**LHCb/LNF 2019**

P. Albicocco (AdR), M. Anelli (Ass.), G. Bencivenni,
S. Cali (Dott.), L. Calero Diaz (Ass.), P. Campana,
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.)

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

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 500 papers using mainly Run 1 (2010-2012) with increasing contributions 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 2021. The installation and the commissioning are processing on schedule during the ongoing Long Shutdown 2 (LS2) of the LHC. 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 2021, 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 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. This measurement will improve the accuracy on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and $B_s^0 \to \mu^+\mu^-$ effective lifetime measurements, aiming also at the first observation of the $B^0 \to \mu^+\mu^-$ mode. The analysis is close to be completed and the group aims at presenting the new results at the upcoming Summer 2020 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 b $\to$ c$\ell\nu$ and the FCNC b $\to$ 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 $\tau$ 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 $\Lambda_b^0$ 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 is working to the measurement of the $R(D_s^\star)$ ratio and just completed the measurement of the $B \to D_s^\star\mu\nu$ form factors, ancillary to the relative $\mathrm{R}_D$ ratio.Another important study led in Frascati is the evaluation of the long-distance electromagnetic contributions of the decay channels involved in the R($D^+$) and ($\mathrm{D}^0$) ratios. The impact on published and ongoing RD ratios has been studied and a paper has been published.

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 b $\to$ s$\ell^+\ell^-$ using the $\Lambda_b^0$ decays. Two measurements are ongoing. The search for the $\Lambda_b^0 \to e^+e^-$ 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 R($\Lambda_b$) ratio increasing the LHCb sensitivity to LFU test processes. Due to lack of person-power, the work on these measurements has been

paused in 2019 and will be resumed in 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.

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. Beyond securing the good running of the system during Run 2 data taking (about 25% of the "Muon expert on call" shifts were taken by Frascati people), a lot of effort has been put in the planning of the activities towards next Runs starting from Run 3 in 2021. 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 2020. 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. Given the full software trigger chosen to run from Run 3 on, the first muon station, M1, became useless. M1 (composed of MWPCs except of its inner region instrumented with GEM detectors) has been dismounted in March 2019 with the Frascati team deeply involved in both the preparatory work and the dismantling itself.

Finally 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) coordinated by P. Ciambrone, has the task of producing, testing and commissioning it. The 24 nODE of the pre-production have been assembled and tested. At the end of 2019 the 166 board full production started and the test is ongoing as they arrive at LNF. In parallel the same LNF-SEA team put in place the full acquisition chain (the so called "miniDAQ") needed for the final

test of all the boards. Since the new ODE board requires to review the architecture of the Electronic Control System (ECS) completely, the first full connectivity test has been performed at CERN on one of the M4 station quadrants using a preliminary version of the nSYNC libraries. In the meantime the development of the full new libraries is ongoing under the Frascati responsibility in close touch with the commissioning team at CERN. As soon as the new ECS will be ready, the systematic test of the muon system connectivity will start as the stations will be 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 will be used in Run 3 selections.

Finally, under the coordination of P. Di Nezza, the SMOG2 project, the first internal fixed gas target at the LHC will be part of LHCb resulting the only object present in the LHC primary vacuum. Its installation is foreseen in 2020 during the LHC LS2. In a productive effort carried on by the proponents and several relevant LHC working groups, the R&D has been finalized in a TDR, then approved by the LHCC. The system, consisting on a storage cell attached upstream of the VELO radio frequency boxes and an advanced Gas Feed System able to give precise determination of the luminosity, completed all the mechanical, thermal and vacuum tests and entered in the construction phase. Also the feasibility of acquiring p−p and SMOG data in parallel has been successfully tested at the end of 2019. Fixed target collisions at LHCb will open new exciting fields of investigation allowing to study production of particles carrying a large momentum fraction of the target nucleon 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 beams with gases like H, D going through the noble gasses up to the heavier Kr and Xe, pave the way to innovative and fundamental measurements. New results from QCD to astroparticle 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, an intense R&D is undergoing by the Frascati Detector Design Group to develop and test new generation of Micro-pattern Gaseous Detectors (MPGDs) 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 ($\mu$-RWELL). The detector is a compact, intrinsically spark-protected, single amplification stage device. The core of the detector is the $\mu$-RWELL_PCB containing 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 $\pi$-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 $30 \times 30$ 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 $\mu$-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 2021. 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 to 40 high school students in March 2019, as part of the IPPOG MasterClass program.

