ALICE activity report 2022

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1 The ALICE experiment

The ALICE collaboration at CERN currently includes 40 countries, 171 institutions, and 1992 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, operation and physics analysis. In fact, the INFN-Frascati group played a key role in the construction and operation of the ALICE electromagnetic calorimeters (the EMCAL and the DCAL), in the upgrade foreseen for RUN3 (2021-24) with the construction of 1/4 of the new Inner Tracker System (ITS) Outer Layers (OL), and in the operation of the entire ALICE detector (Run and Commissioning Coordination, 2013-15 and 2019-22).

This report briefly summarizes the results obtained by the ALICE-LNF group during the restart of data taking in 2022 after the LS2 with the commissioning of the new ALICE Monolithic Active Pixel Sensors (MAPS) ITS which has replaced the old Run 1-2 device (based on hybrid pixel sensors, silicon strips, silicon drifts).

The INFN-Frascati group has been very active also for physics analysis and in particular for the extraction of the π, K, and p spectra from the newest high-energy data set of p-Pb collisions at 8.16 TeV, an essential reference analysis for any light flavor physics as well as for the light antinuclei that can be used to study cosmic-ray interactions and dark-matter annihilation and for the antikaon-deuteron femtoscopic correlations with ALICE.

Since fall 2019 the INFN-Frascati group covered different roles of responsibility, having a leading role to the ALICE Run Coordination, being in charge of the global ALICE commissioning and data taking operations until the end of 2022, and being an elected member of the Management Board of the ALICE experiment, participating by defaults also to the Physics and Technical Boards.

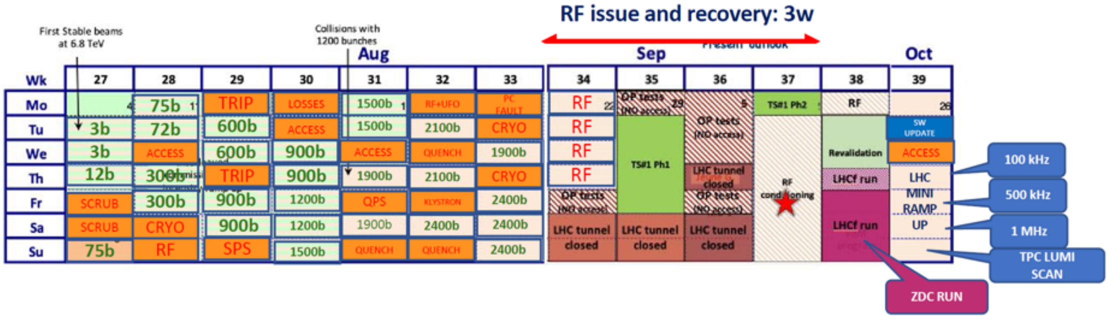
2 Run 3 restart overview

In September 2022, the CERN Council approved measures to reduce power consumption significantly as a mark of social responsibility in view of the ongoing energy crisis. As a result, the 2022 year-end-technical stop (YETS) started on 28 November, two weeks earlier than initially planned. As a consequence of this decision, the effective LHC schedule contraction with respect to the original plan amounts to 5.5 weeks, where 3.5 weeks have been lost for the RF recovery issue and 2 weeks for the extended YETS. Considering the shorter pp period, the Pb-Pb ion run has been postponed to 2023, when a longer ion run is planned to compensate for the lack of the HI run in 2022. Only two Pb-Pb fills at very low interaction rate have been provided in 2022, which turned out extremely useful for the commissioning of the ALICE apparatus.

3 2022 data taking

During 2022 the ALICE detector was fully commissioned with pp collisions during the LHC restart and commissioning phase. In addition, ALICE successfully integrated pp luminosity for the physics program, commissioned the ZDC during the LHCf run, and took data for the VdM scan and for the Pb-Pb test period. After the first collisions at 13.6 TeV on Tuesday, July 5^{th}, three days were dedicated to low rate magnet scans at different intensity steps and with different polarities of the solenoid. An interaction rate ramp-up from 100 kHz to 500 kHz was carried out in July to commission the apparatus and to check the performance at different interaction rates. ALICE also studied the detector response and stability with high-rate tests up to 4 MHz to test the full apparatus and data processing chain, where 4 MHz pp gives a particle occupancy in the TPC similar to Pb-Pb collisions at 50 kHz interaction rate, the ALICE Pb-Pb design value. The commissioning and the tests of the ALICE detector were delayed by the recovery of the LHC RF issue (August 23^{rd} to September 22^{nd}).

As shown in Fig.1, after the restart of LHC on September 22^{nd} during the special LHCf run, ALICE commissioned the ZDC detector, while during the LHC mini ramp up data was collected with gradually increasing interaction rates from 100 kHz to 1 MHz (visible).



