10 Particle Physics with LHCb

C. Abellan (since May 2014), J. Anderson (until September 2014), R. Bernet, E. Bowen, A. Bursche (until December 2014), N. Chiapolini (until December 2014), M. Chrząszcz[1], B. Dey (since April 2014), Ch. Elsasser, E. Graverini, F. Lionetto, P. Lowdon, A. Mauri (since June 2014), K. Müller, S. Saornil (until September 2014), N. Serra, St. Steiner, O. Steinkamp, B. Storaci, U. Straumann, M. Tresch, A. Vollhardt and A. Weiden (since January 2015)

[1] also at Henryk Niewodniczanski Institute of Nuclear Physics, Kraków, Poland (until February 2015)

The full LHCb collaboration consists of 69 institutes from Brazil, China, Colombia, France, Germany, Ireland, Italy, Poland, Romania, Russia, Spain, Switzerland, the Netherlands, Turkey, Ukraine, the United Kingdom and the United States of America.

(LHCb Collaboration)

The LHCb experiment [1] at CERN's Large Hadron Collider (LHC) is dedicated to the study of rare decays of hadrons containing a b or c quark and to precision measurements of CP violating observables. Major goals are the study of the flavour structure in the quark sector and the search for physics beyond the Standard Model (BSM) of particle physics.

The LHCb detector is a single-arm forward spectrometer covering an acceptance close to the LHC beam pipe. This allows to measure particles propagating with a small angle with respect to the direction of the colliding hadrons, which is a typical feature of hadrons containing b or c quarks produced in hadron colliders at energies reached by the LHC.

The Zurich group takes responsibility for the operation and maintenance of silicon detectors in the tracking system. Furthermore, our group significantly contributes to measurements of rare B and τ decays as well as measurements involving W and Z bosons.

[1] A. A. Alves Jr. *et al.* [LHCb Collab.], JINST 3 S08005 (2008).

10.1 LHCb detector

The main features of the detector are an excellent momentum and impact parameter resolution for charged particles achieved by the tracking system consisting of silicon and gaseous sub-detectors. Furthermore, two Ring Imaging Cherenkov detectors can identify charged pions and kaons as well as protons.

The Zurich group played a major role in the construction of the Silicon Tracker (ST) system, especially for the Tracker Turicensis (TT), a large area micro-strip detector located upstream of the LHCb dipole magnet. The group is also has the responsible for its operation and maintenance. Information about the detector and its performance can be found in previous annual reports [1].

During the Long Shutdown 1 (LS1) of LHC between spring 2013 and 2015, consolidation work was done on several sub-detectors. Additionally, a system based on scintillating detectors was installed covering very small angles with respect to the direction of the beams. This allows to better identify proton-proton collisions where at least one of the colliding protons has stayed intact.

[1] `http://www.physik.uzh.ch/reports.shtml`

10.1.1 Detector operation and performance

C. Abellan, E. Bowen, B. Dey, E. Graverini, S. Saornil, O. Steinkamp, and B. Storaci

During the LHC Run 1, the ST had a very high fraction of working channels, which was on average more than 99.6% for TT and 98.4% for the Inner Tracker (IT), the second detector in the ST system. After maintenance work in LS1 these numbers are 99.7% and 99.1%, respectively.

During the LS1 new monitoring algorithms were developed in order to allow an even more detailed analysis of the ST performance. This software will be included in the official LHCb framework and allow to spot issues with the detector alignment or track reconstruction software. Since LHCb will use a novel alignment procedure running online in the upcoming data taking period, these algorithms will play an important role. Their first applications have already revealed possible sources of inaccuracies in the detector description whose correction will allow to improve the LHCb detector alignment. As a consequence, Elena Graverini developed in collaboration with the École Polytechnique Fédérale de Lausanne several in-

