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VEGA 1/0469/15, LG15001

Flow anisotropy due to momentum deposition in ultra-relativistic nuclear collisions

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1. Minijets are plentiful at the LHC

There are many pairs of hard and/or semi-hard partons in a **single event** of a nuclear collision at the LHC.

The energy and momentum of these partons is usually completely dumped into the bulk matter. Those partons which survive become seeds of jets.

Streams are generated in the wakes within the expanding bulk matter, which carry the momentum of the hard partons.

The streams continue to flow even after partons are fully quenched. [1]

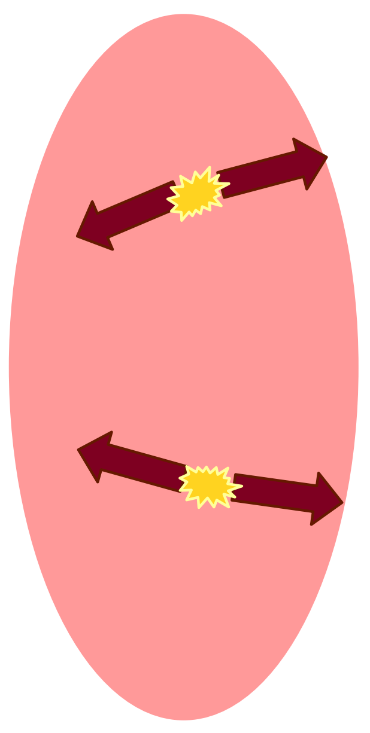
2. Anisotropic flow from the streams

Generated streams in the bulk lead to flow anisotropies event by event.

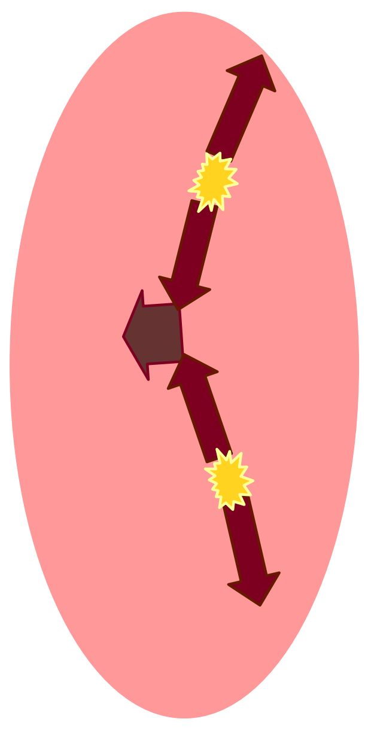
Some streams come together and merge and the generated flow anisotropy becomes correlated with the geometry of the fireball.

Cartoon sketches of how the correlation with geometry is created:

Two pairs of hard partons flying in the reaction plane produce streams which increase the elliptic flow



Streams produced out of reaction plane are more likely to meet and merge. Their contribution to transverse flow will be smaller than in the case on the left-hand side.



The large number of streams is crucial for the mergers to happen.

This mechanism produces all orders of flow anisotropy.

3. The model

- Relativistic 3+1D ideal hydrodynamic simulation with SHASTA
- Realistic lattice-QCD-based Equation of State with phase transition [2]
- **Smooth** initial energy density profile according to optical Glauber model. This is an important feature since any event-by-event fluctuation is due to the investigated effect of momentum deposition from hard partons.
- Fluctuating number of pairs of hard partons
- Pairs of hard partons are generated back-to-back in transverse momentum, but with different rapidities.
- Initial positions of hard partons are generated randomly from the distribution of binary nucleon-nucleon collisions.
- Initial transverse momentum of hard partons generated from [3]

$$\frac{1}{2\pi}\frac{\mathrm{d}\sigma}{p_t \mathrm{d}p_t \mathrm{d}y} = \frac{B}{(1+p_t/p_0)^n}$$

  with B = 14.7 mb/GeV, p_0 = 6 GeV, n = 9.5.
- Energy loss of hard partons scales with entropy density of the quenching medium

$$\frac{\mathrm{d}E}{\mathrm{d}x} = \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_0 \frac{s}{s_0}$$

  where $\mathrm{d}E/\mathrm{d}x|_0$ is a parameter of the model for which we tested several values and s_0 is the entropy density corresponding to the energy density 20 GeV/fm^3.
- Energy and momentum deposition of a parton is spread according to Gaussian with the width of 0.3 fm. (We have checked that varying the width to 0.15 fm and 0.6 fm does not influence the results much.)
- Cooper-Frye freeze-out is handled with the help of THERMINATOR2 package [4]. Production and decays of resonances are included.

