LHCb

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LHCb is a dedicated heavy-flavour physics experiment at the Large Hadron Collider (LHC). The experiment is mainly designed for precision measurements of CP violation and rare decays of beauty and charm hadrons. However, its physics reach has significantly expanded in the recent years, covering areas such as hadron spectroscopy, astroparticle physics, heavy-ion collisions, and dark matter searches. LHCb has published more than 790 papers, including 54 in 2023, mainly using the full Run 1 + Run 2 dataset. During Run 2 (2015-2018), LHCb successfully overcame many operational challenges and collected $\sim$7 fb^{-1}, adding to the $\sim$3 fb^{-1} collected in Run 1.

LHCb collaboration was approved for an upgrade of the spectrometer, aiming to collect $\sim$50 fb^{-1} to be concluded by the end of the LHC LS2. Commissioning of the upgraded detector with beams began in April 2022 and ended at the beginning of 2023 data taking.

Unfortunately, the 2023 physics programme was significantly affected by an incident involving the LHCb VELO vertex detector. This issue happened due to the multiple equipment failures, leading to a differential overpressure of 200 mbar on the VELO rf-foils, thin foils designed to separate the primary and the secondary vacuum of the LHC, where the active detectors are located. The foils were designed to withstand up to 10 mbar, so the excessive pressure caused a significant deformation. The damaged foils had to be replaced, and the successful operation was succesfullty carried out during 2023 Year Technical Stop.

Nevertheless, the commissioning of the Upgrade I system proceeded almost as planned, and about 0.37 fb^{-1} of pp data was succesfully collected.

During the LHC LS2, a gas fixed-target system was installed in front of the VELO detector. The implemented storage cell technology allows for the controlled injection of a limited amount of gas into a well-defined volume within the LHC beam pipe. With beam-gas interactions occurring at approximately

4% of the proton–proton collision rate at LHCb, the beam's lifetime remains largely unaffected. This makes LHCb the first experiment that can operate simultaneously with two distinct interaction regions, Ref [1].

In 2024, LHCb succesfully achieved the ambitious goal of collecting 9.6 fb^{-1} of pp-data and 0.5 fb^{-1} of beam-gas, all with the fully upgraded detector.

As part of the Muon System and SMOG2 projects, the LHCb Frascati group is deeply involved in all the 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

Among various analyses, the LNF group is involved in the study of the $b \to c\ell\nu$ semileptonic processes. These decays are highly sensitive to different kind of new physics and are also very useful tools to extract quantities useful as inputs by other measurements.

In the Standard Model (SM) the couplings of the electroweak bosons to the leptons of different families are the same. This property, known as Lepton Flavour Universality (LFU), is experimentally well-established. However, some tensions with the SM predictions are mainly observed in the three-level decay processes like $b \to c\ell\nu$. Recent updates on these measurements have been reported from Belle II and LHCb experiments. In 2024 LHCb published two measurements of the ratio of branching fractions $R(D^{(*)}) = BF(B \to D^{(*)}\tau\nu_\tau)/BF(B \to D^{(*)}\mu\nu_\mu)$, one using the hadronic $\tau \to 3\pi\nu_\tau$ decays and the other based on the leptonic $\tau \to \mu\nu_\mu\nu_\tau$ decays.

The LNF group is actively investigating the source of this tension by analyzing exclusive B_s decays that include D_s or D_s^* charm hadrons in the final state. Among the various b-hadrons used in the search for LFU violation, the B_s mesons are particularly interesting because they allow to overcome one of the most important backgrounds that affects the measurements of the ratios $R(D^*)$. This background is associated with the decays of orbitally and radially excited charm meson states, that is much less significant in B_s decays. Furthermore, the calculations of the form factors for semileptonic B_s decays, which are essential for modeling the signals and interpreting the results, are more robust for B_s compared to B^0 or B^+. This increased reliability is due to the presence of the heavier s-quark as a spectator.

