10 Particle Physics with LHCb

C. Abellan, R. Bernet, Ch. Betancourt (since February 2016),
I. Bezshyiko (since December 2015), E. Bowen, A. Bursche (May-November 2015),
M. Chrząszcz[1], Ch. Elsasser (until July 2015), E. Graverini, F. Lionetto, A. Mauri,
K. Müller, N. Serra, R. Silva Coutinho (since May 2015), St. Steiner, O. Steinkamp,
B. Storaci, U. Straumann, M. Tresch, A. Vollhardt and A. Weiden

[1] also at Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland

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

(LHCb Collaboration)

The LHCb forward spectrometer at the CERN Large Hadron Collider (LHC) [1], which is fully instrumented in the pseudorapidity range $2 < \eta < 5$, was optimised for precision tests of the Standard Model (SM) and for indirect searches for physics beyond the SM (BSM) through precision measurements of CP violating phases and rare heavy-quark decays. This forward acceptance and the ability to trigger on particles with relatively low transverse momentum allow to probe particle production in a unique kinematic range.

The Zurich group is responsible for the operation and maintenance of silicon detectors in the tracking system and for the luminosity measurements. We also contribute to the R&D for the upgraded LHCb detector. Furthermore, our group makes significant contributions to measurements of rare B-meson and τ lepton decays as well as measurements involving the electroweak gauge bosons. Members of our group play important coordination roles within the collaboration: N. Serra is member of the editorial board, B. Storaci operations coordinator and O. Steinkamp deputy project leader of the silicon tracker.

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

10.1 LHCb detector

The LHCb detector was successfully operated in Run I (2009-2013), where data corresponding to an integrated luminosity of 3 fb^{-1} was collected at centre of mass energies of 7 (1 fb^{-1}) and 8 (2 fb^{-1}) TeV. After the consolidation of LHC (2013-2015) the centre of mass energy increased to 13 TeV for Run II which started in May 2015. The detector coped well with the changed operating conditions at the higher collision energy and the reduction of the proton-proton (pp) bunch collision spacing from 50 to 25 ns. In the short 2015 data taking period, the experiment recorded pp collisions corresponding to an integrated luminosity of 321 pb^{-1}. In addition, the experiment was operated for the first time during $Pb - Pb$ collisions and a data sample corresponding to an integrated luminosity of about 5.6 μb^{-1} was collected.

A major improvement in the operation of the experiment has been the introduction of a novel approach in the software trigger which has been split into two stages. First, based on a partial event reconstruction, selection cuts are applied on generic event properties such as displaced tracks and vertices or pairs of muon candidates. All selected events are then temporarily buffered on disk, while a fully automated calibration and alignment of the detector is carried out on a dedicated computing farm consisting of 50'000 logical CPU cores. In the second stage, a full event reconstruction is performed, using the updated calibration and alignment constants. A mixture of inclusive and exclusive cuts selects the events to be stored for offline analyses. This new approach improves on the quality of the trigger selection algorithms and permits to apply more complex algorithms, thereby increasing the fraction of useful events that are saved for offline reconstruction.

10.1.1 TT Detector performance

E. Graverini, O. Steinkamp and B. Storaci

In 2015 the Tracker Turicensis (TT) detector performed as well as during the first LHC data taking period. At the end of 2015, more than 99.5% of its 143'360 readout channels were operational. The main reason for missing channels was again the failure of light-emitting diodes in the optical transmission lines. The single-hit detection efficiency remained almost 100% and the observed position resolution is 53 μm, compared to a simulated 48 μm. We

