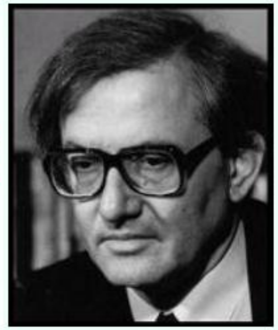
RHIC SCHOOL'11

Gy. Vásárhelyi (V. Vasarely): Fény

11. Zimányi

WINTER SCHOOL ON HEAVY ION PHYSICS

Nov. 28. - Dec. 2., Budapest, Hungary



József Zimányi (1931 - 2006)

Different initial states and the collective flow

Laszlo P. Csernai,
University of Bergen, Norway, &
MTA-KFKI RMKI, Budapest, Hungary

- **At Bergen U., with:**
- **Miss Astrid Skålvik, UoB**
- **Miss Du-juan Wang, UoB**
- **Csaba Anderlik, Uni-Computing**

- **Other institutes:**
- **Prof. Daniel D. Strottman, LANL**
- **Prof. Volodymyr Magas, U Barcelona**
- **Prof. Horst Stöcker, GSI**
- **Dr. Yun Cheng, CCNU Wuhan**
- **Dr. Yu-liang Yan, CIAE Beijing**
- **… et al.**

TODAY – Elliptic flow at LHC

Elliptic flow of charged particles in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

(The ALICE Collaboration)

17 Nov 2010

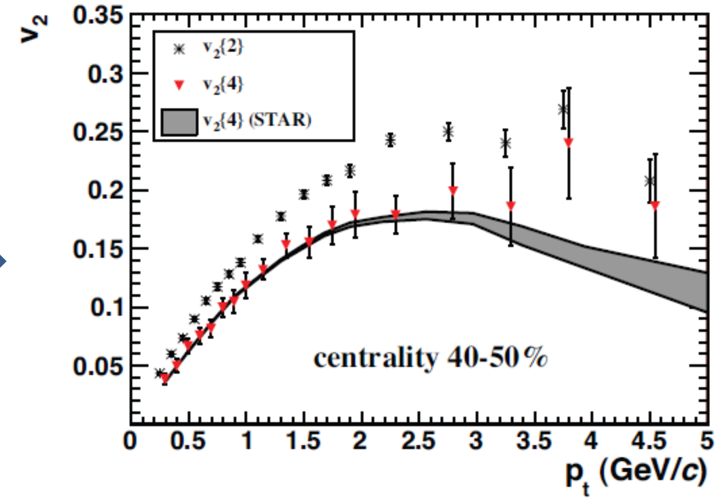
First result of ALICE:

In non-central collisions flow is stronger than ever before.

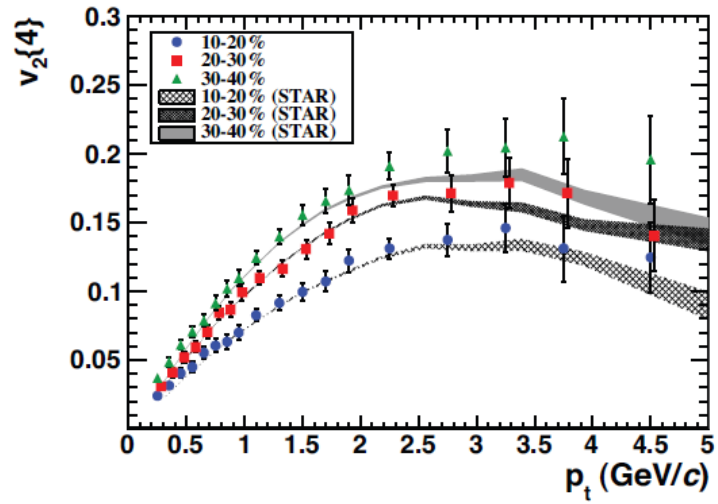
Dominant at higher energies.

Quark number scaling indicates

that flow is created in QGP



(a)



Fluctuating initial states

[1] Gardim FG, Grassi F, Hama Y, Luzum M, Ollitraut PHYSICAL REVIEW C **83**, 064901 (2011); (v_1 also)
[2] Qin GY, Petersen H, Bass SA, Mueller B PHYSICAL REVIEW C **82**, 064903 (2010)

QIN, PETERSEN, BASS, AND MÜLLER

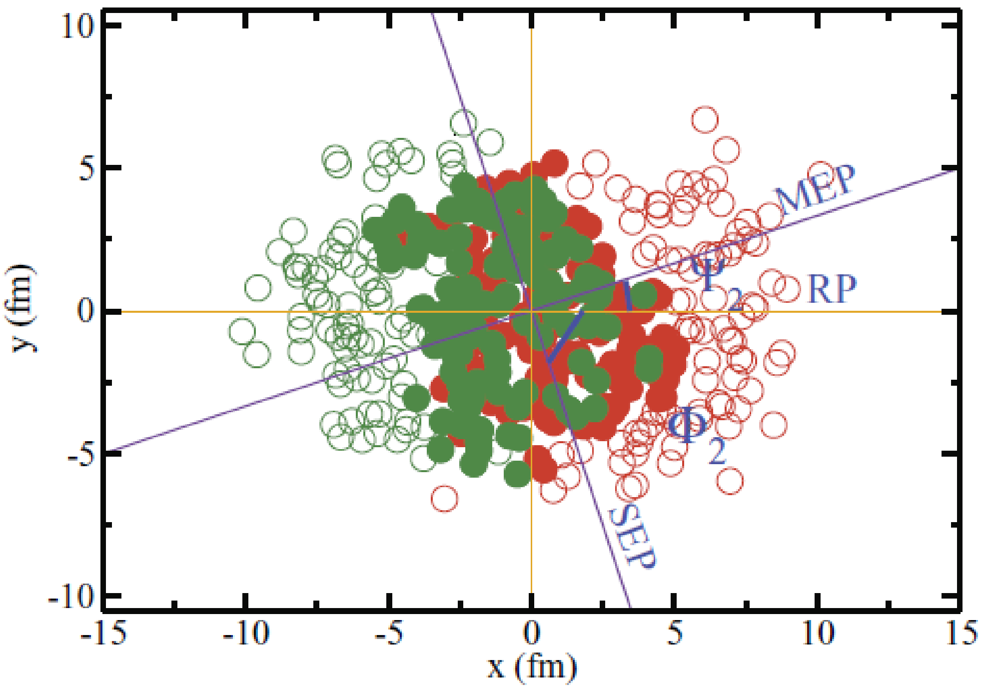


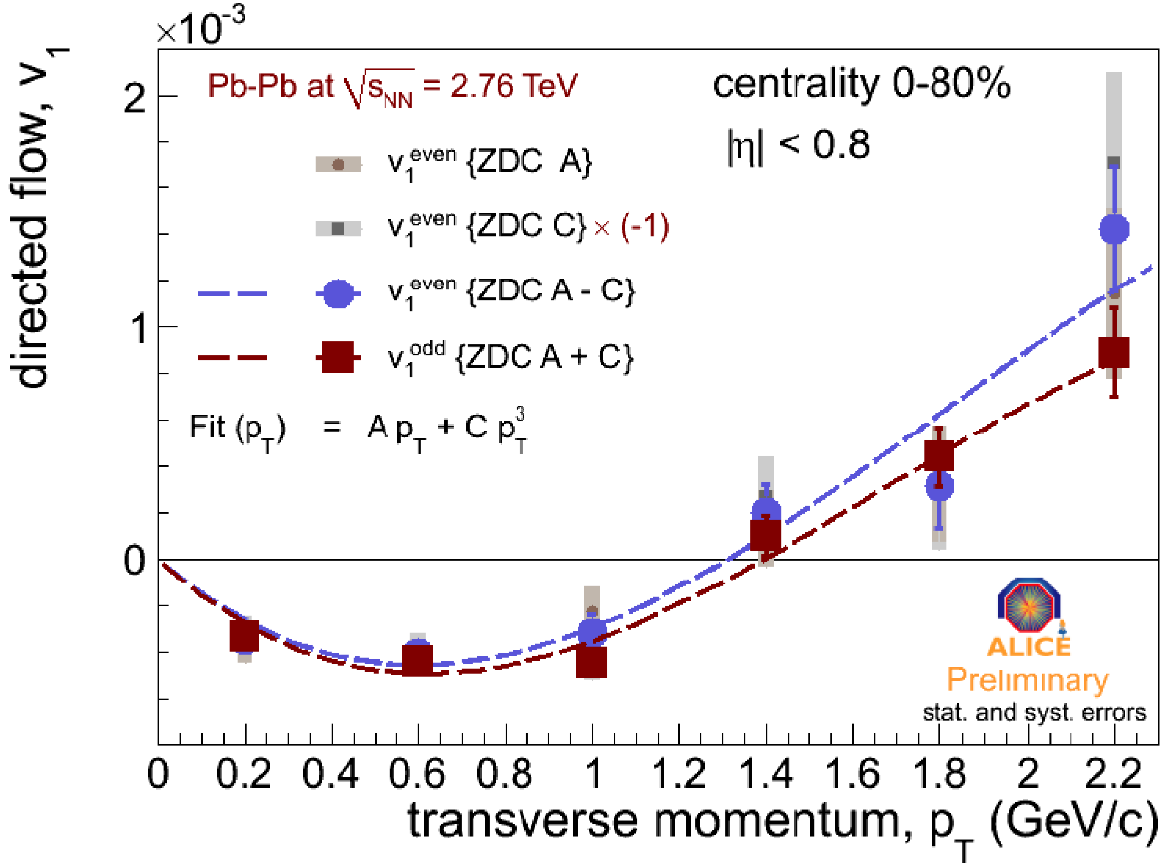
FIG. 3. (Color online) The transverse plane for one typical collision event, where the circles represent nucleons from two nuclei, with shaded ones for participating nucleons. Also shown are the locations of different planes: the reaction plane (RP), the spatial event plane (SEP), and the momentum event plane (MEP) for $n = 2$.

Cumulative event planes show weak correlation with the global collective reaction plane (RP).

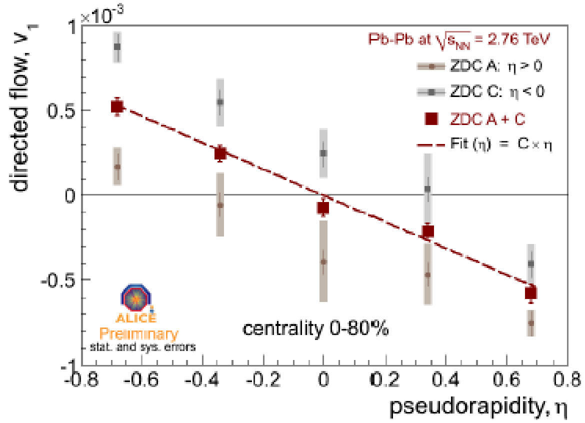
If the MEP is set to zero (by definition) then CM rapidity fluctuations do not appear, and v_1 by definition is zero.

In [2] v1(pt) is analyzed (for RHIC) and the effect is dominated by fluctuations. (Similar to later LHC measurements.)

Extracting even and odd parts of v_1



what we expect for even and odd projections:



V_1 from Global Collective flow ➔ $v_1(p_t) = 0$!!!

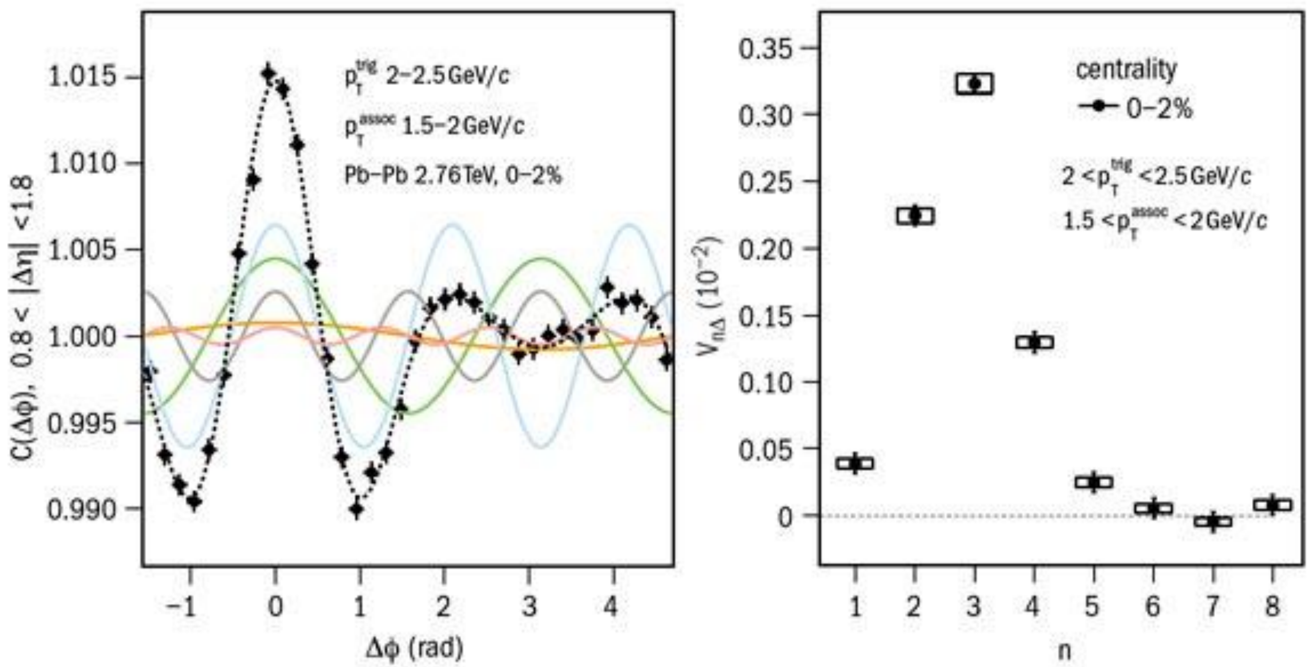
Even and odd parts of v_1 have similar shape and magnitude

CERN COURIER

Sep 23, 2011

ALICE measures the shape of head-on lead-lead collisions

Oct. 2011, p. 6



Flow originating from initial state fluctuations is significant and dominant in central and semi-central collisions (where from global symmetry no azimuthal asymmetry could occur) !

Collective flow

- There are alternative origins:
- (a) Global collective flow (RP from spectators)
- (b) Asymmetries from random I.S. fluctuations
- (c) Asymmetries from Critical Point fluctuations

- **Goal is to separate the these**

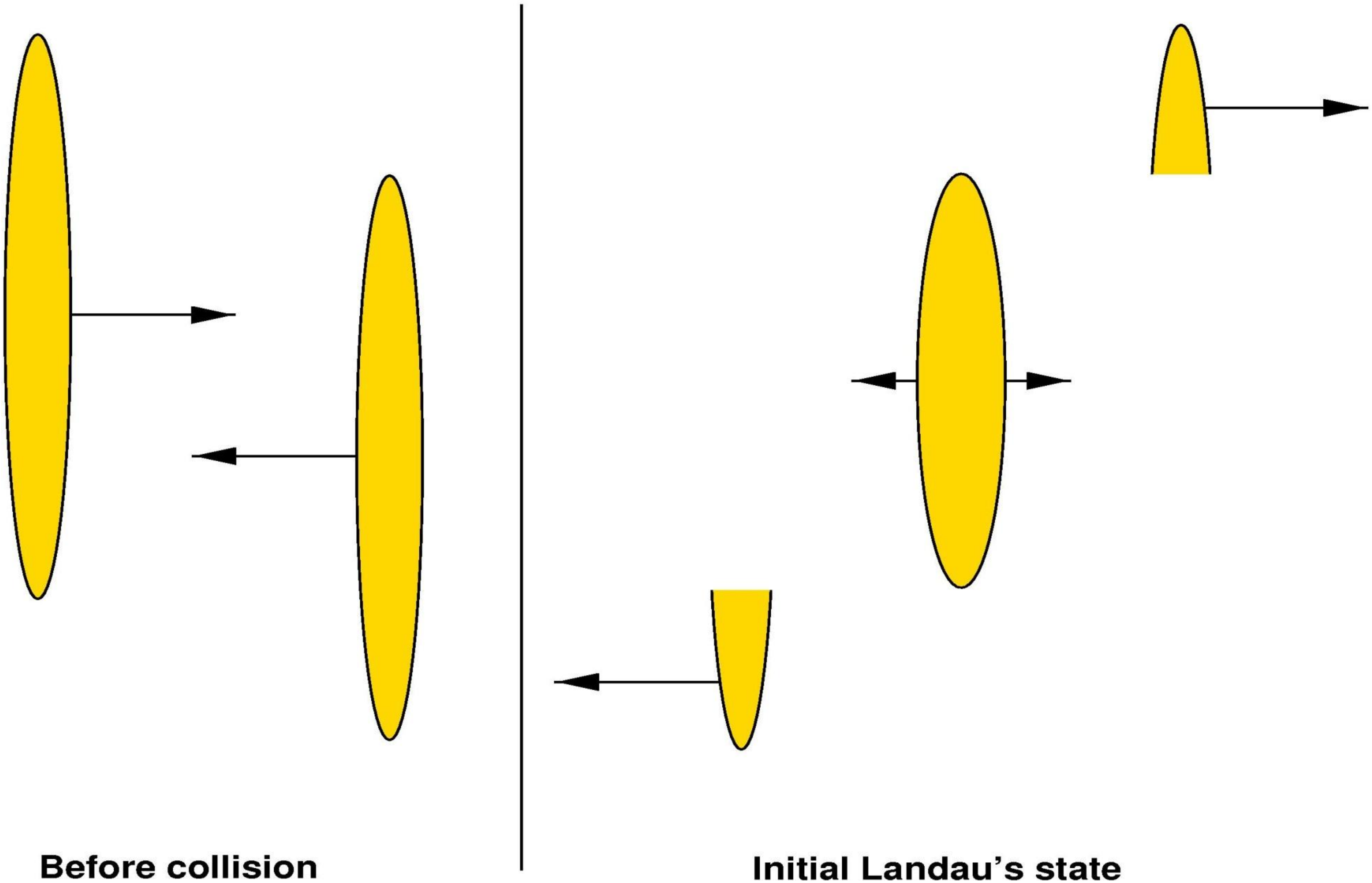
  ➔ This provides more insight

- How can we see the flow of QGP?

