Anisotropic flow generated by hard partons in medium

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Azimuthal anisotropy of hadronic momentum distributions

- parametrized by Fourier expansion

$$\frac{dN}{p_t\, dp_t\, dy\, d\phi} = \frac{1}{2\pi}\frac{dN}{p_t\, dp_t\, dy}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_t, y)\cos\left(n(\phi - \phi_n)\right)\right)$$

- summation over many events in symmetric collision at midrapidity $\Rightarrow$ symmetry constraints: $\phi_n = 0$, $n = 2, 4, 6, \ldots$

- all v_n's non-vanishing in individual events

Anisotropic expansion

- generic effect: blue-shift
  ⇒ more particles and higher p_t in direction of stronger transverse flow
- link between the observable spectrum and the expansion of the fireball
- expansion results from the pressure gradients
- anisotropic expansion ⇐ anisotropic pressure gradients in initial conditions

Hydrodynamics – state of the art

- Conservation laws

$$\partial_\mu T^{\mu\nu} = 0$$

- energy momentum tensor

$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu + p\, g^{\mu\nu} + \Pi^{\mu\nu}$$

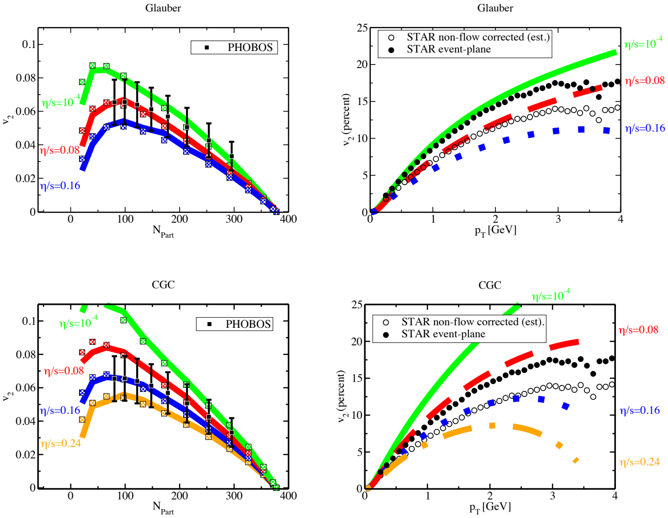
  with stress tensor $\Pi^{\mu\nu} = \pi^{\mu\nu} + \Delta^{\mu\nu}\Pi$
  (split into traceless shear and non-traceless bulk contribution)

- viscous corrections

$$\begin{aligned} \pi^{\mu\nu} &= \eta(\epsilon) \left(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3} \triangle^{\mu\nu} \nabla_\alpha u^\alpha \right) \\ \Pi &= \zeta(\epsilon)\, \nabla_\alpha u^\alpha \end{aligned}$$

- Equation of State $p = p(\epsilon)$

Initial conditions – an ambiguity (illustration)

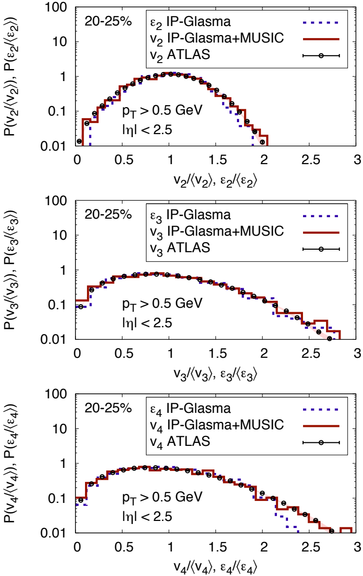


[M. Luzum, P. Romatschke: Phys. Rev. C **78** (2008) 034915]

Fluctuating initial conditions

- Use the fluctuations of v_n's to get the access to initial conditions.
- fluctuations of v_n's seem to follow those of spatial anisotropies ε_n's

[Ch. Gale et al.:
Phys. Rev. Lett. **110** (2013) 012302]



Motivation

We want

- Equation of State
- transport properties (viscosities)

Then we must

- disentangle the influence of (fluctuating) initial conditions
- get under control all other effects influencing the anisotropies of hadronic distributions

Here we propose

a novel mechanism which contributes to anisotropies of hadronic distributions.

The idea

- At the LHC there is copious production of hard partons – may have more than one pair in single event.
- Their momentum is deposited into medium over some time span ⇒ collective flow, wakes, streams
- Anisotropic flow – event by event
- Elliptic flow after summation over all events.

