LHCb

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LHCb is a dedicated heavy-flavour physics experiment at the Large Hadron Collider (LHC), primarly designed for precision measurements of CP violation and rare decays of beauty and charm hadrons. However, its physics reach has significantly expanded in recent years, now covering areas such as hadron spectroscopy, astroparticle physics, heavy-ion collisions, and dark matter searches. LHCb has published more than 900 papers, mainly based on the full Run 1 + Run 2 datasets. During Run 2 (2015-2018), LHCb successfully overcame many operational challenges and collected $\sim$7 fb^{-1}, in addition to the $\sim$3 fb^{-1} collected in Run 1. Run 3 data taking is still ongoing, but the currently collected luminosity of $\sim$20 fb^{-1} (pp collisions) has already significantly exceeded the statistics collected during Run 1+2.

The collaboration is currently deeply involved in the research and development of detectors for the future upgrade-II, in parallel with the demanding data taking activities.

During the LHC LS2, a gas fixed-target system was installed in front of the VELO detector. The implemented storage-cell technology allows the controlled injection of a limited amount of gas into a well-defined volume inside the LHC beam pipe. With beam-gas interactions occurring at $\sim$4% of the proton–proton collision rate at LHCb, the beam lifetime remains largely unaffected. This makes LHCb the first experiment able to operate simultaneously with two distinct interaction regions, Ref [1].

In 2025, LHCb successfully achieved the ambitious and unique goal of collecting data with several collision systems, Fig. 1. In particular, in beam-beam mode: pp (11 fb^{-1}), pO (40 nb^{-1}), OO (4 nb^{-1}), NeNe (0.6 nb^{-1}), and PbPb (0.8 nb^{-1}). In beam-gas mode, the collision systems and the corresponding integrated luminosities are: pH$_2$ (15 pb^{-1}), pD$_2$ (7 pb^{-1}), pHe (1 pb^{-1}), pNe (0.9 pb^{-1}), pAr (2 pb^{-1}), OH$_2$ (1 nb^{-1}), NeNe (0.02 nb^{-1}), PbH$_2$ (0.1 nb^{-1}), PbNe (0.5 nb^{-1}), PbAr (2.5 nb^{-1}).

As part of the Muon System and SMOG2 projects, the LHCb Frascati group is deeply involved in all ongoing experimental activities. These include detector operations (with key hardware responsibilities), flagship data analyses, and R&D for the proposed long-term upgrades.

1 Data analysis activity

The LNF group has a long history of strong involvement in the analysis of $B^0(s) \to \mu\mu$ decays. These decays are extremely rare and provide theoretically clean observables to probe New Physics beyond the Standard Model. A new analysis based on Run 3 data is ongoing and is jointly coordinated by the LNF and Cambridge groups. The analysis is both a strong test bench for the Upgrade-I LHCb detector, in particular concerning the muon detector, and an opportunity to reach unprecedented precision on both the branching fraction and effective lifetime.

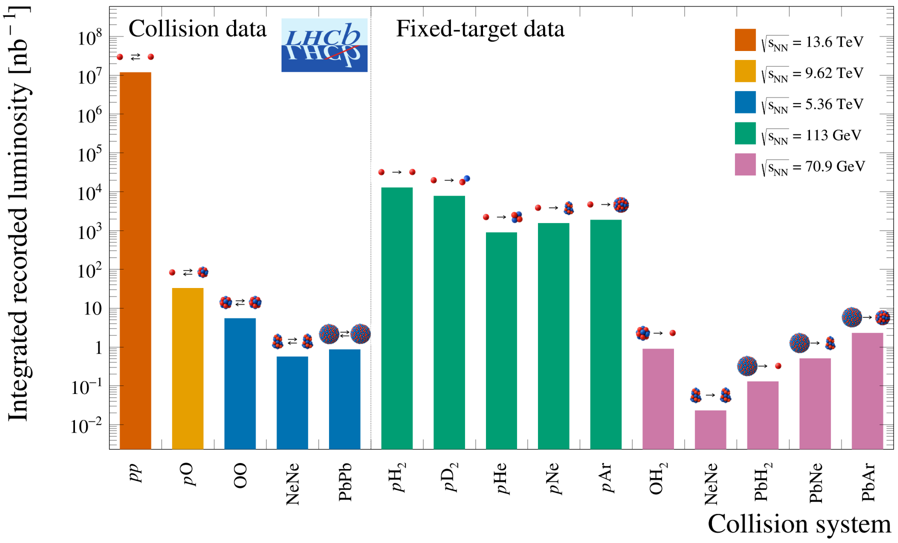

Figure 1: Integrated luminosities collected during the 2025 data taking for all the collision systems.

