Two-pion Bose-Einstein correlations in Pb-Pb collisions at 2.76 TeV with ALICE

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Physics motivation

- Measure the space-time properties of central nuclear collisions by using the Bose-Einstein enhancement of identical pion pairs.
- Look for signatures of collective behavior by studying the source size as a function of particle transverse momentum.
- Compare our measurements to previous ones at lower energies.
- Confront our experimental data with model predictions.
Two-particle interferometry

- The space-time properties of the emitting source can be investigated through measurements of the correlation between two identical bosons, reflected in the pair wave function \( \Psi(q, r) \), using the correlation function

\[
C(q) = \int d^4r \ S(q, r) |\Psi(q, r)|^2.
\]

- Bose-Einstein (BE) correlations modify the wave function such that it can be used to probe the source, i.e. the source emission function \( S(q, r) \) can be deduced from the measured correlation \( C \).
By choosing an appropriate reference frame, three system sizes can be accessed:

- $R_{\text{side}}$ is the *geometrical transverse size*.
- $R_{\text{long}}$ used to deduce *time of freeze-out*.
- $R_{\text{out}}$ depends on both space and time, i.e. has components from *emission duration*.

Experimentally, $C(q) = A(q)/B(q)$, where $A(q)$ is the measured distribution of pair momentum difference $q = p_2 - p_1$, and $B(q)$ is a reference distribution of particles from different events which are expected not to have BE correlations.
Systematic effects I

Track merging effect: two tracks with very similar trajectories inside the TPC are not reconstructed or are reconstructed as a single track.

- Require a minimum two-track separation within the TPC:

\[
\Delta \phi^*(r) = \varphi_2 - \varphi_1 + \arcsin \left( 0.075 \cdot \frac{r}{p_{T,2}} \right)
- \arcsin \left( 0.075 \cdot \frac{r}{p_{T,1}} \right).
\]

- The pair inefficiency in the separation variable \( \Delta \phi^* \) is found to be sharpest at a cylindrical radius \( r = 1.2 \text{ m} \).
Momentum resolution effect: the correlation peak appears wider and smaller due to the finite momentum resolution in the TPC.

Radii reconstructed in Monte Carlo simulations with fixed radii of 5, 7, and 9 fm by applying pair weights.

A correction by up to 4% applied to the measured radii.
Correlation functions for central Pb-Pb collisions

- Correlation functions measured in three dimensions (out, side, long) at $\sqrt{s_{NN}} = 2.76$ TeV.
- Fitted using the Bowler-Sinyukov formula:

$$C(q) = N \{ (1 - \lambda) + \lambda K(q_{inv}) [1 + G(q)] \},$$

$$G(q) = \exp \left[ -(R_{out}^2 q_{out}^2 + R_{side}^2 q_{side}^2) + R_{long}^2 q_{long}^2 \right],$$

with $\lambda$ the correlation strength and $K(q_{inv})$ the Coulomb factor.

- Seven ranges in pair transverse momentum $k_T$ ($0.2 - 1.0$ GeV/$c$).
- BE peak width increases with $k_T$.
- The plot shows projections of the 3D correlation functions (points) as well as of the 3D fits (lines).
Transverse momentum dependence

LHC vs. RHIC radii

- ALICE measures radii up to 35% larger than those measured at RHIC in central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

- The radii show a decreasing trend with increasing $k_T$, characteristic feature of expanding particle sources.

- The ratio $R_{out}/R_{side}$ is flat within errors and comparable or smaller than at RHIC.

- Models tuned to reproduce RHIC data still hold at LHC, e.g. KRAKOW, HKM.
Models overview

**KRAKOW**
Bożek, Chojnacki, Florkowski, et al.

- Hydro-dynamic model.
- Predictions for PbPb are made using LHC pp data and Glauber.
- EoS based on lattice results and hadron-gas model.
- Parameters: $\tau_i = 0.25$ fm/c, $T_f = 150$ MeV.
- $\langle dN_{ch}/d\eta \rangle = 2161$ (central).

**HKM**
Sinyukov, Akkelin, and Karpenko

- Hydro-kinetic model.
- Continuous 4D particle emission of the expanding fireball.
- Initial conditions from Color Glass Condensate (CGC).
- Parameters: $\tau_0 = 1$ fm/c, $T_f = 165$ MeV.
- $\langle dN_{ch}/dy \rangle = 1570$ (central).
Beam energy dependence

- Radii at $k_T = 0.3 \text{ GeV}/c$ are compared with measurements at lower energies.
- Scaling of the radii with $\langle dN_{\text{ch}}/d\eta \rangle^{1/3}$ is observed.
- ALICE measurement significantly extends the range of the radii world systematics.
- The observed growth with energy is roughly reproduced by all model predictions.
Time evolution and homogeneity volume

- $R_{\text{long}}$ is proportional to the total duration of the longitudinal expansion.
- The measured decoupling time $\tau_f$ is about 40% larger than at RHIC.

The quantity \((2\pi)^{3/2} R_{\text{out}} R_{\text{side}} R_{\text{long}}\) is related to the volume of the homogeneity region.

In ALICE, it is found to be about twice the value measured at most central collisions at RHIC.
Summary

ALICE measurements significantly expand the range of the existing radii world systematics.

- The pion source radii measured in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, are larger up to 35% than those at RHIC.
- Transverse momentum dependence is consistent with hydrodynamic models tuned to reproduce RHIC data.
- The homogeneity volume is found to be about twice the size measured at most central collisions at RHIC.
- Besides being larger, the fireball formed in nuclear collisions at LHC lives longer, with a decoupling time that exceeds the one measured at RHIC by 40%.
Backup
Data analysis

- **Data sets:**
  - Runs 137161/162, 137365/366: \( \sim 300k \) events
  - Most central (0-5%): \( \sim 16k \) events
  - **HIJING** LHC10e11: 103032 events
  - **THERMINATOR** LHC10e15: 86796 events

- **Event selection:**
  - For 5% centrality: \( \langle dN_{\text{ch}}/d\eta \rangle = 1601 \pm 60 \) (syst.)
  - Primary vertex within \( \pm 12 \) cm of the nominal IP
  - Pseudorapidity range \( |\eta| < 0.8 \)

- **Track selection:**
  - Primary pions: \( 0.2 \leq p_T \leq 2.0 \) GeV/c
  - Two-track cut: \( \Delta \phi^* = \pm 0.02, \Delta \eta = \pm 0.01 \)
    \( (r \Delta \phi < 1.2 \) cm, \( z < 2.4 \) cm, at \( r = 1.2 \) cm)
More models

AZHYDRO
Frodermann, Chatterjee, and Heinz
- Hydro-dynamic model.
- Vary initial entropy density to control final charged multiplicity.
- EoS with transition from QGP above $T_c$ to hadron resonance gas.
- Predictions defined by initial entropy density $s_0$.

HRM
Humanic
- Hadronic rescattering model.
- Superimpose PYTHIA pp events with respect to atomic number, overlap fraction, and geometry.
- Assume all particles have the same proper time for hadronization ($\tau = 0.1 \text{ fm/c}$).
- Only hadronic degrees of freedom, no partonic contributions.