ALICE activity report 2025

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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.

2 Role of the LNF group in the ALICE experiment

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, Training Shift Coordinator on 2023-2024, Deputy Run Coordination on 2025 and Collaboration Boar Chair starting from July 2025).

This report briefly summarizes the results obtained by the ALICE-LNF group during the data taking and the physics analysis in 2025.

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 first and on 2025 later (S. Pisano), 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. The Frascati group is also present in one of the two higher responsibilities of the ALICE Collaboration, the Collaboration Board Chair (A. Fantoni).

3 ALICE upgrade for RUN 3 and Event Processing Nodes

The ALICE upgrade for Run 3 includes the O^2 project, which introduces a unified computing model integrating online and offline data processing within a single software framework. The same reconstruction and analysis workflow is executed in both contexts, differentiated only by configuration and runtime parameters.

In turn, this new approach required a substantial redesign and upgrade of the experiment's computing farms for data readout, real-time processing, and long-term data handling.

The synchronous part of this computing model processes data concurrently with data taking, requiring both real-time reconstruction and the first calibration pass to happen online, representing a paradigm shift from Runs 1 and 2, where calibration and reconstruction occurred days later.

In fact, the O^2 framework splits processing into two phases: **synchronous**, executed online during data acquisition with strict latency constraints, and **asynchronous**, executed offline to perform complete reconstruction of all events with refined calibrations.

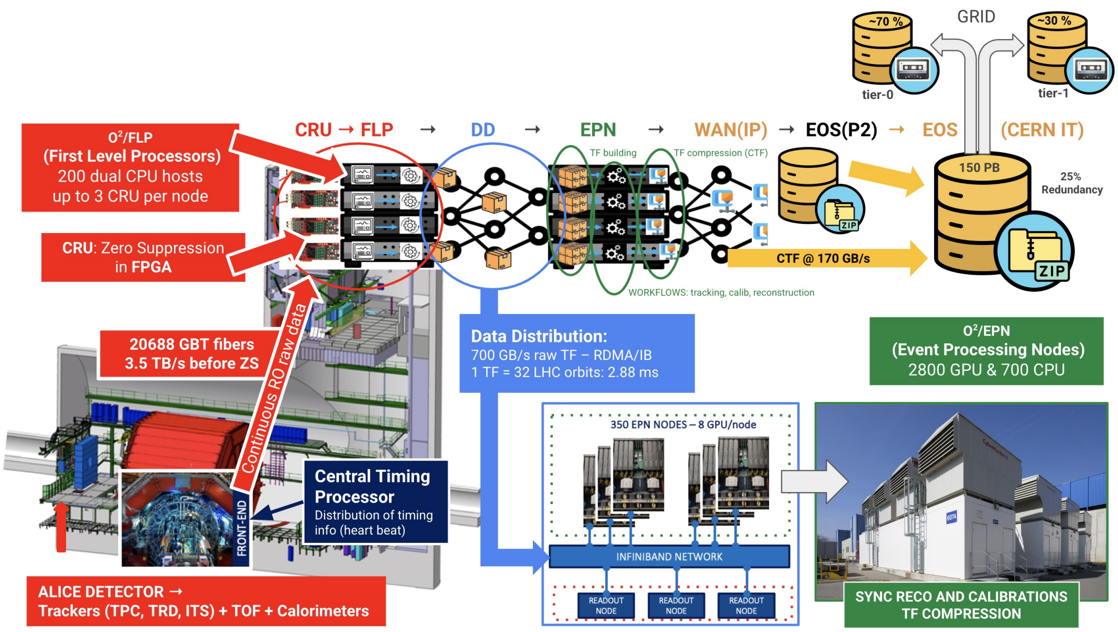

Figure 1: Schematic overview of the ALICE Run 3 online computing architecture. Continuous detector data are read out by the Common Readout Units (CRUs), performing zero suppression in FPGA and delivering the data to the FLPs. The data distribution layer transfers sub–time frames over an InfiniBand RDMA network to the EPNs, where time frames are built, processed, and compressed using GPU-accelerated reconstruction and calibration workflows. The resulting Compressed Time Frames (CTFs) are streamed via IP to EOS for permanent storage and further distribution to the CERN Tier–0/Tier–1 computing infrastructure.