Wk	27	28	29	30	31	32	33	34	35	36	37	38	39
Mo	4	75b	TRIP	LOSSES	1500b 1	RF+UFO	PC FAULT	RF 22	OP tests (NO access) 29	5	TS#1 Ph2	RF	26
Tu	3b	72b	600b	ACCESS	1500b	2100b	CRYO	RF	TS#1 Ph1	OP tests (NO access)	RF conditioning	Revalidation	SW UPDATE
We	3b	ACCESS	600b	900b	ACCESS	QUENCH	1900b	RF					ACCESS
Th	12b	300b	TRIP	900b	1900b	2100b	CRYO	RF		LHC tunnel closed		LHCf run	LHC MINI RAMP UP
Fr	SCRUB	300b	900b	1200b	QPS	KLYSTRON	2400b	OP tests (NO access)		OP tests (NO access)		LHCf run	
Sa	SCRUB	CRYO	900b	1200b	1900b	2400b	2400b	LHC tunnel closed	LHC tunnel closed	LHC tunnel closed			
Su	75b	RF	SPS	1500b	QUENCH	QUENCH	2400b						

Figure 1: *LHC schedule from July to September 2022. During the first months of pp data taking at 13.6 TeV ALICE commissioned the full apparatus and data processing chain, including dedicated data taking for TPC and ZDC commissioning and high rate tests.*

The YETS started two weeks earlier and the HI period has been then postponed to 2023. As shown in Fig.2, two days were dedicated to Pb-Pb collisions at low interaction rates using the LHC proton cycle at top energy. In the last months of the 2022 data taking, ALICE continued to pursue the commissioning campaign and succeeded in taking data with all the 15 detectors during the Pb-Pb test period.

The TPC zero suppression in FW was not yet using the final dense format, designed to effectively handle Pb-Pb collisions at 50 kHz interaction rate. As shown in Fig.2, the dense format firmware has been validated at the end of data taking and it will be available in 2023. For these reasons almost all the EPN GPU farm resources have been used by the data acquisition and they were not available for the pp asynchronous reconstruction. When the final dense format will be available, the synchronous processing of 650 kHz pp collisions with the current level of optimization will require about 40% of the present EPN resources (280 nodes, 2240 GPUs).

3.1 2022 physics pp data taking

ALICE collected 17.6 pb^{-1} of pp at 13.6 TeV with the barrel detectors, of which 16.1 $^{-1}$ have been collected at 500 kHz visible interaction rate, corresponding to 650 kHz inelastic rate.

A higher interaction rate than previously reported has been chosen to compensate for the reduction of LHC running time in 2022. In addition to the pp physics runs, ALICE collected data during the rate scans, tests, special runs with high pileup (μ(INEL)¿0.1) and with inelastic interaction rate higher than 1.3 MHz. The last samples cannot be used for physics because the tracking system cannot discriminate the primary vertices, so they are not included in the physics

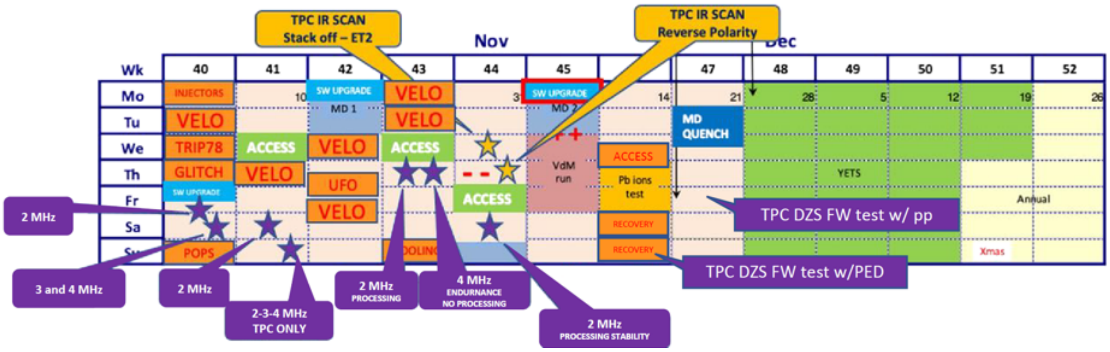


Figure 2: *Revised LHC schedule from October to November 2022. During the last months of pp data taking at 13.6 TeV ALICE continued to commission the full apparatus and data processing chain. Furthermore, ALICE successfully integrated pp luminosity for the physics programme, commissioned the ZDC and took data during the vdM scan and the Pb-Pb tests.*

processing. The total integrated luminosity available for the pp full field physics program amounts to 13.8 pb^{-1} at about 650 kHz and 1.2 pb^{-1} at about 1.3 MHz, which corresponds to 1.1x10^{12}12 and 9.8x10^{11} collisions, respectively.

