9 High-precision CP-violation Physics at LHCb

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LHCb Collaboration

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 2005). The goal of the experiment is to make systematic measurements of CP violation and rare decays in the B-meson system with unprecedented precisions. 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 LHCb group at the University of Zurich was founded when U. Straumann became the successor of W. Kündig at the Physics Institute in September 1999. The group joined LHCb as a full collaboration member in December 1999. LHCb consists now of about 50 institutions from 14 countries.

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 includes a close collaboration with the particle physics group of the university of Lausanne. Furthermore the Max Planck Institute in Heidelberg, Germany, and the University of Santiago de Compostela, Spain, are members of the inner tracking group of LHCb. The R&D will be continued until about end of 2001, when we are expected to define the final system and document it in a technical design report. After that we will contribute to the construction of these detectors, making use of the excellent technical infrastructure provided by our institute.

We also want to contribute to the preparation for the running and analysis strategy, with special emphasis on trigger algorithm development and support. Here we can fortunately rely on the large experience of our colleagues in the "Institut für theoretische Physik" of our faculty in the field of B physics (group of Prof. D. Wyler).

Since this is a new activity this section is somewhat detailed and contains also an extended discussion of the physics motivation. Part of the detector R&D described below, has started in Heidelberg, and was later on continued at the university of Zurich.

9.1 CP – Violation and Physics of B Mesons

9.1.1 CP violation within the standard model and beyond

The past 10 years have seen a tremendous improvement in the quantitative understanding of the standard model (SM) of particle physics, describing three different fundamental interactions and three generations of fundamental particles. The relevant constants of nature (mass of electroweak interaction bosons, Weinberg mixing angle, coupling constants etc.) have been determined consistently. There are, however, two important open issues within the SM: the Higgs particle, yet unobserved, and the CP violation which so far is only understood qualitatively in the SM.

While a discovery of the Higgs during the last year of LEP operation is still possible, the experiments ATLAS and CMS at the LHC project will definitely shed light on the question of its existence and hopefully be able to study its properties in detail.

A very fundamental feature of the standard model is its prediction of CP violation in the weak interaction of quarks. Any violation of the discrete space – time symmetries is by itself certainly very fundamental for our understanding of nature. Moreover, CP violation is one of the three crucial ingredients necessary to explain the present matter – antimatter asymmetry in the universe (Sakharov 1967). The SM can naturally generate some CP violation, but new sources of CP violation in theories beyond the SM are needed [1] to predict the magnitude of this asymmetry.

The SM describes CP violation with a single complex phase in the quark mixing matrix V_{CKM}. In the following we will refer to the Wolfenstein parametrisation, in which η represents the imaginary CP violating component:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\,(\rho - i\,\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\,(1-\rho-i\,\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta\,V_{\mathrm{CKM}} \tag{9.1}$$

The first part is accurate to third order in λ. Once the CP violation in the B system will be measured to an accuracy of order 2 % or better, terms up to order λ^5 will have to be taken into account. This is also needed for the determination of CP violation in the K system:

$$\delta\,V_{\mathrm{CKM}} = \begin{pmatrix} 0 & 0 & 0 \\ -i\,A^2\lambda^5\eta & 0 & 0 \\ A\,(\rho+i\,\eta)\,\lambda^5/2 & (1/2-\rho)\,A\lambda^4 - i\,A\lambda^4\eta & 0 \end{pmatrix} \tag{9.2}$$

Often the phases of the complex numbers are also quoted: $\beta := -\arg V_{\mathrm{td}}$, $\gamma := -\arg V_{\mathrm{ub}}$, $\delta\gamma := \arg V_{\mathrm{ts}} \approx 2\,\%$.

At present the best values of the four independent parameters are [2]:

$$\begin{aligned} \lambda &= 0.2196 \pm 0.0023 \\ A &= 0.82 \pm 0.04 \\ \rho &= 0.20 \pm 0.06 \\ \eta &= 0.340 \pm 0.035 \end{aligned} \tag{9.3}$$

These values were obtained by a global standard model fit, including the CP violation parameter ϵ_K determined in $K^0 - \overline{K^0}$ mixing, $|V_{\mathrm{ub}}|$ from $b \to u l \nu$ branching ratios and the $|V_{\mathrm{td}}|$ obtained from the mass difference Δm_d measured in $B_d^0 - \overline{B_d^0}$ oscillation [3].

9.1.2 Present experimental activities

Recently three new experimental results were announced, which indicate a non zero value of the parameter η, and in fact the standard model seems to describe all presently known CP violation effects more or less in a consistent way:

First of all experiments at FNAL (KTeV [4]) and at CERN (NA48 [5]) presented their observation of direct CP violation in the channel $K^0 \to \pi\pi$. The combined result of the two experiments on the quantity ϵ'/ϵ ($\approx 24 \times 10^{-4}$) lies outside the range predicted by the standard model. Since these calculations have large uncertainties, this discrepancy may not be so significant. However, it stimulated a lot of discussions and more detailed theoretical investigations.