  ➔ Rapid hadronization and freeze-out

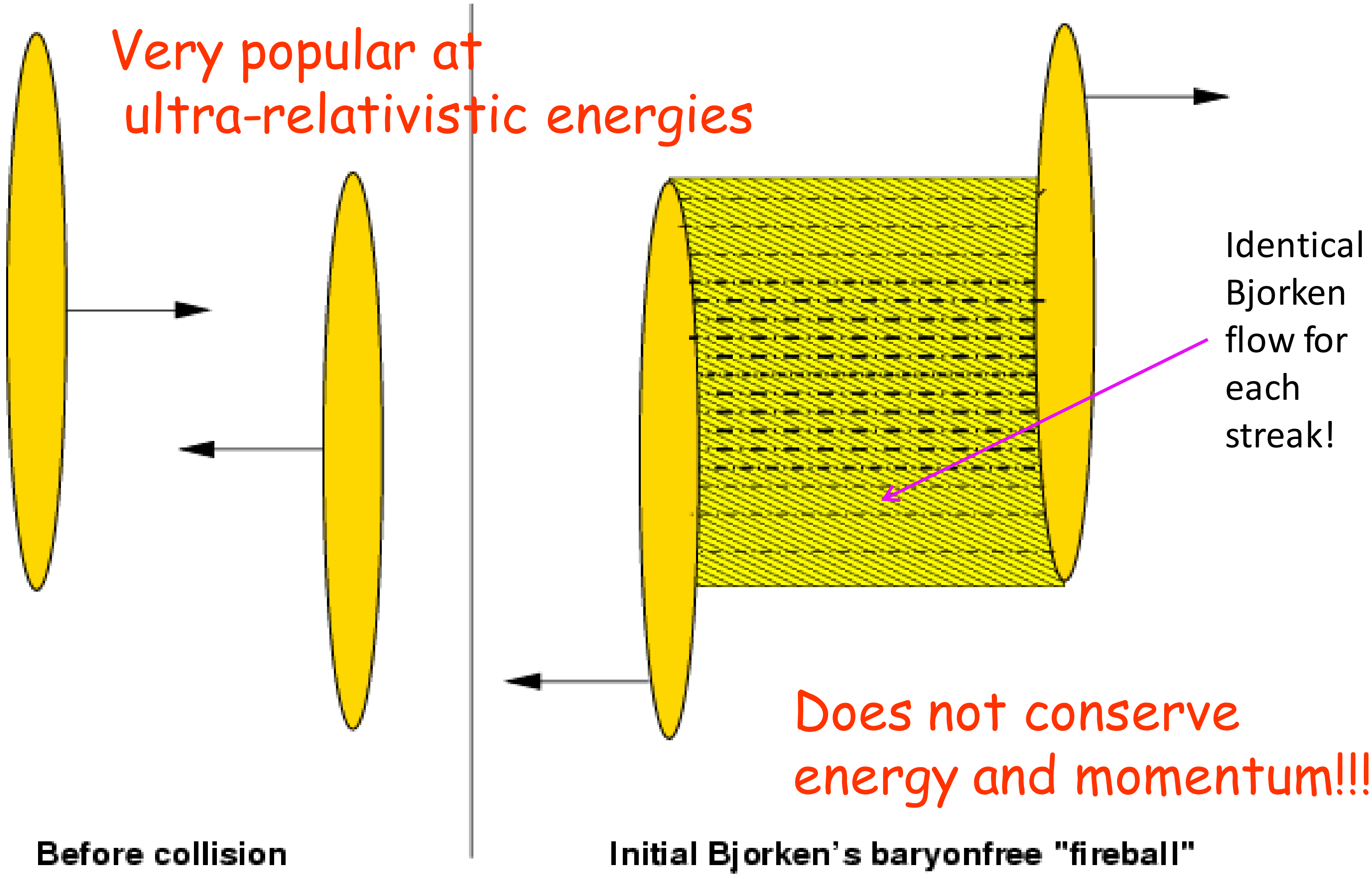
Initial state – Landau, complete stopping

Works well at low energies

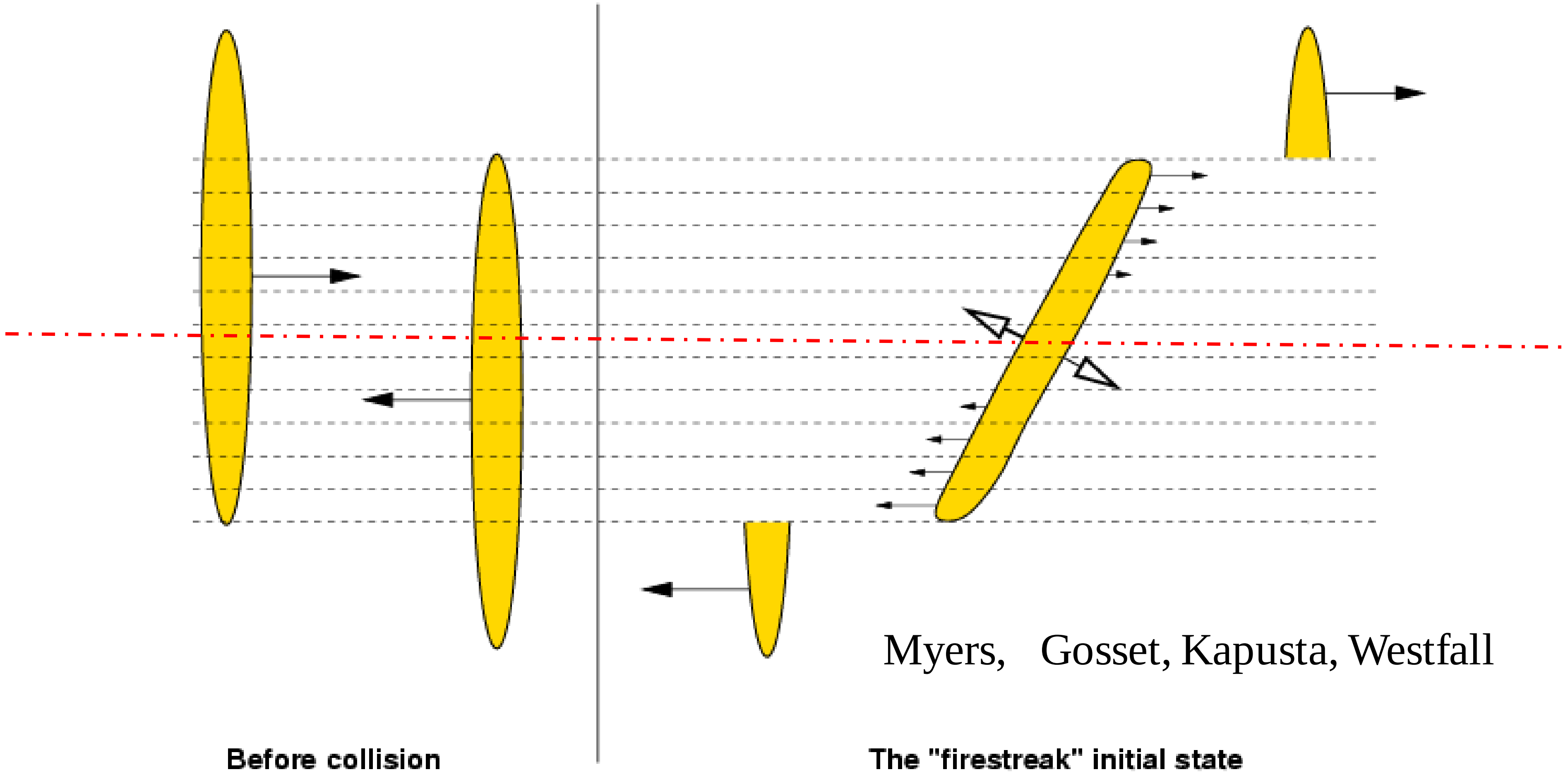


Bjorken initial state – complete transparency

Initial state is boost invariant – all quantities depent only on ♦
not on y → give rise to 2+1D simple hydro models



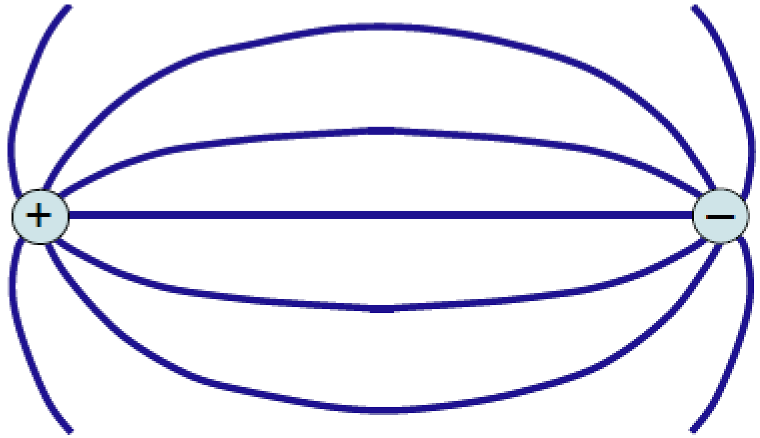
„Fire streak" picture – 3 dim.



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

Flux – tubes

ED or QED:

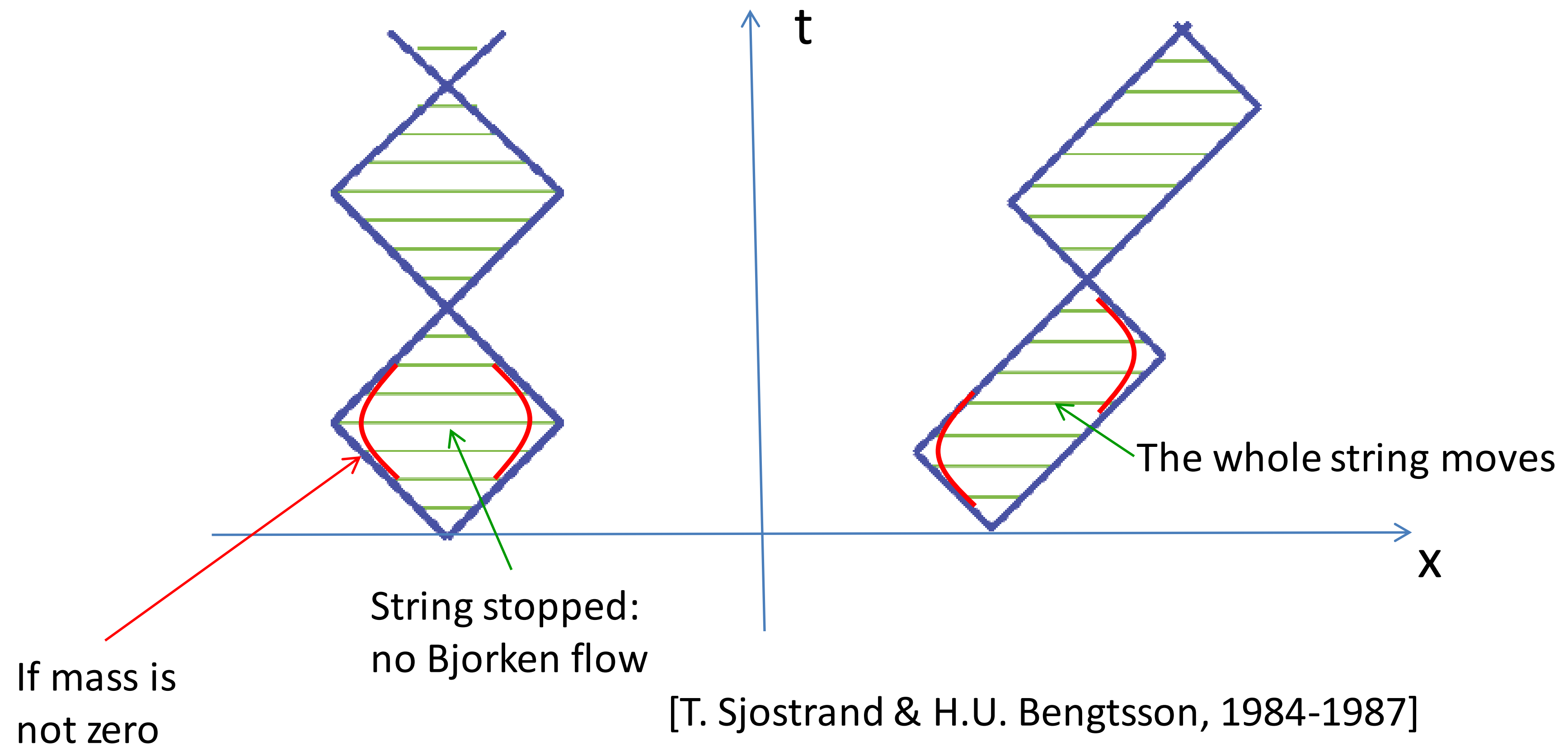


Gluon self-interaction makes field lines attract each other. →
QCD:

→ linear potential → confinement

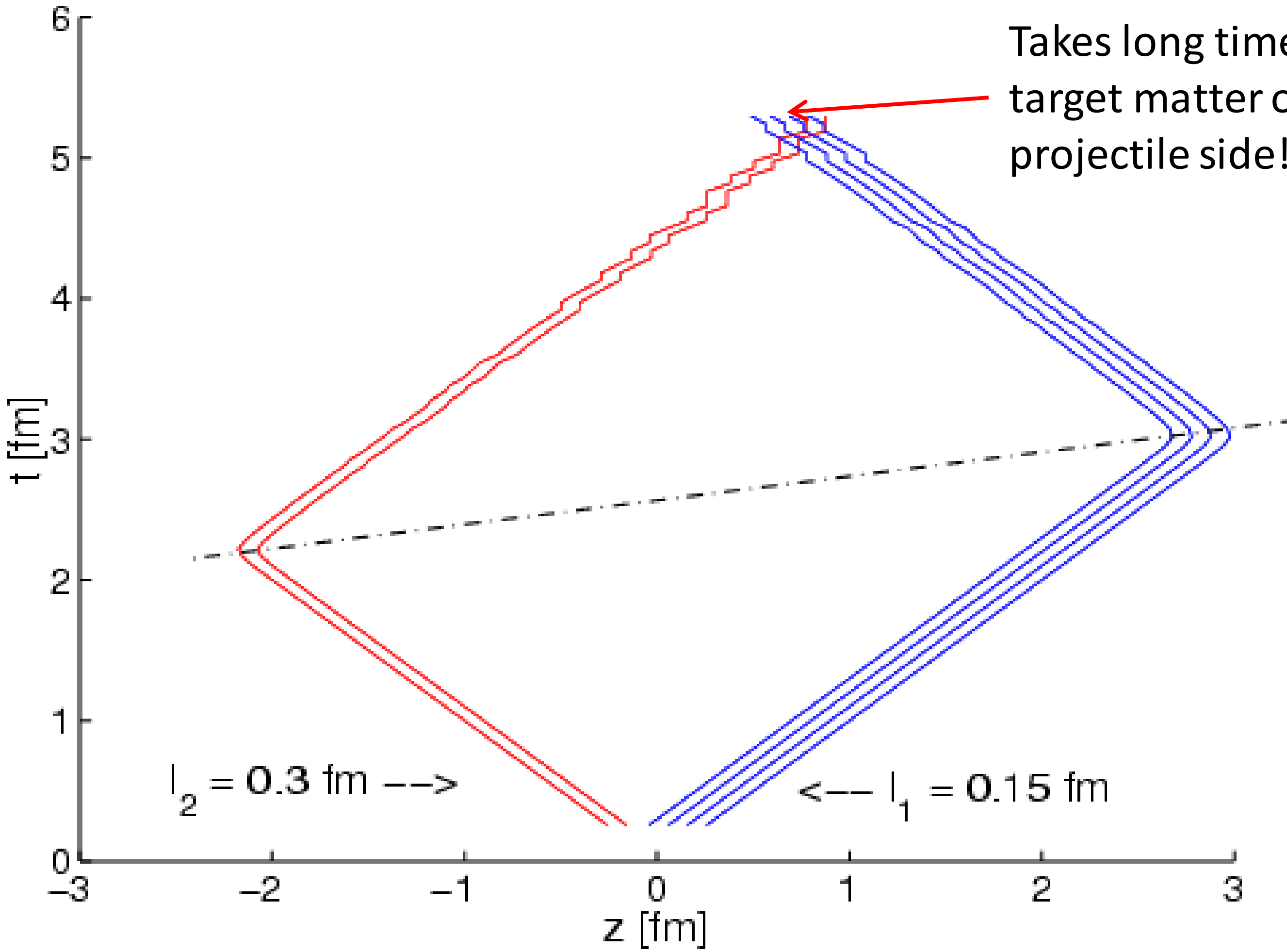
String model of mesons / PYTHIA

Light quarks connected by string → mesons have ‘**yo-yo**’ modes:



[T. Sjostrand & H.U. Bengtsson, 1984-1987]
PYTHIA

Yo – Yo Dynamics



Takes long time to move target matter over to the projectile side!

