



Expected measurement of the Z production rate with the CMS detector and simulation of the Tracker Laser Alignment System

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Introduction

In the past four decades many discoveries of new phenomena in particle physics have led to the formation of a theory, which provides a microscopic description of all known forces except gravity. This theory is known as the *Standard Model*. Despite the success of the Standard Model, the theory is not yet complete. For example, the lack of an explanation for the origin of the particle masses illustrates the shortfalls of the Standard Model.

From Summer 2009 on the Large Hadron Collider (LHC) at the European Center for Nuclear Research (CERN) will provide proton-proton collisions at a center of mass energy of 14 TeV. The high energy, never before reached in a particle collider, allows for the search of the missing parts in our current knowledge of particle physics and for the discovery of new phenomena.

In order to measure the properties of the particles created in the proton-proton collisions, four large experiments have been constructed. One of these is named the Compact Muon Solenoid (CMS) experiment. The CMS detector is build out of several subsystems, each serving different purposes. The so called tracking devices measure the momentum of charged particles. The superconducting magnet of the CMS detector provides a strong magnetic field allowing for a good momentum resolution within a compact detector volume.

The alignment of the tracking devices is an important issue in achieving an accurate track reconstruction. The CMS tracker is therefore equipped with a *Laser Alignment System* (LAS) allowing for the alignment of the larger substructures of the CMS tracker and for the monitoring of the sensor position during data taking.

Apart from an aligned detector and accurate reconstruction of the particles created in the proton-proton collisions, a precise measurement of the luminosity delivered by the Large Hadron Collider to the experiments is needed in order to measure the cross sections of newly discovered phenomena. In the present study the production of muon pairs via the Drell-Yan mechanism, which is theoretically well understood, is used to measure the luminosity. Besides the important determination of the luminosity by means of Z boson production via the Drell-Yan mechanism and the following decay of the Z boson into a muon pair, this process can also be used to search for new phenomena, provided the absolute luminosity were independently determined. The excellent muon reconstruction capabilities of the CMS detector give the possibility to search for new phenomena in this channel by looking for deviations from the theoretically well-known properties of Drell-Yan production.

The first chapter gives an overview of the Standard Model including a possible solution to the origin of particle masses (the Higgs mechanism). The second part of the first chapter discusses the production of lepton pairs at hadron colliders.

The Large Hadron Collider as well as the CMS detector are described in the second chapter. The components of the CMS detector which are important for the present study (the tracker, the Laser Alignment System and the muon system) are described in detail.

Chapter 3 summarizes the work carried out in this study toward the commissioning of the Laser Alignment System (LAS). The software developed for the simulation of the LAS, the reconstruction of the laser beam profiles and the calculation of the corrections to the detector geometry are presented. The results of the analysis of the first LAS data taken during the integration of one of the tracker endcaps are also presented.

The potential of the CMS experiment to measure the luminosity utilizing Drell-Yan events

is presented in chapter 4. The study is based on simulated data obtained from a *Monte Carlo* generator which takes next-to-leading order corrections in quantum chromodynamics (QCD) into account. The full CMS detector simulation was used. Finally the analysis investigates the expected performance and the precision of the cross section measurement for lepton pair production via the Drell-Yan mechanism.

Chapter 1

The Standard Model: Basic concepts and their application

1.1 Overview

High Energy Physics concentrates on the study of the fundamental constituents of matter and their interactions. Particle accelerators together with special purpose detectors are used to study particle collisions in scattering experiments down to subatomic scales ($< 10^{-15}$ m)¹.

The present knowledge about the constituents of matter and their interactions is summarized in the Standard Model [1–4]. Experimental observations made over the past decades are compatible with the predictions of the Standard Model at a high level of accuracy [5, 6]. However, not all building blocks of the model have so far been experimentally established. In particular the explanation of particle masses e.g. through the Higgs mechanism [7–9] still lacks experimental verification.

In spite of the impressive phenomenological success of the Standard Model, it cannot be considered as a complete description of the fundamental forces. Many interesting experimental signals are expected to be seen in the near future. New experiments (see chapter 2) will probe the Standard Model to a much deeper level of sensitivity and will explore the frontier of its possible extensions.

The basic concepts as well as some important features of the Standard Model are briefly discussed in the first part of this chapter. In the present study the production of massive lepton pairs in hadron collisions has been investigated. The second part of this chapter gives a short introduction to the theoretical details of massive lepton pair production as well as the parton distribution functions.

1.1.1 Basic concepts

The Standard Model of the electroweak and strong interactions is a renormalizable [10–12] quantum field theory based on the gauge group

$$G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y \quad (1.1)$$

of unitary gauge transformations. $SU(2)_L$ is the non-Abelian left-handed electroweak isospin (I) symmetry group, with which three gauge fields W are associated. $U(1)_Y$ is the Abelian hypercharge (Y) group. The Gell-Mann-Nishijima relation

$$Y = 2(Q - I_3) \quad (1.2)$$

connects the hypercharge Y with the electric charge Q and the third component of the electroweak isospin I_3 . The gauge field B is associated with the hypercharge group.

¹The high energies reached at the Large Hadron Collider (compare chapter 2) allow for scattering experiments down to scales of $\mathcal{O}(10^{-19}$ m).

Both groups enter as the $SU(2)_L \times U(1)_Y$ group into the Glashow-Salam-Weinberg (GSW) theory, which describes the electroweak interactions [2–4].

$SU(3)_C$ is the non-Abelian symmetry group of the strong interactions [1]. The gluonic gauge fields G are coupled to the color charges as formalized in Quantum Chromodynamics (QCD).

The local invariance of the Standard Model Lagrangian $\mathcal{L}_{\text{SM}}$ under the gauge Group G_{SM} (equation 1.1) results in 12 gauge bosons. They are spin-1 vector fields and mediate the interactions. A more detailed introduction to the theoretical base of the Standard Model can be found in [13–18].

Table 1.1 lists the gauge bosons together with their associated symmetries and coupling constants. The W_μ^1 and W_μ^2 gauge bosons can be identified with the experimentally observed W^+ and W^- particles. The experimentally observable neutral gauge bosons Z^0 and A (i.e. the photon γ) are correlated to W_μ^3 and B_μ by means of the weak mixing angle Θ_W (Weinberg angle) [18]:

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2), \\ A_\mu &= \sin \Theta_W W_\mu^3 + \cos \Theta_W B_\mu, \\ Z_\mu^0 &= \cos \Theta_W W_\mu^3 - \sin \Theta_W B_\mu. \end{aligned} \tag{1.3}$$

group	symmetry	gauge bosons	description	coupling constant
$SU(3)_C$	color	G_μ^a	gluon color octet a = 1...8	α_s
$SU(2)_L$	isospin	W_μ^i	isotriplet i = 1,2,3	g
$U(1)_Y$	hypercharge	B_μ		g'

Table 1.1: The gauge bosons of the Standard Model together with their associated symmetries and coupling constants.

The gravitational interaction might be mediated by a spin-2 field, describing the graviton G . However, gravitation is attached *ad hoc* to the other sectors of the Standard Model and is not yet properly formulated as a quantum field theory. One candidate, superstring theory [19], addresses this problem with some degree of success, but it only presents a qualitative picture which cannot yet be tested by experiment² [17]. Figure 1.1 summarizes the four interactions through exchange of the appropriate gauge bosons.

The basic constituents of matter in the Standard Model are the leptons and quarks, which are spin-1/2 particles (called fermions). They are realised as left-handed isospin ($SU(2)_L$) doublets and right-handed isospin singlets. In addition, quarks are color triplets. The leptons

²Due to the very weak strength of the gravitational force compared to the strength of the strong and electroweak forces at the distances or energies explored experimentally, the non-unification of gravitation in the framework of the standard model is of no concern for the present study. This conceptual problem is noted here only for completeness and also to illustrate that the Standard Model is not yet a complete “Theory of Nature”.

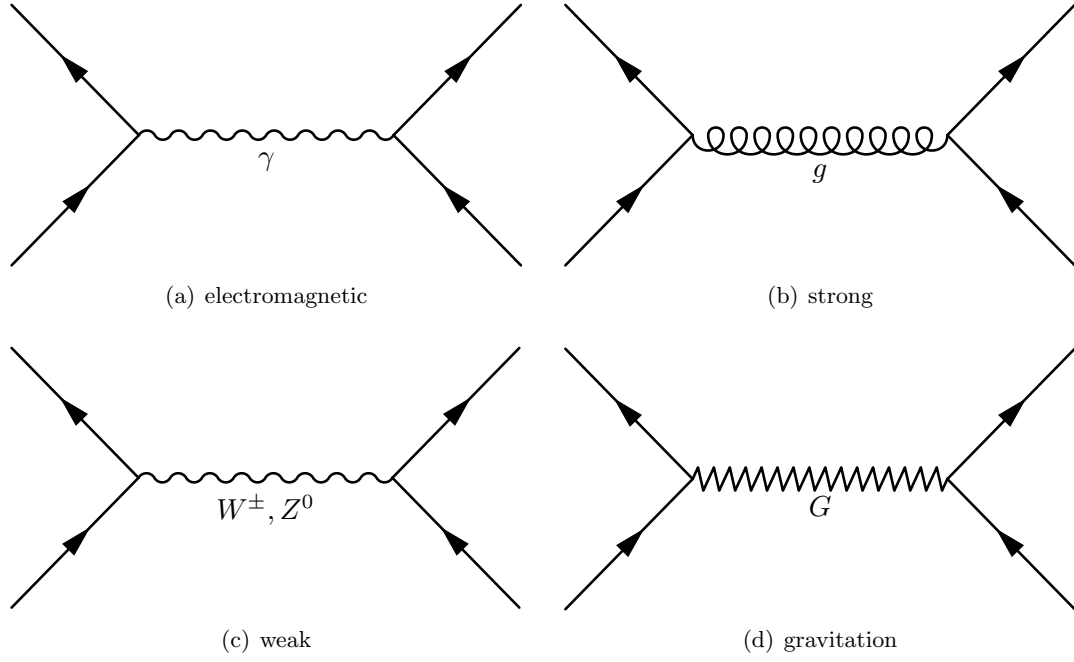


Figure 1.1: The four fundamental interactions through exchange of the appropriate gauge bosons.

and quarks are organized in three generations of fermions:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad (1.4)$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad (1.5)$$

Each particle has an antiparticle with the same mass and opposite quantum numbers. The down-type quark states are Cabibbo-Kobayashi-Maskawa mixtures of the mass eigenstates [20–22]. Table 1.2 summarizes the properties of leptons and quarks in the Standard Model.

Fermion			$\mathbf{I}_3^L$	$\mathbf{Y}^L$	$\mathbf{I}_3^R$	$\mathbf{Y}^R$	$\mathbf{Q}$
u	c	t	$+\frac{1}{2}$	$+\frac{1}{3}$	0	$+\frac{4}{3}$	$+\frac{2}{3}$
d	s	b	$-\frac{1}{2}$	$+\frac{1}{3}$	0	$-\frac{2}{3}$	$-\frac{1}{3}$
ν_e	ν_μ	ν_τ	$+\frac{1}{2}$	-1	-	-	0
e	μ	τ	$-\frac{1}{2}$	-1	0	-2	-1

Table 1.2: Weak isospin (I_3), hypercharge (Y) and electric charge (Q) assignments of the leptons and quarks. The electric charge Q of the fermions is listed in units of the electron charge $|e|$.

1.1.2 Spontaneous symmetry breaking, particle masses and the Higgs mechanism

The local gauge invariance of the Standard Model Lagrangian $\mathcal{L}_{\text{SM}}$ (see section 1.1.1) forbids mass terms for fermions and gauge bosons. The Standard Model Lagrangian contains therefore only massless fields [16, 23]. While this is fine for the photon, the $W^\pm$ and Z bosons as well as the fermions do have a mass. However, adding mass terms in a “simple” way (like e.g. a fermionic mass term $\mathcal{L}_m = -m\bar{\psi}\psi = -m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$ [16]) breaks the gauge invariance of the Standard Model Lagrangian. A solution to this problem is given by the Higgs mechanism.

In the Standard Model the masses of the particles can be generated by introducing interactions with a new scalar field: the Higgs field [9, 24]. The Higgs field can be added to the Standard Model Lagrangian $\mathcal{L}_{\text{SM}}$ in such a way that the masses of the particles are introduced consistently and the gauge invariance of the Standard Model is preserved. The gauge boson and fermion masses arise from the interaction energies with the ground state of the Higgs field, whose symmetry is spontaneously broken. The phenomenon of spontaneous symmetry breaking is illustrated in figure 1.2.

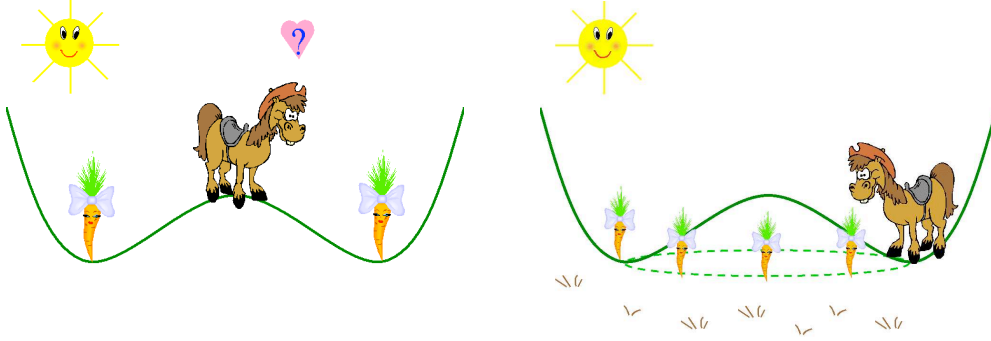


Figure 1.2: Illustration of the principle of spontaneous symmetry breaking. Although Nicolás (the horse) likes the symmetric food configuration, he must break the symmetry if he wants to get the food (left picture). In a three dimensional world, there is a flat circular valley along which Nicolás can move from one carrot to the other without effort (right picture). The existence of flat directions, which connect the degenerate states of minimal energy, is a general property of spontaneous symmetry breaking of continuous symmetries. In a Quantum Field Theory it is connected to the existence of massless degrees of freedom (the Goldstone theorem) [16].

This spontaneous symmetry breaking leads to the transition from the electroweak group $SU(2)_L \times U(1)_Y$ to the electromagnetic $U(1)_{\text{QED}}$ subgroup

$$SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{\text{SSB}} SU(3)_C \times U(1)_{\text{QED}}. \quad (1.6)$$

According to the Goldstone theorem, spontaneous symmetry breaking is accompanied by the appearance of massless spin-0 Goldstone bosons [25]. The Higgs field is a complex isodoublet field which corresponds to four real scalar fields. These fields produce four Goldstone bosons. Due to the underlying local gauge symmetry, three of them are absorbed and result in massive $W^\pm$ and Z gauge bosons. The photon γ (A gauge boson) remains massless because $U(1)_{\text{QED}}$

is an unbroken symmetry [4, 16, 17, 26, 27]. The masses of the $W^\pm$ and Z gauge bosons are related by the Weinberg angle Θ_W [16]

$$M_W = M_Z \cos \Theta_W. \quad (1.7)$$

The fourth Goldstone Boson, which is not absorbed, should be experimentally detectable and is identified as the Higgs boson H . Although the mass of the Higgs boson cannot be predicted in the Standard Model, internal consistency and extrapolations of the Standard Model to higher energies lead to upper and lower bounds on the Higgs boson mass.

Experimental searches for the Higgs boson have so far only provided a lower bound on its mass, corresponding to the exclusion of the kinematical range accessible at LEP and the Tevatron [5, 28, 29]:

$$m_H > 114.4 \text{ GeV}/c^2 \quad (95 \% \text{ CL}). \quad (1.8)$$

The upper limit (based on theoretical calculations) for the Standard Model Higgs boson mass is approximately $1 \text{ TeV}/c^2$ [18]. Furthermore, the precision electroweak measurements imply that the mass of the Standard Model Higgs boson is lower than about $144 \text{ GeV}/c^2$ (one-sided 95 % confidence level upper limit derived from $\Delta\chi^2 = 2.7$ for the blue band (figure 1.3(a)), including both the experimental and the theoretical uncertainty) [5, 28].

Figure 1.3(a) results from the input measurements listed in figure 1.3(b) and motivates searching for the Standard Model Higgs boson in the mass range $114 \text{ GeV}/c^2 < m_H < 144 \text{ GeV}/c^2$ [5, 28].

1.1.3 Higgs production at proton-proton colliders

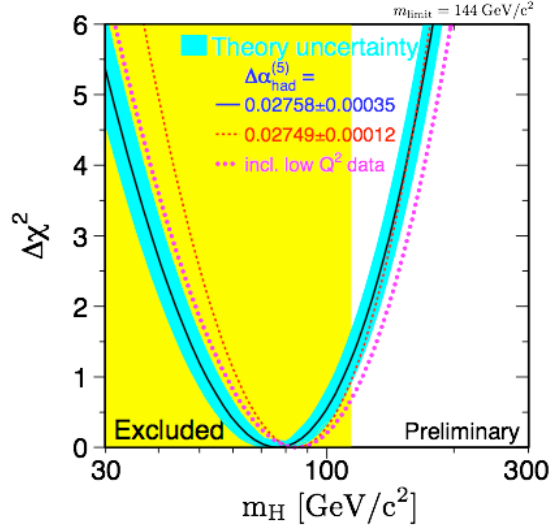
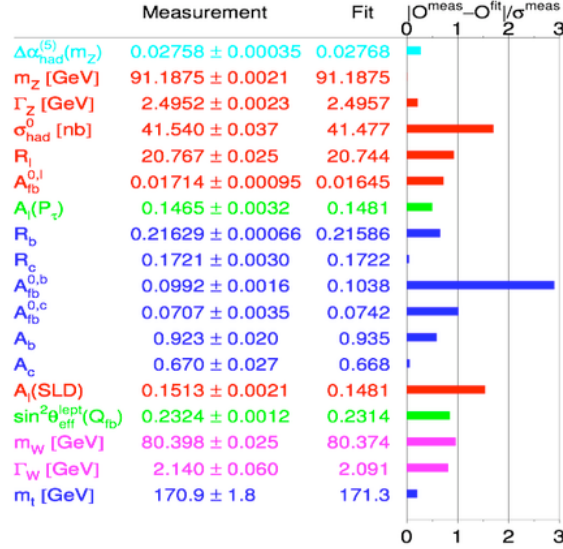
Starting in Summer 2009 the Large Hadron Collider (LHC) will make possible the search for the Higgs boson in proton-proton collisions at a center of mass energy of $\sqrt{s} = 14 \text{ TeV}$ (see also section 2.1). In figure 1.5(a) the cross sections of the several production mechanisms are shown as a function of the Higgs boson mass. There are basically four production mechanisms for Higgs boson production at the LHC:

- gluon-gluon fusion: $gg \rightarrow H$ (figure 1.4(a)),
- vector boson fusion: $qq \rightarrow Hqq$ via W^+W^- or $ZZ \rightarrow H$ (figure 1.4(b)),
- associated production with vector bosons: $q\bar{q} \rightarrow WH, ZH$ (figure 1.4(c)),
- associated production with top quarks: $gg, q\bar{q} \rightarrow t\bar{t}H$ (figure 1.4(d)).

Figure 1.4 shows the leading order Feynman diagrams for these production mechanisms.

At the LHC the dominant mechanism is gluon-gluon fusion $gg \rightarrow H$ via an intermediate bottom or top quark loop (figure 1.4(a)). The Higgs boson has a preference to couple to heavy particles and therefore the top quark loop is preferred over other quark-flavor loops [37]. For very high Higgs boson masses the other production mechanisms also become relevant.

Figure 1.5(b) shows the branching ratios for several Higgs decay channels as a function of the Higgs boson mass. The Higgs boson decays predominantly to $b\bar{b}$ for $m_H < 130 \text{ GeV}/c^2$. In this mass range the decay into $\tau^+\tau^-$ is also important and amounts to 7 %. The branching ratio of e.g. $H \rightarrow \gamma\gamma$ in the intermediate mass range between 120 and $130 \text{ GeV}/c^2$ is quite small but owing to the small natural width $\Gamma_H < 1 \text{ GeV}/c^2$ the decay of the Higgs boson into two photons has a very clear signature. For larger values of m_H , the Higgs boson decays


 (a) $\Delta\chi^2 = \chi^2 - \chi_{\min}^2$ versus m_H


(b) input measurements for the Higgs boson mass prediction

Figure 1.3: Higgs boson mass prediction from the global fit to all available electroweak data [5, 28]. (a) shows the $\Delta\chi^2$ curve derived from high- Q^2 precision electroweak measurements, performed at LEP and by SLD, CDF, and D0, as a function of the Higgs boson mass m_H . The preferred value for its mass, corresponding to the minimum of the curve, is at 76 GeV/ c^2 , with an experimental uncertainty of +33 and −24 GeV/ c^2 (at 68 % confidence level derived from $\Delta\chi^2 = 1$ for the central fit given by the black line, thus not taking the theoretical uncertainty shown as the blue band into account). The result is only little affected by the low- Q^2 results (dotted pink curve). The red dashed line is the result obtained using a revised evaluation of $\Delta\alpha^{(5)}(m_Z^2)$ [30]. (b) shows a summary of the 18 input measurements included in the Standard Model fit. The pulls are defined as deviation from the theoretical values in units of the experimental rms (1σ) deviations.

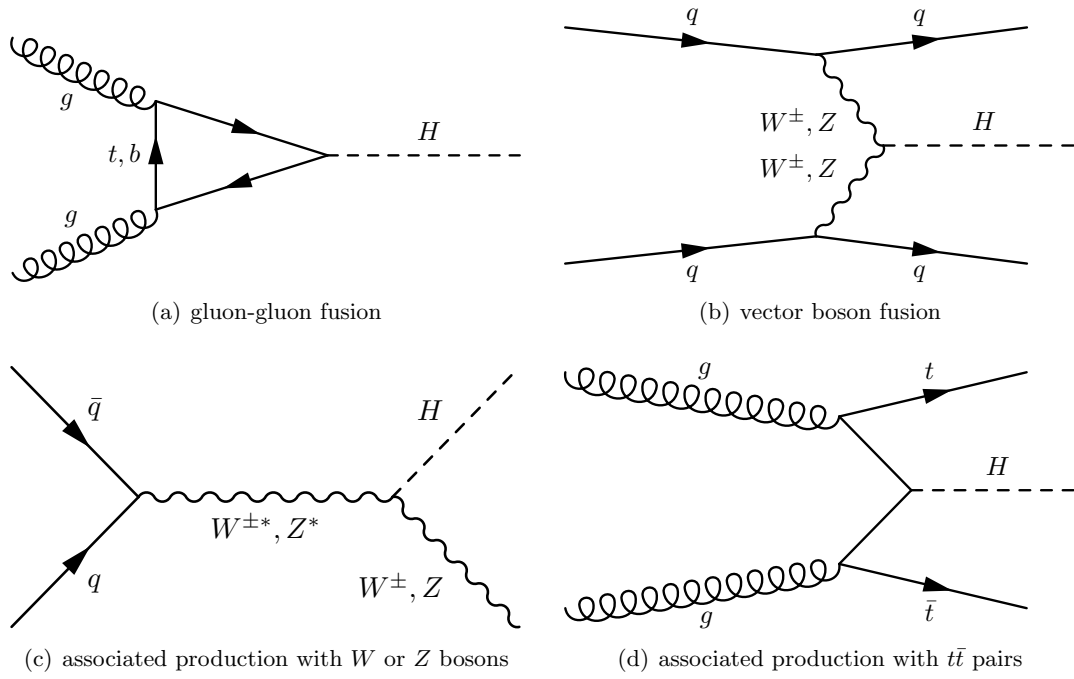


Figure 1.4: The Higgs boson production mechanisms at the LHC: (a) gluon-gluon fusion, (b) vector boson fusion, (c) associated production with a W or Z boson (also known as Higgsstrahlung) and (d) associated production with a $t\bar{t}$ pair.

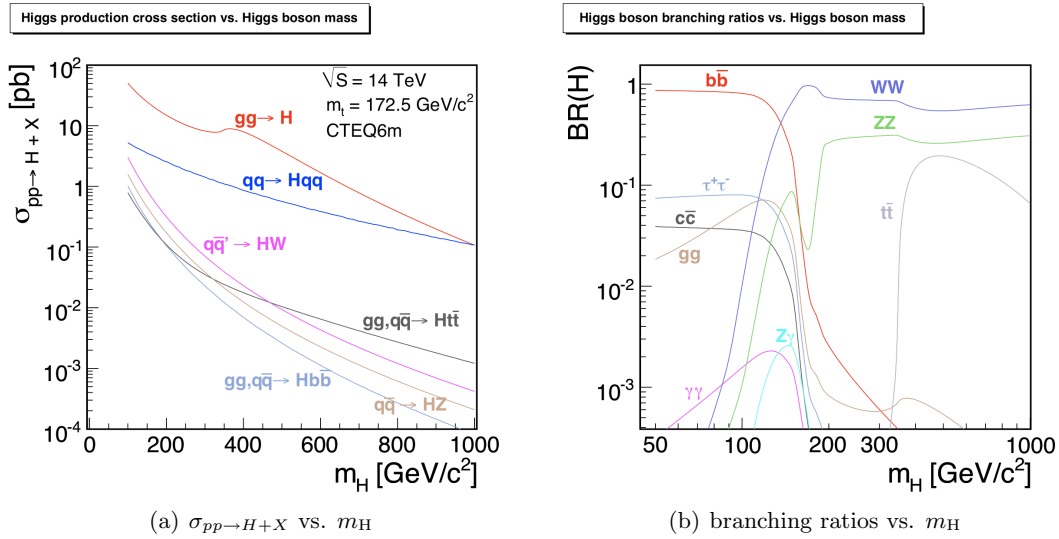


Figure 1.5: Higgs production cross sections at the LHC [31–35] and the branching ratios of the dominant decay modes [35, 36]: (a) Higgs boson production cross section for the various production mechanisms as a function of the Higgs boson mass, (b) branching ratios of the dominant decay modes of the Standard Model Higgs boson as a function of its mass.

mainly through $H \rightarrow ZZ$ and $H \rightarrow W^+W^-$. The branching ratio to $t\bar{t}$ can be almost 20 % at $m_H > 2m_t$ [35, 36].

The Higgs boson discovery potential of the CMS experiment (see section 2.2) is summarized in [38] and described in more detail in [39].

1.2 Parton distribution functions

Parton distribution functions (PDFs) give the probability to find quarks and gluons (partons) in a hadron as a function of the fraction x of the hadron's momentum carried by the parton. The PDFs are determined from experimental results on short distance parton scattering.

Figure 1.6 shows an example for such a process, where hadron A interacts with hadron B resulting in the production of a Z boson. A parton of type a comes from hadron A and carries a fraction x_A of the hadron's momentum. The probability to obtain such a parton a is given by $f_{a/A}(x_A)dx_A$. A second parton b comes from the hadron B . The probability to find it carrying a momentum fraction x_B , is given by $f_{b/B}(x_B)dx_B$. The functions $f_{a/A}$ and $f_{b/B}$ are the parton distribution functions [40]. Together with the relevant parton cross section (in this case for the process $q\bar{q} \rightarrow \gamma^*/Z$) they enter in the calculation of the cross section of the process under consideration. A detailed description of parton distribution functions can be found in [41–43].

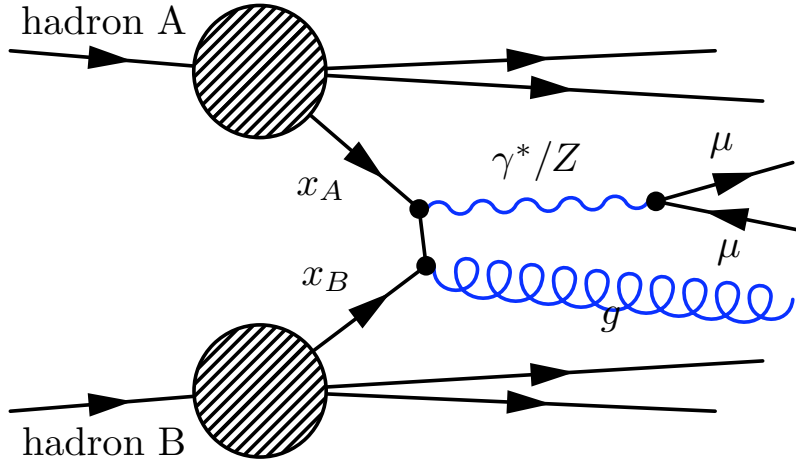


Figure 1.6: Feynman diagram showing the interaction between hadron A and hadron B resulting in two partons with momentum fractions x_A and x_B . The graph illustrates the Drell-Yan production of muon pairs in hadron collisions and also shows the radiation of an additional gluon (in blue).

The cross section for the hard scattering process between hadron A and hadron B can be written as

$$\sigma(P_A, P_B) = \sum_{i,j} \int dx_A dx_B f_i(x_A, \mu_F^2) f_j(x_B, \mu_F^2) \hat{\sigma}_{ij}(p_a, p_b, \frac{Q^2}{\mu_F^2}, \alpha_S(\mu_R^2)), \quad (1.9)$$

where P_A and P_B denote the four momenta of the incoming hadrons and p_a and p_b denote the momenta of the partons participating in the hard interaction [44]. Q is the characteristic scale of the hard scattering process, which can be *e.g.* the mass of the Z boson. The functions $f_j(x, \mu_F^2)$ are the parton distribution functions described before, defined at a factorization

scale μ_F . The parton cross section for the scattering of partons of types i and j is given by $\hat{\sigma}_{ij}$.

The parton cross sections can often be calculated as an expansion in powers of the strong coupling constant α_S

$$\hat{\sigma}_{ij} = \sum_{n=0}^k \alpha_S (\mu_R^2)^n c_n. \quad (1.10)$$

The coefficients c_n in this power expansion are functions of the kinematic variables and the factorization scale. The parameter μ_R , introduced in equation 1.10, is related to the renormalization of the strong coupling constant $\alpha_S(\mu_R^2)$ [44].

Parton cross sections can be easily calculated in leading order (Born level, $n = 0$), but become complicated in the next-to-leading order ($n = 1$) and beyond ($n > 1$), due to the appearance of divergences in naive calculations. These divergences can be removed by introducing the dependence on the renormalization scale μ_R . A detailed introduction to the techniques used in QCD calculations is given in [40, 41, 44, 45].

The factorization scale μ_F can be thought of as the scale which separates the contributions from interactions occurring long before the hard scattering (long-distance physics) from the scattering of the two partons (short distance physics). A parton emitted with a small transverse momentum less than the scale μ_F is considered as a part of the incoming hadron structure and is absorbed into the parton distribution function. However, a parton emitted at large transverse momentum (implying short times and distances) is part of the parton cross section $\hat{\sigma}_{ij}$.

The scale μ_F should be chosen to be of the order of the hard scale Q , characterizing the interaction between the partons. As more terms are included in the power expansion (equation 1.10) of the parton cross section, the dependence on the factorization scale becomes weaker. The same is true for the renormalization scale μ_R and therefore often the simplifying assumption of a single scale $\mu = \mu_F = \mu_R$ is made. Variation of the scales changes the coefficients c_n in the power expansion of the parton cross section (equation 1.10) at higher orders in such a way that the cross section to all orders becomes independent of the scales [44].

1.3 Massive lepton pair production in hadron collisions

In the discussion of the parton distribution functions in the previous section, the production of the lepton pairs in hadron collisions was used as an example (see figure 1.6). This section describes the production of lepton pairs in hadron interactions and the calculation of the cross section for this process in more detail. The experimental methods and analysis techniques needed for the measurement of the cross section with the CMS experiment will be described in chapter 4.

The production by quark-antiquark annihilation of a lepton pair l^+l^- with large invariant mass, $m = \sqrt{(p_{l^+} + p_{l^-})^2} \gg 1 \text{ GeV}/c^2$, is known as the Drell-Yan process [46]. The cross section σ_{AB} for producing such a lepton pair in the collision of beam A with beam B is obtained by a convolution of the subprocess cross section $\hat{\sigma}$ for $q\bar{q} \rightarrow l^+l^-$ with the parton distribution functions (see section 1.2) and by summing over all quark-antiquark combinations³ [44]:

$$\sigma_{AB} = \sum_q \int dx_1 dx_2 f_q(x_1) f_{\bar{q}}(x_2) \hat{\sigma}_{q\bar{q} \rightarrow l^+l^-}. \quad (1.11)$$

³This is a commonly used technique in QCD calculations and is known as the principle of *factorization* [45].

Assuming $m \ll m_Z$ the subprocess cross section corresponds to the annihilation process $q\bar{q} \rightarrow \gamma^* \rightarrow l^+l^-$, which in analogy to the production of quark-antiquark pairs in lepton-antilepton collisions (e.g. $e^+e^- \rightarrow q\bar{q}$), can be calculated to lowest order to be [44]

$$\hat{\sigma}(q(p_1)\bar{q}(p_2) \rightarrow l^+l^-) = \frac{4\pi\alpha^2}{3\hat{s}} \cdot \frac{1}{N} \cdot Q_q^2, \quad (1.12)$$

where $\hat{s} = (p_1 + p_2)^2$ and Q_q is the electric charge of the quarks. Due to *confinement* the annihilation process can take place only when the color of the quark and the antiquark matches and therefore the subprocess cross section $\hat{\sigma}_{q\bar{q} \rightarrow l^+l^-}$ is smaller by the color factor $\frac{1}{N^2} = \frac{1}{9}$ than the subprocess cross section $\hat{\sigma}_{l^+l^- \rightarrow q\bar{q}}$ given by [15]

$$\hat{\sigma}_{l^+l^- \rightarrow q\bar{q}} = \frac{4\pi\alpha^2}{\hat{s}} \cdot Q_q^2. \quad (1.13)$$

The incoming quark and antiquark have in general a spectrum of collision energies and it is appropriate to consider the differential cross section

$$\frac{d\hat{\sigma}}{dm^2} = \frac{4\pi\alpha^2}{3m^2} \cdot \frac{1}{N} \cdot Q_q^2 \cdot \delta(\hat{s} - m^2), \quad (1.14)$$

where m is the mass of the produced lepton pair [44].

Substitution of equation 1.14 in equation 1.11 gives the parton-model cross section for the Drell-Yan process

$$\frac{d\sigma}{dm^2} = \int_0^1 dx_1 dx_2 \sum_q (f_q(x_1) f_{\bar{q}}(x_2) + (q \leftrightarrow \bar{q})) \cdot \frac{d\hat{\sigma}}{dm^2}(q\bar{q} \rightarrow l^+l^-) \quad (1.15)$$

$$= \frac{4\pi\alpha^2}{3m^2 N} \int_0^1 dx_1 dx_2 \delta(x_1 x_2 s - m^2) \cdot \sum_q Q_q^2 (f_q(x_1) f_{\bar{q}}(x_2) + (q \leftrightarrow \bar{q})), \quad (1.16)$$

where the square of the $q\bar{q}$ collision energy $\hat{s}$ has been related to the overall hadron-hadron collision energy s [44].

At higher center of mass energies the contribution from Z boson production has to be taken into account. Owing to the small width of the Z boson compared to its mass, the lepton pair production cross section can be calculated by multiplying the subprocess cross section for Z boson production with the appropriate branching ratios of the final state. The $q\bar{q} \rightarrow Z$ subprocess cross section is derived to leading order from the coupling of the gauge boson to the fermions:

$$\hat{\sigma}_{q\bar{q} \rightarrow Z} = \frac{\pi}{3} \sqrt{2} G_F m_Z^2 (V_q^2 + A_q^2) \delta(\hat{s} - m_Z^2), \quad (1.17)$$

where G_F is the Fermi constant and A_q and V_q are the couplings of the Z boson to the quarks:

$$V_q = I_q^3 - 2Q_q \sin^2 \Theta_W \quad (1.18)$$

$$A_q = I_q^3 \quad (1.19)$$

with Q_q the electric charge of the quarks and I_q^3 the third component of the electroweak isospin (compare section 1.1.1).

The on-shell Z boson decays into a lepton pair l^+l^- with the partial decay width [29, 44]

$$\Gamma(Z \rightarrow l^+l^-) = \frac{G_F m_Z^3}{6\sqrt{2}\pi} (|V_l|^2 + |A_l|^2) = (83.984 \pm 0.086) \text{ MeV}/c^2. \quad (1.20)$$

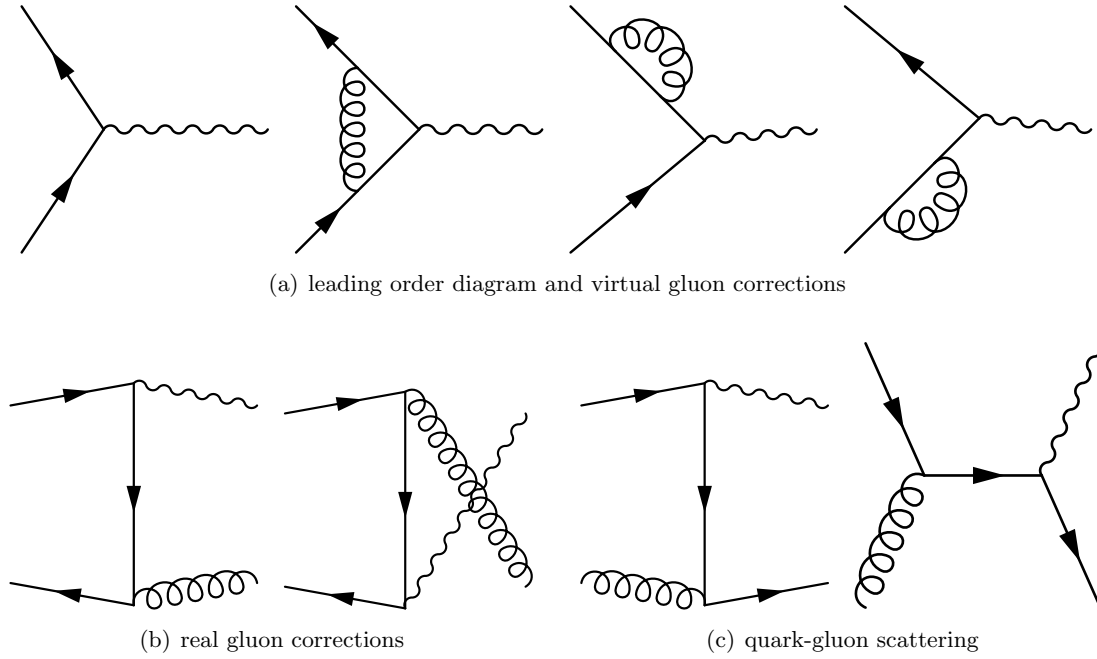


Figure 1.7: The leading order and next-to-leading order diagrams for the Drell-Yan process: (a) shows the leading order and the virtual gluon corrections, (b) the real gluon corrections and (c) the quark-gluon scattering process.

The branching ratio of the Z boson into two muons is [29]

$$\text{BR}(Z \rightarrow \mu^+ \mu^-) = (3.366 \pm 0.007) \%. \quad (1.21)$$

The total width of the Z boson is $\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}/c^2$ [29].

Figure 1.7 shows the leading- and next-to-leading order diagrams for the Drell-Yan process. The contributions of $\mathcal{O}(\alpha_S)$ can be divided into three classes:

- virtual gluon corrections to the leading order contribution (figure 1.7(a)),
- real gluon corrections $q(p_1) + \bar{q}(p_2) \rightarrow \gamma^* + g(k)$ (figure 1.7(b)) and
- quark-gluon scattering $qg \rightarrow \gamma^* q$ and the corresponding $\bar{q}g$ contribution (figure 1.7(c)).

For the Drell-Yan process the QCD next-to-leading order (NLO) corrections (see also section 1.2) have been calculated [47, 48]. Figure 1.8 shows the double differential cross section as a function of rapidity Y ⁴. Compared to the leading order cross section the NLO corrections can be quite large. The $\mathcal{O}(\alpha_S^2)$ corrections (NNLO) to the Drell-Yan process are also known [49–51]. These are generally smaller than the $\mathcal{O}(\alpha_S)$ corrections [44], as shown in figure 1.8. The figure also shows the dependence of the cross section on the choice of the renormalization

⁴The rapidity Y is defined as

$$Y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) = \frac{1}{2} \ln \left(\frac{x_1}{x_2} \right). \quad (1.22)$$

In the following the rapidity is often replaced by the pseudorapidity η

$$\eta = -\ln \tan(\Theta/2), \quad (1.23)$$

which coincides with the rapidity Y in case of massless particles. Since the angle Θ from the beam direction is measured directly in the detector, the pseudorapidity is experimentally a more convenient variable.

and factorization scales: for the leading order cross section the dependence is large (the blue band in figure 1.8), it gets smaller for the next-to-leading order cross section (the green band), while for the next-to-next-to-leading order cross section the dependence is very small (the red band).

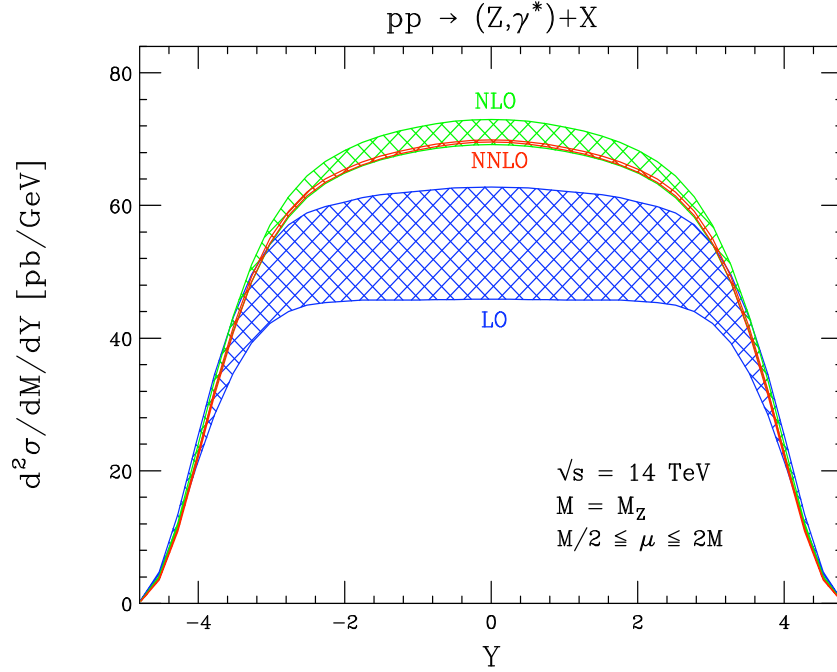


Figure 1.8: The rapidity distribution for on-shell Z boson production at the LHC, including LO, NLO and NNLO results. The bands indicate the variation for values of the renormalization and factorization scales in the range $M_Z/2 \leq \mu \leq 2M_Z$ [52].

Chapter 2

The Large Hadron Collider and CMS experiment

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a two-ring, superconducting accelerator and collider currently under construction at CERN¹ [53]. The LHC machine will be installed in the 26.7 km long tunnel where the e^+e^- collider LEP [54] was located until 2000 [55]. Figure 2.1(a) shows an overall view of the LHC setup.

The beams are prepared for injection into the LHC rings using the accelerator chain (Linac, Booster, PS and SPS) [56] already existing at CERN, which is shown in figure 2.1(b). The SPS accelerates the beams to 450 GeV before they are injected into the LHC ring where each proton beam finally reaches an energy of 7 TeV, resulting in center of mass energies of 14 TeV. The LHC can also be operated as a heavy-ion collider (utilizing *e.g.* lead ions), reaching a center of mass energy of 1.15 PeV corresponding to an energy of 2.76 TeV/nukleon for lead-lead collisions [55]. This offers the opportunity to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected.

The basic layout of the LHC machine follows the design of LEP, with eight straight sections each approximately 528 m long available for experiments or utilities like radio frequency (RF), collimation and beam dump systems (figure 2.2). The two high-luminosity regions are located at diametrically opposite straight sections: at point 1 the ATLAS² experiment [57] is located and the CMS³ experiment [58] is at point 5. ATLAS and CMS are both general purpose particle physics experiments that, starting in 2009, will be used to confirm the Standard Model (see chapter 1) and to search for new phenomena in the head-on collisions of protons at the high energies delivered by the LHC.

Integrated into the CMS experiment at point 5 is the TOTEM experiment [59] for the detection of protons from elastic scattering at small angles and the measurement of the total cross section.

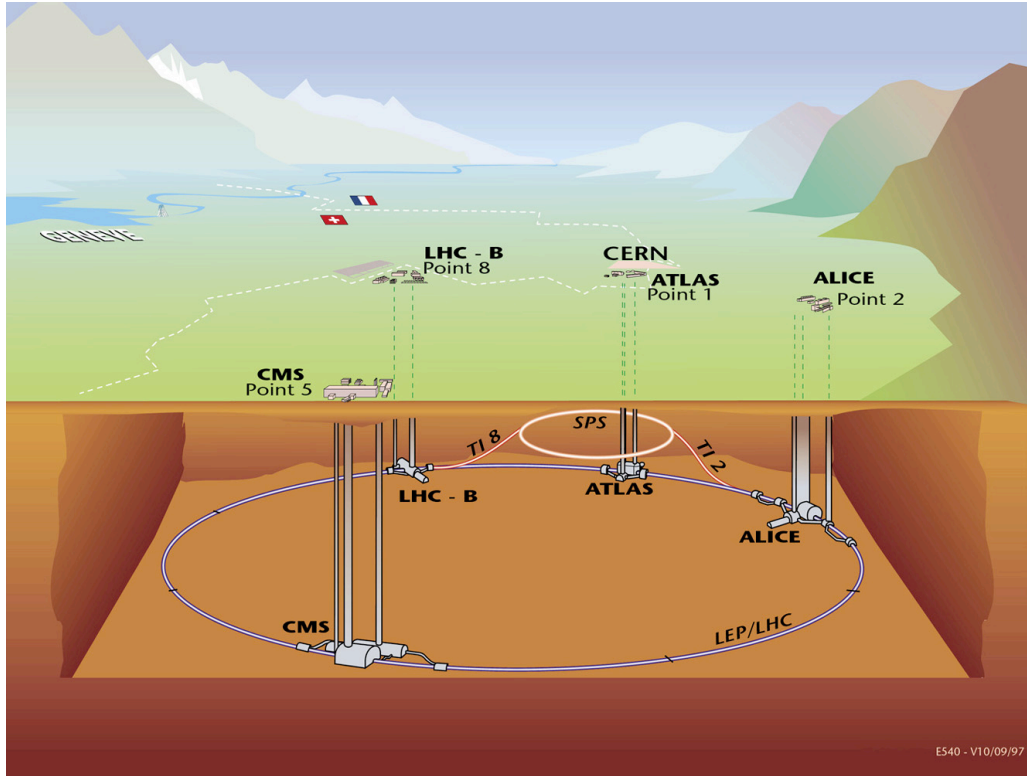
Two further experiments are located at point 2, ALICE⁴, and at point 8, LHCb. The ALICE detector is optimized for heavy-ion collisions [60], which can also be measured with the CMS experiment. LHCb is dedicated to B meson physics with a program of performing precise measurements of CP violation and rare B-decays [61]. The straight sections in these two sectors also contain the injection systems for the beams. The beams are brought to collision only at the location of the four experiments. The remaining straight sections do not have beam interaction regions, but include systems to handle the beams at the very high level

¹Centre Europeen pour la Recherche Nuclaire (European Organization for Nuclear Research)

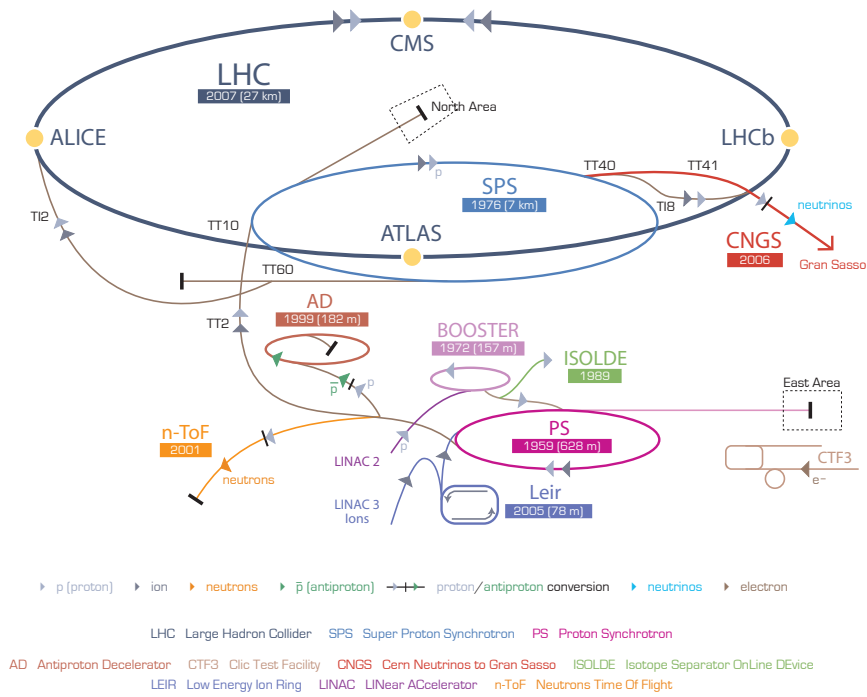
²A large Toroidal LHC ApparatuS

³Compact Muon Solenoid

⁴A Large Ion Collider Experiment



(a) Overall view of the LHC collider with the experiments ALICE, ATLAS, CMS and LHCb (CERN copyright).



(b) The LHC collider with pre-accelerators (CERN copyright).

Figure 2.1: The LHC experimental setup.

of accuracy and safety necessary for the energies and luminosities reached at the LHC.

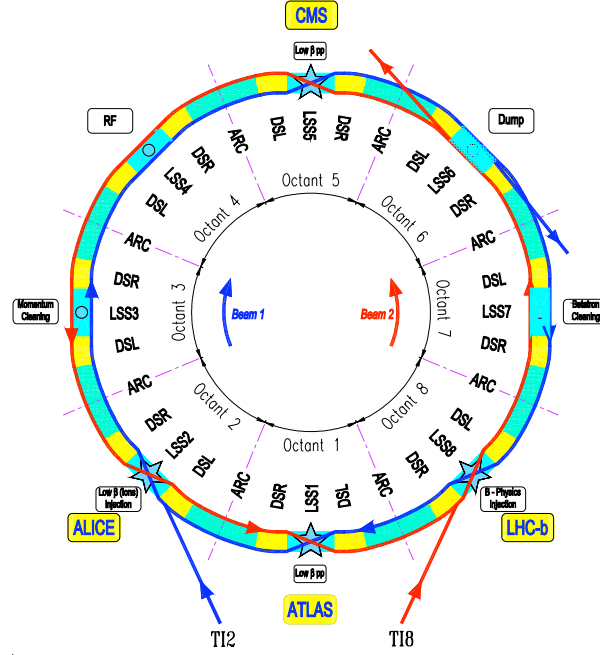


Figure 2.2: Schematic layout of the Large Hadron Collider [55].

In order to reach a high luminosity each proton beam contains a large number of bunches (2808 bunches each with $1.15 \cdot 10^{11}$ protons). There will be a bunch crossing every 25 ns, resulting in a bunch spacing of 7.5 m. The luminosity is given by [62]

$$\mathcal{L} = \frac{\gamma f n_b N_p^2}{4\pi \varepsilon_n \beta^*} F, \quad (2.1)$$

where

- γ = relativistic Lorentz factor,
- f = revolution frequency,
- n_b = number of bunches,
- N_p = number of protons in a bunch,
- ε_n = normalized transverse beam emittance (with a design value of $3.75 \mu\text{m rad}$ [55]),
- β^* = beta function at the collision point,
- F = geometric luminosity reduction factor due to the crossing angle at the interaction point ($F \approx 0.84$ at point 5, the location of the CMS detector [55]).

The design luminosity $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ leads to around 1 billion proton-proton interactions per second. However, the initial luminosity will be lower as part of the beam dump and collimation systems are staged and therefore the beam current cannot exceed half the nominal value. During the first full year of physics running, a peak luminosity of $\mathcal{L} = 2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ should be reached (low-luminosity phase). The integrated luminosity will most likely be about 5 fb^{-1} during this first year [62].

2.2 The CMS experiment

This section describes the design and construction of the CMS detector. CMS will be installed about 100 m underground at point 5 (see figure 2.1(a)), close to Cessy (France), between the lake of Geneva and the Jura. The main features of the CMS detector are:

- An overall diameter of 14.6 m, a length of 21.6 m and a total weight of 12500 tons [63].
- A superconducting solenoid provides a large magnetic field of 4 T.
- An online event selection process (trigger) reduces the observed event rate at design luminosity from approximately 10^9 inelastic events per second to 100 events per second for storage and subsequent analysis.
- A full silicon-based inner tracking system.
- An active scintillating crystal-based electromagnetic calorimeter (ECAL) with a barrel (EB) and two endcaps (EE). A preshower detector (ES) consisting out of two lead radiator/silicon strip layers is installed in front of the endcaps of the electromagnetic calorimeter and serves to reject π^0 s and to improve the position determination for electrons and photons.
- The hadronic calorimeter (barrel HB and endcap HE) is located inside the magnet. A “tail-catcher” part (HO) is integrated in the muon barrel system, while a very forward calorimeter (HF) provides hermeticity up to $|\eta|$ values of 5.
- The CMS muon system provides good muon identification and an independent measurement of the muon momentum in the return field of the magnet iron yoke.

Figure 2.3 shows the overall layout of the CMS detector. The coordinate system is defined at the interaction point with positive x pointing inward toward the center of the LHC ring, the y -axis pointing vertically upward and the z -axis along the beam direction toward the Jura mountains as seen from LHC Point 5 [63]. The azimuthal angle φ is measured from the x -axis in the xy plane. The polar angle Θ is measured from the z -axis. Pseudorapidity is defined as $\eta = -\ln \tan(\Theta/2)$ (compare equation 1.23). Figure 2.4 shows a quarter of the rz view of the CMS detector, also indicating the η ranges covered by the various detector components.

Charged-particle tracks are measured by a silicon pixel detector placed close to the nominal interaction region and by a silicon strip tracker. Furthermore the muon system, which is integrated in the return yoke of the magnet, provides tracking and identification of possible muon candidates. The energy of charged and neutral particles is measured with electromagnetic and hadron calorimeters. Both calorimeters are located inside the superconducting coil [58, 62, 63]. The CMS subdetectors and their (expected) performance are described in the following subsections. After a short introduction to the superconducting magnet the CMS subdetectors will be presented starting with the innermost detector (the pixel detector) followed by a description of the silicon strip tracker and both calorimeters. Finally the outermost subsystem of the CMS detector, the muon system, is presented.

The systems used for triggering, data acquisition and luminosity measurement, as well as the CMS software (CMSSW), which is utilized by the trigger and for the processing and analysis of the data are described in the last three sections of this chapter.

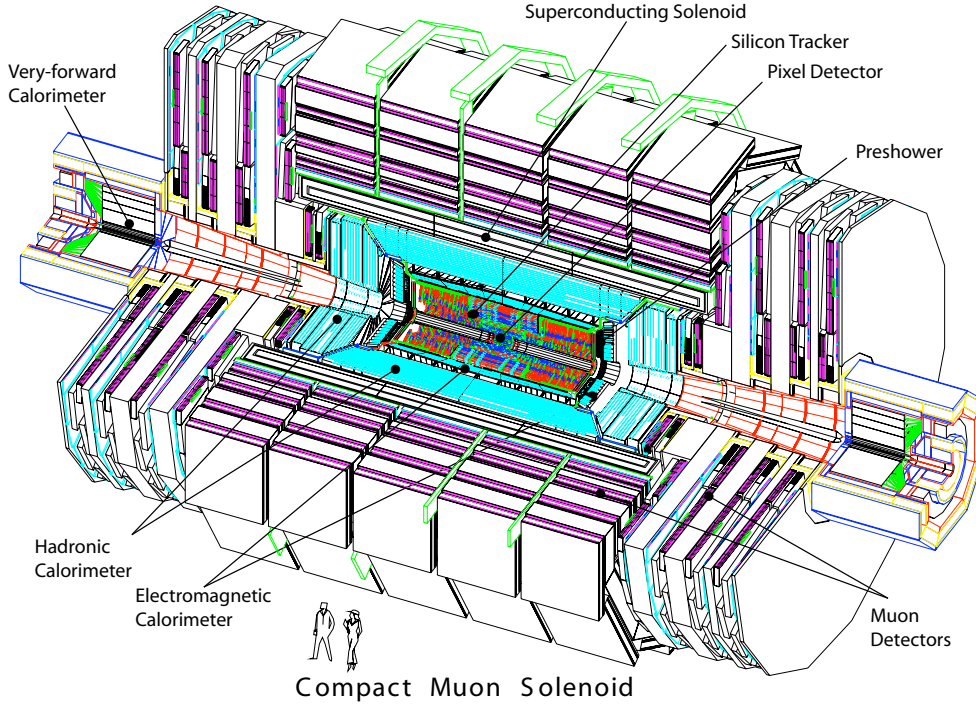


Figure 2.3: A perspective view of the CMS detector [62].

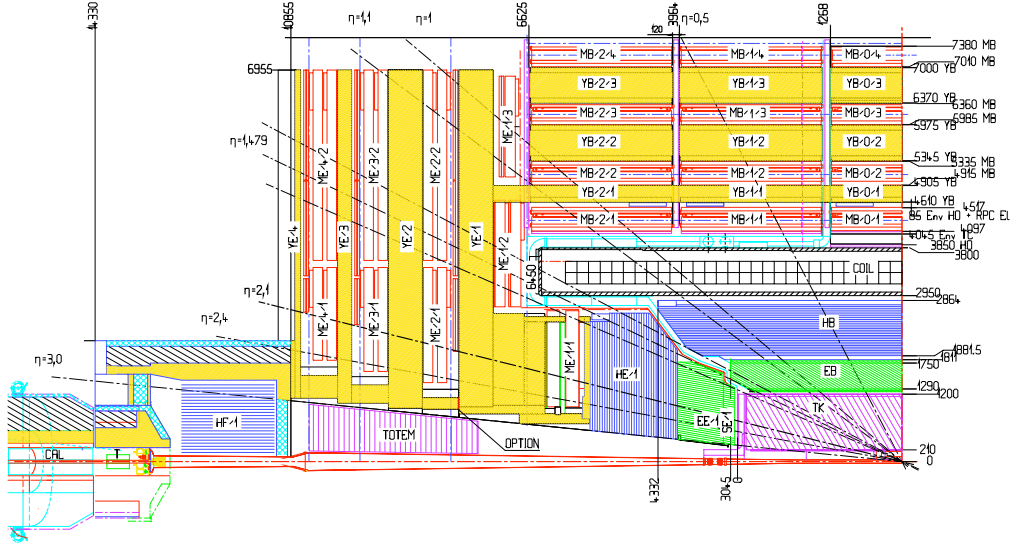


Figure 2.4: One quarter longitudinal view of the CMS experiment. The complete ECAL (EB, EE, ES) and 2 parts of the HCAL (HB, HE) together with the tracker (TK) are located inside the superconducting coil. HF is located downstream of HE, behind the TOTEM experiment. HO is located inside the muon barrel (MB) system. Shown also are the muon endcaps (ME) and the return yoke of the barrel (YB) and endcap (YE). Dimensions are in units of mm [62].

2.2.1 The magnet

The superconducting solenoid of the CMS magnet is 12.5 m long and has a diameter of 6.3 m. The magnet has been designed to reach an induction of 4 T. The magnetic flux is returned via a 1.5 m thick saturated iron yoke [64]. The strong bending power of the magnet makes possible a good momentum resolution for charged particles. The main magnet design parameters are listed in table 2.1.

Magnetic length	12.5 m
Free bore diameter	6.3 m
Central magnetic induction	4 T
Nominal current	19.14 kA
Stored energy	2.6 GJ
Weight of cold mass	220 t
Total mass of iron in return yoke	10000 t

Table 2.1: Main design parameters of the CMS magnet [63].

The CMS magnet has been successfully tested up to the design induction of 4 T. For operational reasons it has been decided to operate it at 3.8 T during data taking. The slightly lower magnetic induction has the advantage that possible aging of the magnet is reduced, which is important since the experiment must run for more than 10 and perhaps even up to 20 years. In addition the general safety margins will be increased [65].

2.2.2 The inner tracking system

The inner tracking system of CMS is designed to provide precise measurements of the trajectories of charged particles emerging from the LHC collisions, as well as a precise reconstruction of secondary vertices. The inner tracking system surrounds the interaction region and has a length of 5.8 m and a diameter of 2.5 m [63].

The CMS tracker is composed of a pixel detector with three barrel layers and 2 forward discs on each side and a silicon strip tracker with 10 barrel layers and a mini endcap (3 discs) and a large endcap (9 discs) on each side (see figure 2.5). The acceptance of the tracker extends up to a pseudorapidity of $|\eta| < 2.5$. The CMS tracker with about 200 m² of active silicon area is the largest silicon tracker ever built [66].

2.2.2.1 The pixel tracker

The pixel detector is the part of the inner tracking system which is closest to the interaction region. It contributes precise tracking points in (r, φ) and z coordinates, which, due to the small distance to the beam pipe, results in good impact parameter resolution, important for a good secondary vertex reconstruction. To achieve comparable resolution of the vertex position in the transverse and the longitudinal planes, a design with a rectangular pixel cell size of $150 \times 100 \mu\text{m}^2$ and a thickness of $290 \mu\text{m}$ has been chosen [67]. The shorter $100 \mu\text{m}$ side is located in the r - φ direction for the barrel and in the r direction for the endcaps. The pixel detector covers a pseudorapidity range of $-2.5 < \eta < 2.5$, matching the acceptance of the silicon strip tracker (compare figure 2.5).

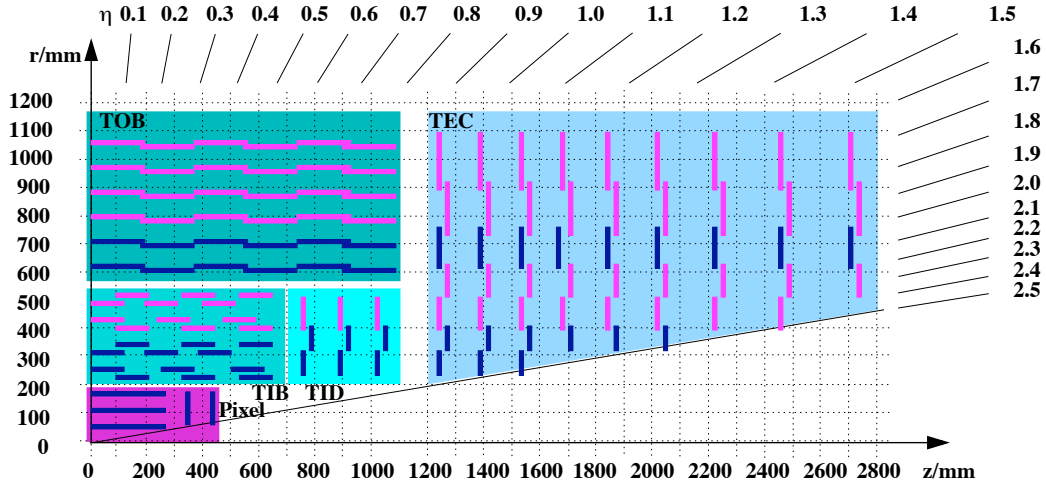


Figure 2.5: The tracker layout (1/4 of the r - z view). Each blue and pink line represents a detector module. Blue colored lines indicate back-to-back modules which deliver stereo hits.

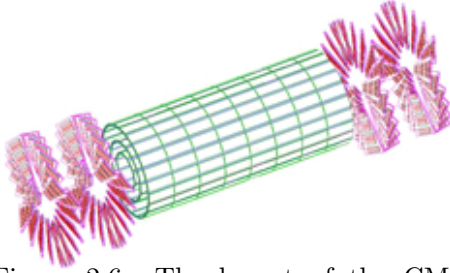


Figure 2.6: The layout of the CMS pixel vertex detector with 3 barrel layers and 2 endcap discs on each side.

As mentioned above, the pixel detector layout consists of three barrel layers and two endcap discs on each side. The barrel layers are positioned at the mean radii of 4.4, 7.3 and 10.2 cm and have a length of 53 cm. The two endcap discs, extending from 6 to 15 cm in radius, are placed at $z = \pm 34.5$ cm and ± 46.5 cm from the interaction point [67].

The barrel comprises 768 pixel modules arranged in so-called half-ladders of four identical modules each. The remaining 632 modules are assembled on the endcap discs in a turbine-like geometry. Figure 2.6 shows a picture of the pixel detector. The pixel barrel detector contains 48 million pixels, whereas the endcap detectors contain 18 million pixels. Together the barrel and endcap detectors cover a total area of approximately 1 m^2 . The spatial resolution is typically about $20 \text{ }\mu\text{m}$ in the r - z plane and about $10 \text{ }\mu\text{m}$ for the r - ϕ measurement [62].

2.2.2.2 The strip tracker

The pixel detector described in the previous section is surrounded by the silicon strip tracker (see figure 2.7), building together the inner tracking system of the CMS detector. The barrel region of the silicon strip tracker is divided in two parts: the tracker inner barrel (TIB) and the tracker outer barrel (TOB). The inner barrel is made out of 4 concentric cylinders (mean radii at 255.0 mm, 339.0 mm, 418.5 mm and 498.0 mm from the beam axis) and extends up to $|z| < 70$ cm [63]. The two innermost layers of the TIB are equipped with double sided modules, while the outer two layers host single sided modules.

Double sided, or “stereo” modules, are able to provide a measurement in both r - ϕ and r - z coordinates. They consist of two single sided modules mounted back to back with a stereo angle of 100 mrad between them [62]. The tracker outer barrel is built out of 6 layers with a total length of 218 cm. The layers are positioned at radii of 608 mm, 692 mm, 780 mm, 868 mm, 960 mm and 1080 mm respectively. The silicon modules used in the TOB are 500 μm thick. Layers 1 and 2 of the outer barrel are equipped with double sided modules providing

a “stereo” measurement like the innermost two layers of the TIB.

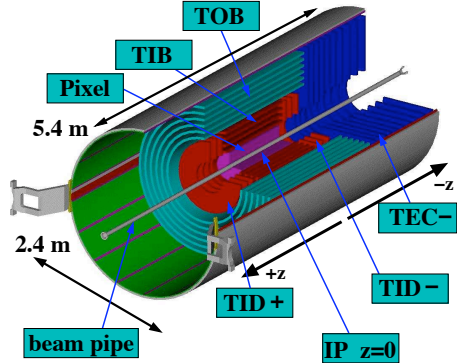


Figure 2.7: The silicon strip tracker has a cylindrical design with a diameter of 2.4 m and a length of 5.4 m. Sub-detectors are marked with a + or - sign according to their location in z in the CMS coordinate system.

the TID and for rings 1 to 4 of the TEC and 500 μm for the rest of the TEC (rings 5 to 7).

The endcaps of the silicon strip tracker are divided into the tracker endcap (TEC) and the tracker inner discs (TID). Each TEC contains 9 discs that extend radially from 220 mm to 1135 mm and from ± 1240 mm to ± 2800 mm along the z direction [63]. The 9 discs carry substructures (petals) on which the individual silicon modules are mounted. In addition each endcap contains two discs which serve as a front and back termination. Figure 2.8 shows a sketch of one tracker endcap.

Each TID contains 3 discs that fill the gap between the tracker inner barrel and the tracker endcaps. The TEC and TID modules are arranged in rings, centred on the beam axis. The first two rings in the TID as well as the innermost two rings and the fifth ring of the TEC are equipped with double sided modules. The thickness of the sensors is 320 μm for the TID and for rings 1 to 4 of the TEC and 500 μm for the rest of the TEC (rings 5 to 7).

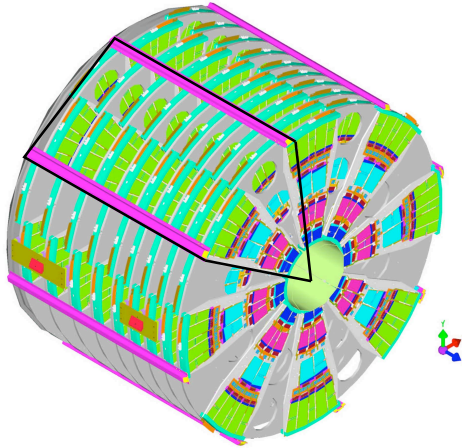


Figure 2.8: Sketch of one tracker endcap. The modules are arranged in rings around the beam axis and they are mounted on trapezoidal sub-structures called petals. One sector, indicated by the black line, consists of nine front petals mounted on the side of each disc facing the interaction point and nine back petals mounted on the opposite disc side.

The entire silicon strip tracker contains 15148 modules distributed among the four different subsystems (TIB, TOB, TID and TEC). They are mounted on carbon-fibre structures installed inside a temperature controlled outer support tube (see figure 2.7). The modules in the inner and outer barrel are rectangular with strips parallel to the z direction, whereas the modules in the endcaps have a wedge-shaped geometry and strips pointing to the beam axis. The distance between two neighbouring strips, called pitch, varies in the radial direction between 80 μm and 205 μm . Table 2.2 lists the module thickness and mean pitch for the several subsystems in the silicon strip tracker.

part	# detectors	thickness [μm]	mean pitch [μm]
TIB	2724	320	80,120
TOB	5208	500	122,183
TID	816	320	100-141
TEC	6400	320, 500	97-184

Table 2.2: The different detector types used in the silicon tracker subsystems [63]. The detectors on the 2 innermost layers of the TIB and the 2 outermost layers of the TOB have a smaller mean pitch compared to the detectors on the other layers.

