Turbulent instability in low viscosity quark-gluon plasma

ID: 23

Based on

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Kelvin-Helmholtz instability in high-energy heavy-ion collisions

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Fluid dynamical prediction of changed v_1 flow at energies available at the CERN Large Hadron Collider

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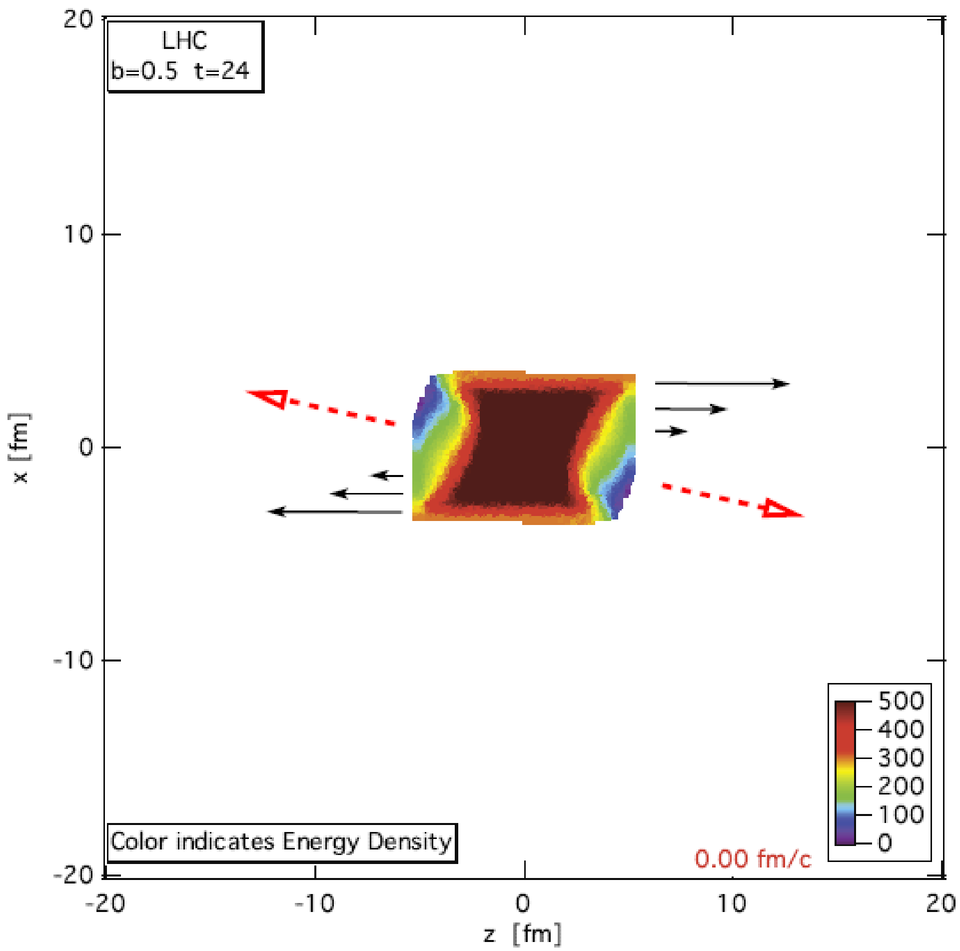
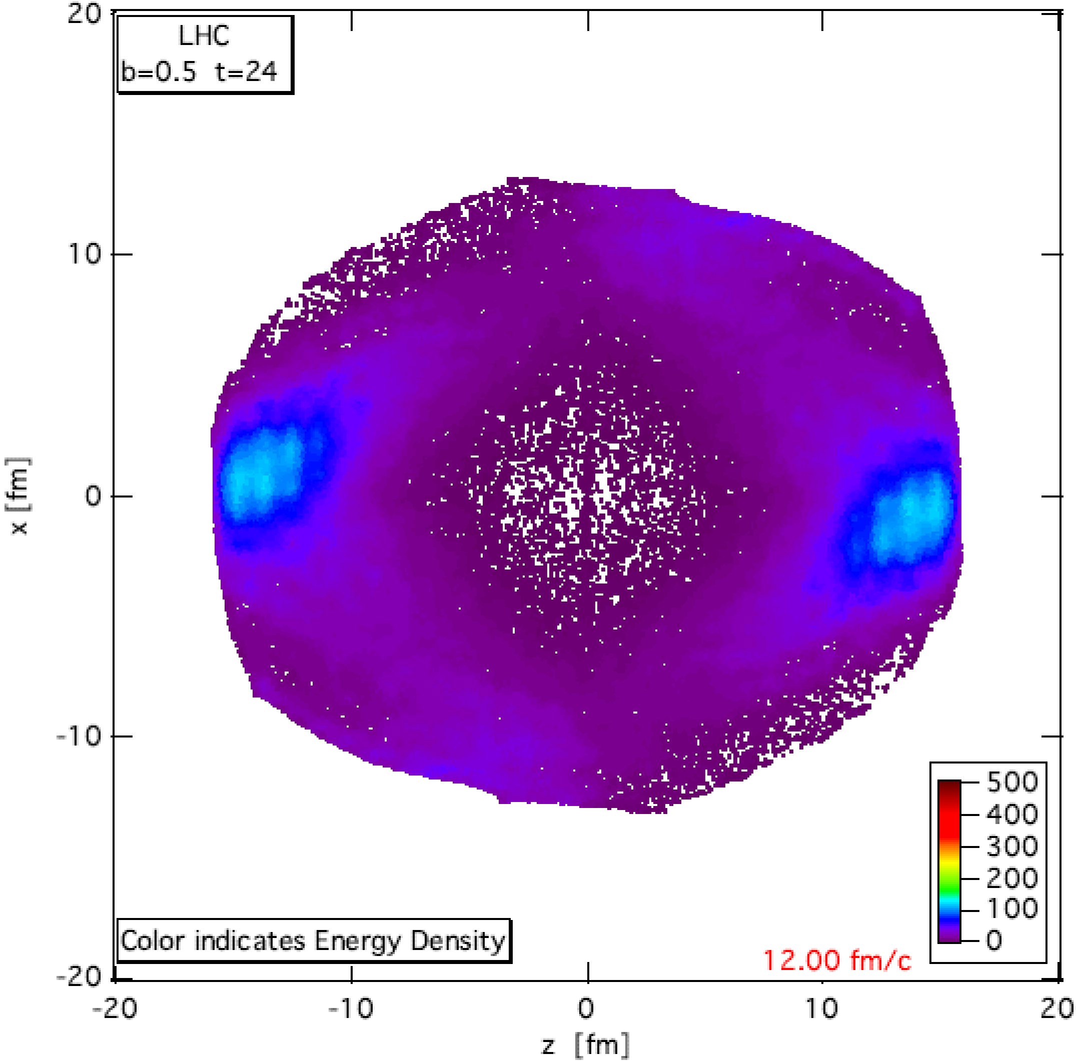