In the Run 3 detector data are continuously acquired and logically organized into time frames (TFs), each corresponding to a fixed-duration slice of the global data stream, typically of the order of 32 LHC orbits (2.88 ms). Each TF contains all detector information recorded within that time window and represents the fundamental unit of data distribution and processing in the O^2 framework.

TF originate by the various ALICE detector sensitive elements which are read out by custom FPGA cards plugged into the the First Level Processors (FLPs) nodes. Hence, one of such ”sub” Time Frames (STFs) spans over the full time window of 32 LHC orbits but contains only information related to a limited geographical area of the detector to which the FLP node and its card are connected to.

The stream of STFs is sent via via RDMA (Remote Direct Memory Access) over the ultra-low latency 200 Gb/s InfiniBand network and ingested by the Event Processing Nodes (EPNs) 1. The overall transfer capacity between the FLP and EPN farms is 14.4 Tbit/s. Operationally the system was proven able to sustain rates up to 1.2 TB/s during high-rate pp collisions for commissioning purposes and up to 0.9 TB/s during real Pb–Pb collisions in 2023 (when the FPGA zero suppression was not yet fully optimized).

At such rates, storing all the raw data produced is not feasible. As a result, there is a need for efficient online tracking and calibration via highly efficient processors as GPUs (Graphic Processing Units) instead of CPUs to accelerate processing and to reduce farm costs and energy consumption as one GPU is able to replace 55 or 80 32-core ”Rome” class CPUs depending on the model used

(AMD-MI50 or MI-100 respectively).

At the level of the EPN farm each complete TF data from each ALICE detector is independently reduced and compressed. The implementation of the Compressed Time Frames (CTFs) is crucial for ALICE's continuous data-taking operations, as the maximum availability of the EOS disk buffer at CERN is limited. Key statistics of the collected data for different collision systems from 2022 to present are given in Tab 1:

Table 1: Data size collected for various collisions systems from 2022–2025. The asterisk in 2025 data taking refers to the TPC operation being limited to 23 kHz due to abnormal discharge of the field cage at higher rates (mitigation work ongoing.)

Year	pp	Pb–Pb
2022	52 PB	
2023	38 PB	42 PB
2024	180 PB	39 PB
2025	187 PB	50^{*} PB

One of the Frascati member (F. Ronchetti) is the Technical Coordinator of the EPN project at CERN. As such, he is directly responsible of the technical infrastructure in terms of preemptive maintenance, monitoring, issue triage and resolution from the different subsystem: electrical power distribution, water purification plant for adiabatic cooling, and overall cooling of the four IT containers. Other responsibilities include the consolidation of the infrastructure ancillary systems and implementation/validation of safety controls. On the operational side, contributions are given to improve of the farm system administration via automation tools (Ansible, Python) and to the on-call operations.

The EPN system was able to sustain smoothly the 2025 data taking, given also the lower operational interaction rates. The LHC provided ALICE a sustained a 23 kHz hadronic interaction rate for several hours and the running efficiency was constantly higher than 95%. The EPN farm could easy cope with these prolonged periods of synchronous processing introducing no inefficiencies into the data taking operations.

In 2025, a sizable fraction of the effort was also absorbed by improving the preemptive maintenance of the IT infrastructure to grant uninterrupted operation as the farm is always processing even in absence of data taking as it carries on the asynchronous processing and acts as a GRID node. Since the memory footprint for processing Pb–Pb data far exceeds the 2GB/core available on the regular GRID sites, the EPN farm provides the only possibility to perform the offline reconstruction of the Pb-Pb data and in average (including pp) the EPN farm provides roughly 17% of the whole ALICE GRID compute capability.

