9 High-precision CP-violation Physics at LHCb

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in collaboration with: The silicon tracking group of LHCb: University of Lausanne; Max Planck Institute, Heidelberg, Germany; University of Santiago de Compostela, Spain; and Ukrainian Academy of Sciences, Kiev, Ukraine.

The full LHCb collaboration consists of 54 institutes from Brazil, China, France, Germany, Ireland, Italy, The Netherlands, Poland, Romania, Russia, Spain, Switzerland, Ukraine, the United Kingdom, and the United States of America.

(LHCb)

9.1 The LHCb Experiment

LHCb (1) is a dedicated b-physics experiment at the Large Hadron Collider (LHC) at CERN. The LHC delivered its first high energy proton-proton collisions at 2.2 TeV centre-of-mass energy in autumn 2009 and has been operating at 7 TeV centre-of-mass energy since the end of March 2010. The LHCb experiment has been operated routinely from the first day of collisions and the recorded data are being used to complete the commissioning of the detectors, tune reconstruction algorithms and validate the expected performance. For example, $\mathrm{K_s}$, Λ and J/ψ invariant-mass signals have been reconstructed showing close-to-nominal masses and mass resolutions. A first B-decay candidate event was recorded in April 2010. The LHC is going to operate at 7 TeV centre-of-mass energy until the end of 2011. The instantaneous luminosity will gradually increase and an integrated luminosity of about 1 fb^{-1} should have been delivered to each of the experiments by the end of 2011. This data set should permit LHCb to confirm its physics potential and to improve on existing measurements in key physics channels. The LHC will then be shut down for about one year for further consolidation work, before increasing the centre-of-mass energy to the nominal 14 TeV.

The main goal of LHCb is to perform precision measurements of CP violating processes in the B meson systems and to search for rare B decays. Unique triggering and particle-identification capabilities will permit to measure CP asymmetries in many different decay modes and to perform consistency checks of the Standard Model. CP-violating asymmetries are generated by processes involving internal loops of virtual particles and are therefore sensitive to contributions from heavy new particles that are predicted in most extentions of the Standard Model. Similarly, the branching fractions of rare decays can be significantly enhanced by virtual contributions from new particles. The measurement of such processes provides a powerful tool to search for "new physics" beyond the Standard Model, complementary to direct searches at the high energy frontier that will be performed by other experiments at the LHC.

Fig. 9.1 shows a vertical cross section through the LHCb detector. LHCb is laid out as a single-arm forward spectrometer. One of the crucial tasks in LHCb is the efficient and precise reconstruction of the trajectories and momenta of the charged particles that are generated in the decays of the B mesons. The tracking system consists of a silicon-microstrip vertex detector (VELO) and four planar tracking stations: the TT (Tracker Turicensis) up-

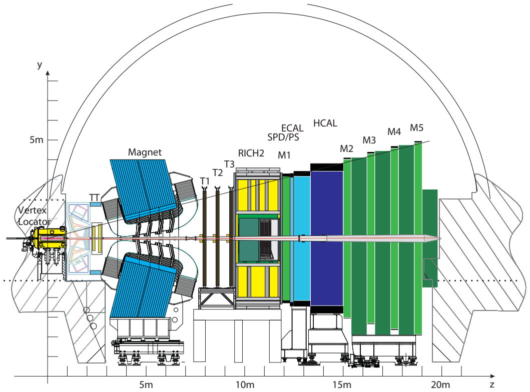

Figure 9.1:
Vertical cross section through the LHCb detector.

stream of the LHCb dipole magnet and T1-T3 downstream of the 4 Tm dipole magnet. The TT has an active area that is 160 cm wide and 130 cm high and is covered by four layers of silicon micro-strip detectors. In the much larger stations T1-T3, two detector technologies are employed: A 120 cm wide and 40 cm high region in the centre of these stations is covered with silicon micro-strip detectors (Inner Tracker, IT), the outer part of these stations is covered by straw drift-tube detectors. Other components of the LHCb detector are two ring-imaging Cherenkov detectors (RICH1 and RICH2), calorimeters (SPD,PS,ECAL,HCAL) and muon chambers (M1-M5).