Anti-flow (v1) at LHC

Initial energy density [GeV/fm3] distribution in the reaction plane, [x,y] for a Pb+Pb reaction at 1.38 + 1.38 ATeV collision energy and impact parameter b = 0.5_bmax at time 4 fm/c after the first touch of the colliding nuclei, this is when the hydro stage begins. The calculations are performed according to the effective string rope model. This tilted initial state has a flow velocity distribution, qualitatively shown by the arrows. The dashed arrows indicate the direction of the largest pressure gradient at this given moment.

Anti-flow (v1)



The energy density [GeV/fm3] distribution in the reaction plane, [x,z] for a Pb+Pb reaction at 1.38 + 1.38 A.TeV collision energy and impact parameter b = 0.5b_max at time 12 fm/c after the formation of the hydro initial state. The expected physical FO point is earlier but this post FO configuration illustrates the flow pattern.

[LP. Csernai, VK. Magas, H. Stocker, D. Strottman, arXiv: 1101.3451 (nucl-th)]

Anti-flow (v1)

In the Fluid Dynamical model with the PIC method, using the Cooper-Frye FO formula, we can obtain the v_n(pt) and v_n(y) flow components, for massless pions:

Conservation laws are satisfied at a constant time FO hyper-surface!

$$v_n(y) = \frac{\sum_i^{cells} J_n(y, \vec{v}^{\,i}, T^i) cos(n\phi_0^i)}{\sum_i^{cells} J_0(y, \vec{v}^{\,i}, T^i)} , \qquad (2)$$

