LHCb

M. Anelli (Tecn.), F.Archilli (Ass. Ric.), G. Bencivenni, P. Campana,
P. Ciambrone, P. De Simone, G. Felici, G. Lanfranchi, F. Murtas,
M. Palutan, R. Rosellini (Tecn.), M. Santoni (Tecn.), A. Saputi (Tecn.),
A. Sarti (Ass.), B.Sciascia, A. Sciubba (Resp. Ass.), F. Soomro (Bors. PD)

In collaboration with “LNF-SEA”
A. Balla, M. Carletti, G. Corradi, M. Gatta

1 Introduction

The LHCb experiment 2012 data taking campaign was very succesful, with 2.2 fb^{-1} of pp collisions integrated at $\sqrt{s} = 8$ TeV. This was possible thanks to the performance of the LHC, to the luminosity leveling technique, consisting of taking data at constant instantaneous luminosity of 4×10^{32} cm^{-2} s^{-1} , and to the excellent run of the detector, which was capable to work at full efficiency far beyond its design parameters. The acquired data add up to the 1 fb^{-1} integrated in 2011 at $\sqrt{s} = 7$ TeV, leading to an unprecedented sample of b and c decays which will allow to considerably increase our sensitivity in the search of physics beyond the Standard Model (SM) in the flavor sector. Already in 2012 LHCb published several “world record” measurements in the core physics channels: the CP violation phase ϕ_s in the B_s^0 decays, the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to K^*\mu^+\mu^-$, and in charm physics.

Among these, most relevant is the evidence for a $B_s^0 \to \mu^+\mu^-$ signal with $3.5\,\sigma$ significance, as discussed in sec. 2, which is the result of the joint analysis of 2011 data and $1.1\,\text{fb}^{-1}$ of the 2012 data. This eagerly awaited result, presented at HCP conference in november 2012 and recently published in Physical Review Letters 8), collecting more than sixty citations in less than two months, represents a milestone in the flavor physics landscape. The LNF team contributed substantially to this achievement, partecipating in all of the aspects of the analysis, and coordinating the effort of the international analysis working group (with G. Lanfranchi and M. Palutan serving as convenors).

In parallel, considerable efforts have been spent by the team on the muon system, covering both aspects of detector operation/maintenance and performance assessment/monitoring. On the first item, we contributed as muon piquet shifters to the daily operation of the detector during the whole data taking period, and thanks to our technical staff we could contribute also to the spare chamber reparation, to the readout board maintenance and we took care of keeping updated the online control software. All these aspects were fundamental to achieve a reliable and efficient operation of the muon trigger, and to ensure a high data quality. On the second item, we developed and ran intensively the software needed to monitor the chamber efficiency. Moreover, we also performed a full scan of the offline muon identification performances on the whole 2011 and 2012 data sets. This study provides, as a function of the time and data taking conditions, the algorithm efficiency on true muons, as measured on J/ψ decays, and the misidentification probability of proton, kaon and pions, as measured on Λ and D decays. These calibrations have been widely used in many LHCb analyses involving muons in the final state.

Even though the physics harvest is now in full flow, the collaboration is already planning for an upgrade of the experiment, intended to collect ~ 50 fb^{-1} starting in 2019, after the long shutdown 2 of LHC. This very large sample should allow to determine several SM variables in the flavor sector to a precision comparable with the ultimate theoretical uncertainty. The LNF team will guarantee the full operation of the muon system readout in the upgrade conditions, the production of the needed spare muon chambers, and the production of new chambers based on GEM technology, on which the group has a leadership position. Detailed studies on the detector hardware performances in special high luminosity runs have been performed at LNF, which are driving the choices for the muon detector upgrade.

As demonstrated above, the LHCb LNF group has a leadeship role in many aspects, and this has been fully recognized by appointing Pierluigi Campana as spokeperson of the LHCb collaboration, with a three years mandate starting June 2011.

2 First evidence of the decay $B_s^0 \to \mu^+\mu^-$

The rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are highly suppressed in the SM. Precise predictions of their branching fractions, $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$, make these modes powerful probes in the search for deviations from the SM, especially in models with a non-standard Higgs sector.

Previous searches already constrain possible deviations from the SM predictions. The lowest published limits are $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ at 95 % confidence level (CL) from the LHCb collaboration using 1.0 fb^{-1} of data collected in pp collisions in 2011 at $\sqrt{s} = 7$ TeV 6). Here we discuss the update of this search with 1.1 fb^{-1} of data recorded in 2012 at $\sqrt{s} = 8$ TeV.