The second important result is the CP violating asymmetry in the channel $B_d \to J/\psi\, K_S^0$ reported first by the CDF experiment at the TEVATRON [6]. There exist also analyses from the OPAL [7] and ALEPH [8] collaborations at LEP, albeit with larger errors.

Although the observed value of $\sin 2\beta \approx 0.8 \pm 0.4$ from CDF represents only a two standard deviation from zero, it does indicate the SM expectation of a sizable CP violation in the $B_d^0 - \overline{B_d^0}$ mixing could be correct. The SM prediction using the values from Eq. 9.3 yields $0.65 < \sin 2\beta < 0.77$ [3], consistent with the experimental result.

It is interesting to note, that information about V_{td} can also be obtained from $K \to \pi\nu\nu$, in a theoretically very clean way. The experiment E787 at Brookhaven has measured the branching ratio of the decay $K^+ \to \pi^+\nu\bar{\nu}$ to be $(1.5\ ^{+3.4}_{-1.2}\ ) \times 10^{-10}$ [9], one of the lowest branching ratios ever determined in particle physics. It is sensitive to $|V_{td}|$ and is in fact predicted to be of order 10^{-10} [2]. Also at Brookhaven National Laboratory the proposed experiment BNL E926 will search for $K_L \to \pi^0\nu\bar{\nu}$. The branching ratio is proportional to η^2 and is calculated to be about 2.8×10^{-11} [10].

Presently, we see the two asymmetric e^+e^- collider B factories at SLAC (experiment BaBar) and KEK (experiment Belle) coming into operation. Together with run II of the TEVATRON with the upgraded experiments D0 and CDF and the experiment HERA-B at DESY they will soon provide a reasonably accurate measurement of the angle β, and thus contribute to a good initial understanding of CP violation in the B_d sector.

9.1.3 Second generation B physics program

The planned LHCb experiment will become operational in 2005 as soon as the LHC collider becomes available. At that moment, the results from the B factories, TEVATRON and HERA-B will have already established CP violation in the B-meson systems in a few decay channels. These measurements will concentrate on $\sin(2\beta)$ which, however, is not sufficient to test the validity of the standard model.

In addition, HERA-B, CDF and D0 will probe B_s-$\overline{B}_s$ oscillations. Their sensitivities cover most of the parameter space allowed by the SM. A B_s-$\overline{B}_s$ oscillation frequency much larger than expected from the SM would be a clear indication of new physics.

A second generation B physics experiment must ask more fundamental questions: It should search for a sign of new physics by measuring ρ and η from many different CP violating B meson decay modes with a high precision. In absence of new physics, all the measurements must give consistent values of ρ and η, while inconsistent values will require new physics. In any case the observations will drastically reduce the parameter space of new physics models.

New physics can also be searched for by studying the decay modes that are rare in the SM. Many rare B meson decay modes are generated by penguin diagrams. Since they are first order in the weak interaction, new physics may not alter the branching fractions significantly. However, a sizable CP violation effect can be produced through the interference between the SM and new physics interactions [11]. There is a growing theoretical interest to identify promising decay modes to probe new physics. Particularly, comparing different determinations of the angle γ is potentially very sensitive to new physics [12]. Recently the use of B_c mesons to measure γ has been rediscovered [13].

Unfortunately, such studies of very low branching fractions or small CP asymmetries require very large numbers of B mesons. Only hadronic interactions at the highest available energies can produce a sufficient number of b quarks. The production cross section of B mesons at the new collider LHC at CERN will exceed those of the B factories and HERA-B by several orders of magnitude and those of the TEVATRON by more than one order of magnitude. At the TEVATRON a B experiment is being considered (BTeV) to be run in collider mode after the year 2006, simultaneous to the LHCb experiment. This experiment will certainly allow to perform many cross checks of LHCb results.

9.2 The design of a B experiment at LHC

Even though the B production cross section is very large at LHC, selecting interesting and accurately measurable B events out of the minimum bias background (due to light quark production in pp scattering) represents a major challenge. The following considerations lead to an optimized second generation B experiment at LHC:

- b quarks are mainly produced through gluon – gluon fusion and gluon splitting processes. Their angular distribution is strongly peaked in the forward direction and the B mesons have larger average momentum here, reducing inaccuracies im momentum and mass resolutions due to multiple scattering. Therefore a forward spectrometer geometry is chosen.

- Because most of the time the $b\bar{b}$ pairs are leaving into the same hemisphere, only a single spectrometer arm already gives an acceptable efficiency to observe both the b and the $\bar{b}$ decay products in the same event. This allows to identify the initial flavour of a given B^0 decay by looking at the sign of the charged lepton or kaon from the decay of the other b quark ("tagging").

