Directed flow v1

ELSEVIER

15 July 1999

PHYSICS LETTERS B

Physics Letters B 458 (1999) 454–459

Third flow component as QGP signal

L.P. Csernai [a,b,1], D. Röhrich [a]

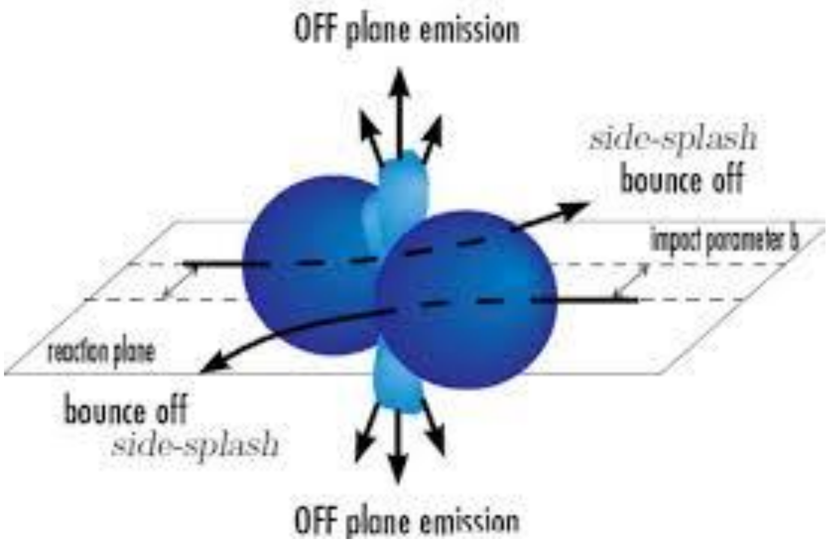
[a] *Department of Physics, University of Bergen, Allégaten 55, 5007 Bergen, Norway*
[b] *KFKI – Research Inst. for Particle and Nuclear Physics, P.O.Box 49, 1525 Budapest 114, Hungary*

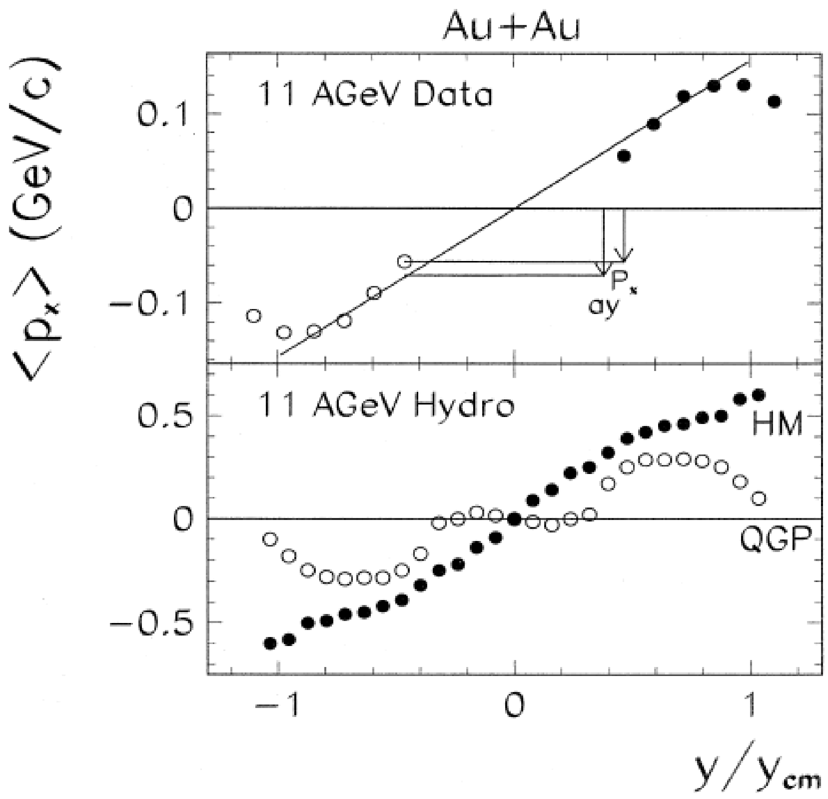
Received 16 February 1999; received in revised form 13 May 1999
Editor: W. Haxton

Abstract

A review of earlier fluid dynamical calculations with QGP show a *softening* of the directed flow while with hadronic matter this effect is absent. The effect shows up in the reaction plane as enhanced emission which is orthogonal to the directed flow. Thus, it is not shadowed by the deflected projectile and target. As both of these flow components are in the reaction plane they form an enhanced 'elliptic flow' pattern. Recent experimental data at 11 AGeV and above show the same *softening*, hinting at QGP formation.