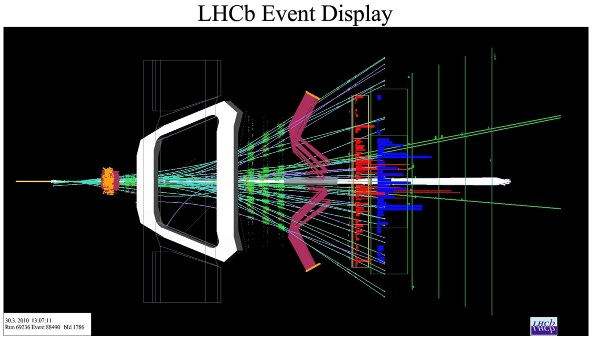

Figure 9.2:
Event display of an event registered during the first LHC proton-proton collisions at 7 TeV centre-of-mass energy.

9.2 The Zürich Group in LHCb

Our group has played a leading rôle in the development and construction of the LHCb Silicon Tracker (ST), which comprises the TT and the IT. The TT was conceived, designed and made in Zürich, and the optical digital readout links for both the TT and the IT were developed and assembled at our institute. We are now responsible for the commissioning, operation and maintenance of the TT and its readout in LHCb. We are also responsible for the software alignment of the TT and contribute to the track reconstruction software.

The preparation of physics analyses takes up an increasing fraction of our effort. This comprises the use of simulated data sets to develop reconstruction strategies and establish the physics reach of the experiment, as well as the analysis of the first data from LHC collisions to test reconstruction algorithms and validate the expected performance of the detector.

9.3 Tracker Turicensis

The installation of the TT in LHCb was completed in 2008 and the detector has been operated routinely since then. In 2009, a large fraction of our efforts went into getting the detector and its readout into the best possible shape for the first LHC collisions. By the time the LHC turned on in October 2009, more than 99% of the 144′000 detector channels were fully operational. Algorithms for automatic monitoring and archiving of operation parameters were developed and deployed. The automatic configuration of operation parameters for different operating conditions, using finite-state-machines, has been implemented and commissioned.

The first LHC collision data have then been used to tune operation parameters such as bias voltage and signal readout timing. Tools and histograms that allow an efficient online

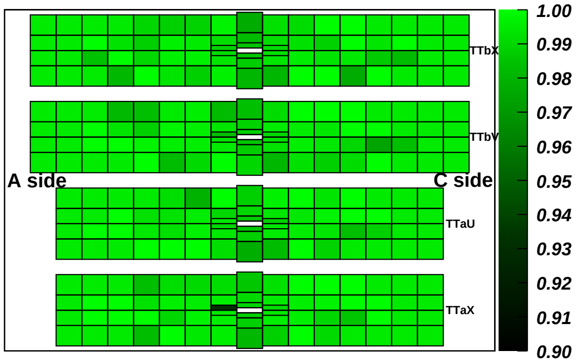

Figure 9.3:
Efficiency map of the TT detector. Each rectangle represents one readout sector and the colour encodes the measured hit efficiency in this sector.

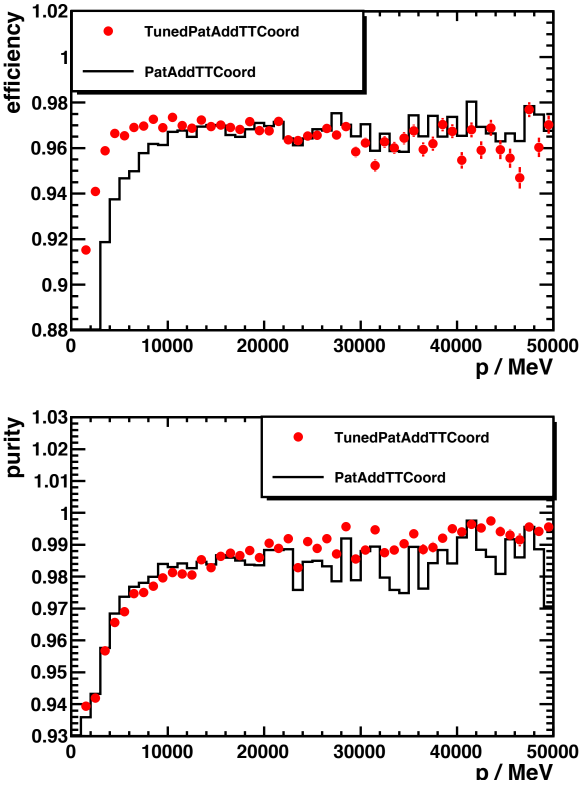

Figure 9.4:
TT hit assignment efficiency (top) and purity (bottom) as a function of the reconstructed particle momentum. The black line shows the performance for the existing algorithm, the red dots show the performance after improvements.

monitoring of the detector performance have been developed and implemented. An example of a monitoring plot showing the hit efficiency for each readout sector of the TT is shown in Fig. 9.3. The average hit-detection efficiency of the detector exceeds 99%.