Silicon sensors The detectors (see figure 2.9) in the silicon strip tracker are single sided p -on- n type silicon micro-strip sensors [68]. A uniform n^+ implantation on the back side of the wafers, covered by aluminium, forms an ohmic contact which is connected to positive voltage up to about 500 V. On the front side, strip shaped diodes are formed by p^+ implantation into the n type bulk. Each implant is covered by an aluminium strip from which it is electrically insulated by means of a $\text{SiO}_2/\text{Si}_3\text{N}_4$ multilayer. This integrated capacitor allows for AC coupling of the signals from the strips to the read-out electronics. For all sensors in the CMS strip tracker the ratio of p^+ implant width over strip pitch is $w/p = 0.25$, resulting in a constant strip capacitance [69].

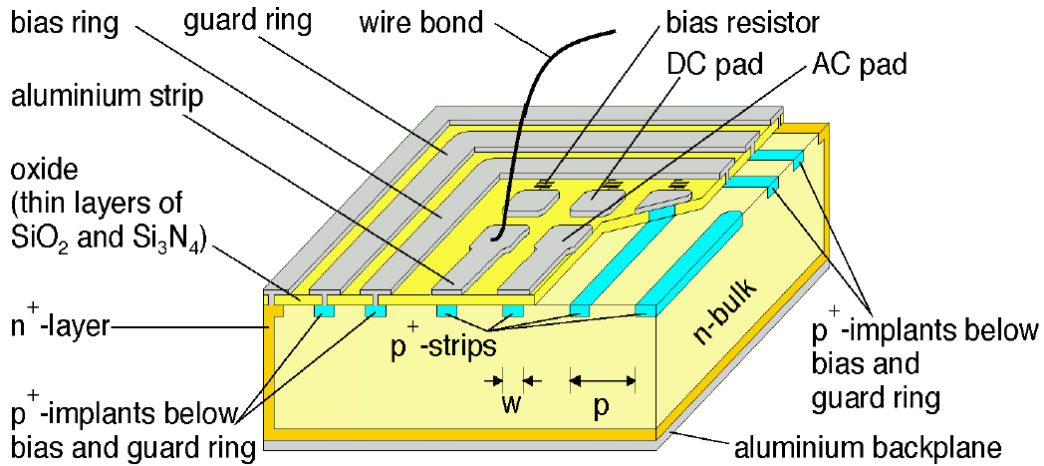


Figure 2.9: Micro-strip sensor as used in the CMS silicon strip tracker.

The design of the silicon sensors was chosen to fulfill the requirements on radiation hardness, signal to noise ratio, response time and granularity imposed by operation in the LHC environment.

Assembly precision As described earlier, the CMS silicon strip tracker is built out of four different subdetectors (TIB, TID, TOB and TEC) and each of them is further divided into several smaller structures, which finally carry the active components: the silicon sensors. Figure 2.10 shows the hierarchy of this modular mechanical design of the tracker for the barrel and the endcap regions:

- The TIB and TOB detectors contain respectively 4 and 6 cylindrical layers. The two endcaps are built out of nine discs each.
- In the outer barrel the rods, each carrying 6 single or double sided rectangular modules, are inserted in the appropriate openings of the support wheels. The TIB half-shells, which are fixed to the support flanges, are built out of strings of modules. The TID inner discs consist of 3 rings of modules mounted on carbon fibre discs, which are supported by the outer TIB flanges. Each TEC disc carries 8 front and 8 back petals with trapezoidal silicon modules arranged in a ring geometry.
- The silicon sensors and front end readout electronics of the detector modules are glued on carbon fibre frames.

Each of these substructures is mounted with a certain precision on the next higher structure in the tracker hierarchy. Table 2.3 lists (in μm) the mounting precision of each tracker structure onto the structure next in the level of hierarchy. Mainly two methods have been used to obtain these results: survey with coordinate measurement machines which have a typical accuracy of a few μm and photogrammetry with an accuracy of approximately 150 μm for relative measurements [63].

TIB		TID		TOB		TEC	
Sensor	10	Sensor	10	Sensor	10	Sensor	10
Module	180	Module	54	Module	30	Module	20
Shell	450	Ring	185	Rod	100	Petal	70
Cylinder	750	Disc	350	Wheel	140 ($r\varphi$), 500 (z)	Disc	150
Tube		Cylinder	450	Tube	1000	TEC	600
		Tube		CMS		Tube	

Table 2.3: Estimated assembly precision (RMS, in μm) of the tracker mechanical structures. Values are given with respect to the next level in the hierarchy [70].

2.2.2.3 Performance of the tracker

As an illustration of the tracker performance figure 2.11 shows the transverse momentum and transverse and longitudinal impact parameter resolution. The plots show the resolution for single muons with a P_t of 1, 10 and 100 GeV/c as a function of pseudorapidity. For high momentum tracks (100 GeV/c) the transverse momentum resolution is around 1-2 % up to $|\eta| \approx 1.6$, beyond which it degrades due to the reduced lever arm. The transverse impact parameter resolution, dominated by the resolution of the first pixel hit, reaches 10 μm for high P_t tracks while at lower momenta it is degraded by multiple scattering. The track reconstruction efficiency for single muons and pions is shown in figure 2.12. For muons, the efficiency is about 99 % over most of the acceptance. For $|\eta| \approx 0$ the efficiency decreases slightly due to gaps between the ladders of the pixel detector at $z \approx 0$. At high $|\eta|$ the

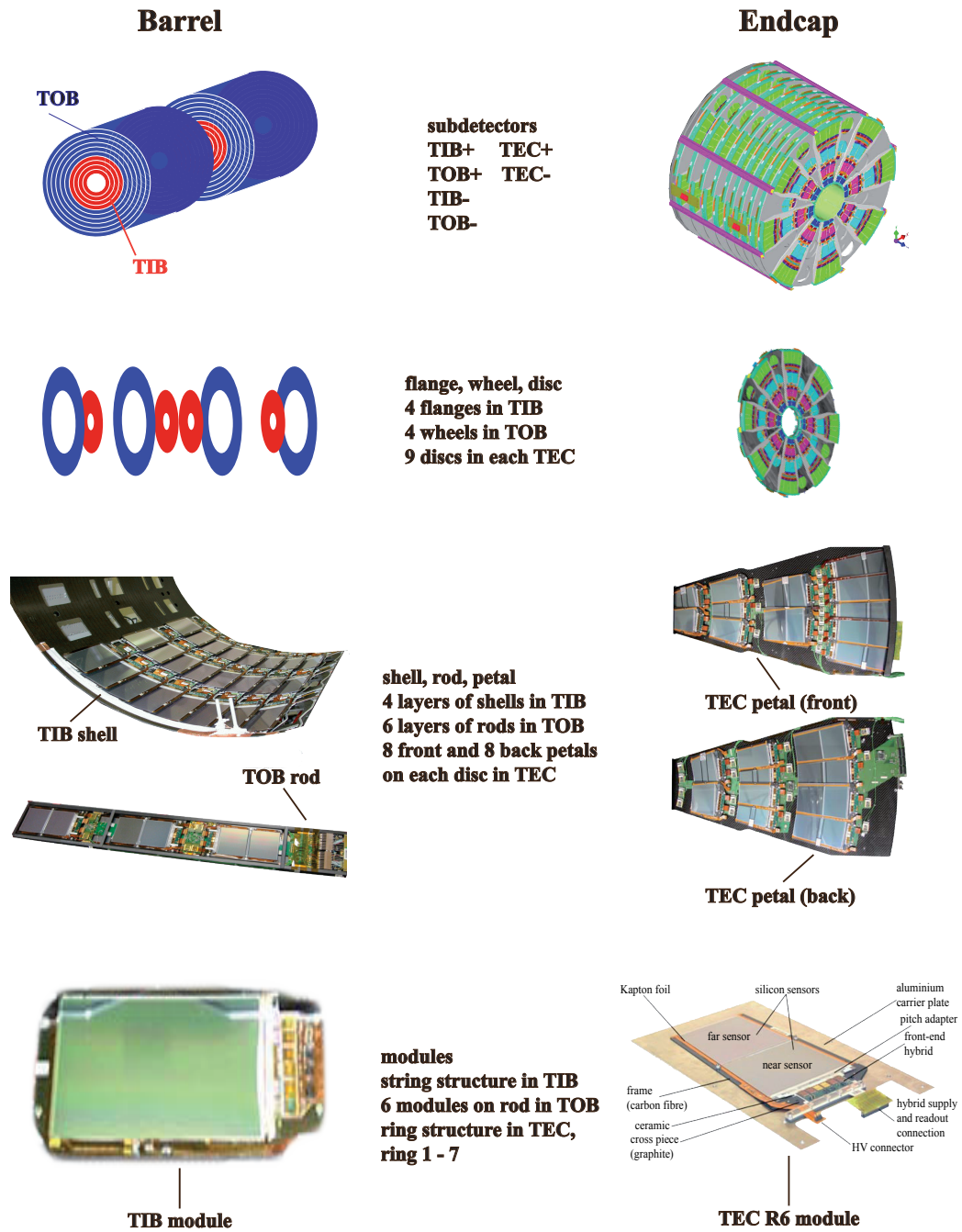
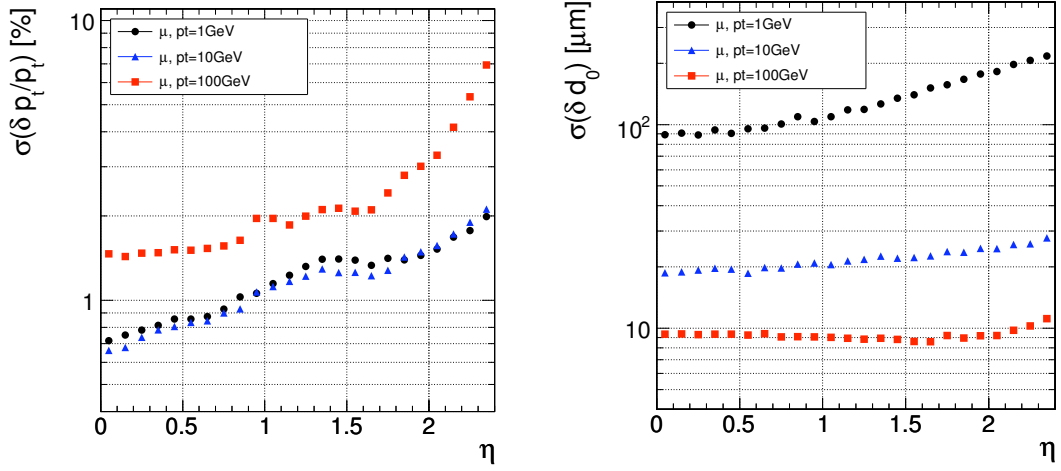


Figure 2.10: Hierarchy of the different mechanical structures in the silicon strip tracker.

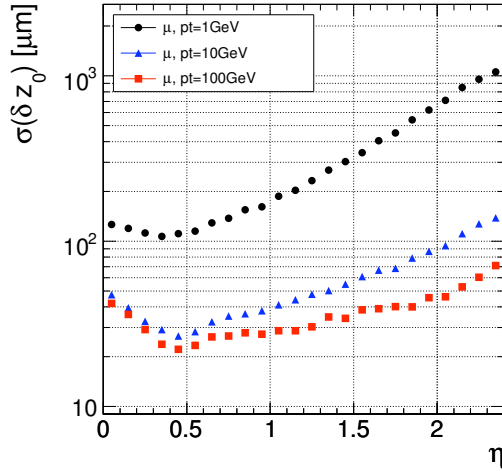
efficiency decreases due to the reduced coverage by the pixel forward discs. For pions (hadrons in general) the efficiency is lower because of interactions with the material in the tracker [62].

In units of radiation length X_0 the material inside the active tracker volume increases from $\approx 0.4 X_0$ at $\eta = 0$ to around $1.7 X_0$ at $|\eta| \approx 1.6$, before decreasing again to $\approx 1.0 X_0$ at $|\eta| = 2.5$ (see figure 2.13).



(a) Transverse momentum resolution.

(b) Transverse impact parameter resolution.



(c) Longitudinal impact parameter resolution.

Figure 2.11: Resolution of several track parameters for single muons with transverse momenta of 1, 10, 100 GeV/c as a function of pseudorapidity: (a) transverse momentum, (b) transverse impact parameter, and (c) longitudinal impact parameter [62].

The performance of the tracker relies on prior knowledge of the position and orientation of the modules. To achieve a robust pattern recognition for track reconstruction purposes an accuracy of approximately $100 \mu\text{m}$ is needed [71]. The deviation of the true position and orientation of the tracker modules from their nominal values depends on many factors with different origin:

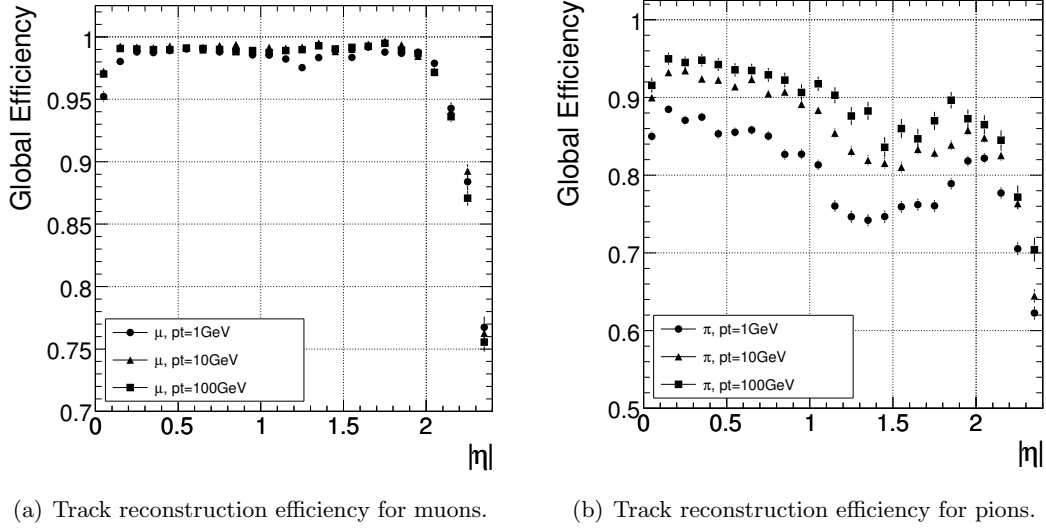


Figure 2.12: Global track reconstruction efficiency for (a) muons and (b) pions of transverse momenta of 1, 10 and 100 GeV/c as a function of pseudorapidity [62].

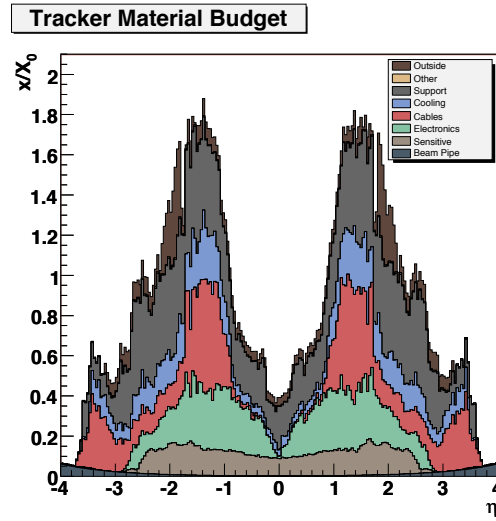


Figure 2.13: Material budget in the tracker in units of radiation length X_0 as a function of pseudorapidity η [63].

- the achieved assembly precision (compare also the previous section) and
- the deformations which arise during operation of the tracker due to cooling, mechanical stress and stress due to the magnetic field, out-gassing of components in dry nitrogen, and thermal stress caused by higher leakage currents due to radiation damage.

This leads to a degradation of the track parameter resolution (compare figure 2.11) which needs to be recovered by determining the true module positions and orientations. This procedure is called “alignment”.

Alignment of the CMS tracker relies on three key components, ordered in increasing order of achievable precision: the various data on assembly precision gathered during the integration process, the Laser Alignment System and the alignment with tracks. The Laser Alignment System and its properties is described in the next section.

2.2.2.4 The Laser Alignment System

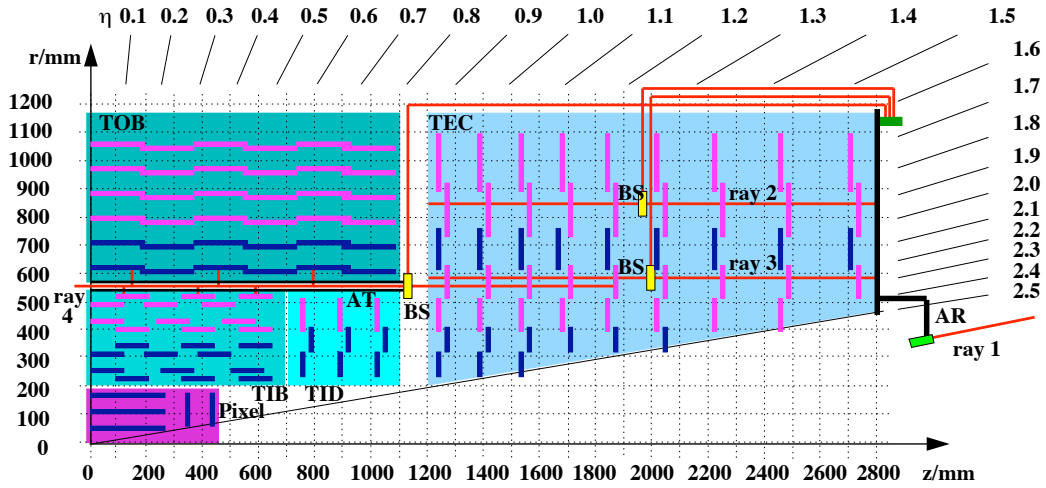


Figure 2.14: The CMS tracker layout (1/4 of the r - z view) including the Laser Alignment System components: beam splitters (BS) and alignment tubes (AT) for light distribution and the alignment ring (AR) for the optical link to the muon system.

The Laser Alignment System (LAS) uses infrared laser beams with a wavelength $\lambda = 1075$ nm and a gaussian beam profile to monitor the position of selected tracker modules. The LAS operates globally on the tracker substructures TIB, TOB and the TEC discs, but is not able to align individual modules. The goal of the system is to generate alignment information on a continuous basis, providing geometry reconstruction of the tracker substructures at a level of $100 \mu\text{m}$. This level of accuracy is needed to guarantee a stable pattern recognition for the track reconstruction algorithms and for the High Level Trigger [63, 71]. With well reconstructed tracks, track based alignment can then be used to align the smaller structures in the tracker hierarchy, like petals, rods and individual modules.

Once the tracker geometry has been aligned, the LAS is able to monitor possible tracker structure movements at the level of $10 \mu\text{m}$. Finally the Laser Alignment System establishes a common coordinate system for the tracker and the muon system via an optical link.

In each tracker endcap, eight laser beams equally distributed in φ (see table 2.4) cross all nine discs in ring 4 (ray 3, radius $r_{\text{ray } 3} = 564$ mm) and ring 6 (ray 2, radius $r_{\text{ray } 2} = 840$ mm)

on the back petals. At these positions special silicon sensors with a 10 mm diameter hole in the backside metalization and an anti-reflective coating are mounted. The beams are used for the internal alignment of the TEC discs. The other eight laser beams (ray 4, radius $r_{\text{ray 4}} = 564$ mm) are foreseen to align TIB, TOB and both TECs with respect to each other. The link to the muon system (ray 1) is established by 12 laser beams (six on each side) having a precise position and orientation in the tracker coordinate system.

Beam	$\varphi_{\text{ray 2/3}}$ [rad]	$\varphi_{\text{ray 4}}$ [rad]
1	0.393	0.393
2	1.178	1.290
3	1.964	1.851
4	2.749	2.749
5	3.534	3.646
6	4.230	4.230
7	5.105	5.217
8	5.890	5.778

Table 2.4: φ positions of the 8 laser beams of ray 2 (3) and ray 4. The beam positions in rays 2 and 3 are equally distributed in φ . Due to the different azimuthal segmentation of TIB, TOB and the two TECs, it is not always possible to use the same TEC Ring 4 alignment module for both rays 3 and 4. Therefore some φ positions are different for rays 3 and 4.

Due to the transmission and absorption characteristics of silicon, the amplitude of the signal induced by the laser beams in the sensors decreases as the beams penetrate through subsequent silicon layers in the tracker endcaps. The intensity of the laser beams is reduced by a factor $\approx 4 - 5$ after crossing a silicon module. The number of modules which can be consecutively traversed by a laser beam is therefore limited by the transmission behaviour of the modules. The intensity of the beams is also reduced while traversing the beam splitters (mirrors) in the alignment tubes (see figure 2.15), that partly deflect the beams onto the TIB and TOB sensors.

To obtain an optimal signal on all sensors, a sequence of laser pulses with increasing intensity (optimized for each position) is generated. Several triggers per intensity are taken and the signals are averaged. In total a few hundred triggers are needed to get a full picture of the tracker structure. Due to the fact that the trigger rate for the alignment system is around 100 Hz this will take only a few seconds. Data will be taken at regular intervals with the Laser Alignment System, both in dedicated runs and during physics data taking.

The laser light is distributed by fibers to optical devices, beam splitters (BS), where it is collimated and split into two back-to-back beams. For rays 2 and 3 the beam splitters are mounted on disc 6 of the tracker endcap. The beam splitters for ray 4 are installed in the alignment tubes and are located between the tracker outer barrel and TEC+ (see figure 2.15).

Figure 2.16(a) shows a picture of a beam splitter and figure 2.16(b) illustrates the working principle. The beam separation perpendicular to the plane defined by disc 6 of the TECs is achieved by using the polarization principle. The incoming beam, containing both s and p polarizations, is collimated onto a 45° inclined surface on which the s -polarized part of the laser light is reflected. The p -polarized fraction of the incoming laser light continues and traverses a $\lambda/4$ -plate before finally being reflected by a mirror. After a second traversal through the $\lambda/4$ -plate, the laser light is s -polarized and is completely reflected on the backside of the 45° inclined surface, resulting in two parallel back-to-back beams with s polarization.

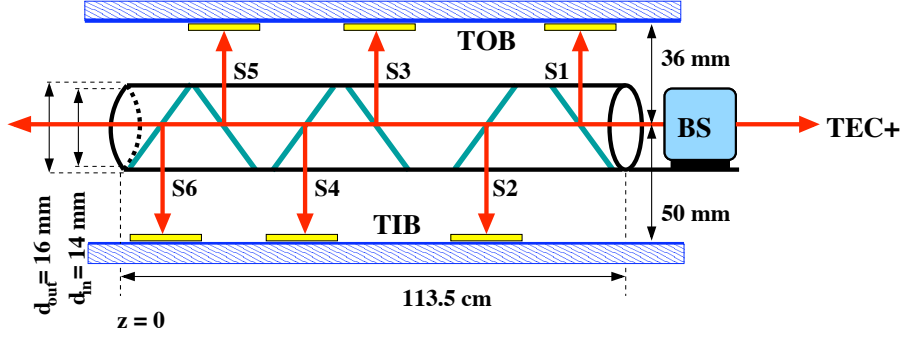


Figure 2.15: Layout of the alignment tubes on the $+z$ side. The beam splitter is fixed on the alignment tube and is located between TOB and TEC+. The alignment tubes have each 6 mirrors, three reflecting the laser beams to the outer barrel and three to the inner barrel. Since there are no radial lines of sight in the barrel region, the Laser Alignment System reaches only the innermost layer of TOB (layer 1) and the outermost layer of TIB (layer 4).

However, it has been shown [72] that the resulting back-to-back beams are not perfectly collinear. Displacements both parallel (θ_P) and perpendicular (θ_C) to the strips on the silicon sensors can occur, although only the displacement perpendicular to the strips can be measured by the sensors. These displacements have been measured for each individual beam splitter before it was mounted on the discs and integrated in the alignment tubes [72, 73]. Thus the laser beam positions measured in the CMS tracker can be corrected for this introduced acollinearity using

$$x_{\text{corr}}^{k,i} = x_{\text{meas}}^{k,i} - \Delta_{BS}^k \cdot \tan(\theta_C^i), \text{ with } k = 1, \dots, 9 \text{ and } i = 1, \dots, 8 \quad (2.2)$$

where

- k numbers the discs in the endcap (from 1 to 9),
- i numbers the beam splitters for the different beams (from 1 to 8),
- $x_{\text{corr}}^{k,i}$ = corrected laser beam position on disc k ,
- $x_{\text{meas}}^{k,i}$ = measured (uncorrected) laser beam position on disc k ,
- Δ_{BS}^k = distance between the beam splitter and disc k ,
- θ_C^i = kink angle of beam splitter i perpendicular to the strips.

Equation 2.2 is valid for the kink angle correction in the tracker endcaps. The correction for the beam splitters in the alignment tubes can be defined in a similar way. The studies in [72] have shown the acollinearity to be $\theta_C \leq 3 \text{ mrad}$ with variations $\sigma_{\theta_C} \leq 50 \mu\text{rad}$.

A detailed description of the Laser Alignment System as well as comprehensive studies on the performance of its various components can be found in [72–75].

2.2.3 The electromagnetic calorimeter

The electromagnetic calorimeter (ECAL) is a homogeneous calorimeter built out of 61200 lead tungstate (PbWO_4) crystals in the barrel part and closed by 7324 crystals in each of the two endcaps. The η coverage of the electromagnetic calorimeter extends up to $|\eta| = 3$ (figure 2.4).

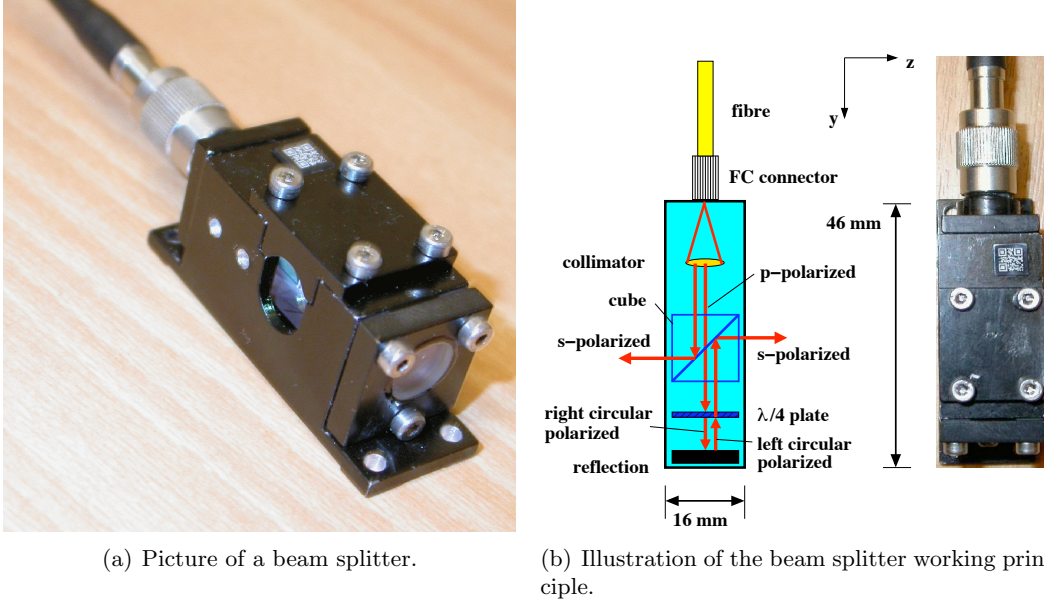


Figure 2.16: The beam splitters used in the Laser Alignment System: (a) shows a picture of a beam splitter and (b) illustrates the working principle of the beam splitters based on polarization of the incoming laser light [72].

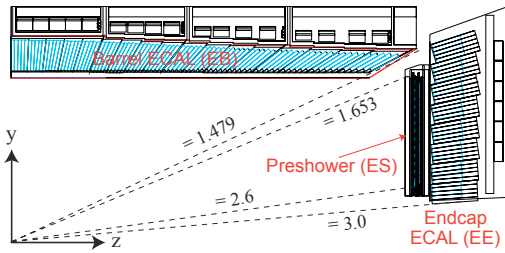


Figure 2.17: The r - z view of the electromagnetic calorimeter showing the geometrical configuration in detail: the EB ($|\eta| < 1.479$) and the EE ($1.479 < |\eta| < 3.0$). In front of the endcaps the preshower ($1.653 < |\eta| < 2.6$) is installed [62].

position in η . They are grouped into 26 identical supermodules, each covering 20° in φ and mounted in a quasi-projective geometry, such that their axes make a small angle (3°) with respect to the vector from the nominal interaction vertex, both in the φ and η projections. The transverse granularity of the crystals in the barrel is 0.0174×0.0174 in η - φ , which corresponds to the Molière radius of PbWO_4 .

The ECAL endcaps (EE) cover the pseudorapidity range $1.479 < |\eta| < 3.0$. The endcaps consist of identically shaped crystals grouped in units of 5×5 supercrystals and like the crystals in the barrel are mounted off-point from the nominal vertex position. However they are arranged in a x - y grid and not in an η - ϕ grid like the EB crystals. The endcap crystals have a front face cross section of $28.6 \times 28.6 \text{ mm}^2$.

The total thickness of 23 cm of the barrel crystals (corresponding to $25.8 X_0$) limits the longitudinal leakage of high energy electromagnetic showers. The preshower detector (ES) contains $3 X_0$ of lead and allows the use of slightly shorter crystals (22 cm) in the endcap

The lead tungstate scintillating crystals have a short radiation length ($X_0 = 0.89 \text{ cm}$) and a small Molière radius (2.2 cm), are fast (80 % of the light is emitted within 25 ns) and radiation hard (up to 10 Mrad) [62]. Silicon avalanche photodiodes (APDs) are used as photodetectors in the barrel and vacuum phototriodes (VPTs) in the endcaps.

The barrel section (EB) has an inner radius of 1.29 m and covers the pseudorapidity range between $0 < |\eta| < 1.479$. The barrel crystals have a tapered shape (the front face is $22 \times 22 \text{ mm}^2$ while it is $26 \times 26 \text{ mm}^2$ at the rear crystal face), slightly varying with their

regions. The active elements of the preshower are two planes of silicon strip detectors with a pitch of 1.9 mm placed behind the lead absorber discs at depths of $2 X_0$ and $3 X_0$ respectively. The preshower detector covers the pseudorapidity range $1.653 < |\eta| < 2.6$ and improves the π^0/γ separation in the forward direction.

Performance of the ECAL The energy resolution σ of the electromagnetic calorimeter can be parametrized as:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{\sigma_n}{E}\right)^2 + c^2 \quad (2.3)$$

where E is in GeV, a is the stochastic term, σ_n the noise and c the constant term. The design values are $a = 2.7\%$, $\sigma_n = 0.155$ GeV, $c = 0.55\%$ for the barrel region and $a = 5.7\%$, $\sigma_n = 0.205$ GeV, $c = 0.55\%$ for the endcap region [76]. The test beam data are in agreement with these design considerations [77].

2.2.4 The hadron calorimeter

The electromagnetic calorimeter described in the previous section is surrounded by the hadron calorimeter (HCAL). Together they build the CMS calorimetry system which measures the energy and direction of electrons, photons and particle jets as well as the missing transverse energy.

As seen from the interaction point the hadron calorimeter barrel (HB) and endcaps (HE) are installed behind the tracker and electromagnetic calorimeter (see figure 2.4). The HB is radially restricted between the outer radius of the ECAL barrel ($R = 1.77$ m) and the inner radius of the superconducting coil of the CMS magnet ($R = 2.95$ m) and hence the amount of material which can be put in to absorb the hadronic shower is constrained. An outer hadron calorimeter (HO), or “tail-catcher”, is therefore placed outside the magnet to complement hadron calorimetry in the barrel region. In the endcap region the pseudorapidity coverage is extended by the forward hadron (HF) calorimeters [63, 78].

Hadron barrel (HB) The hadron barrel is a sampling calorimeter covering the pseudorapidity range $|\eta| < 1.3$ and consists of 36 identical azimuthal wedges which form two half barrels (HB- and HB+). The wedges are composed of brass alloy (70 % copper, 30 % zinc) absorber plates parallel to the beam axis interleaved with layers of plastic scintillator. The absorber material has a short interaction length, is non-magnetic and in addition has a reasonably small Z in order not to degrade the muon reconstruction. The innermost and outermost absorber layers are made out of stainless steel to guarantee a good structural strength. The plastic scintillator is divided into tiles with a size of $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$ [62]. Table 2.5 lists the composition of the hadron calorimeter in the barrel region. At 90° the total absorber thickness is 5.82 absorption lengths (λ). The effective thickness increases with the polar angle as $1/\sin\Theta$, resulting in 10.6λ at $|\eta| = 1.3$. The electromagnetic calorimeter in front of the HB adds an additional 1.1λ [63].

The first layer of scintillator (layer 0) is located in front of the steel support plate and allows the detection of hadronic showers developing in the inert material between the electromagnetic and hadron calorimeter. The larger thickness of the last scintillator layer serves to correct for late developing showers leaking out of the back of the hadron barrel subsystem.

The scintillator tiles are instrumented with a single wavelength shifting fiber (WLS) and the corresponding tiles from each of the 17 active layers are grouped together in η forming 32 so called HCAL “towers” (see figure 2.18). The two towers closest to the endcap transition region (tower 15 and 16) are an exception since they are also segmented in depth. The tower

layer	absorber material	absorber thickness [mm]	scintillator thickness [mm]
0 (front plate)	steel	61	9
1-8	brass	50.5	3.7
9-14	brass	56.5	3.7
15	steel	75	3.7
16 (back plate)	-	-	9

Table 2.5: Scintillator and absorber thickness in the hadron barrel wedges [62]. The hadron barrel contains 16 absorber layers (layer 0-15) and 17 layers of active material (layer 0-16).

segmentation is summarized in figure 2.18. The optical signal from the HCAL towers is detected by a pixelated hybrid photodiode (HPD) mounted at the ends of the barrel mechanical structure. HPDs are used as photodetectors because of their low sensitivity to magnetic fields and their large dynamical range.

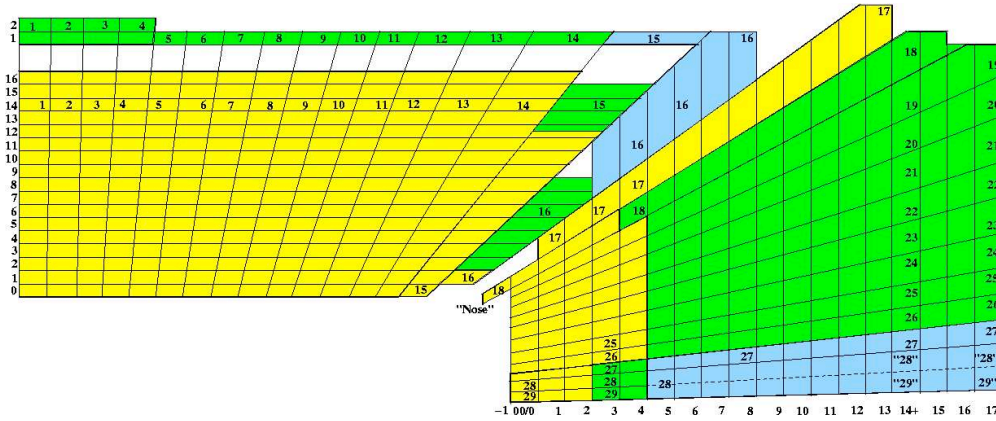


Figure 2.18: A schematic view of the tower mapping in the r - z projection of the hadron calorimeter barrel and endcap regions for one quarter of the HCAL. The HB extends in η from tower 1 to 16, HE from tower 17 to 29 and the HO from tower 1 to 15. The colors correspond to the number of optical readouts in radial direction, e.g. 2 colors (yellow and green) correspond to two-fold radial segmentation [63].

Hadron endcap (HE) The hadron calorimeter endcaps cover the pseudorapidity range $1.3 < |\eta| < 3$, a region containing about 34 % of the particles produced in the final state during a pp collision at the LHC. The hadron endcaps are also brass/scintillator sandwiches with an 18-fold φ -geometry matching the geometry of the hadron barrel. The absorber plates are 78 mm thick while the scintillator thickness is 3.7 mm [62]. The total length of the calorimeter in the endcap region, including the electromagnetic crystals, is about 10 interaction lengths λ [63].

As in the hadron barrel, the scintillator light is collected by wavelength shifting fibers and the towers are readout by multipixel hybrid photodiodes. The granularity of the hadron endcaps is $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$ for $|\eta| < 1.6$, which matches the tower size in the barrel.

For $|\eta| > 1.6$ the tower size is $\Delta\eta \times \Delta\varphi = 0.17 \times 0.17$ [63].

Figure 2.18 shows the segmentation of the hadron endcaps, which is partly motivated by the radiation environment (10 Mrad after 10 years of operation at design luminosity [63]) with the aim of restoring the energy resolution following degradation of the scintillator by adjusting the calibration coefficients. The towers near the beam axis (27, 28 and 29) have 3 divisions in depth which are read out separately. Except for towers 16 and 17 which overlap with the ECAL barrel, the remaining towers each have two readouts in the radial direction.

Hadron outer (HO) The combined stopping power of the ECAL and HCAL barrel detectors does not provide sufficient containment for hadron showers in the central pseudorapidity region. Therefore the hadron calorimeter is extended outside the superconducting coil with a “tail-catcher”: the hadron outer (HO) calorimeter. The HO utilizes the solenoidal coil as an additional absorber and is in the $|\eta| < 1.3$ range used to identify late developing showers and to measure the shower energy deposited after the HB.

Outside the solenoid the magnetic field is returned through an iron yoke, which is subdivided in five rings along the z -axis. HO is placed as the first sensitive layer in each of these five rings. At $\eta = 0$ the hadron barrel detector has the minimal absorber depth and therefore the central ring has two layers of 10 mm thick scintillators on either side of the “tail-catcher” iron (18 cm thick) at $r = 3850$ mm and $r = 4097$ mm respectively [62]. The other rings have one layer at a radial distance of 4097 mm. By including the HO the total depth of the calorimeter system is extended to a minimum of 11.8 radiation lengths [63].

Hadron forward (HF) The hadron forward calorimeters are located at $|z| = 11.2$ m from the interaction point and cover the range $3.0 < |\eta| < 5.0$ thus providing hermetic calorimetric coverage (almost) all the way down to the beam pipe. As a result they experience extremely high particle fluxes: on average 760 GeV per pp interaction is deposited into the two forward calorimeters, compared to only 100 GeV for the rest of the detector [63]. The HF is made of steel absorbers and embedded quartz fibers, which are radiation hard and provide a fast collection of the Cherenkov light.

The detector is divided into two longitudinal segments. Half of the fibers run along the full length of the absorber (165 cm $\approx 10 \lambda$), while the other half starts at a depth of 22 cm from the front of the detector. The separation between the long and short fibers is 5 mm and this arrangement makes it possible to distinguish showers originating from electrons and photons from those generated by hadrons. The former deposit a large fraction of their energy in the first 22 cm, while the latter produce on average equal signals in both segments.

The fibers run parallel to the beam axis and are bundled to form 0.175×0.175 towers in $\Delta\eta, \Delta\varphi$. Photomultiplier tubes (PMTs) are used as photodetectors to read out the fibers.

Performance of the HCAL The energy resolution σ/E of the hadron calorimeter can be parametrized as a function of energy according to equation 2.3. For the HCAL with the ECAL in front the noise term σ_n is negligible and the stochastic and constant terms are $a = 100$ % and $c = 4.5$ % respectively [78].

2.2.5 The muon system

The flux-return yoke of the CMS magnet is equipped with muon stations. The muon system has 3 functions:

- muon identification,
- muon momentum measurement and

- triggering.

Due to the shape of the solenoid magnet, the muon system like the other subdetectors has a cylindrical barrel section and 2 planar endcaps. Three types of gaseous particle detectors are used [79]. Each of the different detector technologies takes into account the specific requirements on the resolution of both spatial and time coordinates, as well as the differences in the radiation environment and magnetic field configuration in the barrel and endcap regions of the muon system.

In the barrel region, where the muon rate as well as the neutron-induced background are low, drift chambers are used. The barrel drift tube (DT) chambers (see figure 2.19) cover the pseudorapidity range $|\eta| < 1.2$ and are organized in 4 stations (MB1 to MB4) which are installed between the layers of the flux-return plates. Each station contains 3 (or 2) so called “superlayers” (SL) and each SL is constructed out of 4 drift chambers. The first 3 stations are built out of 3 superlayers: two of them measure the muon coordinate in the r - φ plane while the third, located between the other two, measures the z coordinate along the beam axis. The fourth station does not provide the z measurements.

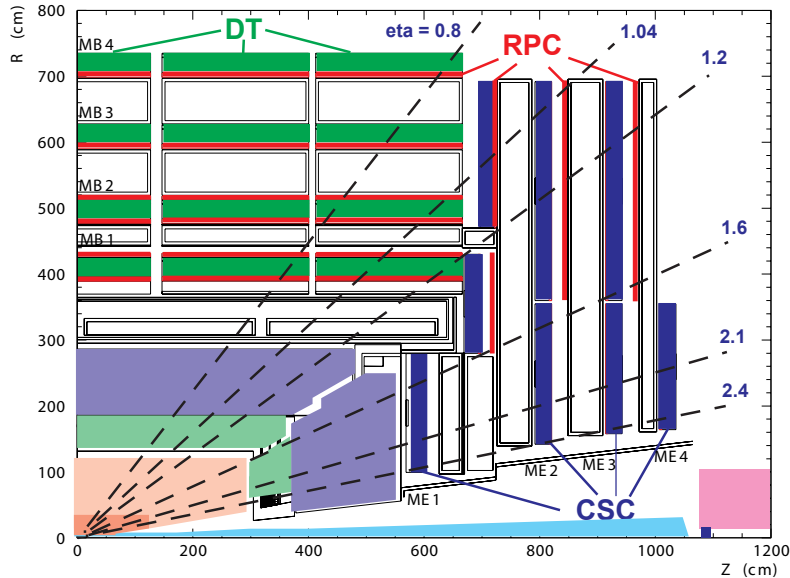


Figure 2.19: Layout of one quarter of the CMS muon system in r - z view. The drift tube (DT) detectors in the barrel and the cathode strip chambers (CSC) in the endcap are complemented with resistive plate chambers (RPC). The RPC system beyond $|\eta| > 1.6$ has been staged [62].

Cathode strip chambers (CSC) are used in the endcap region, where the muon and background rates are high. Important properties of the CSCs are their fast response time, fine segmentation and radiation resistance. The four stations of CSCs in each endcap identify muons in the $0.9 < |\eta| < 2.4$ range [63]. The chambers are positioned perpendicular to the beam axis and the cathode strips of each chamber run radially outward to provide a precision measurement in the r - φ plane. The anode wires, oriented approximately perpendicular to the strips, are also read out to measure the pseudorapidity and the beam-crossing time of the muons.

Both the detectors in the barrel and endcap regions of the muon system are complemented with resistive plate chambers (RPC). The RPCs enhance the trigger and bunch-crossing

identification capabilities of the muon system. A total of 6 layers of RPCs are installed in the barrel: 2 in each of the first two stations (MB1 and MB2) and 1 in each of the last two stations (MB3 and MB4). The redundancy in the first two stations allows the trigger to work even for low p_T tracks that eventually stop before reaching the outer stations. In the endcap region a RPC layer has been integrated in each of the first 3 stations. A shortfall of funds has led to the staging of the RPC chambers positioned beyond $|\eta| > 1.6$ [62].

Finally, in order to optimize the muon momentum resolution a sophisticated alignment system is available to measure the positions of the muon detectors with respect to each other and to the inner tracker [62, 63, 79].

Performance of the muon system Because the muon detector elements cover the full pseudorapidity interval $|\eta| < 2.4$, muon identification is guaranteed over the range corresponding to $10^\circ < \Theta < 170^\circ$. Reconstruction efficiency is typically 95-99 % except in the regions around $|\eta| = 0.25$ and 0.8 (the regions between two DT wheels) and $|\eta| = 1.2$ (the transition between the barrel and endcap systems), where the efficiency drops.

The muon momentum resolution of the standalone muon system is about 9 % for small values of η and p due to multiple scattering in the detector material before the first muon station [39, 62]. A global fit, also taking into account the measurements of the muon track in the inner tracker, improves the momentum resolution by an order of magnitude at low momenta. At high momenta, typically around 1 TeV, the global fit gives a momentum resolution of about 5 % (see figure 2.20), whereas the standalone resolution varies between 15 % and 40 % depending on $|\eta|$.

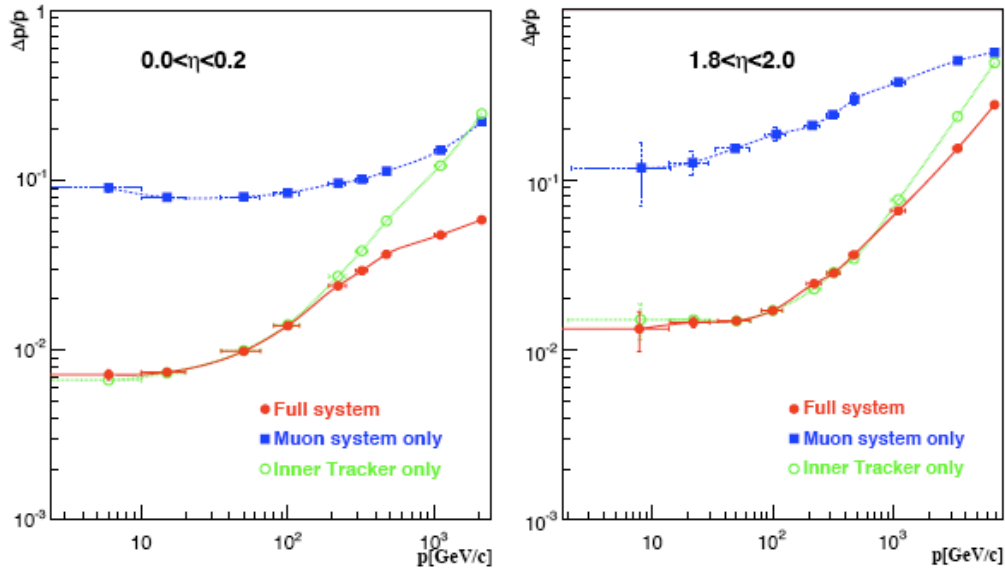


Figure 2.20: The muon momentum resolution as a function of the momentum p using the muon system only (in blue), the inner tracker only (in green) or both (in red) for two different η regions [63].

2.2.6 The CMS trigger system and data acquisition system

The CMS trigger and data acquisition (DAQ) system is designed to reduce the event rate of about 1 GHz at the nominal luminosity of $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to a rate of $\mathcal{O}(10^2)$ Hz filling the readout bandwidth with event samples of physics interest. This task is performed in two steps: the Level-1 trigger system, which consists of custom-designed electronics, operates on a subset of the data collected for each LHC bunch-crossing. The resulting event rate of $\mathcal{O}(10^2)$ kHz is further reduced by the High-Level Trigger (HLT), which is a software system implemented in a computer farm (the Event Filter farm) based on commercially available processors. The use of a computer farm allows benefitting from the latest developments in computing technology and avoids built-in architectural or design limitations. The DAQ system also collects events for calibration and alignment purposes, monitors the status of the CMS detector and provides information on what is rejected [80, 81].

Level-1 Trigger The Level-1 Trigger has local, regional and global components. At the bottom, the Local Triggers (or TPG - Trigger Primitive Generator⁵) are based on energy deposits in calorimeter towers and track segments or hit patterns in the muon chambers. Regional Triggers combine the information from the Local Triggers to create objects like electron and muon candidates in limited spatial regions. Candidates are ranked and sorted according to their energy or momentum and quality, to reflect the level of confidence attributed to the L1 parameter measurement. The Global Calorimeter and Global Muon Triggers determine the highest-rank candidates across the entire experiment and transfer them to the top entity in the L1 hierarchy (see figure 2.21), the Global Trigger. Finally the Global Trigger takes the decision whether or not to accept the event for further processing by the HLT [80].

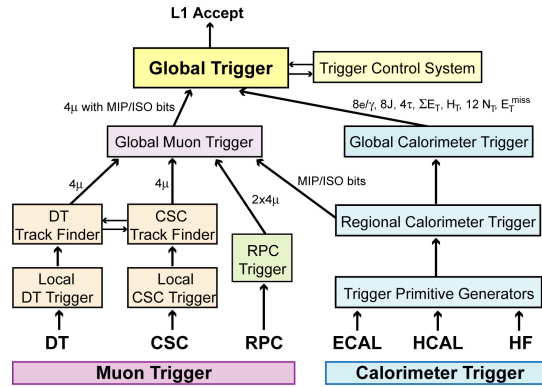


Figure 2.21: The architecture of the Level-1 trigger. The Local Triggers provide Trigger Primitives to the Regional Triggers, which pass the ranked candidate objects to the Global Trigger for the final L1 decision [63].

High-Level Trigger The High-Level Trigger has access to the complete readout data and can therefore perform complex calculations to select especially interesting events for specific physics processes. To achieve this goal those objects and regions of the detector which are actually needed are reconstructed for events accepted by the Level-1 Trigger. This reconstruction is done with the CMS software (CMSSW), which is also used for offline processing of the data (see section 2.2.8).

To obtain the desired rejection rate the High-Level Trigger tries to discard uninteresting events as soon as possible. This design leads to the concept of many virtual trigger levels, e.g. muon data is used followed by inner tracker data to define a HLT muon candidate [81].

⁵Trigger Primitives are objects such as photon, electron, muon and jet candidates above a given E_t or P_t threshold and sums of E_t and E_t^{miss} .

2.2.7 The luminosity measurement

The luminosity measurement is needed to monitor the LHC performance in real time and to provide the normalization for physics analyses. The design goal for the real time measurement is to determine the average luminosity with a 1 % statistical accuracy in 0.1 s. For offline analyses the goal is to achieve a systematic accuracy of 5 % [62].

The normalization of physics analyses will depend on careful measurements of known cross sections such as the pp total cross section, the $W^\pm$ and Z production rates. However, these methods are not suitable for real time determination of the luminosity and therefore the real time monitoring will be based on the measurement of high cross section processes utilizing comparatively simple hardware. One method to measure the luminosity in real time utilizes the signals from the forward hadron calorimeter (HF, see section 2.2.4), while another, the Pixel Luminosity Telescope (PLT), utilizes particle tracking telescopes based on custom-built pixel detectors [63].

A summary of the general strategies for the luminosity measurement with the CMS detector is given in [62]. The determination of the luminosity using the Z production rate will be discussed in chapter 4.

2.2.8 The CMS software and computing

The CMS software and computing systems are designed to cover several activities including the storage of data taken with the CMS detector and access to these data by physicists all over the world. Furthermore, the CMS software and computing infrastructure facilitates the reconstruction and analysis of the data in a distributed computing environment.

The CMS software (CMSSW) is based on the object-oriented programming language C++ [82, 83] and the CMS Event Data Model (EDM) [62, 84]. CMSSW has a modular architecture and provides the following functionality

- the core application framework as well as several services,
- the modules for physics and detector simulation, reconstruction, calibration and alignment and physics analysis,
- the software for the High Level Trigger and the algorithms used therein and
- the software to assure the quality and integrity of the CMS data.

The modules in CMSSW are used both for detector and *Monte Carlo* data.

The CMS Event Data Model is centered around a C++ object container called *Event* which holds all raw and reconstructed data objects belonging to a physics event. Events are processed by putting the *Event* through a sequence of modules specified in a configuration file by the user at runtime. All objects in the *Event* can be accessed by the modules and new data can be added to the *Event*. The objects in the *Event* may be stored in ROOT [85] files for further processing or analysis purposes [86]. The framework automatically keeps track of all processing results in order to guarantee reproducibility [62]. A comprehensive description of the CMS software is given in [62, 84, 86].

CMS presents challenges not only in terms of physics discovery and detector operation but also in terms of data volume and necessary computing resources. Therefore, the CMS computing environment has been constructed as a distributed system of services and resources that interact with each other in the “LHC Computing Grid”. In this Grid the primary computing centre at CERN (“Tier-0”) is augmented by several regional Tier-1 and Tier-2 centres at national laboratories and universities [62].

The Tier-0 centre at CERN will archive the raw detector data and perform prompt reconstruction. The raw data as well as the results of the prompt reconstruction will be distributed to the Tier-1 centres. Once updated calibration and alignment constants are available, re-reconstruction of the data will be performed at the Tier-1 centres. The Tier-2 centres will provide services for the local community and grid-based analysis for the whole CMS community. Furthermore, the *Monte Carlo* production for the CMS experiment will be carried out at the Tier-2 centres.

More information about the CMS computing model can be found in [62, 86, 87].

Chapter 3

Simulation and Reconstruction Software for the Laser Alignment System

3.1 Introduction

This chapter describes the development, implementation and testing of the simulation and reconstruction software for the Laser Alignment System (see section 2.2.2.4) within the CMS software framework (CMSSW, see section 2.2.8). This software is based on the functionality already contained in CMSSW and adds further functionality when necessary. Table 3.1 gives a short overview of the software packages for the Laser Alignment System.

The next sections give a description of the modules building together the simulation and reconstruction software for the Laser Alignment System: first an overview of the simulation is presented, followed by sections describing the reconstruction routines and the data quality monitoring (DQM) modules. The analysis of the data taken during the TEC integration test and the results of this analysis are discussed at the end of this chapter.

Subsystem	Package	Description
Alignment	LaserAlignment	reconstruction of beam positions and calculation of alignment parameters
Alignment	LaserAlignmentSimulation	simulation of the laser beams
Alignment	LaserDQM	Data Quality Monitors for the Laser Alignment System
DataFormats	LaserAlignment	stores data and results in the Event Data

Table 3.1: Packages in CMSSW for the Laser Alignment System.

3.2 Simulation of the Laser Alignment System

Goal of the simulation of the Laser Alignment System is to provide a realistic description of the response of the CMS detector to the laser beams. Therefore the interaction of optical photons from the laser beams with both the active and passive detector materials are simulated by utilizing the GEANT4 toolkit [88].

GEANT4 provides a rich set of physics processes describing electromagnetic and hadronic interactions in detail. It also provides tools for modelling the full CMS detector geometry and the magnetic field. The functionality of GEANT4 is interfaced to the core CMSSW Framework. The simulation of the Laser Alignment System follows the object oriented design and fulfills the CMSSW design principles [62].

The GEANT4 toolkit includes optical processes to simulate effects like refraction, reflection and absorption of the laser beams. However these processes are not usable by default in the

CMSSW framework and they have to be activated utilizing a custom-made *PhysicsList* [89]. Figure 3.1 shows the program flow for the simulation of the Laser Alignment System.

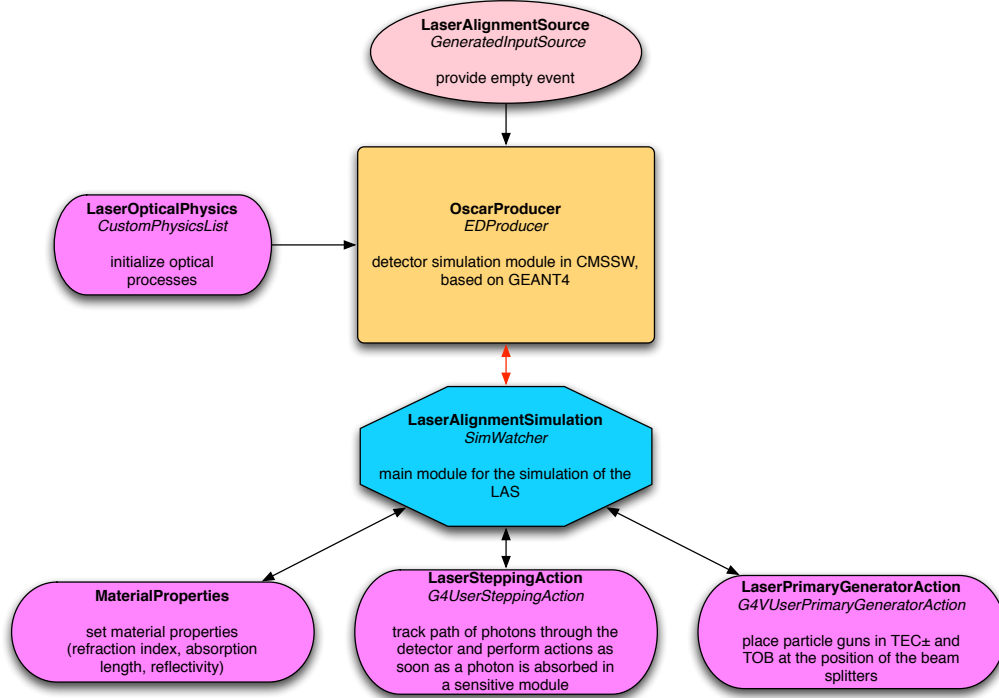


Figure 3.1: Program flow during simulation. The *LaserAlignmentSimulation* module is the interface between the general detector simulation module (*OscarProducer*) and the simulation routines specific to the Laser Alignment System (*MaterialProperties*, *LaserPrimaryGeneratorAction* and *LaserSteppingAction*).

Each process in CMSSW needs a source to provide it with events, whether these come from a *Monte Carlo* generator or from the detector during data taking. The Laser Alignment System software contains an *InputSource* (*LaserAlignmentSource*) to provide empty events to the detector simulation. The content of these events will be created by other means, which are described in the following.

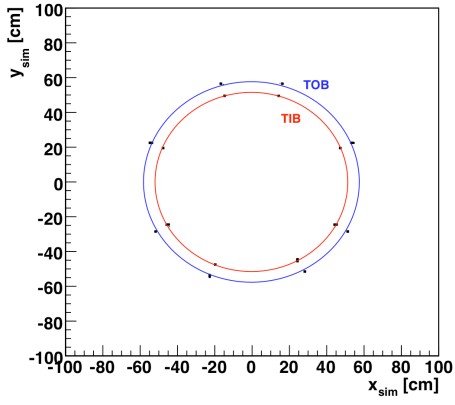
In CMSSW a module called *OscarProducer*¹ takes care of the detector simulation. CMSSW provides the possibility to interact with the simulation process by catching signals sent by the *OscarProducer* at different stages of the simulation process (e.g. at the beginning of an event) in a *SimWatcher*, which in fact is a so called observer².

The *LaserAlignmentSimulation* module is such a *SimWatcher* and takes care of the following actions during the simulation of an event:

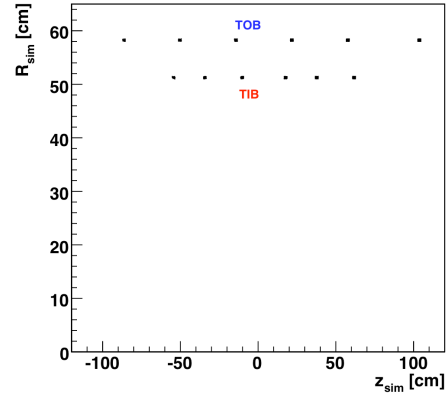
¹Object-oriented Simulation for CMS Analysis and Reconstruction, short OSCAR, was already the detector simulation program in the old framework [90].

²An observer is a “C++ design pattern” [91]. This feature is mainly used to implement a distributed event handling system. In this particular case the *SimWatcher* observes the *OscarProducer* and waits for the occurrence of a given operation (e.g. the creation of a new event) to perform some actions in the simulation process.

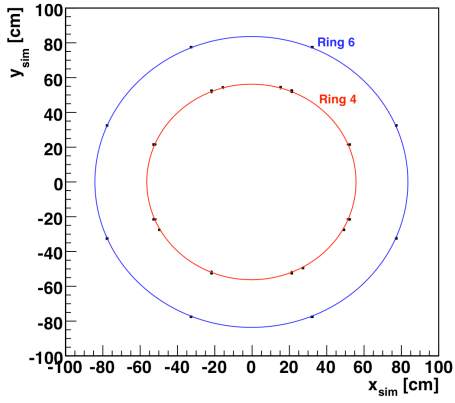
Y vs X Position of the SimHits


 (a) SimHits in the barrel: y vs. x

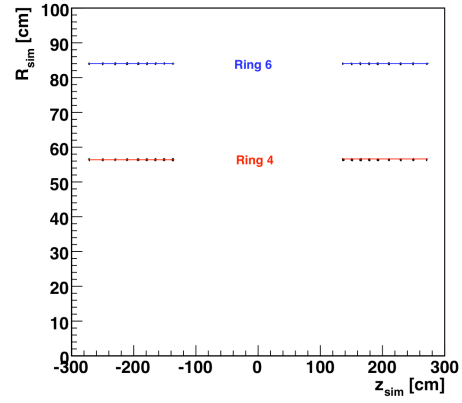
R vs Z Position of the SimHits


 (b) SimHits in the barrel: R vs. z

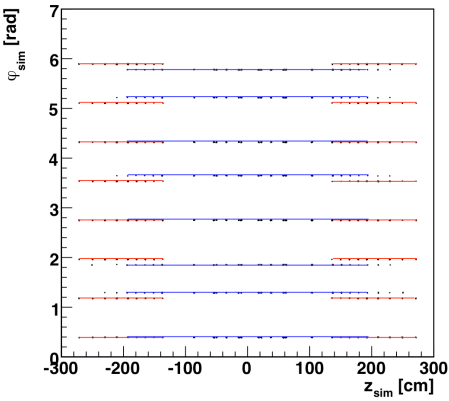
Y vs X Position of the SimHits


 (c) SimHits in the endcaps: y vs. x

R vs Z Position of the SimHits


 (d) SimHits in the endcaps: R vs. z

Phi [rad] vs Z Position of the SimHits


 (e) SimHits for the complete Laser Alignment System: φ vs. z

R vs Z Position of the SimHits

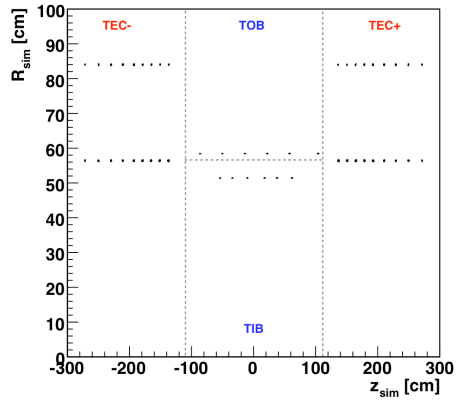

 (f) SimHits for the complete Laser Alignment System: R vs. z

Figure 3.2: Simulated hits in both barrel and endcap detectors showing the complete simulation of the Laser Alignment System.

- setting the optical properties of both active and passive materials in the detector, needed for the simulation of optical processes,
- placing the particle guns at the position of the beam splitters,
- shooting optical photons into the detector volume in order to simulate the laser beams,
- simulating gaussian beam profiles by giving each photon in a laser beam a random starting point according to a gaussian distribution.

Using GEANT4 functionality, the *OscarProducer* will track each photon through the detector volume and simulate optical processes like refraction and reflection at the borders of the various structures in the CMS Tracker.

On the occurrence of absorption in an active area of the detector, i.e. a silicon module, the *LaserAlignmentSimulation* module modifies the energy deposit in the given detector to simulate the absorption of several photons. In this way the CPU time needed for the simulation of all the laser beams can be greatly reduced³.

Once a photon has been absorbed the framework will take care of the creation of a simulated hit (*SimHit*). These SimHits are stored in the Event Data and can be processed by other modules. Figure 3.2(a) shows in the (x, y) plane the positions of the simulated hits from the eight laser beams in the barrel detector. For both TIB and TOB the hits at several z positions, those of the mirrors in the alignment tubes, are shown in figure 3.2(b). Figures 3.2(c) and (d) show the same picture for the simulated hits in the endcaps. The simulated hits for the complete Laser Alignment System are shown in 3.2(e) and (f). These plots demonstrate that the laser beams create hits in all nine layers of the endcaps and at six different z positions in both TOB and TIB.

3.3 Reconstruction

Following the hit creation step as described in section 3.2, the digitization step involves the simulation of the electronic readout used to acquire data by the detector and the Data Acquisition (DAQ) systems. It starts from the hit positions and simulated energy losses in the sensitive detectors and produces an output that must be as close as possible to real data coming from the CMS detector⁴ [62]. The objects produced during the digitization step are called *digis* and are stored in the Event Data. Reconstruction of data within the CMSSW framework usually consists out the following processing steps, realized by executing the appropriate reconstruction modules in the CMS software (see section 2.2.8)

- conversion of the *digis* to *clusters*,
- creation of reconstructed hits (*RecHits*) out of the *clusters* and
- construction of higher level objects, e.g. particle tracks, utilizing the reconstructed hits.

³Each beam contains $O(10^7)$ photons, which is in fact a huge amount to simulate. In the current implementation of the software this amount is reduced by a factor of 10^4 . The limited light transmission efficiency through the silicon modules [72] is also taken into account: the energy deposit of an absorbed photon is adjusted according to the z position in the detector where the absorption occurred.

⁴Thus after the digitization step the Event Data look exactly the same for simulated events and for events coming from the DAQ system during data taking. Hence the reconstruction software described in this section will work equally well with simulated laser events as with laser data measured with the tracker.

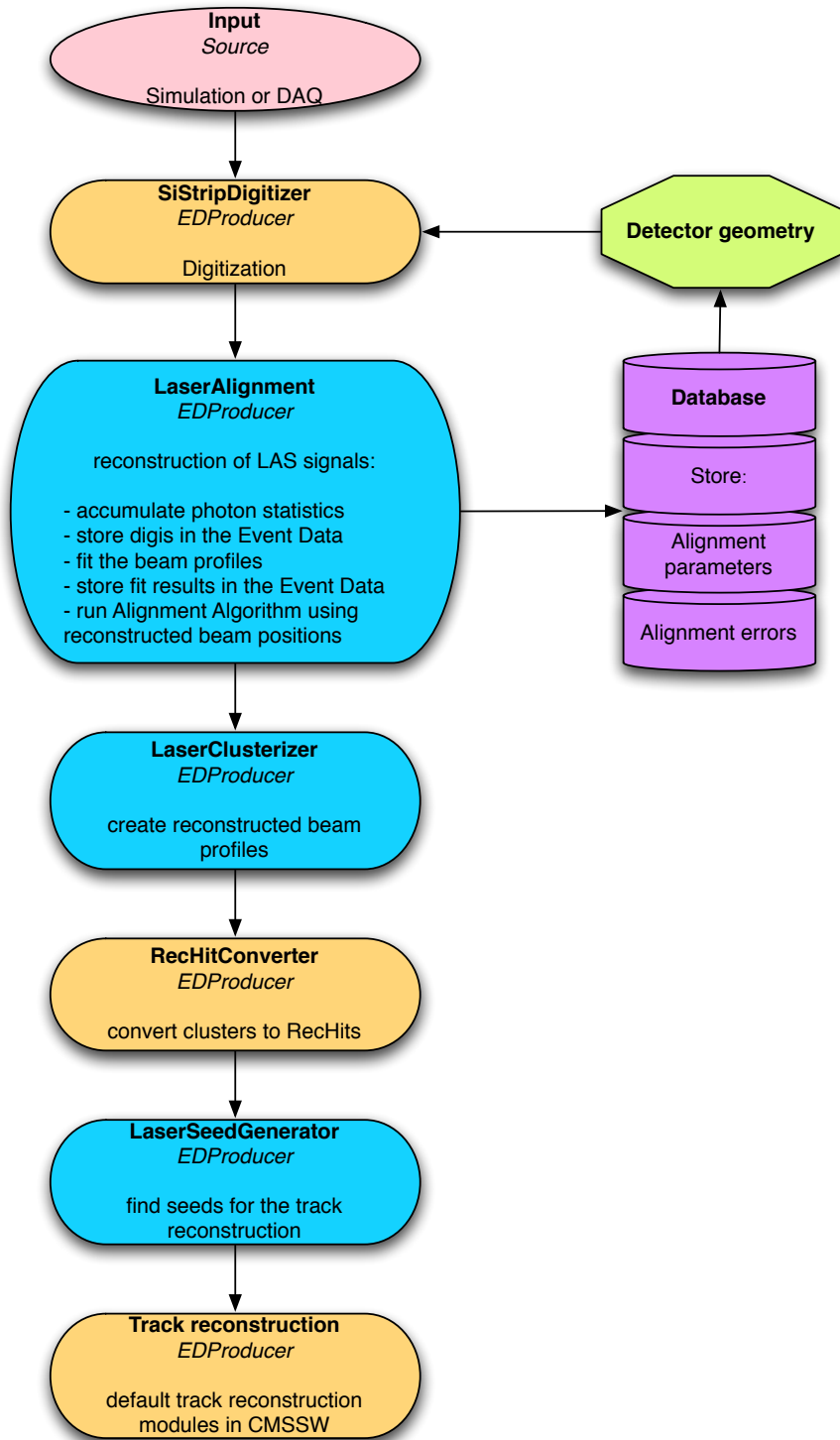


Figure 3.3: Program flow during reconstruction. In blue the modules for the Laser Alignment System, in yellow default CMSSW modules. The calculated alignment corrections are stored in the CMS conditions database. The information from the database is utilized to construct a realistic description of the detector geometry in CMSSW.