## 5 List of Talks by LNF Authors in Year 2019

1. G. Bencivenni, Talk at VCI 2019, 15th Vienna Conference on Instrumentation, 18 -23 February 2019, Vienna (Austria) *"High space resolution micro-RWELL for high particle rate"*. Proceedings to be published on Nucl. Inst. & Meth. A, NIMA62050, on-line version on https://doi.org/10.1016/j.nima.2019.04.004

2. S. Calì, Comunicazione al 105° Congresso Nazionale SIF September 2019 *"Measurement of the shape of the $B_s^0 \to D_s^{*+}\mu^-\nu_\mu$ differential distribution"*

3. P. De Simone, Talk at 6th KEK Flavour Factory Workshop, 14-16 February, 2019, Japan *"Semitauonic B decays at LHCb"*

4. P. De Simone, Talk at Workshop on Flavour Changing and Conserving Processes, 29-31 August, 2019, Capri Island, Italy *"Experimental Review on Lepton Universality and Lepton Flavour Violation tests in B Decays"*

5. P. Di Nezza, Invited Talk, Physics Beyond Collider, Jan 2019, CERN *"LHC-FT SMOG2 and LHCspin"*

6. P. Di Nezza, Invited Talk at Initial Stages 2019, Columbia University, Jun 2019, NYC - US *"LHCb fixed target results and prospects"*

7. P. Di Nezza, Invited Talk at LHCspin kick-off workshop, Jul 2019, Ferrara - Italy *"A polarised and unpolarised target at he LHC: where we are"*

8. P. Di Nezza, Invited Talk at Heavy Ion Workshop: Exploring Matter, Sep 2019, Chia - Italy *"Experimental prospects with polarised fixed targets at LHC"*

9. P. Di Nezza, Talk at Quark & Matter, Nov 2019, Wuhan - China *"LHC Run 3 and Run 4 prospects for heavy-ion physics with LHCb"*

10. P. Di Nezza, Invited Talk at MSO5 workshop, Nov 2019, Lushan - China *"Fixed targets at the LHC"*

11. P. Di Nezza, Talk at Implication workshop, Nov 2019, CERN *"Physics opportunities with SMOG2"*

12. M. Giovannetti, Talk at IFAE 19, 8-10 April 2019, Napoli *"The $\mu$-RWELL detector for high particle rate"*

13. N. Kazeev, Talk at 19th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT-2019), Saas-Fee 10-15 March 2019 *"Machine Learning on sWeighted data"*

14. N. Kazeev, Talk at 19th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT-2019), Saas-Fee 10-15 March 2019 *"Fast Data-Driven simulation of Cherenkov Detectors Using Generative Adversarial Networks"*

15. N. Kazeev, Poster at 19th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT-2019), Saas-Fee 10-15 March 2019 *"Machine Learning for Muon Identification at LHCb"*

16. N. Kazeev, Poster at Machine Learning and the Physical Sciences Workshop at the 33rd Conference on Neural Information Processing Systems (NeurIPS 2019) *"Data Driven Simulation of Cherenkov Detectors using Generative Adversarial Network"*

17. N. Kazeev, Digital contribution at Machine Learning and the Physical Sciences Workshop at the 33rd Conference on Neural Information Processing Systems (NeurIPS 2019) *"Training machine learning algorithms on background-contaminated data"*

18. S. Klaver, Plenary Talk at FPCP International Conferenze, Canada 6-10 May 2019 *Lepton flavour universality in charged-current B decays*

19. S. Klaver, Talk at FPCP International Conferenze, Canada 6-10 May 2019 *Impacts of radiative corrections on measurements of LFU in* $B \to D\ell\nu$ *decays*

20. S. Klaver, Seminar at Manchester University, 5 April 2019 *Lepton flavour universality*

21. S. Klaver, General INFN-LNF Seminar (Frascati), 19 May 2019 *New measurements using semileptonic* $B_s$ *decays*

22. M. Poli Lener, Talk at the MPGD19, 5-10 May 2019, La Rochelle *"High space resolution* $\mu$*-RWELL for high particle rate"*

23. M. Rotondo, Talk at Gordon Research Conference 30/06/2019 Hong Kong China *"New tools for next generation of particle physics and cosmology"*

24. M. Rotondo, Talk at Gordon Research Conference 30/06/2019 Hong Kong China *"Prospects of flavour physics at LHCb"*

25. M. Rotondo, Talk at Beauty 2019, 30/09/2019 Ljubljana Slovenia, *"Heavy Flavour production at LHCb"*

26. M. Santimaria, Invited Talk at SIF 2019 - 105° Congresso Nazionale della Societ Italiana di Fisica L'aquila (Italy), September, 23-27th *"Study of rare b-hadron decays at LHCb"*

