

Collective Dynamics of the p+Pb Collisions

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[Piotr Bożek & WB,

PLB 718 (2013) 1557, 720 (2013) 250, [arXiv:1304.3044](#)]

Signatures of sQGP

Main signatures of sQGP in ultra-relativistic A+A collisions

- Collective flow
- Jet quenching

Flow manifests itself in harmonic components in the momentum spectra, certain features in correlation data (ridges), interferometry (femtoscopy), ...

- Bozek 2010: p+A and p+p in hydro
- Ridges discovered in small systems, p+A and high-multiplicity p+p

3-stage approach

Our three-phase approach: initial \rightarrow hydro \rightarrow statistical hadronization

- **Initial phase** - Glauber model
- **Hydrodynamics** - 3+1 D viscous event-by-event
- **Statistical hadronization**

Main questions:

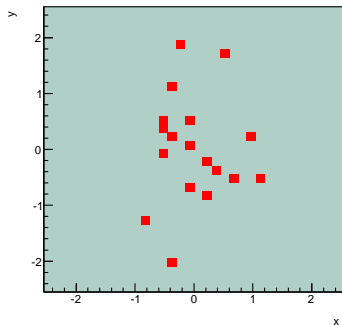
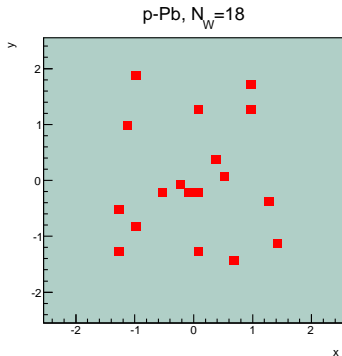
Are the central p-Pb collisions collective?

What is the nature of the initial state?

What are the limits on applicability of hydrodynamics?

Snapshots of initial Glauber condition in central p+Pb

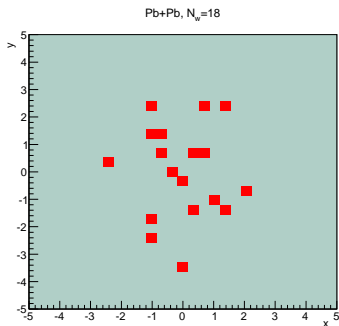
Typical transverse-plane configuration of centers of the participant nucleons in a p+Pb collision generated with GLISSANDO
5% of collisions have more than 18 participants, rms ~ 1.5 fm – large!



Snapshot of peripheral Pb+Pb

Most central values of N_w in p-Pb would fall into the 60-70% or 70-80% centrality class in Pb+Pb

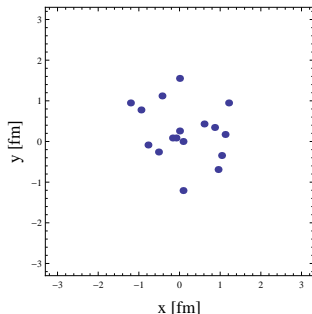
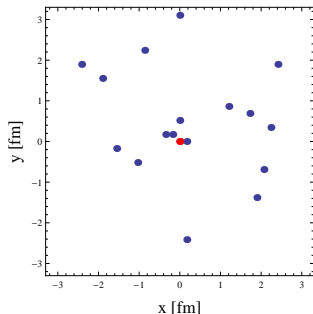
Pb+Pb: $c=60-70\% \equiv 22 \leq N_w \leq 40$, $c=70-80\% \equiv 11 \leq N_w \leq 21$



in Pb+Pb larger size than in p+Pb

Positions of sources

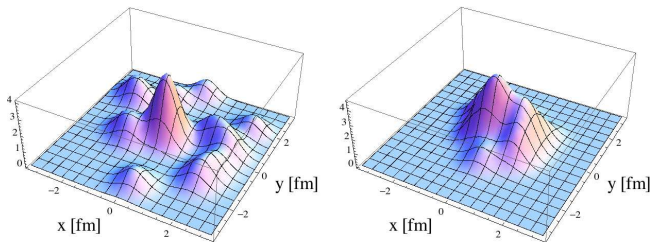
placed in the centers of the colliding nucleons or in the centers-of-mass of the colliding pairs



shrinkage by a factor of 2

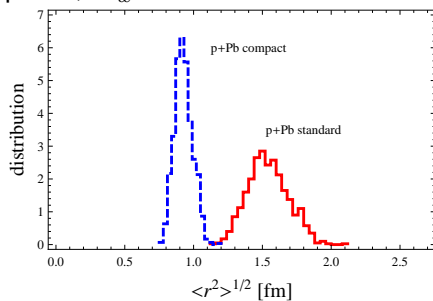
Smearing

Gaussian smearing with width 0.4 fm (physical effect)



