Flow in p-Pb collisions at the LHC

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[**Piotr Bożek** & WB,
PRL **109** (2012) 062301, PLB 718 (2013) 1557, arXiv:1301.3314]

Signatures of sQGP

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

- Collective flow
- Jet quenching

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

3-stage approach

Our approach ("Standard Model of heavy-ion collisions"):
initial $\rightarrow$ hydro $\rightarrow$ statistical hadronization

- **Initial phase** - "geometric"
- **Hydrodynamics** - 3+1 D viscous event-by-event
- **Statistical hadronization**

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What are the limits on applicability of hydrodynamics?

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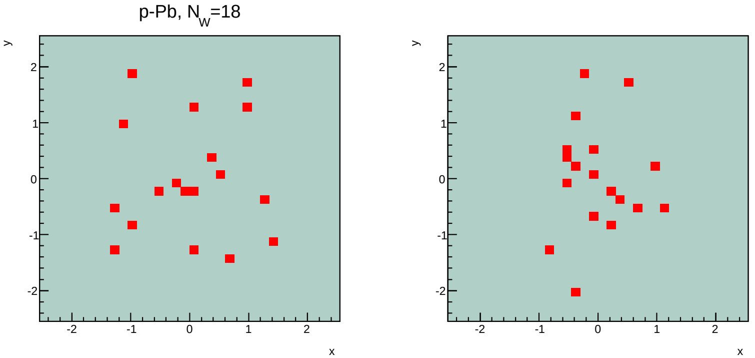
p-Pb collisions used to "prove" the CGC scenario [Dusling & Venugopalan '12]

Glauber approach

Typical configuration of participant nucleons from Pb nucleus in the transverse plane generated with GLISSANDO
3% of collisions have more than 18 participants, rms ~ 1.5 fm – large!



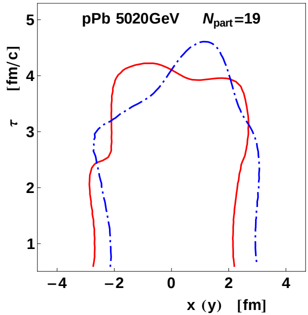
Hydrodynamics [Bożek 2011]

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**), $T_f = 150$ MeV

Initial temperature in the center of the fireball $T_i = 242$ MeV, lattice spacing 0.15 fm (**thousands of CPU hours**)

Realistic equation of state (lattice + hadron gas [Chojnacki & Florkowski, 2007]), viscosity necessary for small systems

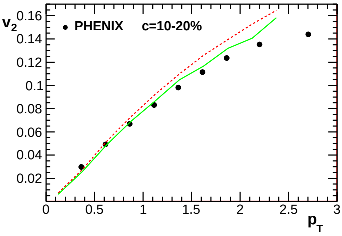


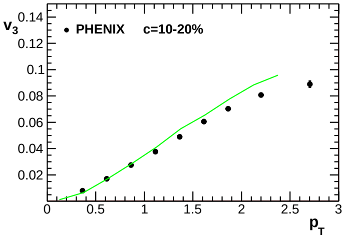
isotherms at freeze-out $T_f = 150$ MeV for two sections in the transverse plane

Some results for p+Au at RHIC

sample results → the method works for one-body observables in the soft domain (transverse-momentum and rapidity spectra, ...)

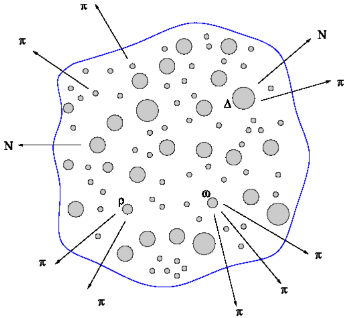
Below: elliptic and triangular flow [Bożek 2011]





solid: e-by-e, dashed: averaged initial condition

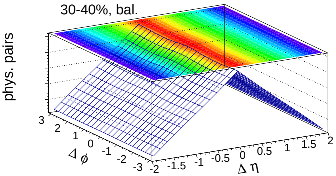
Statistical Hadronization

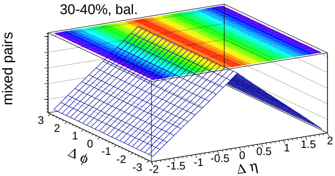


Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR), transverse-momentum conservation approximately imposed, local charge conservation included

