12 Particle Physics with LHCb

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The full LHCb collaboration consists of 67 institutes from Brazil, China, 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) was designed to perform precision measurements of *CP* violating observables and to study rare decays of hadrons containing a b or c quark. Its main physics goals are to study the flavour structure in the quark sector and to search for possible New Physics (NP) beyond the Standard Model (SM) of particle physics. Of special interest for NP searches are processes that involve loop diagrams, such as box or penguin diagrams. Heavy new particles, which are predicted by most NP models, can appear virtually in the loops and modify production cross sections and angular distributions of final state particles with respect to SM predictions.

The forward acceptance of the detector and the ability to trigger on particles with relatively low transverse momentum also open up unique opportunities for particle production studies in proton-proton (pp) collisions at the LHC. The scope of such studies was extended to proton-lead collisions during dedicated data taking periods in early 2013.

The present long shutdown (LS1) of the LHC is being used by LHCb to install scintillator counters around the beam line for a better identification of diffractive events and to improve the software trigger for the next data taking period, which is scheduled to begin in spring 2015.

Our group contributed significantly to the construction and operation of the LHCb detector. We make crucial contributions to two key analyses of rare B meson decays. We lead studies of the production of W and Z bosons and low mass Drell-Yan pairs. We lead the development of improved algorithms for the trajectory reconstruction of charged particles in the trigger, both for the LHCb upgrade and for the data taking period starting in 2015. Finally, we have started to contribute to the R&D of the upgraded LHCb detector.

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

12.1 LHCb detector

The LHCb detector [1] is a single-arm forward spectrometer with pseudo-rapidity coverage in the range 2 to 5. The detector has excellent vertex and momentum resolution, needed to distinguish between primary and secondary vertices and to provide high invariant mass resolution. Two Ring Imaging Cherenkov (RICH) detectors allow discrimination between pions and kaons over a wide momentum range. The detector and its performance have been described in previous annual reports [2].

The Zurich group is responsible for the operation and maintenance of the Silicon Tracker (ST) system, in particular for the Tracker Turicensis (TT), a large planar silicon-strip tracking detector located in front of the LHCb dipole magnet that has been designed and constructed in Zurich.

12.1.1 Shutdown activities

S. Saornil

During LS1 the detectors are operated for short tests only or during regular LHCb commissioning weeks.

The control software of the ST has been completely revised to improve the robustness and maintainability of the code and to significantly shorten the time needed for the configuration of the detector for data taking.

12.1.2 Radiation damage studies

Ch. Elsasser, O. Steinkamp

Radiation damage in the TT is monitored by studying the detector leakage currents and by analysing dedicated charge-collection efficiency (CCE) scans, performed several times per year. Those allow to reconstruct the evolution of the full depletion voltage of the sensors. The results from the CCE scans as well as the luminosity dependence of the leakage currents (Fig. 12.1) show good agreement with the predictions which indicates that the TT

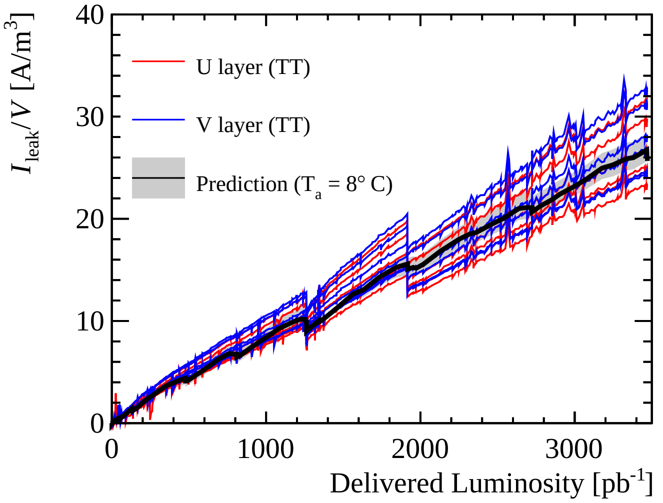

FIG. 12.1 – The measured distributions of volume leakage current versus delivered luminosity show good agreement with the predictions.

will survive well beyond the date of the LHCb upgrade.