Nuclear Physics A460 (1986) 723–754
North-Holland, Amsterdam

BARYON RECOIL AND THE FRAGMENTATION REGIONS IN ULTRA-RELATIVISTIC NUCLEAR COLLISIONS*

M. GYULASSY

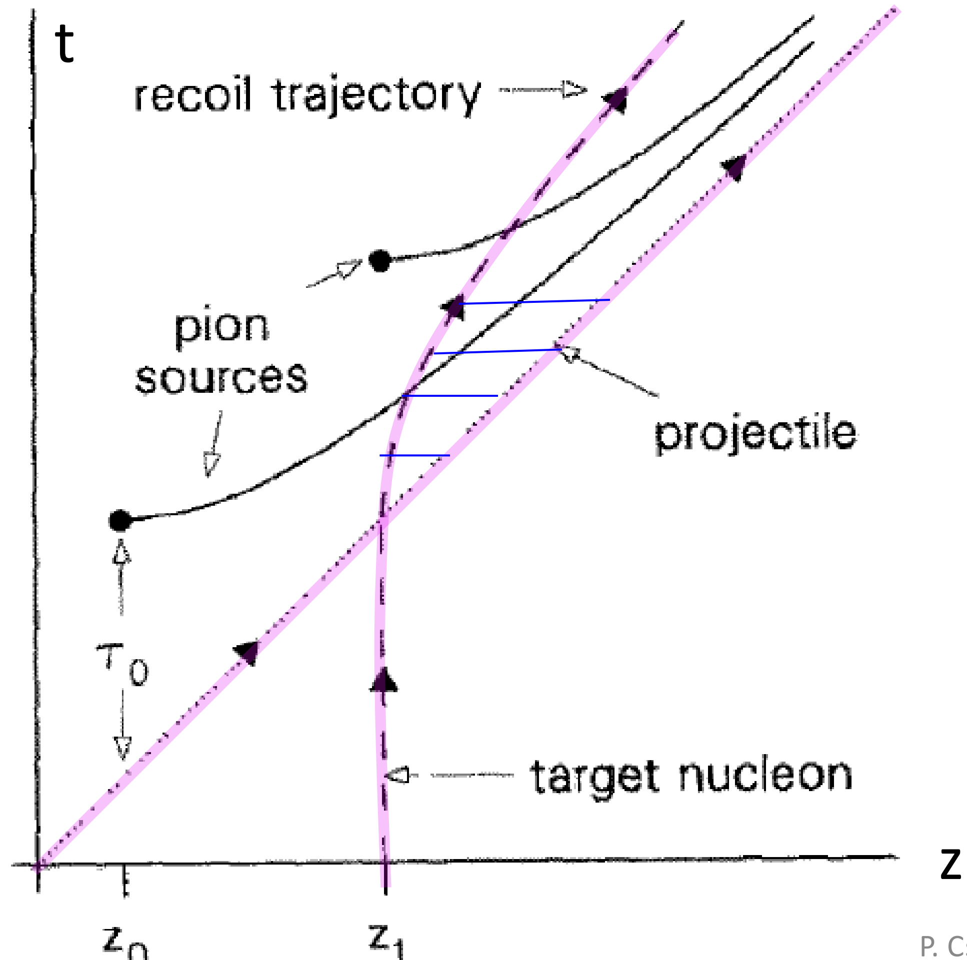
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA

L.P. CSERNAI[1]

School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA

Received 11 June 1986

Yo-yo in the fixed target frame → target recoil → density and energy density increase in the "fragmentation region"



Initial stage: Coherent Yang-Mills model

[Magas, Csernai, Strottman, Pys. Rev. C ‘2001]

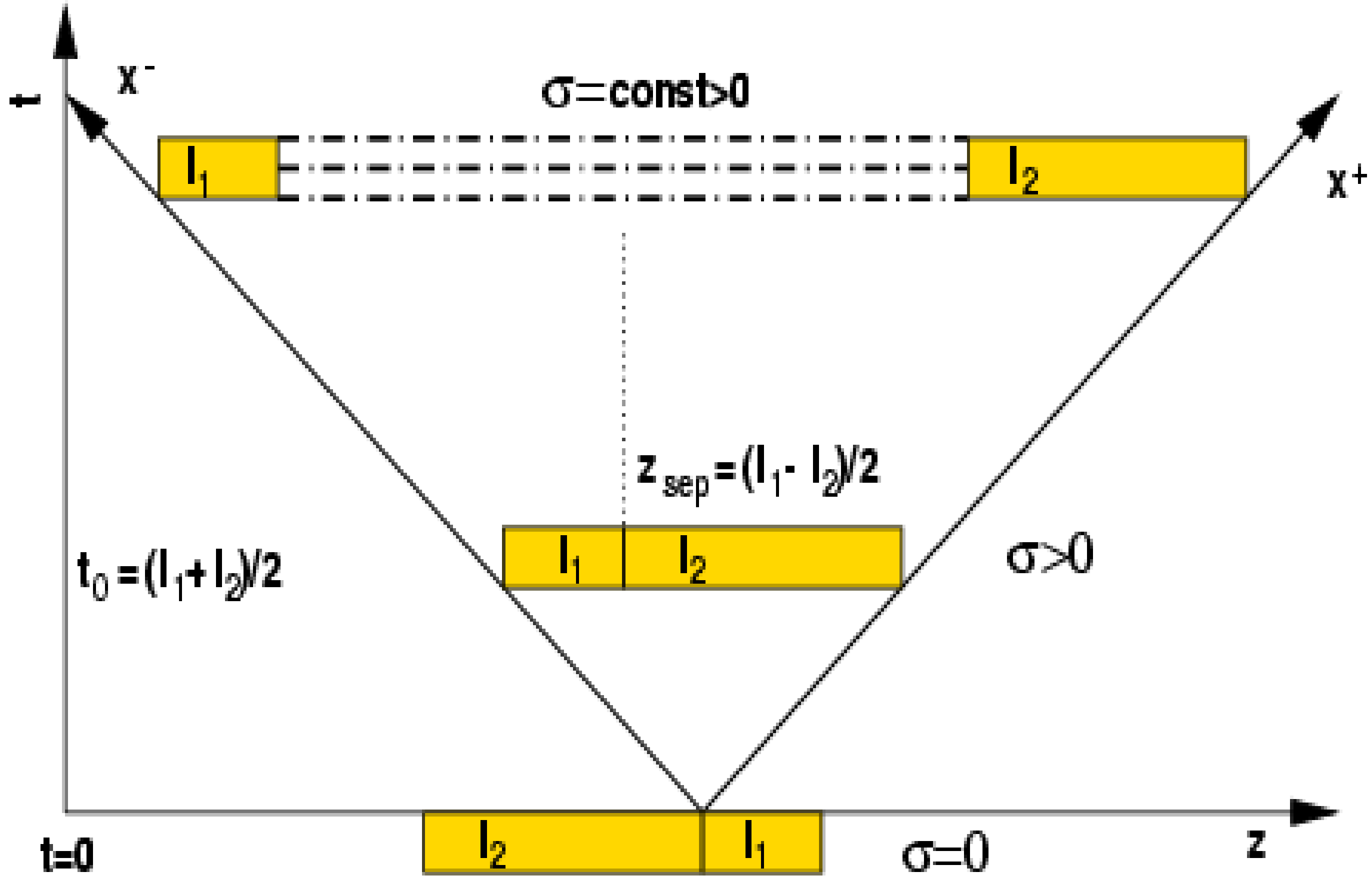
M. Gyulassy, L. Csernai Nucl. Phys. A660 (1986) 723-754.

$$\partial_\mu T^{\mu\nu} = F^{\nu\mu} n_\mu + \Sigma_\pi^\nu$$
$$\partial_\mu n^\mu = 0$$

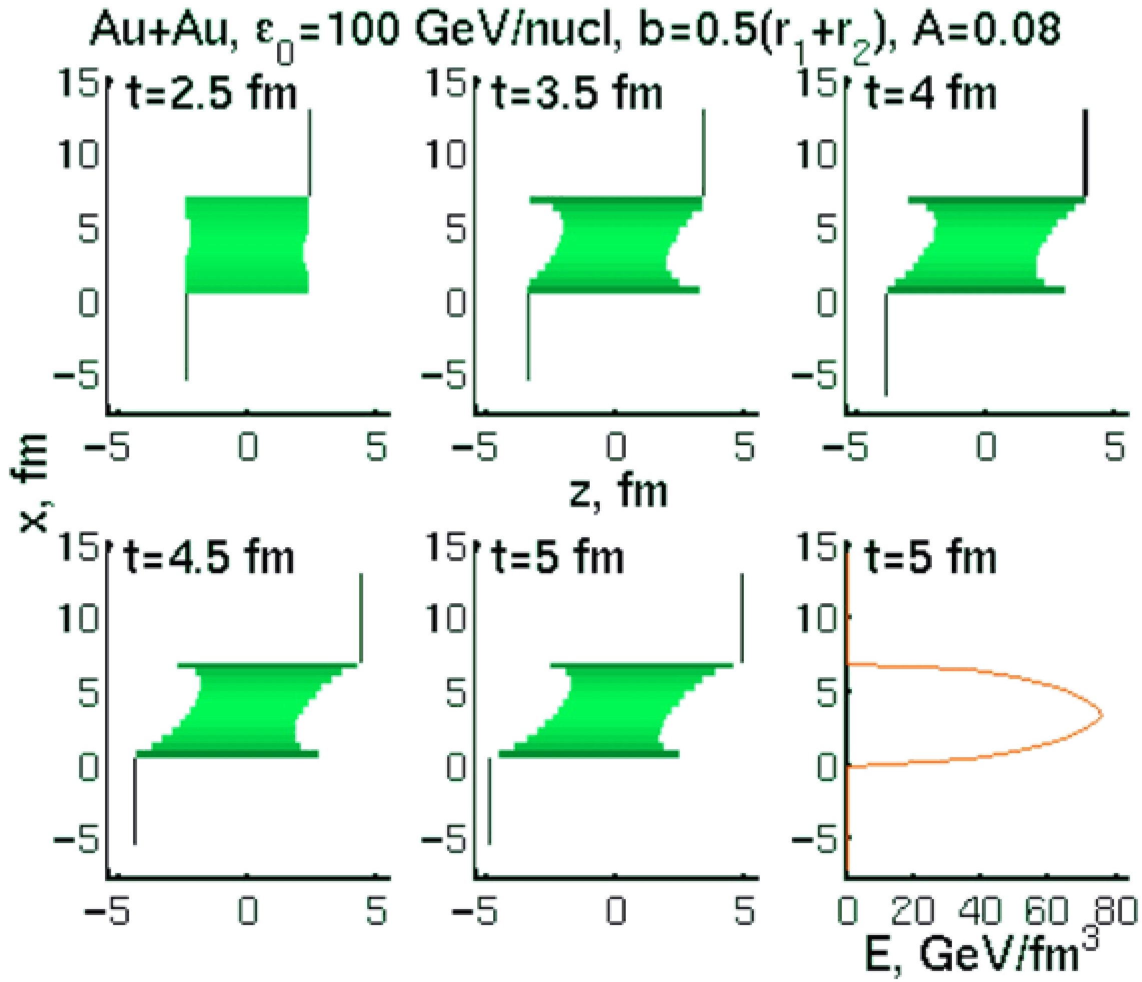
- $T^{\mu\nu} = e_t \left(\left(1 + c_0^2 \right) u_t^\mu u_t^\nu - c_0^2 g^{\mu\nu} \right)$
- Σ_π^ν – pion source term.
- $F^{\mu\nu}$ – effective field, describes interaction between target and projectile.

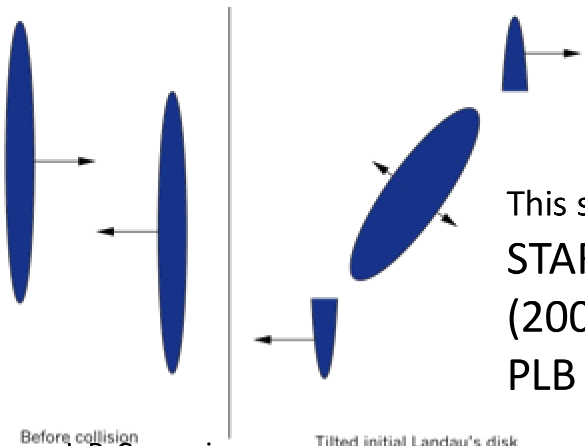
$$F^{\mu\nu} = \begin{pmatrix} 0 & -\sigma \\ \sigma & 0 \end{pmatrix} \quad ,$$

String rope --- Flux tube --- Coherent YM field



Initial State

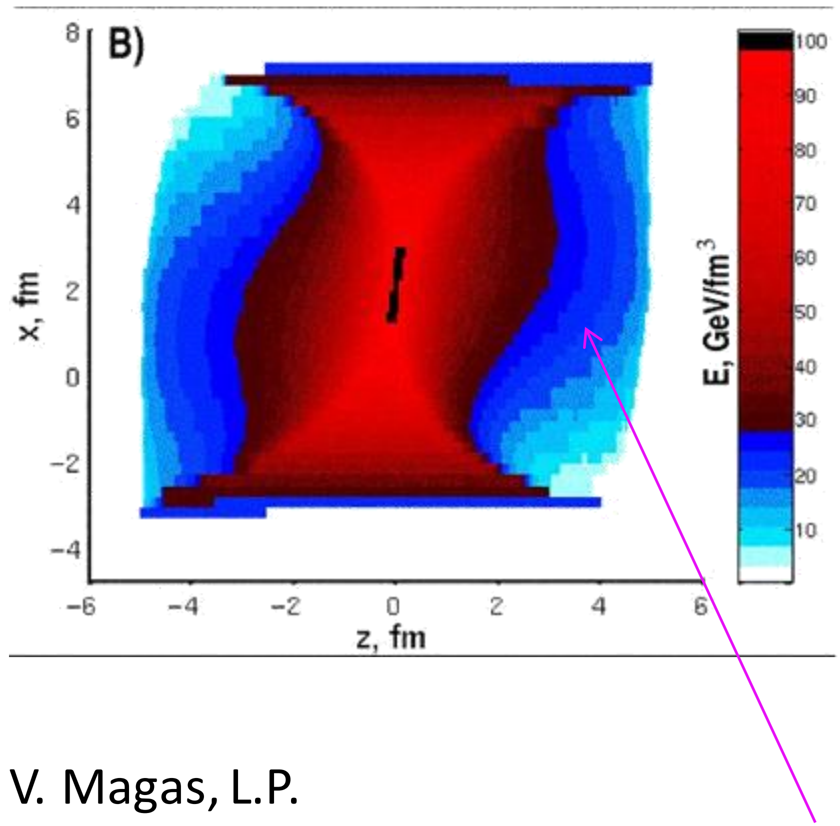




This shape is confirmed by STAR HBT: PLB496 (2000) 1; & M.Lisa &al. PLB 489 (2000) 287.

