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LHCb: Triplets born from proton collisions are correlated with each other

For the first time, by studying quantum correlations between triplets of secondary particles created during high-energy collisions in the LHC accelerator, it has been possible to observe their coherent production. This achievement confirms the validity of the core-halo model, currently used to describe one of the most important physical processes: hadronisation, during which individual quarks combine to form the main components of matter in the Universe.

Quarks and the gluons that bind them are the most numerous prisoners in today's Universe, locked inside protons, neutrons and mesons. However, at sufficiently high energies – such as those that existed shortly after the Big Bang or those that occur today in proton collisions in the LHC accelerator – quarks and gluons are released, forming an exotic 'soup': quark-gluon plasma. Under normal conditions, this plasma is not stable, and as soon as it cools down sufficiently, the quarks and gluons bind together again, producing particles of matter in a process called hadronisation. New details of this fascinating phenomenon, obtained through the analysis of so-called three-body quantum correlations, have been reported by physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow, working as part of the LHCb experiment conducted by the European Organisation for Nuclear Research (CERN) in Geneva.

When protons collide with protons at high energies in the LHC accelerator, the quarks that make up these particles, together with the gluons that bind them, form a mixture: quark-gluon plasma. It is during its cooling, in a process called hadronisation, that secondary particles are formed, which are later recorded in detectors as collision products. Research into the process of hadronisation is crucial to understanding how the particles that make up our everyday world were formed (and continue to be formed). However, hadronisation is extremely difficult to analyse because it occurs in an extremely short time, in the order of trillionths of a trillionth of a second, and at distances in the order of millionths of a billionth of a metre. Its direct observation is not possible today, nor will it be in the foreseeable future. Physicists are therefore trying to obtain information about the phenomena occurring during hadronisation indirectly, among others on the basis of analyses of quantum correlations that can be detected between particles escaping from the collision area.

"In quantum mechanics, wave functions are used to describe particles. When there are many particles in a system, their wave functions overlap and interference occurs, as in the case of ordinary waves. We talk about Bose-Einstein correlations when the interfering wave functions cancel each other out. If they were to reinforce each other, we would refer to Fermi-Dirac correlations," explains Prof. Marcin Kucharczyk (IFJ PAN).

In an article published in the *Journal of High Energy Physics*, quantum correlations were studied within the core-halo model. It assumes that the spatial area of hadronisation, from which the secondary particles recorded after the collision originate, can be divided into two parts: the central part called the core, where they are produced directly from quark-gluon plasma or in the decays of short-lived particles formed from it, and a halo, where they originate only from the decays of

particles with longer lifetimes. It is important to note that the main parameters of the core-halo model can be determined on the basis of parameters describing quantum correlations between emitted particles.

“Thanks to the Bose-Einstein correlations between particles recorded by the LHCb experiment detectors, we can extract information about the size and shape of the source from which they are emitted, and even about how this source changes over time and how many particles are emitted from the core and how many from the halo. In this way, we gain knowledge about the details of hadronisation itself, about the dynamics of the early stage of particle production,” adds Dr. Miłosz Zdybal, co-author of the analysis.

The analyses were performed on proton-proton collisions observed in the LHCb experiment, focusing on those cases that led to the formation of triplets of pions (π mesons) with the same electric charge sign. The data, collected in 2013, concerned collisions with an energy of seven teraelectronvolts (TeV) and pions emitted in the so-called ‘forward’ area, i.e. only slightly diverging from the direction of the original proton beam. During their work, the Cracow physicists drew on their earlier analyses from two years ago, when they were able to demonstrate the existence of quantum correlations between pairs of emitted pions for similar collisions.

“The production of triplets in the cases currently studied, for particles propagating ‘forward’ from the collision area, has for some reason turned out to be coherent. So we are dealing with the first observation of coherent particle production using three-body Bose-Einstein correlations for so-called small systems, i.e. those in which a proton collides with a proton or an ion,” emphasises Prof. Kucharczyk.

Observing a phenomenon is one thing, explaining it is another. What processes occurring during hadronisation could be responsible for the coherent production of particles emitted along the original direction of the proton beams? There is growing evidence that some form of collective phenomena may occur in small collision systems. However, current models do not include mechanisms capable of explaining the discovered phenomenon, and it is difficult to predict when theoretical physicists will fill this gap. What is certain, however, is that when this happens, we will be richer in information about the course of hadronisation – a process that is fundamentally important for the shape of our physical reality, yet still holds so many secrets.

The analyses conducted by a group of scientists from the IFJ PAN were co-financed by the Polish National Science Centre.

The Henryk Niewodniczański Institute of Nuclear Physics (IFJ PAN) is currently one of the largest research institutes of the Polish Academy of Sciences. A wide range of research carried out at IFJ PAN covers basic and applied studies, from particle physics and astrophysics, through hadron physics, high-, medium-, and low-energy nuclear physics, condensed matter physics (including materials engineering), to various applications of nuclear physics in interdisciplinary research, covering medical physics, dosimetry, radiation and environmental biology, environmental protection, and other related disciplines. The average yearly publication output of IFJ PAN includes over 600 scientific papers in high-impact international journals. Each year the Institute hosts about 20 international and national scientific conferences. One of the most important establishments of the Institute is the Bronowice Cyclotron Centre (CCB), which is an infrastructure unique in Central Europe, serving as a clinical and research centre in the field of medical and nuclear physics. In addition, IFJ PAN runs four accredited research and measurement laboratories. IFJ PAN is a member of the Marian Smoluchowski Kraków Research Consortium: “Matter-Energy-Future”, which in 2012-2017 enjoyed the status of the Leading National Research Centre (KNOW) in physics. In 2017, the European Commission granted the Institute the HR Excellence in Research award. As a result of the categorization of the Ministry of Education and Science, the Institute has been classified into the A+ category (the highest scientific category in Poland) in the field of physical sciences.

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SCIENTIFIC PUBLICATIONS:

“Three-pion Bose-Einstein correlations measured in proton-proton collisions”
The LHCb collaboration
Journal of High Energy Physics (JHEP) 2025, 174, 2025
DOI: [10.1007/JHEP08\(2025\)174](https://doi.org/10.1007/JHEP08(2025)174)

LINKS:

<http://www.ifj.edu.pl/>

The website of the Institute of Nuclear Physics, Polish Academy of Sciences.

<http://press.ifj.edu.pl/>

Press releases of the Institute of Nuclear Physics, Polish Academy of Sciences.

IMAGES:

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HR: http://press.ifj.edu.pl/news/2025/10/15/IFJ251015b_fot01.jpg

In collisions of counter-propagating proton beams, hadronisation processes can be studied. Detectors register secondary particles produced directly in the collision region or from the decays of long-lived particles within the surrounding halo. Quantum correlations between triplets of pi mesons (on the right) provide information about the details of the process, indicating coherent particle emission. (Source: IFJ PAN)