This is an unprecedented pp data sample for ALICE, compared with about 2.6 10^9 events collected in Run 2. As already discussed in the previous report, the luminosity integrated in 2022 has been dedicated to the Run 3 pp physics program, for which a highly-discriminating software-based event selection has been applied after the asynchronous reconstruction passes. Since the Pb-Pb data taking and the related processing has been postponed to 2023, almost all pp physics have been accommodated in the O2 disk buffer (see for example Fig.3). This allowed further optimization of the pp processing plan with the aim of improving the physical selections. Two large processing calibration campaigns on the full statistics were run in December with a partial detector alignment and in January with the final detector alignment. The last pass with the central barrel alignment allowed to extract the correction maps of the TPC space-charge distortions. In addition, the two calibration passes allowed to verify the quality of the data, to validate the detector calibrations and to validate the reconstruction on GPU and on CPU.

The asynchronous reconstruction pass of the pp data with all calibrations is expected to begin before the end of February 2023 and to take about 20 days. This will enable the highly-selective event selection with similar accuracy as in physics analysis. At the end of event selection, the original CTFs will be further compressed by removing all information not associated with any of the collisions of interest. To include TPC clusters potentially belonging to the secondary tracks that are not pointing to the primary vertex (e.g. from strange hadron decays) all clusters attached to tracks that point to the tagged primary vertex within a fiducial region of ±30 cm along the beam direction are kept. Thus, taking into account the TPC drift time of 97 μs for 250 cm length and the interaction rate of 650 kHz, 15 events per tagged collision will be kept, corresponding to 1.5% of the original CTF size. This will amount to about 0.8 PB of data using a more conservative compression strategy for the CTF files, where only the clusters that are identified as background or attached to a background track are removed during the synchronous processing. To compensate for the lack of a Minimum Bias (MB) pp reference sample that was planned to be collected at 5.36 TeV during the HI period, the ALICE collaboration opted to retain on tape 1 pb^{-1} of minimum bias pp at 13.6 TeV, which corresponds to about 4 PB of CTF files. This sample will be used for the analyses that are not based on the software trigger selections, such as heavy-flavour production

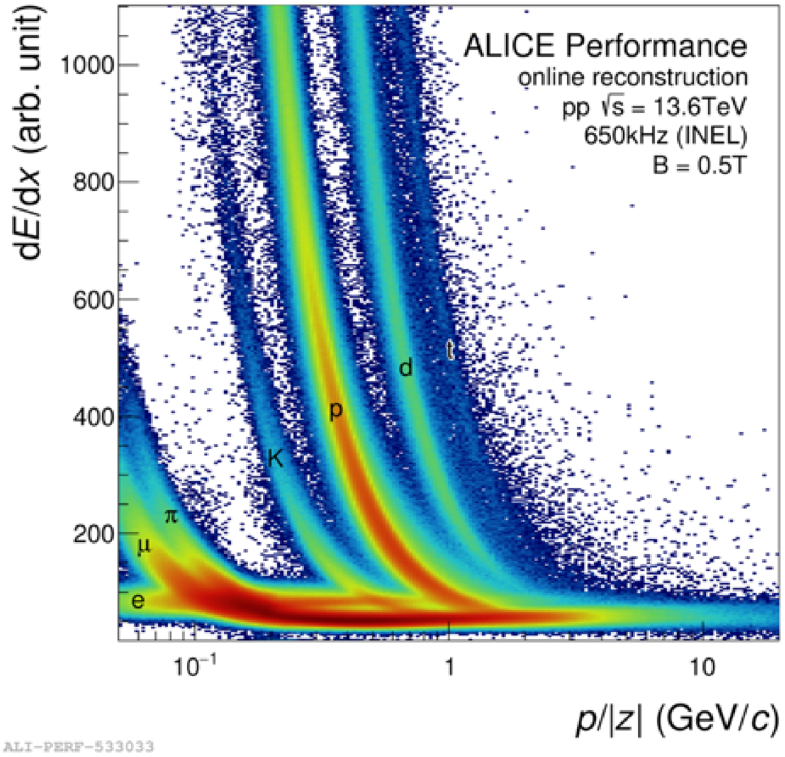


Figure 3: *TPC energy loss (dE/dx) as a function of momentum from the synchronous processing on the EPN farm.*

at low momentum and low event multiplicity, photon and dielectron production.

