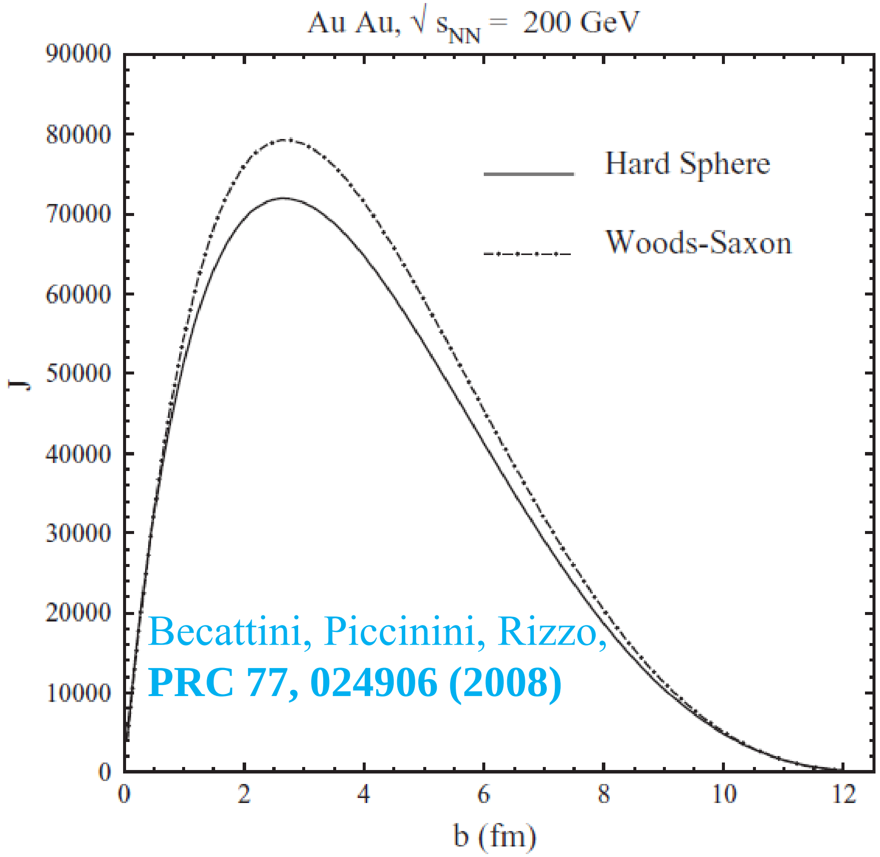
Volodymyr Magas
University of Barcelona, Spain

Tilted initial state: reasons and consequence

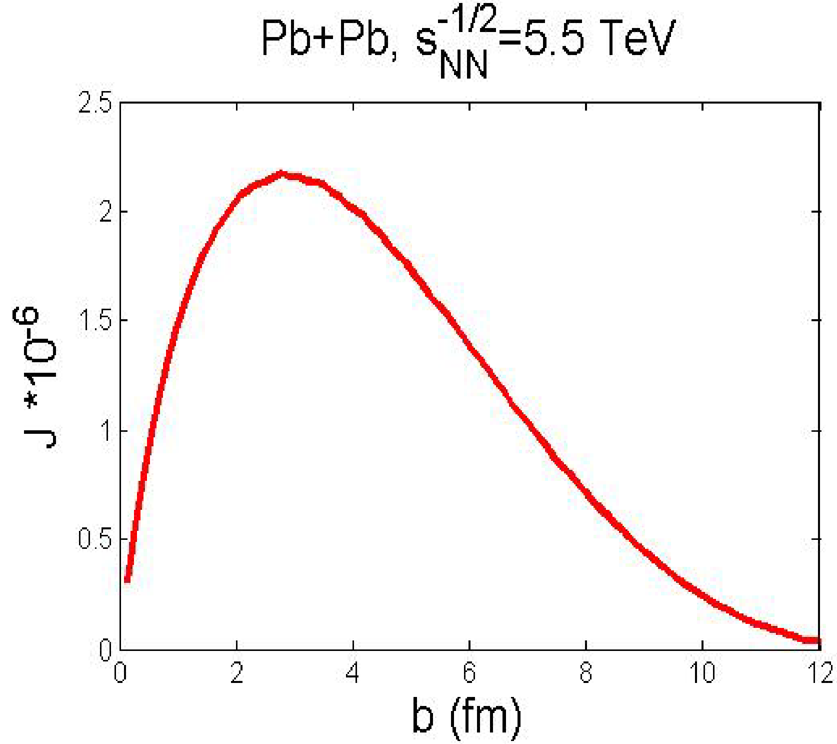
Nuclei colliding at ultra-relativistic energies with nonzero impact parameter have a large initial angular momentum,

which is usually ignored in the initial conditions assumed for hydro calculations

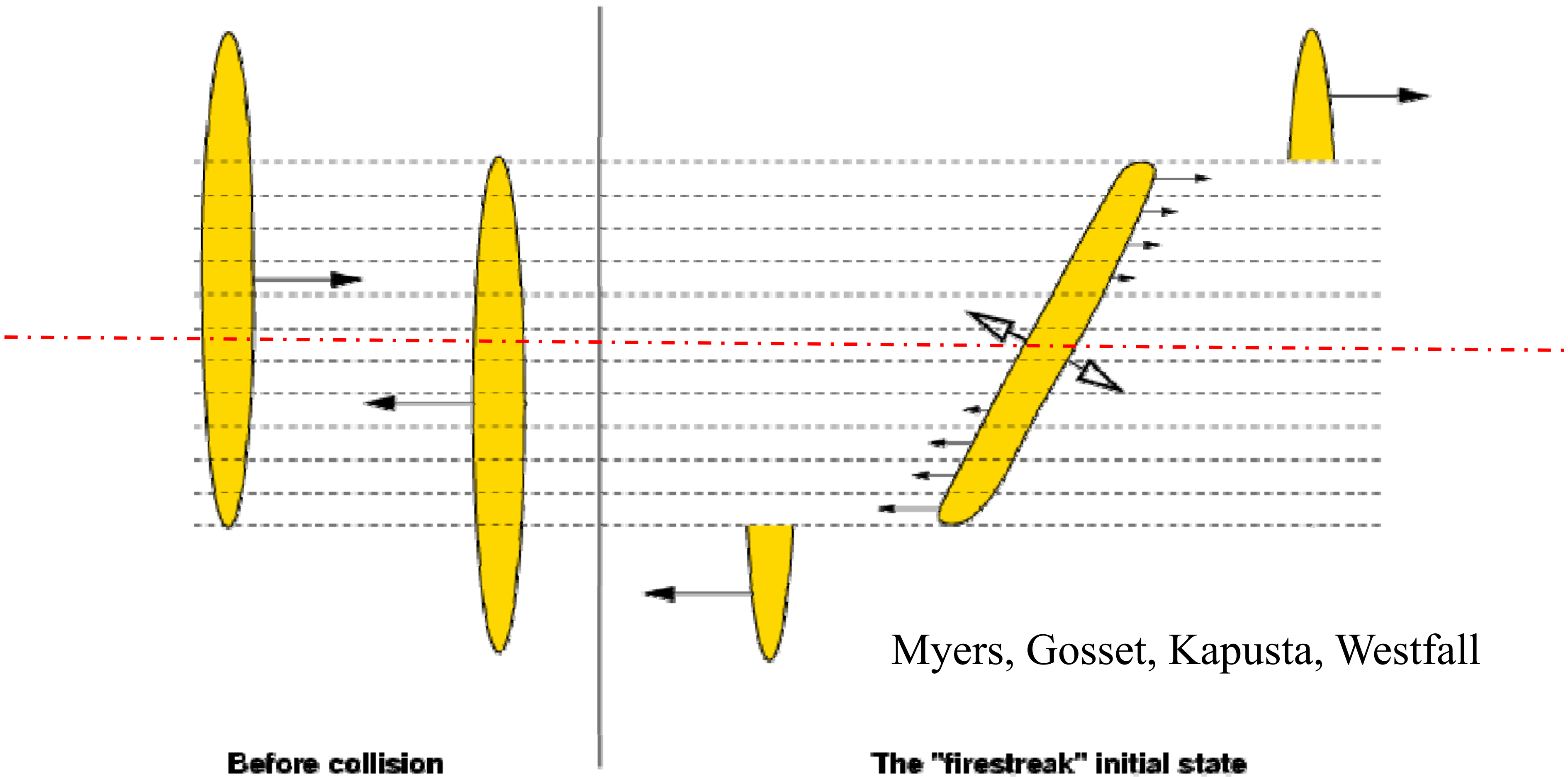
RHIC: $J \simeq 5 \cdot 10^4$



LHC: $J \simeq 1.5 \cdot 10^6$



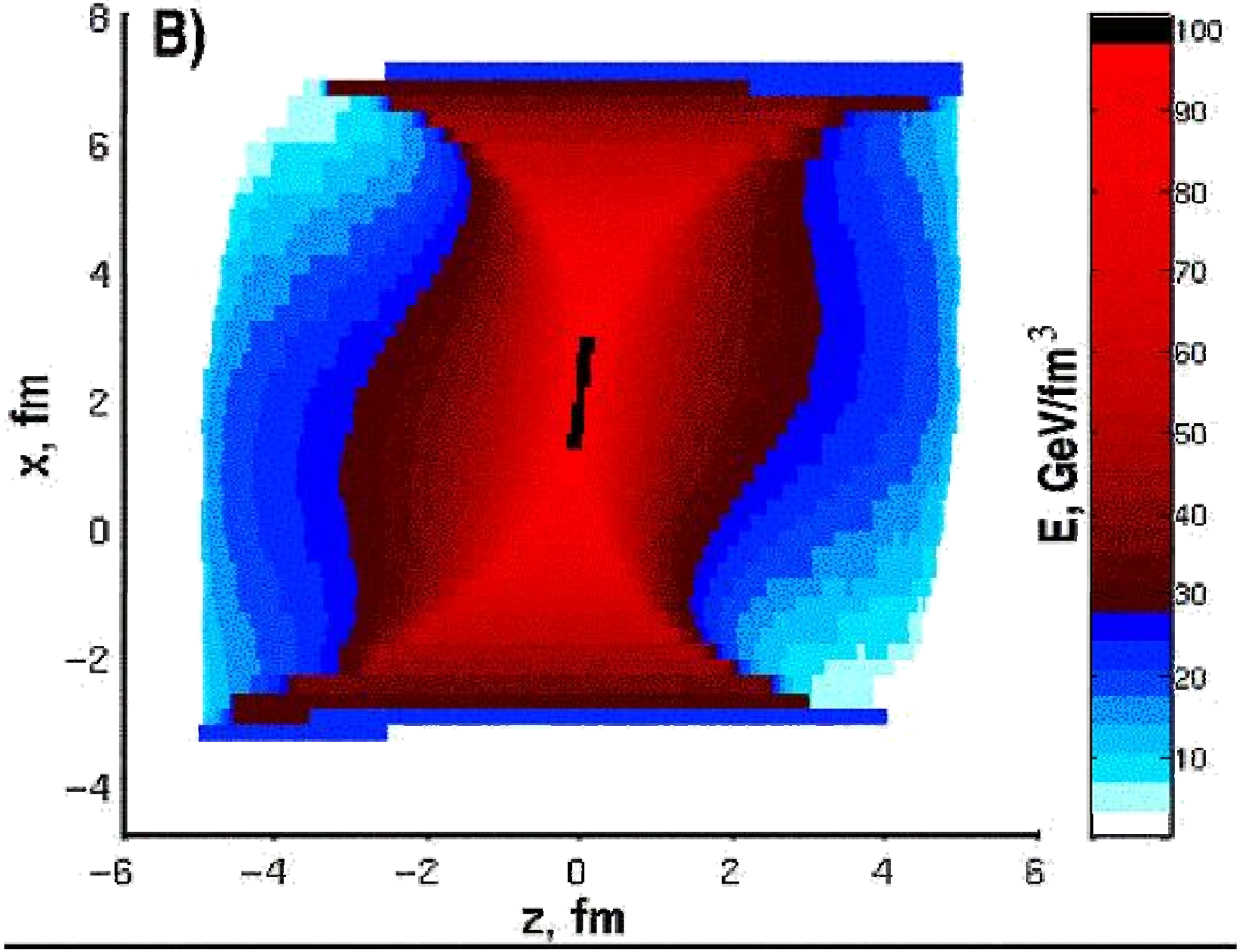
Nuclei colliding at ultra-relativistic energies with nonzero impact parameter have a large initial angular momentum



Symmetry axis = z-axis. Transverse plane divided into streaks

Initial state from effective string rope model

Magas, Csernai, Strottman, PRC 64 (2001) 014901, NPA 712 (2002) 167

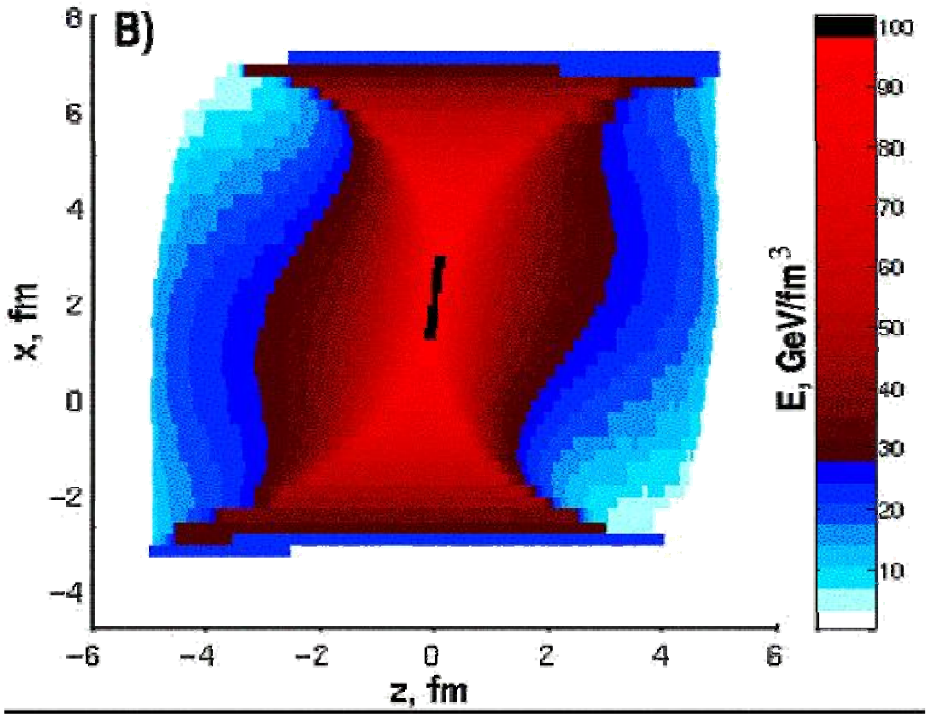


Tilted !

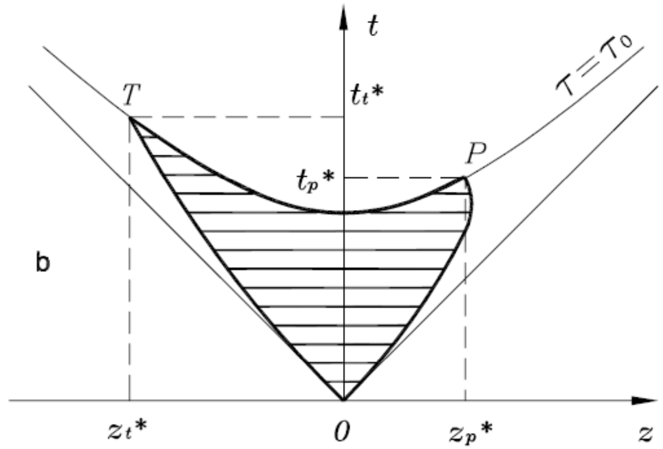
Au+Au at 100+100 GeV/nucl, b=0.25*2R

Initial state from effective string rope model

Magas, Csernai, Strottman, PRC 64 (2001) 014901, NPA 712 (2002) 167



There are similar models,
with different string decay mechanism,
which produce
initial state in (τ,z) coordinates:
Mishustin, Kapusta,
PRL 88 (2002) 112501;
Mishustin, Lyakhov,
Phys.Atom.Nucl. 75 (2012) 371



Au+Au at 100+100 GeV/nucl, b=0.25*2R

Initial State in (t,z) coordinate

FIG. 2. Schematic space-time representation of a symmetric (a) and asymmetric (b) slab-slab collision in the $t-z$ plane. The projectile and target slab trajectories are shown by thick solid lines which start at the origin and terminate at points P and T, respectively. The quark-gluon plasma is produced at the portion of the hyperbola $\tau = \tau_0$ between these points (thick solid line). Horizontal solid lines represent strings. For symmetric collisions $t_p^* = t_t^* = t^*$, $z_p^* = -z_t^* = z^*$.

