Hydrodynamics of 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 → hydro → statistical hadronization

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

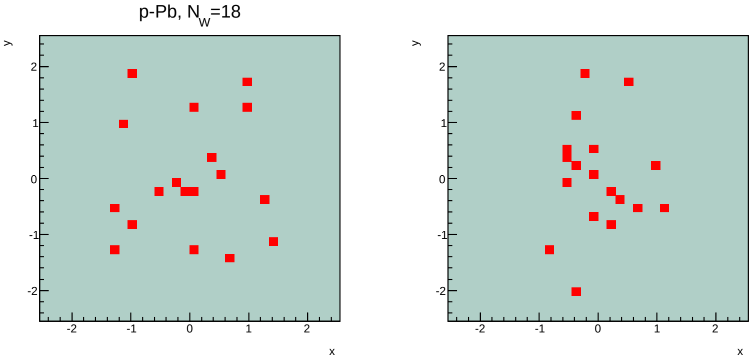
Main questions:

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

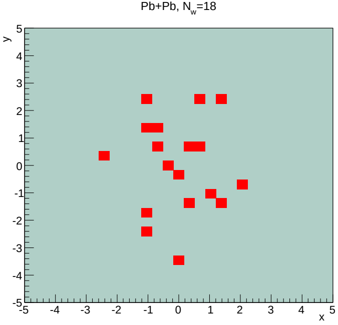
Typical transverse-plane configuration of centers of the participant nucleons in a p+Pb collision generated with GLISSANDO
5% of collisions have more than 18 participants, rms ~ 1.5 fm – large!



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

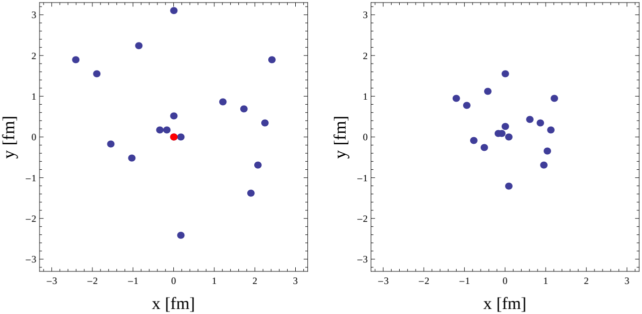
Pb+Pb: c=60-70% $\equiv 22 \leq N_w \leq 40$, c=70-80% $\equiv 11 \leq N_w \leq 21$



in Pb+Pb larger size than in p+Pb

Positions of sources

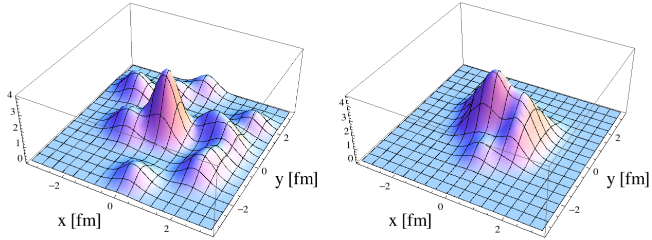
placed in the centers of the colliding nucleons or in the centers-of-mass of the colliding pairs



shrinkage by a factor of 2

Smearing

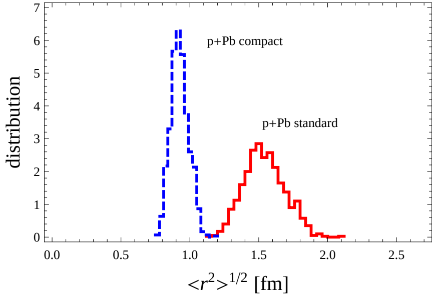
Gaussian smearing with width 0.4 fm (physical effect)