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

[2] Physik-Institut, University of Zürich, Annual Reports 1996/7 ff., available at *http://www.physik.uzh.ch/reports.html*.

12.2 LHCb upgrade

The LHCb collaboration plans to perform a comprehensive upgrade of the detector and its readout electronics during the next long shutdown (LS2) resulting in a significant increase in physics reach [1]. The upgrade [2, 3] comprises two main areas: preparing the detector for the larger luminosity of up to 2×10^{33} cm^{-2}s^{-1} and allowing to read out the detector at the higher bunch crossing rate of 40 MHz. It is expected that reconstruction efficiencies for b hadron decays with fully hadronic final states will increase by a factor two.

12.2.1 Development of a new Upstream Tracker

F. Lionetto, S. Saornil, O. Steinkamp

The front-end electronics of the present TT detector is incompatible with the foreseen 40 MHz readout. The main purpose of the new Upstream Tracker (UT) [4], replacing TT, will be to reduce the time required for track reconstruction at trigger level by providing a fast momentum estimate for track candidates. Major improvements over the current TT are:

- less clearance between the beam pipe and the detector to increase the acceptance in the very forward region,
- finer readout granularity along the readout strips for lower strip occupancy and faster and more efficient pattern recognition and
- a finer readout pitch of the silicon sensors closest to the interaction region for higher spatial resolution and lower detector occupancy.

Our group has recently joined the UT detector project, together with Syracuse University and University of Maryland (USA), Universita degli Studi di Milano (Italy) and University of Science and Technology, Krakow (Poland). Building on our experience with TT, we have taken over the responsibility for the detector control system, including the low-voltage and bias-voltage distribution and the monitoring of environmental and operational parameters. In addition, we will participate in silicon sensor prototype studies and quality assurance of detector modules.

12.2.2 Track reconstruction at software trigger level

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

The reconstruction of charged tracks at the software trigger level is one of the greatest challenges of the upgrade. We have developed a new pattern recognition algorithm based on UT information which lowers the reconstruction time by a factor 3. The algorithm significantly reduces the fraction of wrongly reconstructed tracks while maintaining high reconstruction efficiency and was adopted as the baseline algorithm for the full software trigger.

We are now adapting this new algorithm to the existing LHCb detector and study if it can be employed already for the upcoming LHC run. Initial studies gave encouraging results.

[1] R. Aaij *et al.* [LHCb Collab.], arXiv:1208.3355 [hep-ex].

[2] R. Aaij *et al.* [LHCb Collab.], *Letter of Intent for the LHCb Upgrade*, CERN-LHCC-2011-001, LHCC-I-018.

[3] I. Bediaga *et al.* [LHCb Collab.], *Framework TDR for the LHCb Upgrade: TDR*, CERN-LHCC-2012-007, LHCb-TDR-012.

[4] A.A. Alves Jr *et al.* [LHCb Collab.], *LHCb Tracker Upgrade TDR*, CERN-LHCC-2014-001, LHCb-TDR-015.

12.3 Physics results

During the past twelve months, LHCb published more than 70 new physics results [1] in a wide range of topics, including measurements of mixing parameters and *CP* violating observables in the beauty and charm meson systems, of branching ratios and angular observables in rare b decays and studies of b hadron and electroweak boson production.

New results of *CP* violating observables included the first observation of *CP* violation in the B_s^0 meson system, using the decay $B_s^0 \to K^-\pi^+$ [2], and a new determination of the CKM angle γ from a combination of $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ decays [3]. The γ measurement is competitive and in agreement with earlier measurements from the B factories. LHCb also published the currently most precise measurement of the flavour-specific *CP* violating asymmetry, $a_{\rm sl}^s$, in semileptonic B_s^0 decays [4], in good agreement with the SM prediction of a small asymmetry. The LHCb result does not corroborate the large value found earlier by the D0 collaboration.

