9 Particle Physics with LHCb

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The full LHCb collaboration consists of 71 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)

LHCb is a dedicated heavy flavour physics experiment at the CERN Large Hadron Collider (LHC) [1] 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. The detector is designed as a forward spectrometer, fully instrumented in the pseudorapidity range $2 < \eta < 5$. 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 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 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, K. Müller deputy chair of the speakers bureau and O. Steinkamp deputy project leader of the silicon tracker.

[1] LHCb Collab., JINST 3 S08005 (2008).

9.1 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 ($\sqrt{s}$) of 7 and 8 TeV. In Run II, which started in May 2015, the centre of mass energy increased to 13 TeV. In 2016 LHCb collected about 1.7 fb^{-1} of good quality data in pp collisions. In addition, data samples were collected in pPb collisions and pHe fixed target collisions using the internal gas target. This sample with an integrated luminosity of 0.4 nb^{-1} was used for the first measurement of antiproton production outside of the Earth's atmosphere [2].

[2] LHCb Collab., LHCb-CONF-2017-002.

9.1.1 TT Detector performance

E. Graverini, A. Mauri, O. Steinkamp, B. Storaci

The Tracker Turicensis (TT) detector continued to perform excellently in 2016. At the end of the year, more than 99.5% of its 143'360 readout channels were fully operational. Towards the end of the year, a small number of detector modules began to suffer from the breaking of wire bonds in between silicon sensors and front-end readout chips. This phenomenon had already been observed during the first months of operation in 2010, but the cause for these failures have never been fully understood. The newly affected modules were repaired in January 2016. We acknowledge the excellent work of Stefan Steiner and our former colleague Tariel Sakhelashvili, now at Dectris Ltd., Baden-Daettwil, for their invaluable contribution to this effort. The single-hit detection efficiency remained very close to 100%; the observed position resolution is 53 µm, compared to 48 µm expected from simulation. Studies of the spatial alignment of the detector elements are still ongoing and a further improvement in position resolution can be expected.

The radiation damage of the silicon detectors was monitored regularly by measuring leakage currents and by performing charge-collection efficiency scans (details have been reported in previous annual reports). The results of our studies agree well with expectations and no degradation of the detector performance is expected until its foreseen replacement during the LHCb upgrade in the next long LHC shutdown in 2019.

9.2 LHCb upgrade

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

The LHCb collaboration prepares for a comprehensive upgrade during the second long shutdown of the LHC in 2019/2020 [3]. The upgraded detector is going to be able to operate at a five times higher instantaneous luminosity, permitting to collect interesting events at increased rate. Moreover, the detector will be fully read out at the LHC bunch-crossing frequency of 40 MHz, eliminating the need for a hardware-based low-level trigger and thereby significantly increasing selection efficiencies for many final states of interest.

The current TT detector will have to be replaced as part of this upgrade, 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 by a collaboration including our group as well as CERN and six institutions from Italy, Poland and the US [4]. To best exploit our experience in operating the existing detector, we have taken the responsibility for the development of detector control software, power distribution, the monitoring of operational and environmental parameters, and detector safety. Moreover, we play a prominent role in the testing of the newly developed front-end readout chip (SALT) and have contributed in test beam efforts to qualify radiation-hard silicon sensors for the UT. Due to recent funding cuts, our future involvement in the upgrade project is currently unclear.

[3] LHCb Collab., CERN-LHCC-2012-007.

[4] LHCb Collab., CERN-LHCC-2014-001.

9.3 Track reconstruction at software trigger level

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

Fast and efficient track reconstruction algorithms are crucial for the successful operation of the all-software trigger of the upgraded LHCb detector. We developed a novel algorithm connecting track segments in the vertex detector to hits in the UT, which allowed to speed up the track reconstruction to the required level, with no loss in reconstruction efficiency [5]. We back-ported this algorithm for use with the current detector. This back-ported algorithm was introduced in the software trigger during 2015 and was used also throughout 2016. The faster track reconstruction allowed to apply less stringent trigger requirements, increasing data collection rates for various analyses and reducing systematic uncertainties due to selection biases in others. Moreover, the successful operation of the algorithm in actual data taking provided an important proof-of-principle for the upgrade. We remain responsible for the maintenance of the code.