3.2 Pb-Pb test

On November 18^{th} after one day of commissioning and crystal collimation tests (needed to reduce the rate of luminosity induced dumps due to secondary ion beam), two fills of stable beam collisions of Pb-Pb ions were provided, totaling 16 hours of data taking and reaching a maximum of 60 Hz interaction rate. LHC adapted the proton cycle with the record energy of 6.8 Z TeV, i.e. 5.36 TeV centre-of-mass energy per nucleon pair. In the first fill, individual bunches collided, while in the second fill 50 ns slip stacked Pb trains for each beam were injected into LHC for the first time. The newly commissioned slip-stacking technique allows the SPS to inject train of Pb-Pb bunches with a 50 ns spacing (to be compared with the 75 ns spacing used in 2018) allowing for a further boost of the instantaneous luminosity expected in Pb-Pb collisions. All 15 detectors were involved in the data taking, reaching an efficiency of 97.6% during the second fill (see Fig.4).

ALICE succeeded in collecting 1.1x10^6 Pb-Pb collisions, both CTF and raw TF files were recorded on the O2 disk buffer and later archived on tape, totaling 3.68 PB. Since 1M events are enough for many basic measurements to validate the performance, the Pb-Pb sample underwent 5 subsequent asynchronous reconstruction passes with increasing quality of the calibrations. The resources needed to accomplish the processing of the Pb-Pb test data in 2022 are negligible compared to those needed for the pp data taking.

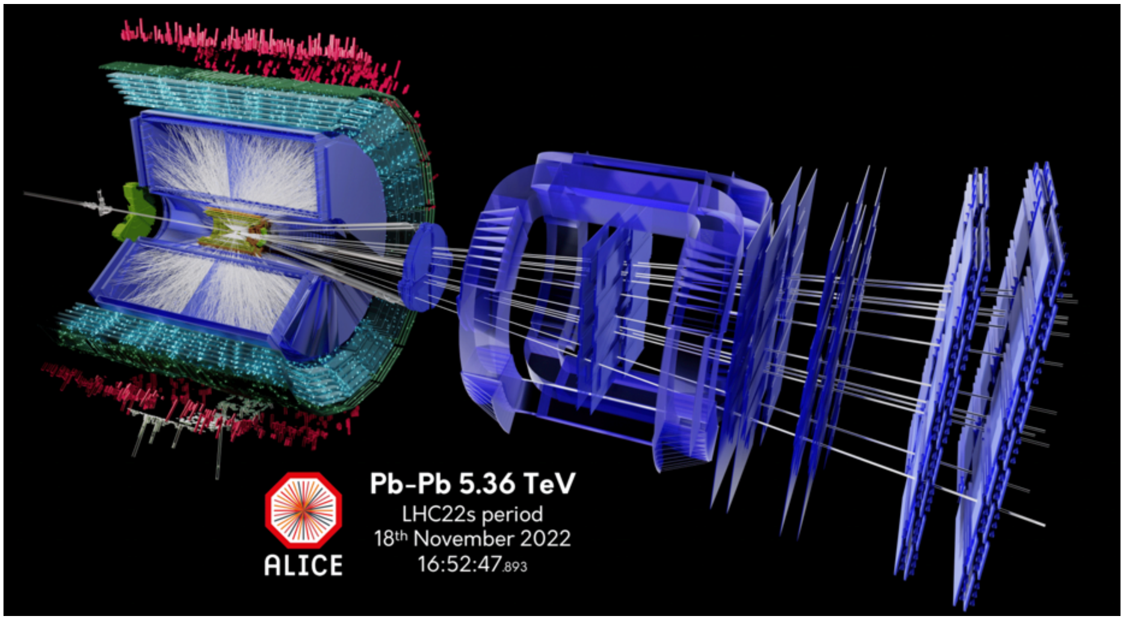


Figure 4: *A central Pb-Pb collision event recorded during the test collisions at 5.36 TeV in November 2022.*

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 contributed to the commissioning of the detector and during the data taking in 2022 (Run3) has contributed 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).

With the restart of Run3 data taking, in 2022 there have been 159 physics fills with stable collisions, 34.7 pb^{-1} of luminosity delivered to ALICE (with about 18 pb^{-1} as the recorded one) $\sim$620 physics runs with ITS, $\sim$690 hours of data taking and $O(10^{12})$ interactions recorded for pp physics, while 2 fills in stable collisions with a total of 5 runs, 10.6 hours and $O(10^{6})$ hadronic interactions record for PbPb physics. The QA team has analyzed the new run period 3 times per week, coordinated via the JIRA ticket system.

In order to define a bad run from the 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.

ITS demonstrated stable performance in the initial stage of Run 3. The Quality Check (QC) is an effective tool for the run quality assessment and filtering bad data. From the beginning of Run 3, the full ITS QA Team (including also the analysis of Fake-hit rates and Front-End-Electronics done by other groups) considered 5.6% of physical runs as bad.