Bozek, Wyskiel, PRC81 (2010) 054902; PRC 83 (2011) 024910

3+1D hydro

Bjorken flow: $u^\mu(\tau_0, x, y, \eta_\parallel) = (\cosh \eta_\parallel, 0, 0, \sinh \eta_\parallel)$

"Tilted" initial state:

$$\epsilon(\tau_0) = \epsilon_0 \left[2 \left(N_+(x,y) f_+(\eta_\parallel) + N_-(x,y) f_-(\eta_\parallel) \right) (1-\alpha) + 2\alpha N_{bin}(x,y) f(\eta_\parallel) \right] / N_0 \ . \quad (13)$$

where N+ and N− are the densities of participants from the two colliding nuclei

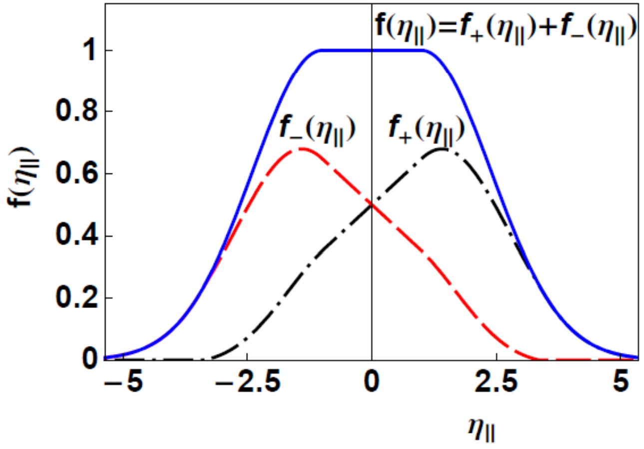


FIG. 2. (Color online) Initial profile in the longitudinal (space-time rapidity) direction. The symmetric function $f(\eta_\parallel)$ is composed from two contributions f_+ and f_- representing the emission from forward and backward going participant nucleons.

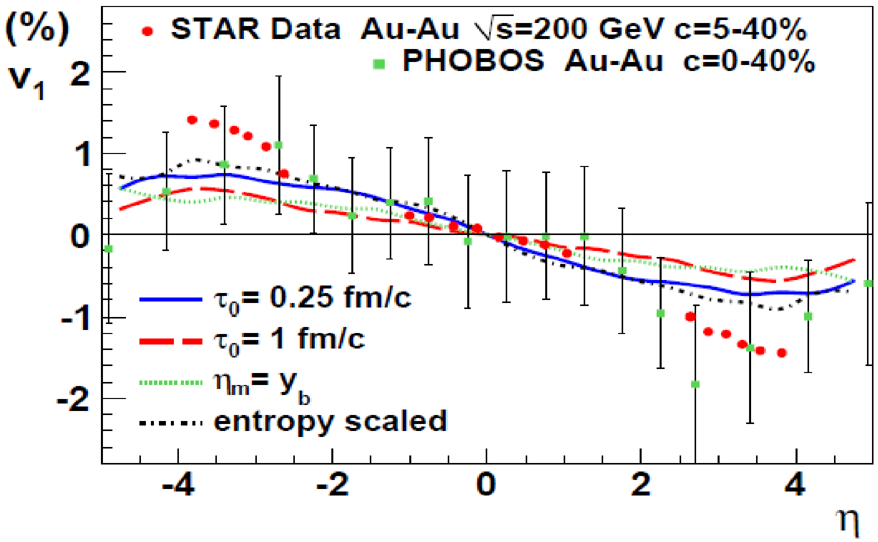
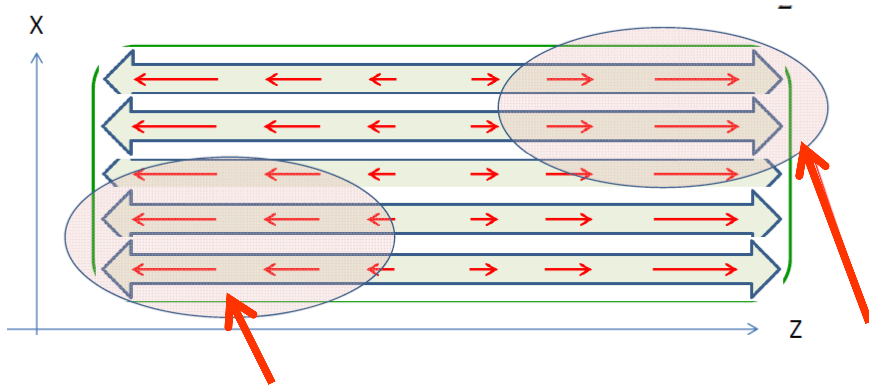


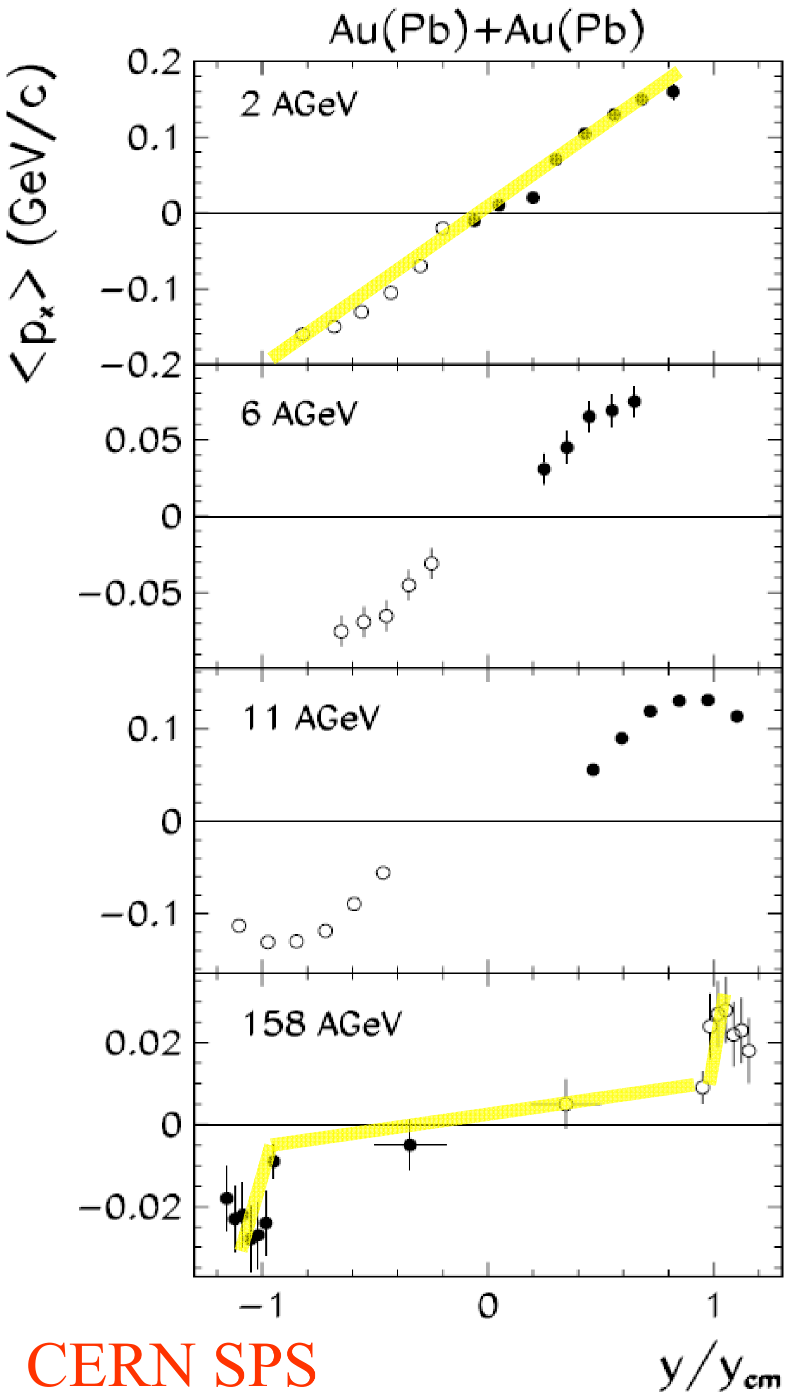
FIG. 9. (Color online) Directed flow coefficient as function of pseudorapidity for tilted initial conditions (Eq. 13) in Au-Au



Matter is redistributed to the edges

Which potential output such an initial state may have?

- Directed flow, v_1
- Elliptic flow, v_2
- Vorticity $\Rightarrow$ particle polarization
- HBT



CERN SPS

Directed flow
starts to deviate
from straight line behavior:

not just a simple **Bounce-off** –
there is some matter
accelerated by pressure

Antiflow or 3rd flow
component

Was proposed as a possible
QGP signal in

Csernai, Röhrich, PL B458 (1999) 454

Strong antiflow in v_1 is observed at **RHIC**

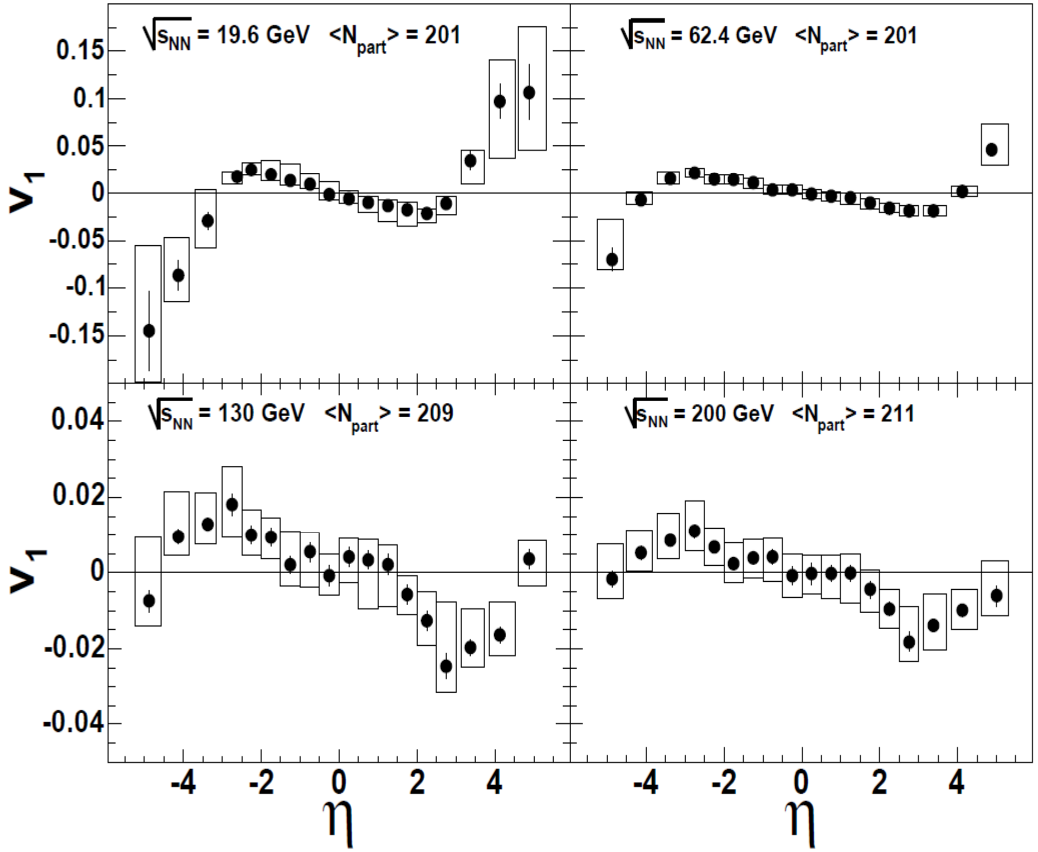
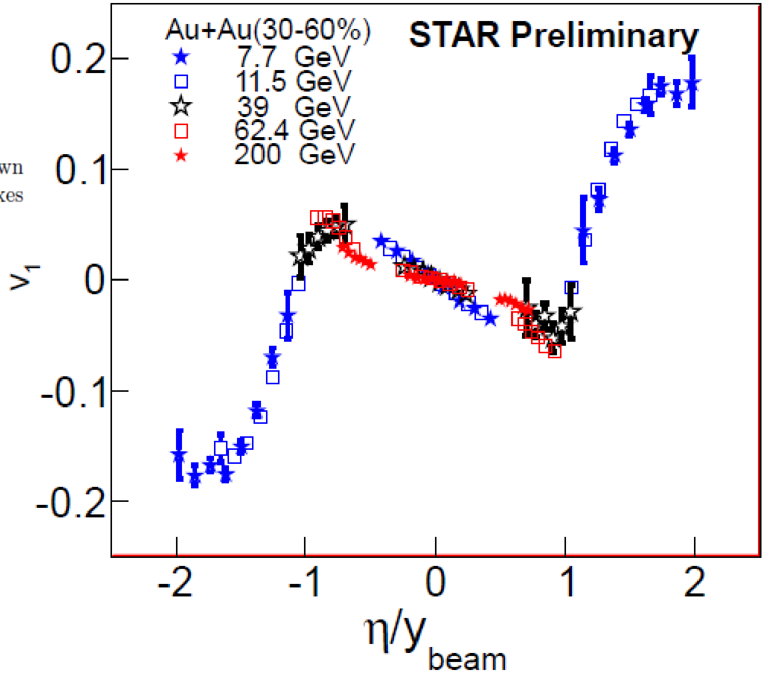


FIG. 2: Directed flow of charged particles in Au+Au collisions as a function of η, averaged over centrality (0–40%), shown separately for four beam energies. Note the different vertical axis scales between the upper and lower panels. The boxes represent systematic uncertainties at 90% C.L., and $\langle N_{part} \rangle$ gives the average number of participants for each data sample.