LHCb reported the first observation of a non-zero photon polarization in $b \to s\gamma$ transitions, from the analysis of angular distributions in the decay $B^+ \to K^+\pi^+\pi^-$ [5]. In the SM, $b \to s\gamma$ transitions are mediated by the exchange of a virtual W boson and photons are almost 100% (left-handed) polarized. In NP models deviations from full polarization are possible.

Several new measurements of *CP* violating asymmetries in neutral D meson decays were published. Two new measurements were performed of the difference ΔA_{CP} between the decay rates of D^0 and $\overline{D}^0$ mesons into K^+K pairs and into $\pi^+\pi$ pairs. An earlier LHCb measurement of ΔA_{CP}, using a subset of the data collected in 2011, had hinted at an unexpectedly large *CP* asymmetry, triggering intensive theoretical activity. The two new analyses used the full 2011 data set. One analysis [6] used the charge of the pion in $D^{*-} \to \overline{D}^0\pi^-$ decays to distinguish $\overline{D}^0$ and D^0 decays, the other analysis [7] made use of the muon charge in $B^+ \to \overline{D}^0\mu^+\nu_\mu$ decays for this purpose. Both results are in agreement with no direct *CP* asymmetry. Another analysis, looking for possible asymmetries $A_\Gamma(K^+K)$ and $A_\Gamma(\pi^+\pi)$ in the inverse effective lifetimes of D^0 and $\overline{D}^0$ in decays to the K^+K and $\pi^+\pi$ final states, respectively, gave results consistent with no indirect *CP* violation [8]. Finally, measurements of D^0–$\overline{D}^0$ oscillation parameters also result in values consistent with no indirect *CP* violation in mixing [9].

Measurements of b hadron properties included the world's most precise measurement of the B_c^+ lifetime [10] and a new measurement of the Λ_b^0 lifetime relative to the B^0 lifetime [11]. From Heavy Quark Expansion (HQE) theory, the Λ_b^0-to-B^0 lifetime ratio is expected to be close to one. While earlier measurements at LEP had found a ratio around 80%, the LHCb result is good agreement with the predictions.

LHCb also published new measurements of the masses and quantum numbers of the $X(3872)$ and the $Z(4430)^-$, two states that do not seem to fit into the standard spectrum of $q\overline{q}$ states. The $X(3872)$ was discovered ten years ago by the Belle collaboration and has been speculated to be a $D\overline{D}^*$ molecule, a tetraquark state or a charmonium-molecule mixture. The LHCb measurement [12] unambiguously determined the $X(3872)$ quantum numbers to be $J^{PC} = 1^{++}$, compatible with a $D\overline{D}^*$ molecule or a tetraquark state. A classical interpretation of the $X(3872)$ as a pure charmonium state is not excluded by these quantum numbers, but this assignment is made unlikely by the measured mass.

First evidence for the $Z(4430)^-$ was presented by the Belle collaboration in 2008. The recent LHCb measurement [13], using the full combined 2011/2012 dataset, confirms the signal with a significance of 13.9 standard deviations and establishes its resonant nature via a phase-shift analysis. The observed quantum numbers of the state are $J^P = 1^+$. The minimal quark content of this state is $c\overline{c}d\overline{u}$, making this the first unambiguous observation of an exotic particle that cannot be classified within the traditional quark model.

Analyses of the data samples collected in proton-lead ion runs are ongoing, a first published result is the measurement of J/ψ production and cold nuclear matter effects [14].

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

[2] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **110** (2013) 22, 221601.

[3] R. Aaij *et al.* [LHCb], Phys. Lett. B **726** (2013) 151.

[4] R. Aaij *et al.* [LHCb], Phys. Lett. B **728** (2014) 607.

[5] R. Aaij *et al.* [LHCb], arXiv:1402.6852 [hep-ex].

