9 High-precision CP-violation Physics at LHCb

R. Bernet, P. Sievers, O. Steinkamp, U. Straumann, D. Wyler, M. Ziegler

in collaboration with the inner tracking group of LHCb*:*
University of Lausanne; Max Planck Institute, Heidelberg, Germany; University of Santiago de Compostela, Spain; Budker Institute for Nuclear Physics (INP), Novosibirsk, Russia and Ukrainian Academy of Sciences, Kiev, Ukraine.

The full LHCb collaboration consists of 50 institutes from the countries Brazil, China, Finland, France, Germany, Italy, Netherlands, Poland, Romania, Russia, Spain, Switzerland, Ukraine, United Kingdom.

(LHCb)

9.1 Introduction

LHCb is a second generation experiment on b quark physics which will run from the beginning of the LHC (Large Hadron Collider) operation at CERN (around the year 2006). The production rate of B-mesons will be about three orders of magnitude larger than in all preceding B - physics experiments.

The goal of the experiment is to make systematic measurements of CP violation and rare decays in the B-meson system with unprecedented precision. By measuring CP violation in many different decay modes of B_d, B_s and B_c mesons and comparing the results with the predictions from the Standard Model, the experiment will open a new and very sensitive window for searching for new physics.

The Zurich group concentrates on development, construction, operation and data analysis of the inner tracking part of this experiment. The present research and development phase is done in close collaboration with the particle physics group of the university of Lausanne and should result in a technical design report by the end of 2001.

U. Straumann is project leader for the inner tracking system within the LHCb collaboration and is thus a member of the technical board of LHCb. Olaf Steinkamp leads the silicon task force for developing the silicon microstrip option for the inner tracking system. Furthermore he is a member of the LHCb editorial board, which has to ensure that coherent and correct publications are produced by the LHCb collaboration.

9.2 CP – Violation in the B Meson system: recent developments

The interest in the study of CP – violation in the B System, and its relevance for understanding fundamental interactions, in particular its role in the evolution of the early universe (Baryogenesis) have been elucidated in detail in the previous anual report.

The CP violation effects, expected in the standard model of particle physics, are usually discussed in terms of so-called unitarity triangles, graphical representations of the 6 equations describing the unitarity of the quark mixing matrix V_{ij} (CKM matrix), resulting from the weak interactions of the quarks. For a review of the present knowledge of these triangles see [3].

Recently two experiments on the observation of CP violation in the B system have published results on $\sin 2\beta$, where $\beta \equiv \arg[-(V_{cb}^* V_{cd})/(V_{tb}^* V_{td})]$ is an inner angle of one of these unitarity triangles. The values obtained, by measuring the time dependent asymmetry in the decays of B_d^0 and $\bar{B}_d^0$ into $J/\psi K_S$ are:

$$\sin 2\beta = \begin{cases} 0.34 \pm 0.20(\text{stat}) \pm 0.05(\text{syst}) & \text{BaBar [1]} \\ 0.58 \ {}^{+0.32}_{-0.34} \ (\text{stat}) \ {}^{+0.09}_{-0.10} \ (\text{syst}) & \text{Belle [2]} \end{cases}$$

These results can be compared with a recent analysis in the standard model, assuming the unitarity of the CKM quark mixing matrix and making use of the following experimentally accessible quantities: the CP violation parameter of the Kaon system $|\epsilon_K|$, the ratio of the two CKM elements responsible for b quark decay rates $|\frac{V_{ub}}{V_{cb}}|$, and the oscillation frequencies of the neutral B_d and B_s - Mesons Δm_d and Δm_s. (The status of the mixing and oscillation measurements are summarized in a recent review [4]). The resulting standard model prediction is [3]

$$\sin 2\beta_{\text{SM}} = 0.67 \pm 0.17. \tag{9.1}$$

Whereas the more accurate result of BaBar is lower by 1.2 σ (adding all errors quadratically) the Belle result with its larger errors is in perfect agreement with the standard model.

To use the B system as a probe for new physics requires much higher accuracy. Supersymmetry, for instance, will mainly affect rare processes which in the standard model involve quark loop diagrams in lowest order already. New Physics may lead to inconsistencies between channels that are redundant in the standard model so all relevant CKM phases should be measured directly, with the highest precision possible.