PHOBOS Coll.
Phys.Rev.Lett. 97 (2006) 012301

STAR Coll.
Acta Phys.Polon.Supp. 5 (2012) 439



Strong antiflow in v_1 is observed at **RHIC**

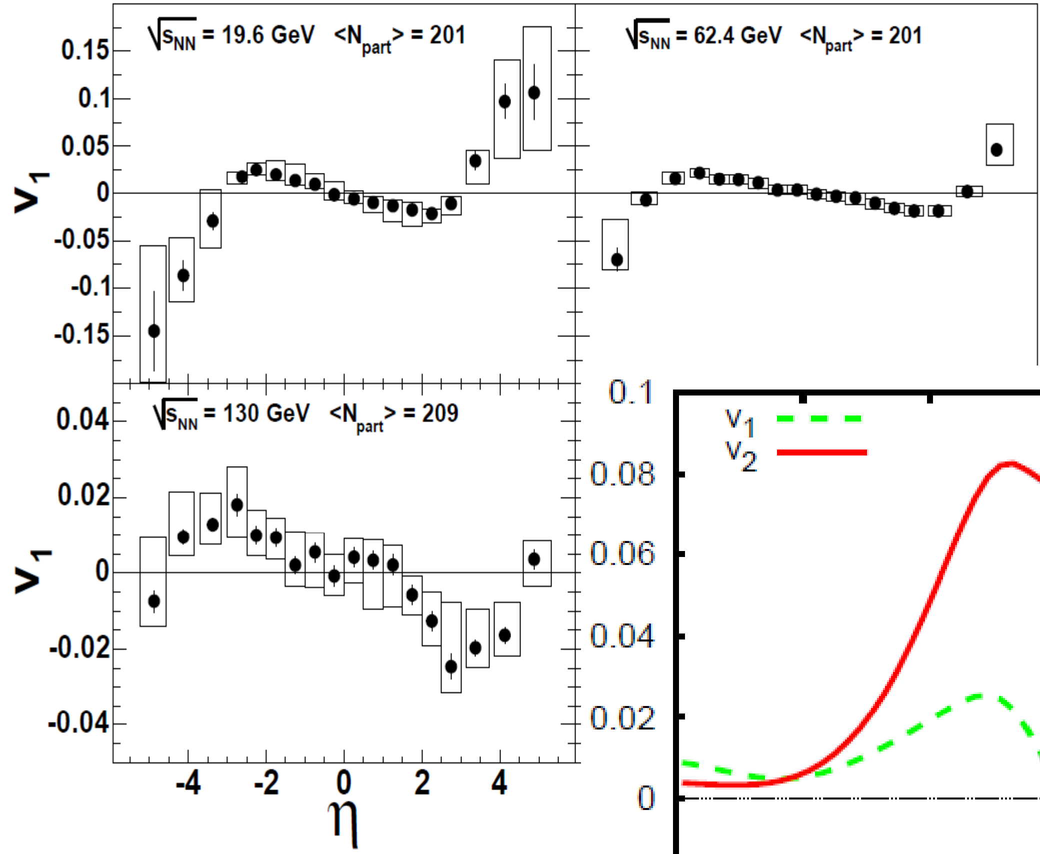


FIG. 2: Directed flow of charged particles in Au+Au collisions as a
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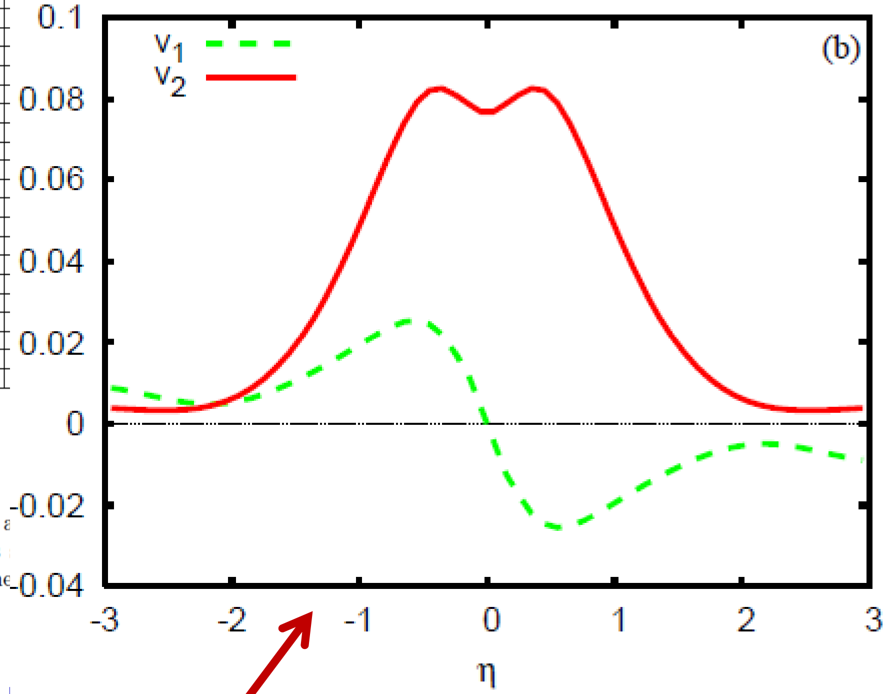
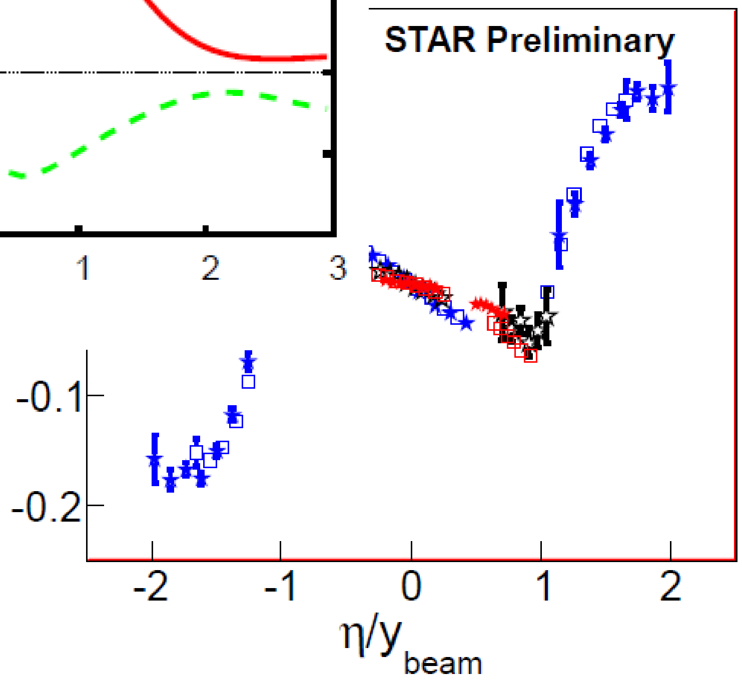
represent systematic uncertainties at 90% C.L., and $\langle N_{part} \rangle$ gives the



PHOBOS Coll.

Phys.Rev.Lett. 97 (2006) 012301

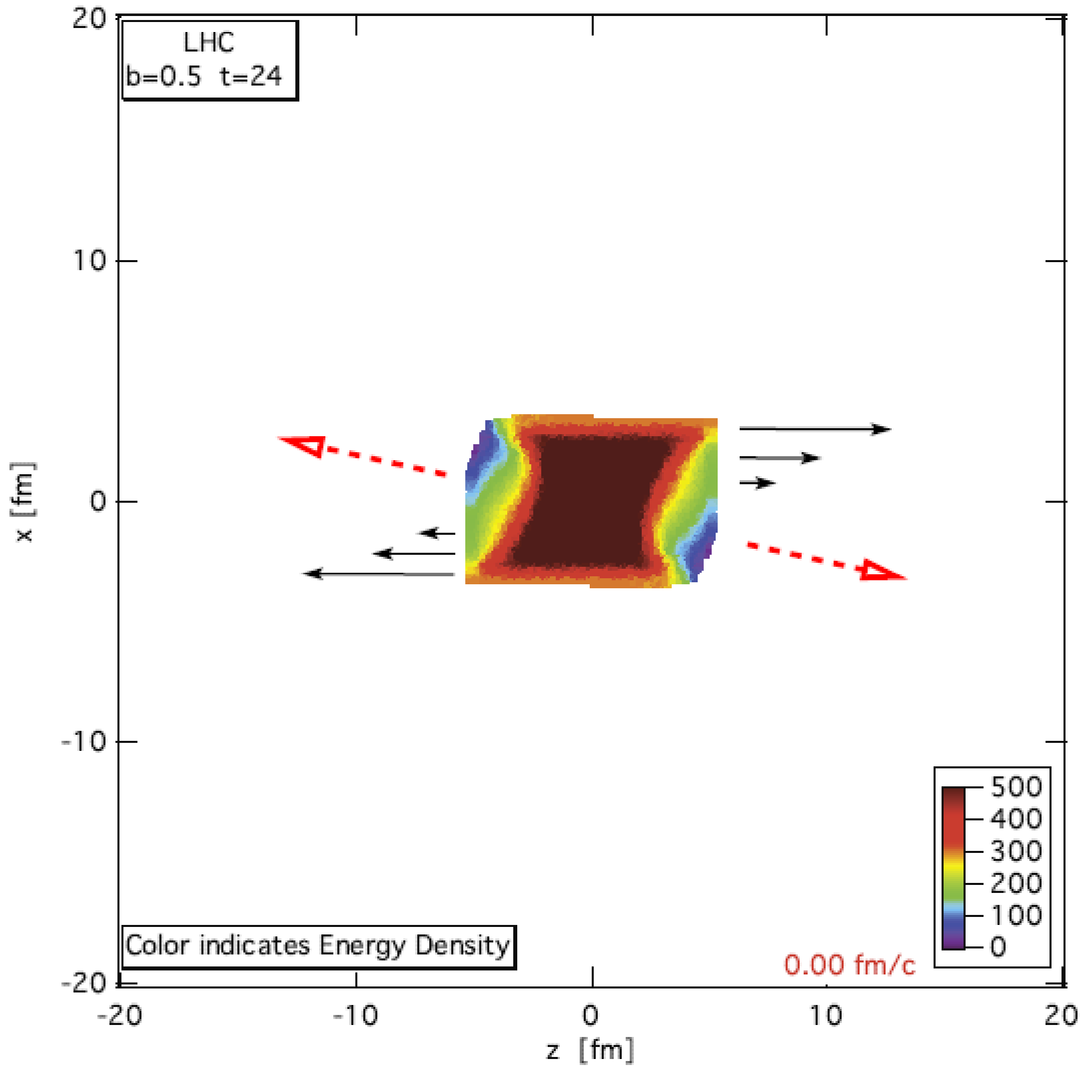
upp. 5 (2012) 439



Csernai et al, J. Phys. G34 (2007) S1077

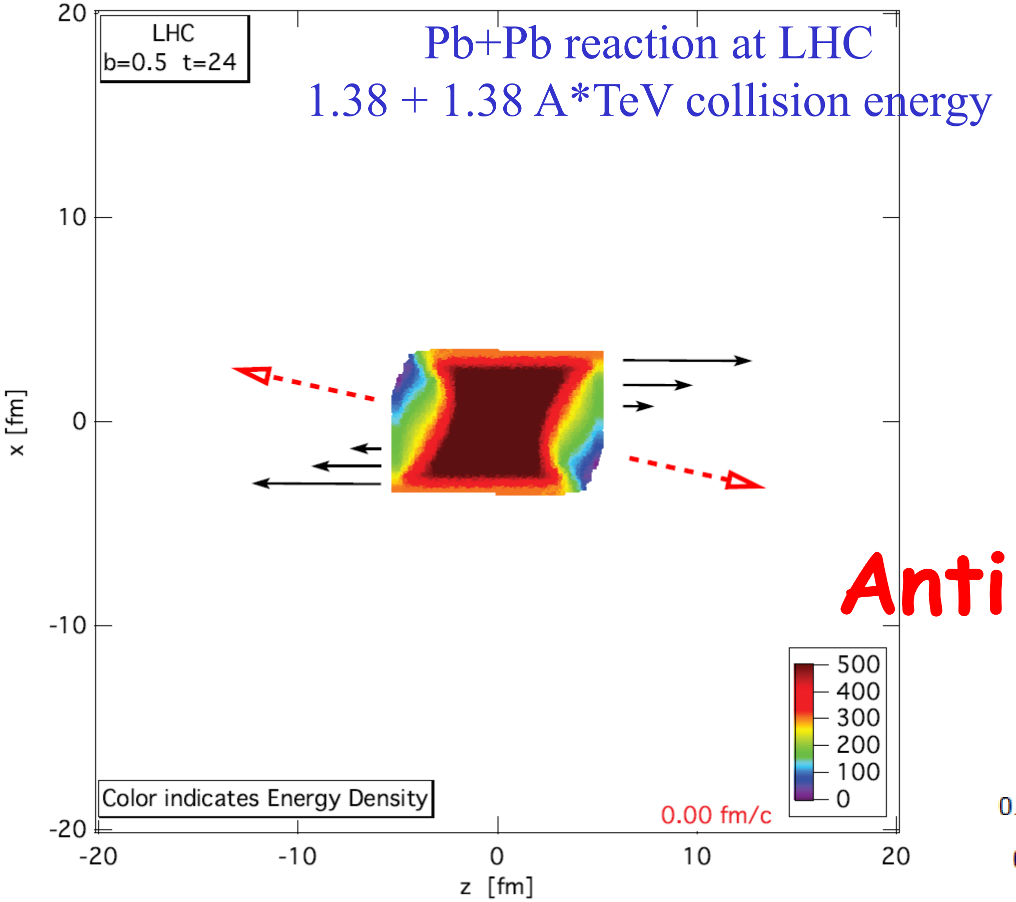
Au+Au, $\sqrt{s_{NN}} = 130$ GeV; $b = 0.7 \cdot 2R_{Au}$

Csernai, Magas, Stöcker, Strottman,
Phys. Rev. C84 (2011) 024914

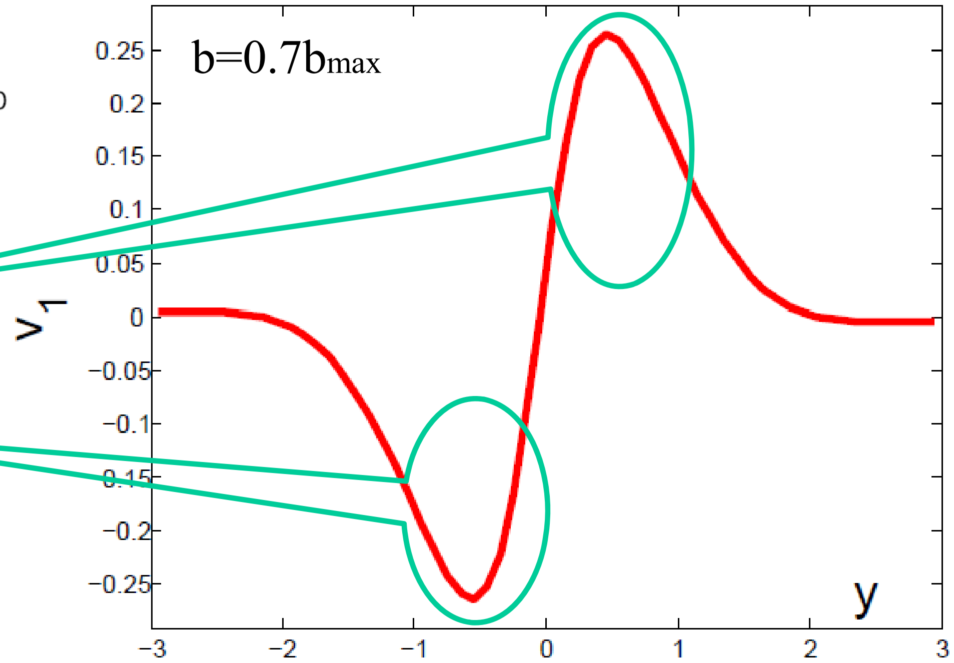


Pb+Pb at 1.38 + 1.38 ATeV
Initial energy density [GeV/fm3]
in the reaction plane
b = 0.5_bmax
t=4 fm/c after the first touch of
the colliding nuclei

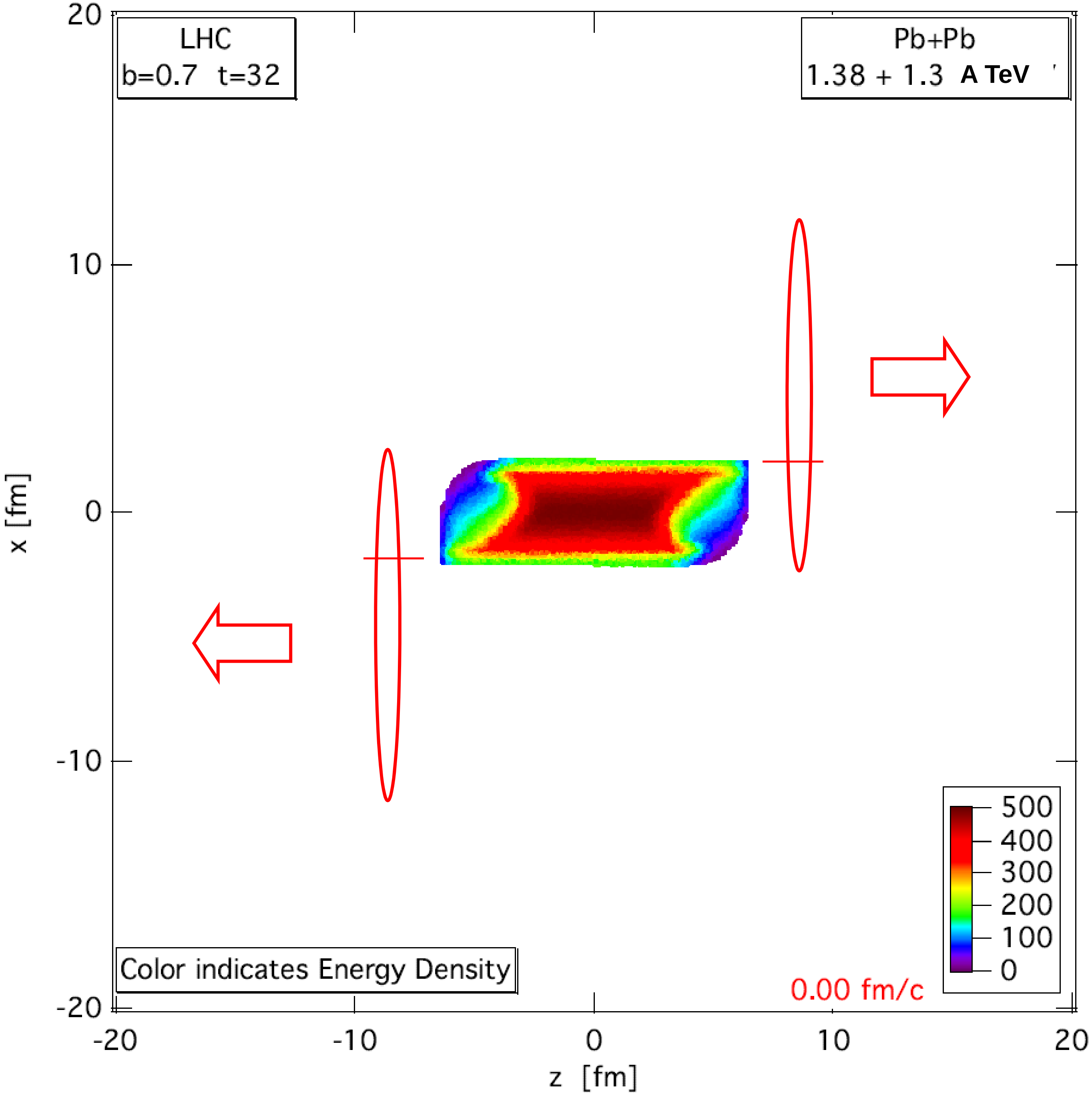
Csernai, Magas, Stöcker, Strottman,
Phys. Rev. C84 (2011) 024914



Anti-flow (v1) at LHC



Peaks in opposite directions!!!
What happened?



