LHCb/LNF 2021

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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 about 600 papers using mainly the full Run 1 + Run 2 dataset. During 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} starting in 2022. The installation and the commissioning foreseen for the ongoing Long Shutdown 2 (LS2) of the LHC, 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 will start the commissioning with beams on April 2022 with only half of the vertex detector (VELO C-side) and without the first tracking detector (UT). These missing detectors will be installed along 2022 (VELO side-A and UT side-C) or at End of the Year Technical Stop, starting in December 2022 (UT side-A). Only about $2fb^{-1}$ out of the 27-38 fb^{-1} expected in Run 3 will be collected in 2022 with the incomplete LHCb. The commissioning of LHCb during 2022 will be fundamental to be ready to start the 2023 data taking with the full detector. The very large sample that will be collected from Run 3 on, should allow to determine several SM variables in the flavour sector to a precision comparable with the ultimate theoretical uncertainty.

Being part of the *Muon System* and *SMOG2* 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 in 2022, to the R&D in view of possible future upgrades after LS3 and LS4 of the LHC.

1 Data analysis activity

Since tens of years, the $B_s^0 \to \mu^+\mu^-$ decay has been identified as a very interesting measurement that could show clear indications of NP and/or constrain the parameter space of models describing physics beyond the SM. After the publication in March 2017 by LHCb of the new result for the search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ using data collected in pp collisions during the Run 1 + Run 2 (2015 and 2016 only), in late 2018 the LNF group restarted the data analysis to perform the measurement using the 10 fb^{-1} collected in the full Run 1 + Run 2. The analysis has been completed and published in 2021. The $B_s^0 \to \mu^+\mu^-$ branching fraction and effective lifetime are measured, while no significant signal for $B^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-\gamma$ decays is found (the upper limits at 95% confidence level are determined). Additionally, the ratio between the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ branching fractions is measured to be in agreement with the Standard Model predictions.

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, tensions with respect to the SM predictions are observed in some b-hadron decay processes, of which the most recent updates come from the LHCb experiment. The observables involving b-hadron decays that show tensions with respect to the SM come from two different elementary processes: the tree-level $\mathrm{b} \to \mathrm{c}\ell\nu$ and the FCNC $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$. LNF group is directly involved in both areas, namely through the study of the semileptonic decays of B_s^0 with a τ lepton in the final state, working in particular on the measurement of exclusive $R(D_s^\star)$ and inclusive $R(D_s)$ ratios, and through the study of the Λ_b^0 decays.

Among the B mesons, B_s are particularly interesting because allow to overcome one the most important background that affects the B semi-tauonic decays. This background, associated with the decays of orbitally and radially excited charm-meson states, is in fact 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, ancillary to the relative R_D ratio, and is now working to the measurement of the $R(D_s^\star)$ ratio for which the result is expected for the 2022 Summer conferences.

2 Operation and Upgrade activities

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. Between the two trigger stages the real-time alignment and calibration of the detector are performed. The brand new 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 participates 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. 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.

For what concerns the Muon System, coordinated since Jan 2021 by a member of the Frascati LHCb group, 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 in the second half of 2021. Also, in the last years 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 190 nODE boards; the apparatus is now fully instrumented with the needed 144 nODE and ready to take data. 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 start of the systematic connectivity tests (CT) of the stations, all equipped with the new nSB and nODE boards.

In October 2021, LHCb participated to the first LHC test for Run 3. The Muon System took successfully part to the test being able to time align to the global LHC clock. Studies are ongoing to use the counters available in the very front-end electronics board to build an online luminosity monitor. First results from the test with LHC are promising for a $<2\%$ accuracy in the luminosity measurement and a paper is in preparation to describe the adopted method.

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.

Since many years Frascati team contributes also to both the Technical Coordination Team (TCT) and the Online project. For the TCT in 2021 the team worked in particular to the installation of the M2 beam plug and the tungsten shielding, and the coordination for the mechanical installations of SciFi. For the Online in 2021 the team focused its action on the virtualisation cluster hosting the LHCb ECS control system and on the commissioning of the HLT2 output storage; both systems have been successfully used during the test with LHC in October 2021.