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

9.4 Physics results

The LHCb collaboration published about 60 physics papers during the past year [6], covering a wide range of topics. Some of the main results are highlighted below, while analyses with direct contributions from our group will be discussed in more detail in the next sections.

The study of the very rare decays $B^0_{(s)} \to \mu\mu$ is one of the key analyses of LHCb. Since New Physics (NP) may contribute at the same order of magnitude as the SM, the measurements of the branching fractions strongly constrain the allowed parameter space for NP models. LHCb published the first observation by a single experiment of the decay $B^0_s \to \mu\mu$, with a statistical significance of 7.8 standard deviations [7]. The measured branching fraction $(3.0 \pm 0.6 + 0.3 - 0.2) \cdot 10^{-9}$ is in agreement with the SM prediction and is the most precise measurement of this quantity to date. The effective lifetime of B^0_s lifetime was measured to be $2.04 \pm 0.44 \pm 0.05$ ps in agreement with the SM prediction.

A combination of measurements sensitive to the CKM angle γ, which is a measure of the amount of *CP* violation in the SM, was performed [8]. The combination yields $\gamma = (72.2^{+6.8}_{-7.3})^\circ$ corresponding to the most precise determination of γ from a single experiment to date. 35

The parameter A^Δ, which is related to the photon polarisation in $b \to s\gamma$ transitions, was determined from a time-dependent analysis of the $B^0_s \to \Phi\gamma$ decay rate. The measured value of $A^\Delta = 0.98^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$ is consistent with the SM prediction [9].

The hadronic B^0 decay into a K^+K^- pair was observed for the first time and the branching fractions for $B^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ measured with unprecedent precision [10]. The decay into a kaon pair is the rarest fully hadronic B decay mode ever observed. Precise knowledge of the branching fractions of these decays is needed to improve the understanding of QCD dynamics in the more general sector of two-body B-hadron decays. The invariant mass distribution of the K^+K^- is shown in Fig. 9.1.

The phenomenon of *CP* violation has been observed so far in the K and B-meson systems. LHCb published first evidence of *CP* violation in baryons using the decays $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ and $\Lambda^0_b \to p\pi^-K^+K^-$ [11] with a statistical significance corresponding to 3.3 standard deviations. *CP* violation was also searched for in charm decays where mixing induced and direct *CP* asymmetries are expected to be small, but can be highly enhanced by NP contributions. The LHCb measurements of asymmetries in the time-dependent rates of $D^0 \to K^+K$ and $D^0 \to \pi^+\pi$ decays show no evidence for *CP* violation and improve on the precision of the previous best measurements by nearly a factor of two [12].

Besides many significant contributions in studies of b-hadrons, results from spectroscopy and production measurements at LHCb have caught considerable attention. LHCb

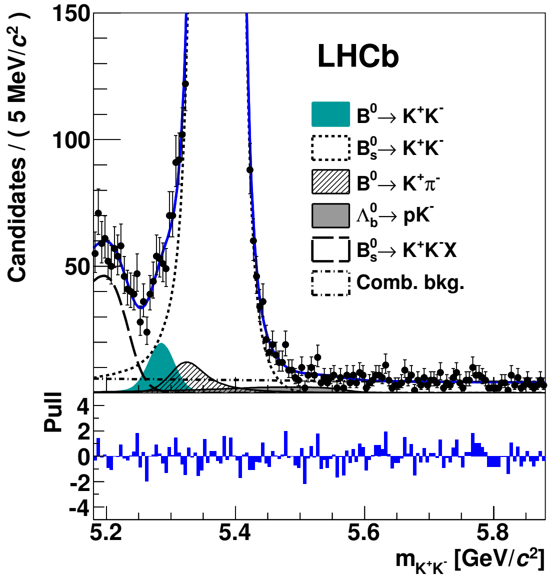

FIG. 9.1 – Invariant mass $m_{K^+K^-}$ distribution. The fitted contribution for $B^0 \to K^+K^-$ is shown as full area.

reported the observation of four exotic particles decaying into a J/ψ and a Φ meson in $B^+ \to J/\psi \Phi K^+$ decays [13]. Their properties are consistent with their interpretation as four-quark particles (tetraquarks or strange charm charged meson pairs). Evidence for exotic hadron production consistent with the previously observed states $P_c^+(4450)$, $P_c(4380)$ and $Z_c(4200)$ was also found in the decay $\Lambda_b^0 \to J/\psi p \pi^-$ [14].

