Flow in p-Pb collisions at the LHC

Wojciech Broniowski

IFJ PAN Cracow & UJK Kielce

Excited QCD 2013, Bjelašnica, 3-8 February 2013

[Piotr Bożek & WB,
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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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 $\sim 1.5$ fm – large!

\[ \text{p-Pb, } N_w = 18 \]
Hydrodynamics [Bożek 2011]

3+1 D viscous event-by-event hydrodynamics

\[ \tau_{\text{init}} = 0.6 \text{ fm/c}, \; \eta/s = 0.08 \text{ (shear)}, \; \zeta/s = 0.04 \text{ (bulk)}, \; T_f = 150 \text{ MeV} \]

Initial temperature in the center of the fireball \( T_i = 242 \text{ MeV} \), 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

\( T_f = 150 \text{ MeV} \) for two sections in the transverse plane

\[ \text{pPb 5020GeV} \quad N_{\text{part}} = 19 \]
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 via Frye-Cooper formula + resonance decays (THERMINATOR), transverse-momentum conservation approximately imposed, local charge conservation included.
Definition

\[ C(\Delta \eta, \Delta \phi) = \frac{N^\text{pairs}_{\text{phys}}(\Delta \eta, \Delta \phi)}{N^\text{pairs}_{\text{mixed}}(\Delta \eta)} \]
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Sources of correlations

- jets $\rightarrow$ central peak (same jet), away-side ridge (back-to-back jets)
- collective harmonic flow $\rightarrow$ near- and away-side ridges
- charge balancing $\rightarrow$ central peak, shape of the near-side ridge
- resonance decays $\rightarrow$ away-side ridge
- Bose-Einstein $\rightarrow$ 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
Unexpected 'ridge' seen in CMS collision data again

Oct 31, 2012 15 comments

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).
Jet kinematics

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

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

ridges at $\Delta \phi \sim 0$ and $\Delta \phi \sim \pi$, insensitive to $\Delta \eta$
Ridge in p-Pb, CMS

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{ch}} \geq 110$

(a) $N_{\text{trk}} \geq 110, 1 < p_T < 3$ GeV/c

(b) $90 \leq N_{\text{trk}} < 110, 1 < p_T < 3$ GeV/c
Ridge in p-Pb, ATLAS

\[ C(\Delta \eta, \Delta \phi) \]

\( \Sigma E_T^{Pb} < 20 \text{ GeV} \)

\( \int L = 1 \mu b^{-1} \ 0.5 < p_T < 4 \text{ GeV} \)

\( \Sigma E_T^{Pb} > 80 \text{ GeV} \)

\( c = 0.3.4\%, 0.5 < p_T < 4 \text{ GeV} \)
Projection on $2 \leq |\Delta \eta| \leq 5$

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

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

\[ R_{\text{side}} \]

\[ R_{\text{out}} \]

\[ R_{\text{long}} \]

ALICE Data
- p-p 900GeV
- p-p 7TeV
- Pb-Pb 2.76TeV

STAR Data
- Cu-Cu 62.4GeV
- Cu-Cu 200GeV
- Au-Au 62.4GeV
- Au-Au 200GeV

hydro model
- p-Pb 5.02eV
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 → 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