LHCb/LNF 2023

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LHCb is a dedicated heavy flavour physics experiment at the Large Hadron Collider (LHC). The experiment is designed for precision measurements of CP violation and rare decays of beauty and charm hadrons. LHCb published more than 680 papers (49 of which in 2023) using mainly the full Run 1 + Run 2 data set [1]. During LHC Long Shutdown 1 (LS1) in 2013-2014, the LHCb detector remained essentially unchanged, while major upgrades were foreseen for subsequent long shutdowns. During Run 2 (2015-2018), LHCb successfully afforded many operational challenges and collected $\sim$7 fb^{-1} that sum up to the $\sim$3 fb^{-1} collected in Run 1. LHCb collaboration has been approved for an upgrade of the experiment intended to collect $\sim$ 50 fb^{-1} whose harvest began in 2022. The installation and the commissioning during the LS2, have been heavily touched by the CoViD19 pandemic. The Collaboration was able to arrange a new effective plan but not all the sub-detectors were able to recover the delay. LHCb started the commissioning with beams of the Upgraded detector on April 2022 with only half of the vertex detector (VELO C-side) and without the first tracking detector (UT). The VELO A-side was then installed in September 2022, while the UT installation has been postponed to the 2022 End of the Year Technical Stop. The UT was in place for the beginning of 2023 data taking, even though it has still to be commissioned which happened in parallel with the data taking of the rest of LHCb.

The physics programme of 2023 has been significantly affected by an incident happened to the LHCb vertex detector, nevertheless the commissioning of Upgrade system proceeded almost as planned and about 0.37 fb^{-1} of pp-data have been collected. The VELO is installed in a secondary vacuum inside the LHC primary vacuum, and primary and secondary volumes are separated by two thin-walled aluminium RF foils. On 10th January 2023, multiple equipment failures resulted in a build up of pressure beyond specification between VELO and beam volumes. A pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only. Investigations showed no damage to the VELO modules, correct leakage currents, and not leak on microchannels, while RF foils have suffered plastic deformation up to 14 mm and had to be replaced. The successful replacement underwent during 2023 EYETS and teh VELO is now preparing for the recomissioning with beams in 2024. For 2024 the ambitious plan is to collect about 7 fb^{-1} of pp-data with the full upgrade detector, including the UT.

Being part of the *Muon System* and *SMOG2* projects the LHCb Frascati group is deeply involved in all the ongoing experimental activities. These range from the operation of the detector (with important responsibilities on the hardware) to the data analysis for flagship measurements, from the preparation of the upgrade and Run 3, to the R&D in view of possible future upgrades after LS3 and LS4 of the LHC.

1 Data analysis activity

In the SM the couplings of the electroweak bosons to the leptons of different families are exactly the same. This property called Lepton Flavour Universality (LFU), is experimentally well-established. However, some tensions with respect to the SM predictions are observed in decays dominated by three-level dominated processes like $b \to c\ell\nu$ [2]. Most of the recent updates on these measurements come from Belle and the LHCb experiment, in particular, LHCb in 2023 published two measurements of the ratio of branching fractions $R(D^{(\star)}) = BF(B \to D^{(\star)}\tau\nu_\tau)/BF(B \to D^{(\star)}\mu\nu_\mu)$ using two different ways to reconstruct the *tau* leptons.

LNF group is directly involved in the study of these $b \to c\ell\nu$ processes, in particular through the analysis of the exclusive semileptonic decays of B_s^0 with a D_s or D_s^* charm hadron in the final state.

Among the various b-hadrons for the search of LFU violation, the B_s are particularly interesting because they allow to overcome one of the most important backgrounds that affect the B semi-tauonic decays. This background, associated with the decays of orbitally and radially excited charm-meson states, is much less relevant in B_s decays. Moreover, semileptonic B_s decays offer many interesting kinematic observables that can be exploited to constrain various plausible new physics scenarios.

Frascati group already published the measurement of the $B \to D_s^\star\mu\nu$ form factors, which is ancillary to the relative $R(D_s^\star)$ ratio. The measurement of $R(D_s^\star)$ is expected by the end of 2024. The same sample is currently used for a full angular analysis of the $B \to D_s^\star\mu\nu_\mu$ decays with $D_s^\star \to D_s\gamma$), aiming to extract the relevant form factors and to constrain some models of new physics which can affect the kinematics of semileptonic decays. This is expected to be finalized within 2024.