In charge of these efforts and responsible for the operation of the TT is J. van Tilburg, who is permanently stationed at CERN. He receives major support from J. Anderson and M. Tobin, who are based in Zürich but spend significant fractions of their time at CERN taking shifts as detector operators. In addition, J. Anderson looks into the offline study of the TT performance and its impact on track reconstruction, and M. Tobin is responsible for the online monitoring of the detector performance.

These efforts will continue to require a significant amount of manpower for the coming year. In addition to the continual effort required to maintain smooth operation and high efficiency, the detector performance will have to be monitored carefully as the LHC luminosity increases and operation parameters might have to be re-adjusted.

9.4 Track reconstruction and alignment

The reconstruction of the trajectories and momenta of charged particles in LHCb relies on the Vertex Locator, the tracking stations T1-T3 downstream of the magnet and the TT just in front of the magnet. Simulation studies have demonstrated that adding TT measurements to a track significantly improves the momentum resolution. Using existing pattern recognition algorithms, the efficiency for adding TT measurements to a track is of the order of 97% for particle momenta above 10 GeV but decreases sharply for momenta below 10 GeV. M. De Cian has developed improvements to the pattern recognition algorithm that improve its efficiency for particles with low momenta while keeping the purity constant (see Fig. 9.4).

The TT is assembled from 896 individual silicon micro-strip sensors. In order to fully exploit the detector information and to avoid biases in the momentum reconstruction, the position of each of these detector elements should be known to significantly better than the intrinsic hit resolution of 50 μm. For a detector of the size of the TT, such a positioning precision is impossible to achieve in hardware. The position of each detector element must therefore be reconstructed from the data. C. Salzmann is working on this as part of his PhD thesis. He will be joined by N. Chiapolini and A. Bursche, who have recently started their PhD theses in our group. The TT is a single tracking station with only four detection layers and its alignment relies on tracks reconstructed in the other parts of the tracking system. The alignment of the TT is therefore sensitive to residual misalignments of these other detectors, making it an excellent tool for monitoring problems in the overall detector alignment. An example of this is shown in Figs. 9.5 and 9.6. Figure 9.5 shows a distribution of the residual misalignments of the detector elements with respect to external tracks. The width of this distribution shows that the TT elements are aligned to a precision of about 20 μm with respect to the remainder of the tracking system. Figure 9.6 shows by how much each of the detector elements has to be shifted from its nominal position in order to achieve this agreement in the alignment procedure. A clear "scaling" is observed in two of the detection layers: The shift increases linearly with the position of the detector element. This correlation points to a remaining problem with the LHCb alignment procedure and is currently under investigation.

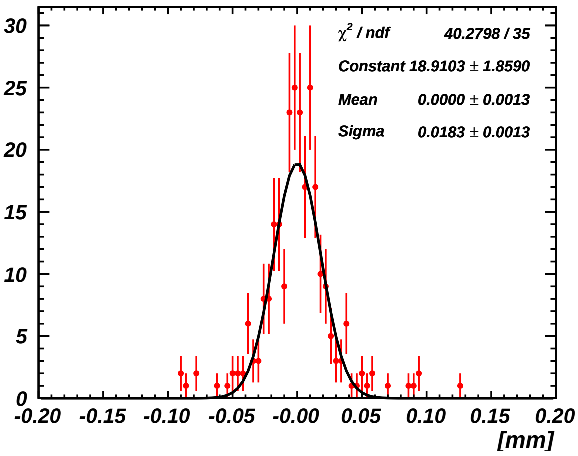

Figure 9.5:
Distribution of residual misalignments of detector elements in the TT, after software alignment.