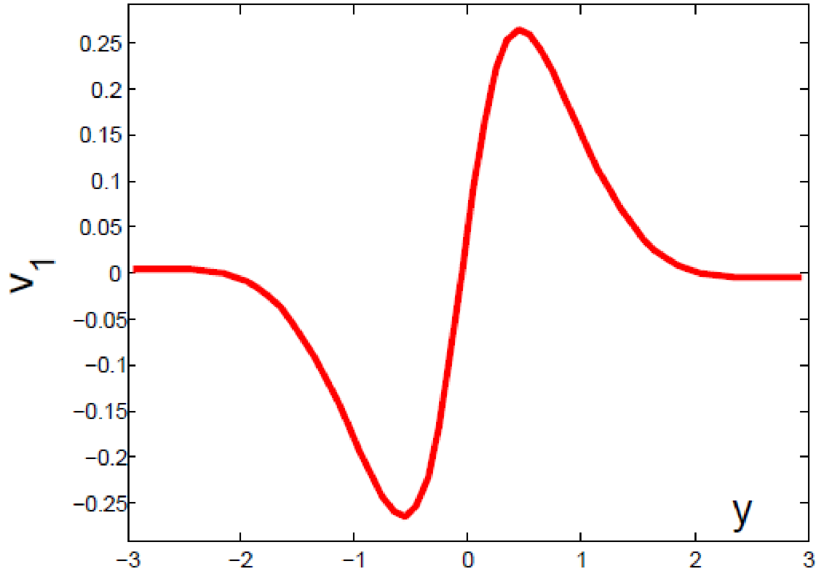
$$J_n(y, \vec{v}^{\,i}, T^i) = \int_0^\infty dp_t p_t^2 I_n(\gamma_t^i v_t^i p_t / T^i) e^{-\gamma_t^i p_t cosh(y - y_0^i)/T^i} ,$$

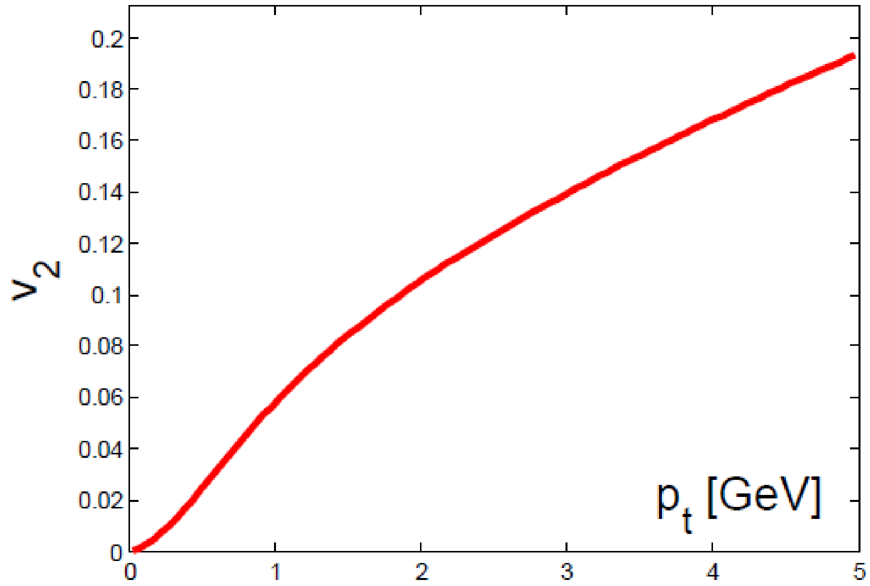
$$v_n(p_t) = \frac{\sum_i^{cells} B(\vec{v}^{\,i}, T^i, p_t) I_n(\gamma^i v_t^i p_t / T^i) cos(n\phi_0^i)}{\sum_i^{cells} B(\vec{v}^{\,i}, T^i, p_t) I_0(\gamma^i v_t^i p_t / T^i)} , \qquad (3)$$

$$B(\vec{v}, T, p_t) = e^{-\gamma p_t / T} \frac{1}{1 - v_z^2} \left(v_z \frac{T}{\gamma} - p_t |v_z| \right)$$

$$+ \frac{p_t}{\sqrt{1 - v_z^2}} K_1 \left(\frac{\gamma p_t \sqrt{1 - v_z^2}}{T}, \frac{\gamma p_t}{T} \right) .$$

Anti-flow (v1)