[6] http://lhcb.web.cern.ch/lhcb/
[7] LHCb Collab., arXiv:1703.05747 [hep-ex].
[8] LHCb Collab., JHEP **12** (2016) 087.
[9] LHCb Collab., Phys. Rev. Lett. **118** 021801.
[10] LHCb Collab., Phys. Rev. Lett. **118** (2017) 081801.
[11] LHCb Collab., Nature Phys. (2017).
[12] LHCb Collab., arXiv:1702.06490 [hep-ex].
[13] LHCb Collab., Phys. Rev. Lett. **118** (2017) 022003.
[14] LHCb Collab., Phys. Rev. Lett. **117** (2016) 082003.

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

E. Bowen, M. Chrząszcz, N. Serra, R. Coutinho, A. Mauri

The decay $B^0 \to K^*\mu^+\mu^-$ is a flavour changing neutral current with a branching ratio of about 10^{-6}. Since new particles may enter in loops with competitive amplitudes angular observables are sensitive probes of NP. Measurements of this decay performed by our group with an integrated luminosity corresponding to 1 fb^{-1} [15] have shown significant tensions with respect to SM predictions, corresponding to about 3.7 standard deviations. These measurements are widely discussed in the literature. Several authors have interpreted these measurements as a possible sign of physics beyond the SM [16],while others have pointed out to possible underestimated QCD uncertainties [17].Our group has been leading the measurement of angular observables with 3 fb^{-1} [18]. We have contributed to various aspects of the analysis including the signal selection, the correction of detector acceptance and the determination of angular observables. In particular, we proposed a novel method based on the moments of the angular distribution [19]. This method allows to measure the angular observables in small bins of dimuon invariant mass. In addition, we have shown that the method of moments is more robust against mis-modelling of the angular distribution. Figure 9.2 shows the comparison between the SM predictions from [20] (yellow bands) and the measurement of P_5' with a likelihood (black points) and the method of moments (red points).Good agreement is observed with the different methods. The new measurement exhibit a deviation with respect to the theory predictions of about 3 standard deviations for each of the two bins in the region $4.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$, where q^2 is the invariant mass squared of the two muons.

The $B \to K\pi\mu^+\mu^-$ system above the $K^*(892)$ resonance has so far received little attention. We have pioneered the measurement of angular observables for this decay, in the region dominated by the resonances $K^{*0,2}(1430)$. This measurement is challenging, since several different K^* resonances contribute to this $K\pi$ invariant mass. Considering $S-$, $P-$ and $D-$ waves there are in total 41 independent moments, which give access to the full angular distribution. This analysis led to the world's first measurement of this decay. In addition to the 41 independent angular moments (20 are shown in Fig. 9.3), we measured the differential branching ratio as a function of q^2 and the fraction of $D-$wave (f_D). While it was naively expected to observe a dominant $D-$wave contribution, we have no evidence of such a contribution and we set an upper limit $f_D < 0.29$ at 95% CL. This result is unexpected since the $B^0 \to J/\psi K\pi$ decay has a dominant $D-$wave contribution in this region (around 70%) of the $K\pi$ invariant mass. This effect could be due to a large breaking of QCD factorisation.

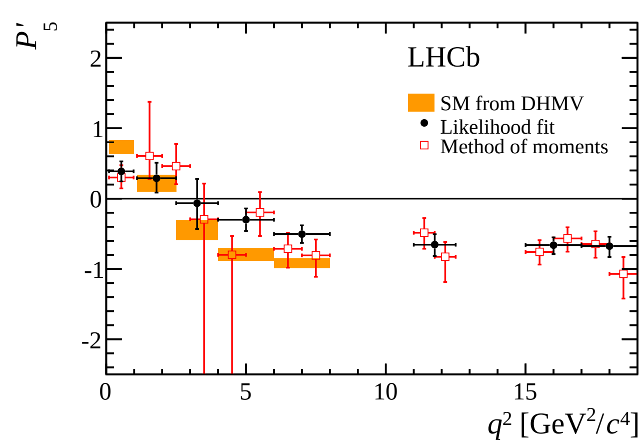

FIG. 9.2 – The angular observable P_5' in the decay $B^0 \to K^{*0}\mu^+\mu^-$ measured by LHCb with a data set corresponding to 3 fb^{-1} compared to the SM predictions from Ref. [20].