The analysis of 2012 data was similar to what we did in the past (and described in Ref. 6)), but we greatly improved our estimate of the exclusive backgrounds. To avoid potential bias, the events in the signal region were not examined until all the analysis choices were finalized. The updated estimate of the exclusive backgrounds is also applied to the 2011 data 6) and the results re-evaluated.

The $B^0_{(s)} \to \mu^+\mu^-$ candidates are selected by requiring two high quality muon candidates $^{4)}$ $^{5)}$ displaced with respect to any pp interaction vertex (primary vertex, PV), and forming a secondary vertex separated from the PV in the downstream direction by a flight distance selection. The surviving background comprises mainly random combinations of muons from semileptonic decays of two different b hadrons ($b\bar{b} \to \mu^+\mu^- X$, where X is any other set of particles).

Two channels, $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$, serve as normalization modes. The first mode has trigger and muon identification efficiencies similar to those of the signal, but a different number of tracks in the final state. The second mode has a similar topology, but is triggered differently. The selection of these channels is as close as possible to that of the signal to reduce the impact of potential systematic uncertainties.

A multivariate analysis, based on a boosted decision tree (BDT), is used to fully exploit the kinematic and topological information of the event to discriminate the signal from the background. The BDT output is then used, together with the dimuon invariant mass, to classify the selected candidates. The BDT discriminant is trained using simulated samples consisting of $B^0_s \to \mu^+\mu^-$ for signal and $b\bar{b} \to \mu^+\mu^- X$ for background. The BDT response is defined such that it is approximately uniformly distributed between zero and one for signal events and peaks at zero for the background. The BDT response is independent of the invariant mass for signal inside the search window. The probability for a $B^0_{(s)} \to \mu^+\mu^-$ event to have a given BDT value is obtained from data using $B^0 \to K^+\pi^-$, $\pi^+\pi^-$ and $B^0_s \to \pi^+K^-$, K^+K^- exclusive decays selected as the signal events.

The invariant mass lineshape of the signal events is described by a Crystal Ball function. The peak values for the B^0_s and B^0 mesons, $m_{B^0_s}$ and m_{B^0}, are obtained from the $B^0_s \to K^+K^-$ and $B^0 \to K^+\pi^-$, $B^0 \to \pi^+\pi^-$ samples. The resolutions are determined with a power-law interpolation between the measured resolutions of charmonium and bottomonium resonances decaying into two muons. The results are $\sigma_{B^0_s} = 25.0 \pm 0.4\,\mathrm{MeV}/c^2$ and $\sigma_{B^0} = 24.6 \pm 0.4\,\mathrm{MeV}/c^2$, respectively.

The $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ yields are translated into branching fractions using

$$\begin{aligned}\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) &= \frac{\mathcal{B}_{\rm norm}\, \epsilon_{\rm norm}\, f_{\rm norm}}{N_{\rm norm}\, \epsilon_{\rm sig}\, f_{d(s)}} \times N_{B^0_{(s)}\to\mu^+\mu^-} \\ &= \alpha^{\rm norm}_{B^0_{(s)}\to\mu^+\mu^-} \times N_{B^0_{(s)}\to\mu^+\mu^-}, \end{aligned} \qquad (1)$$

where $\mathcal{B}_{\rm norm}$ represents the branching fraction, $N_{\rm norm}$ the number of signal events in the normalization channel obtained from a fit to the invariant mass distribution, $\alpha^{\rm norm}_{B^0_{(s)}\to\mu^+\mu^-}$ the normalization factors, and $N_{B^0_{(s)}\to\mu^+\mu^-}$ is the number of observed signal events.

The factors $f_{d(s)}$ and $f_{\rm norm}$ indicate the probabilities that a b quark fragments into a $B^0_{(s)}$ meson and into the hadron involved in the given normalization mode, respectively. We assume $f_d = f_u$ and use $f_s/f_d = 0.256 \pm 0.020$ measured in pp collision data at $\sqrt{s} = 7$ TeV

The efficiency $\epsilon_{\rm sig(norm)}$ for the signal (normalization channel) is the product of the reconstruction efficiency of the final state particles including the geometric detector acceptance, the selection efficiency and the trigger efficiency. The normalization factors $\alpha^{\rm norm}_{B^0_{(s)}\to\mu^+\mu^-}$ for $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$ are in agreement within the uncertainties, and their weighted average, taking correlations into account, gives $\alpha_{B^0_s\to\mu^+\mu^-} = (2.52 \pm 0.23) \times 10^{-10}$ and $\alpha_{B^0\to\mu^+\mu^-} = (6.45 \pm 0.30) \times 10^{-11}$.