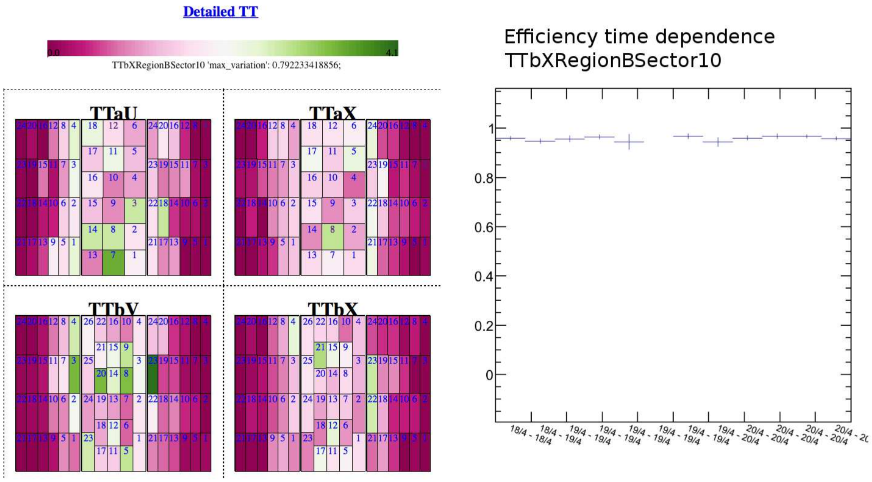

Fig. 10.1 – A view of the new ST interactive monitoring interface. The left panel shows the summary of a certain performance indicator for the whole TT on read-out sector (i.e. a group of sensors) level. Hovering over a region of the detector in the left panel allows to visualize more details about the performance for that specific region, shown in the right panel.

teractive monitoring tools, which allow to study the detector performance down to a single-sensor, even during data taking (cf. Fig. 10.1). The restart of the LHC for Run 2 will pose new challenges for the operation of the ST. The increase in collision energy from 8 TeV to 13 TeV will affect the detector occupancy, and the change of bunch spacing from 50 ns to 25 ns makes it necessary to re-evaluate ST's operation parameters in order to properly deal with the spill-over of detector signals between consecutive bunch crossings.

10.1.2 Luminosity measurements

K. Müller and A. Weiden

Among the LHC experiments, LHCb performed the most precise determinations of the luminosity. One method is based on the change in interaction rate when the overlap of the two proton beams is varied by scanning their relative position (van der Meer scan) [1]. Alternatively one measures the collision rate of protons from a single beam with residual gas atoms inside the beam pipe [2]. The combined uncertainty on the luminosity measurement is 1.12% [3].

Since a precise determination of the luminosity in LHCb is a pre-requisite for cross-section measurements, effort is ongoing to get an accurate evaluation already a few weeks after the start of the Run 2 data taking. Andreas Weiden is working on the optimization of the dedicated trigger setup to identify collisions of protons with residual gas atoms and will be responsible for the analysis of the Van der Meer scans in the upcoming running period.

[1] S. van der Meer, CERN-ISR-PO68-31 (1968).

[2] M. Ferro-Luzzi, Nucl. Instrum. Meth. A553 (2005) 388.

[3] R. Aaij *et al.* [LHCb Collab.], JINST **9** (2014), P12005.

10.2 LHCb upgrade

C. Abellan, B. Dey, F. Lionetto, S. Saornil, and O. Steinkamp

The upgraded LHCb detector [1], planned to be installed in the LHC cavern in 2019, will cover the same pseudo-rapidity region but run at an instantaneous luminosity five times higher than in the current configuration. The readout time will have to be reduced from the present 1 μs to 25 ns which means that several sub-detectors have to be redesigned.

The TT was a major responsibility of our group and so is its upgraded version, the Upstream Tracker (UT) [2]. The UT will contribute to speed up the formation of the trigger decision. It will have a finer granularity, required to stand the higher particle density after 2019. The Zurich group is developing a test board used to examine the functionalities of the new read-out chip developed for a rate of 40 MHz, is contributing to the design and development of the high- and low voltage distribution systems, and is responsible for detector control and safety and for environmental monitoring.