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

Size in p+Pb

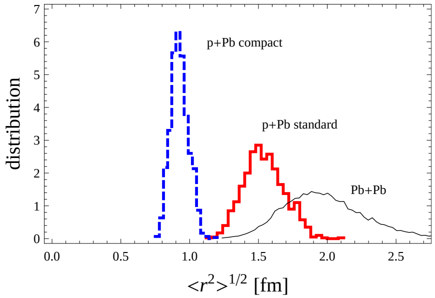
p+Pb, $N_w = 18$



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

Size in p+Pb vs Pb+Pb

fixed $N_w = 18$

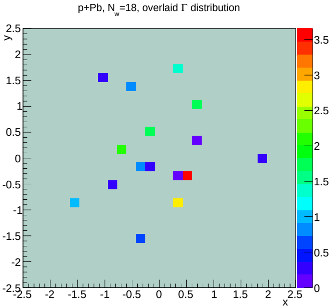


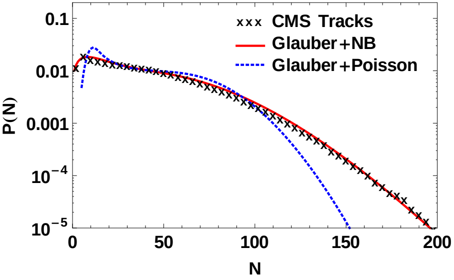
smaller size in p+Pb $\rightarrow$ larger entropy density $\rightarrow$ more rapid expansion

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

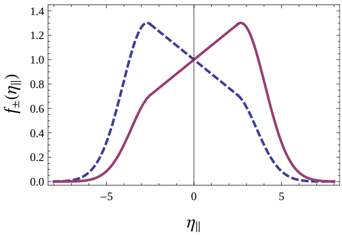




Initial condition in spatial rapidity

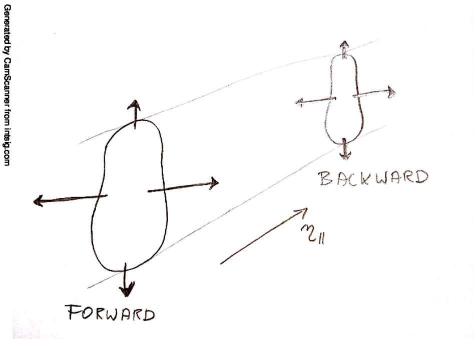
$$f(\eta_\parallel)_\pm \quad = \quad \exp\left(-\frac{(|\eta_\parallel| - \eta_0)^2}{2\sigma_\eta^2}\theta(|\eta_\parallel| - \eta_0)\right) \frac{(y_b \pm \eta_\parallel)}{y_b}\theta(y_b \pm \eta_\parallel),$$

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



[Bialas & Czyż 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!

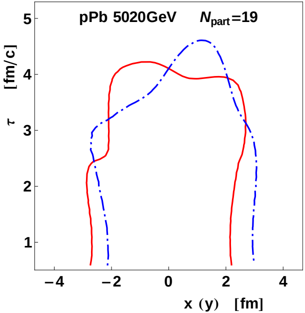
Surfers - the near-side ridge

Hydrodynamics [Bożek 2011]

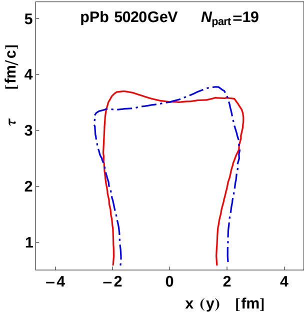
3+1 D viscous event-by-event hydrodynamics

- $\tau_{\text{init}} = 0.6$ fm/c, $\eta/s = 0.08$ (**shear**), $\zeta/s = 0.04$ (**bulk**)
- freezeout at $T_f = 150$ MeV
- average initial temperature in the center of the fireball $T_i = 242$ MeV ($< R^2 >^{1/2} = 1.5$ fm), or 319 MeV ($< R^2 >^{1/2} = 0.9$ 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

$< R^2 >^{1/2} = 1.5$ fm



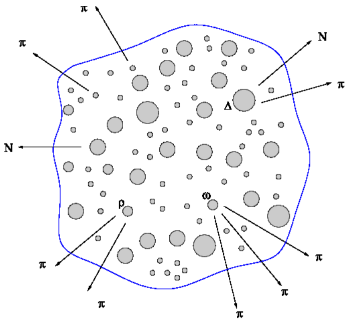
$< R^2 >^{1/2} = 0.9$ fm



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

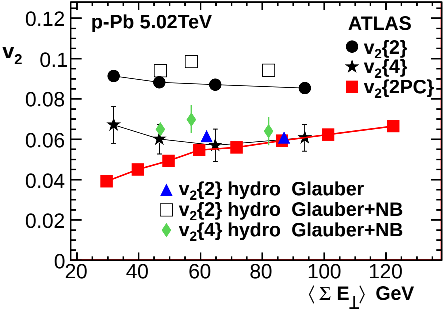
evolution lasts about 4 fm/c - shorter but more rapid than in A+A