In the 2012 data sample, 24 044 muon pairs with invariant mass between 4900 and 6000 MeV/c^2 pass the trigger and selection requirements. Given the measured normalization factors and assuming the SM branching fractions, the 2012 data sample is expected to contain about 14.1 $B^0_s \to \mu^+\mu^-$ and 1.7 $B^0 \to \mu^+\mu^-$ decays. The signal regions are defined by $m_{B^0_{(s)}} \pm 60\,{\rm MeV}/c^2$.

The expected number of combinatorial background events is determined by interpolating from the invariant mass sideband regions defined as $[4900\,{\rm MeV}/c^2, m_{B^0} - 60\,{\rm MeV}/c^2]$ and $[m_{B^0_s} + 60\,{\rm MeV}/c^2, 6000\,{\rm MeV}/c^2]$. The low-mass sideband and the B^0 and B^0_s signal regions are potentially polluted by exclusive backgrounds with or without misidentification of the muon candidates.

The first category includes $B^0 \to \pi^-\mu^+\nu_\mu$, $B^0_{(s)} \to h^+h'^-$, $B^0_s \to K^-\mu^+\nu_\mu$ and $\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$ decays. The second category includes $B^+_c \to J/\psi(\mu^+\mu^-)\mu^+\nu_\mu$, $B^0_s \to \mu^+\mu^-\gamma$ and $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$ decays. Apart from $B^0_{(s)} \to h^+h'^-$, all background modes are normalized relative to the $B^+ \to J/\psi K^+$ decay. The $B^0 \to \pi^-\mu^+\nu_\mu$, $B^0_{(s)} \to h^+h'^-$ and $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$ decays are the dominant exclusive modes in the range BDT > 0.8, which accounts for 70 % of the sensitivity. Of these, $B^0_{(s)} \to h^+h'^-$ double misidentified events are the only contributing significantly in the signal region.

The compatibility of the observed distribution of events with that expected for a given branching fraction hypothesis is computed using the binned $\rm CL_S$ method. The method provides $\rm CL_{S+B}$, a measure of the compatibility of the observed distribution with the signal plus background hypothesis, $\rm CL_B$, a measure of the compatibility with the background-only hypothesis, and $\rm CL_S = CL_{S+B}/CL_B$. As inputs to the $\rm CL_S$ computation, we count the number of observed candidates, and compute the expected number of signal and background events in each bin of the two-dimensional space formed by the dimuon mass and the BDT output.

The expected and observed $\rm CL_S$ values for $B^0 \to \mu^+\mu^-$ as a function of the branching fraction are shown in Fig. 1. The observed $\rm CL_B$ value at $\rm CL_{S+B} = 0.5$ is 89 %, corresponding to a p-value for background-only observation of 11%. From our data we constrain the $B^0 \to \mu^+\mu^-$ branching fraction to be less than 9.4×10^{-10}, at 95% CL $^{8)}$, which is the world-best limit from a single experiment.

The probability that background processes can produce the observed number of $B^0_s \to \mu^+\mu^-$ candidates or more is 5×10^{-4} and corresponds to a statistical significance of $3.5\,\sigma$. The value of the $B^0_s \to \mu^+\mu^-$ branching fraction is obtained

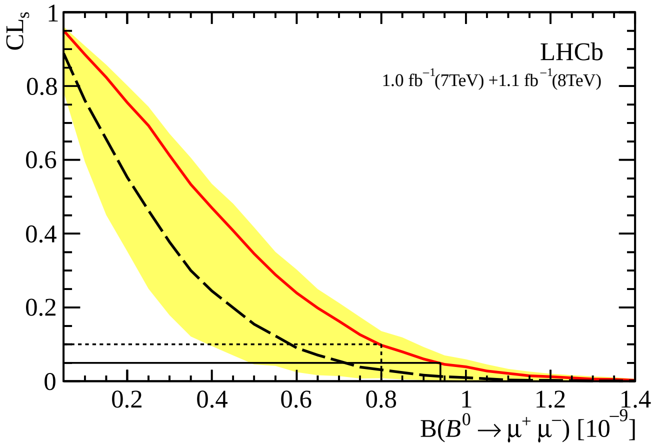

Figure 1: $\mathrm{CL_S}$ as a function of the assumed $B^0 \to \mu^+\mu^-$ branching fraction for the combined 2011+2012 dataset. The dashed gray curve is the median of the expected $\mathrm{CL_S}$ distribution if background and SM signal were observed. The shaded yellow area covers, for each branching fraction value, 34 % of the expected $\mathrm{CL_S}$ distribution on each side of its median. The solid red curve is the observed $\mathrm{CL_S}$.