- The most important selection mechanism for B meson decay events is their finite lifetime. Therefore a vertex detector with very high resolution is mandatory. Vertex information should also be available for trigger decisions at the earliest possible stage. The second level trigger operating at an input rate of 1 MHz allows to reconstruct two or more vertices and to cut on the distance between them.

- Another important event selection method is the reconstruction of the invariant mass and the momentum of the B from its decay products. The magnetic dipole spectrometer is designed in such a way, that the invariant mass resolution receives similar contributions from measurement inaccuracies from the vertex detector and from the spectrometer.

- The rare decays are often hidden behind backgrounds of other very similar B decays, which can only be separated by a good particle identification. A muon system and for electron identification a shashlik type electromagnetic calorimeter (ECAL) is foreseen. To distinguish between pions and kaons a sophisticated ring imaging Cerenkov counter system is being designed, which consists of three different radiators in two detector stations, allowing excellent π/K separation over the whole momentum range.

- Many of the interesting B decay channels contain only hadrons in the final states. Simple lepton triggers do not allow to select such events, therefore a hadronic calorimeter (HCAL) is introduced together with a high p_T trigger system.

- The optimal luminosity, providing a high B production rate and – at the same time – avoiding too many multiple interactions to avoid confusion in the event reconstruction, is presently believed to be $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$, about 2 % of the design luminosity of LHC. The luminosity in the LHCb area will be adjustable with a dynamic range of about a factor 100, therefore we will be able to run at our optimal value, independent of the maximum luminosity of LHC, which might be lower during initial operation.

These considerations lead to a detector design for LHCb, which is shown in Fig. 9.7.

The LHCb detector is described extensively in a technical proposal [16], which has been accepted by the CERN scientific committee (LHCC) and was approved by the CERN management in 1998.