The group has also focused on the measurement of $R(D_s^*)$ using data collected during Run 2. This work is well advanced and is expected to be completed by the middle 2026. The same dataset is currently used also for the full angular analysis of the $B_s \to D_s^*(\to D_s\gamma)\mu\nu_\mu$ decay, with the goal to extract the form factors and to constrain possible new physics contributions. In addition, the full differential spectra, properly unfolded for the resolutions and corrected for the efficiency effects, will be published. This will allow a reinterpretation of the data. The analysis is expected to be finalized by summer 2026. One of the main results will be the publication of the full differential rate as open data.

Recently, the LNF group joined the effort to measure the production fractions of B_s and Λ_b hadrons using the Run 3 data collected in 2024. This measurement is being conducted in collaboration with the US Syracuse LHCb group. The analysis involves a simultaneous study of the semileptonic decays of various b-hadrons and is expected to be finalized toward middle 2026. It will represent one of the first analyses of the LHCb semileptonic WG based on Run 3 data. Using the same dataset, and in collaboration with Maastricht University, we started in 2025 a measurement of the production fraction of the B_s relative to the B^+, using exclusive semileptonic decays $B_s \to D_s\mu\nu$ and $B^0 \to D^+\mu\nu$. This is a novel approach to measure the b-hadron production fractions, which exploits the ongoing precise calculation of the form factors for these processes expected with Lattice-QCD. This approach could also be extended to other b-hadron species.

Neutral feebly interacting particles (FIPs) (also dubbed long-lived particles, LLPs) with masses at the weak scale are a highly theoretically motivated possibility for physics beyond the Standard Model, as possible solutions for outstanding problems in modern particle physics as the nature of Dark Matter, the mechanism of baryogenesis, and the hierarchy problem. The LHCb experiment, thanks to the new software trigger, has the potential to explore lifetimes up to $\sim$30 ns. This new LHCb potential is opening a new avenue in the search for FIPs, as it increases the decay volume by about one-two orders of magnitude with respect to what is currently possible at the other LHC detectors. The analysis developed at LNF (in collaboration with Valencia, NIKHEF, and EPFL groups) mostly focuses on searches for scalar or pseudo-scalar particles ϕ coming from $b \to s\phi$ decays. The considered dataset corresponds to $\sim$ 3.3 fb^{-1} collected with the new software trigger. Preliminary studies show an improvement in the sensitivity of the coupling strength of about two orders of magnitude with respect to the current limits between the dimuon mass and the kinematic limit. The result has been already presented and the finalization of the analysis is foreseen in about one year.

Other relevant analyses have been conducted using fixed target data. A novel measurement focused on the double-differential production cross-section of the ϕ meson, decaying into two kaons, as a function of transverse momentum and rapidity. This measurement, the first of its kind at this centre-of-mass energy and unique in this kinematic range, also provided constraints on models based on predictions generated by Pythia or Epos. A second, ongoing analysis aims to measure, again for the first time and in a largely explored kinematic domain, the $\Upsilon(nS)$ particle. This bottomonium meson, characterized by three different bounding energies corresponding to the 1S, 2S, and 3S states, is considered a thermometer for the Quark–Gluon Plasma (QGP), since its production and survival probabilities are strongly sensitive to the temperature of the medium created in heavy-ion collisions.

2 Operations during Run3

The goal of LHCb detector to take data for pp collisions at an instantaneous luminosity of $2 \times 10^{33}\ cm^{-2}s^{-1}$, which is five times higher than during LHC Run 2. A key requirement is the ability to process the full 30 MHz bunch crossing rate of the LHC using a dedicated computing centre. This software-only approach requires two stages: a fast reconstruction and selection stage, referred to as HLT1 and running on GPUs, and a second step with full reconstruction and real-time analysis, known as HLT2 and running on CPUs. Between the two trigger stages, the real-time alignment and calibration of the detector are performed. The Real Time Analysis (RTA) is fully working aiming to develop and maintain the full software trigger and the real-time processing of LHCb's data for Run 3 and beyond. The Frascati group has contributed to the RTA project by developing the software for decoding the muon system data and for identifying muons in both HLT1 and HLT2. Data collected during 2025 were also used to measure the Muon Identification performance in both trigger stages.