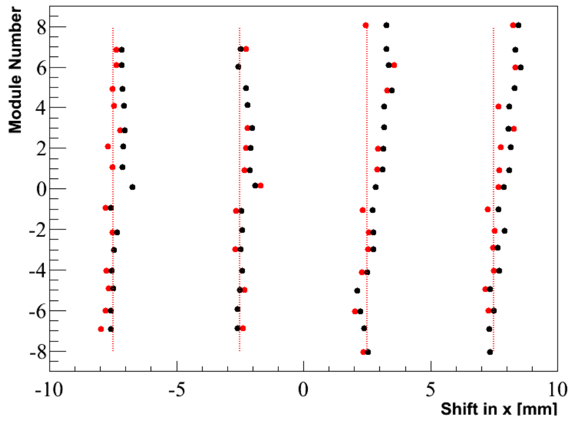

Figure 9.6:
Horizontal shift of each detector element with respect to its nominal position. The dotted vertical lines indicate the nominal positions for each of the four detection layers of the TT, the red and black points show the positions of individual detector elements after the software alignment.

9.5 Physics studies

We have chosen four physics topics that we will pursue in our group: the measurement of the branching ratio of the rare decay $B_s^0 \to \mu^+\mu^-$; the measurement of the CP-violating phase β_s of $B_s^0\overline{B}_s^0$ mixing; the measurement of the forward-backward asymmetry and other observables in $b \to s\ell^+\ell^-$ decays; and the measurement of parton distribution functions in decays $\gamma^\star/Z \to \mu^+\mu^-$. Each of these topics builds upon previous experience of members of our group, from earlier simulation studies in LHCb or from analyses performed in other experiments (e.g. search for $B_s^0 \to \mu^+\mu^-$ at D0 (2), search for $B \to K^\star\mu^+\mu^-$ at D0 (3), measurement of proton parton distribution functions at H1 (4)).

The measurement of the branching fraction of the decay $B_s^0 \to \mu^+\mu^-$ is one of the early key measurements for LHCb. The branching fraction for this decay is predicted to be of the order of 3×10^{-9} in the Standard Model but can be significantly enhanced within extensions of the Standard Model. Currently, the best measured upper limit has been reported by the CDF experiment at the Tevatron. Using 3.7 fb^{-1} of data, they set an upper limit of 3.6×10^{-8} at 90% confidence level (5). Simulation studies show that LHCb should be able to reach this limit with only 50 pb^{-1} of proton-proton collisions at 7 TeV centre-of-mass energy. The analysis strategy is described in detail in the recently published LHCb road map document (6). One of the crucial steps for the extraction of a possible signal will be a precise modeling of the B_s^0 mass resolution from data, using control channels such as $B_s^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$. A. Büchler is working on this aspect of the analysis as part of her PhD thesis, supervised by J. van Tilburg and O. Steinkamp. Using the first collision data, she is currently looking at $K_s \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ and other decays to develop appropriate tools and study possible biases from particle identification cuts. An example of a K_s signal is shown in Fig. 9.7. C. Elsasser is about to join this effort for his Master thesis.

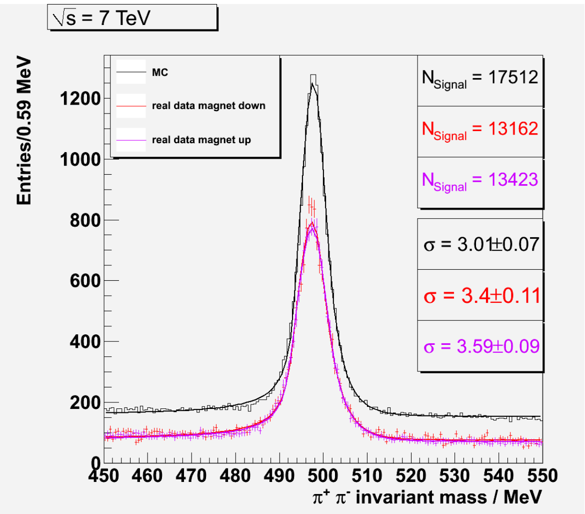

Figure 9.7: $\pi^+\pi^-$ **invariant-mass distributions showing a** K_s^0 **peak. Here, the mass resolution in collision data is slightly worse than in simulated data and the event yield is significantly lower. This is attributed to a not yet perfect alignment of the tracking detectors.**