References

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

[2] P. Petreczky and P. Huovinen, Nucl. Phys. A **897** (2010) 26

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

[4] M. Chojnacki *et al.*, Comp. Phys. Commun **183** (2012) 746

[5] M. Schulc, B. Tomášik, Phys. Rev. C **90** (2014) 064910

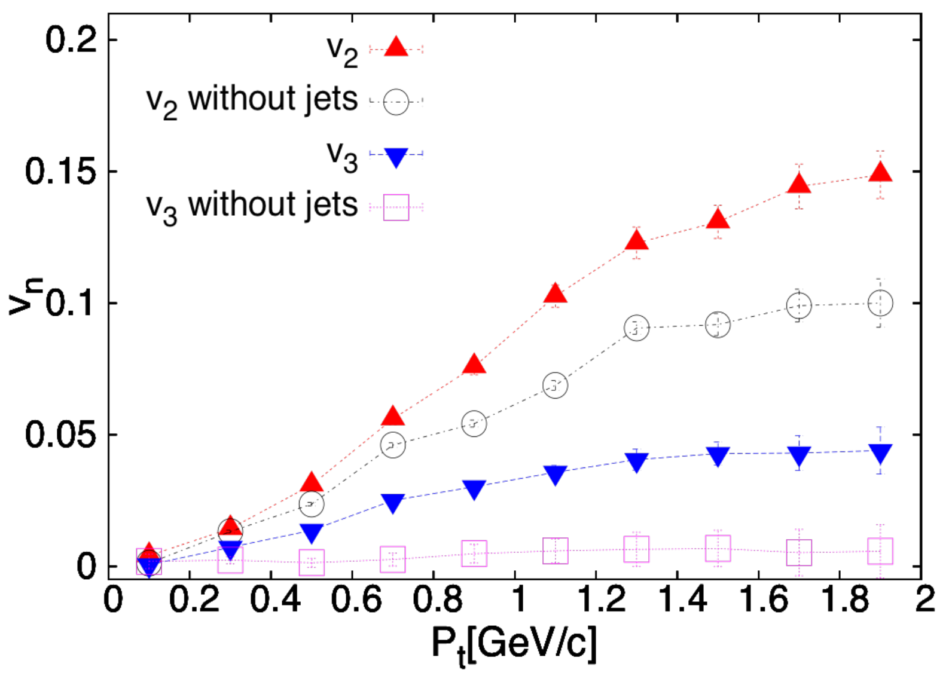
[6] M. Schulc, B. Tomášik, arxiv:1512.06215

4. Results for 30–40% centrality

Simulations confirm that the contribution of **momentum deposition** from the hard partons to the elliptic flow is constructive and of the order 50%.

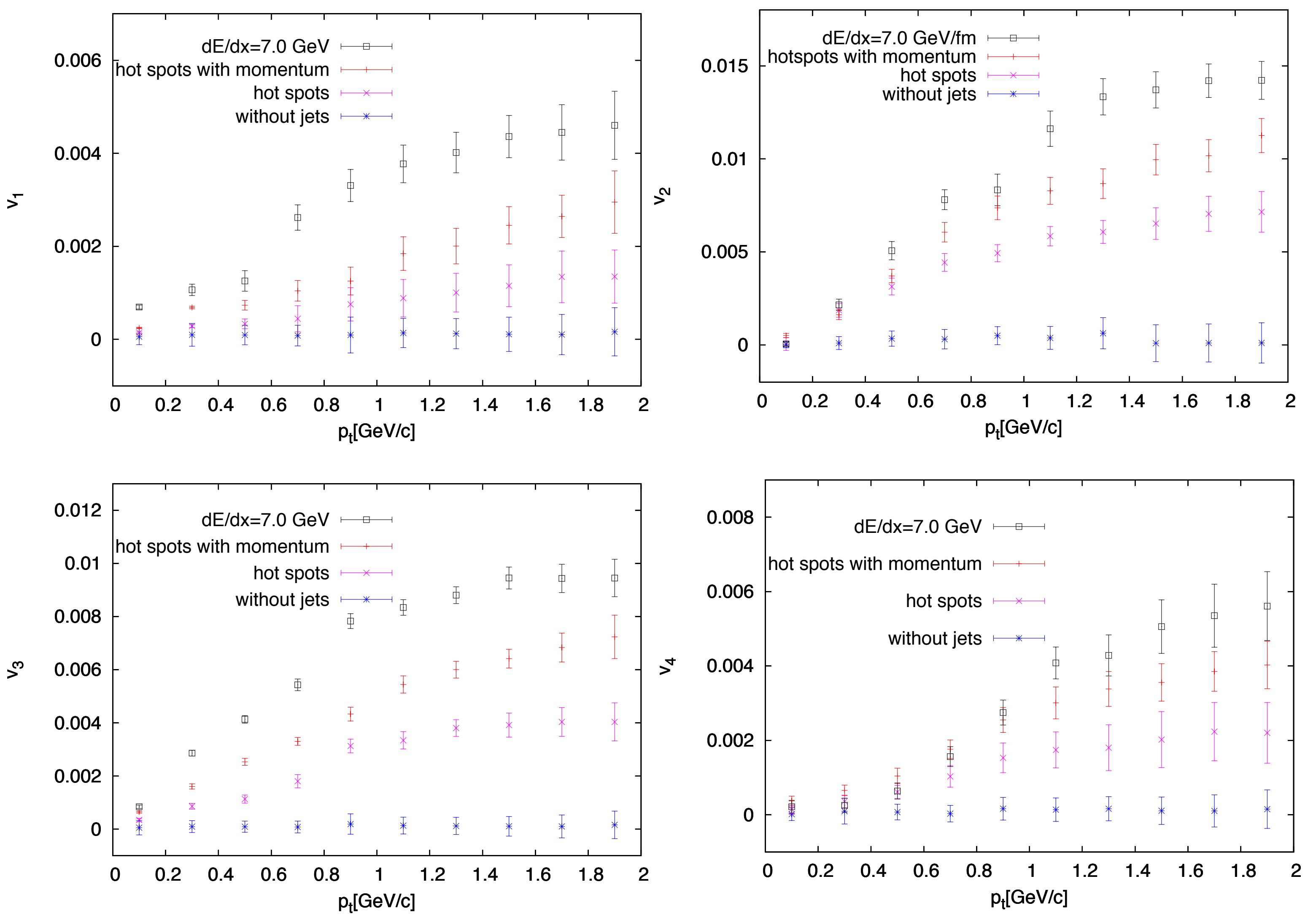
We show v_2 and v_3 for two scenarios:

- with hard partons depositing momentum, smooth initial conditions
- without hard partons and with smooth initial condition (marked ”without jets“)



5. Results for ultra-central collisions

All flow anisotropies fluctuate from event to event and are exclusively caused by the momentum deposition from the hard partons.



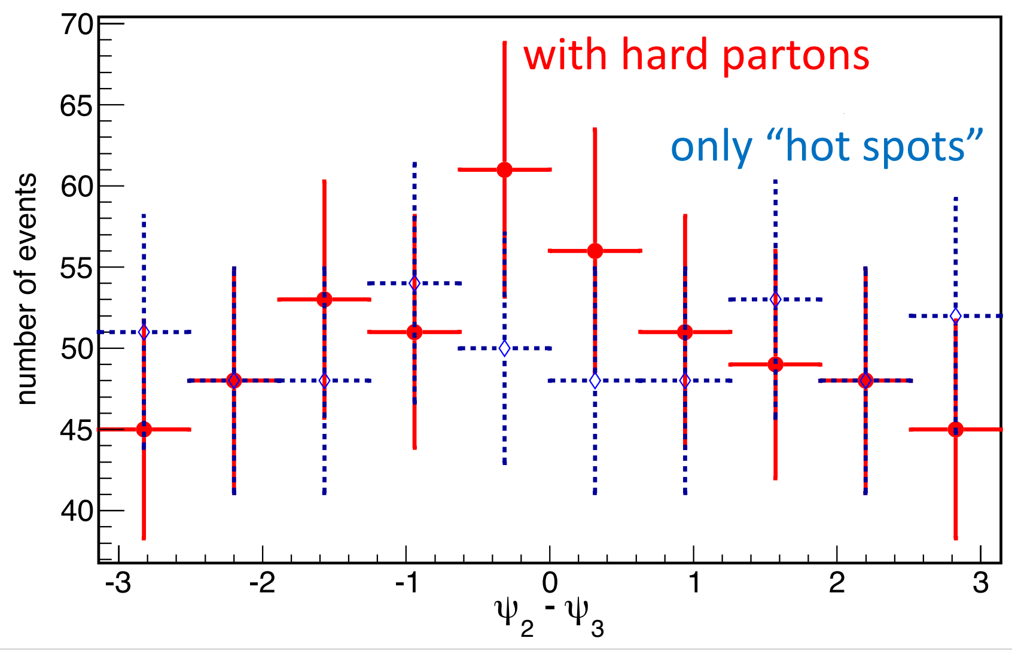
The effect of momentum deposition **during** fireball expansion cannot be simulated by simply putting in spots with the same amount of energy and/or momentum into the initial conditions. This is shown by these results:

- dE/dx = 7 GeV/fm: simulations with momentum deposition from hard partons
- hot spots: simulations with no hard partons, but the same energy as would be deposited by hard partons is superimposed as hot spots on top of the smooth energy density profile. Hot spots are distributed as would have been the hard partons at the beginning. No momentum is deposited.
- hot spots with momentum: as the “hot spots” scenario, but also with momentum deposited in the hot spots. It is the same momentum as would have been carried by the hard partons.
- without jets: simulation with only smooth initial conditions, just for reference purposes.

5. Identification of the effect

It is a question, how to distinguish the flow anisotropies due to momentum deposition from the hard partons from the ones which are due to inhomogeneities of the initial conditions.

It seems that our mechanism might lead to a correlation between second-order and third-order event planes. We tested this on a limited number of 500 events. (Statistics is too low to draw clear conclusion.)



6. Conclusions

Momentum deposition from hard jets into bulk quark-gluon plasma has an important influence on the anisotropies of hadron distributions in ultra-relativistic nuclear collisions at the LHC.

This mechanism must be included in simulations which aim at extracting the transport properties of strongly interacting matter at extreme conditions.

Results reported on this poster are published in [5,6].