3rd flow component

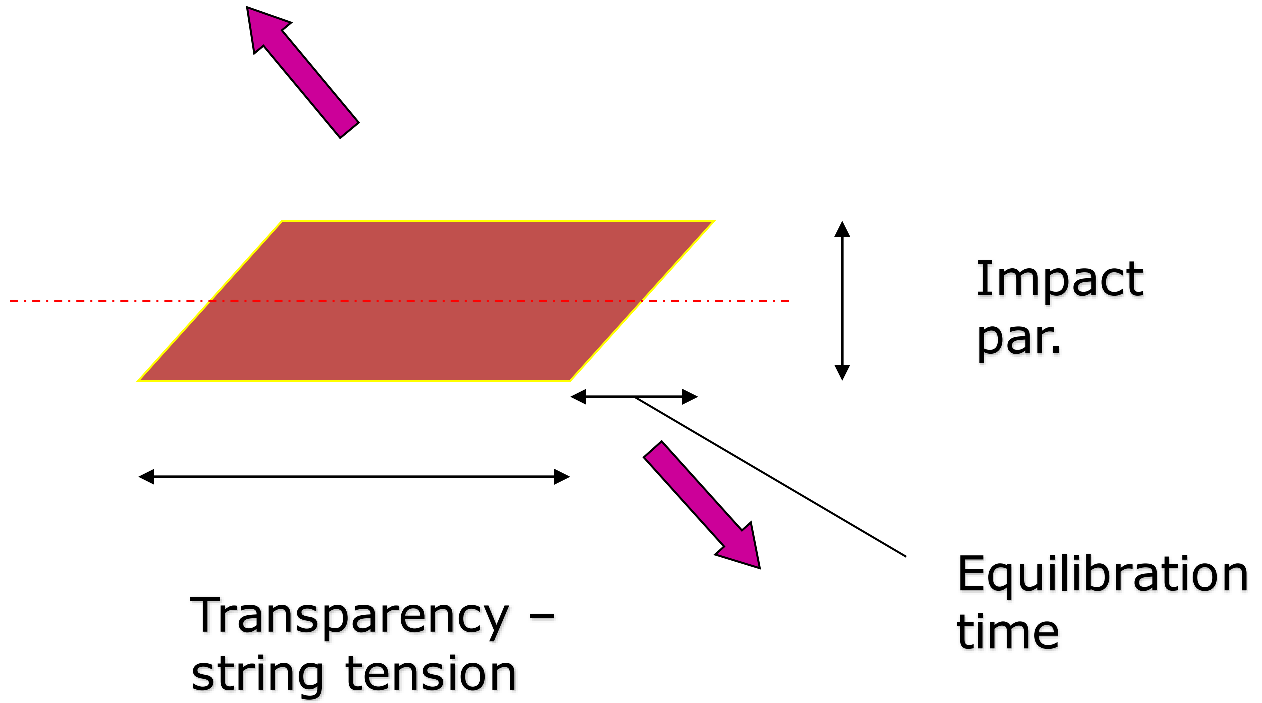
Initial state – reaching equilibrium



Initial state by V. Magas, L.P. Csernai and D. Strottman
Phys. Rev. C64 (01) 014901

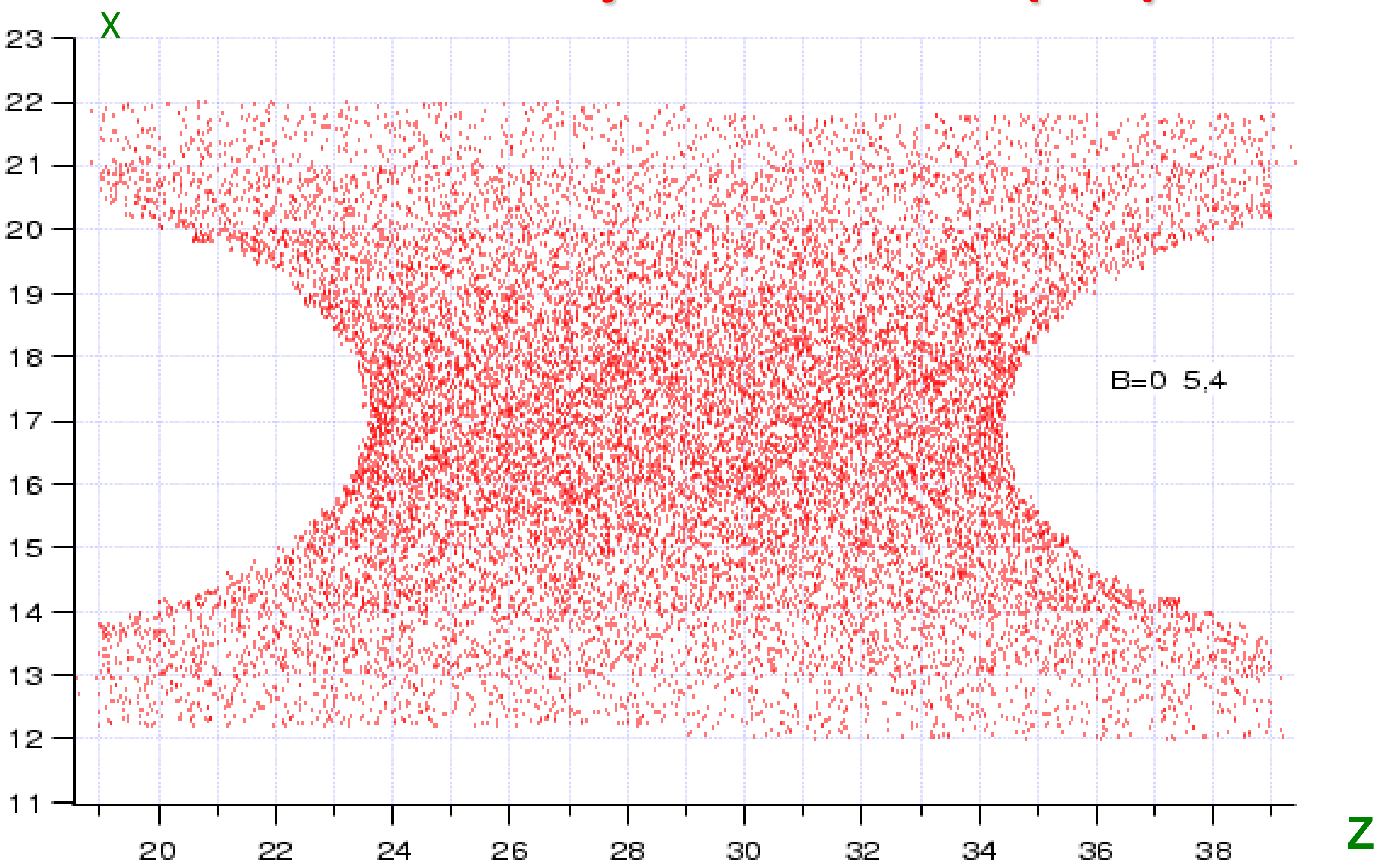
Relativistic, 1D Riemann expansion is added to each stopped streak

Flow is a **diagnostic** tool

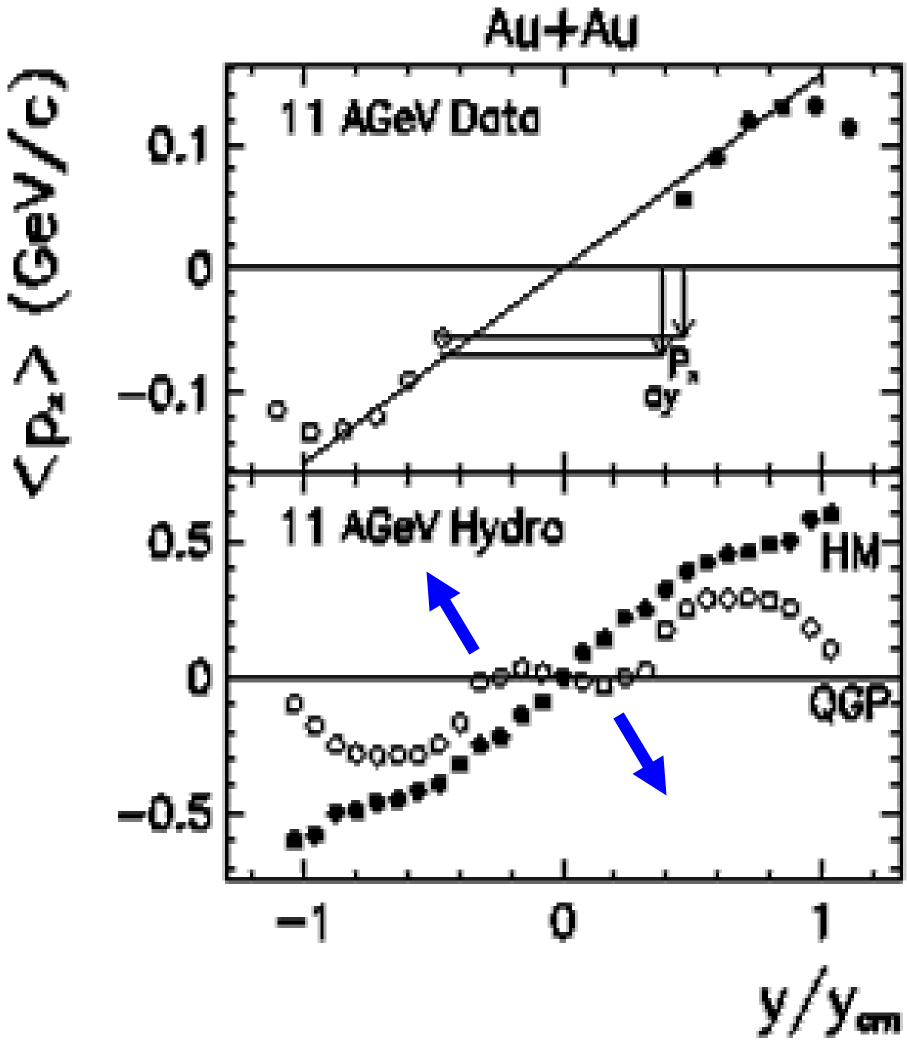


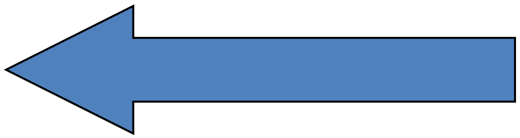
Consequence:
$v_1(y)$, $v_2(y)$, …

3-Dim Hydro for RHIC (PIC)



3rd flow component



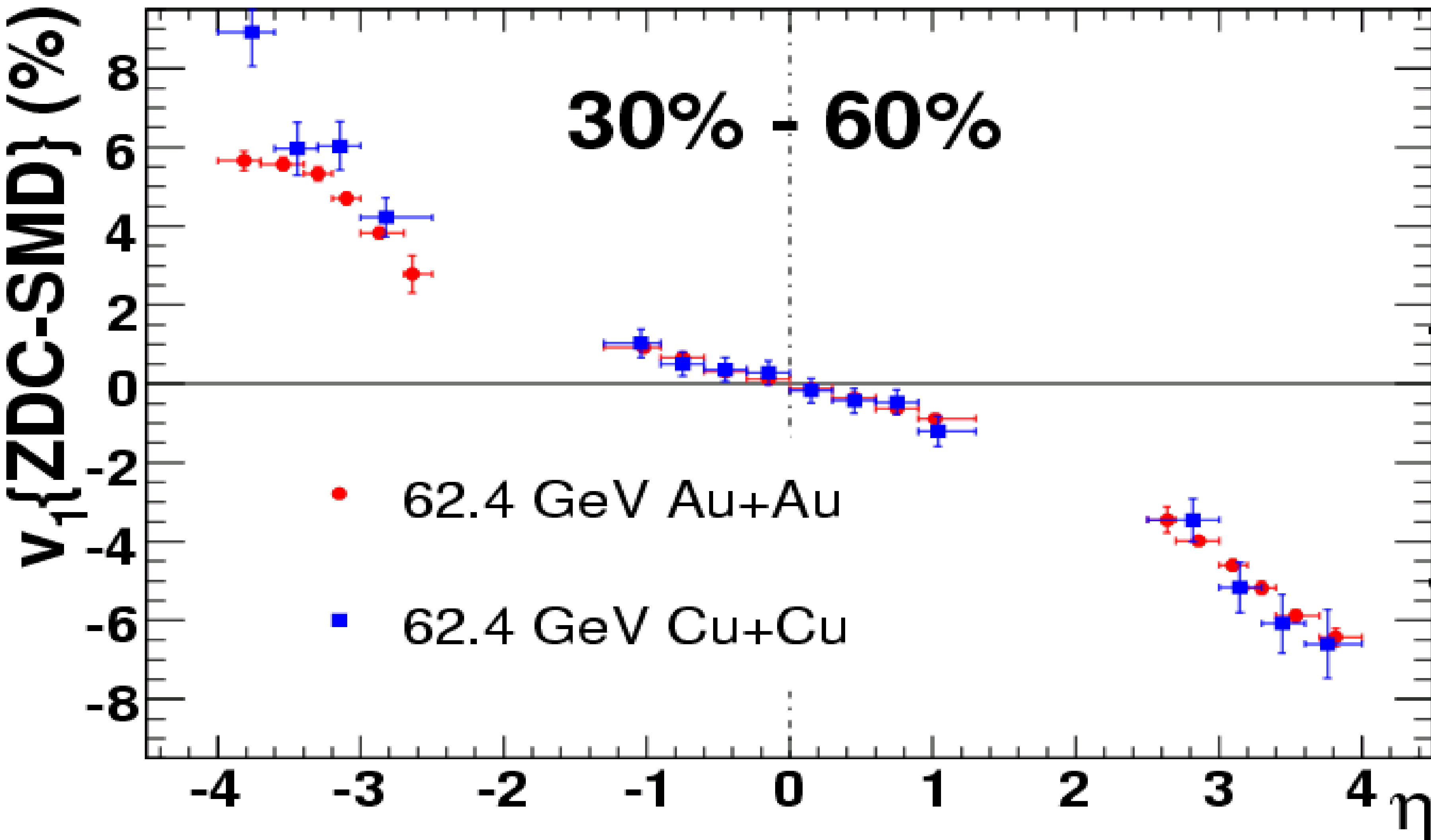


Hydro

[Csernai, HIPAGS’93] &
[Csernai, Röhrich, 1999]

G. Wang / STAR
QM 2006 :

$v_1(\eta)$: system-size dependence



System size doesn't seem to influence $v_1(\eta)$.