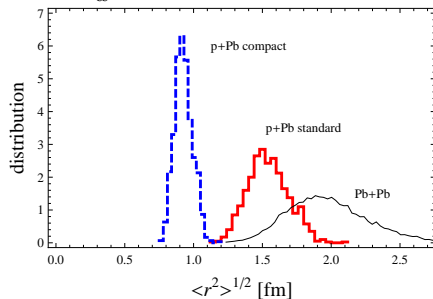
This is fed into e-by-e hydro as initial condition

Size in p+Pb

p+Pb, $N_w = 18$ 

red - centers of participants, blue - center-of-mass of colliding pairs

Size in p+Pb vs Pb+Pb

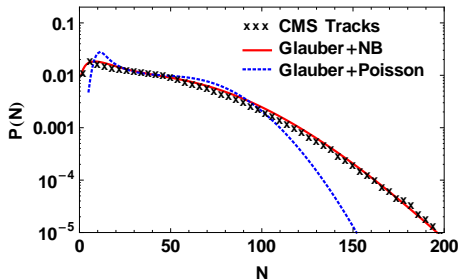
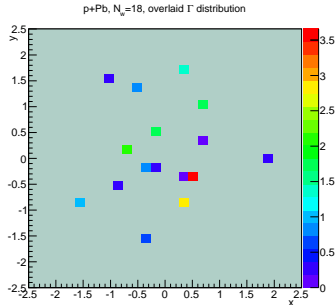
fixed $N_w = 18$ 

smaller size in p+Pb \rightarrow larger entropy density \rightarrow more rapid expansion

All in all, initial conditions in most central p+Pb not very far from peripheral Pb+Pb

Multiplicity distribution

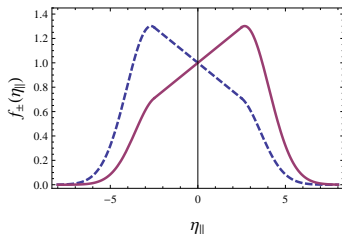
To reproduce the multiplicity distribution of the most central events in p+Pb one needs to fluctuate the strength of the Glauber sources. We overlay the Gamma distribution (Gamma + Poisson = negative binomial). At statistical hadronization Poissonian fluctuations are generated



Initial condition in spatial rapidity

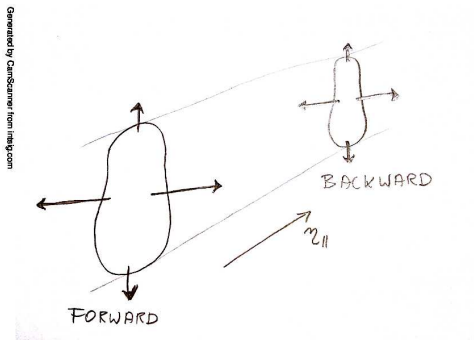
$$f(\eta_{\parallel})_{\pm} = \exp\left(-\frac{(|\eta_{\parallel}| - \eta_0)^2}{2\sigma_{\eta}^2}\theta(|\eta_{\parallel}| - \eta_0)\right) \frac{(y_b \pm \eta_{\parallel})}{y_b} \theta(y_b \pm \eta_{\parallel}),$$

$\eta_0 = 2.5$, $\sigma_{\eta} = 1.4$, $y_b = 8.58$ - beam rapidity, +/- indicates the forward/backward moving participant nucleons



[Bialas & Czyz 2005, Adil & Gyulassy 2005, Gazdzicki & Gorenstein 2006, Bzdak 2009, ...]

Assumed factorization of the transverse and longitudinal distributions



alignment of F and B event planes (can be checked experimentally)
collimation of flow at distant longitudinal separations → ridges!