In spring 2000 the results of a one year workshop on physics at LHC were published. The study group for B Decays at LHC [5] was able to show, that specially from channels which allow direct measurement of the angle $\gamma = \arg V_{\text{ub}}$, LHCb will provide a unique facility to explore the various CP violating modes. Examples are $B_s \to J/\psi K_s$ and $B_s \to D_s K$, which need a very good eigentime resolution of the decaying B_s, or $B \to \pi K$ and $B_{d(s)} \to D^+_{d(s)} D^-_{d(s)}$, which can only be isolated with reliable particle identification, as provided by the RICH system of LHCb.

9.3 Development of an inner tracking detector for LHCb

The inner tracking setup, which is presently being discussed, deviates considerably from the one described in the technical proposal [11]. On the basis of results from extensive R&D on various different micro-pattern gas detectors as well as background simulation studies with realistic beam pipe assumptions the inner tracking group decided in February 2000 to concentrate on triple GEM gas and silicon microstrip detectors and drop all other gas micro-pattern technologies which proved unstable in high density hadronic beams. Detailed design studies for an implementation of the remaining two technologies and prototype construction are presently going on.

9.3.1 Triple GEM option

Our group in Zurich has built a full-size prototype of a triple GEM detector and has measured all its relevant properties. We have shown, that the triple GEM is a stable and robust detector with spark probabilities much below 10^{-10}, which provides enough safety margins in the operating parameters to be used as an inner tracking technology of LHCb. First results had been mentioned already in the last years annual report. The final analysis of the measurements on the pulse height distributions, detection efficiencies, geometrical cluster size, position resolution, detector homogeneity w.r.t. to signal size and performance as a function of incident angle have been published in [6] and [7].

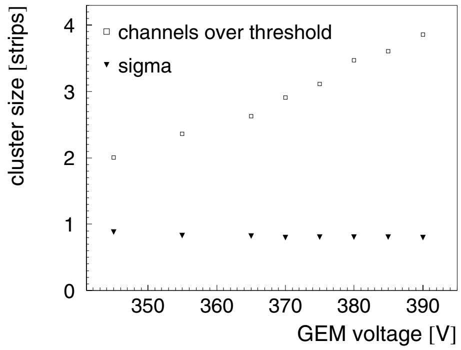

Figure 9.3: *Cluster width for perpendicular tracks as a function of detector gain. Shown are the mean number of channels above a threshold of 3.5 times the noise (sigma) and the width of a Gaussian fit to the pulse shape. The pitch of the readout strips is 300 μm.*

As an example, the analysis of the cluster-size is worth mentioning in this report. Two different methods were used, a simple counting of number of adjacent channels above a fixed signal to noise ratio and a Gaussian fit to the signal amplitude versus channel position. Figure 9.3 shows the resulting values as a function of the GEM voltage, which determines the total gas amplification. A typical operating point is $V_{\mathrm{GEM}} = 370$ V. The Gaussian width of the clusters does in fact not depend on the detector gain. The value of $\sigma = 0.8$ strip pitches (240 μm) is consistent with an estimate [8], based only on the transverse diffusion ($D_t \approx 300\ \mu\mathrm{m}/\sqrt{\mathrm{cm}}$ for a gas mixture of Ar:CO_2 = 70:30) of the charged cloud along an average drift path of 4.5 mm. The GEM foils thus do not influence the cluster size.

Large cluster sizes increase the channel occupancy of the detector, which is a major limitation of such a device in the LHCb environment. Electrons and positrons generated in the beam pipe may pass the inner tracker with large incident angles corresponding to even larger clusters, increasing the occupancy further.

Because of these rate effects it seems unlikely, that the inner tracking of LHCb will be a pure triple GEM solution. Since triple GEM detectors have the advantage over silicon microstrip devices, that larger sensor planes can be built with smaller number of readout channels a mixed solution may turn out optimal. We also expect shifts in the boundaries between inner and outer tracking, to be determined in on-going simulation studies.