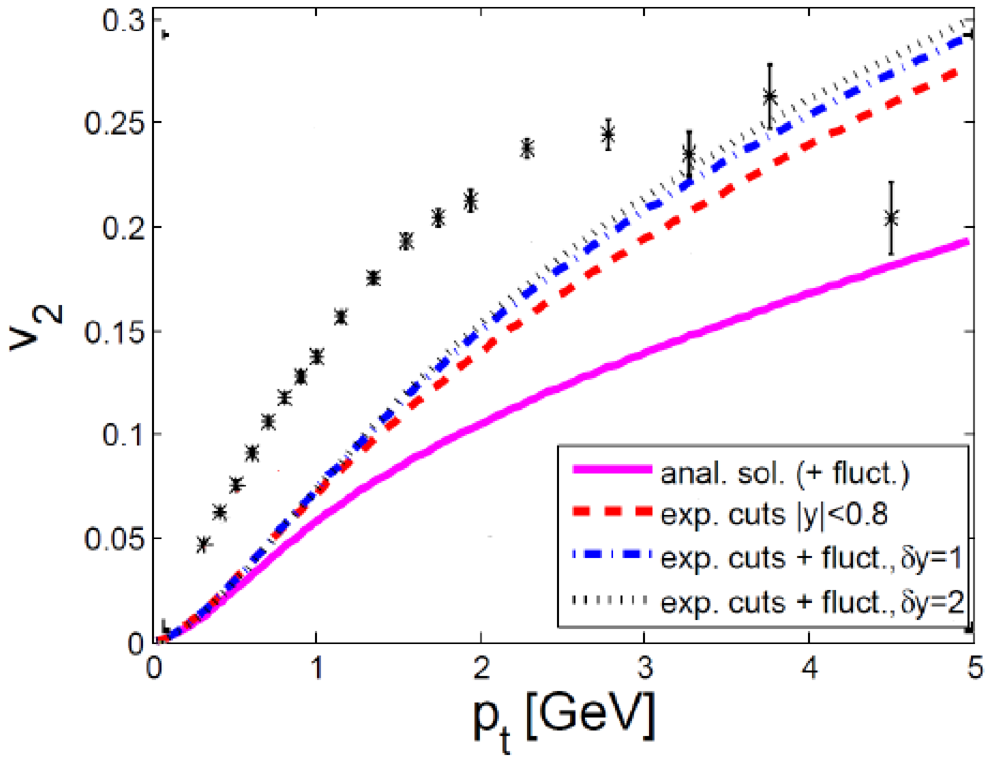




The v_1 & v_2 parameter calculated for ideal massless pion Juttner gas, versus the transverse momentum, p_t, for b = 0.7b_max, at t = 8 fm/c FO time. The magnitude of v_2 is comparable to the observed v_2 at 40-50 % centrality. The v_2 value is slightly below the experimental data, which can be attributed to integral over the whole rapidity range, while the experiment is only for η < 0.8. The v1 peak appears at positive rapidity, in contrast to lower energy calculations and measurements.

Elliptic-flow (v2)

Estimating the effect of longitudinal rapidity fluctuations of the initial state:



The v_2 parameter calculated for ideal massless pion Juttner gas, versus the transverse momentum, p_t for b = 0.7 b_max, at t = 8 fm/c FO time. The magnitude of v_2 is comparable to the observed v_2 at 40-50 % centrality (black stars).

Anti-flow (v1)

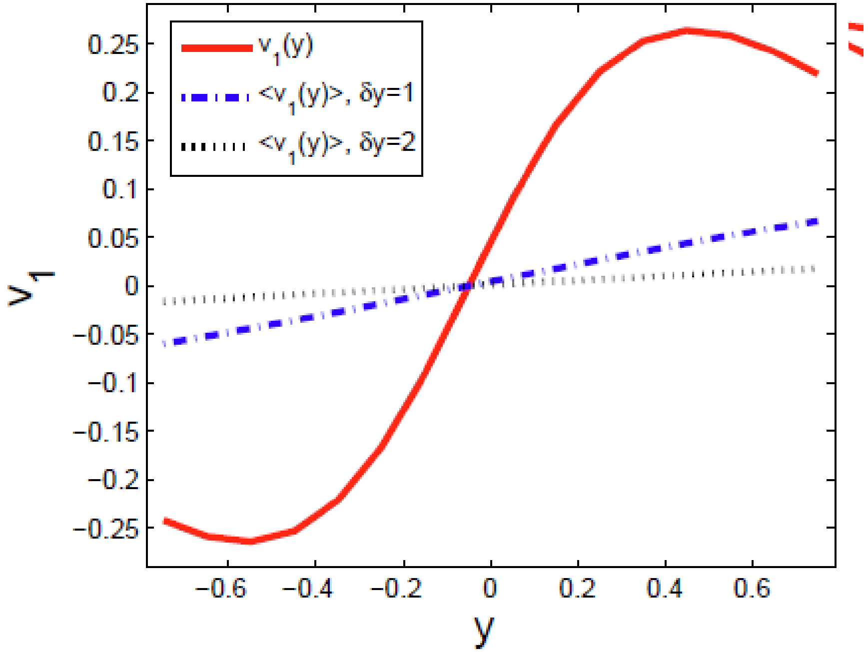
Estimating the effect of longitudinal rapidity fluctuations of the initial state:

Initial fluctuations in the positions of nucleons in the transverse plane

→different number of participants from projectil and target

→Reduce v_1 at central rapidities, as v1 has a sharp change at y=0, and the initial fluctuations have not.