10.2.1 Test stand

Last year, a laser test stand has been assembled in Zurich, allowing R&D activities on silicon micros-trip sensors. It is used to characterize the prototype sensors with different geometries (cf. Fig. 10.2). A large effort was made in automating the measurement procedures and in a precise monitoring of the environmental variables (temperature, humidity, and dew point), which will ultimately allow to inspect the sensors before installation in the LHC cavern.

10.2.2 Test beam

Federica Lionetto and Biplab Dey joined the first two beam tests organized in the context of the UT project. An exploratory campaign in July and August allowed to

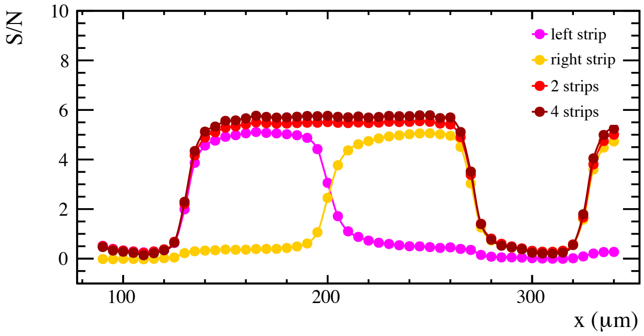

Fig. 10.2 – Charge signal, in terms of signal over noise ratio, versus the position of the laser beam between two adjacent strips. No charge is lost in this situation. Shown are the signal over noise ratio measured on these two strips, their sum and the sum over four adjacent strips. The low but finite values on the sides are caused by laser light reflected by the aluminum read-out strips.

test the readout system and the synchronisation between the detector under test and the beam telescope. Later that year sensors of both p-in-n and n-in-p type, irradiated with doses up to 23.3 MRad, were tested at the CERN SPS with a 180 GeV/c proton beam. Charge collection properties and spatial resolution were studied [3].

[1] LHCb Collab., CERN-LHCC-2012-007, LHCB-TDR-012.
[2] LHCb Collab., CERN-LHCC-2014-001, LHCB-TDR-015.
[3] A. Abba *et al.*, CERN-LHCb-PUB-2015-006.

10.3 Track reconstruction at software trigger level

E. Bowen, E. Graverini, B. Storaci, and M. Tresch

Until now the interaction rate of up to 40 MHz has been reduced to an acceptable detector read-out rate of 1 MHz in an electronic trigger system based on rough signatures such as energy deposits in the calorimeters. This scheme inhibits the operation of the detector at higher luminosities as trigger rates for decays with only hadronic final state particles would saturate. As a major goal of the LHCb upgrade a trigger system, based purely on software, should remove this bottleneck. Such a software trigger allows great flexibility in defining selection topologies. The resulting efficient triggering on low momentum tracks is normally beyond the scope of a hadron collider.

There exist strict requirements on the execution time of the applied pattern recognition algorithms. An algorithm [1], developed by our group, using information from the two most upstream tracking sub-detectors gives a factor three reduction of the execution time of the overall tracking sequence, well within the allowed CPU budget, maintaining very high efficiency. At the same time the fraction of ghost tracks is lower by a factor 4. The new algorithm has therefore been adopted into the baseline tracking sequence of the upgrade trigger [2] and a modified version will be implemented in the software trigger of Run 2 already.

[1] E. Bowen and B. Storaci, CERN-LHCb-PUB-2013-023.
[2] LHCb Collab., CERN-LHCC-2014-016, LHCB-TDR-016.

10.4 Physics results

During the past twelve months LHCb published more than 70 physics papers [1] covering a broad range of topics. Here some results will be presented followed by more detailed discussions of our own contributions.

During the reporting period LHCb discovered two baryons, $\Xi_b'^-$ and Ξ_b^{*-}, containing one beauty, one strange and one down quark. While the first state has spin 1/2, the spins of the quarks in the second state line up, leading to a 3/2 spin of the baryon [2]. LHCb also discovered a spin-3 hadron containing a charm quark, called $D_{sJ}^*(2860)^-$, with a mass of about 2.86 GeV/c^2 [3].