2 Operations during Run 3

The LHCb detector has been be upgraded in 2019 - 2022, during the LS2. The goal of this upgrade is to allow the LHCb detector to take data at an instantaneous luminosity of $2 \times 10^{33} cm^{-2} s^{-1}$, a factor of five more than during LHC Run 2. A key requirement is 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 [3]. Between the two trigger stages the real-time alignment and calibration of the detector are performed. The Real Time Analysis (RTA) project started beginning of 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 the decoding of the muon system data and for the identification of the muons in the HLT1 and the HLT2. Data taken during 2023 were used to optimise the Muon Identifcation performance of HLT. The group is also deeply involved in the development of the new online monitoring system. The latter is an important component of the operation of the upgraded LHCb detector. A lot of experience was gained during Runs 1 and 2 but the foreseen large increase of the data rate imposes new constraints on the monitoring system. Finally, Frascati team strongly contributed to the shifts needed to run the experiment, assuming a large variety of roles (Shift Leader, Muon piquet, SMOG2 piquet, Run Chief, 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. A lot of effort has been put in the planning of 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 has been designed and built. The installation started in 2019 and has been completed at the beginning of 2021. Also, in the years 2015-2018 a good 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 in 2022 and 2023. Since the new ODE board requires 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. The final nSYNC and nODE libraries are under completion and will be deployed before the beginning of 2024 data taking. Still using the ECS features, studies are ongoing to use the currents measured through the HV system to build an online luminosity monitor. First results from 2023 data taking are promising and there are plans for 2024 to add the Muon-luminosity monitor 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. 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 bunch of data collected in 2023 using the full suite of detectors. MuonID performance were found lower than expected and the root cause of this has been found on the not perfect time alignment of the nODE channels. To complete the time alignment new tools have been developed during the 2023 YETS (namely a new data format and a new trigger line selection to be used during the collection of the special Time Alignment Event) and are ready to be used at the first good LHC collision in 2024.

Since many years Frascati team contributes also to the Online project. In 2023 the team focused its action on completing the virtualisation cluster hosting the LHCb ECS control system and on the final commissioning of the HLT2 output storage; both systems have been successfully and reliably used during the whole Run 3 data taking.

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 which 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, reaching a level of 1%. The system primarily operated by injecting argon gas, producing beam-gas collision data with both proton and lead beams. A pressure profile was studied to precisely evaluate the data throughput, detector occupancy, and the achievable pressures into the VELO vessel. It has been clearly observed that the gas injection does not affect LHC beam lifetimes, and no negative feedback has been observed. This enabled LHCb to inject gas as needed without explicit authorisation from the LHC operators. The reconstruction code and

HLT1+HLT2 triggers have been successfully implemented. Studies to measure the beam-gas luminosity have been finalised, showing a very low value of 1.4% systematic uncertainty. In the YETS 2023-2024, the Gas Feed System has been upgraded to include two additional gas reservoirs for gettable gases. The system now has the capability to inject up to six different gases: three noble gases (currently He, Ne, Ar) whose line passes through a NEG cartridge, and three other gases (currently H2, D2, O2) that follow a different gas line. This will allow LHCb to switch between non-noble gases quickly, even during the same beam fill, without replacing the reservoir. 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, D passing through the 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 Future LHCb upgrades

Further upgrades are proposed for the LHCb experiment in order to take full advantage of the flavour-physics opportunities at the HL-LHC, and other topics that can be studied with a forward spectrometer. These Upgrades, which will be installed starting from LS3 onward, will build on the strengths of the Run 1 and Run 2 experience and on the Phase-I Upgrade during Run 3, and will consist of re-designed sub-systems that can operate at a luminosity $2 \times 10^{34} cm^{-2} s^{-1}$ ten times that of the Phase-I Upgrade detector.

For the phase-2 upgrade foreseen for the LHC Run 5, the excellent performance of the current muon detector will need to be maintained at 40 times the pile-up level experienced during Run-2. The rate requirements have been estimated using the counters available through the actual very front-end electronics board. Single channel rates as a function of the μ have been acquired during the two Van der Meer scans performed during the 2022 data taking, and have been studied to derive an accurate estimate of the rates that will hit the MWPC at the U2 luminosity. Many paths have been followed in the last years by Frascati team, within the Muon Project, to prepare the Muon system for the future upgrades. To mitigate the challenging conditions of Upgrade 2, an improved shielding that decreases the rate, particularly in the inner region, has been studied. Since the HCAL is not used in the trigger from Run 3 onward, and plays a limited role in muon PID, the option exists to remove it and exploit the freed volume for new shielding to reduce the rate by about a factor two at the M2 station. The proposed shielding consists of an iron core covering the acceptance of regions R1 to R3, an iron/concrete/iron sandwich on the median plane of region R4, with an effective thickness similar to HCAL and a full concrete part on the top/bottom bands of region R4, where the input rate does not pose problems even with a slightly reduced effective thickness compared to HCAL. With the above design the simulated occupancy on the M2 station is reduced to 58%, 31% and 36% of those values found with the HCAL in place, in regions R1, R2, and R3 respectively. The iron to be used has been discarded from the OPERA experiment taking data at LNGS and now finished. The Frascati LHCb team organised the transport at CERN where a suitable shed has been found to store the plates pending future processing. The use of Opera plates instead of an brand new filter implies an estimated saving at current market prices of around 200 kEuro. Furthermore, in ecological terms, recycling the slabs implies the emission of 150 t of CO2 (due to various transports) compared to ∼950 t released during the new production.