In 2025 the good performance of the EPN farm both in terms of computing and energetic efficiency have been documented by several publications, conferences and seminars

4 ALICE data taking in 2025

In 2025, the data taking was successfully completed, leading also to the collection of data with new collision systems, *i.e.* pO, OO and Ne-Ne. The pO collisions were planned for the LHCf experiment with the goal of properly tuning the hadronic interaction models used by ground-based cosmic rays experiments to extract the average composition of Ultra High Energy Cosmic Rays, but data were collected also by ALICE, ATLAS, CMS and LHCb. OO and Ne-Ne collisions are of interest because, given the mass number of oxygen and neon, and their overall nuclear structure, they allow to test the possible emergence of a deconfined medium also in the collision of low-mass elements, and to test how the nuclear shape itself - different for oxygen and neon - can influence the dynamic of the collision. ALICE successfully took data, by exceeding of factors between 2 and 10 (for the oxygen case) the target statistics, amounting to 7.3 nb^{-1} for pO, 5 nb^{-1} for OO and 0.87 nb^{-1} for Ne-Ne. In addition to this, also pp and Pb-Pb data have been collected, for a total of 50 pb^{-1} and 2 nb^{-1} respectively. Included in the total pp sample, 3 pb^{-1} were recorded at low-magnetic field. For the latter, a new background appeared, that was eventually mitigated by adapting the read-out frame rate of the ITS. The Pb-Pb campaign was then carried out in the last part of the year, and while the collision rate was decreased to 23 kHz due to the appearance of instabilities in the field-cage of the Time-Projection Chamber - with respect to the operational value in the first part of 2024, equal to 50 kHz - the collected statistics targeted the goal of the year.

LNF group is strongly involved in data taking operations. S. Pisano covered the role of *Deputy Run Coordinator*, and several shifts in different central roles have been covered by the group (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.

5 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 2025 (Run 3) 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) Quality Checks (QC).

The LNF QC team (A. Fantoni, V. Muccifora and O. Vazquez Doce) has analyzed the 2025 data taking coordinated via the JIRA ticket system. In particular pp and OO data have been analyzed 3 times per week, while during the Pb-Pb data taking a daily analysis has been performed. This allows 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 in the QC analysis:

- 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 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. During p–p ref data 4 end-of-run have been registered while 1 end-of-run during O–O 2 end-of-run during the Pb-Pb data taking periods have been registered. Only two small periods for a total of about one hour have been excluded from the reconstruction due to ITS, demonstrating the very high reliability of the detector. Moreover, no 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 for the whole data tacking period, 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 with respect to the pp data taking.

6 Femtoscopy and correlations studies

In 2025, the INFN Frascati group was involved in a recent ALICE milestone with the publication in *Nature* of the study of pion–deuteron correlations in pp collisions at $\sqrt{s} = 13$ TeV (1). The results provide the first model-independent experimental evidence on the microscopic mechanism responsible for the formation of light nuclei in high-energy hadronic collisions, in particular referred to small systems, such as pp collisions. The work represents the culmination of a research line initiated within the ALICE Collaboration by the Frascati group.

The contribution from the LNF group been strengthened within the ALICE Physics Board in 2025, in particular within the Correlations and Flow Physics Working Group, convened by a member of the Frascati group (O. Vazquez Doce) that is also member of the Editorial Board of ALICE.