The LNF group is also deeply involved in developing the new online monitoring system, a key component of the operation of the upgraded LHCb detector. While extensive experience was gained during Runs 1 and 2, the foreseen large increase of the data rate imposes new constraints on the monitoring system.

Regarding the Muon System, an excellent design with large redundancy factors and high construction quality allowed to run the detector at ×2 with respect to the design luminosity for the whole Run 1 and Run 2, and to move forward for another decade of operation at ×10 of the original design luminosity. Significant effort has been devoted to planning the activities towards next Runs starting from Run 3 in 2022. To mitigate the high rates expected in the inner regions of the second station (M2) an additional shielding behind the HCAL was designed and built. The installation, started in 2019, was completed at the beginning of 2021. In addition, in the years 2015-2018 a substantial number of MWPC spares have been produced at LNF, such as to guarantee efficient operation for the next 10 years.

The off-detector electronics boards (Service Boards, nSB, Pulse Distribution Module, nPDM, and Off-Detector, nODE) of the Muon system have been completely redesigned to be compliant with the 40 MHz readout of the detector. The LNF electronic team (LNF-SEA), has produced, tested and commissioned the 185 nODE boards; the apparatus is fully instrumented with the needed 144 nODE and successfully took data since 2022. Since the new ODE board required to review the architecture of the Electronic Control System (ECS) completely, a new version of the nSYNC libraries with all the basic functions implemented has been deployed beginning of 2021 allowing for the systematic connectivity tests (CT) of the stations, all equipped with the new nSB and nODE boards. Still using the ECS features, we built an online luminosity monitor using the currents measured through the HV system. A Muon-luminosity monitor has been added to the others already in operation in LHCb.

The Muon software trigger lines for the upgrade phase will have to guarantee an adequate signal to background ratio, while respecting, at the same time, the severe timing constraints required by the full software trigger adopted for the upgrade. For this another important contribution to the present performance of the Muon System has been the in deep review of the software used to reconstruct the muon information and to make it available for the collaboration. This code, mostly produced at the beginning of the 2000's demonstrated to be highly performing and needed a review mainly for the increasingly stringent timing requests. The measurement of the muon hit efficiency and its online implementation confirmed MWPC still operate at efficiencies above 99%, with localized inefficiencies being addressed during technical stops. A thorough study of the muon identification performance has been carried out with 2024 and 2025 data, confirming results similar to those of Run 2 but under a much higher event occupancy. Both studies have been documented in a thesis [2] and two detailed internal notes [3, 4]. Additionally, a dedicated study on simulation has been carried out to help determining the quality of the recorded data in case of issues with the muon detector [5]

