Search for heavy resonances in the dimuon channel with the D0 detector
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Chapter 5

Experimental Analysis

With the simulated backgrounds and signal in place, the first step of the search for heavy resonances in the dimuon spectrum consists of defining a data set and a number of selection cuts which reduce (known and unknown) backgrounds, but preserve signal, in order to increase the sensitivity of a counting experiment to the presence of a signal (see the next chapter).

The main background comes of course from $\gamma^*/Z \rightarrow \mu^+\mu^-$ decays, which have similar characteristics as the signal events except for the invariant mass (and, depending on the model, the opening angle between the muons). Because of this, the cut on this quantity is optimized explicitly - this is presented in the next chapter.

Since the amount of signal events for which $M_{\mu\mu} \sim M_Z$ is negligible compared to the expected background, the measured $Z$ peak cross section can be used to determine the effective luminosity around the $Z$ peak, assuming the $Z$ cross section is known.

The first cuts described below are efficient (loose) cuts requiring at least two muon objects in the event with matched high-$p_T$ central tracks, one of which is required to be isolated. The efficiencies of these cuts were measured independently on $Z \rightarrow \mu^+\mu^-$ decays using a tag-and-probe method.

Additional loose cuts further reduce backgrounds and increase the quality of the event sample. The efficiencies of these cuts are determined by looking at the number of $Z$ events in the complement samples (the samples of events which fail one cut but pass all other cuts). Backgrounds which are not included in the simulation are shown to be negligible after these cuts.

5.1 Data Set

This analysis is based on the entire "RunIIa" dataset, which was taken between April 2002 and February 2006.

Skim In order to process more quickly the large amount of data included in the entire dataset, events are tagged during reconstruction, which allows one to ‘skim’
CHAPTER 5. EXPERIMENTAL ANALYSIS

<table>
<thead>
<tr>
<th>Trigger Lists</th>
<th>Run Range</th>
<th>delivered (pb⁻¹)</th>
<th>recorded (pb⁻¹)</th>
<th>rec. + DQ (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v8 - v10.3</td>
<td>160582 - 173101</td>
<td>100.4</td>
<td>84.3</td>
<td>52.6</td>
</tr>
<tr>
<td>v10.3 - v13</td>
<td>173352 - 194597</td>
<td>364.7</td>
<td>337.0</td>
<td>304.1</td>
</tr>
<tr>
<td>v13</td>
<td>194567 - 208500</td>
<td>463.1</td>
<td>425.6</td>
<td>374.8</td>
</tr>
<tr>
<td>v14</td>
<td>207217 - 215670</td>
<td>416.8</td>
<td>389.1</td>
<td>332.0</td>
</tr>
<tr>
<td>pre-shutdown</td>
<td></td>
<td>541.2</td>
<td>490.2</td>
<td>411.6</td>
</tr>
<tr>
<td>post-shutdown</td>
<td></td>
<td>803.7</td>
<td>745.7</td>
<td>652.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1345</strong></td>
<td><strong>1236</strong></td>
<td><strong>1064</strong></td>
</tr>
</tbody>
</table>

Table 5.1: Delivered and recorded integrated luminosity before and after data quality requirements, per trigger list, totals before and after the 2004 shutdown (run number 200000), and total.

over the data. The skim\(^1\) definition used for this analysis requires 2 loose muons with a central track \(p_T > 10\) GeV (see below for definition). Because the skim definition is included in the selection, the skimming efficiency is not taken into account separately.

5.1.1 Data Quality

Runs that are marked bad for the calorimeter, SMT, CFT or muon systems, because of some problem with the (sub)detector, are removed from the data using standard tools. Events and luminosity blocks (see 3.2.2) which had been marked as displaying known patterns of calorimeter noise were removed as well. Together these data quality requirements remove about 13% of the initial data sample (see table 5.1).

