8 High-precision CP-violation Physics at LHCb

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The full LHCb collaboration consists of 52 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)

LHCb (1) is a dedicated B-physics experiment at the new 14 TeV proton-proton collider LHC at CERN. 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 enable LHCb to measure CP asymmetries in many different decay modes and to perform consistency tests of the Standard Model explanation of CP violation. Since CP violating asymmetries are generated by processes that involve internal loops of virtual particles, they are sensitive to contributions from new particles that are predicted in most extentions of the Standard Model. Measurements of these asymmetries therefore provide a powerful tool for searches of "new physics" beyond the Standard Model. They are complementary to the direct searches at the high energy frontier that will also be performed at the LHC.

Figure 8.1 shows a vertical cross section through the LHCb detector, which is layed 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: TT (Tracker Turicensis) upstream of the LHCb dipole magnet and T1-T3 downstream of the 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 the stations is covered with silicon micro-strip detectors (Inner Tracker, IT), whereas 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).

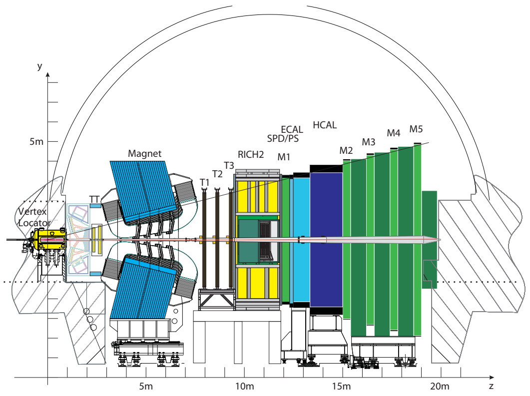

Figure 8.1: Vertical cross section through the LHCb detector.

The installation of the detector was essentially completed in 2008. By autumn 2008, the experiment was ready to record the first proton-proton collisions expected from the LHC. First beam-related events were indeed collected beginning of September during proton injection tests into the LHC ("TED runs"). A few days later, the commissioning of the accelerator was unfortunately interrupted by an incident involving the release of several tons of liquid Helium into the LHC tunnel. This incident resulted in a one-year delay in the startup of the LHC and first beams are now expected for autumn 2009. LHCb is using the additional time to fix minor problems, improve detector monitoring and operating procedures, and perform stress tests of the data acquisition system. Data collected during the TED runs has been used to test algorithms for the alignment of detector elements.

8.1 The Zürich Group in LHCb

Our group has played a leading rôle in the design, construction and operation of the LHCb Silicon Tracker (ST), which comprises TT (1; 2) and IT (3). The TT was entirely developed and constructed in Zürich. In addition, we have been responsible for the silicon sensors and for the optical readout link for both TT and IT.

The installation of the TT and the readout electronics was completed in spring 2008. Since then, a large fraction of our efforts has gone into the integration of the TT into the LHCb data acquisition and detector control systems, and the commissioning of the detector and its readout.

In addition to our contributions to the detector, we have started to participate in a number of simulation studies in preparation for physics analyses. We have continued our participation in the production of large samples of simulated data necessary for such studies, and we have worked on alignment algorithms for the TT.

8.2 Tracker Turicensis

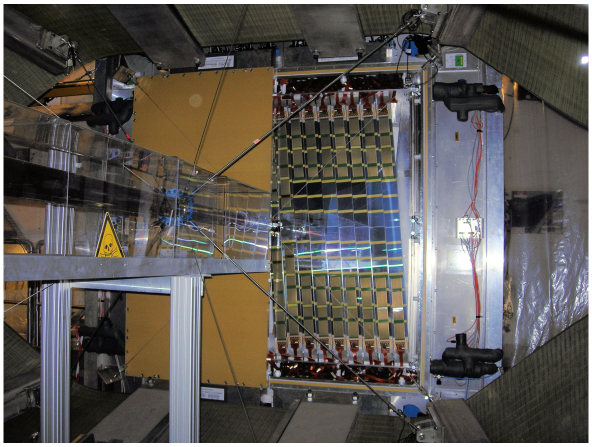

Figure 8.2: The TT viewed through the LHCb dipole magnet. One half of the detector box is open and the modules can be seen.

A photograph of the TT during its installation in LHCb is shown in Fig. 8.2. By the time of the expected startup of the LHC in September 2008, the detector was fully installed and more than 97% of the 143′000 detector channels were fully working.

The first beam-related signals in the TT were recorded during the TED runs early September 2008. J. van Tilburg, J. Anderson and A. Büchler led this effort, supported by other members of our group. The full detector was powered at nominal bias voltage and signal amplitudes were measured with varying time delays with respect to the beam trigger. The observed distributions (see Fig. 8.3) reflect the signal shape at the output of the pre-amplifier and are compatible with expectations from prototype beam tests.