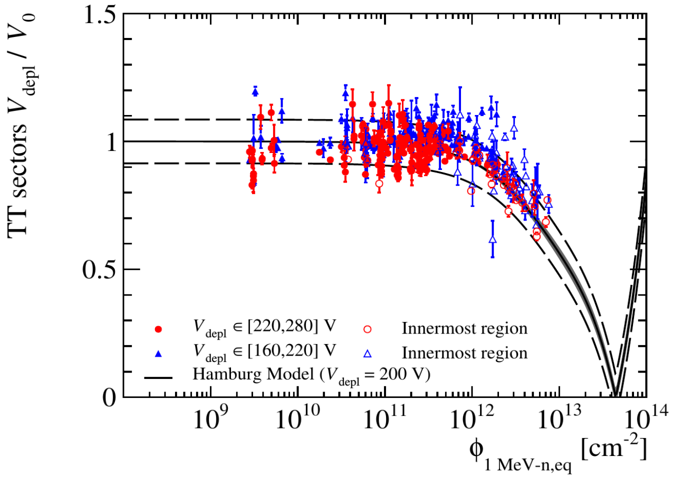

FIG. 10.1 – Measured full-depletion voltage as a function of the received particle fluence. Symbols show measurements done at different times and for various regions of the detector, while full and dashed lines indicate the expectation from model calculations with its uncertainty.

go on studying the spatial alignment of the detector elements and expect a further improvement in position resolution.

In view of the harsh radiation environment at the LHC, the monitoring of radiation damage in the silicon detectors remains an important task. Leakage currents in the detector are monitored continuously and regular charge-collection efficiency scans allow to determine the bias voltage at which the silicon sensors fully deplete. The evolution of this full-depletion voltage versus received radiation, which ultimately limits the lifetime of the detectors, is well described by a detailed model calculation (see Fig. 10.1) which gives confidence that radiation damage will not affect the performance of the detector until its foreseen replacement during the LHCb upgrade.

10.2 LHCb upgrade

C. Abellan, Ch. Betancourt, I. Bezshyiko, F. Lionetto and O. Steinkamp

The LHCb collaboration prepares for a comprehensive upgrade during the second long shutdown of the LHC in 2019/2020 [2] after which the instantaneous luminosity will have increased by a factor five. The detector will be fully read out at the LHC bunch-crossing frequency of 40 MHz, eliminating the need for a hardware-based trigger and thereby significantly increasing the trigger efficiencies for many final states of interest.

The current TT detector will have to be replaced, since its front-end readout electronics is not compatible with the new readout scheme. The replacement for the TT, dubbed Upstream Tracker (UT), is being developed in collaboration with CERN and six institutions from Italy, Poland and the US [3]. To best exploit our experience, we have taken the responsibility for the development of the hardware and control software for high- and low-voltage power, the monitoring of operational and environmental parameters, and the detector safety system. Moreover, we play a prominent role in the testing of the new front-end readout chip (SALT) and in test beam efforts to qualify radiation-hard silicon sensors for the UT.

[2] LHCb Collab.,
CERN-LHCC-2012-007, LHCB-TDR-007.

[3] LHCb Collab.,
CERN-LHCC-2014-001, LHCB-TDR-015.

10.3 Track reconstruction at software trigger level

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

Fast and efficient track reconstruction algorithms are crucial for the successful operation of the software trigger of the upgraded detector. We developed a new algorithm connecting track segments in the vertex detector to hits in the UT, significantly speeding up the track reconstruction at no loss in overall reconstruction efficiency [4]. We already back-ported this algorithm for use with the current TT in the software trigger during 2015. The faster track reconstruction allows for less stringent trigger requirements. This way selection biases due to trigger conditions could be removed in various analyses and trigger efficiencies could be increased correspondingly.

The successful operation of the algorithm in actual data taking provides an important proof-of-principle for the upgrade.

[4] E. Bowen and B. Storaci, CERN-LHCb-PUB-2013-023.

10.4 Luminosity measurements

K. Müller and A. Weiden

Absolute cross-section measurements require the precise knowledge of the luminosity. At LHCb the luminosity scale is calibrated periodically using Van der Meer scans [5] and a beam-gas imaging method [6].

A few weeks after the restart of LHC a luminosity calibration, based on the beam-gas imaging method, was available already with a precision of 3.8%. Our group is responsible for the analysis of the Van der Meer scans. We are presently studying the stability in time of the ratio between observed event rates and luminosity. The final luminosity calibration of the 2015 dataset should be available in summer 2016.