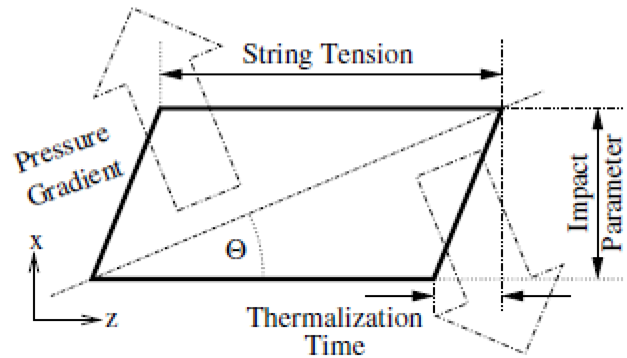
IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

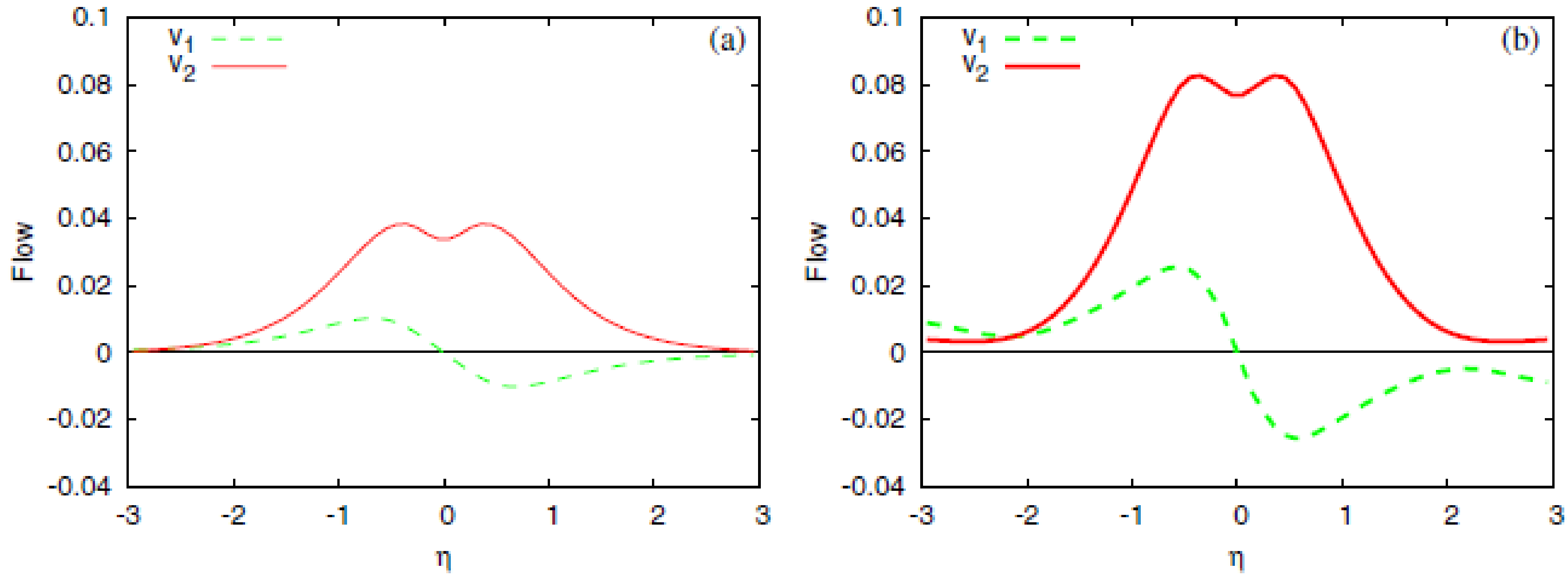
J. Phys. G: Nucl. Part. Phys. **34** (2007) S1077–S1081 doi:10.1088/0954-3899/34/8/S160

[QM'06 Shanghai]

Fluid dynamics as a diagnostic tool for heavy-ion collisions

Björn Bäuchle[1,2], Yun Cheng[1], László P Csernai[1,3], Volodymyr K Magas[4], Daniel D Strottman[5], Péter Ván[1,3] and Miklós Zétényi[1]



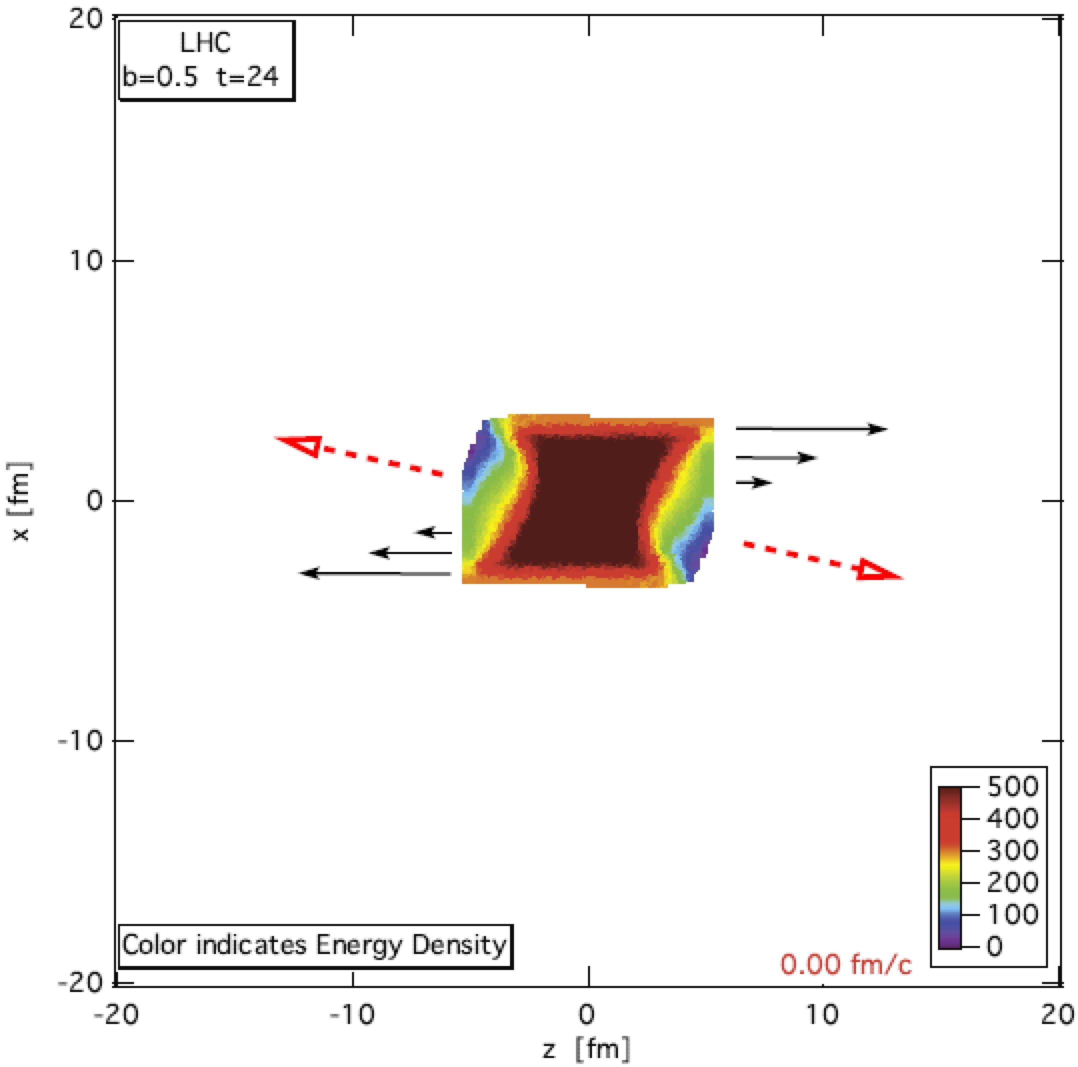


*v*1 and *v*2 as a function of pseudorapidity *η* at two different times (after 0.3 fm/*c* (a) and 2.7 fm/*c* (b)) in Au+Au-collisions at $\sqrt{s_{NN}}$ = 65 A.GeV at impact parameter *b* = 0.7(*R*1 + *R*2).

L. P. Csernai,[1,2,3] V. K. Magas,[4] H. Stöcker,[3] and D. D. Strottman[1,3]

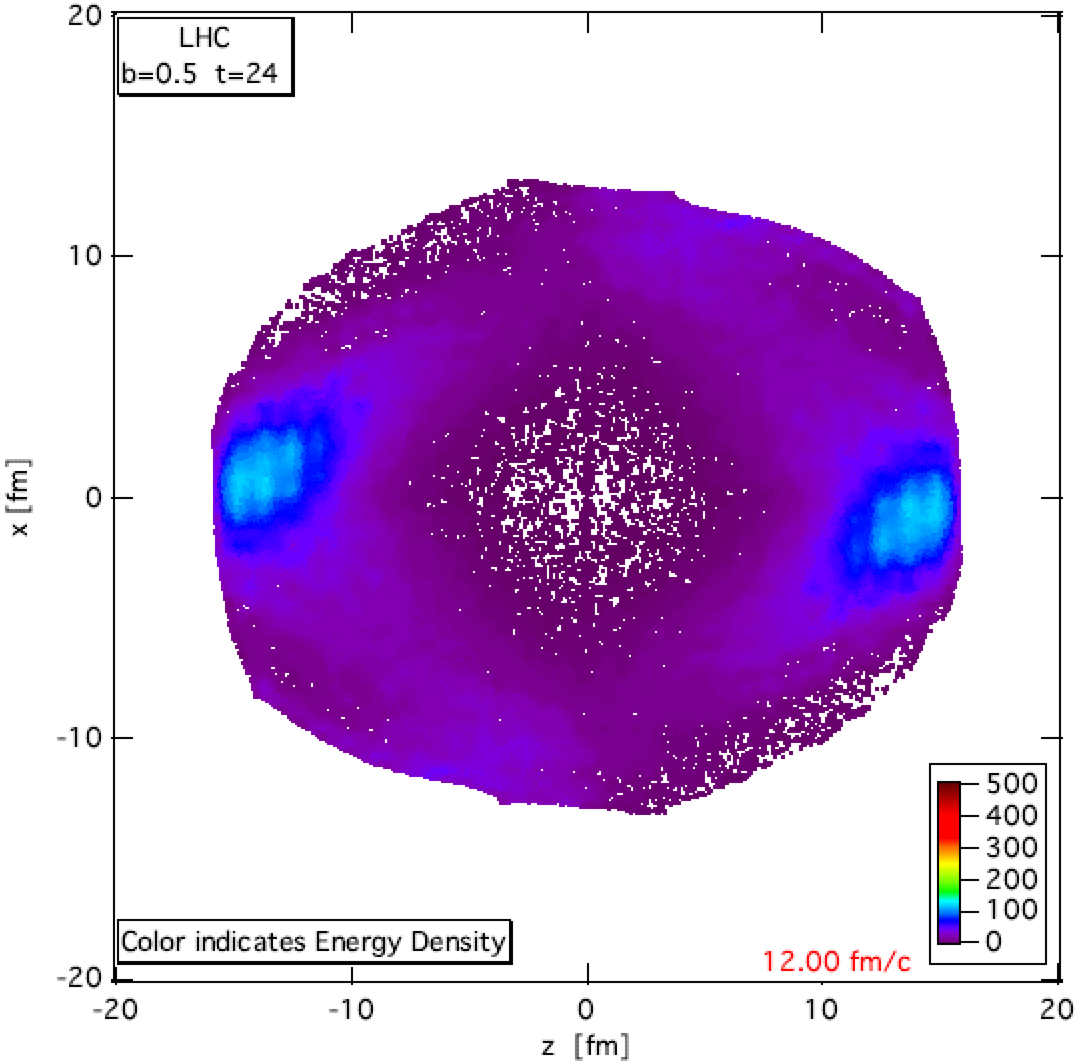
PHYSICAL REVIEW C **84**, 024914 (2011)

Anti-flow (v1) at LHC



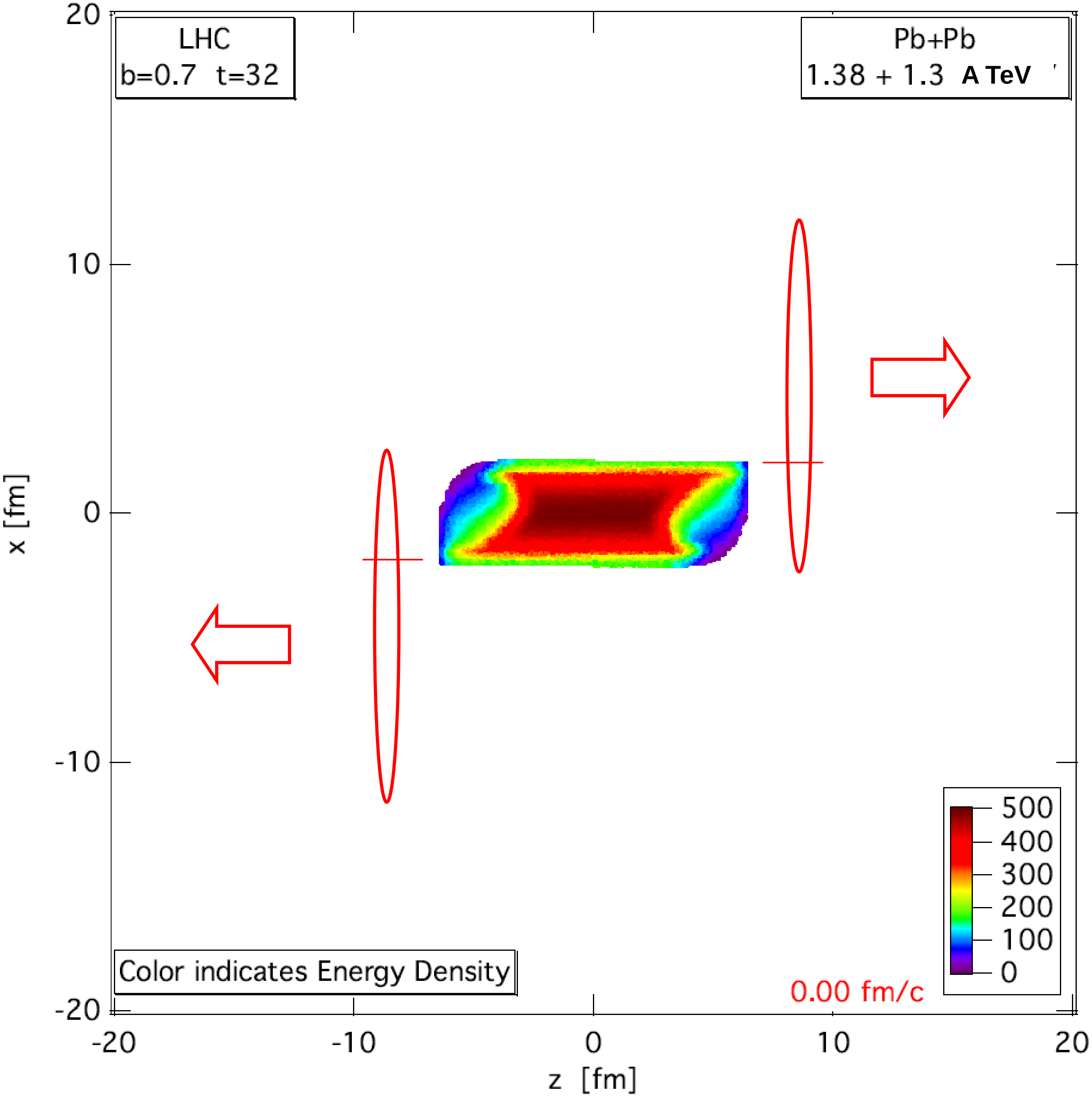
Initial energy density [GeV/fm3] distribution in the reaction plane, [x,y] for a Pb+Pb reaction at 1.38 + 1.38 ATeV collision energy and impact parameter b = 0.5_bmax at time 4 fm/c after the first touch of the colliding nuclei, this is when the hydro stage begins. The calculations are performed according 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, V.K. Magas, H. Stöcker, D. Strottman, Phys. Rev. **C84** (2011) 02914]



PIC-hydro

Pb+Pb 1.38+1.38 A TeV, b= 70 % of b_max

Lagrangian fluid cells, moving, ~ 5 mill.

MIT Bag m. EoS

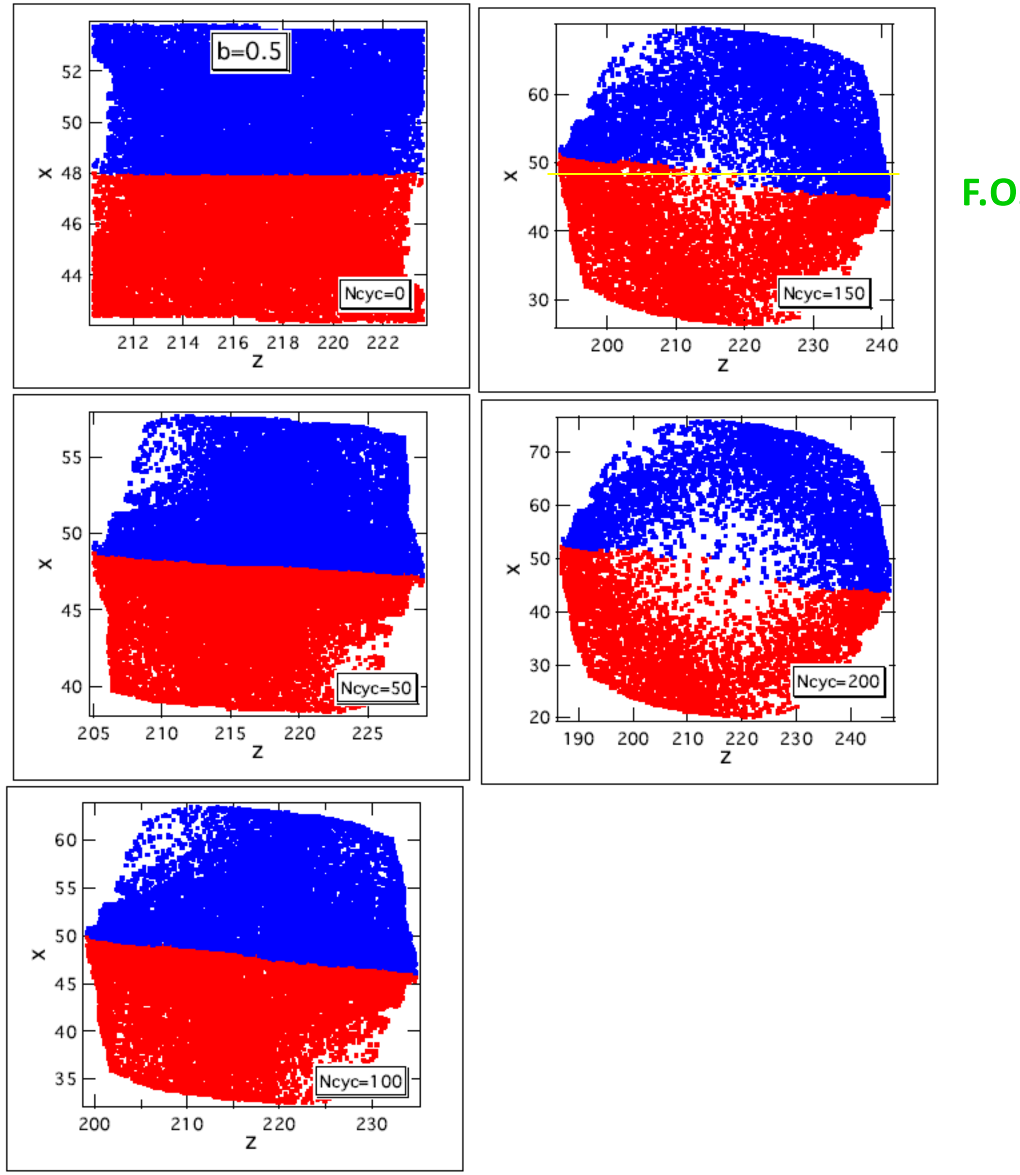
FO at T ~ 200 MeV, but calculated much longer, until pressure is zero for 90% of the cells.