PIC-hydro

Pb+Pb

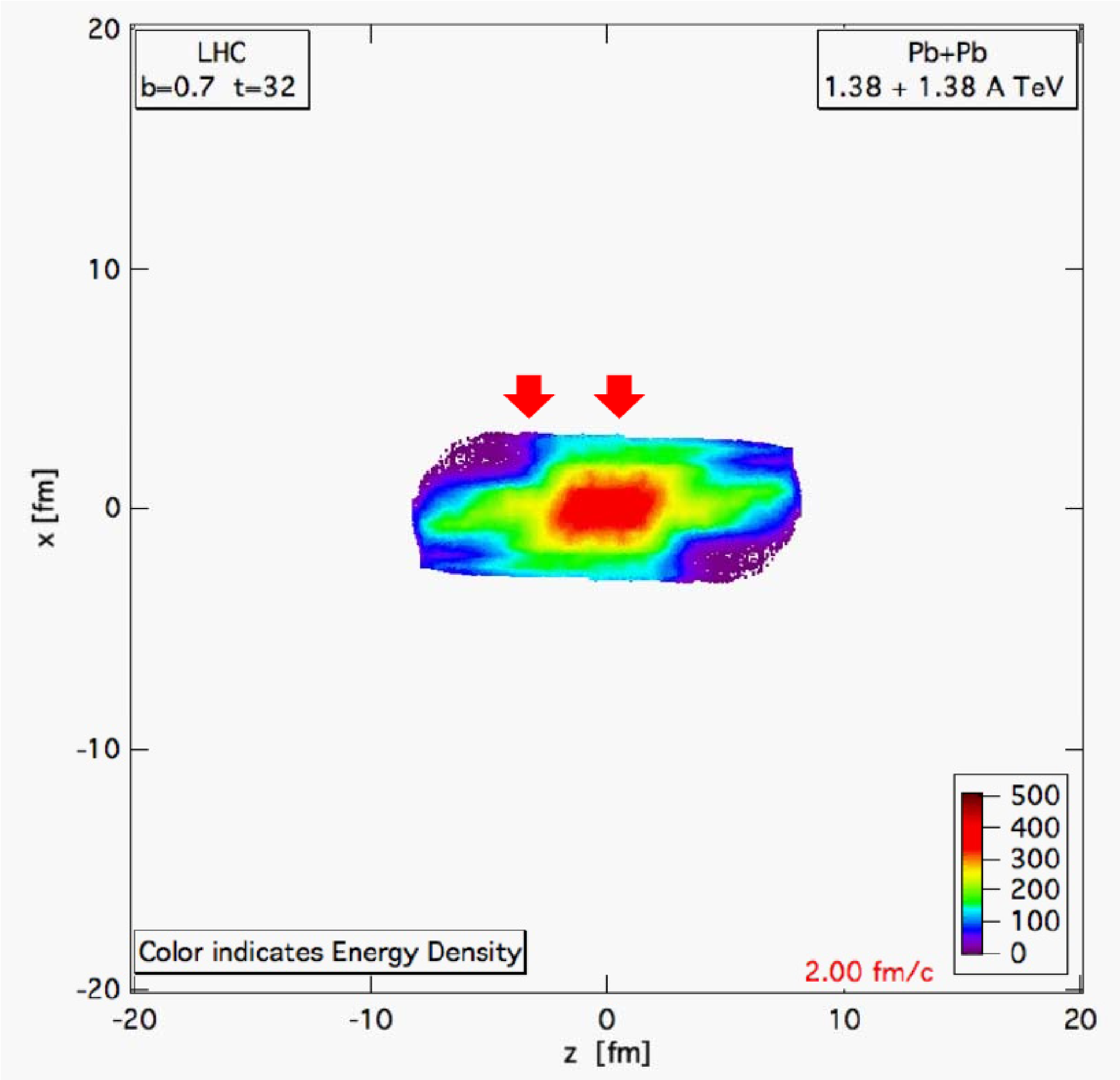
1.38+1.38 A TeV

b= 0.7b_max

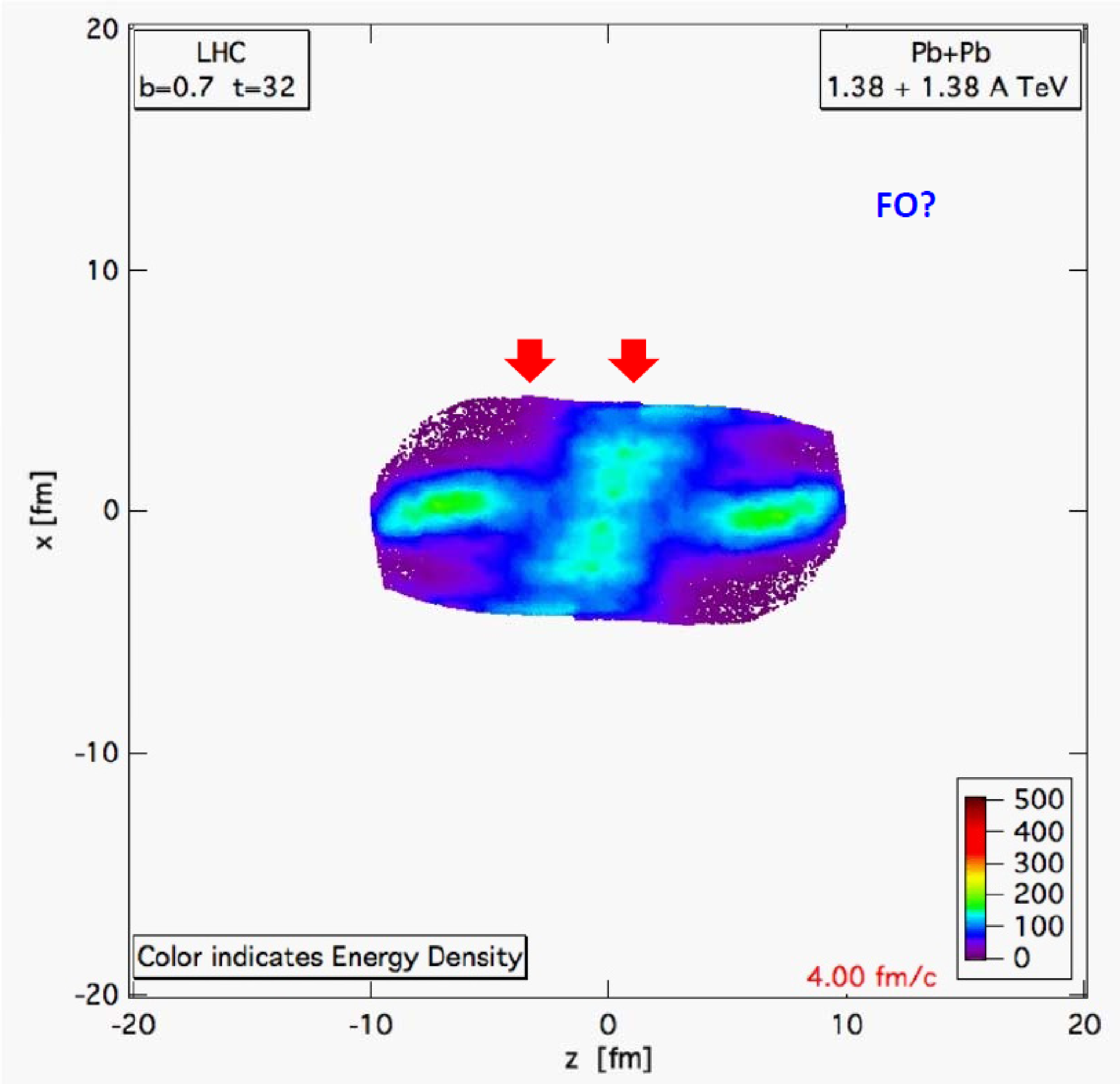
MIT Bag EoS

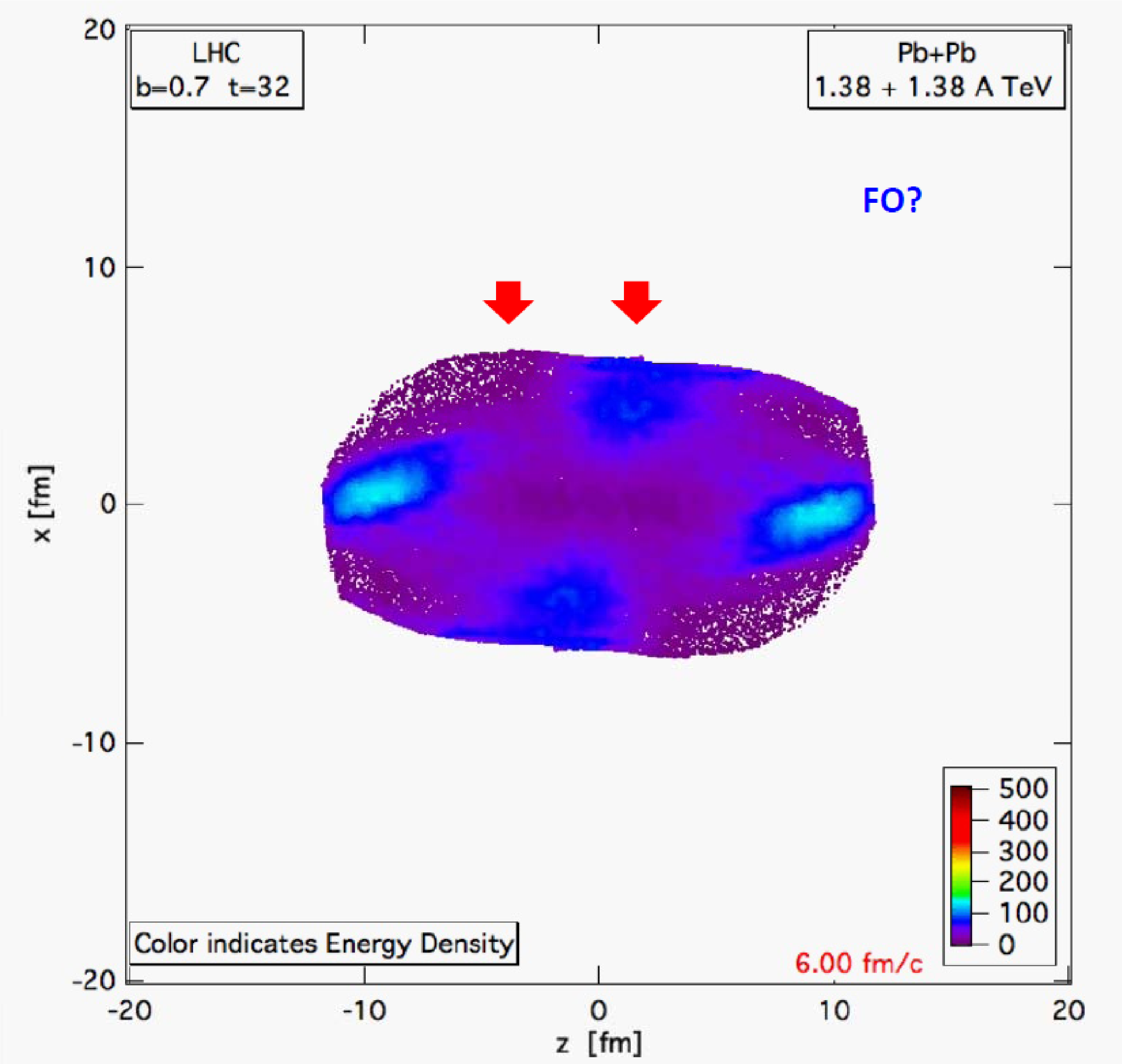
FO: T~200 MeV but calculated much longer, until pressure is zero for 90% of the cells.

Structure and asymmetries of init. state are maintained in nearly perfect expansion.

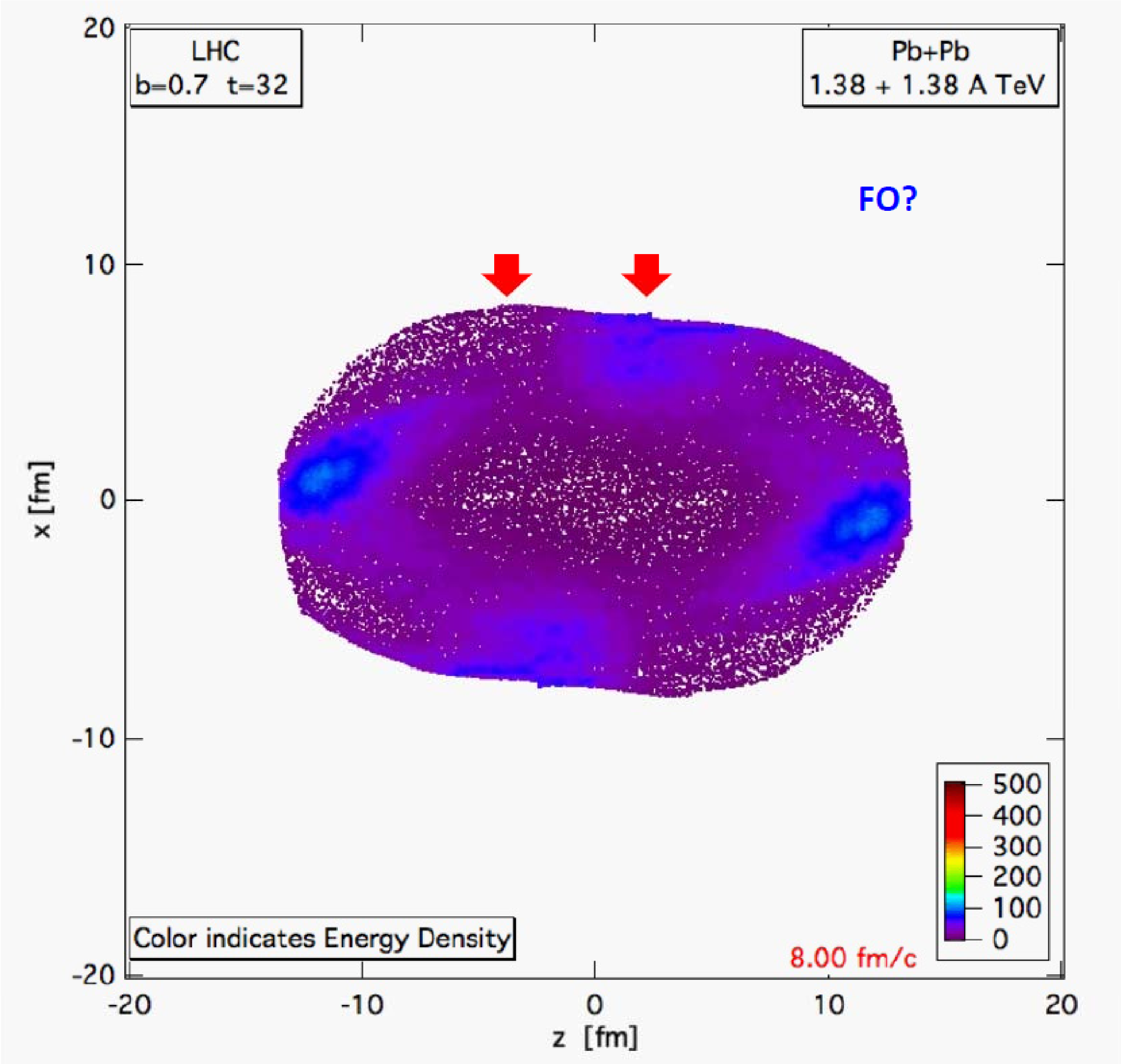


LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
20
10
0
-10
-20
x [fm]
-20
-10
0
10
20
z [fm]
Color indicates Energy Density
2.00 fm/c
500
400
300
200
100
0

