PION AND KAON PAIR PRODUCTION IN DOUBLE-GAP EVENTS IN ALICE RUN 3*

Rainer Schicker

for the ALICE Collaboration

Physikalisches Institut, Universität Heidelberg
Im Neuenheimer Feld 226, Heidelberg, Germany

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The ALICE detector at the LHC has undergone a major upgrade in the long shutdown 2019–2021 to be able to take data at much-increased rates in Runs 3 and 4. The upgrades of the detector systems used for analysing double-gap events are described, and the improvement in data taking capability for such double-gap events is presented.

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1. Introduction

In the long shutdown LS2 of 2019–2021, the ALICE experiment at the LHC was upgraded in order to take data at much-increased rates in Run 3 (2022–2025) and Run 4 (2029–2032) [1]. The readout was changed to continuous mode, with data collected in proton–proton collisions at rates up to 650 kHz, and subsequently being processed to identify the events of interest. The selected events are permanently stored for future processing. All data taken in heavy-ion collisions at up to 50 kHz are permanently stored, and available for later analysis.

2. The detector upgrades

The Time Projection Chamber (TPC) is not only the main tracking detector of the ALICE experiment but also provides information on the specific ionisation energy loss $\mathrm{d}E/\mathrm{d}x$ for particle identification. The ionisation electrons drift in the electric field of 400 V/cm to the endplates of the cylindrical field cage. The ionisation charges were amplified in Run 1 (2009–2013) and Run 2 (2015–2018) by multiwire proportional chambers (MWPCs), with the backflow of positive ions controlled by gating grids. The effective rate was

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limited in Runs 1 and 2 to about 1 kHz for Pb–Pb and about 3 kHz for *pp* collisions. In order to increase the rate capability to about 50 kHz in Pb–Pb, the MWPCs were replaced by chambers with a stack of four Gas Electron Multipliers (GEMs) with continuous readout and synchronous data processing [2].

In Runs 1 and 2, the readout rate of the Inner Tracking System (ITS) was limited to 1 kHz. The new ITS system implemented for Run 3 features improved resolution, less material, and faster readout. The new system consists of 7 layers of Monolithic Active Pixel Sensors, with a spatial resolution ($r\phi \times z$) improved from (11×100) μm^2 of the old ITS to (5×5) μm^2. The readout rate of this new ITS system is 100 kHz in Pb–Pb [3].

With these TPC and ITS upgrades, data have been taken so far in *pp* collisions at rates up to 650 kHz, and tests for rates up to 1 MHz are planned.

Outside of the central barrel pseudorapidity range $|\eta| < 0.9$, a Fast Interaction Trigger (FIT) system was built for Run 3 to provide precise collision time information for time-of-flight-based particle information, for online luminosity monitoring and measuring forward multiplicity [4]. This FIT system consists of the following detectors:

— **FT0:** Two Cherenkov arrays for minimum bias triggering, for determining the collision time and for vertex position calculation.

— **FV0:** A large scintillator array consisting of five rings and eight sectors is positioned on the opposite side of the ALICE muon spectrometer. In conjunction with FT0, it is used for centrality and event plane determination in heavy-ion collisions.

— **FDD** (Forward Diffractive Detector): This double-sided scintillator array is essential for tagging diffractive events by establishing rapidity gaps in the event.

The parameters of the different FIT subsystems are shown in Table 1.

Table 1. The pseudorapidity range and the z-position of the FIT subsystems.

Detector	η_{min}	η_{max}	z [cm]
FDD-A	4.8	6.3	1696.0
FT0-A	3.5	4.9	334.6
FV0	2.2	5.1	320.8
FT0-C	−3.3	−2.1	−84.3
FDD-C	−7.0	−4.9	−1956.6

Events with particle production measured in the ALICE central barrel and absence of signals in the FIT systems are tagged as double-gap events.

3. The computing system upgrade

After the upgrade of the ALICE detector systems in LS2, the raw data flow to the data acquisition system increased a hundredfold, up to 3.5 TB/s. A new Online/Offline Computing system, O^2, was developed to cope with this challenge [5]. The O^2 system incorporates continuous readout of most subdetectors, data compression using partial synchronous reconstruction and calibration, and the sharing of common computing resources during and for asynchronous reconstruction after data taking. The reconstructed data are written to disk while the raw data are discarded. The O^2 architecture consists of two major computing layers, the First Level Processors (FLPs) and the Event Processing Nodes (EPNs). Both layers are highly heterogeneous, with specialized acquisition cards embedding FPGAs on the FLPs, and GPUs on the EPNs. The raw data rate of 3.5 TB/s is reduced by the FLP layer to $\sim$ 635 GB/s and by the EPN layer to 100 GB/s. This compressed data stream is stored and, after later asynchronous processing, distributed to the Tier 0 and Tier 1 analysis facilities.

