LHCb/LNF 2020

M. Anelli (Ass.), G. Bencivenni, L. Calero Diaz (Ass.),
S. Cali (Dott.), P. Campana, G. Capon (Ass.),
P. Ciambrone, P. De Simone, P. Di Nezza, G. Felici,
M. Giovannetti (Dott), N. Kazeev (Dott.), S. Klaver (Bors. PostDoc),
G. Lanfranchi, S. Liuti (Ass.), G. Morello (Art. 23),
M. Palutan, M. Poli Lener, M. Rotondo, M. Santimaria (AdR), A. Saputi (Tec.),
A. Sarti (Ass.), F. Sborzacchi (Tec.), B. Sciascia (Resp.), A. Sciubba (Ass.)

In collaboration with "LNF-SEA"
A. Balla (Tec.), M. Carletti (Tec.), M. Gatta (Tec.)

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 550 papers using mainly Run 1 (2010-2012) with a steadily increasing number of papers using also the full Run 1 + Run 2 dataset. During Long Shutdown 1 (LS1) in 2013-2014, the LHCb detector remained essentially unchanged, while major upgrades are 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 ongoing pandemic but the Collaboration was able to arrange a new effective plan and almost all of sub detectors are on track with the new schedule and will be ready for the first circulating beams in 2022. The very large sample that will be collected from Run 3 on, should allow to determine several SM variables in the flavor sector to a precision comparable with the ultimate theoretical uncertainty.

Being part of the *Muon System*, *SMOG2*, and *Real Time Analysis* 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 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 $B^0_s \to \mu^+\mu^-$ 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 $B^0_s \to \mu^+\mu^-$ 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. This measurement will improve the accuracy on $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ and $B^0_s \to \mu^+\mu^-$ effective lifetime measurements, aiming also at the first observation of the $B^0 \to \mu^+\mu^-$ mode. The analysis is completed and is now under the internal review by the Collaboration. The new results will be presented at the Spring 2021 conferences.

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^0_s with a τ lepton in the final state, working in particular on the measurement of exclusive $R(D^\star_s)$ and inclusive $R(D_s)$ ratios, and through the study of the Λ^0_b 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. In 2020 Frascati group published the measurement of the $B \to D^\star_s\mu\nu$ form factors, ancillary to the relative R_D ratio, and is now working to the measurement of the $R(D^\star_s)$ ratio for which the result is expected for the 2021 Summer conferences.

LFV from baryon decays is less explored than the analogous phenomenon from mesons. Being fermions, the baryons obey to different Lagrangian interaction terms and have a different (half-integer) spin, which generates decays with different angular structures. They therefore can provide complementary and independent information on new physics phenomena. Frascati group is involved in studying the FCNC processes $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$ using the Λ^0_b decays. Two measurements are ongoing. The search for the $\Lambda^0_b \to e^+e^-$ decay, whose BR is predicted to be $(4.6 \pm 1.6) \times 10^{-6}$ in the SM and that has not yet been observed so far; if observed it could led also to the measurement of the $\mathrm{R}(\Lambda_b)$ ratio increasing the LHCb sensitivity to LFU test processes. These can be explored also searching for the $\Lambda^0_b \to e\mu$ decay. While being practically zero in the SM, its branching fraction would be significantly enhanced in alternative models in which the existence of new mediators contribute to the process. The result for $e\mu$ channel is expected to be completed by the end of 2021, while, due to lack of person-power, the work on the e^+e^- has been paused for a while and has been slowly resumed at the end of 2020.

2 Operation and Upgrade activities

The LHCb detector will be upgraded in 2019 - 2021, during the LS2. The goal of this upgrade is to allow the LHCb detector to take data at an instantaneous luminosity of $2\times10^{33}cm^{-2}s^{1}$, 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 a second step with full reconstruction and real-time analysis, known as HLT2. 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. In 2020 Frascati group developed, also thank to the thesis work of a Master Student in computer engineering, the tools and the framework for the interactive monitor of any process ongoing in the control room, greatly increasing the capability of understanding any unexpected behaviour.

For what concerns the Muon System, a perfect design with large redundancy factors and excellent construction quality allowed to run the detector at $\times2$ with respect to the design luminosity for the whole Run 1 and Run 2, and to move forward for another decade of operation at $\times10$ 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 it will be completed in the first months of 2021 (this was foreseen for the first half of 2020 but the ongoing pandemic delayed some activity at pit). 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.