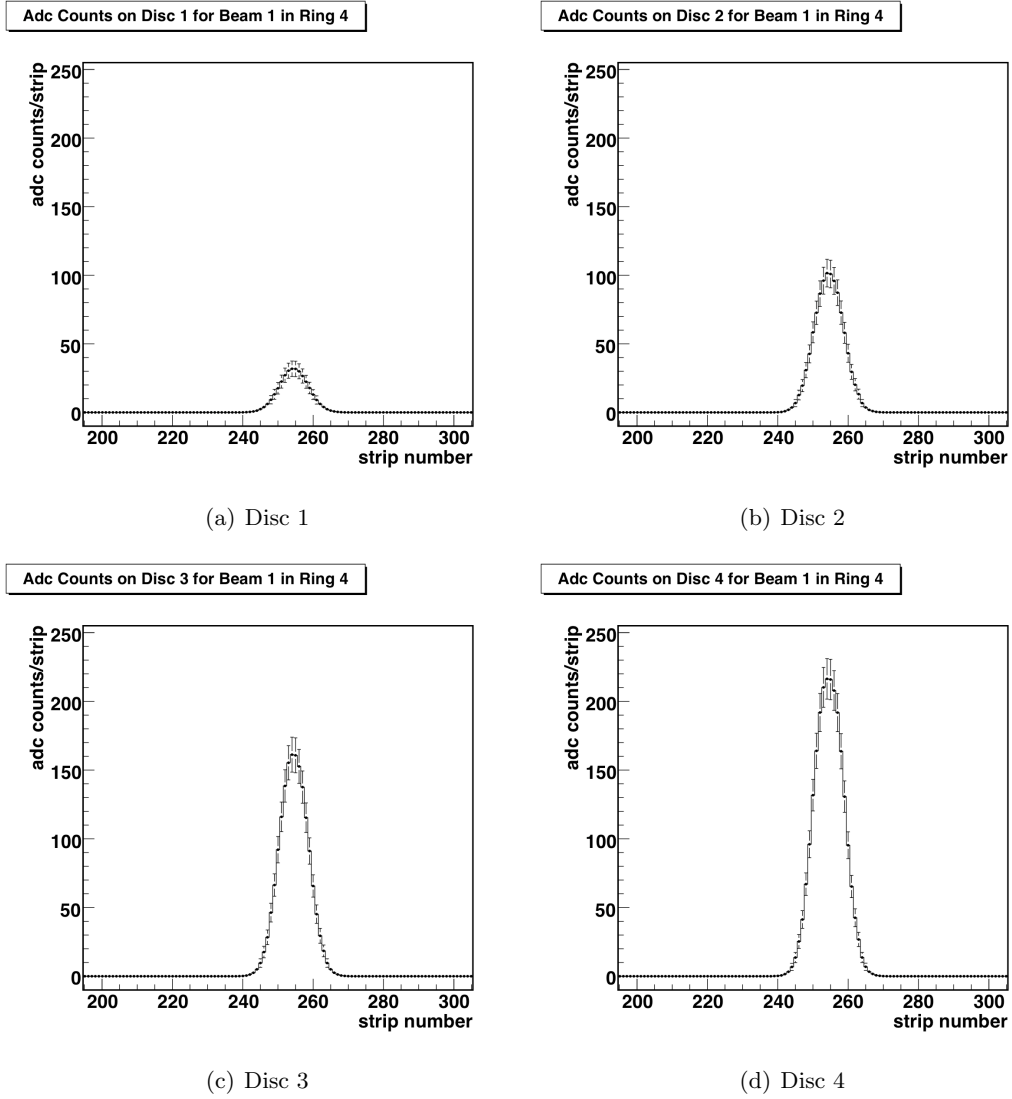
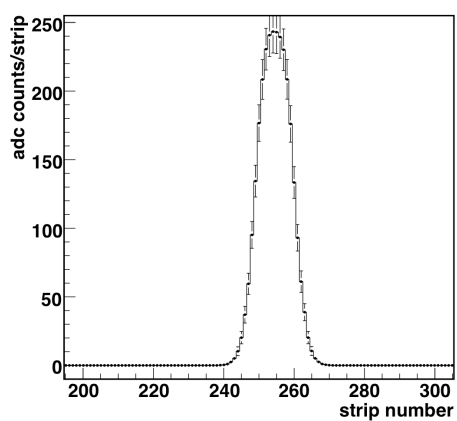


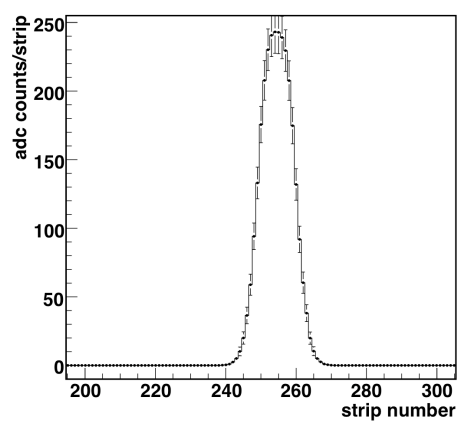
Figure 3.4: Simulated beam profiles in ring 4 on all 9 discs. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 47.

Adc Counts on Disc 5 for Beam 1 in Ring 4



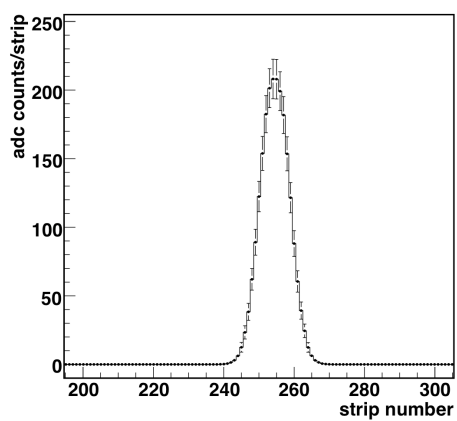
(e) Disc 5

Adc Counts on Disc 6 for Beam 1 in Ring 4



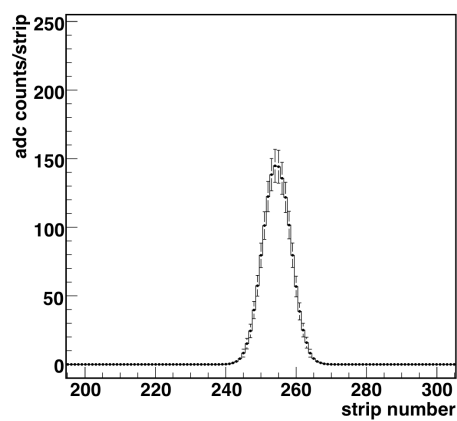
(f) Disc 6

Adc Counts on Disc 7 for Beam 1 in Ring 4



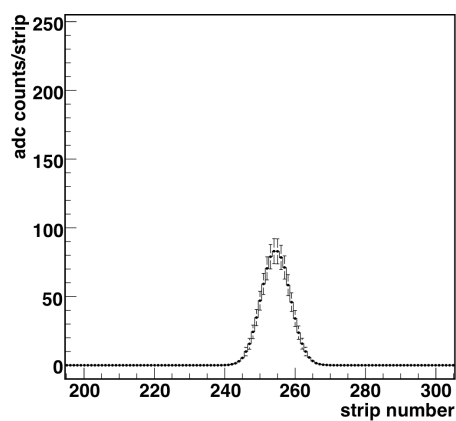
(g) Disc 7

Adc Counts on Disc 8 for Beam 1 in Ring 4



(h) Disc 8

Adc Counts on Disc 9 for Beam 1 in Ring 4



(i) Disc 9

Figure 3.4: Continued from page 46.

However, the reconstruction software for the Laser Alignment System is organised in a different way: the reconstruction of the laser beams is primarily carried out directly on the *digis*, finally resulting in the reconstructed beam positions. The details of this procedure as well as the structure of the software are described in the following.

Figure 3.3 shows the program flow during reconstruction. The *LaserAlignment* module contains the functionality to reconstruct the signals coming from the LAS and to calculate the alignment parameters. As described in section 2.2.2.4, the signal of the laser beams decreases while traversing several layers of silicon modules. Therefore the *LaserAlignment* module accumulates photon statistics by collecting for each laser beam the digis of several events. The resulting beam profiles, which should be gaussian due to the beam properties, are fitted with a Gauss function to estimate their mean and width. In case of real detector data the fitted mean value is corrected for the beam splitter kink using the method described in section 2.2.2.4 (equation 2.2)⁵.

Figure 3.4 shows the simulated laser beam profiles in ring 4 on all 9 discs of a tracker endcap. Due to the limited transmission of the laser beams through the silicon modules, the height of the signal decreases with increasing distance from the beam splitters, which are mounted on disc 6.

Figure 3.5 shows the beam profile measured during data taking at the Tracker Integration Facility (TIF) at CERN for ring 4 in sector 3 of disc 2. The aluminium strips of the sensors (see figure 2.9) act as a diffraction grating for the laser beams [72]. The resulting diffraction pattern⁶ is shown in figures 3.5(a) and 3.5(b). The gaussian fit used to reconstruct the beam position has been applied to the central maximum as shown in figure 3.5(c).

The collection of the digis originating from the laser beams and the procedure to fit the beam profiles are the first two steps performed by the *LaserAlignment* module. Figure 3.6 illustrates all processing steps. The *LaserAlignment* module stores both the digis, which contribute to the laser signals, as well as the fit results in the Event Data. The stored data can be used in subsequent reconstruction steps or they can be used for re-reconstruction of the laser events as the Event Data are permanently kept.

The positions of the laser beams in the global CMS coordinate frame can be derived from the fit results. They are utilized to reconstruct an eventual misalignment of the CMS tracker and to estimate corrections to the geometry description, which are stored in the CMS conditions database [62]. The alignment algorithms used to this purpose are the subject of the next subsection.

3.3.1 Alignment Algorithms

To estimate alignment corrections from the reconstructed beam positions two different alignment algorithms are currently implemented in the software for the Laser Alignment System: MILLEPEDE [93, 94] and a second algorithm as described in [75].

MILLEPEDE is a program package for alignment which has been used and tested successfully at several high energy physics experiments, *e.g.* at H1 [95] and CDF [96]. MILLEPEDE is a linear least square fit algorithm. Such an algorithm is usually stable, fast, and accurate and can take into account correlations among parameters [62].

MILLEPEDE distinguishes between global and local parameters. Global parameters are

⁵A simulation of the beam splitter kink could also easily be realized in CMSSW. However, for the simulated events used to produce the results presented in this chapter no beam kink has been simulated.

⁶This effect is not visible in the simulated data because GEANT4 does not keep track of the overall phase of the optical photons during the propagation of the particles through the detector [92].

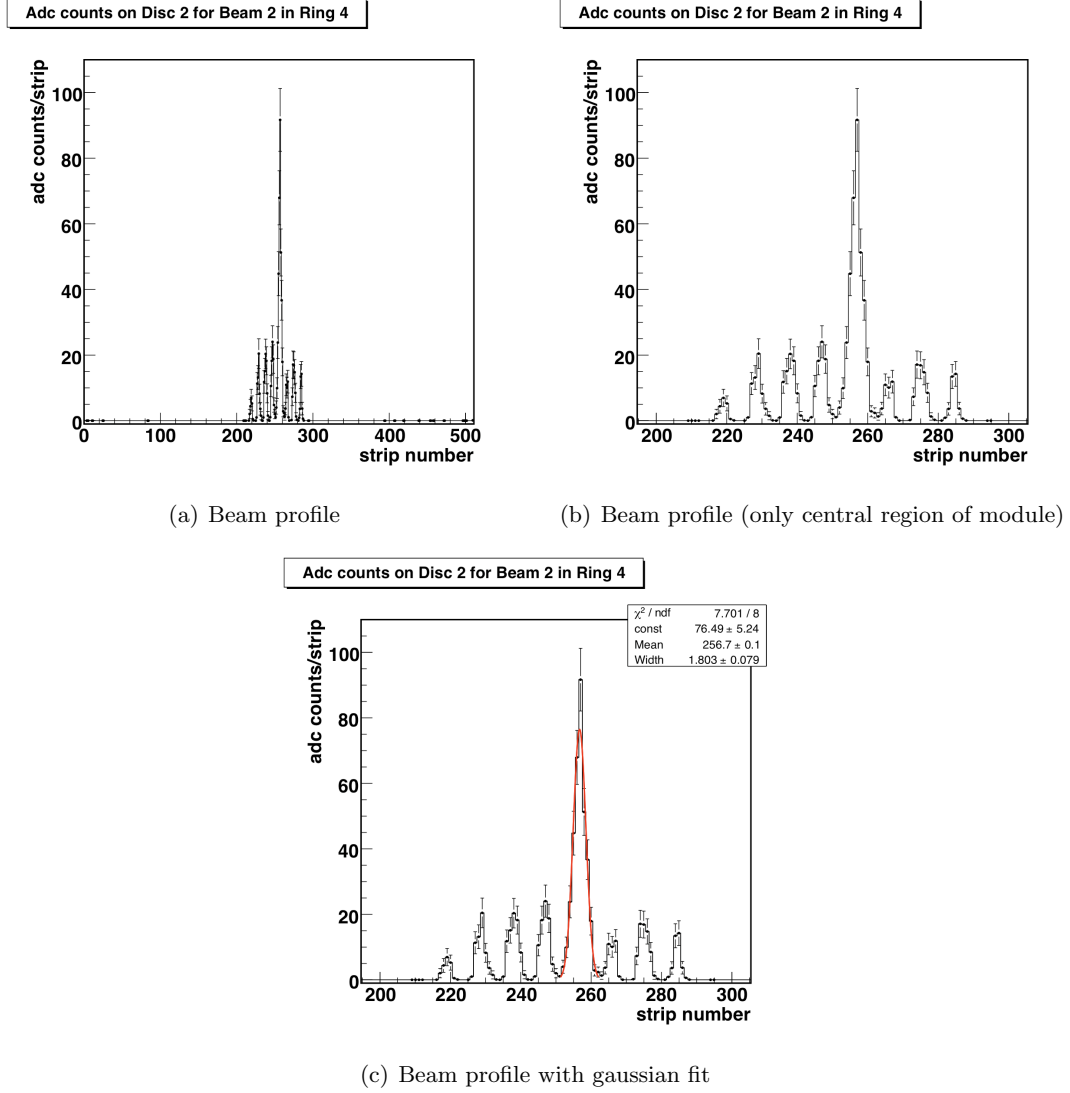


Figure 3.5: Beam profile for ring 4 in sector 3 of disc 2 from Run 8346 taken in the TIF. (a) shows the full strip range of the silicon module, (b) shows only the central region of the module and (c) shows the beam profile together with the gaussian fit. The error bars indicate the statistical errors.

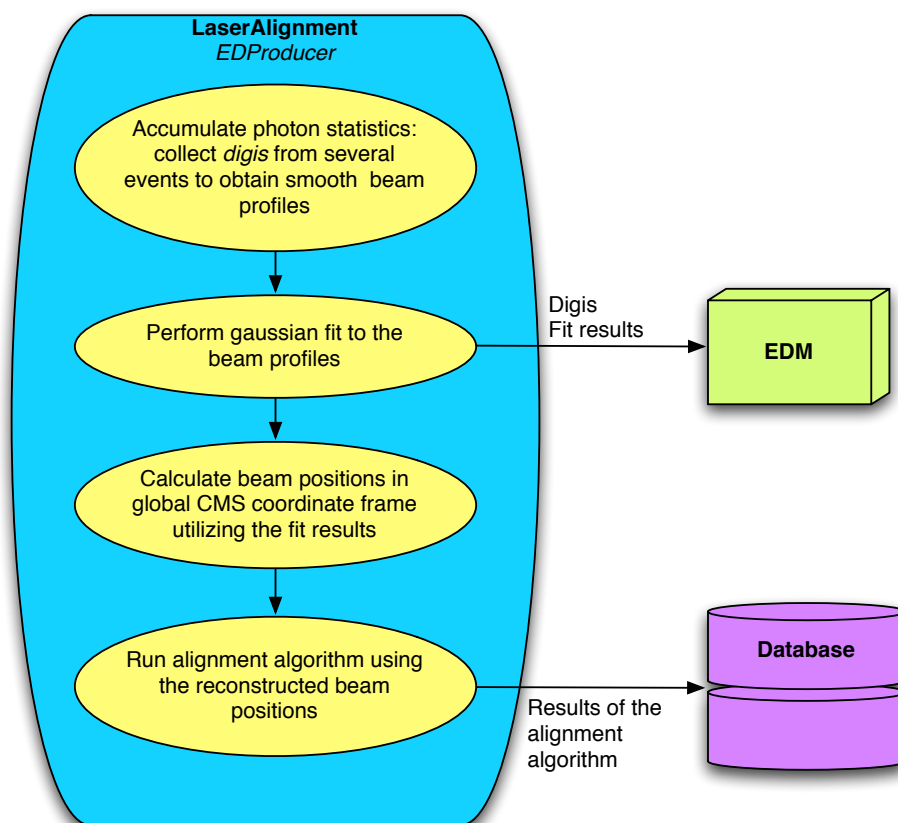


Figure 3.6: Process flow in the *LaserAlignment* module. The first step is to accumulate photon statistics in order to obtain smooth laser beam profiles. The beam profiles are fitted with a Gauss function and the fit results together with the *digis* are stored in the Event Data. The reconstructed positions of the laser beams in the global CMS coordinate frame are derived from the fit results and used as input to the alignment algorithms. The results of the alignment algorithm are stored in the database as corrections to the geometry.

common to all data, namely the parameters describing the positions of the detectors. Local parameters are only present in a subset of the data. Track parameters and, in case of the Laser Alignment System, the parameters describing the path of the laser beams are local parameters as they are specific to a single event. MILLEPEDE performs a simultaneous least squares fit of all global and all local parameters in a single step. A complete description of the formalism can be found in [93, 94]

The second alignment algorithm, which was only recently added to the LAS software, parametrizes the possible movements and deformations of the mechanical tracker structure and performs a fit of these parameters to the set of reconstructed beam positions. This approach results in a set of linear equations, the solution being the desired alignment parameters. A detailed description of the equations used and their solutions can be found in [75].

The tools needed to apply misalignment to the detector were implemented in the predecessor of the current CMS software framework [97] and were ported to CMSSW. These tools have been used to check whether the alignment algorithm and the storage of the alignment parameters in the database are functioning as expected. To this purpose the simulated tracker has been misaligned according to the values listed in table 3.2 and the detector positions were stored in the database.

	TEC+			TEC-		
	Δx [μm]	Δy [μm]	$\Delta\varphi$ [μrad]	Δx [μm]	Δy [μm]	$\Delta\varphi$ [μrad]
Disc 1	17	8	50	0	0	-260
Disc 2	30	-25	230	30	-25	330
Disc 3	-20	17	-70	-200	170	-110
Disc 4	100	30	120	10	130	140
Disc 5	9	-50	180	90	-150	210
Disc 6	-15	23	-140	-150	23	-140
Disc 7	22	-12	150	220	-7	50
Disc 8	33	-130	190	33	-13	-190
Disc 9	-110	31	300	-110	310	300

Table 3.2: Shifts in x and y direction and rotations around the z axis used to misalign the tracker endcaps.

In the first run, the geometry description of the detector was read from the database and the laser events were reconstructed, resulting in beam positions displaced in comparison to the design positions in the ideal geometry. The calculated alignment parameters were added to the database at the end of the reconstruction job. In the second run, both the applied misalignment and the estimated alignment parameters were read from the database and applied to the detector geometry, resulting in an aligned detector before the reconstruction of the laser events started. The alignment parameters calculated in the second run were also stored in the database. Figure 3.7 illustrates the described procedure used to test the alignment algorithm and the storage of the corrections in the database.

In the simulated events, where the beam kinks have not been taken into account as described before, the hits of one laser beam on consecutive discs in the endcap are on a straight line.

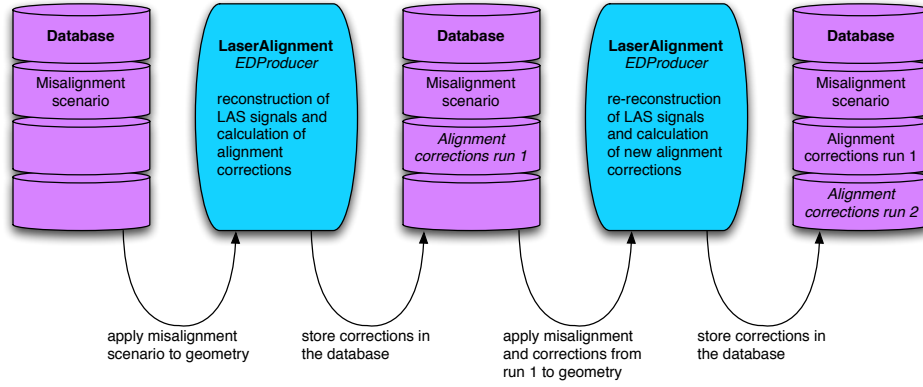


Figure 3.7: Schematic overview of the alignment procedure. The misalignment scenario has been stored in the database and then used to construct the geometry of the simulated tracker. In the first run the laser beam positions are reconstructed using the misaligned geometry and corrections are calculated by the alignment algorithm. The corrections are added to the database. The second run applies the corrections obtained in the first run to the misaligned geometry before reconstruction of the laser beam positions. The corrections calculated in the second run are also added to the database.

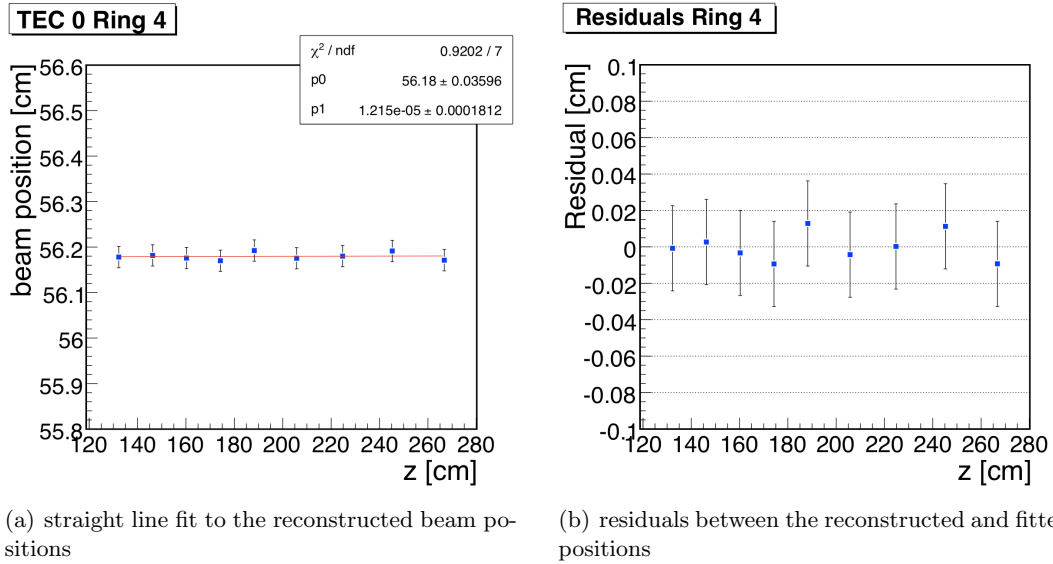


Figure 3.8: Straight line fit to the reconstructed beam positions and the residuals between the reconstructed and the fitted positions in the first run: (a) straight line fit in ring 4 of sector 6 in TEC+, (b) residuals. The error bars indicate the error of the reconstructed beam positions.

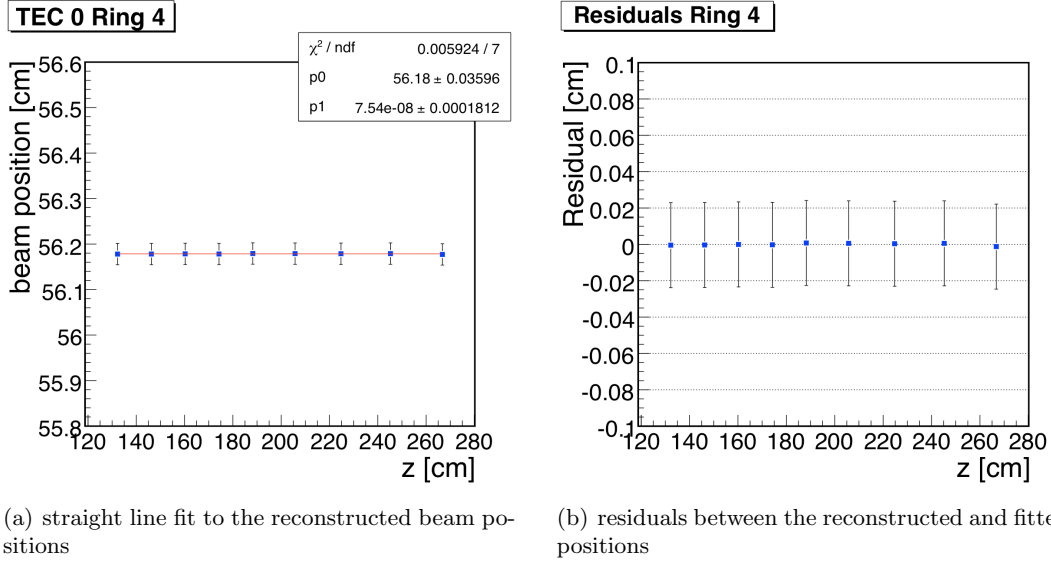


Figure 3.9: Straight line fit to the reconstructed beam positions and the residuals between the reconstructed and the fitted positions in the second run after the corrections from run 1 have been applied: (a) straight line fit in ring 4 of sector 6 in TEC+, (b) residuals. The error bars indicate the error of the reconstructed beam positions. The small χ^2/ndf is due to the very small residuals obtained in the second run.

Therefore, for both runs a straight line fit has been applied to the reconstructed laser beam positions and the residuals between the measured and fitted positions have been calculated. For the first run figure 3.8(a) shows the straight line fit applied to the reconstructed laser beam positions in ring 4. On the right side of the plot (figure 3.8(b)) the residuals are shown. Figure 3.9 shows the result obtained from the second run after applying the alignment corrections calculated in the first run. The deviations between the fitted and the measured positions are much smaller than those observed in the first run, resulting in a very small χ^2/ndf of the straight line fit⁷.

The distribution of the residuals for all the laser beams are shown in the histograms in figure 3.10. A gaussian fit applied to the residuals of run 1 (figure 3.10(a)), resulting in a width of approximately 56 μm , does not describe the data very well, which is also shown by the large χ^2/ndf . The RMS of the distribution is also large (approximately 95 μm). However, the width of the residuals distribution decreases to about 10 μm in the second run (figure 3.10(b)), after the alignment corrections calculated in run 1 have been applied to the geometry.

These results show the ability of the Laser Alignment System to align the tracker endcaps. Furthermore, the results show that the dataflow and processing logic in the *LaserAlignment* module behave properly and that the database objects written into the CMS conditions database are in a correct state and can be read again by the *LaserAlignment* module.

⁷The χ^2 distribution is commonly used for goodness of fit tests. The value of χ^2 is defined as [98]

$$\chi^2 = \sum_{i=1}^k \frac{(x_{i,\text{measured}} - x_{i,\text{fit}})^2}{\sigma_i^2}.$$

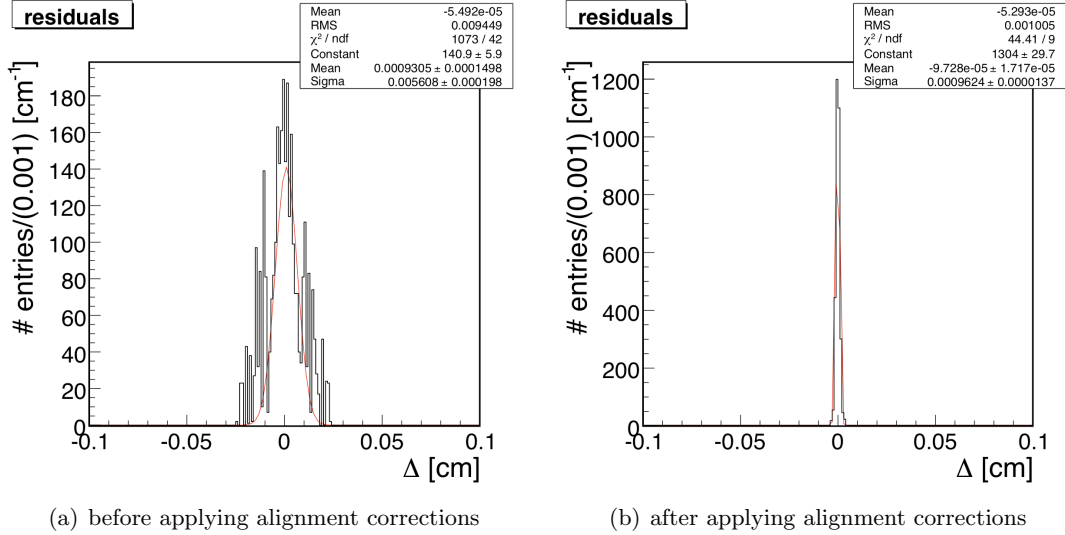


Figure 3.10: Residuals for all laser beams in both endcaps before and after applying alignment corrections. The deviations between the measured and the fitted positions are much smaller after aligning the detector.

3.3.2 Laser Tracks

As stated in section 3.3 the digis are used by the *LaserAlignment* module for the reconstruction of the laser beam positions. In order to create higher level objects out of the laser signals, *e.g.* reconstructed tracks, the digis have to be converted into *clusters* and reconstructed hits (*RecHits*). In the default case the digis stored in the Event Data by the *LaserAlignment* module are utilized by the reconstruction algorithms to search for charge above threshold collected in neighbouring strips and to merge these strips into clusters. The hit positions are then calculated from the cluster position and stored in the Event Data as reconstructed hits (*RecHits*). For LAS data however, the *LaserClusterizer* module (see figure 3.3) takes care of the clustering of the signals originating from the laser beams. However, it does not search for neighbouring strips above threshold, but uses directly the result of the gaussian fit, which has been stored in the Event Data by the *LaserAlignment* module, to estimate the cluster position.

The algorithm gets the fitted mean of the beam profile from the Event Data and selects the digis in a 1σ range⁸ around the strip corresponding to this mean value. The reconstructed cluster is created out of these digis and the framework takes care of the calculation of the correct position. The *LaserClusterizer* module stores the created clusters in the Event Data and in the next step of the reconstruction the *RecHitConverter* converts the clusters to reconstructed hits containing three dimensional position information. Figure 3.11 shows the laser beam hits reconstructed in both the barrel and endcap detectors of the CMS tracker.

Information from the Laser Alignment System also provides an additional constraint for track based alignment algorithms. Therefore the capability to create tracks out of the hits created by the laser beams has been implemented in the CMS software. After the creation of the clusters and reconstructed hits, four subsequent steps (embedded in the blocks “LaserSeed-Generator” and “Track reconstruction” at the bottom of the flow diagram in figure 3.3) are

⁸The cluster width can be configured using the appropriate options in the parameter set of the reconstruction process (see Appendix A).

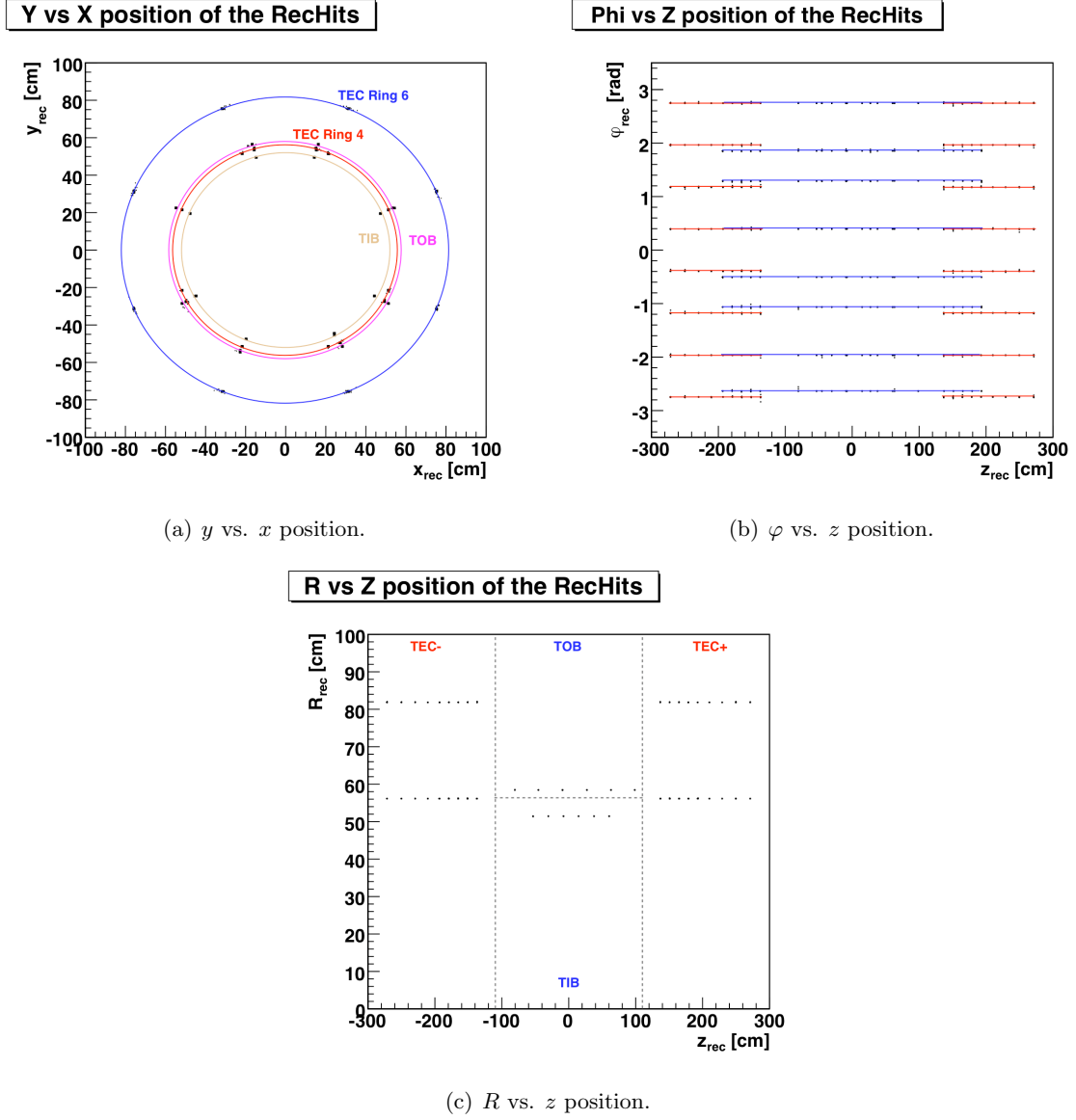


Figure 3.11: Positions of the laser beam hits reconstructed in both barrel and endcap detectors. For visibility reasons no errors have been added to the plots shown here.

The *LaserSeedGenerator* module searches for hits on two discs in the tracker endcaps in a given $R - \varphi$ region, corresponding to the beam position. A hit pair consists of an outer hit (at larger $|z|$) and an inner hit (at smaller $|z|$) coming from two different discs. The various combinations of discs used to find hit pairs are shown in figure 3.12. The combinations were chosen to provide redundancy in searching for pairs of hits in order to maximize the efficiency for generating seeds. Tracks missing a hit in any of the discs may still be reconstructed in the other discs.

After seed generation, the other steps during track reconstruction are the same for laser tracks as for tracks originating from charged particles. Therefore the default track reconstruction modules implemented in the CMS software framework (see section 2.2.8) are used.

Figure 3.13 shows a picture from the CMS Event Display software IGUANA⁹ [99–102], which was used to visualize the reconstructed tracks originating from the laser beams of the Laser Alignment System.

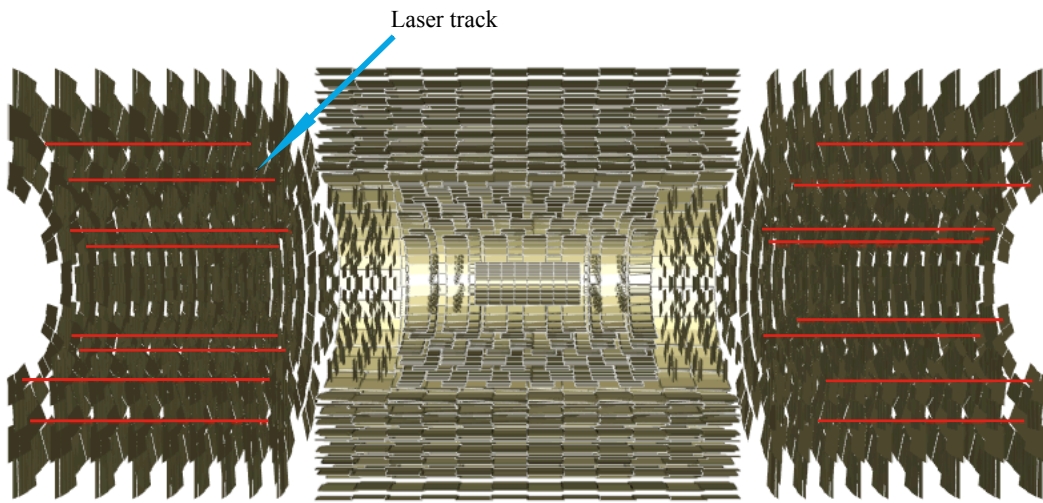


Figure 3.13: Laser tracks in the tracker endcap. Shown is a y - z view of the CMS tracker (half of the detector has been cut away to allow a look inside the detector). The red lines in both the endcaps indicate the reconstructed tracks originating from the laser beams of the Laser Alignment System (in order to make the laser tracks more visible, the result from the IGUANA visualization has been edited).

3.4 Data Quality Monitoring

The Physics and Data Quality Monitoring system (DQM) aims at providing a universal monitoring environment for various applications related to data taking at CMS. Applications that can benefit from such a unified approach to monitoring range from the high-level trigger algorithms in the Filter Farm to local DAQ supervision for a subdetector all the way to validation of the data by offline reconstruction jobs [62].

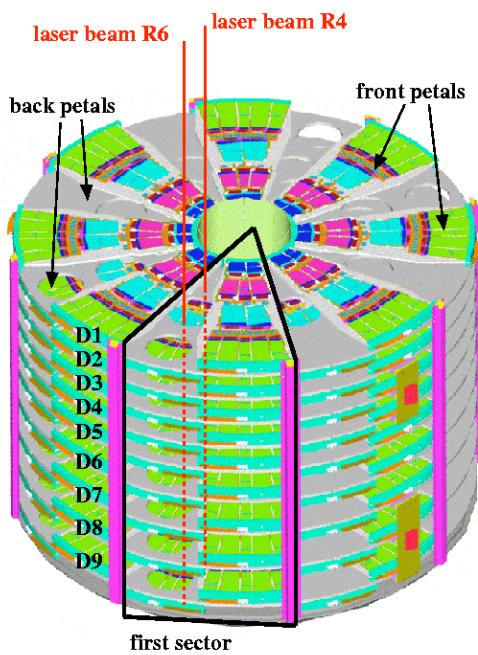
The Data Quality Monitoring system provides a set of tools containing tree-like directories with *e.g.* histograms and strings, quality tests that can produce warnings, errors and alarms,

⁹Interactive Graphics for User Analysis

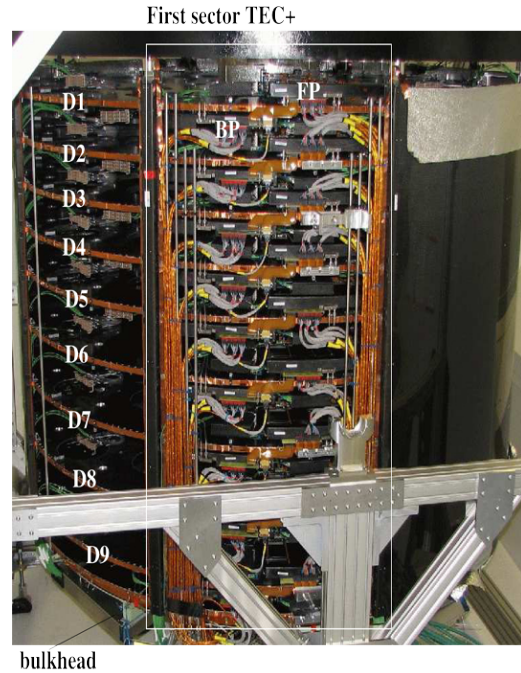
visualization tools and the transfer of monitoring information to remote nodes [62]. The DQM system will in the future also set data quality bits, which will be used for data certification in order to provide lists of good runs for physics analysis [103].

The DQM infrastructure is utilized by the software of the Laser Alignment System to provide several histograms to monitor the quality of the beam profiles during data taking. The *LaserDQM* module accumulates photon statistics in the same way as the *LaserAlignment* module does during reconstruction (see section 3.3) and updates the content of the monitor histograms on a periodical basis. The monitor histograms can be viewed online, remotely via a web server and it is even possible to dump “snapshots” of the monitors to a ROOT [85] file.

3.5 Analysis of the TEC+ sector test data



(a) Subdivision of TEC+ into 8 sectors, each consisting of 9 front and 9 back petals. The R4 and R6 laser beams for the first sector are also indicated.



(b) Petal integration in the first sector of TEC+.

Figure 3.14: TEC+ during petal integration and sector test [72]: (a) schematic view of the tracker endcap together with the subdivision into 8 sectors and (b) photograph of the TEC+ after integration of the first sector has finished.

The Laser Alignment System was tested in Aachen during petal integration and system commissioning of all eight sectors of the TEC+ (see figure 3.14). Due to the early development status of CMSSW at the time, it was decided to analyse the data with standalone tools based on the ROOT Analysis Framework [85]. Part of the functionality of these standalone tools (*e.g.* fitting the laser beam profiles) has been implemented in the CMSSW modules for the Laser Alignment System as described in the previous sections.

The analysis of the data taken during this integration and commissioning phase of TEC+ is the subject of this section. The analysis consists of the following steps

- fit the beam profiles to reconstruct the beam positions,
- take the beam splitter kink into account,
- apply a straight line fit to the positions of each laser beam,
- calculate residuals between the measured and fitted beam positions.

Each of these steps will be discussed in more detail in the following paragraphs. The assembly precision of TEC+ can be derived from the distribution of the residuals presented at the end of this section. The results are compared with information obtained from survey measurements and from alignment with cosmic muon tracks.

Reconstruction of the beam positions Figure 3.15 and 3.16 show the signals in ring 4 and 6 respectively for sector 1 of TEC+¹⁰. The signals in the other 8 (including sector 1 after the exchange of petals) sectors are shown in Appendix B. The x axis of the plots shows the beam position (in μm) on the modules, which is calculated according to

$$\text{beam position } [\mu\text{m}] = \text{strip number} \cdot \text{pitch } [\mu\text{m}]. \quad (3.1)$$

The pitch in ring 4 modules is $126 \mu\text{m}$ and in ring 6 modules $187 \mu\text{m}$.

To all beam profiles a gaussian fit (in red) has been applied to reconstruct the beam position. During the sector test the intensity of the laser beams has not been tuned to get optimal beam profiles on all discs. Therefore the limited quality of some of the profiles, especially on the outermost layers of the TEC, results in a poor fit characterized by a too small or too large value of χ^2/ndf .

In the final setup of the Laser Alignment System it is foreseen to tune the laser intensities in order to improve the quality of the beam profiles on all layers of the tracker endcaps. Since this was not done here and in order to take the aforementioned issues into account, positions deviating by at least $200 \mu\text{m}$ from the straight line fit applied to the reconstructed beam spots (see the next paragraph) have been treated in a special way. Those cases (occurring only in the data shown in figures B.1 – B.23) are indicated by marking all data points in red.

¹⁰All petals in sector 1 had to be exchanged due to problems with the modules. However, this exchange took place after the sector had been tested with the Laser Alignment System and therefore the data from the old sector 1 (sometimes referred to as sector 0) are also included in this analysis. In fact there are thus data for nine sectors in TEC+ available.

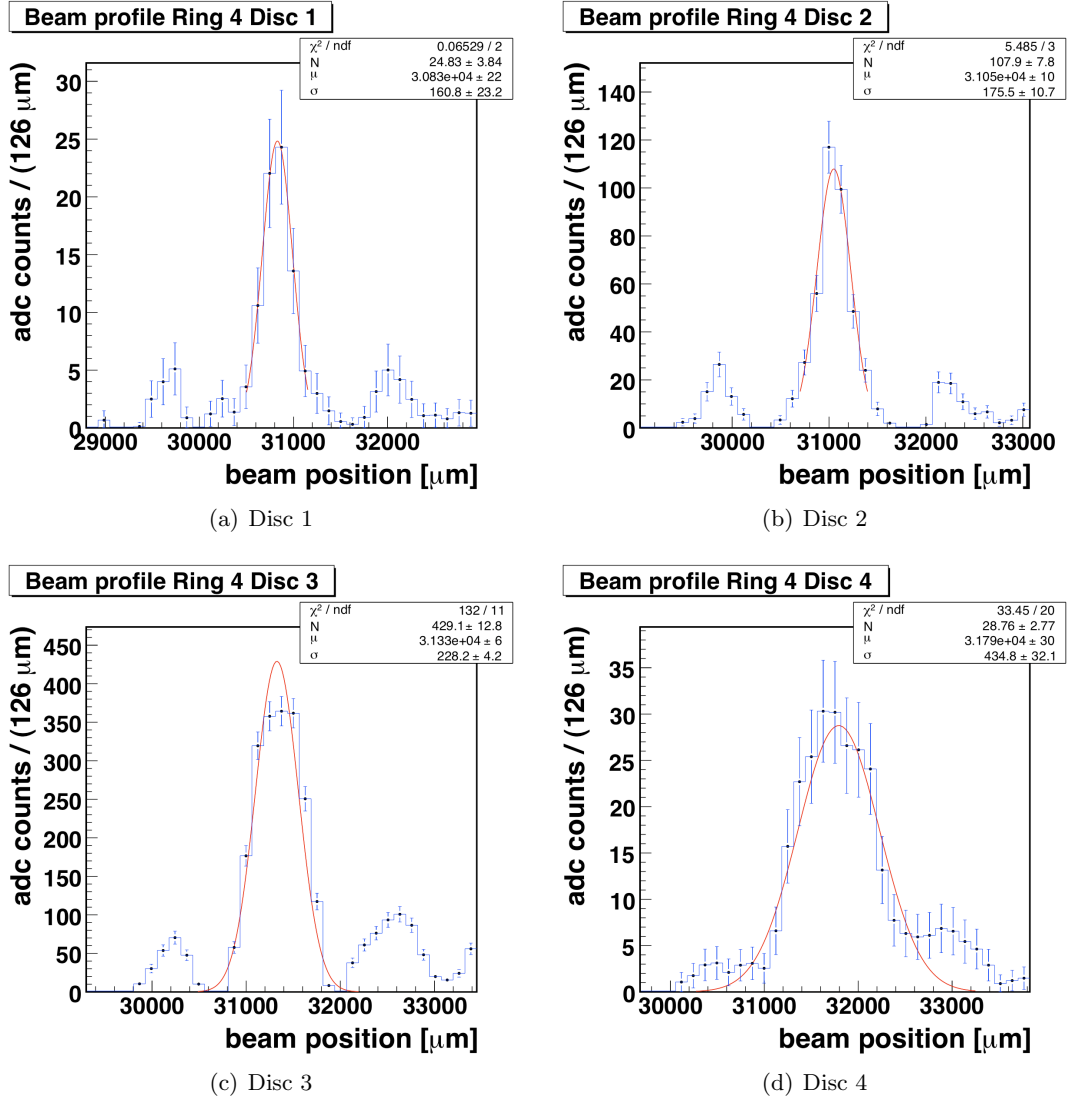


Figure 3.15: Signals (in adc counts/126 μm) of the laser beams in ring 4 for sector 1 before the exchange of the petals. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 61.

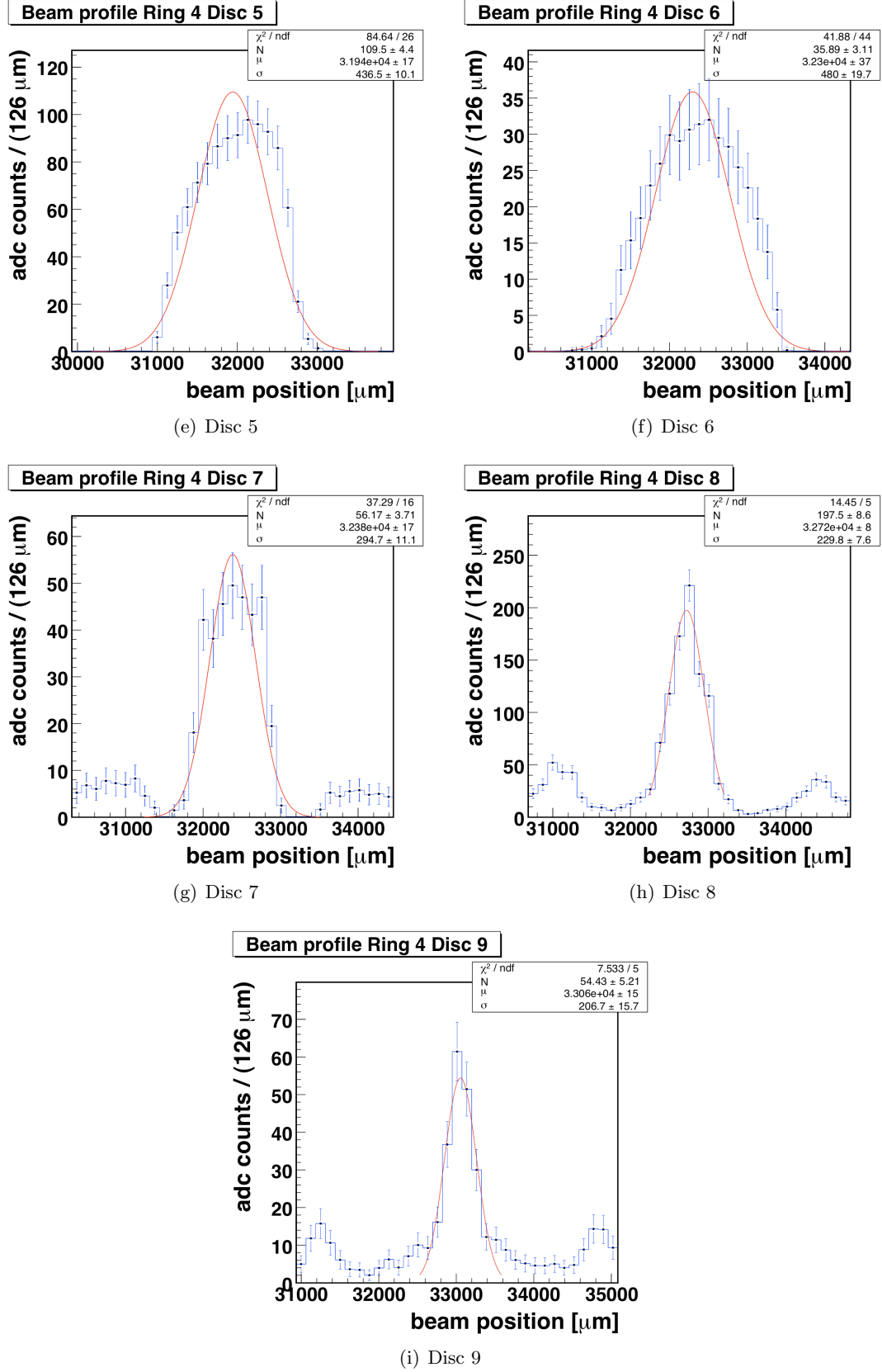


Figure 3.15: Continued from page 60.

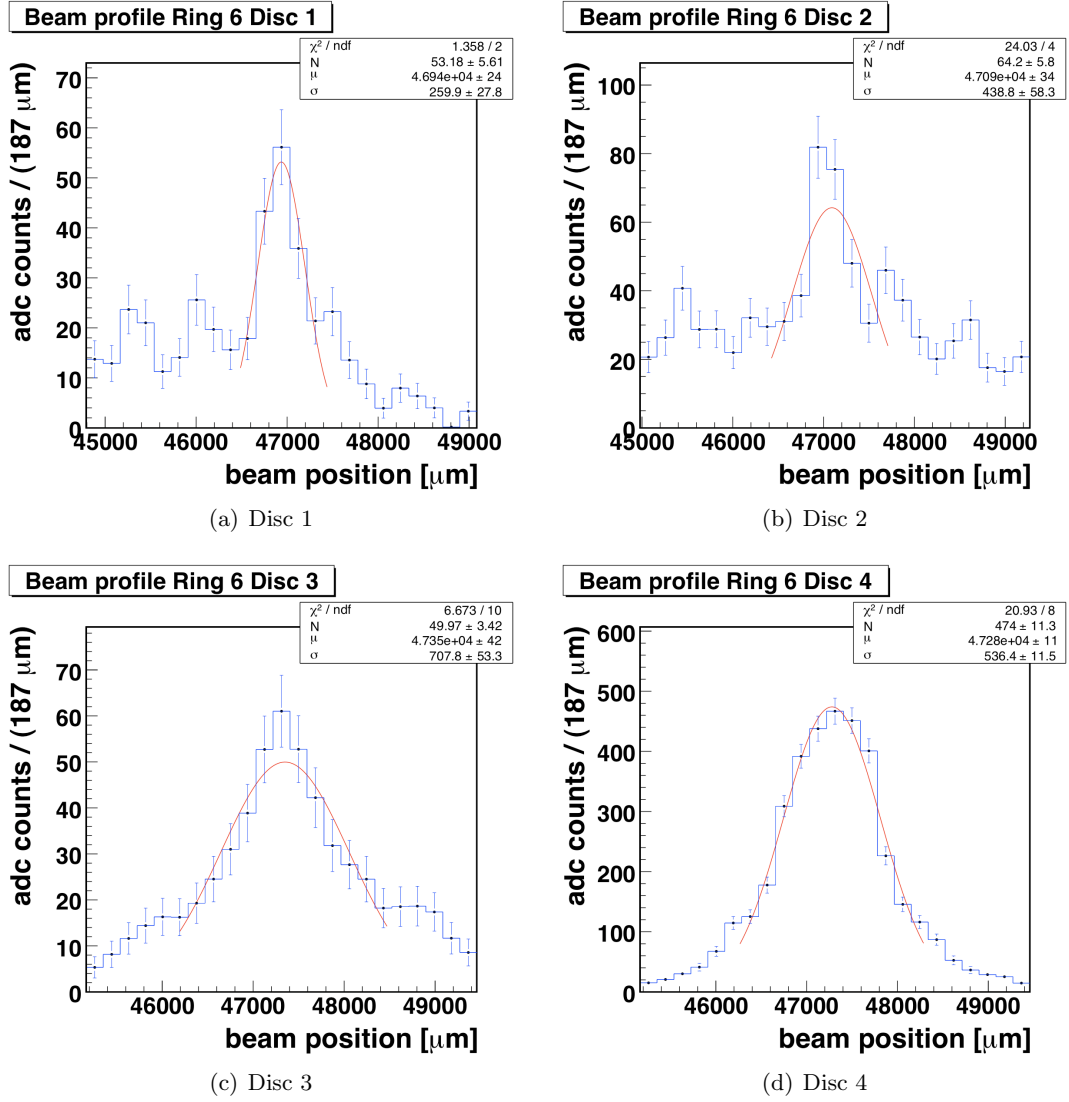


Figure 3.16: Signals (in adc counts/187 μm) of the laser beams in ring 6 for sector 1 before the exchange of the petals. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 63.

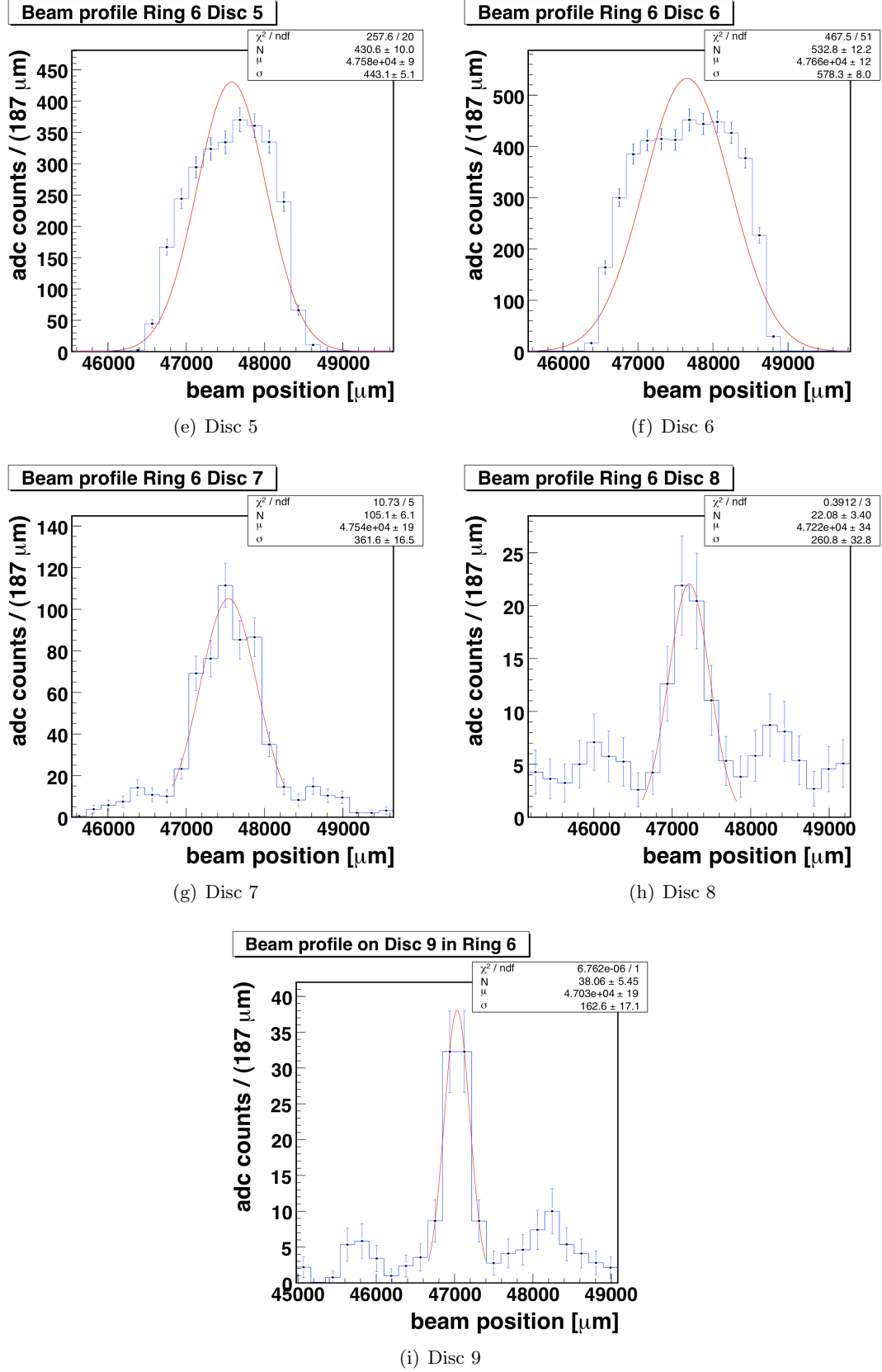


Figure 3.16: Continued from page 62.

Straight line fits to the beam positions For each laser beam a straight line fit has been applied to the reconstructed beam positions, obtained from the gaussian fit to the beam profile as described in the previous paragraph. To take the beam splitter kink into account, the following fit function was used

$$f(z) = \begin{cases} a + b \cdot z & \text{for } z \leq 0 \\ a + (b + \Delta b) \cdot z & \text{for } z > 0 \end{cases} \quad (3.2)$$

where z is the position of the discs (in mm) relative to the position of the beam splitters located at $z = 0$ (figure 3.17) and b and Δb are the measured beam splitter kink angle and its error taken from [72]. The analysis program includes the option either to constrain b within a 2σ range of its measured value or to include it as a free parameter in the fit in order to check whether the fitted values are in agreement with the measured values of the beam splitter kink angles.

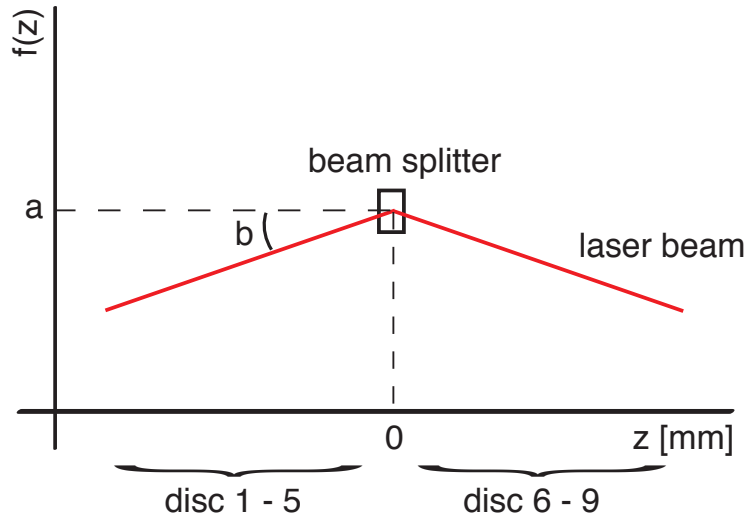


Figure 3.17: Schematic view of the straight line fit applied to the reconstructed beam positions. The beam splitter is located on disc 6 at $z = 0$. Discs 1 to 5 are located to the left of the beam splitter while discs 6 to 9 are to the right. The red lines illustrate the laser beams.

Figure 3.18 shows the result of fitting equation 3.2 (with b constrained as discussed above) to the measured beam positions for the laser beams in rings 4 and 6 in sector 1. Appendix B contains figures for the other eight sectors measured during the TEC+ integration test. The figures also show the residuals between the reconstructed beam positions and the fit.

In case a reconstructed beam position deviated more than $200 \mu\text{m}$ from the fitted line, the error of this measurement was enlarged and the fit was repeated. An example can be seen in figure B.3: the beam position in ring 4 on disc 1 has quite a large deviation from the straight line through the other measurements. The discrepancy seen for discs 8 and 9 in ring 6 (the lower part of B.3) was caused by refraction of the laser beam through an optical fibre, which was in the path of the beam.

Residuals between measured and fitted beam splitter angles Figure 3.19 gives a comparison between the measured [72] and the fitted beam splitter angles resulting from this analysis.

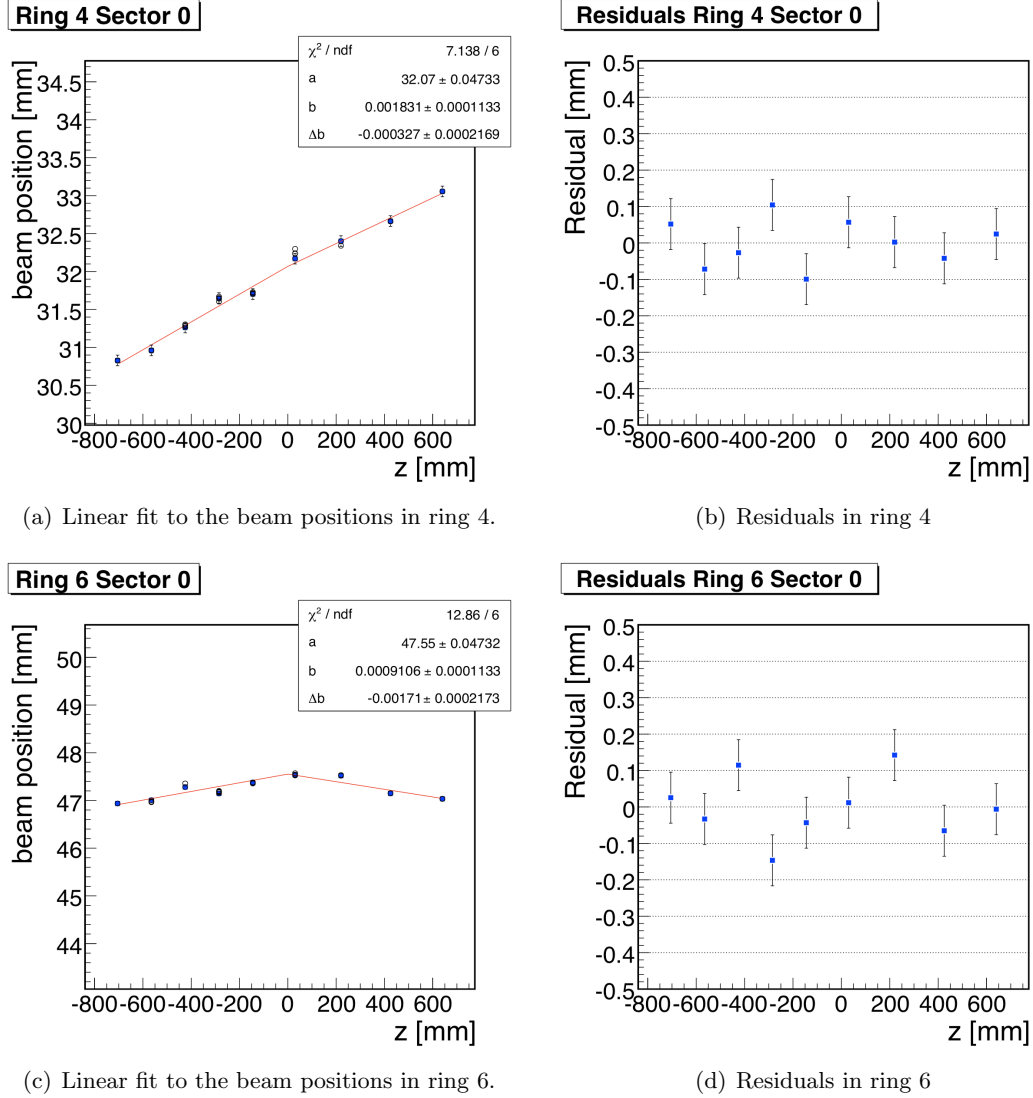
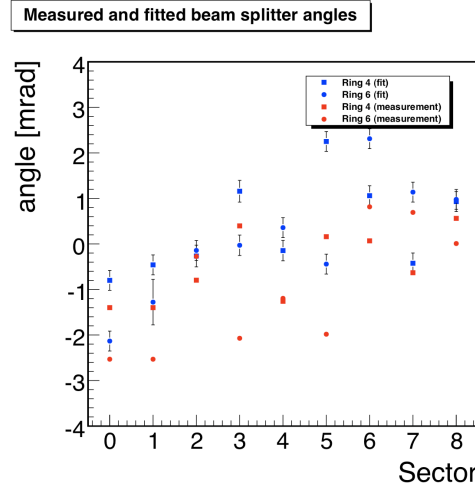


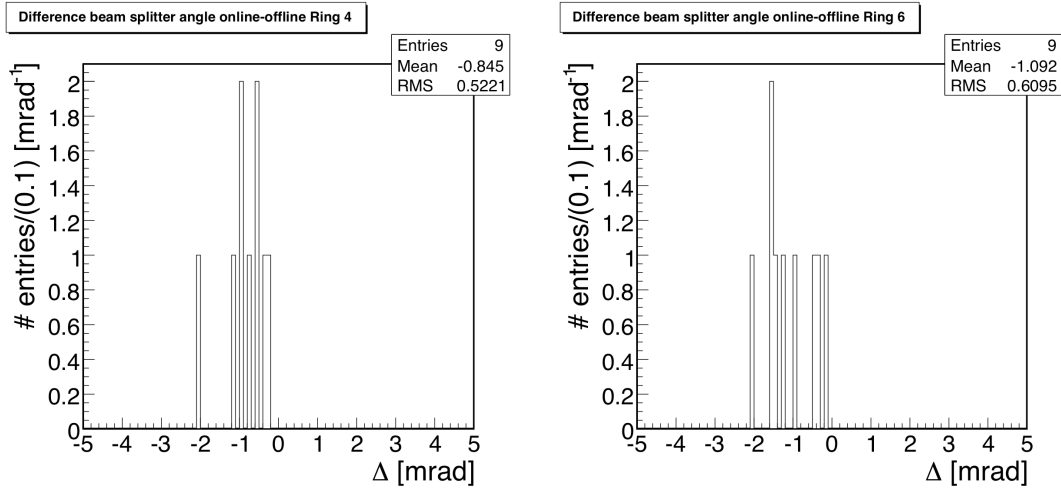
Figure 3.18: Straight line fit applied to the reconstructed beam positions in (a) ring 4 and (c) ring 6 for sector 1 before the exchange of the petals. (b) and (d) show the residuals between the reconstructed beam positions and the straight line fit. The error bars indicate the error of the reconstructed beam positions. The measurements indicated by the open white circles in (a) and (c) are from different runs, where a beam profile has been reconstructed on the same disc. For each disc the measurement resulting in the smallest residual (indicated by the blue markers in the plots) has been used for the straight line fit.

For this comparison the beam splitter angles were treated as a free parameter in the straight line fit described in the previous paragraph.

The agreement is not very good: the fitted angles are shifted with respect to the measured angles resulting in a rather broad residuals distribution (see figure 3.19(b) and 3.19(c)). An independent analysis of the same data confirmed this discrepancy [104].



(a) Comparison between fitted and measured beam splitter angles.



(b) Residuals of the fitted and measured beam splitter in ring 4 angles.

(c) Residuals of the fitted and measured beam splitter in ring 6 angles.

Figure 3.19: (a) comparison between the fitted and measured beam splitter kink angles. (b) and (c) show the residuals between the fitted and measured beam splitter angles in rings 4 and 6 respectively. The error bars in (a) for the fitted angles (blue markers) indicate the uncertainty of the fitted values. The errors of the measured beam splitter angles (red markers) are too small to be visible.

Correcting the measured angles by an offset (mean value of the residuals distribution) and taking the distribution width in addition to the errors of the measured angles into account, the results from figure 3.20 are obtained. The agreement between the measured and fitted

angles is better, although not perfect, and the systematic shift of the angles has disappeared.