This upgrade of the ALICE experiment resulted in a considerably increased data-taking capability. The double-gap data sample collected in Run 2 amounts to about 10 pb^{-1}. As shown in Fig. 1, the ALICE data sample was about 10 pb^{-1} per 6 weeks of data taking in 2022, and about 16 pb^{-1} per 6 weeks of data taking in 2024.

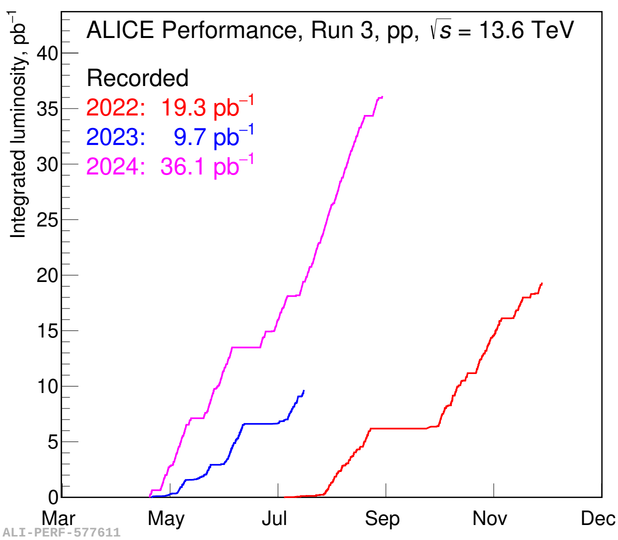

Fig. 1. The Run 3 ALICE data sample amounts to about 10 pb^{-1} per 6 weeks of data taking in 2022, and to about 16 pb^{-1} per 6 weeks in 2024.

4. Central diffractive production at the LHC

Central diffractive events are characterized by particle production at midrapidity, and by rapidity gaps up to the rapidity of the beam particle or its remnants. The ALICE experiment is ideally suited for studying such events due to the excellent global tracking in the central barrel by the combined information of TPC and ITS and the superb particle identification of the TPC. The absence of particles at forward/backward rapidities can be established by requiring no signals in the FIT detector systems. In the following, only events with two particles at midrapidity are shown.

In Fig. 2 on the left, the transverse momentum p_{T} of unlike-sign pion pairs is shown *versus* the pair mass $M_{\pi\pi}$, reflecting the ALICE pair acceptance. Integrating this distribution over the pair p_{T} yields the pion-pair invariant mass distribution shown on the right of Fig. 2. The corresponding distributions of kaon pairs are shown in Fig. 3.

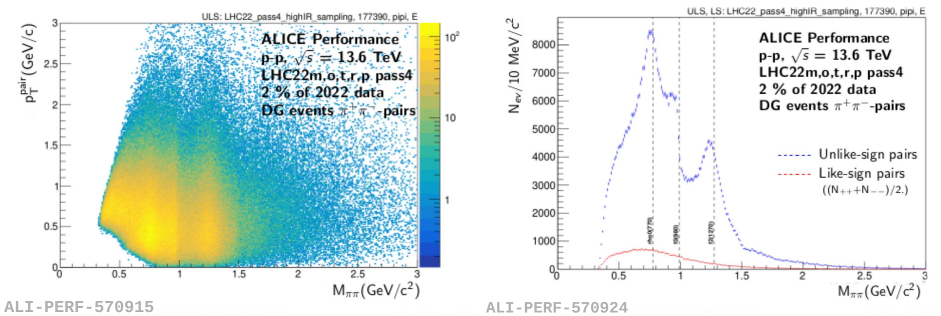

Fig. 2. Transverse momentum *versus* invariant mass of unlike-sign pion pairs on the left, invariant mass distribution for like and unlike-sign pion pairs on the right.