LHCb combined several of its measurements of the angle γ in CKM-triangle. This angle is a measure of the amount of CP violation in the SM and is a sensitive observable in a search for BSM physics. The resulting $\gamma = 72.9^{\circ}{}^{+9.2^{\circ}}_{-9.9^{\circ}}$ [4, 5] is more accurate than the combined value from the B-factories Belle and BaBar.

Another important observable in the study of CP violation is the phase ϕ_s describing CP violation in $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays. The value obtained by LHCb, $\phi_s = -0.010 \pm 0.039$ rad, is in agreement with the very low SM prediction [6].

The branching ratio R_K, between the decays $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$, was measured for an invariant mass of the lepton pair squared in the range 1 to 6 GeV^2/c^4. This observable has small theoretical uncertainties and lepton universality postulated in the SM predicts $R_K = 1 \pm \mathcal{O}(10^{-3})$. The LHCb value of $R_K = 0.745^{+0.090}_{-0.074}$ represents a 2.6σ deviation from unity [7].

[1] http://lhcb.web.cern.ch/lhcb/
[2] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. Lett. **114** (2015), 062004.
[3] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. Lett. **113** (2014), 162001.
[4] R. Aaij *et al.* [LHCb Collab.], JHEP **10** (2014), 097.
[5] LHCb Collab., LHCb-CONF-2014-004.
[6] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. Lett. **114** (2015), 041801.
[7] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. Lett. **113** (2014), 151601.

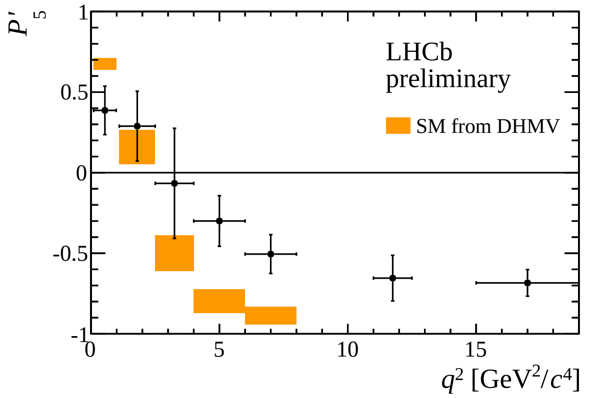

FIG. 10.3 – The angular observable P'_5 in the decay $B^0 \to K^{*0}\mu^+\mu^-$ measured by LHCb with a data set corresponding to 3 fb^{-1} compared to the SM predictions from Ref. [8].

10.4.1 $B^0 \to K^{*0}\mu^+\mu^-$

E. Bowen, M. Chrząszcz, B. Dey, N. Serra, B. Storaci, and M. Tresch

The rare decay $B^0 \to K^{*0}\mu^+\mu^-$ is a flavour-changing neutral current process that is very sensitive to BSM physics [1]. The kinematics can be described by three helicity angles and the invariant mass of the muon pair. The analysis performed on the 1 fb^{-1} data sample showed a 3.7σ discrepancy with respect to SM predictions [2].

Our group played a key role in an updated measurement with the full 3 fb^{-1} data set. We were responsible for particle identification and event selection, based in part on training algorithms in which data subsets alternate for training and testing. This way the data are used most efficiently and with high discriminating power. We introduced the method of moments to determine the angular observables [3] which appears more stable than a conventional likelihood fit and allows finer mass binning. Preliminary results [4] confirm the discrepancy mentioned above (cf. Fig. 10.3).

Several explanations for the deviation have been brought up [5] such as the existence of an additional boson, Z', with a mass above 10 TeV [6]. It has also been pointed out that the discrepancy might be explained by QCD effects ignored in the SM predictions [7].

[1] J. Matias *et al.*, JHEP 04 (2012) 104.
[2] R. Aaij *et al.* [LHCb Collab.], JHEP 1308 (2013) 131.
[3] F. Beaujean, M. Chrząszcz, N. Serra and D. van Dyk, arXiv:1503.04100 [hep-ex].
[4] LHCb Collab., LHCb-CONF-2015-002.
[5] S. Descotes-Genon *et al.*, arXiv:1503.03328 [hep-ph].
[6] R. Gauld, F. Goertz and U. Haisch, JHEP 1401 (2014) 069.
[7] J. Lyon and R. Zwicky, arXiv:1406.0566 [hep-ph].
[8] S. Descotes-Genon *et al.*, JHEP 01 (2013) 048.