6.1 Pion–deuteron femtoscopy and the mechanism of light-nuclei formation

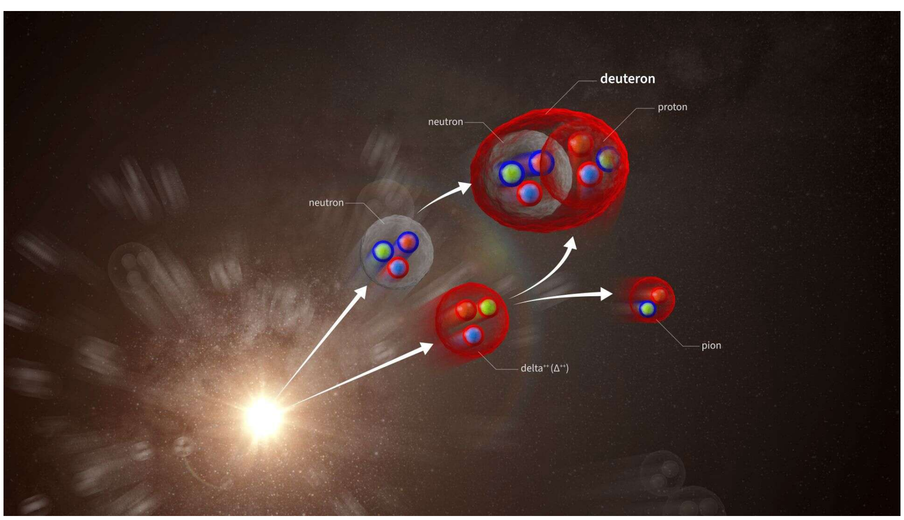

Figure 2: Representation of mechanism of formation of deuterons in pp collisions at the LHC, via nuclear fusion following resonance decay.

Understanding how weakly bound nuclear systems, such as the deuteron, can be produced and survive in the extreme environment created in ultra-relativistic collisions has remained an open question for decades. The deuteron is bound by only about 2 MeV, whereas the typical kinetic energies of hadrons produced at the LHC are of the order of 100 MeV. Two main classes of models have been proposed to describe the formation of light nuclei: statistical hadronisation models, which assume direct production of nuclei at chemical freeze-out, and coalescence-based approaches, in which independently produced nucleons combine through nuclear binding processes. So far, by using both frameworks one could reproduce inclusive yields, but a direct experimental access to the microscopic formation mechanism remained out of reach.

The ALICE measurement exploits femtoscopy techniques to investigate correlations of pion–deuteron pairs produced in high-multiplicity pp collisions. The correlation functions of $\pi^{\pm}$–d pairs are measured as a function of the relative momentum k^* and interpreted through a detailed modelling of Coulomb and strong final-state interactions, as well as residual correlations originating from resonance decays. The measured correlation functions exhibit a pronounced and wide peak structure at $k^* \approx 150$ MeV/c, which cannot be reproduced by models that assume thermal production or direct emission of deuterons.

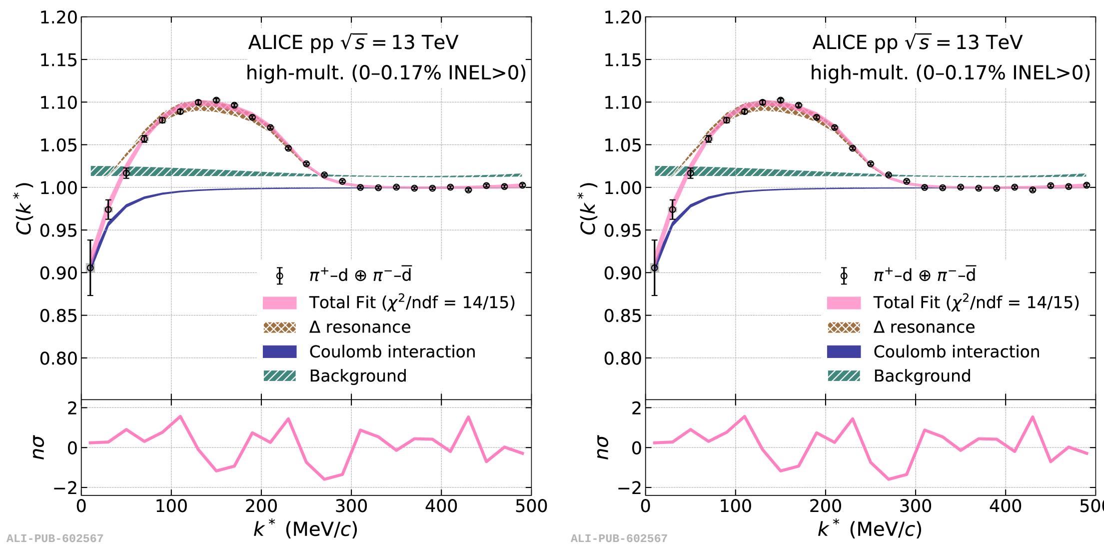

Figure 3: The black symbols represent the π^+–d (left panel) and π^-–d (right panel) correlation functions in high-multiplicity pp collisions measured by ALICE as a function of the relative momentum k^*. The total fit (pink) includes contributions from background (green), Coulomb final-state interaction (blue) and the effect of the Δ resonance decay (brown).

