

Collective dynamics of the p-Pb collisions at the LHC

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and PB+WB+G. Torrieri, arXiv:1307.5060]

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 (v_n), in correlation data (**ridges**), in **mass hierarchy** of p_T spectra and v_n of identified particles, in certain features of interferometry (femtoscopy), ...

- Ridges found experimentally at the LHC in small systems, p+Pb and p+p (high-multiplicity events)
- Large elliptic and triangular flow measured in p+Pb
- Mass hierarchy recently found in p+A

Collectivity in small systems?

Main questions:

Are the central p-Pb collisions collective?

What is the nature of the initial state and correlations therein?

What are the limits/conditions on applicability of hydrodynamics?

Other analyses of collectivity in small systems:

Romatschke, Luzum, arXiv:0901.4588, Prasad et al., arXiv:0910.4844,
Bozek, arXiv:0911.2393, Werner et al., arXiv:1010.0400,
Deng, Xu, Greiner, arXiv:1112.0470, Yan et al., arXiv: 0912.3342,
Bozek, arXiv:1112.0912 Shuryak, Zahed, arXiv:1301.4470,
Bzdak et al., arXiv:1304.3403, Qin, Müller, arXiv:1306.3439,
Werner et al., arXiv:1307.4379

3-stage approach

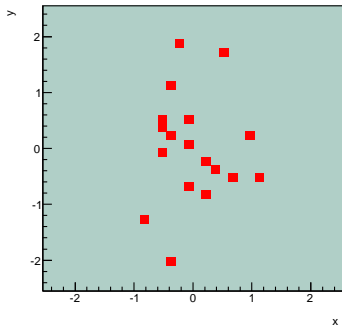
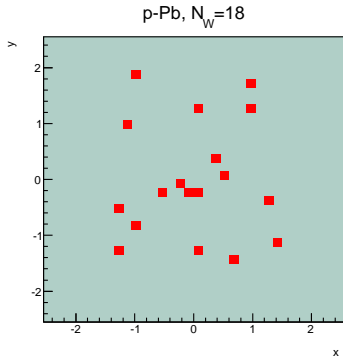
Our three-phase approach: initial \rightarrow hydro \rightarrow statistical hadronization (successful in description of A+A collisions)

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

The transverse size in central p+Pb

A typical transverse-plane configuration of the participant nucleons in a p+Pb collision generated with GLISSANDO

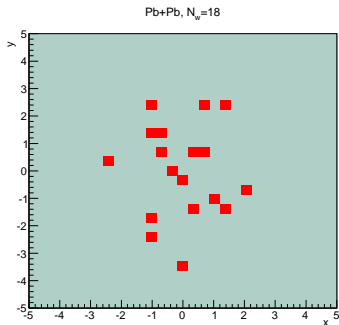
5% of collisions have more than 18 participants, $r_{ms} \sim 1.5$ fm – quite large!



Snapshot of peripheral Pb+Pb

5% most central values of N_w in p-Pb fall between the 60-70% and 70-80% centrality class in Pb+Pb

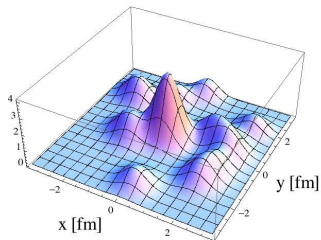
Pb+Pb: $c=60-70\% \equiv 22 \leq N_w \leq 40$, $c=70-80\% \equiv 11 \leq N_w \leq 21$



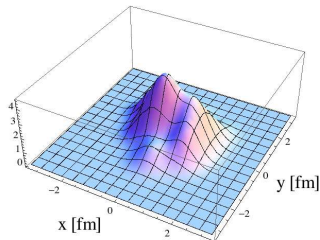
in Pb+Pb somewhat larger size than in p+Pb (all for $N_w = 18$)

Smearing

Gaussian smearing with width 0.4 fm (physical effect)



two variants: standard
(sources at centers of participants)

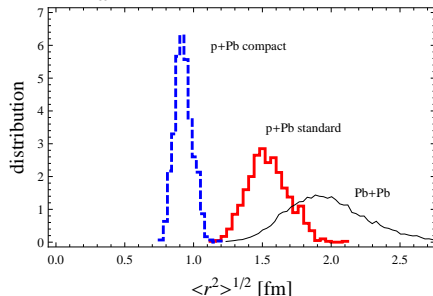


compact
(sources at centers-of-mass of pairs)