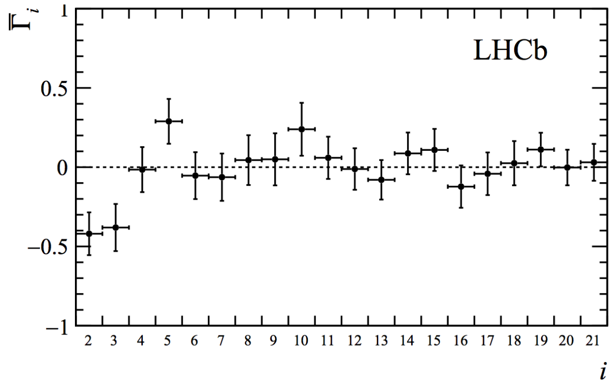

FIG. 9.3 – Measurement of the 20 out of 41 moments in the decay $B^0 \to K^{*0}\mu\mu$.

[15] LHCb Collab., Phys.Rev.Lett. 111 (2013) 191801.

[16] A. Karan et al., arXiv:1603.04355;
S. Descotes-Genon, J. Matias and J. Virto,
Phys. Rev. D 88, 074002 (2013);
R. Gauld, F. Goertz and U. Haisch,
JHEP 1401 (2014) 069;
A. J. Buras and J. Girrbach, JHEP 1312 (2013) 009;
W. Altmannshofer and D. M. Straub,
Eur. Phys. J. C73 (2013) 2646;
D. Ghosh, M. Nardecchia and S. A. Renner,
arXiv:1408.4097.

[17] F. Beaujean, C. Bobeth, D. van Dyk,
Eur. Phys. J. C 74 (2014) 2897;
J. Lyon, R. Zwicky, arXiv:1406.0566;
M. Ciuchini et al., JHEP 1305 (2013) 043.

[18] LHCb Collab., JHEP 02 (2016) 104.

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

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

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

R. Coutinho, F. Lionetto, A. Puig, N. Serra
The measurement of the ratio of branching fractions $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ was found to be 2.6 standard deviations in tension with respect to SM predictions [21]. Several authors have argued that this deviation is consistent with the deviations observed in $b \to s\mu\mu$ decays, which could be an indication of NP that breaks the lepton universality of the SM. The recent LHCb result on the ratio of branching fractions $R_{K^*} = \mathcal{B}(B^+ \to K^*\mu^+\mu^-)/\mathcal{B}(B^+ \to K^*e^+e^-)$ [22], also showing deviations above two sigma with respect to the SM, has added even more interest to these tantalising hints of NP. Our group is involved in several tests of lepton universality in $b \to se^+e^-$ transitions. The main goal will be to measure the asymmetry $A(P_5') = (P_5^{ee\prime} - P_5^{\mu\mu\prime})/(P_5^{ee\prime} + P_5^{\mu\mu\prime})$ using $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ decays; this analysis is of key importance to reinforce the R_X measurements, as its dependency on experimental effects is very different. To provide a quick and robust check to the R_X anomalies, we also plan to study these angular asymmetries using a simplified counting experiment. In addition, the measurements of the ratio of branching ratios $R_{K\pi} = \mathcal{B}(B^0 \to K\pi\mu^+\mu^-)\mathcal{B}(B^0 \to K\pi e^+e^-)$ and $R_{K\pi\pi} = \mathcal{B}(B^+ \to K\pi\pi\mu^+\mu^-)\mathcal{B}(B^+ \to K\pi\pi e^+e^-)$ in a wide range of $K\pi$ and $K\pi\pi$ masses, which our group is leading, have the potential to confirm or disprove lepton universality hints in rare decays. In both cases, the di-electron mode has never been observed, so a first observation will also need to be performed.

[21] LHCb Collab., Phys. Rev. Lett. **113** (2014), 151601.

[22] LHCb Collab., arXiv:1705.05802.