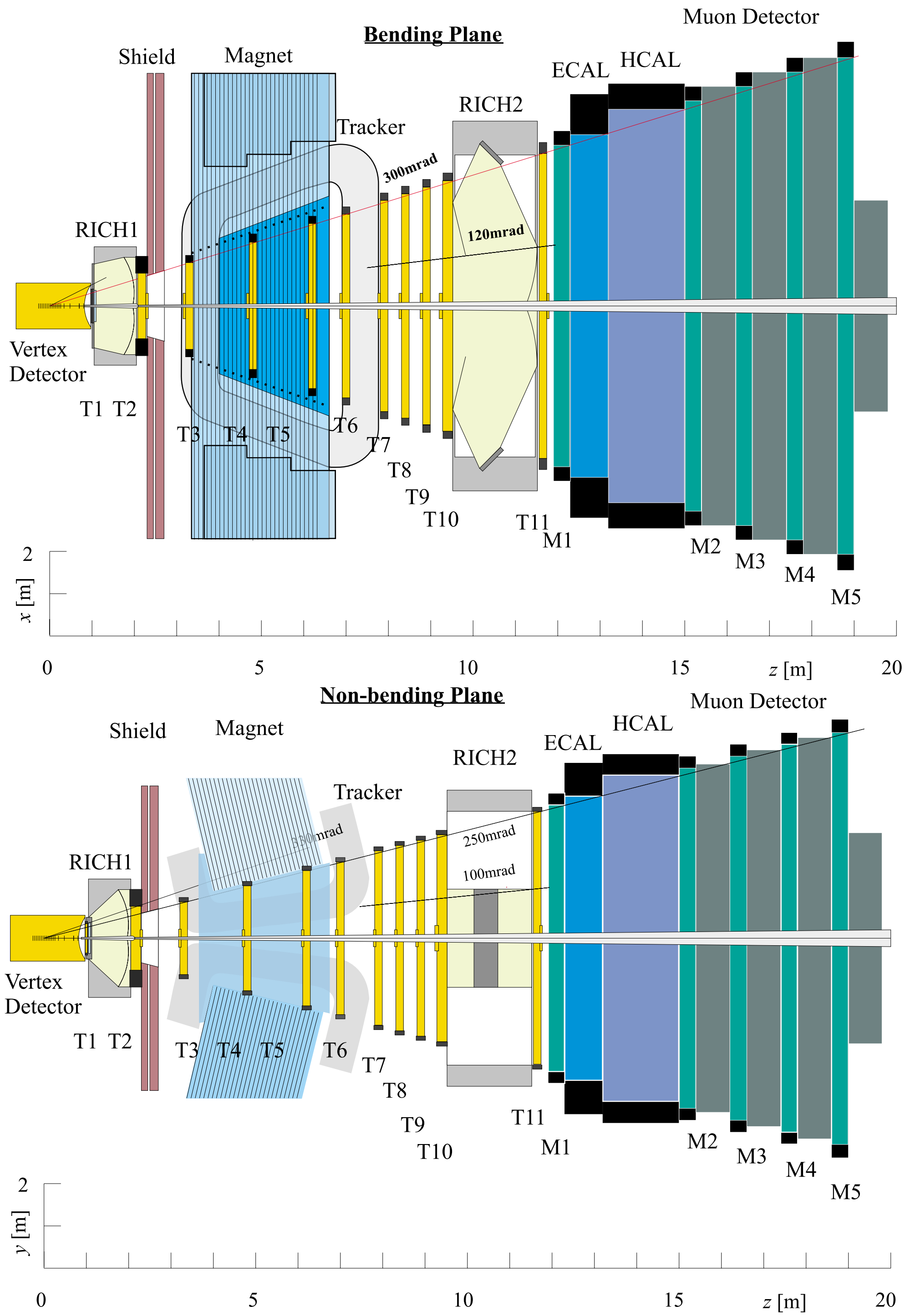

Figure 9.7: *Schematic layout of the experiment LHCb in top (bending plane) and side (non-bending plane) view. The pp interaction point is on the left. Each tracking station consists of an inner and an outer part, indicated by T1 ... T11.*

Presently detailed design studies are being performed, which should lead to final system definitions in the next two years. They will be described in technical design reports (TDR) separately for each of the various subsystems. The construction period will extend until the year 2004, such that commissioning may coincide with the initial startup of LHC.

9.3 B physics at LHC

The LHCb experiment will run with an optimised luminosity of $2 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and produce more than 10^{11} B_d and B_s mesons per year. The large improvement of LHCb over the first generation B experiments allows to access many more interesting B decay channels thanks to much larger event samples.

In this context the question arises, whether an extended B – physics program could be done also with the planned universal detector facilities ATLAS and CMS at LHC. Since these detectors are designed to run at full LHC luminosity, they will produce even more B mesons, which one could use for B physics studies.

At a closer look there are, however, four important reasons to build a special experiment dedicated to the second generation B physics program:

1. For time dependent CP asymmetry analysis of B_s decays, but also for efficient event selection, a very good eigentime resolution is needed. The LHCb experiment with its forward geometry has much higher average momenta of the B decay products and therefore the eigentime resolution is less affected by multiple scattering.

2. Many of the interesting channels can only be selected with a very good particle identification, which allows to separate π and K over a wide range of momenta. One example is the decay $B_s^0 \to D_s^{\pm} K^{\mp}$, which suffers from a high background from the channel $B_s^0 \to D_s^- \pi^+$, which has a much larger branching fraction. The RICH detectors in LHCb provide an elegant solution to this problem, while no such possibility is foreseen in the ATLAS and CMS experiments.

3. A trigger system, especially optimised for B decay channels is needed to make optimal use of the existing B production rate. ATLAS and CMS can neither trigger on secondary vertices nor on high p_t hadrons.

4. Due to the specific optimisations for the large forward spectrometer the reconstructed invariant mass resolution of the B turns out to be typically a factor of two better than in ATLAS and CMS, depending on the decay channel.

Table 9.2 compares the possibilities of the three LHC experiments. Shown are the expected statistical accuracies for the various CP violation parameters. Systematic errors are generally smaller.

It is obvious that, compared to the first generation experiments, much larger samples of many more different decay channels will be available. This will allow to measure not only the angle β very accurately as a test of the standard model description of CP violation, but also the other significant phase angles of the CKM matrix elements γ and $\delta\gamma$.

It is evident, that for simple channels like $B_d \to J/\psi\ K_S^0$ all LHC experiments can do equally well. However, for the more sophisticated measurements good π/K separation, well resolved B_s oscillation determination or an efficient hadron trigger are mandatory, which explains the superior performance of LHCb. Only LHCb is able to do the various measurements of γ, which allows high precision cross checking of the standard model predictions and thus provides access to a variety of windows to New Physics. Different supersymmetric

Table 9.2: *Statistical sensitivities*[a] *for some quantities in* B *– decay [14] as expected from the LHC experiments. The event numbers include detector acceptance, trigger and offline efficiencies. Ranges of sensitivity correspond to range of actual values of:* $\alpha \equiv \pi - \beta - \gamma$ *(50°* *. . . 100°) and* Δm_s *(15 . . . 45* ps^{-1}*).*

			Atlas		CMS		LHCb	
channel	quantity	method[b]	error	events	error	events	error	events
$B_d \to J/\psi K^0_S$	$\sin(2\beta)$	t-dep	0.017	165 k	0.015	430 k	0.021	88 k
$B_d \to \pi^+\pi^-$	$\sin(2\alpha)$	t-dep		2.3 k[c]		0.9 k[c]	0.07	4.9 k
$B_d \to \rho\pi$	α	t-dep					0.04-0.09	1.3 k
$B_d \to D^{*\pm}\pi^{\mp}$, $D^{*\pm}a_1^{\mp}$	$2\beta + \gamma$	t-dep					0.26	703 k
$B_s \to D_s K$	$\gamma - \delta\gamma$	t-dep					0.11-0.23	2.4 k
$B^0_d \to DK^{*0}$	γ	BR					0.07-0.31	300
$B_s \to J/\psi\phi$	$2\delta\gamma$	t-dep	0.03	300 k	0.14	600 k	0.02	370 k
$B \to \pi K$	γ	BR					0.03-0.10	90-175 k
$B_s \to J/\psi K_s$	γ	t-dep				4100[c]		
$B \to DD$, $B_s \to D_s D_s$	γ						0.02	300 k, 190 k
$B_d \to \pi\pi$, $B_s \to K^+K^-$	γ	t-dep	0.09-0.13	1.4 k	0.10-0.33	1 k	0.34-0.68	4.6 k
$B_s \to D_s\pi$	x_s		46[d]	3.5 k	42[d]	4.5 k	75[d]	86 k
$B \to K^*\gamma$							0.01	26 k
$B \to K^*\mu^+\mu^-$				2 k		13 k		22 k

