ALICE activity report 2024

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1 The ALICE experiment

The ALICE collaboration at CERN currently includes 39 countries, 164 institutions, and 1892 members. In turn, INFN participates with 12 groups for a total of about 200 physicists. The INFN-Frascati group is a very active contributor to the scientific output of the collaboration in terms of detector construction, run operation and physics analysis. In fact, the INFN-Frascati group played a key role in the construction and operation of the ALICE electromagnetic calorimeters EMCAL and DCAL, in the upgrade for RUN3 (2022-26) with the construction of 1/4 of the new Inner Tracker System (ITS) Outer Layers (OL), as well as in the operation of the entire ALICE detector (Run and Commissioning Coordination on 2013-15 and 2019-22 and Training Shift Coordinator on 2023-24).

This report briefly summarizes the results obtained by the ALICE-LNF group during the data taking and the physics analysis in 2024.

Since fall 2019 the INFN-Frascati group covered different roles of responsibility, having a leading role to the ALICE Run Coordination (F. Ronchetti), being in charge of the global ALICE commissioning and data taking operations until the end of 2022, being an elected member of the Management Board of the ALICE experiment (A. Fantoni first and F. Ronchetti later), participating by defaults also to the Physics and Technical Boards, being the Training shift Coordinator (S. Pisano) and also the EPN Technical Coordinator (F. Ronchetti) for the Run 3. The Frascati group is present in the Physics Coordination with O. Vazquez Doce as a conveener of the Physics Working Group (PWG) of Correlations and Flow (CF) and also as one of the Editorial Group members.

2 ALICE upgrade for RUN3 and Event Processing Nodes

The ALICE upgrade for Run 3 includes the O^2 project, a new computing model that combines online and offline data processing into a single framework. The same code runs both online and offline with different parameters. This required upgrading the experiment's computing farms for data readout and processing.

Due to the increasing volume of data, storing all the raw data produced is not feasible. As a result, there is a need for efficient online compression and the use of highly efficient processors GPUs (Graphic Processing Units) instead of CPUs to accelerate processing and to reduce farm costs and energy consumption.

This data stream is pushed by the ALICE readout farm (FLP, First Level Processors) via an InfiniBand (IB) network to the Event Processing Nodes (EPN) using a data distribution software running on both farms. One of the Frascati member (F. Ronchetti) is the Technical Coordinator of the EPN system at CERN.

The main objectives for 2024 focused on consolidating farm operations, including support infrastructure and computing, to ensure maximum reliability during the data-taking campaign for both p-p and Pb-Pb runs. Special attention was given to farm performance and stability during ALICE Pb-Pb collisions, which presented significant challenges. In 2024, the LHC sustained a 50 kHz hadronic interaction rate for over an hour, subjecting the EPN farm to prolonged stress on both software and hardware components. Unlike in 2023, when no effective luminosity leveling was achieved during heavy-ion running, the system in 2024 handled a peak input rate of 800 GB/s of raw time frames for extended periods.

Despite these increased demands, the EPN farm remained stable, introducing no inefficiencies into ALICE's 2024 data-taking operations. The farm's performance from the start of Run 3 through the latest 2024 Pb-Pb run has been documented in a peer-reviewed article published in Frontiers in Physics under the section Promoting Green Computing in High-Energy Physics and Astrophysics.

3 ALICE operations

2024 has been a crucial year for data taking, both for pp collisions and for pPb and PbPb. For the latter, significant improvements have been observed in the machine with respect to 2023, in particular thanks to a clear reduction of losses during the ramp phase of the beams and a mitigation of quenches. A higher bunch intensity from injectors was also provided. This, together with the excellent performances of ALICE, brought to surpass the total luminosity production projections for PbPb, with an average collection of 0.144 nb^{-1} per day.

LNF group is being active in data taking operations by contributing to several shifts in different central roles (in particular, as *Detector Control System* operator (V. Muccifora) and as *Shift Leader* (A. Fantoni, O. Vazquez Doce), especially during the heavy-ion run, when expert shifters are required. It also contributed to the operations covering three weeks of Run Manager shift (S. Pisano), in May and in October.