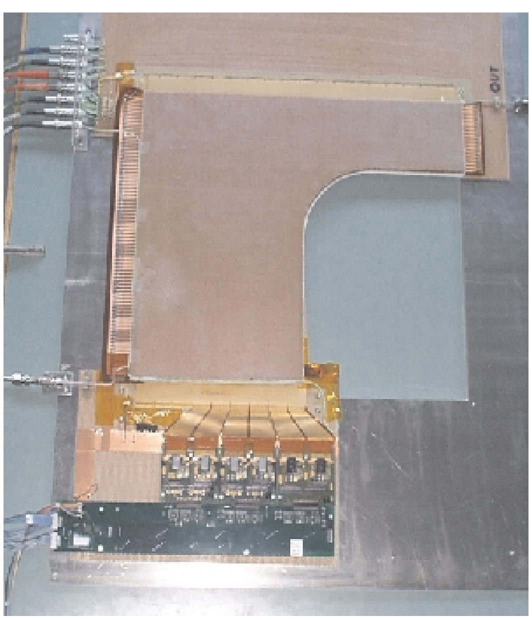

Figure 9.4: *A full size triple GEM prototype suitable for tracking station 7 to 10. It measures 415 mm in height and 430 mm in width (active detector area). Two such "L" shape detectors would be mounted around the beam pipe, allowing to measure two coordinates (x,u). On the bottom electronics readout boards bonded to the detector can be seen. These consist of HELIX chips, which have a similar front-end behaviour as the foreseen Beetle chips.*

A new full size triple GEM prototype with correct geometry for LHCb, suited for one of the tracking stations 7 to 10 has been constructed (see Fig. 9.4) in cooperation with the university of Lausanne. The device is presently being studied in the laboratory, and beam tests will start soon. It has a new readout board, with much lower capacity, allowing to run the detector at lower gain (see the conclusion in [6]).

9.3.2 Silicon microstrip option

The importance of the silicon solution has increased, mainly due to the higher backgrounds from the beam-pipe. Silicon is considered to be a realistic option despite its higher costs and slightly larger radiation length.

We foresee an arrangement of silicon detectors in ladders, which will be mounted vertically. The conical beam pipe of LHCb makes it necessary to have different arrangements for each of the 11 tracking stations. We plan to use only one sensor type, with an active size of 100 mm length, 90 mm width and readout strip pitch of 235 μm. Such a sensor can be produced on a 6 inch wafer and is similar to those used in the CMS tracking system. It is almost identical to the silicon detectors used in the satellite GLAST[2]. A possible layout of such a system we described in [9]. The same time a more realistic definition of the space requirements and positions of the different tracking stations was provided [10].

22 prototype sensors with 67 mm strip length and different strip width have been designed and built at the company DETECTOR in Kiev, Ukraine. They consist of 63 strips with a pitch of 240 μm. We are currently constructing ladders of different length for performance measurements at particle beams at PSI (high rate) and CERN (large momentum to measure position resolution) soon.

We also have started to install in Zurich the relevant equipment for silicon microstrip detector development and tests: a manual wedge bonding machine from Devotek, type 5425, is used to connect electronics to the detectors, both for the triple GEM prototypes and for the silicon microstrip detectors. It will also be used to combine several sensors into longer ladders.

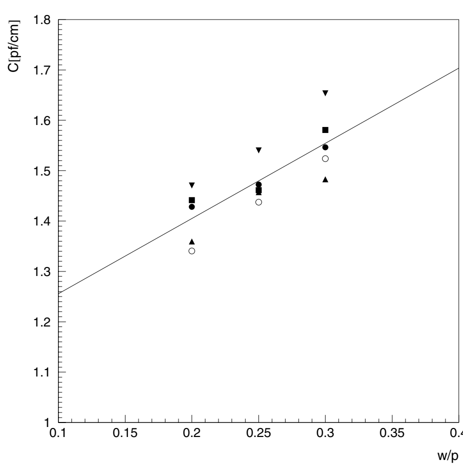

Figure 9.5: *Total strip capacitance as a function of the ratio implant width to strip pitch (w/p), measured at a depletion voltage of 75 V and a frequency of 1 MHz. The different markers belong to different detectors. A linear fit to all points yields an average systematic dependence of* $C_{tot} = 1.49 \times \frac{width}{pitch} + 1.11$ *[pF/cm].*

A new manual wafer probe station from the company Karl Suss, type PM5, in connection with an existing impedance analyzer HP 4192A was used to measure the electrical characteristics of prototype sensors. Figure 9.5 shows the total strip capacitance for our prototype detectors for different width and pitch geometries. For each detector a dependence of the

[2]see www-glast.stanford.edu/

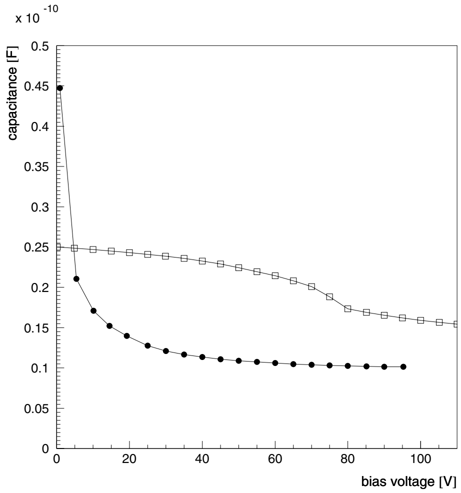

Figure 9.6: *Capacitance versus depletion voltage of a silicon detector prototype. Filled points before irradiation, open squares after irradiation with a maximum of* 10^{14} *protons.*

ratio width/pitch can be observed, however the variation from detector to detector seems to be at least as large as the width over pitch effect.

