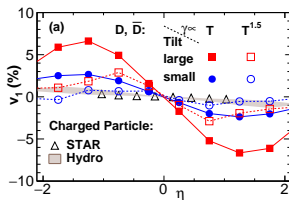
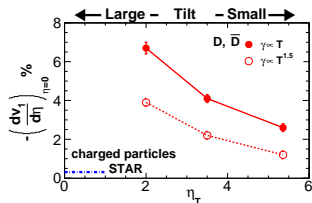
Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

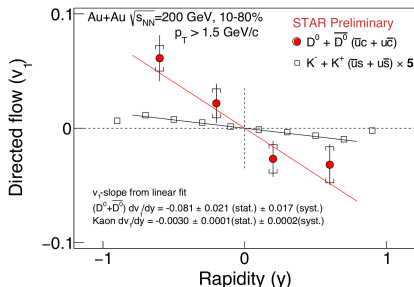


SC, Bożek PRL, **120**, 192301 (2017)

fresh from QM 2018: largest measured directed flow



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

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

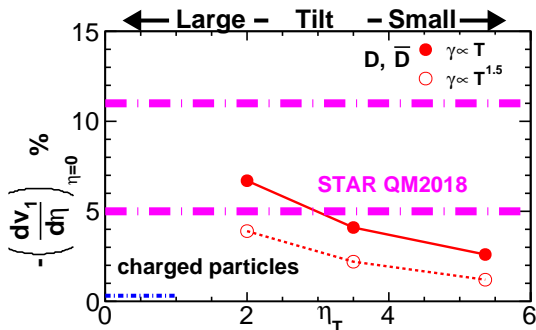
Directed flow:
electromagnetic +
geometric

Summary

Backup

comparison to data

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



SC, Božek PRL, **120**, 192301 (2017)

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

comparison to data

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

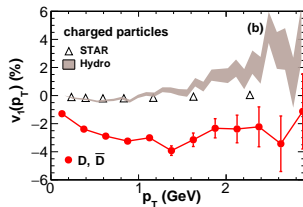
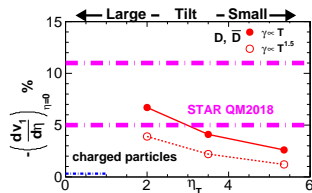
Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

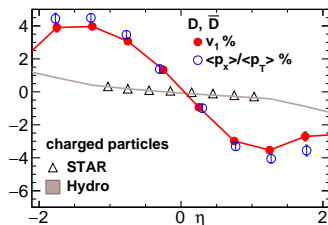
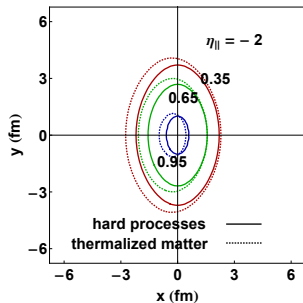
Backup



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

SC, Bożek PRL,**120**, 192301 (2017)

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



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

SC, Bożek PRL,**120**, 192301 (2017)

Directed flow:
Electromagnetic origin

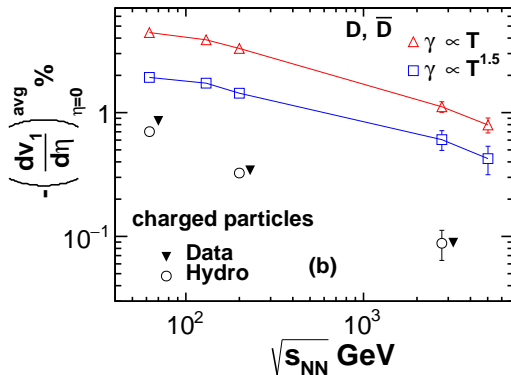
Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

Beam energy dependence



Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

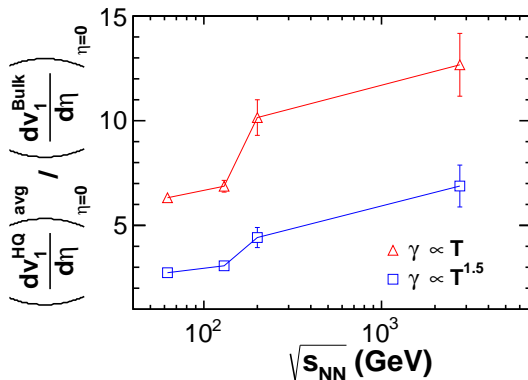
Directed flow:
electromagnetic +
geometric