from an unbinned likelihood fit to the mass spectrum, performed simultaneoulsy in different BDT bins. We obtain [8]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\mathrm{stat})\,^{+0.5}_{-0.3}(\mathrm{syst})) \times 10^{-9},$$

which is in agreement with the SM expectation. This is the first evidence for the decay $B_s^0 \to \mu^+\mu^-$. The invariant mass distribution of the $B_{(s)}^0 \to \mu^+\mu^-$ candidates with BDT > 0.7 is shown in Fig. 2.

After decades of experimental efforts, the present result represents a major achievement of the LHC. However the current precision on the decay rate is not sufficient to exclude contributions from new physics processes. In particular, even if strong enhancements from scalar Higgs have been already ruled out, we start to experimentally probe only now possible new physics contributions from the semileptonic operators.

Present effort by the LNF group is in the finalization of the analysis on the full 2012 dataset, adding more than 1 fb^{-1} to what used to publish the above result. All data have been reprocessed for this purpose, with a better tracking alignement and optimized calibration parameters. For what concern the analysis we're aiming at improving the signal sensitivity by means of a better performing multivariate discriminant, based on a novel algorithm and new training procedure.

3 The LHCb upgrade

The LHCb experiment, by the end of 2017, will collect ~ 5 fb^{-1} at the energy of $\sqrt{s} = 14$ TeV. However, pinning down the theoretical error on several variables on

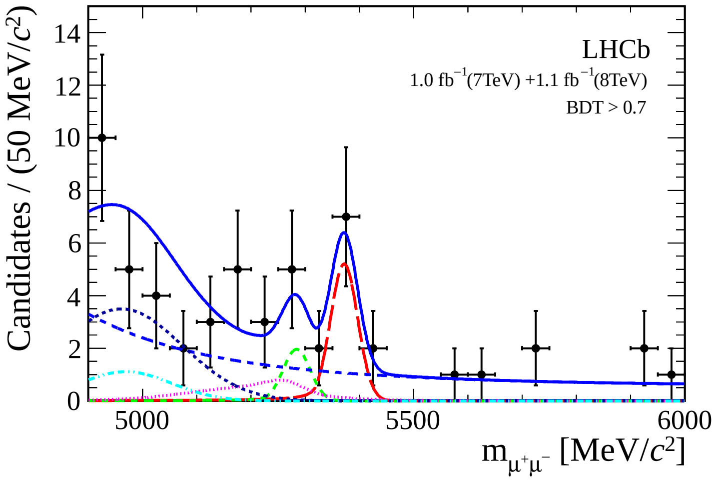

Figure 2: Invariant mass distribution of the selected $B_s^0 \to \mu^+\mu^-$ candidates (black dots) with BDT $>$ 0.7 in the combined 2011+2012 dataset. The result of the fit is overlaid (blue solid line) and the different components detailed: $B_s^0 \to \mu^+\mu^-$ (red long dashed), $B^0 \to \mu^+\mu^-$ (green medium dashed), $B_{(s)}^0 \to h^+h'^-$ (pink dotted), $B^0 \to \pi^-\mu^+\nu_\mu$ (black short dashed) and $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$ (light blue dot dashed), and the combinatorial background (blue medium dashed).

which SM is able to provide theoretically precise predictions, such as γ, the angular variables of the $B^0 \to K^*\mu^+\mu^-$ decay, ϕ_s or the $B^0 \to \mu^+\mu^-/B_s^0 \to \mu^+\mu^-$ ratio, will require more statistics. The main limitation of current LHCb experiment is due to the built-in maximum bandwidth of 1 MHz. Even increasing the luminosity, the efficiency for channels with hadrons will decrease, caused by the need of increasing the E_T threshold, to stay within the bandwidth limit. Consequently, the LHCb upgrade plans to remove this limitation, allowing for a fully software 40 MHz readout trigger. To achieve this challenging goal, and to perform optimally up to a luminosity of $\sim 2 \times 10^{33}$ cm^2 s^1 and at an average pile-up of ~ 4, intense planning is underway for a detector upgrade, which foresees a new vertex detector, a new tracking system and 40 MHz readout on all subsystems. The plan is to have the experiment ready to restart data taking just after the long shutdown 2 (LS2) in 2019 and to collect 50 fb^{-1} afterwards.