→v_1 is reduced but still measurable

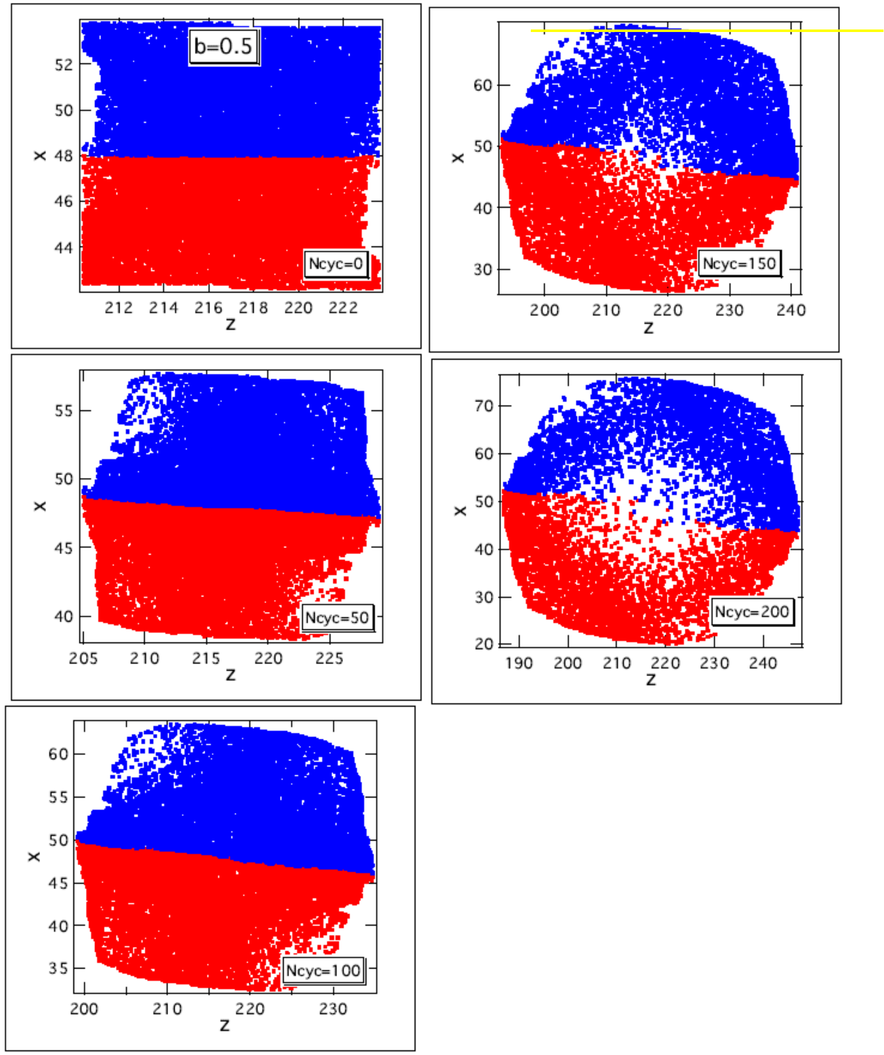


[*Yun Cheng, et al., Phys. Rev. C* ***84*** *(2011)* 034911.]

Making Rotation Visible

The rotation is illustrated by dividing the upper / lower part (blue/red) of the initial state, and following the trajectories of the marker particles.

The marker particles in the reaction plane are plotter in a peripheral Pb+Pb reaction at LHC energy.

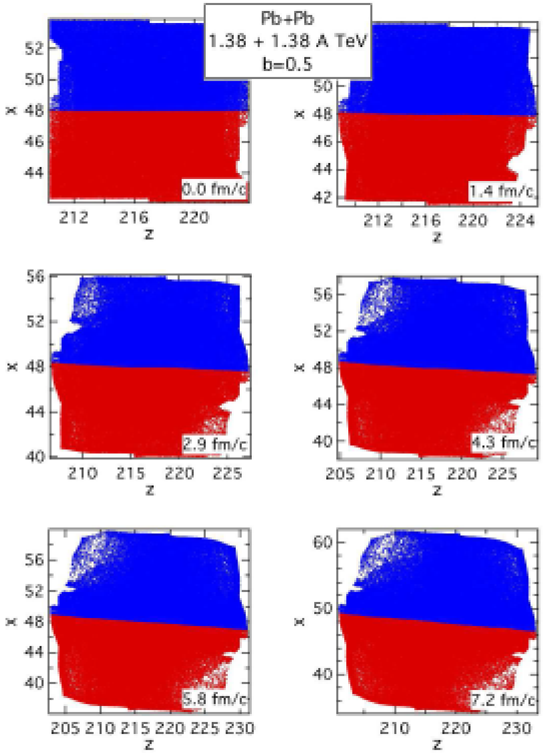


F.O.