Residuals between reconstructed and fitted beam positions The reconstructed and fitted beam positions obtained by the methods described in the previous paragraphs are used to calculate the residuals. Apart from some outliers most residuals are well below 100 μm . Figure 3.22(a) shows the residuals obtained when constraining the beam splitter angles in a 2σ range around the (offset corrected) measured value, resulting in a width of $\sigma = 90.2 \mu\text{m}$.

Survey measurements are based on the reconstruction of well defined reference targets on the TEC discs and on the back flange of the tracker endcaps (see figure 3.21). The results of the analysis of the survey measurements were used to correct the reconstructed beam positions for the disc displacements (see table 3.3). Afterwards the straight line fit for each laser beam was repeated with the corrected positions as input. Figure 3.22(b) shows the resulting residual distribution. The width decreases from $\sigma = 90.2 \mu\text{m}$ to $\sigma = 75.7 \mu\text{m}$ after the survey corrections have been applied.

Disc	1	2	3	4	5	6	7	8	9
Δx [mm]	0.000	-0.008	-0.070	0.064	0.167	0.045	-0.134	-0.050	0.000
Δy [mm]	0.000	0.090	0.052	0.166	0.316	0.152	-0.098	0.038	0.000
$\Delta\varphi$ [mrad]	0.000	0.004	-0.021	0.041	0.136	0.044	-0.141	-0.036	0.000

Table 3.3: Corrections derived from the survey measurements for the discs in TEC+ [105–107].

Results The width of the residuals distribution, discussed in the previous paragraph contains contributions from several sources:

- the precision of the beam splitters,
- the reproducibility of the measurement of the laser beam position,
- the assembly precision of the tracker endcap.

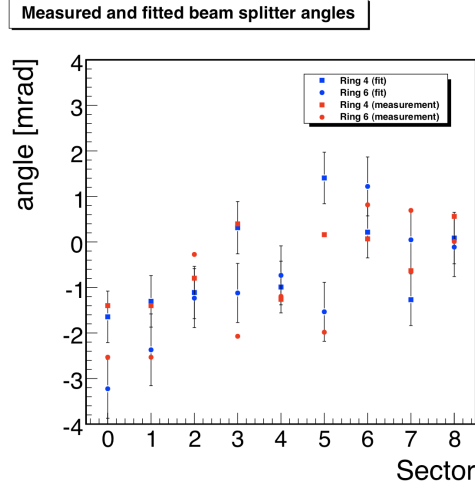
The variation of the acollinearity resulting from the beam splitter kink angle is less than 50 μrad as discussed in section 2.2.2.4. The maximum distance between the beam splitters and the discs (in this case disc 1) is 0.705 m. This results in a maximum uncertainty of the beam spot position due to the beam splitter precision of

$$\sigma_{BS} = 0.705 \text{ m} \cdot \tan(50 \mu\text{rad}) = 35.25 \mu\text{m}. \quad (3.3)$$

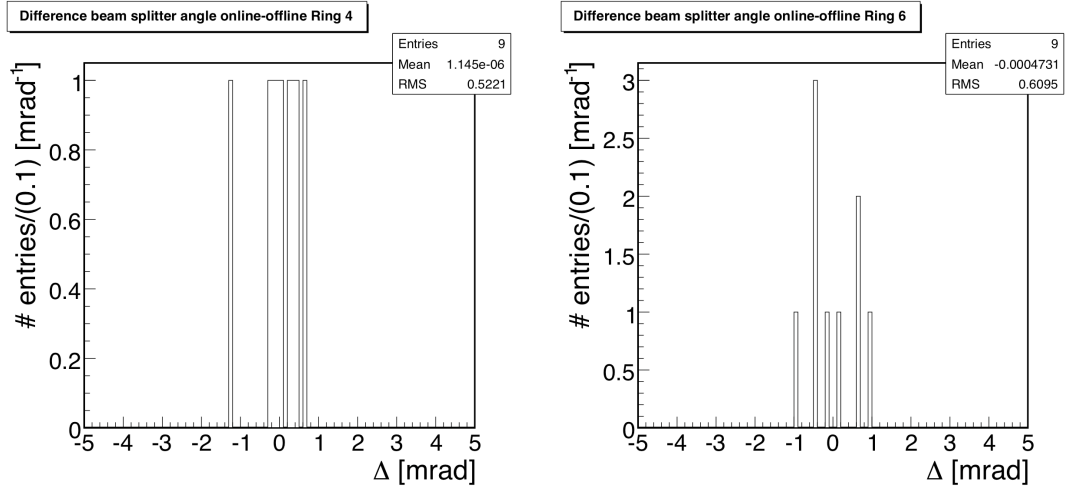
The reproducibility of the measurement of the laser beam position was estimated in [73] to be $\sigma_{\text{spot position}} = 6.9 \mu\text{m}$. Together with the result of equation 3.3 one obtains the combined accuracy of the Laser Alignment System¹¹:

$$\sigma_{LAS} = \sigma_{BS} \oplus \sigma_{\text{spot position}} \approx 36 \mu\text{m}. \quad (3.4)$$

¹¹The notation $a = b \oplus c$ is used in the present study as an abbreviation for $a = \sqrt{b^2 + c^2}$. $\ominus$ is defined in an analogous way to be: $b \ominus c = \sqrt{b^2 - c^2}$.



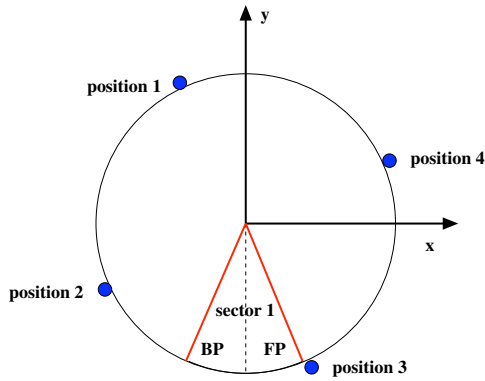
(a) Comparison between fitted and measured beam splitter angles.



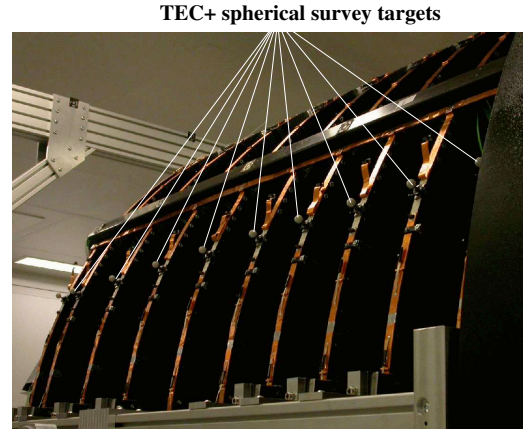
(b) Residuals of the fitted and measured beam splitter in ring 4 angles.

(c) Residuals of the fitted and measured beam splitter in ring 6 angles.

Figure 3.20: (a) comparison between the fitted and measured beam splitter kink angles. (b) and (c) show the residuals between the fitted and measured beam splitter angles. The fitted values of the beam splitter angles are corrected for the offset as described in the text. The error bars in (a) for the fitted angles (blue markers) indicate the uncertainty of the fitted values. The errors of the measured beam splitter angles (red markers) are too small to be visible.



(a) Survey measurements coordinate system. Due to the larger lever arm, changes $\Delta\varphi$ in the azimuthal orientation φ are more sensitive to changes Δx of the x coordinate at positions 1 and 3. In the same way, the sensitivity of $\Delta\varphi$ is greater to changes Δy for positions 2 and 4.



(b) Picture of the survey targets on the Endcap discs.

Figure 3.21: Four spherical targets have been installed on each TEC disc for survey purposes. (a) shows the coordinate system for the survey measurement; (b) shows a picture of the targets on the discs [72].

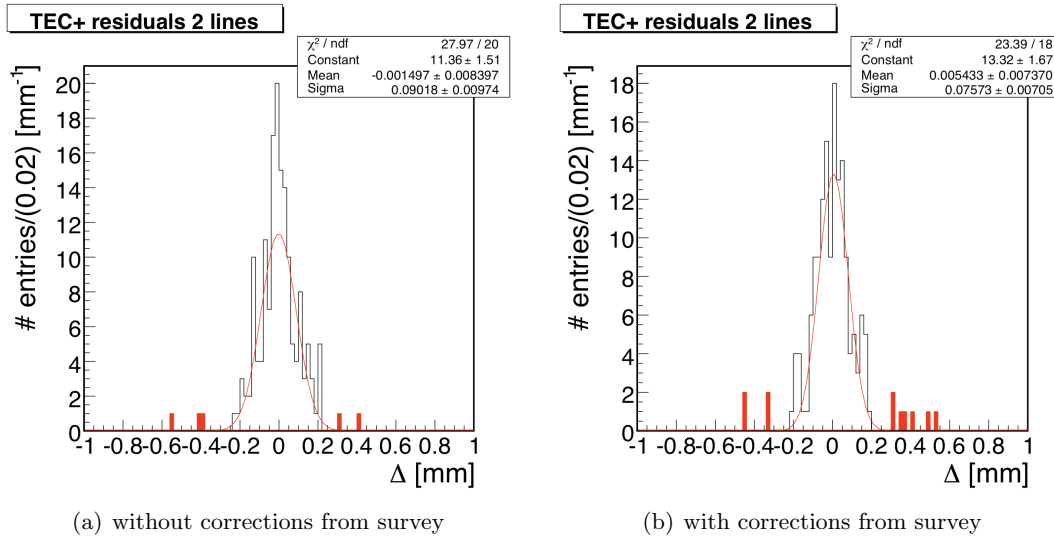


Figure 3.22: Residuals of the straight line fits and the reconstructed beam positions. The red colored entries in the histogram originate from the outliers described in the text (i.e. residual $> 200 \mu\text{m}$). (a) residuals without taking corrections from the survey measurements into account. The resulting width of the distribution is $\sigma = 90.2 \mu\text{m}$. (b) residuals after the survey corrections from table 3.3 have been applied. In this case the width of the distribution is $\sigma = 75.5 \mu\text{m}$.

From these results the assembly precision of the TEC+ can be calculated:

$$\sigma_{TEC+} = \sigma_{\text{residuals}} \oplus \sigma_{LAS} \approx 76 \mu\text{m} \oplus 36 \mu\text{m} \approx 67 \mu\text{m}. \quad (3.5)$$

With the numbers from table 2.3 the assembly precision of the tracker endcaps is given by

$$\begin{aligned} \sigma_{TEC} &= \sigma_{\text{sensor} \rightarrow \text{module}} \oplus \sigma_{\text{module} \rightarrow \text{petal}} \oplus \sigma_{\text{petal} \rightarrow \text{disc}} \oplus \sigma_{\text{disc} \rightarrow \text{TEC}} \\ &= 10 \mu\text{m} \oplus 20 \mu\text{m} \oplus 70 \mu\text{m} \oplus 150 \mu\text{m} \approx 167 \mu\text{m}. \end{aligned} \quad (3.6)$$

These results show the capability of the Laser Alignment System to measure the TEC geometry with an accuracy well below the required $100 \mu\text{m}$.

During the integration of TEC+, disc displacements and rotations away from the nominal values were determined from survey with photogrammetry methods, with the Laser Alignment System and using cosmic muon tracks. Figure 3.23 shows the results of the three different methods. The values agree within $70 \mu\text{m}$ (displacements) and $60 \mu\text{rad}$ (rotations) with each other, which can be taken as an upper limit for the precision of each method [108].

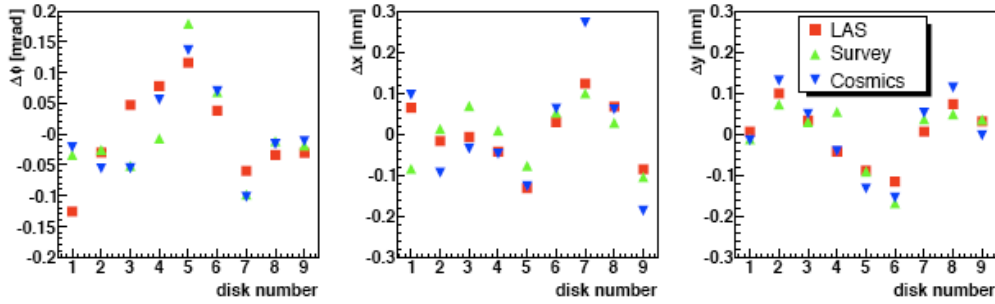


Figure 3.23: TEC+ disc rotation $\Delta\varphi$ (around the z axis) and displacements Δx , Δy (in the disc plane) as determined from the survey measurements, the Laser Alignment System and cosmic muon tracks [63].

Chapter 4

Hadron collider physics: measuring the luminosity using the Z production rate

4.1 Introduction

The production of muon and electron pairs via the Drell-Yan mechanism ($pp \rightarrow \gamma^*/Z^0 \rightarrow l^+l^-$) [46] (compare section 1.3) is an important part of the physics program of the LHC: the large production rate and clean experimental signature facilitate several important measurements. During the initial stages of LHC running the charged particle tracks originating from these channels can already be used for tracker and muon system alignment. In case of the electron channel the events in which a Z boson is produced, set the lepton momentum and energy scales (due to the Z mass constraint) and therefore can be used for the calibration of the calorimeters [62, 109]. Searching for deviations from Standard Model predictions in di-lepton events with large invariant mass, missing energy, or missing transverse momentum probes extensions of the Standard Model which can contain *e.g.* new gauge bosons or other exotic resonances [110].

Furthermore the Z boson production rate can be used to measure either the luminosity or the cross section of this process [111, 112], once one of these two quantities is known by other means. In order to estimate *e.g.* the integrated luminosity the following observables have to be measured:

$$\int \mathcal{L} dt = \frac{N_{\text{cand}} (1 - f_{b\bar{b}}) (1 - f_{t\bar{t}}) (1 - f_{\text{cosmics}}) (1 - f_{\tau\tau}) (1 - f_{pp \rightarrow \mu X}) (1 - f_{W \rightarrow \mu\nu})}{\varepsilon_{\text{total}} \cdot \sigma} \quad (4.1)$$

where

- N_{cand} = number of signal candidates,
- f_i = fraction of candidate events assigned to $b\bar{b}$, $t\bar{t}$, cosmic muons, $Z \rightarrow \tau\tau$, $pp \rightarrow \mu X$ or $W \rightarrow \mu\nu$ background events,
- $\varepsilon_{\text{total}}$ = total efficiency with contributions from the muon reconstruction, trigger, selection cuts and detector acceptance,
- σ = production cross section of the studied channel (including the branching ratio for the $Z \rightarrow \mu^+\mu^-$ decay).

Equation 4.1 illustrates again the fact that either the luminosity or the cross section can be measured utilizing the Z boson production rate: both observables enter in the formula requiring that one of them has to be measured by other means in order to estimate the other.

To measure the luminosity to a high level of accuracy a precise prediction of the cross section is desired. Section 1.3 showed that the next-to-leading order (NLO) corrections to the cross section can be large compared to the leading order (LO) cross section. Also the dependence of the leading order cross section on the renormalization and factorization scales is large, resulting in a large uncertainty for the leading order cross section.

Ideally, one would use a *Monte Carlo* generator package which includes QCD as well as electroweak next-to-leading order corrections for the Drell-Yan process with γ^* and Z boson

exchange and contributions from γ^*/Z interference. Unfortunately such a generator does not exist at present. A method to mix the events from two generators in order to take as many effects as possible into account is currently under investigation. For the present study MC@NLO [113, 114] was used to generate Drell-Yan events, including the production of γ^* and Z bosons. Contributions from γ^*/Z interference have not been taken into account. The results obtained with the MC@NLO program will be the subject of the next section.

Furthermore, the signal events have to be reconstructed before the number of signal candidates N_{cand} can be extracted from the invariant mass distribution of the Z boson. The reconstruction of the signal candidates will be discussed in section 4.3.

The determination of the background to signal ratios f_i will be the subject of section 4.4. The individual background channels will be described in more detail and selection criteria to reduce background contamination of the signal events will be presented. Once real detector data are available, data samples (so called *skims*) will be made available for analysis purposes utilizing selection criteria to reduce as much as possible the contamination with background events. Nevertheless it is important to understand the possible sources of background events to a high level of accuracy.

The last observable in equation 4.1, which has to be estimated, is the total efficiency $\varepsilon_{\text{total}}$. The various contributions to the total efficiency will be discussed in section 4.5 and techniques to estimate the efficiency directly from data will be presented.

Finally, possible sources of systematic uncertainties are studied in section 4.6 before the final results are presented in section 4.7.

4.2 Monte Carlo at NLO

In section 1.3 it was shown that the next-to-leading order (NLO) corrections to the production cross section of the Drell-Yan process are quite large. As stressed in the previous section, to achieve an accurate measurement of the luminosity it is important to obtain as precise as possible a prediction for the cross section. Therefore the program package MC@NLO has been used for event generation in the present study.

The MC@NLO package [113, 114] is based on the HERWIG [115] event generator and consistently incorporates NLO QCD matrix elements into a parton shower *Monte Carlo* simulation. The implementation of the NLO matrix elements into the parton shower has been done in a way which avoids double-counting [114]. Some important features of the MC@NLO program are

- fully exclusive events are generated including hadronisation,
- total rates are accurate to next-to-leading order,
- NLO results for distributions are recovered upon expansion in α_s ,
- hard emissions are treated as in NLO computations while soft (collinear) emissions are handled by the *Monte Carlo* simulation with the same logarithmic accuracy as implemented in the *Monte Carlo*,

MC@NLO is able to generate events containing color-singlet final states, such as W and Z bosons, or pairs of these bosons or the Higgs boson and can be used for the production of heavy quarks, like the top and bottom quarks.

The inclusion of next-to-leading order contributions provides a more accurate determination of the total cross section. MC@NLO computes all QCD next-to-leading order diagrams (see figure 4.1) before starting the hadronisation, which is done by HERWIG.

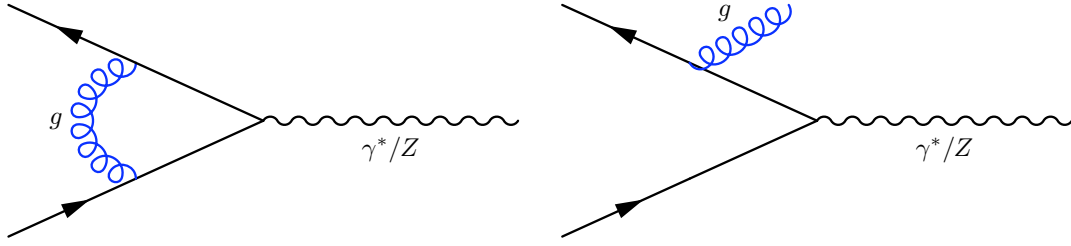


Figure 4.1: Example diagrams for next-to-leading order QCD contributions to the Drell-Yan production of γ^* and Z bosons in hadron collisions. See figure 1.7 for the complete set of NLO diagrams contributing to the Drell-Yan process. In case of a real emission, as shown in the diagram on the right, the event contains an additional jet originating from the radiated gluon.

Figures 4.2(a) and 4.2(b) show the transverse and total momentum distribution of the generated Z bosons. The pseudorapidity distribution is shown in figure 4.2(c). The majority of the generated Z bosons has a small transverse momentum and a large total momentum, resulting in Z bosons which are travelling in the forward direction. This effect is also visible in the pseudorapidity distribution, which peaks at larger values of $|\eta|$. Also shown in this figure is the comparison between MC@NLO and PYTHIA [116], which is a leading order generator with respect to this process. The radiation of additional gluons does not have a large impact on the kinematics of the Z boson and therefore the comparison between the events generated with MC@NLO and PYTHIA does not show large deviations.

To check the results obtained by using MC@NLO several consistency checks have been performed. Figure 4.3 shows the invariant mass obtained by combining the momentum vectors of the two muons in the final state of the generated events. The distribution can be fitted with a Breit-Wigner function (see appendix D.1) resulting in a mean of $91.133 \pm 0.015 \text{ GeV}/c^2$ and a width of $2.499 \pm 0.033 \text{ GeV}/c^2$. Comparison with the expected values for the mass $M_Z = 91.1876 \pm 0.0021 \text{ GeV}/c^2$ and the width $\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}/c^2$ of the Z boson [29] shows reasonable agreement.

NLO contributions were already discussed in section 1.3, where the rapidity distribution for the on-shell Z bosons was shown (figure 1.8). Integration of the curves in this plot yields the total cross section times the branching ratio. Assuming a narrow width approximation in the mass M and numerical integration over rapidity Y results in a NLO cross section of $\sigma_{\text{theory}} = 2.011 \text{ nb}$. This result can be compared with the values for the cross section obtained by the simulation with MC@NLO:

$$\sigma_{\text{MC@NLO}} = 1.910 - 2.053 \text{ nb.} \quad (4.2)$$

The cross section determined by MC@NLO depends of course on the choice of parton distribution function (PDF). Using several PDFs also leads to good agreement between the values expected for the cross section and the ones obtained from the *Monte Carlo* program.

As mentioned earlier and shown in figure 1.8 calculations in next-to-next-to-leading (NNLO) order are also available for the cross section. Unfortunately no event generator at present is able to generate events utilizing the matrix elements containing these NNLO contributions. However a program code called FEWZ (Fully Exclusive W, Z production) is available, which computes the production cross section of W and Z bosons in hadron collisions through order α_s^2 in perturbative QCD [110]. The leptonic decays of the gauge bosons with full spin cor-

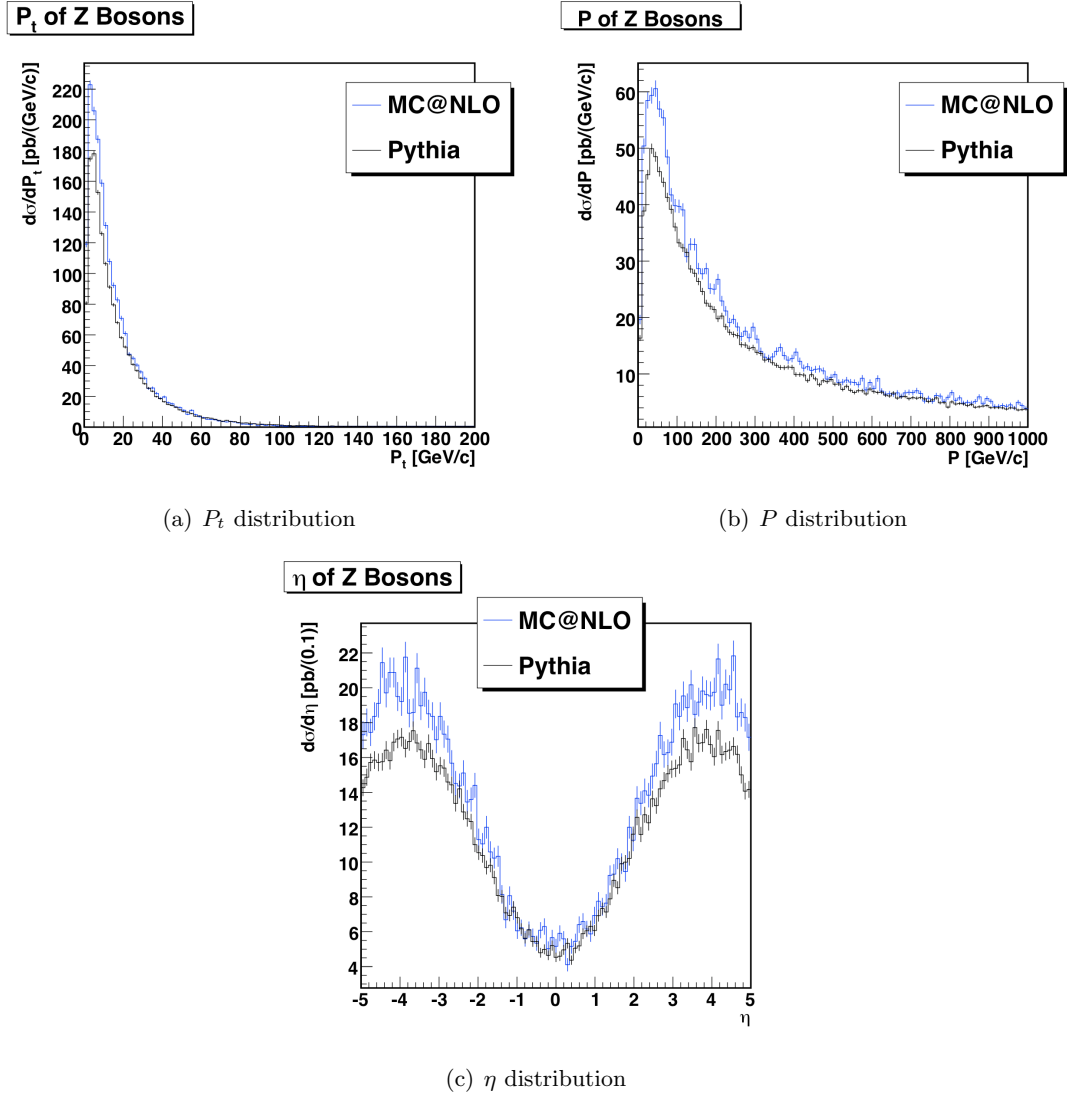


Figure 4.2: Transverse momentum, momentum and pseudorapidity distribution of the generated Z bosons in the $Z \rightarrow \mu\mu$ events. (a) transverse momentum distribution, (b) total momentum and (c) pseudorapidity distribution. No large deviations due to next-to-leading order corrections are visible in the comparison between the distribution generated with MC@NLO (in blue) and the distribution generated with PYTHIA (in black). Statistical errors are indicated by the error bars in the histograms.

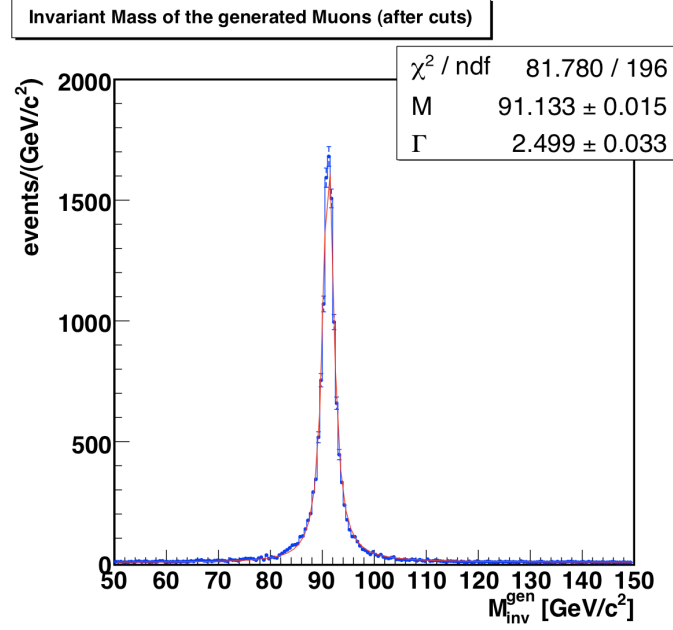


Figure 4.3: Invariant mass distribution of the muons at generator level together with a Breit-Wigner fit (in blue). The events have been generated with MC@NLO and each of the two oppositely charged muons fulfills the requirements $P_{t,gen} > 10 \text{ GeV}/c$, $|\eta| < 2.4$. Statistical errors are indicated by the error bars. The χ^2 per degree of freedom (ndf) of ≈ 0.4 indicates that the generated invariant mass distribution is described quite well by the Breit-Wigner function used for the fit.

relations as well as finite width effects and γ^*/Z interference are included. FEWZ is able to calculate the cross section in LO, NLO and NNLO order and therefore the program has been used to verify once again the cross section obtained from MC@NLO.

Using the same parton distribution function, renormalization and factorization scales and constraining the invariant mass of the leptons to $66 \text{ GeV}/c^2 \leq M_{l+l-} \leq 116 \text{ GeV}/c^2$ in order to suppress the importance of photon exchange we obtain with this program

$$\sigma_{\gamma^*/Z \rightarrow \mu\mu}^{\text{FEWZ}} = (2.031 \pm 0.002) \text{ nb} \quad (4.3)$$

for the cross section in next-to-leading order while MC@NLO predicts a value of

$$\sigma_{\gamma^*/Z \rightarrow \mu\mu}^{\text{MC@NLO}} = (1.988 \pm 0.014) \text{ nb}. \quad (4.4)$$

In both cases spin correlations are taken into account. Both values agree within $\Delta \approx 2 \%$, which is another indication that the MC@NLO generator program performs well.

Table 4.1 lists the production cross section for Z boson production in NNLO for different factorization and renormalization scales (see section 1.2). The scale dependence of the cross section σ can be estimated to be [117]

$$\Delta\sigma = \frac{2(\max[\sigma(\mu)] - \min[\sigma(\mu)])}{\max[\sigma(\mu)] + \min[\sigma(\mu)]}. \quad (4.5)$$

With the minimum and maximum values for the scale choices listed in table 4.1, the scale dependence is

$$\Delta\sigma = 1.5 \%. \quad (4.6)$$

The small dependence on the factorization and renormalization scales is also shown in [52, 110]. The NNLO value for the cross section is slightly smaller than the NLO value (equation 4.3). This effect is also visible in figure 1.8.

Scales	cross section ($\sigma_{\gamma^*/Z \rightarrow \mu\mu}$) [nb]
$\mu_f = \mu_r = \frac{1}{2}M_Z$	1.971 ± 0.018
$\mu_f = \mu_r = M_Z$	1.964 ± 0.020
$\mu_f = \mu_r = 2M_Z$	1.994 ± 0.020

Table 4.1: Cross sections times branching ratio into muons for Z boson production at the LHC to order α_S^2 as calculated by the FEWZ program. The invariant mass of the lepton pair has been restricted to $66 \text{ GeV}/c^2 \leq M_{l+l-} \leq 116 \text{ GeV}/c^2$. The errors indicate the accuracy of the numerical integration performed by FEWZ [110, 117]. The dependence on different factorization and renormalization scales is rather small.

For W and Z boson production also electroweak next to leading order corrections are known. However these NLO electroweak corrections are not implemented in the MC@NLO package. To study the effect of QED final state radiation for the muons MC@NLO has been interfaced with PHOTOS [118]. PHOTOS is a universal Monte Carlo algorithm, which is able to simulate the effects of QED radiative corrections in decays of particles and resonances. Figure 4.4 shows the dimuon invariant mass distribution for events generated with MC@NLO alone and MC@NLO together with PHOTOS.

Fitting the invariant mass distribution with a Breit-Wigner function results in a difference between MC@NLO alone and MC@NLO together with PHOTOS for the number of events in the Z boson mass region

$$\Delta(\text{MC@NLO}, \text{MC@NLO} + \text{PHOTOS}) = 0.27 \%. \quad (4.7)$$

The effect on the number of events in the signal region due to QED final state radiation of the muons is therefore small, at least for invariant masses around $90 \text{ GeV}/c^2$. The shape of the distribution however would change due to the energy loss of the muons after radiating a photon. The current implementation of PHOTOS in MC@NLO does not show these effects. While the present study focusses on the determination of the number of signal candidates, the shape of the invariant mass distribution has not been studied in further detail. An ongoing study using HORACE [119] as event generator shows larger effects on the shape of the invariant mass distribution due to QED final state radiation [120].

The strategy for the analysis presented here is to use MC@NLO to generate the Drell-Yan events and HERWIG for hadronization. For the production cross section the results obtained from the FEWZ program as listed in table 4.1 are used.

The events generated with MC@NLO are simulated and reconstructed in the CMS detector utilizing the CMSSW software framework described in section 2.2.8. The generated particles create simulated hits during the simulation step. The simulated hits are converted to digis and reconstructed hits during digitalisation and reconstruction as described in chapter 3. Finally high level objects, in this case muons, are built out of the reconstructed hits.

In the next section the results of the reconstruction of the simulated events are shortly discussed.

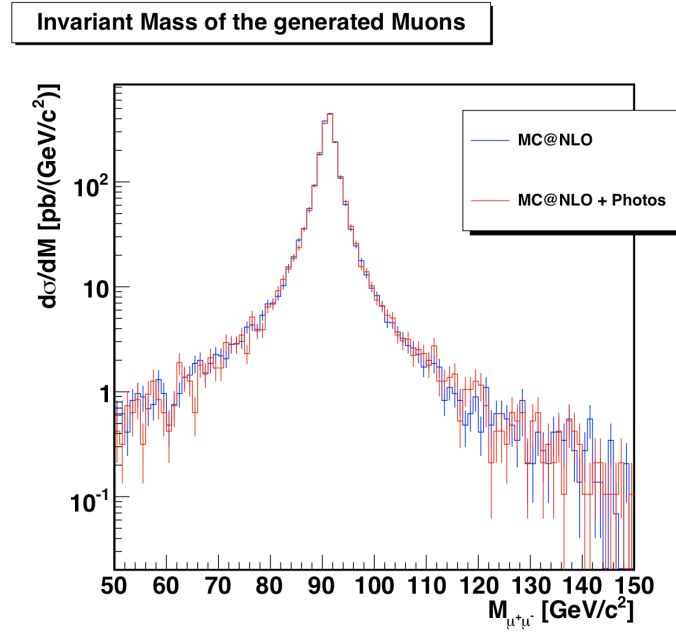


Figure 4.4: Dimuon invariant mass distribution for different event generators. Shown is the comparison between events generated with MC@NLO (blue curve) and MC@NLO together with PHOTOS (red curve). The effect of final state radiation of the muons on the number of events in the region around the Z boson mass is small. Statistical errors are indicated by the error bars. The event samples generated with MC@NLO are limited in statistics, resulting in larger errors in the tails of the distribution.

4.3 Reconstruction of the signal candidates

In this section the performance and the results of the reconstruction of the signal events will be discussed. Figure 4.5 shows good agreement between the generated and reconstructed transverse momentum and pseudorapidity of the muons.

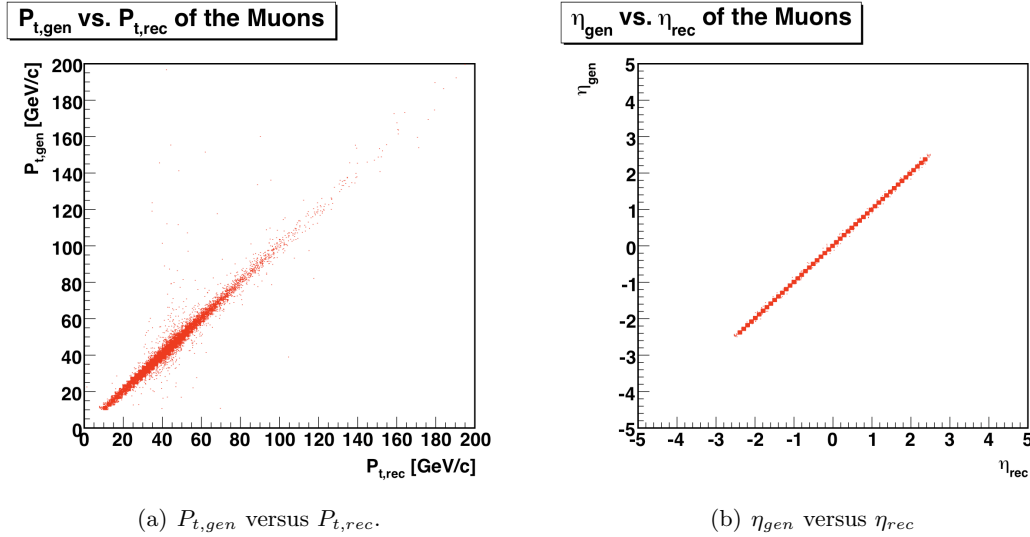


Figure 4.5: Comparison between generated and reconstructed transverse momentum and pseudorapidity of the muons: (a) generated versus reconstructed transverse momentum and (b) generated versus reconstructed pseudorapidity.

Figure 4.6 shows the residual distribution of the inverse transverse momentum¹ for the reconstructed muons.

The reconstruction combines the hits in the tracker and in the muon system resulting in so-called global muons (see also appendix C). The width of the residual distribution gives the transverse momentum resolution: the better the transverse momenta of the muons are reconstructed, the smaller the residuals and therefore the smaller the width of the distribution. Over the full η range a transverse momentum resolution of 1.7 % is reached. In figure 4.6(b) and 4.6(c) the residual distribution of the inverse transverse momentum for the barrel and the endcap region respectively is shown: in the barrel region the resolution is 1.4 %, whereas in the endcap region the resolution (2.2 %) is slightly worse due to the reduced lever arm [63] (see also section 2.2.2.3 and 2.2.5). The results shown here are in agreement with similar results shown in [81] and [62].

Figure 4.7(a) shows the transverse momentum distribution of the reconstructed muons in the $Z \rightarrow \mu\mu$ events. Generally one would expect a steeply falling distribution (compare also figure 4.14); however, most of the muons in figure 4.7(a) stem directly from $Z \rightarrow \mu\mu$ decays and therefore the P_t distribution peaks around half the Z boson mass. The pseudorapidity distribution is shown in figure 4.7(b). The sharp edge at $\eta = -2.4$ and $\eta = 2.4$ is due to the geometry of the muon system, which covers the pseudorapidity range between -2.4 and 2.4 (see section 2.2.5). The histogram in figure 4.7(b) contains a few entries in the region

¹In the parameterization of particle tracks in the CMS detector the transverse momentum enters in the denominator. Therefore the distribution for the inverse transverse momentum is shown. A detailed description of available track parameterizations can be found in [121].

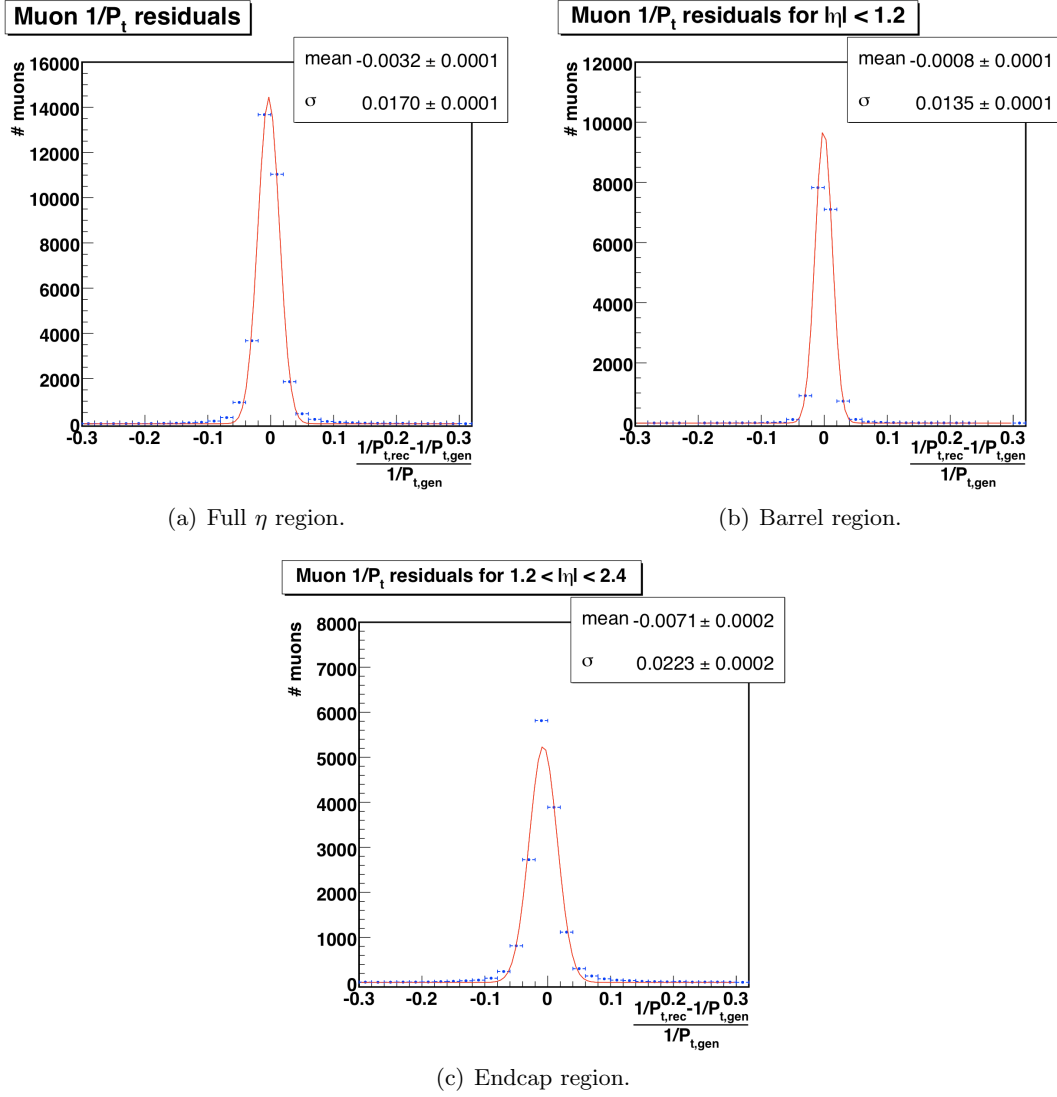


Figure 4.6: Residual distribution of the inverse transverse momentum measured for the global muon reconstruction algorithm: (a) residual distribution of $1/P_t$ for the full η range, (b) for the barrel region ($|\eta| < 1.2$) and (c) for the endcap region ($1.2 < |\eta| < 2.4$). Statistical errors are indicated by the error bars.

$2.4 < \eta < 2.45$, which originate from muons hitting the outermost regions of the tracker and muon detectors (see figure 2.5 and 2.19). The detector acceptance will be discussed in more detail in section 4.5.5.

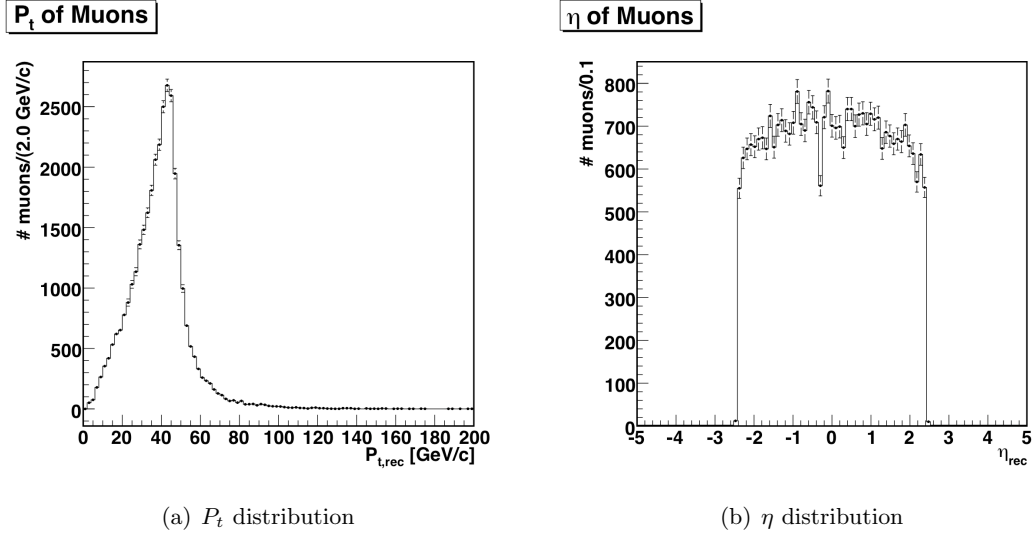


Figure 4.7: Transverse momentum and pseudorapidity distribution of the reconstructed muons in the $Z \rightarrow \mu\mu$ events. (a) transverse momentum distribution and (b) pseudorapidity distribution. Statistical errors are indicated by the error bars.

The number of candidate signal events N_{cand} in equation 4.1 can be obtained from the invariant mass distribution of the reconstructed muon pairs shown in figure 4.8(a). The distribution has been fitted with a relativistic Breit-Wigner function (see appendix D.1). However, due to the limited momentum resolution of the detector (see figure 4.6), one should fit a Breit-Wigner plus a sum of Gaussian functions to take into account the detector resolution in the different η ranges. In figure 4.8(b) a Breit-Wigner together with a Gaussian (see appendix D.2) has been fitted to the invariant mass distribution. As can be seen from figure 4.8 the quality of the fit in the signal region increases when the Breit-Wigner together with the Gaussian rather than only the Breit-Wigner has been used to fit the distribution.

To study the width of the invariant mass distribution in more detail, events where the width of the Z boson has been artificially set to zero ($\Gamma_Z \approx 0$) have been generated. Figure 4.9(a) shows the distribution resulting from the reconstructed muons in these so-called “narrow width” events. The width of this distribution is determined only by the detector resolution. For comparison figure 4.9(b) shows the corresponding distribution for the “normal” events (from figure 4.8(b)).

Figure 4.10 shows the corresponding distributions when both muons are in the barrel region of the detector, where the transverse momentum resolution is better (see figure 4.6). A single gaussian accounting for the detector resolution, together with the Breit-Wigner function, should be sufficient to fit the signal in this case, because in the $|\eta| < 0.8$ range the variation of the material budget is rather small and therefore the effect on the momentum resolution of multiple scattering and energy loss in the material should be limited [62]. Indeed, for “narrow width” events ($\Gamma_Z \approx 0$), the resolution in the barrel region (figure 4.10(a)) is $\sigma = 0.775 \text{ GeV}/c^2$ compared to $\sigma = 1.177 \text{ GeV}/c^2$ for $|\eta| < 2.4$ (figure 4.9(a)). Thus the dimuon

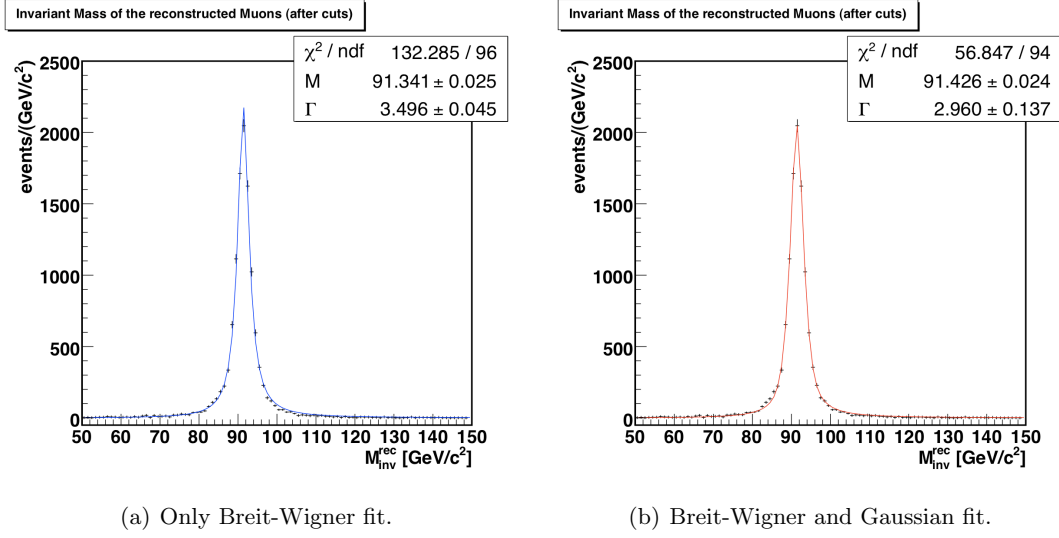


Figure 4.8: Invariant mass distribution of the reconstructed muon pairs. Each of the oppositely charged muons fulfills the requirements $P_{t,rec} > 15 \text{ GeV}/c$, $|\eta| < 2.4$. Figure (a) shows the invariant mass distribution where only a Breit-Wigner function has been fitted; figure (b) shows the result of the fit with a Breit-Wigner and Gauss function. Statistical errors are indicated by the error bars.

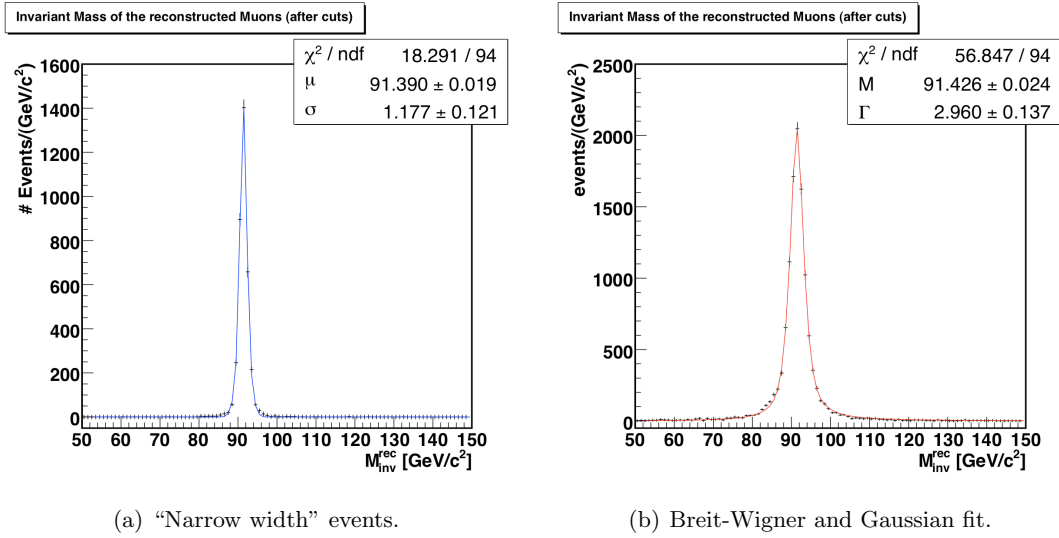


Figure 4.9: Invariant mass distribution of the reconstructed muon pairs. Each of the oppositely charged muons fulfills the requirements $P_{t,rec} > 15 \text{ GeV}/c$, $|\eta| < 2.4$. Figure (a) shows the invariant mass distribution for events generated with $\Gamma_Z \approx 0$. The plot shows the contribution of detector resolution to the invariant mass resolution. For comparison, figure (b) shows again the result of the fit with a Breit-Wigner and Gauss function (from figure 4.8(b) above). Statistical errors are indicated by the error bars.

invariant mass resolution in the barrel region (figure 4.10(b)) is dominated by the natural width of the Z boson and is slightly better compared to the resolution over the full η range (see figure 4.9).

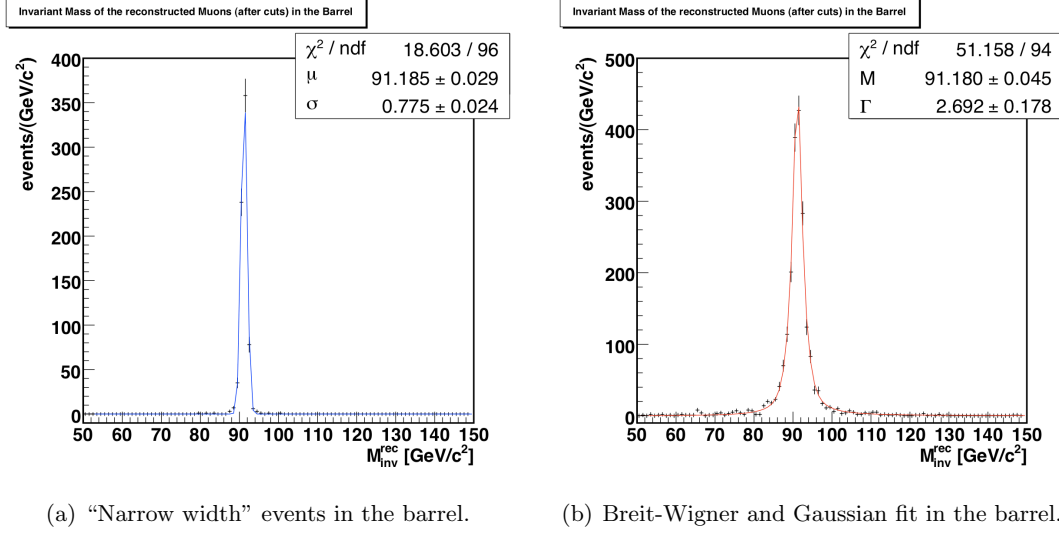


Figure 4.10: Invariant mass distribution of the reconstructed muon pairs. Each of the two oppositely charged muons fulfills the requirements $P_{t,rec} > 15$ GeV/c, $|\eta| < 0.8$. Figure (a) shows the invariant mass distribution for the events which were generated with $\Gamma_Z \approx 0$. The plot shows the contribution of detector resolution to the invariant mass resolution. Figure (b) shows the result of the fit with a Breit-Wigner and Gauss function for the events where both muons are in the central barrel region. Statistical errors are indicated by the error bars.

The width of the invariant mass distribution obtained for $\Gamma_Z \approx 0$ together with the natural width of the Z Boson $\Gamma_Z = 2.4952 \pm 0.0023$ GeV/c² [29] give the value expected for the reconstructed width of the Z boson:

$$\begin{aligned} \Gamma_Z^{\text{expected}} &= 1.177 \oplus 2.495 \text{ GeV/c}^2 = 2.759 \pm 0.052 \text{ GeV/c}^2 \quad \text{for } |\eta| < 2.4, \\ \Gamma_Z^{\text{expected}} &= 0.775 \oplus 2.495 \text{ GeV/c}^2 = 2.613 \pm 0.007 \text{ GeV/c}^2 \quad \text{for } |\eta| < 0.8. \end{aligned} \quad (4.8)$$

The quoted error is obtained by error propagation (see appendix F.1). The result of the fit in figures 4.9(b) and 4.10(b) is

$$\begin{aligned} \Gamma_Z^{\text{fit}} &= 2.960 \pm 0.137 \text{ GeV/c}^2 \quad \text{for } |\eta| < 2.4, \\ \Gamma_Z^{\text{fit}} &= 2.692 \pm 0.178 \text{ GeV/c}^2 \quad \text{for } |\eta| < 0.8, \end{aligned} \quad (4.9)$$

in agreement with the expectation (equation 4.8). This result shows that it is possible to find the width of the Z boson with the CMS detector without having to apply large corrections to the reconstructed value.

The studies presented above concerning the width of the Z boson were carried out into some detail, although the estimation of the width of the Z boson is not subject of the present study, to see whether the reconstruction of the signal events and the influence of the detector resolution agree with the expected values.

Process	Generated events	Cross section [nb]	Simulated events
$pp \rightarrow \gamma^* \rightarrow \mu\mu$	49881	6.711	19853
$pp \rightarrow Z^0 \rightarrow \mu\mu$	29745	1.964	27896
$pp \rightarrow \gamma^*/Z^0 \rightarrow \mu\mu$ ($P_t > 100$ GeV/c)	3986471	6.711	5999

Table 4.2: The Drell-Yan event samples. The number of generated events, the cross sections and the number of events in the simulated datasets are shown.

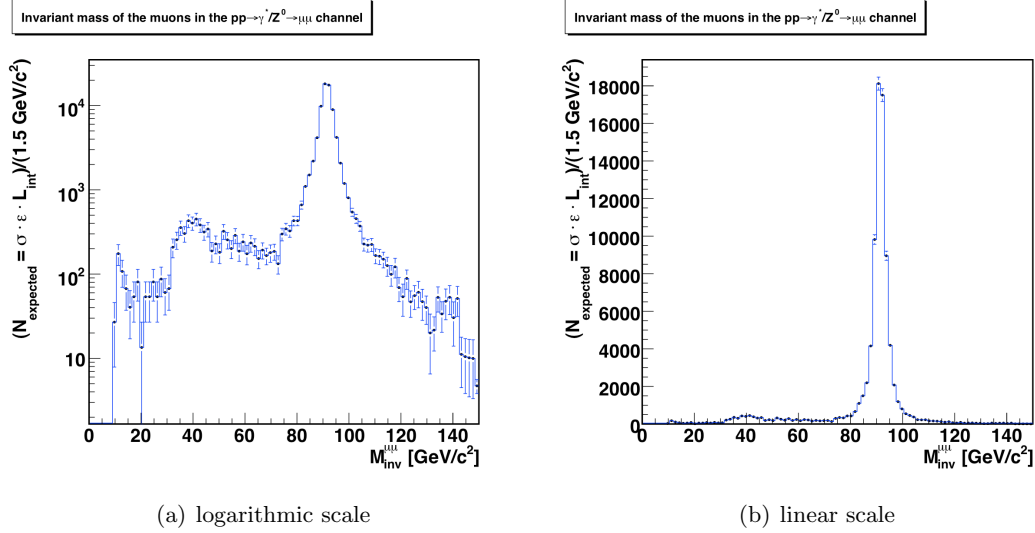


Figure 4.11: Invariant mass distribution of the signal events (for an integrated luminosity of 0.1 fb^{-1}). (a) shows the distribution on a logarithmic scale (b) on a linear scale. Each of the two oppositely charged reconstructed muons fulfill the following requirements: $P_t > 15 \text{ GeV}/c$, $|\eta| < 2.4$. Statistical errors are indicated by the error bars. Due to the limited statistics of the $pp \rightarrow \gamma^*/Z^0 \rightarrow \mu\mu$ with $P_t > 100 \text{ GeV}/c$ dataset, the statistical errors are larger for $M_{\text{inv}}^{\mu\mu} > 100 \text{ GeV}/c^2$. The applied cuts also reduce the number of events with $M_{\text{inv}}^{\mu\mu} < 40 \text{ GeV}$ resulting in larger statistical errors in this region compared to the region around the Z boson mass. The spikes around $10 \text{ GeV}/c^2$, $40 \text{ GeV}/c^2$ and $130 \text{ GeV}/c^2$ are artefacts due to cuts applied in the event generator, the chosen selection criteria for the reconstructed muons (in this case $P_t > 15 \text{ GeV}/c$) and the limited statistics of the used datasets.

Table 4.2 lists the number of generated events and the corresponding cross sections for the event samples containing the signal Drell-Yan events. The invariant mass distribution of the muons reconstructed in these samples is shown in figure 4.11.

4.4 Background events

To measure the luminosity using equation 4.1 the fractions of candidate events assigned to the several possible background processes have to be estimated. For the $Z \rightarrow \mu\mu$ production studied in this analysis the following processes have been taken into account as a possible background:

- $b\bar{b}$ and $t\bar{t}$ events for which muons are often found in the final state,
- $pp \rightarrow \mu + X$ events², where the “ X ” contains an additional high P_t muon,
- $W \rightarrow \mu\nu$ events for which an additional high P_t muon is reconstructed,
- $pp \rightarrow \gamma^*/Z^0 \rightarrow \tau\tau$ events for which both τ leptons decay into a muon and two neutrinos.

Furthermore cosmic muons can be a possible source of background. However, contamination of the signal sample with cosmic muon events will be small, since cosmic muons are mostly out of time with respect to the LHC bunch crossing. Therefore this background source has not been studied in more detail in this analysis.

Table 4.3 lists the background channels considered, the corresponding cross sections and the efficiencies of the event filters used to produce the event sample. The Drell-Yan processes with two τ leptons in the final state are a priori an irreducible source of background events when both τ leptons decay in a muon and two neutrinos.

Background process	Generated events	Cross section [nb]	Filter efficiency
$pp \rightarrow \mu + X$	17781626	$5.50 \cdot 10^{+7}$	0.0008
$b\bar{b}$ ($30 \text{ GeV}/c \leq \hat{P}_t \leq 50 \text{ GeV}/c$)	223821	$1.55 \cdot 10^{+5}$	0.041
$b\bar{b}$ ($50 \text{ GeV}/c \leq \hat{P}_t \leq 80 \text{ GeV}/c$)	589652	$2.09 \cdot 10^{+4}$	0.054
$b\bar{b}$ ($80 \text{ GeV}/c \leq \hat{P}_t \leq 120 \text{ GeV}/c$)	430634	$2.95 \cdot 10^{+3}$	0.067
$b\bar{b}$ ($170 \text{ GeV}/c \leq \hat{P}_t \leq 230 \text{ GeV}/c$)	230252	$1.01 \cdot 10^{+2}$	0.087
$W \rightarrow \mu\nu$	1975650	$1.77 \cdot 10^{+1}$	1
$t\bar{t}$	6854658	$4.89 \cdot 10^{-1}$	1
$pp \rightarrow \gamma^* \rightarrow \tau\tau$	29519	$2.02 \cdot 10^{-1}$	1
$pp \rightarrow Z^0 \rightarrow \tau\tau$	263638	$5.79 \cdot 10^{-2}$	1

Table 4.3: Event samples used to estimate the background to signal ratios. For each background channel the number of generated events, the cross section and the filter efficiency is shown. In case of the $\gamma^* \rightarrow \tau\tau$ and $Z^0 \rightarrow \tau\tau$ channels both τ leptons decay into a muon and two neutrinos and the cross section listed here contains the branching ratio for the $\tau \rightarrow \mu\nu_\mu\nu_\tau$ decay.

²These are events stemming from $qq \rightarrow qq$, $gg \rightarrow gg$, $gq \rightarrow gq$ and $gg \rightarrow qq$ processes. On the generator level a cut on $\hat{P}_t > 10 \text{ GeV}/c$ is imposed and only reconstructed events containing at least one muon with $P_t > 3 \text{ GeV}/c$ and $|\eta| < 2.5$ are accepted.

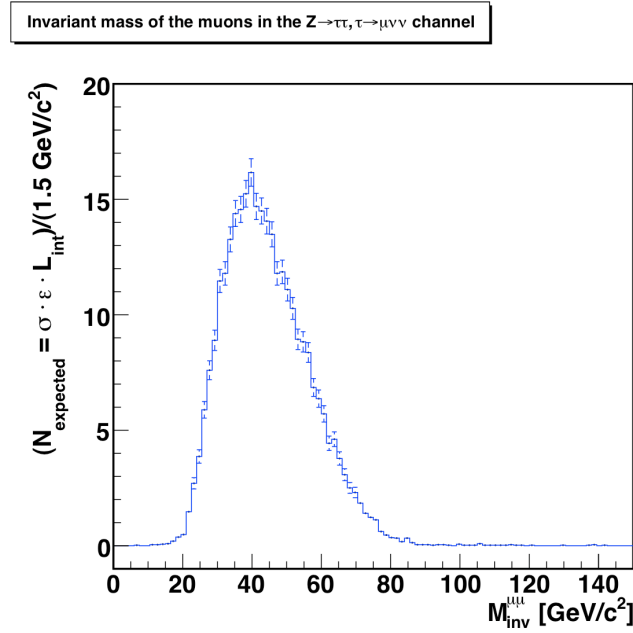


Figure 4.12: Invariant mass distribution of the muons in the $Z \rightarrow \tau\tau$ channel for 0.1 fb^{-1} . Both muons fulfill $P_t > 10 \text{ GeV}/c$ and $|\eta| < 2.4$. Statistical errors are indicated by the error bars.

However, due to the fact that the four final state neutrinos carry energy away, the contribution of the resulting less energetic muon pair to the dimuon invariant mass distribution is rather small in the region of the Z boson mass (see figure 4.12). The reduced muon energy together with the small cross section, compared to the cross section of the signal events, strongly reduces the contribution of these two Drell-Yan processes³ to the background events.

The main contribution to the background stems from the $b\bar{b}$ ⁴ and $pp \rightarrow \mu + X$ channels as shown in figure 4.13, where the contributions from the other sources are also included. There is considerable background in the signal region which gets reduced in case a larger P_t cut on both muons is applied (see e.g. figure 4.13(d)). Nevertheless, as shown in table 4.4, even for $P_t > 25 \text{ GeV}/c$ the background to signal ratio for $b\bar{b}$ events is still large ($\mathcal{O}(1 \%)$).

Figure 4.14 shows the transverse momentum distribution of the muons for both signal and background channels. From this figure it is obvious that the background contribution can be reduced by increasing the cut on the transverse momentum of the muons.

The background can be further reduced by using an isolation criterion: the muons are not allowed to have neighboring tracks in a cone around the muon direction. The cone size is

³For practical purposes these two samples have been produced separately and therefore both samples are listed in table 4.3. The contributions from these events to the background will be summarized in the following under the label $pp \rightarrow \gamma^*/Z^0 \rightarrow \tau\tau$.

⁴The $b\bar{b}$ events have been produced by the production team in several $\hat{P}_t$ bins. All samples, which were available for CMS software version CMSSW_1.3.1, have been used for this study. For completeness table 4.3 lists the cross sections for the different $\hat{P}_t$ bins. In the following the contributions stemming from these samples to the number of background events will be summarized as $b\bar{b}$ events.

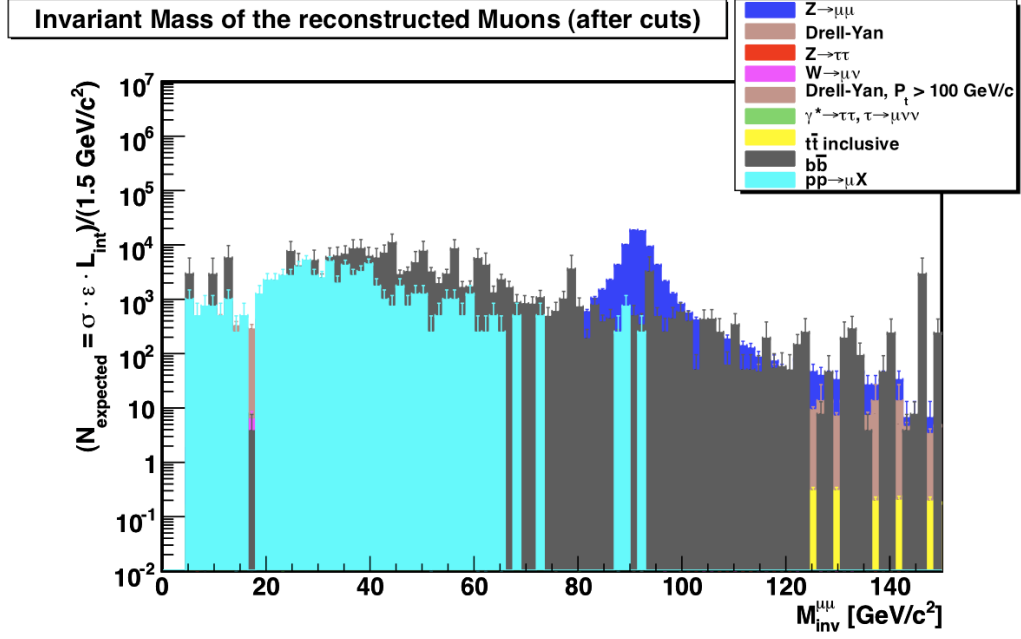
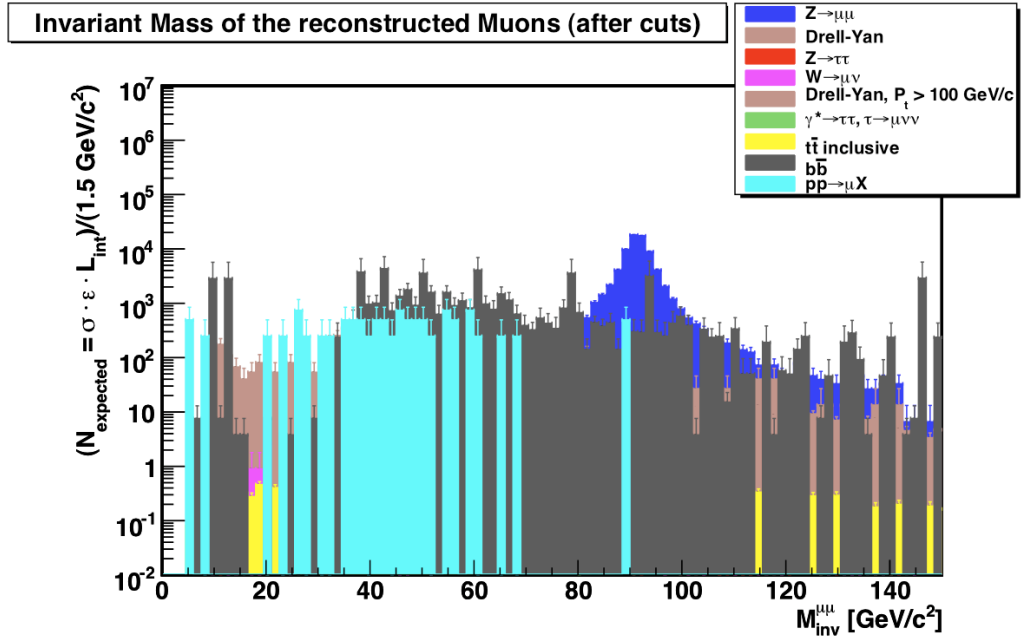

 (a) $P_t(\text{muons}) > 10 \text{ GeV}/c$

 (b) $P_t(\text{muons}) > 15 \text{ GeV}/c$

Figure 4.13: Invariant mass distribution of the signal (in blue) and background channels for different P_t cuts (for an integrated luminosity of 0.1 fb^{-1}). The invariant mass is shown for the cases where both muons have a transverse momentum larger than (a) 10, (b) 15, (c) 20 or (d) 25 GeV/c . Figures (c) and (d) are shown on page 87. The background is dominated by events stemming from $pp \rightarrow \mu + X$ (in light blue) and by events in which pairs of b quarks (in gray) are involved. In all four cases the muons fulfill $|\eta| < 2.4$ and have opposite charge. Statistical errors are indicated by the error bars.