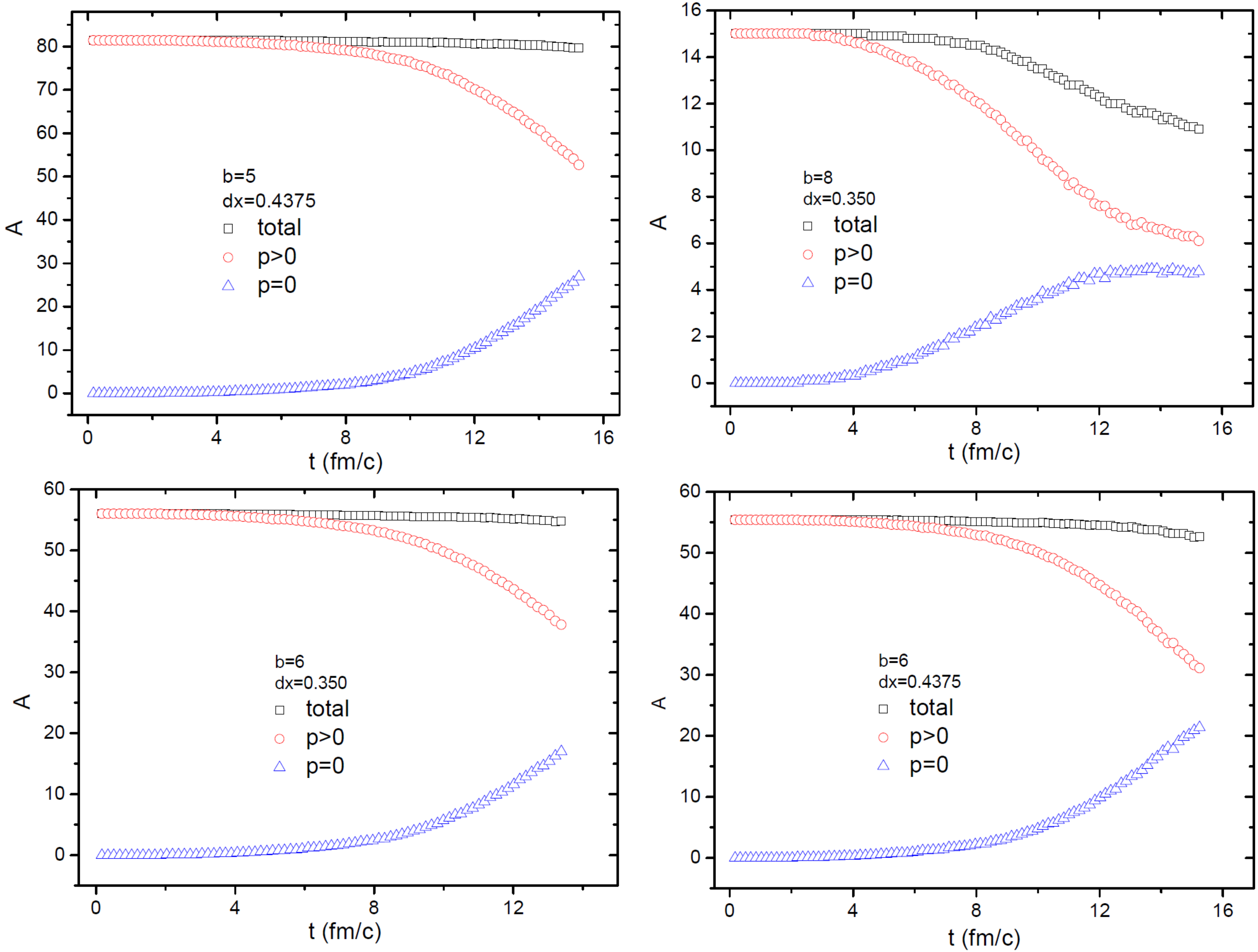
Structure and asymmetries of init. state are maintained in nearly perfect expansion.

..\zz-Movies\LHC-Ec-1h-b7-A.mov

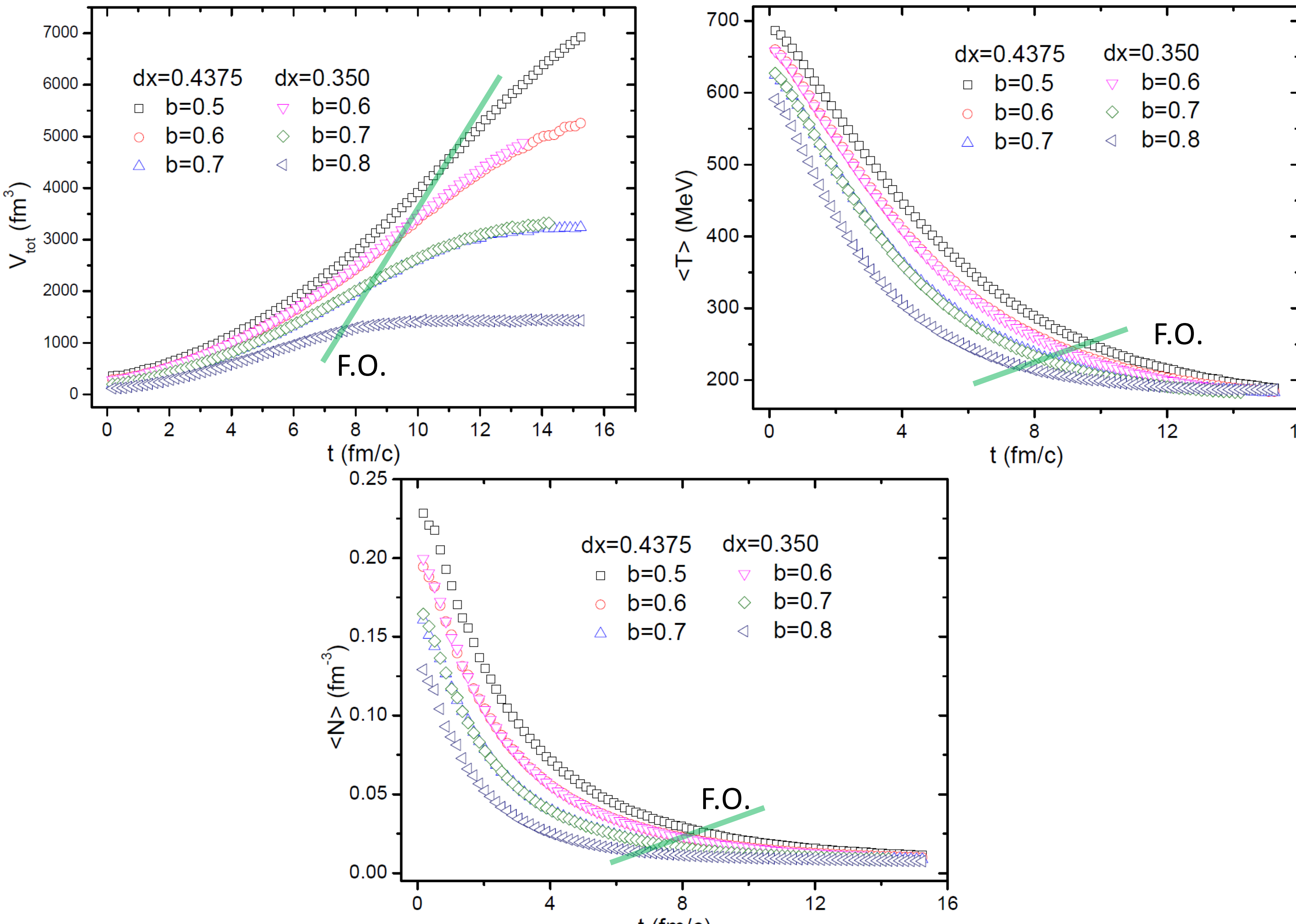
Rotation

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

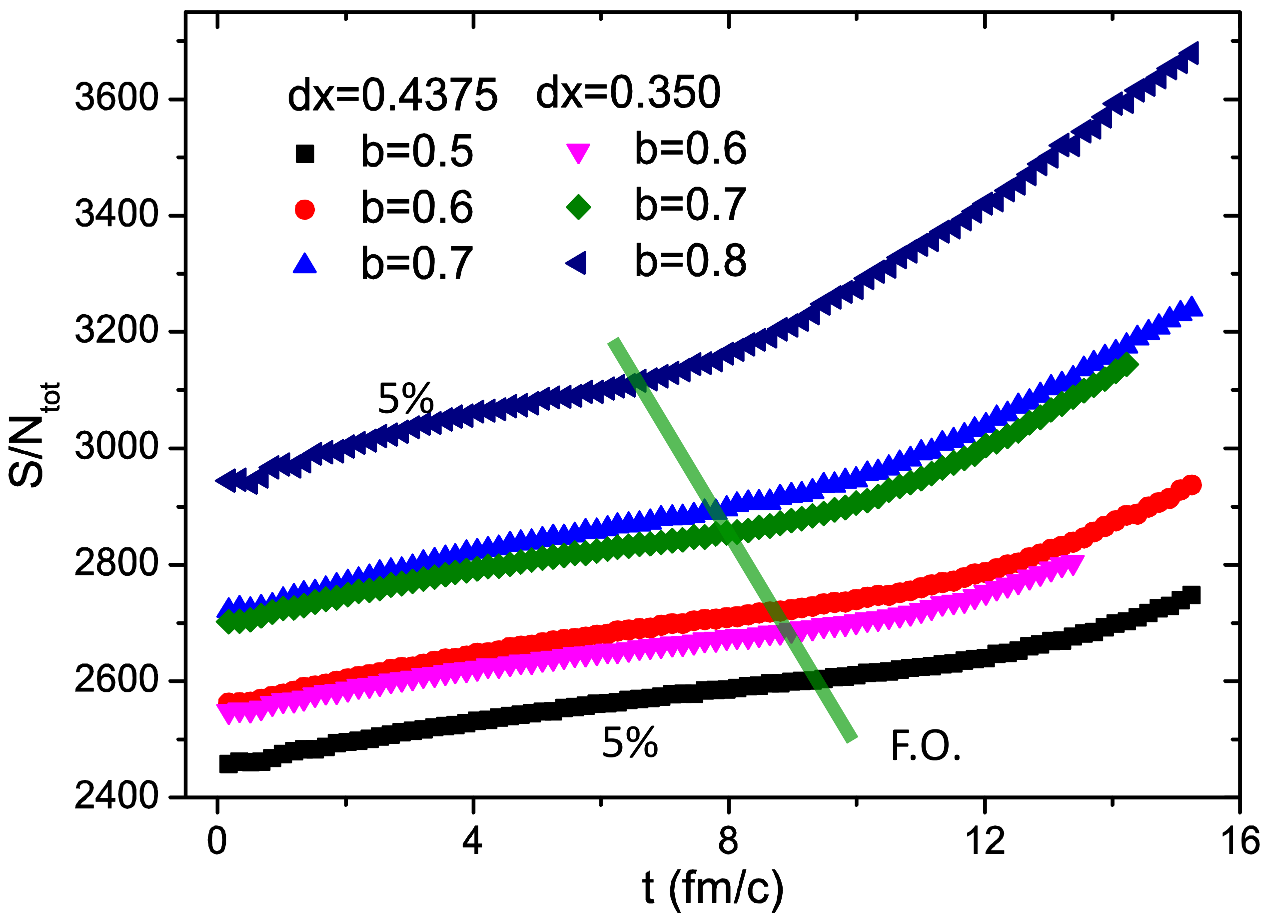


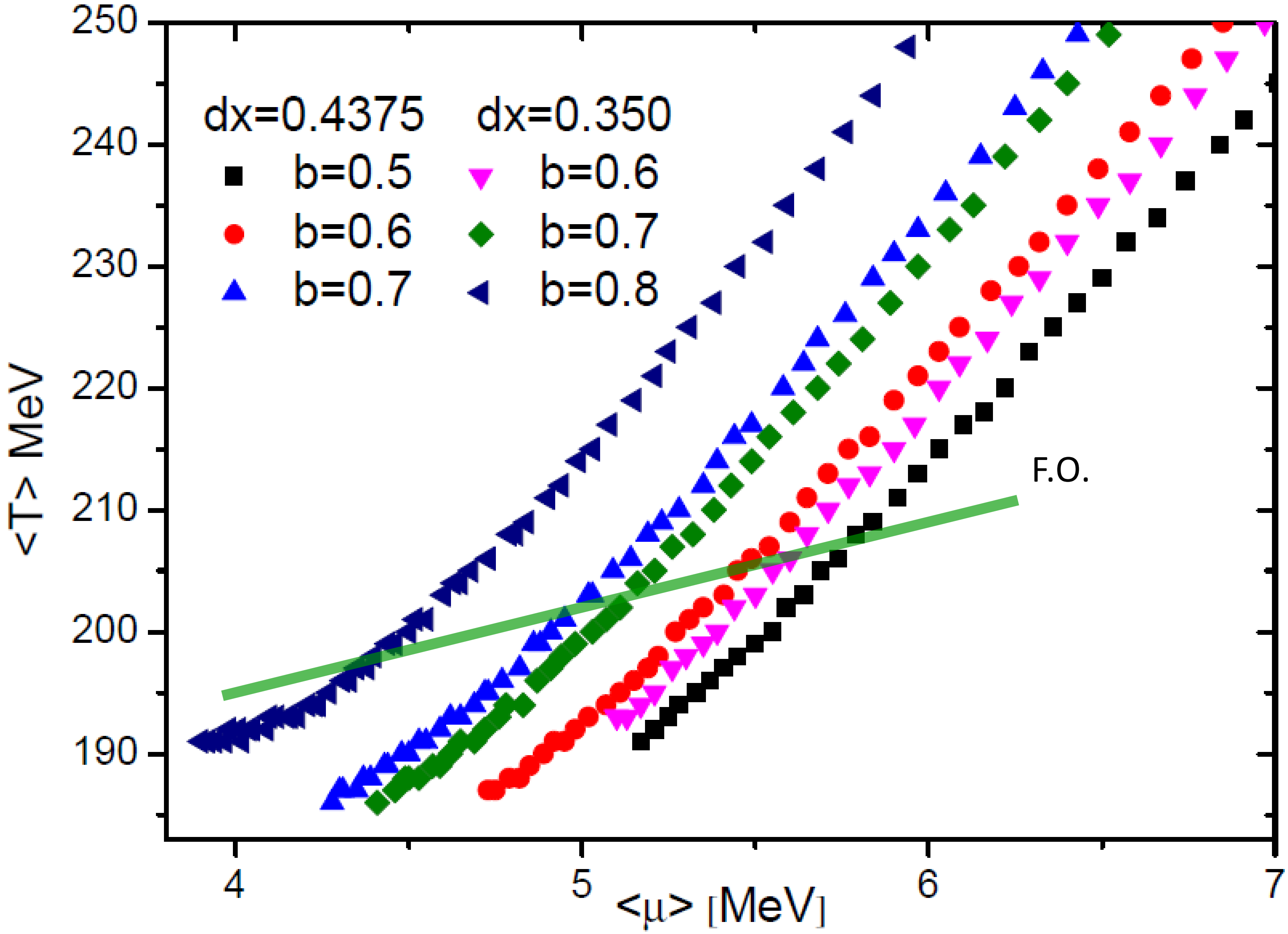


b=5
dx=0.4375
total
p>0
p=0
A
t (fm/c)
b=8
dx=0.350
total
p>0
p=0
A
t (fm/c)
b=6
dx=0.350
total
p>0
p=0
A
t (fm/c)
b=6
dx=0.4375
total
p>0
p=0
A
t (fm/c)


dx=0.4375
dx=0.350
b=0.5
b=0.6
b=0.7
b=0.6
b=0.7
b=0.8
F.O.
V_{tot} (fm^3)
t (fm/c)
<T> (MeV)
<N> (fm^{-3})