Requirements for the innermost regions of the muon stations are challenging: the detectors should exhibit a rate capability up to 1 MHz/cm^2 and capable to stand an integrate charge up to $\sim$ 1 C/cm^2. For some years now, an intense optimisation program of the micro-RWELL technology has been launched by the Frascati Detector Design Group, together with a technology transfer to the industry operating in the PCB field. The micro-RWELL detector (μ-RWELL) is a single amplification stage resistive Micro Pattern Gaseous Detector (MPGD), based on a copper-clad polyimide foil patterned with a micro-well matrix coupled with the readout PCB through a DLC resistive film ($10 \div 100 M\Omega/\square$). In order to fulfil the requirements, a new layout of the detector with a very dense current evacuation grid of the DLC has been designed. The detector, co-produced by the CERN-EP-DT-MPT Workshop and the ELTOS Company, has been characterised achieving a rate capability exceeding 10 MHz/cm^2, while the long term stability tests are in progress. Further details about latest developments and plans are report in the DGG_LAB Activity Report.

For what concerns the outer regions of the muon stations, the strategy rely on the observation that, in the nine years of operation of Run 1 and Run 2, the collected charge on the most irradiated MWPC, in M1R2, reached values of up to ∼0.6 C/cm per wire without any drop in performance being observed. In the low-rate regions R3 and R4, which represent 94% of the instrumented area, this charge will only be accumulated after 350 fb^{-1} of integrated luminosity, and then only for M2R3, with the other sub-regions being comfortably below this value. Hence there exists the opportunity to profit from the re-use of the current MWPC detectors and also exploit the existing detector infrastructure, for Run 5 and beyond. This project is now challenged by the consequences of the Russia attack to Ukraine, with the end of cooperation agreement by Russian Federation and CERN by the end of November 2024. Alternative solutions are under study. After the publication of the framework TDR of the phase-2 LHCb upgrade [4], the next goal is the preparation by the end of Summer 2024 of the so called "scoping document" where different cost and performance scenarios will be illustrated. The TDR of the single sub-detectors will follow in the next couple of years.

4 Conclusions

The Frascati LHCb group is active in most of the areas of the experiment, ranging from data collection and analysis, to the development of solutions for beyond-Phase-I upgrades. The group is deeply involved in the activities ongoing to ensure the finalisation of the Phase-I Upgrade commissioning and the successful restart of Run 3 data taking in 2024. The support of all the LNF services is fundamental to keep the high quality of results the group is obtaining. As usual, the scientific work has been complemented with some LHCb-specific outreach activity. In particular, the LHCb masterclass has organised for about 60 high school students meeting for a whole week in March 2023, as part of the IPPOG MasterClass program.

5 Thesis supervised by LNF Authors in Year 2023

1. "Measurement of the differential distributions of Bs→ Ds* mu nu decays with the LHCb detector" F. Manganella, La Sapienza, a.a. 2022/2023, deended on 30/10/2023 (Supervisors: M. Rotondo, A. Sarti)

6 Internal Notes by LNF Authors in Year 2023

1. P. Albicocco, M. Carletti "Upgrade on Muon ECS" CERN, EDMS-2869134v.1
2. P. Di Nezza, M. Santimaria "SMOG2: temperature calibration and luminosity measurement" CERN, LHCb-INT-2023-002
3. P. De Simone, M. Santimaria "Measurement of branching fraction of the $\Lambda_b^0 \to J/\psi\Lambda$ decay" CERN LHCb-ANA-2023-027

