Flow in p-Pb collisions at the LHC

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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 → hydro → statistical hadronization

- **Initial phase** - "geometric"
- **Hydrodynamics** - 3+1 D viscous event-by-event
- **Statistical hadronization**
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Main question: *Are the (central) p-Pb collisions hydro-like, i.e. collective?*
Initial fluctuations in the 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 \( \sim 1.5 \text{ fm} \) – large!
Hydrodynamics [Bożek 2011]

3+1D viscous event-by-event hydrodynamics

standard set of parameters:

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

realistic equation of state (lattice + hadron gas)

viscosity necessary for small systems
Some results for p+Pb at RHIC

[Bożek 2011]

sample results → the method works for one-body observables

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

Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR), transverse-momentum conservation approximately imposed, charge balancing
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, ...
flows in p-Pb

Correlations

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
flows in p-Pb

Correlations

Physics World

physicsworld.com

Unexpected 'ridge' seen in CMS collision data again

Oct 31, 2012 | 96 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).
Ridge in p-Pb, CMS

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

1 < $p_T$ < 3 GeV/c

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

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

\[ \Sigma E_T^{Pb} < 20 \text{ GeV} \]
\[ \int L = 1 \mu b^{-1} \quad 0.5<p_{T}^{a,b}<4 \text{ GeV} \]

\[ \Sigma E_T^{Pb} > 80 \text{ GeV} \]

\[ c=0-3.4\%, \quad 0.5<p_T<4 \text{ GeV} \]
Projection on $2 \leq |\Delta \eta| \leq 5$

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

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

(a) $R_{\text{side}}$

(b) $R_{\text{out}}$

(c) $R_{\text{long}}$

![Graph showing HBT radii comparisons between ALICE and STAR data, and different hydro models across various energies and nuclei.]
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