The Network Workshop 'TORIC'

Questions on rotating or torqued flow, instabilities, viscosity and their measurement

Laszlo P. Csernai, University of Bergen, Norway
Heraklion, Crete, Sept. 7, 2011

- U of Bergen:
- Laszlo P. **Csernai**, UoB
- Miss Astrid **Skålvik**, UoB
- Miss Du-juan **Wang**, UoB

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

Collective flow

- To initial origins:
- > Global collective flow (RP from spectators)
- > Asymmetries from random I.S. fluctuations

  (Axes of different harmonics are not correlated!)

- Goal is to separate the two $\rightarrow$ this provides more insight

TODAY – Elliptic flow at LHC

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

(The ALICE Collaboration)

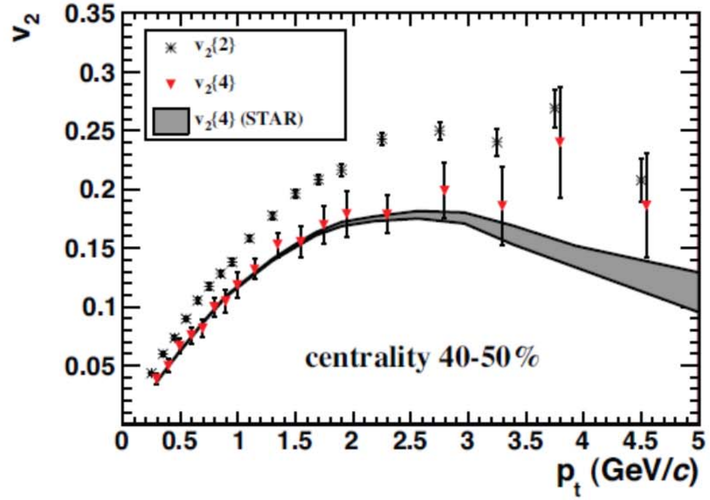
17 Nov 2010

Flow is stronger than ever before,

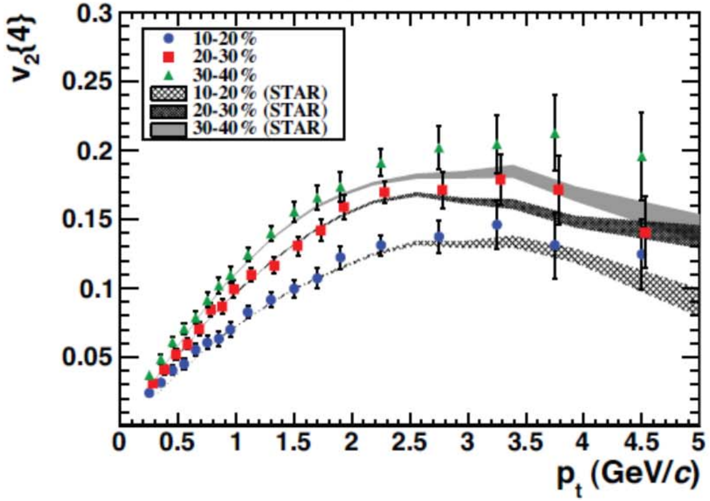
Dominant at higher energies,

Quark number scaling indicates

that flow is created in QGP

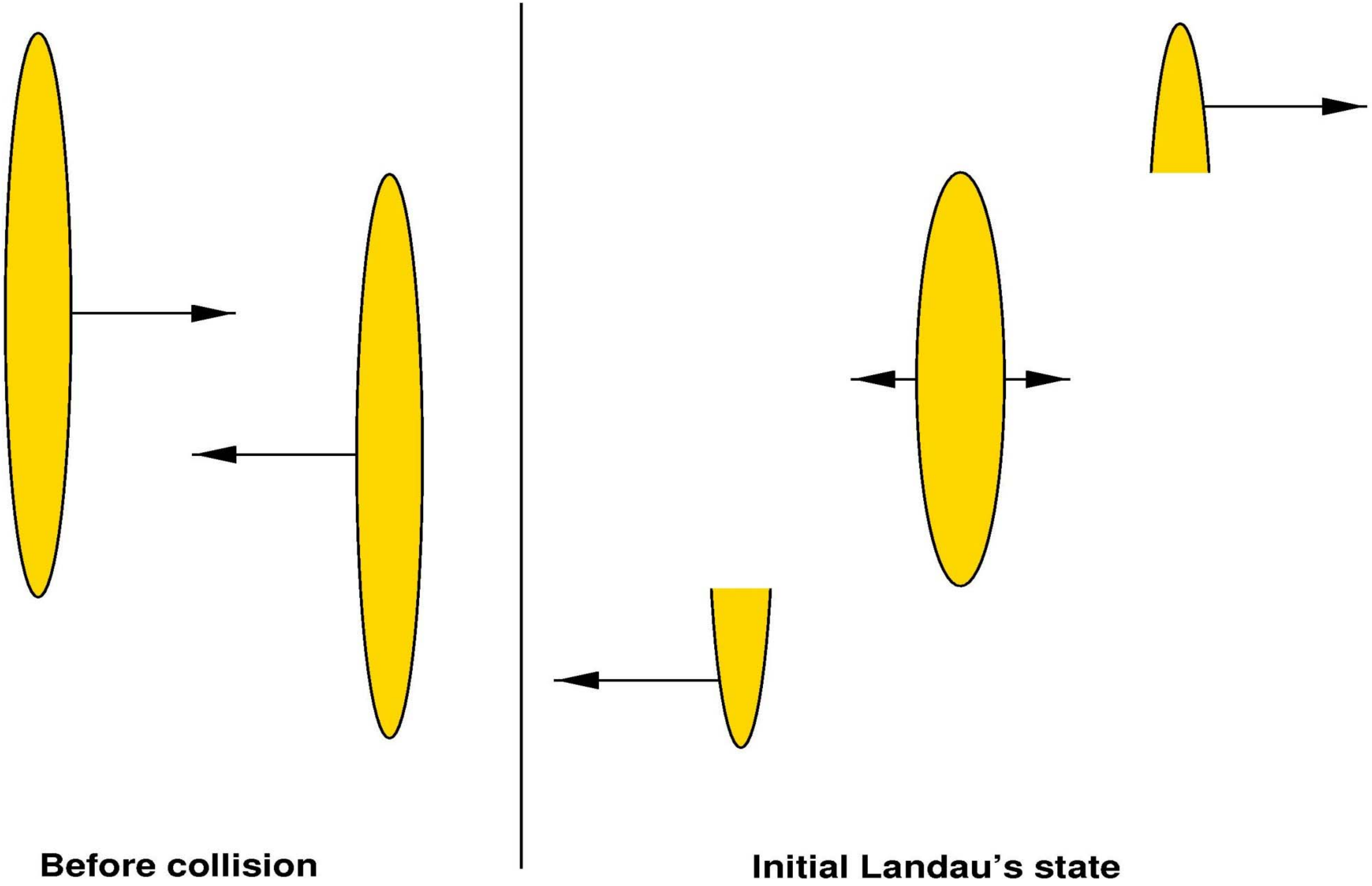


(a)