These data were used to reconstruct particle trajectories through both VELO and TT. A clear signal was observed (see Fig. 8.4) which was used to train the alignment algorithms for the TT. C. Salzmann is working on this analysis under the supervision of J. van Tilburg.

Since September, the TT has been regularly operated and read out, both in stand-alone

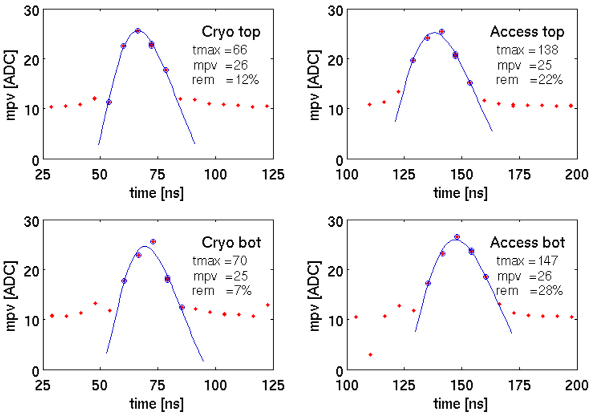

Figure 8.3: Results from the TED run. Shown are delay curves of the mean amplitude of the TT signals with respect to the beam time. The four panels correspond to different regions of the detector.

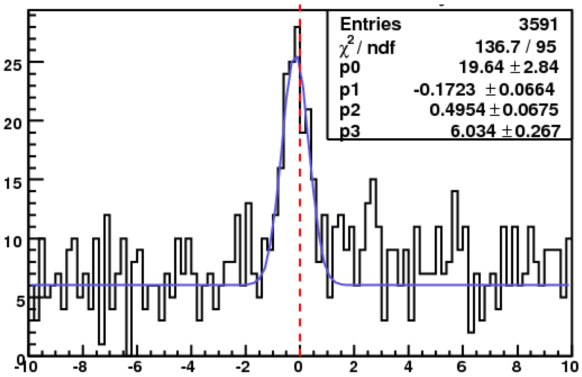

Figure 8.4: Residuals distribution (in mm) of hit positions measured in TT with respect to trajectories reconstructed with VELO. The observed position resolution is dominated by the uncertainties in the trajectory.

mode and in conjunction with other LHCb sub-detectors. These "dry runs" without beam absorb a significant amount of manpower but are vital for getting the detector into the best possible shape for the start-up of the LHC. Goals of this exercise are to gain experience in the operation of the detector, to improve user interfaces and to develop and test automated operation and monitoring procedures. This effort is organized by J. van Tilburg. J. Anderson, M. Tobin (who joined our group in February 2009), A. Büchler and C. Salzmann spend large fractions of their time at CERN to participate in these tests. N. Chiapolini contributes significantly to the development of online monitoring tools which were also adopted for other sub-detectors in LHCb. V. Hangartner is investigating the data to improve the understanding of the noise behaviour of the detector.

Another important goal of the commissioning effort is to "burn-in" the various components of the detector and to identify and replace weak components. Potentially the most serious problem we have encountered concerns a small number of detector modules on which a fraction of wire bonds has broken during operation in LHCb. The cause of this problem is under careful investigation to ensure it is not due to a principle design mistake which might cause it to appear on a larger number of modules later on. J. van Tilburg, S. Steiner and O. Steinkamp are involved in these investigations.

An easily fixed problem concerned the optical readout links for TT and IT. It had already been found during quality assurance tests in Zürich that a significant fraction of the VCSEL diodes used for the optical transmission had been damaged during the assembly of the electronics boards. These VCSELs showed a too low output and had to be replaced. During the readout tests in LHCb we found, however, that a number of faulty VCSELs had escaped detection during the acceptance tests. These VCSELs have meanwhile been replaced. At the same time some other minor modifications were implemented to further improve the operation stability of detector and readout. A. Vollhardt was in charge of these repairs, with help from S. Steiner.

8.3 Physics studies

We will focus on topics known from previous work that members of our group have done either in LHCb or elsewhere. Data from the TT will play an important rôle in all these analyses as position measurements in the TT significantly improve the momentum resolution for charged particles. This is crucial for the suppression of backgrounds, especially in measurements of rare decays, and for obtaining the excellent decay-time resolution required in time-dependent measurements of CP asymmetries in the B_s system.