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

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

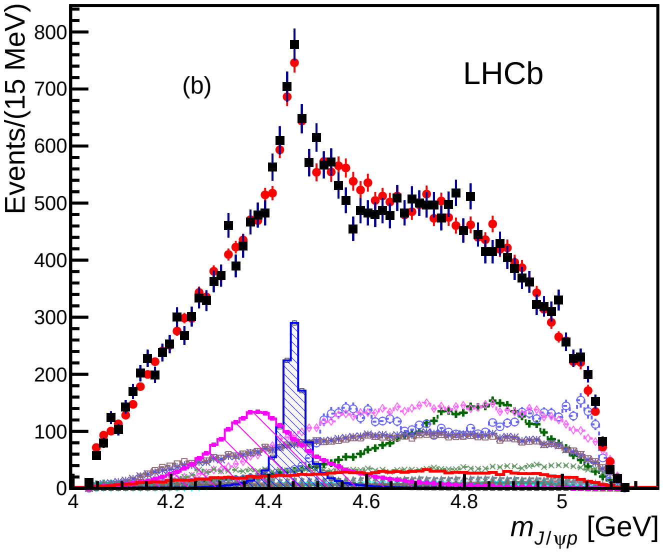

FIG. 10.2 – Fit to $m_{J/\Psi p}$ in $\Lambda_0 \to J/\Psi K p$. Data are shown as black squares and the fit result as red circles, blue open and purple solid squares show the two pentaquark states.

10.5 Physics results

The LHCb collaboration published about 40 physics papers during the past year [7], covering a wide range of topics. Here we briefly highlight some of the main results, while in the next sections we will discuss in more detail analyses with direct contributions from our group.

In addition to b-hadron studies, LHCb has published several important results in the fields of spectroscopy and cross section measurements such as the first measurement of forward top production [8]. LHCb observed for the first time two resonances consistent with pentaquark states in decays $\Lambda_b^0 \to J/\psi K^- p$ [9]. Figure 10.2 shows the invariant $J/\psi p$ mass with the two exotic structures, $P_c^+(4450)$ and $P_c(4380)$. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2. Another exotic state is the resonance $X(3872)$. Its J^{PC} quantum numbers were measured by LHCb in the decay $B^+ \to X(3872)K^+$ with $X(3872)$ decaying into $\rho^0 J/\psi$ [10] to be 1^{++}. These results demonstrate that the LHCb experiment should be considered a general purpose detector in the forward region rather than a mere b-physics experiment.

Measurements of the parameters of the Unitarity Triangle and tests of the CKM paradigm are part of the core physics programme of the LHCb experiment. The element V_{ub} of the CKM matrix can be measured in semileptonic transitions of the type $b \to u$. There is a longstanding disagreement between inclusive and exclusive measurements of V_{ub}. LHCb measured the ratio $|V_{ub}|/|V_{cb}|$ using the exclusive decays $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ and $\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu$ for the first time. The measured value is in good agreement with other exclusive measurements [11].

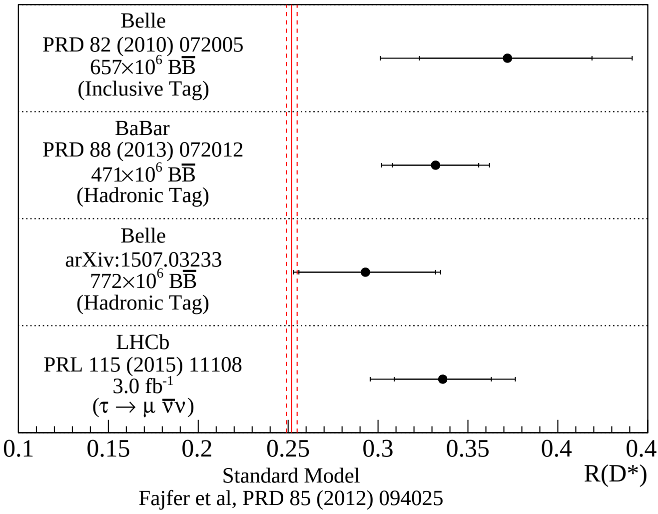

FIG. 10.3 – Experimental results for $\mathcal{B}(B \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B \to D^{*-}\mu^+\nu_\mu)$.