9.4.3 Measuring the Breaking of Lepton Flavour Universality in $B \to K^*\ell^+\ell^-$

R. Coutinho, N. Serra in collaboration with D. van Dyk
Inspired by the recent measurements of $b \to s\ell^+\ell^-$ transitions we proposed a new set of observables D_i ($i = 4, 5, 6s$), sensitive to LFU-breaking effects in the decays $B \to K^*\ell^+\ell^-$ ($\ell = e, \mu$) [23]. These observables are branching-ratio-weighted averages of differences (with respect to the final-state lepton flavour) of the angular observables $S_{4,5,6s}$. In the presence of LFU-breaking NP effects in $\mathcal{C}_9^{(\ell)}$ their theoretical uncertainties due to charm-induced hadronic contributions are kinematically suppressed to $< 7\%$ in the region of $1 \leq q^2 \leq 6\,\text{GeV}^2$. This allows predictions in the NP scenarios that can be systematically improved as our knowledge of the $B \to K^*$ form factors and CKM Wolfenstein parameters improves.

The D_i observables can be measured at the LHCb or at the Belle II experiments, either by performing likelihood fits of the angular distribution of the decays $B \to K^*\ell^+\ell^-$ or by using the method of moments. We found that in order to obtain 3σ evidence for NP in only these observables and using the method of moments, roughly 1500 $B \to K^*e^+e^-$ signal events are necessary in either experiment (Figure 9.4).

[23] N. Serra, R. Silva Coutinho and D. van Dyk,
Phys. Rev. D 95, 035029 (2017).

9.4.4 Search for new scalar particles in B decays

M. Chrząszcz, A. Mauri, N. Serra
At LHCb the light inflaton, or more in general any other light scalar from the hidden sector mixing with the Higgs, can be searched for by analysing the decay $B^+ \to K^+\chi$, where the light scalar χ subsequently decays into a pair of muons. We have carried out this analysis setting the world's best limits as a function of the mass and lifetime of the χ scalar particle [24]. Our analysis sets severe limits on the inflaton

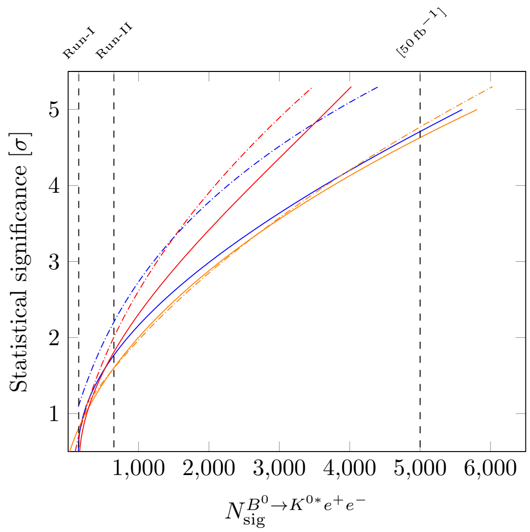

FIG. 9.4 – Projected statistical-only significance as a function of the extrapolated yields in LHCb for the (blue) $\langle D_5 \rangle_{1,6}$ and (orange) $\langle D_{6s} \rangle_{1,6}$ observables, obtained from the (solid line) method-of-moments and (dash-dotted line) likelihood fit. The red lines indicate the combined significance.

model (Fig. 9.5) and now only corners of the phase-space are allowed, making the model highly unlikely.

[24] LHCb Collab., Phys. Rev. D **95**, 071101 (2017).

9.4.5 Semileptonic decays

M. Chrząszcz, E. Graverini, P. Owen, N. Serra

The strongest evidence for a violation of lepton universality is seen in the branching fraction of semileptonic decays involving a τ lepton. In particular, the measurement of the observables $R(D)$ [25, 26] and $R(D^*)$ [25–27]. This enhancement can be explained in many extensions to the SM which preferentially couple to third generation leptons, such as an additional charged Higgs boson.