In addition to the data taking, LNF group was in charge for the Training Coordination (S. Pisano). In such a role, regular classes for training shift leaders and run managers were held during the year, and tests were organized for the assignment of the eligibility as ALICE shifters. In cooperation with the *Run Coordination* the documentation for the data taking operations was developed and mantained.

4 Contribution to the ITS QA

It is worth to remind that the Frascati group provided 1/4 of the total Outer Barrel staves, building and assembling 29 staves between the end of 2018 and end of 2019. After the installation, the Frascati group has participated to the commissioning of the detector and during the data taking in 2024 (Run3) has continued to contribute in the Offline Data Quality Assurance (QA) of the whole detector, being responsible for the Cluster (cluster size and occupancy) and for the Tracks (vertex parameters and track angular distributions).

In 2024 53.1 pb^{-1} of luminosity has been delivered to ALICE for pp data taking at 13.6 TeV with production for physics at 500 kHz interaction rate and 5.3 pb^{-1} has been delivered for pp reference data at 5.36 TeV. In this situation a 23 hours-long run was taken. Duing the Pb-Pb data taking at 5.36 TeV, 1.6 nb^{-1} of luminosity was collected, reaching the target luminositu of 6400 b/s and stable operation at 50 hHz IR. The QA team has analyzed the new whole periods 3 times per week, coordinated via the JIRA ticket system. During the Pb-Pb data taking, a daily analysis has been performed to continuously check the detector offline via the Web Gui and long-time trends.

In order to define a bad run from the ITS cluster point of view, the following criteria have been applied:

- at least 1 layer with >25% empty staves (cluster occupancy is 0 cluster/pixel/ nChip);
- the run has >10% empty lanes overall;
- the average cluster size is out of limits by 3-7 pixels

The detector occupancy has been studied also with the cluster task and it has been found that cluster size is independent of the Interaction Rate (IR) and that the decrease of the cluster size by the end of the fill can be due to the beam-gas interactions.

From the Tracks point of view a run is defined good if the following quality criteria for offline QA have been satisfied:

- no anomalies in angular track distribution;
- the Z vertex shape ranging between -1.5 and 1.5 cm;
- the average nClusters per track ranging between 5 to 6.

All runs have been defined as good for the ITS during the heavy ions data taking. No end-of-run during p–p ref data and only 4 end-of-run during Pb–Pb data have been registered. Only two small periods for a total of 45 minutes have been excluded from the reconstruction due to ITS, demonstrating the very high affidability of the detector. Moreover, nu run crashes due to corrupted data have been observed and the in-run recovery procedure was successfully utilized throughout the heavy ions period.

ITS demonstrated stable performance to both periods, so the Quality Check (QC) is an effective tool for the run quality assessment and filtering bad data, showing no significant differences in average efficiency wrt p-p data taking.

5 Femtoscopy and correlations studies

The INFN Frascati group has been involved in a recent highlight from ALICE, contributing to the Collaboration's first-ever publication in the high-impact journal Physical Review X. The article demonstrates how femtoscopy studies of proton–deuteron pairs enable access to three-body dynamics at short distances, providing new insights into nuclear forces. A second article, with contributions from the INFN ALICE group, reanalyzes ALICE data on kaon–deuteron correlations to measure the delay time for deuteron emission relative to other hadrons in proton–proton collisions. Finally, a new analysis has been presented, with preliminary approved results, on femtoscopy studies of Ξ–π and Ξ–K pairs.

The Frascati group has also reinforced its presence in the ALICE Physics Board, with a member of the group (O. Vazquez Doce) becoming conveener of the Correlations and Flow Physics Working Group from June 2024.

5.1 Accessing three-body dynamics and deuteron formation mechanism via femtoscopy

In an article published by ALICE in 2024 in Phys. Rev. X (1), the dynamics of three-body systems are accessed by using studies of hadron-deuteron correlations.

Following recent ALICE studies of hadron-hadron interactions via femtoscopy, the correlations of kaon–deuteron and proton–deuteron pairs as a function of the relative momentum k^* have been measured in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV. The results show that, for the K^+–d pairs, predictions based on a model that assumes the effects of the coulomb and strong interaction in a two-particle system at the small distances typical of pp collisions successfully describe the experimental data. This agreement demonstrates that the relative distances at which kaons and deuterons are produced are approximately 1–2 fm, consistent with what have been observed for other hadron-hadron pairs.