In preparation of the upgrade, an intense phase of RD has started, with the aim of preparing a TDR for the end of 2013. At LNF, several activities have been scheduled for this year, focussing on the muon detector.

First, in order to test the muon system performances in the upgrade conditions, special high-luminosity runs have been performed at the end of the 2012 data taking period. Here at LNF a careful analysis of these data is being performed, with the tools developed for muon chamber efficiency monitoring. The preliminary results of

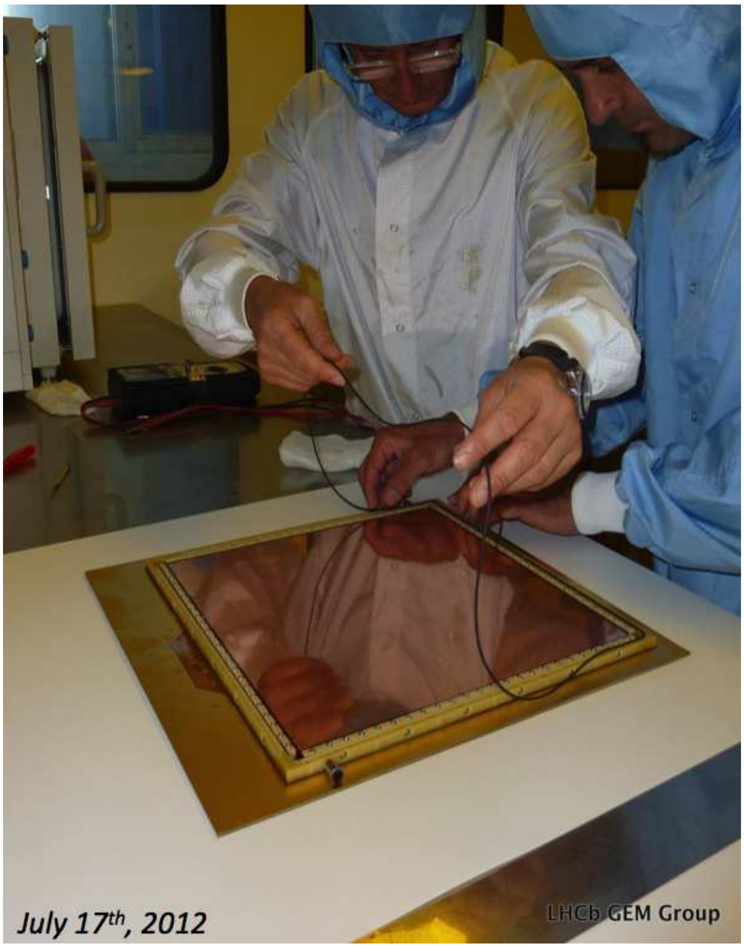

Figure 3: Assembly of a GEM detector.

this survey show a good performance of the muon detector, and suggest that the reduction of efficiency, estrapolated to the upgrade scenario, will not have dramatic effects on muon trigger performances. However, due to ageing effects, the MWPC installed in the inner regions are not adequate to stand the whole upgrade phase. For this reason, we definitely need to build new detectors: the baseline choice is triple-GEM detectors with PAD readout. Prototypes of these detectors will be built at LNF in 2013, using a novel assembly tecnique, developed in cooperation between LNF and CERN (see Fig. 3).

Besides that, additional efforts will be spent in the preparation of the new readout boards, which will be able to increase the data bandwidth towards the data acquisition system up to a design rate of 40 MHz. A dedicated RD has been scheduled this year at LNF, which aims at putting in operation one of such acquisition chains.