10.4.2 Search for $\tau^- \to \mu^-\mu^+\mu^-$

M. Chrząszcz and N. Serra

A huge number of τ leptons are produced in the acceptance of LHCb which makes LHCb well suited to perform, for example, a search for the Lepton Flavour Violating (LFV) decay $\tau^- \to \mu^-\mu^+\mu^-$. In the SM this decay occurs via neutrino mixing but the branching ratio of $\mathcal{O}(10^{-40})$ is far below experimental sensitivity. Several BSM models including an extended neutrino sector [1] can enhance the branching fraction to values that are in reach of LHCb.

Our group had a leading role in a search in the full 3 fb^{-1} data set collected by LHCb. The sensitivity was raised with a new multivariate selection technique, called blending, which combines information from different classifiers and different τ sources (e.g. promptly produced, produced in decay of b hadrons, etc.). A new limit $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 4.6 \times 10^{-8}$ at 90% CL [2] was set.

Marcin Chrząszcz is member of PDG's Heavy Flavour Averaging Group (HFAG) focusing on τ lepton properties including LFV τ decays [3].

[1] R. H. Bernstein and P. S. Cooper, Phys. Rep. **532** (2013) 27.
[2] R. Aaij *et al.* [LHCb Collab.], JHEP **1502** (2015) 121.
[3] Y. Amhis *et al.* [Heavy Flavor Averaging Group (HFAG) Collab.], arXiv:1412.7515 [hep-ex].

10.4.3 Search for new scalar particles in B decays

M. Chrząszcz, A. Mauri, and N. Serra

The LHCb experiment offers the possibility to search for long lived particles produced in B decay with higher sensitivity than reached by Belle [1]. Many BSM models [2, 3] predict the existence of light particles, such as an inflaton or a dark matter mediator, that, mixing with the Higgs boson, can couple to the visible SM sector.

We are analyzing the 3 fb^{-1} of data collected in 2011 and 2012 looking for the decay sequence $B^+ \to K^+\chi$, $\chi \to \mu^+\mu^-$ with χ a light scalar particle. The lifetime of such a particle can be long so that it could travel several centimeters before decaying. Simulations were made for different mass and lifetime values as a guidance to the optimal event selection based on machine-learning algorithms.

[1] J.-T. Wei *et al.* [Belle Collab.], Phys.Rev.Lett.103:171801 (2009).
[2] J. D. Clarke, R. Foot and R. R. Volkas, JHEP 02 (2014) 123.
[3] K. Schmidt-Hoberg, F. Staub and M. W. Winkler, Phys. Lett. B727 (2013) 506-510.

10.4.4 $B^0_{(s)} \to \mu^+\mu^-$ in combination with CMS

Ch. Elsasser

In 2013 both LHCb and CMS presented results on the rare decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ [1, 2]. These decays are sensitive to BSM physics since the non-SM particles can act as propagator.

The two collaborations aligned their procedures and the combined measurement resulted in the first observation of the decay $B^0_s \to \mu^+\mu^-$ and the first evidence for $B^0 \to \mu^+\mu^-$ [3] with measured branching fractions in agreement with the SM prediction at the 1.2σ and 2.2σ level, respectively [4].

[1] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. Lett. **111** (2013) 101805.

[2] S. Chatrchyan *et al.* [CMS Collab.], Phys. Rev. Lett. **111** (2013) 101804.

[3] V. Khachatryan *et al.* [LHCb+CMS Collab.], arXiv:1411.4413.