5.1.2 Luminosity

Table 5.1 lists the delivered luminosity, the recorded luminosity and recorded with data quality requirements, per trigger list, in total and before and after the 2004 shutdown (a trigger list is a combination of triggers used in contiguous runs). The integrated luminosity, as measured by the luminosity system, was determined for the

\(^1\)The Common Sample Group skims that were used correspond to the following SAM dataset definitions for the ROOT-tuples:
- CSG_CAF_2MUhighpt_PASS3_p17.09.06
- CSG_CAF_2MUhighpt_PASS3_p17.09.06b
- CSG_CAF_2MUhighpt_PASS3_p17.09.03

The suffixes denote the version of the d0reco program that were used to reconstruct the events in that part of the skim. The ROOT-tuples were created with TMBAnalyze p18.05.00. In addition, duplicate events that occurred due to mistakes in the reconstruction process were removed from the skim. Versions caf_dq v02-01-01 and dq_defs v2006-11-30 were used to apply data quality criteria.
5.2. MUON RECONSTRUCTION

2MUhighpt skims for an unprescaled trigger which was used during the entire data taking period; the trigger that was used is JT\_125TT. These numbers are not used in the calculation of the cross-section limits, but only as a consistency check to the calculation of the integrated effective luminosity.

5.1.3 Triggers

To ensure the highest possible trigger efficiency, the events are required to have fired any single muon or dimuon trigger in a trigger list (a trigger list is a collection of trigger requirements). These triggers typically require a number of PDT and/or scintillator hits, muon tracks, and possibly a (matched) track. A few triggers in v14 require an isolated track at level 3. Table B.1 on page 124 lists all used triggers per trigger list period.

Since the expected contribution from signal (i.e., $Z'$ decays) is negligible for events with an invariant dimuon mass around the $Z$ mass, assuming a known $Z$ peak cross section the Monte Carlo can be normalized to the measured $Z$ cross section in order to find the effective luminosity $L_{\text{eff}} = \text{acceptance} \cdot \text{efficiency} \cdot L$. This is explained in section 5.4.1.

5.2 Muon Reconstruction

Offline muon objects are identified by using information from the muon detector system, in combination with the central tracker and/or the calorimeter.

For each layer of the muon system, an attempt is made to fit hits into track stubs called segments. Where segments can be matched together, they are fitted into a local muon track.

For muon segments with A-layer hits in the central region of the muon detector ($|\eta| < 1$), PDT pad information is used to improve the resolution in the $\phi$ direction (see below).

Various muon object quality definitions exist, and are detailed in [82]. They differ with respect to the number of required drift tube and scintillator hits and the number of layers in which hits occur. For maximal efficiency, this analysis uses only ‘loose’ muons that are matched to a central track. A central track-matched muon object is called ‘loose’ if it satisfies at least one of the following hit requirements:

- One A-layer scintillator hit and 2 A-layer wire hits; or
- One BC-layer scintillator hit and 2 BC-layer wire hits

In addition to the loose hit requirements, the muons are required to have their scintillator hit(s) occur within 10 ns of the beam crossing time, to reject cosmic events and ensure nominal tracking efficiencies. This does not remove all cosmic muons in the sample, but the muon ID efficiencies are measured relative to this cut. See the discussion in section 5.4.5 for further cuts to reject cosmic muons.
TABLE 5.2: $\sigma$ of a Gaussian fitted over $\mu \pm 3\sigma$ of the difference between the reconstructed muon track position in the direction along the wire at the A-layer and the extrapolated central track position, per octant, with and without using the PDT pad information. Only muons with at least 2 good pad readouts are considered. Errors are statistical only.