Initial state - Landau, complete stopping

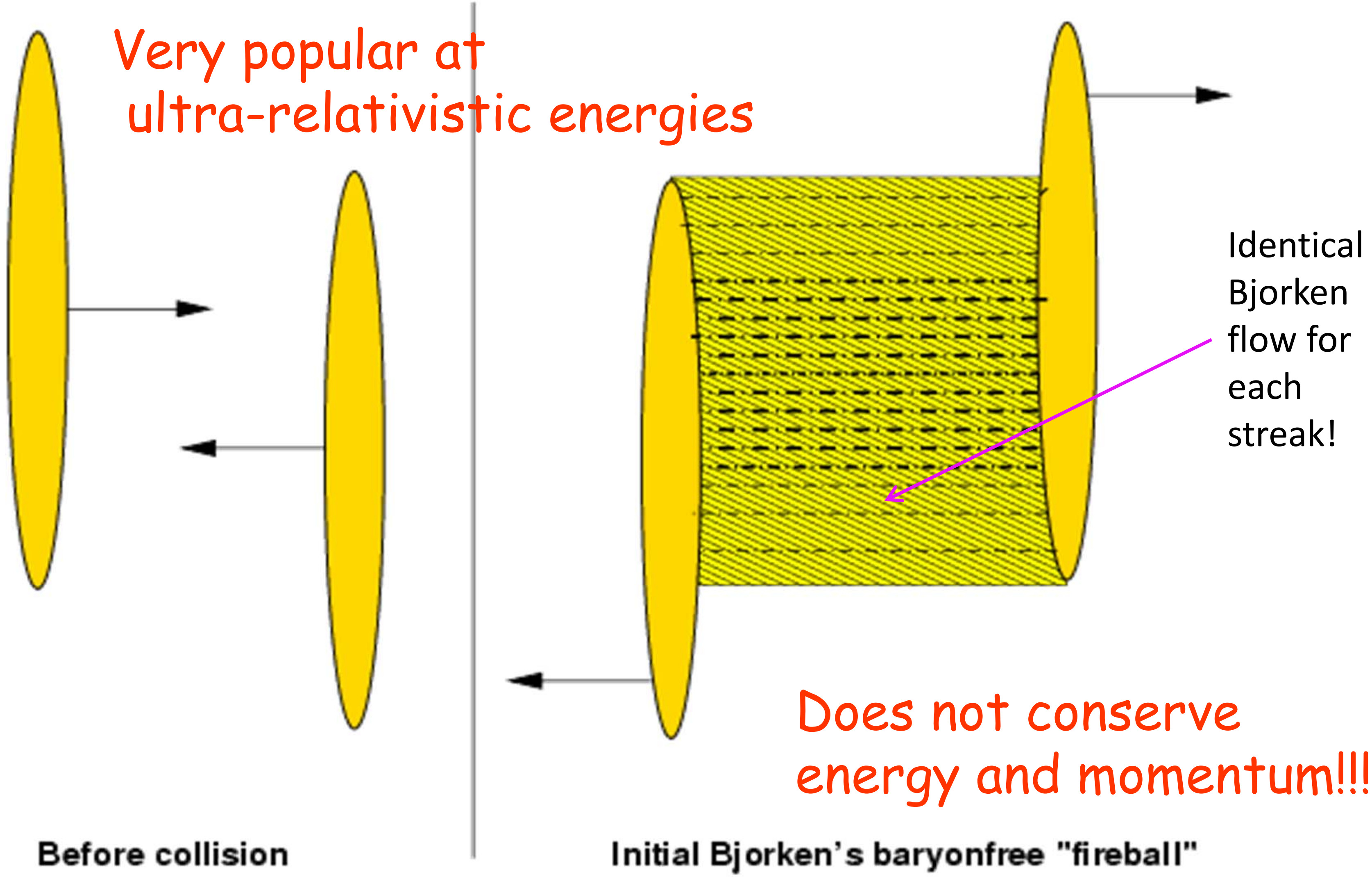
Works well at low energies



Bjorken initial state – complete transparency

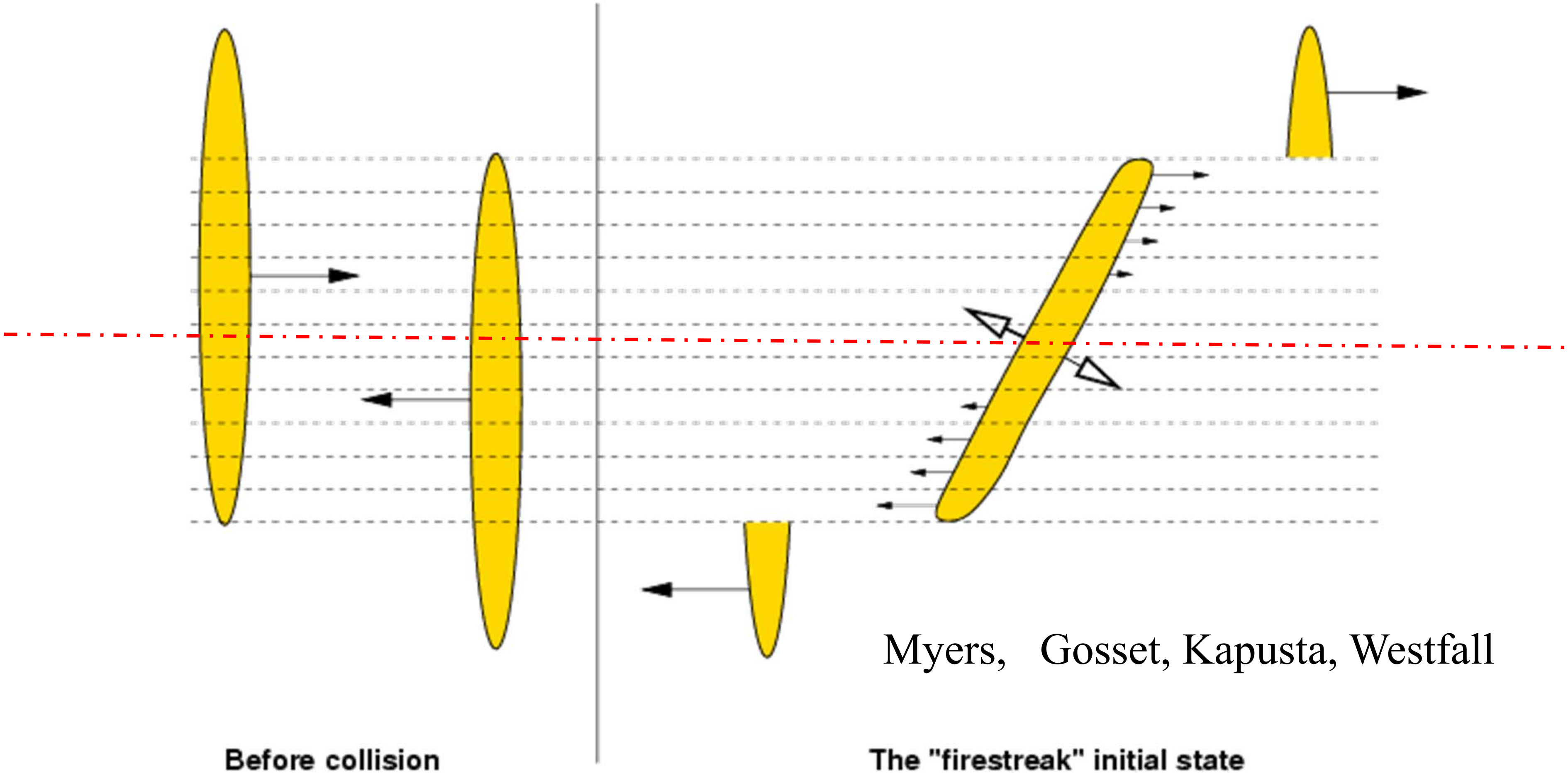
Initial state is boost invariant – all quantities depent only on τ, not on y → give rise to 2+1D simple hydro models

Very popular at ultra-relativistic energies



Does not conserve energy and momentum!!!

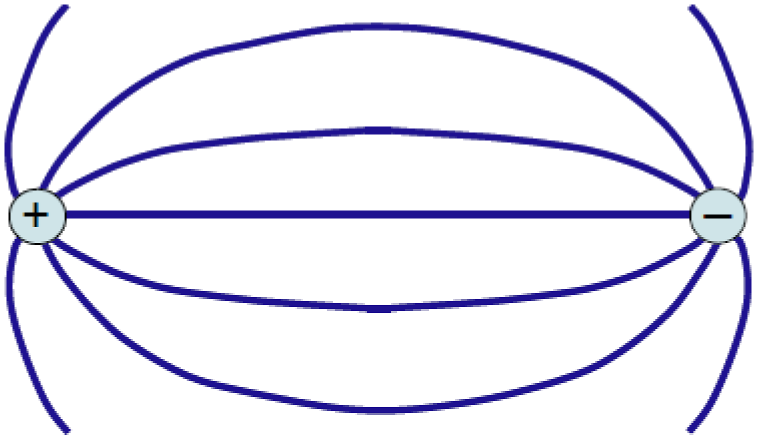
„Fire streak" picture – 3 dim.



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

Flux – tubes

ED or QED:

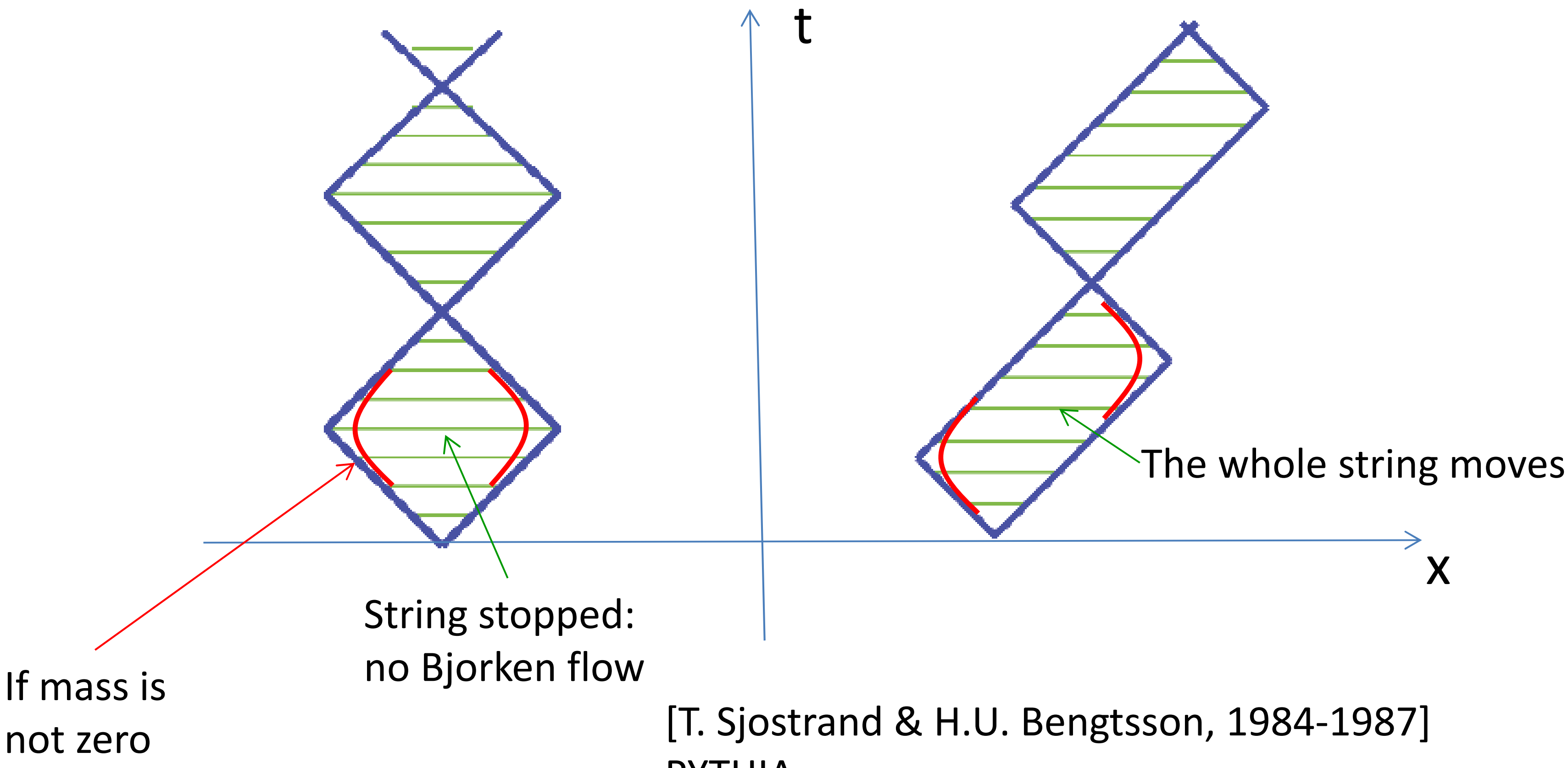


Gluon self-interaction makes field lines attract each other. →
QCD:

→ 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

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

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

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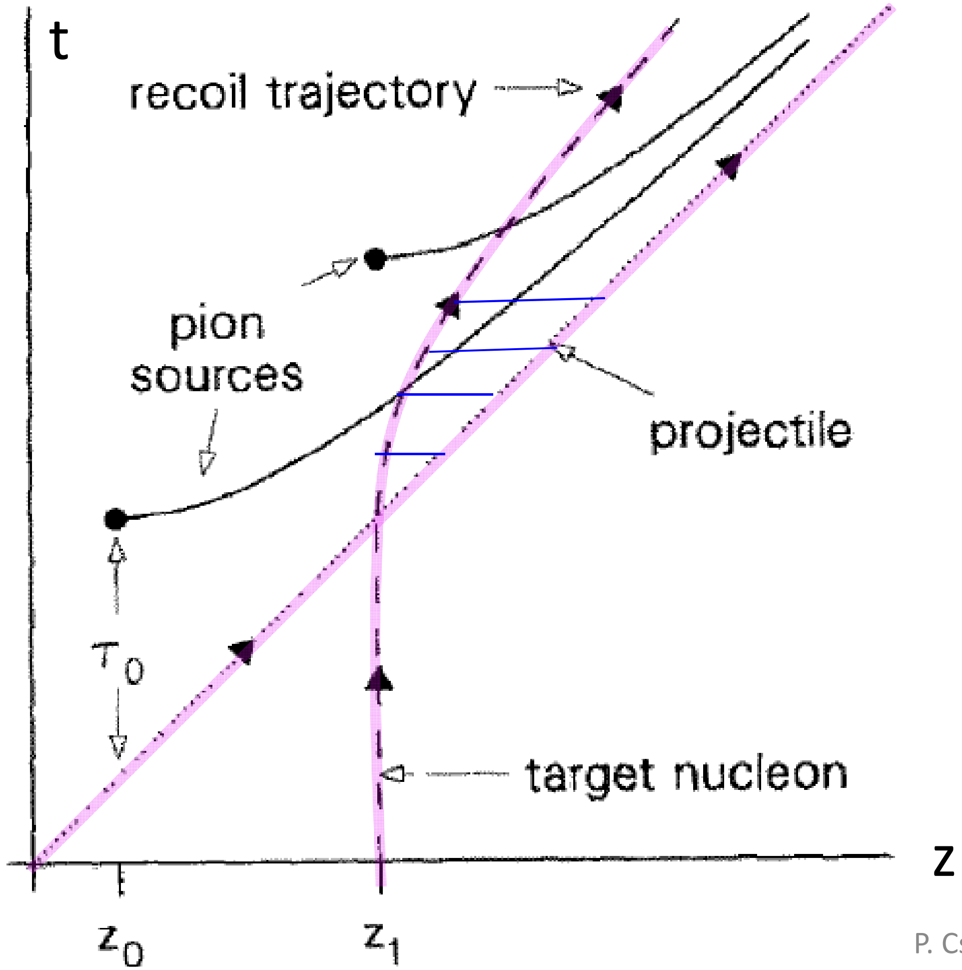
L.P. CSERNAI[1]

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]