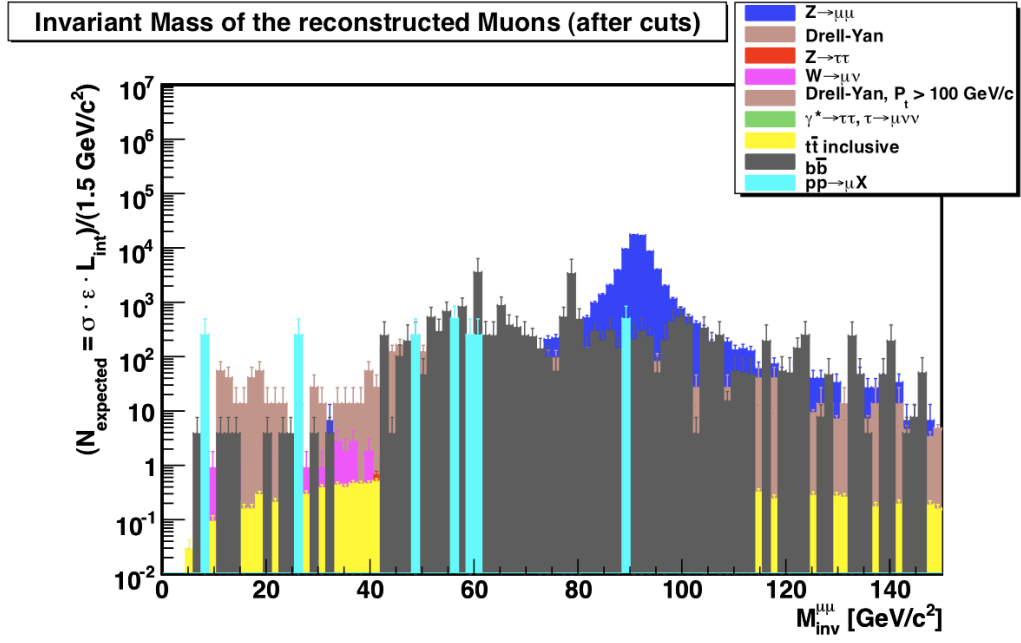
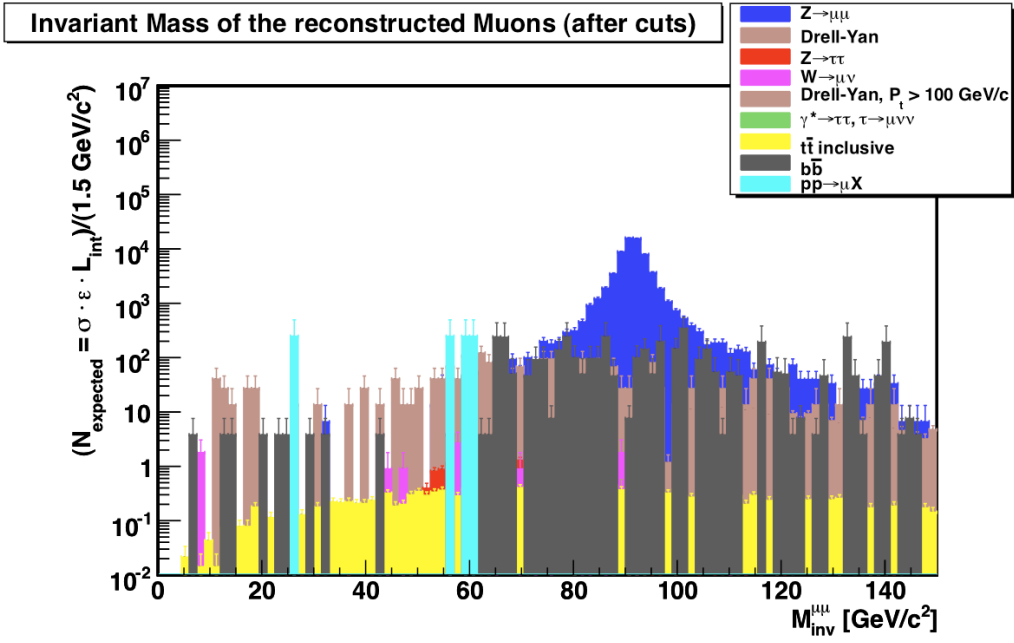
(c) $P_t(\text{muons}) > 20 \text{ GeV}/c$ (d) $P_t(\text{muons}) > 25 \text{ GeV}/c$

Figure 4.13: Continued from page 86.

Background process	P_t cut [GeV/c]			
	10	15	20	25
$pp \rightarrow \mu + X$	$1.81 \cdot 10^{-2}$	$7.43 \cdot 10^{-3}$	$8.16 \cdot 10^{-3}$	$< 8 \cdot 10^{-3}$
$b\bar{b}$	$7.89 \cdot 10^{-2}$	$7.23 \cdot 10^{-2}$	$2.31 \cdot 10^{-2}$	$1.32 \cdot 10^{-2}$
$W \rightarrow \mu\nu$	$4.85 \cdot 10^{-4}$	$3.23 \cdot 10^{-4}$	$2.81 \cdot 10^{-4}$	$1.67 \cdot 10^{-4}$
$t\bar{t}$	$7.17 \cdot 10^{-5}$	$6.56 \cdot 10^{-5}$	$5.79 \cdot 10^{-5}$	$4.72 \cdot 10^{-5}$
$pp \rightarrow \gamma^*/Z^0 \rightarrow \tau\tau$	$5.78 \cdot 10^{-6}$	$5.93 \cdot 10^{-6}$	$5.49 \cdot 10^{-6}$	$5.22 \cdot 10^{-6}$

Table 4.4: Background to signal ratios (f_i) in a 2Γ window around the Z mass ($85.6 \text{ GeV}/c^2 < M_{\mu\mu} < 97.2 \text{ GeV}/c^2$) for different cuts on the transverse momentum of the muons. Except for $b\bar{b}$ events, the contributions from the other channels are small.

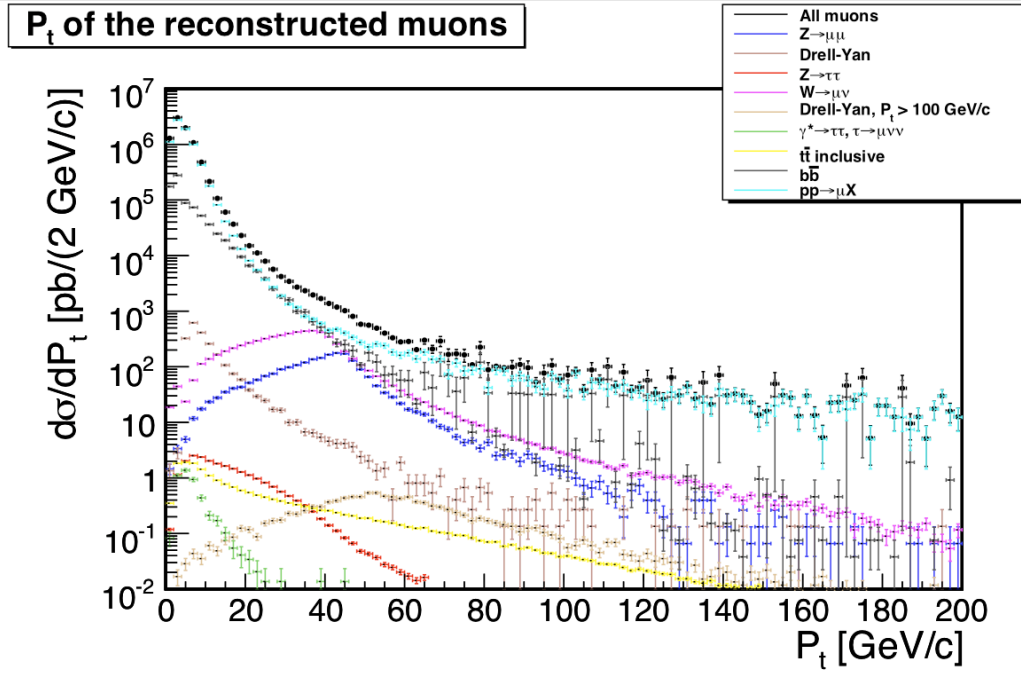


Figure 4.14: Transverse momentum distribution of the muons for both signal and background channels. The black symbols show the P_t distribution for all muons (the contributions from the single channels have been added up). Statistical errors are indicated by the error bars.

defined in (η, φ) space as

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} = \sqrt{(\eta_{\text{muon}} - \eta_{\text{track}})^2 + (\varphi_{\text{muon}} - \varphi_{\text{track}})^2}. \quad (4.10)$$

For the signal and the background channels figure 4.15 shows the distance (measured in ΔR) between the reconstructed muon and all other tracks in the event. The majority of the tracks are far away from the muons (large values of ΔR), but some are close by (small values of ΔR), especially for some of the background channels. By requiring a distance between the muons and other tracks of at least $\Delta R = 0.3$ the background can be further reduced without losing too many signal events. Figure 4.16 shows the resulting invariant mass distributions for four different P_t cuts and table 4.5 lists the corresponding background to signal ratios.

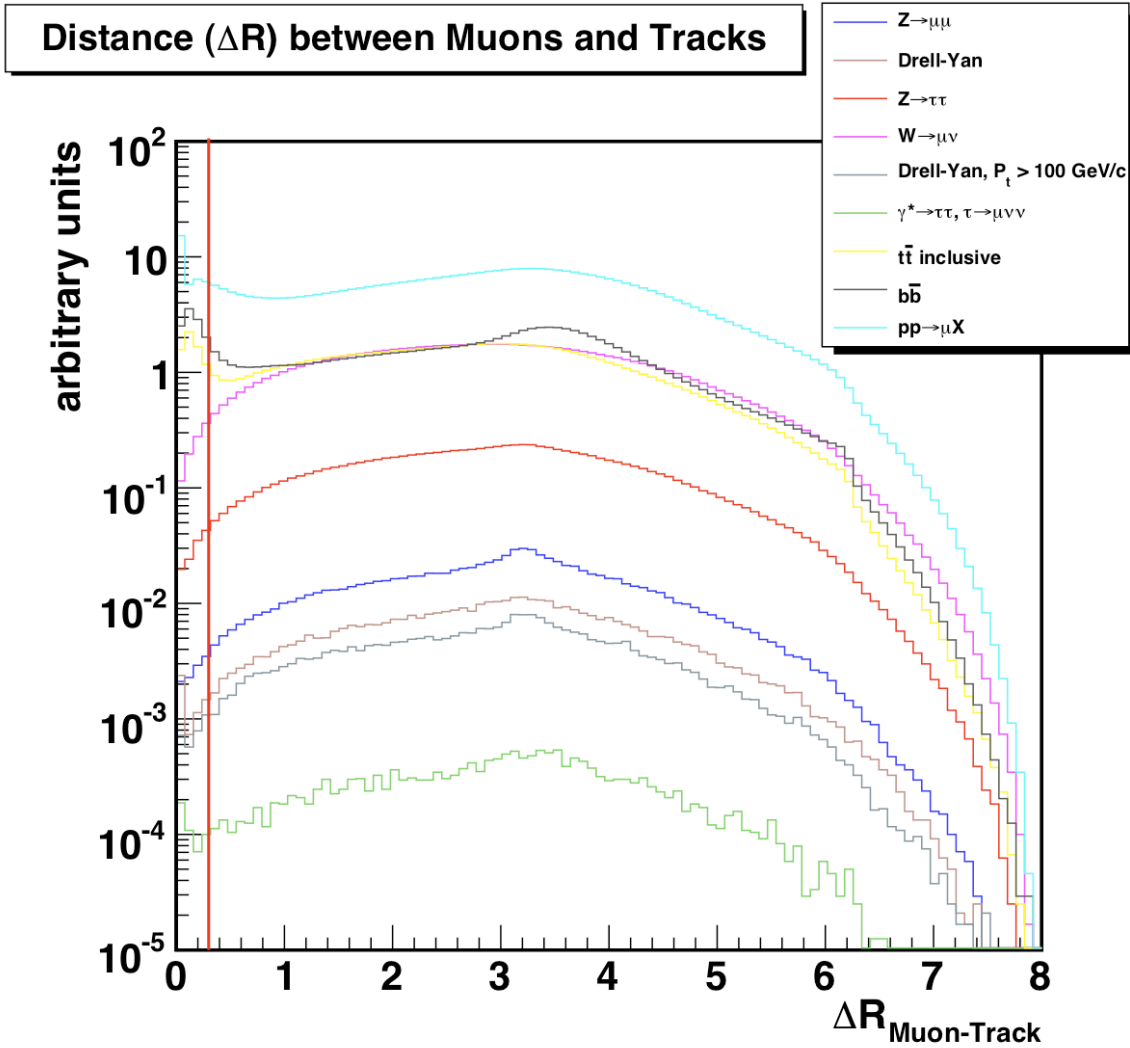


Figure 4.15: The distance (measured in ΔR) between the reconstructed muons and all other tracks in the event for both signal and background. The line (in red) indicates the value $\Delta R = 0.3$ used to define the isolation cone for the muons.

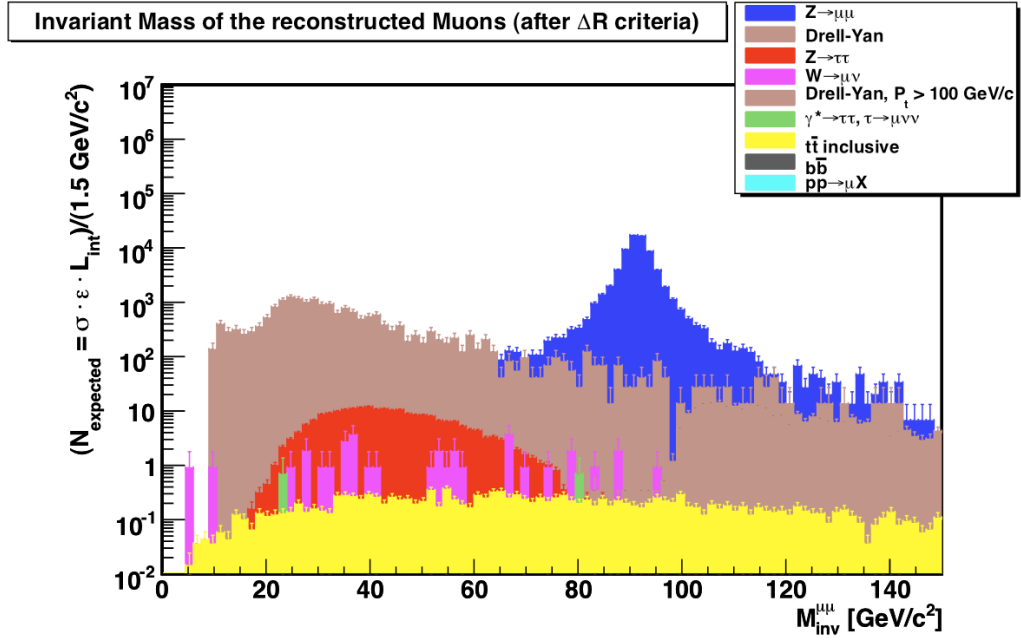
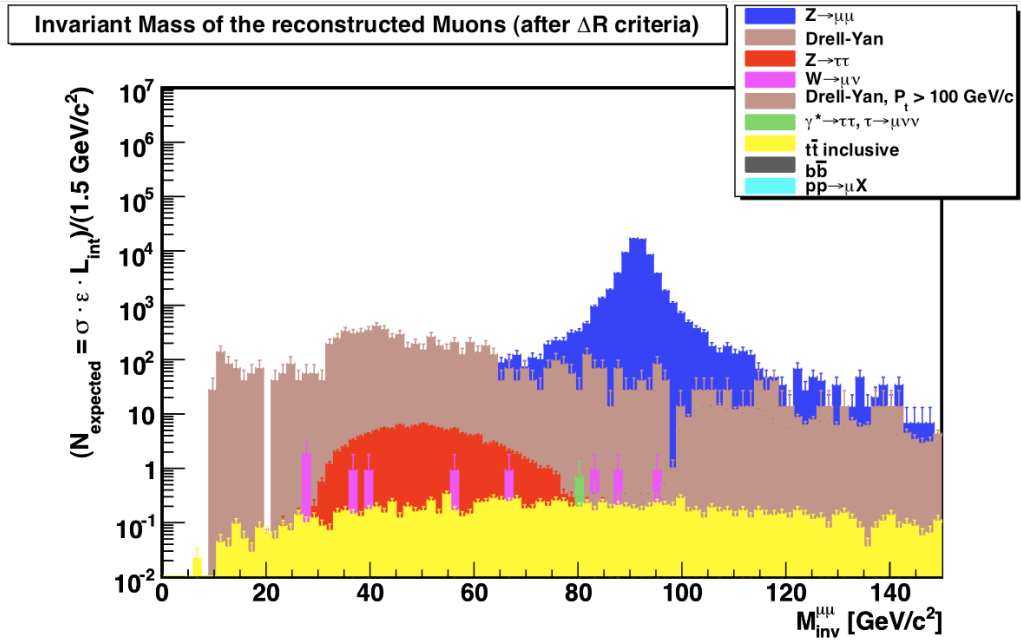

 (a) $P_t(\text{muons}) > 10 \text{ GeV}/c$

 (b) $P_t(\text{muons}) > 15 \text{ GeV}/c$

Figure 4.16: Invariant mass distribution of the signal (in blue) and background channels for different P_t cuts using the isolation criterion as described in the text (for an integrated luminosity of 0.1 fb^{-1}). The invariant mass is shown for the cases where both muons have a transverse momentum larger than (a) 10, (b) 15, (c) 20 or (d) 25 GeV/c . Figures (c) and (d) are shown on page 91. In all four cases the muons fulfill $|\eta| < 2.4$ and have opposite charge. Compared to figure 4.13 the background is smaller when requiring two isolated muons and the contribution from $b\bar{b}$ events vanishes. Statistical errors are indicated by the error bars.

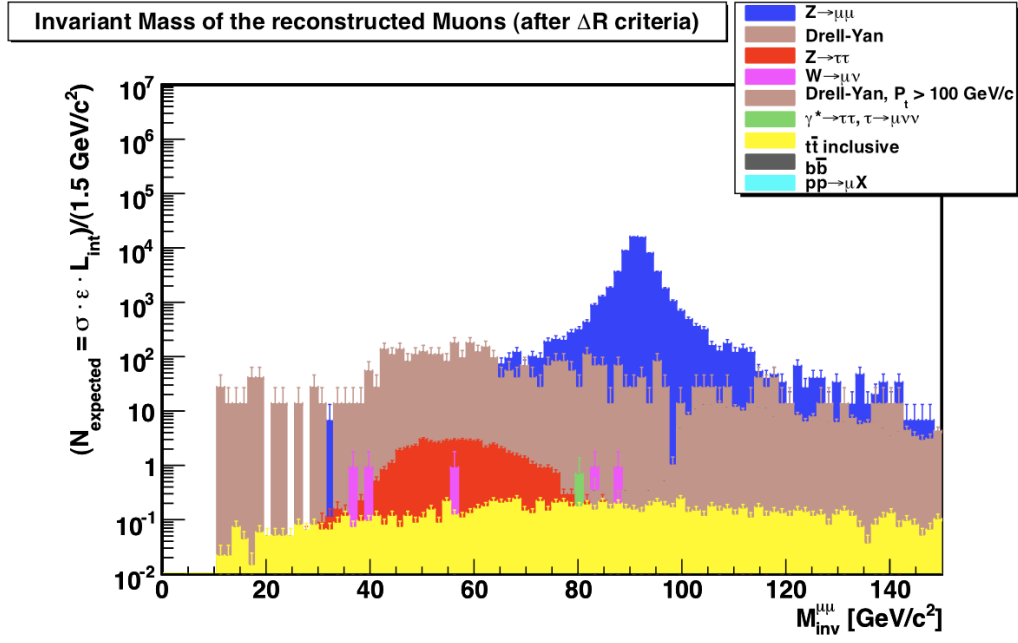
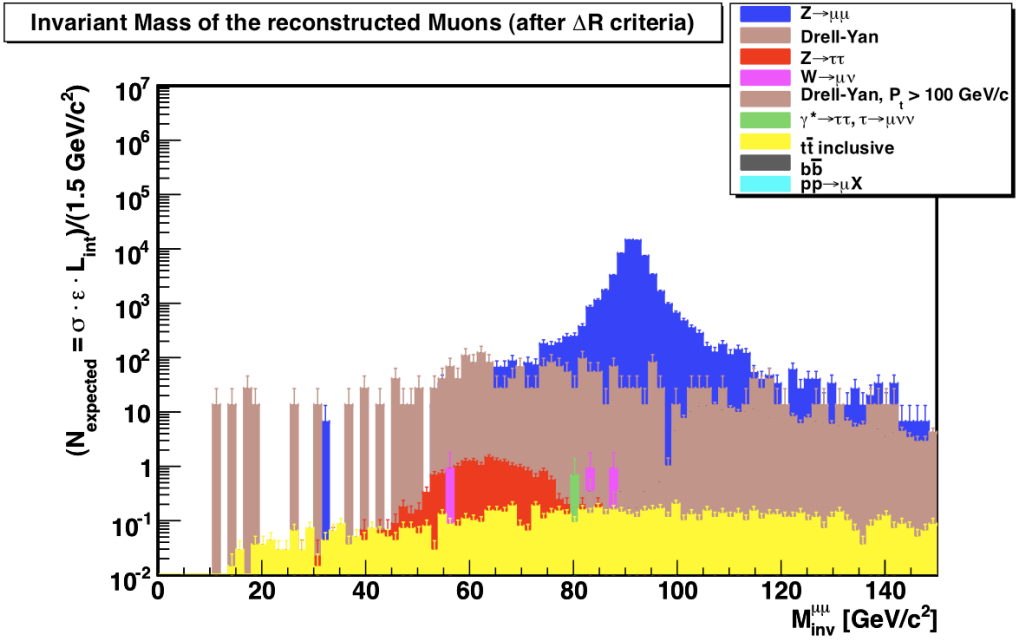
(c) $P_t(\text{muons}) > 20 \text{ GeV}/c$ (d) $P_t(\text{muons}) > 25 \text{ GeV}/c$

Figure 4.16: Continued from page 90.

Background process	P_t cut [GeV/c]			
	10	15	20	25
$pp \rightarrow \mu + X$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
$b\bar{b}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
$W \rightarrow \mu\nu$	$4.29 \cdot 10^{-5}$	$2.93 \cdot 10^{-5}$	$1.54 \cdot 10^{-5}$	$1.65 \cdot 10^{-5}$
$t\bar{t}$	$2.58 \cdot 10^{-5}$	$2.54 \cdot 10^{-5}$	$2.32 \cdot 10^{-5}$	$2.11 \cdot 10^{-5}$
$pp \rightarrow \gamma^*/Z^0 \rightarrow \tau\tau$	$4.56 \cdot 10^{-6}$	$4.67 \cdot 10^{-6}$	$3.76 \cdot 10^{-6}$	$4.05 \cdot 10^{-6}$

Table 4.5: Background to signal ratios (f_i) in a 2Γ window around the Z mass ($85.6 \text{ GeV}/c^2 < M_{\mu\mu} < 97.2 \text{ GeV}/c^2$) for different cuts on the transverse momentum of the isolated muons. The contribution to the background from $b\bar{b}$ events is suppressed by requiring two isolated muons (compare table 4.4). The isolation criterion also reduces the contribution from $W \rightarrow \mu\nu$ events by an order of magnitude.

Requiring isolated muons with $P_t > 25 \text{ GeV}/c$ results in very low background levels and a very clean signal peak in the region of the Z boson mass (see figure 4.17). By requiring the presence of two isolated muons in the event, the contributions of the $pp \rightarrow \mu + X$ and the $b\bar{b}$ channels disappear, showing the strong discriminating power of this particular cut against background events. However, the statistics of the available background samples are limited, especially for high P_t muons, and therefore table 4.5 contains only limits for these background channels.

Currently no real data are available and therefore the number of events stemming from background channels have been estimated using *Monte Carlo* studies. Once real data become available the determination of the background (also including cosmic muon contributions) will be based on the data using other techniques than described here [111].

Taking the contributions from the signal and all background channels into account, the inclusive dimuon invariant mass distribution is shown in figure 4.18. The number of signal candidates obtained by fitting the signal region with a Breit-Wigner function together with a Gaussian as discussed before is

$$N_{\text{cand}} = (6.43 \pm 0.33) \cdot 10^4. \quad (4.11)$$

There is still one quantity missing in order to calculate the luminosity (or cross section) using formula 4.1: the total efficiency $\varepsilon_{\text{total}}$. The methods used to extract from data the contributions to $\varepsilon_{\text{total}}$ are described in the next section.

4.5 Efficiencies

The total efficiency, which enters in the formula for the measurement of the luminosity (equation 4.1), contains contributions from the following sources:

- muon reconstruction efficiency,
- isolation efficiency,
- trigger efficiency,
- detector acceptance and
- efficiency of the selection criteria.

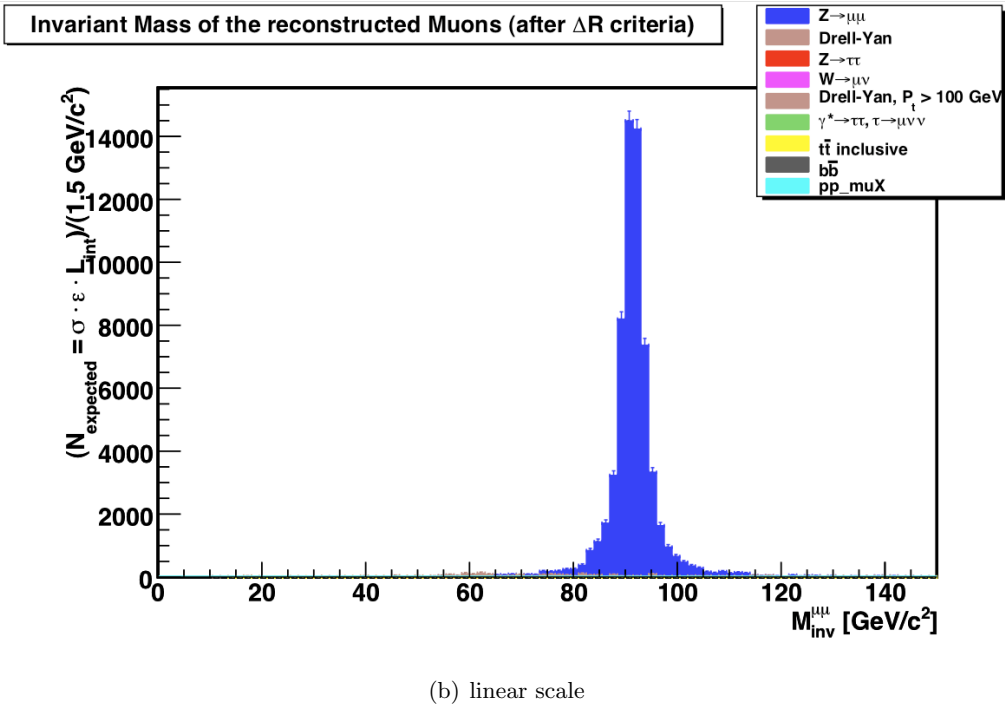
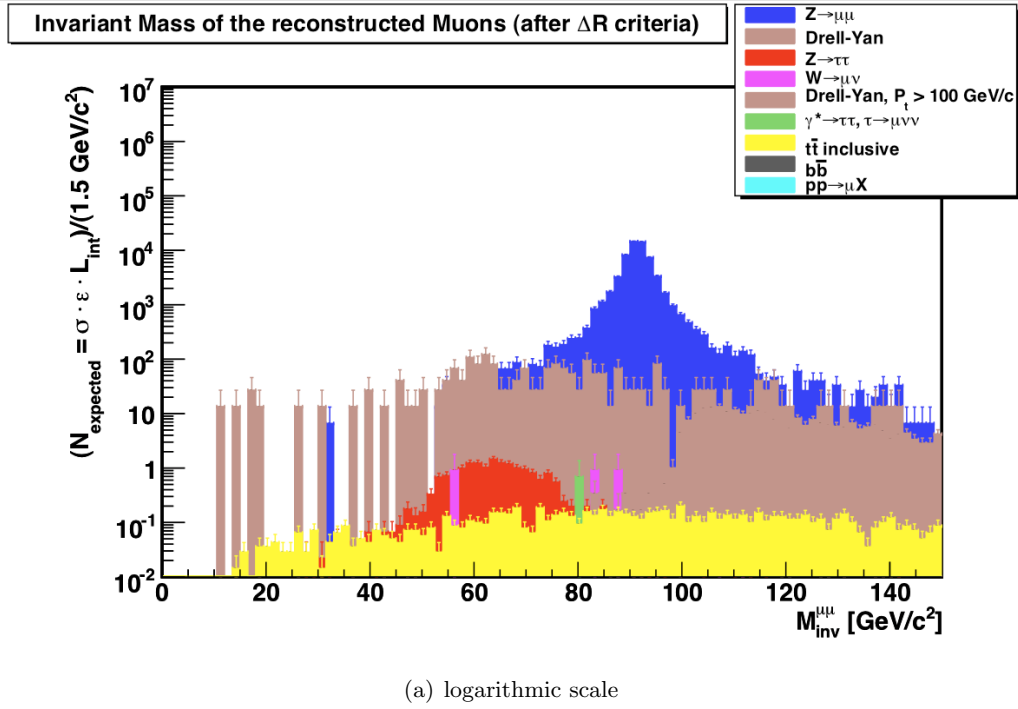


Figure 4.17: The invariant mass distribution of the muons for both signal and background events (for an integrated luminosity of 0.1 fb^{-1}). The isolation criterion as described in the text has been imposed ($\Delta R(\text{muon}, \text{tracks}) > 0.3$) and in addition $P_t > 25 \text{ GeV}/c$ and $|\eta| < 2.4$ resulting in a strong reduction of the background. (a) shows the distribution on a logarithmic scale and (b) on a linear scale demonstrating the purity of the signal. Statistical errors are indicated by the error bars.

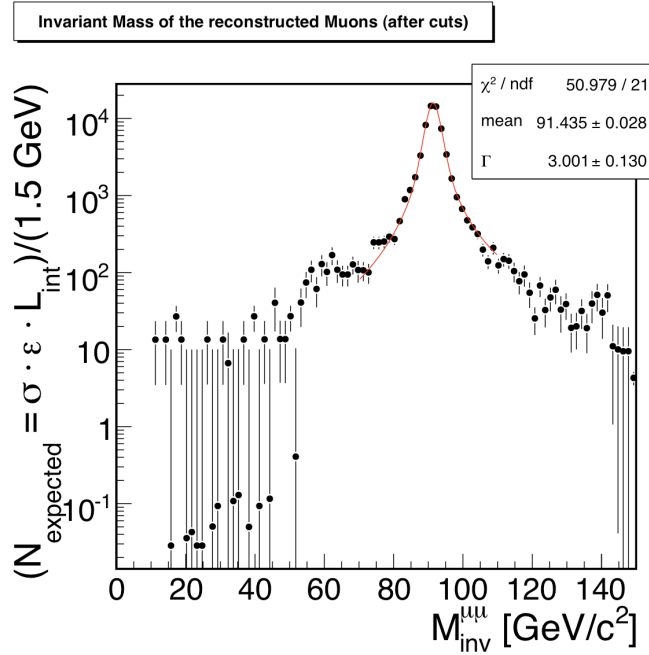


Figure 4.18: Inclusive dimuon mass, including all background and signal contributions (for an integrated luminosity of 0.1 fb^{-1}). The reconstructed muons fulfill the following cuts: $P_t > 25 \text{ GeV}/c$, $|\eta| < 2.4$ and the isolation criterion $\Delta R(\text{muon}, \text{tracks}) > 0.3$. The signal region has been fitted (red line) with a Breit-Wigner function together with a Gaussian as discussed in the text. Statistical errors are indicated by the error bars.

These efficiencies are discussed in more detail in the following sub sections. First however, a method to determine an efficiency from data only, without the reliance on *Monte Carlo* information, will be presented in the next subsection.

4.5.1 The “tag & probe” method

The “tag & probe” method has been successfully used by both Tevatron experiments [122]. The method relies on $Z \rightarrow \mu\mu$ decays to provide an unbiased, high-purity muon sample with which the efficiency of a particular cut or trigger can be studied.

One of the muons (the “tag”) is required to pass stringent muon identification criteria. The second muon (the “probe”) has to pass a set of identification criteria depending on the efficiency under study. Furthermore the invariant mass of the tag and the probe muons should be within a window around the mass of the Z boson. The stringent criteria required for the tag together with the invariant mass requirement result in sufficiently high muon purity. This remains true even if one of the probe muon candidates has no track associated with it or is not identified in the muon system (see section 4.5.2) and fails to fulfill the trigger requirements.

The next sections will discuss the details of the “tag & probe” methods used to estimate the muon reconstruction efficiency, the isolation efficiency and the High-Level Trigger (HLT) efficiency.

4.5.2 Muon reconstruction efficiency

The global muon reconstruction efficiency can be factorized as

$$\varepsilon_{\text{muon reconstruction}} = \varepsilon_{\text{standalone}} \times \varepsilon_{\text{tracker}} \times \varepsilon_{\text{matching}}, \quad (4.12)$$

where $\varepsilon_{\text{standalone}}$ is the efficiency to find a muon candidate in the muon system, $\varepsilon_{\text{tracker}}$ is the efficiency to find a muon candidate in the tracker and finally $\varepsilon_{\text{matching}}$ is the efficiency to find a correct matching between the standalone and the tracker muon candidates.

A muon is considered as a *tag* muon if it fulfills the following requirements: $P_t > 30$ GeV/c and the *tag* muon should be matched with a level-3 muon⁵ that triggered the isolated single muon HLT⁶. The *probe* muon can be a global muon, a standalone muon track or a tracker track. The standalone muons must have a transverse momentum larger than 10 GeV/c, should be separated from the *tag* muon in ΔR space by $\Delta R > 0.5$ and have a back-to-back configuration in the transverse plane ($\Delta\varphi > 1.5$). Furthermore, the invariant mass of the tag-probe system should be in the mass window ± 15 GeV/c² around the mass of the Z boson. The tracker track probes must have $P_t > 15$ GeV/c, $\Delta R > 0.2$, $\Delta\varphi > 1.5$ and fulfill a tight mass window constraint⁷ (± 5 GeV/c² around the Z boson mass) [111]. Finally all *tag* and *probe* muons have to be isolated from other tracks according to the isolation criteria described in section 4.4.

The following five disjoint categories of *probe* candidates have been considered:

1. probes which meet the criteria to be a *tag* candidate; they are labeled as “G” (golden),
2. probes which are identified as a global muon, but do not satisfy the golden criteria; they are labeled as “M” (matched),
3. probes which are standalone (tracker) muons having a tracker (standalone) muon in a small η - φ window around them; they are labeled as “U” (unmatched),
4. probes, consisting only out of a tracker muon without a corresponding standalone muon in the η - φ window; they are labeled as “T” (tracker only),
5. probes, built out of a standalone muon without a corresponding track in the tracker in the η - φ window; they are labeled as “S” (standalone only).

With these probe definitions, the standalone, tracker and matching efficiencies from equation 4.12 can be calculated by event counting [111, 123]

$$\begin{aligned}\varepsilon_{\text{standalone}} &= \frac{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}}} \\ \varepsilon_{\text{tracker}} &= \frac{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GS}}} \\ \varepsilon_{\text{matching}} &= \frac{2N_{\text{GG}} + N_{\text{GM}}}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}\end{aligned}\tag{4.13}$$

where N_{Gx} is the number of events containing a *probe* muon of type x .

Application of the “tag & probe” method to the signal events results in the following efficiencies (for the calculation of the errors see appendix F.3)

$$\begin{aligned}\varepsilon_{\text{standalone}} &= 0.917 \pm 0.003, \\ \varepsilon_{\text{tracker}} &= 0.990 \pm 0.001, \\ \varepsilon_{\text{matching}} &= 0.998 \pm 0.001.\end{aligned}\tag{4.14}$$

⁵Level-3 muon is the HLT nomenclature for a global muon: both muon and tracker hits are used to reconstruct the muon track in the detector.

⁶This trigger path requires the muon to be isolated and to have a transverse momentum larger than 19 GeV/c.

⁷The tight constraint on the invariant mass of the tag muon and the tracker track probe allows the identification of the track as a “muon”, although the information from the muon system is missing.

The standalone, tracker and matching efficiencies can be combined into the muon reconstruction efficiency $\varepsilon_{\text{muon reconstruction}}$ utilizing equation 4.12

$$\varepsilon_{\text{muon reconstruction}} = 0.907 \pm 0.003. \quad (4.15)$$

The reconstruction efficiency for single muon events is typically 95 – 99 % for the CMS detector [62]. For dimuon events efficiencies in the range 90 – 98 % are achieved, which is still in agreement with the result in equation 4.15. The result from the “tag & probe” method was obtained with an early version of the CMS software⁸. It has been known that there was plenty of room for improvements and optimisation of the reconstruction algorithms included in this version. Therefore, and also to exclude possible biases due to the limited statistics of the signal event sample, the estimation of the muon reconstruction efficiency has been repeated utilizing a newer version of the CMS software⁹ and a larger sample of $Z \rightarrow \mu\mu$ events generated with MC@NLO. These studies result in a muon reconstruction efficiency of approximately 97 %.

4.5.3 Isolation efficiency

The “tag & probe” method can also be used to determine the isolation efficiency. The simple method presented here is based on the selection of a clean sample of $Z \rightarrow \mu\mu$ events.

The determination of the isolation efficiency will be restricted to events having two global muons with $P_t > 20$ GeV/c and $|\eta| < 2.4$ and a dimuon mass in the range 70 – 110 GeV/c². These selection cuts ensure that the isolation efficiency is the only effect still to be taken into account. Once the events have been selected, the *tag* muons are defined as those that are isolated, i.e. no tracks are present in a cone $\Delta R < 0.3$ around the muon. The other muon selected in the event will be the *probe* muon [111].

In a way similar to the muon reconstruction efficiency above, the isolation efficiency can be calculated as the fraction of events with an isolated probe to the total number of tags and probes [111]

$$\varepsilon_{\text{isolation}} = \frac{2N_{\text{Iso,Iso}}}{2N_{\text{Iso,Iso}} + N_{\text{Iso,NoIso}} + N_{\text{NoIso,Iso}}}. \quad (4.16)$$

With this method the isolation efficiency has been estimated to be

$$\varepsilon_{\text{isolation}} = 0.956 \pm 0.002 \quad (4.17)$$

The error has been calculated using error propagation (see appendix F.4).

4.5.4 Trigger efficiency

The design of the trigger system was discussed in section 2.2.6. For a luminosity of $\mathcal{L} = 2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ (low-luminosity phase) the following four High-Level Trigger paths¹⁰ are available to select events containing muons [39, 81]

- single muon with isolation (threshold: $P_t > 19$ GeV/c),
- single muon without isolation (threshold: $P_t > 37$ GeV/c),
- dimuon with isolation (threshold: $P_t > 7$ GeV/c),

⁸As well as the complete analysis presented in this chapter, this study, has been performed with CMSSW_1.3.1.

⁹For the additional estimation of the muon reconstruction efficiency CMSSW_1.6.8 has been used.

¹⁰Newer versions of CMSSW contain trigger paths which are optimized for the first months of data taking with CMS. These trigger paths include thresholds lower than used in the present study.

- dimuon without isolation (threshold: $P_t > 10 \text{ GeV}/c$).

Figure 4.19 shows the number of HLT paths that have accepted an event. The majority of the $Z \rightarrow \mu^+ \mu^-$ events is accepted by all four muon triggers. This shows the high redundancy of the trigger paths for the signal events: if one trigger path fails, only a small number of events is lost due to the fact that most of the events are accepted by at least one of the other three muon triggers. This is also demonstrated in figure 4.20 where the number of rejected events is shown for each of the four muon triggers (red line). Also shown for each trigger path is the number of events which were rejected by the given trigger, but have been accepted by one of the other triggers (blue line). The number of events rejected by all four triggers is actually quite small.

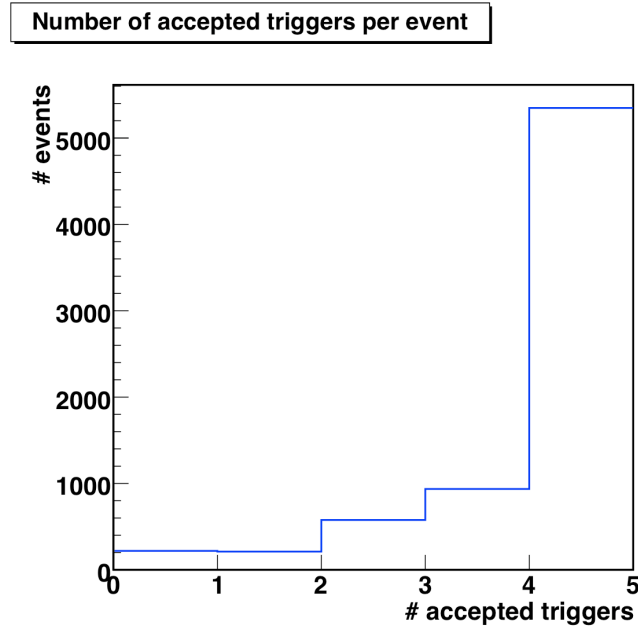


Figure 4.19: Number of HLT muon triggers per event. The majority of the $Z \rightarrow \mu\mu$ events is accepted by all four muon triggers.

number of accepted triggers	number of events	efficiency [%]
0	219	3.0
1	211	2.9
2	577	7.9
3	936	12.8
4	5348	73.4

Table 4.6: The number of HLT triggers per event as well as the corresponding efficiencies are shown. The event sample used for the trigger studies contained 7291 $Z \rightarrow \mu\mu$ events, which were generated with MC@NLO.

Table 4.6 summarizes the number of events accepted by 0, 1, 2, 3 or all 4 trigger paths as well as the corresponding efficiencies (compare figure 4.19). Adding all four muon triggers

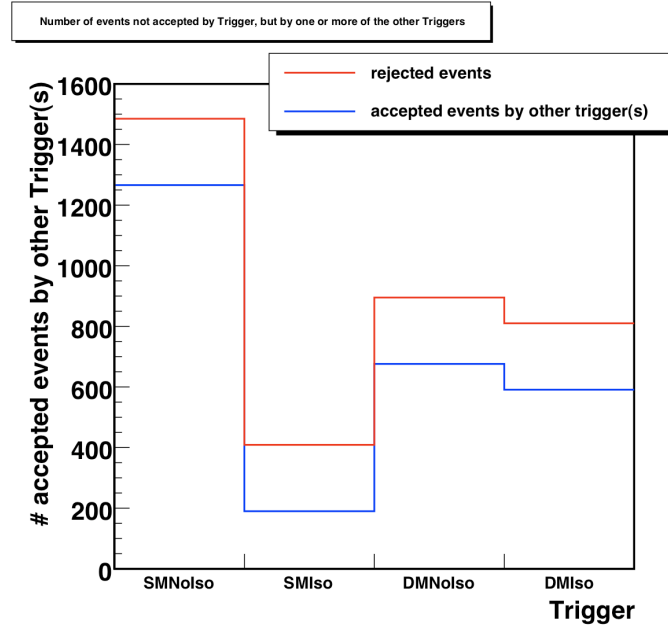


Figure 4.20: Number of events rejected by the different HLT muon triggers. The red line shows the number of rejected events for each trigger path. In blue the number of events accepted by at least one of the other three trigger paths is shown.

together, an overall selection efficiency of

$$\varepsilon_{\text{HLT}} = 97 \% \quad (4.18)$$

is obtained.

Once real data are available a data-based method to determine the trigger efficiency is preferable over a method based on “Monte Carlo” information. The “tag & probe” method can be used to extract the trigger efficiency from data only.

To estimate the trigger efficiency with the “tag & probe” method a clean sample of $Z \rightarrow \mu\mu$ events containing two global muons with $P_t > 20 \text{ GeV}/c$, $|\eta| < 2.4$ and dimuon mass between 83.7 and 98.7 GeV/c^2 has been selected.

A muon is selected as the *tag* if, in addition to the P_t and η cuts, the muon is isolated and the event is accepted by the HLT trigger criteria currently under study. The efficiency can be calculated by dividing the number of events in which the second muon (the *probe*) meets the trigger requirements by the total number of *tag* muons. The equation to determine the trigger efficiency is [111]

$$\varepsilon_{\text{trigger}} = \frac{2N_{\text{TT}}}{2N_{\text{TT}} + N_{\text{TN}} + N_{\text{NT}}} \quad (4.19)$$

where the index “T” denotes a muon satisfying the trigger criteria.

The number of events in which the *probe* meets the trigger requirements, the total number of *tag* muons and the efficiency of each individual muon High-Level Trigger path is shown in table 4.7. The results obtained with the “tag & probe” method are similar to the results based on *Monte Carlo* information. Three out of the four trigger paths show the same efficiency of approximately 96 % in agreement with the estimated 97 % from equation 4.18. Only the single muon without isolation trigger shows a lower efficiency due to the stringent requirement on the transverse momentum of the muons (compare also figure 4.20).

HLT trigger	N_{TT}	N_{TN}	N_{NT}	efficiency
single Muon, isolation (SMIso)	5328	276	198	0.957 ± 0.002
single Muon, no isolation (SMNoIso)	2925	1950	99	0.741 ± 0.006
di Muon, isolation (DMIso)	5328	276	198	0.957 ± 0.002
di Muon, no isolation (DMNoIso)	5328	276	198	0.957 ± 0.002

Table 4.7: Efficiencies of the four HLT muon trigger paths as obtained with the “tag & probe” method. The event sample used for the trigger studies contained 7291 $Z \rightarrow \mu\mu$ events generated with MC@NLO.

In the calculations carried out in the following sections, the trigger efficiency is taken to be

$$\varepsilon_{\text{HLT}} = 0.957 \pm 0.002. \quad (4.20)$$

The error has been obtained by utilizing methods similar to those presented in appendix F.4.

4.5.5 Detector acceptance

An additional contribution to the total efficiency is the detector acceptance. Figure 4.21 shows the pseudorapidity distribution of the generated muons. A large fraction of the muons is situated outside the detector acceptance $|\eta| < 2.4$. The measurable fraction of the total production cross section in the $Z \rightarrow \mu\mu$ channel is therefore restricted: only those events with both muons in the pseudorapidity range covered by the muon system can be reconstructed.

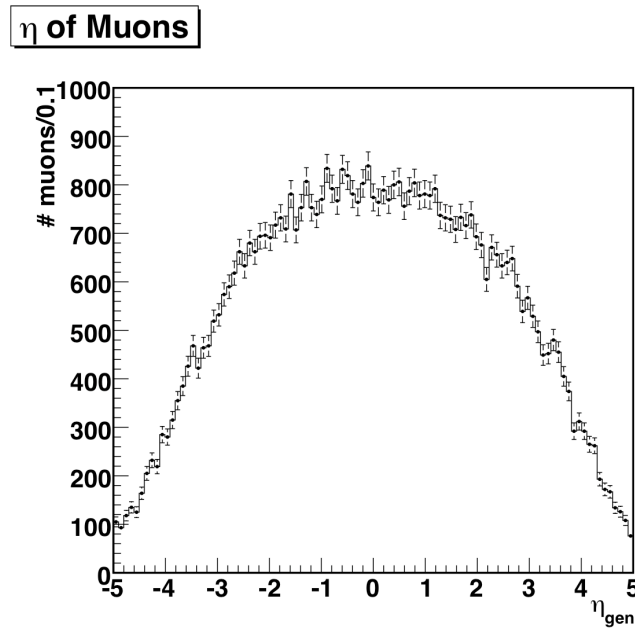


Figure 4.21: Pseudorapidity distribution of the generated muons in the $Z \rightarrow \mu\mu$ channel. The events have been generated with MC@NLO. A large fraction of the Z events decays into muons with a pseudorapidity outside the detector acceptance $-2.4 < \eta < 2.4$. Statistical errors are indicated by the error bars.

The acceptance has been determined by counting on the generator level the number of events having both muons in the pseudorapidity range $|\eta| < 2.4$:

$$\varepsilon_{\text{acceptance}} = \frac{N_{2 \text{ muons with } |\eta| < 2.4}}{N_{\text{events}}}. \quad (4.21)$$

With $N_{2 \text{ muons with } |\eta| < 2.4} = (1.36 \pm 0.12) \cdot 10^4$ and $N_{\text{events}} = (2.79 \pm 0.02) \cdot 10^4$ the acceptance is

$$\varepsilon_{\text{acceptance}} = 0.487 \pm 0.005. \quad (4.22)$$

The error of the acceptance has been calculated utilizing error propagation (see appendix F.5).

4.5.6 Efficiency of the used selection criteria

Not only the efficiencies and acceptance discussed in the previous sections, but also the cuts applied in the analysis (see section 4.4) reduce the total efficiency $\varepsilon_{\text{total}}$.

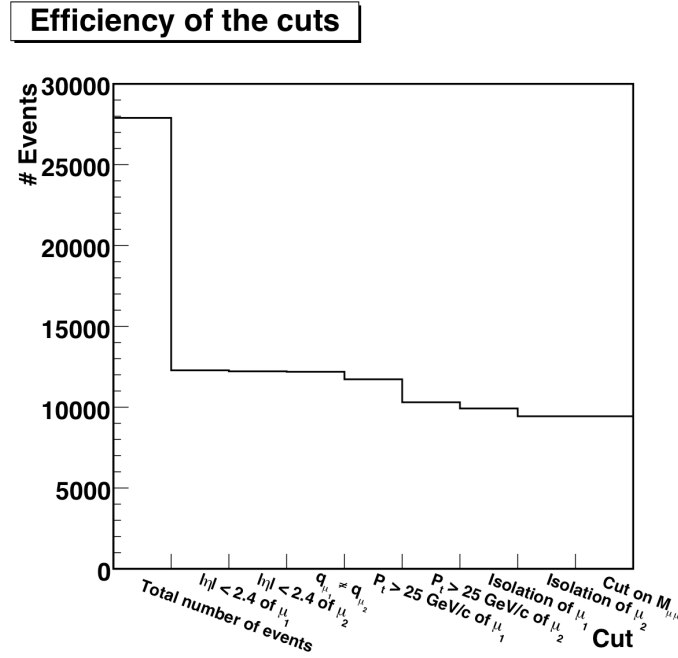


Figure 4.22: Effect of the different cuts applied after reconstruction on the number of selected $Z \rightarrow \mu\mu$ events generated with MC@NLO. Each cut reduces the number of selected events further. The cut on the pseudorapidity of both muons shows the effect of the detector acceptance as discussed in the previous section.

After reconstruction, figure 4.22 shows the effect of the different cuts on the number of selected signal events. The figure also illustrates the effect of the detector acceptance: the cuts on η for both muons reduce the number of events by roughly a factor of two compared to the total number of events in the data sample, in agreement with the acceptance found in section 4.5.5. The other cuts further reduce the number of selected events. The largest reduction stems from the P_t cut on the second reconstructed muon. No stringent cut on the invariant mass of the two reconstructed muons has been imposed and therefore this does not affect the number of selected events.

In order to take the effect of detector acceptance and the muon reconstruction efficiency into account only once, the efficiency of the cuts is calculated by dividing the number of events left after all cuts have been applied by the number of events left after the two η cuts

$$\varepsilon_{\text{cuts}} = \frac{N_{\text{after all cuts}}}{N_{\text{after both } \eta \text{ cuts}}}. \quad (4.23)$$

This definition assures the presence of two reconstructed muons in the fiducial volume of the muon system and $\varepsilon_{\text{cuts}}$ contains only contributions from the selection cuts.

With $N_{\text{after all cuts}} = (9.436 \pm 0.097) \cdot 10^3$ and $N_{\text{after both } \eta \text{ cuts}} = (12.216 \pm 0.111) \cdot 10^3$ the efficiency of the cuts is

$$\varepsilon_{\text{cuts}} = 0.772 \pm 0.011. \quad (4.24)$$

The error of the efficiency of the cuts has been determined utilizing the same methods as used for the acceptance in the previous section.

4.5.7 Total efficiency

The muon reconstruction efficiency, the isolation efficiency, the trigger efficiency, the detector acceptance and the efficiency of the selection cuts as discussed in the previous sections can be combined into the total efficiency

$$\varepsilon_{\text{total}} = \varepsilon_{\text{muon reconstruction}} \times \varepsilon_{\text{isolation}} \times \varepsilon_{\text{trigger}} \times \varepsilon_{\text{acceptance}} \times \varepsilon_{\text{cuts}}. \quad (4.25)$$

With the results from the previous sections the total efficiency can be calculated to be

$$\varepsilon_{\text{total}} = 0.312 \pm 0.006 \quad (4.26)$$

In [111] it has been shown that the dependence of the muon reconstruction, isolation and trigger efficiency on the transverse momentum and pseudorapidity of the muons is small (in the order of a few percent at most).

Before presenting the final results of this analysis, systematic uncertainties will be discussed in the next section.

4.6 Systematic uncertainties

Several sources of systematic uncertainties affecting the luminosity measurement have been studied, including

- systematic uncertainties due to parton distribution functions (PDFs),
- influence of the underlying event,
- influence of muon and tracker misalignment,
- effect of the triggers,
- influence of the magnetic field.

These systematic uncertainties, which originate from experimental as well as theoretical sources, will be shortly discussed in the following sections.

4.6.1 Parton distribution functions

The parton distribution functions have been already discussed in section 1.2, while in section 1.3 it has been shown that the parton distribution functions $f_q(x_1)$ and $f_{\bar{q}}(x_2)$ enter in the calculation of the cross section (see equation 1.16). Uncertainties in these functions thus affect the uncertainty in the cross section and therefore also the luminosity measurement. Furthermore the event topology can be affected so that in case of the cross section measurement the resulting uncertainty in the acceptance should be determined.

Several different sources contribute to uncertainties in the parton density functions:

- experimental statistical and systematic errors,
- non-gaussian uncertainties in perturbative QCD calculations (*e.g.* higher order and power law corrections),
- nuclear corrections to the results of experiments using at nuclear targets.

These uncertainties are in general complicated and they have to be studied separately. In the end the individual contributions should be combined to give the final uncertainty of the parton distribution functions.

In this analysis the uncertainties in the PDFs arising from the experimental statistical and systematic errors and their effect on the production cross section of the Z boson as well as on the acceptance have been studied using the standard methods proposed in [124, 125].

For the standard set of PDFs, corresponding to the minimum in the PDF parameter space, a complete set of eigenvector PDF sets have been simultaneously calculated, characterizing the region in the neighborhood of the minimum. From these sets the best estimate as well as the uncertainty for the Z cross section has been obtained. The cross section uncertainty due to the PDFs is evaluated using the methods described in [125].

Table 4.8 lists the results for the used CTEQ [125] and MRST [126] PDF sets. The difference of approximately a factor 2 for the cross section uncertainty obtained from the CTEQ and MRST sets is due to different assumptions made by the groups while creating the eigenvector PDF sets. In order to be on the safe side and also to take into account the fact that this systematic uncertainty does not include the theoretical errors, it was decided to use the larger value as the systematic uncertainty due to the PDFs:

$$\sigma_{\text{cross section}}^{\text{PDF}} \approx 3.8 \%. \quad (4.27)$$

PDF	$\Delta\sigma_Z$ [nb]	$\frac{\Delta\sigma_Z}{\langle\sigma_Z\rangle}$ [%]
41 CTEQ6m sets	2.1	3.8
31 MRST sets	0.9	1.5
PDF	$\Delta\varepsilon_{\text{acc}}$	$\frac{\Delta\varepsilon_{\text{acc}}}{\langle\varepsilon_{\text{acc}}\rangle}$ [%]
41 CTEQ6m sets	0.009	1.9
31 MRST sets	0.009	1.9

Table 4.8: Results of the study of the uncertainties due to the PDFs. The upper part of the table shows the resulting uncertainty of the cross section, whereas the lower part shows the result for the uncertainty of the acceptance.

The uncertainty of the acceptance has been estimated in the same way. The choice of the parton distribution functions has only a small effect on the acceptance, resulting in an

uncertainty of

$$\sigma_{\text{acceptance}}^{\text{PDF}} \approx 1.9 \%. \quad (4.28)$$

4.6.2 Underlying event

The underlying event is the softer component of the collision which accompanies the hard scattering and accounts for a large part of the activity in the overall event. Although the influence of the underlying event on studies like the present one is expected to be small (due to the high transverse momentum of the muons), some checks have been performed to see whether a possible effect of the underlying event could be found utilizing the currently available tools. To study its influence on the signature of the signal in the $pp \rightarrow \gamma^*/Z^0 \rightarrow \mu^+\mu^-$ channel, event samples have been analysed in which the underlying event was enabled or disabled.

Only a purely phenomenological description of the underlying event is available in HERWIG. Therefore JIMMY [127], which implements a more realistic multiple parton interaction model for the simulation of the underlying event, has been interfaced with MC@NLO and HERWIG. No significant deviations in the cross section, event topology and the efficiencies were observed when using these *Monte Carlo* programs.

Once real data are available, detailed studies of the effect of the underlying event should be performed to make sure that the currently available simulation is accurate at the high energies the LHC will provide. A detailed description of the plans and strategy to measure the underlying event with the CMS detector is given in [128].

4.6.3 Muon and tracker misalignment

The systematic uncertainty due to misalignment has been studied using the appropriate tools in the CMS software framework. The events generated with MC@NLO have been misaligned using a misalignment scenario based on the so-called First Data scenario [97]¹¹ and the events have been re-reconstructed. This procedure has been repeated for 40 different misalignment scenarios: each scenario is based on the same assumptions about the size of the misalignment, but has a different random seed resulting in different misalignment of the tracker and muon system detectors.

Figure 4.23 shows the reconstructed invariant mass distribution of the muons both for an ideal geometry and for one of the misalignment scenarios. The same fit as described in section 4.3 has been applied¹². The misalignment of the tracker and muon system not only causes an increase of the width of the invariant mass distribution, thus influencing the estimation of the number of signal candidates (N_{cand}), but also displaces the mean, resulting in a shift of the Z boson mass.

To estimate the systematic effect of misalignment on the signal, the number of events in a 2Γ window around the Z mass as well as the quantity

$$\psi = \frac{\text{number of events}(\text{without misalignment}) - \text{number of events}(\text{with misalignment})}{\text{number of events}(\text{without misalignment})} \quad (4.29)$$

¹¹The First Data scenario is based on the numbers shown in table 2.3 which reflect current knowledge regarding mounting precision. However, the misalignment scenario used here is based on an earlier version of this table. Unfortunately the updated misalignment scenario was not available at the time these studies were performed. The old misalignment scenario should therefore overestimate the effect of the misalignment at the beginning of LHC running and the numbers presented here can be seen as an upper limit.

¹²Due to the limited statistics of the event sample used for these misalignment studies, the errors are quite large resulting in a small value of χ^2/ndf . Nevertheless the fit describes the data well in the region around the Z boson mass.

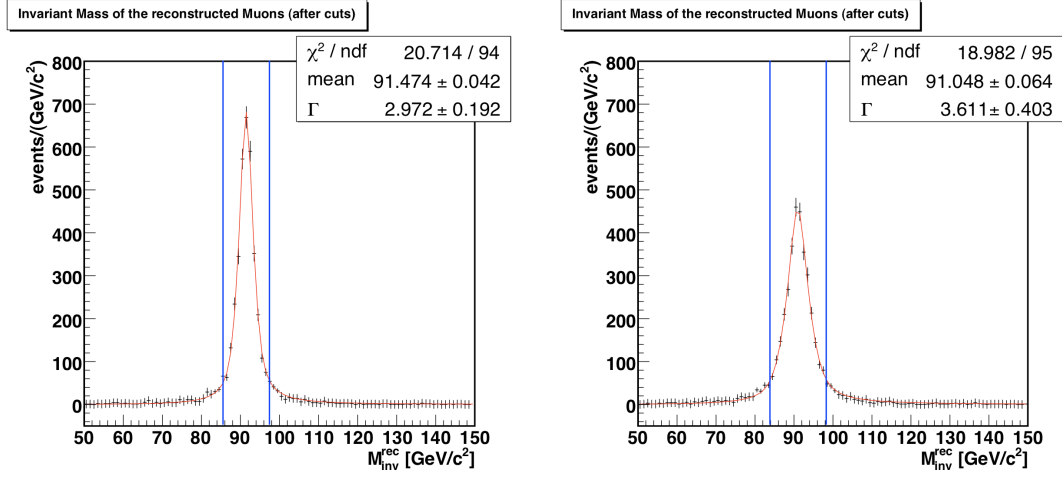


Figure 4.23: Comparison of $Z \rightarrow \mu^+\mu^-$ invariant mass distribution (generated with MC@NLO) for an ideal detector geometry (left plot) and with a misaligned detector geometry (right plot). The vertical lines (in blue) indicate the 2Γ window around the Z boson mass region used to estimate the number of events in the peak region. Statistical errors are indicated by the error bars.

has been calculated. Figure 4.24 shows the distribution of the quantity defined in equation 4.29. The mean $\bar{\psi} = 2.9\%$ and the variance $\sigma_{\bar{\psi}}^2$ of $\bar{\psi}$ give an estimate for the systematic uncertainty due to misalignment of the detector. A non-parametric bootstrap method [129–132] (see appendix E) has been used to determine the variance. The bootstrap method is especially useful in cases where the distribution function is in principle unknown, as is the case for ψ , and where the data samples are small. The variance $\sigma_{\bar{\psi}}^2$ has been calculated for a 68.3 % confidence level in a two-sided interval with equal tails, resulting in a range for variance of (2.7 %, 3.0 %). Utilizing the results from the Laser Alignment System (see previous chapter) and track based alignment algorithms once real data are available, a value $\bar{\psi} \approx 0$ with a smaller variance interval can be achieved. For the first data, however, a systematic uncertainty of

$$\sigma_{\text{misalignment}}^{\text{sys}} \approx 2.9\%. \quad (4.30)$$

has to be taken into account.

4.6.4 Trigger

To estimate the systematic uncertainty originating from the trigger, the thresholds in the various muon trigger paths (see section 4.5.4) have been varied. A shift of -2 , -1 , $+1$ and $+2$ GeV/c relative to their nominal values was applied. The dimuon invariant mass distributions of the resulting event samples have been fitted using the methods described earlier in this chapter. Using a method similar to the one employed to estimate the systematic uncertainty due to misalignment, the number of triggered events was counted and the quantity

$$\xi = \frac{\text{number of events(nominal threshold)} - \text{number of events(shifted threshold)}}{\text{number of events(nominal threshold)}} \quad (4.31)$$

was calculated. Figure 4.25 shows the resulting distribution of ξ . The mean value $\bar{\xi}$ is around

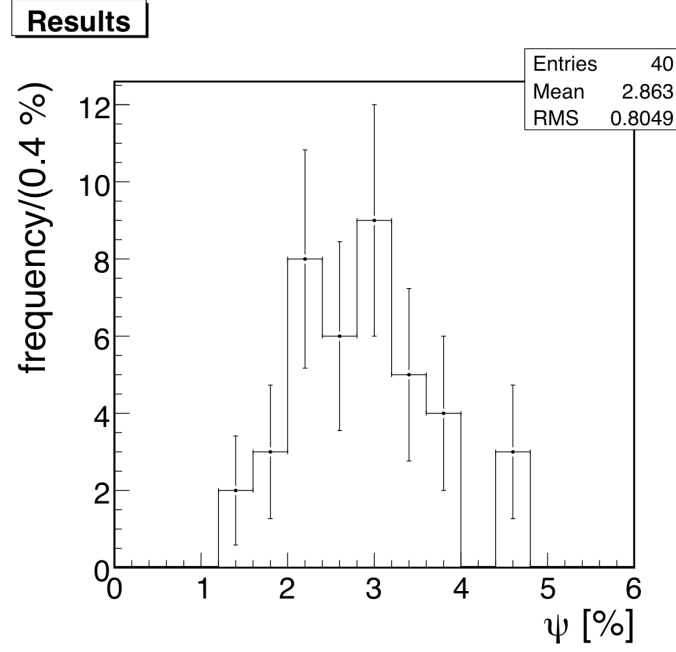


Figure 4.24: Results of the studies on the systematic uncertainty due to misalignment. Shown is the distribution of the quantity ψ defined in equation 4.29, which gives the change in the number of events in the region around the Z boson mass due to a misaligned tracker and muon system. The statistical errors, indicated by the error bars, are quite large due to the small data sample.

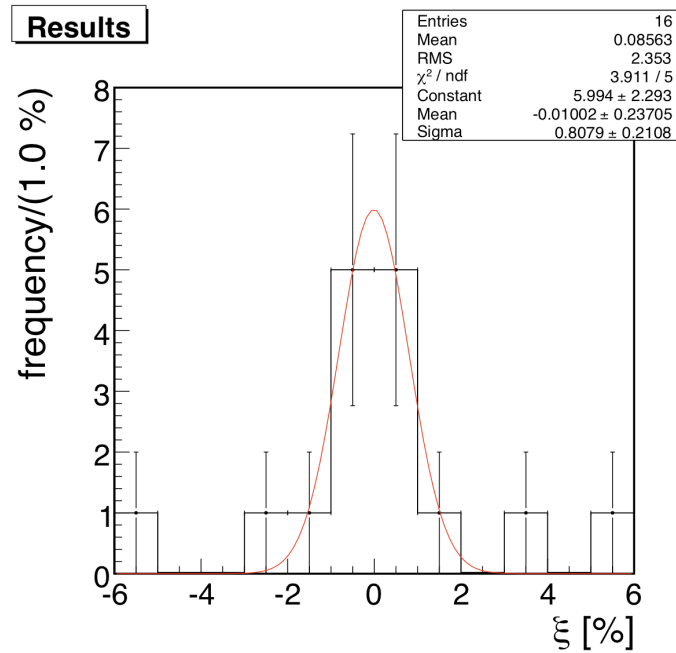


Figure 4.25: Results of the studies on the systematic uncertainties due to the trigger. Shown is the distribution of the quantity ξ defined in equation 4.31, which gives the change in the amount of triggered events due to a shift of the trigger thresholds. Statistical errors, indicated by the error bars, are quite large due to the small data sample.

zero as expected. Using a non-parametric bootstrap method (again for a 68.3 % confidence level) in a two-sided interval with equal tails a range of $(-0.5 \%, 0.7 \%)$ for the variance σ_ξ^2 of the mean is obtained. A gaussian fit has been applied to the distribution of ξ , finally resulting in a systematic error of

$$\sigma_{\text{HLT}}^{\text{sys}} \approx 0.8 \%. \quad (4.32)$$

4.6.5 Final remarks on systematic uncertainties

The systematic uncertainty due to the magnetic field of the CMS detector has been studied in [111]. The effect of a distorted magnetic field on the measurement of the Z production cross section has been estimated by applying a fluctuation of the B field intensity during the reconstruction of the events and was found to be

$$\sigma_{B \text{ field}}^{\text{sys}} = 0.5 \%. \quad (4.33)$$

Adding all the systematic variances presented in this section, we obtain for the total systematic uncertainty of the integrated luminosity measurement a value of

$$\sigma_{\text{total}}^{\text{sys}} = \sigma_{\text{PDF, cross section}}^{\text{sys}} \oplus \sigma_{\text{misalignment}}^{\text{sys}} \oplus \sigma_{\text{HLT}}^{\text{sys}} \oplus \sigma_{B \text{ field}}^{\text{sys}} = 4.9 \%. \quad (4.34)$$

For the measurement of the cross section for the reaction $pp \rightarrow \gamma^*/Z^0 \rightarrow \mu^+\mu^-$ the systematic uncertainty of the acceptance should be taken into account (see section 4.6.1), resulting in

$$\sigma_{\text{total}}^{\text{sys}} = \sigma_{\text{PDF, acceptance}}^{\text{sys}} \oplus \sigma_{\text{misalignment}}^{\text{sys}} \oplus \sigma_{\text{HLT}}^{\text{sys}} \oplus \sigma_{B \text{ field}}^{\text{sys}} = 3.6 \%. \quad (4.35)$$

Furthermore, one should keep in mind the additional uncertainty of the luminosity of the LHC (the design goal is to achieve a systematic accuracy of approximately 5 % [62]).

4.7 Conclusions

With the results presented in the previous sections (summarized in table 4.9) and the formula from equation 4.1 the integrated luminosity can be estimated to be

$$L = (0.100 \pm 0.006^{\text{stat}} \pm 0.005^{\text{sys}}) \text{ fb}^{-1}. \quad (4.36)$$

This result shows the large potential of the $pp \rightarrow \gamma^*/Z^0 \rightarrow \mu^+\mu^-$ channel to deliver an accurate measurement of the integrated luminosity at LHC using the CMS experiment.

The measurement of the cross section depends on the uncertainty of the luminosity. Once there is an accurate value for the luminosity of the LHC available, we can turn things around and measure the cross section instead of the luminosity. Assuming a luminosity of $(0.10 \pm 0.01) \text{ fb}^{-1}$ we obtain for the cross section

$$\sigma_{pp \rightarrow \gamma^*/Z^0 \rightarrow \mu\mu} = (1.989 \pm 0.114^{\text{stat}} \pm 0.071^{\text{sys}} \pm 0.199^{\text{lumi}}) \text{ nb}. \quad (4.37)$$

The accuracy of the measured cross section is limited by the accuracy to which the luminosity is known, at least at the beginning of the LHC era.

Figure 4.26 compares the result for the cross section of this analysis with the Z production cross section measured at several hadron collider experiments.

	value	error
N_{cand}	$6.43 \cdot 10^{+4}$	$0.33 \cdot 10^{+4}$
$f_{pp \rightarrow \gamma^*/Z^0 \rightarrow \tau\tau}$	$2.95 \cdot 10^{-4}$	$5.61 \cdot 10^{-5}$
$f_{t\bar{t}}$	$1.15 \cdot 10^{-4}$	$2.85 \cdot 10^{-5}$
$f_{W \rightarrow \mu\nu}$	$7.21 \cdot 10^{-5}$	$7.22 \cdot 10^{-5}$
ϵ_{total}	0.3119	0.0056
$\sigma_{pp \rightarrow \gamma^*/Z^0 \rightarrow \mu\mu}^{NNLO}$	1.964 nb	0.020 nb

Table 4.9: Results of the analysis used to calculate the measured value of the integrated luminosity. The number of signal candidates (N_{cand}) and the background to signal ratios have been estimated in a wide range (15Γ) around the mass of the Z boson in order to include the contributions from the reaction $pp \rightarrow \gamma^* \rightarrow \mu^+\mu^-$. The errors have been calculated using error propagation (see appendix F.2).

