

# 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
- Werner, Karpenko, Pierog 2010: ridge in p+p
- Ridges discovered experimentally 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:

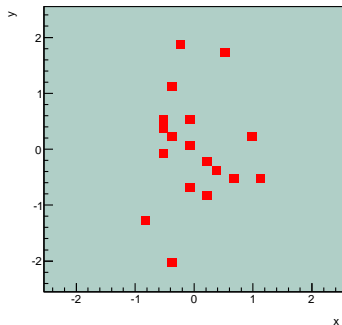
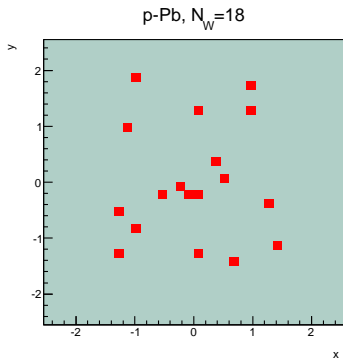
**Are the central p-Pb collisions collective?**

What is the nature of the initial state?

What are the limits/conditions on applicability of hydrodynamics?

## Snapshots of initial Glauber condition in central p+Pb

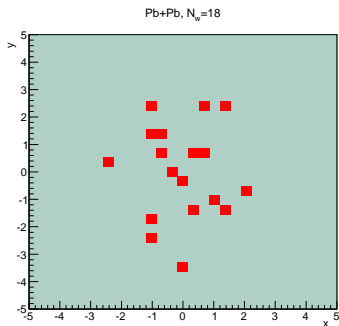
Typical transverse-plane configuration of centers of the participant nucleons in a p+Pb collision generated with GLISSANDO  
5% of collisions have more than 18 participants, rms  $\sim 1.5$  fm – quite large!



## 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

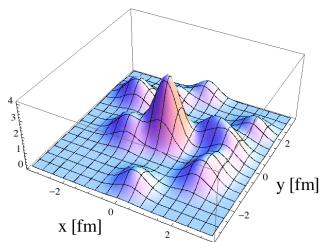
Pb+Pb:  $c=60-70\% \equiv 22 \leq N_w \leq 40$ ,  $c=70-80\% \equiv 11 \leq N_w \leq 21$



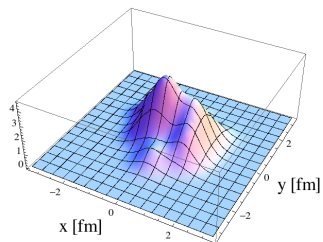
in Pb+Pb somewhat larger size than in p+Pb

## Smearing

Gaussian smearing with width 0.4 fm (physical effect)



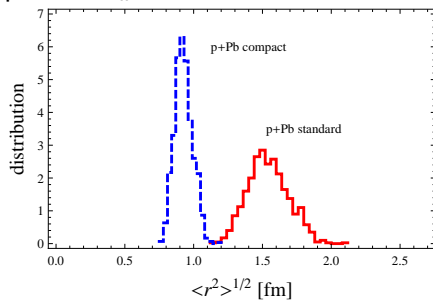
standard



compact

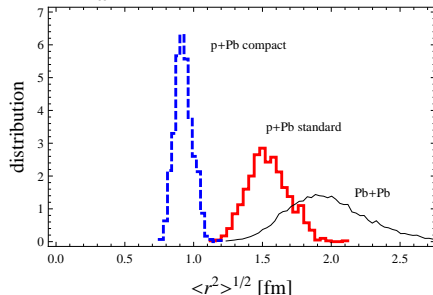
This is fed into e-by-e hydro as initial condition

## 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  $N_w = 18$ 

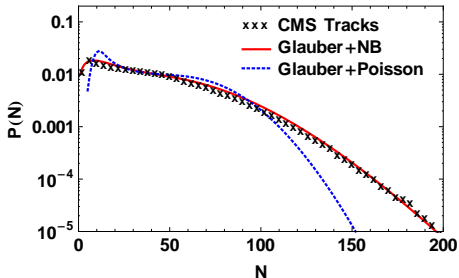
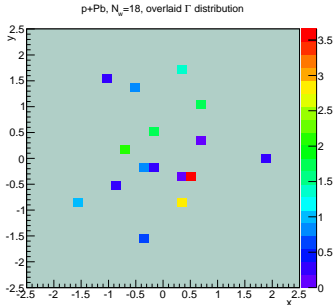
smaller size in p+Pb  $\rightarrow$  larger entropy density  $\rightarrow$  more rapid expansion