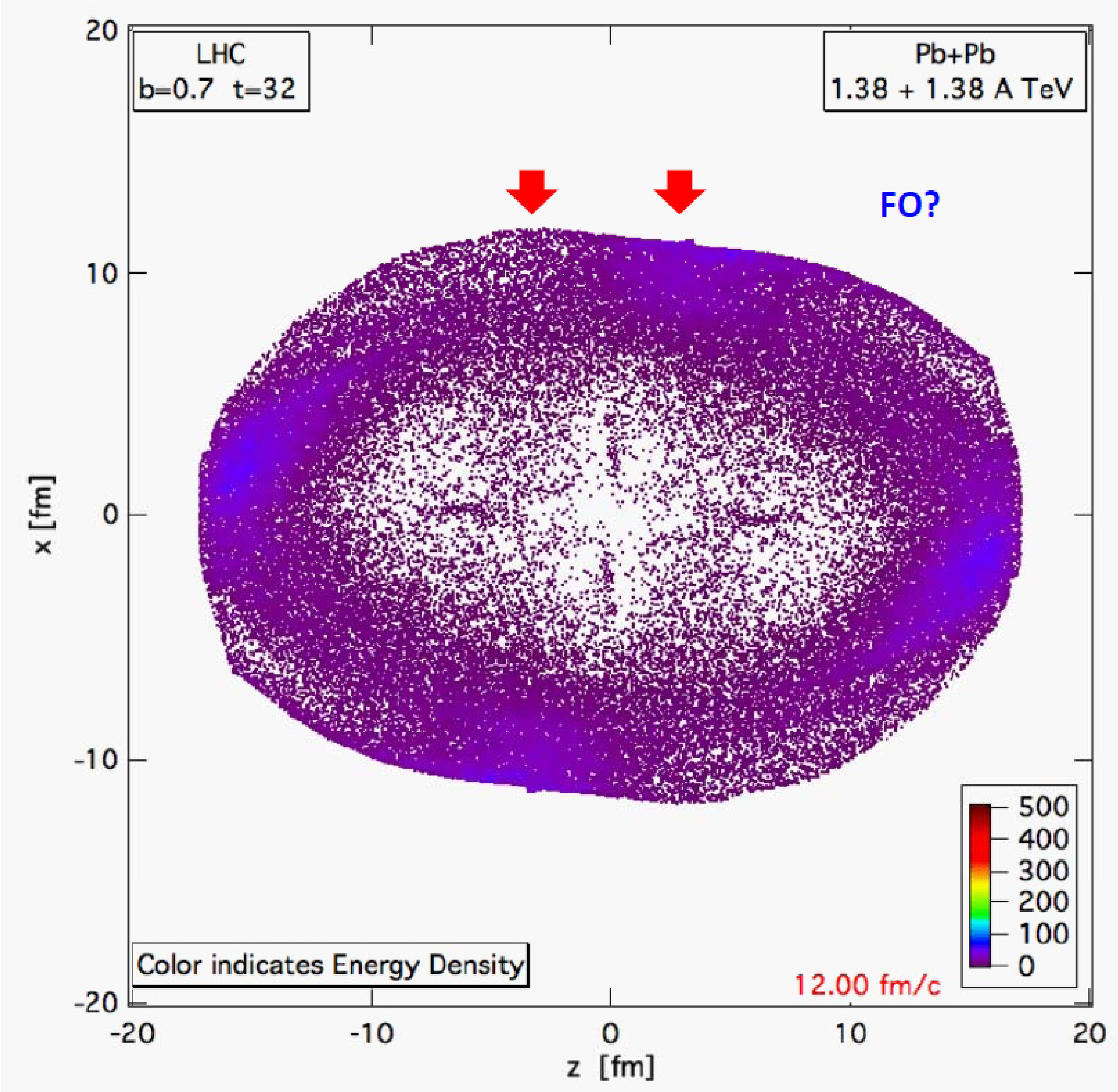

LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
FO?
x [fm]
z [fm]
20
10
0
-10
-20
-20
-10
0
10
20
500
400
300
200
100
0
Color indicates Energy Density
4.00 fm/c



LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
FO?
x [fm]
z [fm]
Color indicates Energy Density
6.00 fm/c
500
400
300
200
100
0
20
10
0
-10
-20

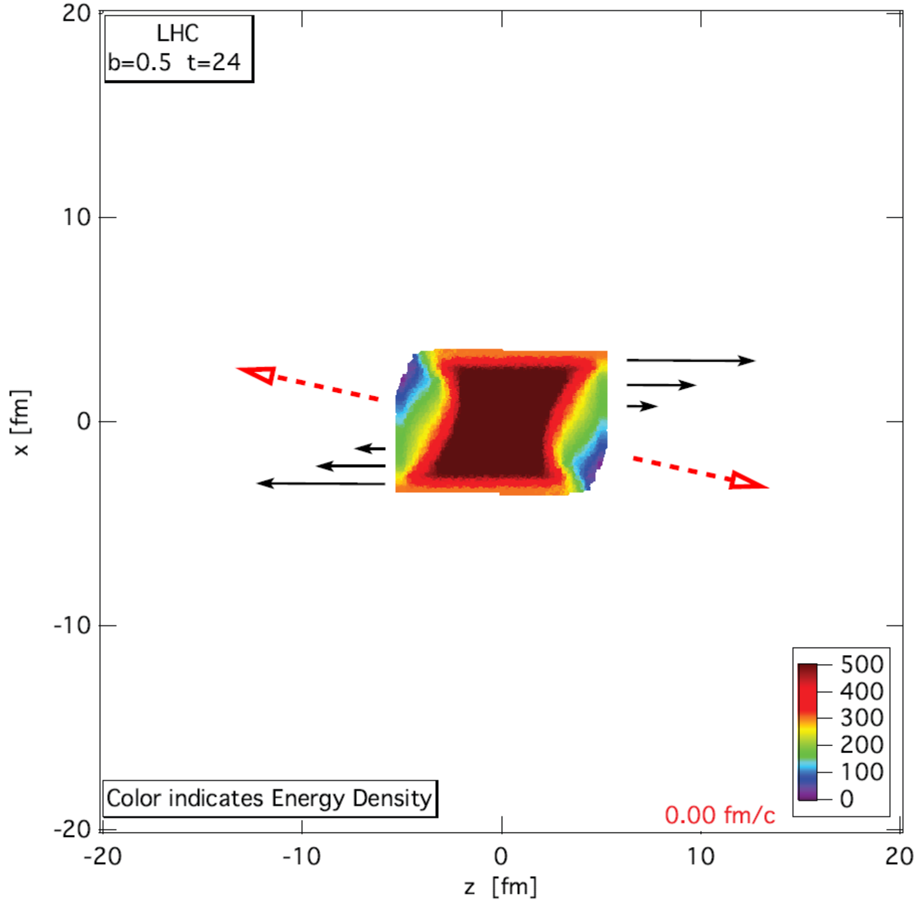


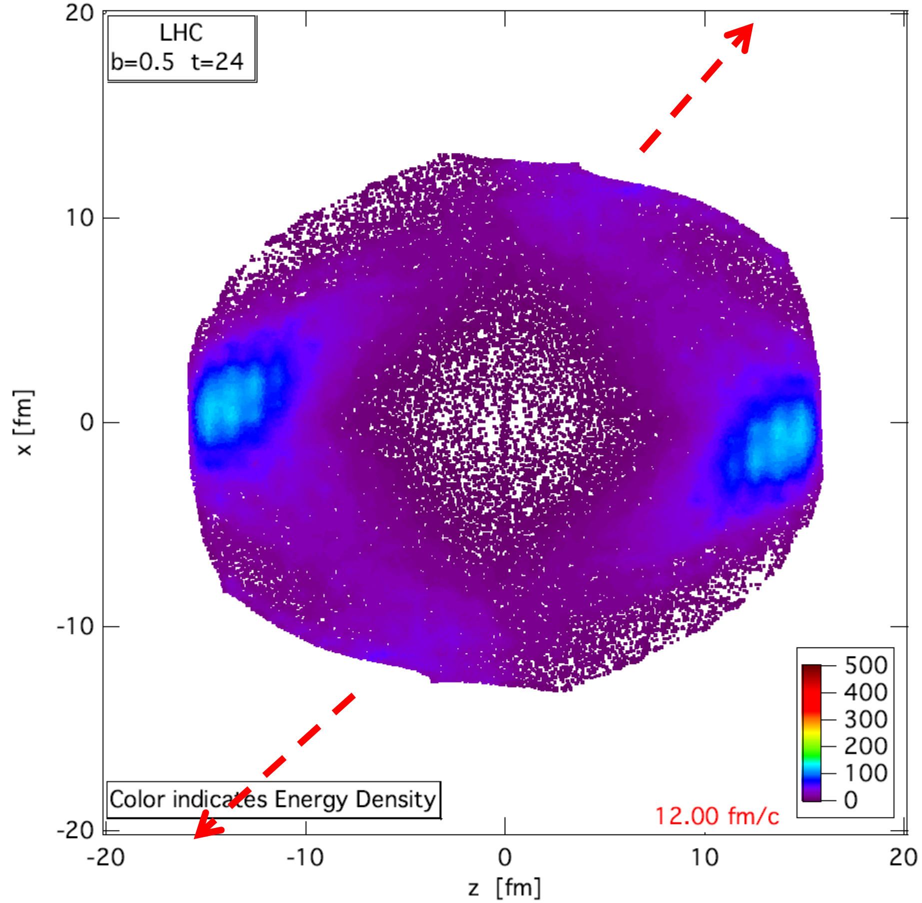
LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
FO?
Color indicates Energy Density
8.00 fm/c
500
400
300
200
100
0
x [fm]
z [fm]



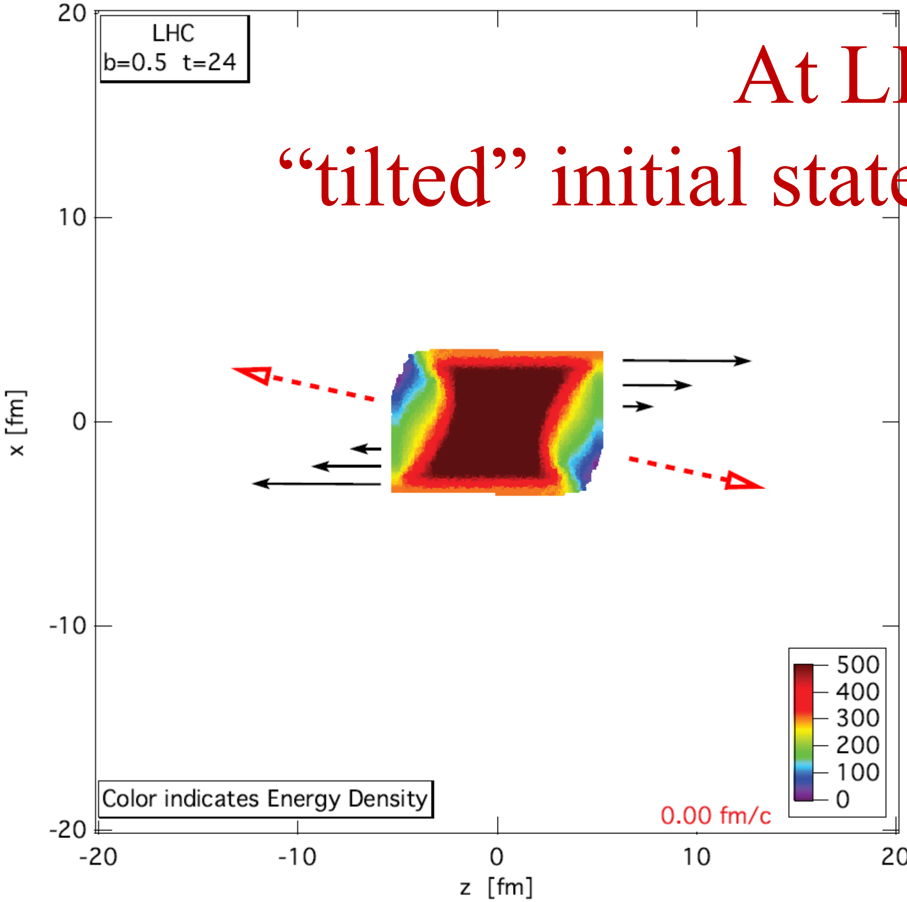
LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
FO?
Color indicates Energy Density
12.00 fm/c
500
400
300
200
100
0
20
10
0
-10
-20
x [fm]
-20
-10
0
10
20
z [fm]

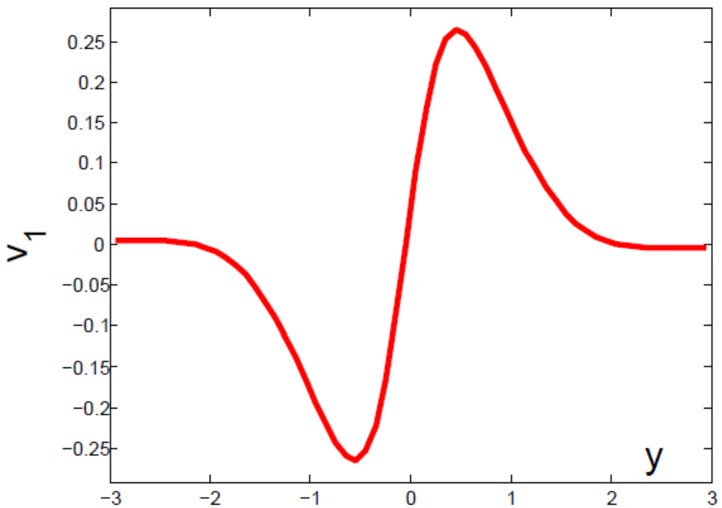
Csernai, Magas, Stöcker, Strottman,
Phys. Rev. C84 (2011) 024914

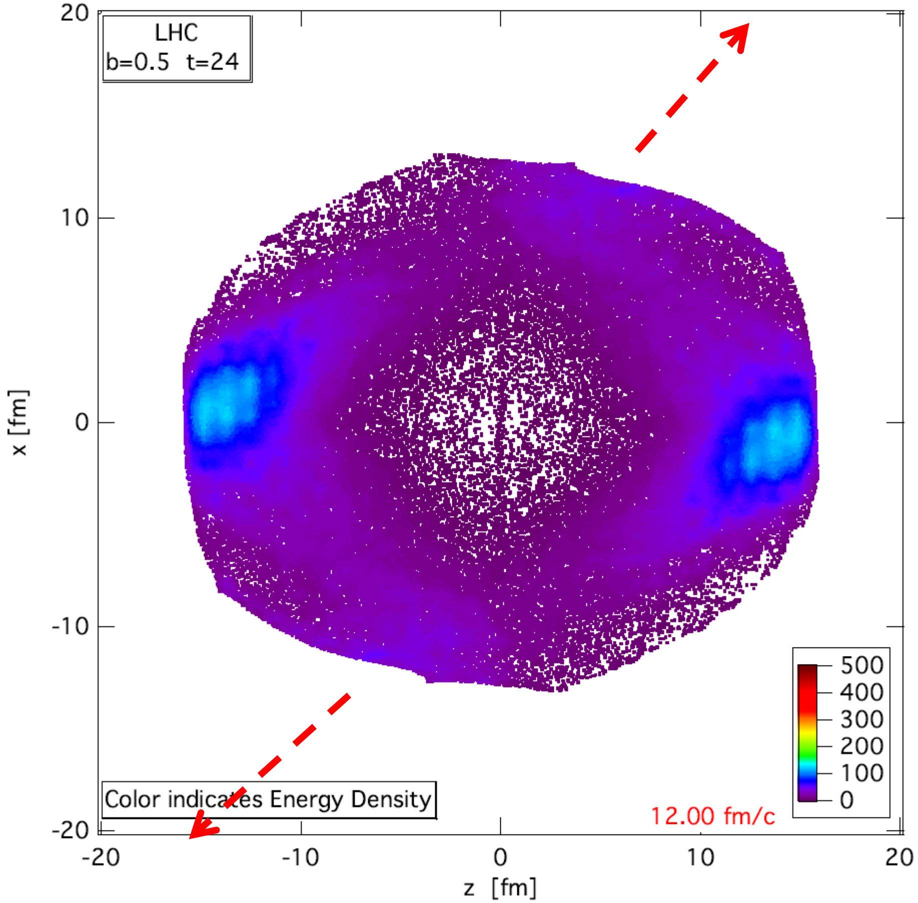




At LHC energies
“tilted” initial state → “rotating” initial state







ALICE Coll., arXiv: 1306.4145[nucl-ex]

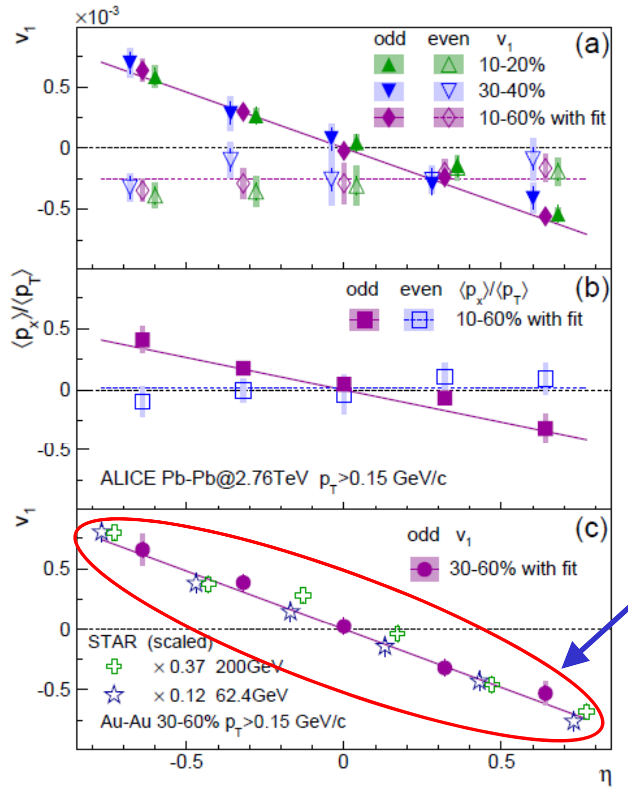


Fig. 2: (color online) (a) v_1 and (b) $\langle p_x\rangle / \langle p_T\rangle$ versus pseudorapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The statistical (systematic) uncertainties are indicated by the error bars (shaded bands). Lines represent fits with linear (constant) function for v_1^{odd} (v_1^{even}). (c) v_1^{odd} in Pb-Pb collisions compared to the STAR data [32] for Au-Au collisions at $\sqrt{s_{NN}} = 200$ (62.4) GeV downscaled with a factor 0.37 (0.12).