<table>
<thead>
<tr>
<th>Octant</th>
<th>$\sigma$ (no pads) (cm)</th>
<th>$\sigma$ (pads) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.14 ± 0.098</td>
<td>5.32 ± 0.046</td>
</tr>
<tr>
<td>2</td>
<td>9.70 ± 0.092</td>
<td>5.23 ± 0.045</td>
</tr>
<tr>
<td>3</td>
<td>10.06 ± 0.097</td>
<td>4.94 ± 0.039</td>
</tr>
<tr>
<td>4</td>
<td>9.88 ± 0.098</td>
<td>4.66 ± 0.039</td>
</tr>
<tr>
<td>5</td>
<td>10.18 ± 0.097</td>
<td>4.63 ± 0.038</td>
</tr>
<tr>
<td>6</td>
<td>10.65 ± 0.12</td>
<td>7.93 ± 0.20</td>
</tr>
<tr>
<td>7</td>
<td>10.31 ± 0.12</td>
<td>8.46 ± 0.11</td>
</tr>
<tr>
<td>8</td>
<td>10.47 ± 0.10</td>
<td>5.24 ± 0.046</td>
</tr>
</tbody>
</table>

PDT pad reconstruction

The muon segment position is precisely measured in the directions orthogonal to the drift chamber wires (thus, parallel to the beam direction), but not in the direction along the wires. A rough estimate is obtained by using the position of the scintillator (with a length of approximately 60 cm) and from the delay between signals measured in two adjacent, connected PDTs (‘axial time’) (see section 3.2.5).

Inside a PDT, charge is collected on an inner cathode pad and an cathode outer pad (see section 3.2.5). Because the pads are tapered, the ratio of the charge collected by the two pads provides information on the position along the wire. Since the tapered geometry of the pads is repeated 11 times along the wire, there is a remaining 11-fold ambiguity. This ambiguity can be resolved by comparing the position measurements of more than one deck and the scintillator / axial time measurements.

By using the pad information, the estimate of the local muon track position is improved (but note that in this analysis, the muon track position is used only for matching the muon to a central track). In order to assess the position resolution improvement obtained by using the pad information, a sample of $Z \rightarrow \mu^+ \mu^-$ events was taken from Run IIa data. The reconstructed muon object position was then compared with the position of the central track, extrapolated to the A-layer.

The events were selected requiring two muon objects, with at least 1 scintillator and 2 wire hits in the A-layer and at least 1 scintillator and 3 wire hits in the B+C layers, matched to central tracks with a $p_T > 15$ GeV/$c$, and an invariant dimuon mass between 70 and 110 GeV/$c^2$. One of the two muons was required to be well within the nominal geometric acceptance for the PDTs. To make sure the muon was matched to the right track, no other tracks were allowed to be within a cone of $\Delta R(\eta, \phi) < 0.5$ (see below for definitions).
Table 5.2 lists the position resolution in each octant of the central muon system, before using PDT pads and after, for muons that had at least 2 good pads read out; this happens in about 65% of the muons, except for octants 6 and 7 where it happens only for about 50%. Octant 6 and 7 are the bottom octants in which some instrumentation is missing due to the presence of the support beams in the ‘bottom hole’.

5.2.1 Central track matching

The loose muons are required to be matched to a central track. The central track can have hits in both the SMT and the CFT, or be CFT-only. The central track resolution is much better than the local muon track resolution.

Even for tight muons (with wire and scintillator hits in every layer and a converged local muon track fit), the local muon track $p_T$ resolution for muons with a $p_T \sim 10$ GeV is around 25% (WAMUS, wide-angle or central part of the muon system) or 20% (FAMUS, forward part of the muon system), for muons with a $p_T \sim 40$ GeV it is around 40%. The loose muons required for this analysis may have a local muon track which is not fit through all layers (and hence have a significantly worse local muon $p_T$ resolution) or which did not converge for some reason. Since the muon $p_T$ is taken from the central track, the more efficient loose muon definition can be used without worsening the resolution (and hence the sensitivity). In addition the analysis is less sensitive to the degree of accuracy to which the muon system geometry is modeled in the detector simulation.