Another challenging measurement at hadron colliders is the determination of the ratio of the branching fractions $R(D^*) \equiv \mathcal{B}(B \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B \to D^{*-}\mu^+\nu_\mu)$ [12]. In Fig. 10.3 our result and those from other measurements [13, 14] are compared with the SM prediction. A combination of these measurements by the HFAG collaboration gives a tension of about 4 standard deviations with the SM prediction [15].

CP violation parameters, measured in the decay $B_s^0 \to J/\psi K_s^0$, are in good agreement with the current world average and with SM predictions. In addition, the decay-time-dependent *CP* asymmetry in the decay $B_s^0 \to J/\psi K_s^0$ was measured for the first time. The $B^0 \leftrightarrow \overline{B}^0$ oscillation frequency was measured with the highest accuracy to date [16]. Determinations of parameters sensitive to the angle γ of the Unitarity Triangle, using several tree-level decays such as $B^\pm \to DK^\pm$, $B^\pm \to D\pi^\pm$, $B \to DK\pi\pi$ [17] and $B \to D\pi\pi\pi$ [18] yields the most precise determination of γ to date.

Several charmless B-meson decays have been studied. In particular, the angular analysis of the decay $B_s^0 \to K^{*0}\overline{K}^{*0}$ yielded the longitudinal polarisation fraction. An amplitude analysis was performed for the decay $B^0 \to \rho^0\rho^0$ [19]. In addition, LHCb observed for the first time the decay $B_s^0 \to \eta'\eta'$ [20].

Rare decays of b-hadrons are sensitive BSM probes, since the SM contribution is suppressed whereas BSM could enter at a similar level. The world's best measurements of the branching fractions and the forward-backward asymmetry of the decay $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ [21] were done by LHCb. The differential branching fraction of the decay $B_s^0 \to \phi\mu^+\mu^-$ as a function of the di-muon invariant mass squared (q^2) was found in tension with current SM predictions at the level of 3 standard deviations [22]. Angular observables in this decay are in agreement with theory predictions. In addition, the angular analysis of the decay $B^0 \to K^* e^+ e^-$ in the low q^2 region found good agreement with SM predictions [23].

[7] http://lhcb.web.cern.ch/lhcb/

[8] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. Lett. 115 (2015) 112001.

[9] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. Lett. 115 (2015) 072001.

[10] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. D 92 (2015) 011102.

[11] R. Aaij *et al.* [LHCb Collab.], Nature Phys. 11 (2015) 743-747.

[12] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. Lett. 115 (2015) 111803.

[13] J. P. Lees *et al.* [BaBar Collab.], Phys.Rev.D 88, 072012 (2013).

[14] M. Huschle *et al.* [Belle Collab.], Phys. Rev. D 92, 072014 (2015).

[15] HFAG Collaboration, http://www.slac.stanford.edu/xorg/hfag/

[16] LHCb Collaboration, CERN-LHCb-CONF-2015-003.

[17] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. D 91 (2015) 112014.

[18] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. D 92 (2015) 112005.

[19] R. Aaij *et al.* [LHCb Collab.], Phys. Lett. B 747 (2015) 468-478.

[20] R. Aaij *et al.* [LHCb Collab.], Phys. Rev. Lett. 115 (2015) 051801.

[21] R. Aaij *et al.* [LHCb Collab.], JHEP 06 (2015) 115.

[22] R. Aaij *et al.* [LHCb Collab.], JHEP 09 (2015) 179.

[23] R. Aaij *et al.* [LHCb Collab.], JHEP 04 (2015) 064.

10.5.1 Angular analysis of the decay $B^0 \to K^* \mu^+ \mu^-$

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

The decay $B^0 \to K^* \mu^+ \mu^-$ is a flavour changing neutral current process with a branching ratio of about 10^{-6}. Angular observables in this decay are sensitive probes of BSM physics since heavy new particles can appear virtually in the loop processes with competitive amplitudes. The analysis, performed by our group with an integrated luminosity of 1 fb^{-1} [24], showed tension with respect to SM predictions at about 3.7 standard deviations. These results are widely discussed in the literature. Several authors interpret them as a possible sign of BSM physics [25, 26], while others point to possibly underestimated QCD uncertainties [27, 28].