***V*1 at LHC has the same negative slope as at RHIC, but smaller magnitude**

V1 consistent with ideal hydrodynamic model calculations for **dipole-like energy fluctuations** in the overlap zone:

Gardim et al., PRC83, 064901 (2011);

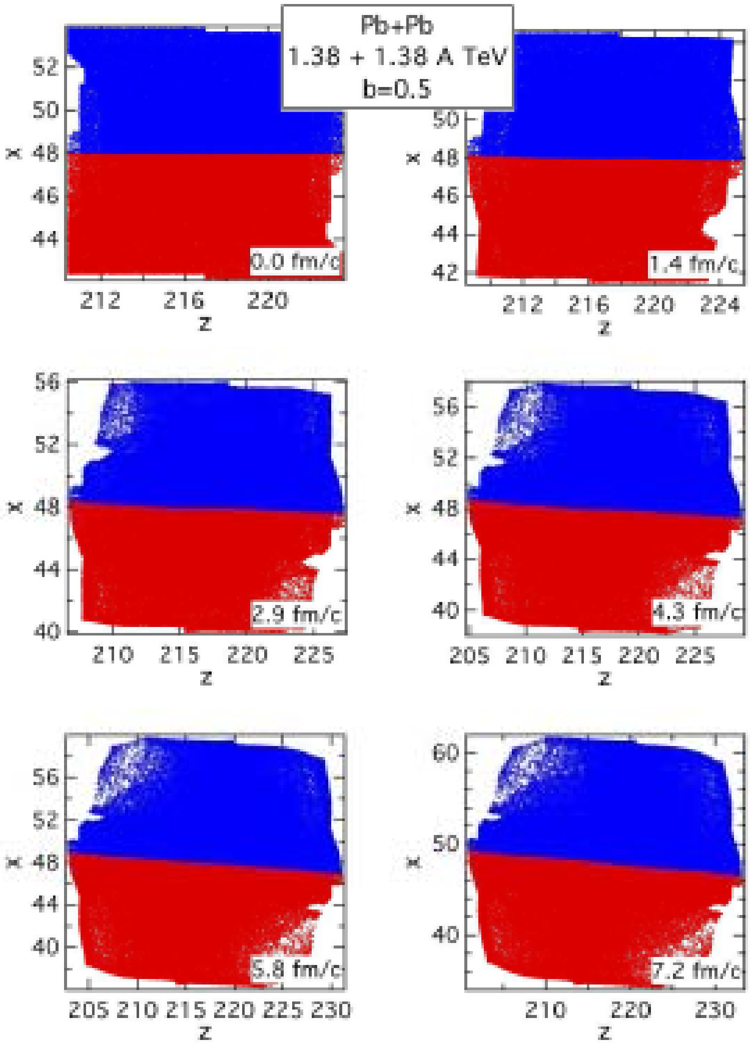
Retinskaya, Luzum, Ollitrault, PRL108, 252302 (2012)

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

L.P. Csernai[1,2,3], D.D. Strottman[2,3], and Cs. Anderlik[4]

PHYSICAL REVIEW C **85**, 054901 (2012)

ROTATION



KHI →

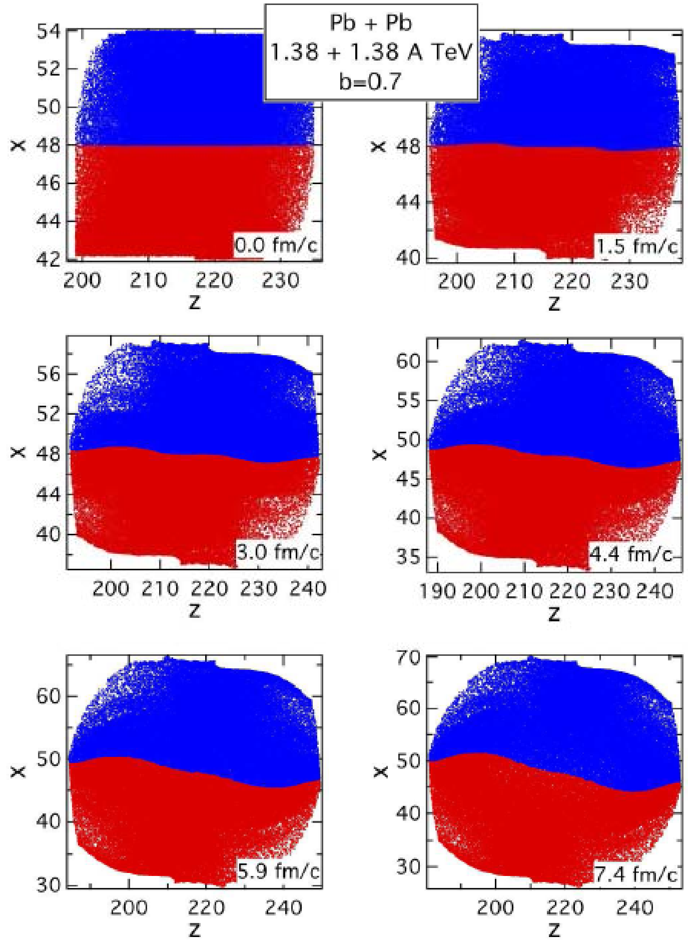


FIG. 1: (color online) Growth of the initial stage of Kelvin-Helmholtz instability in a $1.38A + 1.38A$ TeV peripheral, $b = 0.7b_{\max}$, Pb+Pb collision in a relativistic CFD simulation using the PIC-method. We see the positions of the marker particles (Lagrangian markers with fixed baryon number content) 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).

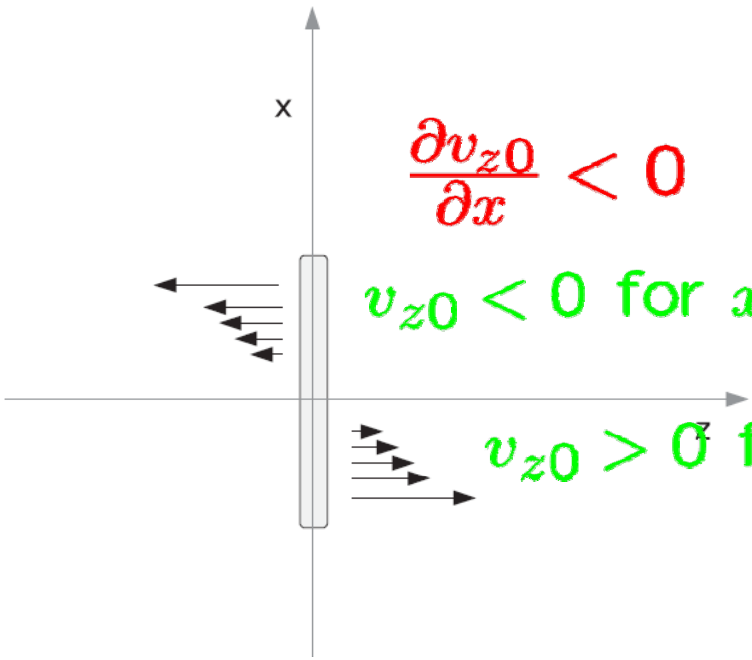
Elliptic flow from rotating initial state

Euler equation

$$(e+P)(\mathbf{u}\cdot\partial)\mathbf{u}^{\mu} = \mathbf{g}^{\mu\nu}\partial_{\nu}\mathbf{P} - (\mathbf{u}\cdot\partial\mathbf{P})\mathbf{u}^{\mu}$$

$$t=0:\ v_x = v_y = 0,\ \gamma_0^2 = 1/(1-v_{z0}^2);\ P = e/3$$

$$e_0\gamma_0^3\frac{\partial u_i}{\partial t}\Big|_{t=0} = \underbrace{-\frac{1}{4}\frac{\partial e\gamma^2}{\partial x_i}\Big|_{t=0}}_{\Omega_1} + \underbrace{\frac{1}{4}2e_0\gamma_0^4 v_{z0}\frac{\partial v_{z0}}{\partial x_i}\Big|_{t=0}}_{\Omega_2}$$



$$\frac{\partial v_{z0}}{\partial x} < 0$$

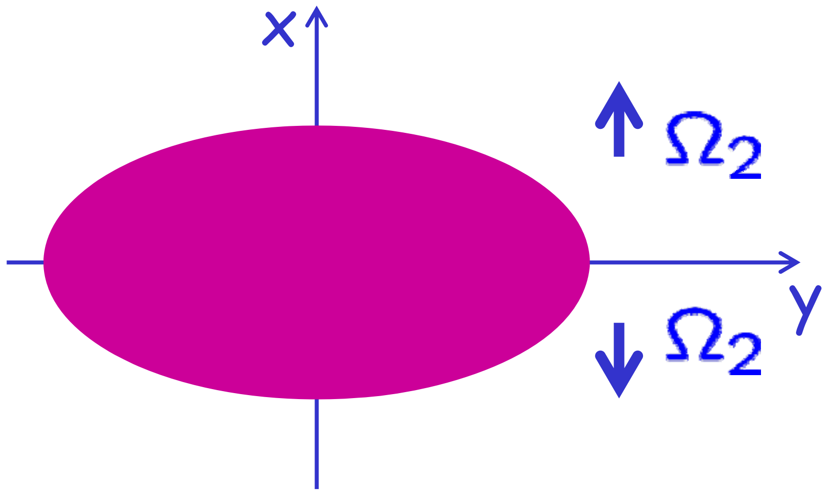
$v_{z0} < 0$ for $x > 0$ $\quad \Omega_2 \uparrow$

$v_{z0} > 0$ for $x < 0$ $\quad \Omega_2 \downarrow$

Elliptic flow from rotating initial state

Euler equation

$$e_0\gamma_0^3\frac{\partial u_i}{\partial t}|_{t=0} = \underbrace{-\frac{1}{4}\frac{\partial e\gamma^2}{\partial x_i}|_{t=0}}_{\Omega_1} + \underbrace{\frac{1}{4}2e_0\gamma_0^4 v_{z0}\frac{\partial v_{z0}}{\partial x_i}|_{t=0}}_{\Omega_2}$$



$$\left|\frac{\partial v_{z0}}{\partial x}\right| > \left|\frac{\partial v_{z0}}{\partial y}\right|$$

Ω_2 helps to produce elliptic flow!

Simple toy model initial state

Becattini, Piccinini, Rizzo, **PRC 77, 024906 (2008)**

Landau disc

but with initial flow velocity $\mathbf{v}_z$

$$J = -\int d^3\vec{r}\, x\, T^{0z} = -\int d^3\vec{r}\, x\, (e+P)\gamma^2 v_z(x)$$

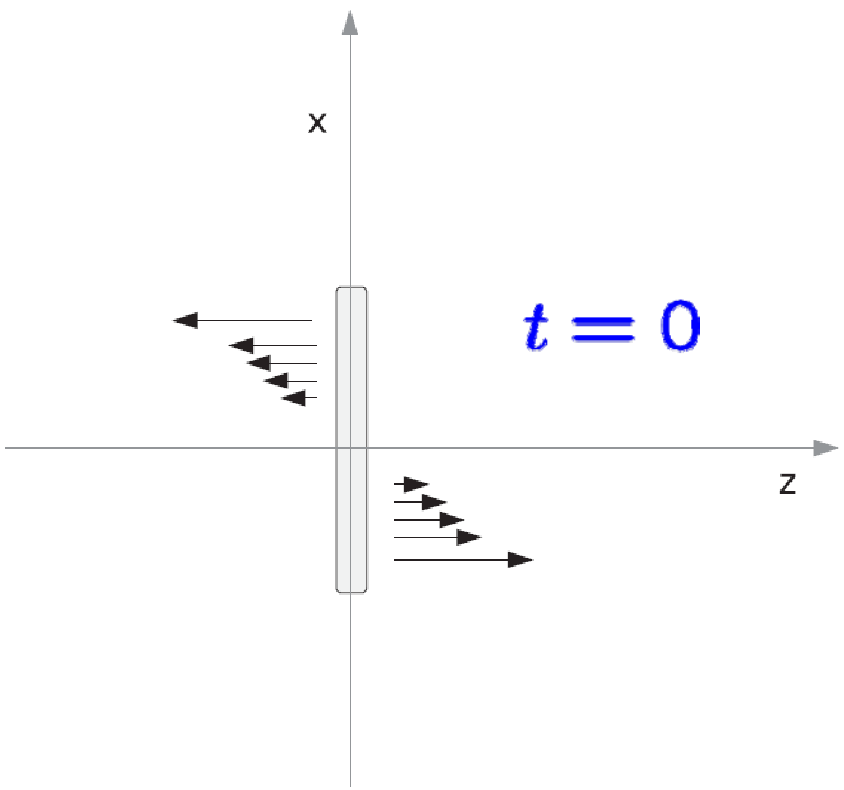


FIG. 4. Initial longitudinal velocity profile for the limiting case of sudden thermalization in the very thin overlap region of the colliding ultrarelativistic nuclei.

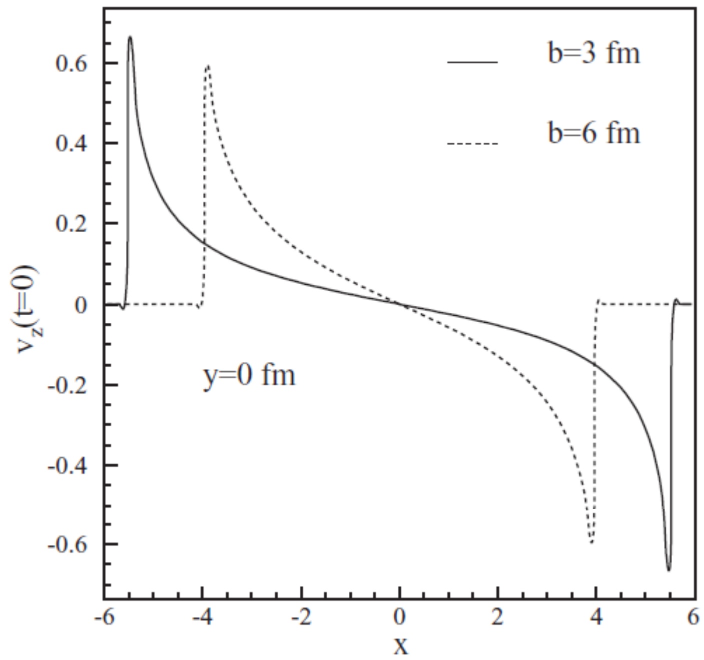


FIG. 5. Initial longitudinal velocity profile along the reaction plane $y = 0$ for two different impact parameters for the collision of two hard-sphere nuclei with 7-fm radius.