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

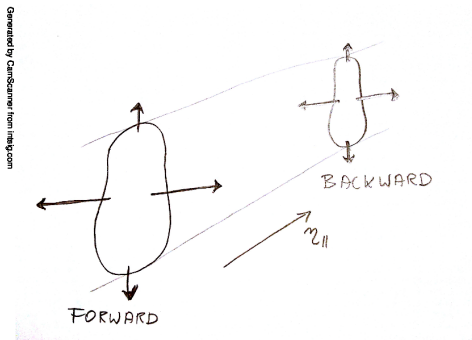


## Multiplicity distribution

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



## 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

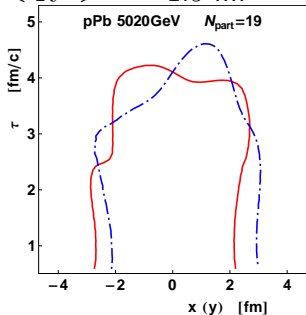


## Hydrodynamics [Bożek 2011]

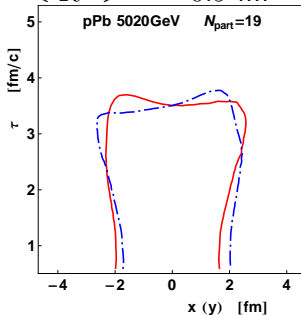
### 3+1 D viscous event-by-event hydrodynamics

- $\tau_{\text{init}} = 0.6 \text{ fm}/c$ ,  $\eta/s = 0.08$  (**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  
 $319 \text{ MeV}$  ( $\langle R^2 \rangle^{1/2} = 0.9 \text{ fm}$ ) – adjusted to fit multiplicity
- realistic equation of state (lattice + hadron gas [Chojnacki & Florkowski 2007]), viscosity necessary for small systems
- lattice spacing of  $0.15 \text{ fm}$  (**thousands of CPU hours**)

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



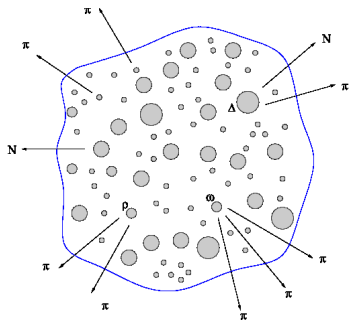
$$\langle R^2 \rangle^{1/2} = 0.9 \text{ fm}$$



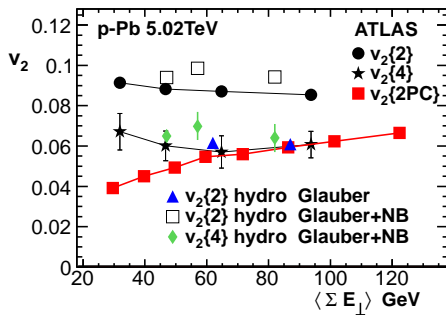
isotherms at freeze-out  $T_f = 150$  MeV for two sections in the transverse plane

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

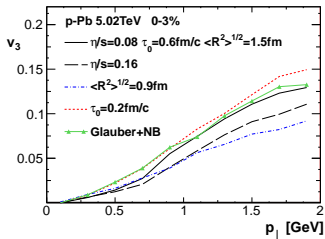
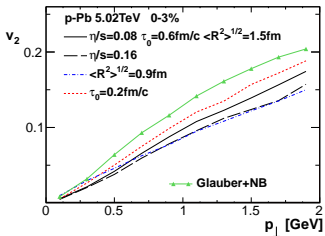
## Statistical Hadronization



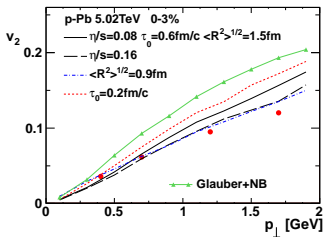
Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR), transverse-momentum conservation approximately imposed, local charge conservation included

LHC:  $v_2$  vs ATLAS

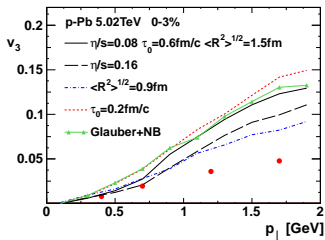
# $v_2\{2\}$ and $v_3\{2\}(p_T)$ vs CMS data





$v_2\{2\}$  and  $v_3\{2\}$  vs  $p_T$ 

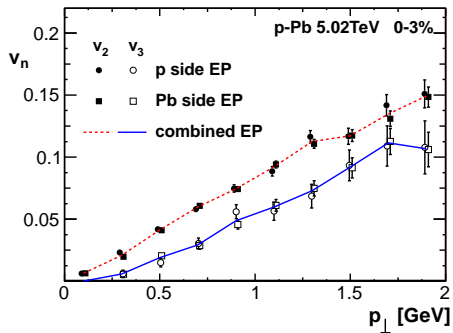
Red dots: CMS



(even too much flow)