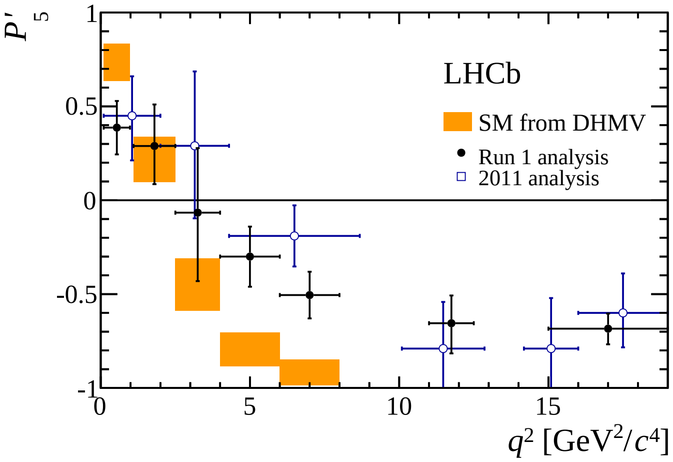

FIG. 10.4 –
The angular observable P'_5 in the decay $B^0 \to K^{*0} \mu^+ \mu^-$ as a function of q^2 compared to the SM predictions [30].

The analysis has been extended to the full Run I dataset, increasing the statistics by a factor 3. The results are in good agreement with the 2011 analysis. We contributed to various aspects including the signal selection, the correction of the detector acceptance and the determination of the angular observables. In particular, we introduced a novel method based on the moments of the angular distribution [29].

In Fig. 10.4 our measurements of the angular observable P'_5 are compared with SM predictions [30]. Discrepancies of about three standard deviations are found for each of the two bins in the region $4.0 < q^2 < 8.0\,\text{GeV}^2$.

A natural extension of this analysis is the measurement of the angular terms in the higher $K\pi$ invariant mass region, outside the $K^{*0}(892)$ resonance. In this region several resonances with different spins ($S-$, $P-$ and $D-$wave) contribute, therefore there are 41 independent moments. Our group is performing this measurement, which is at the moment under the review by the collaboration.

[24] R. Aaij *et al.* [LHCb Collab.], Phys.Rev.Lett. 111 (2013) 191801.

[25] S. Descotes-Genon, J. Matias and J. Virto, Phys. Rev. D 88, 074002 (2013).

[26] W. Altmannshofer and D. M. Straub, Eur. Phys. J. C73 (2013) 2646.

[27] J. Lyon, R. Zwicky, arXiv:1406.0566.

[28] M. Ciuchini et al., JHEP 1305 (2013) 043.

[29] F. Beaujean, M. Chrzaszcz, N. Serra and D. van Dyk, Phys. Rev. D 91, 114012 (2015).

[30] S. Descotes-Genon *et al.*, JHEP 01 (2013) 048.

10.5.2 Study of $b \to se^+e^-$ transitions

F. Lionetto, N. Serra and R. Silva Coutinho

The measurement of the ratio of branching fractions $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ by LHCb is found to be in tension with respect to SM predictions at the level of 2.6 standard deviations [31]. It has been argued that this deviation is consistent with the deviation observed in $B^0 \to K^*\mu^+\mu^-$ decays, which could be an indication of new physics breaking the lepton flavour universality of the SM [32, 33]. Our group is involved in several tests of lepton flavour universality comparing $b \to se^+e^-$ to $b \to s\mu^+\mu^-$ transitions. The first goal will be to measure asymmetries in combined angular observables, using $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ decays. In addition, measurements of the ratio of branching ratios in the electron and muon channels have the potential to test lepton flavour universality in rare decays.

[31] R. Aaij *et al.* [LHCb Collab.],
Phys. Rev. Lett. **113** (2014), 151601.

[32] S. Descotes-Genon, J. Matias and J. Virto,
Phys. Rev. D 88, 074002 (2013).