Kelvin-Helmholtz Instability (KHI)

- Turbulent fluctuations are common in **air*** and **water***
- Usually ∃ source*
- Usually damped, but weakly
- ∃ quasi-stationary and developing instabilities
- For KHI the source is shear-flow

ROTATION



KHI →

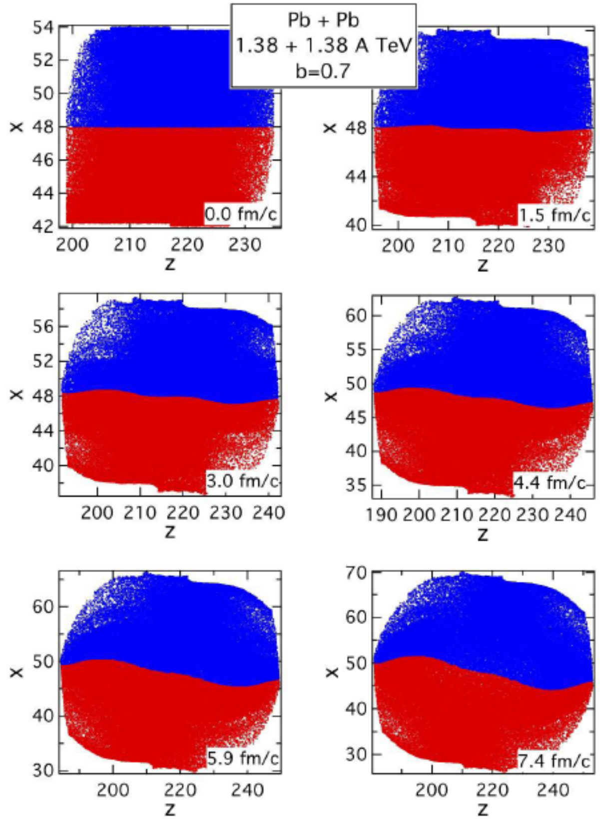
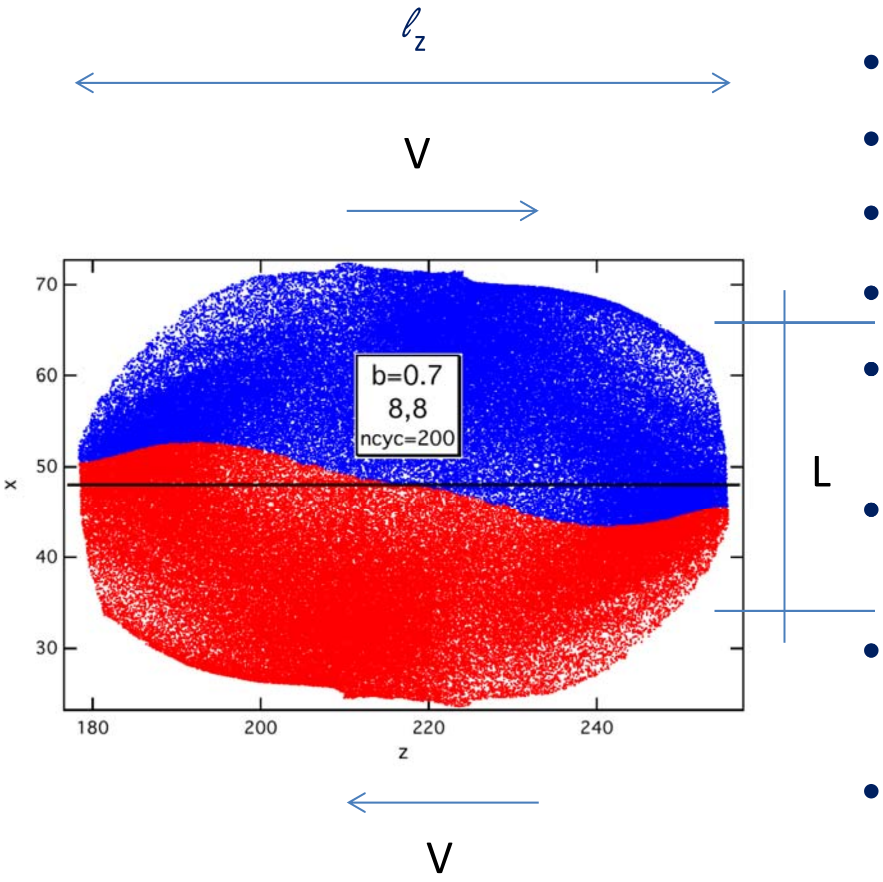