Such transverse entropy profiles are fed into e-by-e hydro as initial conditions

Size in p+Pb vs Pb+Pb

fixed $N_w = 18$



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

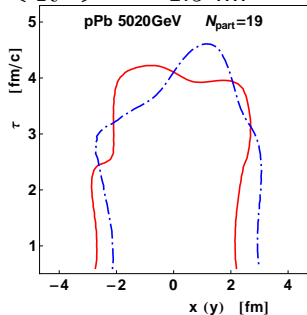
All in all, initial conditions in most central p+Pb not very far from peripheral Pb+Pb

Hydrodynamics [Božek 2011]

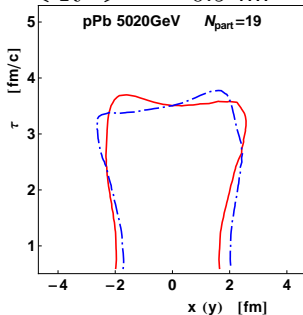
3+1 D viscous event-by-event hydrodynamics (viscous corrections essential due to large gradients)

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

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



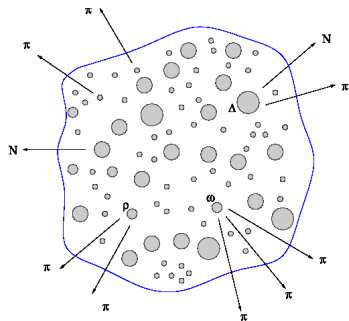
$$\langle R^2 \rangle^{1/2} = 0.9 \text{ fm}$$



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

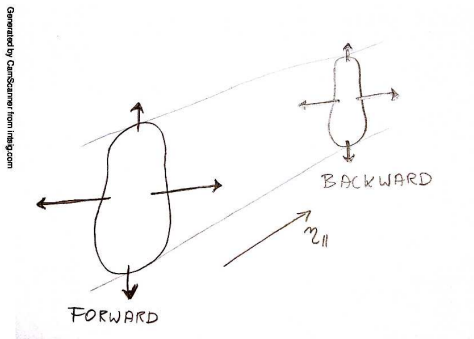
evolution lasts about 4 fm/c - shorter but more rapid than in A+A

Statistical Hadronization



Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR)

Factorization of the transverse and longitudinal distributions



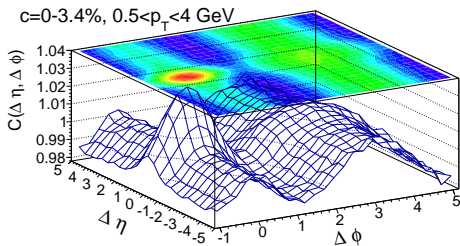
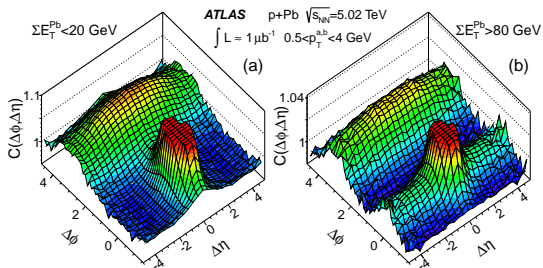
alignment of F and B event planes (can be checked experimentally)
 collimation of flow at distant longitudinal separations → ridges!

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)

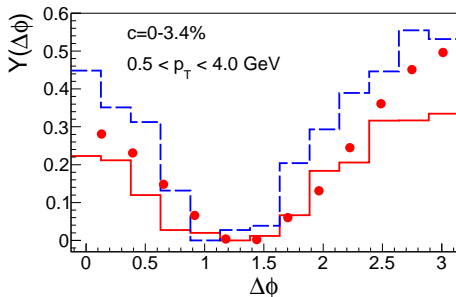
Ridge in p-Pb, ATLAS



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

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

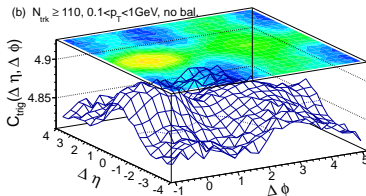
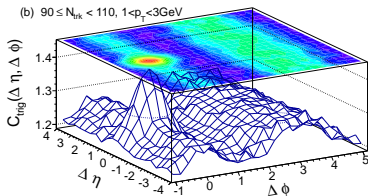
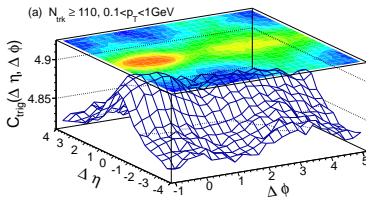
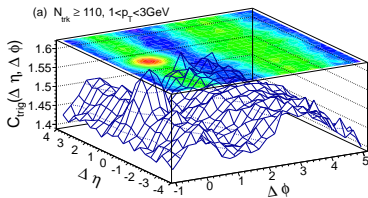
The near-side ridge from our model:



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

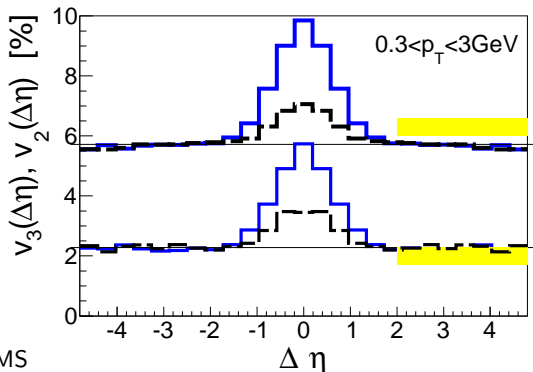
[CGC: Dusling, Venugopalan, arXiv:1210.3890, 1211.3701, 1302.7018]

Ridge in p-Pb



Flow from correlations (two-particle cumulants, η gap)

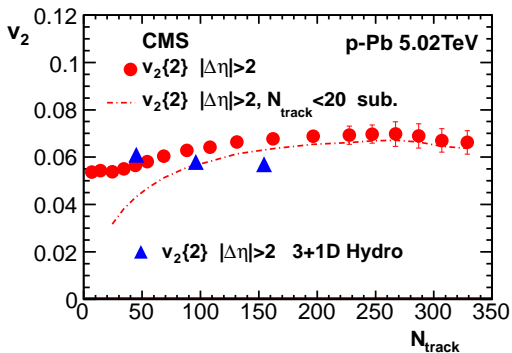
$$v_n\{2, |\Delta\eta| > 2\text{GeV}\}$$

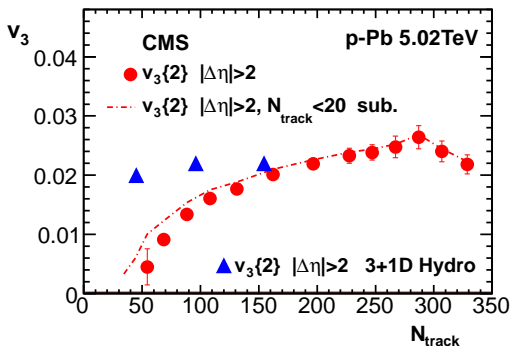


bands - CMS

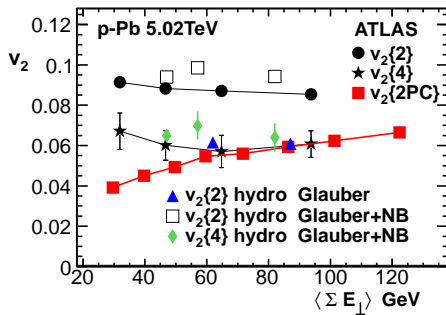
same-sign pairs, **opposite-sign pairs**

(compact source: $\langle R^2 \rangle^{1/2} = 0.9$ fm, $\langle N_{\text{trk}} \rangle = 154.5$)

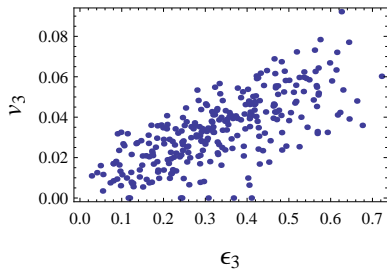
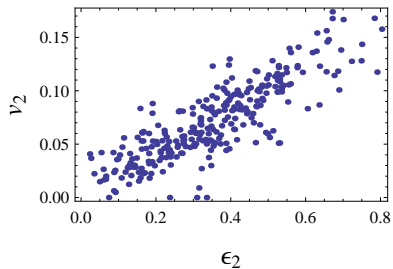
v_2 vs CMS

v_3 vs CMS

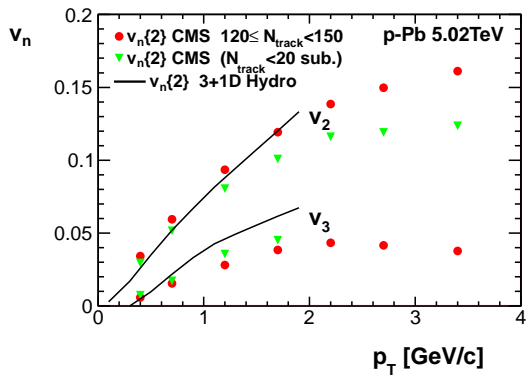
v_3 too large for peripheral collisions → limit of validity of the model