[33] W. Altmannshofer and D. M. Straub,
Eur. Phys. J. C73 (2013) 2646.

10.5.3 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 decays with higher sensitivity than reached by previous experiments [34]. Many BSM models [35, 36] predict the existence of light particles, such as an inflaton or a dark matter mediator, that, via mixing with the Higgs boson, can couple to the visible SM sector.

We are analysing the full Run I dataset 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 centimetres before decaying. Simulations were made for different mass and lifetime values as a guidance to the optimal event selection based on machine-learning algorithms.

[34] J.-T. Wei *et al.* [Belle Collab.],
Phys.Rev.Lett.103:171801 (2009).

[35] J. D. Clarke, R. Foot and R. R. Volkas,
JHEP 02 (2014) 123.

[36] K. Schmidt-Hoberg, F. Staub and M. W. Winkler,
Phys. Lett. B727 (2013) 506-510.

10.5.4 Semileptonic decays

M. Chrząszcz, E. Graverini and N. Serra

The most significant deviation from SM predictions in B-meson decays comes from measurements of the branching fraction of semi-tauonic decays [37–39]. Our group is presently involved in a similar test of lepton universality, measuring the observable $R(\Lambda_c^*) \equiv \mathcal{B}(\Lambda_b \to \Lambda_c^*\tau\nu)/\mathcal{B}(\Lambda_b \to \Lambda_c^*\mu\nu)$. This measurement is important to test present tensions and also to provide complementary information, since it would be the first of such measurement using b-baryons.

[37] R. Aaij *et al.* [LHCb Collab.],
Phys. Rev. Lett. 115 (2015) 111803.

[38] J. P. Lees *et al.* [BaBar Collab.],
Phys.Rev.D 88, 072012 (2013).

[39] M. Huschle *et al.* [Belle Collab.],
Phys. Rev. D 92, 072014 (2015).

10.5.5 Charmless *b*-hadron decays

E. Graverini, N. Serra and R. Silva Coutinho

The Standard Model gives no explanation for the observed imbalance between baryonic and antibaryonic abundances in the universe. *CP* violation in weak interactions could allow matter to be produced more commonly than antimatter in conditions immediately after the Big Bang. Searches for new sources of *CP* violating asymmetries in addition to those predicted by the SM are thus among the main goals of current particle physics. In particular, studies of charmless three-body decays of either $B^0_{(s)}$ mesons or beauty baryons with a long-lived particle in the final state (*i.e.* K^0_s or Λ^0) are of great interest for improving the understanding of hadronic interactions and in the search for *CP* violation effects.

Amplitude analyses of the most prominent modes and a search for the as yet unobserved channel $B^0_s \to K^0_s K^+K^-$, lead by our group, may well provide new insights into the field.

Our group has also been involved in the searches for b-baryon decays to $\Lambda^0\pi^+\pi^-$, $\Lambda^0K^\pm\pi^\mp$ and $\Lambda^0K^+K^-$ [40]. The $\Lambda^0_b \to \Lambda^0K^\pm\pi^\mp$ and $\Lambda^0_b \to \Lambda^0K^+K^-$ decay modes were observed for the first time (see Fig. 10.5) and no evidence is seen for a *CP* asymmetry in their phase-space integrated decay rates. Finally, evidence is seen for the $\Lambda^0_b \to \Lambda^0\pi^+\pi^-$ decay and limits are set on the branching fractions of the decays $\Xi^0_b \to \Lambda^0\pi^+\pi^-$, $\Xi^0_b \to \Lambda^0K^\pm\pi^\mp$, and $\Xi^0_b \to \Lambda^0_b K^+K^-$.