The group also focused on measuring $R(D_s^*)$ using data collected during Run 2. This work is well advanced and is expected to be completed by the end of 2025. The same sample 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 effect, will be published. This will allow a reinterpretation of the data, and the analysis is expected to be finalized by the summer 2025. 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. It is expected to be finalized within the year and will be one of the first analyses of the LHCb semileptonic WG based on Run 3 data.

Other relevant analyses have been conducted using fixed target data. A novel measurement of the transverse polarization of Λ and $\bar{\Lambda}$ hyperons in pNe collisions at $\sqrt{s_{NN}} = 68.4$ GeV has been published. This measurement, performed in a new collision system and region of phase space, provides additional insights on the mechanism of Λ polarization, which cannot yet be fully calculated in quantum chromodynamics. The polarization is measured through the decay $\Lambda \to p\pi^-$ and its charge conjugate. The polarization values obtained are consistent with previous measurements, in particular with the HERA-B results, which cover a similar x_F interval.

A second analysis conducted in the framework of the beam-gas collisions focuses 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 is the first of this kind at this centre-of-mass energy and is unique in this kinematic range.

2 Operations during Run3

The LHCb detector was upgraded between 2019 and 2022, during the LHC LS2. The goal of this upgrade is to allow the LHCb detector to take data 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) project started in 2019 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 participated to the RTA project contributing to the software for decoding the muon system data and for identifying muons in both HLT1 and HLT2. Data collected during 2024 were also used to measure the Muon Identification performance in both trigger stages.

The group is also deeply involved in developing the new online monitoring system, an important 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. 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.

For what concerns the Muon System a perfect design with large redundancy factors and excellent construction quality, allowed to run the detector at $\times 2$ with respect to the design luminosity for the whole Run 1 and Run 2, and to move forward for another decade of operation at $\times 10$ luminosity. To mitigate the high rates expected in the inner regions of the second station (M2), an additional shielding was designed, built, and installed behind the HCAL.

The off-detector electronics boards of the Muon system (Service Boards, nSB, Pulse Distribution Module, nPDM, and Off-Detector, nODE) were completely redesigned to be compliant with the 40 MHz readout of the detector. The LNF electronic team (LNF-SEA), produced, tested and commissioned the 185 nODE boards. The apparatus, fully instrumented with the needed 144 nODE, has been successfully taking 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, was deployed. This enabled 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 are coded 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. Because of 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 to the collaboration. This code, mostly developed at the beginning of the 2000's, demonstrated to be highly performing and needed an optimization mainly for the increasingly stringent timing requirements. Under the coordination of the RTA project, a complete review has been done keeping the final performance of the involved algorithms while paving the way for the changes needed for the upgrade. Additionally, 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, thanks mainly 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 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 observed during Run 1 and Run 2. Performance evaluated with the first 2024 data [2] have been presented at major conferences, while the a paper with a full suite of MuonID results is in preparation.

The SMOG2 project, the first internal fixed gas target at the LHC, was part of the major upgrade of the LHCb detector and began its operation in 2022 with the LHC Run 3. However, during 2023, due to the VELO incident that damaged the VELO rf-foil, the storage cell remained open, and the target system operated at low pressure. The temperature behaviour of the storage cell, monitored by 5 thermocouples, was understood in connection to the beam conditions. The Gas Feeding System was calibrated, and operational procedures were developed to ensure the highest stability in gas flow, achieving a precision level of 1%. The system operated by injecting H_2, D_2, He, Ne, and Ar gases during proton beam operations, and Ne and Ar when circulating lead beam, producing 0.5 fb^{-1} beam-gas collision data. It was clearly observed that the gas injection does not affect LHC beam lifetimes, and no negative feedback on the spectrometer was observed. This enables LHCb to inject gas as needed without explicit authorization from the LHC operators. The reconstruction code and HLT1+HLT2 triggers were successfully implemented. Studies to measure the beam-gas luminosity have been finalised, showing a very low value of only a few percent systematic uncertainty. In the YETS 2024-2025, the Gas Feed System was upgraded adding high-pressure gas bottles, which will prevent pressure instabilities and reduce the need for frequent reservoires refills.