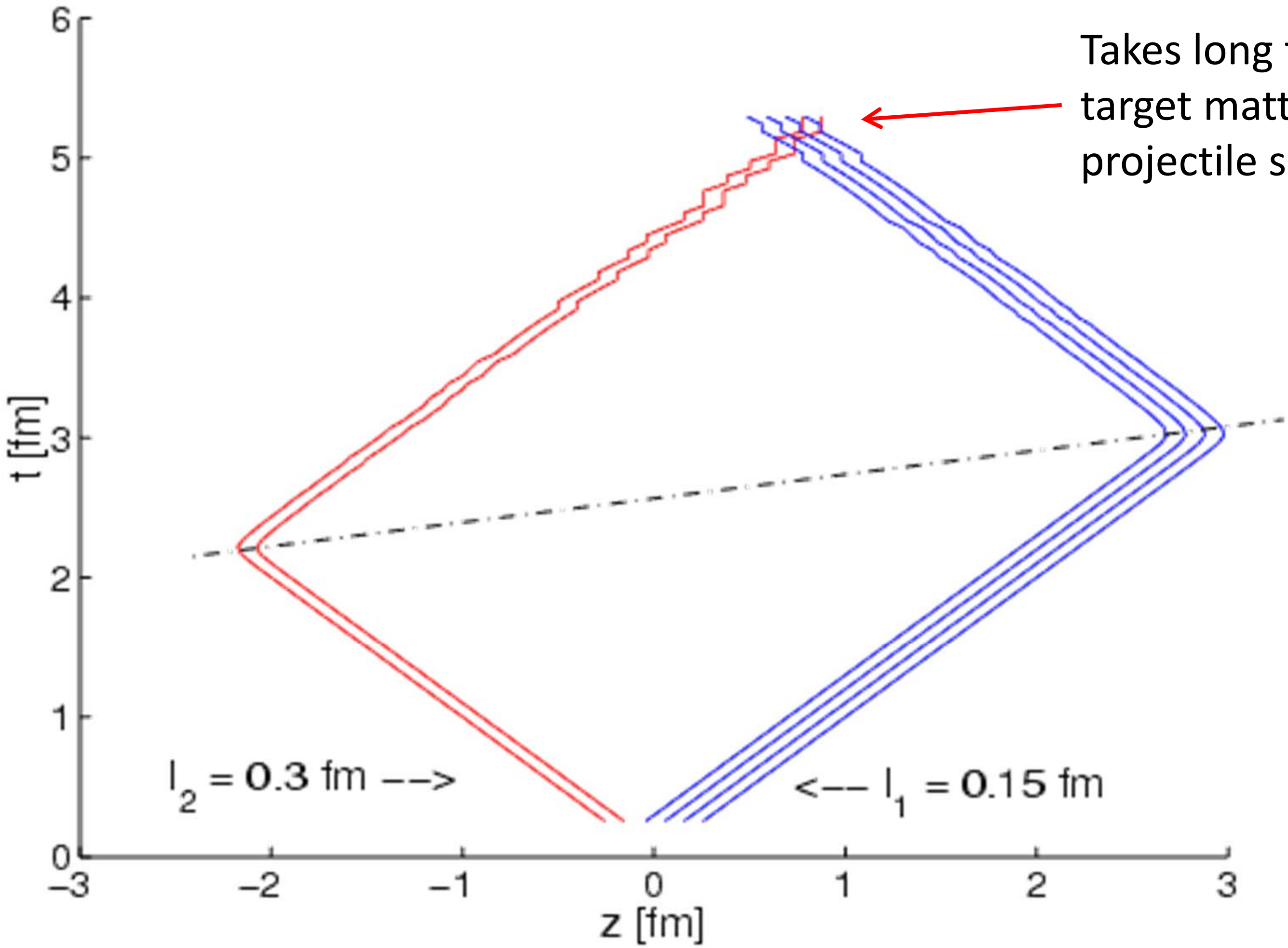
M. Gyulassy, L. Csernai Nucl. Phys. A660 (1986) 723-754.

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

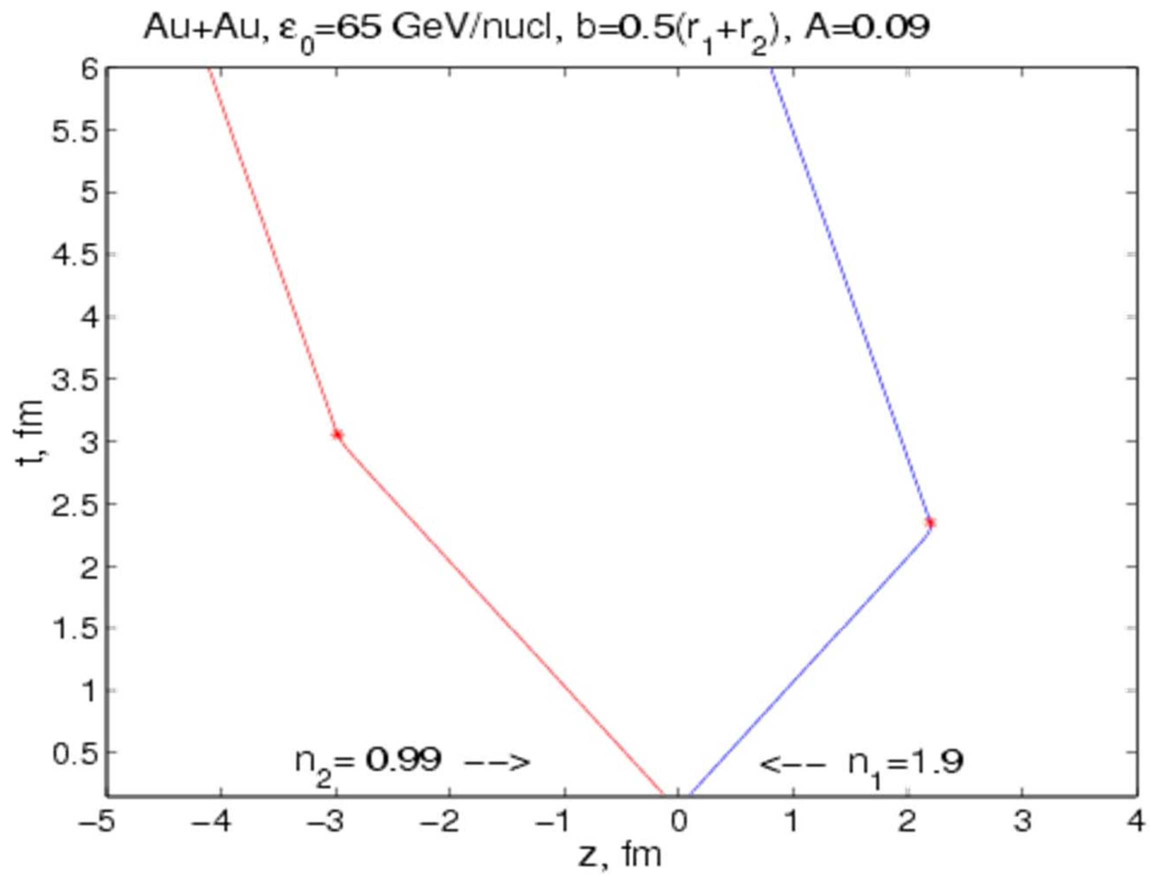
- $T^{\mu\nu} = e_t \left(\left(1 + c_0^2\right) u_t^\mu u_t^\nu - c_0^2 g^{\mu\nu} \right)$
- Σ_π^ν – pion source term.
- $F^{\mu\nu}$ – effective field, describes interaction between target and projectile.

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

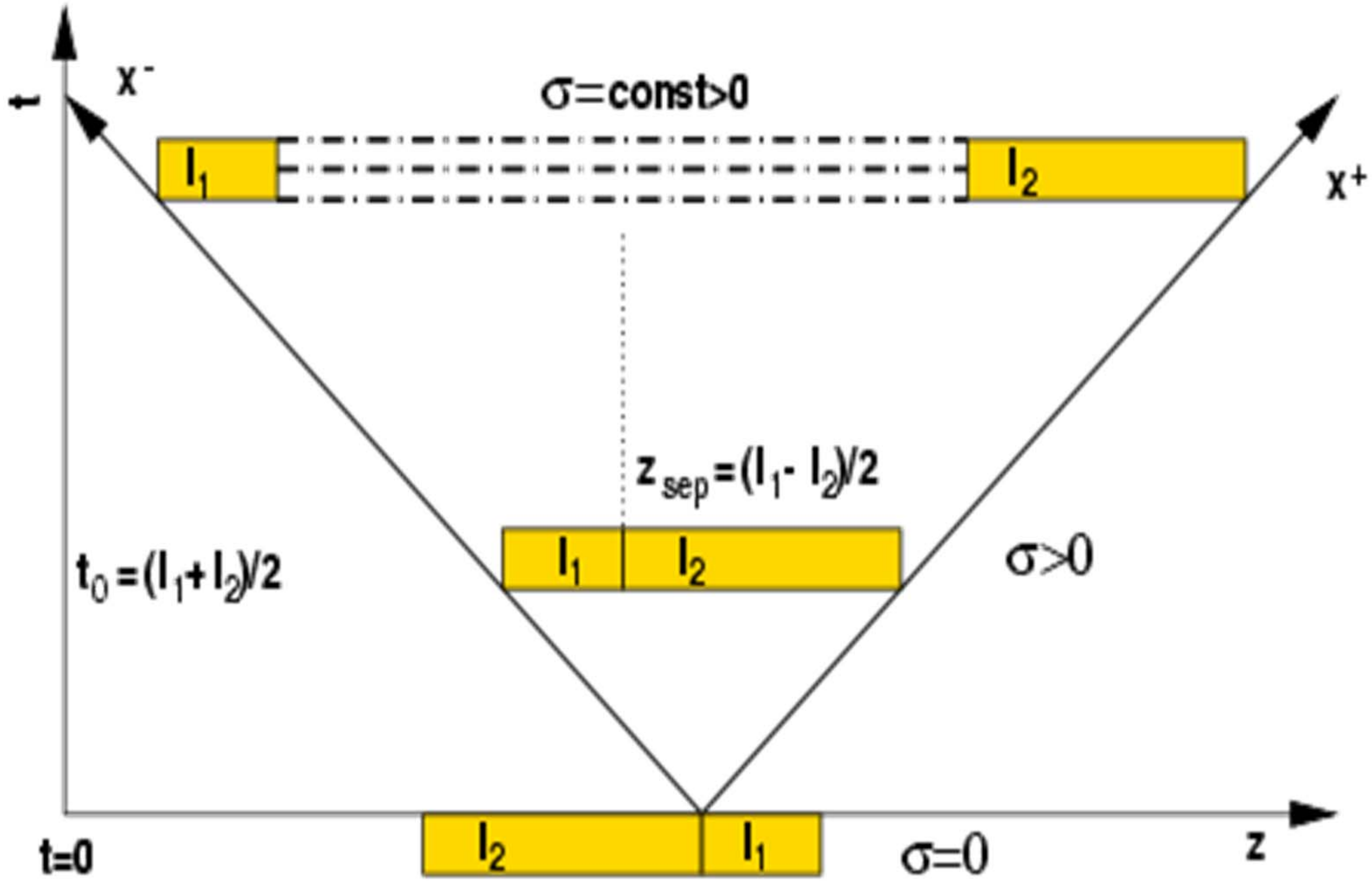
Yo – Yo Dynamics



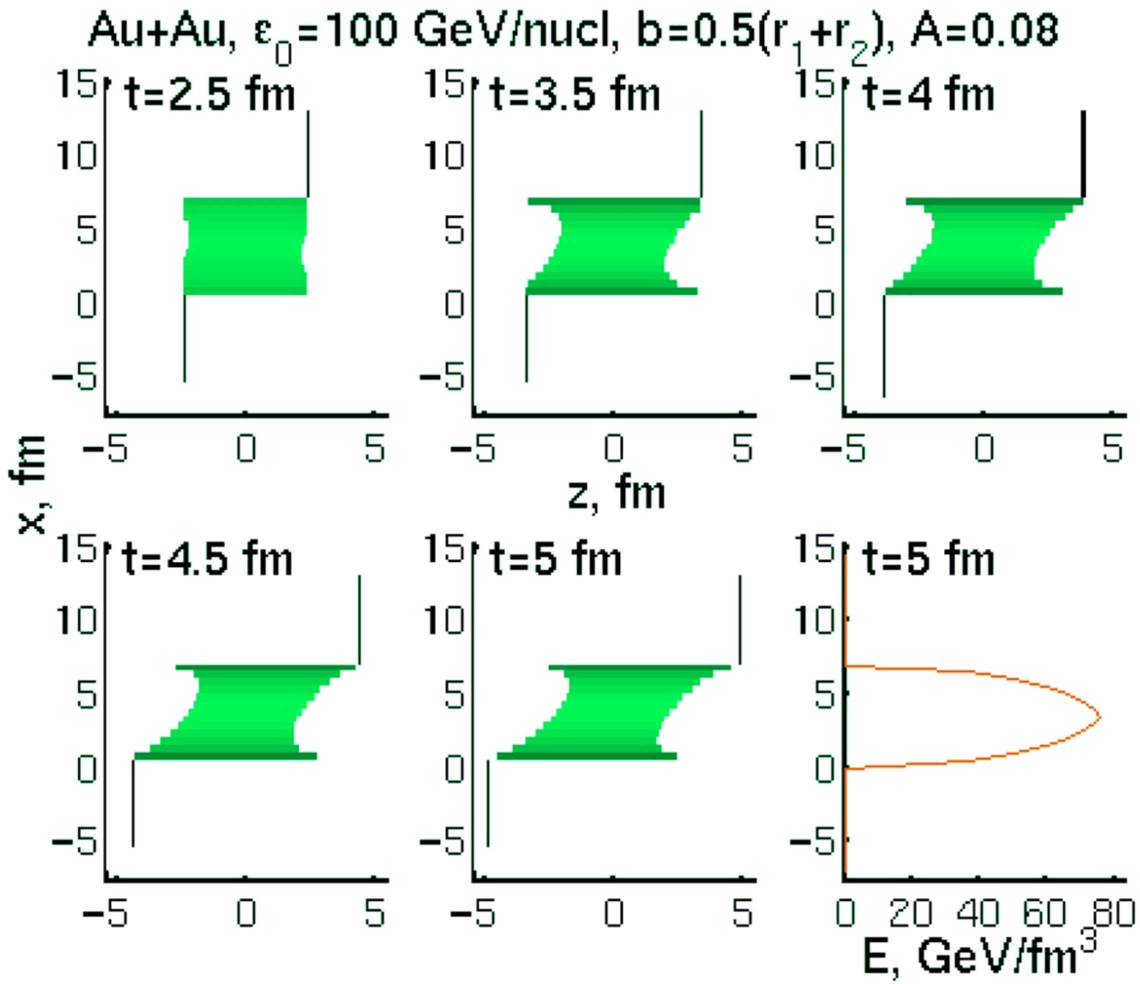
Takes long time to move target matter over to the projectile side!