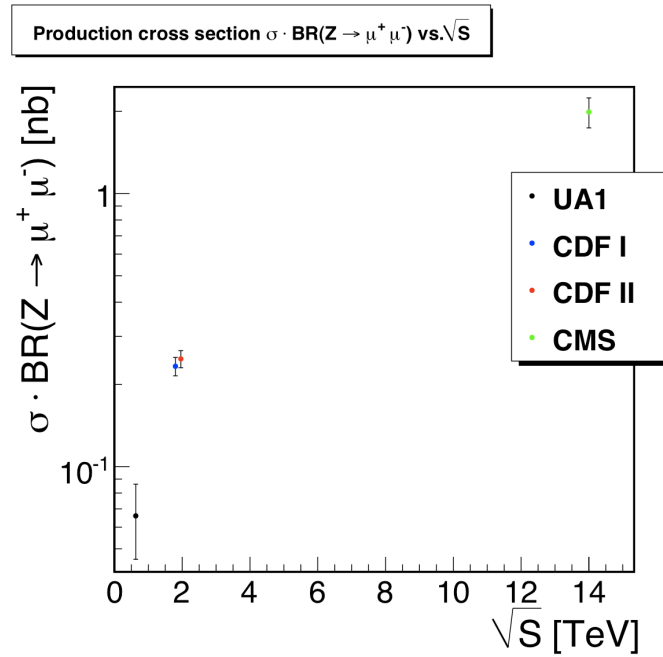


Figure 4.26: The Z boson production cross section ($\sigma \cdot \text{BR}(Z \rightarrow \mu^+\mu^-)$) versus center of mass energy ($\sqrt{S}$) for several hadron collider experiments: UA1 [133] (in black) at the SPS, CDF Run I [134] (in blue) and CDF Run II [135] (in red) at the Tevatron and the expected measurement with CMS (in green) at the LHC. The error bars include the statistical and systematic errors as well as the uncertainty of the luminosity measurement.

It has been shown in section 4.4 that the number of background events can be reduced by applying a limited number of cuts on the reconstructed muons. For real data, pileup effects, not considered in the simulations used in this work, will have to be taken into account. Because of the high LHC luminosity (see section 2.1) more than one proton-proton collision per bunch crossing will occur. Most of these pileup interactions are quite soft resulting in the presence of low P_t tracks in the detector. These soft tracks may affect the efficiency of the isolation criteria presented in section 4.4¹³.

Therefore additional cuts may become necessary to reduce the background while keeping the signal efficiency sufficiently high. Cuts on the distance between the two muons in ΔR space and on the correlation between the transverse momenta of the muons have been considered. Although these methods are not discussed in the present study, they appear to be very useful in reducing the background even further and therefore they offer an effective solution to the difficulties caused by pileup events.

Once real data are available, methods to estimate the number of background events directly from these data are favoured over methods based on *Monte Carlo* information. Two candidates of such methods, the so called “matrix method” and “template method”, are discussed in [111].

¹³The isolation criteria used throughout this study differ a little from the isolation criteria commonly used in [39] and more recently in [111]: a muon is considered as being isolated if $\sum P_t(\text{tracks}) < 3 \text{ GeV}/c$ in a cone $\Delta R < 0.3$ around the muon. This additional requirement may also account for a solution of the pileup problems.

Conclusions

The Large Hadron Collider is a two-ring, superconducting accelerator and collider which can provide both proton and heavy-ion beams. First collisions are foreseen for 2009. The Compact Muon System (CMS) detector will measure the particles created in the hadron collisions and can confirm the Standard Model by establishing the existence of the Higgs boson, but also search for new phenomena. In order to provide a robust and precise track reconstruction, which can already be used in the High-Level Trigger systems, the positions of the silicon sensors in the CMS tracker have to be known with an accuracy of $\mathcal{O}(100\text{ }\mu\text{m})$. Therefore the CMS tracker has been equipped with a dedicated alignment system.

The Laser Alignment System (LAS) aligns the tracker subdetectors with respect to each other and can also monitor the stability of the sensor positions during data taking. A realistic simulation of the LAS has been implemented in the CMS software framework (CMSSW). With the help of this simulation the LAS reconstruction software has been developed, which is able to reconstruct the position of the laser beams in the CMS tracker. Reconstructed laser beam positions are used as input to the alignment algorithms in order to calculate corrections to the detector geometry, which are then stored in the CMS conditions database.

Utilizing the reconstructed hits created by the laser beams, tracks can be built representing the path of the laser beams in the CMS tracker. In this way the information from the LAS can also be used as input to track based alignment algorithms.

The Laser Alignment System has been successfully tested during the integration of the tracker endcaps. The data collected during the integration of one of these endcaps (TEC+) has been analysed using the ROOT analysis framework. The beam spot positions have been corrected for the beam splitter kink angles and results from survey measurements have been included in the analysis. The results of this analysis show the potential of the Laser Alignment System to align the CMS tracker endcaps. In the present study it has been found that the alignment of the endcaps is possible with an accuracy of approximately $76\text{ }\mu\text{m}$. These results are in agreement with independent measurements of the TEC geometry using cosmic muons or photogrammetry measurements. The accuracy of $\approx 100\text{ }\mu\text{m}$ needed for track pattern recognition and reconstruction can be assured by the Laser Alignment System as shown in this study.

Accurate knowledge of the luminosity delivered by the LHC to the experiments is an essential ingredient for many physics studies. The present work uses the production of lepton pairs via the Drell-Yan mechanism to determine the integrated luminosity with the CMS detector. The Drell-Yan production of lepton pairs at hadron colliders is theoretically well under control and the production cross section is known to $\mathcal{O}(\alpha_S^2)$ with a small residual uncertainty due to the dependence on the factorization and renormalization scales.

A *Monte Carlo* generator (MC@NLO) including next-to-leading order QCD diagrams has been used to generate Drell-Yan events decaying into two muons. After a full CMS detector simulation, the events have been reconstructed using the CMS software framework (CMSSW). The production cross section of the Drell-Yan events was calculated in next-to-next-to-leading order with the software package FEWZ.

Several sources contributing to the background have been studied. The main background stems from $b\bar{b}$ and $pp \rightarrow \mu + X$ events. However, the present study has shown that the background levels can be reduced significantly even with simple cuts and isolation criteria,

resulting in a clear signal of $Z \rightarrow \mu\mu$ events.

The reconstruction efficiency of the two muons in the final state, as well as the trigger and isolation efficiencies, have been estimated with the “tag & probe” method. This method is based on the selection of a high purity sample by requiring hard cuts on the *tag* muon in the $Z \rightarrow \mu\mu$ event sample. The second muon, the *probe*, has to fulfill softer cuts together with requirements specific to the efficiency under study. Once such an event sample is selected, the efficiency can be extracted by event counting. The “tag & probe” allows for the determination of efficiencies utilizing only data, without any reliance on *Monte Carlo*, thus making this method especially suitable once data taking with the CMS detector has started.

Various possible sources of systematic uncertainties have been investigated. The effect of the uncertainties of the parton distribution functions on the cross section and acceptance, uncertainties due to misalignment of the CMS detector, uncertainties of the trigger acceptance as well as the effect of the magnetic field and the underlying event have been taken into account.

The analysis of Drell-Yan muon pairs has proved to be an accurate way to measure the integrated luminosity with the CMS detector. The precise theoretical prediction for the production cross section ($\sigma_{pp \rightarrow \gamma^*/Z \rightarrow \mu\mu}^{\text{NNLO}} = 1.964 \pm 0.020$ nb) results in a total uncertainty of 8 % in the luminosity. The main contribution to the uncertainty of the luminosity measurement stems from the uncertainty of the parton distribution functions.

The accuracy with which the production cross section of the Drell-Yan process $pp \rightarrow \gamma^*/Z \rightarrow \mu\mu$ can be measured at the LHC, is limited by the accuracy to which the luminosity is known, at least at the beginning of data taking with the CMS detector.

To obtain the results presented in this study, signal and background event samples with a total size of $\mathcal{O}(5\text{M})$ events have been analysed. In order to save CPU time (several minutes are needed to simulate and reconstruct a single event) the production and reconstruction of the events with the CMS software has been decoupled from the actual analysis. Therefore reconstructed events were preselected and stored in a common data format. The event samples stored in this way have been analysed using a standalone package developed for this purpose, which is based on the object-oriented data analysis framework ROOT.

The full simulation, reconstruction and pre-selection of the data samples was done by means of the worldwide LHC Computing Grid. The data collected by the LHC experiments (roughly 15 PB per year) will be distributed to computing centers around the world granting thousands of physicists access to these data. In addition to the development of new tools and data structures for physics analysis purposes, the methods used in the present study reflect the global way in which the analysis of CMS data will be performed in the near future.

Appendix A

Software for the Laser Alignment System

This appendix summarizes the options which can be utilized in the CMSSW job configuration files to customize the behaviour of the software for the Laser Alignment System. The first section describes the configuration for the simulation modules, followed by a section for the reconstruction modules. Finally a description of the configuration options for the DQM modules is given in section A.3.

A.1 Simulation options

Due to the design of the simulation of the Laser Alignment System (see section 3.2) a few additions to the default CMSSW configuration file for the simulation process are needed.

Add the source which provides empty events to the *OscarProducer*

```
source = LaserAlignmentSource
{
    untracked uint32 firstRun = 1  # set the run number
}
```

Add the description of the alignment tubes to the geometry

```
# add the description of the Alignment Tubes
replace XMLIdealGeometryESSource.geomXMLFiles +=
    "Alignment/LaserAlignmentSimulation/data/AlignmentTubes.xml"
```

Finally activate the optical physics and configure the *LaserAlignmentSimulation* module

```
# default simulation sequence of CMSSW
include "SimG4Core/Configuration/data/SimG4Core.cff"
# activate optical physics
replace g4SimHits.Physics.type = "SimG4Core/Physics/LaserOpticalPhysics"
replace g4SimHits.Watchers = # add the laser alignment simulation
{
    {
        # name of the SimWatcher
        string type = "LaserAlignmentSimulation"
        # used for debugging
        untracked int32 DebugLevel = 0
        untracked int32 MaterialPropertiesDebugLevel = 1
        # scale the absorption lenght in silicon
        untracked double SiAbsorptionLengthScalingFactor = 1.0
        # energy deposit of each optical photon
        untracked double EnergyLossScalingFactor = 1739.130435
        # energy of the photons (wavelength = 1064 nm)
```

```

        untracked double PhotonEnergy = 1.15
        # number of photons shoot for each starting point
        untracked int32 NumberOfPhotonsInParticleGun = 50
        # number of photons in beam with different starting point
        untracked int32 NumberOfPhotonsInEachBeam = 50
    }
}

```

A.2 Reconstruction options

This section gives an overview of the configuration options for several reconstruction modules in the software of the Laser Alignment System.

LaserAlignment As described in section 3.3 the *LaserAlignment* module is the main reconstruction module for the Laser Alignment System. The available options are shown in the configuration file fragment below:

```

module LaserAlignment = LaserAlignment
{
    # number of events for each laser intensity
    untracked int32 NumberOfEventsPerLaserIntensity = 1000
    # number of events for all intensities; afterwards profiles
    # will be fitted
    untracked int32 NumberOfEventsForAllIntensities = 1000
    # run alignment algorithm after n events
    untracked int32 DoAlignmentAfterNEvents = 25000
    # for debugging
    untracked int32 DebugLevel = 4
    # save alignment corrections to the database?
    untracked bool saveToDbase = true
    # save histograms of profiles to root file
    untracked bool saveHistograms = false
    untracked string ROOTFileName = "LaserAlignment.histos.root"
    untracked int32 ROOTFileCompression = 1
    # set to true to align TEC+ with Millepede
    untracked bool AlignPosTEC = false
    # set to true to align TEC- with Millepede
    untracked bool AlignNegTEC = false
    # set to true to align TEC-TIB-TOB-TEC with Millepede
    untracked bool AlignTECTIBTOBTEC = false
    # use Bruno's algorithm for alignment
    untracked bool UseBrunosAlignmentAlgorithm = true
    # range to search for modules hit by laser beams
    untracked double SearchWindowPhiTIB = 0.05
    untracked double SearchWindowPhiTOB = 0.05
    untracked double SearchWindowPhiTEC = 0.05
    untracked double SearchWindowZTIB = 1.0
    untracked double SearchWindowZTOB = 1.0
    # scale the error of fitted phi position (sometimes
    # needed by Millepede)

```

```

untracked double PhiErrorScalingFactor = 1.0
# minimum number of Adc Counts required
untracked int32 MinAdcCounts = 0

# configuration of the BeamProfileFitter
include "Alignment/LaserAlignment/data/BeamProfileFitter.cff"

# configuration of Millepede
include "Alignment/LaserAlignment/data/LaserAlignmentAlgorithm.cff"
# configuration of Bruno's algorithm
untracked bool UseBeamSplitterFrame = true

# list of digi producers used as input
VPSet DigiProducersList =
{
    {
        string DigiProducer = "SiStripDigis"
        string DigiLabel    = "ZeroSuppressed"
    },
    {
        string DigiProducer = "siStripZeroSuppression"
        string DigiLabel    = "VirginRaw"
    },
    {
        string DigiProducer = "siStripZeroSuppression"
        string DigiLabel    = "ProcessedRaw"
    },
    {
        string DigiProducer = "siStripZeroSuppression"
        string DigiLabel    = "ScopeMode"
    }
}
}

```

The fit of the laser beam profiles can be configured in the following way

```

PSet BeamProfileFitter =
{
    # delete the beam profile for the next run
    untracked bool ClearHistogramAfterFit = true
    # normalize the histograms with the beam profiles
    # taking into account the number of events used to
    # accumulate photon statistics
    untracked bool ScaleHistogramBeforeFit = true
    # minimal signal height required
    untracked double MinimalSignalHeight = 0.0
    # correct for beam splitter kinks (set to false
    # for monte carlo events)
    untracked bool CorrectBeamSplitterKink = true
    # systematic deviation of the measured BS angles w.r.t.
    # the reconstructed ones from the Sector tests

```

```

    untracked double BSAnglesSystematic = 0.0007
}

```

When using MILLEPEDE as alignment algorithm, fix some parameters in the fit to avoid ambiguities in the solution of the problem

```

PSet AlignmentAlgorithm =
{
    # parameters to fix in Millepede (x,y for disc 1)
    untracked int32 FirstFixedParameterPosTEC = 2
    untracked int32 SecondFixedParameterPosTEC = 3
    untracked int32 FirstFixedParameterNegTEC = 2
    untracked int32 SecondFixedParameterNegTEC = 3
    untracked int32 FirstFixedParameterTEC2TEC = 2
    untracked int32 SecondFixedParameterTEC2TEC = 3
}

```

LaserClusterizer The *LaserClusterizer* is described in 3.3.2 and takes care of the creation of clusters out of the laser signals. A few options are available to customize the behaviour of the clusterizer

```

module siStripClusters = LaserClusterizer
{
    # name of the clusterizer
    string ClusterMode = "LaserBeamClusterizer"
    # width of the clusters in sigma's
    double ClusterWidth = 1.0
    # name of the beam profile fit producer, needed
    # to retrieve the fit result from the Event Data
    string BeamFitProducer = "LaserAlignment"
    # digi producers, used as input
    VPSet DigiProducersList =
    {
        {
            string DigiProducer = "LaserAlignment"
            string DigiLabel    = "\0"
        },

        {
            string DigiProducer = "RawToDigi"
            string DigiLabel    = "ZeroSuppressed"
        },

        {
            string DigiProducer = "theSiStripZeroSuppression"
            string DigiLabel    = "fromVirginRaw"
        },

        {
            string DigiProducer = "theSiStripZeroSuppression"
            string DigiLabel    = "fromProcessedRaw"
        }
    }
}

```

```

    },
    {
        string DigiProducer = "theSiStripZeroSuppression"
        string DigiLabel    = "fromScopeMode"
    }
}
}

```

LaserSeedGenerator The seed generator for the laser beams (see section 3.3.2) accepts the options below and takes care of creating seeds for the reconstruction of laser tracks.

```

module LaserSeedFinder= LaserSeedGenerator
{
    # RecHit collections used as input
    InputTag matchedRecHits = siStripMatchedRecHits:matchedRecHit
    InputTag rphiRecHits    = siStripMatchedRecHits:rphiRecHit
    InputTag stereoRecHits  = siStripMatchedRecHits:stereoRecHit
    # some cuts
    double ptMin = 0.0
    double originRadius = 150
    double originHalfLength = 90
    double originZPosition = 0
    string TTRHBuilder = "WithTrackAngle"
    # propagator to use: Analytical or WithMaterial
    string Propagator = "Analytical"
}

```

A.3 Data Quality Monitoring options

The parameters accepted by the *LaserDQM* module are listed in the configuration file fragment below.

```

module mon = LaserDQM
{
    # used for debugging
    untracked int32 DebugLevel = 3
    # root file with histograms
    untracked string DQMFileName = "testDQM.root"
    # range to search for modules hit by laser beams
    untracked double SearchWindowPhiTIB = 0.05
    untracked double SearchWindowPhiTOB = 0.05
    untracked double SearchWindowPhiTEC = 0.05
    untracked double SearchWindowZTIB = 1.0
    untracked double SearchWindowZTOB = 1.0
    # list of digis used as input
    VPSet DigiProducersList =
    {
        {
            string DigiProducer = "siStripDigis"

```



```
        string DigiLabel    = "\0"
    },

    {
        string DigiProducer = "RawToDigi"
        string DigiLabel    = "ZeroSuppressed"
    },

    {
        string DigiProducer = "theSiStripZeroSuppression"
        string DigiLabel    = "fromVirginRaw"
    },

    {
        string DigiProducer = "theSiStripZeroSuppression"
        string DigiLabel    = "fromProcessedRaw"
    },

    {
        string DigiProducer = "theSiStripZeroSuppression"
        string DigiLabel    = "fromScopeMode"
    }
}
}
```

Appendix B

Data from the TEC+ sector test

This appendix summarizes the results of the analysis of the data taken during the TEC+ integration and commissioning phase. The next sections show the signals of the laser beams as well as the straight line fits to the reconstructed laser beam positions for sectors 1 to 8 (sector 1 data taken following the petal replacement (see comment in section 3.5)). The results of the analysis of these data are discussed in detail in section 3.5.

B.1 Sector 1

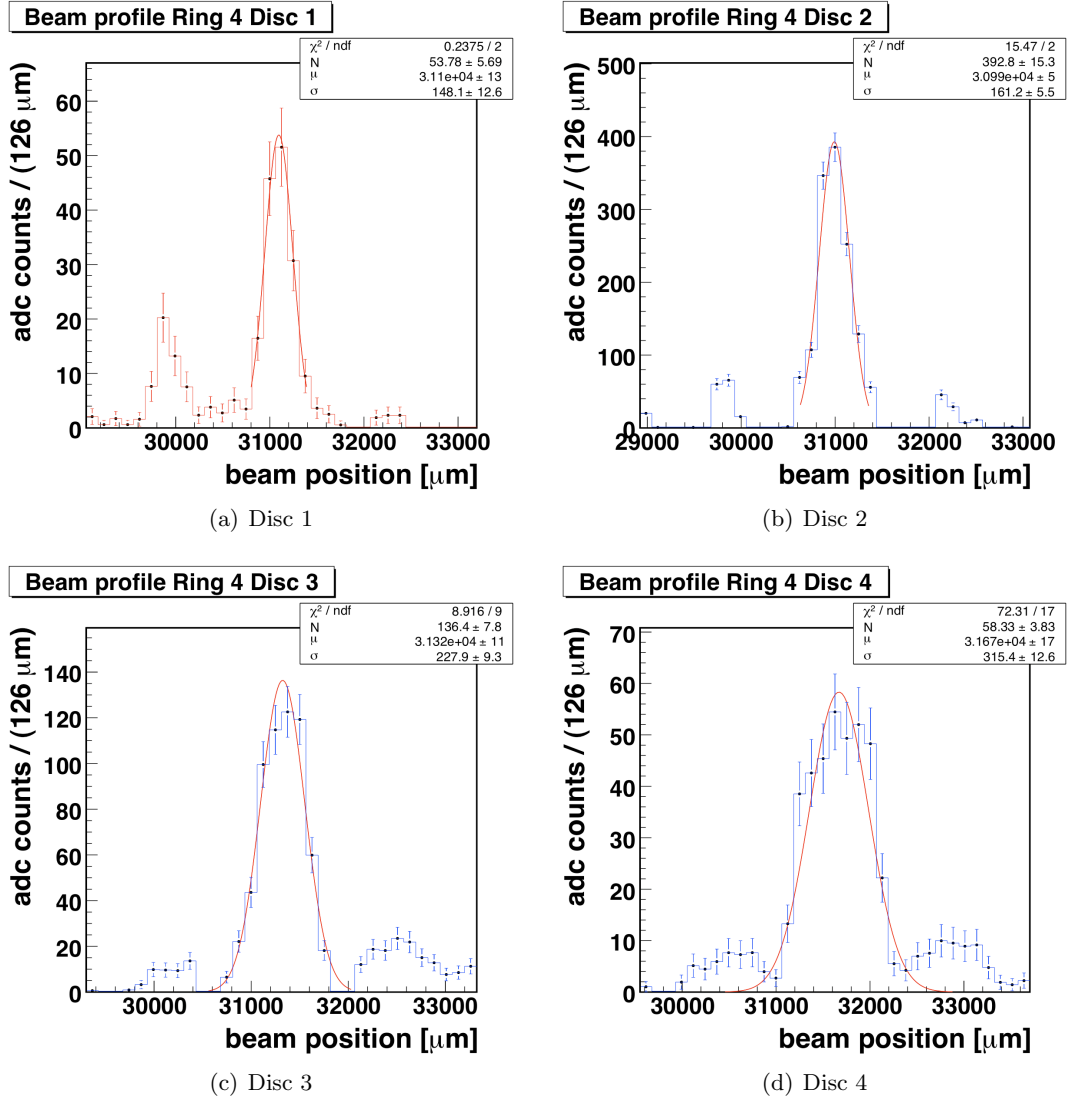


Figure B.1: Signals (in adc counts/126 μm) of the laser beams in ring 4 for sector 1 after the exchange of the petals. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 119.

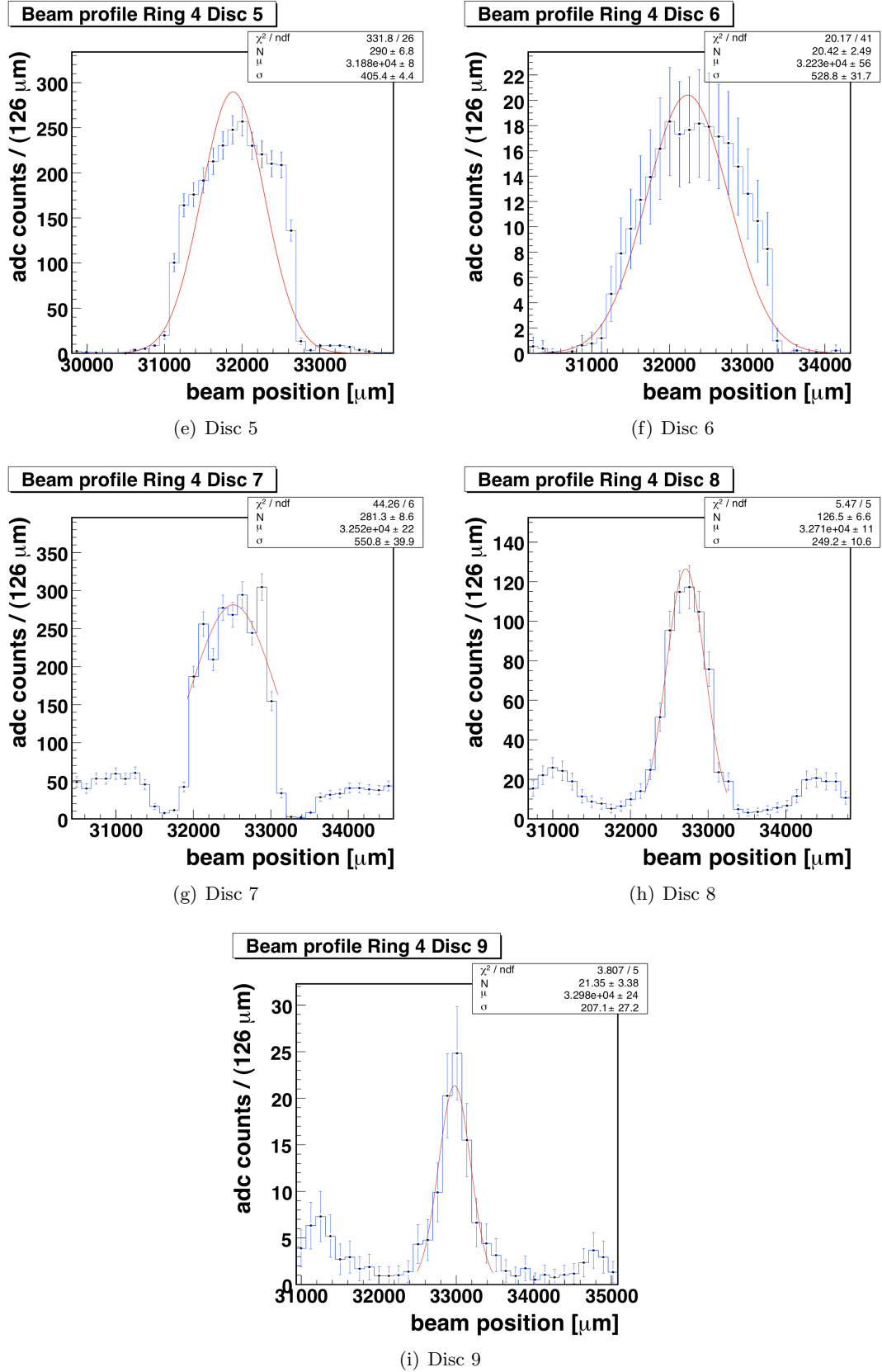


Figure B.1: Continued from page 118.

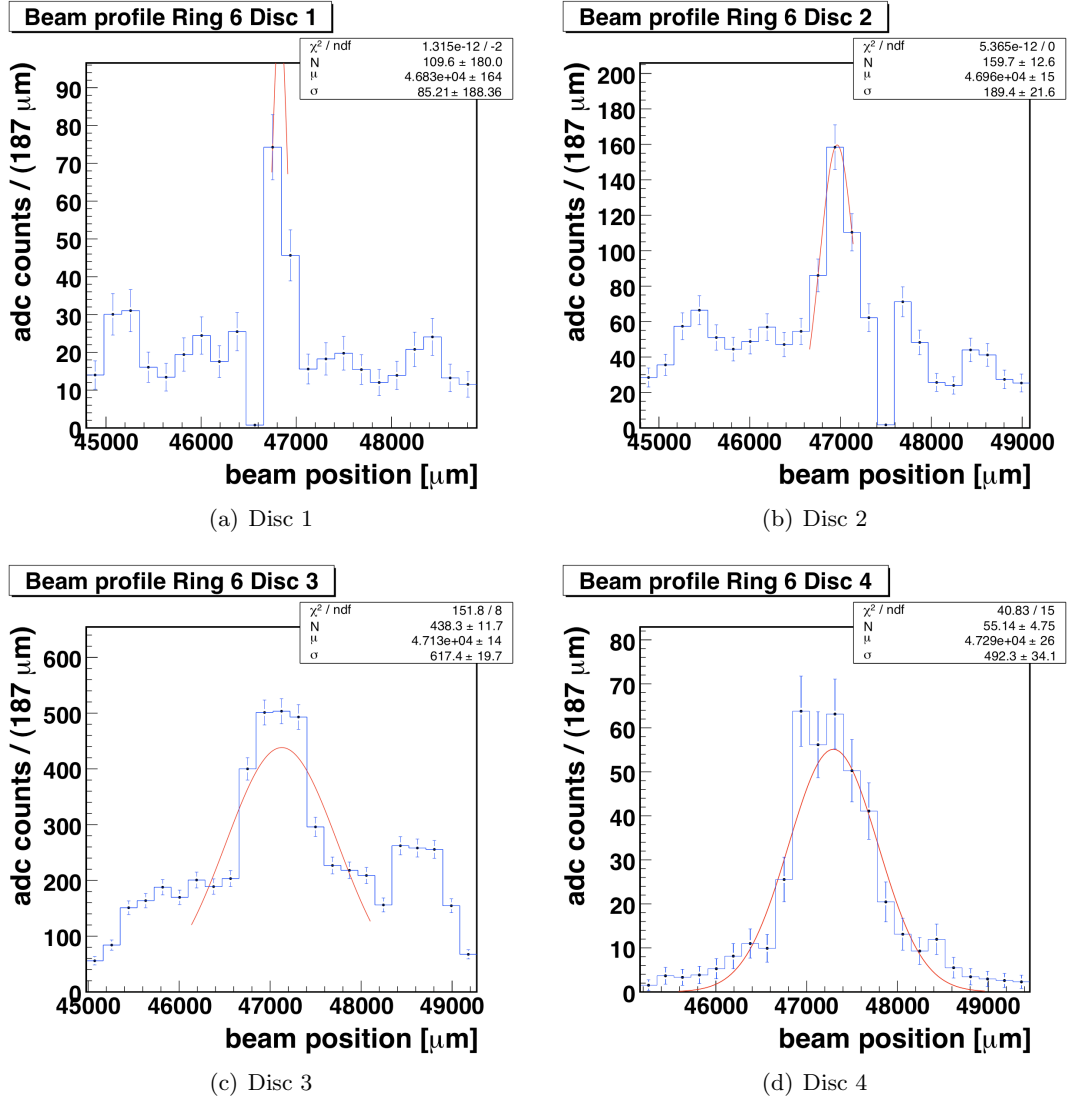


Figure B.2: Signals (in adc counts/187 μm) of the laser beams in ring 6 for sector 1 after the exchange of the petals. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 121.

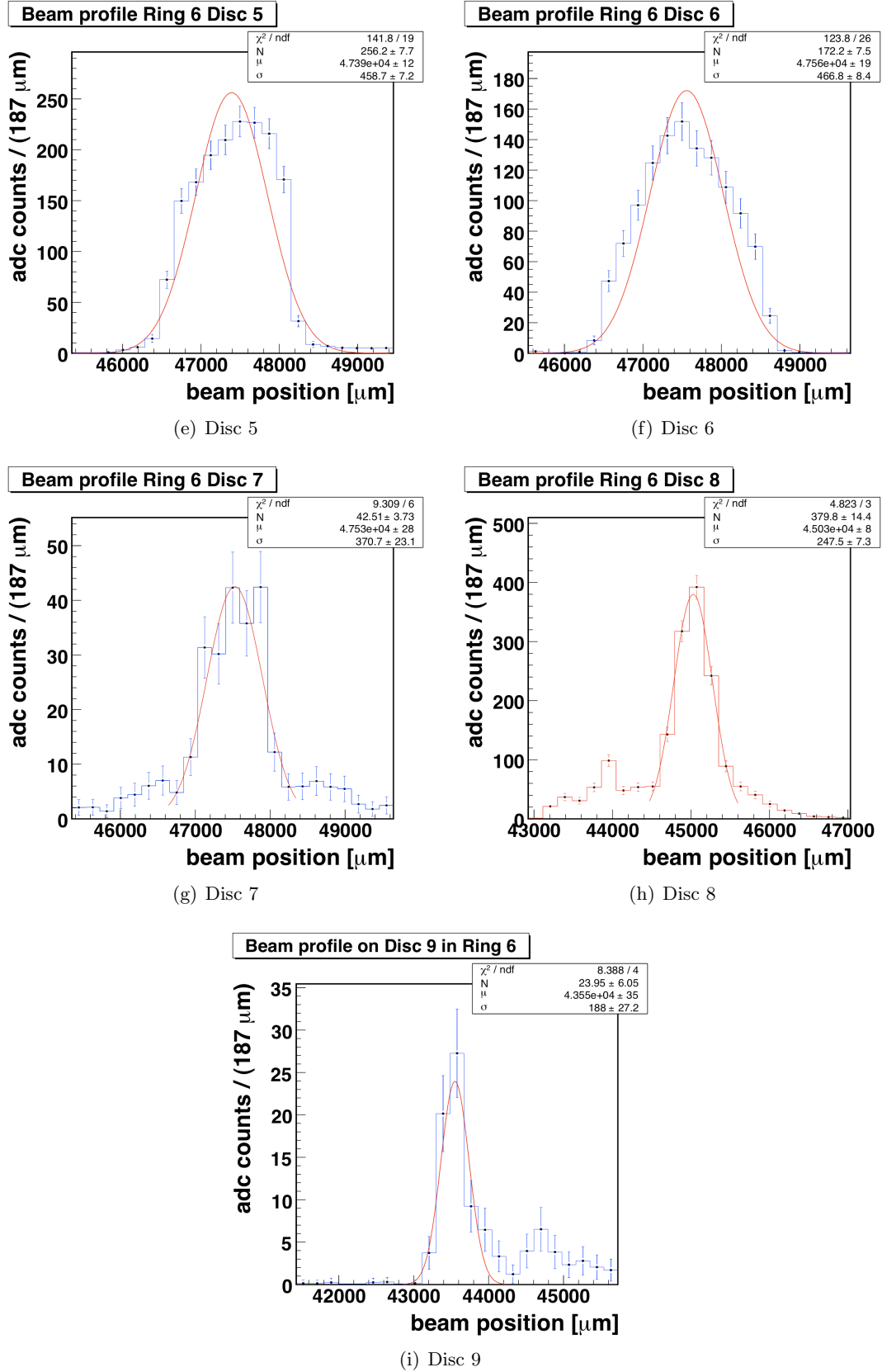


Figure B.2: Continued from page 120.

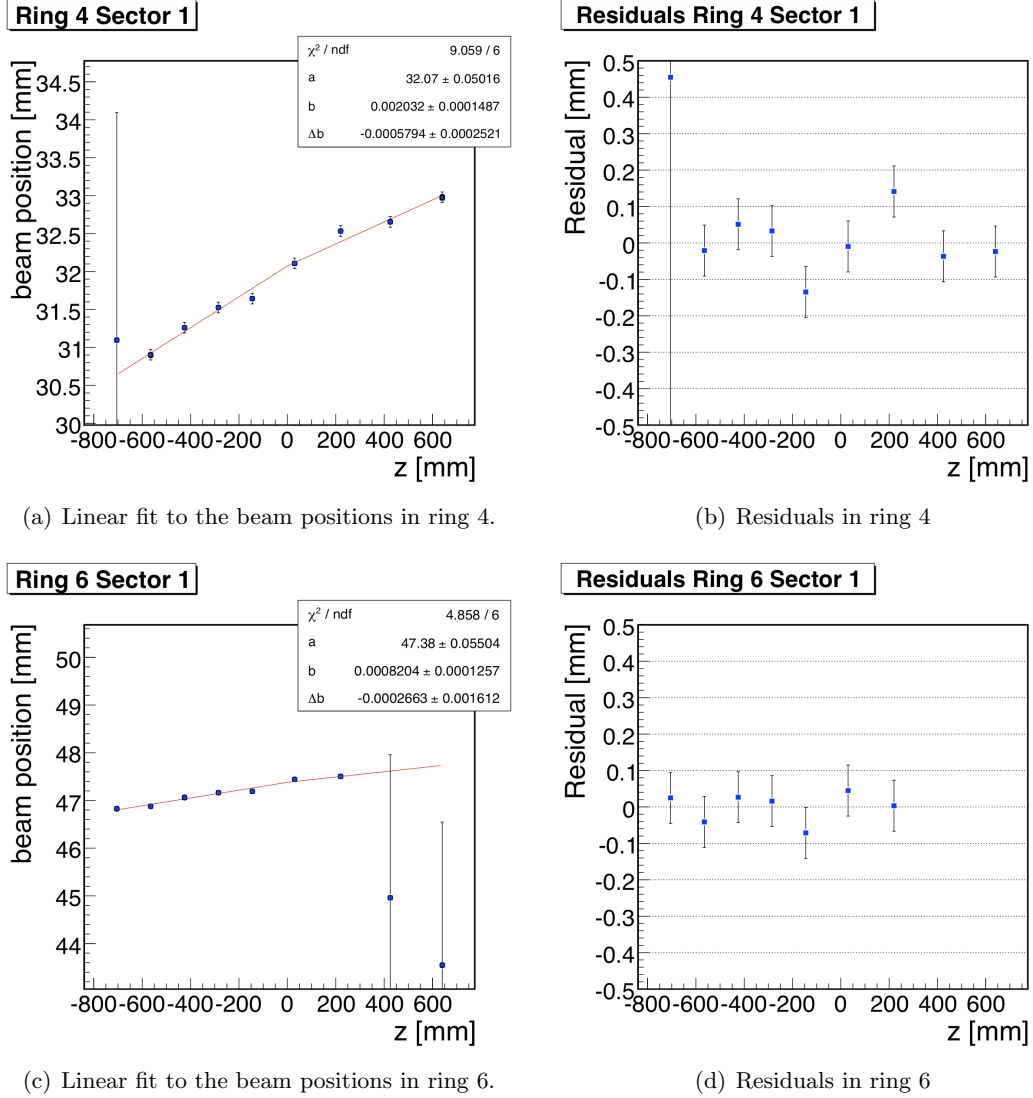


Figure B.3: Straight line fit applied to the reconstructed beam positions in (a) ring 4 and (c) ring 6 for sector 1 after the exchange of the petals. (b) and (d) show the residuals between the reconstructed beam positions and the straight line fit. The error bars indicate the error of the reconstructed beam positions. The measurements indicated by the open white circles in (a) and (c) are from different runs, where a beam profile has been reconstructed on the same disc. For each disc the measurement resulting in the smallest residual (indicated by the blue markers in the plots) has been used for the straight line fit.

B.2 Sector 2

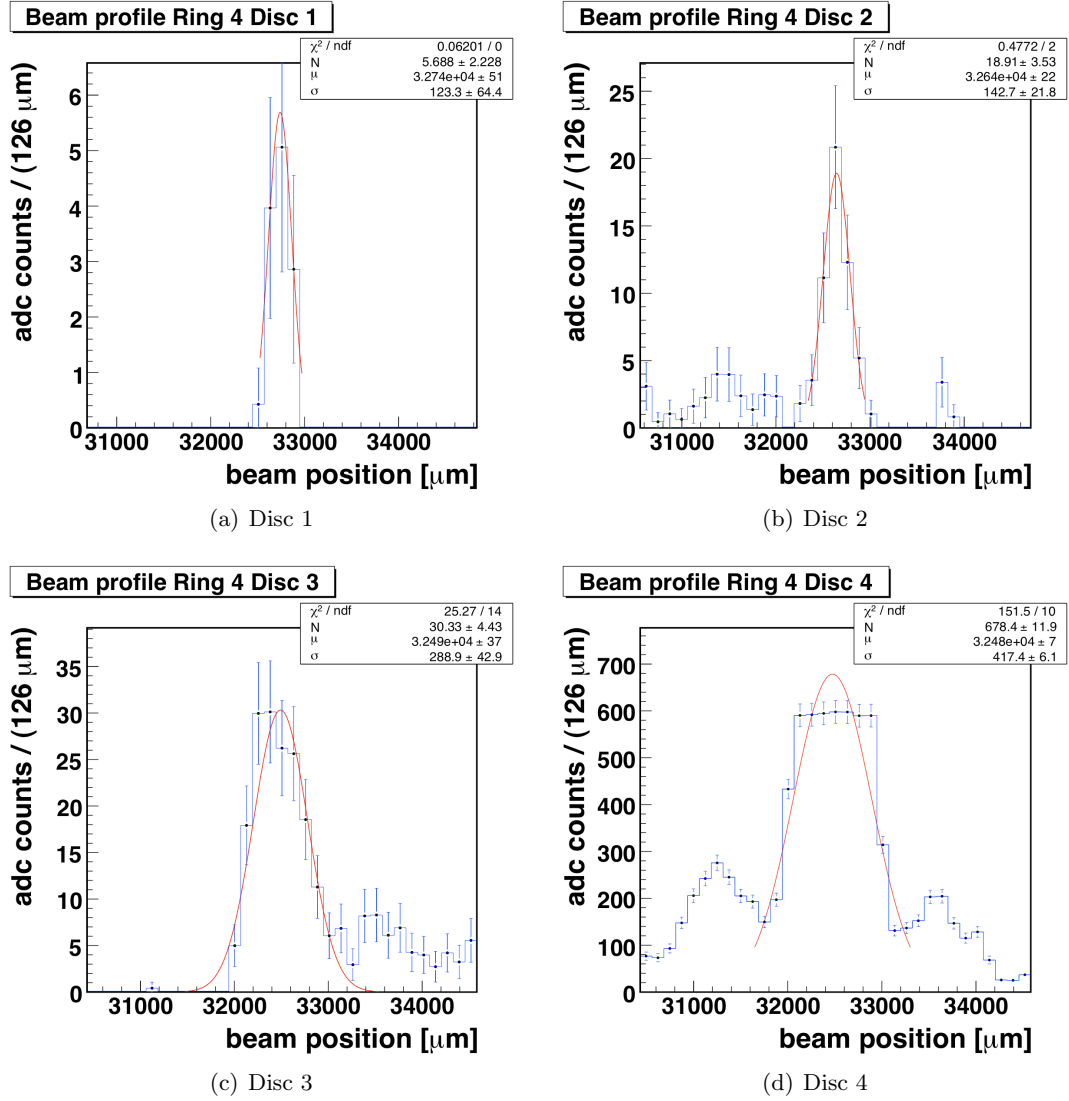
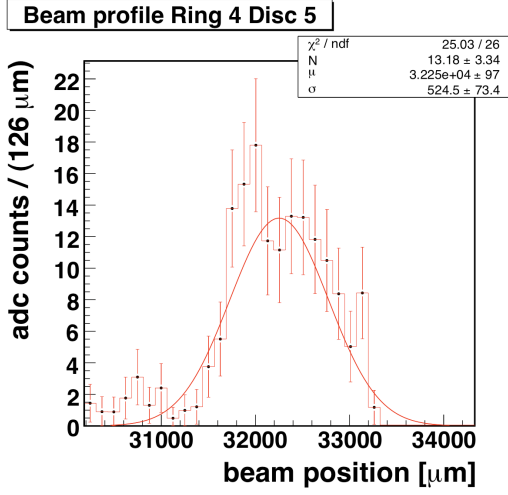
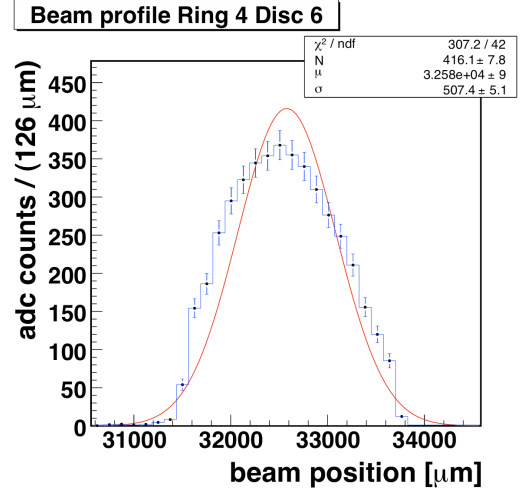


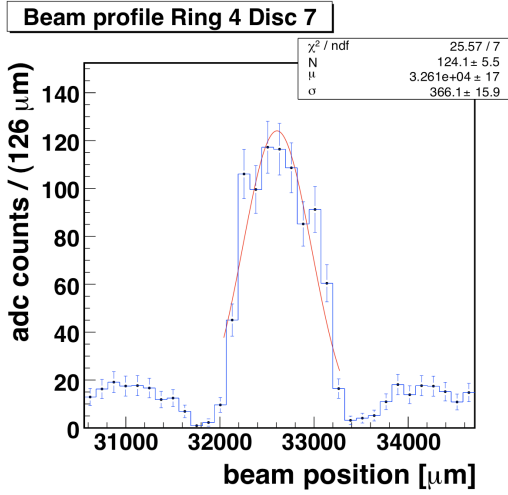
Figure B.4: Signals (in adc counts/126 μm) of the laser beams in ring 4 for sector 2. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 124.



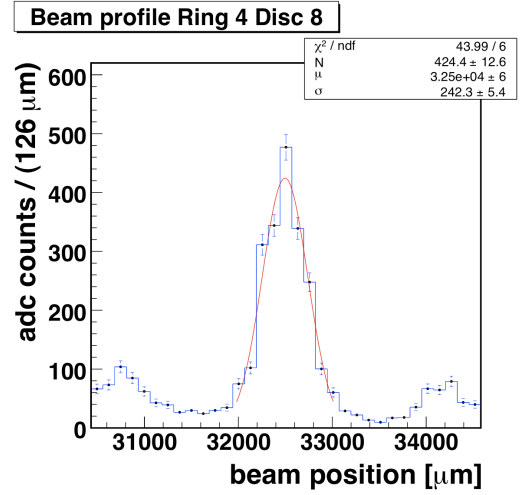
(e) Disc 5



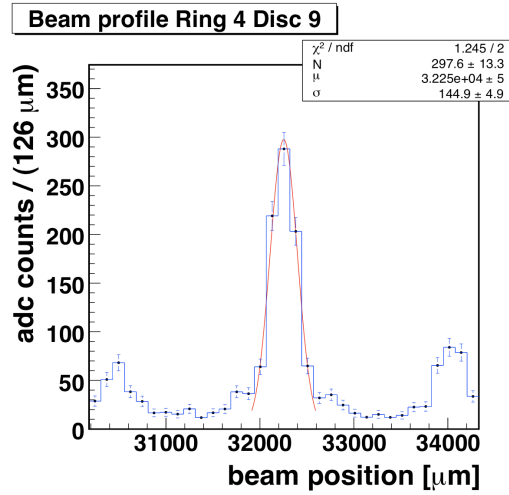
(f) Disc 6



(g) Disc 7



(h) Disc 8



(i) Disc 9

Figure B.4: Continued from page 123.

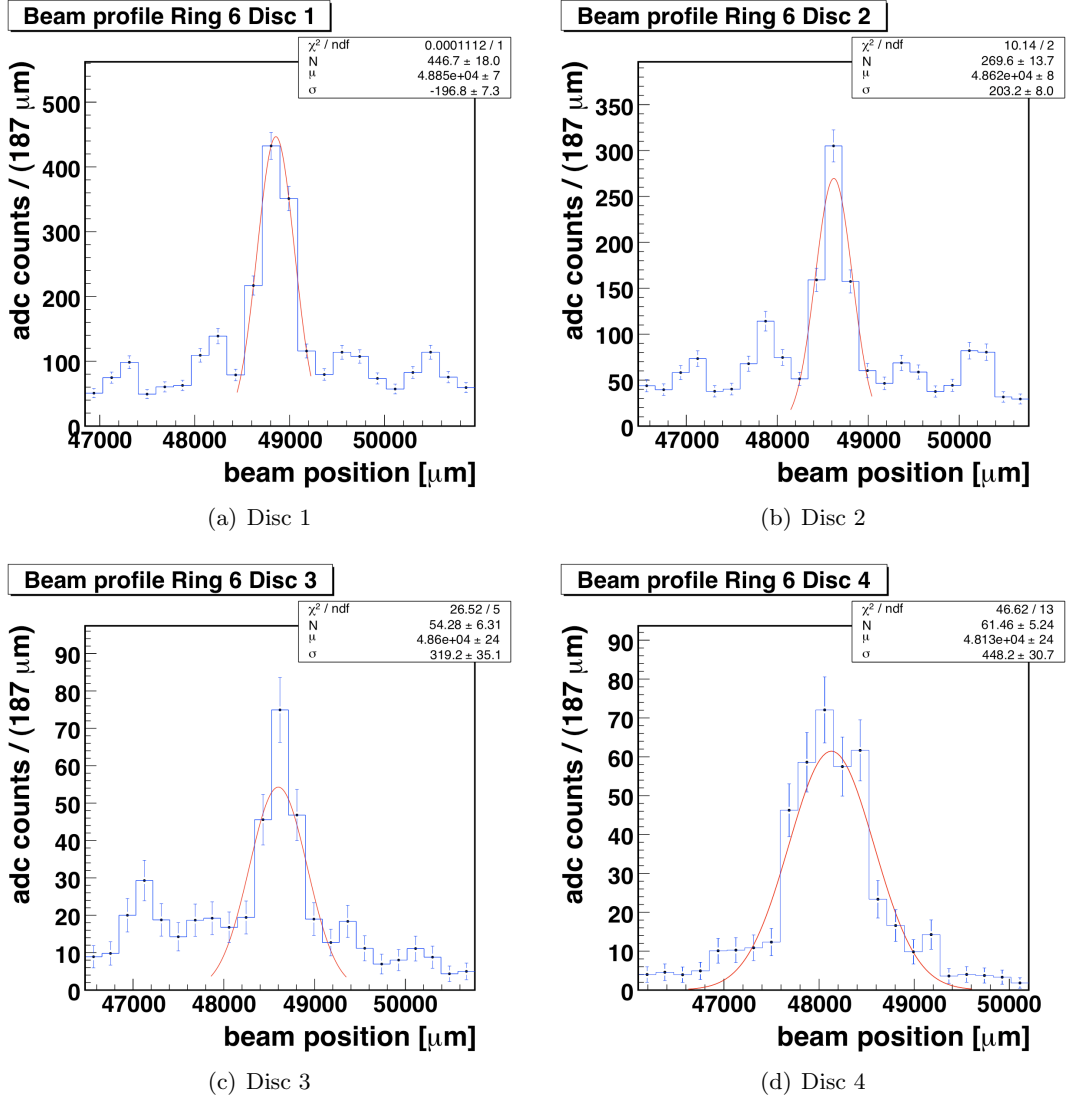


Figure B.5: Signals (in adc counts/187 μm) of the laser beams in ring 6 for sector 2. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 126.

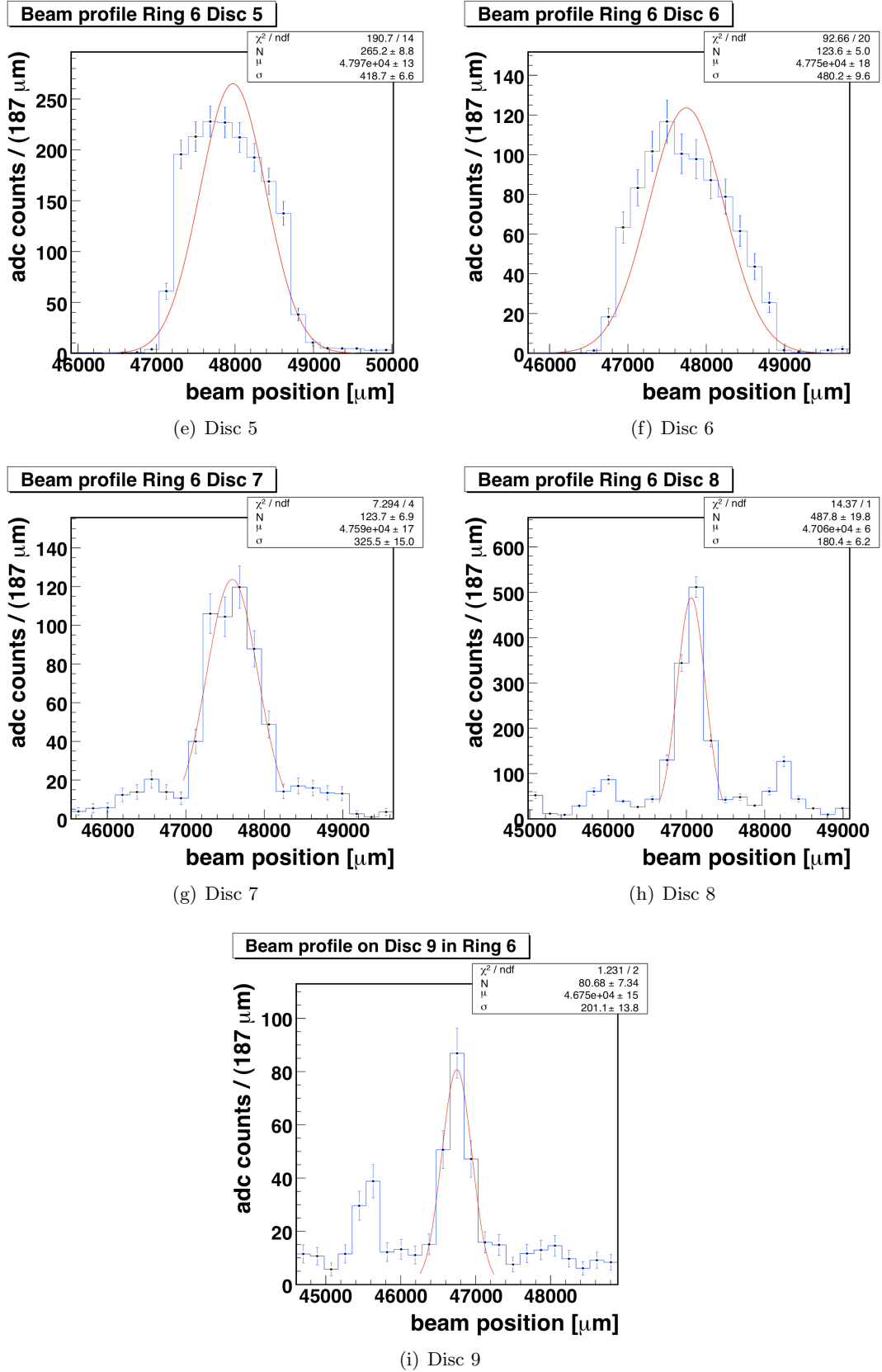


Figure B.5: Continued from page 125.

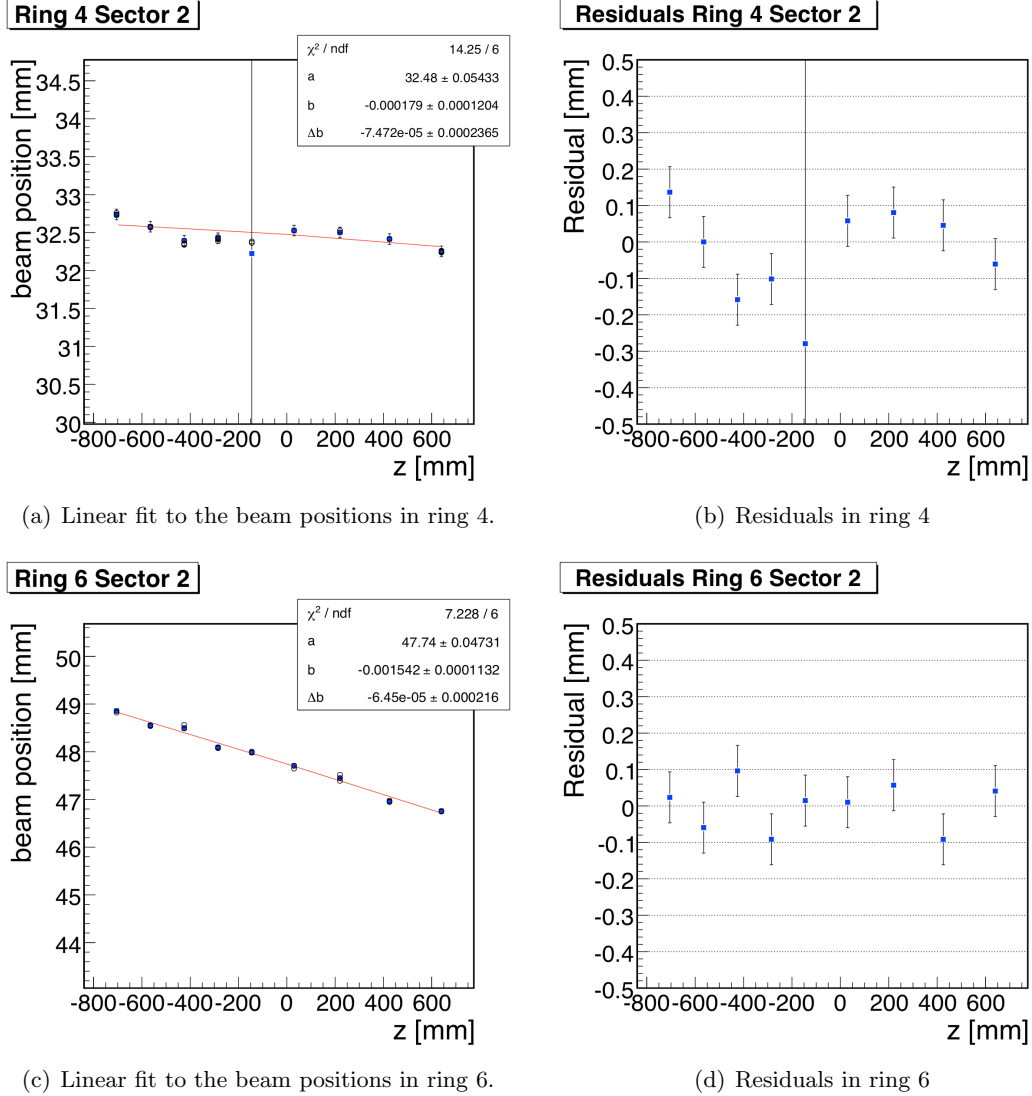


Figure B.6: Straight line fit applied to the reconstructed beam positions in (a) ring 4 and (c) ring 6 for sector 2. (b) and (d) show the residuals between the reconstructed beam positions and the straight line fit. The error bars indicate the error of the reconstructed beam positions. The measurements indicated by the open white circles in (a) and (c) are from different runs, where a beam profile has been reconstructed on the same disc. For each disc the measurement resulting in the smallest residual (indicated by the blue markers in the plots) has been used for the straight line fit.

B.3 Sector 3

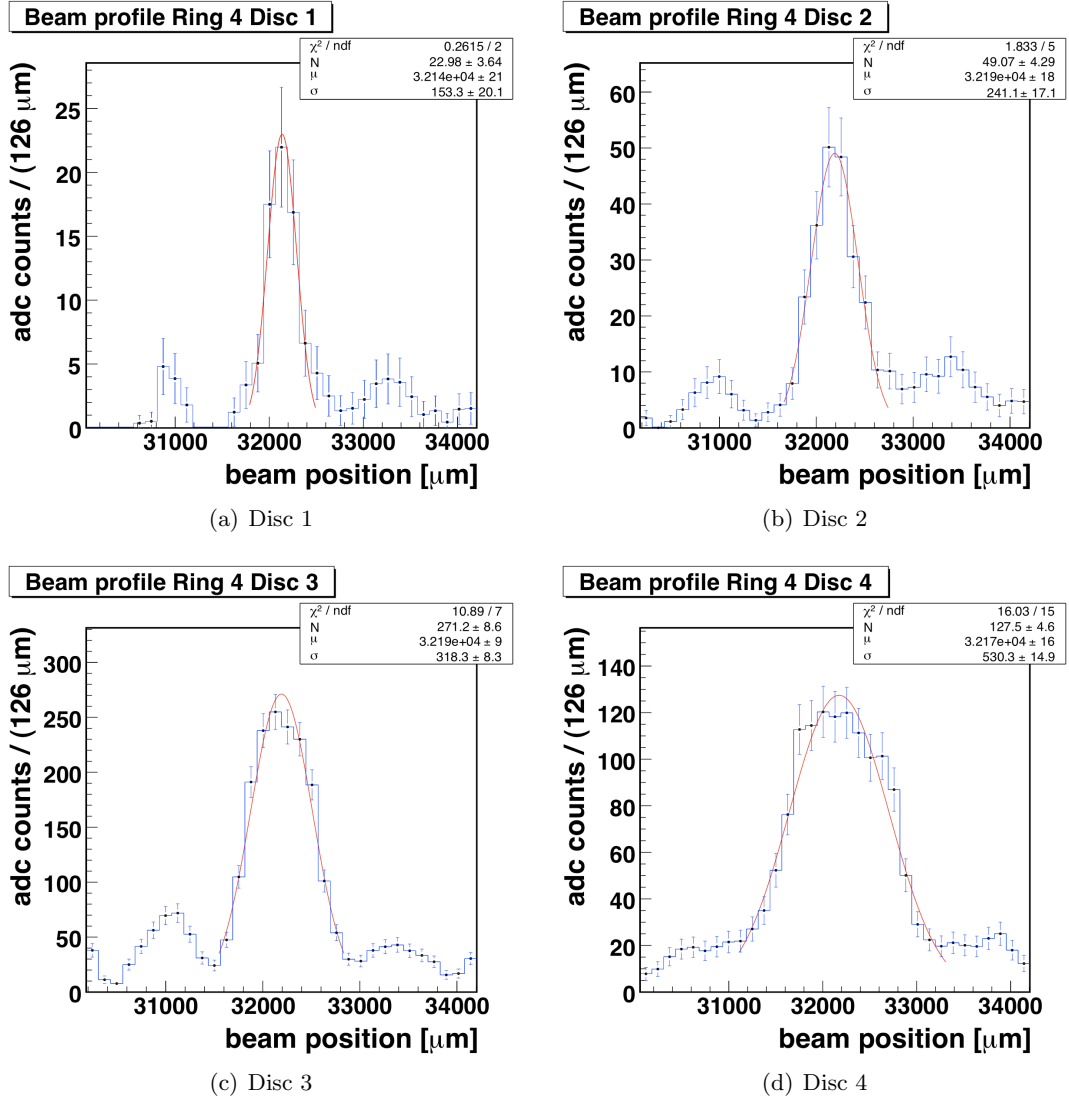


Figure B.7: Signals (in adc counts/126 μm) of the laser beams in ring 4 for sector 3. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 129.

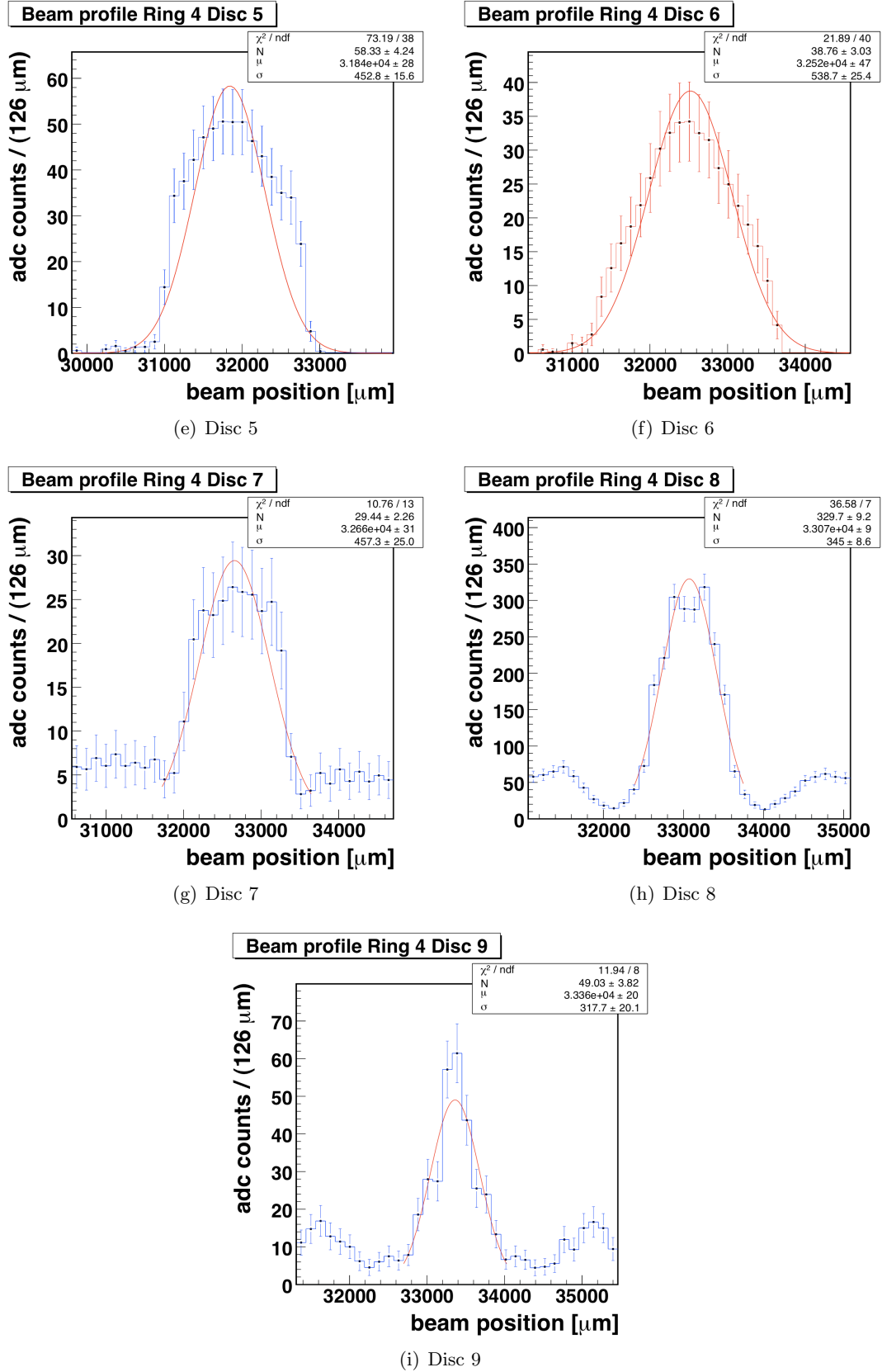


Figure B.7: Continued from page 128.

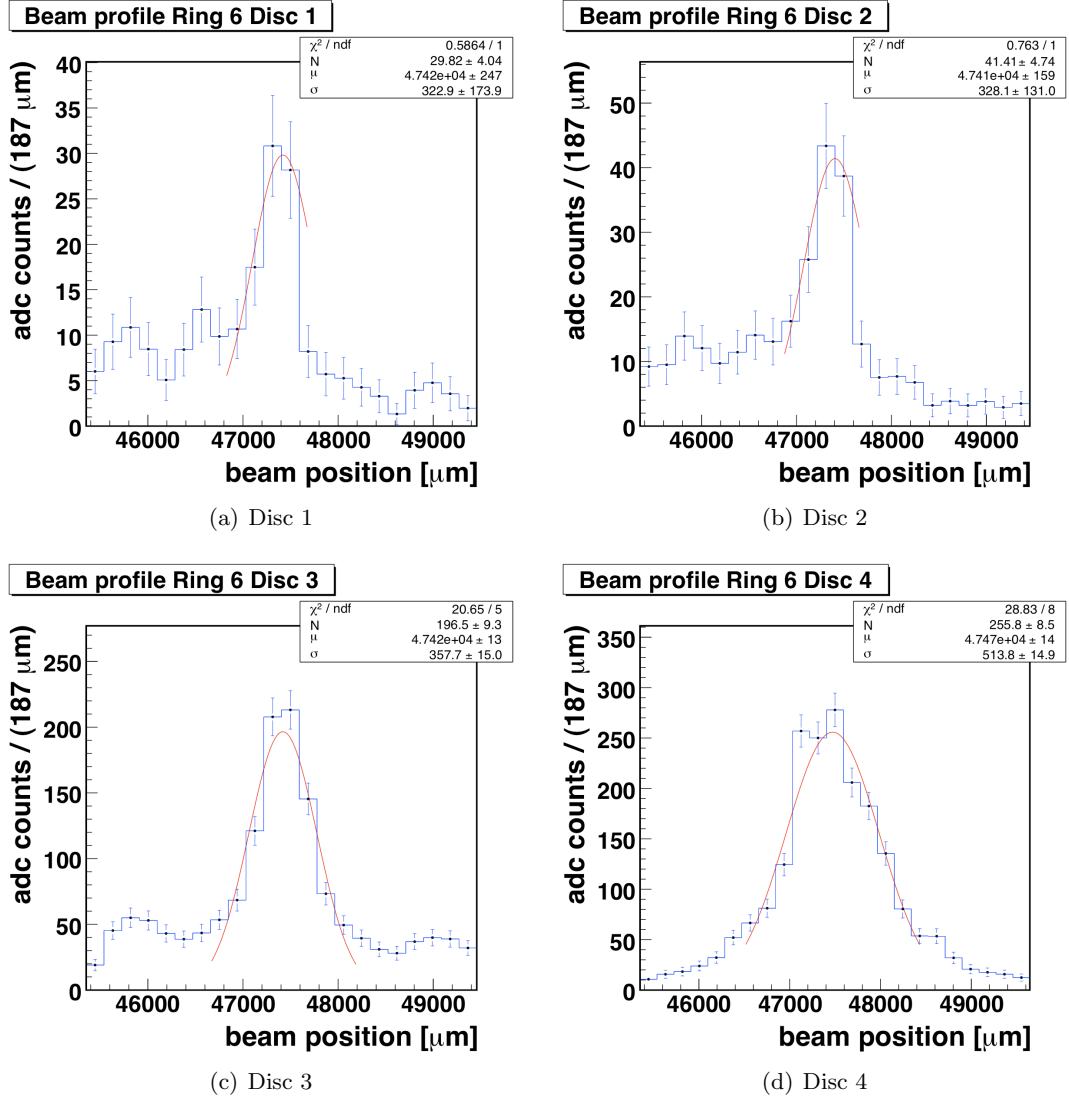


Figure B.8: Signals (in adc counts/187 μm) of the laser beams in ring 6 for sector 3. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 131.