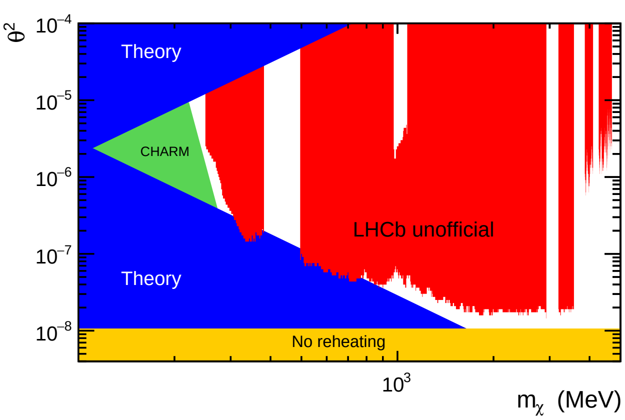

FIG. 9.5 – Interpretation of the limits of the $B^+ \to K^+\chi$ analysis in the context of the inflaton model. The phase space of allowed regions (white) is severely reduced, leaving only corners.

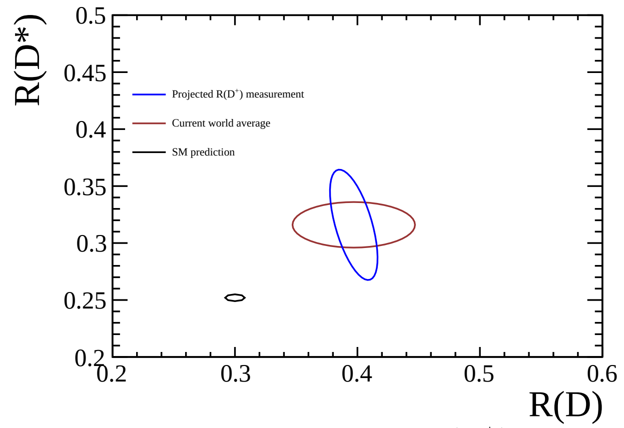

FIG. 9.6 – Projection for the observable $R(D^+)$ for Run II of LHCb, compared with the current world average [28] of the observable $R(D^{(*)})$. This measurement has the potential to break the correlation between $R(D)$ and $R(D^*)$.

Our group is presently involved in supplementing this information with the measurement of $R(D^+)$, which has the potential to disentangle enhancements to the observables $R(D)$ and $R(D^*)$. We are also involved in a new test of lepton universality, measuring the ratio $R(\Lambda_c^*) = \mathcal{B}(\Lambda_b^0 \to \Lambda_c^* \tau\nu)\mathcal{B}(\Lambda_b^0 \to \Lambda_c^* \mu\nu)$. This measurement is important to confirm present tensions and also to provide complementary information as this is a measurement of a fermion decay, which behaves differently under the laws of angular momentum conservation. An illustration of the sensitivity for $R(D^+)$ can be seen in Fig. 9.6.

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

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

[27] LHCb Collab., Phys. Rev. Lett. 115 (2015) 111803.

[28] HFAC Collaboration http://www.slac/stanford.edu/xorg/hfag

9.4.6 Charmless

R. Coutinho

The study of charmless three-body decays of neutral B mesons and beauty baryons to final states containing K_S^0 mesons is of great interest for improving the understanding of hadronic interactions and in the search for CP violation effects. Searches for the remaining unobserved mesonic channel $B_s^0 \to K_S^0 K^+ K^-$ has been performed using a sample of pp collision data. An indication for this decay is obtained and its branching fraction, relative to the $B^0 \to K_S^0 \pi^+\pi^-$ decay, is determined. Updated branching fraction measurements of the other $B^0_{(s)} \to K_S^0 h^+ h'^-$ decay modes (where $h^{(\prime)} = \pi, K$), are also presented prior to the forthcoming Dalitz plot analyses with the Run I data sample. The paper draft of this result is under final collaboration circulation and will be submitted to JHEP soon.

Dalitz-plot analyses of the most prominent modes, *i.e.* $B^0 \to K^0_S \pi^+\pi^-$ and $B^0_s \to K^0_S K^+\pi^-$, have been performed and are close to completion. The first observation of a non-vanishing *CP* asymmetry in the decay $B^0 \to K^*(892)^+\pi^-$ is obtained, with a significance of 6 standard deviations. Moreover, the results from the first untagged decay-time-integrated amplitude analysis in the B^0_s mode are either first to date or in good agreement with, and more precise than, the previous measurements.