Surfers - the near-side ridge

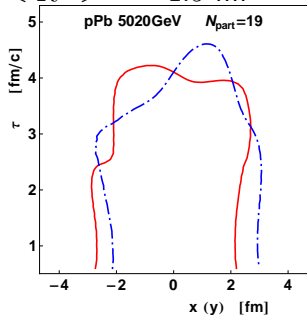


Hydrodynamics [Bożek 2011]

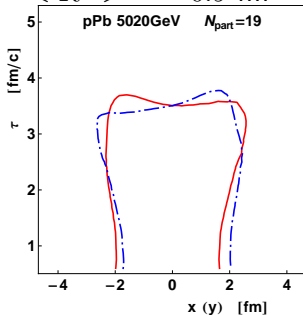
3+1 D viscous event-by-event hydrodynamics

- $\tau_{\text{init}} = 0.6 \text{ fm}/c$, $\eta/s = 0.08$ (**shear**), $\zeta/s = 0.04$ (**bulk**)
- freezeout at $T_f = 150 \text{ MeV}$
- average initial temperature in the center of the fireball
 $T_i = 242 \text{ MeV}$ ($\langle R^2 \rangle^{1/2} = 1.5 \text{ fm}$), or
 319 MeV ($\langle R^2 \rangle^{1/2} = 0.9 \text{ fm}$)
- lattice spacing of 0.15 fm (**thousands of CPU hours**)
- realistic equation of state (lattice + hadron gas [Chojnacki & Florkowski 2007]), viscosity necessary for small systems

$$\langle R^2 \rangle^{1/2} = 1.5 \text{ fm}$$



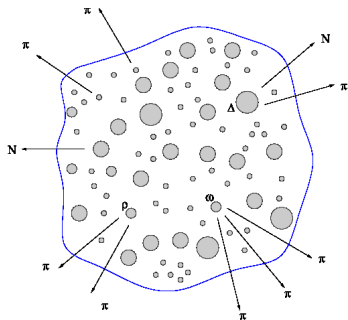
$$\langle R^2 \rangle^{1/2} = 0.9 \text{ fm}$$



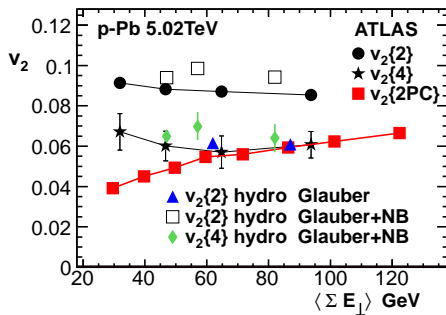
isotherms at freeze-out $T_f = 150$ MeV for two sections in the transverse plane

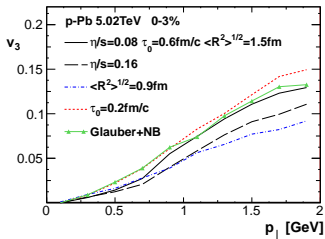
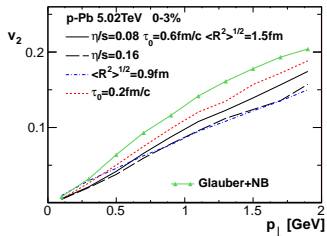
evolution lasts about 4 fm/c - shorter but more rapid than in A+A

Statistical Hadronization



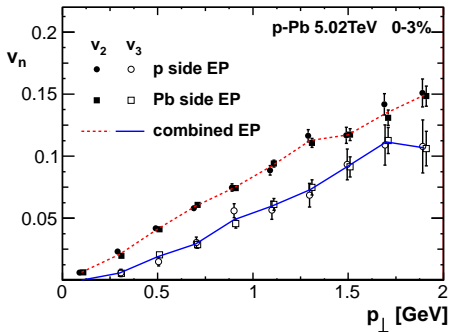
Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR), transverse-momentum conservation approximately imposed, local charge conservation included

LHC: v_2 vs ATLAS

v_2 and v_3 vs p_T 

v_2 and v_3 from the scalar-product method

[STAR 2002, Luzum & Ollitrault 2012]