Definition

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





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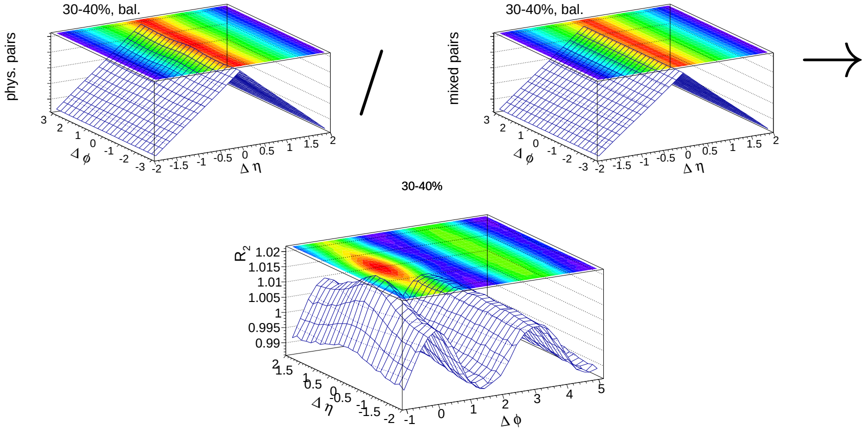
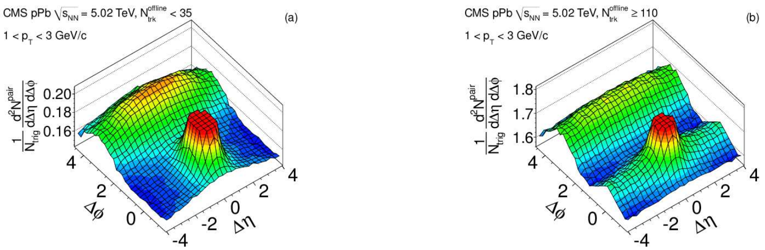


Sources of correlations

- jets → central peak (same jet), away-side ridge (back-to-back jets)
- collective harmonic flow → near- and away-side ridges
- charge balancing → central peak, shape of the near-side ridge
- resonance decays → away-side ridge
- Bose-Einstein → central peak
- Coulomb, final-state, ...

p-Pb from CMS, 5.02 TeV

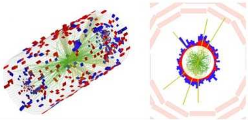


(released in October 2012)
"Observation of long-range near-side angular correlations in proton-lead collisions at the LHC", CMS Collaboration

Physics World

Unexpected 'ridge' seen in CMS collision data again

Oct 31, 2012 6 comments



p-Pb collision event display, CMS

The first data from proton–lead collisions at the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN include a "ridge" structure in correlations between newly generated particles. According to theorists in the US, the ridge may represent a new form of matter known as a "colour glass condensate".

This is not the first time such correlations have been seen in collision remnants – in 2005, physicists working on the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory in New York found that the particles generated in collisions of gold nuclei had a tendency to spread transversely from the beam at very small relative angles, close to zero. A similar correlation was seen in 2010 at CMS in proton–proton collisions and then later that year in lead–lead collisions. (See image below, parts *a* and *b*.)

Observing ridges

When a graph is plotted of the fraction of particles versus the relative transverse emission angle and the relative angle to the beam axis, the correlation appears as a distinct ridge. Now, this ridge has been seen in proton–lead collisions for the first time – within a week of data collection at CMS (see image below, part *c*) (arXiv:1210.5482).

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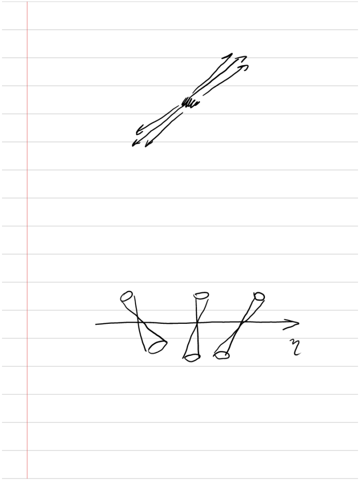
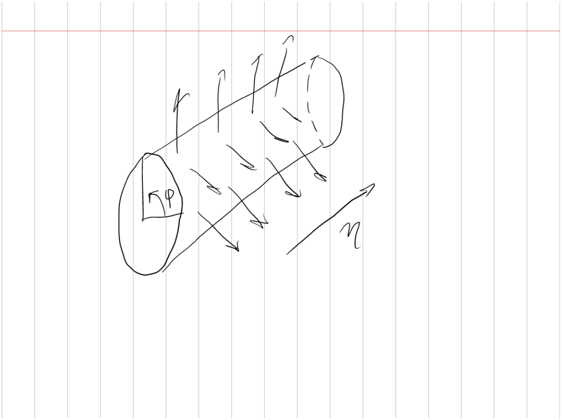
Jet kinematics