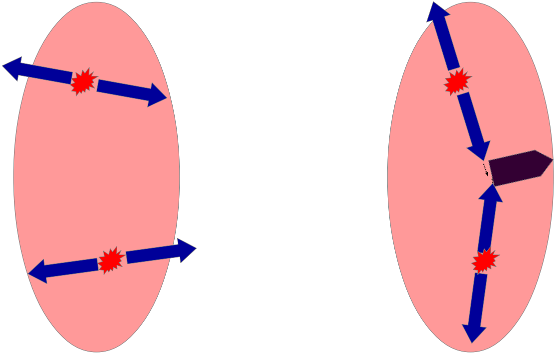
Anisotropic flow from isotropic jets

Streams are more likely to merge if they are directed out of reaction plane

$\Rightarrow$ less contribution to flow out of plane

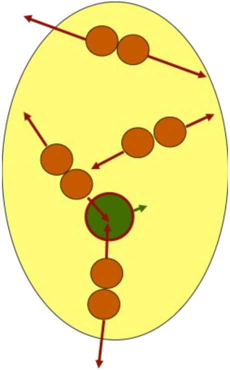
$\Rightarrow$ enhance v_2 correlated with the reaction plane

$\Rightarrow$ also contribute to v_3



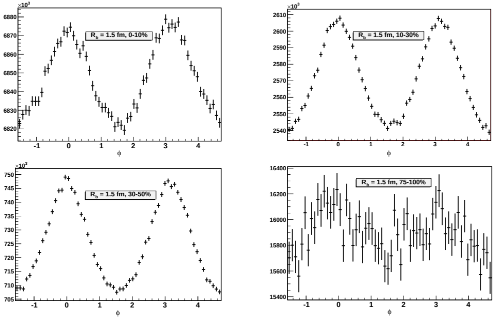
Check the idea with a toy model

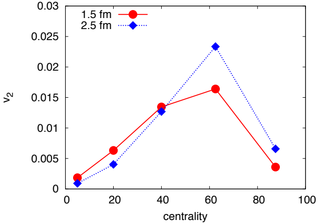
- Streams represented by drops
- Pairs of drops back-to-back (with some k_t smearing)
- Drops merge after they meet
- Size of the drop represents the radius of the stream
- Pions evaporate from droplets ($T = 175$ MeV)



Toy model – results

Azimuthal distribution of hadrons





[B. Tomášik, P. Lévai: J.Phys.G **38** (2011) 095101]

Hydrodynamic implementation

[B. Betz et al.: Phys. Rev. C **79** (2009) 034902]

Ideal hydrodynamics with source term

$$\partial_\mu T^{\mu\nu} = J^\nu$$

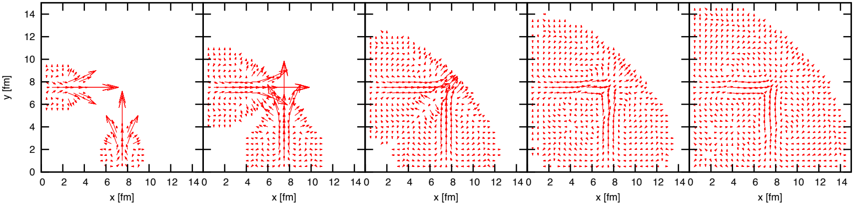
$$J^\nu = \sum_i \frac{1}{(2\,\pi\,\sigma_i^2)^{3/2}}\ \exp\left(-\frac{\left(\vec{x}-\vec{x}_{\mathrm{jet},i}\right)^2}{2\,\sigma_i^2}\right)\ \left(\frac{dE_i}{dt},\frac{d\vec{P}_i}{dt}\right)$$

with $\sigma = 0.3$ fm

Test of the concept: static medium

Two streams meet perpendicularly

Plot momentum density



[M. Schulc, B. Tomášik: J. Phys. G **40** (2013) 125104]

Hydrodynamic simulations of nuclear collisions

- 3+1D ideal hydrodynamics
- EoS from P. Petreczky, P. Huovinen: Nucl. Phys. A **897** (2010) 26
- smooth initial energy density scaled with