4 List of Conference Talks by LNF Authors in Year 2011

1. F. Archilli, "Rare heavy flavour decays at LHCb", International Conference on Heavy Quarks and Leptons 2012, Prague, Jun 2012.
2. F. Archilli, "Search for rare purely leptonic decays at LHCb" , CKM 2012, Cincinnati, Ohio, Sep 2012.
3. G. Bencivenni, A. Cardini, P. De Simone, "Operational Experience of the Triple-GEM Detectors of the LHCb Muon System: Summary of 2 years of data taking", 2012 IEEE Nuclear Science Symposium and Medical Imaging Conference, Anaheim, California, USA, Oct 2012.
4. P. Campana , "Heavy flavour physics at the LHC", Symposium "Symmetries and Phases in the Universe" 2012, Kloster Irsee, Germany, Feb 2012.
5. P. Campana , "Recent results from LHCb and future prospects" , Fifth Annual Meeting of the US LHC Users Organization, Fermilab, Batavia, Illinois, Oct 2012.
6. P. Campana , "Recent results from LHCb and future prospects", 10th International Conference on Beauty Charm Hyperons in Hadronic interactions, Wichita, Kansas, USA, Jul 2012.
7. P. Campana , "The LHCb Upgrade", XL International Meeting on Fundamental Physics, Benasque, Spain, May 2012.
8. P. Campana , "Recent results from LHCb and future prospects", Fermilab - Joint Experimental-Theoretical Seminar, Batavia, Illinois, USA, Feb 2012.
9. P. De Simone, "Heavy flavour production and spectroscopy at LHCb", 10th International Conference on Beauty Charm Hyperons in Hadronic interactions, Wichita, Kansas, USA, Jul 2012.
10. G. Lanfranchi, " CP violation and Rare Decays", 24th Rencontres de Blois on Particle Physics and Cosmology, Blois, Loire Valley, France, May 2012.
11. G. Lanfranchi, "Rare decays at LHCb", 3rd Meeting on Implications of LHC Results for TeV-scale Physics, CERN, Geneva, Switzerland, Jul 2012.
12. G. Lanfranchi, convener of the WG III *Rare Decays* at the CKM Conference, Cincinnati, Ohio, Sep 2012.
13. M. Palutan, "New results in the search for $B^0_{(s)} \to \mu^+\mu^-$ from LHCb", LHC seminar, CERN, Geneva, Switzerland, Nov 2012.
14. A. Sarti, "Rare decays at LHCb", APS April Meeting 2012: 100 Years of Cosmic Ray Physics, Atlanta, Georgia, United States, Mar 2012.

15. B. Sciascia, "Rare B decays as probe for new physics", 1st International Conference on New Frontiers in Physics, Kolymbari, Crete, Greece, Jun 2012.

16. B. Sciascia, convener of the WG I *Precise determination of* V_{ud} *and* V_{us} at the CKM Conference, Cincinnati, Ohio, Sep 2012.

17. F. Soomro, "Rare decays at LHCb", Cracow Epiphany Conference on Present and Future of B-physics, Krakow, Poland, Jan 2012.

18. F. Soomro, "Recent LHCb Results", Miami 2012, Fort Lauderdale, Florida, USA, Dec 2012.

5 Publications and internal notes

References

1. C. Adrover *et al.*, "Search for the rare decays $B^0_s \to \mu^+\mu^-$ $B^0 \to \mu^+\mu^-$ with 1.02 fb−1", CERN-LHCb-ANA-2011-102.

2. F. Archilli, G. Lanfranchi and F. Soomro, "Searches for the lepton flavour violating decays $B_s \to e\mu$ and $B_d \to e\mu$ at LHCb", CERN-LHCb-ANA-2012-079

3. C. Adrover *et al.*, "Search for the rare decays $B^0_s \to \mu^+\mu^-$ $B^0 \to \mu^+\mu^-$ with 1 fb−1 of 2012 data", CERN-LHCb-ANA-2012-081.

4. X. Cid Vidal *et al.*, "Performance of the Muon Identification in LHCb with 2011 data", CERN-LHCb-INT-2012-016.

5. X. Cid Vidal *et al.*, "Muon Identification efficiency and non-muon misidentification rates: 1 fb^{-1} results", CERN-LHCb-INT-2012-004.

6. R. Aaij *et al.*, The LHCb Collaboration, "Strong constraints on the rare decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$", Phys. Rev. Lett. 108 (2012) 231801.

7. The ATLAS, CMS and LHCb Collaborations, "Search for the rare decays $B^0_{(s)} \to \mu^+\mu^-$ at the LHC with the ATLAS, CMS and LHCb experiments", LHCb-CONF-2012-017.

8. R. Aaij *et al.*, The LHCb Collaboration, "First evidence for the decay $B^0_s \to \mu^+\mu^-$", Phys. Rev. Lett. 110 (2013) 021801.

9. R. Aaij *et al.*, The LHCb Collaboration, "Implications of LHCb measurements and future prospects", CERN-PH-EP-2012-334, submitted to Eur. Phys. J. C.