Muons are matched to central tracks by considering all possible matches between muons (both local muon tracks and single segments) and central tracks propagated to the muon system, and also all matches between central tracks and muons propagated to the central track’s point of closest approach to the center of the detector. The unique match with the lowest $\chi^2$ (of all 5 track parameters) is used. No cut on the matching $\chi^2$ is performed. The track matching efficiency is typically on the order of 99%, [82]; it is however not considered separately from the muon ID efficiency.

The track that is matched to the muon object, also loose, is required to have a distance of closest approach (dca) to the primary vertex of at most 0.02 cm if the track has at least one hit in the SMT, or 0.2 cm if it is a CFT-only track. These are loose cuts; the typical resolution for muons coming from $Z$ decays are 20 $\mu$m and 500 $\mu$m respectively.

5.2.2 Efficiency measurements

The muon ID group has measured the loose muon identification times track matching times cosmic veto efficiency and the loose track efficiency, as well as the isolation efficiency on $Z \rightarrow \mu^+\mu^-$ data found in a selected sample from the same dataset used for the analysis, using a tag-and-probe method. The details can be found in [82].

To measure an efficiency with the tag-and-probe method, one requires the control or “tag” muon to satisfy tight selection criteria, designed to filter out all but the $Z \rightarrow \mu^+\mu^-$ events, on both the muon object and the track.
CHAPTER 5. EXPERIMENTAL ANALYSIS

Figure 5.1: *Loose* muon ID efficiency in data as a function of the muon (a) pseudo-rapidity and (b) azimuthal angle at the A-layer of the muon system, and both (c).

Figure 5.2: *Loose* track efficiency in data as a function of (a) the (detector) pseudo-rapidity of the track at the outermost layer of the CFT (at a radius of 51.43 cm) and (b) the $z$ position at the detector center.
The "probe" object is then required to pass all criteria except the one of which the efficiency is being measured; also, the event topology should match that of a $Z \rightarrow \mu^+\mu^-$ event. One then looks at the fraction of events in which the "probe" object passes that selection as well.

When measuring the muon ID $\times$ track matching $\times$ anti-cosmic timing efficiency, as the "probe" one requires a second track satisfying the same criteria as the "tag", and the tracks are required to be back-to-back in the transverse plane only and be isolated in the calorimeter and in the tracker (see below). The efficiency is measured as a function of muon $\eta$ and $\phi$. The results for data are shown in figures 5.1.

When measuring the track reconstruction times $|dca|$ (distance of closest approach) cut efficiency, the "probe" is a muon object which is well separated from the "tag" muon, has a local muon transverse momentum $p_{T \text{local}} > 15$ GeV and a scintillator hit time difference $|\Delta t| < 6$ ns relative to the "tag" muon. The tracking efficiency is measured as a function of the $z$-position of the track at the (3-dimensional) distance of closest approach to the primary vertex. The results for data are shown in figures 5.2.

The efficiencies are measured on data and on Monte Carlo. Because the Monte Carlo does not reproduce the measured efficiencies accurately, it is reweighted with parameterized correction factors; these are presented in section 5.3.

### 5.2.3 CFT-only track correction

CFT-only tracks, i.e., central tracks with no hits in the SMT, are corrected using the run-average beam spot position and uncertainty. (The beam spot is the region of interaction between the colliding beams.)

The reason that the primary vertex is not used to correct tracks (with or without SMT hits) is that a typical high-$p_T$ dimuon event has only a few tracks coming from the true primary vertex (namely, the central tracks of the two muons). Therefore, the primary vertex position and error can be biased towards the muon track vertex.

The run-average beam spot position is reconstructed (using the AATrack package [83]) using from each event the vertex with the maximal track multiplicity, with at least 3 tracks. A given run must have at least 5 events with such a vertex for a beam spot measurement to be made.