[a] absolute error assuming one year of data taking (except for $B_d \to \pi\pi$ / $B_s \to K^+K^-$ where five years are assumed) at design luminosities
[b] *t-dep*: time-dependent asymmetry analysis, *BR*: comparison of branching ratios.
[c] signal/background < 1
[d] largest value observable

models predict a different values for the energy asymmetry of the lepton pairs produced in $b \to sl^+l^-$ decays [15]. LHCb will produce a large sample of $B \to K^{*0}\mu^+\mu^-$ per year allowing to distinguish between different supersymmetric models.

In summary the LHCb experiment will provide a second generation B physics facility, allowing highest precision determination of the CP violation parameters of the standard model, exploring extensively heavy flavour physics of b and c quarks and looking for new physics through CP violation interference effects and other methods using rare B decays.

9.4 The inner tracking detector of LHCb

The obvious requirement for the LHCb spectrometer is a very high momentum resolution, as explained above. Detailed studies indicate that the crucial quantity is not the spatial resolution but rather multiple scattering in the spectrometer chambers and very high particle fluxes, originating partially in minimum bias events and to a larger extent in photon conversions in the beam pipe and other dead material in the spectrometer. The somewhat contradictory requirements of a low material budget and a high pattern recognition efficiency lead to an optimal number of 11 tracking stations, each being capable of determining an accurate track space point in all three dimensions.

The design considerations of the tracking chambers are dominated by the search for a technology which can withstand the high particle fluxes (up to $10^4\,\mathrm{sec}^{-1}\mathrm{mm}^{-2}$). The granularity of the detector should be sufficiently high, resulting in an average occupancy low enough not to spoil pattern recognition.

Since in the HERA-B [17] experiment at DESY the particle rate conditions and the geometrical arrangement in the tracking is very similar to LHCb, it is obvious that any development for LHCb may benefit from the experience with the HERA-B detector, which is being commissioned right now.

Already in early studies for the HERA-B experiment it turned out, that the tracking chamber needed to be divided into two areas: An outer tracking part with relatively low particle density, where in the HERA-B case honeycomb drift chambers turned out to be an adequate implementation. In the inner tracking a finer granularity and therefore larger number of electronic readout channels were necessary to keep the channel occupancy below a few percent. The area of the inner tracking in LHCb measures 60cm x 40cm around the beam pipe (in HERA-B slightly smaller). For installation reasons the chamber needs to be divided up in at least two halves.

Originally HERA-B had chosen MSGCs for their inner tracking chambers (four quadrants with an active size of typically 28cm x 25cm each). In first beam tests with hadronic particles at the Paul Scherrer Institut it turned out, that this technology is inadequate to withstand very high hadronic particle rates, as explained in more detail below. Therefore an additional gas electron multiplier foil (GEM) was added as "preamplifier" allowing to run the MSGC's at lower gas gain [18].

In LHCb the choice of the technology for the inner tracking is not made yet. Various gas avalanche multiplication techniques have been studied by the inner tracking group. In February 2000 it has, however, been decided to concentrate on one gas chamber technique (triple GEM, see below) and a silicon option.

9.4.1 Preparatory studies for the HERA-B inner tracking

U. Straumann joined the R&D effort of the Heidelberg–Siegen–Zuerich collaboration to develop inner tracking devices for HERA-B and LHCb in 1996 and initiated a series of beam tests with the already existing MSGC prototypes for HERA-B. The πM1 area in the Paul Scherrer Institut was chosen for these studies, since here hadronic particle fluxes can be achieved which are comparable to those expected for LHCb and HERA-B. The beam allows to irradiate the prototype chambers over a significant fraction of their sensitive area. The goal was to measure all relevant performance parameters and to check the operation stability in a realistic environment.

Already in the first beam test in spring 1996 it turned out, that the MSGC were irreversibly damaged due to frequent beam induced HV breakdowns. Further investigations in the laboratory (with α particles) and at the HERA-B beam at DESY showed, that these breakdowns are triggered by very large primary ionization events, which most likely originate from heavily ionizing particles like nuclear fragments originating from nuclear reactions of the beam hadrons with the detector material. These observations initiated a lot of other studies in various research groups and were also recognised at conferences [19].