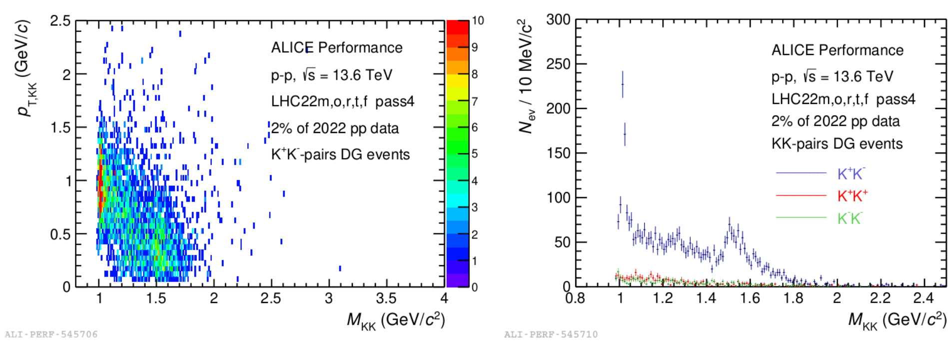

Fig. 3. Transverse momentum *versus* invariant mass of unlike-sign kaon pairs on the left, invariant mass distribution for like and unlike-sign kaon pairs on the right.

The invariant pair mass spectra in both the pion and kaon sectors shown in Figs. 2 and 3 exhibit clear resonance structures. The study of resonance production in double-gap events is of high interest since such events are dominated at LHC energies by Pomeron–Pomeron fusion. In Quantum Chromodynamics (QCD), the Pomeron is understood to be a colour-neutral exchange of an even number of gluons. Pomeron–Pomeron fusion events are hence thought to produce a gluon-rich environment with quark degrees of freedom largely missing in the initial state. Such a medium is the ideal place to hunt for exotic hadronic states such as hybrids and glueballs. A first step in such a hunt is, however, the analysis of the data for known $q\bar{q}$ states.

5. A model of $q\bar{q}$ bound states

A unified framework formulated by Godfrey and Isgur for calculating $q\bar{q}$ bound states of light and heavy mesons relies on a relativistic potential [6]

$$V(\boldsymbol{p}, \boldsymbol{r}) = H^{\text{conf}} + H^{\text{so}} + H^{\text{hyp}} + H_{\text{A}} \tag{1}$$

with H^{conf} the confining potential, H^{so} the spin–orbit interaction, H^{hyp} the hyperfine interaction, and H_{A} the annihilation interaction.

The solutions of Eq. (1) are grouped according to their quantum numbers J^{PC}, and associated to ground and excited states in spectroscopic notation $n\,^{2S+1}L_J$ in the different flavour sectors.

In Table 2, the S-, P-, D-, F-, and G-wave solutions of the Godfrey–Isgur model in the isoscalar sector with hidden strangeness are listed. The S-wave solution with a calculated mass of 1020 MeV/c^2 is identified with the well known $\phi(1019)$. The P-wave solution with a calculated mass of 1530 MeV/c^2 is identified with the well-known $f_2^{'}$ of mass 1525 MeV/c^2. Both the $\phi(1019)$ and the $f_2^{'}(1525)$ are clearly visible in the kaon-pair mass spectrum shown in Fig. 3. The D-wave solution of the Godfrey–Isgur model with a calculated mass of 1900 MeV/c^2 is identified with the $\phi_3(1850)$ listed

Table 2. Isoscalar mesons with hidden strangeness.

PDG	J^{PC} (G–I)	$n\,^{2S+1}L_J$ (G–I)	Mass (G–I)
ϕ	1^{--}	1^3S_1	1020 MeV/c^2
$f_2^{'}$	2^{++}	1^3P_2	1530 MeV/c^2
ϕ_3	3^{--}	1^3D_3	1900 MeV/c^2
$f_4^{'}$	4^{++}	1^3F_4	2200 MeV/c^2
ϕ_5	5^{--}	1^3G_5	2470 MeV/c^2

by the Particle Data Group [7]. The kaon-pair invariant mass spectrum shown in Fig. 3 presently shows very little statistics in the mass range above 1700 MeV/c^2. The data sample shown in Fig. 3 represents, however, only about 2% of the data sample recorded in 2022. There are no states listed by the Particle Data Group corresponding to the F-wave ($J^{PC} = 4^{++}$) and G-wave ($J^{PC} = 5^{--}$) solutions of the Godfrey–Isgur model, hence the last two entries of Table 2 labeled f_4' and ϕ_5 represent *terra incognita.*

6. Summary and outlook

The ALICE experiment is taking data at unprecedented rates in Run 3 after a major upgrade in LS2. First analyses of kaon-pair production in double-gap events show clear evidence for strangeonia states $\phi(1019)$ and $f_2'(1525)$. There is a 50 times larger data sample for analysis from data taking 2022/2023, and an even larger sample available from data taking 2024. The analysis presented here can be extended to $(u,d)\bar{s}$ kaonia and $(\bar{u},\bar{d})s$ antikaonia states by studying πK pairs.

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