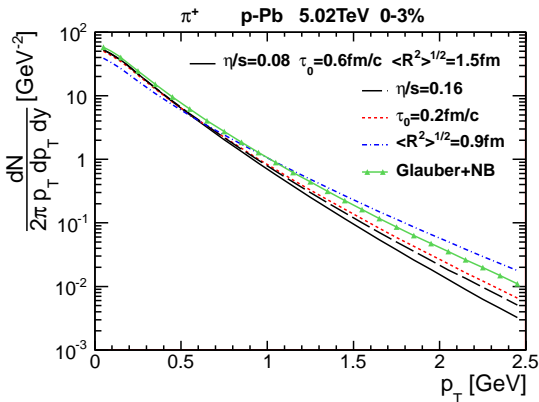
v_2 and v_3

cuts: $|\eta| < 2.5$, $0.3 < p_T < 5$ GeV
 $\langle R^2 \rangle^{1/2} = 1.5$ fm

	$c=0-3.4\%$	$c=3.4-7.8\%$
Glauber+Poisson		
$v_2\{2\}^2 [10^{-3}]$	3.70(1)	3.78(2)
$v_3\{2\}^2 [10^{-3}]$	1.04(1)	0.95(1)
$v_2\{4\}^4 [10^{-6}]$	-0.4(4)	1.83(5)
Glauber+NB		
$v_2\{2\}^2 [10^{-3}]$	8.18(12)	8.24(10)
$v_3\{2\}^2 [10^{-3}]$	1.52(8)	1.51(6)
$v_2\{4\}^4 [10^{-6}]$	15(7)	16(6)

more fluctuations \rightarrow more harmonic flow

$v_2\{4\}$ very sensitive (fluctuations)

p_T spectra of π^+ 

$\langle R^2 \rangle^{1/2} = 1.5$ fm case, $|\eta| < 2.4$:

$\langle p_T \rangle_\pi = 0.48$ GeV, $\langle p_T \rangle_K = 0.72$ GeV, $\langle p_T \rangle_p = 0.99$ GeV

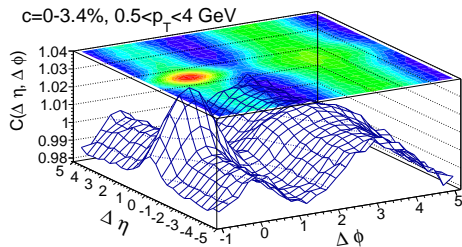
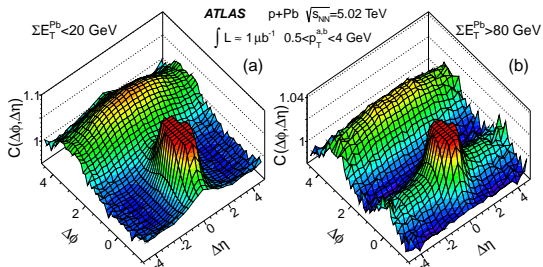
(mass ordering)

Definition of the 2D correlation function

$$C(\Delta\eta, \Delta\phi) = \frac{N_{\text{phys}}^{\text{pairs}}(\Delta\eta, \Delta\phi)}{N_{\text{mixed}}^{\text{pairs}}(\Delta\eta)} = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

(more convenient than the “per-trigger” correlations)

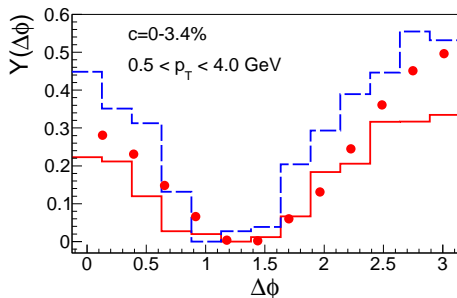
Ridge in p-Pb, ATLAS



Projection on $2 \leq |\Delta\eta| \leq 5$, ATLAS

$$Y(\Delta\phi) = \frac{\int B(\Delta\phi)d(\Delta\phi)}{N}C(\Delta\phi) - b_{ZYAM}$$