5 Physics contribution

5.1 Analysis on light-flavor

During 2022, the LNF activity on the data analysis in the light-flavor field has been focused on the completion of the measurement of the light hadron spectra. The distributions in transverse momentum of pions, kaons and protons have been extracted on the pPb data set collected at a center-of-mass energy of 8.16 TeV. The so-called small systems (where at least one of the colliding beam is composed of protons), indeed, represent an essential reference for the under- standing of the collision dynamics, and allow to disentangle the effects due to the emergence of a deconfined state (the Quark Gluon Plasma) - expected to occur only in PbPb collisions - from the so-called cold nuclear matter effects, that can mimic the former. The spectra for pions and kaons are going through the final stages of the paper proposal process. Proton spectra have been included in the study of the formation mechanism of light nuclei and anti-nuclei, in particular deuterium and ^{3}He. Two main models, indeed, are presently used to describe the mechanism that nucleons undergo for forming a two or three-nucleon nucleus: the Statistical Hadronization Model and the Coalescence model. These two approaches are sensitive to different characteristics of the formation process: while the former, indeed, is mainly sensitive to the mass and the spin degeneracy of the formed nucleus, the second is also sensitive to the size of the latter, since the coalescence process implies the proximity of two nucleons (that should also be close in the phase space) and is then sensitive to the source size. A possible approach for disentangling between the two models consist in testing them for nuclei of different sizes, and, in this perspective, ALICE produced the most accurate sets of data extracting the relevant observables for different light nuclei (as deuterium and helium) in different colliding systems and at different energies. In this perspective, one of the most interesting observable is the ratio of the deuteron and helium yields to the proton ones, and the evolution of this ratio as a function of the final charged particle multiplicity. The proton spectra measured in the Frascati group entered this measurement by providing the latter. The paper has been submitted to Physics Letters B and is presently undergoing the review process. A preprint is available at the link https://arxiv.org/pdf/2212.04777.pdf

5.2 Analysis on light antinuclei

The observation of antinuclei such as $^3\bar{\mathrm{He}}$ is one of the most promising signatures of Dark Matter (DM) annihilation of weakly interacting massive particles. The kinetic-energy distribution of antinuclei produced in DM annihilation peaks at low kinetic energies (E_{kin} per nucleon $\leq$0.1 GeV/A) for most assumptions of DM mass. In contrast, for antinuclei originating from cosmic-ray interactions the spectrum peaks at much larger E_{kin} per nucleon ($\simeq$10 GeV/A). Thus, the low-energy region is almost free of background for DM searches. Since no $^3\bar{\mathrm{He}}$ beams are available, the antimatter production at the LHC and the excellent identification and momentum determination for ^{3}He in ALICE has been used as an equivalent setup. In this study, the ALICE detector itself has served as a target for the inelastic processes.

The disappearance probability of $^3\bar{\mathrm{He}}$ when it encounters matter particles and annihilates or disintegrates within the ALICE detector at the Large Hadron Collider has been determined. The inelastic interaction cross section has been extracted (Fig 5) and then used as input to calculations of the transparency of our Galaxy to the propagation of $^3\bar{\mathrm{He}}$ stemming from dark-matter annihilation and cosmic-ray interactions within the interstellar medium.

For a specific DM profile, a transparency of about 50% has been estimated, varying with increasing $^3\bar{\mathrm{He}}$ momentum from 25% to 90% for cosmic-ray sources. The results indicate that $^3\bar{\mathrm{He}}$ nuclei can travel long distances in the Galaxy, and can be used to study cosmic-ray interactions and dark-matter annihilation. The Frascati group has been involved in this analysis and one of the member has been one of the main analyser and author of the paper, published on Nature Physics (1).

The measured $\sigma_{inel}(^3\bar{\mathrm{He}})$ and the developed methodology can be employed to carry out the propagation of $^3\bar{\mathrm{He}}$ using any DM or cosmic-ray interaction modelling as a source. Since a large separation between signal and background is retained for low kinetic energies,our results clearly underline that the search for $^3\bar{\mathrm{He}}$ in space remains a very promising channel for the discovery of DM. These studies will be extended to $^4\bar{\mathrm{He}}$ and to the lower momentum region in the near future with much larger data sets that will be collected in the coming few years.

5.3 Fellini Project

In the framework of the project "Femto-Strong" carried out by Fellini MSCA-EU fellow Oton Vazquez Doce, studies of the strong interaction among kaon-deuteron and antikaon-deuteron pairs, via experimental determination of their correlations in the momentum space (femtoscopy) have been performed. The project has been extended with the application of three-body femtoscopy technique to p-p-K^- and p-p-K^+ triplets.