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 such as H_2, D_2 as well as noble gasses up to the heavier Kr and Xe, 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.

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 in a Framework Technical Design Report [3] that was approved in 2022. Later in 2024, a Scoping Document [4] was presented to the LHC Scientific Committee, discussing scenarios for the upgrade at different cost and physics performance. The discussion is now advanced, and a final decision is expected in 2025, 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 (a member of the team was the main editor of Ref [4]) and in the preparation of the upgrades of the Muon system and of the gas target, as briefly discussed in the following.

The muon detector is composed of four stations, each comprising 276 MWPC chambers arranged in four regions, R1-R4, with increasing distance from the beam axis. The stations are interleaved with three iron absorbers, 80 cm thick. The maximum rate at Upgrade II will exceed 1 MHz/cm^2 in the innermost region, while rapidly decreasing to several kHz/cm^2 in the outer regions far from the beam. For this reason, the baseline design proposed for the muon upgrade foresees to replace MWPCs in regions R1 and R2 with new highly-granular μ-RWELL chambers, a new type of micro-pattern gas detector (MPGD) with a rate capability of several MHz/cm^2. New MWPCs with higher granularity will be installed in region R3, while the MWPCs in regions R4, 70% of the total, will be recycled. In addition, a new readout scheme will be implemented in all regions, which is expected to reduce substantially the background counts. Finally, to mitigate the high rates, the replacement of the present hadron calorimeter with enhanced shielding in front of the M2 station is being considered.

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 optimisation of this hybrid version of the detector (the so-called G-WELL), and its coupling to the front-end electronics.

LHCb also has unique capability to record data from fixed-target collisions, achieved by injecting gases into the interaction region. The system has been recently upgraded with the installation of a gas target, SMOG2, in front of the vertex detector [1]. This project, which is coordinated by the Frascati LHCb team, allows to acquire proton-gas collision data in parallel with a normal proton-proton run. A further upgrade [5] of the injection system could allow studies of interactions between beam particles and polarised hydrogen or deuterium gases, enabling a rich programme of spin physics within a unique kinematic range for different final states, including heavy flavour hadrons. Ongoing R&D is addressing all aspects of integrating a polarised target system into the LHC vacuum. 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. A small transverse magnetic field of about 300 mT will maintain the transverse spin direction of the target nuclei. This complex apparatus is based on an existing target system [6], which will need to be adapted to the stringent requirements of the LHC vacuum limits and beam dynamics, as well as to the LHCb constraints. The decision between adopting a free jet or a storage cell is a goal of the currently ongoing R&D. As for the present gas target, the Frascati group is coordinating the project, in collaboration with the LHCb team of INFN Ferrara.

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 2024

1. "Measurement of the $R(D_s^*)$ ratio in p-p collisions at $\sqrt{s} = 13$ TeV with the LHCb experiment", PhD student S. Calì, Tor Vergata Rome University, a.a. 2023/2024, Supervisors: E. Santovetti, M. Rotondo

2. "Produzione di J/Ψ tramite collisioni polarizzate con LHCspin", Master Student A. Tralli, Università degli Studi di Ferrara, a.a. 2023/2024 - Supervisors: P. Di Nezza, M. Santimaria

3. "Studio del Processo Drell-Yan in Collisioni Polarizzate con LHCspin", Master Student F. Di Nunno, Università degli Studi di Ferrara, a.a. 2023/2024

- Supervisors: P. Di Nezza, M. Santimaria

4. "Performance of the Muon Identification at LHCb Upgrade I and development of μ-RWELL detectors for Upgrade II", PhD student L.M.S. Dreyfus, École polytechnique fédérale de Lausanne (EPFL), a.a. 2023/2024 - Supervisors: M. Santimaria, B. Sciascia

6 Other LHCb publications by LNF Authors

1. T. El-Kordy et al., "Amorphous Carbon-coated Storage Cell Tests for the Polarized Gas Target at LHCb", NIM A 1068 (2024) 169707, doi.org/10.1016/j.nima.2024.169707