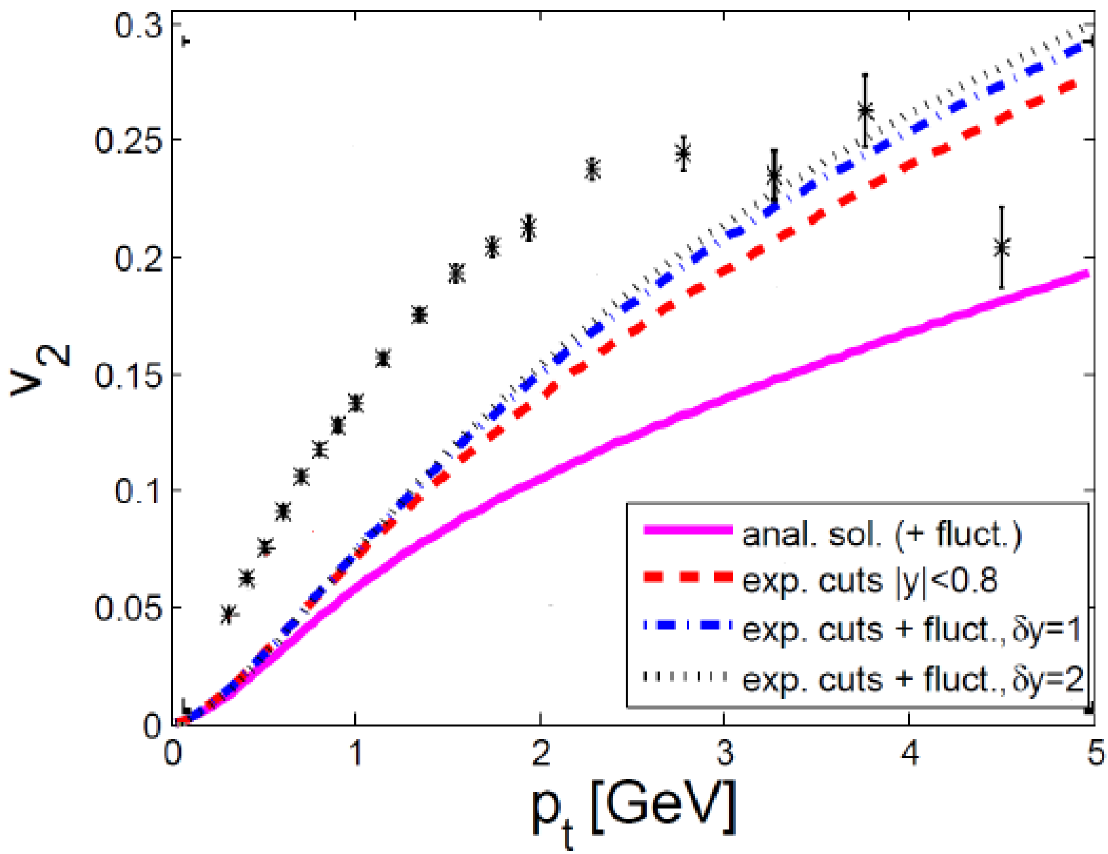
Entropy per Baryon charge





dx=0.4375
dx=0.350
b=0.5
b=0.6
b=0.6
b=0.7
b=0.7
b=0.8
F.O.
<T> MeV
<μ> [MeV]
250
240
230
220
210
200
190
4
5
6
7

Elliptic-flow (v2)



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).

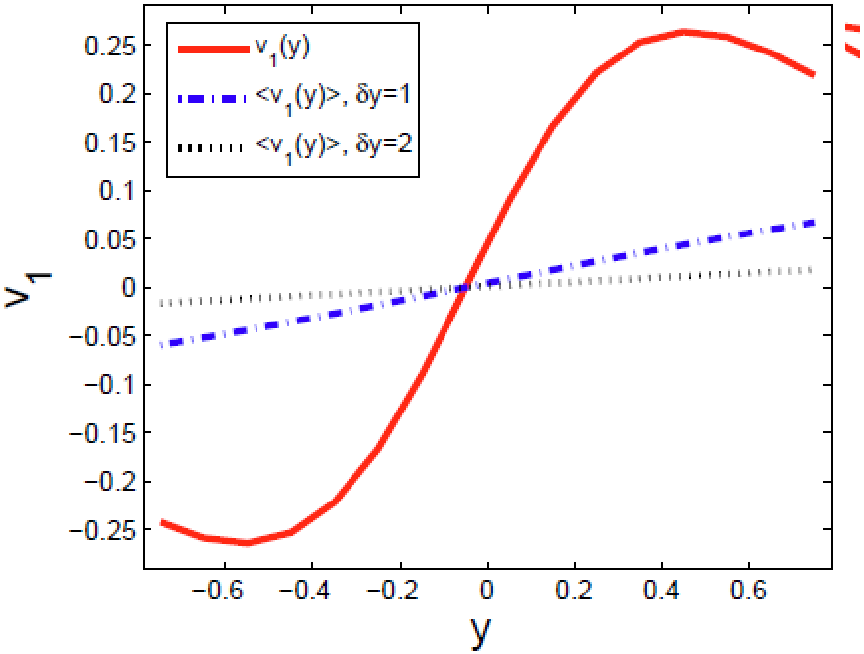
Anti-flow (v1)

Initial fluctuations in the positions of nucleons in the transverse plane

→different number of participants from projectil and target

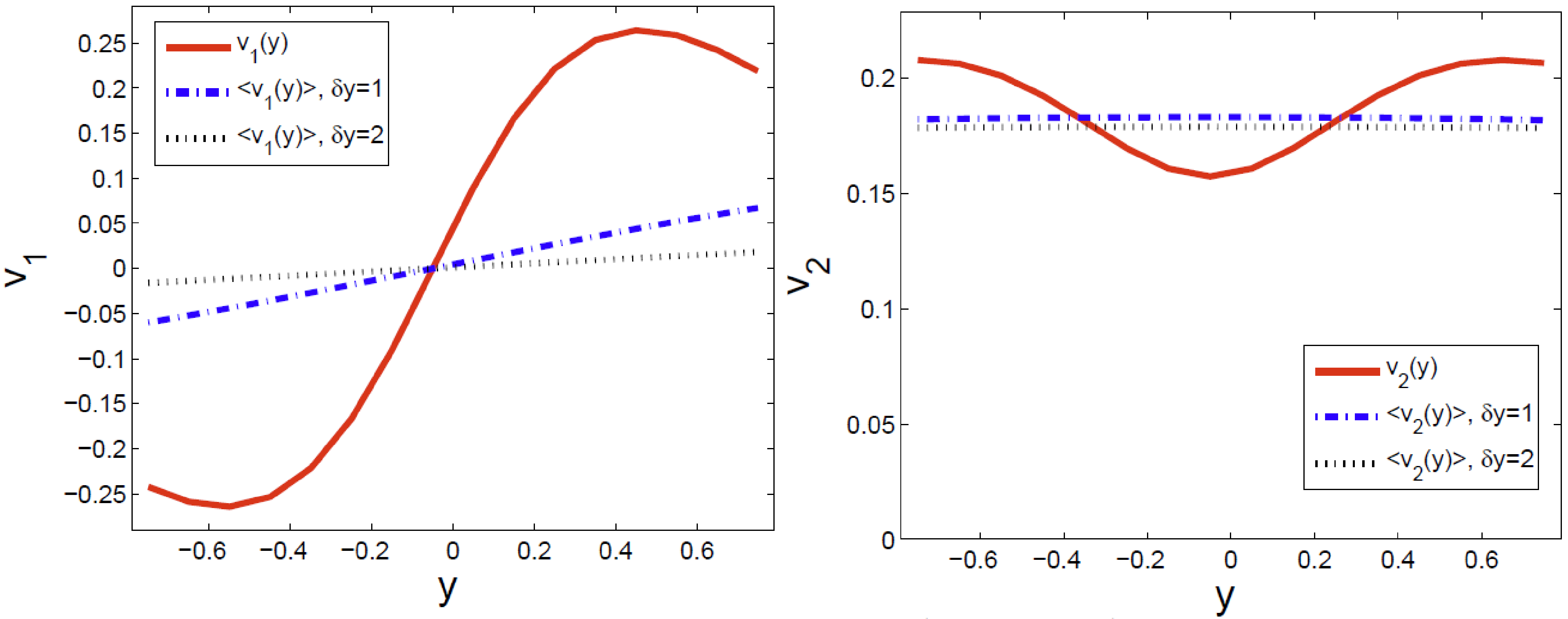
→Reduce v_1 at central rapidities, as v1 has a sharp change at y=0, and the initial fluctuations have not.

→v_1 is reduced but still measurable



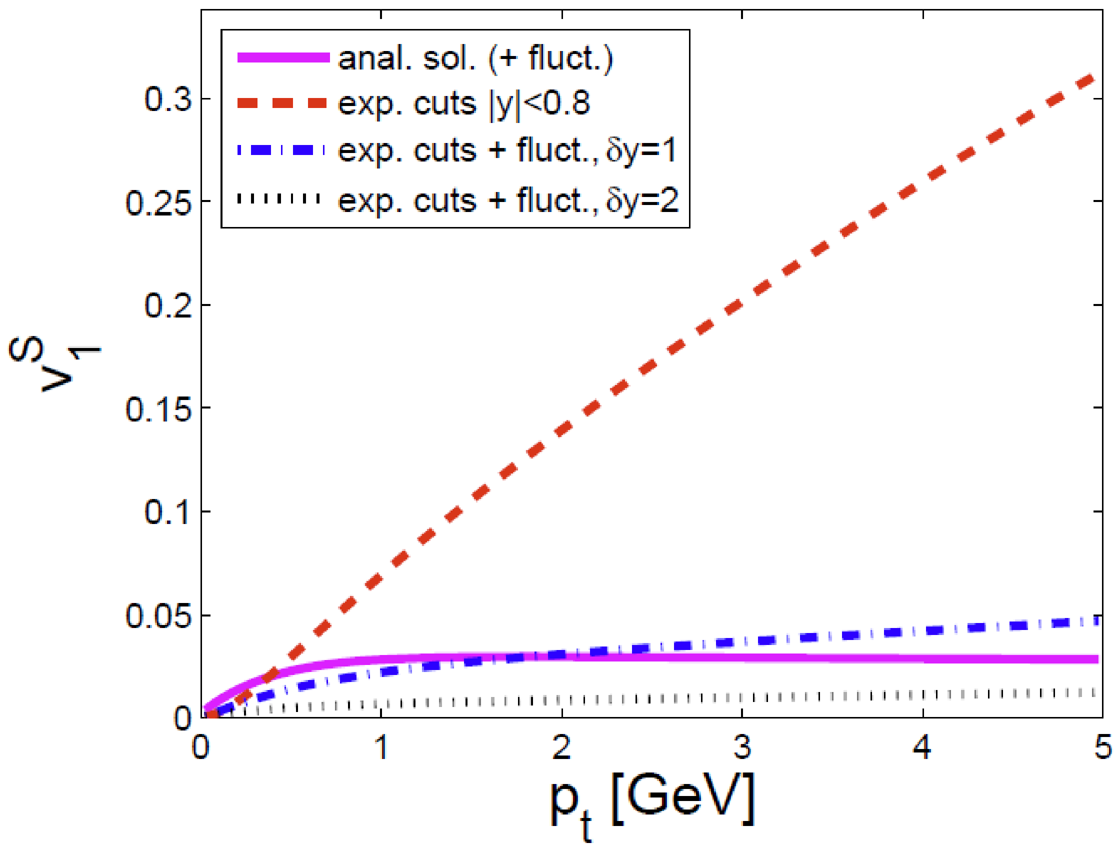
[Yun Cheng, et al., Phys. Rev. C ***84*** *(2011)* 034911.]

Anti-flow (v1)



The v_1 & v_2 parameters calculated for ideal massless pion Juttner gas, versus the rapidity y for b = 0.7 b_max, at t = 8 fm/c FO time. Full curve presents semi analytical calculations according to eq. (2); the v_1 peak appears at positive rapidity, in contrast to lower energy calculations and measurements. The dash-dotted and dotted curves present v_1 & v_2 calculated taking into account initial CM rapidity fluctuations.

Anti-flow (v1)



The vS_1 flow parameter calculated according to the eq. (4) 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.

Adil & Gyulassy (2005) initial state

x, y, η, τ coordinates → Bjorken scaling flow

PHYSICAL REVIEW C **72**, 034907 (2005)

Considering a longitudinal *"local relative rapidity slope",* based on observations in D+Au collisions:

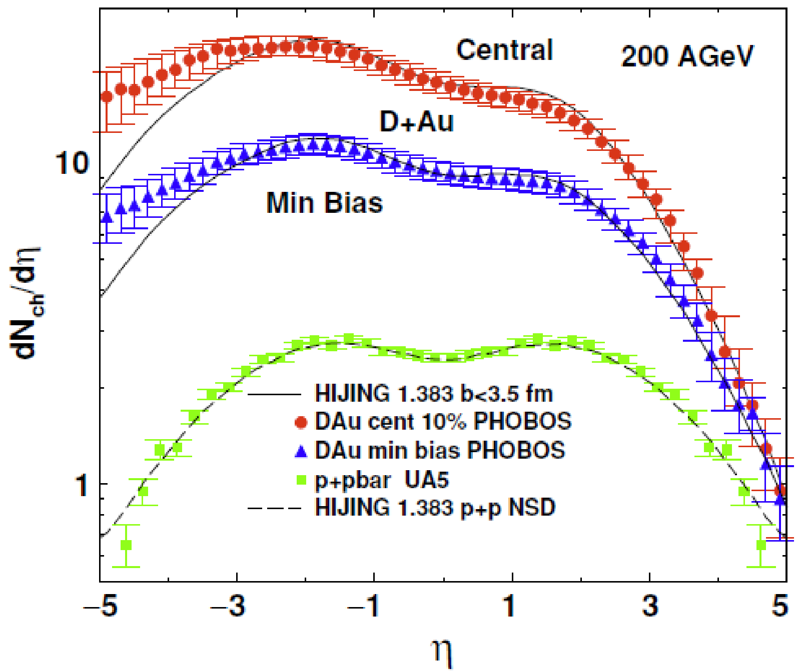
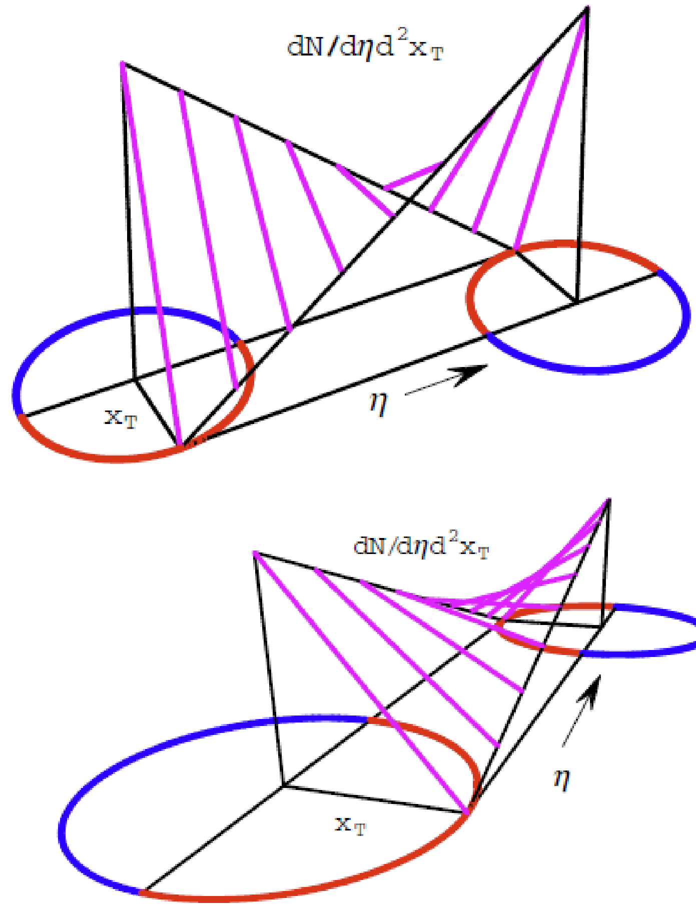