For each CFT-only track, the distance of closest approach to the beam spot, $dca_{\text{beam}}$, is computed as

$$dca_{\text{beam}} = r_{dca, \text{signed}} - (x_{\text{beam}} + \Delta x_{\text{beam}} \cdot z) \cdot \sin \phi + (y_{\text{beam}} + \Delta y_{\text{beam}} \cdot z) \cdot \cos \phi$$

where $r_{dca, \text{signed}}$ and $z$ are the track’s signed radial impact parameter ($r_{dca, \text{signed}} = r_{dca} \cdot \text{sign}(\phi_{\text{position}} - \phi_{\text{direction}}$) and $z$-coordinate at the distance of closest approach to the center of the detector, $\phi$ is the track azimuthal angle, $x, y_{\text{beam}}$ is the position of the beam spot at $z = 0$ cm and $\Delta x, \Delta y_{\text{beam}}$ is the slope of the beam. The track curvature is then corrected as
Figure 5.3: Relative additional resolution $\sigma'/p_T$ (see equation (5.1)), (a) pre-shutdown and (b) post-shutdown. Central muons with $|\eta_{CFT}| = 0$, forward muons with $|\eta_{CFT}| = 1.6$.

$$q/p_T \rightarrow q/p_T - dca_{\text{beam}} \cdot \frac{\sigma_T \frac{q}{p_T}}{\sigma_{rr}}$$

where $q$ is the charge and $p_T$ the transverse momentum, $\sigma_T \frac{q}{p_T}$ is the correlation between the curvature and the radial impact parameter and $\sigma_{rr}$ is the uncertainty on the latter.

For runs for which, for whatever reason, no beam position measurement was found in the beam spot database, the measurement from the nearest run in the same store is used instead, since the beam position does not in general experience significant shifts during a store. This happens in only 47 events out of 6 runs in the final sample.

In the Monte Carlo, the center of the detector is used as the beam spot position.

### 5.3 Muon track $p_T$ resolution correction in Monte Carlo

The detector simulation uses an idealized geometry of the tracking system and some of the dead material is not implemented in the simulation. Because of this, and possibly other unknown effects, the resolution of the transverse momentum of the muons is overestimated. Therefore, the muon transverse momentum is ‘smeared’ to fix the detector simulation. This correction becomes large for highly energetic muons (see
5.3. MUON $P_T$ SMEARING

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
 & A ($10^{-3}$ GeV$^{-1}$) & B ($10^{-2}$) \\
\hline
central, & $1.7 \pm 0.1$ (stat) $\pm 0.1$ (syst) & $0.9 \pm 0.3$ (stat) $\pm 0.4$ (syst) & \\
$\geq 1$ SMT hits & $2.1 \pm 0.2$ (stat) $\pm 0.4$ (syst) & $1.2 \pm 0.2$ (stat) $\pm 0.3$ (syst) & \\
\hline
forward, & $2.3 \pm 0.4$ (stat) $\pm 0.5$ (syst) & $1.5 \pm 0.6$ (stat) $\pm 0.7$ (syst) & \\
$\geq 1$ SMT hits & $3.1 \pm 0.4$ (stat) $\pm 0.6$ (syst) & $1.7 \pm 0.5$ (stat) $\pm 0.5$ (syst) & \\
\hline
no SMT hits & $2.7 \pm 0.3$ (stat) $\pm 0.3$ (syst) & $2.1 \pm 0.6$ (stat) $\pm 1.1$ (syst) & \\
 & $2.8 \pm 0.6$ (stat) $\pm 1.0$ (syst) & $2.5 \pm 0.9$ (stat) $\pm 1.1$ (syst) & \\
\hline
\end{tabular}
\caption{Muon smearing parameters, defined in equation 5.1. ‘Shutdown’ refers to the 2004 shutdown.}
\end{table}

The smearing procedure consists of replacing, for a given muon in an event, the reconstructed (or corrected, cf. section 5.2.3) $q/p_T$ of the central track matched to the muon with the ‘smeared’ $q/p_T$ which is sampled from the following distribution,

$$
\frac{q}{p_T} + AG_1 + \frac{B\sqrt{\cosh \eta}}{p_T}G_2
$$

(5.1)

where $q$ is the reconstructed charge, $p_T$ is the original reconstructed transverse momentum, $\eta$ is the reconstructed track (physics) pseudo-rapidity and $G_{1,2}$ are two independent normal distributions.