The experimental results are instead quantitatively described by a scenario in which deuterons are formed through nuclear fusion processes involving nucleons originating from the decay of short-lived baryonic resonances, in particular the $\Delta(1232)$. In this sequential formation mechanism, the Δ resonance first decays into a nucleon and a pion. The nucleon emerging from this decay subsequently fuses with a nearby nucleon to form the deuteron, while the accompanying pion carries away the excess energy required for the binding process. The presence of a residual correlation between the pion from the Δ decay and the nucleon participating in the fusion process generates a distinctive signature in the pion–deuteron correlation function, which is directly observed in the experimental data.

A data-driven analysis enables the extraction of the fraction of deuterons produced through Δ resonance decays. After correcting for detector acceptance and reconstruction effects, this fraction is determined to be $(60.6 \pm 4.1)\%$. By extrapolating this result to include contributions from all strong baryonic resonances, it is inferred that $(88.9 \pm 6.3)\%$ of the observed (anti)deuterons are produced through secondary binding processes involving nucleons emitted in resonance decays. These results demonstrate that the production of light nuclei in pp collisions is dominated by sequential nucleon fusion processes rather than direct emission at hadronization.

Additional information on the dynamical evolution of the system is obtained by studying the spectral properties of the Δ resonance extracted from the correlation measurements. The analysis indicates that the effective spectral temperature of the resonances involved in the deuteron formation is approximately 20 MeV, significantly lower than the average kinetic energy scale of hadrons produced during the early stages of the collision. This observation supports a scenario in which deuteron formation occurs at a later and colder stage of the system evolution, increasing the survival probability of these loosely bound states. The measurement also disfavors alternative production mechanisms, such as contributions from hypothetical di-baryon states, which are found to be compatible with at most a negligible fraction of the observed signal.

The implications of this result extend beyond collider nuclear physics. Light nuclei and antinuclei are also produced in cosmic-ray interactions and constitute important observables in indirect searches for dark-matter decay and annihilation. A precise determination of their microscopic formation mechanism provides essential input for modeling their production in astrophysical environments and for improving the interpretation of cosmic-ray measurements.

This publication represents one the most significant scientific highlights of ALICE in 2025 and establishes femtoscopy correlations as a powerful tool for investigating the formation of light nuclei in high-energy collisions.

7 ALICE scientific output

The ALICE Collaboration has published 42 papers in 2025 and to date 550 papers submitted to international referred physics journals, of which 524 already published (Fig. 4) since the birth of the ALICE experiment in 2009.