We have chosen the following four physics topics:

- **The CP-violating phase β_s in $B_s\overline{B}_s$ mixing**
  This phase is very small in the SM (4) but could be enhanced in new-physics models due to virtual contributions of new particles. The most promising channel for measuring this phase is $B_s^0 \to J/\psi\phi$ since it is theoretically clean, has a relatively high branching fraction of $\approx 3 \times 10^{-5}$ and a clean experimental signature. However, the final state is not a CP eigenstate and a time-dependent angular analysis is required to statistically separate the CP-even and CP-odd contributions. A simulation study for this decay has been performed for LHCb showing that a measurement of $2\beta_s$ with a sensitivity of 0.030 using 2 fb^{-1} of data should be possible (5). The decay $B_s^0 \to J/\psi\eta'$ has a lower event yield than the mode $B_s \to J/\psi\phi$ but is a decay to a pure CP eigenstate so that no angular analysis is needed to disentangle the two CP contributions. A simulation study of this decay has been performed by D. Volyanskyy as part of his PhD thesis in our group. He found that a measurement of $2\beta_s$ with a sensitivity of 0.08 can be expected using 2 fb^{-1} of data (6). C. Salzmann will study these channels as part of his PhD thesis, supervised by J. van Tilburg.

- **Branching ratio of the rare decay $B_s \to \mu^+\mu^-$**
  This branching ratio is of order 10^{-9} in the Standard Model but can be significantly enhanced within specific extensions of the Standard Model. An LHCb simulation study has shown that assuming the Standard Model cross-section a 3σ observation should be possible using 2 fb^{-2} of data (7). A. Büchler has started to work on this analysis as part of her PhD thesis, supervised by J. van Tilburg. This study is a natural continuation of the work of R. P. Bernhard, who did an analysis of this channel at the D0 experiment as part of his PhD thesis (8) in our group.

- **$b \to s\ell^+\ell^-$ decays**
  These decays proceed through suppressed loops in the Standard Model and are therefore sensitive to 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. It can be measured in the exclusive decay channel $B_d \to K^\star\mu^+\mu^-$ and a study for LHCb has shown that a measurements of its zero-crossing with a sensitivity of 0.46 GeV^2 can be achieved using 2 fb^{-1} of data (9). Another interesting observable is the cross-section ratio of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$ decays. In the Standard Model, this ratio is predicted to be close to unity, with theoretical uncertainties $<$ 1% (10). A measurement of this ratio will test the Standard Model as well as a variety of Minimum Flavour Violating extentions of the Standard Model, which predict a deviation of this ratio from unity that is closely related to the branching ratio of the rare decay $B_s \to \mu^+\mu^-$ (10). The measurement can be performed in the exclusive modes $B_u \to K\ell^+\ell^-$ and $B_d \to K^\star\ell^+\ell^-$. An LHCb study has shown that a measurement with

an uncertainty of $\approx 10\%$ can be expected using a dataset of 2 fb^{-1} (11). M. De Cian is investigating these channels as part of his PhD thesis work under the supervision of J. Anderson. These studies are a logical continuation of the work of A. Wenger, who studied the channel $B \to K^\star \mu^+\mu^-$ at the D0 experiment as part of his PhD thesis, which he completed in our group end of 2008 (12).

- **Parton distributions in $\gamma^\star/Z \to \mu^+\mu^-$**
  Previous measurements of Parton distribution functions (PDFs) have been performed in fixed target experiments, at HERA, and at the Tevatron. For Z production at LHCb, the momentum fractions x carried by the two interacting partons are very asymmetric. A measurement of the Z cross-section will allow to improve the PDFs down to $x = 4.8 \times 10^{-5}$ and up to $x = 0.87$. By measuring di-muon production through Drell-Yan process at low invariant masses, LHCb will have the unique ability to measure PDFs down to $x \approx 10^{-6}$, exploring a totally unknown kinematic domain. Preparations for a measurement of the $Z \to \mu^+\mu^-$ cross-section are well advanced. J. Anderson worked on this channel as part of his PhD thesis work at UC Dublin before joining our group. He showed that systematic uncertainties are expected to be $\approx 1\%$ and that with an integrated luminosity of only 50 pb^{-1} a total cross-section measurement will already be systematics limited (see (13)). This is therefore a measurement for the early days of LHCb. Work on extending the analysis to the low mass region is still at an early stage. J. Anderson is interested in continuing these analyses together with a new PhD student. The measurement of PDFs is a logical continuation of the involvement of our group in similar measurements at H1 at HERA.

8.4 Outreach activities

In response to the growing public interest in the LHC, we have engaged in various outreach activities. A. Büchler participated in the "LHC first beam" event in September 2008, guiding journalists through the LHCb exhibition and control room. Also in September 2008, we had a joint exhibition stand with particle physicists from ETH at the "Nacht der Forschung" in Zürich. A. Büchler also appeared in the popular science programme "Einstein" on the Swiss public television channel SF1 (see Fig. 8.5).

Figure 8.5: Angela Büchler explaining the TT detector to journalist Monika Schärer, in the television programme "Einstein im CERN" [14].

8.5 Summary and Outlook

The installation of the LHCb experiment in general, and of the Tracker Turicensis in particular, is completed and the commissioning of the detector is well advanced. We are looking forward to the first beams from the LHC, which are now expected for autumn 2009. The commissioning of the detector with beams will still take up a significant fraction of our resources for the coming year, but event reconstruction and physics analyses are playing a more and more important rôle.

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