Deuterons play an important role in nuclear physics since their properties can be used to constrain nuclear interactions between three- and few-body systems that are essential ingredients to understand the structure of nuclei, hypernuclei and the characteristics of dense nuclear matter (3). The three-body forces are actually relevant as well for the description of the anti-kaon deuteron interaction. It has been demonstrated that full three-body calculations are necessary to perform accurate predictions of the characteristics of the antikaon-deuteron systems and the expected shift and width of the X-rays from the lower energy levels transitions of the antikaonic deuterium (2).

However the formation mechanism of deuterons and light nuclei in hadron–hadron collisions is still not well-understood. Two different scenarios are under discussion: i) The thermal model, based on results from heavy ion collisions, assumes that deuterons are formed from their six constituent quarks at the same time as any other hadron; ii) The coalescence model supports the idea of deuterons resulting from final state interactions of nucleons with other hadrons.

The correlation function in momentum space of deuterons and kaons and antikaons have been studied using the data collected by ALICE during RUN-2, specifically high-multiplicity pp collisions at 13 TeV. The kaon-deuteron correlation function, that reveals the repulsive character of both the Coulomb and strong interaction, is compared with theoretical expectations. The scattering parameters for the kaon-deuteron system have been provided by theoreticians T. Hyodo and R. Haidenbauer, based in the kaon-nucleon scattering lengths and the impulse approximation. By using the Lednický formalism(4), one can calculate the s-wave relative wave function for non-identical charged particles starting from such scattering parameters and considering the pertinent corrections for Coulomb effects. The two-particle wave-function describing the interaction, and the distribution of relative distances between the particles at emission are the necessary ingredients in