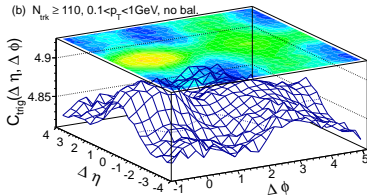
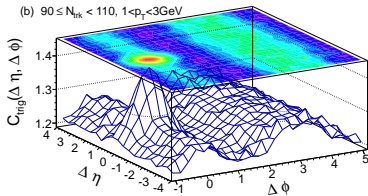
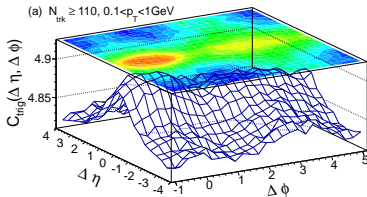
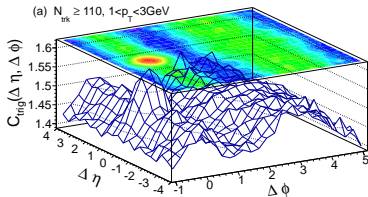
The near-side ridge from our model:



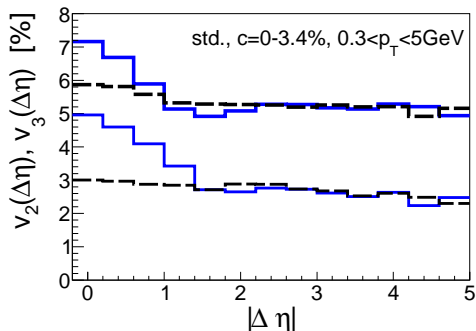
red - $\langle R^2 \rangle^{1/2} = 1.5 \text{ fm}$, blue - $\langle R^2 \rangle^{1/2} = 0.9 \text{ fm}$

[CGC-based calculation: Dusling & Venugopalan]

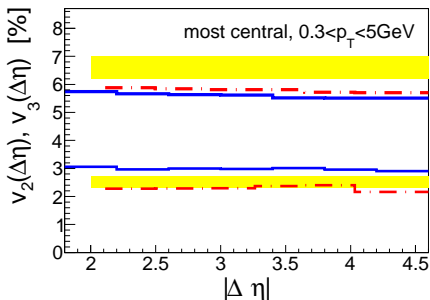
Ridge in p-Pb



Flow from correlations (two-particle cumulants)



blue - unlike-sign pairs, black - like-sign pairs ($\langle R^2 \rangle^{1/2} = 1.5 \text{ fm}$ case)

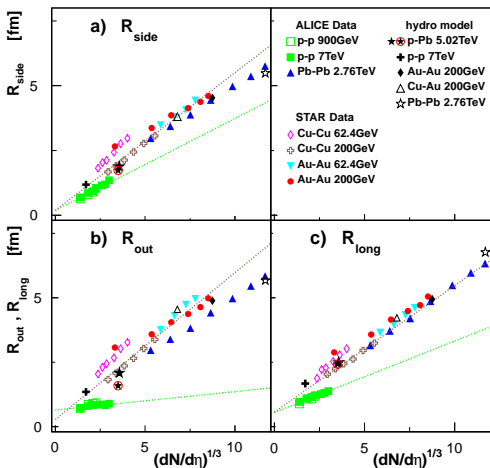
LHC: $v_n\{2, |\Delta\eta| > 2\text{GeV}\}$ vs CMStop - v_2 , bottom - v_3 

yellow - CMS

blue - standard ($\langle R^2 \rangle^{1/2} = 1.5\text{ fm}$)red - compact ($\langle R^2 \rangle^{1/2} = 0.9\text{ fm}$)

HBT radii

Interferometric radii due to Bose-Einstein correlations - measure of the size of the system at freeze-out



Conclusions

In hydro there is flow! Is there collectivity in small systems?

→ collective dynamics is compatible with high-multiplicity LHC data for p-Pb

- v_n coefficients measured in p-Pb reproduced semiquantitatively
- Model 2-D correlations exhibit the two ridges, in particular the near-side ridge (“surfers”)
- Interferometric radii for p+Pb are close to the A+A line, away from the p+p line - way to distinguish, will be verified shortly by ALICE
- Other effects (jets, corona, ...)
- p+p, other approaches
- Other models of the initial collision [Bzdak et al. 2013, CGC+hydro]