In order to derive the values for the parameters $A$ and $B$, the predicted reconstructed widths of both the $Z$ and $J/\psi$ resonance were compared with the resonance width observed in dimuon data. The parameters are derived for muons with hits in the SMT and with either $|\eta_{CFT}| < 1.6$ (‘central’) or $|\eta_{CFT}| > 1.6$ (‘forward’), where $\eta_{CFT}$ is the (detector) pseudo-rapidity of the track at the outermost layer of the CFT (at a radius of 51.43 cm); and for muons without hits in the SMT. In addition, the parameter values were derived separately for data taken before and after the fall 2004 shutdown (see figure 3.2), since it was observed that the track resolution changed significantly over the shutdown [82] (for unknown reasons). For each period, the parameters are determined on three separate samples, with the two selected muons either both with SMT hits and both central, both with SMT hits and one muon forward, or with one muon with SMT hits and one without. Table 5.3 lists the parameters derived for each muon type and period.

Figure 5.3 shows the relative additional resolution

$$
\frac{\sigma'(p_T)}{p_T} = \sqrt{A^2 p_T^2 + B^2 \cosh \eta}
$$
5.3.1 \( p_T \) resolution uncertainties

The statistical and systematic uncertainties on the smearing parameters are taken into account as a systematic uncertainty on the expected background. Systematic uncertainties that were taken into account are effects due to the variation of the fit ranges around the \( Z \) and \( J/\Psi \) peaks, variation of the shift of the reconstructed invariant mass, variation of the muon and track quality requirements and \( p_T \) cut.

Figure 5.4 shows the uncertainty propagated to the invariant mass distribution for the combined Monte Carlo background sample. This uncertainty is one of the largest systematic uncertainties, but it is reduced after a kinematic fit, which will be described in section 5.5.

5.4 Event selection

The signal final state is expected to contain opposite-sign muons with high invariant mass coming from the same vertex. The dimuon system is expected to be boosted in the longitudinal direction because of the boost of the parton-parton system, but the muons are expected to be roughly back-to-back in the transverse plane in the majority of the events. The muons are expected to be isolated, i.e., they leave little energy in the calorimeter and have few or low-energetic tracks around them, but a highly energetic muon can radiate and thus be non-isolated in the calorimeter.
5.4. EVENT SELECTION

In the following, the Standard Model Monte Carlo (described in the previous chapter), with the aforementioned $K^{(QCD)}$-factor and $Z\,p_T$ corrections applied, is weighted with parameterized muon, track and isolation efficiency corrections as described above. The corrected background Monte Carlo is normalized to the number of $Z$ events in data, counted with a binned likelihood fit, described here.

A series of one dimensional selection cuts is applied. As a verification of the simulation, the efficiency of each cut on $Z \rightarrow \mu^+ \mu^-$ events is compared between the Standard Model Monte Carlo and data.

5.4.1 $Z$ peak fit

The number of $Z$ events is estimated by a binned likelihood fit on the dimuon invariant mass distributions around the $Z$ mass. The fitted function is a Breit-Wigner resonance shape plus exponential falling background convoluted with a single (shifted) Gaussian with mean $\Delta$ and width $\sigma$, i.e.,

$$f(m; A_{\text{signal}}, A_{\text{bkg}}, \Delta, \sigma, s) = \int_0^\infty dx \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(\frac{x-\Delta}{\sigma})^2} \times \left( A_{\text{bkg}} \cdot e^{-s\cdot(M_Z-m+x)} + A_{\text{signal}} \cdot \frac{\Gamma_Z^2}{\Gamma_Z^2 + (M_Z-m+x)^2} \right)$$

where $M_Z$ and $\Gamma_Z$ are the $Z$ boson mass and width respectively (and are kept fixed). The number of $Z$ events is counted as the integral over the “peak” part of the function

$$N_Z = \int_{M_Z+\Delta-5\cdot\sigma}^{M_Z+\Delta+5\cdot\sigma} dm \ f(m; \ldots) \bigg|_{A_{\text{bkg}}=0}$$