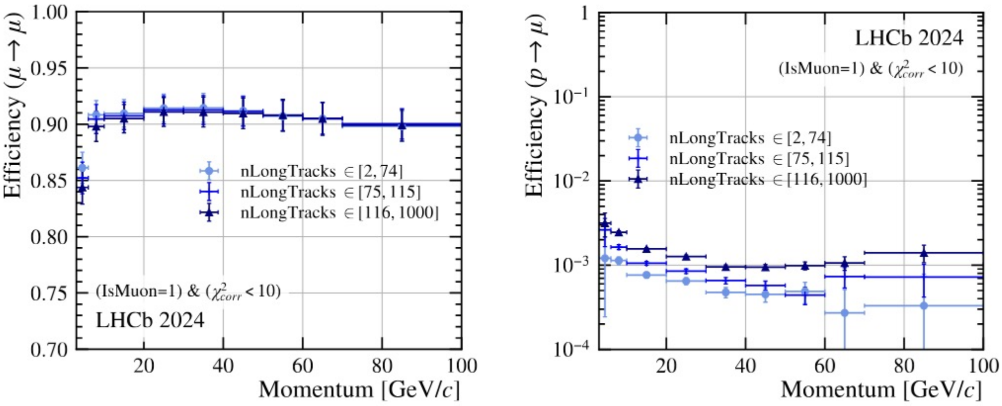

Figure 2: *Proton to Muon misidentification rate as measured in 2024 data.*

Finally, a paper describing the performance of the muon detector in Run 3 has been submitted to NIM-A and is currently under review by the journal. One of the main results is the proton to muon misidentification rate below per mil. Figure 2 shows the misidentification rate has measured on 2024 data, with muon efficiencies above 90% by exploiting only the pattern of hits in the muon detector. Thanks to a Master Thesis [6], further improvements on the software muon identification for both the present future experiment were carried out using machine learning.

Under the coordination of the RTA project, a complete review has been done keeping the final performance of the involved algorithms and paving the way for the changes needed for the upgrade. Also a new identification operator, rooted in the GAN algorithm class (one of the most used in modern machine learning), has been developed with improved performance and deployed in the HLT sequence mainly thanks to a PhD thesis work conducted under the supervision of the Frascati team. The performance of the MuonID algorithms has been studied using the large data samples collected in 2024 using the full suite of detectors. While in 2023 the MuonID performance were found lower than expected due to a not perfect time alignment of the nODE channels, the new Time Alignment Events taken at the beginning of 2024 data taking allowed an almost perfect time alignment and to recover the performance we were used in Run 1 and Run 2. Performance evaluated with the first 2024 data [7] have been presented at major conferences, while a paper with a full suite of MuonID results is in preparation.

The LNF group contributes to the LHCb Simulation Project with a focus on the Muon system, ensuring the correct modeling of its geometry, materials, and operational conditions. Updates for Run 3 include Low Energy Background parameterizations with the new infrastructure description and the inclusion of detector inefficiencies in the simulation, leading to corresponding improvements in Muon identification and overall Data/MC agreement. Simulation monitoring in LHCb is performed through MONET, a web-based interface for visualization and validation of detector and simulation data quality, via the Simulation Data Quality (SimDQ) chain. In the past year, the Muon monitoring has been fully integrated in SimDQ, establishing a solid foundation for systematic validation in future production campaigns. In addition, the LNF group is engaged in future developments for Upgrade II, supporting the implementation of the chosen sub-detector design and its simulation.

Beyond the Muon system, the group holds the convenership of the Detector Modeling Work Package (WP D) within the LHCb Simulation Project. The project encompasses the development and maintenance of simulation software and processing infrastructure for the production of simulated samples, ensuring continuous support for physics analyses. LNF responsibilities include coordinating sub-detector geometry descriptions, overseeing simulation digitization and conditions, supporting detector commissioning and data taking, and contributing to future detector studies.

The SMOG2 project, the first internal fixed-gas target at the LHC, was part of the major upgrade of the LHCb detector and began operation in 2022 with the start of LHC Run 3. The system operated by injecting H_2, D_2, He, Ne, and Ar during proton beam operations, and H_2, Ne and Ar during circulating lead beams, collecting large sample of beam-gas collision data, as mentioned before. It was clearly demonstrated that gas injection does not affect LHC beam lifetimes, and no negative impact on the spectrometer performance was observed. This enables LHCb to inject gas continuously during the full year in parallel data taking beam-gas and beam-beam collisions. The reconstruction code and HLT1+HLT2 triggers are successfully operated in this configuration. Studies to measure the beam-gas luminosity have been finalized, showing a very low value of only a few percent systematic uncertainty. In the YETS 2025-2026, the Gas Feed System was upgraded adding a Xenon gas bottles, allowing to inject the heaviest noble gas ever used in a collider experiment.

Fixed target collisions at LHCb open exciting new fields of investigation, enabling the study of particles carrying a large momentum fraction of the target nucleon in kinematic regions poorly explored up to now. In the nucleon-nucleon centre-of-mass frame, at an energy scale up to 115 GeV, interactions of the LHC beam with gasses pave the way for innovative and fundamental measurements. All of these make LHCb the first experiment ever to run with two completely different interaction points simultaneously, opening new frontiers in QCD and astroparticle research.