Also the apparatus of the new Muon system off-detector electronics (nODE) has been redesigned to be compliant with the 40 MHz readout of the detector, and the LNF electronic team (LNF-SEA), has the task of producing, testing and commissioning it. The 190 board full production has been shipped to LNF by the end of 2020 (with quite some delay due to the pandemic). All the boards have been tested and - the 147 ones found good - sent to CERN where have been installed in the apparatus. In November 2020 the commissioning of the whole Muon system started with a substantial contribution by the Frascati team. Since the new ODE board requires to review the architecture of the Electronic Control System (ECS) completely. A preliminary version of the nSYNC libraries with all the basic functions implemented has been deployed in August 2020 allowing the start of the systematic connectivity tests of the stations, all equipped with the new nSB and nODE boards.

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 without modifying 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 new muon identification algorithms and their performance in terms of signal efficiency versus background reduction have been described in a published paper.

Since many years Frascati team contributes also to both the Technical Coordination Team (TCT) and the Online project. For the TCT in 2020 the team worked in particular to the installation of the HCAL beam plug and the tungsten shielding, and the coordination for the mechanical installations of SciFi and Muon sub-detectors. For the Online in 2020 the team focused its action on the design, the purchase, the installation, and the migration of both the new data centre of the experiment and the virtualisation cluster hosting the LHCb ECS control system, and also carried out the test of different configurations for the HLT2 output storage.

Finally, under the coordination of a member of the Frascati team, 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 in Summer 2020. The injection system construction is underway and will be completed within the LHC LS2 along with the readout implementation in the LHCb DAQ. 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 Run 3, making LHCb the first experiment with two interaction points able to run simultaneously. (The feasibility of acquiring p−p and SMOG data in parallel - a key point for the upcoming data taking - was successfully tested at the end of Run 2.)

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, an intense R&D is undergoing by the Frascati Detector Design Group to develop and test new generation of Micro-pattern Gaseous Detectors which are suitable for rates as high as several MHz/cm^2. In particular the activity for the LHCb muon system focuses on the Micro-Resistive WELL (μ-RWELL). The detector is a compact, intrinsically spark-protected, single amplification stage device. The core of the detector is the μ-RWELL_PCB contining the readout plane, properly segmented, glued to the amplification stage. This latter is realized by chemical etching of a polyimide foil coated with copper on one side and Diamond-Like Carbon (DLC) on the other. Once applied a potential drop between copper and DLC, the electric field inside the blind holes is large enough to allow the multiplication of the primary ionization electrons created in the drift/conversion gap. After a finalization of the resistive stage in order to allow the detector to stand particles rate of the order of MHz/cm^2, the characterization of this technology has been focused on the stability response under irradiation. Some $10 \times 10\ cm^2 \mu$-RWELLs have been operated under X-ray flux for long time integrating 180 mC/cm^2, with the final goal of integrating the 2 C/cm^2 expected after 10 years of operations in the most irradiated region of the LHCb Muon detector.

Four more prototypes have been irradiated with pions at the π-M1 test beam area of the Paul Scherrer Institute (PSI) for ageing studies performed with m.i.p and the analysis of the collected data is ongoing. A direct test on the resistive material is running: two DLC foils of different thickness are supplied up with voltage and the current monitored to check the stability of the material. So far 0.8 C/cm^2 have been integrated in this test, showing current fluctuations below 2% around the average value. Meanwhile the production of medium-size prototypes 30×30 cm^2 has started and is in queue for the final production. For a complete validation of the technology for the adoption in LHCb, a slice test is under discussion. The tentative plan is to install several μ-RWELLs of different size in the inner regions of the second station of the LHCb muon system (namely in M2R1 and M2R2, with expected rates from 100 to 700 kHz/cm^2). The detectors will be operated in current mode with the same gas mixture used for MWPC installed on the muon apparatus (Ar/CO2/CF4 45/15/40). Considering the foreseen rate and setting a gain of 4000, we expect to integrate about 220 mC/cm^2.

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.