Statistical Hadronization

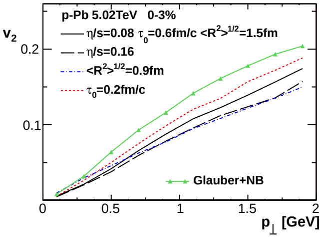


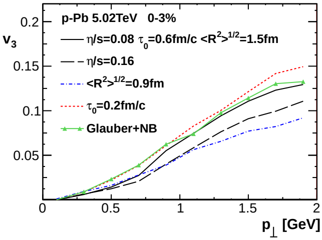
Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR), transverse-momentum conservation approximately imposed, local charge conservation included

LHC: v_2 vs ATLAS



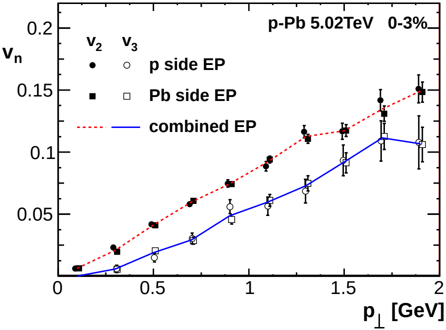
v_2 and v_3 vs p_T





v_2 and v_3 from the scalar-product method

[STAR 2002, Luzum & Ollitrault 2012]



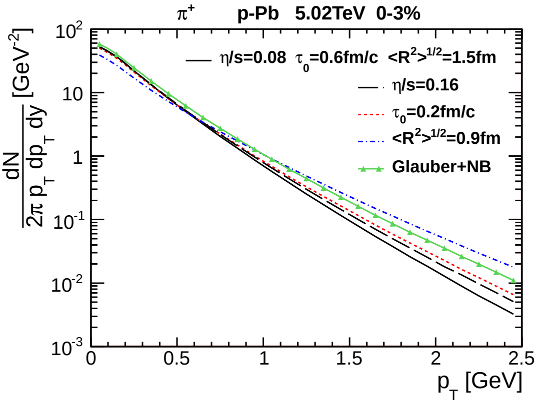
v_2 and v_3

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



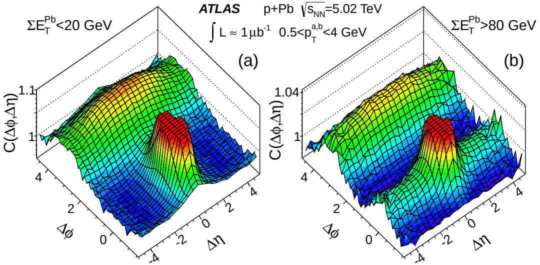
$< R^2 >^{1/2} = 1.5$ fm case, $|\eta| < 2.4$:
$< p_T >_\pi = 0.48$ GeV, $< p_T >_K = 0.72$ GeV, $< p_T >_p = 0.99$ GeV (mass ordering)

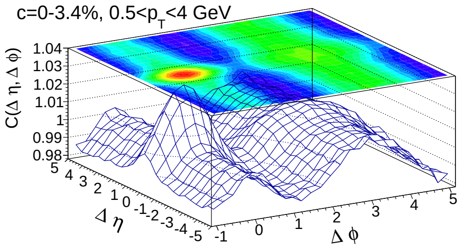
Definition of the 2D correlation function

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

(more convenient than the "per-trigger" correlations)

Ridge in p-Pb, ATLAS

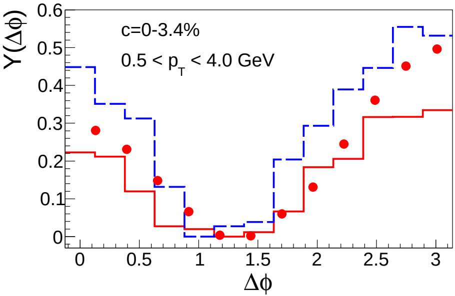




Projection on $2 \leq |\Delta\eta| \leq 5$, ATLAS

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

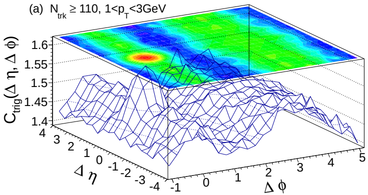
The near-side ridge from our model:

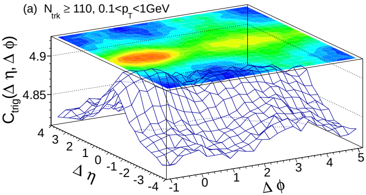


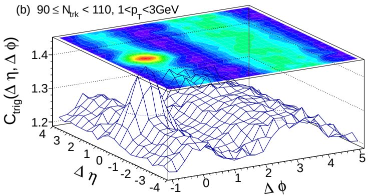
red - $< R^2 >^{1/2} = 1.5$ fm, blue - $< R^2 >^{1/2} = 0.9$ fm

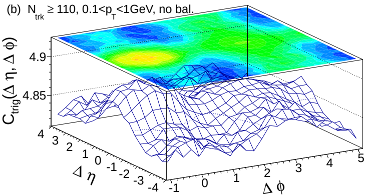
[CGC-based calculation: Dusling & Venugopalan]

Ridge in p-Pb

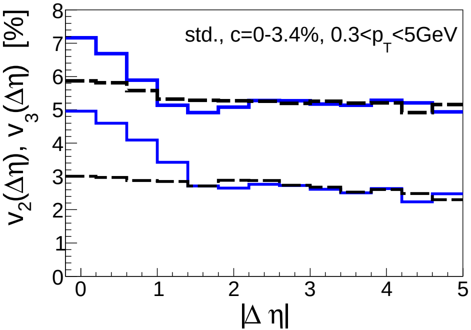

(a) $N_{trk} \geq 110$, $1<p_T<3$GeV
$C_{trig}(\Delta\eta, \Delta\phi)$
1.6
1.55
1.5
1.45
1.4
$\Delta\eta$
$\Delta\phi$


(a) $N_{trk} \geq 110$, $0.1<p_T<1$GeV
$C_{trig}(\Delta\eta, \Delta\phi)$
4.9
4.85
$\Delta\eta$
$\Delta\phi$


(b) $90 \leq N_{trk} < 110$, $1<p_T<3$GeV
$C_{trig}(\Delta\eta, \Delta\phi)$
1.4
1.3
1.2
$\Delta\eta$
$\Delta\phi$


(b) $N_{trk} \geq 110$, $0.1<p_T<1$GeV, no bal.
$C_{trig}(\Delta\eta, \Delta\phi)$
4.9
4.85
$\Delta\eta$
$\Delta\phi$

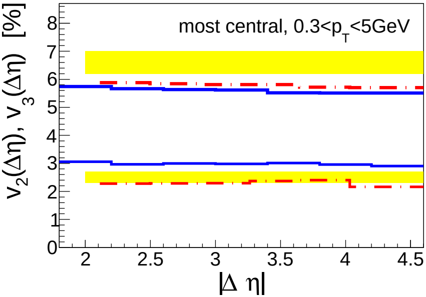
Flow from correlations (two-particle cumulants)



blue - unlike-sign pairs, black - like-sign pairs ($< R^2 >^{1/2} = 1.5$ fm case)

LHC: $v_n\{2, |\Delta\eta| > 2\text{GeV}\}$ vs CMS

top - v_2, bottom - v_3



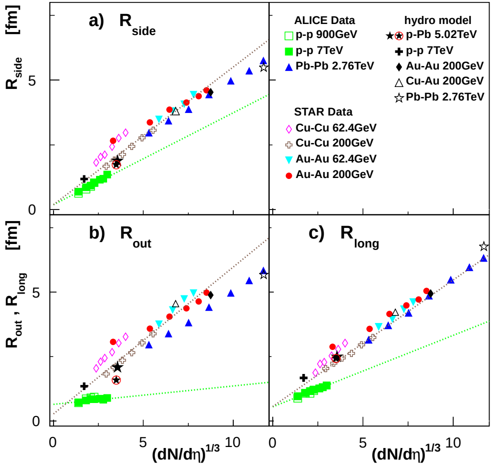
yellow - CMS

blue - standard ($< R^2 >^{1/2} = 1.5$ fm)

red - compact ($< R^2 >^{1/2} = 0.9$ 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]