The CP-violating phase β_s is very small in the Standard Model (7) but can be significantly enhanced in new-physics models. The most promising approach to measuring this phase in LHCb is via the time-dependent CP asymmetry in the decay $B_s^0 \to J/\psi\phi$. A simulation study of an alternative approach, using the decay $B_s^0 \to J/\psi\eta'$, was performed in our group earlier (8). As a first step towards an analysis using LHC collision data, C. Salzmann is looking into the calibration channel $B_d^0 \to J/\psi K^\star$ which has a similar topology as $B_s^0 \to J/\psi\phi$ but a much higher branching fraction. In particular, he is studying the effect of residual detector misalignments on the invariant-mass resolution of the J/ψ and B_s^0 signals. He is supervised in this work by J. van Tilburg.

Decays $b \to s\ell^+\ell^-$ proceed through suppressed loops in the Standard Model and are therefore sensitive to possible contributions from new physics. One of the interesting observables is the forward-backward asymmetry, A_{FB}, which is defined through the angle between the ℓ^+ and the direction of flight of the B meson in the di-lepton rest frame. This asymmetry as a function of the di-lepton invariant mass can be predicted with small theoretical uncertainties. An LHCb simulation study of the decay channel $B_d^0 \to K^\star\ell^+\ell^-$ has shown that the zero-crossing of the asymmetry can be measured with a precision of 0.46 GeV^2 using 2 fb^{-1} of data at 14 TeV centre-of-mass energy. Again, $B_d^0 \to J/\psi K^\star$ serves as a calibration channel and $J/\psi \to \mu^+\mu^-$ decays are used to determine muon identification efficiencies from collision data. M. De Cian works on this analysis as part of his PhD thesis work under the supervision of J. Anderson. A $J/\psi \rightarrow \mu^+\mu^-$ invariant-mass signal is shown in Fig. 9.8.

Previous measurements of the proton's parton distribution functions (PDFs) have been performed at fixed target experiments, at HERA and at the Tevatron. At LHCb, the proton's PDF can be probed through a measurement of the differential cross-section for di-muon production via the Drell-Yan process. The cross-section for this process at LHC energies has been calculated at NNLO (9). The dominant theoretical uncertainties, due to the knowledge of the PDFs, are largest at higher production rapidities and lower di-muon invariant masses. LHCb will be able to explore these regions due to its high rapidity coverage and low momentum trigger thresholds. By measuring the differential Drell-Yan cross-section as a function of di-muon mass and rapidity, LHCb will therefore probe a large, partially unknown kinematic domain, providing constraints on the PDFs down to Bjorken-x values of 10^{-6}. Preparations for a measurement of the Drell-Yan cross-section at LHCb are well advanced. As part of his PhD thesis work at UC Dublin before joining our group, J. Anderson investigated a cross-section measurement at the Z mass. He showed that systematic uncertainties are expected to be 1% and that with an integrated luminosity of 50 pb^{-1} a total cross-section measurement will already be systematics limited (10). Since joining our group he has extended this analysis to the low-mass region (11). Again it is expected that cross-section measurements in this region will rapidly become systematics limited. A. Bursche and N. Chiapolini have recently started their PhD theses on this topic. Under the supervision of J. Anderson and K. Müller they commenced investigations of the systematic uncertainties associated with the trigger, tracking and muon identification efficiencies for these events using the first collision data collected by LHCb.

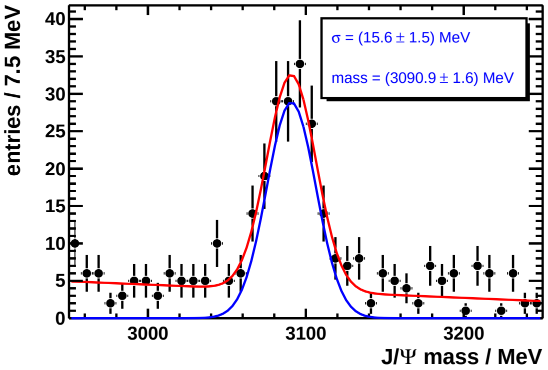

Figure 9.8: $\mu^+\mu^-$ invariant-mass distribution from collision data, showing a clear J/ψ signal.