Directed flow v1



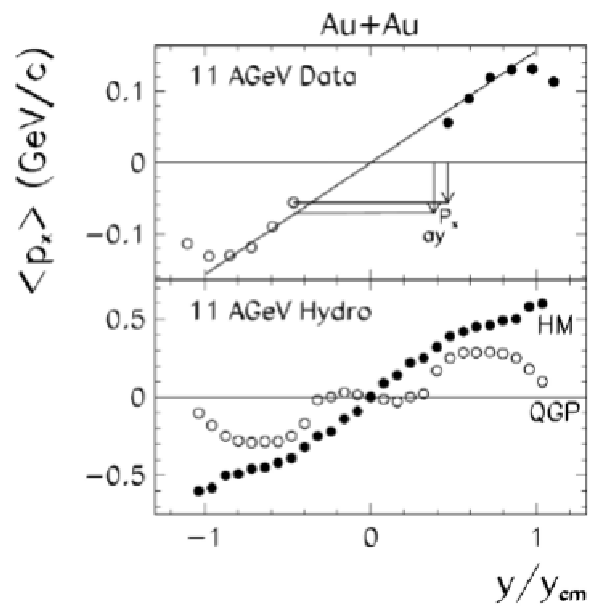


Directed flow v1 – NA61

Directed flow and the onset of deconfinement

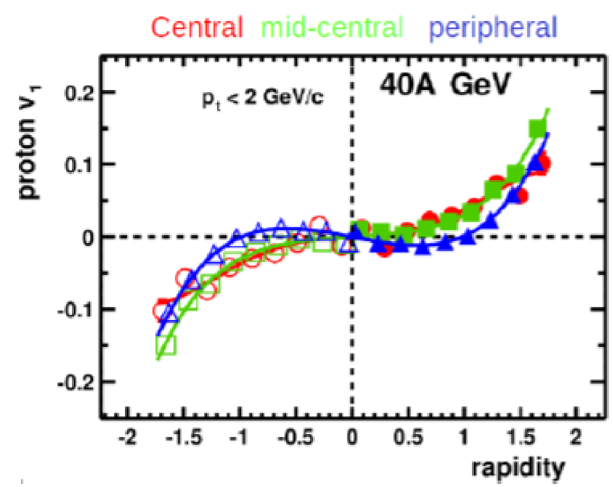
Directed flow v_1 is considered to be **sensitive to 1st order phase transition** (softening of EOS). Expected: **non-monotonic behavior** (positive→negative→positive) **of proton dv_1/dy as a function of beam energy** - "collapse of proton flow"

Predictions of hydrodynamical model:



$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

Directed flow measured by NA49 at middle SPS energy ("anti-flow" of protons at mid-rapidity):



Csernai, Rohrich, PL B458, 454, 1999 H. Stoecker NP 750, 121, 2005

NA49, Phys. Rev. C68, 034903, 2003

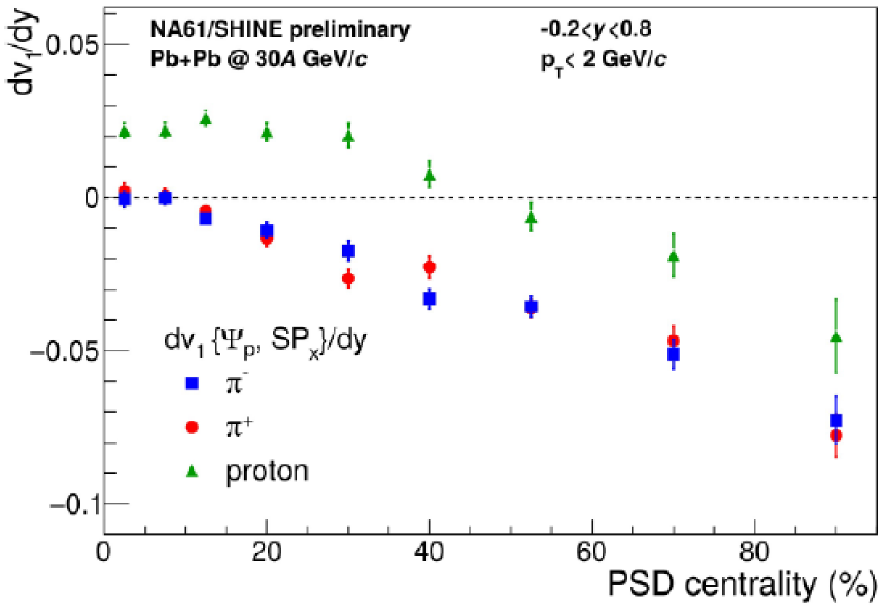
Directed flow v1 – NA61

Centrality dependence of dv_1/dy in Pb+Pb at $\sqrt{s_{NN}} = 7.6$ GeV

NA61/SHINE fixed target setup → tracking and particle identification over wide rapidity range

Flow coefficients are measured relative to the **spectator plane estimated with Projectile Spectator Detector** (PSD) → unique for NA61/SHINE

NEW



Close to mid-rapidity (-0.2 < y < 0.8)

- slope of pion v_1 is negative for all centralities

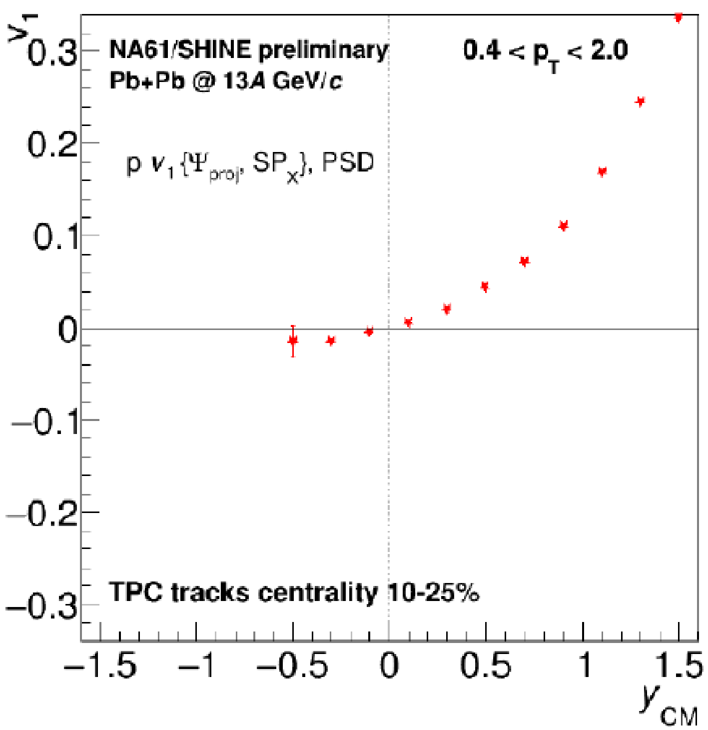
- slope of proton v_1 changes sign at centrality of about 50%