LHC: v_2 vs ATLAS

Digression: eccentricity \rightarrow flow

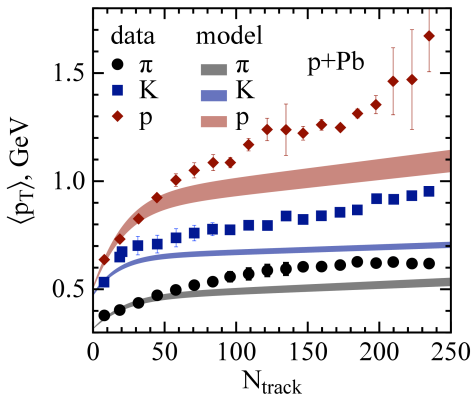


larger fluctuations in the initial distribution \rightarrow larger flow

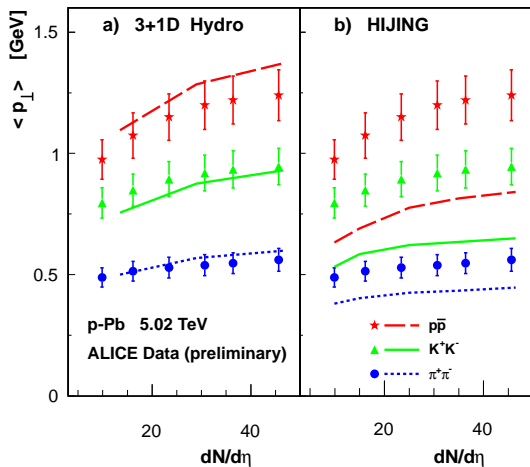
v_2, v_3 VS p_T 

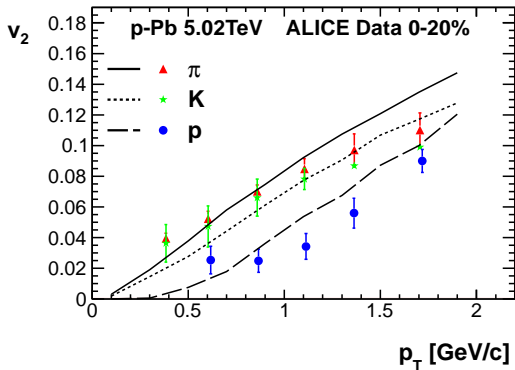
Identified spectra

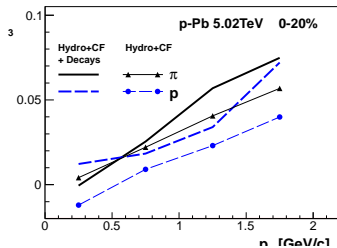
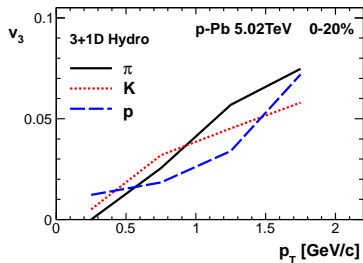
Linear superposition not enough!



[Bzdak, Skokov, arXiv:1306.5442: Wounded Nucleon Model with experimental pp data at 7 TeV]

Identified $\langle p_T \rangle$ 

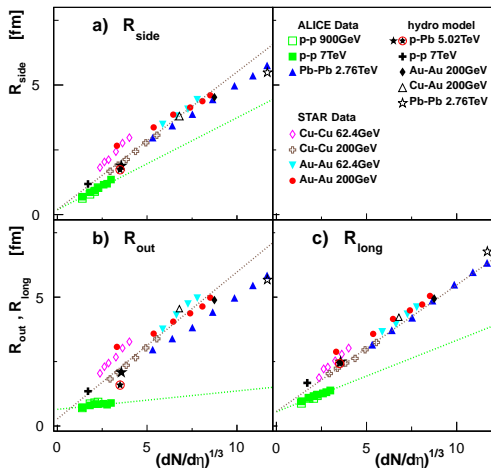
Identified v_2 

Identified v_3 

Resonance decays affect the mass ordering!

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 soft data for p-Pb

- Large v_2 and v_3 coefficients measured in p-Pb reproduced, including the p_T dependence
- Model 2D correlations exhibit the two ridges, in particular the near-side ridge (hydro → “surfers”) [flow \equiv near-side ridge!]
- Mass ordering in $\langle p_T \rangle$ and flow coefficients reproduced
- Model predictions for the interferometric radii for p+Pb are closer to the A+A line, farther from the p+p line - way to distinguish
- Numerous effects should still be incorporated (jets, core-corona, ...), more important for the lower-multiplicity events