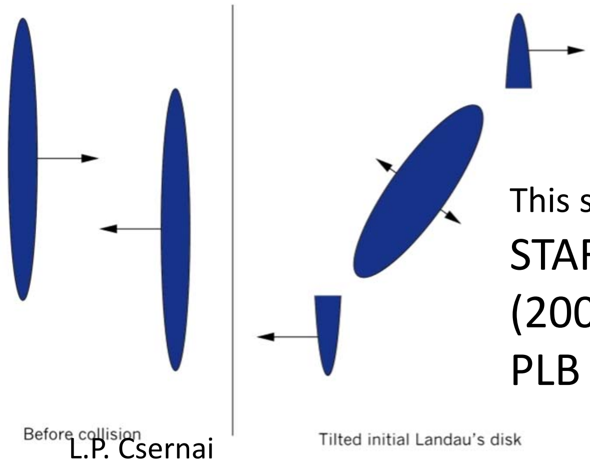

Au+Au, ε0=65 GeV/nucl, b=0.5(r1+r2), A=0.09
t, fm
z, fm
n2= 0.99 -->
<-- n1=1.9
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
−5
−4
−3
−2
−1
0
1
2
3
4

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



Initial State

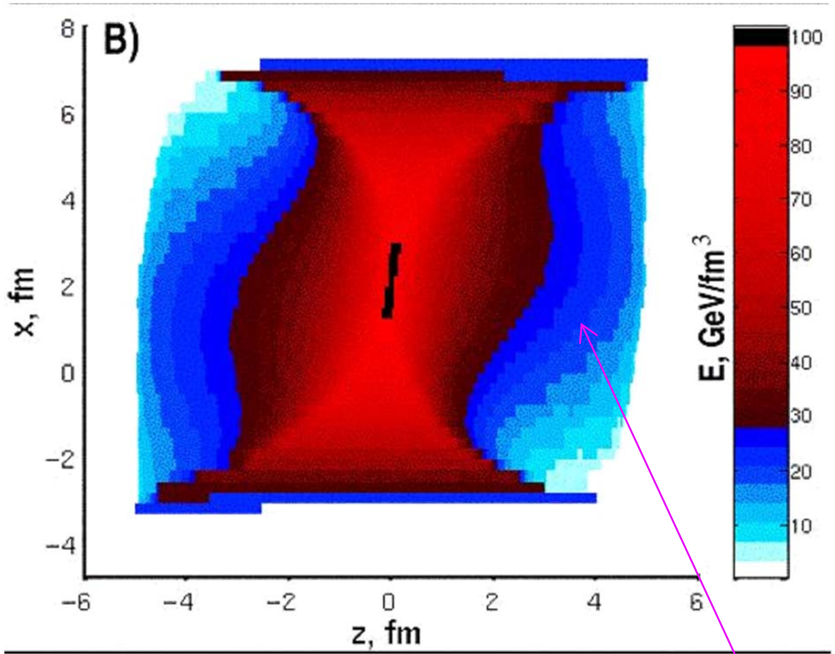




This shape is confirmed by STAR HBT: PLB496 (2000) 1; & M.Lisa &al. PLB 489 (2000) 287.

3rd flow component

Initial state – reaching equilibrium

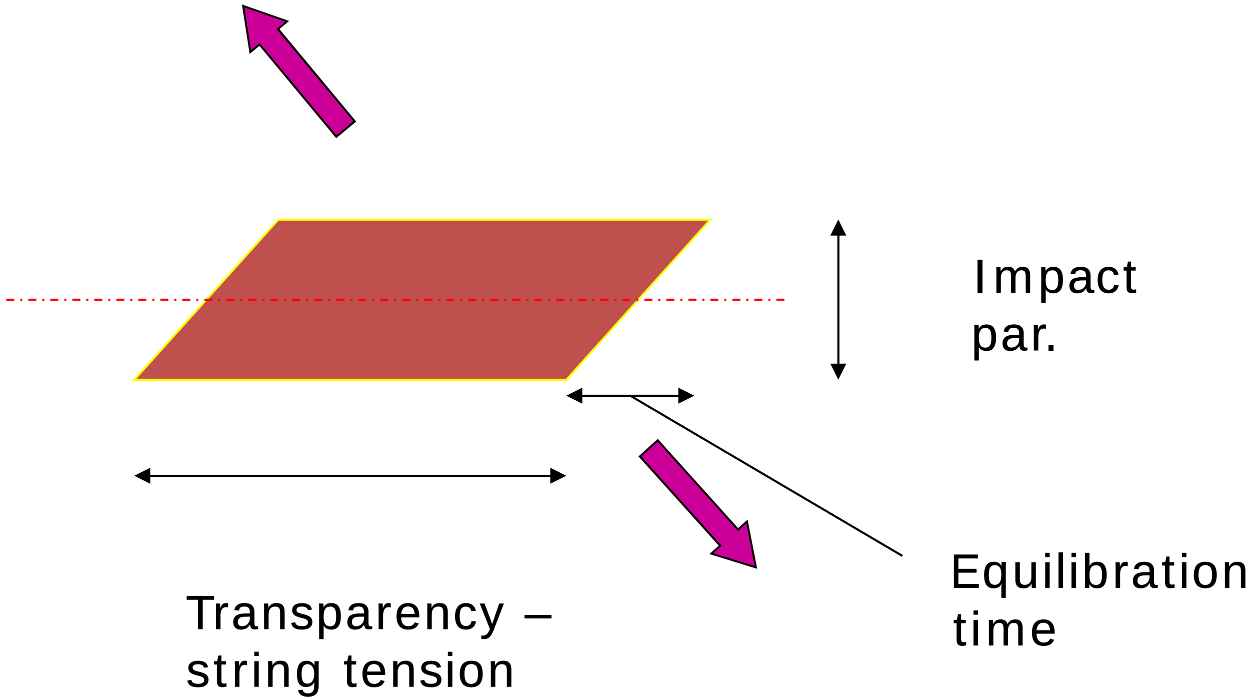


Initial state by V. Magas, L.P. Csernai and D. Strottman
Phys. Rev. C64 (01) 014901