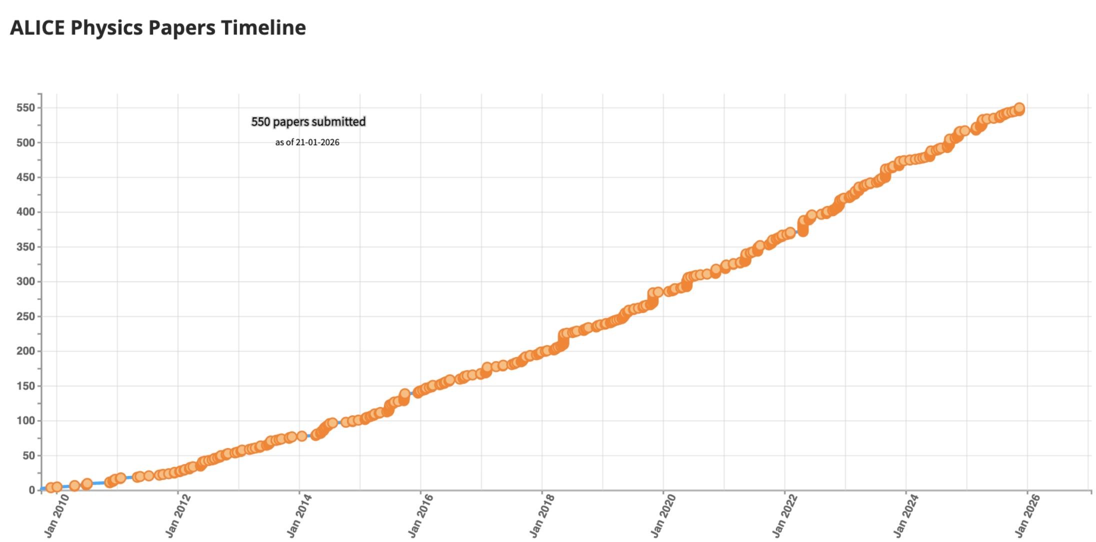

Figure 4: *Timeline of the total number of ALICE papers ("submitted" is to be intended as published+submitted) since the fist LHC beam at 900 GeV on November 23, 2009).*

The full list of ALICE publications for the year 2025 can be found online at the link:

https://alice-publications.web.cern.ch/statistics/2025
while the full list from 2009 is available at the link:
https://alice-publications.web.cern.ch/publications.

8 ALICE LNF talks

- A. Fantoni "Diversity, Equity and Inclusion in Astroparticle, Nuclear and Particle Physics", 3^{rd} Joint ECFA-NuPECC-APPEC Symposium (JENAS 2025), 08-11 April 2025, Didcot (United Kingdom)
- A. Fantoni "Outreach and Science Education in the European Physics Community", 29^{th} International Physics Conference (INPC 2025), 25-30 May 2025, Daejeon (Korea)
- F. Ronchetti, G. Erba, "Efficient Computing with the ALICE Event Processing Nodes GPU farm", Sustainable HEP 4^{th} edition, 12–15 May 2025, https://indico.global/event/4745
- F. Ronchetti, "EPN Overview", FSP ALICE Meeting, 02 September 2025, Grasellenbach (Germany), https://indico.cern.ch/event/1547695
- F. Ronchetti, "From Quarks to Bytes", closing lecture at the 2025 Cusanuswerk Physics Students Council, 14 September 2025, Bonn (Germany).
- O. Vazquez Doce, "Physics Highlights from PWG-CF related to QM2025 and additional new results from Run 3", ALICE Week, 17-21 March 2025, CERN, Geneva (Switzerland).
- O. Vazquez Doce, "Constraints with femtoscopy data in pp collisions", FemTUM25 Workshop, 14-16 April 2025, Sofia (Bulgaria).
- O. Vazquez Doce, "Adressing hadron interactions and exotic states via femtoscopy", Hadron2025, 27-31 March 2025, Osaka (Japan).
- O. Vazquez Doce, "Study of the deuterons emission time in pp collisions at the LHC", Quark Matter 2025, 6-12 April 2025, Frankfurt (Germany).
- O. Vazquez Doce, "Femtoscopy studies with ALICE: Accessing hadronic interactions and nuclei formation", HYP2025, 29 September - 3 October 2025, Tokyo (Japan).
- O. Vazquez Doce, "PWG-CF status and perspectives", ALICE Italy 2025, 24-26 November 2025, Catania (Italy).
- O. Vazquez Doce, "ALICE femtoscopy: Accessing hadronic interactions and nuclei formation", Zimanyi Winter School, 1-5 December 2025, Budapest (Hungary).

9 ALICE LNF publications (not as ALICE collaboration)

- F. Ronchetti and EPN Project, "Efficient high performance computing with the alice event1 processing node GPU-based farm," Frontiers in Physics 13 (Feb., 2025) 1541854. Section: High-Energy and Astroparticle Physics.
- ALICE Collaboration, "Online data processing with the EPNs", to be submitted to Computer Physics Communications (F. Ronchetti and Sarah La Pointe as main editors, in the ALICE internal review phase).
- O. Vázquez Doce et al., "Study of the deuterons emission time in pp collisions at the LHC via kaon-deuteron correlations", European Physical Journal A Vol.61, Article number 53 (2025)

References

1 . ALICE Collaboration, “Observation of deuteron and antideuteron formation from resonance-decay nucleons”, Nature **648** (2025) 306.