[6] LHCb Collab., LHCb-CONF-2013-003.

[7] R. Aaij *et al.* [LHCb], Phys. Lett. B **723** (2013) 33.

[8] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **112** (2014) 041801.

[9] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **111** (2013) 251801.

[10] R. Aaij *et al.* [LHCb], arXiv:1401.6932 [hep-ex].

[11] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **111** (2013) 102003.

[12] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **110** (2013) 22, 222001.

[13] R. Aaij *et al.* [LHCb], arXiv:1404.1903 [hep-ex].

[14] R. Aaij *et al.* [LHCb], JHEP **1402** (2014) 072.

12.3.1 Search for the lepton flavour violating decay $\tau^- \to \mu^-\mu^+\mu^-$

M. Chrząszcz, N. Serra

The LHCb experiment offers the possibility to search for lepton flavour violating τ decays, such as $\tau^- \to \mu^-\mu^+\mu^-$. The branching ratio of this decay, mediated by neutrino mixing, is negligibly small in the SM but could be strongly enhanced in several extensions of the SM [1], such as Supersymmetry, Extended Extra Dimensions and models with an extended neutrino sector. Limits on the branching ratio of this decay have been set at the B-factories [2] and by LHCb with 1 fb^{-1} [3]. The LHCb limit was the first result for this decay mode at a hadron collider and had a crucial contribution by M. Chrząszcz.

At present, the Zurich group is the driving force for the update of this result with 3 fb^{-1}. The event selection has been optimised taking into account that the τ leptons come from (semi)-leptonic decays of charm and beauty mesons. A multi-variate event selection has been trained to optimise the sensitivity to the admixture of these two sources using a procedure known as "blending". We also contribute to the modelling of the background and the extraction of the branching ratio. The improvements in the event selection result in an upper limit sensitivity of 5.6×10^{-8} at 90% C.L., similar to the limits set by the B-factories in a much cleaner environment.

M. Chrząszcz is a new member of the HFAG collaboration and is contributing to the averaging of τ-lepton properties.

[1] W.J. Marciano, T. Mori and J.M. Roney, Ann. Rev. Nucl. Part. Sci 58 (2008) 315-341.

[2] K. Hayasaka *et al.* [Belle Collab.], Phys. Lett. B 687 (2010) 139 ; J. P. Lees *et al.* [BaBar Collab.], Phys. Rev. D 81 (2010) 111101(R).

[3] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. B 724 (2013) 36.

12.3.2 $B^0 \to K^*\mu^+\mu^-$

E. Bowen, M. Chrząszcz, 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 proceeds via box and loop diagrams. This decay has been widely studied in the literature from the theoretical perspective, since its angular distributions and differential branching fraction are sensitive to a large number of NP scenarios (see Ref. [1] and references therein). This decay is kinematically described by three angles and the di-muon invariant mass q^2.

In the year 2012 LHCb determined several angular observables in bins of q^2 and made a first measurement of the zero-crossing point of the forward-backward asymmetry of the di-muon system with a key contribution from our group [2]. The remaining angular observables had never been measured, since they are not accessible via angular projections. We developed a method exploiting the symmetries of the angular distribution. The result, based on 1 fb^{-1}, for the observable P_5' is compared with SM predictions in Fig. 12.2. A 3.7σ discrepancy is observed in the low q^2 region.

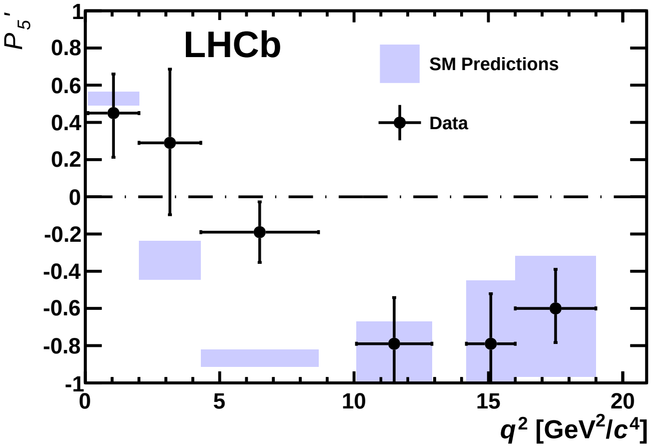

FIG. 12.2 – Observable P_5' as a function of q^2 [4], compared to SM predictions [3].