Under the coordination of a member of the Frascati LHCb group, the SMOG2 project, the first internal fixed gas target at the LHC, is part of the ongoing major upgrade of the LHCb detector. In a productive effort carried on by the proponents and several relevant LHC working groups, and following the LHCC approval, the installation of the storage cell, the only object in the LHC primary vacuum, was successfully completed. Also the innovative injection system, that includes four different gas reservoirs has been completed, calibrated and will be installed in the LHCb cavern before the conclusion of the LS2. During the LHC test beam in October 2021, the system was carefully monitored and no interference neither negative feedback in the mutual interaction beam-cell was found during the different stages of the beam injection and running. The reconstruction codes and HLT1 trigger have been successfully implemented and the system is ready for the next Run 3 data taking. Studies for measuring the beam-gas luminosities are going on and simulations show the promising values of 2-3% for systematic uncertainties connected to this fundamental determination. Running strategies for using the SMOG2 system for the commissioning of the new LHCb subdetectors and for an Early Measurement campaign are under development. Fixed target collisions at LHCb will open exciting new fields of investigation, allowing the production of particles carrying a large momentum fraction of the target nucleon to be studied in kinematical regions poorly explored. In the nucleon-nucleon center-of-mass frame, at an energy scale up to 115 GeV, interactions of the LHC beam with gasses such as H, D going through the noble gasses up to the heavier Kr and Xe, pave the way for innovative and fundamental measurements. New results from QCD to astroparticles are expected from Run3, making LHCb the first experiment with two interaction points able to run simultaneously.

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 onwards, will build on the strengths of the current experiment and on the Phase-I Upgrade, but 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 what concerns the Muon System, the requirements for the phase-2 upgrade of the LHCb experiment, proposed for LHC Run-5, are very challenging for the innermost regions of the muon stations, where detectors with rate capability of few MHz/cm^2 and capable to stand an integrated charges up to 10 C/cm^2 are required. For this an intense R&D is undergoing by the Frascati Detector Design Group to develop and test new generation of Micro-pattern Gaseous Detectors (MPGD) which are suitable for rates as high as several MHz/cm^2. The micro-RWELL is a single amplification stage resistive MPGD. The amplification element, a copper-clad polyimide foil patterned with a matrix of blind holes, is embedded with the readout board through a relatively high resistivity DLC film (10 $\div$100 MΩ/square). The resistive layer of the detector, strongly suppressing the transition from streamer to spark gives the possibility to safely achieve large gains ($> 10^4$), while partially reducing the capability to stand high particle fluxes due to the Ohmic voltage drop. An intense optimization program of the micro-RWELL has been launched in the last year, together with a technology transfer to the industry operating in the PCB field. In order to fulfil the requirements several high rate layouts, characterised by a high density grounding network of conductive dots or lines patterned on the resistive stage, have been designed. The detectors were co-produced by CERN-EP-DT-MPT Workshop and ELTOS Company. The different high rate layouts have been characterised by irradiating the devices with high intensity 5.9 keV X-rays over beam spots of different diameter (10$\div$50 mm). Rate capabilities with X-rays of about 6$\div$7 MHz/cm^2 are achievable, corresponding to 15$\div$20MHz/cm^2 of m.i.p., in good agreement with the results obtained in 2019 at PSI.

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 timely completion of the Phase-I Upgrade and a successful start of Run 3 in 2022. 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 been given online to about 80 high school students in March 2021, as part of the IPPOG MasterClass program.