More NA61/SHINE flow results:
Klochkov, Selyuzhenkov (QM2018 talk)

Directed flow v1 – NA61

Proton directed flow vs rapidity

NA61 Pb+Pb at 13*A* GeV/c

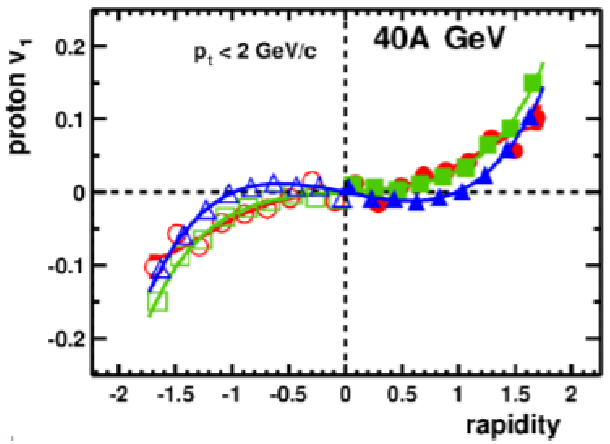


No evidence for the collapse of proton directed flow in Pb+Pb at 13*A* GeV/c

NEW

Directed flow measured by NA49 at middle SPS energy ("anti-flow" of protons at mid-rapidity):

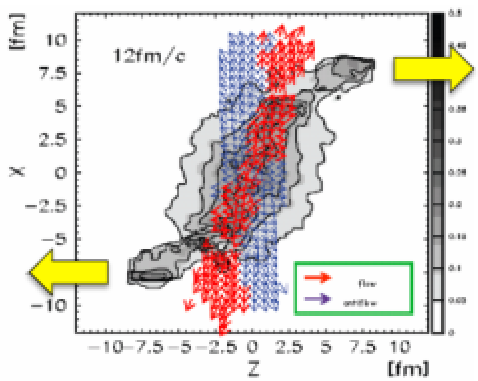
Central mid-central peripheral



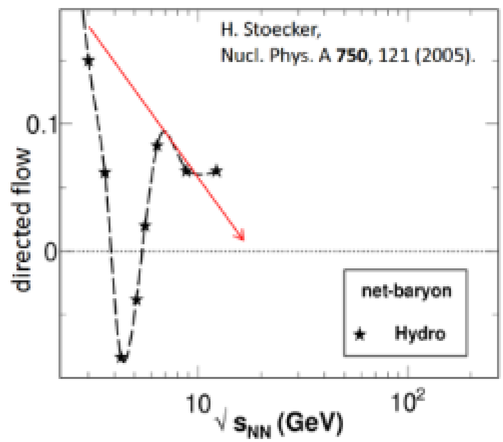
Directed flow v1 – STAR

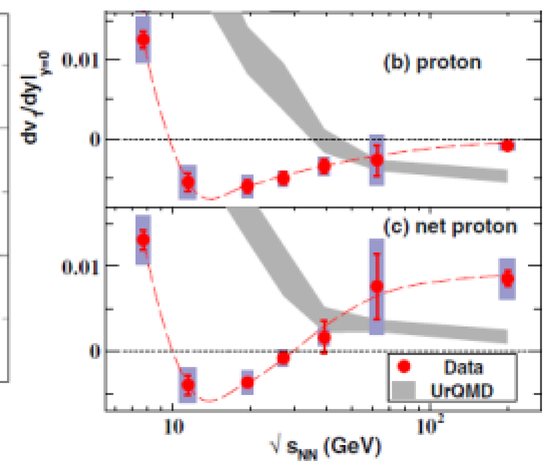
Directed Flow (v_1)

STAR, Phys. Rev. Lett. 112 (2014) 162301



J. Brachmann et al., PRC 61, 24909 (2000).



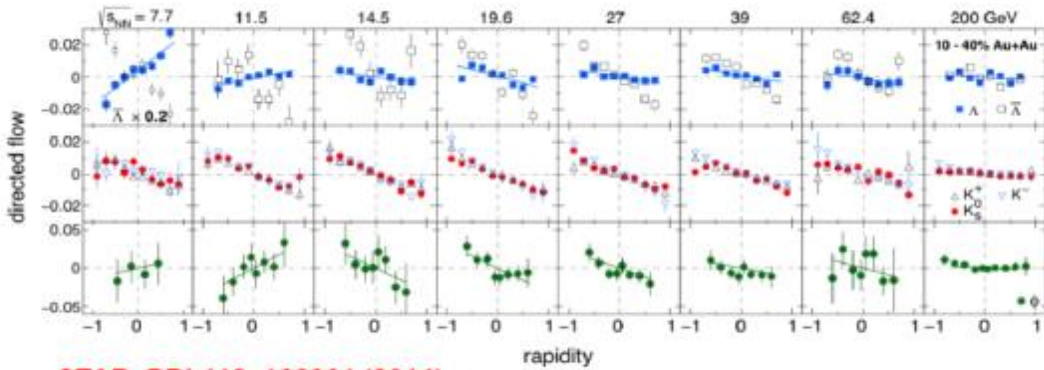


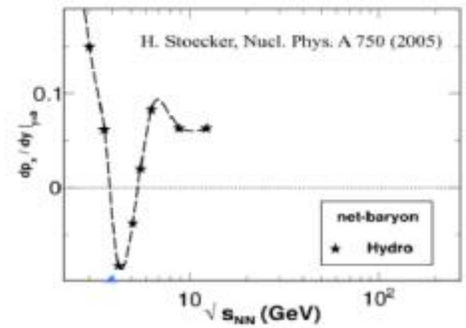
Probe of the softening of the Equation of State