The fit error on this quantity is then computed as the fit error on the integral over the complete (peak and background) function, keeping the size of the interval fixed at $10\sigma$.

In sections 5.4.2ff., we will make a number of selection cuts. For the events failing the cut, the dimuon invariant mass will be shown with a fit to the $Z$ peak as described above. The results of the fits are shown with a dashed error band corresponding to the (approximate) $1\sigma$ confidence intervals of the fit. Also indicated are $N_Z$ and the efficiency $\epsilon$ relative to $N_Z$ measured on the events passing all cuts (see below). The Monte Carlo histograms depict the mass distributions for all background samples, corrected to reproduce the muon ID, track reconstruction and muon isolation efficiencies as described above.

The selection efficiency on $Z \rightarrow \mu^+ \mu^-$ events for each single cut (other than the muon ID, track ID and isolation efficiencies, of which the efficiencies are estimated using the tag-and-probe method) is estimated by counting the number of events coming from a $Z$ decay that fail only that cut. The selection efficiencies are measured on the data as
\[ \epsilon = \frac{N_{Z, \text{pass}}}{N_{Z, \text{fail}} + N_{Z, \text{pass}}} \]

where \( N_{Z, \text{fail}} \) is the number of \( Z \) events failing that specific cut but passing all other cuts and \( N_{Z, \text{pass}} \) the number of \( Z \) events passing all cuts. The uncertainty on \( \epsilon \) is then calculated simply by error propagation of the independent fit errors \( \Delta N_{Z, \text{fail}} \), \( \Delta N_{Z, \text{pass}} \):

\[
(\Delta \epsilon)^2 = \frac{(\Delta N_{Z, \text{fail}})^2 N_{Z, \text{pass}}^2 + (\Delta N_{Z, \text{pass}})^2 N_{Z, \text{fail}}^2}{(N_{Z, \text{pass}}^2 + N_{Z, \text{fail}}^2)^2} \]

this neglects all correlations, and is therefore an upper limit.

The efficiencies in data and their uncertainties are found to be compatible with the same quantities calculated on the Monte Carlo.

**Normalization**

The normalization \( n \) is calculated, for the measured and predicted invariant mass distribution after the kinematic fit, as

\[
n = \frac{N_{Z, \text{data}}}{\sigma_{\text{eff}}(Z)}
\]

where

\[
\sigma_{\text{eff}}(Z) = \epsilon_{\text{MC}}(Z) \cdot \sigma_{Z\to\mu^+\mu^-}
\]

Here the Monte Carlo \( Z \to \mu^+\mu^- \) event selection efficiency \( \epsilon_{\text{MC}}(Z) \) is determined with the binned likelihood fit to the \( Z \) peak in the full Standard Model Monte Carlo (i.e., including all samples). \( \sigma_{Z\to\mu^+\mu^-} \) is the inclusive theoretical NNLO (QCD) \( Z \) production cross section times branching ratio [78],

\[
\sigma_{Z\to\mu^+\mu^-}(\text{CTEQ6.1M}) = 241.59 \text{ pb}^{+8.6}_{-7.7}(\text{PDF})^{+0.6}_{-0.7}(\text{scale})
\]

where the positive and negative errors due to the PDF uncertainty and the factorization / renormalization scale errors are indicated (see section 4.2).