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Universität Zürich

Campus Info

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Weltrekord am LHC

30. März, 13.06 Uhr: Erste Proton- Proton Kollisionen am LHC mit einer Energie von 7 Tera Elektronenvolt. Ein grosser Erfolg auch für die LHCb Gruppe von Ueli Straumann: Die 'Zürcher Spurkammer' hilft mit, die Grundbausteine der Materie mit unerreichter Präzision zu erforschen.

Figure 9.9: Celebrating the first 7 TeV collisions in LHCb. This page was shown on information screens throughout Universität Zürich.

9.6 Outreach activities

The successful startup of the LHC has spawned great interest in the public and in public media. We have engaged in a number of outreach activities trying to meet this interest. We have prepared a German-language brochure explaining the LHCb experiment and its goals in laymen's terms (12), we participated with a stall at the "Nacht der Forschung" that took place in downtown Zürich in September 2009. A. Büchler participated as a guide for journalists on the media day organized by CERN on the occasion of the first collisions at 7 TeV centre-of-mass energy. A page celebrating the first collisions in LHCb was shown on information screens throughout Universität Zürich (see Fig. 9.9).

9.7 Summary and Outlook

The LHCb experiment was ready and in good shape to collect the first high-energy proton-proton collisions from the LHC and has been collecting data routinely from the first day of LHC operation. Invariant-mass signals of K_s, Λ and J/ψ have been reconstructed and permit detailed studies of the detector performance. A first B-decay candidate has been recorded. Our group will continue to play an important rôle in the operation of the detector. More work is needed to study the detector performance in detail and to fine-tune operation parameters as the instantaneous luminosity of the LHC increases. Reconstruction algorithms that have been developed on simulated datasets can now be exercised on the first collision data. The LHC is foreseen to run continuously until the end of 2011, delivering an integrated luminosity of about 1 fb^{-1} at a centre-of-mass energy of 7 TeV. The data collected during this time will permit LHCb to verify its physics potential and to improve on existing measurements in key analyses. We are engaged in a number of physics analyses, to which we expect to make significant contributions, building on existing expertise in the group. We are looking forward to exciting results for the coming years.

[1] The LHCb detector at the LHC, 2008 JINST 3 S08005.

[2] R. P. Bernhard, *Search for rare decays of the* B_s^0 *meson with the D0 experiment*, PhD thesis, Universität Zürich (2006).

[3] A. Wenger, *Search for the Rare Decays* $B^\pm \to K^\pm\mu^+\mu^-$ *and* $B^0 \to K^\star\mu^+\mu^-$ *with the D0 experiment*, PhD thesis, Universität Zürich (2008).

[4] for example: F. D. Aaron et al. [H1 Collaboration and ZEUS Collaboration], *Combined Measurement and QCD Analysis of the Inclusive ep Scattering Cross Sections at HERA*, JHEP 1001 (2010) 109 [arXiv:0911.0884 [hep-ex]].

[5] CDF collaboration, *Search for* $B_s \to \mu^+\mu^-$ *and* $B_d \to \mu^+\mu^-$ *decays in 3.7* fb^{-1} *of* $\overline{p}p$ *collisions with CDF-II*, CDF public note 9892.

[6] The LHCb Collaboration, *Roadmap for selected key measurements of LHCb*, LHCb-PUB-2009-029, arxiv/0912.4179 (2010).

[7] CKMfitter 2008, see webpage.

[8] D. Volyanskyy, *The Trigger Tracker and a Monte Carlo Study of the* $B_s \to J/\psi\eta'$ *Decay in the LHCb Experiment*, PhD thesis, Universität Zürich (2007).

[9] C. Anastasiou, L.J. Dixon, K. Melnikov and F. Petriello, Phys. Rev. Lett. 91 (2003).

[10] J. Anderson, *Testing the electroweak sector and determining the absolute luminosity at LHCb using dimuon final states*, PhD thesis, University College Dublin (2007); J. Anderson and R. McNulty, *Measuring* $\sigma_Z \cdot Br(Z \to \mu^+\mu^-)$ *at LHCb*, LHCb note 2007-114 (2007).

[11] J. Anderson, *Probing low-x with Drell-Yan events at LHCb*, Proc. XVII International Workshop On Deep-inelastic Scattering And Related Subjects, Prog. High Energy Phys. 3 (2009).

[12] available for download at http://lhcb-public.web.cern.ch/lhcb-public/en/LHCb-outreach/documentation/LHCb_German_mod_zh2.pdf