## $v_2$ 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

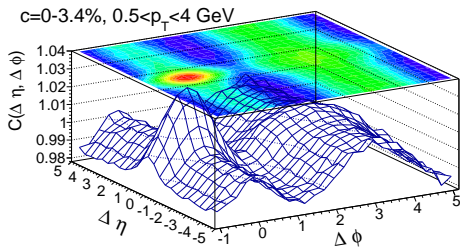
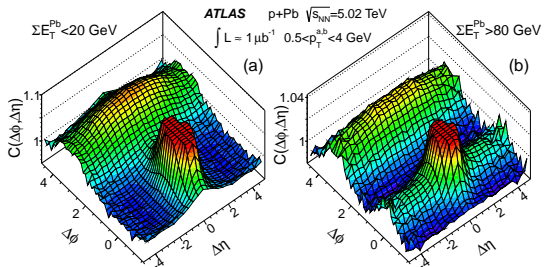
$v_2\{4\}$  very sensitive (fluctuations)

## 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)

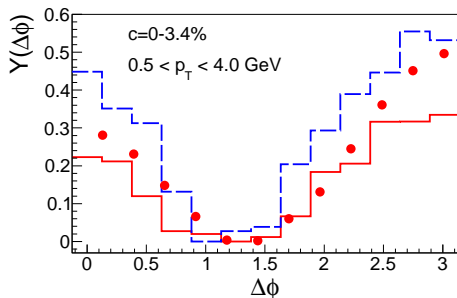
## Ridge in p-Pb, ATLAS



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

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

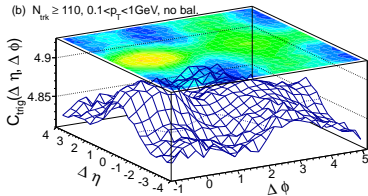
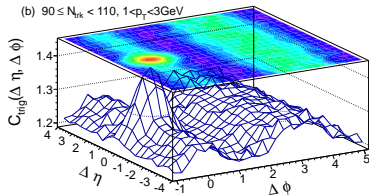
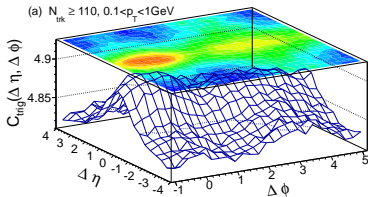
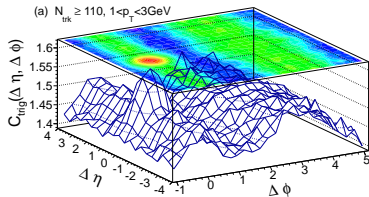
The near-side ridge from our model:



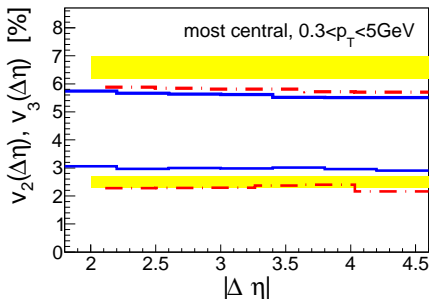
red -  $\langle R^2 \rangle^{1/2} = 1.5 \text{ fm}$ , blue -  $\langle R^2 \rangle^{1/2} = 0.9 \text{ fm}$

[CGC-based calculation: Dusling & Venugopalan]

## Ridge in p-Pb



## Flow from correlations (two-particle cumulants)

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

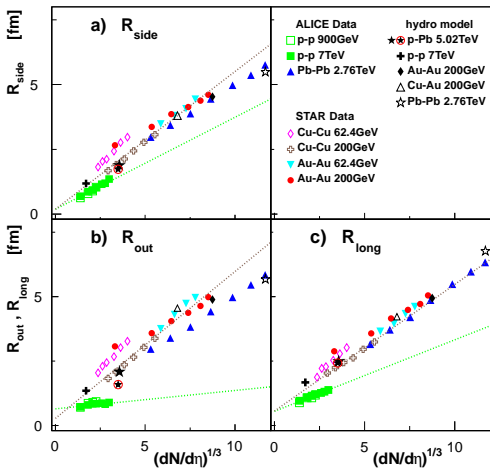
yellow - CMS

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

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 –  $v_3$  large
- Model 2D correlations exhibit the two ridges, in particular the near-side ridge (hydro → “surfers”) [flow  $\equiv$  near-side ridge!]
- Interferometric radii for p+Pb are close to the A+A line, far from the p+p line - way to distinguish, should be verified shortly by ALICE
- Other effects (jets, core-corona, ...) – not included
- p+p [Bozek, Werner et al.] – needs structure of the proton
- Yet other models of the initial collision [Bzdak et al. 2013 – CGC+hydro]