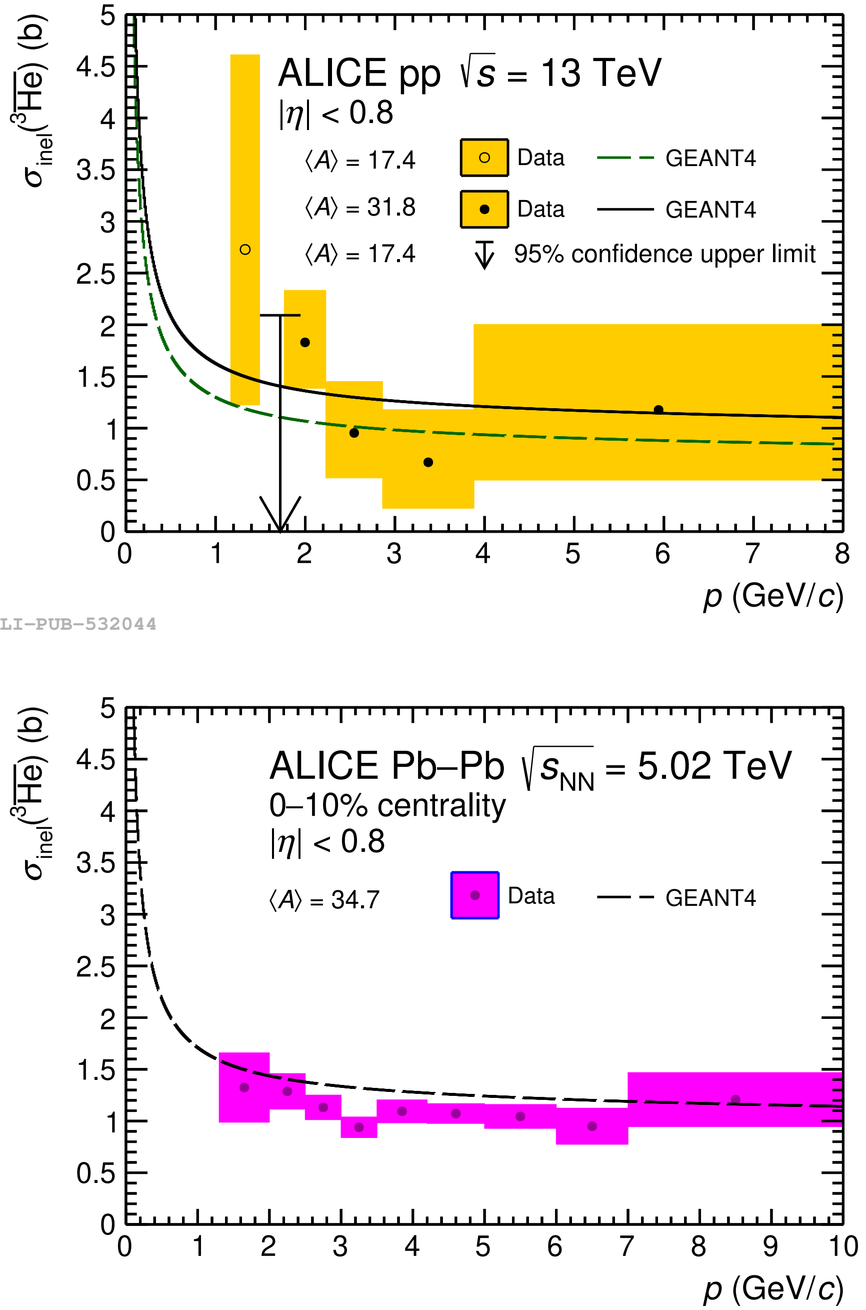


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Figure 5: *Results for* $\sigma_{inel}(^{3}\bar{\mathrm{He}})$ *as a function of* $^{3}\bar{\mathrm{He}}$ *momentum. Results obtained from pp collisions at* $\sqrt{s}$*=13 TeV (up); results from the 10% most central Pb–Pb collisions at* $\sqrt{s_{NN}}$*=5.02 TeV (down). The curves represent the GEANT4 cross sections corresponding to the effective material probed by the different analyses. The arrow on the upper plot shows the 95% confidence limit on* $\sigma_{inel}(^{3}\bar{\mathrm{He}})$ *for* $< A >$*=17.4. The different values of average mass number* $< A >$ *correspond to the three different effective targets (see the paper for details). All the indicated uncertainties represent standard deviations.*

order to compare our experimental correlation function with a theoretical expectation. From the comparison one can see that the relative distances at which kaon-deuteron pairs emerge from the collision are compatible with those observed in the production of baryon-baryon pairs, as studied in (5) where small source sizes of around 1 fm where observed. This result hints for a scenario where the deuteron formation follows the nucleon production.

The results from kaon-deuteron femtoscopy have been combined with similar studies performed on proton-deuteron pairs in the same collision system. On the contrary to the kaon-deuteron result, the proton-deuteron correlation function cannot be explained by using the available scattering parameters and applying the Lednický formalism. Such approach leads to a huge discrepancy with the data showing that the proton-deuteron system cannot be explained as a two body system of indistinguishable particles. A full-fledged three-body calculation that considers a detailed description of the deuteron wave function is necessary to interpret the experimental data for proton-deuteron pairs.

An alternative method to access the dynamics of three-body systems with kaons is the study of the femtoscopic study of p-p-K^- and p-p-K^+ triplets. The study is also performed using high-multiplicity pp collisions at 13 TeV and follows the method described in (6). The three-body p-p-K^- and p-p-K^+ correlation functions are obtained, and via the Kubo expansion method, a three-body cumulant is calculated, where the lower order correlations (two-body correlations in this specific case) are removed from the original correlation function. In order to extract such lower order correlations, a simultaneous measurement of the correlation function of all possible particle pairs within the triplet of interest is performed, and used to obtain continuous distribution as a function of the relative momentum of the three particles. The resulting cumulant for the p-p-K^- case, approved as preliminary result during 2022, can be seen in Fig 6, where effects beyond the two-body interaction are absent. The result indicates that the dynamics of the p-p-K^- system is dominated by two-body interactions and no three-body effect arises with statistical significance with the current precision with Run-2 data.

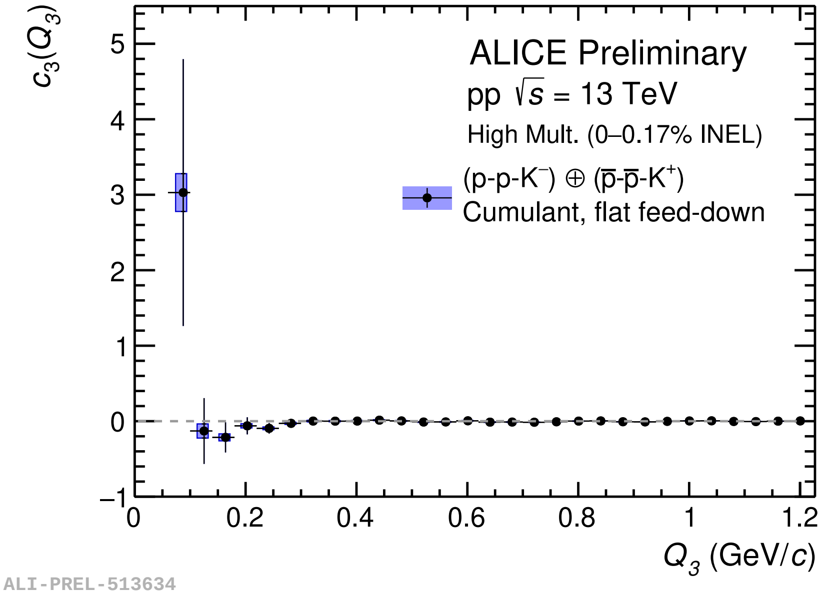

Figure 6: *Cumulants for the primary triplets p–p–K^-*

Two paper proposals were approved by the ALICE physics forum during 2022 for each of the presented analyses. The paper committees, including in both cases Oton Vazquez Doce, are currently working the corresponding drafts with tentative titles "Accessing three-body forces with femtoscopy at the LHC" and "Study of the p–p–K^+ and p–p–K^- dynamics using the femtoscopy technique". It is demonstrated how the strong interaction in three baryon systems can be studied via femtoscopy in small collision systems and how by using hadron-deuteron and three-body correlation functions one can access the three-body effects.