This result has attracted a considerable interest from the flavour physics community and it is widely discussed in the literature. It has been interpreted as a reduced C_9 Wilson coefficient with respect to the SM prediction [5]. It was also pointed out that it is numerically consistent with the systematically lower branching ratios with respect to predictions, measured at LHCb for several $b \to s\ell^+\ell^-$ transitions. New physics interpretations of a heavy Z' of about 10 TeV have been suggested [6]. It has also been suggested that this discrepancy is explained by an underestimation of the theoretical uncertainty associated with non-factorizable QCD contributions [7]. At the moment we are updating the analysis to include the full 3 fb^{-1} data set. In addition, B. Storaci and N. Serra are trying to extract the theoretical corrections to QCD factorisation directly from data.

[1] J. Matias *et al.*, JHEP 04 (2012) 104.

[2] R. Aaij *et al.* [LHCb Collab.], JHEP 1308 (2013) 131.

[3] S. Descotes-Genon *et al.*, JHEP 1305 (2013) 137.

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

[5] S. Descotes-Genon, J. Matias and J. Virto, Phys. Rev. D88 (2013) 074002.

[6] R. Gauld, F. Goertz and U. Haisch, JHEP 1401 (2014) 069.

[7] F. Beaujean, C. Bobeth and D. van Dyk, arXiv:1310.2478 [hep-ph].

12.3.3 The decays $B^0_{(s)} \to \mu^+\mu^-$

Ch. Elsasser

The decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are very rare in the SM, with branching fractions of $(3.23 \pm 0.27) \times 10^{-9}$ and $(1.07 \pm 0.10) \times 10^{-10}$, respectively [1]. NP contributions could be of the same order of magnitude so measurements of these branching fractions, one of the key LHCb measurements, may strongly constrain the allowed parameter space for various NP models.

Our group has made significant contributions to these measurements such as the calibration of the di-muon invariant mass and the multivariate classifier used to distinguish signal and background events. The distributions of both variables were determined from the observed exclusive $B^0_{(s)} \to h^+h^-$ decays, where $h^\pm$ is a kaon or a pion. Information from the RICH detectors is used to separate kaons and pions. The particle identification efficiencies were evaluated using the control channels $B^\pm \to J/\psi(1S)K^\pm$ and $B^0_s \to J/\psi(1S)\phi$. Alternatively, the di-muon invariant mass resolution has been interpolated between values found at the di-muon resonances J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. The results of both methods are in perfect agreement.

A combined analysis of 1 fb^{-1} collected in 2011 at a centre-of-mass energy of $\sqrt{s} = 7$ TeV and 2 fb^{-1} collected in 2012 at $\sqrt{s} = 8$ TeV, yielded a 4.0 σ statistical significance for the observation of the decay $B^0_s \to \mu^+\mu^-$. The measured branching fraction

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9},$$

is in good agreement with the the SM prediction.

The experimental sensitivity for B^0 decays is four times larger than for B^0_s due to the different hadronization fractions. For $B^0 \to \mu^+\mu^-$ the number of candidate events is consistent with the background expectation, yielding an improved limit on the branching fraction [2]:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}, \quad 95\%\ \text{C.L.}$$

[1] A. J. Buras *et al.*, Eur. Phys. J. C72 (2012) 2172.

