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TWO-PARTICLE CORRELATIONS IN p–Pb COLLISIONS AT THE LHCb*

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This paper describes the analysis of two-particle angular correlations in proton–lead collisions at $\sqrt{s_{NN}} = 5$ TeV nucleon–nucleon center-of-mass energy performed by the LHCb experiment. Correlations in function of relative pseudorapidity $\Delta\eta$ and relative azimuthal angle $\Delta\phi$ are measured in different event activity classes and bins of particle transverse momentum. The analysis is done separately for the two beam configurations corresponding to the two proton beam directions. Long-range near-side correlations are observed in high-activity events, thus extending previous analyses of this effect to the forward region ($2.0 < \eta < 4.9$). The near-side effect becomes stronger with increasing event activity and seems to be more prominent in the lead–proton mode. However, when comparing both beam configurations for events with similar absolute activity, the results are compatible with each other.

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1. Introduction

Multi-particle production is a basic process in particle physics whose complex dynamics is not well-understood. Measuring two-particle angular correlations is one of the tools that are used to study this phenomenon. Usually, a two-dimensional correlation function of $(\Delta\eta, \Delta\phi)$ in the laboratory system is used in this type of analyses. Structures that can be observed are classified by the values of $\Delta\eta$, $\Delta\phi$. They can be near-side ($|\Delta\phi| \approx 0$) or away-side ($|\Delta\phi| \approx \pi$). Remaining possibilities are long-range for $|\Delta\eta| > 2$ or short-range for $|\Delta\eta| < 2$. The dominant structure is a short-range near-side

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jet peak ($|\Delta\eta| < 2$, $|\Delta\phi| \approx 0$) which emerges due to the fact that final-state particles are collimated around the initial parton. This peak is accompanied by a long-range away-side ridge ($|\Delta\eta| < 2$, $|\Delta\phi| \approx \pi$) which is caused by particles that are opposite in the azimuthal angle and balance the momentum of particles in the jet peak.

Both near-side and away-side long-range correlations have been observed in the form of ridges by the Relativistic Heavy Ion Collider (RHIC) in p–Au and Au–Au collisions [1, 2]. Unexpectedly, the near-side ridge has been seen also in p–p interactions by the CMS experiment [3]. Later, the same effect has been reported for p–Pb collisions by ALICE [4], ATLAS [5] and CMS [6]. Theoretical explanation for the near-side ridge is still under discussion. There are several models that aim to describe this effect. Among them, there is gluon saturation in the framework of colour-glass condensate [7–10], hydrodynamic evolution of a high-density partonic medium [11], jet-medium interactions [12, 13], collective effects in the high-density system [14–18] and multiparton interactions [19–21].

The LHCb detector [23, 24] is a single-arm spectrometer covering the range of $2.0 < \eta < 5.0$, which is unique among other experiments at the LHC. Thus, it can give additional input to understanding the ridge effect, by extending this type of research to the forward region. Data used in this analysis consist of proton–lead collisions collected by the LHCb experiment in 2013 at $\sqrt{s_{NN}} = 5$ TeV nucleon–nucleon center-of-mass energy. Two beam configurations are used: proton–lead (p–Pb) and lead–proton (Pb–p), where the first beam points toward the LHCb acceptance. The rapidity range with respect to the proton beam in the nucleon–nucleon center-of-mass frame is $1.5 < y < 4.4$ for p–Pb configuration and $-5.4 < y < -2.5$ for Pb–p mode. Data used for this analysis in both types of collisions correspond to 0.46 nb^{-1} and 0.30 nb^{-1} integrated luminosity, respectively. Analysis described here has been published as Ref. [22].

2. Data and analysis method

Most of proton–lead collisions give a single interaction per bunch crossing. In this analysis, only events with one PV reconstructed from at least five tracks are chosen. Two-particle correlations between charged, prompt particles coming from such primary vertices are studied.

The analysis is based on a minimum bias subset of data collected from proton–lead collisions. Minimum bias samples for each beam configuration contain around 1.1×10^8 events. Since the hit multiplicity in the vertex detector (VELO) is proportional to the number of particles produced in an event, this parameter is used to define activity classes. Five relative activity classes are assigned separately for each beam configuration as fractions of distribution of VELO hit multiplicity for corresponding minimum bias sample. For example, the 0–3% bin contains the 3% of events with highest VELO hit multiplicity.