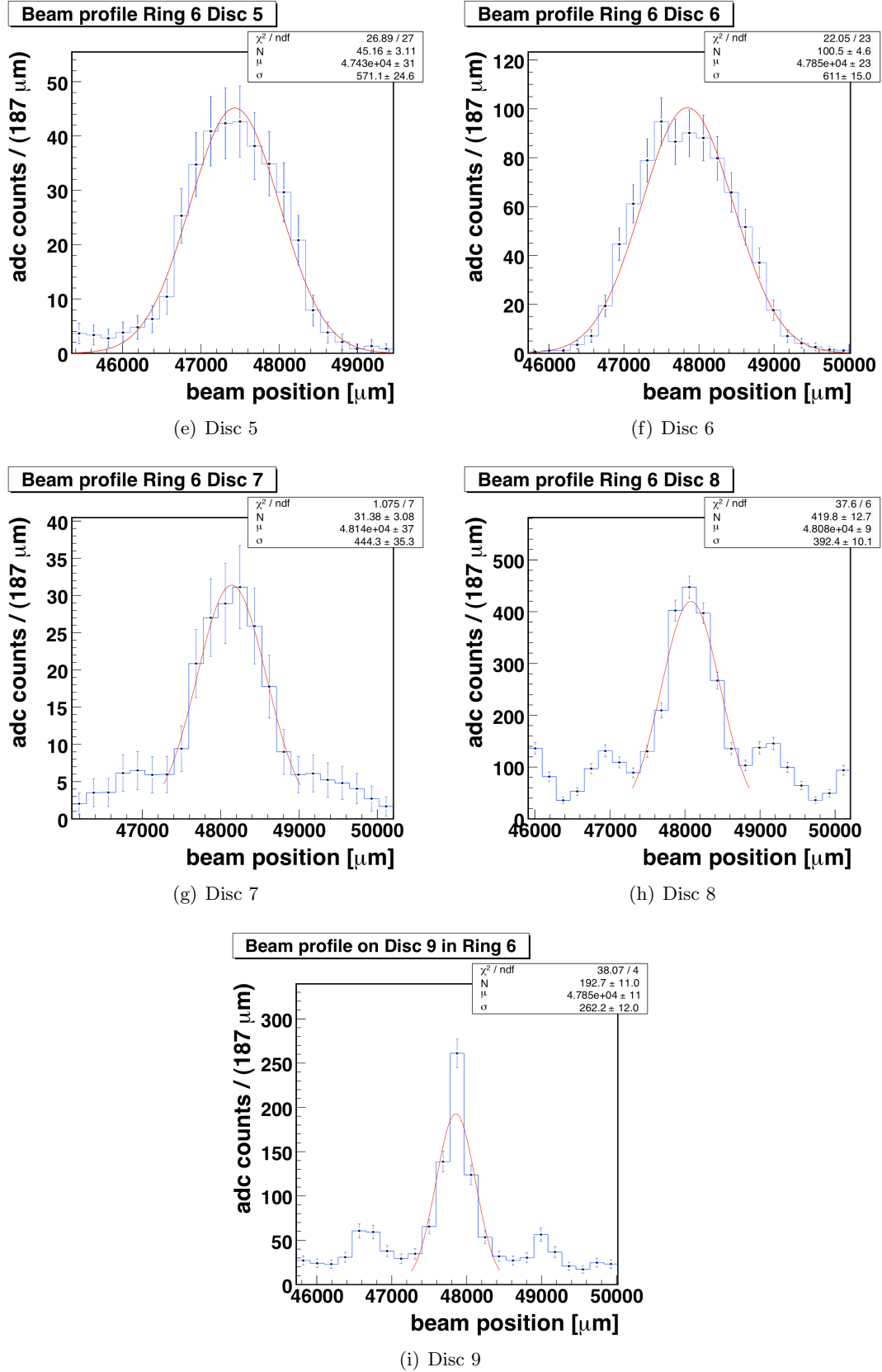


Figure B.8: Continued from page 130.

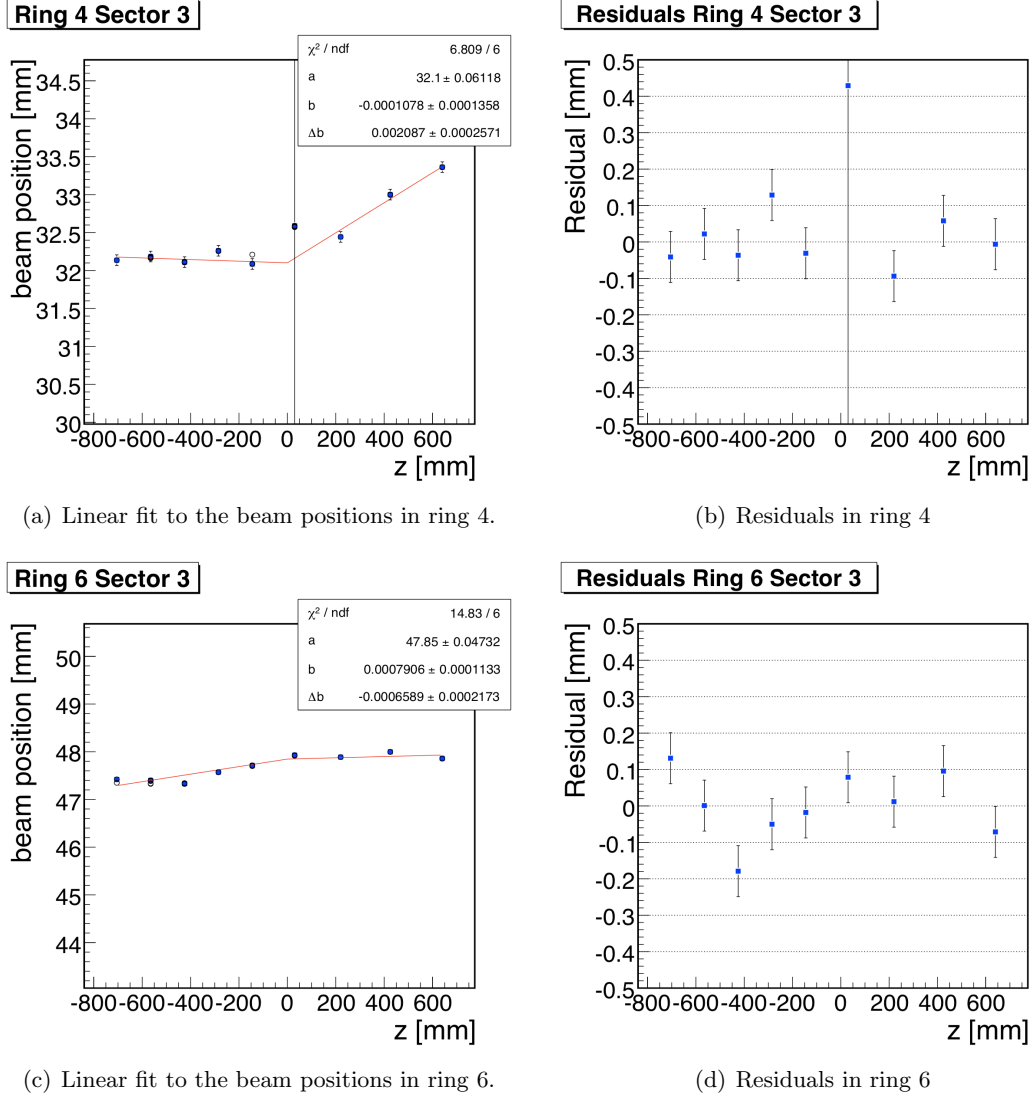


Figure B.9: Straight line fit applied to the reconstructed beam positions in (a) ring 4 and (c) ring 6 for sector 3. (b) and (d) show the residuals between the reconstructed beam positions and the straight line fit. The error bars indicate the error of the reconstructed beam positions. The measurements indicated by the open white circles in (a) and (c) are from different runs, where a beam profile has been reconstructed on the same disc. For each disc the measurement resulting in the smallest residual (indicated by the blue markers in the plots) has been used for the straight line fit.

B.4 Sector 4

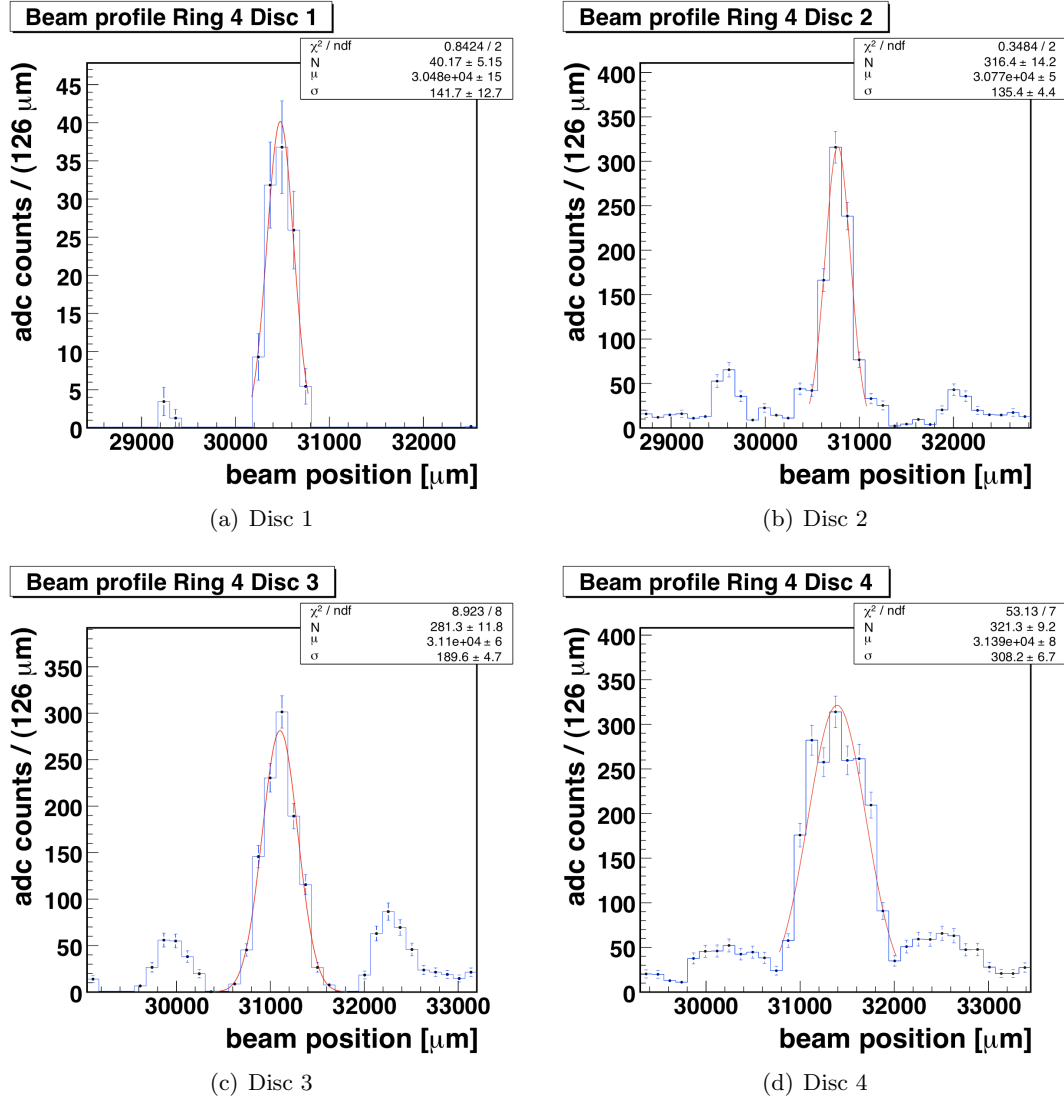


Figure B.10: Signals (in adc counts/126 μm) of the laser beams in ring 4 for sector 4. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 134.

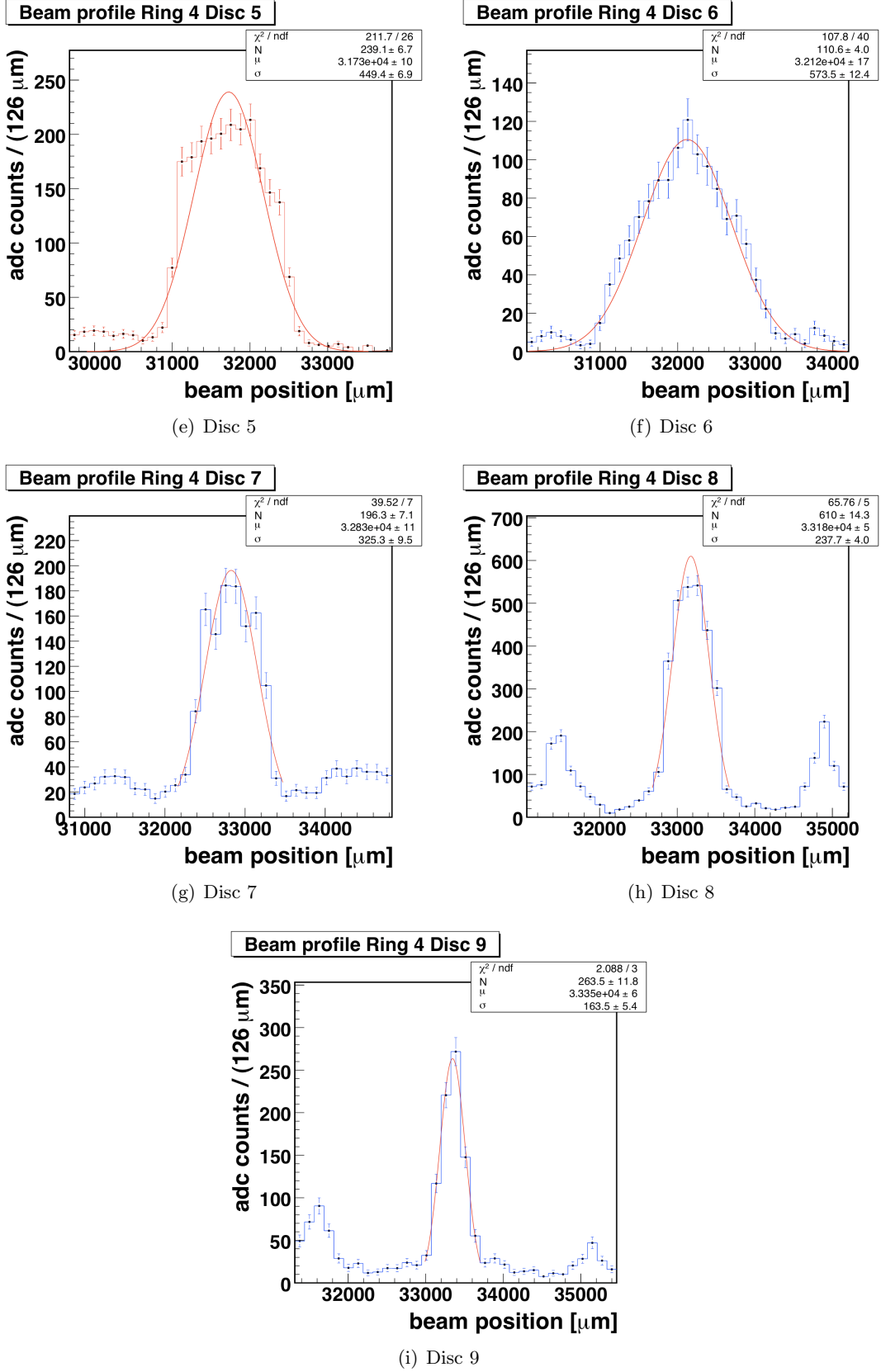


Figure B.10: Continued from page 133.

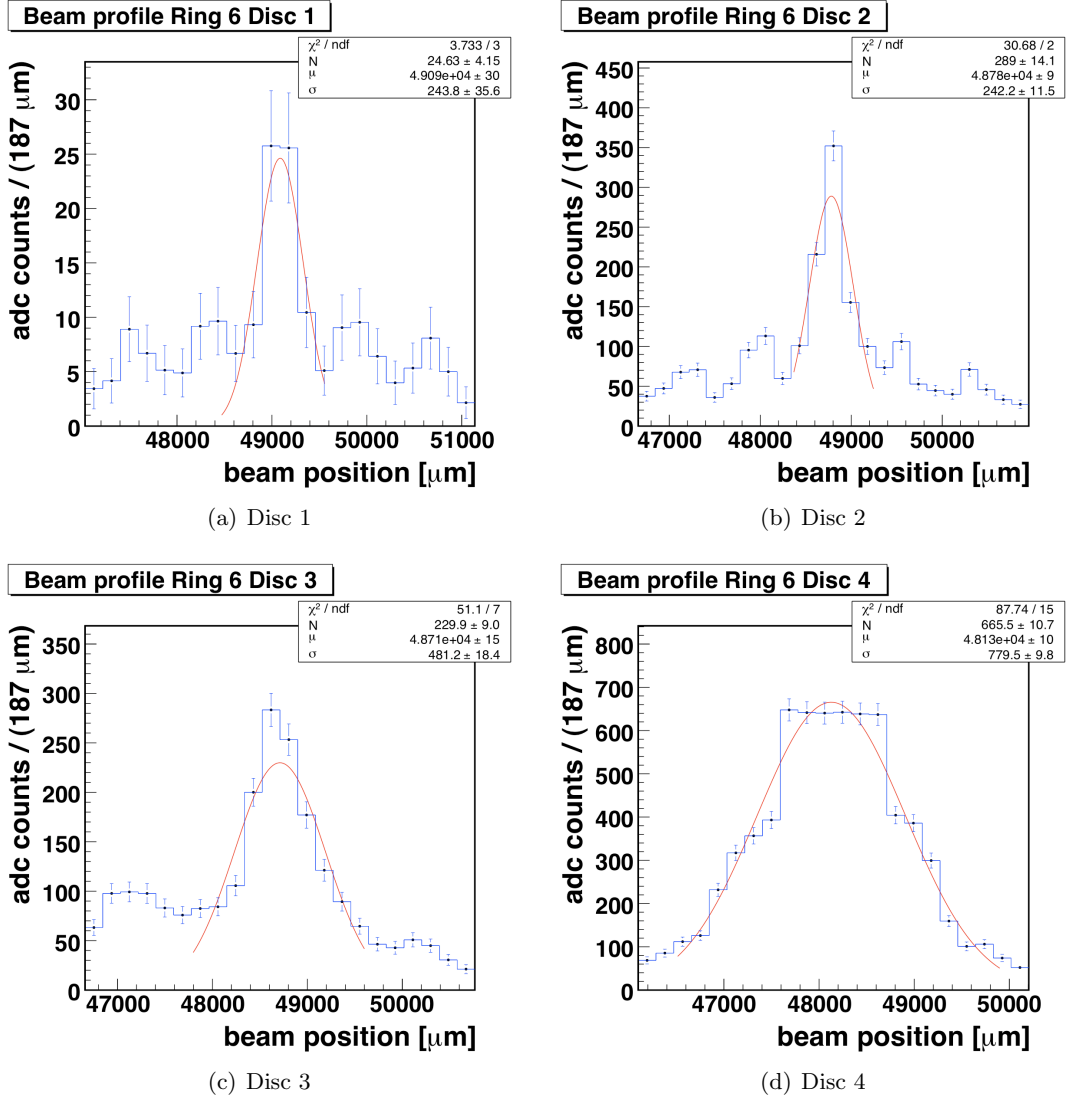


Figure B.11: Signals (in adc counts/187 μm) of the laser beams in ring 6 for sector 4. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 136.

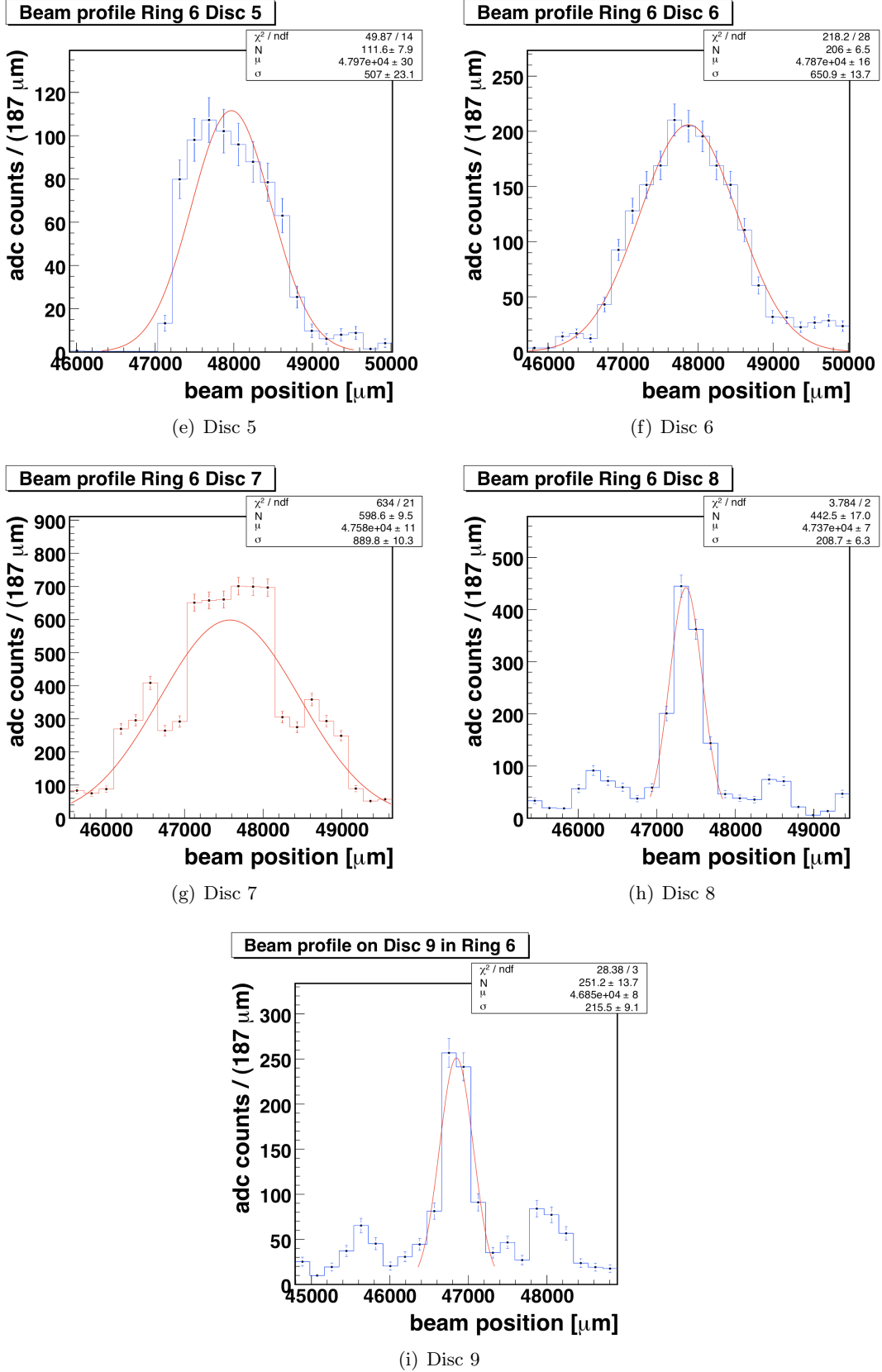


Figure B.11: Continued from page 135.

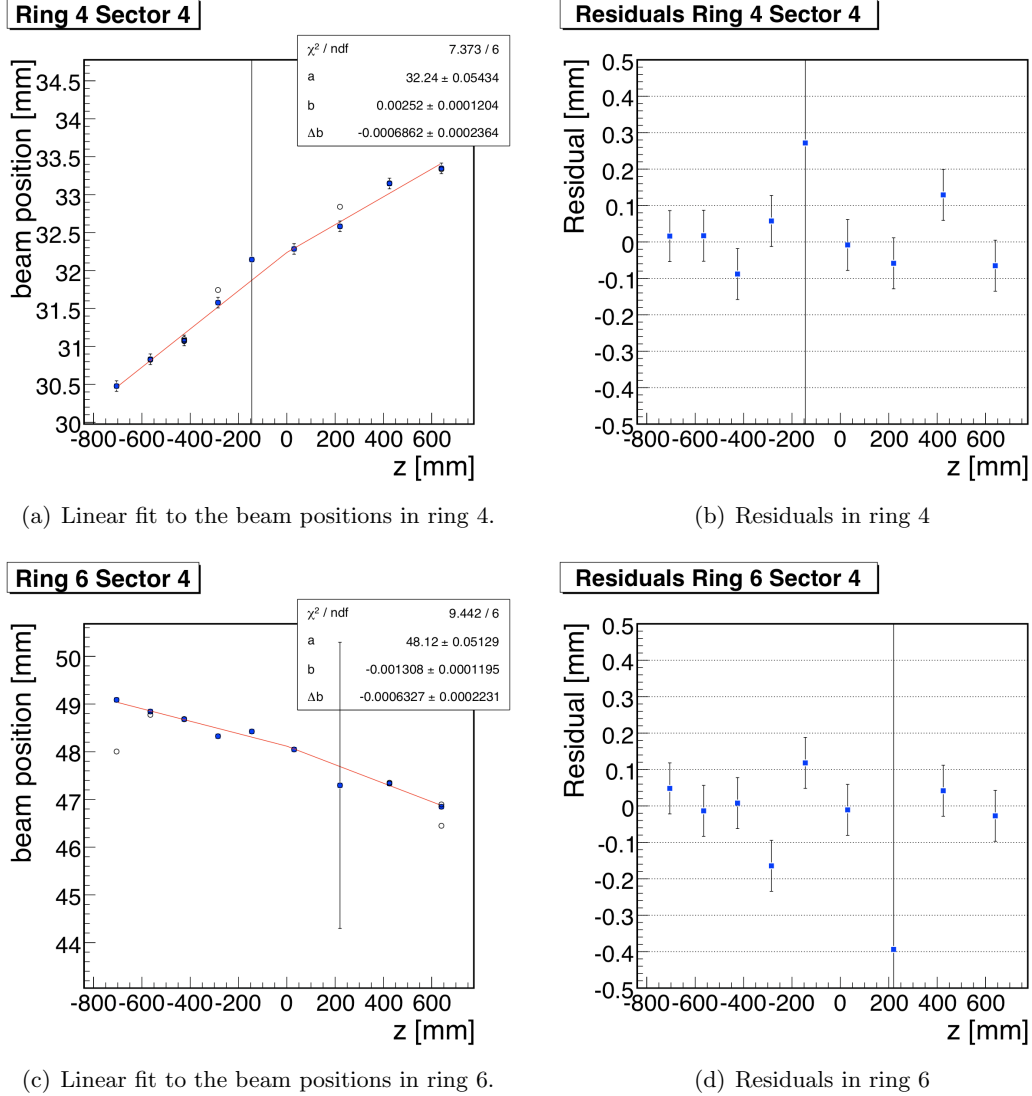


Figure B.12: Straight line fit applied to the reconstructed beam positions in (a) ring 4 and (c) ring 6 for sector 4. (b) and (d) show the residuals between the reconstructed beam positions and the straight line fit. The error bars indicate the error of the reconstructed beam positions. The measurements indicated by the open white circles in (a) and (c) are from different runs, where a beam profile has been reconstructed on the same disc. For each disc the measurement resulting in the smallest residual (indicated by the blue markers in the plots) has been used for the straight line fit.

B.5 Sector 5

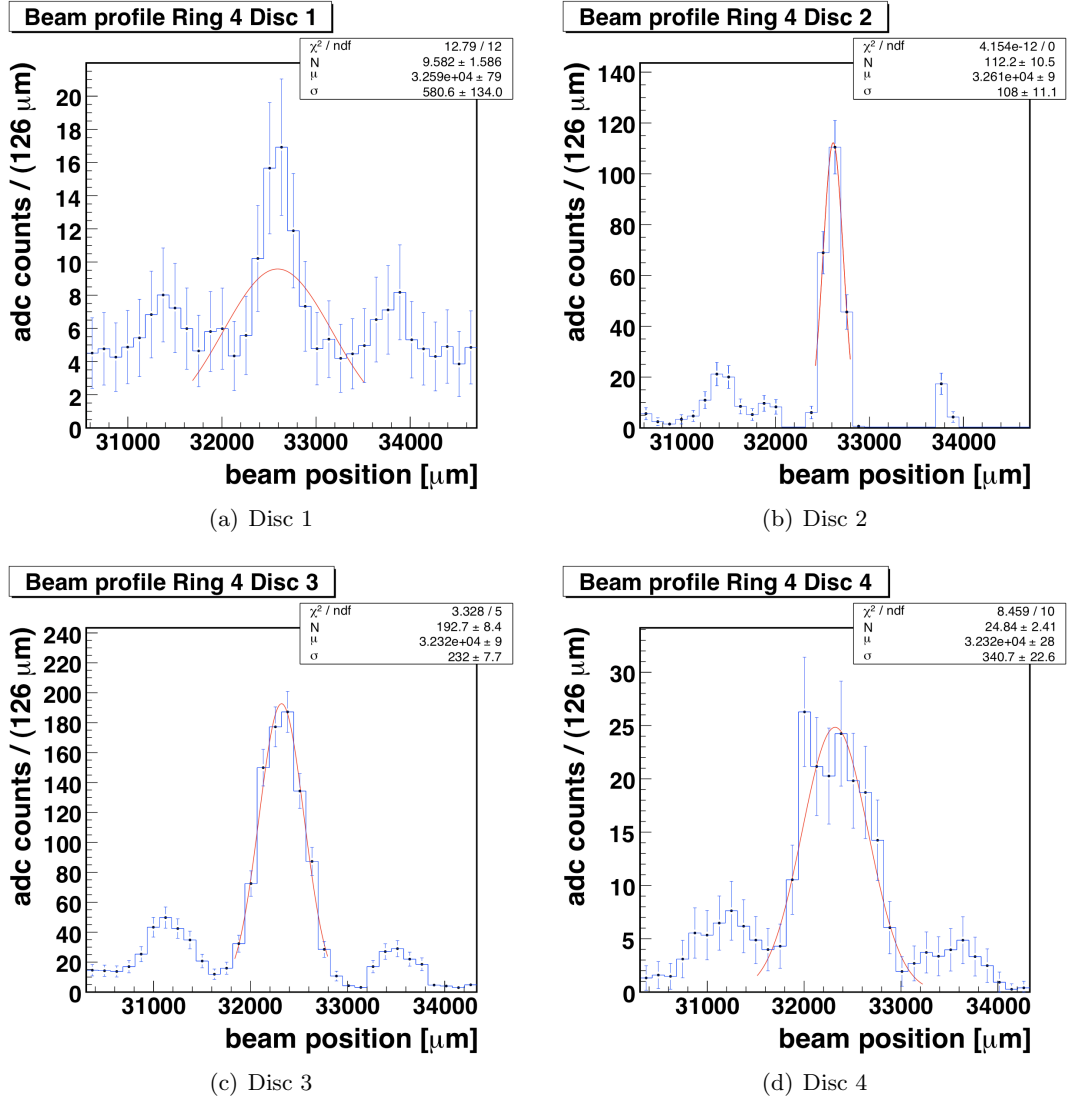


Figure B.13: Signals (in adc counts/126 μm) of the laser beams in ring 4 for sector 5. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 139.

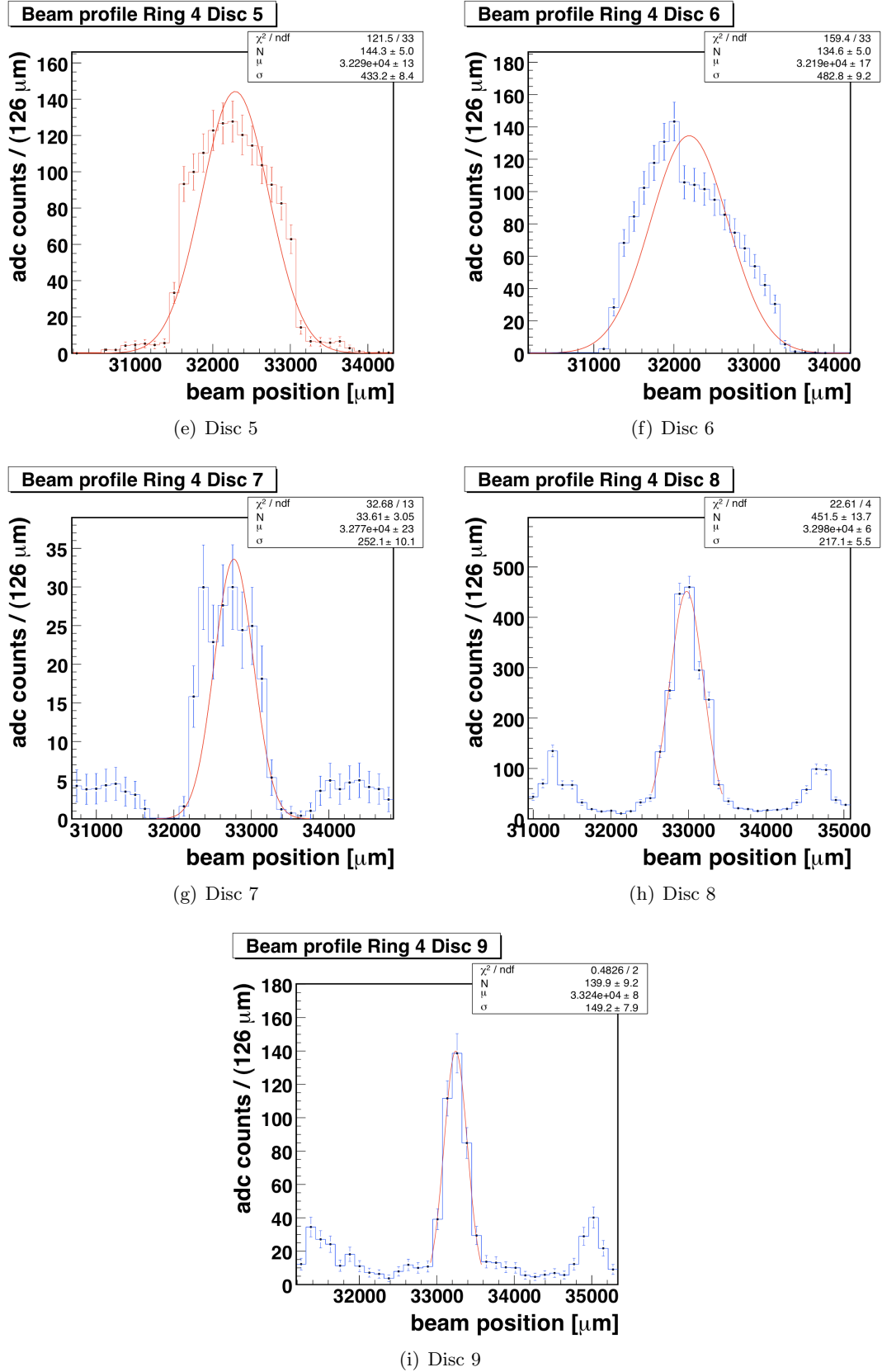


Figure B.13: Continued from page 138.

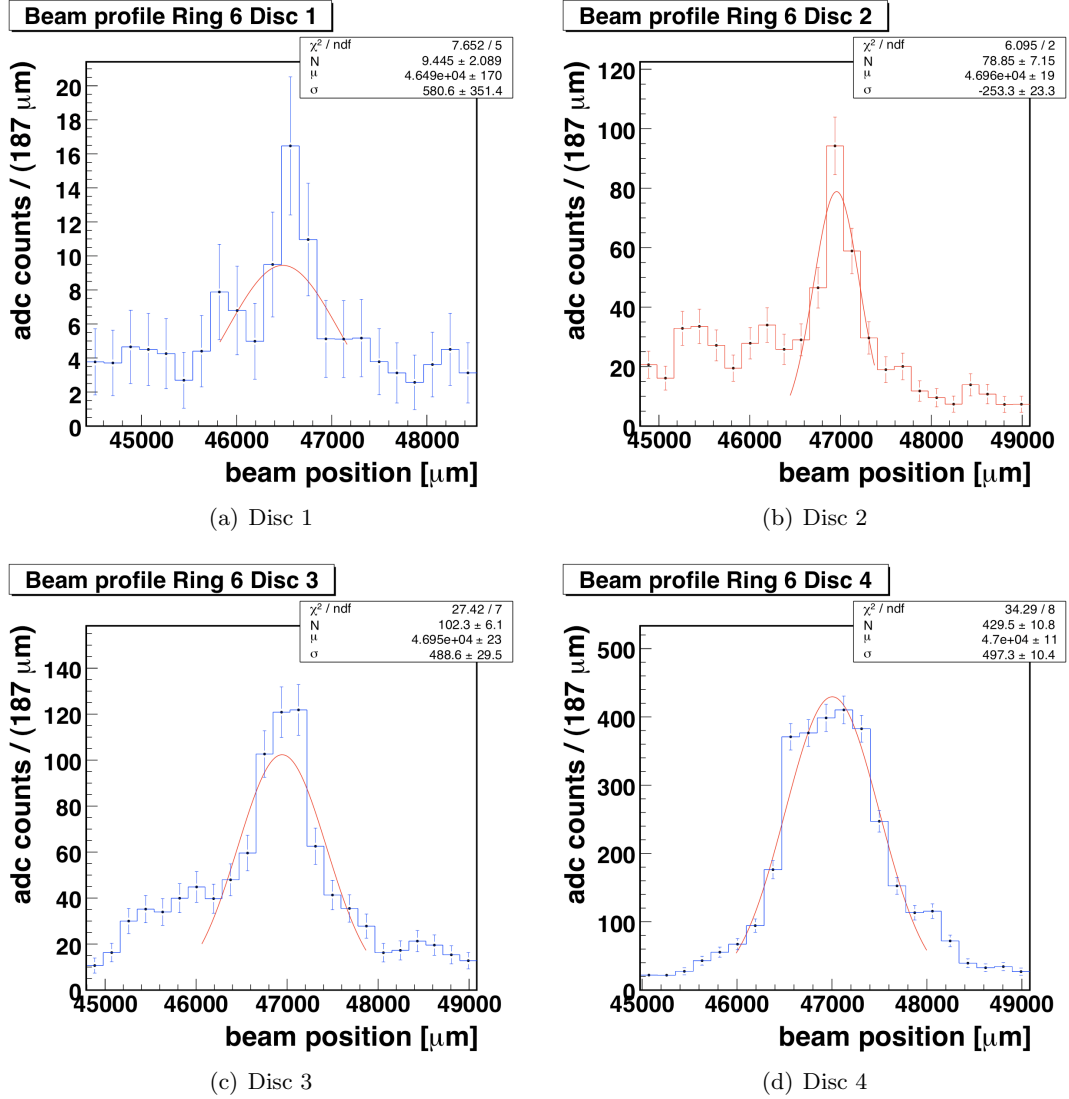


Figure B.14: Signals (in adc counts/187 μm) of the laser beams in ring 6 for sector 5. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 141.

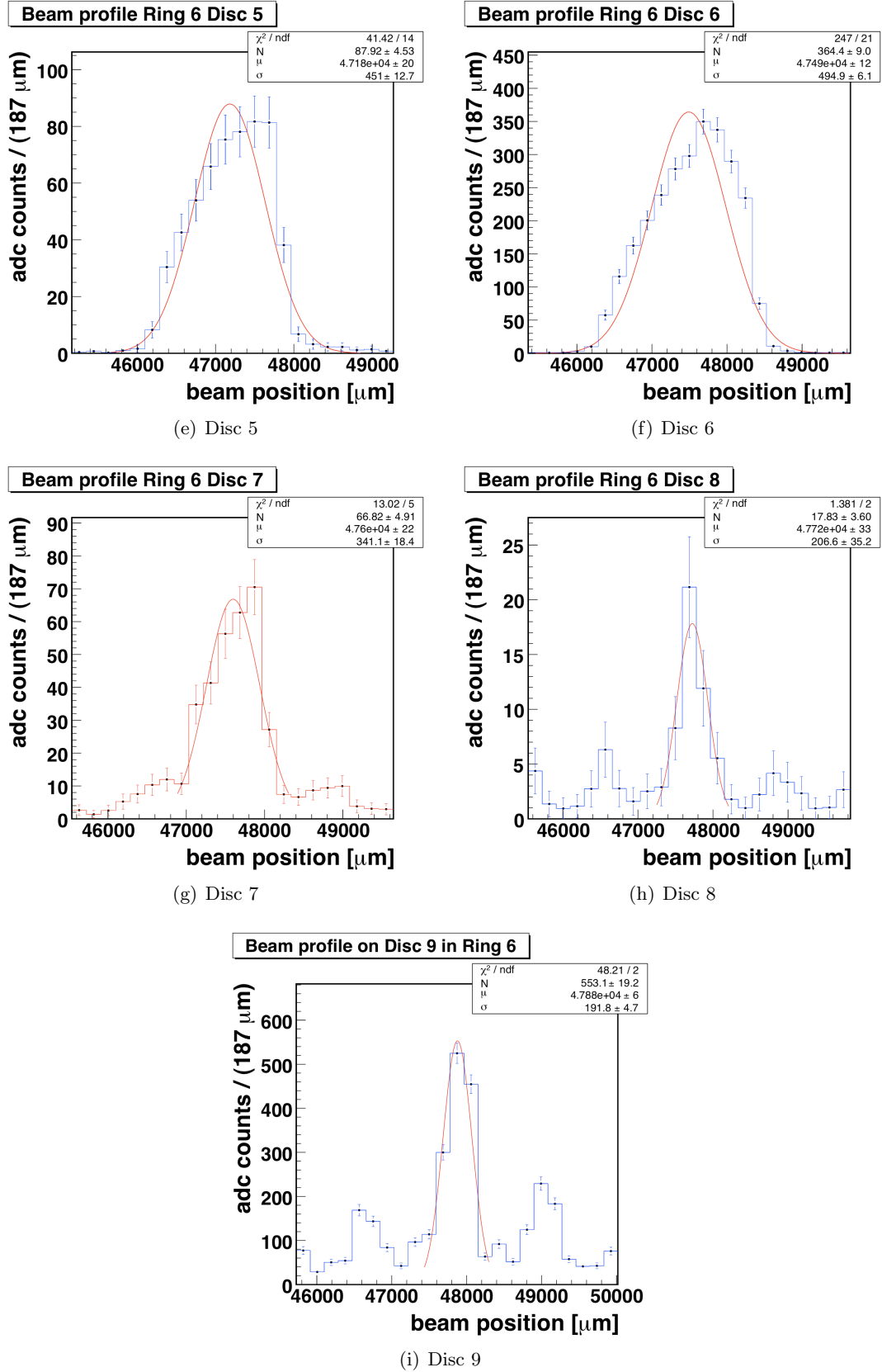


Figure B.14: Continued from page 140.

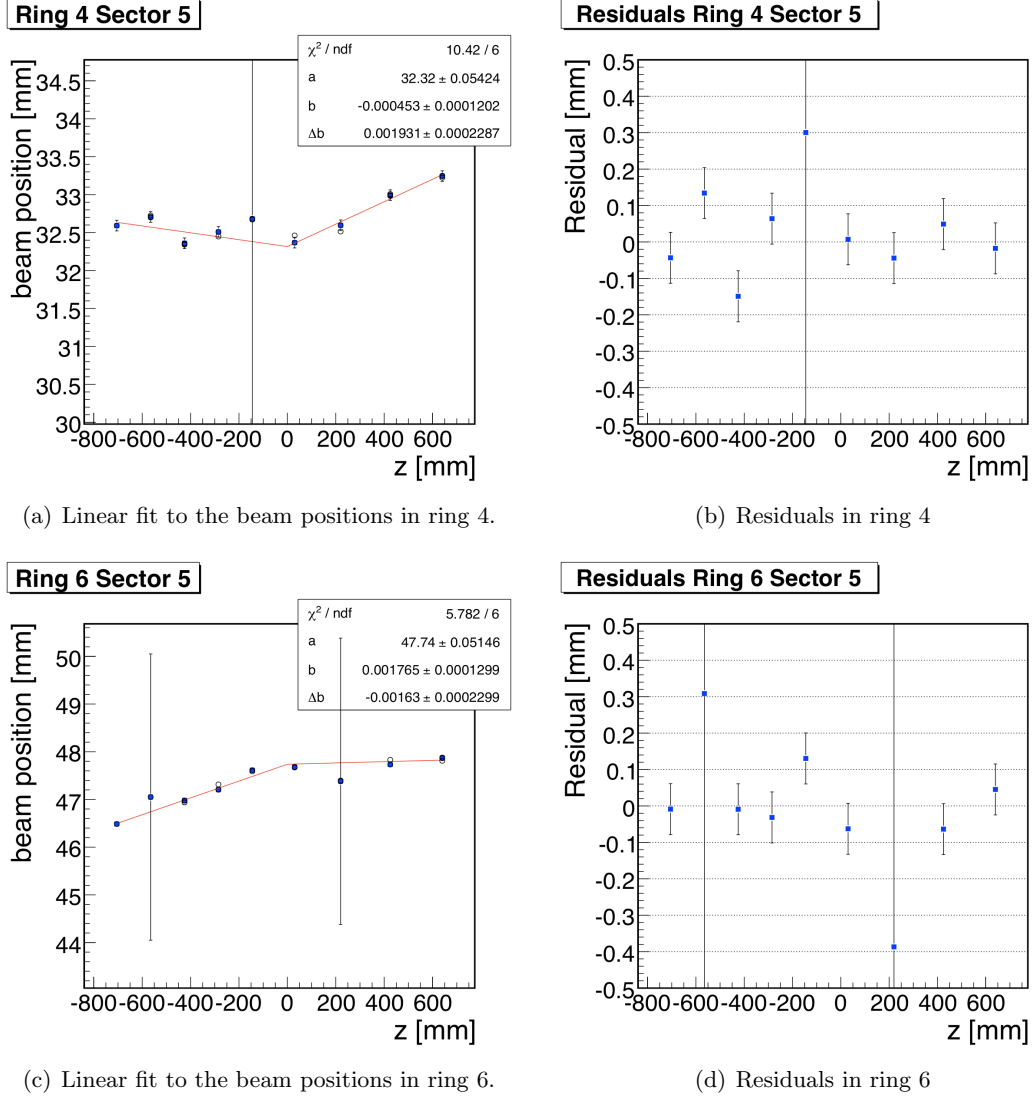


Figure B.15: Straight line fit applied to the reconstructed beam positions in (a) ring 4 and (c) ring 6 for sector 5. (b) and (d) show the residuals between the reconstructed beam positions and the straight line fit. The error bars indicate the error of the reconstructed beam positions. The measurements indicated by the open white circles in (a) and (c) are from different runs, where a beam profile has been reconstructed on the same disc. For each disc the measurement resulting in the smallest residual (indicated by the blue markers in the plots) has been used for the straight line fit.

B.6 Sector 6

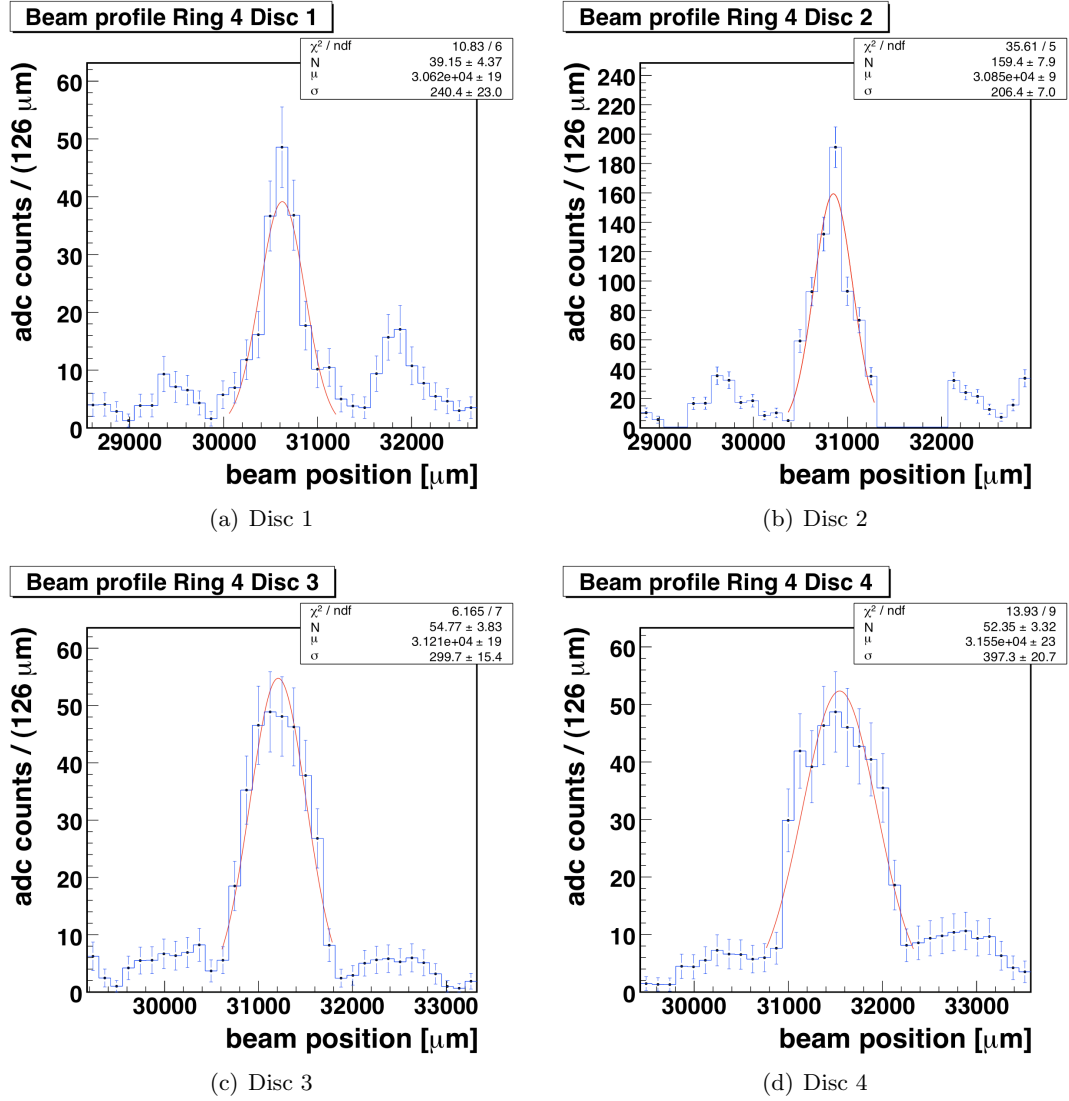


Figure B.16: Signals (in adc counts/126 μm) of the laser beams in ring 4 for sector 6. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 144.

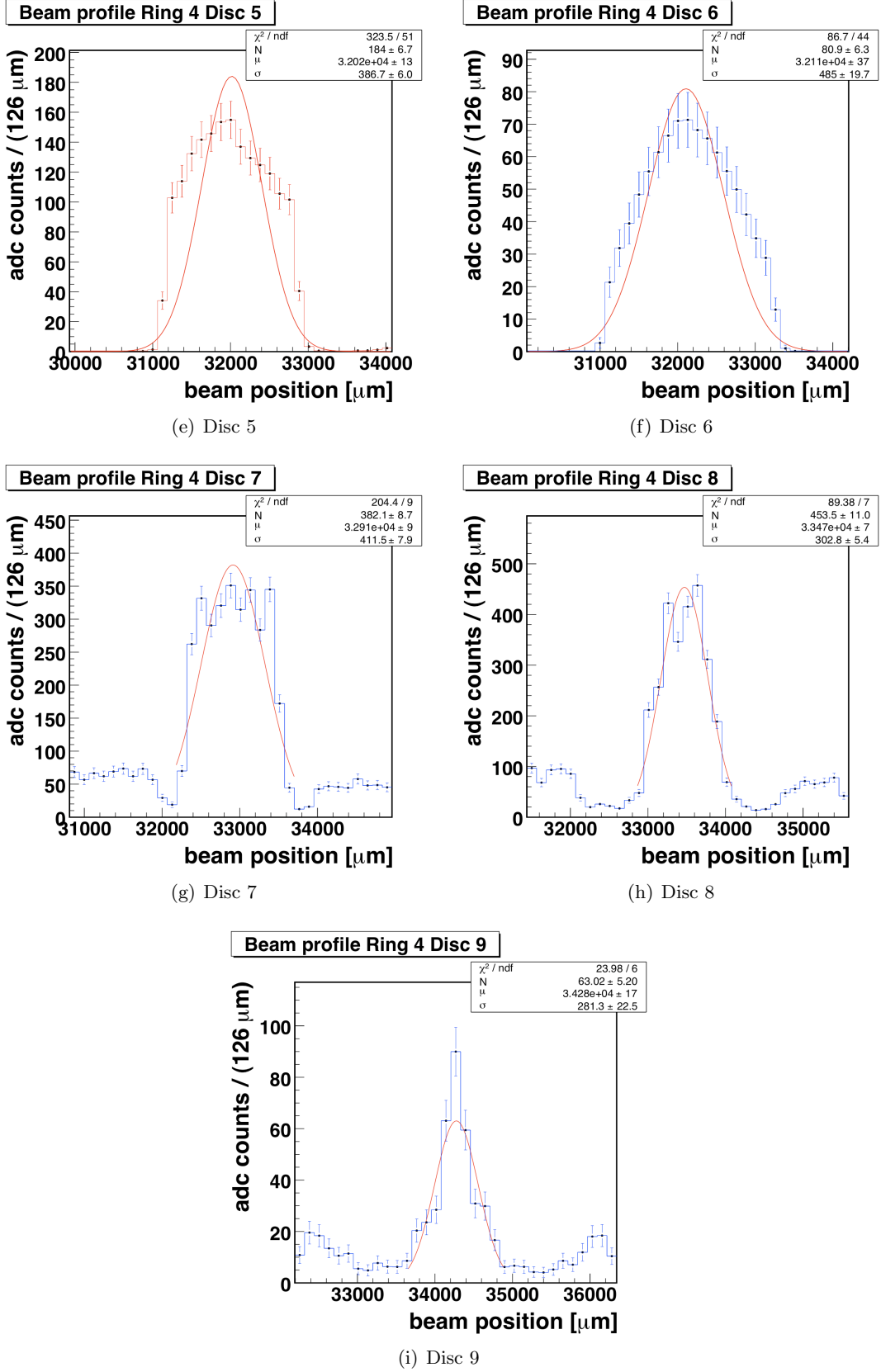


Figure B.16: Continued from page 143.

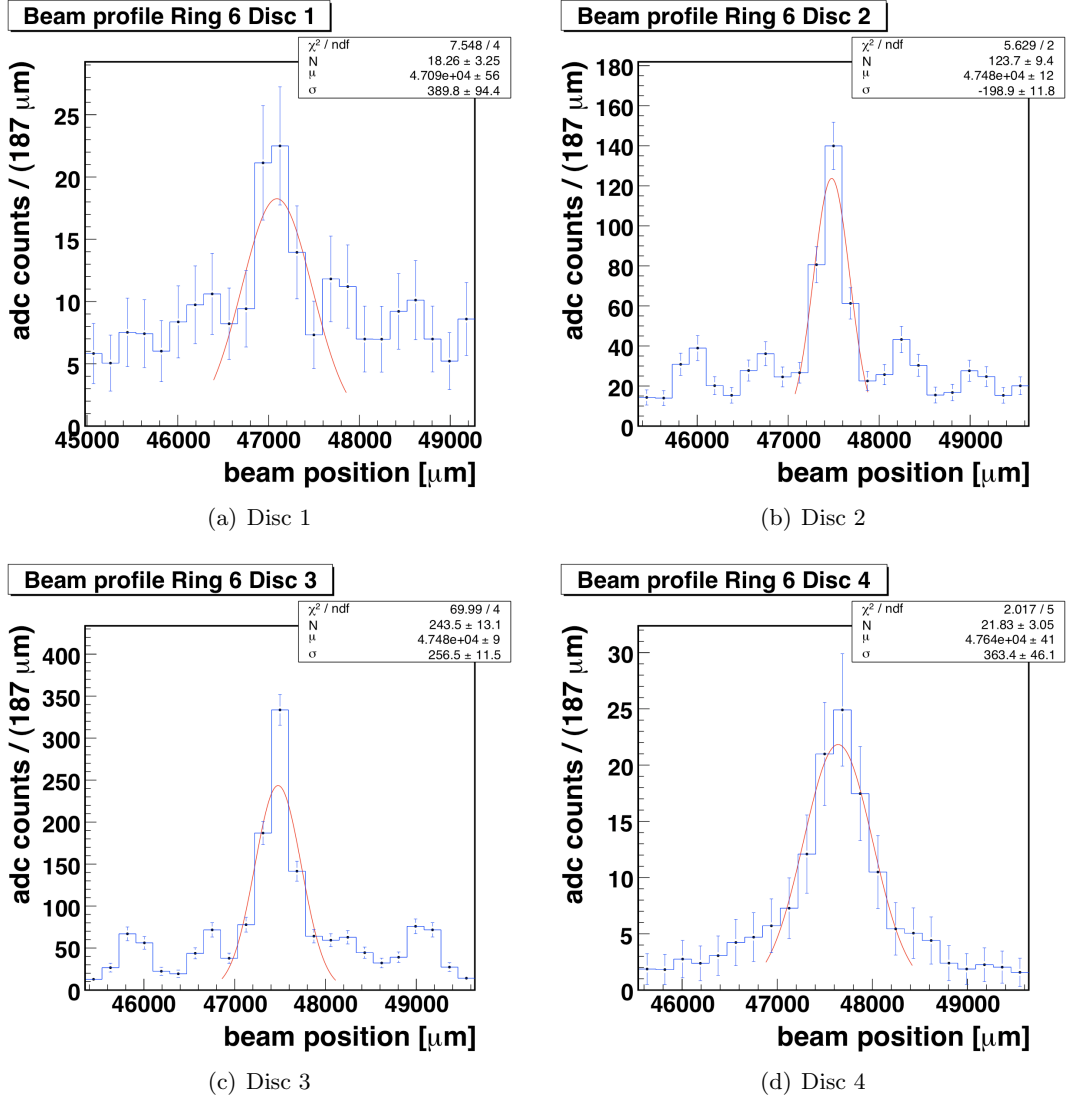


Figure B.17: Signals (in adc counts/187 μm) of the laser beams in ring 6 for sector 6. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 146.

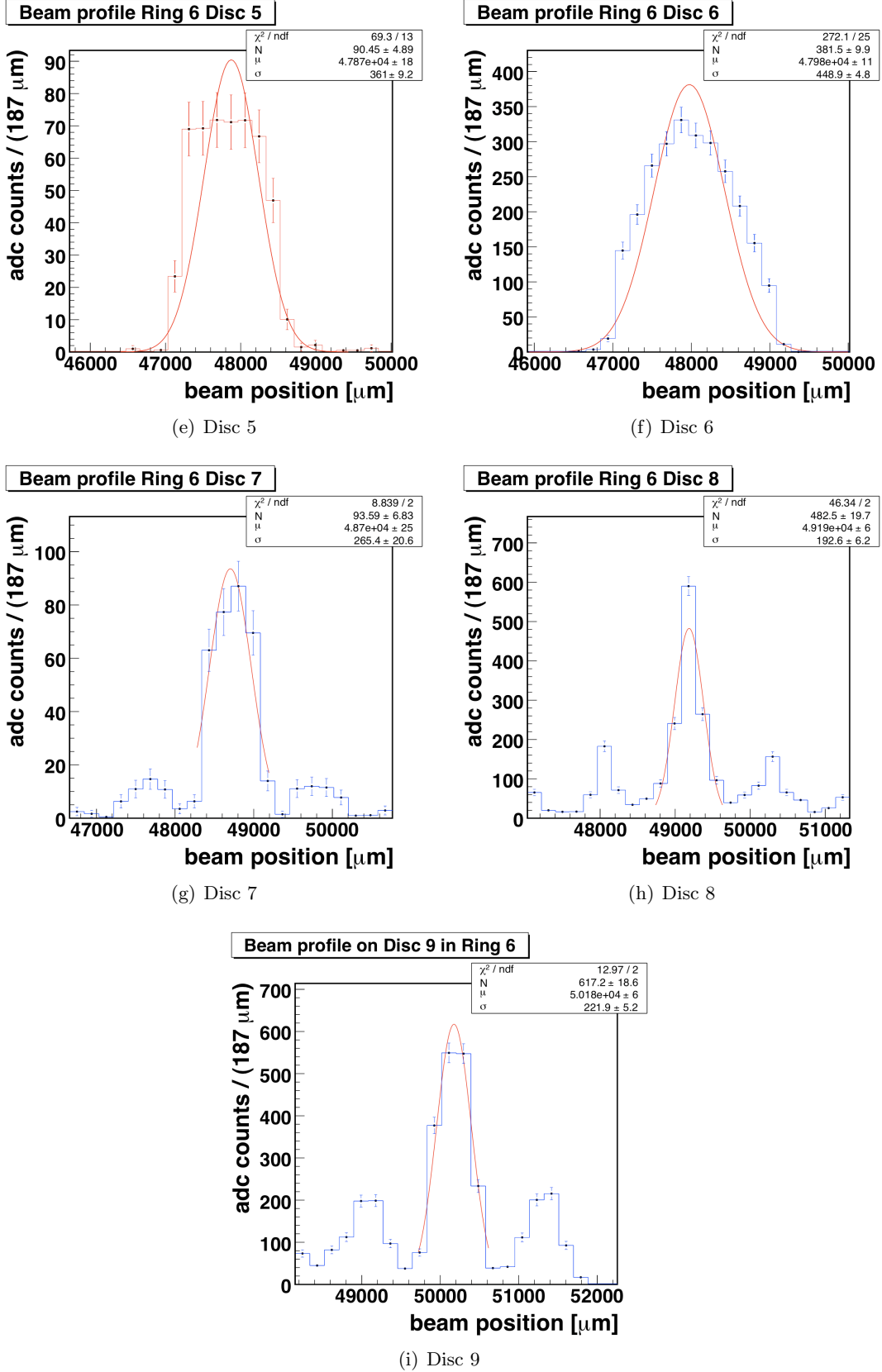


Figure B.17: Continued from page 145.

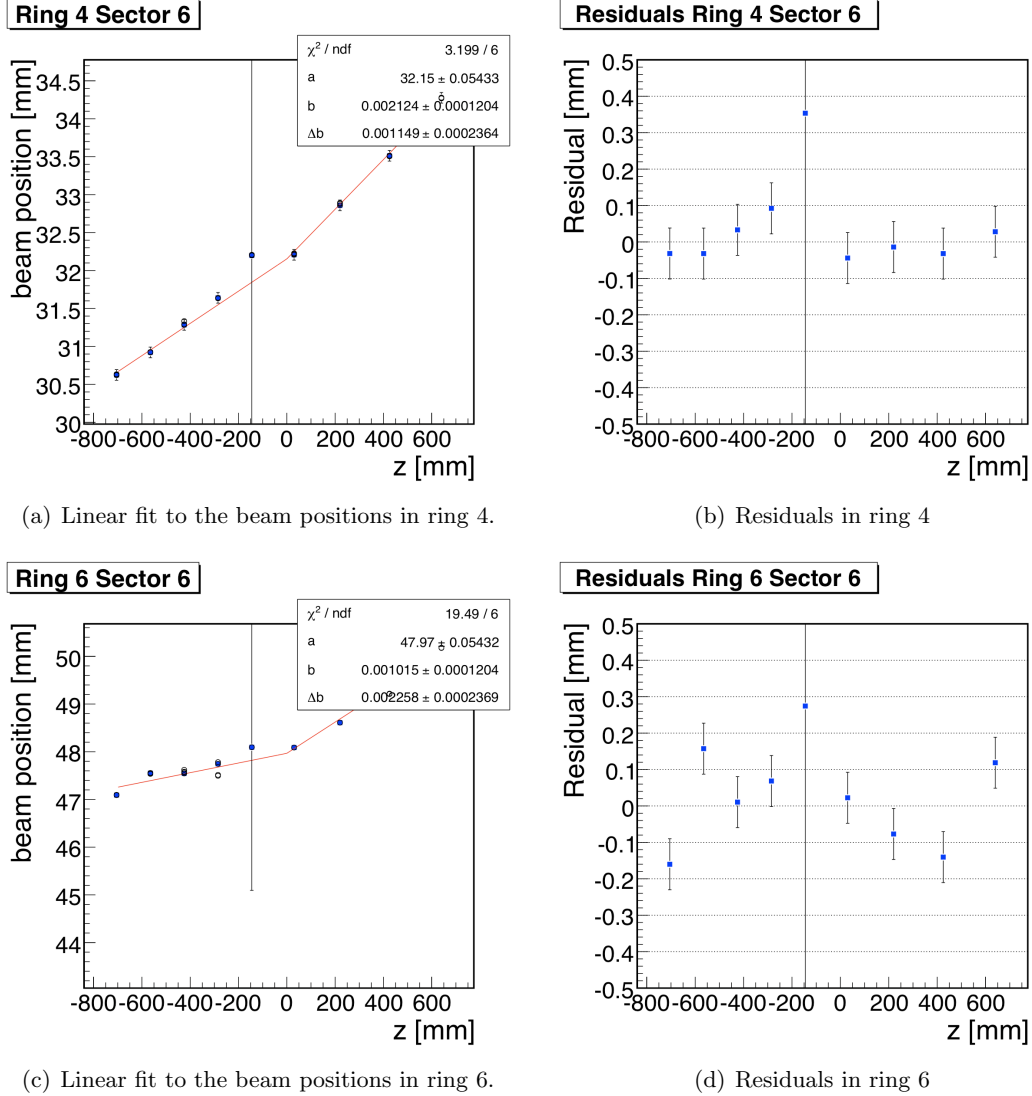


Figure B.18: Straight line fit applied to the reconstructed beam positions in (a) ring 4 and (c) ring 6 for sector 6. (b) and (d) show the residuals between the reconstructed beam positions and the straight line fit. The error bars indicate the error of the reconstructed beam positions. The measurements indicated by the open white circles in (a) and (c) are from different runs, where a beam profile has been reconstructed on the same disc. For each disc the measurement resulting in the smallest residual (indicated by the blue markers in the plots) has been used for the straight line fit.

B.7 Sector 7

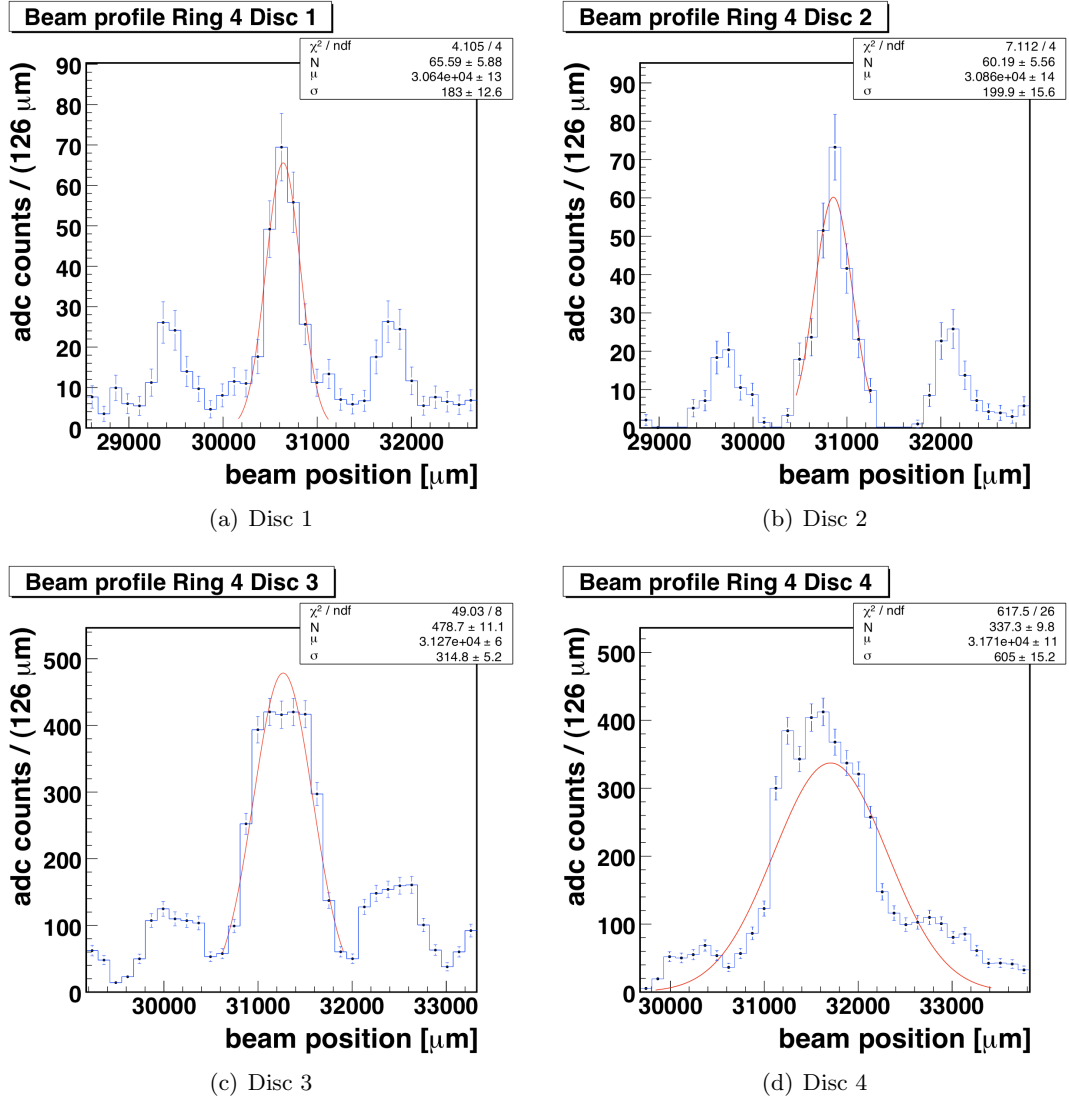
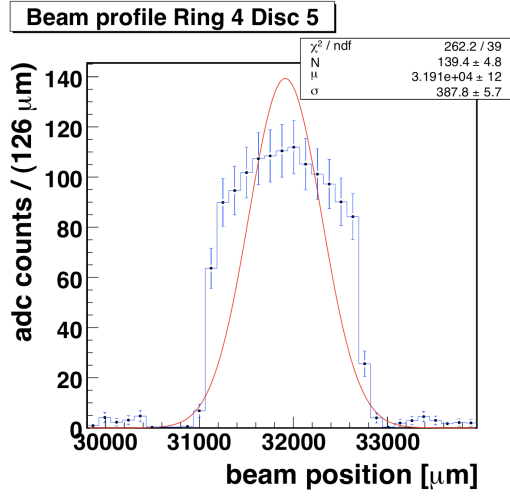
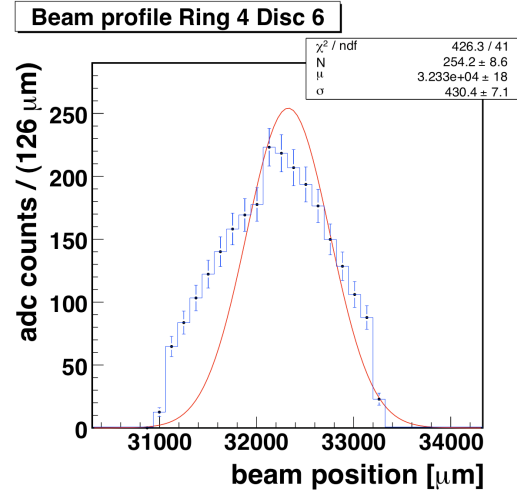


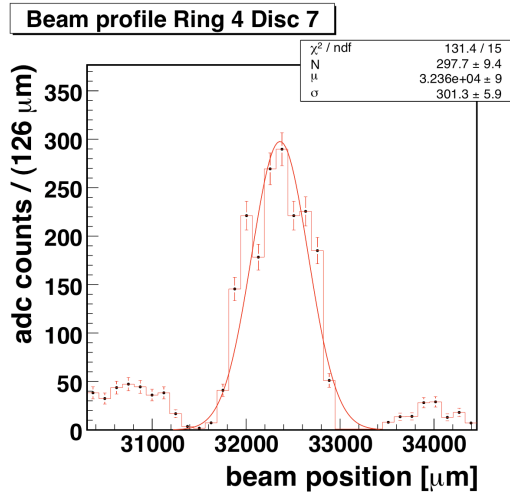
Figure B.19: Signals (in adc counts/126 μm) of the laser beams in ring 4 for sector 7. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical error. Figures (e) – (i) for discs 5 – 9 are shown on page 149.