FIG. 1: (color online) Growth of the initial stage of Kelvin-Helmholtz instability in a $1.38A + 1.38A$ TeV peripheral, $b = 0.7b_{\max}$, Pb+Pb collision in a relativistic CFD simulation using the PIC-method. We see the positions of the marker particles (Lagrangian markers with fixed baryon number content) in the reaction plane. The calculation cells are $dx = dy = dz = 0.4375$fm and the time-step is 0.04233 fm/c The number of randomly placed marker particles in each fluid cell is 8^3. The axis-labels indicate the cell numbers in the x and z (beam) direction. The initial development of a KH type instability is visible from $t = 1.5$ up to $t = 7.41$ fm/c corresponding from 35 to 175 calculation time steps).

The Kelvin – Helmholtz instability (KHI)



Our resolution is $(0.35\text{fm})^3$ and
8^3 markers/fluid-cell →
~ 10k cells & 10Mill m.p.-s

- Shear Flow:
- L=(2R-b) ~ 4 – 7 fm, init. profile height
- ℓ_z=10–13 fm, init. length (b=.5-.7b_{max})
- V ~ ±0.4 c upper/lower speed →
- Minimal wave number is
  k = .6 - .48 fm^{-1}
- KHI grows as $\propto \exp(st)$, where
  $s = kV$ →
- Largest k or shortest wave-length will grow the fastest.
- The amplitude will double in
  2.9 or 3.6 fm/c for (b=.5-.7b_{max})
  without expansion, and with favorable viscosity/Reynolds no. Re=LV/ν .
- → this favors large L and large V

The Kelvin – Helmholtz instability (KHI)

- **Formation of critical length KHI (Kolmogorov length scale)**
- ∃ critical minimal wavelength beyond which the KHI is able to grow. Smaller wavelength perturbations tend to decay. (similar to critical bubble size in homogeneous nucleation).
- **Kolmogorov**: $\lambda_{Kol} = [\nu^3/\epsilon]^{1/4}.$
- Here $\epsilon = \dot{e}/\rho \quad \propto \quad T\dot{\sigma}/\rho \quad \propto \quad \nu,$ is the specific dissipated flow energy.
- We estimated: $$\lambda_{Kol} = \begin{cases} 2.1 \div 5.4 \text{ fm for } b = 0.5 b_{max} \\ 1.4 \div 3.6 \text{ fm for } b = 0.7 b_{max} \end{cases}$$
- It is required that $l_z > \lambda_{Kol}$. → we need $b > 0.5\ b_{max}$
- Furthermore
  Re = 0.3 – 1 for "$\eta/s = 1$" and
  Re = 3 – 10 for "$\eta/s = 0.1$"