Since no other affordable technology was at hand, the only way out of this dilemma was to add a gas electron multiplier (GEM) developed at the CERN gas detector development group (GDD) by F. Sauli and collaborators.

With this two amplification stage detector we were able to perform various crucial rate and stability tests mainly at PSI [18]. These included the final readout electronics with the HELIX [20] chip used at HERA, which contains 128 preamplifiers, discriminated trigger outputs, 12 μsec analog pipeline and readout multiplexing logic. In summer 1998 we were able to run the full electronic chain the first time in a real beam and full size detector environment.

In October 1998, a package of three consecutive chambers were operated at PSI [21] for the first time. We observed gain differences up to a factor 2 between chambers of identical construction. Also non-uniformities within single chambers were found. Detailed inspection of the chambers showed, that there were sizeable gap variations (up to ± 0.4 mm) between the MSGC wafer and the GEM foil. These cause small changes of the electrical field in and around the GEM holes, which correspond to the measured gain variation of about a factor 2. There are indications, that the GEM foil looses its mechanical tension, after having been exposed to DME (the quencher gas used at that time).

Furthermore it turned out, that after an irradiation time, which corresponded only to a fraction of the expected HERA-B doses per year, significant ageing occurred, resulting in an almost completely dead chamber. Several investigations with X-ray and chemical analysis of the surface of the wafers showed, that the conductive coating, which was put onto the glass substrate for high rate stability reasons had been etched away by the heavy irradiation load.

Running with an Ar/CO_2 mixture solved that problem partially, such that these chambers should survive at least enough time to take physics data with the HERA-B detector.

9.4.2 Extended investigations for LHCb

It soon became clear that the MSGC-GEM combination, as it is used for the HERA-B detector, is not suited for LHCb. Since this experiment is designed for precision physics and should be running for about 10 years, the long term stability of the electrode structure on the MSGC wafer in harsh hadronic beam environment is by far not good enough. The signal size is only just marginally above the thermal noise of the electronics at an operation high voltage, just above which sparking occurs.

The inner tracking group of LHCb chaired by U. Straumann has therefore decided to start an extended R&D program to look for alternative technologies, which would satisfy the requirements of the inner tracking and would operate more reliably over long time periods. We would accept only technologies which avoid all the problems mentioned above, showing narrow signal shapes both in time (extending over at most two LHC bunch crossing, i.e. 50 ns) and and space, such that the channel occupancy stays low.

The options studied in more detail, including tests at the Paul Scherrer Institut, were Micromegas [22], Microwire [23] and triple GEM [24]. We also profit very much from the studies of the CERN GDD group [25] and the efforts made within the CMS collaboration, including those by the University of Zurich.

Apart from these experimental investigations a detailed simulation of all the technologies considered has been developed [26]. Three-dimensional field maps are considered and Monte Carlo methods are used to study the relevant gas parameters.

9.4.3 Triple GEM

Our group concentrated on developing a multistage GEM detector consisting of several GEM foils placed behind each other. As a result the gas gain in a single stage can be kept low. The amplification planes are followed by a simple printed circuit board with readout strips, which see the charge induced by the drifting electron cloud, originating from the last GEM stage.

Using two GEM foils, different groups [25] had already achieved promising results. However, the spark probabilities in hadronic beams seemed to be still rather high. The prototypes studied by other groups were all of small size (typically 10 cm $\times$ 10 cm or less), which makes

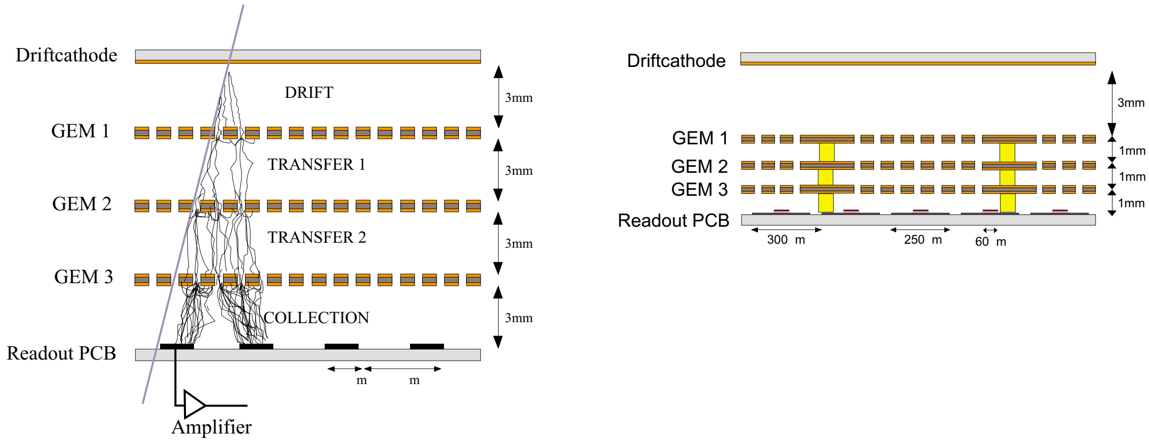

Figure 9.8: *Cross section through the triple GEM prototypes. First prototype with 3 mm spacing between the GEM stages (left), second prototype with 1 mm spacing (right).*

them much easier to operate due to their lower capacitance resulting in lower thermal noise in the charge sensitive amplifiers.