pair from the same jet $\to$
$\Delta\phi \sim 0$, $\Delta\eta \sim 0$

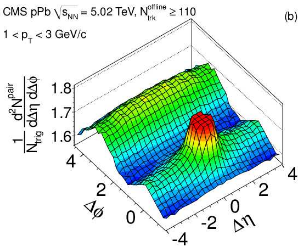
pair from back-to-back jets $\to$
$\Delta\phi \sim \pi$, $\Delta\eta$ smeared

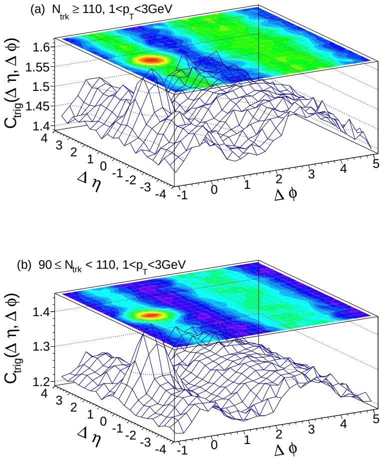
Flow kinematics



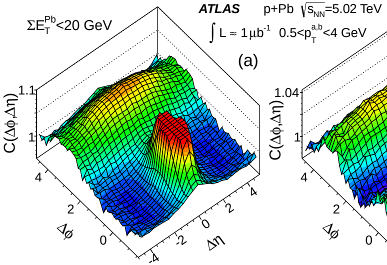
ridges at $\Delta\phi \sim 0$ and $\Delta\phi \sim \pi$, insensitive to $\Delta\eta$

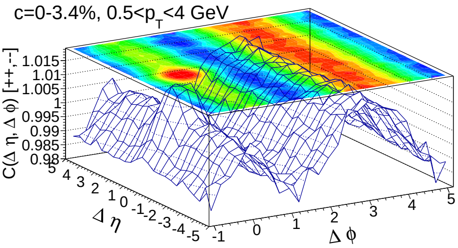
Ridge in p-Pb, CMS





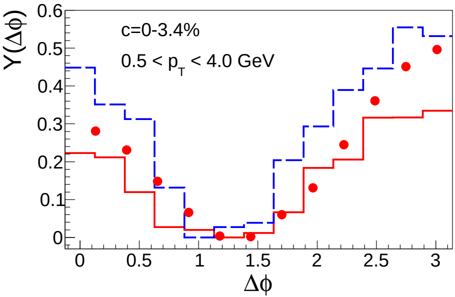
Ridge in p-Pb, ATLAS





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

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



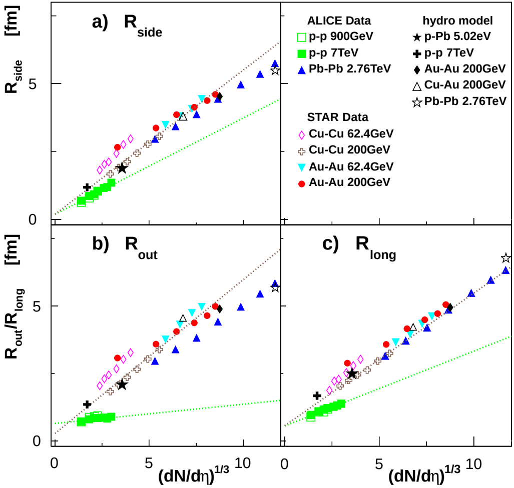
Two variants:

red - standard Glauber-model (sources at centers of participants)

blue - “compact” (sources at center-of mass points)

HBT radii

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



Conclusions

- E-by-e hydro in semi-quantitative agreement with the (soft) data for 2-particle 2D correlations from RHIC and LHC for A-A and p-A collisions
- Hydrodynamic explanation of the same-side ridge in p-Pb

  $\rightarrow$ **collective behavior in high-multiplicity p-Pb systems**
- Hydro: interferometric radii for p-Pb on the A-A line, away from the p-p line - way to distinguish
- Data on interferometric radii for p-Pb expected shortly