Such studies will be continued by Oton Vazquez Doce as permanent Researcher at the Frascati laboratories.

6 ALICE scientific output

The ALICE Collaboration has published 32 papers in 2022 and to date 426 papers submitted to international referred physics journals, of which 366 already published (Fig. 7).

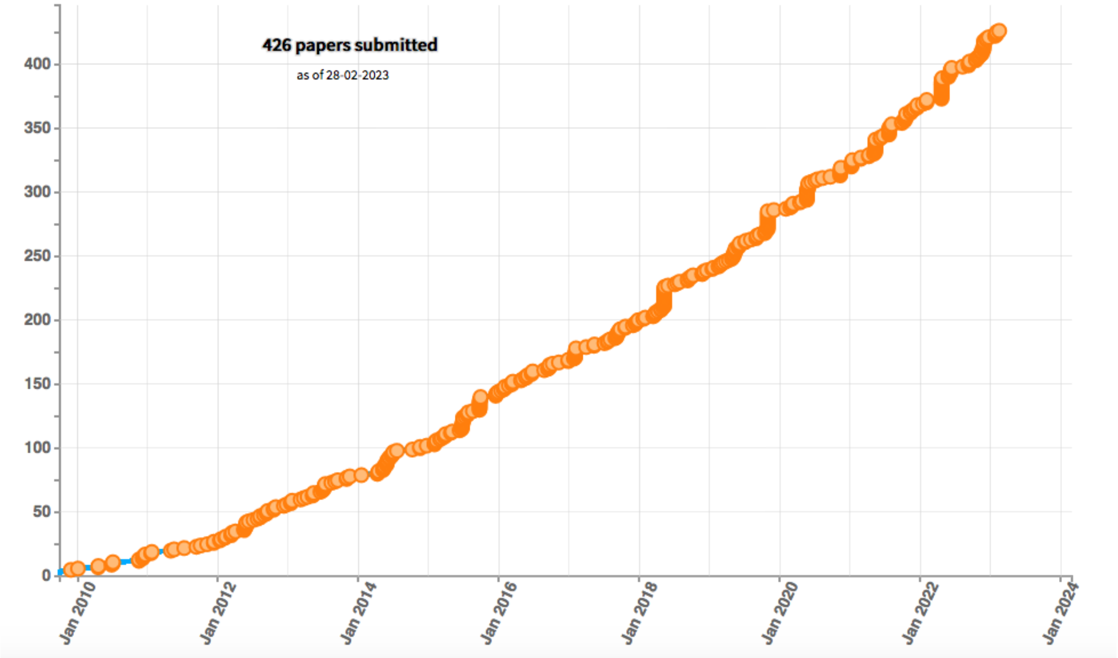

Figure 7: *Timeline of the total number of ALICE papers ("submitted" is to be intended as published+submitted) since the fist LHC beam at 900 GeV on November 23, 2009).*

The full list of ALICE publications for the year 2022 can be found online at the link: https://alice-publications.web.cern.ch/statistics/2022 while the full list is available at the link: https://alice-publications.web.cern.ch/publications

References

1 . ALICE Collaboration Nature Phys. 19 (2023) 1, 61-71; e-Print: 2202.01549 [nucl-ex]

2 . W. Horiuchi, T. Hyodo and W. Weise, “Kaonic deuterium and low-energy antikaon-nucleon interaction”, EPJ Web Conf. **181**, 01006 (2018)

3 . A. Akmal, V. R. Pandharipande and D. G. Ravenhall, “The Equation of state of nucleon matter and neutron star structure”, Phys. Rev. C **58**, 1804-1828 (1998)

4 . R. Lednicky, “Finite-size effects on two-particle production in continuous and discrete spectrum”, Phys. Part. Nucl. **40**, 307-352 (2009)

5 . S. Acharya *et al.* [ALICE], “Search for a common baryon source in high-multiplicity pp collisions at the LHC”, Phys. Lett. B **811**, 135849 (2020)

6 . [ALICE], “Towards the understanding of the genuine three-body interaction for p−p−p and p−p−Λ”, [arXiv:2206.03344 [nucl-ex]].