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

12.3.4 Electroweak boson and low mass Drell-Yan production

J. Anderson, A. Bursche, N. Chiapolini, Ch. Elsasser, P. Lowdon and K. Müller

The inclusive production cross section of the Z boson has been measured by LHCb using final states with pairs of muons [1, 2], electrons [3] or taus [4]. The large statistics available with the 2011 and 2012 data will allow for very precise measurements of differential cross sections as well. The analysis includes a time consuming evaluation of the systematic uncertainties and final results are not yet available.

The large data sets also allow for measurements of Z production with exclusive final states. In the past year, measurements have been published of Z production with jets [5] and Z production in association with a D meson [6], both with a large contribution from our group. A measurement of Z in association with b-quarks will be published soon. All these measurements are sensitive to the substructure of the proton which is described by parton density functions (PDFs). Our group (P. Lowdon) got also involved in the extraction of PDFs from HERA and LHC data sets.

Jet production in association with a Z boson is sensitive to the gluon content of the proton and serves furthermore as a sensitive test of perturbative QCD as higher orders must be included. Results based on an integrated luminosity of 1 fb^{-1} have been published [5] (A. Bursche in close collaboration with the Cambridge group). The dominant uncertainty originates in the jet energy scale. Simulation indicates jet energy resolutions of 10-15% for jets with p_T between 10 and 100 GeV. Studies of events with a Z and a jet back-to-back show agreement between measured and simulated energy scale and resolution. The normalised differential cross section as a function of p_T of the leading jet is shown in Fig. 12.3. Predictions at different order of α_s and with different PDF sets are shown for comparison. As expected, the measurements are best described by the $\mathcal{O}(\alpha_s^2)$ predictions calculated using POWHEG [7] interfaced to PYTHIA [8].

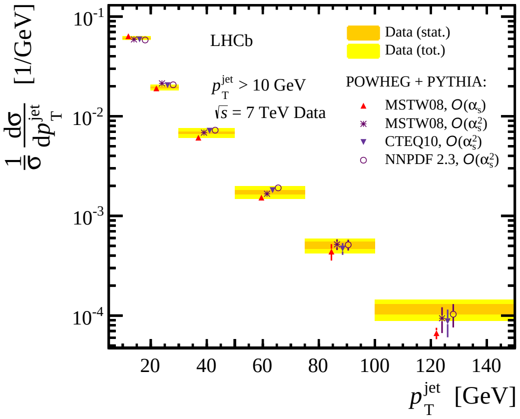

FIG. 12.3 – Normalised experimental cross section of Z production in association with a jet as a function of p_T of the leading jet compared to model predictions at different order of α_s and with different PDF sets.

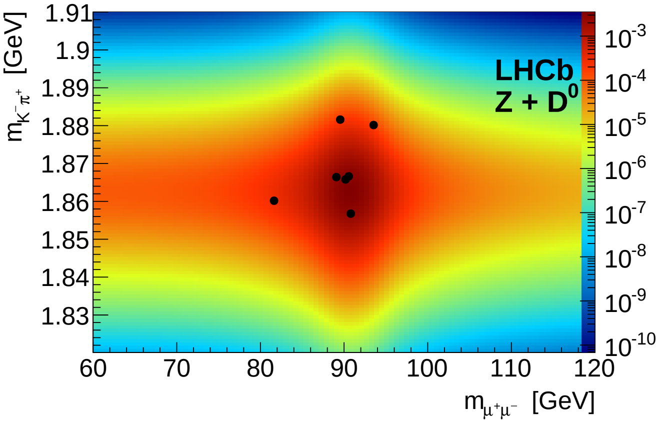

FIG. 12.4 – Distribution of the reconstructed invariant masses of the 7 $Z + D^0$ candidates superimposed on the expected distribution containing both signal and background.