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

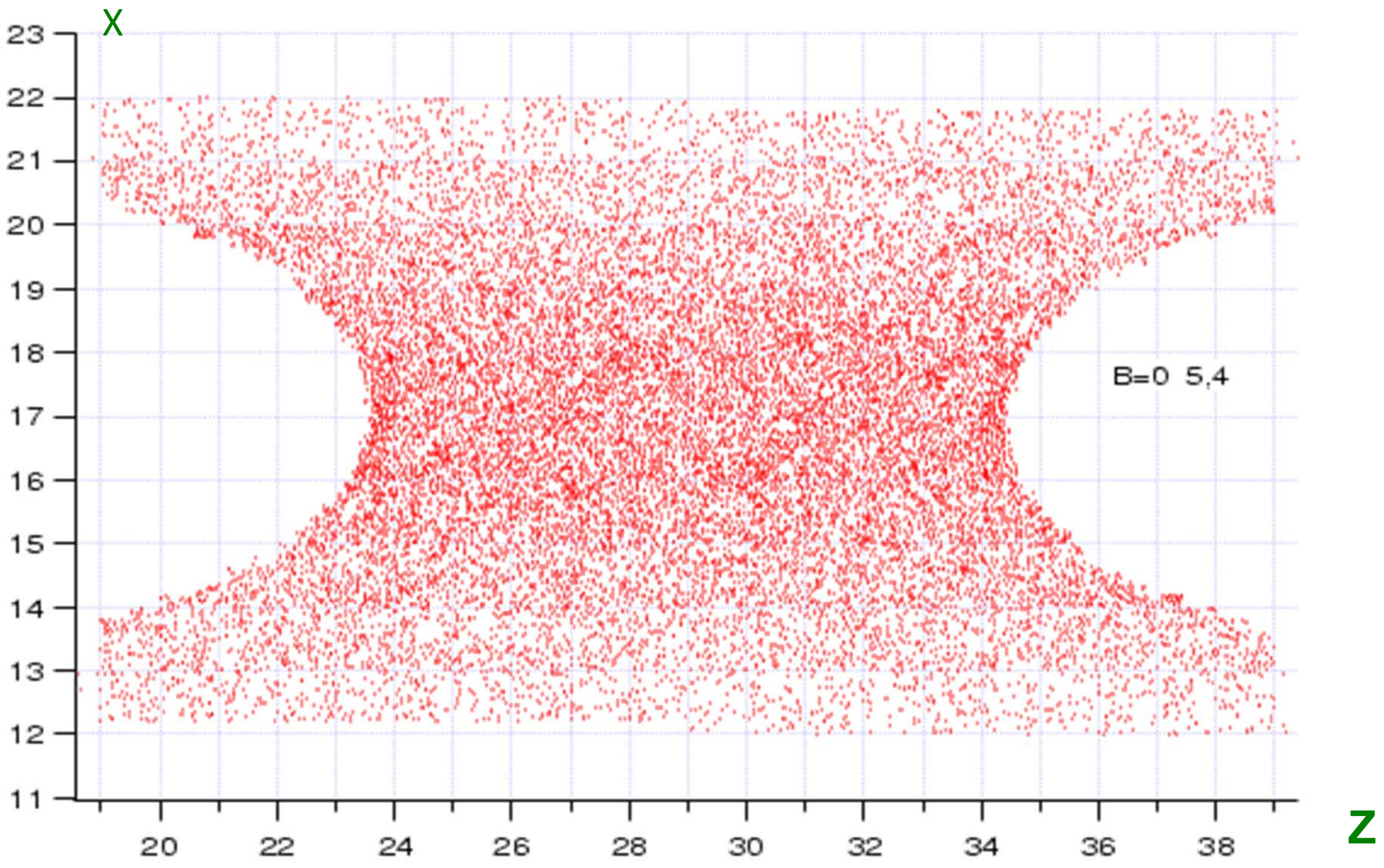
M1

Flow is a **diagnostic** tool

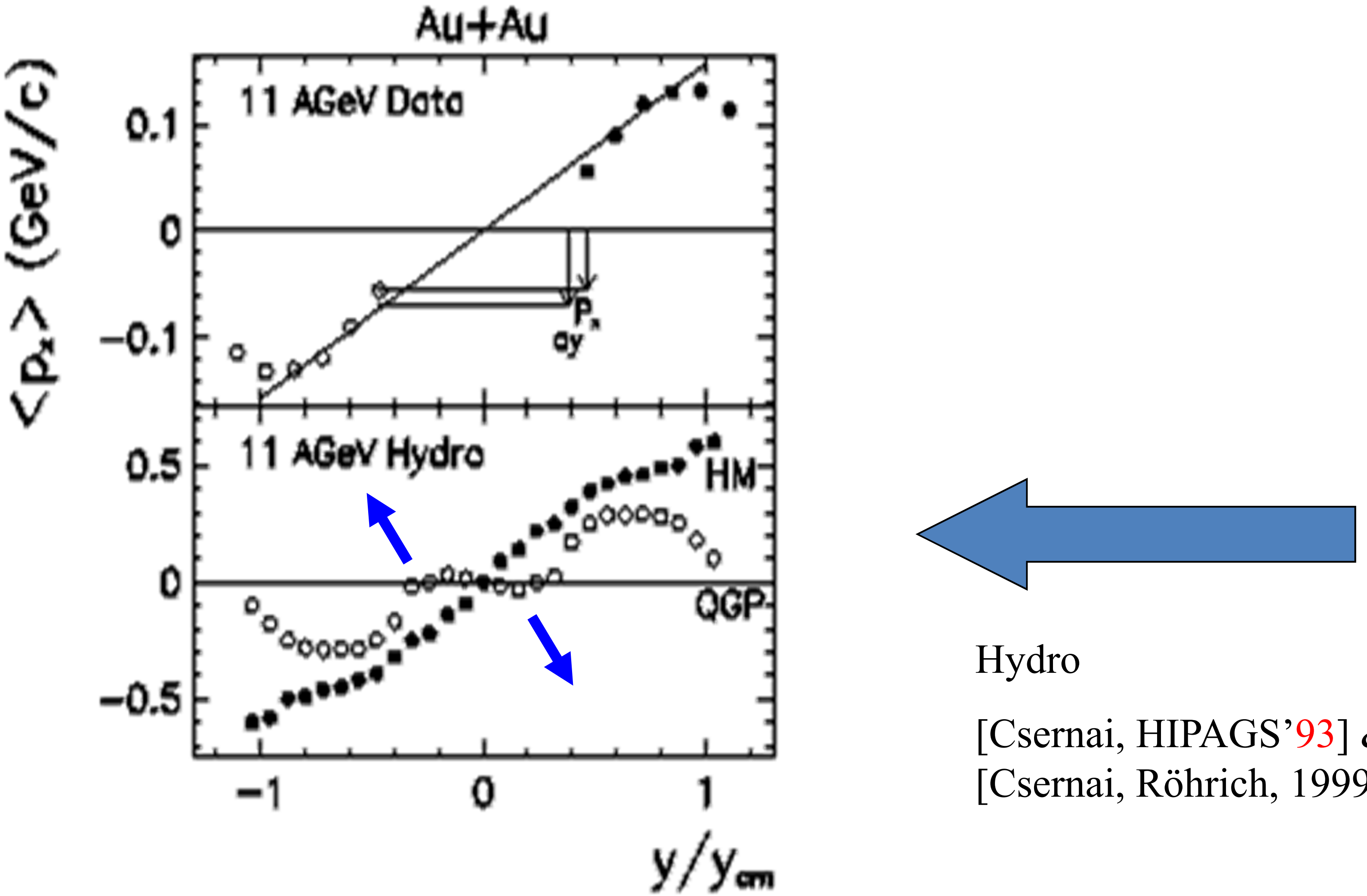


Consequence:
$v_1(y)$, $v_2(y)$, ...

3-Dim Hydro for RHIC (PIC)



3rd flow component

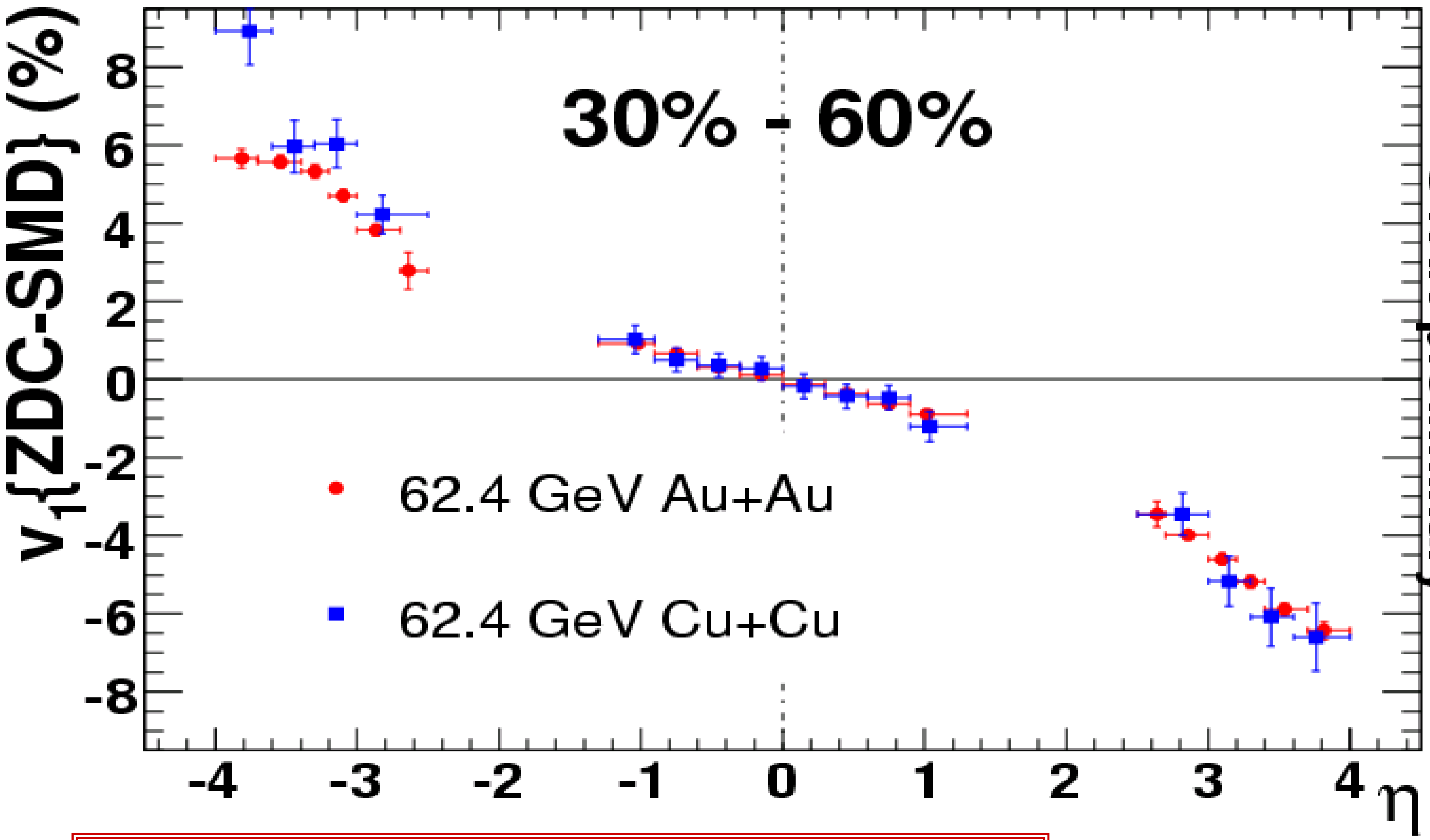


Hydro

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

G. Wang / STAR
QM 2006 :

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



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

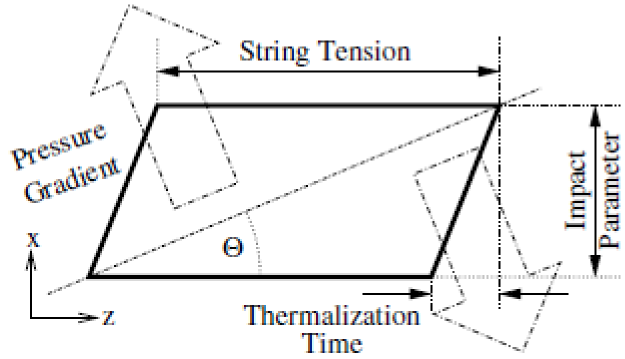
IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

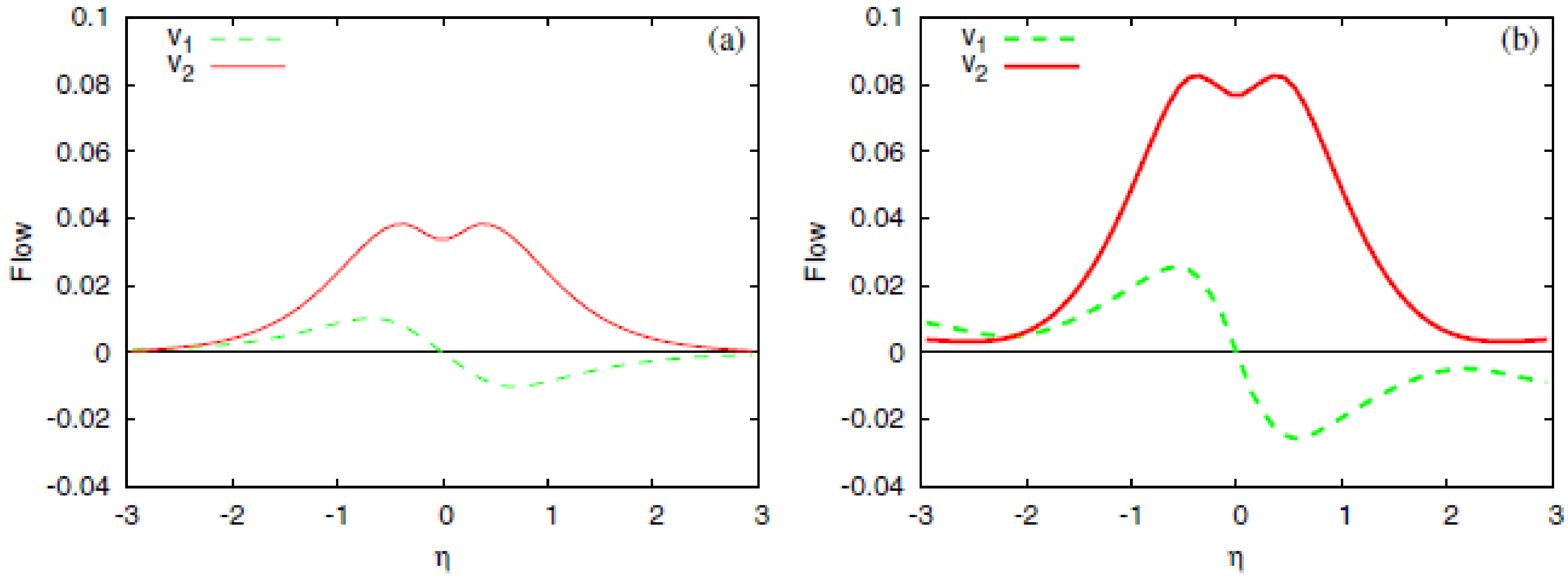
J. Phys. G: Nucl. Part. Phys. **34** (2007) S1077–S1081 — doi:10.1088/0954-3899/34/8/S160

[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).

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:

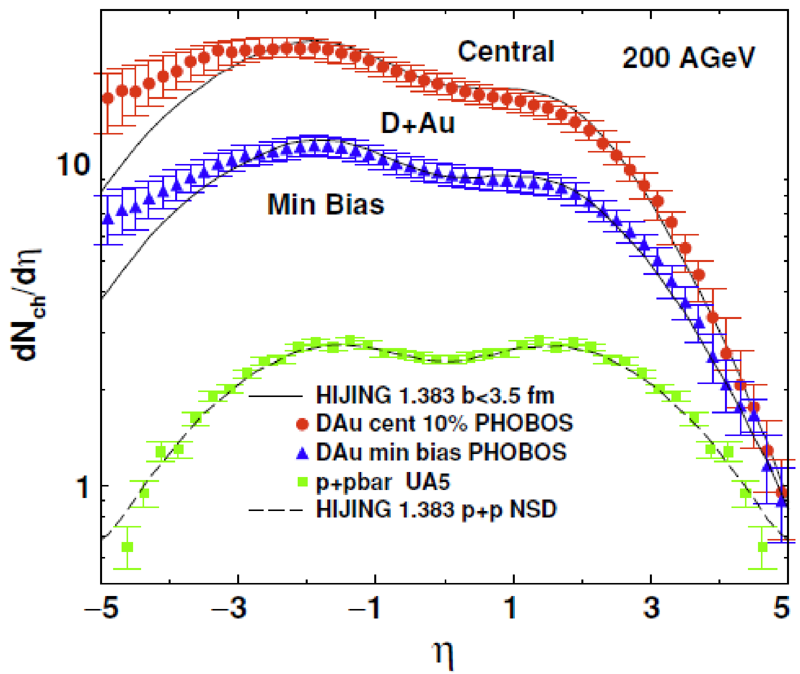
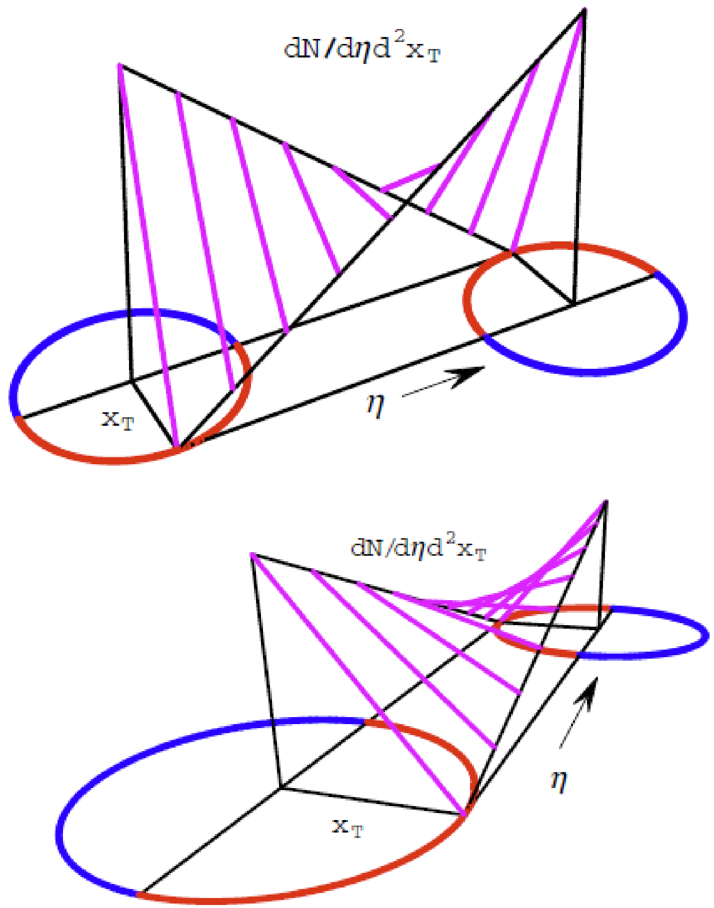