Additionally, the Frascati team has strongly contributed to the shifts needed to run the experiment, taking on various roles as Shift Leader, Muon piquet, SMOG2 piquet, Run Chief, and DQCS.

3 Long term LHCb upgrades

The current LHCb experiment is established as the world's leading flavour physics facility. Results from the LHC to date continue to demonstrate that SM effectively describes phenomena up to an energy scale of order 1 TeV. There must be physics beyond the SM, however, and therefore there's a strong motivation to keep pursuing the SM tests in the flavour domain by improving further the sensitivity of our experiment. This will be possible by installing a new detector during Long Shutdown 4 (LS4), which will operate at a maximum luminosity of 1.5×10^{34} cm^{-2} s^{-1}. The LHCb Upgrade II will allow to collect an unprecedented data sample for dedicated heavy flavour measurements. In addition to the vastly increased data sample, improvements in the detector will enable access to several new observables and reduce the uncertainties of other key measurements to levels comparable to their theory predictions. The sensitivity to the quantum imprints of new particles will push to new physics scales of 10 TeV and higher, far beyond what is currently achievable at the energy frontier.

The Upgrade II detector builds on the existing infrastructure of the LHCb experiment, including the magnet, with upgrades foreseen to all subdetector systems. These will also add new capability to resolve particles from different collisions in the same bunch crossing through the use of precision timing information. The project also features new subdetectors that will expand the physics programme and enable improved sensitivity beyond that from the increase in sample size alone. LHCb's unique detection capability additionally enables a broad range of measurements beyond flavour, including direct searches for dark sector particles and studies of QCD in both hadron spectroscopy and heavy ion collisions. In the latter, the improved granularity of the LHCb Upgrade II tracking system will allow studies of the most central heavy ion collisions, pushing the physics potential in this field far beyond what has been possible with LHCb to date. The baseline Upgrade II detector has been presented and approved in a Framework Technical Design Report [8]. Later, an international Scoping Document [9] was presented to the LHC Scientific Committee, discussing scenarios for the upgrade at different cost and physics performance. An additional document dedicated only to the INFN activities was produced and submitted and will be reviewed by an international technic and scientific committee (INFN CTS). The discussion is now advanced and close to the final approval, which will eventually pave the way to subdetector TDRs. The Frascati LHCb team is fully involved in this project, both at the level of coordination and in the preparation of the upgrades of the Muon system and of the gas target, as briefly discussed in the following.

The LHCb detector has been operating stably during Run 3, delivering large volumes of high-quality data and providing excellent opportunities for physics measurements. Accurate agreement between real data and Monte Carlo (MC) simulations is essential for precise physics analyses.

The μ-RWELL detector technology has been developed by the Frascati Detector Design Group (DDG) in collaboration with CERN-EP-DT-MPT Workshop and the ELTOS Company (Italy). The high-rate design developed for the LHCb Upgrade II will be the first large-scale application of this technology at a collider experiment. In particular, new prototypes have been tested this year at CERN PS, which reached the needed performance in terms of time resolution and efficiency. As it is discussed in the activity report of the Frascati DDG group, a particularly promising version of the detector implies the coupling of a μ-RWELL with a GEM pre-amplication stage, which allows to keep stable operation of the detector for a considerably wider range of gains. Present focus is on the optimization of this hybrid version of the detector (the so-called G-WELL), and its coupling to the front-end electronics.

LHCb also has the unique capability to record data from fixed-target collisions, achieved by injecting gases into the interaction region. This project, which is coordinated by the Frascati LHCb team, allows to acquire proton-gas collision data in parallel with standard proton-proton data taking. A further upgrade of the injection system [10], which recently became an official R&D of LHCb, could allow studies of interactions between beam particles and polarized hydrogen or deuterium gases. This would open a rich spin physics programme within a unique kinematic range for different final states, including heavy-flavour hadrons. Ongoing R&D addresses all aspects of integrating a polarized target system into the LHC vacuum environment. The core of the proposed gas target system includes an atomic beam source, a polarimeter, and an additional vacuum chamber integrated in the design of the future vertex detector. This complex apparatus is based on an existing target system [11], which will not only need to be adapted to the stringent LHC vacuum and beam-dynamics requirements, but will also undergo an innovative evolution aimed at realizing the first ever molecular polarized gas target. The decision between adopting a free-jet or a storage-cell configuration, the latter implying the polarized molecular recombination, is one of the main goals of the undergoing R&D programme. As with the current gas target, the Frascati group is coordinating the project in collaboration with the INFN Ferrara LHCb team.