In order to reduce the total radiation length the Karlsruhe group has tried to use readout boards with two layers of readout strips, allowing to determine two space coordinates with only one detector plane [27]. Unfortunately, this scheme reduces the detector signals by at least a factor two.

All these considerations (large detector increasing the thermal noise, two-dimensional readout lowering the signal, sparking demanding low gas gain) led to the idea to try chambers with three stages of GEM foils.

In 1999 we built two generations of prototypes. Both are full size (about 30 cm $\times$ 25 cm) with different sizes of the gap between the GEM foils (see Figures 9.8 and 9.9).

While the first prototype has 3 mm gaps between the GEM foils, the second one was built with 1 mm spacing in order to profit from several advantages of small gaps: It needs less space, needs less total high voltage and most importantly has lower cluster width due to a shorter total drift path. This improves the position resolution and reduces the total occupancy.

In order to keep the gap variations sufficiently low, small spacers (Fig. 9.9) were put between the GEM foils at $\approx$ 4 cm intervals. These consist of Polytek H72 Epoxy glue and

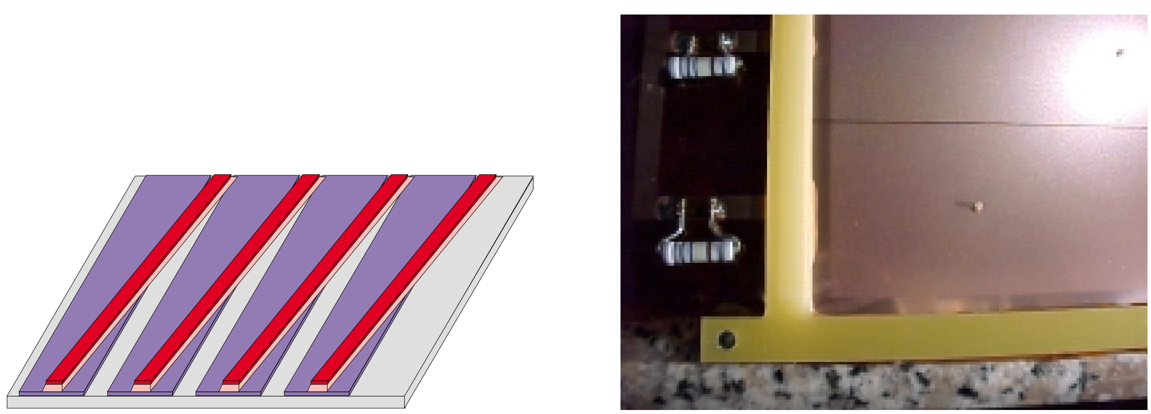

Figure 9.9: *Details of the construction of the second prototype. Two-dimensional readout board (left). Frames and spacers (right).*

have a diameter of 1.1 mm. In order to avoid any glue to flow into GEM holes, a special mask for GEM foil production makes sure, that at the spacer position there are no GEM holes. The size of this inactive area has a diameter of 2 mm, corresponding to a total inefficient area of less than 0.15 % of the detector.

The chambers are operated with Ar/CO_2 (70:30). Most channels are equipped with HELIX [20] readout, a few channels have a fast amplifier connected (rise time 0.5 ns) to study the signal shape.

The readout strips see in first order only the electron signal from the collection gap and no ion current, therefore this detector produces a very short output signal. Using an iron source we could indeed observe pulse durations consistent with the drift time in the lowest gap (40 ns and 15 ns for the 3 mm and 1 mm gap chamber, respectively) without any indication of an ion tail.

9.4.4 Triple GEM operation in high intensity hadronic beams

After test and calibration of the chambers in the laboratory we operated the detectors in two periods of two weeks each at the πM1 PSI test beam in April and December 1999 respectively.

In the first period we studied the performance of the 3 mm prototype. With a beam containing 50 kHz/mm^2 π^+ and protons we were able to operate the chamber at a total gain of 20'000 for more than 8 hours without any spark.