5 List of Talks by LNF Authors in Year 2021

1. C. De Angelis, Λ_0 traverse polarisation at LHCb using the gaseous fixed target system, SIF2021, L'Aquila, Sep 2021
2. P. Di Nezza, LHCb Fixed-target results and prospects (Panel talk) P. Di Nezza, HADRON 2021, July 2021, Mexico
3. P. Di Nezza, The SMOG2 project, GDR-QCDshort distances and Strong2020, CERN, May 2021
4. P. Di Nezza, Gaseous targets at LHCb, Physics Beyond Colliders, CERN, Mar 2021
5. P. Di Nezza, The LHCspin project, PANIC21, Lisbon, Sep 2021
6. M. Giovannetti - Rate performance of μ-RWELL irradiated with high intensity X-rays, IEEE NSS-MIC 2021, online
7. M. Rotondo, Talk a Physics in Collision, Lepton flavour violation (all experiments, CMS, ATLAS, LHCb, B-Factories, BesIII) https://pic2021.physik.rwth-aachen.de/
8. M. Rotondo, HQL, Organizzatore sessione CKM https://warwick.ac.uk/fac/sci/physics/research/epp/meetings/hql2021/
9. M. Santimaria, Seminario su invito dal titolo "New results on theoretically clean observables in rare B-meson decays from LHCb" al "CERN seminar" Link al contributo: https://indico.cern.ch/event/976688/ dal 23-03-2021 al 23-03-2021
10. M. Santimaria, Seminario su invito dal titolo "Risultati recenti da LHCb" alla "Riunione del consiglio direttivo INFN" Link al contributo su indico (accesso protetto): https://agenda.infn.it/event/26377/contributions/133799/
11. M. Santimaria, Talk parallelo dal titolo "The LHCspin project" a "DIS 2021 - XXVIII International Workshop on Deep- Inelastic Scattering and Related Subjects" (Stony Brook University, USA)
    Link ai proceedings: https://arxiv.org/abs/2105.10012
12. M. Santimaria, Seminario su invito dal titolo "Measurement of B0(s)-¿mu+mu- decays with Run 1 + Run 2 data at LHCb" a "LNF+Rome joint General Seminar Miniworkshop" (INFN-LNF e Roma, Italia)

13. M. Santimaria, Talk plenario dal titolo "LHCspin" al "Joint workshop GDR-QCD/QCD@short distances and STRONG2020 / PARTONS / FTE@LHC / NLOAccess" (IJCLab, Francia)

14. M. Santimaria, Talk plenario dal titolo "The LHCspin project" al "Sar Wors 2021 - Sardinian Workshop on Spin" (Cagliari, Italia)

15. M. Santimaria, Relazione su invito dal titolo: "Tests of Lepton Flavour Universality and rare B meson decays at LHCb" a SIF2021-107 congresso nazionale della Società Italiana di Fisica

16. M. Santimaria, Talk plenario dal titolo "The LHCspin project" in "Low-x workshop" (Isola d'Elba, Italia)
Link ai proceedings: https://arxiv.org/abs/2111.04515

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1. R. Aaij *et al.* [LHCb], "Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decays," Phys. Rev. D **105** (2022) no.1, 012010 doi:10.1103/PhysRevD.105.012010 [arXiv:2108.09283 [hep-ex]].

2. R. Aaij *et al.* [LHCb], "Analysis of Neutral B-Meson Decays into Two Muons," Phys. Rev. Lett. **128** (2022) no.4, 041801 doi:10.1103/PhysRevLett.128.041801 [arXiv:2108.09284 [hep-ex]].

3. R. Aaij *et al.* [LHCb], "Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate," JHEP **12** (2020), 144 doi:10.1007/JHEP12(2020)144 [arXiv:2003.08453 [hep-ex]].

4. P. Di Nezza, F. Fabiano, M. Santimaria "Strangeness Enhancement in Fixed-Target Pb-Ne Collisions with LHCb SMOG Experiment" https://cds.cern.ch/record/2778492?ln=en

5. M. Rotondo et al., "Averages of b-hadron, c-hadron and tau-lepton properties as of 2018" HFLAV collaboration, Eur.Phys.J.C 81 (2021) 3, 228

6. LHCb Collaboration, "LHCb Upgrade II - Framework TDR", CERN-LHCC-2021-012 ; LHCB-TDR-023, 2021.

7. P.Di Nezza, "LHC Run 3 and Run 4 prospects for heavy-ion physics with LHCb", Nuclear Physics A 1005 (2021) 121872

8. "A Neural-Network-defined Gaussian Mixture Model for particle identification applied to the LHCb fixed-target programme" G.Graziani, L.Anderlini, S.Mariani, E.Franzoso, L.L.Pappalardo, P. Di Nezza arXiv: 2110.10259, JINST in print

9. "The LHCspin project", P. Di Nezza et al. Proceedings PANIC2021 arXiv:2111.09611, PoS (PANIC2021)347

10. C. De Angelis, P. Di Nezza, M. Santimaria "Fixed target physics at LHC with LHCb"

11. C. De Angelis, Tutor: P. Di Nezza Lambda0 traverse polarisation at LHCb using the gaseous fixed target system Sapienza University of Rome - Dec 2021