As-yet no confirmation of *CP* violation has been found in *b*-hadron decays, further studies are rather compelling. An interesting channel to investigate is the $\Lambda^0_b \to K^0_S p\pi^-$, which has been previously studied with $1.0\,\text{fb}^{-1}$ [29]. Although the *CP* asymmetry observed shows no significant deviation from zero, this measurement is statistically dominated. Therefore, an update of this analysis with full Run I and a subset of Run II dataset is of great interest and it is being performed by our group. Moreover, inspired by the methodology implemented in $B^\pm \to h^\pm h^\mp h^\pm$ decays that recently revealed large anisotropies in the phase-space distribution [30], we are extending this treatment for this baryonic mode, that significantly enhances the discovery potential of *CP* violation. In particular, this approach is able to measure asymmetries in the decay $\Lambda^0_b \to pK^{*-}$, which is predicted to have a large *CP* violation effect.

[29] LHCb Collab., J. High Energy Phys. **04** (2014) 087
[30] LHCb Collab., Phys. Rev. D **90** (2014) 112004

9.4.7 Measurements with electroweak bosons

M. Chrząszcz, K. Müller, M. Tresch, A. Weiden

Our group has been constantly contributing to the LHCb measurements involving electroweak bosons in the past years. A measurement of Z production at $\sqrt{s} = 13\,\text{TeV}$ has been published recently [31]. These measurements are of general interest as they are sensitive to the momentum distribution of the partons in the proton (PDFs) in a kinematic region not accessible to other experiments. The description of the PDFs is important for all production measurements at LHC and their uncertainty limits the reach of direct searches for rare or new processes. Besides the inclusive production of electroweak bosons new measurements have been performed by LHCb of exclusive final states such as electroweak bosons with jets [32] or W plus $b\bar{b}$ or $c\bar{c}$ production [33].

In the past year work in our group concentrated on the measurement of Z bosons with the associated production of a long lived particle (K^0_s or Λ^0). This probes the soft part of the interaction (hadronisation, fragmentation and multiple interactions) which cannot be calculated perturbatively but is modelled in Monte Carlo programs which need to be tuned to data. As the LHC is a hadron collider, the understanding

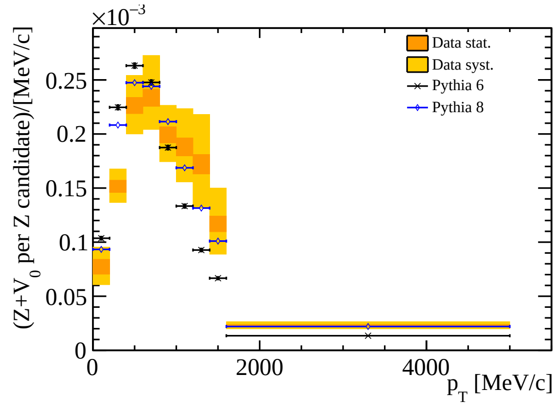

FIG. 9.7 – Number of K^0_S per Z boson as a function of p_T for data and predictions by PYTHIA.

of the soft part of QCD plays a crucial role also for measurements at ATLAS and CMS, such as searches for new particles or precision measurements of the Higgs boson. For a full picture the soft contribution should be measured in as many different processes as possible. The analysis of Z boson production in association with strange hadrons was the topic of the thesis of Marco Tresch, where a first measurement of the number of K^0_S or $\Lambda/\overline{\Lambda}$ in events with a Z boson decaying into two muons was performed as function of the opening angle between the Z boson and the strange composite particle or the transverse momentum of the latter.

As an example Fig. 9.7 shows the p_T distribution of the K^0_s in comparison to predictions from PYTHIA 6 and PYTHIA 8. For ZK^0_S production PYTHIA 8 better describes the distribution at high p_T, being a reflection of the hard diffractive processes which are included in the latter. For $Z\Lambda$ production both predictions significantly underestimate the data in agreement with observations by LHCb at lower scales [34]. The measurements however suffer from large uncertainties mainly due to limited statistics in the simulation samples needed for the efficiency correction.

[31] LHCb Collab., JHEP **09** (2016) 136.
[32] LHCb Collab., JHEP **05** (2016) 131.
[33] LHCb Collab., Phys. Lett. **B767** (2017) 110.
[34] LHCb Collab., JHEP **08** (2011) 034.

9.5 Summary and Outlook

The LHCb experiment has performed very well throughout the 2016 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.