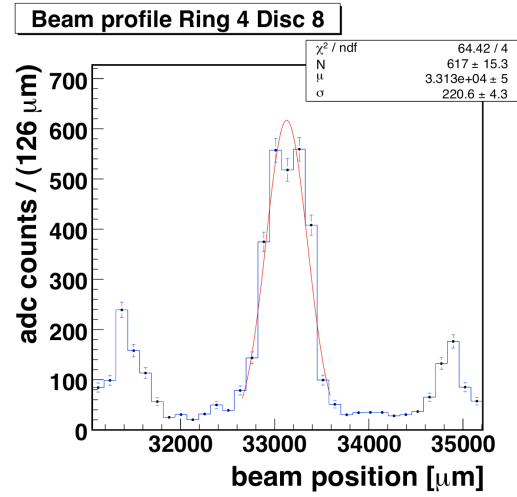
(e) Disc 5



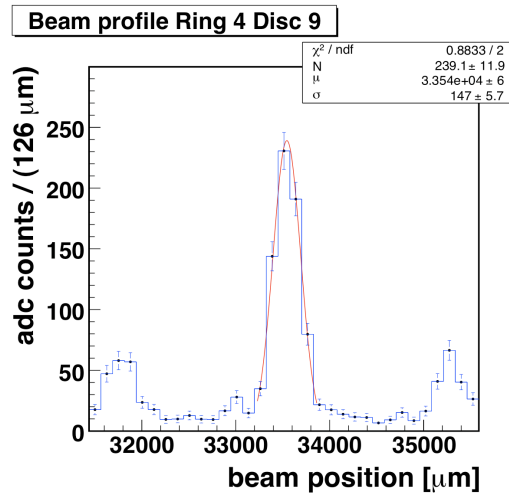
(f) Disc 6



(g) Disc 7



(h) Disc 8



(i) Disc 9

Figure B.19: Continued from page 148.

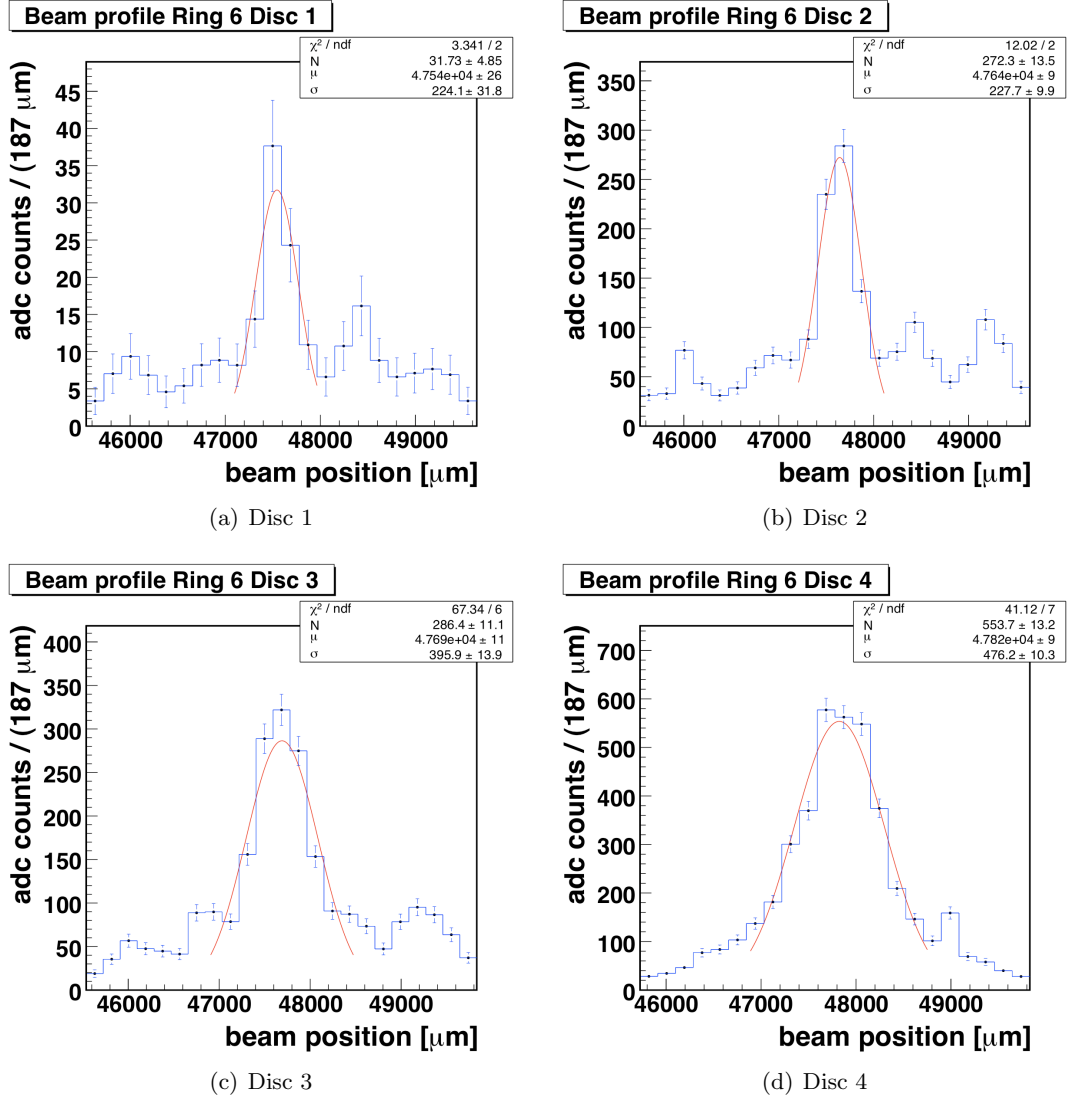
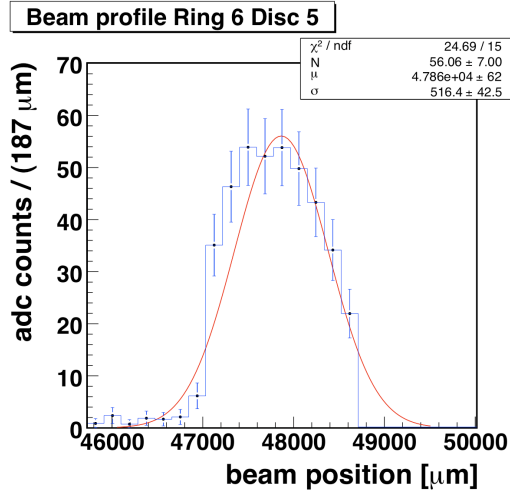
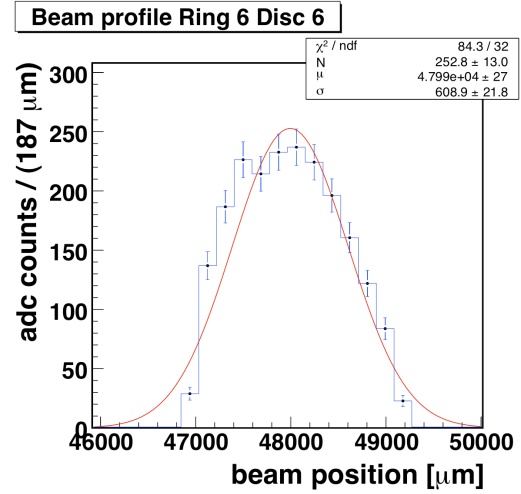


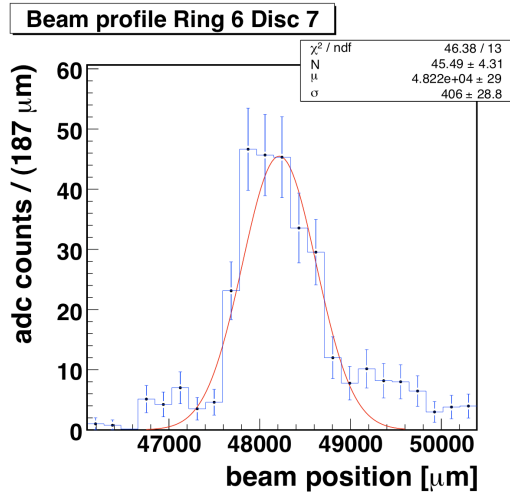
Figure B.20: Signals (in adc counts/187 μm) of the laser beams in ring 6 for sector 7. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 151.



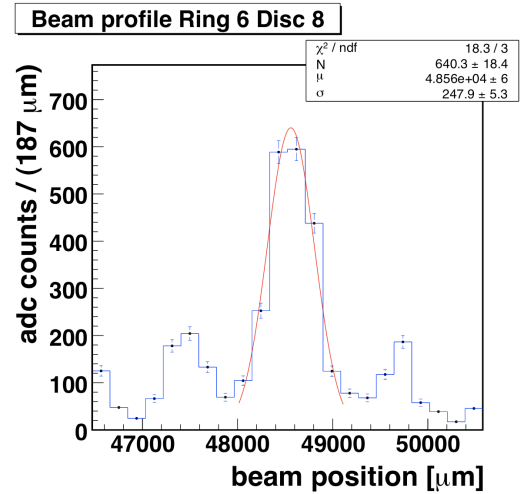
(e) Disc 5



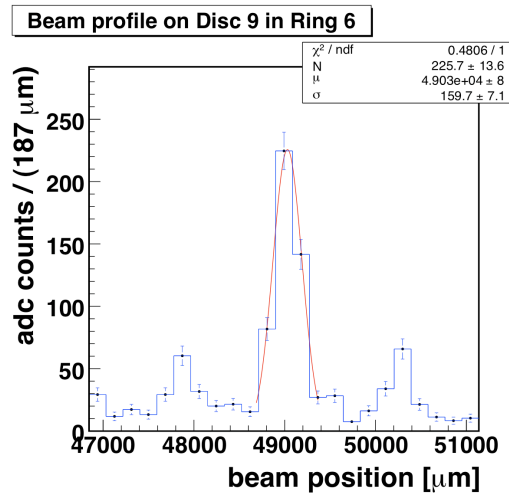
(f) Disc 6



(g) Disc 7



(h) Disc 8



(i) Disc 9

Figure B.20: Continued from page 150.

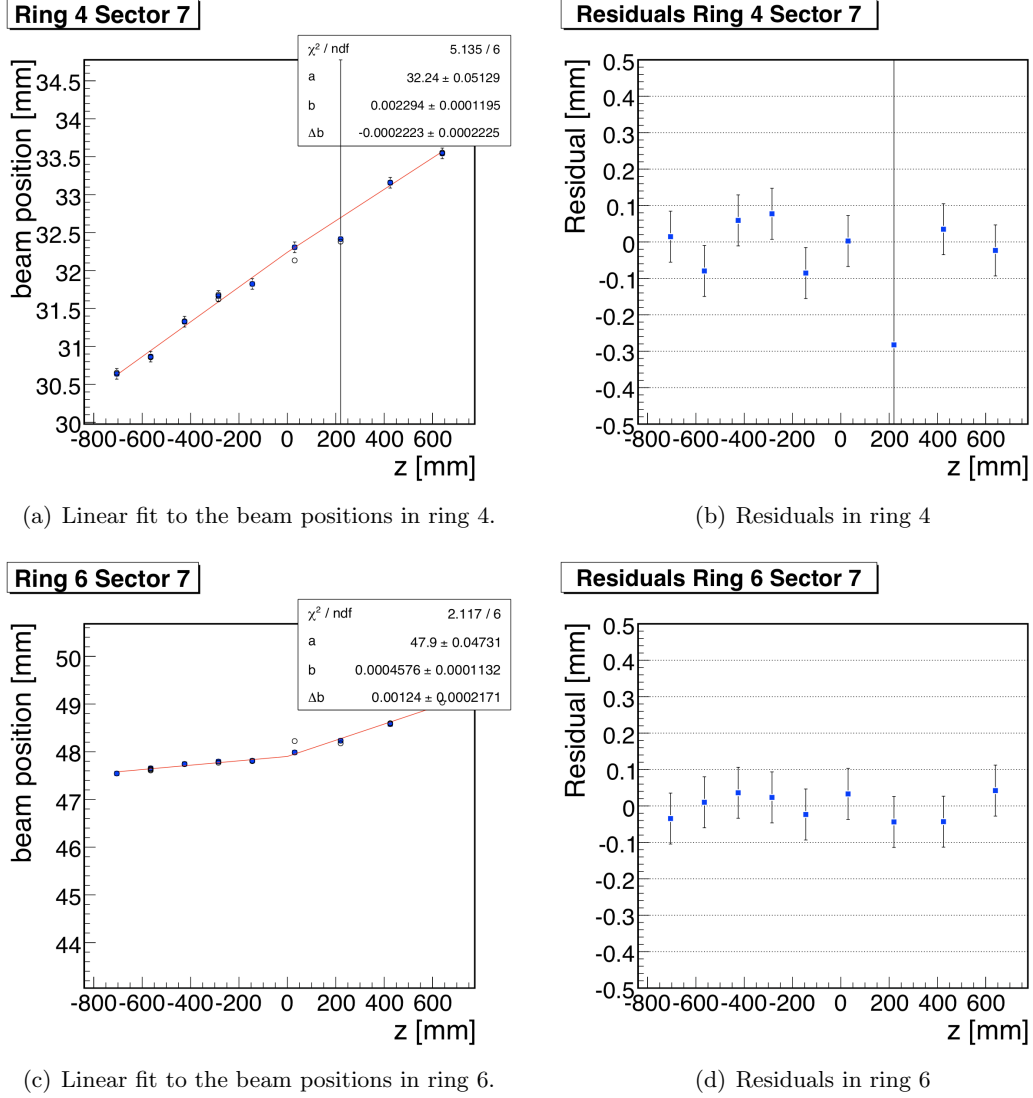


Figure B.21: Straight line fit applied to the reconstructed beam positions in (a) ring 4 and (c) ring 6 for sector 7. (b) and (d) show the residuals between the reconstructed beam positions and the straight line fit. The error bars indicate the error of the reconstructed beam positions. The measurements indicated by the open white circles in (a) and (c) are from different runs, where a beam profile has been reconstructed on the same disc. For each disc the measurement resulting in the smallest residual (indicated by the blue markers in the plots) has been used for the straight line fit.

B.8 Sector 8

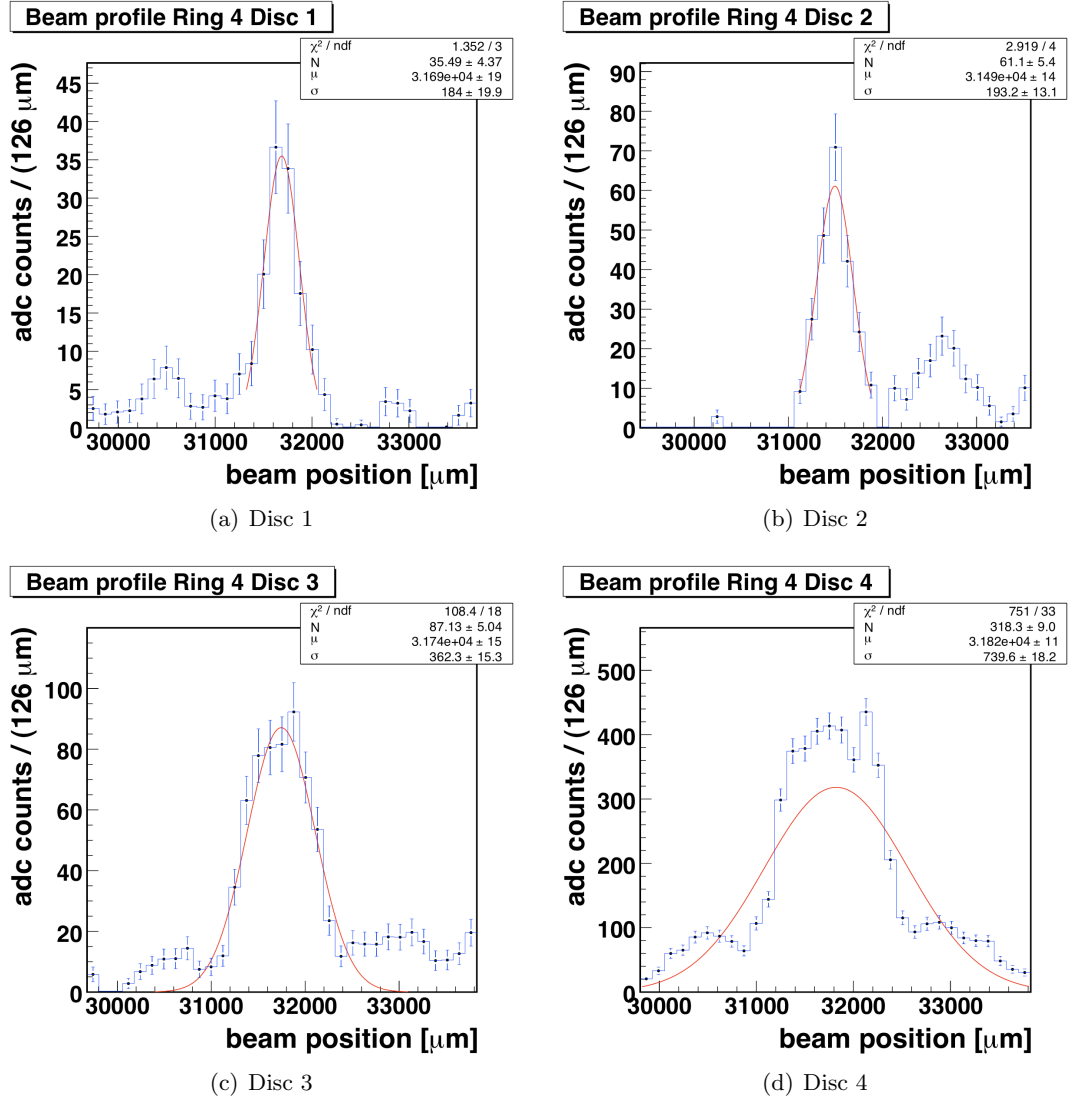


Figure B.22: Signals (in adc counts/126 μm) of the laser beams in ring 4 for sector 8. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 154.

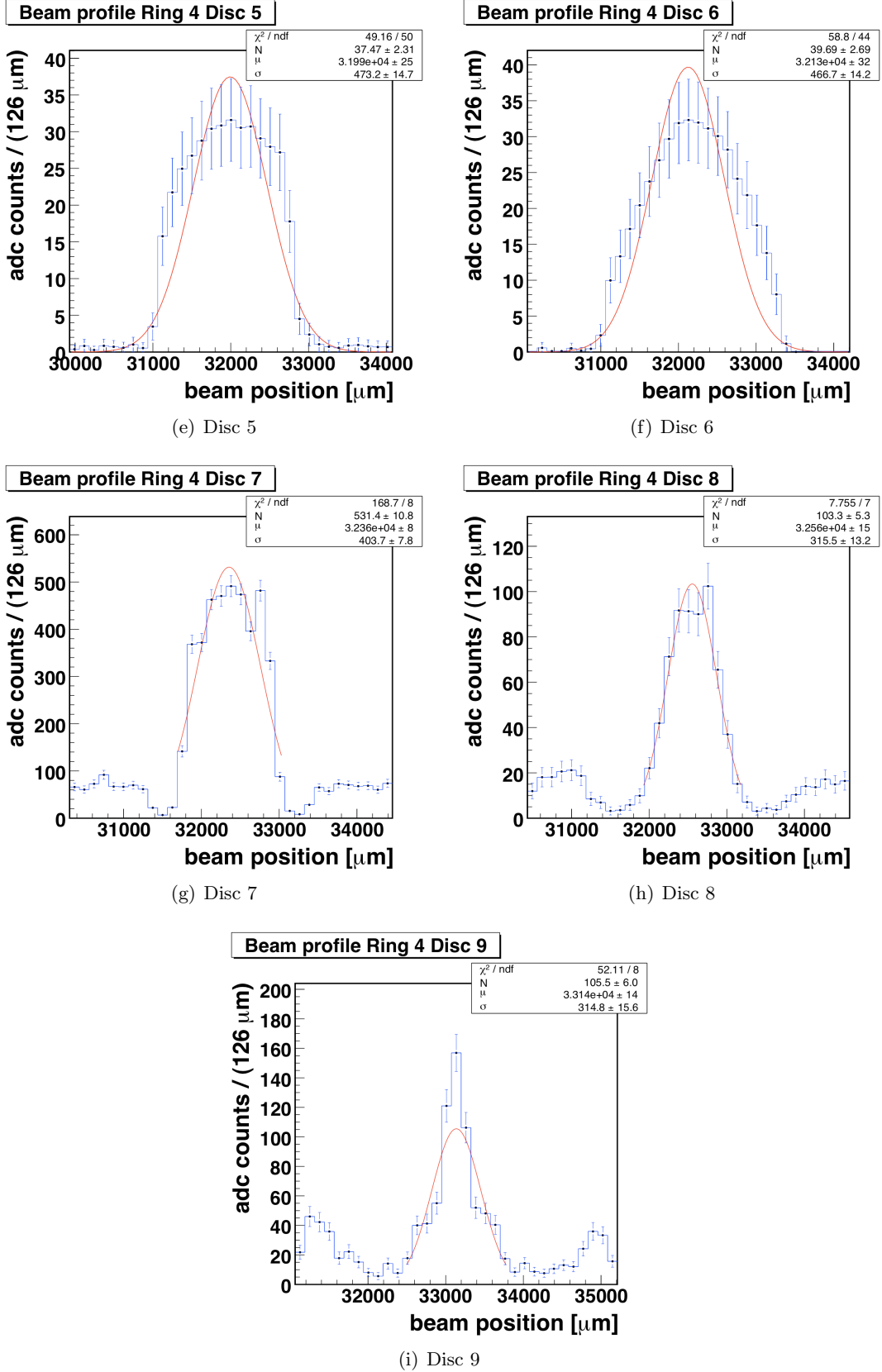


Figure B.22: Continued from page 153.

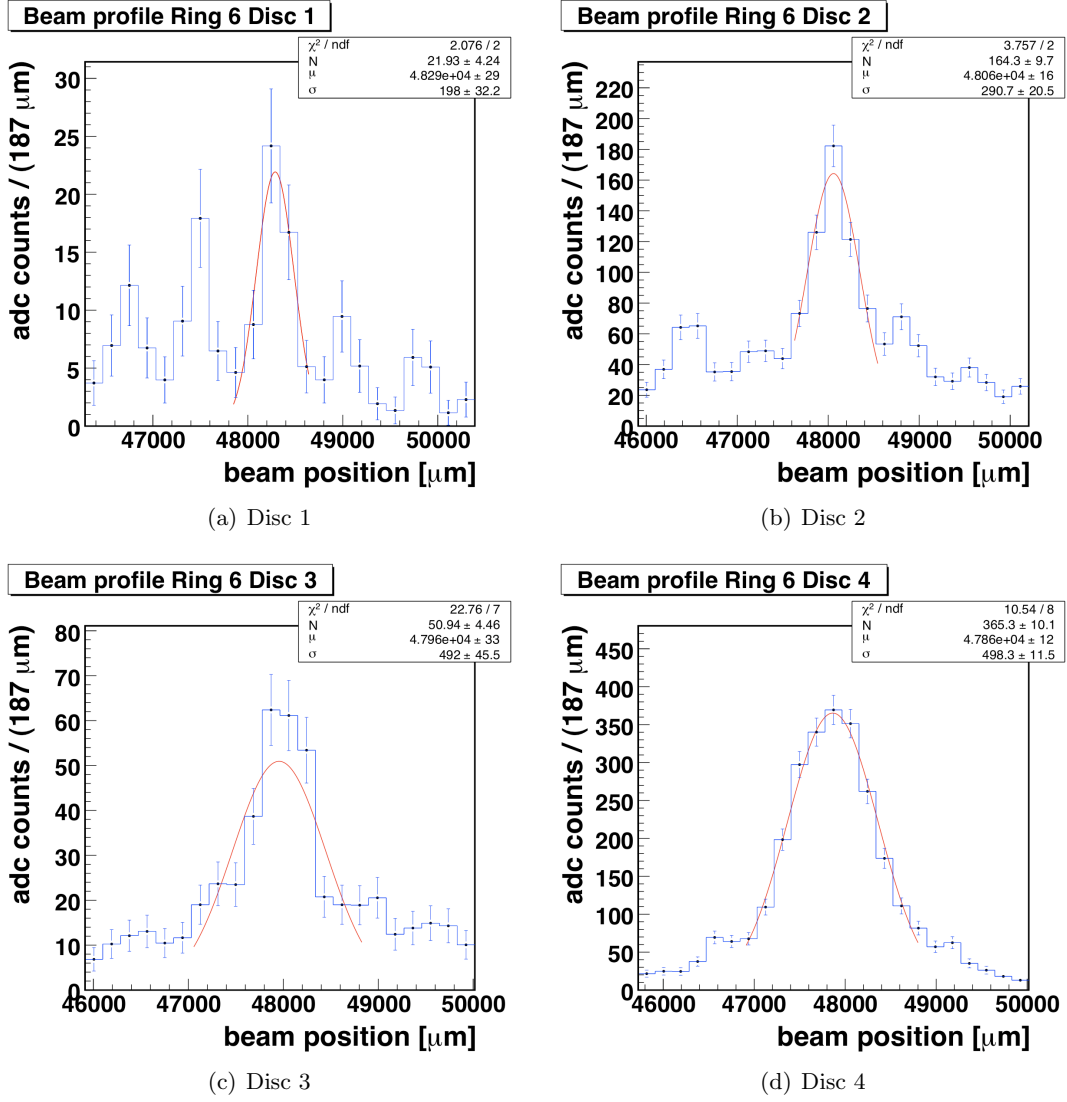


Figure B.23: Signals (in adc counts/187 μm) of the laser beams in ring 6 for sector 8. The fit of a gaussian profile to estimate the beam position is also shown. The error bars indicate the statistical errors. Figures (e) – (i) for discs 5 – 9 are shown on page 156.

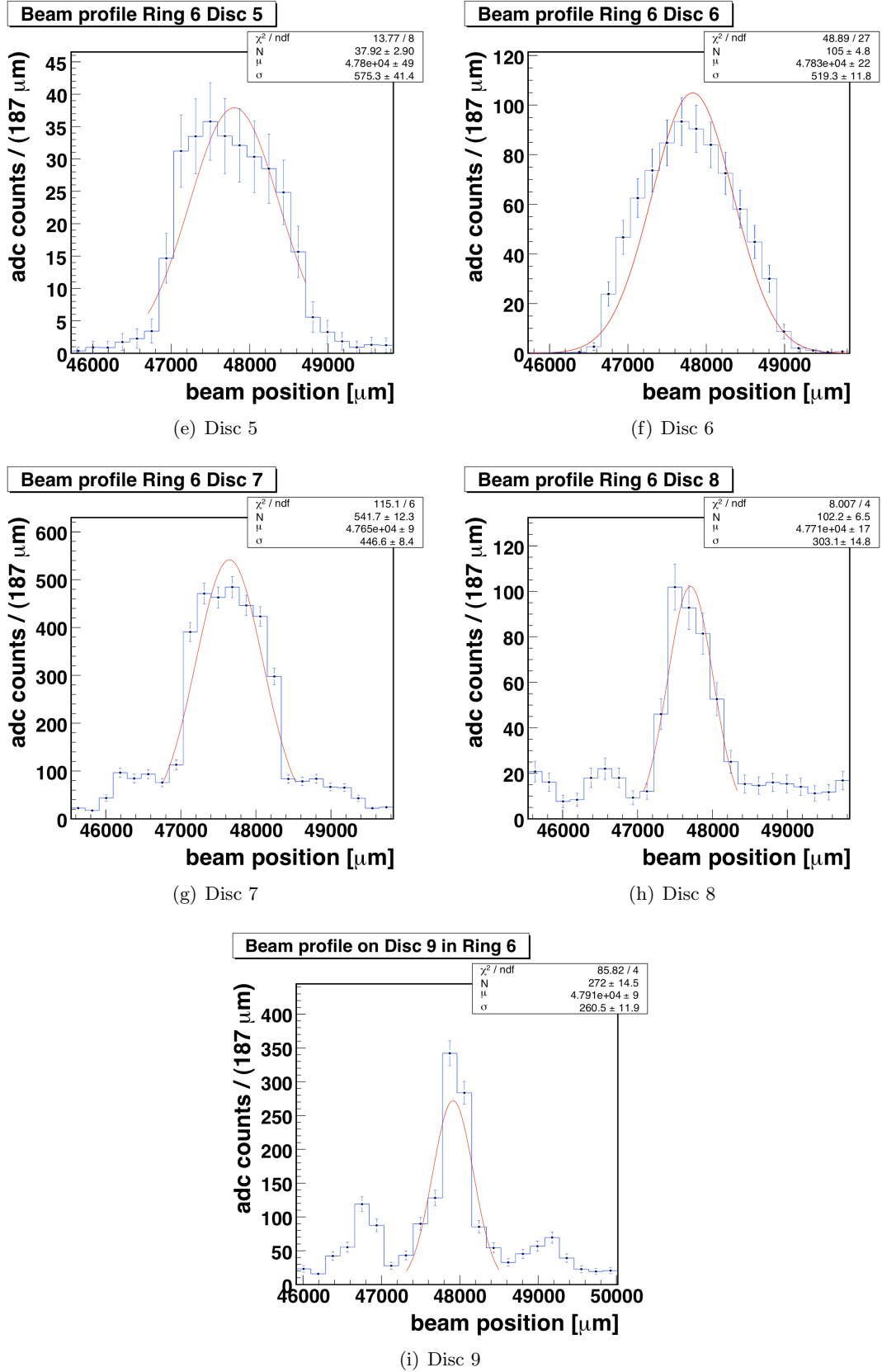


Figure B.23: Continued from page 155.

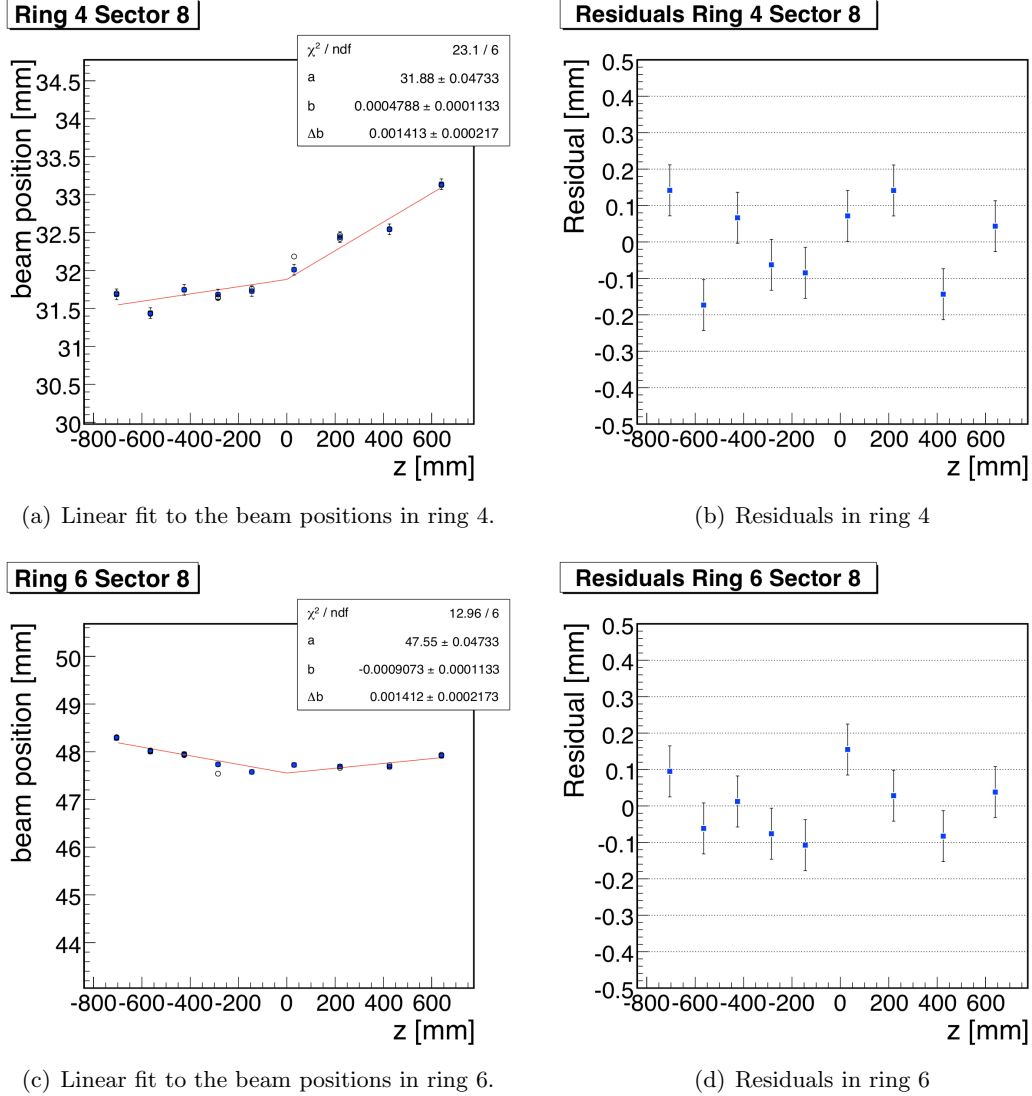


Figure B.24: Straight line fit applied to the reconstructed beam positions in (a) ring 4 and (c) ring 6 for sector 8. (b) and (d) show the residuals between the reconstructed beam positions and the straight line fit. The error bars indicate the error of the reconstructed beam positions. The measurements indicated by the open white circles in (a) and (c) are from different runs, where a beam profile has been reconstructed on the same disc. For each disc the measurement resulting in the smallest residual (indicated by the blue markers in the plots) has been used for the straight line fit.

Appendix C

Muon reconstruction in CMS

The reconstruction of muons with the CMS detector is performed in three stages:

- local reconstruction (local pattern recognition)
- standalone reconstruction
- global reconstruction.

Starting from reconstructed hits, track segments are built in the DT and CSC chambers (see section 2.2.5). The standalone muon reconstruction uses only information from the muon system, whereas the global reconstruction utilizes both the information from the muon system and the silicon tracker.

The starting point of the standalone reconstruction are reconstructed track segments from the muon chambers obtained by the local reconstruction. The track position, momentum and direction associated with the track segments in the innermost muon chambers are used to grow the muon trajectories, working from inside out, utilizing methods based on a Kalman filter technique [136, 137]. At each step the track parameters and the corresponding errors are propagated to the next layer of muon detectors. A suitable propagator takes into account material effects like multiple scattering and energy losses due to ionization and bremsstrahlung in the muon chambers and the return yoke of the magnet. In order to reject bad hits originating from such effects a suitable χ^2 cut is applied.

In case no matching segments or hits are found, *e.g.* due to detector inefficiencies or geometrical cracks, the search for compatible segments and hits is continued in the next station of the muon system. The procedure continues until the outermost surface of the muon system has been reached. Afterwards a backward Kalman filter is applied and the track parameters on the innermost surface are estimated.

At least two measurements, one of which must be of a DT or CSC track segment, are required to be present in order to accept a trajectory as a muon track. The RPCs, in addition to their trigger role, allow to reduce combinatorics due to noise in the DTs and CSCs and help the reconstruction of low momentum muons and of muons in the barrel-endcap overlap region, where the geometrical coverage is problematic and it may occur that only one DT or CSC station has been hit by the muon.

Finally the track is extrapolated to the interaction point and a fit constrained to the interaction vertex is applied in order to improve the P_t resolution.

The global muon reconstruction extends the standalone muon tracks to include hits in both the silicon strip and pixel trackers. The muon trajectory is extrapolated from the innermost layer of the muon system to the outermost layer of the silicon tracker. The extrapolation takes into account the energy loss of the muons in the material and the effect of multiple scattering. After extrapolation to the outer tracker surface, the silicon layers compatible with the muon trajectory are determined and a region of interest is defined in the tracker. The region of

interest is based on the track parameters and the errors of the extrapolated muon trajectory, assuming that the muon originates from the nominal interaction point as described above.

Inside the region of interest pairs of reconstructed hits are used to find initial candidates for the muon trajectory (so-called regional seeds). These two hits must come from different tracker layers and, in order to achieve a high efficiency, all possible combinations from compatible pixel and silicon layers are used.

The regional seeds are used to reconstruct tracks in the selected region of interest. The track reconstruction algorithm consists of three steps

- trajectory building (seeded pattern recognition) followed by
- trajectory cleaning to take care of ambiguity resolution and finally
- trajectory smoothing to perform the final fit.

In the first step the trajectory builder transforms each seed into a collection of trajectories. Each of these trajectories is propagated from the innermost layer to the next reachable tracker layer and updated with compatible measurements on that layer. In the next step, the trajectory cleaner resolves ambiguities of multiple trajectories that may originate from a single seed on the basis of the number of hits and the χ^2 of the track fit. In the third step, the selected trajectories are refitted together with the reconstructed hits of the original standalone track in the muon system. The final global muon tracks are selected on the basis of a χ^2 cut. More details about the muon reconstruction algorithms can be found in [62, 138–140].

An additional method to reconstruct muons has been recently added to the CMSSW framework. This method was not available in the CMSSW version utilized for the present study and is mentioned here only for completeness. Tracker muons are objects reconstructed with an algorithm that starts from a track in the silicon tracker and looks for compatible segments in the muon chambers. At least one muon segment has to match the track in the inner tracker in order to select the track as a muon candidate. This allows for higher efficiency at lower muon momenta since standalone and global muons use at least 2 segments to seed a track. More information about this new reconstruction algorithm can be found in [86].

Appendix D

Analytical functions used to fit the invariant mass distributions

In this chapter the functions used to fit the signal shape shown in chapter 4 are shortly discussed.

D.1 Relativistic Breit-Wigner function

To fit the Z boson resonance in the generated events (see figure 4.3) a relativistic Breit-Wigner distribution has been used with the following form [141]

$$f(x) = \frac{C}{(x^2 - M^2)^2 + M^2\Gamma^2} \cdot \frac{x^2}{M^2}. \quad (\text{D.1})$$

The fit has 3 parameters: the constant C , the mass M of the Z boson and the width Γ of the Z boson.

D.2 Relativistic Breit-Wigner and Gaussian

The invariant mass distribution of the reconstructed muons (see figure 4.8(b)) has been fitted with a relativistic Breit-Wigner function together with a Gaussian distribution:

$$f(x) = \frac{C_1}{(x^2 - M^2)^2 + M^2\Gamma^2} \cdot \frac{x^2}{M^2} + C_2 \cdot e^{-\frac{(x-M)^2}{2\sigma^2}}. \quad (\text{D.2})$$

The Gaussian part of this function takes the detector resolution into account. This is a five dimensional fit. The parameters are: the constant C_1 of the Breit-Wigner, the mass M of the Z boson, the width Γ of the Z boson, the constant C_2 of the Gaussian distribution and the width σ of the Gaussian distribution.

To calculate the mean (corresponding to the mass of the Z boson) and the width (corresponding to the width of the Z boson) from the results of the fit, the following formulae have been used

$$\begin{aligned} M &= \int x \cdot f(x) dx, \\ \Gamma &= \sqrt{\int (x - M)^2 \cdot f(x) dx}. \end{aligned} \quad (\text{D.3})$$

Appendix E

Bootstrap methods

This chapter gives a short overview of the bootstrap methods used in chapter 4. More detailed information can be found in [129–132].

E.1 Introduction

Most of the standard and more familiar statistical methods, like *e.g.* linear regression or analysis of variance, were originally designed to be implemented on mechanical calculators. The huge increase of computing power over the last decades allowed the development of new statistical methods that require fewer distributional assumptions than their predecessors [130].

Suppose that we have data $F(\mathbf{x} = (x_1, \dots, x_n))$ that are obtained by random sampling from an unknown distribution. Suppose further that there is a parameter $\theta = t(F)$ that we are interested in estimating. A point estimate of this parameter is obtained by using *e.g.* an empirical distribution function based on data, $\hat{\theta} = t(\hat{F})$.

A point estimate is usually supplemented by a confidence interval $I = (\hat{\theta}_{\text{lower}}, \hat{\theta}_{\text{upper}})$ with approximate coverage $1 - 2\alpha$, which means that the probability of finding the true value of the parameter inside this interval is exactly $1 - 2\alpha$. Similarly this can be formulated as $P(\theta < \hat{\theta}_{\text{lower}}) = \alpha$ and $P(\theta > \hat{\theta}_{\text{upper}}) = \alpha$ [129].

Statistical inference is based on the sampling distributions of sample statistics. The bootstrap method allows for finding the sampling distribution from just one sample and therefore permits the estimation of the parameter $\hat{\theta}$ and the corresponding confidence interval I utilizing *Monte Carlo* techniques. The next section gives a description of the bootstrap algorithm.

E.2 The algorithm

A usual sampling distribution is based on many random samples from a population. Sometimes however there is only one random sample available. The bootstrap idea is to use many resamples by repeatedly sampling with replacement¹ from this one available random sample ($F(\mathbf{x} = (x_1, \dots, x_n))$) instead of utilizing many samples from the population. Each resample has the same size n as the original sample and the bootstrap samples are denoted as $F^*(\mathbf{x}^* = (x_1^*, \dots, x_n^*))$.

The sampling distribution of a statistic $t(F)$ collects the values of the statistic from many samples. Analogously the bootstrap distribution of a statistic collects its values from many resamples. Finally the bootstrap distribution gives information about the sampling distribution [131].

¹Sampling with replacement means, that after an observation from the original sample has been drawn, this observation is put back before the next observation is drawn. In this way, any observation can be drawn more than once, or not at all. Sampling without replacement would result in a sample containing exactly the same observations as the original sample, although the order of the observations could be different.

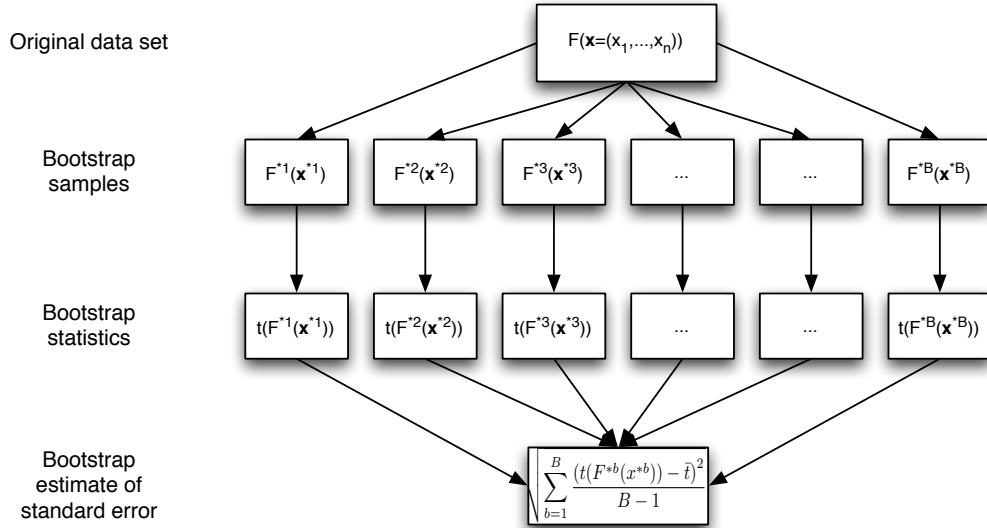


Figure E.1: Diagram of the bootstrap algorithm for the calculation of the standard error of a statistic $t(F)$. Each of the B bootstrap samples is a random sample of size n drawn with replacement from the original data sample $F(\mathbf{x} = (x_1, \dots, x_n))$. $\bar{t}$ is the average of the B bootstrap statistics $t(F^{*b})$, $b = 1, \dots, B$. The second step, estimation of the bootstrap statistics, is responsible for most of the computation time needed for the bootstrap algorithm.

The bootstrap algorithm consists out of three major steps:

1. a large number B of independent bootstrap samples F^{*b} ($b = 1, \dots, B$), each of size n , is generated using a random number generator,
2. the statistic $\hat{\theta}^* = t(F^{*b})$ is calculated for each individual bootstrap sample, and
3. the empirical standard deviation of the B bootstrap statistics $t(F^{*b})$ is the bootstrap estimate of the standard error for the statistic $t(F)$.

Figure E.1 shows a schematic diagram of the bootstrap algorithm.

Some interesting properties of the bootstrap algorithm are [130]

- the individual data points x_i can be single data points, vectors, matrices and even general quantities, like *e.g.* maps or graphs,
- the statistic $t(F)$ can be anything as long as $t(F^*)$ can be calculated for each bootstrap data sample F^* ,
- measures of statistical accuracy other than the standard error (*e.g.* confidence intervals) can be calculated at the final stage of the algorithm.

In the case where $t(F)$ is the mean $\bar{x}$ of the x_i 's it is not necessary to calculate the bootstrap standard error. It can namely be proven that for $B \rightarrow \infty$ the bootstrap standard deviation estimate goes to $\sqrt{(n-1)/n}$ times the standard deviation

$$\sigma(\bar{x}) = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n(n-1)}}. \quad (\text{E.1})$$

The factor $\sqrt{(n-1)/n}$ is equal to 0.943 for $n = 9$ and 0.999995 for $n = 100000$. For the statistic $\bar{x}$ the bootstrap algorithm gives about the same result as equation E.1.

E.3 Confidence Intervals

Several methods exist to calculate a confidence interval for a statistic calculated by means of the bootstrap method. Some examples are the bootstrap t confidence intervals and bootstrap percentile confidence intervals. They are discussed in detail in the literature [131]. In the following a short description of the bootstrap bias-corrected accelerated (BCa) confidence intervals is given. The bootstrap bias-corrected accelerated interval is a modification of the percentile² method that adjusts the percentiles to correct for bias and skewness and was used to obtain the confidence intervals presented in section 4.6.

The BCa interval is given by $I_{\text{BCa}} = (\hat{\theta}^{*(\alpha_1)}, \hat{\theta}^{*(\alpha_2)})$ where the modified percentile points are calculated as [129]

$$\alpha_1 = \Phi \left(\hat{z}_0 + \frac{\hat{z}_0 + z^{(\alpha)}}{1 - \hat{a}(\hat{z}_0 + z^{(\alpha)})} \right) \quad (\text{E.2})$$

$$\alpha_2 = \Phi \left(\hat{z}_0 + \frac{\hat{z}_0 + z^{(1-\alpha)}}{1 - \hat{a}(\hat{z}_0 + z^{(1-\alpha)})} \right) \quad (\text{E.3})$$

Here Φ is the standard normal cumulative distribution function and $z^{(\alpha)}$ is $(100 \cdot \alpha)$ th percentile point of a standard normal distribution.

The bias-correction constant $\hat{z}_0$ is obtained directly from the percentage of bootstrap statistics less or equal to the original estimate $\hat{\theta}$, and the acceleration constant $\hat{a}$ can be most conveniently estimated with jackknife values³ of the statistic $\hat{\theta}_i$ (obtained from the original sample with the i th point removed) [129]:

$$\hat{z}_0 = \Phi^{-1} \left(\frac{\#(\hat{\theta}^* < \hat{\theta})}{B} \right) \quad (\text{E.4})$$

$$\hat{a} = \frac{\sum_{i=1}^n (\hat{\theta} - \hat{\theta}_i)^3}{6 \left\{ \sum_{i=1}^n (\hat{\theta} - \hat{\theta}_i)^2 \right\}^{3/2}} \quad (\text{E.5})$$

with $\hat{\theta} = \sum_{i=1}^n \hat{\theta}_i / n$.

E.4 Example: systematic uncertainty due to misalignment

In section 4.6.3 the bootstrap method was used to estimate a confidence interval for the mean of the distribution shown in figure E.2(a).

The mean of the original distribution $\bar{\psi} = 2.863\%$ is in agreement with the result from the bootstrap method $\bar{\psi}_{\text{bootstrap}} = 2.864\%$. For this small example $B = 2000$ bootstrap samples

²A percentile is the value of a variable below which a certain percent of observations fall: *e.g.* the 10th percentile is the value below which 10 percent of the observations are found.

³Jackknifing is a method similar to bootstrapping. The basic idea lies in systematically recomputing the statistic estimate (the jackknife values) leaving out one observation at a time from the sample set.

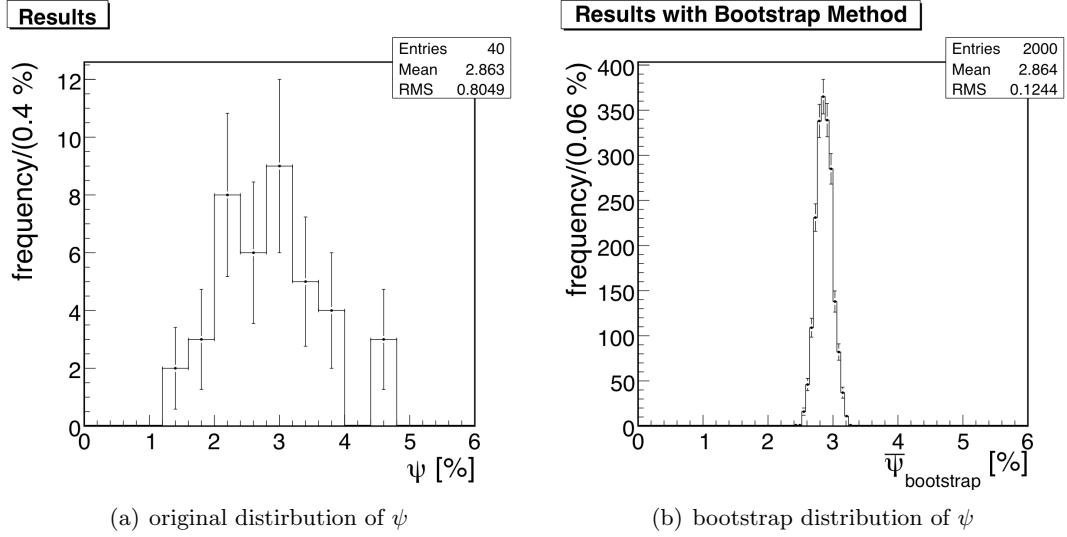


Figure E.2: Results of the studies on the systematic uncertainty due to misalignment. Shown is the quantity ψ defined in equation 4.29. The distribution in (a) shows how much the number of events in the region around the Z boson mass changes due to a misaligned tracker and muon system. (b) shows the resulting distribution for the mean $\bar{\psi}$ using the bootstrap method. Statistical errors are indicated by the error bars.

were generated. For the results presented in section 4.6.3 and 4.6.4 $B = 100000$ bootstrap samples have been used.

Appendix F

Formula for error propagation

This chapter summarizes the formulae used to estimate the errors of the quantities needed to measure the cross section and luminosity.

Given a formula $x = f(u, v, \dots)$, where the parameters $u, v, \dots$ have errors $\sigma_u, \sigma_v, \dots$, the error of x can be calculated with the general formula for error propagation [142]

$$\sigma_x^2 = \sigma_u^2 \left(\frac{\partial f}{\partial u} \right)^2 + \sigma_v^2 \left(\frac{\partial f}{\partial v} \right)^2 + 2\sigma_{uv} \left(\frac{\partial f}{\partial u} \right) \left(\frac{\partial f}{\partial v} \right) + \dots \quad (\text{F.1})$$

In case of uncorrelated parameters, the covariance σ_{uv} between u and v equals zero and equation F.1 transforms to

$$\sigma_x^2 = \sigma_u^2 \left(\frac{\partial f}{\partial u} \right)^2 + \sigma_v^2 \left(\frac{\partial f}{\partial v} \right)^2 + \dots \quad (\text{F.2})$$

The next sections summarize a few applications of the formula above, which were used to estimate the errors in the previous chapters of this thesis.

F.1 Width of the Z boson

In section 4.3 the fit of the invariant mass distribution of the reconstructed muon pairs has been discussed and the width of this distribution has been studied into detail. The expected width of the Z boson can be calculated from the “narrow width” invariant mass distribution and from the natural width of the Z Boson:

$$\Gamma_Z^{\text{expected}} = \Gamma_Z^{\text{narrow}} \oplus \Gamma_Z^{\text{natural}}. \quad (\text{F.3})$$

Equation F.2 gives the error of the expected width

$$\sigma_{\Gamma_Z^{\text{expected}}} = \sqrt{\left(\frac{\partial \Gamma_Z^{\text{expected}}}{\partial \Gamma_Z^{\text{narrow}}} \right)^2 \sigma_{\Gamma_Z^{\text{narrow}}}^2 + \left(\frac{\partial \Gamma_Z^{\text{expected}}}{\partial \Gamma_Z^{\text{natural}}} \right)^2 \sigma_{\Gamma_Z^{\text{natural}}}^2}, \quad (\text{F.4})$$

where

$$\begin{aligned} \frac{\partial \Gamma_Z^{\text{expected}}}{\partial \Gamma_Z^{\text{narrow}}} &= \frac{1}{2} \left(\left(\Gamma_Z^{\text{narrow}} \right)^2 + \left(\Gamma_Z^{\text{natural}} \right)^2 \right)^{-\frac{1}{2}} 2\Gamma_Z^{\text{narrow}}, \\ \frac{\partial \Gamma_Z^{\text{expected}}}{\partial \Gamma_Z^{\text{natural}}} &= \frac{1}{2} \left(\left(\Gamma_Z^{\text{narrow}} \right)^2 + \left(\Gamma_Z^{\text{natural}} \right)^2 \right)^{-\frac{1}{2}} 2\Gamma_Z^{\text{natural}}. \end{aligned} \quad (\text{F.5})$$

Substitution of F.5 in equation F.4 gives finally

$$\sigma_{\Gamma_Z^{\text{expected}}} = \frac{1}{\Gamma_Z^{\text{expected}}} \sqrt{\left(\Gamma_Z^{\text{narrow}} \sigma_{\Gamma_Z^{\text{narrow}}} \right)^2 + \left(\Gamma_Z^{\text{natural}} \sigma_{\Gamma_Z^{\text{natural}}} \right)^2} \quad (\text{F.6})$$

where equation F.3 has been used again.

Example In section 4.3 the width of the “narrow width” invariant mass distribution for the full pseudorapidity range was $\Gamma_Z^{\text{narrow}} = 1.177 \pm 0.121 \text{ GeV}/c^2$. Together with the natural width of the Z boson $\Gamma_Z^{\text{natural}} = 2.4952 \pm 0.0023 \text{ GeV}/c^2$ [29], the expected width is calculated to be

$$\Gamma_Z^{\text{expected}} = 1.177 \oplus 2.495 \text{ GeV}/c^2 = 2.759 \text{ GeV}/c^2. \quad (\text{F.7})$$

Substitution of these values in equation F.6 results in the error of the expected width

$$\begin{aligned} \sigma_{\Gamma_Z^{\text{expected}}} &= \frac{1}{2.759 \text{ GeV}/c^2} \sqrt{(1.177 \cdot 0.121 \text{ GeV}^2/c^4)^2 + (2.495 \cdot 0.002 \text{ GeV}^2/c^4)^2} \\ &= 0.052 \text{ GeV}/c^2. \end{aligned} \quad (\text{F.8})$$

F.2 Error of the background to signal ratios f_i

The background to signal ratios f_i have been estimated by summing up (integrating) for each background channel the number of events in the bins of the histogram in a given window around the Z boson mass (see section 4.4). This number is afterwards divided by the number of signal events to obtain the background to signal ratio. The error σ_{f_i} on the background to signal ratio can be estimated using error propagation. The formula to calculate the errors will be derived by discussing a simple example.

Given are 3 bins with entries n_1, n_2, n_3 and errors e_1, e_2 and e_3 . The sum (integral) of these bins is given by

$$S = (n_1 + n_2 + n_3) \cdot \text{bin width}. \quad (\text{F.9})$$

With equation F.2 the error of S is

$$\begin{aligned} \sigma_S &= \sqrt{\left(\frac{\partial S}{\partial n_1}\right)^2 e_1^2 + \left(\frac{\partial S}{\partial n_2}\right)^2 e_2^2 + \left(\frac{\partial S}{\partial n_3}\right)^2 e_3^2} \\ &= \text{bin width} \cdot \sqrt{e_1^2 + e_2^2 + e_3^2}. \end{aligned} \quad (\text{F.10})$$

Now consider the case where two sums are available: one for the number of signal events (S_{signal}) and one for the background events ($S_{\text{background}}$). For both sums the error can be calculated with equation F.10 and we obtain $\sigma_{S_{\text{signal}}}$ and $\sigma_{S_{\text{background}}}$.

Finally the background to signal ratio and its error are given by

$$\begin{aligned} f &= \frac{S_{\text{background}}}{S_{\text{signal}}}, \\ \frac{\partial f}{\partial S_{\text{background}}} &= \frac{1}{S_{\text{signal}}}, \\ \frac{\partial f}{\partial S_{\text{signal}}} &= -\frac{S_{\text{background}}}{S_{\text{signal}}^2}, \\ \sigma_f &= \sqrt{\left(\frac{\partial f}{\partial S_{\text{background}}}\right)^2 \sigma_{S_{\text{background}}}^2 + \left(\frac{\partial f}{\partial S_{\text{signal}}}\right)^2 \sigma_{S_{\text{signal}}}^2}, \\ &= \sqrt{\left(\frac{1}{S_{\text{signal}}}\right)^2 \sigma_{S_{\text{background}}}^2 + \left(-\frac{S_{\text{background}}}{S_{\text{signal}}^2}\right)^2 \sigma_{S_{\text{signal}}}^2}, \\ &= \frac{S_{\text{background}}}{S_{\text{signal}}} \sqrt{\frac{1}{S_{\text{background}}^2} \sigma_{S_{\text{background}}}^2 + \frac{1}{S_{\text{signal}}^2} \sigma_{S_{\text{signal}}}^2}, \\ &= f \sqrt{\left(\frac{\sigma_{S_{\text{background}}}}{S_{\text{background}}}\right)^2 + \left(\frac{\sigma_{S_{\text{signal}}}}{S_{\text{signal}}}\right)^2}. \end{aligned} \quad (\text{F.11})$$

For histograms with the same bin width, the latter cancels out completely in the equation above.

F.3 Error of the muon reconstruction efficiency

In section 4.5.2 the muon reconstruction efficiency has been estimated using the “tag & probe” method. The following sections summarize the formulae for the errors of the standalone muon efficiency, the matching efficiency and the tracker efficiency, which were obtained by error propagation utilizing equation F.2.

F.3.1 Standalone muon efficiency

The standalone muon efficiency is given by

$$\varepsilon_{\text{standalone}} = \frac{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}}}. \quad (\text{F.12})$$

The partial derivatives are given by

$$\begin{aligned} \frac{\partial \varepsilon_{\text{standalone}}}{\partial N_{\text{GG}}} &= -\frac{2(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}})}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}})^2} + \frac{2}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}}}, \\ \frac{\partial \varepsilon_{\text{standalone}}}{\partial N_{\text{GM}}} &= -\frac{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}})^2} + \frac{1}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}}}, \\ \frac{\partial \varepsilon_{\text{standalone}}}{\partial N_{\text{GU}}} &= -\frac{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}})^2} + \frac{1}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}}}, \\ \frac{\partial \varepsilon_{\text{standalone}}}{\partial N_{\text{GT}}} &= -\frac{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}})^2}. \end{aligned} \quad (\text{F.13})$$

Substitution of these derivatives in equation F.2 under the assumption that the errors of N_{Gx} are given by $\sigma_{N_{\text{Gx}}} = \sqrt{N_{\text{Gx}}}$ gives finally the error of the standalone muon reconstruction efficiency

$$\begin{aligned} \sigma_{\varepsilon_{\text{standalone}}} &= \sqrt{\frac{N_{\text{GT}} (4N_{\text{GG}}^2 + 4N_{\text{GG}} (N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}}))}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}})^4} + \dots} \\ &\quad \dots + \frac{N_{\text{GT}} (N_{\text{GM}} + N_{\text{GU}}) (N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}})}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GT}})^4}. \end{aligned} \quad (\text{F.14})$$

F.3.2 Tracker efficiency

The error for the tracker efficiency can be obtained by substituting N_{GS} for N_{GT} in all equations of the previous section. The error of the tracker efficiency is given by

$$\begin{aligned} \sigma_{\varepsilon_{\text{standalone}}} &= \sqrt{\frac{N_{\text{GS}} (4N_{\text{GG}}^2 + 4N_{\text{GG}} (N_{\text{GM}} + N_{\text{GU}} + N_{\text{GS}}))}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GS}})^4} + \dots} \\ &\quad \dots + \frac{N_{\text{GS}} (N_{\text{GM}} + N_{\text{GU}}) (N_{\text{GM}} + N_{\text{GU}} + N_{\text{GS}})}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}} + N_{\text{GS}})^4}. \end{aligned} \quad (\text{F.15})$$

F.3.3 Matching efficiency

The matching efficiency is defined in section 4.5.2 as

$$\varepsilon_{\text{matching}} = \frac{2N_{\text{GG}} + N_{\text{GM}}}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}. \quad (\text{F.16})$$

The partial derivatives are

$$\begin{aligned} \frac{\partial \varepsilon_{\text{matching}}}{\partial N_{\text{GG}}} &= -\frac{2(2N_{\text{GG}} + N_{\text{GM}})}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}})^2} + \frac{2}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}, \\ \frac{\partial \varepsilon_{\text{matching}}}{\partial N_{\text{GM}}} &= -\frac{2N_{\text{GG}} + N_{\text{GM}}}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}})^2} + \frac{1}{2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}}}, \\ \frac{\partial \varepsilon_{\text{matching}}}{\partial N_{\text{GU}}} &= -\frac{2N_{\text{GG}} + N_{\text{GM}}}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}})^2}. \end{aligned} \quad (\text{F.17})$$

Substitution of these derivatives in equation F.2, again under the assumption that the errors of N_{Gx} are given by $\sigma_{N_{\text{Gx}}} = \sqrt{N_{\text{Gx}}}$, gives the error of the matching efficiency

$$\sigma_{\varepsilon_{\text{matching}}} = \sqrt{\frac{N_{\text{GU}} (4N_{\text{GG}}^2 + 4N_{\text{GG}} (N_{\text{GM}} + N_{\text{GU}}) + N_{\text{GM}} (N_{\text{GM}} + N_{\text{GU}}))}{(2N_{\text{GG}} + N_{\text{GM}} + N_{\text{GU}})^4}}. \quad (\text{F.18})$$

F.4 Error of the isolation efficiency

In section 4.5.3 the isolation efficiency has been estimated using the “tag & probe” method. The efficiency is given by

$$\varepsilon_{\text{isolation}} = \frac{2N_{\text{Iso,Iso}}}{2N_{\text{Iso,Iso}} + N_{\text{Iso,NoIso}} + N_{\text{NoIso,Iso}}}. \quad (\text{F.19})$$

The partial derivatives are in this case

$$\begin{aligned} \frac{\partial \varepsilon_{\text{isolation}}}{\partial N_{\text{Iso,Iso}}} &= -\frac{4N_{\text{Iso,Iso}}}{(2N_{\text{Iso,Iso}} + N_{\text{Iso,NoIso}} + N_{\text{NoIso,Iso}})^2} + \dots \\ &\quad \dots + \frac{2}{2N_{\text{Iso,Iso}} + N_{\text{Iso,NoIso}} + N_{\text{NoIso,Iso}}}, \\ \frac{\partial \varepsilon_{\text{isolation}}}{\partial N_{\text{Iso,NoIso}}} &= -\frac{2N_{\text{Iso,Iso}}}{(2N_{\text{Iso,Iso}} + N_{\text{Iso,NoIso}} + N_{\text{NoIso,Iso}})^2}, \\ \frac{\partial \varepsilon_{\text{isolation}}}{\partial N_{\text{NoIso,Iso}}} &= -\frac{2N_{\text{Iso,Iso}}}{(2N_{\text{Iso,Iso}} + N_{\text{Iso,NoIso}} + N_{\text{NoIso,Iso}})^2}, \end{aligned} \quad (\text{F.20})$$

Together with the derivatives from equation F.20, the formula for error propagation in equation F.2 and the assumption that the errors of N_{xy} are given by $\sigma_{N_{\text{xy}}} = \sqrt{N_{\text{xy}}}$, the error of the isolation efficiency can be calculated to be

$$\sigma_{\varepsilon_{\text{isolation}}} = 2 \cdot \sqrt{\frac{N_{\text{Iso,Iso}} (N_{\text{Iso,NoIso}} + N_{\text{NoIso,Iso}}) (N_{\text{Iso,Iso}} + N_{\text{Iso,NoIso}} + N_{\text{NoIso,Iso}})}{(2N_{\text{Iso,Iso}} + N_{\text{Iso,NoIso}} + N_{\text{NoIso,Iso}})^4}}. \quad (\text{F.21})$$

F.5 Error of the acceptance

In section 4.5.5 the acceptance has been estimated by counting the events which contain two generated muons within the fiducial volume of the muon system and dividing this number by the total number of events:

$$\varepsilon_{\text{acceptance}} = \frac{N_{2 \text{ muons with } |\eta| < 2.4}}{N_{\text{events}}}. \quad (\text{F.22})$$

Utilizing equation F.2 we obtain

$$\sigma_{\varepsilon_{\text{acceptance}}} = \sqrt{\left(\frac{1}{N_{\text{events}}}\right)^2 \sigma_{N_{2 \text{ muons with } |\eta| < 2.4}}^2 + \left(-\frac{N_{2 \text{ muons with } |\eta| < 2.4}}{N_{\text{events}}^2}\right)^2 \sigma_{N_{\text{events}}}^2}. \quad (\text{F.23})$$

With the assumption that the errors of the event numbers are given by

$$\sigma_{N_{2 \text{ muons with } |\eta| < 2.4}} = \sqrt{N_{2 \text{ muons with } |\eta| < 2.4}} \quad (\text{F.24})$$

and

$$\sigma_{N_{\text{events}}} = \sqrt{N_{\text{events}}}, \quad (\text{F.25})$$

equation F.23 can be simplified to

$$\begin{aligned} \sigma_{\varepsilon_{\text{acceptance}}} &= \sqrt{\frac{1}{N_{\text{events}}^2} N_{2 \text{ muons with } |\eta| < 2.4} + \frac{N_{2 \text{ muons with } |\eta| < 2.4}^2}{N_{\text{events}}^4} N_{\text{events}}} \\ &= \sqrt{\frac{N_{2 \text{ muons with } |\eta| < 2.4}}{N_{\text{events}}^2} + \frac{N_{2 \text{ muons with } |\eta| < 2.4}^2}{N_{\text{events}}^3}} \\ &= \sqrt{\frac{N_{\text{events}} N_{2 \text{ muons with } |\eta| < 2.4} + N_{2 \text{ muons with } |\eta| < 2.4}^2}{N_{\text{events}}^3}} \\ &= \varepsilon_{\text{acceptance}} \sqrt{\frac{1}{N_{2 \text{ muons with } |\eta| < 2.4}} + \frac{1}{N_{\text{events}}}}. \end{aligned} \quad (\text{F.26})$$

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