Simple toy model initial state

Becattini, Piccinini, Rizzo, **PRC 77, 024906 (2008)**

Landau disc

but with initial flow velocity $\mathbf{v}_z$

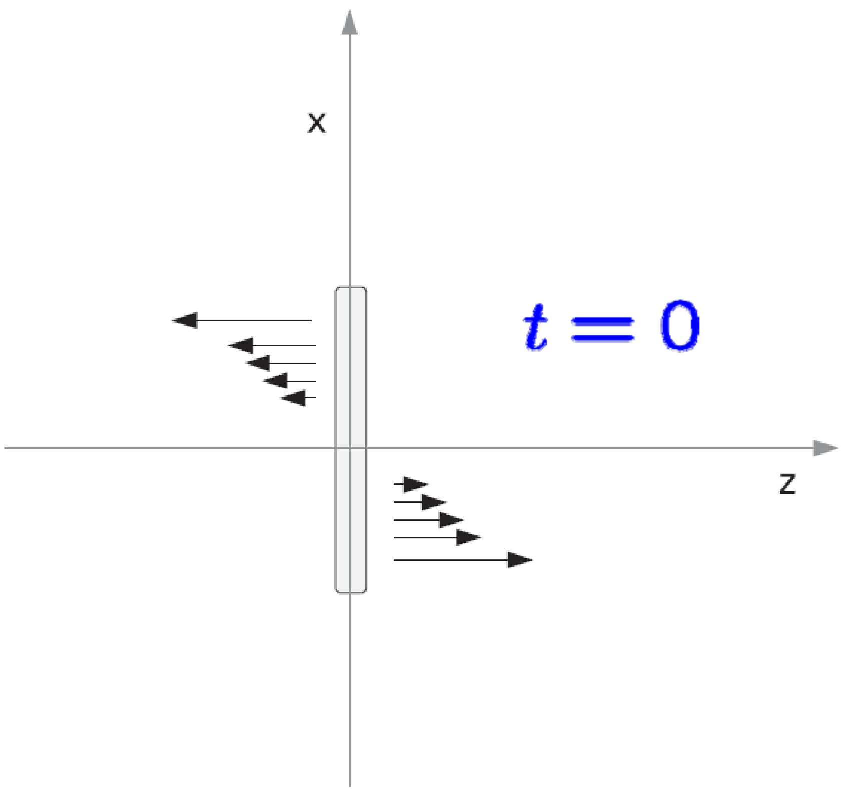


FIG. 4. Initial longitudinal velocity profile for the limiting case of sudden thermalization in the very thin overlap region of the colliding ultrarelativistic nuclei.

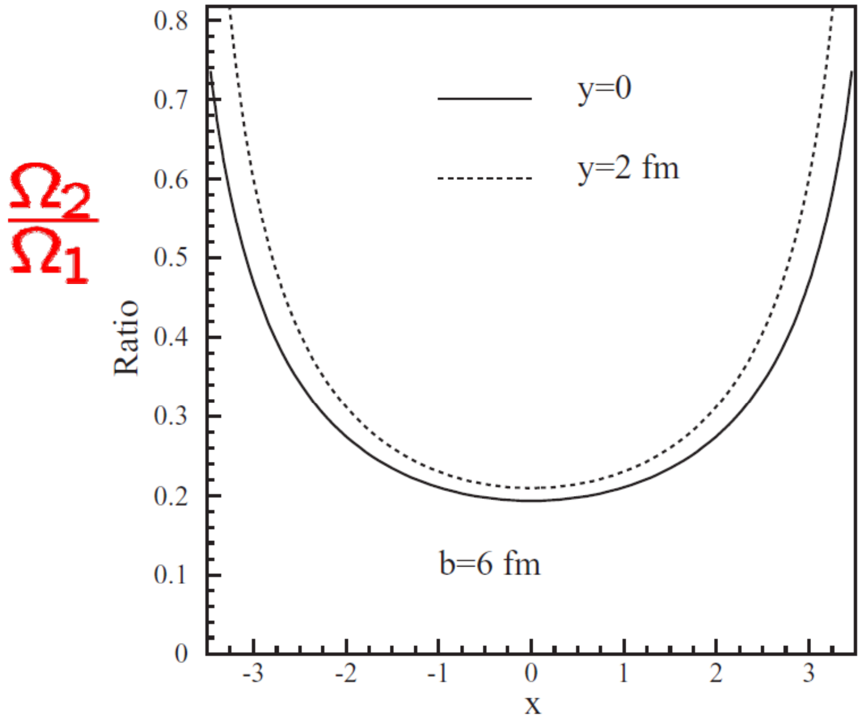


FIG. 6. Ratio of the term proportional to the vorticity and the term proportional to energy density gradient along x in Eq. (16) as a function of x for $y = 0$ and $y = 2$ fm for the collision of two hard-sphere nuclei with 7-fm radius at an impact parameter $b = 6$ fm.

Becattini, Piccinini, Rizzo, **PRC 77, 024906 (2008)**

Elliptic flow from spinning system

$$v_2^{(J)} = \frac{\int d^3x \, \frac{K_1\left(m_T\sqrt{1-|\omega\times\mathbf{x}|_\parallel^2}/T\right)}{\sqrt{1-|\omega\times\mathbf{x}|_\parallel^2}} I_2\left(\frac{p_T z\omega}{T}\right)}{\int d^3x \, \frac{K_1\left(m_T\sqrt{1-|\omega\times\mathbf{x}|_\parallel^2}/T\right)}{\sqrt{1-|\omega\times\mathbf{x}|_\parallel^2}} I_0\left(\frac{p_T z\omega}{T}\right)}$$

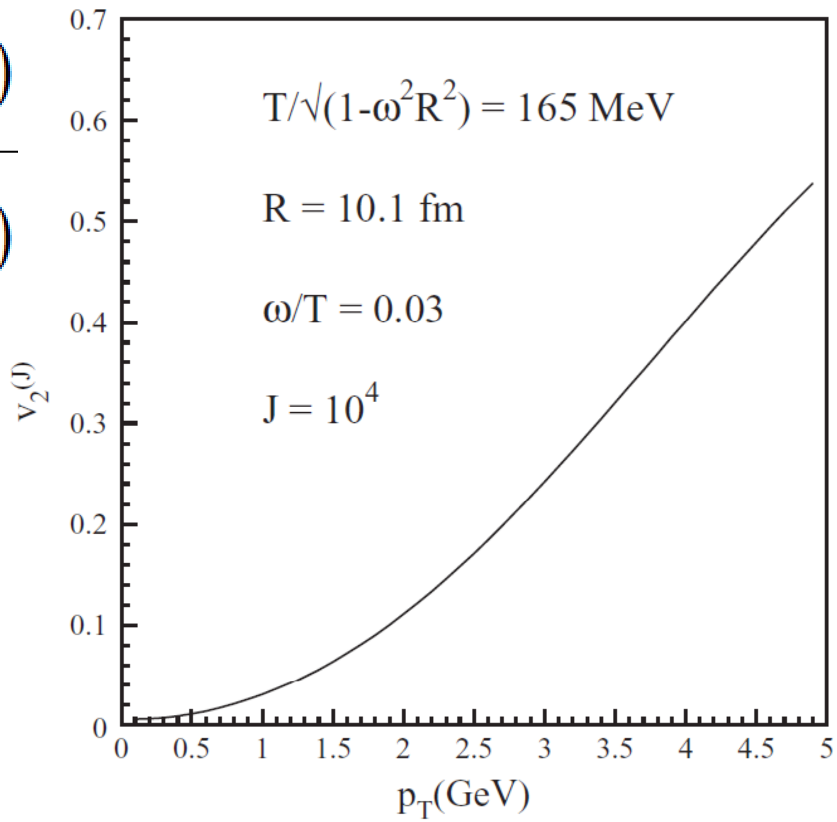


FIG. 7. Elliptic flow coefficient $v_2^{(J)}$ as a function of p_T for hadrons originated from a spherical spinning plasma at a chemical freeze-out $T = 165$ MeV and a radius of 10.1 fm for $\omega/T = 0.03$. The elliptic flow would simply vanish if $J = 0$.

Flow Vorticity

Classical

$$\omega \equiv \frac{1}{2}\text{rot } v = \frac{1}{2}\nabla \times v$$

$$\Omega_{zx} \equiv w(z,x)\ \omega_{zx}$$

energy density weighted vorticity

Relativistic

$$\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$$

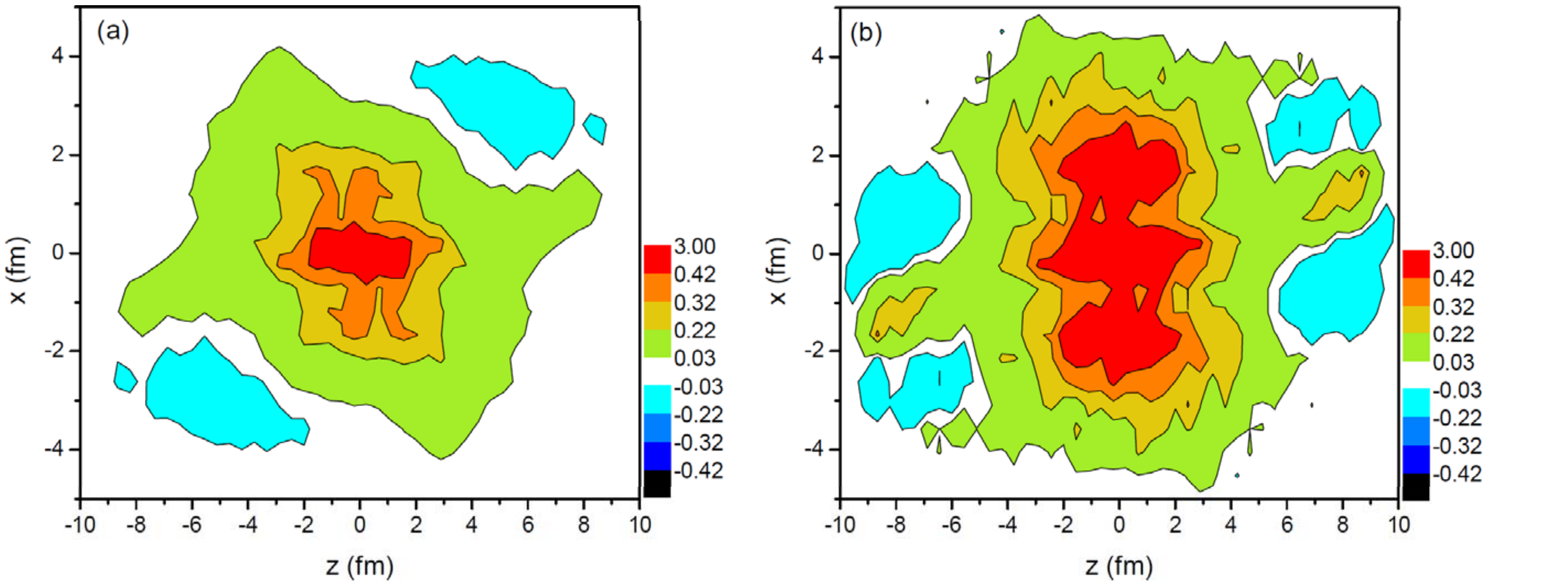


FIG. 5: The classical (left) and relativistic (right) weighted vorticity calculated for all [x-z] layers at t=3.56 fm/c. The collision energy is $\sqrt{s_{NN}} = 2.76$ TeV and $b = 0.7b_{max}$, the cell size is $dx = dy = dz = 0.4375 fm$. The average vorticity in the reaction plane is 0.0538 / 0.10685 for the classical / relativistic weighted vorticity respectively.

Csernai, Magas, Wang, **PRC 87 (2013) 034906**

Vorticity ⇒ particle polarization

- T. Liang, X. N. Wang, PRL 94 (2005) 102301 [Erratum-ibid. 96 (2006) 039901]

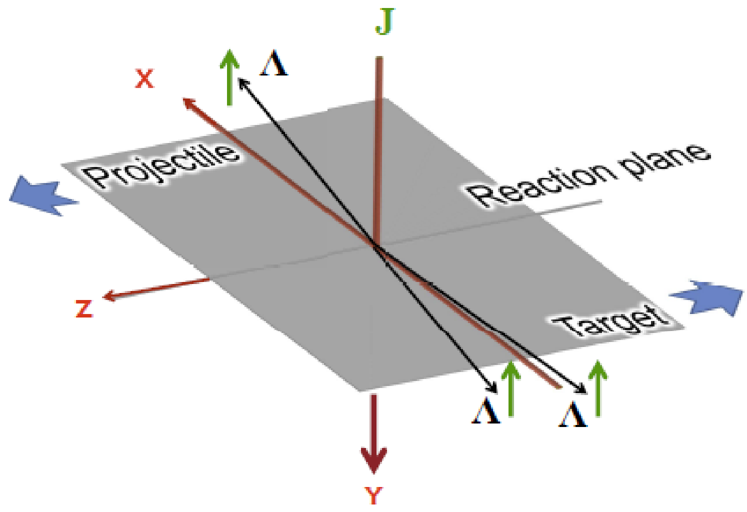
- B. Betz, M. Gyulassy, G. Torrieri, PRC 76 (2007) 044901 (2007)

- J. H. Gao et al., PRC 77 (2008) 044902

- Becattini, Piccinini, Rizzo, **PRC 77, 024906 (2008)**

- Becattini, Csernai, Wang, arXiv:1304.4427, accepted to PRC

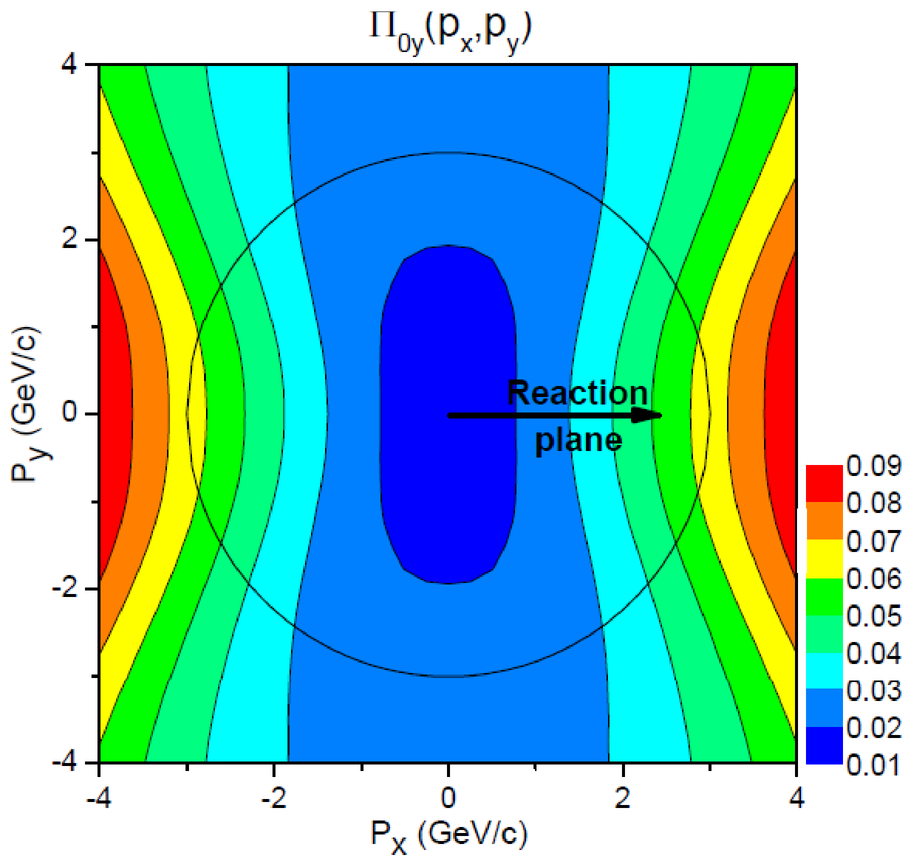
Detecting rotation: Lambda polarization



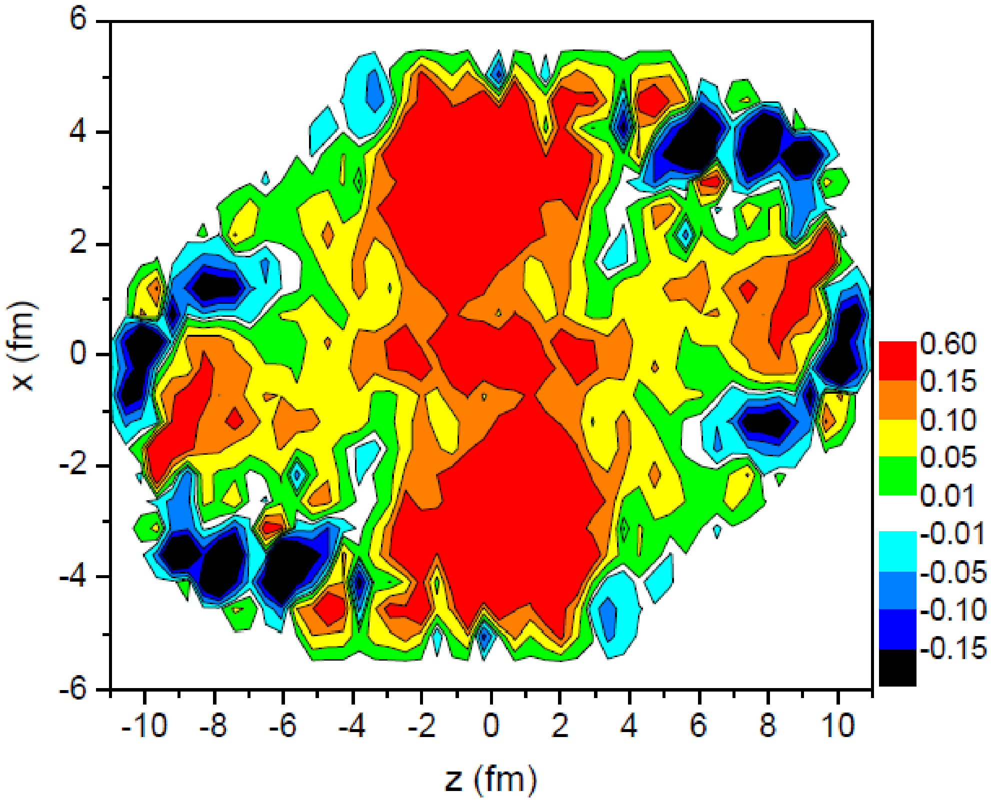
$$\mathbf{\Pi}(p) = \frac{\hbar\varepsilon}{8m}\frac{\int \mathrm{d}V\, n_F\, (\nabla\times\beta)}{\int \mathrm{d}V\, n_F}$$

$$\beta^\mu(x) = (1/T(x))u^\mu(x)$$ ← *from hydro*

$$\mathbf{\Pi}_0(p) = \mathbf{\Pi}(p) - \frac{\mathbf{p}}{\varepsilon(\varepsilon+m)}\mathbf{\Pi}(p)\cdot\mathbf{p}$$