In the case of p–d correlations, however, the data cannot be explained using a simple two-body model. Instead, it is necessary to incorporate a full three-body calculation that accounts for the internal structure of the deuteron and the three-body dynamics between the proton and the deuteron constituents. Such calculations, developed in collaboration with the INFN theoretical group in Pisa, show excellent agreement with the ALICE measurements. This result highlights the sensitivity of femtoscopy with proton–deuteron pairs to the three-body dynamics at play in the system.

Additionally, it is shown how, by performing the analysis as a function of the transverse mass of the pair, it becomes possible to disentangle the contributions from pure three-body forces, see right panel of Fig. 1. This capability opens exciting opportunities for extending the method to the strange sector, for instance by studying Λ–d correlations. Such studies could provide a novel approach to probing three-body forces beyond traditional hypernuclei experiments, offering new avenues to understand multi-body interactions in nuclear and hadronic systems.

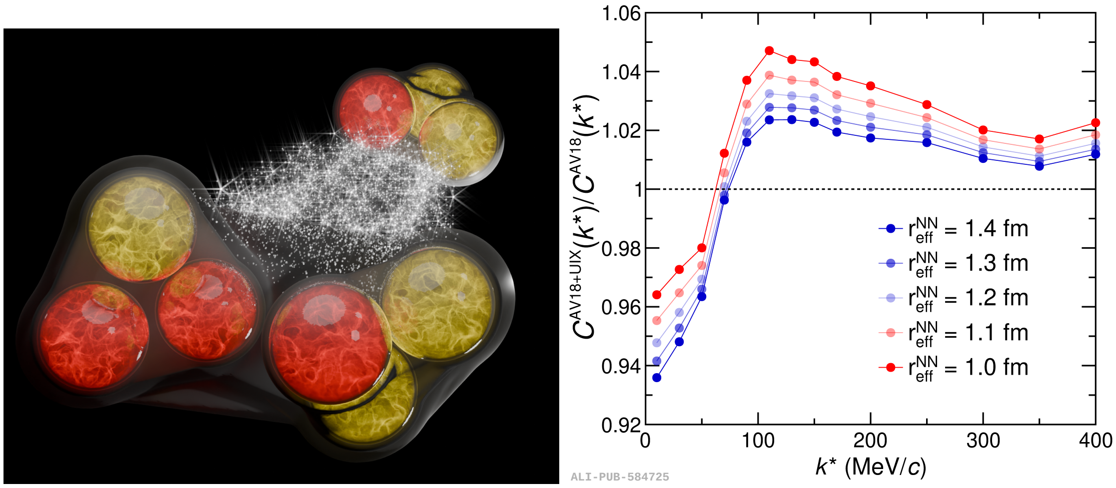

Figure 1: Left panel: Artistic illustration of the proton-deuteron interaction at the LHC. This picture is presented in the Popular Summary of (1). Right panel: Ratio of theoretical p-d correlation functions obtained with full three-body calculations to those obtained using an two-body interaction only for different values of the two-nucleon effective source size and hence different transverse mass values.

In a recent article (2), submitted to Eur. Phys. J. A, the K^+–d data shown in (1) by ALICE, is employed to investigate the time delay of deuteron emission relative to other hadrons with help of a model of emission of particles in proton-proton collisions. Two scenarios are considered: the first (A) assumes that deuterons are produced following the decays of short-lived strong resonances, with their formation occurring through the assisted nuclear fusion of available nucleons. The second scenario (B) assumes that deuteron production occurs simultaneously with all other primary hadrons.

In both cases, an additional emission time delay is introduced, and its value is extracted by fitting the measured K^+–d correlation function. For scenario A, where deuteron production is affected by baryonic resonances, the upper limit of the time delay is found to be 2.25 fm/c. For scenario B, which assumes simultaneous deuteron production with all other hadrons, the upper limit is 4.75 fm/c.

These results support the hypothesis of an early formation of the deuteron as an extended, weakly bound composite object in ultra-relativistic proton-proton collisions at the LHC. Moreover, the small time delay values indicate that deuterons in such collisions cannot be formed as compact, non-interacting entities, as hypothesized in thermal models applied to heavy-ion collisions.