- strong softening: consistent with the 1st-order phase transition
- weaker softening: more likely due to crossover

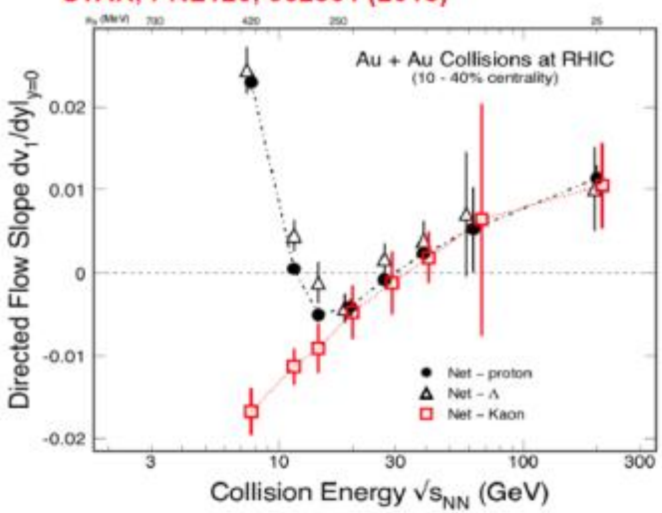
Directed flow v1 – STAR

Directed flow (STAR BES-I)





STAR, PRL112, 162301 (2014)
STAR, PRL120, 062301 (2018)

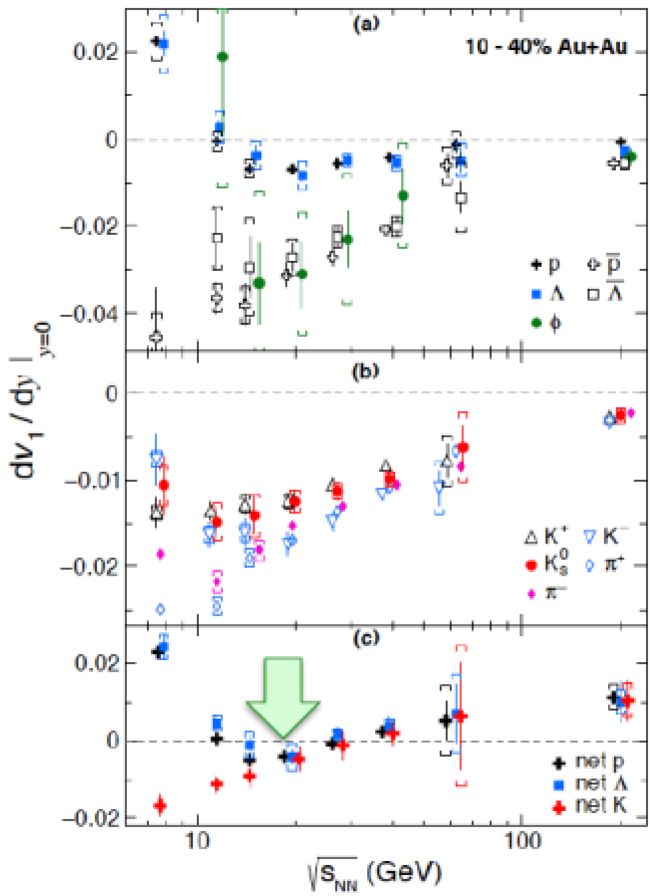


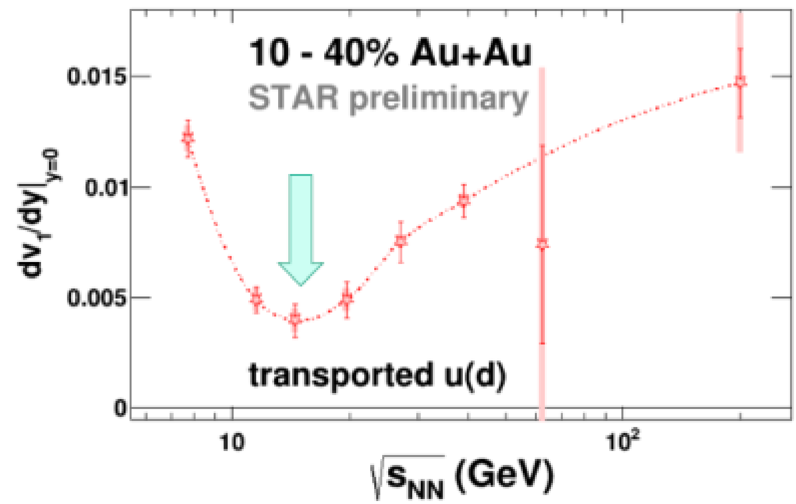
- Sign change of proton dv_1/dy, softening of EOS, first-order phase transition
- Double sign change seen in net-proton, net-Λ, not seen in net-kaon
- Need theory to explain