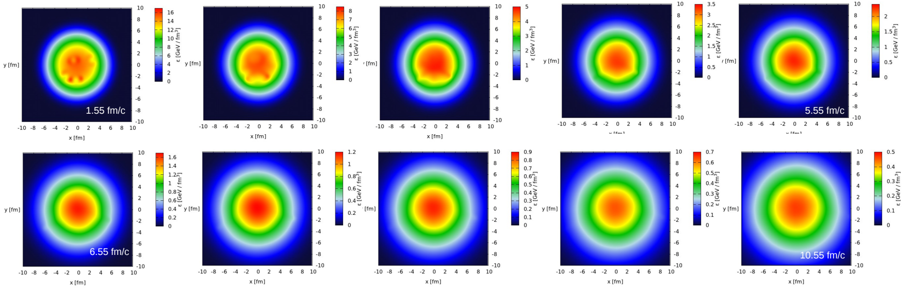
$$W(x,y;b) = (1-\alpha)n_w(x,y;b) + \alpha n_{\mathrm{bin}}(x,y;b)$$

  with $\alpha = 0.16$, $\varepsilon(0,0,0) = 60$ GeV/fm^3 at $\tau_0 = 0.55$ fm/c
  rapidity plateau over 10 units of rapidity
- $$\frac{dE}{dx} = \left.\frac{dE}{dx}\right|_0 \frac{s}{s_0}$$
- fluctuating number of jet pairs

Illustration: evolution of energy density

Evolution of an event with four pairs of jets at the beginning.

frames follow with time delay 1fm/c



Results from ultra-central collisions

Anisotropy coefficients

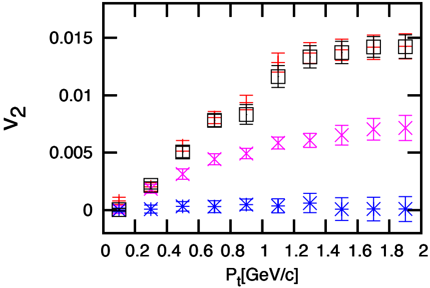
compare:

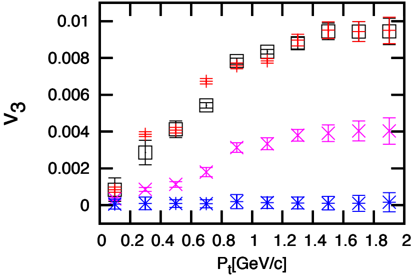
$dE/dx = 7$ GeV/fm

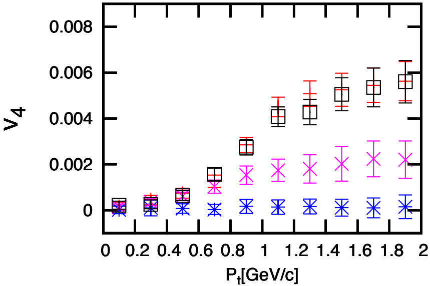
$dE/dx = 4$ GeV/fm

hot spots

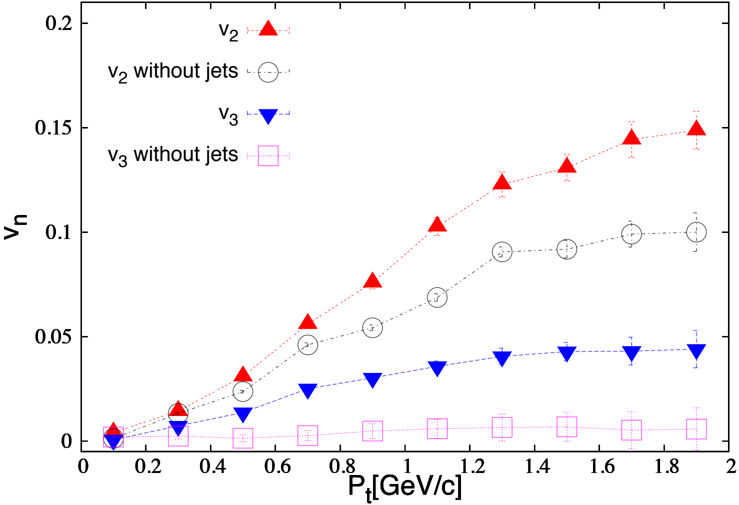
smooth initial conditions







Results from 30–40% centrality



Similar approaches

- Y. Tachibana, T. Hirano: Phys. Rev. C **90** (2014) 021902
  reponse of medium to only one dijet
- R.P.G. Andrade, J. Noronha, G. Denicol: arxiv:1403.1789
  one dijet, 2+1D hydrodynamics
- S. Floerchinger and K. Zapp: arxiv:1407.1782
  1+1D hydrodynamics

Conclusions and Outlook

- Momentum deposition from hard partons gives large contribution to anisotropic flow
  $\Rightarrow$ must be included in simulations
- The interplay of many induced streams is important
- Outlook: simulations with viscous hydrodynamics and fluctuating initial conditions