Further studies of similar modes are rather compelling as no hints for *CP* violation have been found in b-hadron decays yet. An interesting channel to investigate is $\Lambda^0_b \to K^0_s p\pi^-$, which has been previously studied by LHCb with

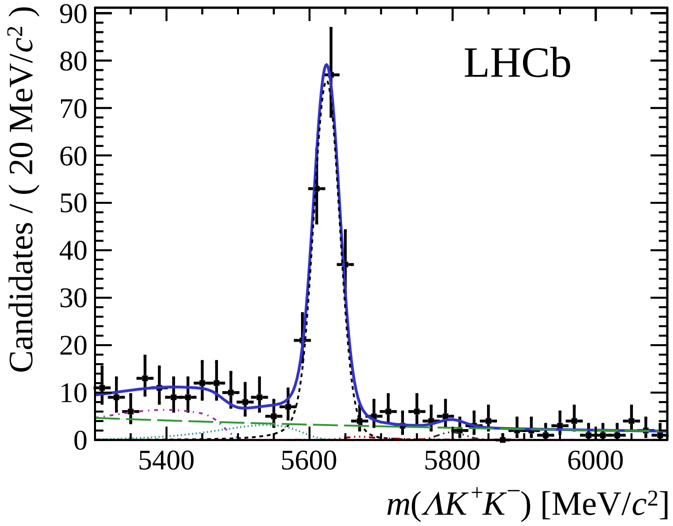

FIG. 10.5 – Invariant mass distribution for the $\Lambda^0K^+K^-$ final states. A signal for $\Lambda_b^0 \to \Lambda^0K^+K^-$ (shown as short-dashed black lines) is observed for the first time with a significance $15.8\,\sigma$ [40].

$1.0\,\mathrm{fb}^{-1}$ [41]. This measurement is statistically limited. An update of this analysis with the full Run I dataset is of great interest and is being performed by our group. Moreover, inspired by the methodology implemented in $B^\pm \to h^\pm h^\mp h^\pm$ (where h stands for pions or kaons) decays that recently revealed large anisotropies in the phase-space distribution [42], we are extending this treatment for $\Lambda_b^0 \to K_s^0 p\pi^-$ decays, significantly enhancing the discovery potential of *CP* violation.

[40] R. Aaij *et al.* [LHCb Collab.], arXiv:1603.00413.

[41] R. Aaij *et al.* [LHCb Collab.],
J. High Energy Phys. **04** (2014) 087.

[42] R. Aaij *et al.* [LHCb Collab.],
Phys. Rev. D **90** (2014) 112004.

10.5.6 Electroweak boson and low mass Drell-Yan production

A. Bursche, M. Chrząszcz, Ch. Elsasser, K. Müller and M. Tresch

Measurements of the production cross-section of electroweak bosons constitute an important test of the SM at LHC energies. Since predictions in pQCD are known at the percent level these measurements are sensitive to the momentum distribution of the partons in the proton (PDF). Our group contributed to various aspects of these analyses in the past years. Precision measurements of the differential cross sections and cross section ratios of W and Z bosons have been published using the datasets at centre of mass energies of 7 [43] and 8 TeV [44]. The systematic uncertainties are at the percent level and thus comparable to or even smaller than the theoretical uncertainties. A first measurement of Z production at 13 TeV has been released using a small dataset of the new Run II data [45]. All the cross sections are measured to be in good agreement with theoretical predictions.

In order to further exploit the unique phase space region of LHCb a measurement is performed by our group of Z bosons with the associated production of a long lived particle (K_s^0 or Λ^0). These measurements are important for the understanding of the hadronisation process and the tuning of Monte Carlo generators.

Another measurement performed in our group is the analysis of low mass Drell-Yan production down to invariant masses of 10 GeV. It was extended to include also the data at 8 TeV which allows to access lower momentum fractions of the struck quark. Backgrounds of jet-production are determined by a fit to the isolation distribution of the two muons with the templates determined from data. The analysis will enter the LHCb review process shortly.

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

[44] R. Aaij *et al.* [LHCb Collab.], JHEP **01** (2016) 155.

[45] LHCb Collab., LHCb-CONF-2016-002.

10.6 Summary and Outlook

The LHCb experiment has performed very well throughout the 2015 LHC run with a very high data taking efficency and stable running even with heavy ion collisions. The LHCb collaboration continued to produce high quality results, which resulted in more than 40 publications and many conference contributions, many of these already based on the new data collected at a centre of mass energy of 13 TeV. The Zurich group made important contributions to the operation of the experiment, physics analyses and preparation for the upgrade.