The measurement of Z production with an open charm meson provides information on the charm parton distribution, the charm production mechanism and double parton scattering [9, 10]. For this analysis, the Z boson is reconstructed in the di-muon channel, while charmed mesons are identified in the final states $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$. Seven candidates with a D^0 and four with a D^+ are found with a background contamination below 5%. The invariant mass of the Z and D^0 candidates is shown in Fig. 12.4. The full analysis was performed by A. Bursche and published recently [6]. The experience on charmed meson reconstruction gained in this analysis is now applied in a measurement of the double-charm production cross section at a centre of mass energy of 2.76 TeV (master thesis E. Crivelli).

The study of proton-nucleus collisions is a crucial component of the physics program with nuclear beams performed at hadron colliders. Measurements in proton-nucleus collisions can serve as reference for nucleus-nucleus collisions and may be used as an input to nuclear parton distribution function (nPDF) fits. nPDFs are poorly constrained by experimental data, especially in the kinematic region accessible by LHCb. A measurement of the Z production cross section in proton-lead (with the proton beam pointing into the LHCb forward direction) and lead-proton (proton beam pointing backwards) data was performed by Ch. Elsasser. Unfortunately, the available statistics is very low with an integrated luminosity of 1.1 and 0.5 nb^{-1}, respectively. The analysis closely follows Ref. [2] but accounts for the different track multiplicities in proton-proton and proton-lead collisions. The background for both beam configurations is below 0.5%. The results are:

$$\sigma_{Z\to\mu^+\mu^-} = 13.5^{+5.4}_{-4.0}(stat.) \pm 1.2(syst.) \text{ nb, for } p\text{-Pb}$$
$$\sigma_{Z\to\mu^+\mu^-} = 10.7^{+8.4}_{-5.1}(stat.) \pm 1.0(syst.) \text{ nb, for Pb-}p$$

These cross-sections are limited to the fiducial region of 60 - 120 GeV for the di-muon mass, p_T of the muons larger than 20 GeV and pseudo-rapidity in the range range 2.0 - 4.5 and are in agreement with next-to-next-to leading order calculations. The present large uncertainties prevent any conclusion on the presence of nuclear effects but show the great potential of the study of electroweak boson production in proton-lead collisions at LHCb. The result has been submitted for publication [11].

Further ongoing studies in our group are:

- precise measurement of the differential $Z \to \mu^+\mu^-$ production cross section at 7 TeV (J. Anderson),
- low mass Drell-Yan production in the di-muon channel at 7 TeV (J. Anderson, N. Chiapolini, K. Müller) [12],
- a measurement of the low energy $Z \to \mu^+\mu^-$ production cross section at 2.76 TeV (A. Bursche),
- the determination of the di-boson ($Z + \gamma$) production cross section at 8 TeV (master thesis M. Küng),
- studies of W production in proton-lead data (bachelor thesis Ch. Marentini).

[1] R. Aaij *et al.* [LHCb Collab.], JHEP **1206** (2012) 058.
[2] LHCb Collab., LHCb-CONF-2013-005.
[3] R. Aaij *et al.* [LHCb Collab.], JHEP **1302** (2013) 106.
[4] R. Aaij *et al.* [LHCb Collab.], JHEP **1301** (2013) 111.
[5] R. Aaij *et al.* [LHCb Collab.], JHEP **1401** (2014) 033.
[6] R. Aaij *et al.* [LHCb Collab.], arXiv:1401.3245 [hep-ex].
[7] P. Nason, JHEP **0411** (2004) 040.
[8] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP **0605** (2006) 026.
[9] J. M. Campbell *et al.*, Phys. Rev. D **69** (2004) 074021.
[10] J. M. Campbell, arXiv:0808.3517 [hep-ph].
[11] arXiv:1406.2885 [hep-ph].
[12] LHCb Collab., LHCb-CONF-2012-013.

12.4 Summary and Outlook

The LHCb experiment has collected a large data set at different energies during the data taking period 2010-2013. The results obtained so far have allowed to take a leading role in the field of b and c-physics; to considerably reduce the parameter space for many models beyond the SM and to show world best and world first measurements of B-hadron branching ratios. The physics program of LHCb was significantly extended with measurements with electroweak bosons as well as diffractive physics.