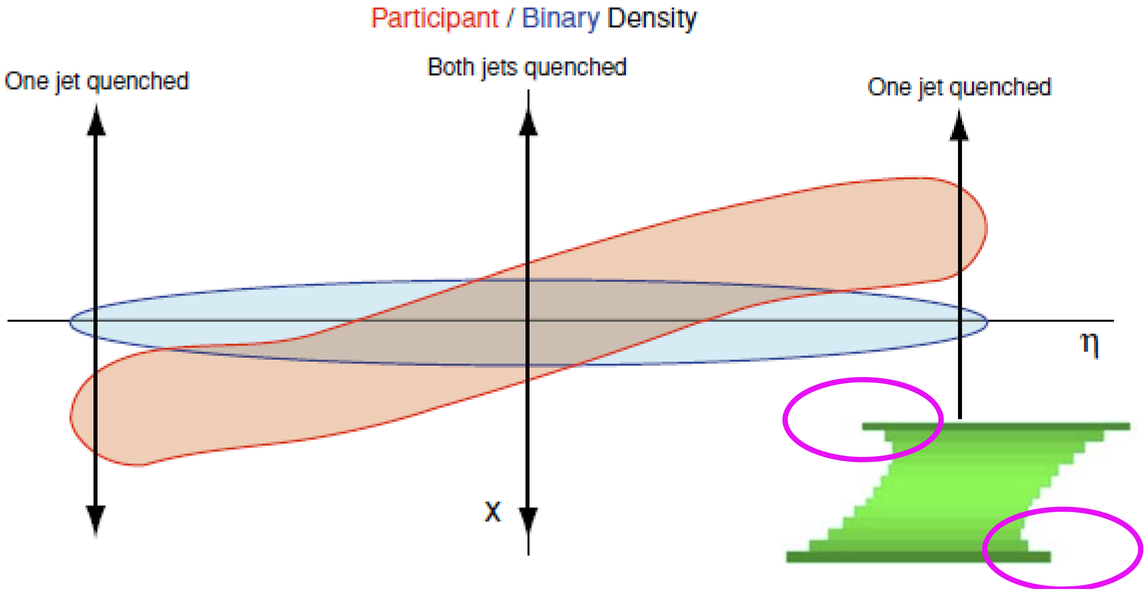
FIG. 2. (Color online) Asymmetric pseudorapidity distributions of charged hadrons produced in D+Au minimum bias and central 0–10% reactions at 200*A* GeV from PHOBOS [12] are compared to $p+\bar{p}$ data from UA5 [13]. The curves show predictions using the HIJING v1.383 code [14,15].

→

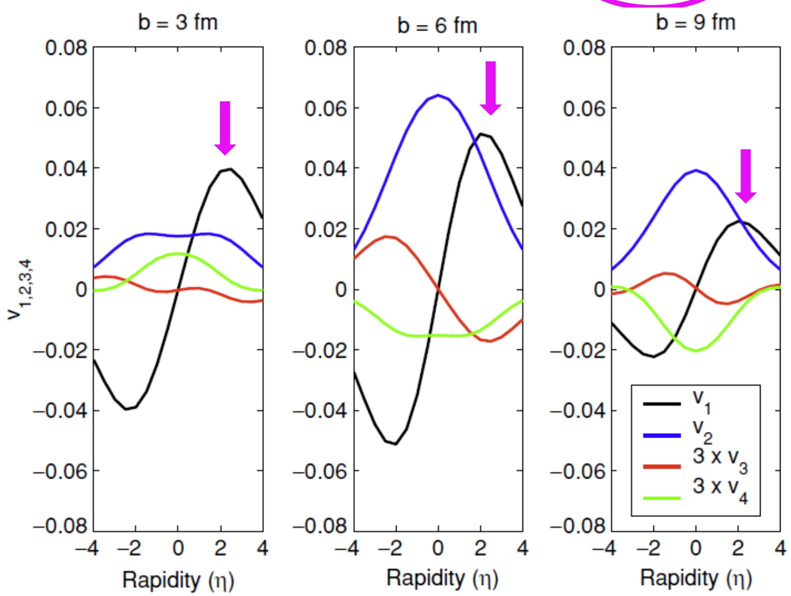


This is similar to our model, with several flux-tubes in each fire-streak, with different rapidities at their ends. This leads to a "*diffuse nuclear geometry*" :

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 !)

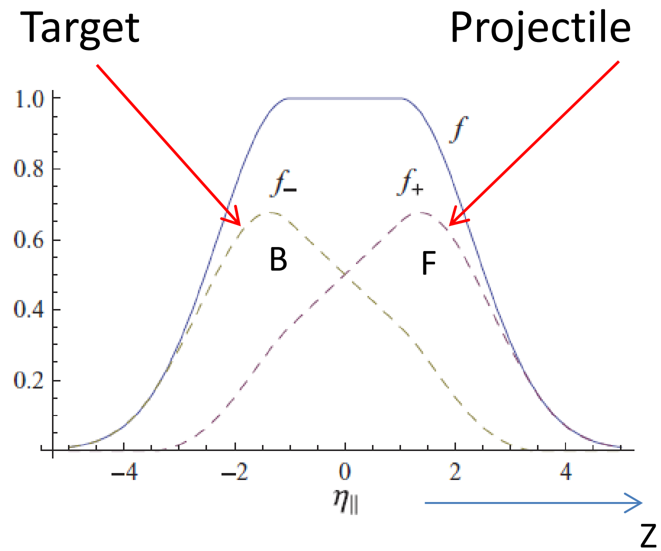
v_1 is opposite side then in the experiment.

Bozek, Wyskiel (2010): Directed flow

x, y, η, τ coordinates

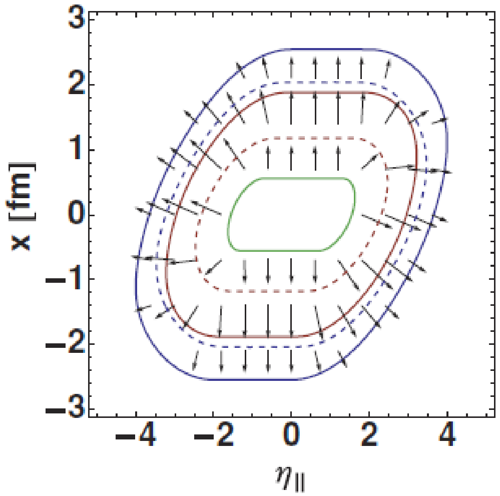
PHYSICAL REVIEW C **81**, 054902 (2010)

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 →

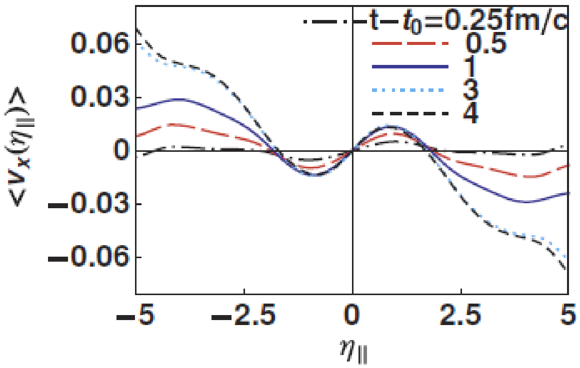


$$u^{\mu}(\tau_0, x, y, \eta_{\|}) = (\cosh \eta_{\|}, 0, 0, \sinh \eta_{\|}).$$

Bjorken flow



→

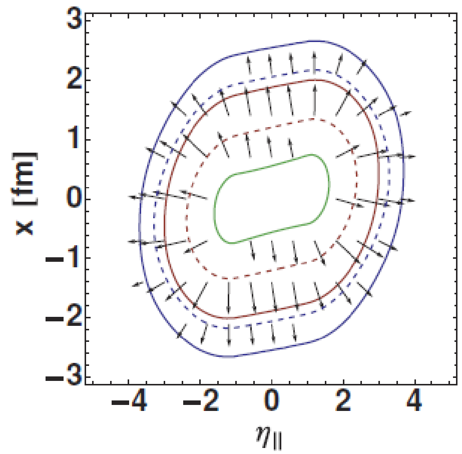


Global collective coordinates

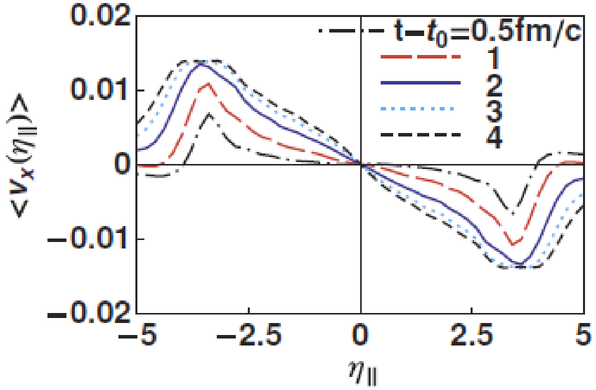
Directed flow (v_1) peaks at positive rapidities! (as A&D)