5 List of Talks by LNF Authors in Year 2020

1. M. Giovannetti, talk and proceedings,INSTR2020 (Instrumentation for Colliding Beam Physics), Novosibirsk, Russia, "The μ-RWELL for high rate application", JINST 15 (2020) C09034, https://indico.inp.nsk.su/event/20/contributions/790/
2. N. Kazeev, lectures at "Sixth Machine Learning in High Energy Physics Summer School 2020", https://indico.cern.ch/event/838377/
3. M. Rotondo, Heavy Flavour Physics Workshop, 17 Feb 2020, La Sapienza, "Semileptonic B decays: recent results and opportunities"
4. M. Rotondo, Conference on Flavour Physics and CP violation (FPCP 2020), 8-12 June 2020, virtual, "Experimental status of $|V_{cb}|$ and $|V_{ub}|$ with semileptonicb-hadron decays"
5. M. Santimaria, Proceedings for *"Search for Lepton Flavour Violating decays at LHCb"* talk at EPS-HEP 2019 - European Physical Society Conference on High Energy Physics Ghent (Belgium), July, 10-17th (https://pos.sissa.it/364/249/pdf)
6. M. Santimaria, Proceedings for *"Outreach activities at LHCb"* talk at EPS-HEP 2019 - European Physical Society Conference on High Energy Physics Ghent (Belgium), July, 10-17th (https://pos.sissa.it/364/453/pdf)
7. M. Santimaria, Talk at 3rd World Summit on Exploring the Dark Side of the Universe, 9-13 March 2020, Guadeloupe Islands, *"B-Physics Anomalies"*, proceedings available here https://kuscholarworks.ku.edu/handle/1808/30804
8. M. Santimaria, Talk at the Implications of LHCb measurements and future prospects, CERN 28-30 October 2020, *"Opportunities with Rare Decays in the LHCb upgrade"* (https://indico.cern.ch/event/857473/timetable/#18-opportunities-with-rare-dec)

References

1. L. Anderlini, F. Archilli, A. Cardini, V. Cogoni, M. Fontana, G. Graziani, N. Kazeev, H. Kuindersma, R. Oldeman, *et al.* "Muon identification for LHCb Run 3," JINST **15** (2020) no.12, T12005 doi:10.1088/1748-0221/15/12/T12005 [arXiv:2008.01579 [hep-ex]].

2. N. Kazeev, "Machine Learning for particle identification in the LHCb detector", 21 October 2020 http://www.infn.it/thesis/thesis_dettaglio.php?tid=528889, https://cds.cern.ch/record/2744601

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. D. Derkach, N. Kazeev, F. Ratnikov, A. Ustyuzhanin and A. Volokhova, "Cherenkov Detectors Fast Simulation Using Neural Networks," Nucl. Instrum. Meth. A **952** (2020), 161804 doi:10.1016/j.nima.2019.01.031 [arXiv:1903.11788 [hep-ex]].

5. R. Aaij, J. Albrecht, P. Billoir, T. Boettcher, *et al.* "Allen: A high level trigger on GPUs for LHCb," Comput. Softw. Big Sci. **4** (2020) no.1, 7 doi:10.1007/s41781-020-00039-7 [arXiv:1912.09161 [physics.ins-det]].

6. A. Maevskiy *et al.* [LHCb], "Fast Data-Driven Simulation of Cherenkov Detectors Using Generative Adversarial Networks," J. Phys. Conf. Ser. **1525** (2020) no.1, 012097 doi:10.1088/1742-6596/1525/1/012097 [arXiv:1905.11825 [physics.ins-det]].

7. P. Di Nezza, "New SMOG on the horizon", CERN Courier, Vol.60 n.3, 2020

8. C.Aidala et al., "Probing Nucleons and Nuclei in High Energy Collisions", arXiv:2002.12333

9. C. Barschel et al., "LHC fixed target experiments: Report from the LHC Fixed Target Working Group of the CERN Physics Beyond Colliders Forum", CERN Yellow Reports: Monographs CERN-2020-004

10. E.Manosperti, Tutor: P. Di Nezza, "Development of Molecular Diffusion Codes for SMOG2 Storage Cell" University of Pisa - Nov 2020

11. P. Gambino, A. S. Kronfeld, M. Rotondo, C. Schwanda, F. Bernlochner, A. Bharucha, C. Bozzi, M. Calvi, L. Cao and G. Ciezarek, *et al.* "Challenges in semileptonic B decays," Eur. Phys. J. C **80** (2020) no.10, 966 doi:10.1140/epjc/s10052-020-08490-x [arXiv:2006.07287 [hep-ph]].

12. G. Ricciardi and M. Rotondo, “Determination of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$,” J. Phys. G **47** (2020), 113001 doi:10.1088/1361-6471/ab9f01 [arXiv:1912.09562 [hep-ph]].

13. M. Rotondo [LHCb], “Heavy flavour production at LHCb,” PoS *Beauty2019* (2020), 025 doi:10.22323/1.377.0025