In addition to the LNF LHCb group's activities on the muon system and SMOG in preparation for Upgrade II, in 2025, new members from the LNF NA62 group began work on R&D activities in support of the Upgrade II plans for the electromagnetic calorimeter (ECAL). In LHC Run 5, the ECAL must operate at significantly higher luminosity and radiation levels while achieving $\sim$20 ps timing to mitigate pile-up. The upgrade strategy combines multiple technologies: retaining and reconditioning outer shashlik modules, developing radiation-tolerant plastic-fiber sampling calorimetry (SpaCal) for intermediate regions, and introducing crystal-fiber solutions in the innermost region. In 2025, the LNF group members, in collaboration with groups at CERN and the University of Milano-Bicocca, started a project to manufacture, irradiate, and test perylene-based orange plastic scintillating fibers, which are expected to offer improved radiation hardness (since orange light propagates more effectively in radiation-damaged material) and faster scintillation decay ($\sim$4 ns vs. $\sim$7.5 ns), enabling reduced pile-up effects and improved energy resolution within short readout gates. In summer 2025, 750 m of this new fiber was produced by Kuraray, and a new SpaCal lead-polystyrene fiber prototype using this fiber was constructed at CERN and for testing at DESY in December. The evaluation of the fiber performance is ongoing, with a decision to be made during 2026 for inclusion in the Upgrade II Technical Design Report towards the end of the year. In the meantime, in collaboration with the newly formed LHCb group at INFN Napoli, whose members have a long history of collaboration with LNF on NA62, the LNF group has begun to set up an infrastructure at LNF for QA/QC testing of the photomultiplier (PMT) tubes for the lead-polystyrene fiber SpaCal modules for the LS3 Enhancement of the ECAL. These PMTs are to be acquired in batches starting in 2027. Finally, together with the INFN Napoli group, the LNF group is contributing to R&D for the reconditioning and resegmentation of the shashlik modules from the existing ECAL, to be carried out during LS4.

4 Conclusions

The LNF LHCb group is active in most areas of the experiment, ranging from data collection, where it includes Project Leaders and holds key responsibilities in data taking, to data analysis, with several first authors in publications. The group has a clear vision for developing solutions beyond the Phase-I upgrades, driving future decisions for the experiment. The support of all LNF services is essential to maintaining the high quality of results the group is achieving. As usual, scientific work has been complemented by LHCb-specific outreach activities, such as the LHCb Masterclass, carried on within the framework of the IPPOG international program.

5 Theses supervised by LNF Authors in Year 2025

1. Masters Thesis: "Machine learning for real-time muon identification of the LHCb experiment at CERN". Student: Giuseppe Costantino. Supervisors: Gabriele Tolomei (Sapienza University),

Marco Santimaria (LNF).

6 Other LHCb publications by LNF Authors

1. Feebly-Interacting Particles: FIPs at LHCb, J. Alimena et al., arXiv:2510.05257v2;
2. Summary Report of the Physics Beyond Colliders Study at CERN, R. Alemany Fernández et al., arXiv:2505.00947;
3. LHCspin: a Polarized Gas Target for LHC, A. Accardi et al.,arxiv:2504.16034;
4. Tests of amorphous carbon-coated storage cells for a polarized gas target at LHCb and further results, T. El-Kordy et al., 2025 Chinese Phys. C 49 084002;
5. Heavy Flavor Averaging Group (HFLAV), Sw. Banerjee et al., ”Averages of b-hadron, c-hadron, and tau-lepon properties as of 2023” arxiv: 2411.18639, Phys.Rev.D 113 (2026) 1, 012008, Editor’s suggestion;