Summary

Backup

SC, Bozek 1804.04893

Ratio of HQ to bulk v_1



Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

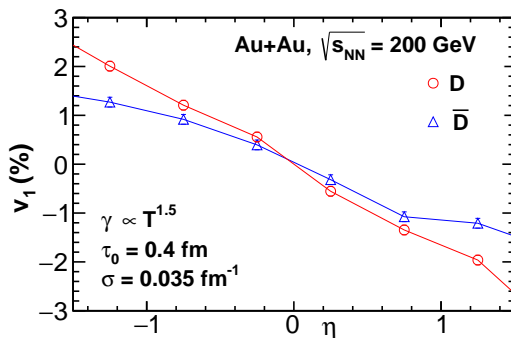
Directed flow:
electromagnetic +
geometric

Summary

Backup

SC, Bożek 1804.04893

HQ v_1 with Tilt+EM field



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

SC, Bozek 1804.04893

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

Dependence on conductivity and initialization time

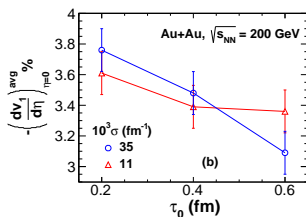
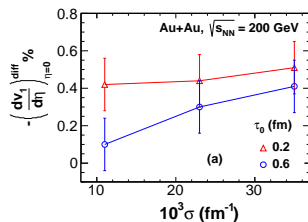
Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

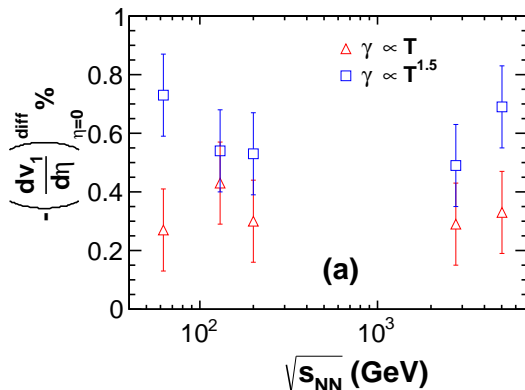
Summary

Backup



SC, Bożek 1804.04893

Beam energy dependence



Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

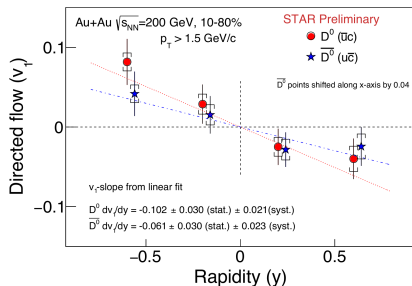
Backup

SC, Bożek 1804.04893

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



D^0 and \bar{D}^0 v_1



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

$$D^0 \, dv_1/dy = -0.102 \pm 0.030 \pm 0.021$$

$$\bar{D}^0 \, dv_1/dy = -0.061 \pm 0.030 \pm 0.023$$

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

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

Directed flow:
Electromagnetic origin

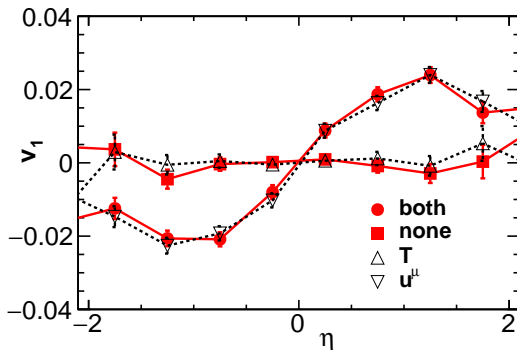
Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup

BACKUP: what causes the large v_1 : T or u^μ ?



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

Directed flow:
Electromagnetic origin

Directed flow:
Geometric origin

Directed flow:
electromagnetic +
geometric

Summary

Backup