Directed flow v1 – STAR

Directed Flow of Identified Particles

STAR, Phys. Rev. Lett. 120 (2018) 62301





$$(v_1)_{trans.u(d)} = [(v_1)_{net\ p} - (3 - N_{trans.u(d)})(v_1)_{\bar{u}(\bar{d})}]/N_{trans.u(d)}$$

$$N_{trans.u(d)} = 3[1 - exp(-2\mu_{u(d)}/T_{ch})]/(1 - r_{\bar{p}/p})$$

- 10 species & 8 energies allow a detailed study of constituent-quark v_1. In most cases, the coalescence picture works for both “produced” particles and “net” particles
- “Transported quark” v_1 has a local minimum at ~14.5 GeV

Heavy quarks directed flow v1

Heavy Flavour dynamics: sources of v_1 for charm quarks

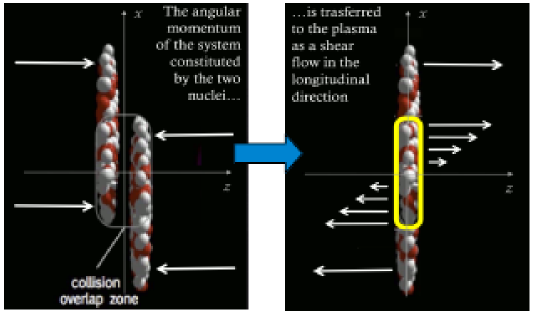
- Vorticity due to the large orbital angular momentum in uRHIC $J \approx 10^5 - 10^6\ \hbar$

  Becattini, Piccinini e Rizzo, PRC 77, 024906 (2008)
  Csernai, Magas and Wang - Phys. Rev. C 87 (2013) 034906
  Becattini et al, EPJ C 75, 406 (2015)
  Deng and Huang, PRC 93, 064907 (2016)
  Jiang, Lin and Liao, PRC 94, 044910 (2016); PRC 95, 049904 (2017)

  - ***Are HQ affected by the initial vorticity of the QGP?***

    Solving the relativistic Langevin eq. with tilted initial distribution in the reaction plane produce a v_1 of D meson several times larger than that of charged particle.

    S. Chatterjee, P. Bożek PRL 120 (2018) no.19, 192301



- Intense magnetic field B:

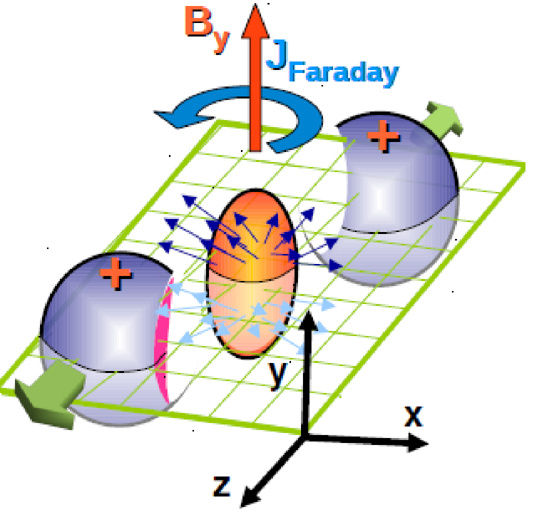
  created on Earth ≈ 10^7 Gauss
  in Neutron Star ≈ 10^{13} Gauss
  in uRHIC ≈ 10^{19} Gauss ≈ $10\ m_\pi^2$

  A. Bzdak, V. Skokov, PLB **710** (2012) 171-174
  K. Tuchin, PRC **88**, 024911 (2013).
  K. Tuchin, Adv. High Energy Phys. 2013, 1 (2013).
  K. Hattori, X.-G. Huang Nucl.Sci.Tech. 28 (2017) no.2, 26.

  - ***Are HQ affected by the initial EM field produced in a HIC?***

    Solving the relativistic Langevin eq. with Lorentz force a sizeable v_1 for charm (anti-charm) quarks is produced.

    *S.K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB **768** (2017) 260.*

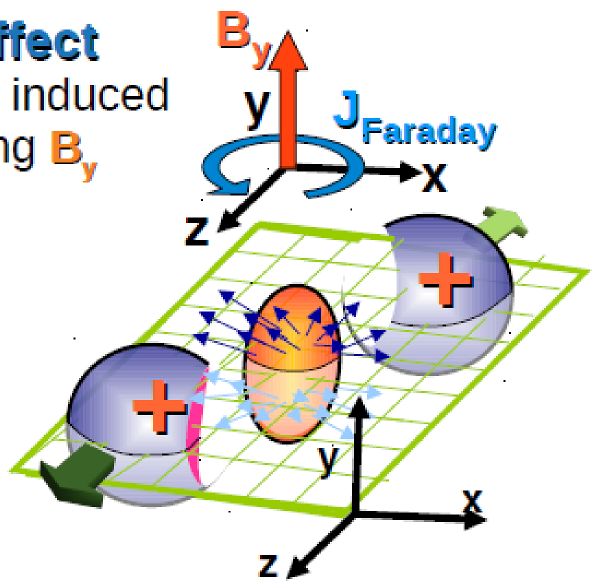


Heavy quarks directed flow v1

The direct flow v_1 originates from two competing effects:

Faraday effect

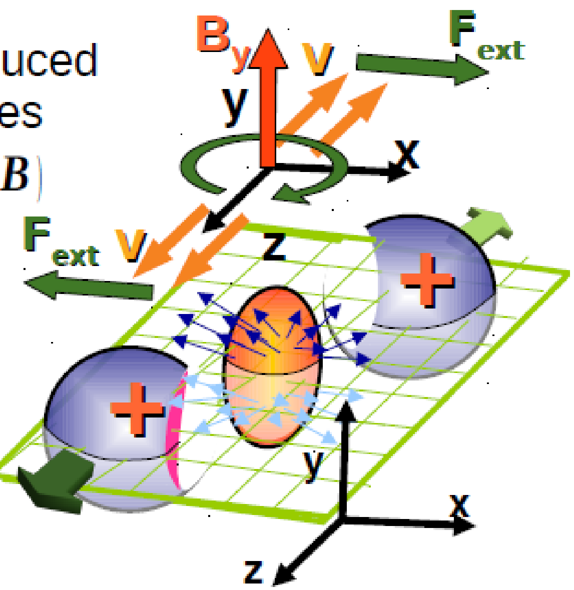
Electric field induced by decreasing B_y



Hall effect

Lorentz force induced by moving charges

$$F_{ext} = q\,E + \frac{q}{E_p}(\mathbf{p} \times \mathbf{B})$$



Transport properties of Heavy Quarks and their correlations to the bulk dynamics and the initial Electromagnetic field

S. Plumari

Università degli Studi di Catania

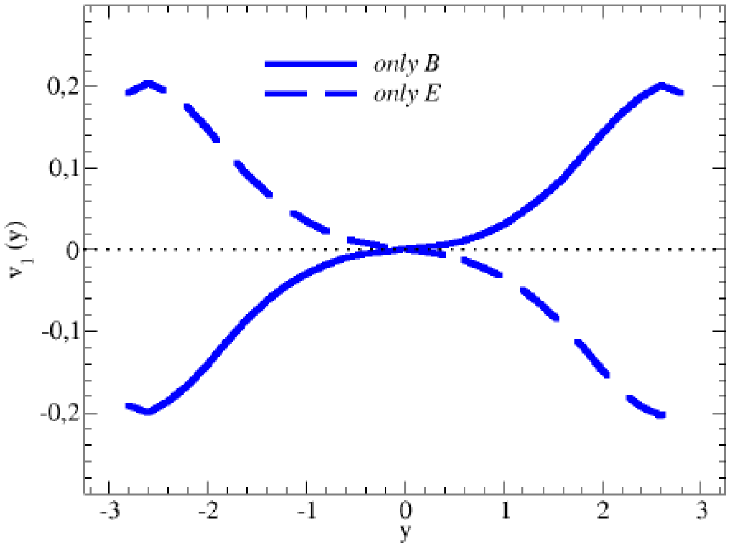
INFN-LNS

IN COLLABORATION WITH:

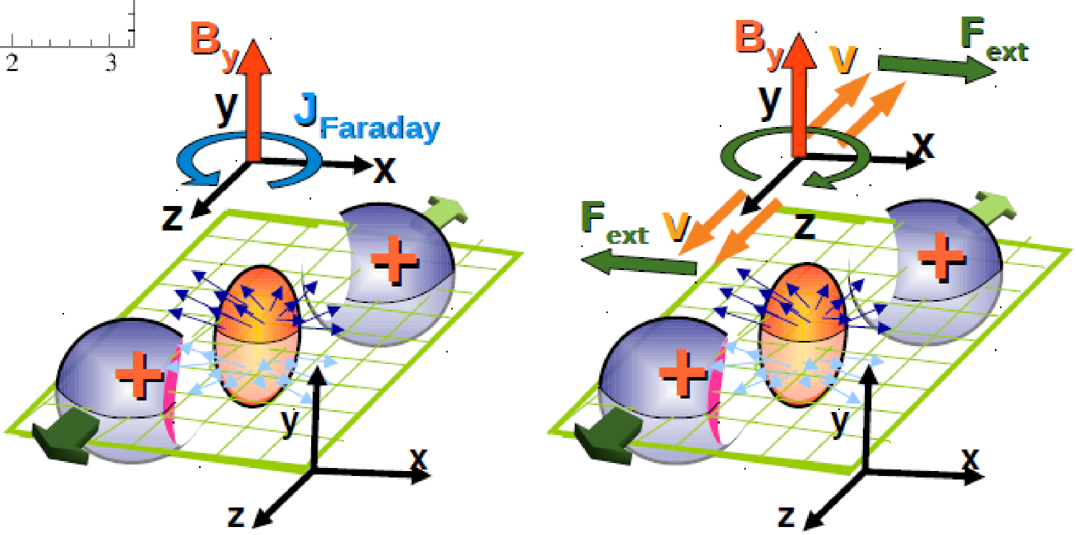
V. Minissale, G. Coci, L. Oliva, S. K. Das, V. Greco

Heavy quarks directed flow v1

Balance between Magnetic and Electric fields

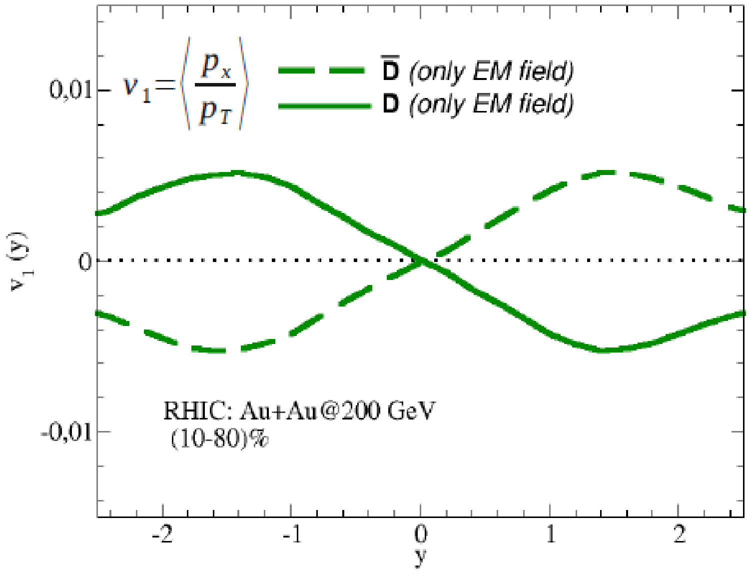


- Decreasing magnetic field B_y creates E_x that induces a current in opposite direction w.r.t. to the Magnetic Hall drift: delicate balance!
- Larger initial (t<1 fm/c) field important to determine a sizeable v_1 flow
  S.K. Das et al., PLB 768 (2017)