A member of the INFN Frascati group (O. Vazquez Doce) took part of the Paper Committee designed by ALICE to write the Phys. Rev. X article (1) and has been the main analyzer of the K^+–d correlations, and it is the first author of the publication on the deuteron delay (2).

5.2 Studies of the baryon-meson strong interaction with strangeness and molecular states

In 2024, new femtoscopy studies have been initiated within ALICE with contribution from researchers from the INFN group. The study of meson-baryon interactions in the $S = -1$ and $S = -2$ sectors have been extended by performing femtoscopy analyses of Ξ-π and Ξ-K pairs in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV.

The Ξ-K studies complement previous femtoscopy studies in the $S = -1$ sector, in particular studies using K^-–p pairs, in which the goal is to be sensitive, in the small momentum region, to the effects of the strong interaction, complementing as well antiKaonic atoms studies and the scattering data available. Similarly, in the $S = -2$ sector, the Λ-K femtoscopy is now extended with Ξ-π studies, which provide not only a precise description of the strong interaction at low relative momentum, but also access to signals from resonance decays. In this context, the debated states $\Xi(1620)$ and $\Xi(1690)$, which are candidates for molecular states, are of particular interest. These measurements, therefore, contribute to both the study of the strong interaction and hadron spectroscopy by probing exotic hadronic states that are challenging to identify through conventional approaches.

The correlation functions for Ξ-K and Ξ-π pairs have been measured (see Fig. 2) and interpreted using the Lednicky model accounting for the Coulomb and strong interactions, while the underlying background has been modeled through PYTHIA simulations. These analyses represent the most precise measurements of the strong interaction in both channels to date. By extracting the scattering lengths that characterize the interactions, the results have been compared to predictions from state-of-the-art chiral SU(3) effective field theories. This comparison provides a critical benchmark for understanding meson-baryon interactions in the strangeness sector and helps refine theoretical models.

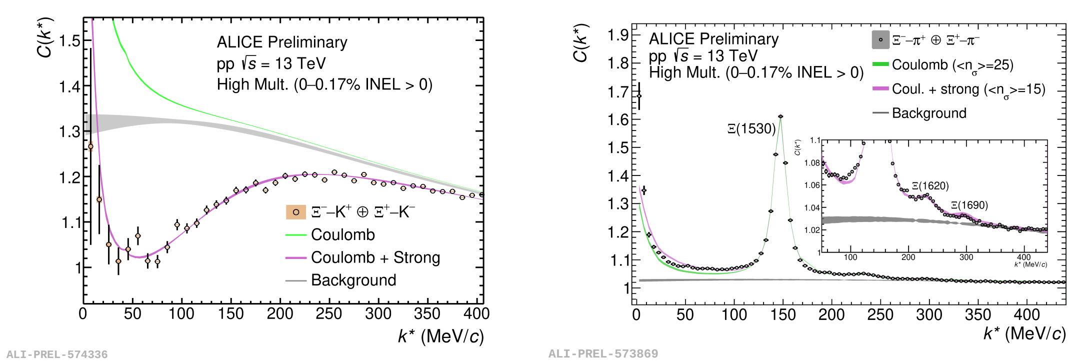

Figure 2: Experimental correlation function of Ξ-K (left) and Ξ-π (right) pairs in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV. The preliminary data is shown as black markers, with vertical lines (boxes) depicting the statistical (systematic) uncertainties. The gray band represents the non-femtoscopic background modelled with Pythia, while the green and magenta lines show the expectation from Coulomb only or Coulomb+Strong interaction assumption, respectively.

The results have been approved as preliminary for the Strangeness in Quark Matter (SQM 2024) conference, with a researcher from INFN Frascati as lead analyst.

Complementary to this studies, in the framework of the "Scientific and Technological Summer Student Fellowship Program", during the last two months of 2024, a research activity was carried out by the master student Marta Piscitelli, who completed the study on "Tuning of $N\Omega$ Meson-Exchange Model Potential with Femtoscopy Data". The project consisted of modifying a meson-exchange potential approach to describe the nucleon-omega baryon interaction in order to reproduce the ALICE data on proton-omega femtoscopy in *pp* collisions (3). The fitting procedure determined the level of attraction in this interaction that best fits the femtoscopy data and suggests the formation of a proton-omega di-baryon bound state.