[4] C. Bobeth *et al.*, Phys. Rev. Lett. **112** (2014) 101801

10.4.5 Electroweak boson and low mass Drell-Yan production

J. Anderson, A. Bursche, N. Chiapolini, Ch. Elsasser,
K. Müller, and M. Tresch

Measurements on W and Z production constitute sensitive SM tests at LHC energies. We were largely involved, determining detection efficiencies, estimating background contaminations, and calculating theoretical predictions which are presently computable at next-to-next-to-leading order (NNLO) in perturbative QCD. They rely on the parametrisations of the parton distributions inside the proton – described by the parton density functions (PDF), which are determined from experiment. The ratio of the W^+ to W^- production cross sections, for example, allows a determination of the ratio of up to down valence quark densities since both the experimental and the theoretical systematic uncertainties tend to cancel.

The measurements of the W production in the muon channel have been updated with the full 2011 dataset [1]. The precision improved significantly due to the larger data sample, a better understanding of the detector, and an improved luminosity determination. The measurement of Z production using the full dataset benefits from a similar improvement in precision and will be published shortly. The systematic uncertainties of the inclusive cross sections are below 1% and even for the differential measurements the experimental errors are comparable or below the theoretical uncertainties. Figure 10.4 shows the ratio of the W^+ to W^- cross section as a function of the pseudo-rapidity of the muon, in good agreement with NNLO predictions for various PDF parametrisations.

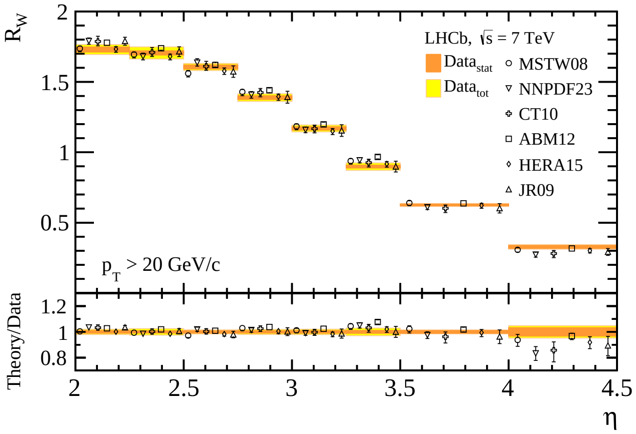

FIG. 10.4 – R_W, the ratio of W^+ to W^- cross sections in bins of muon pseudo-rapidity. Measurements, represented as bands corresponding to the statistical and total uncertainty, are compared to NNLO predictions for various parametrisations of the PDFs (black markers, displaced horizontally for presentation).

The analysis of low mass Drell-Yan production in the dimuon channel is described in the thesis of Nicola Chiapolini [2]. This measurement is sensitive to Bjorken-x values (the momentum fraction carried by the quark taking part in the actual scattering) as low as 8×10^{-6}. These measurements are challenging since the backgrounds are very high. The purity is estimated from a fit to a variable describing the amount of activity in the detector close to the two muons. The variable can be determined from the background free sample of Z decays. The systematic studies will be finalized by Marcin Chrząszcz before results can be published. A refined analysis is planned with the data to be collected in Run 2.

Further ongoing studies in our group are:
- production of K^0_S, Λ^0 and protons in events with a Z boson (Marco Tresch),
- $Z\gamma$ diboson production (Moritz Küng (Master student 2013-2014) [3] and Christian Elsasser), and
- low energy $W \to \mu^+\nu^-$ (Christian Elsasser) and $Z \to \mu^+\mu^-$ (Albert Bursche [4]) production at 2.76 TeV.

[1] R. Aaij *et al.* [LHCb Collab.], JHEP **12** (2014) 079.

[2] Nicola Chiapolini, PhD thesis, 2014.

[3] Moritz Küng, Master thesis, 2014.

[4] Albert Bursche, PhD thesis, 2014.

10.5 Summary and Outlook

With the end of LHC's long shutdown LHCb is ready for Run 2. The experiment will continue, primarily, to shed light on the field of physics involving c and b quarks.

In parallel preparations for the next upgrade, planned to begin in 2019, are running at full steam including the work by the Zurich group on the new Upstream Tracker.