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→

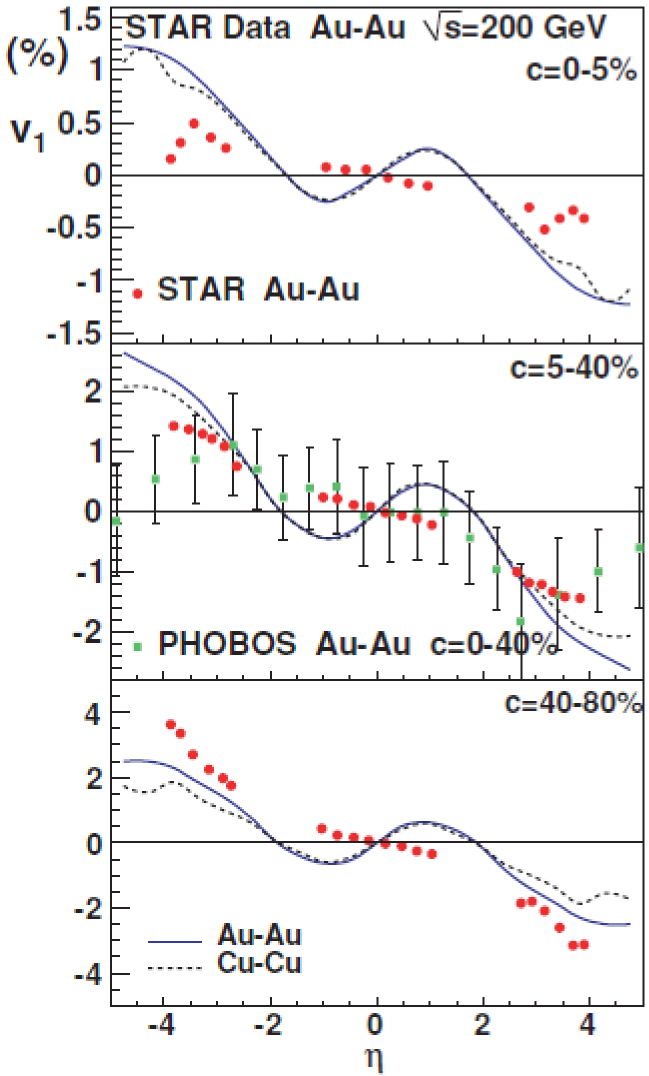


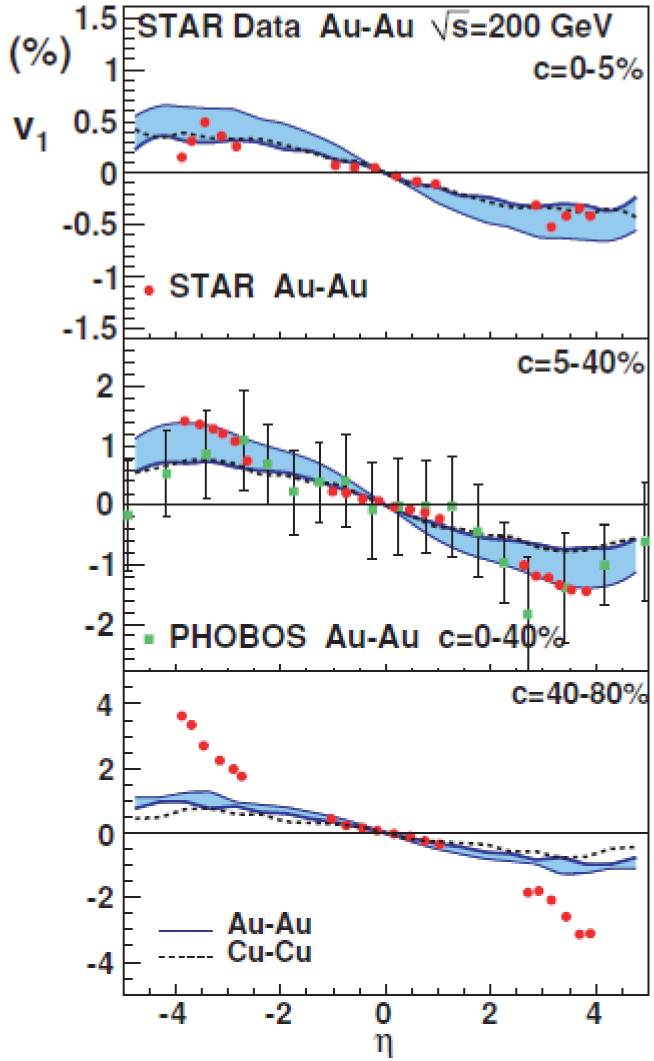
→



Not a dynamical model

3, Directed flow at different centralities





'tilted' i.s.

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

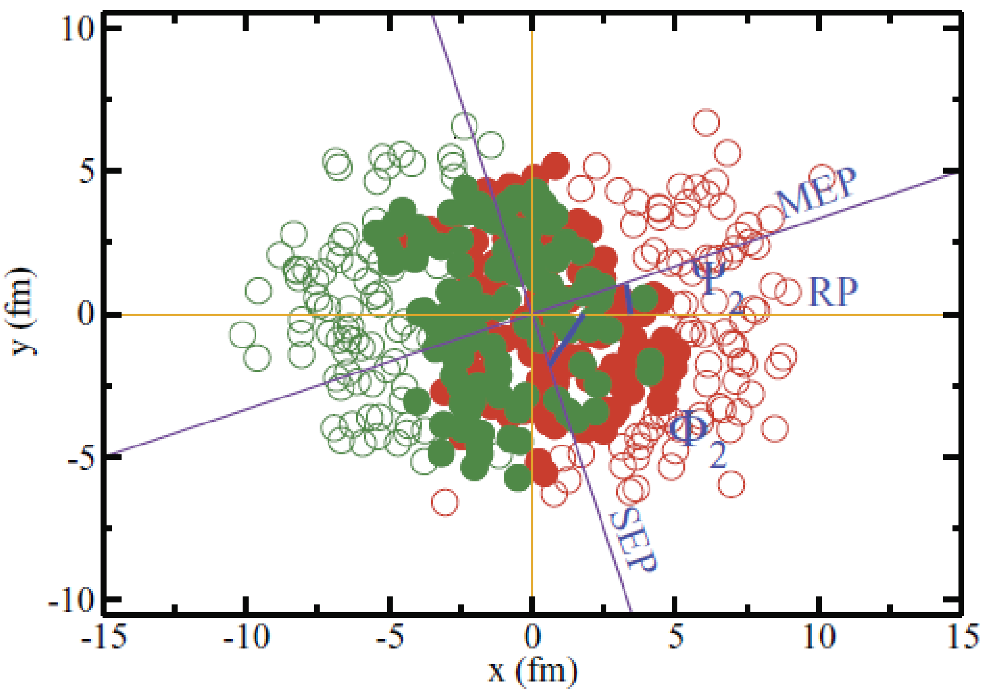


FIG. 3. (Color online) The transverse plane for one typical collision event, where the circles represent nucleons from two nuclei, with shaded ones for participating nucleons. Also shown are the locations of different planes: the reaction plane (RP), the spatial event plane (SEP), and the momentum event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

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

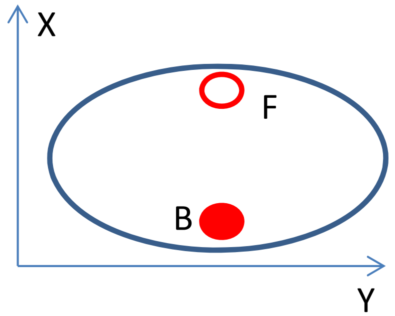
If the MEP is set to zero (by definition) then CM rapidity fluctuations do not appear, and v_1 by definition is zero.

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

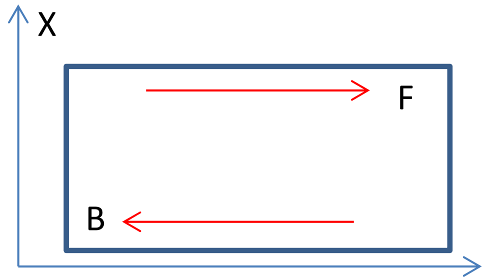
Bozek, Broniovski, Moreira (2011): 'Torqued initial state'

PHYSICAL REVIEW C **83**, 034911 (2011)

Similarly to Adil & Gyulassy this is also based on the Wounded nucleon [1] picture. The P & T distributions are given →[1: A. Białas, M. Bleszynski, and W. Czyz, Nucl. Phys. B **111**, 461 (1976)]



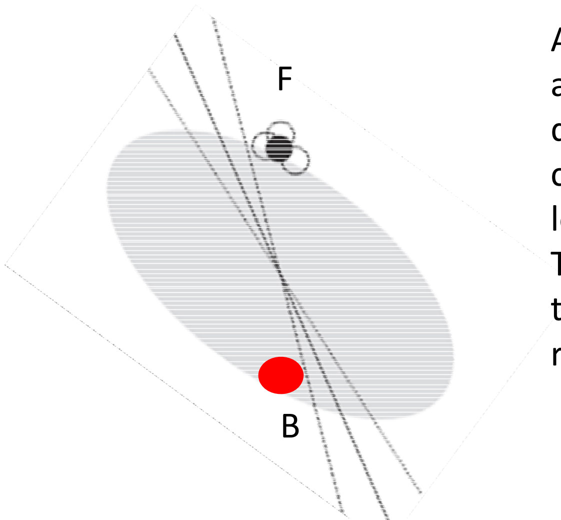
Transverse plane



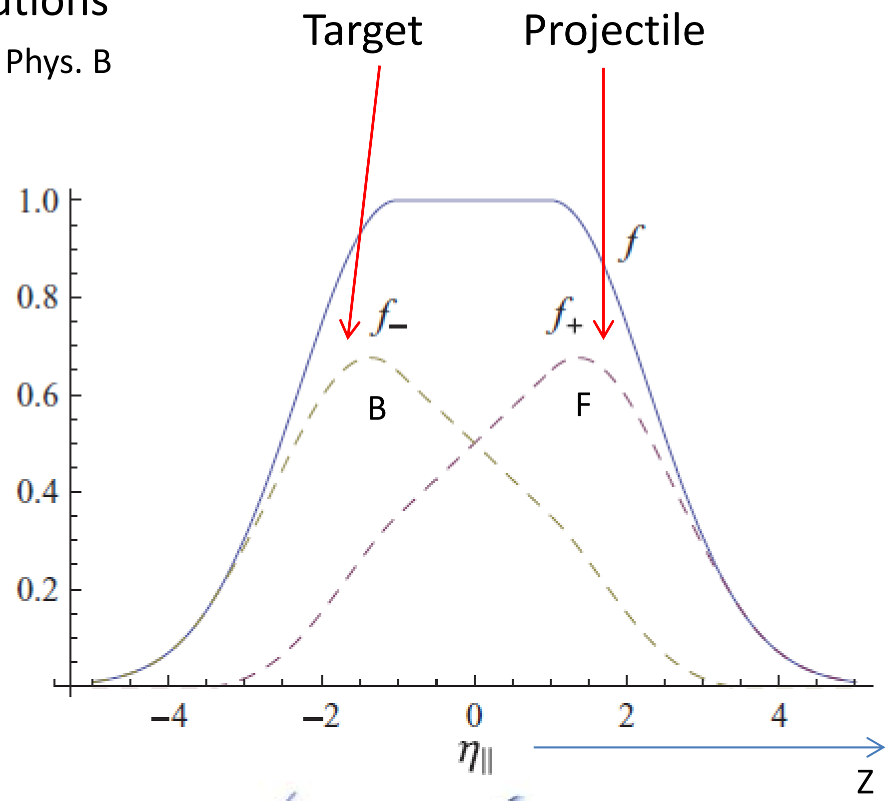
Reaction plane

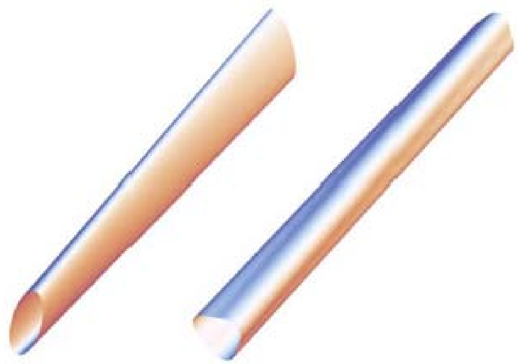
global collective coordinates

In case of i.s. fluctuations the transverse plane axes may differ from the global coordinates →



At different rapidities the amount of the torque is different, which leads to a changing torque along the longitudinal (beam) axis. This leads to different torque effects at different rapidities →





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 →

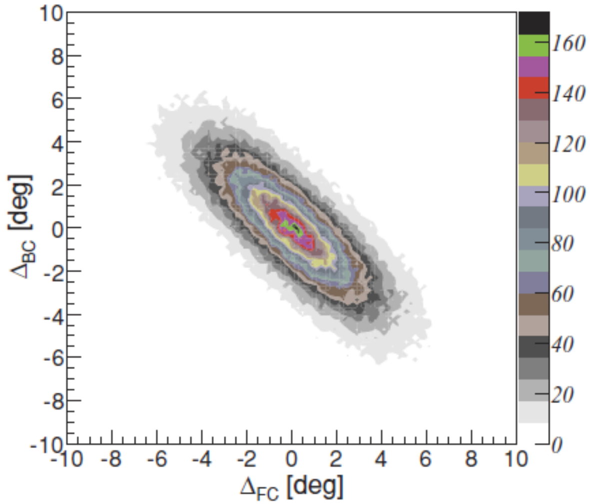


FIG. 7. (Color online) The two-dimensional distribution plot of the relative torque angles Δ_{FC} and Δ_{BC}, for centrality 50%–60%, space-time rapidity $\eta_{\|} = 2.5$. The corresponding correlation coefficient is $\rho_{FCB} = -0.61$.