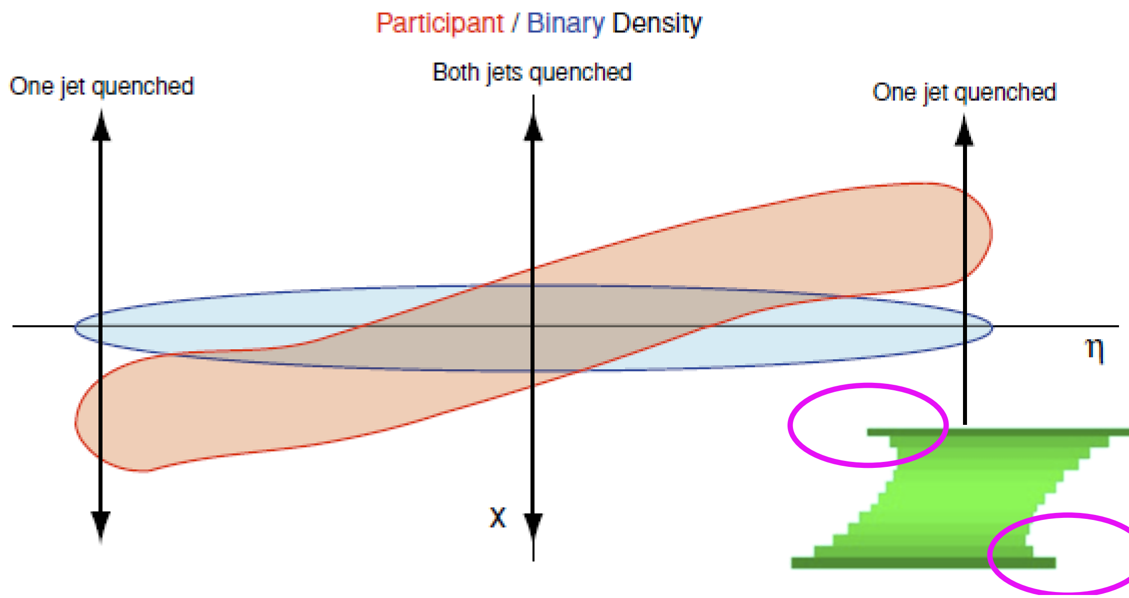
FIG. 2. (Color online) Asymmetric pseudorapidity distributions of charged hadrons produced in D+Au minimum bias and central 0–10% reactions at 200*A* GeV from PHOBOS [12] are compared to $p+\bar{p}$ data from UA5 [13]. The curves show predictions using the HIJING v1.383 code [14,15].

→

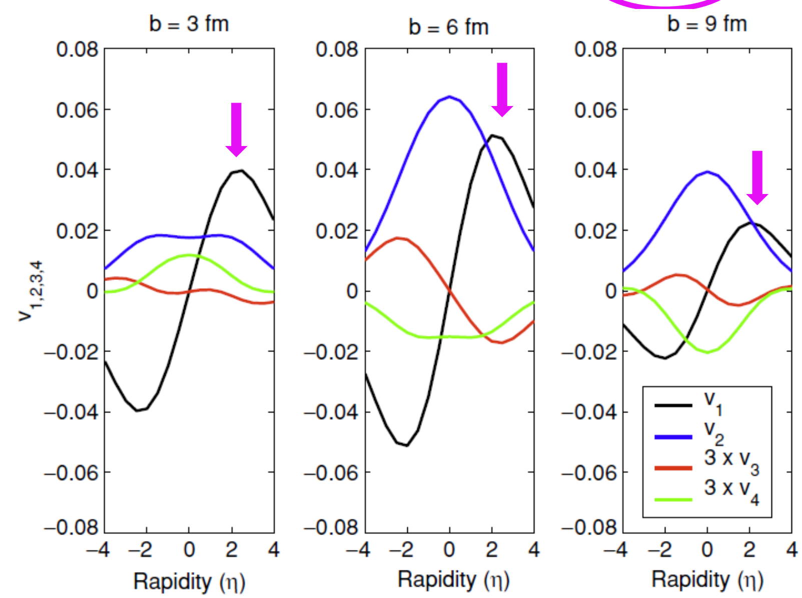


This is similar to our model, with several flux-tubes in each fire-streak, with different rapidities at their ends. This leads to a "*diffuse nuclear geometry*" :

Here in a given streak on the projectile side, there is a distribution[1] of the ends of the flux tubes, so that the energy is shifter more to the positive rapidity side. [1: Wounded nucleon model, Brodsky etal. PRC (1977)]



$$R_{BA}(\eta;\mathbf{b}) = \frac{dN^{BA}/d\eta}{dN^{pp}/d\eta} \approx \frac{1}{2}(N_A + N_B) + \frac{\eta}{2Y}(N_B - N_A),$$



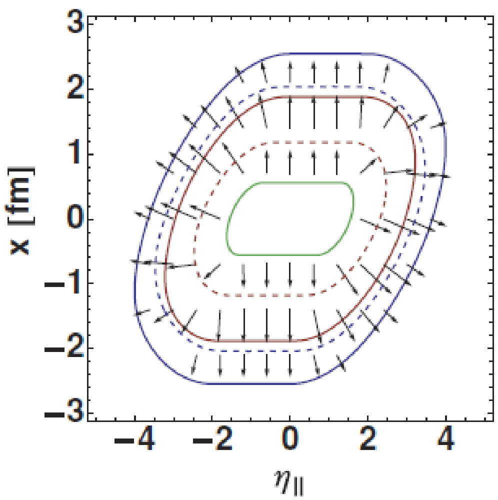
The consequence is that the energy is shifted forward on the projectile side → (RHIC - 200 A.GeV, - v_1 is black !)
v_1 is opposite side then in the experiment.

Bozek, Wyskiel (2010): Directed flow

x, y, η, τ coordinates

PHYSICAL REVIEW C **81**, 054902 (2010)

Similarly to Adil & Gyulassy this is also based on the Wounded nucleon picture. η and x coordinates are used. The P & T distributions are given →

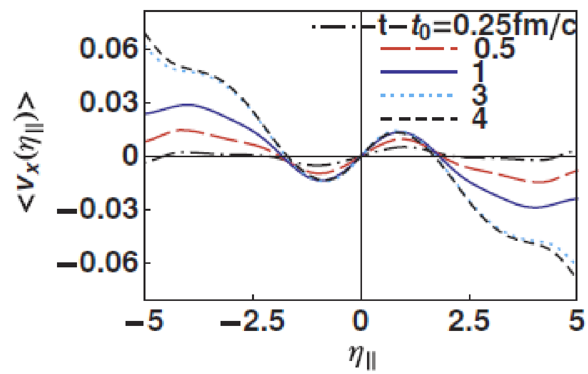


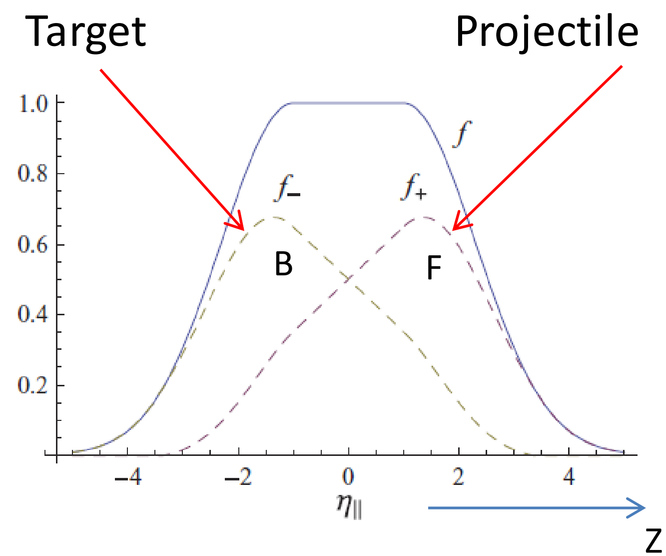
Global collective coordinates

$$u^{\mu}(\tau_0, x, y, \eta_{\parallel}) = (\cosh \eta_{\parallel}, 0, 0, \sinh \eta_{\parallel}).$$

Bjorken flow

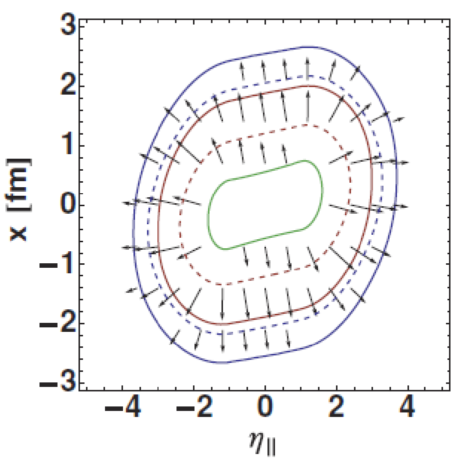
→





Directed flow (v_1) peaks at positive rapidities! (as A&D)

Notice: the arrows are pressure gradients!



The authors re-parametrized their initial state to a **'tilted' i.s.** and with modified distributions, and this could reproduce the observations at RHIC→

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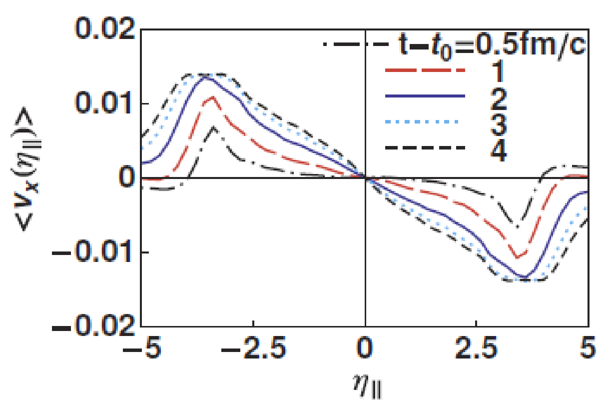
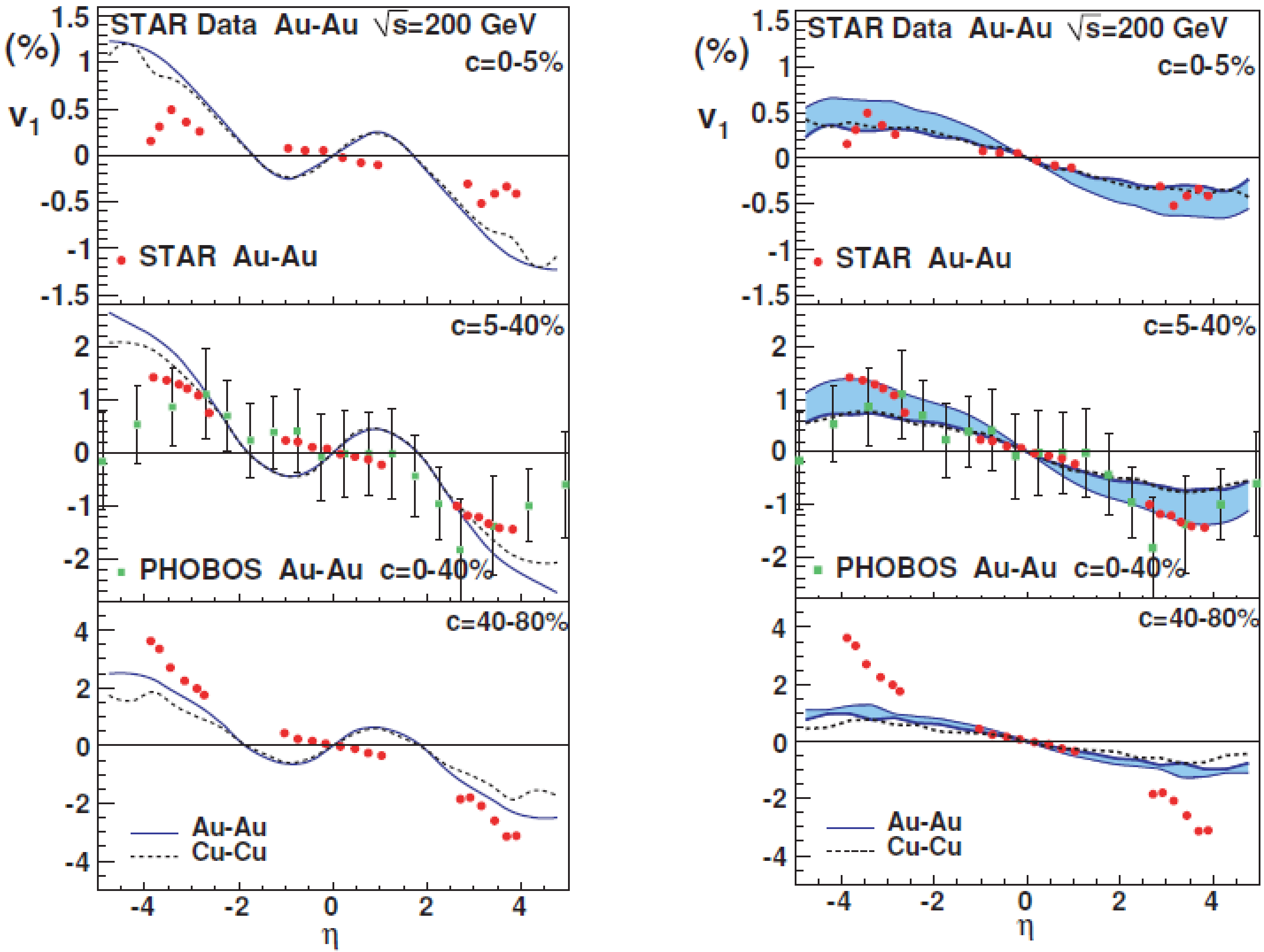


Not a dynamical model

3, Directed flow at different centralities



'tilted' i.s.

This leads to a different rotation at different rapidities, and so the observed main axis of the elliptic flow will be different at different rapidities →

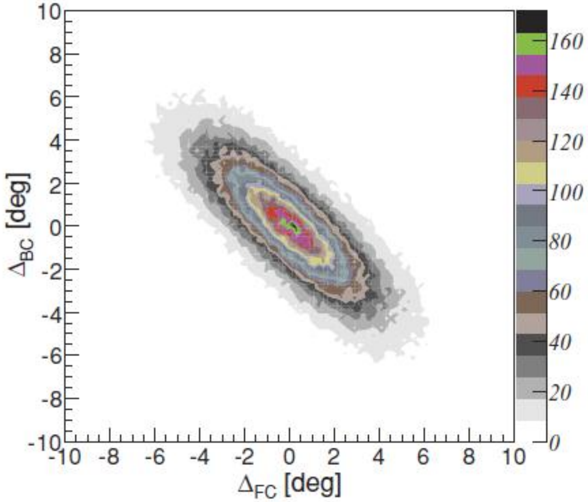


FIG. 7. (Color online) The two-dimensional distribution plot of the relative torque angles Δ_{FC} and Δ_{BC}, for centrality 50%–60%, space-time rapidity $\eta_{\parallel} = 2.5$. The corresponding correlation coefficient is $\rho_{FCB} = -0.61$.

Prediction →

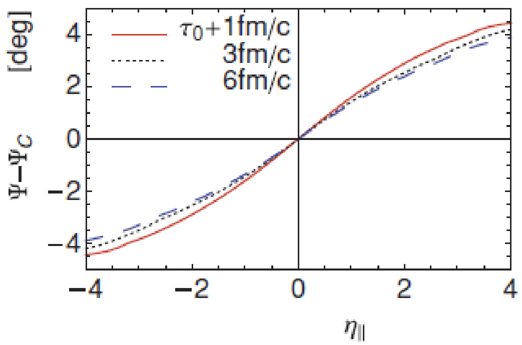


FIG. 10. (Color online) The dependence of the torque angle of the fluid velocity field on space-time rapidity after the (3 + 1)-dimensional hydrodynamics of Ref. [8] (solid, dotted, and dashed lines). Subsequent curves are for different evolution times.

It may be possible to verify this effect experimentally as the FO shape of the emitting source and the azimuthal asymmetry are measured. The effect of fluctuations and of the global collective flow effects may be separated better. The effect exists with the **CMS(2001) initial state** also, although it is smaller.

Summary

- The initial state is decisive in predicting global collective flow
- Consistent I.S. is needed based on a dynamical picture, satisfying causality, etc.
- Several I.S. models exist, some of these are oversimplified beyond physical principles.
- Experimental outcome strongly depends on the I.S.

Thank you