Heavy quarks directed flow v1

Direct Flow v_1 of charm quarks



For light quarks was predicted $v_1 \approx 10^{-3}$ -10^{-4}

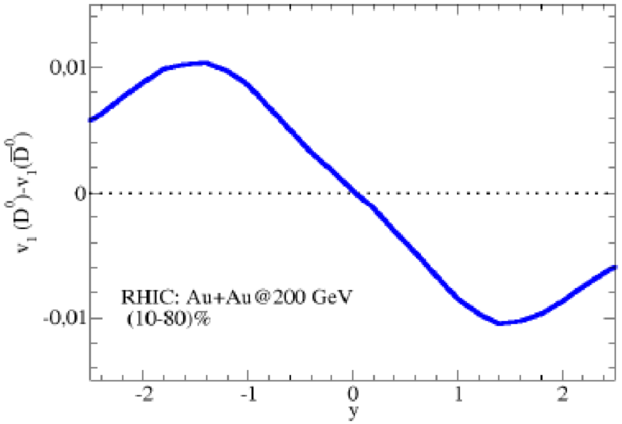
U. Gürsoy, D. Kharzeev, K. Rajagopal PRC 89, 054905 (2014).

For charm quarks due to early production we find a sizeable v_1 with the same E-B evolution

S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB768 (2017) 260-264.

HQ best probe for v_1 from e.m. field:

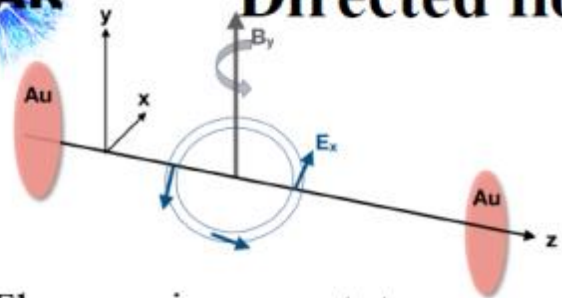
- $t_{form} \approx 0.1$ fm/c
- $\tau_{th}(c) \approx \tau_{QGP} >> \tau_{e.m}$
- do not mix vorticity [Odd- parity]

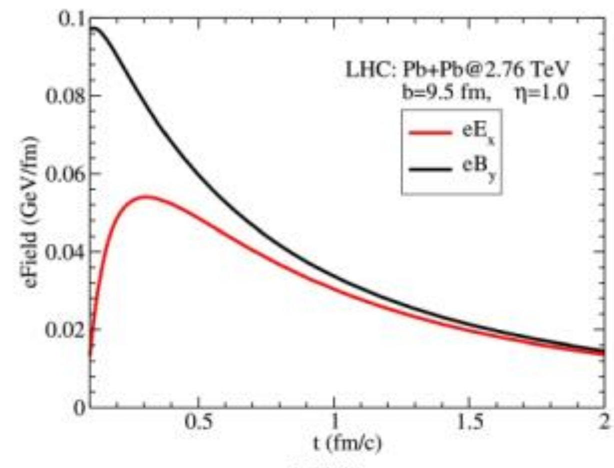


Heavy quarks directed flow v1 - STAR

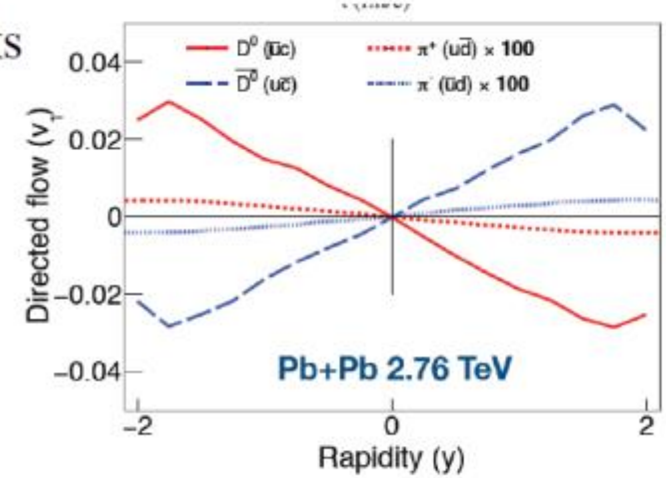
STAR

Directed flow (v1) due to EM fields





- The moving spectators can produce enormously large electromagnetic field (eB ~ 10^{18} G at RHIC)
- Due to early production of heavy quarks (τ_{CQ} ~ 0.1 fm/c) positive and negative charm quarks (CQs) can get deflected by the initial EM force
- D^0 and $\overline{D}^0$ v_1 can offer insight into the early time EM fields