Figure 9.6 shows the capacitance as a function of the depletion voltage. Before irradiation the detectors show a decrease of the capacitance with voltage and the full depletion is reached at about 50 V. After irradiation the capacitance is increased. Further investigations are ongoing to try to understand the performance of the irradiated detectors and the possible implications of the higher capacitance on the readout electronics.

We also have studied a first version of the readout chip to be used in LHCb (Beetle from ASIC Laboratory in Heidelberg), connecting it to a silicon microstrip detector and observing the signals from radioactive sources. A crucial question is the dependence of the pulse shape on the load capacity at the input of the amplifier, since we intend to build long silicon ladders, with total capacitance of the order of 20 to 30 pF. The measured pulse shapes (Fig. 9.7) are relatively wide, however seem to be acceptable. This pulse shape data is used in the LHCb simulation software to determine the additional occupancy by particles originating in neighbouring bunch crossings of LHC (so called spill over), which occur with a period of 25 ns.

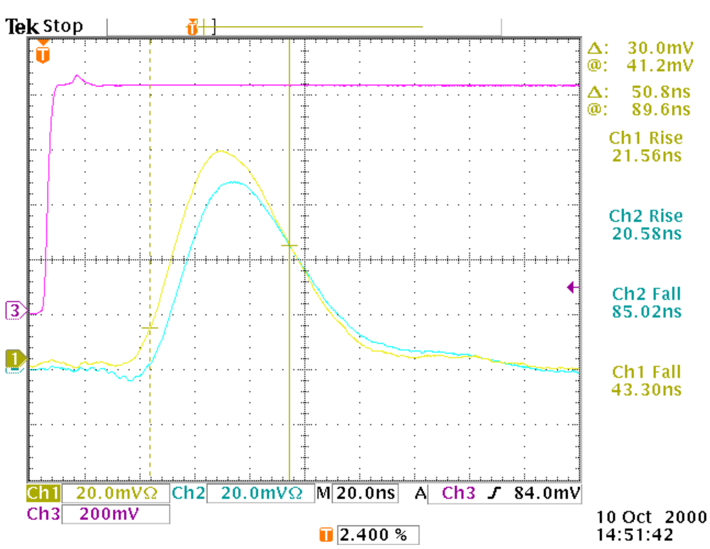

Figure 9.7: *Signal from the front end stage of a Beetle prototype chip, using a pulser to simulate a charged particle signal (upper signal) and SMD capacities of 22 and 33 pF (middle and lower signal, respectively) to simulate a large silicon detector.*

9.4 Other collaboration activities

9.4.1 Hardware developments

An essential part of the dipole spectrometer to be realized in LHCb is its magnet, which should provide enough magnetic field to reach the momentum resolution anticipated in the experiment. For the Technical Proposal [11] a window-frame dipole magnet with super-conducting coils and horizontal pole faces had been assumed. Contacts with industry revealed, that the complicated shape of the coils and the high magnetic forces would lead to high cost and mechanical risks. LHCb has therefore moved to the design of a warm magnet. The new magnet is described in a technical design report [14], which was accepted by the CERN LHCC and all relevant committees.