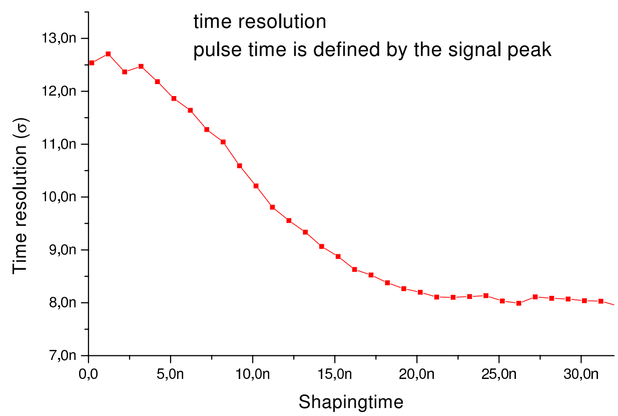

Figure 9.10: *Time resolution, that could be obtained with an ideal zero crossing discriminator, as a function of shaping time.*

With the fast amplifiers signal shapes of the minimum ionizing pions were recorded. They show in fact a complex structure, caused by the overlap of several primary ionization clusters with different size and arrival times. These signals were filtered offline, simulating the influence of a hypothetical electronic shaping circuit. The time resolution was estimated simulating a zero-crossing timing discriminator which determines the time of the pulse maximum. Figure 9.10 shows, that an optimum shaping time exists, which gives good timing resolution and avoids long occupancy times. More details of this pulse shape analysis are given in [24].

The second prototype (1 mm gap) was tested in December 1999 at PSI. It ran very nicely, a plateau curve is shown in Fig. 9.11. The 380 V GEM voltage needed for good efficiency corresponds to a gas multiplication factor of about 20'000. Such a high value is needed, because the two dimensional readout geometry as shown in Fig. 9.9 has a high capacitance of about 90 pF per channel, which causes a very high thermal noise in the connected charge amplifier. We are considering improved geometries to reduce these capacitances by about a factor 3.

At this high gain the 1 mm triple GEM chamber showed a small, but measurable spark probability of order 10^{-9} per incoming π. No damage was observed.

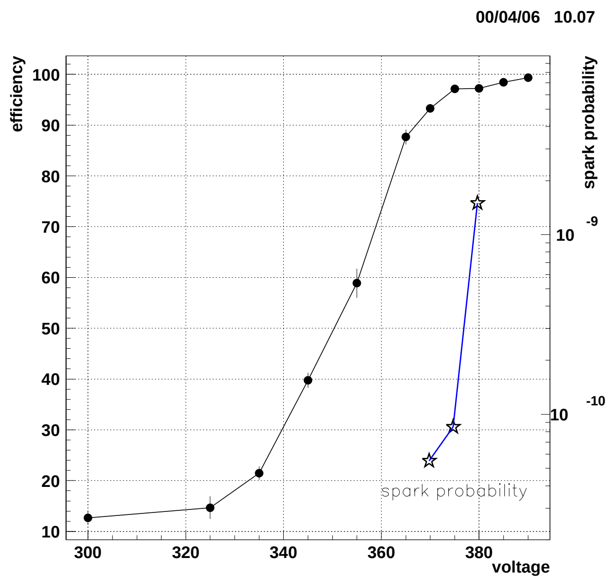

Figure 9.11: *Plateau curve of the 1mm gap prototype measured with 300 MeV/c pions at PSI. The efficiency is given by using a coincidence of two scintillators as a trigger. The spark rate is normalised to the total number of pions impinging onto the detector.*

The cluster size has been measured to be $\sigma = 230\mu$m, which agrees well with simulations [26].

9.4.5 Conclusions and outlook

The investigations of the other groups within the LHCb collaboration showed, that the sparking rate in both micromegas and microwire is of order 10^{-5} to 10^{-7} per incoming π, which would lead up to 1 kHz of sparking at LHCb running conditions. We therefore abandoned those technologies in a meeting of the inner tracking group in February 2000. LHCb concentrates now on the triple GEM chamber as a gas detector for the inner tracking.

From our experience with gas detectors as well as many other test experiments [25], we learned that chambers with an electrical field configuration which drops significantly slower than 1/r away from the anode, are likely to be sensitive to sparking in hadronic environment induced by streamer developments. While a good old fashioned MWPC has a very high HV breakdown limit due to an almost perfect 1/r electrical field, chambers with constant electrical fields, like parallel plate chambers or micromegas are very sensitive to sparking. This is also consistent with the observation, that MSGC with surface coating are significantly more sensitive to sparking than those with a high resistive carrier material [28].

There are, however, more effects which are not understood yet, especially the fact, that the spark limits depend very strongly on the chosen nobel gas and the quencher gas fraction used.

We therefore started in parallel to look into a silicon microstrip detector solution, which is the only known alternative to the micro pattern gas detectors. They allow to increase the granularity to tackle large occupancies, and they avoid high occupancies due to large angle background tracks originating from the beam pipe, since they have a 10 times shorter active detector length. The total radiation length of the two technologies is comparable (about 0.3 % per active layer). Also signal shape and time occupancy look similar in the two technologies, as well as the infrastructure needed (Triple GEM needs gas, silicon needs cooling). Triple GEM detectors are in principle more radiation hard than silicon microstrip detectors.

A final decision for silicon or triple GEM technology will be made before writing the technical design report (about end of 2001).

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