7 Internal Notes by LNF Authors

1. A. Codovini, P. De Simone, M. Rotondo, ”Muon mis-identification studies at LHCb”, LHCb-INT-2025-003; CERN-LHCb-INT-2025-003;
2. R. Litvinov, M. Santimaria, Muon hit efficiency in the Run 3, LHCb-INT-2025-008, CERN-LHCb-INT-2025-008’
3. L. Dreyfus, M. Santimaria, Performance of the muon identification with the Run 3 muon detector, LHCb-INT-2025-009, CERN-LHCb-INT-2025-009;
4. M. Santimaria, B. Sciascia, and J. Swallow, Impact of the muon “holes” on the efficiency, LHCb-INT-2025-016, CERN-LHCb-INT-2025-016;

8 List of Conference Talks by LNF Authors in Year 2025

1. P. Di Nezza (invited) - ”Polarized collisions at the LHC”, Colloquium at University of Torino, Feb 2025;
2. M. Pepe Altarelli (invited) - ”LHCb Highlights”, 61st course of the International School of Subnuclear Physics, Ettore Majorana Foundation and Centre for Scientific Culture, Erice (Italy) Jun 2025;
3. P. Di Nezza (invited) - ”Nucleon Structure at LHCspin”, PAW ’25, Kloster Irsee (Germany) Jun 2025;
4. P. Di Nezza (invited) - ”SMOG and other projects”, VELO U2 workshop, Santiago (Spain) Jun 2025;
5. M. Santimaria (invited) - ”The LHCspin project”, Low-x 2025, Medulin (Croatia) Sep 2025;
6. M. Rotondo - ”CKM elements at LHCb Upgrade II and Belle II”, CKM 2025, Cagliari (Italy) Sep 2025;
7. G. Lanfranchi (invited) - ”Feebly Interacting Particles in the MeV-GeV range: Experimental Landscape”, SI2025 Workshop, PSI (Zurich) Sep 2025;
8. P. Di Nezza (invited) - ”LHC future projects: LHeC and LHCspin”, IS2025, Taiwan Sep 2025;
9. P. Di Nezza (invited) - ”Unpolarized and polarized high-density gas target at the LHC”, EIC Fixed-Target Workshop, Stony Brook University (US) Oct 2025;

10. G. Lanfranchi (invited) - ”Overview of experimental results of the Physics Beyond Colliders benchmarks”, LHC BSM Working Group Workshop, CERN Nov 2025;
11. G. Lanfranchi (invited) - ”Search for light Dark Matter: experimental landscape”, Colloquium at University of Genova, Nov 2025;
12. P. Di Nezza (invited) - ”Flavour production in fixed-target measurements at LHCb”, Strangeness in Hard Processes, LNF Dec 2025;

References

[1] O. Boente Garcia et al., ”High-density gas target at the LHCb experiment”, Phys. Rev. Accel. Beams 27, 111001 (2024), arXiv:2407.14200;

[2] L. Dreyfus, M. Santimaria, Performance of the Muon Identification at LHCb Upgrade I and development of μ-RWELL detectors for Upgrade II, LHCb Internal Note CERN 2024;

[3] R. Litvinov, M. Santimaria, Muon hit efficiency in the Run 3, LHCb-INT-2025-008, CERN-LHCb-INT-2025-008;

[4] L. Dreyfus, M. Santimaria, Performance of the muon identification with the Run 3 muon detector, LHCb-INT-2025-009, CERN-LHCb-INT-2025-009;

[5] M. Santimaria, B. Sciascia, and J. Swallow, Impact of the muon “holes” on the efficiency, LHCb-INT-2025-016, CERN-LHCb-INT-2025-016;

[6] G. Costantino, Machine learning for real-time muon identification of the LHCb experiment at CERN, Master Thesis Sapienza University of Rome, May 2025;

[7] LHCb Collaboration, Charged PID performance in early 2024 data, 2024, LHCB-FIGURE-2024-010, https://cds.cern.ch/record/2898816;

[8] LHCb collaboration, LHCb Framework TDR for the LHCb Upgrade II CERN-LHCC-2021-012, 2022;

[9] LHCb Collaboration, LHCb Upgrade II Scoping Document, CERN-LHCC-2024-010, 2024;

[10] A. Accardi et al., LHCspin: a Polarized Gas Target for LHC, arXiv:2504.16034;

[11] HERMES collaboration, A. Airapetian et al., The HERMES polarized hydrogen and deuterium gas target in the HERA electron storage ring, Nucl. Instrum. Meth. A540 (2005) 68, arXiv:physics/0408137.