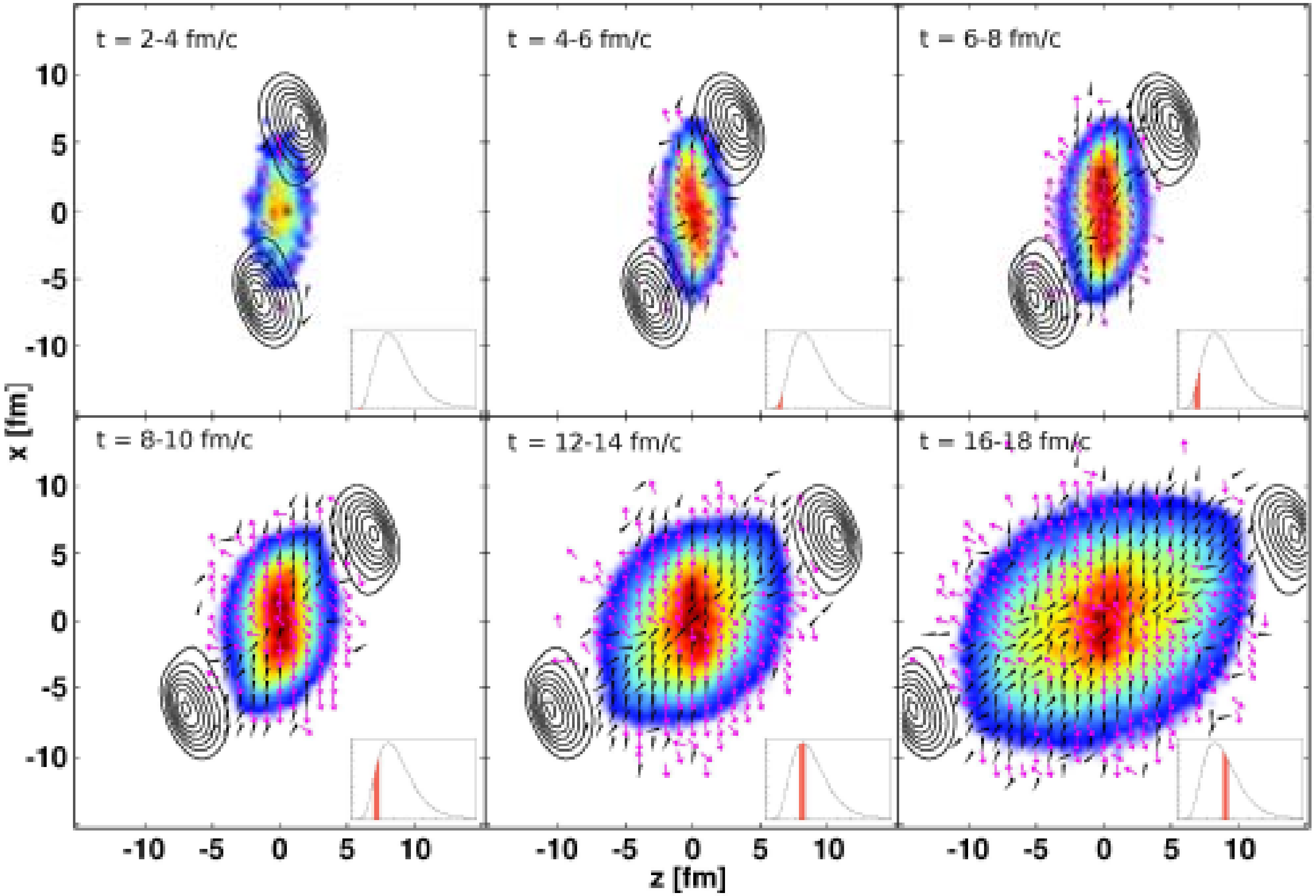


Becattini, Csernai, Wang, arXiv:1304.4427



Detecting initial rotation: Azimuthally sensitive HBT

UrQMD simulation



Pb+Pb

$E_{lab} = 8\,AGeV$

Graef, Lisa, Bleicher, arXive 1302.3408

Figure 3. Shape of the freeze out region from pions frozen out at different times (colored surface). The contour lines depict the position of the spectators in each timestep. The vector field shows the direction of movement at each position and time. The black arrowheads contribute to the directed flow while the magenta arrows contribute to the antiflow. The inlay shows the freeze out luminosity of pions versus freeze out time. The shaded region in the inlay highlights the luminosity corresponding to the timestep in the overall picture.

Detecting initial rotation: Differential HBT

L.P. Csernai, S. Velle , arXive 1305.0385

L.P. Csernai, S. Velle, D.J. Wang , arXive 1305.0396

$$\Delta C(k_\pm, q_{out}) \equiv C(k_+, q_{out}) - C(k_-, q_{out}) = \frac{4\exp(-R^2q^2)\ \epsilon \sinh\left(\frac{2u_z\, bk}{T_s}\right)\ (1-\epsilon^2)\left[1-\cosh\left(\frac{u_z\, bq}{T_s}\right)\cos\left(aqd_x\right)\right]}{\left[(1+\epsilon^2)\cosh\left(\frac{2u_z\, bk}{T_s}\right) + (1-\epsilon^2)\right]^2 - 4\epsilon^2 \sinh^2\left(\frac{2u_z\, bk}{T_s}\right)}.$$

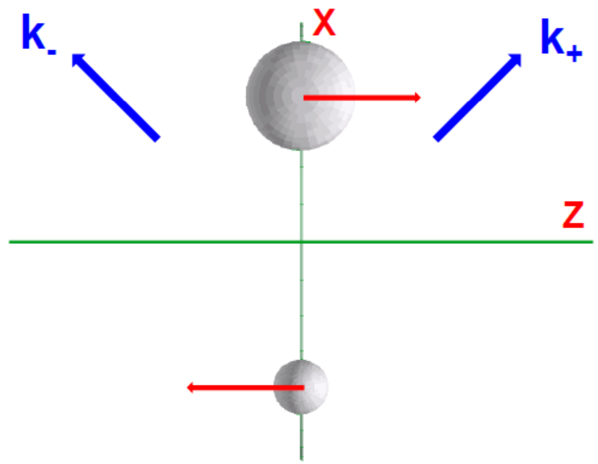


FIG. 14. (color online) Two moving sources in the reaction ($[x-z]$) plane, separated in the $x-$ direction. The sources are moving in the directions indicated by the (red) arrows. The two "tilted" detector directions are indicated by the (blue) arrows labeled with k_+ and k_-.

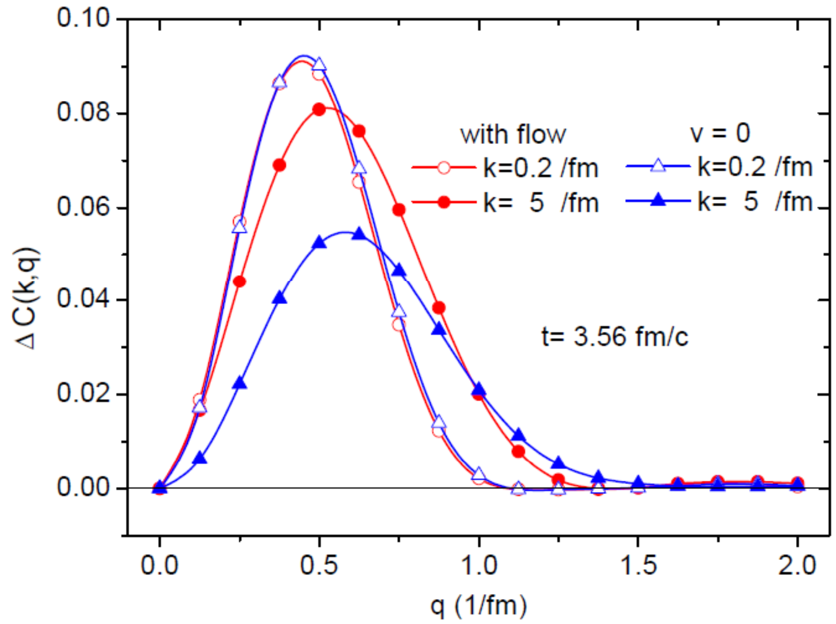


FIG. 3. (color online) The flow velocity dependence of the differential correlation function at the final time.

Conclusions

Initial state with large initial angular momentum at LHC energies results in rotating "fireball"

The effect of such a rotation may be seen in:

- Directed flow, v_1
- Elliptic flow, v_2
- Particle polarization
- HBT

Back up

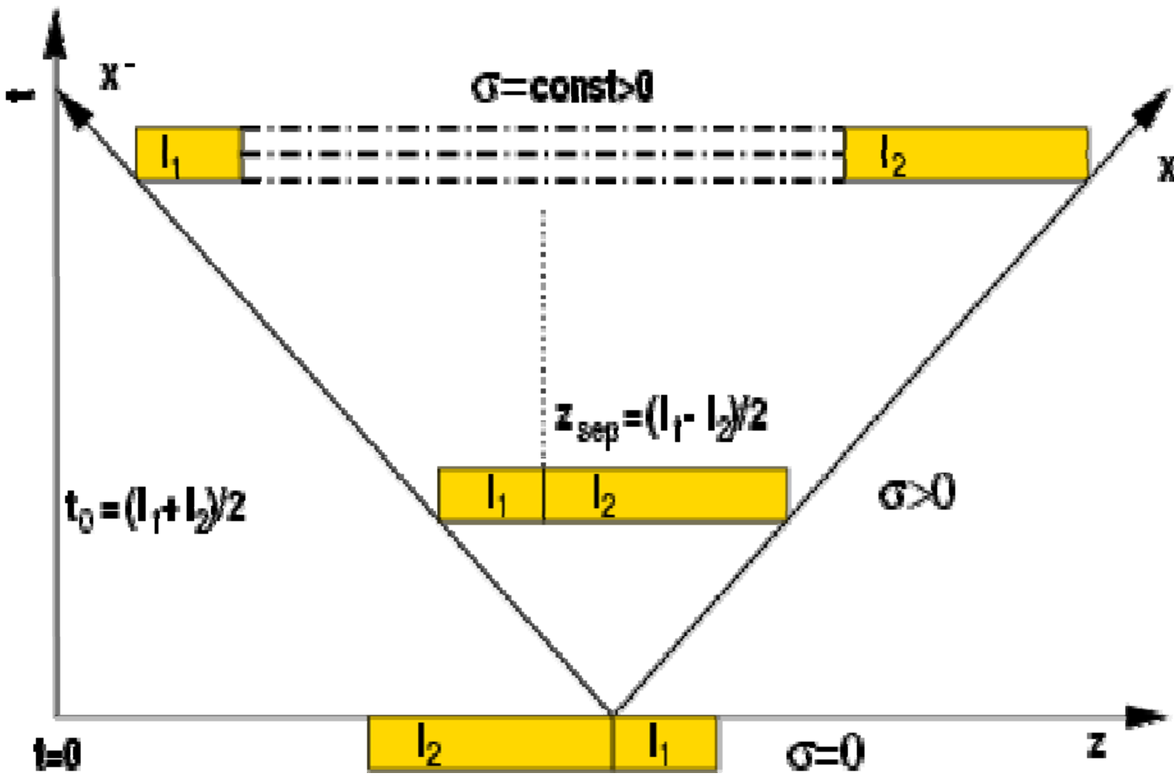
Effective string rope model

Magas, Csernai, Strottman, PRC 64 (2001) 014901, NPA 712 (2002) 167

Transparency in the first moment

+ stretching chromoelectric field

+ energy-momentum conservation →
deceleration of the colliding partons



Vovchenko, Anchishkin, Csernai,
Phys. Rev. C88 (2013) 014901

Csernai, Magas, Stöcker, Strottman,
Phys. Rev. C84 (2011) 024914

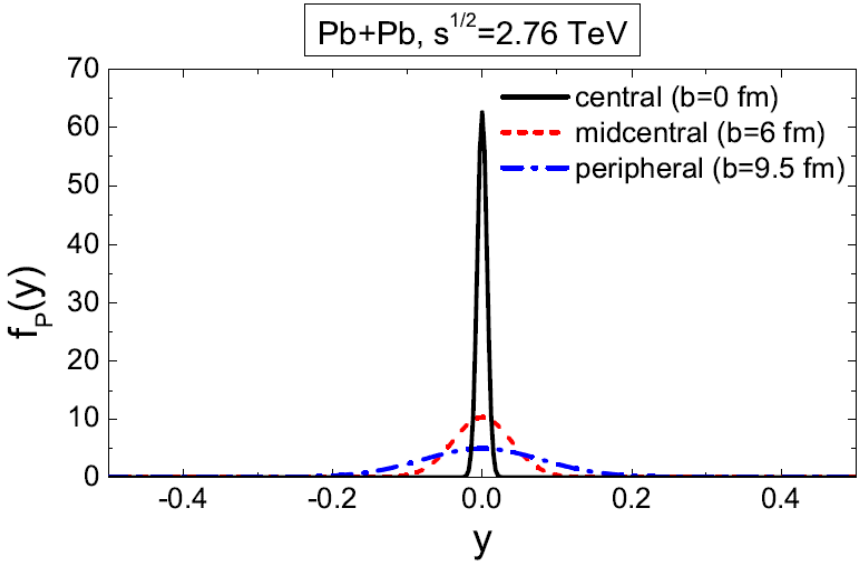
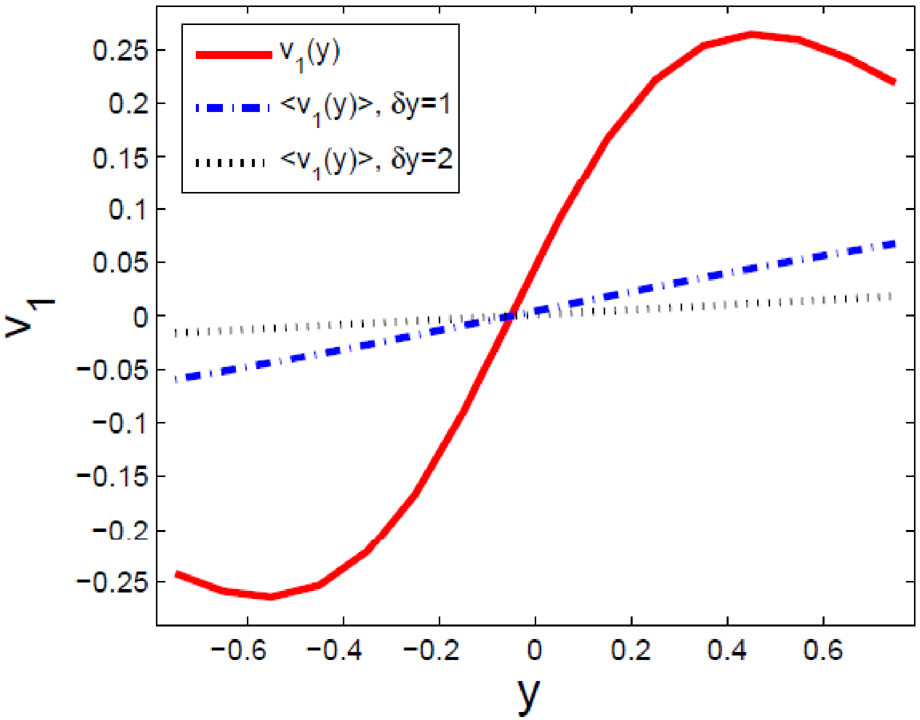


FIG. 5. Participant center-of-mass rapidity distribution for Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV for three different centralities.

y_{CM} is fluctuating around "0" with Gaussian distribution

$$f(y_{CM}) = \frac{1}{\sqrt{2\pi\delta y^2}} e^{-y_{CM}^2/\delta y^2}$$

Drastic effect:
no peaks !



Bleibel, Burau, Fuchs, PL B659, 520 (2008)

Similar results within
quark-gluon string model
with parton rearrangement