Very late, post-FO stage: t = 10.16 fm/c

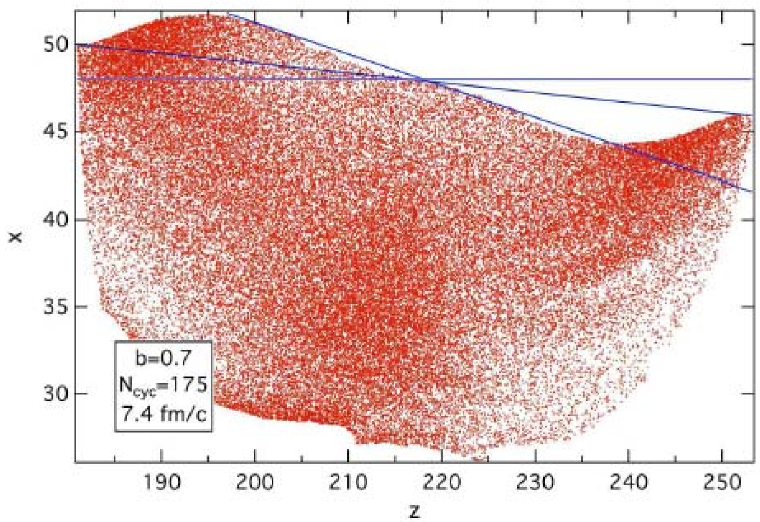
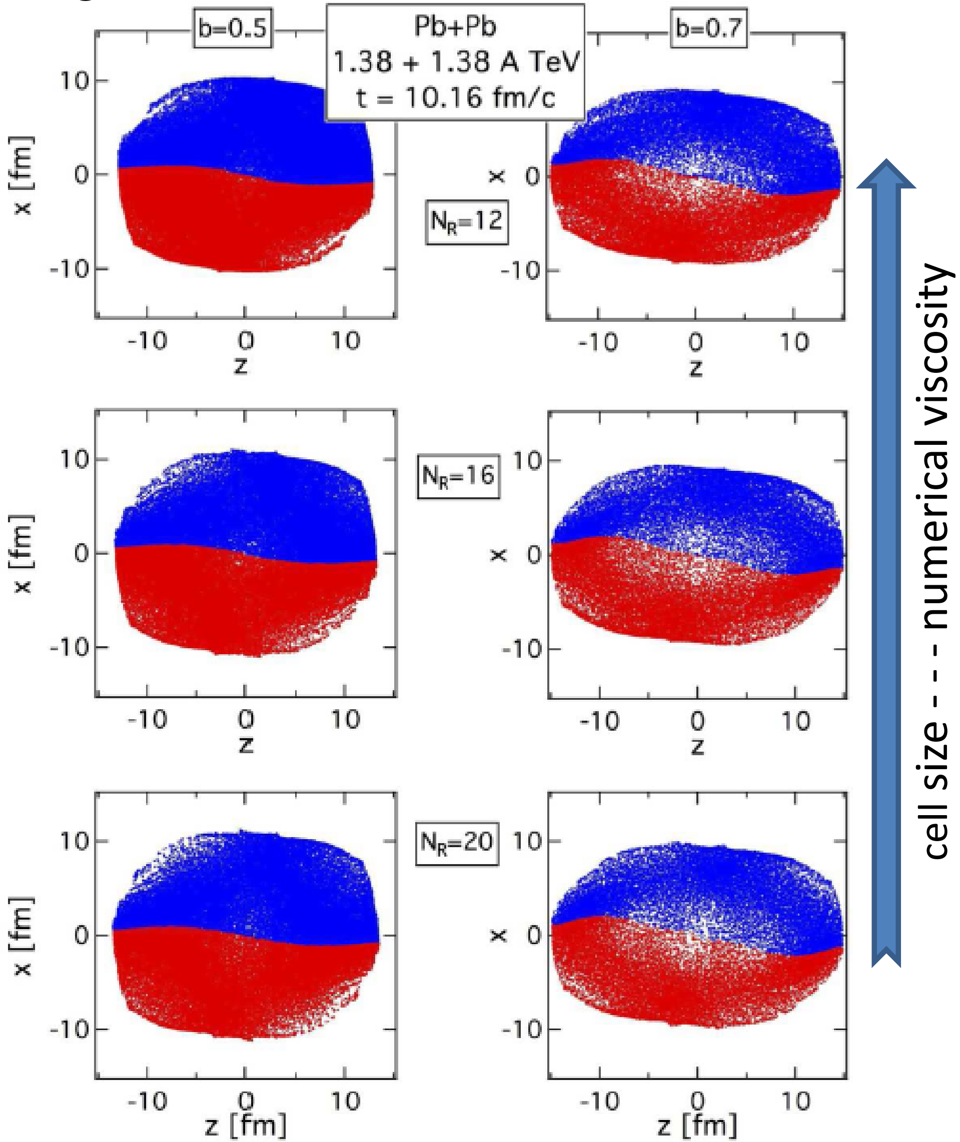


FIG. 5: (color online) The detailed view of the marker particle positions in the lower half of the initial state markers after 175 time-steps. A $1.38A + 1.38A$ TeV energy Pb+Pb peripheral collision is shown, at $b = 0.7\ b_{\max}$ impact parameter with $7^3 = 343$ markers per initial, normal density fluid cell resolution. The lines across the collision center point indicate the initial dividing axis, the change of this axis due to rotation and the additional change of rotation arising from the start-up of a Kelvin-Helmholtz type of instability. This additional effect more than doubles the rotation. In this calculation the cell size is $dx = dy = dz = 0.35$ fm, with a total number of 1814814 marker particles.



Summary

- Flow effects arise from **global** initial asymmetries and **random** initial fluctuations
- These sources can be separated experimentally (at LHC global v_2 & random v_1-v_8)
- New global collective flow effects are predicted, **Rotation** & **KHI**
- These are to be measured yet (*) See ID: 584 !!!
- Fluctuations have interesting consequences on the phase transition and hadronization dynamics, relevant also to astrophysics