27. M. Santimaria, Talk at EPS-HEP 2019 - European Physical Society Conference on High Energy Physics Ghent (Belgium), July, 10-17th *"Search for Lepton Flavour Violating decays at LHCb"* (https://pos.sissa.it/364/)

28. M. Santimaria, Talk at EPS-HEP 2019 - European Physical Society Conference on High Energy Physics Ghent (Belgium), July, 10-17th *"Outreach activities at LHCb"* (https://pos.sissa.it/364/)

29. M. Santimaria, General INFN-LNF Seminar (Frascati), 19th May 2019 *"Recent discoveries at LHCb"*

30. M. Santimaria, Talk at INFN-CSN1, Trieste September 2019: *"Physics highlights at LHCb"*

31. B. Sciascia, Talk at the GDR-Intensity-Frontier Workshop on QED corrections to (semi)leptonic B decays, 8-9 July 2019, LPNHE, Paris *Impacts of radiative corrections on measurements of lepton flavour universality in $B \to D\ell\nu$ decays"*

## References


1. C.A.Aidala et al. The LHCspin Project arXiv:1901.08002

2. L. Anderlini et al. *New muon identification operators*. Tech. rep. LHCb-INT-2019-020. CERN-LHCb-INT-2019-020. Geneva: CERN, 2019. url: https://cds.cern.ch/record/ 2687369.

3. G. Bencivenni et al. *High space resolution micro-RWELL for high particle rate* to be published on Nucl. Inst. & Meth. A, NIMA62050, on-line version on https://doi.org/10.1016/j.nima.2019.04.004

4. G. Bencivenni et al. *The micro-RWELL layouts for high particle rate* 2019_JINST_14_P05014, on-line version on https://doi.org/10.1088/1748-0221/14/05/P05014

5. M. Borisyak and N. Kazeev. *Machine Learning on data with sPlot back-ground subtraction* In: Journal of Instrumentation 14.08 (Aug. 2019), P08020P08020. doi: 10.1088/1748-0221/14/08/p08020.

6. S. Calì, S. Klaver, M. Rotondo, and B. Sciascia *Impacts of radiative corrections on measurements of lepton flavour universality in $B \to D\ell\nu_\ell$ decays* EPJC79 (2019) 744

7. S. Calì et al. *"Measurement of the shape of the $B_s^0 \to D_s^{\star+}\mu^-\nu_\mu$ differential distribution"*, LHCb-ANA-2018-045; related paper in preparation.

8. A.Dainese et al. *Physics Beyond Colliders: QCD Working Group Report* arXiv:1901.04482

9. D. Derkach, N. Kazeev, F. Ratnikov, A. Ustyuzhanin, & A. Volokhova *Cherenkov detectors fast simulation using neural networks* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. https://doi.org/10.1016/j.nima.2019.01.031

10. P. Di Nezza et al. *Internal gas target experiments at the LHC* Proceedings of Science, Vol.346 (2019), https://doi.org/10.22323/1.346.0011

11. M. Giovannetti *The $\mu$-RWELL detector for high particle rate* to be published on Nuovo Cimento - Colloquia on Physics.

12. HFLAV Collaboration *Averages of b-hadron, c-hadron, and tau-lepton properties as of 2018* arXiv:1909.12524 Submitted to EPJC

13. LHCb Collaboration *LHCb SMOG Upgrade* CERN-LHCC-2019-005, LHCB-TDR-020

14. L.Pappalardo et al. *The LHCspin project* Vol.352 (2019), https://doi.org/10.22323/1.352.0233

15. M. Poli Lener *High space resolution $\mu$-RWELL for high particle rate* submitted to Journal of Physics: Conference Series (JPCS).

16. G. Ricciardi and M. Rotondo *Determination of the Cabibbo-Kobajashi-Maskava matrix element $|V_{cb}|$* arXiv:1912.09562, invited review on J. Phys. G: Nucl. Part. Phys

17. L. Serricchio, *"Studio delle prime collisioni con bersaglio fisso a LHC"* Sapienza, Universit di Roma - Dic 2019

18. E.Steffens et al. *Design Consideration on a Polarized Gas Target for the LHC* Proceedings of Science, Vol.346 (2019), https://doi.org/10.22323/1.346.0098