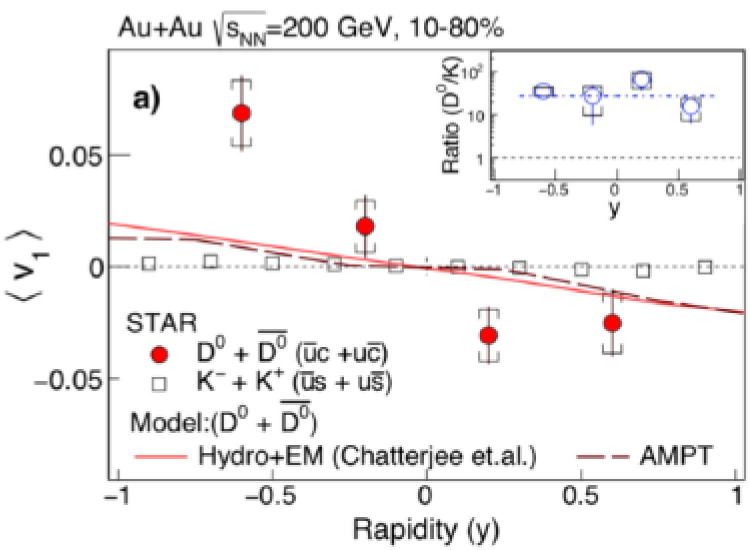
Das et. al., Phys Lett B 768, 260 (2017)

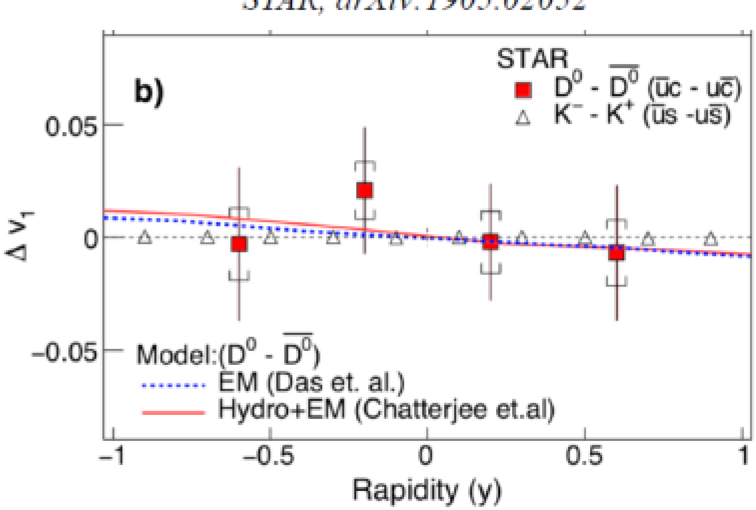
Heavy quarks directed flow v1 - STAR

D^0 Directed Flow (v_1)

S.K. Das et al, PLB 768 (2017) 260

- Charm quarks interact with bulk medium → D^0 v_1 sensitive to the initial tilt of the source (bulk) *S. Chatterjee and P. Bożek, PRL 120 (2018) 192301*
- Charm and anti-charm quarks can be deflected differently by the initial EM field → difference between D^0 and $\overline{D^0}$ v_1 sensitive to EM field
- First observation of non-zero (negative) $D^0(\overline{D^0})$ v_1 slope, much larger than that of kaons $D^0 + \overline{D^0}$ $dv_1/dy = -0.081 \pm 0.021(stat) \pm 0.017(sys)$
- More precise data are needed for Δv_1 $d\Delta v_1/dy = -0.041 \pm 0.041(stat) \pm 0.020(sys)$





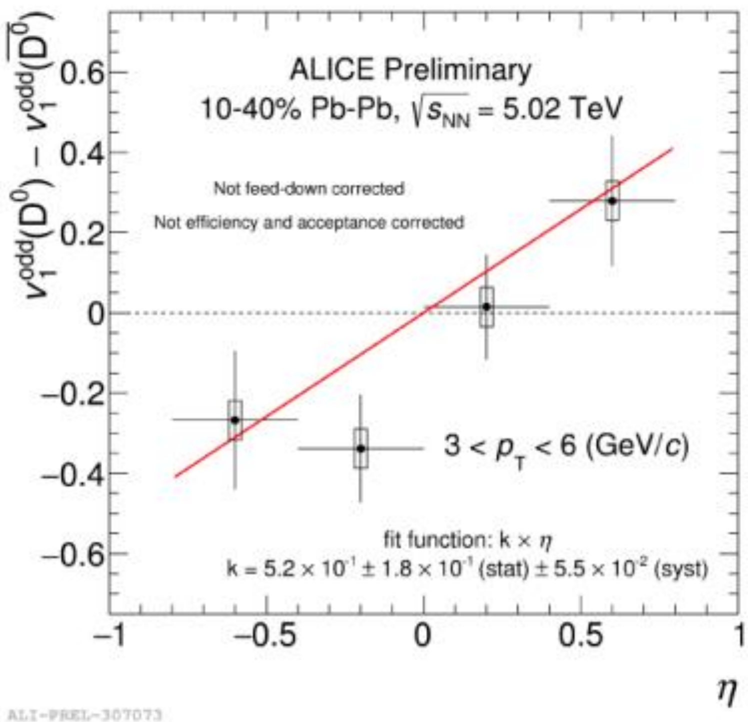
Guannan Xie 17

Heavy quarks directed flow v1 - ALICE

Universiteit Utrecht

Delta v_1 low p_T for D^0 meson

ALICE



- The difference of the directed flow, Δv_1 → quantify the effect of the charge separation due to the presence of an electromagnetic field
- Rapidity dependence of the charge difference Δv_1 is fitted using a linear function with slope ***k***
- ***k* = 0.52 ± 0.18(stat) ± 0.05(syst)**
- The significance of the measurement **2.7σ**.