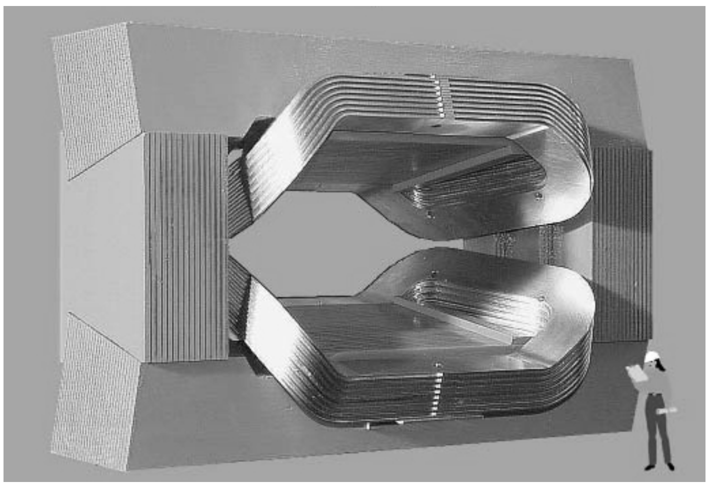

Figure 9.8: *Sketch of the LHCb magnet*

To reduce electrical power requirements to about 4.2 MW, the pole faces are shaped to follow the acceptance of the experiment (Fig. 9.8). The total bending power amounts to $\int B\mathrm{d}l = 4$ Tm over a total track length of 10 m. The useful aperture is 2.6 m x 2.2 m, increasing along the beam axis to 4.2 m x 3.5 m, fitting the acceptance shape of the experiment. The coils will be made of Aluminum (AL-99.7) and the total weight of the magnet will be about 1500 tons.

A market survey has been performed by CERN, resulting in 4 firms interested in the conductor production, 7 firms for the coil winding and 16 firms for the yoke production. The magnet will be ordered soon, and the financial contribution from the swiss FORCE pool is well received for this purpose.

In the year 2000 technical design reports both on the calorimeters [12] and the RICH [13] were well received by the CERN program committee LHCC and construction of these detectors can start now.

9.4.2 Software

All LHCb data processing applications are being built using the LHCb software framework, GAUDI. The latest releases allow simulated events stored in the old ZEBRA format to be read and new data to be written using an object oriented persistence tool taken from the ROOT package, a general object oriented analysis tool. Other new components include a structured description of the detector and its geometry, and support for statistical data e.g. histograms. Work is now in progress to extend the framework in many specialized areas, such as integration with the new object oriented GEANT4 simulation package, the addition of components for managing calibration and alignment data, the development of a visualization framework and analysis tools. A new LHCb reconstruction program, called BRUNEL, has been developed that is based on the above mentioned object oriented framework "GAUDI", but uses most of the existing physics algorithms written in FORTRAN. At the same time much effort has gone into developing new algorithms, redesigned using object oriented methods and written in C++. This new code is gradually being incorporated into BRUNEL with the aim of eventually producing a reconstruction program that conforms entirely to an object oriented design.

In the Zurich group we have started to use parts of these simulation packages to predict the behaviour of the proposed inner tracking design and optimize its parameters.

References

[1] BaBar Collaboration, B. Aubert *et al.*, hep-ph/0102030 (submitted to Phys. Rev. Lett.).

[2] Belle Collaboration, A. Abashian *et al.*, hep-ph/0102018 (submitted to Phys. Rev. Lett.).

[3] A.J. Buras, hep-ph/0101336;

[4] Colin Gay: *B-mixing*, Ann. Rev. Nucl. Part. Sci. (2000) 50:577-641

[5] P. Ball, R. Fleischner, G.F. Tartarelli, P. Vikas, G. Wilkinson et al., *B decays at LHC*, CERN-TH/2000-101, hep-ph/0003238.

[6] M. Ziegler, P. Sievers and U. Straumann, *A triple GEM detector with two dimensional readout*, hep-ex/0007007 and LHCb internal note LHCb-2000-056, July 2000.

[7] M. Ziegler, P. Sievers and U. Straumann, *A triple GEM detector with two dimensional readout*, Proceedings of the International Conference on Imaging Techniques in the borderlands of High Energy Physics, Astrophysics, Nuclear Physics, Medicine and Biology (Imaging 2000), 28 June - 1 July 2000, Stockholm, submitted to Nucl. Instr. and Meth.

[8] P. Cwetanski, *Studies on detector prototypes for the inner tracking system of LHCb*, Diplomarbeit Heidelberg, März 2000.

[9] O. Steinkamp, *A Possible Layout of an Inner Tracker Silicon Detector*, LHCb-2000-109, November 2000.

[10] O. Steinkamp: *Space Requirements and z Positions for Tracking Stations*, LHCb-2000-108, November 2000.

[11] LHCb Collaboration: *LHCb technical proposal*, CERN LHCC 98-4, Feb. 20, 1998.

[12] LHCb Collaboration: *LHCb Calorimeter, Technical Design Report*, CERN/LHCC/2000-036, Sep. 6, 2000.

[13] LHCb Collaboration: *LHCb RICH, Technical Design Report*, CERN/LHCC/2000-037, Sep. 7, 2000.

[14] LHCb Collaboration: *LHCb Magnet: Technical Design Report*, CERN/LHCC/2000-007, Dec. 17, 1999.