Common absolute activity classes are also defined (labelled I–V), which allows for direct comparison of results for both beam configurations. A scaling factor is introduced to ensure the same average number of tracks in each beam mode. It is done for a different, high-activity sample (in this case correlations are expected to be more prominent). This data subset contains events with more than 2200 VELO hits and corresponds to 1.1×10^8 events in p–Pb and 1.3×10^8 events in Pb–p collisions.

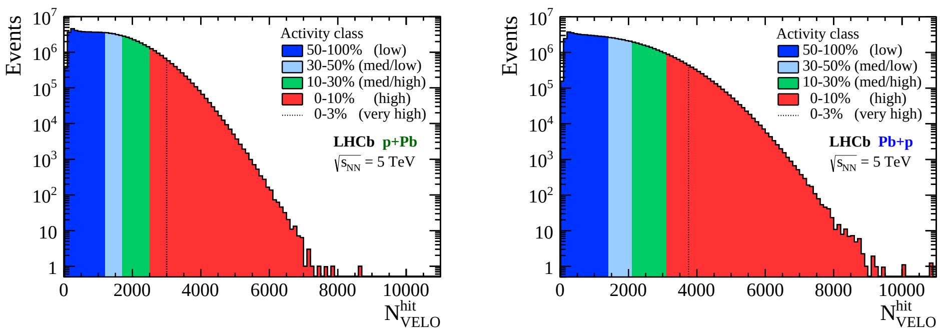

Fig. 1. VELO hit multiplicity for events from minimum bias sample from (left) p–Pb and (right) Pb–p configuration. Activity classes are defined as fractions of the full distribution. Figures are taken from Ref. [22].

This analysis follows the general approach formulated *e.g.* in Ref. [4]. Two-particle correlations depend on event activity and particles transverse momenta p_{T}. Therefore, correlation function is constructed for five different activity classes (relative and absolute) and three p_{T} intervals (0.15–1.0 GeV/c, 1.0–2.0 GeV/c and 2.0–3.0 GeV/c). For each of these subsets, particles in an event are treated in sequence as *trigger* particles, while other become *associated* ones. Pairs are constructed by combining *trigger* particles with every *associated* one. The correlation function is given by

$$\frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\, \mathrm{d}\Delta\phi} = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}\, B(0,0)\,, \tag{1}$$

where $S(\Delta\eta, \Delta\phi)$ is the number of pairs coming from the same PV and falling into given $(\Delta\eta, \Delta\phi)$ bin, $B(\Delta\eta, \Delta\phi)$ is the distribution for pairs of particles from different events, representing the combinatorial association, N_{trig} stands for number of all *trigger* particles and $B(0,0)$ is a normalization factor for background. Such definition of correlation function accounts for effects related to detector acceptance, occupancy and material, since the signal is divided by background distribution.

3. Results

Examples of correlation functions obtained for Pb–p configuration are shown in Fig. 2. Jet peak is the dominant structure and it is truncated to make other effects visible. The away-side ridge can be seen at $\Delta\phi \approx \pi$ and the near-side ridge appears for events with high enough activity at $\Delta\phi \approx 0$.