6 ALICE scientific output

The ALICE Collaboration has published 47 papers in 2024 and to date 523 papers submitted to international referred physics journals, of which 484 already published (Fig. ??) since the birth of the ALICE experiment in 2009.

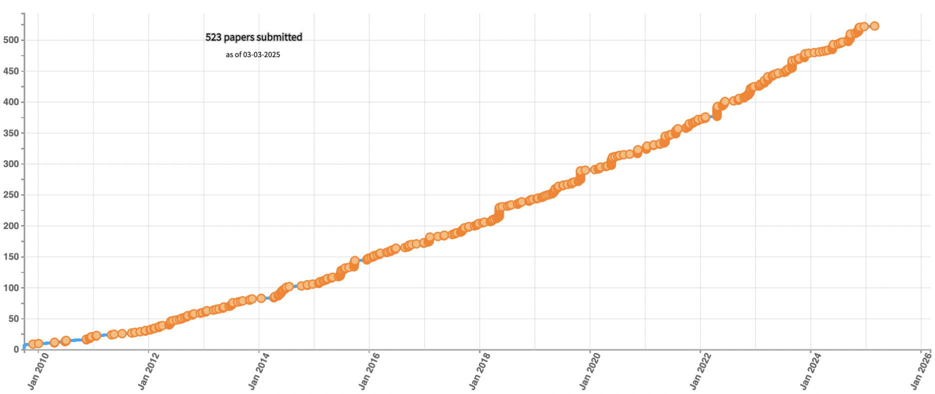

Figure 3: *Timeline of the total number of ALICE papers ("submitted" is to be intended as published+submitted) since the fist LHC beam at 900 GeV on November 23, 2009).*

The full list of ALICE publications for the year 2023 can be found online at the link: https://alice-publications.web.cern.ch/statistics/2024 while the full list is available at the link: https://alice-publications.web.cern.ch/publications

7 ALICE LNF talks

- A. Fantoni "From ITS2 to ITS3", Workshop on Advances, Innovations and Future PErspectivesin High Energy Nuclear Physics, 19-24 October 2024, Wuhan (China)
- F. Ronchetti "EPN Stauts Report", DPG Spring Meeting, Giessen (Germany), March 2024
- F. Ronchetti "EPN Status Report", FSP-ALICE Meeting, Bad Staffelstein (Germany), September 2024
- F. Ronchetti "Efficient Computing with the ALICE Event Processing Nodes GPU Farm", Workshop on Advances, Innovations and Future PErspectivesin High Energy Nuclear Physics, 19-24 October 2024, Wuhan (China)

- O. Vazquez Doce ”Study of the three-body dynamics at short range via femtoscopy by ALICE at the LHC”, Fourth International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility (HEF-ex 2024), 19–21 February 2024, J-PARC
- O. Vazquez Doce ”High-precision measurements of the strong interaction”, Workshop on Present and future perspectives in Hadron Physics, INFN Frascati, June 2024
- O. Vazquez Doce ”Accessing the multi-strange meson-baryon interaction via femtoscopy with ALICE”, QNP2024 - The 10th International Conference on Quarks and Nuclear Physics, Barcelona, July 2024
- O. Vazquez Doce ”Novel constraints for the multi-strange meson-baryon interaction using correlation measurements”, WPCF 2024 - 17th Workshop on Particle Correlations and Femtoscopy, Toulouse, November 2024
- O. Vazquez Doce ”Exploring the Strong Interaction of Three-Body Systems at the LHC”, LNF General Seminar, December 11th, 2024
- O. Vazquez Doce ”Esperienze di un ricercatore emigrante”, International day of women and girls in science, STEM, LNF Frascati, 9 February 2024

References

1 . ALICE Collaboration, “Exploring the strong interaction of three-body systems at the LHC”, Phys. Rev. X **14** (2024) 3, 031051.

2 . O. Vázquez Doce et al., “Study of the deuterons emission time in pp collisions at the LHC via kaon-deuteron correlations”, arXiv:2412.04562 [nucl-ex], submitted to Eur. Phys. J. A.

3 . ALICE Collaboration, “Unveiling the strong interaction among hadrons at the LHC”, Nature **588** (2020) 232.