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

3. M. De Cian, N. Feliks, M. Rotondo, K. Keri Vos, "Inclusive semileptonic B_s^0 meson decays at the LHC via a sum-of-exclusive modes technique: possibilities and prospects" JHEP 06(2024) 158, arXiv:2312.05147

4. S. Klaver, M. Rotondo, "Lepton Flavor Universality Tests in Semileptonic $b \to c$ Decays", Symmetry 16 (2024) 8, 864 DOI: 10.3390/sym16080964

5. Sw. Banerjee et al., "Averages of b-hadron, c-hadron, and tau-lepton properties as of 2023" Heavy Flavor Averaging Group (HFLAV) Collaboration, arXiv:2411.18639 (submitted to PRD)

7 Internal Notes by LNF Authors

1. F. Fabiano, G. Manca, M. Santimaria, P. Di Nezza, L. Pappalardo, B. Passalacqua, "Strangeness production in fixed-target pNe collisions at $\sqrt{s_{NN}}$=68.5 GeV at LHCb" LHCb-ANA-2024-035; CERN-LHCb-ANA-2024-035

8 List of Conference Talks by LNF Authors in Year 2024

1. P. Di Nezza, "Polarized physics at the LHC", invited seminar at CEA Institute, Feb 2024, Paris - France

2. M. Rotondo, "B-hadron semileptonic and rare decays: a laboratory for challenging the Standard Model", invited seminar at Sapienza Rome University, Apr 2024, Rome - Italy

3. M. Santimaria, "LHCspin simulations", (invited) 8th COMPASS Analysis Phase Workshop (COMAP-VIII), May 2024, Cern

4. M. Pepe Altarelli, “Flavour Physics: Experimental stats and prospects”, (invited) Workshop on Future Accelerators, May 2024, Corfu - Greece
5. M. Rotondo, ”LFU tests in semileptonic decays at LHCb”, FPCP 2024, May 2024, Bangkok - Thailand
6. P. Di Nezza, ”The LHCspin proposal”, (invited) 8th COMPASS Analysis Phase Workshop (COMAP-VIII), May 2024, Cern
7. P. De Simone, ”LFU tests in semi-letonic decays at LHCb”, BEACH 2024, XV International Conference on Beauty, Charm, Hyperons in Hadronic Interactions, Jun 2024, Charleston, SC, USA
8. P. Di Nezza, ”Fixed Target Experiments at the LHC”, Strong-2020 Annual Workshop, Jun 2024, Frascati Rome - Italy
9. M. Santimaria, ”The LHCspin project”, (invited) Diffraction and Low-x 2024, Sep. 2024, Palermo - Italy
10. P. Di Nezza, ”The LHCspin project: present and future”, (invited) 20th International Workshop on Hadron Structure and Spectroscopy, Sep 2024, Yerevan - Armenia
11. M. Pepe Altarelli, “Flavour Physics: current experimental status and prospects, with focus on LHCb”, Invited colloquium at IHEP, Oct 2024, Beijing - China
12. M. Pepe Altarelli, “CERN, seven decades of global collaboration, scientific achievements and technology innovation”, Invited colloquium at University of Chinese Academy of Sciences (UCAS), Nov 2024, Beijing - China
13. P. Di Nezza, ”Polarized collisions at LHC”, (invited) Science at the Luminosity Frontier: Jefferson Lab at 22 GeV, Dec 2024, Frascati Rome - Italy
14. P. Di Nezza, ”LHCb collision samples (heavy-ion and fixed target)”, (invited) LHC Forward Physics December 2024 Workshop, Dec 2024, Cern

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

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

[4] LHCb Collaboration, LHCb Upgrade II Scoping Document, CERN-LHCC-2024-010 (in review) 2024.

[5] L. L. Pappalardo et al., The LHCspin project: A polarized target experiment at LHC, Il Nuovo Cimento 47 (2024) 235; C.A. Aidala et al., arXiv:1901.08002

[6] 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.