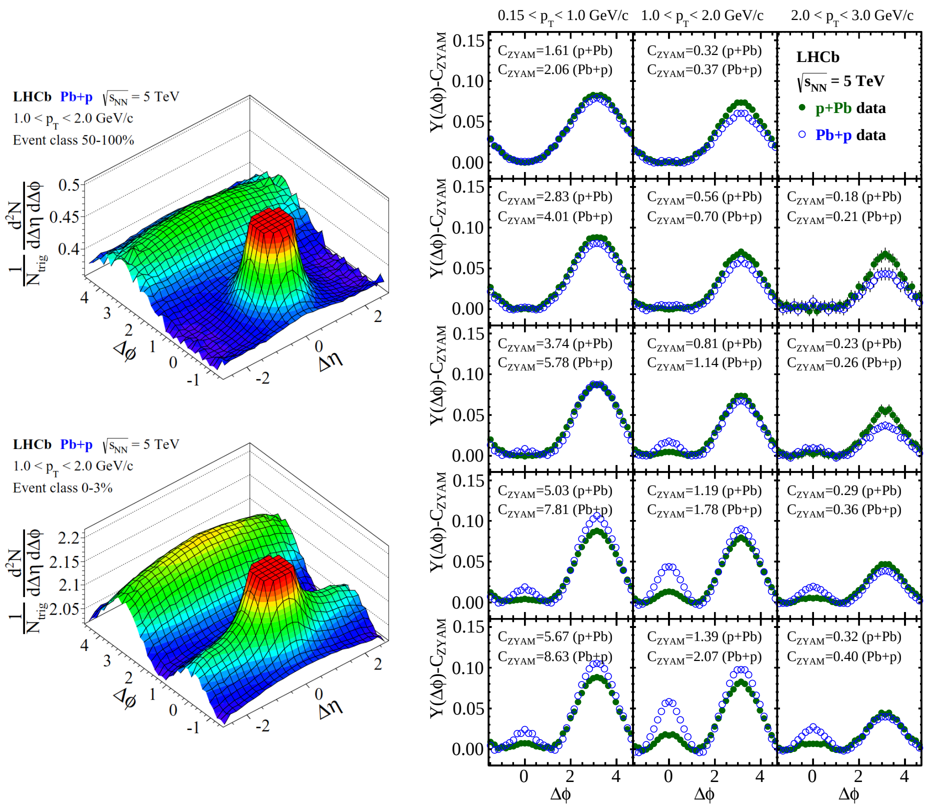

Fig. 2. (Colour on-line) (Left) Two-particle correlation functions for Pb–p configuration, showing the (top) low and (bottom) high activity classes for $1.0 < p_{\mathrm{T}} < 2.0$ GeV/c. (Right) One-dimensional correlation yield as a function of $\Delta\phi$ for relative activity classes in p–Pb (full/green dots) and Pb–p (open/blue circles) collisions. Figures are taken from Ref. [22].

To study the ridge effects in more detail, a one-dimensional projection of the correlation function is used

$$Y(\Delta\phi) = \frac{1}{\Delta\eta_b - \Delta\eta_a} \int\limits_{\Delta\eta_a}^{\Delta\eta_b} \frac{\mathrm{d}^2 N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\phi}\,, \tag{2}$$

where integration is performed in $2.0 < \Delta\eta < 2.9$ range to exclude the jet peak region. The zero-yield-at-minimum (ZYAM) method [25] is used to subtract flat pedestals coming from random particle combinations.

Ridge evolution in relative activity classes is shown in Fig. 2. It can be observed that correlations increase with event activity. The away-side ridge seems to be slightly dependent on the activity and beam configuration, and it decreases towards higher p_{T} values, where less particles are found. On the other hand, the near-side ridge is strongest for the middle p_{T} interval and appears only above high enough event activity. It is also more prominent in the Pb–p collisions, since in this case, we expect more particles emitted towards the detector acceptance than in the p–Pb mode. Similar distributions for common absolute activity classes are shown in Fig. 3. The p–Pb events are scaled to match the hit multiplicity for Pb–p collisions. After that, near-side and away-side ridge effects are compatible for both beam configurations.

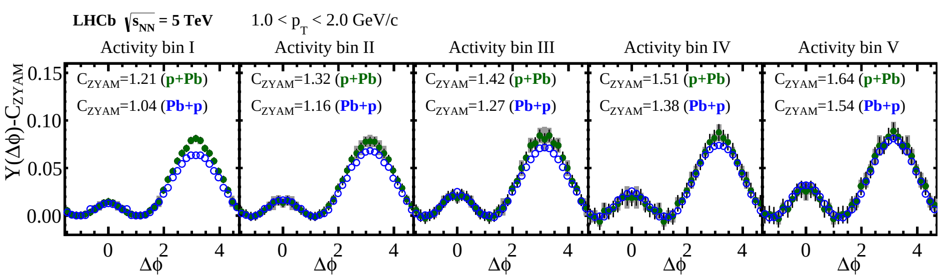

Fig. 3. (Colour on-line) One-dimensional correlation yield as a function of $\Delta\phi$ for common absolute activity classes in p–Pb (full/green dots) and Pb–p (open/blue circles) collisions. Figure is taken from Ref. [22].

4. Summary

Two-particle correlations in proton–lead collisions at $\sqrt{s_{NN}} = 5$ TeV have been measured for the first time in the forward region $2.0 < \eta < 4.9$ by the LHCb experiment. This analysis has been performed separately for p–Pb and Pb–p collisions, which allowed to probe rapidity ranges of $1.5 < y < 4.4$ and $-5.4 < y < -2.5$, respectively, in nucleon–nucleon center-of-mass frame. Correlations have been studied in different activity classes and transverse momentum intervals. The near-side ridge has been observed for high activity events in both beam configurations, but it is more prominent for Pb–p collisions. However, in common absolute activity bins, both ridge effects are compatible for two beam modes. Correlations effects are getting stronger with increasing event activity. Observation of the ridge in the forward region extends previous measurements from other LHC experiments.

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