7 List of Contributions at conferences prepared by LNF Authors in Year 2023

1. P. Di Nezza "Polarised Physics at the LHC" (invited) XXIX The Cracow Epiphany Conference, Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences, Warsaw Poland, Jan 2023
2. P. Di Nezza "Fixed Target and Heavy-Ion Results at LHCb" LISHEP 2023 Conference, Rio de Janeiro, Brazil Mar 2024
3. P. Di Nezza "Spin Physics with LHCspin" (invited) LISHEP 2023 Conference, Rio de Janeiro, Brazil Mar 2024
4. P. Di Nezza "Polarised physics at LHC: the LHCspin project" (invited) Sar WorS 2023 - 3rd Sardinian Workshop on Spin, Mar 2023, Pula, Italy

5. P. Di Nezza "The fixed target program at the LHC" (invited) SPIN2023 Conference, Durham, US Sep 2023

6. P. Di Nezza "Polarized Target Experiments at LHC", JPS Conf. Proc. 37, 011008 (2022)

7. P. Di Nezza "LHCspin: Unpolarized gas target SMOG2, and prospects for a polarized gas target at the LHC" POS(PSTP2023)002 DOI: https://doi.org/10.22323/1.433.0002

8. R. Farinelli et al., uRANIA: a micro-Resistive WELL for neutron detection, NIM 2023, 7^{th} International Conference on Micro Pattern Gaseous Detectors 2022, Rehovot, Israel

9. M. Poli Lener et al., The state of art of the μ-RWELL technology, NIM 2023, 7^{th} International Conference on Micro Pattern Gaseous Detectors 2022, Rehovot, Israel

10. G. Morello "The μ-Resistive WELL in HEP and beyond", at 59^{th} International Winter Meeting on Nuclear Physics, Bormio, 23-27 Gennaio 2023

11. M. Pepe Altarelli Invited talk at APS March meeting in Las Vegas on "100 Years of Existence of the International Union of Pure and Applied Physics" (as IUPAP vice-president) 7 March 2023

12. M. Pepe Altarelli Invited talk on "LHCb Upgrades" at "Anomalies 2023" meeting held at the Simon Center for Geometry and Physics (SCGP) at Stony Brook University on March 8-10 2023

13. M. Pepe Altarelli Invited talk on "Selected highlights and prospects from LHCb" at Planck 2023, Warsaw, 22-26 May 2023

14. M. Pepe Altarelli Invited lecture on "Selected highlights and prospects from LHCb" at Ettore Majorana Foundation and Centre for Scientific Culture, 59th course: Searching the Unexpected: Energy, Luminosity, Precision, Small Signals - Proceedings and discussions to be published in a dedicated world scientific press volume.

15. M. Pepe Altarelli Scientific organisation of the Rencontres du Vietnam, 30th Anniversary, August 6-12, 2023, ICISE, Quy Nhon, Vietnam

16. M. Pepe Altarelli Invited introductory LHCb talk at workshop on "Implications of LHCb measurements and future prospects", CERN, 25-27 October 2023

17. M. Pepe Altarelli Invited talk on "Selected highlights and prospects from LHCb", 5th International Workshop on Heavy Quark Physics National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan 11-15 December 2023 (Online presentation).

18. M. Rotondo "LHCb prospects on Semileptonic Decays" Talk a CKM2023, 18-22 September 2024, Santigo de Compostela:

19. M. Santimaria "The LHCspin project". Talk at International Workshop on Hadron Structure and Spectroscopy 25/06/2023

20. M. Santimaria "The LHCspin project". Talk at Low-x workshop 08/09/2023

21. M. Santimaria "The LHCspin project". Talk at Joint ECFA-NuPECC-APPEC Activity Workshop "Synergies between the EIC and the LHC" 15/12/2023

22. M. Santimaria "Rare decays at LHCb". Talk and proceedings at KAON2022. Proceedings in 2023: J. Phys.: Conf. Ser. 2446 012025

References

1. All LHCb publications are accessible here https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html

2. M. De Cian, N. Feliks, M. Rotondo and K. K. Vos, "Inclusive semileptonic B_s^0 meson decays at the LHC via a sum-of-exclusive modes technique: possibilities and prospects," [arXiv:2312.05147 [hep-ph]].

3. R. Aaij *et al.* [LHCb], "A Comparison of CPU and GPU Implementations for the LHCb Experiment Run 3 Trigger," Comput. Softw. Big Sci. **6**, no.1, 1 (2022) doi:10.1007/s41781-021-00070-2 [arXiv:2105.04031 [physics.ins-det]].

4. LHCb Collaboration, "Framework TDR for the LHCb Upgrade II; Opportunities in flavour physics, and beyond, in the HL-LHC era", CERN-LHCC-2021-012, LHCB-TDR-023, https://cds.cern.ch/record/2776420",