Prediction →

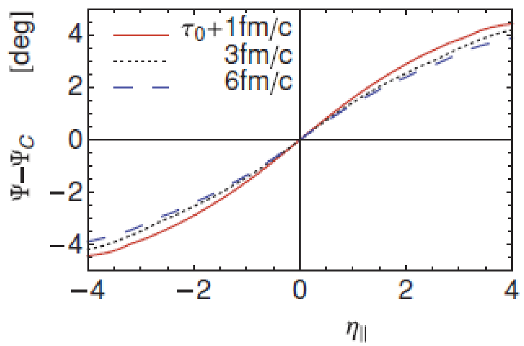


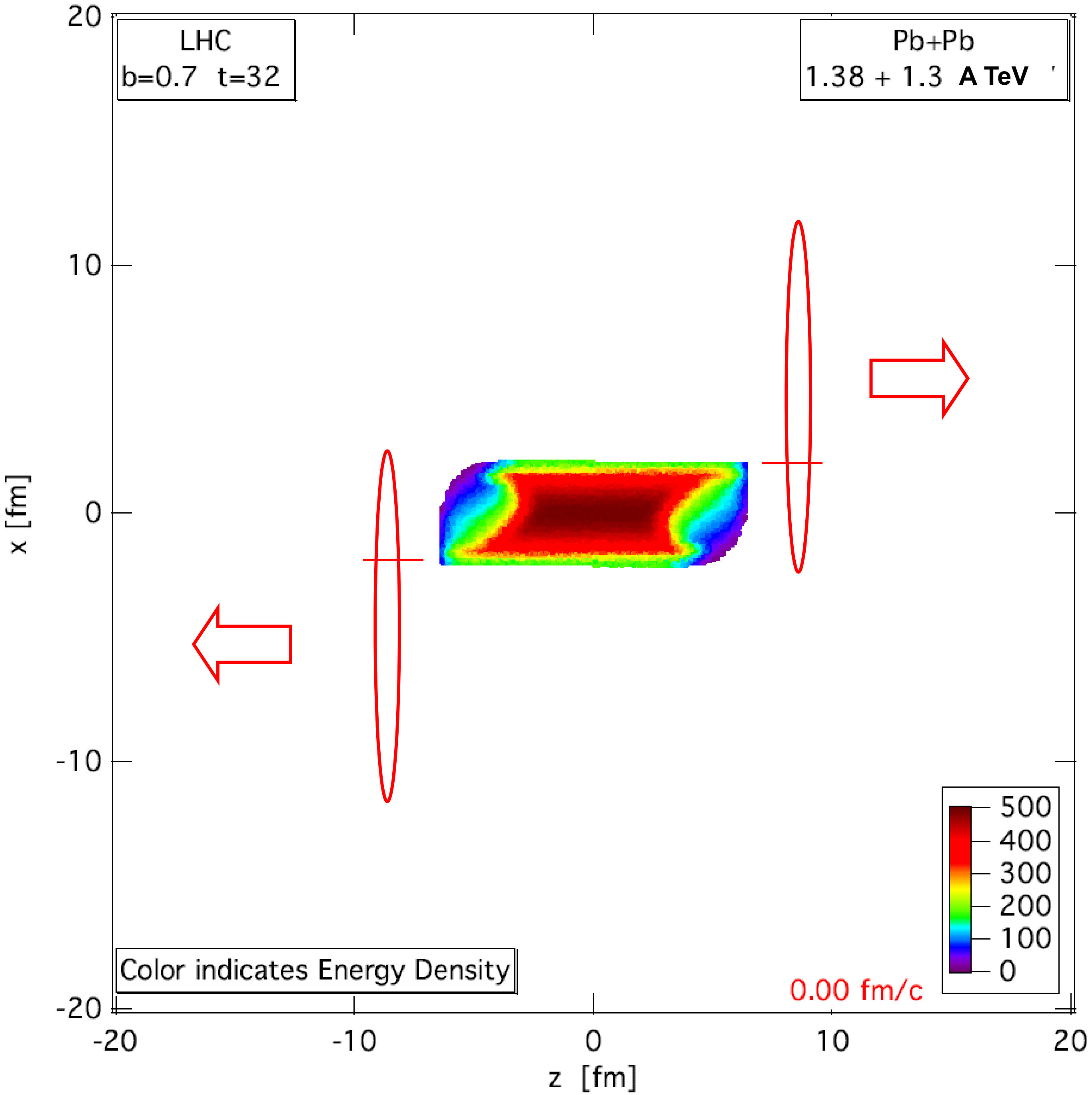
FIG. 10. (Color online) The dependence of the torque angle of the fluid velocity field on space-time rapidity after the (3 + 1)-dimensional hydrodynamics of Ref. [8] (solid, dotted, and dashed lines). Subsequent curves are for different evolution times.

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



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

Entropy increase in FD expansion

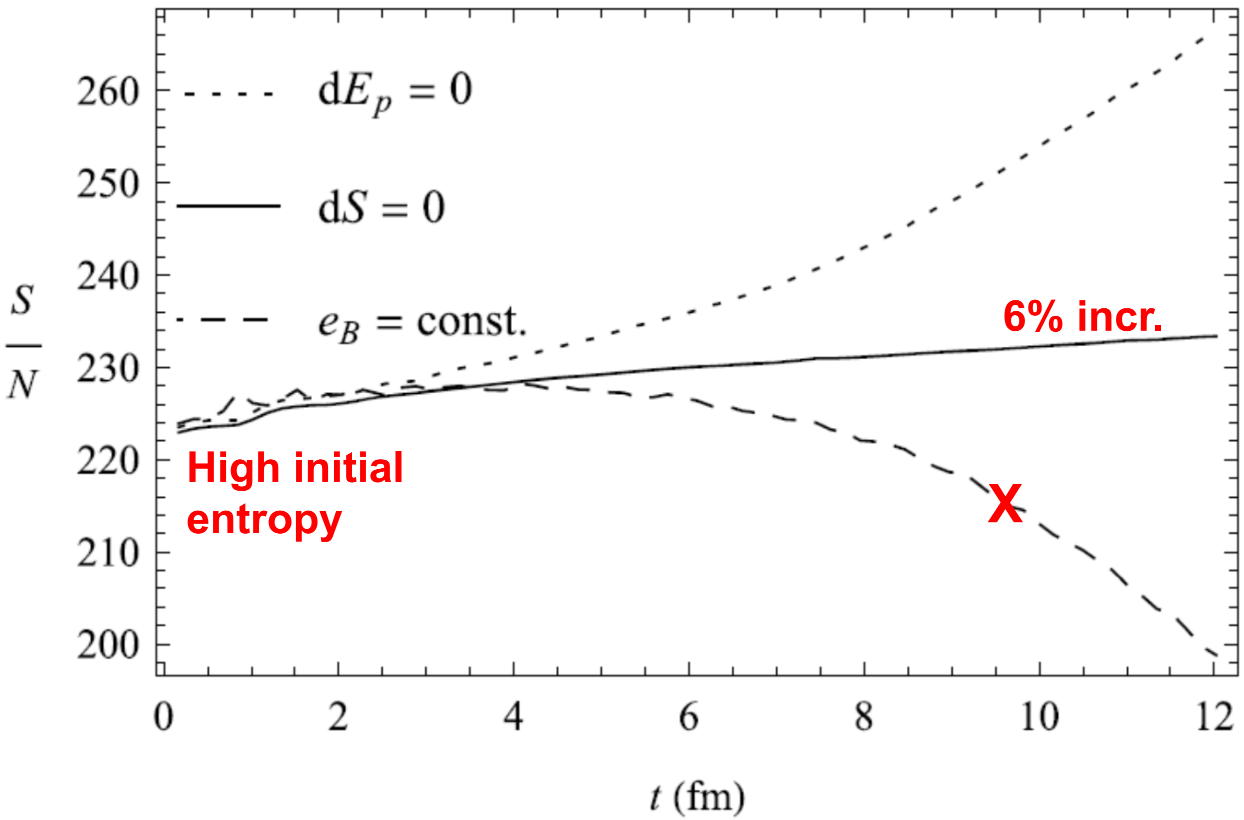


Fig. 4. Results for an Au + Au collision at 65 + 65 A GeV energy at impact parameter $b = 0$, from a CFD calculation with the Particle in Cell (PiC) method with cell size $dx = dy = dz = 0.575$ fm. The mean specific entropy of the Au + Au system, S/N, as a function of time in the numerical fluid dynamics simulation of a heavy ion collision. Solid line: adiabatic expansion of the ideal gas component, dashed line: $e_B = B = \text{const}$, dotted line: $E_p = \text{const}$. The slight entropy increase in the "adiabatic" case is due to numerical viscosity.

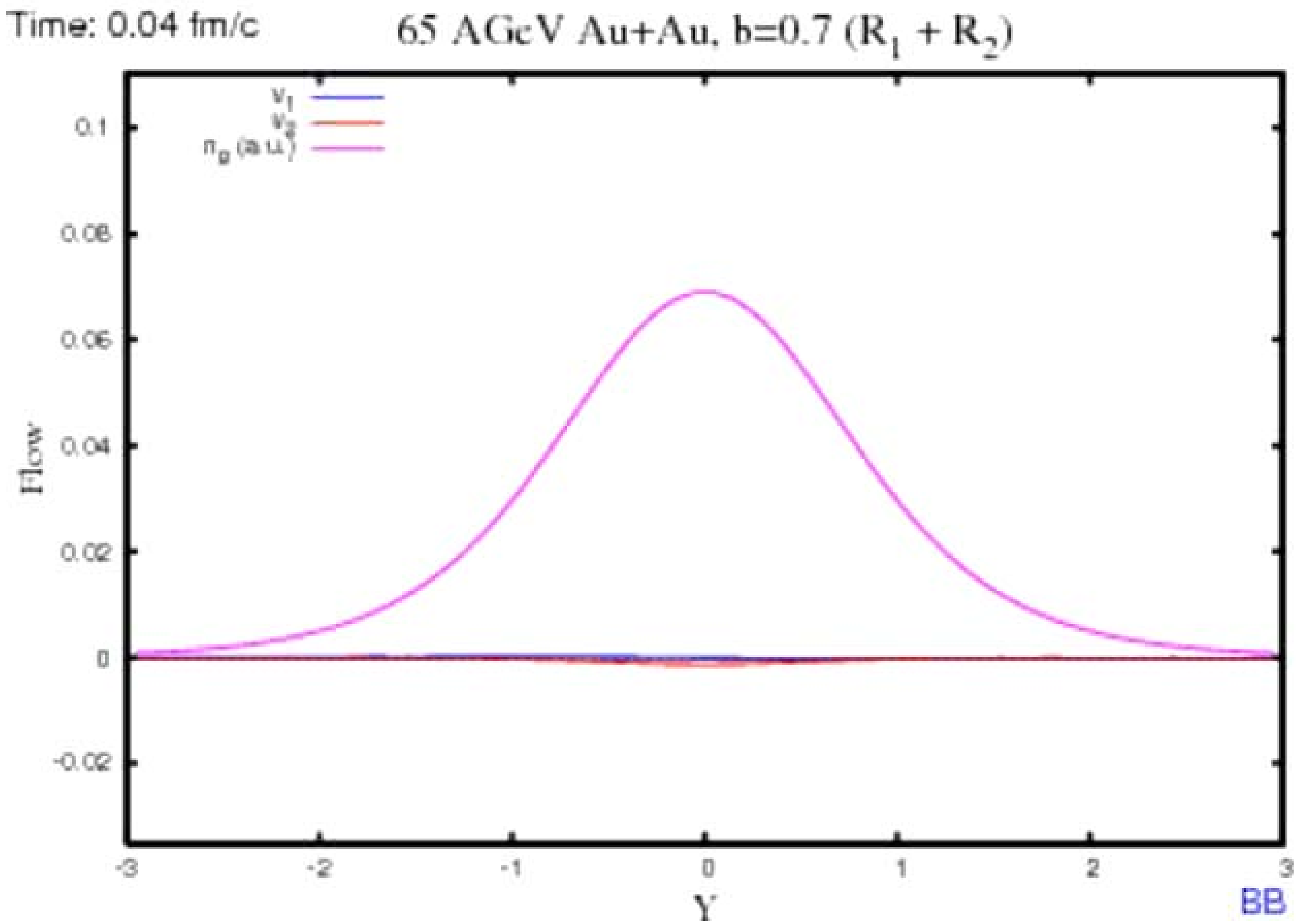
[Sz. Horvat et al., PLB 2010]

Rapidity distribution of v_1, v_2, nq

b = 70%

n_q scaling

$p_T = p_T / n_q$



Björn Bäuchle