The uncertainty on the normalization is calculated as

\[
(\Delta \pm n)^2 = \left( \frac{\Delta N_{Z, \text{data}}}{\sigma_{\text{eff}}(Z)} \right)^2 + \left( \frac{\Delta \pm \sigma_{\text{eff}} N_{Z, \text{data}}}{\sigma_{\text{eff}}^2} \right)^2 + (\delta_{\text{kin.fit.}})^2
\]

where \( \Delta N_{Z, \text{data}} \) is the fit error, \( \delta_{\text{kin.fit.}} = |n(\text{reconstructed}) - n(\text{kin. fit.})| \) is the difference of \( n \) calculated for the fits to the reconstructed mass distributions with the normalization calculated for the fits to the mass distributions after the kinematic fit, (see section 5.5) and
5.4. EVENT SELECTION

\[ \Delta^{\pm}\sigma_{\text{eff}} = \sqrt{\Delta\epsilon_{MC}(Z)^2 + \Delta^{\pm}\sigma_{Z\rightarrow\mu^+\mu^-}^2} \]

where \( \Delta\epsilon_{MC}(Z) \) is the fit error.

The final result is then

\[ N_{Z,\text{data}} = 78561 \pm 1144 \]

(see figure (5.22(a))), resulting in

\[ n = 1.15 \text{ fb}^{-1} \pm 0.025(\text{fit}) \pm 0.014(\text{reco-kin.fit})^{+0.041}_{-0.037}(\text{theory}), \quad (+0.050_{-0.047} \text{ total}) \]

This number is compatible with the integrated luminosity as measured by the luminosity system (see table 5.1), \( \mathcal{L} = 1.064 \pm 0.064 \text{ fb}^{-1} \) for a high trigger efficiency, as expected (the most probable value of the trigger efficiency is 1).

5.4.2 Track quality

- number of CFT hits \( \geq 6 \)

Figure 5.5 shows the number of CFT hits of events passing all other cuts. As can be seen when the reconstructed width of the \( Z \) peak for events exclusively failing this cut (figure 5.6) is compared with that of the selected events (figure 5.19) (14.0 GeV vs. 7.2 GeV) the invariant mass resolution for these events is considerably worse than...
5.4.3 Isolation

Of the selected muons, one muon in a muon pair is required to be isolated in the tracker and in the calorimeter. This cut suppresses muons coming from heavy quark jets, since these will have tracks and energy deposits coming from other particles in the jet close to the muon track.

Although neither muon in a signal event is expected to originate from a jet, only one muon out of a muon pair is required to satisfy these isolation criteria. This is because at higher energies, it becomes increasingly likely that at least one muon will lose a significant amount of energy in the calorimeter by Bremsstrahlung, which means that a tight isolation cut on the second muon would lead to a loss of sensitivity.

Specifically, it is required that, first

$$\sum_{\Delta R<0.5} |p_T^{(\text{track})}| < 2.5 \text{ GeV}$$

Here, the sum is over the (other) tracks within a cone of $\Delta R(\text{track, muon track}) < 0.5$ around the muon track, where $\Delta R(\phi, \eta) = \sqrt{\Delta \phi^2 + \Delta \eta^2}$ and $\Delta (\phi, \eta)$ is the difference with the muon track angle; this sum is called the “track halo”. Secondly,
5.4. EVENT SELECTION

Figure 5.7: (a) Track halo (cf. equation (5.2)) and (b) calorimeter halo (b) (cf. equation (5.3)), for events passing the cuts on other quantities.

\[ \sum_{0.1<\Delta R<0.4} E_{T}^{(cell)} < 2.5 \text{ GeV} \]  

(5.3)

where here the sum is over the calorimeter cells with a hollow cone of 0.1 < \Delta R(track, cell) < 0.4 around the muon track extrapolated to the calorimeter; this is called “calorimeter halo”. Figures 5.7(a) and 5.7(b) show the track and calorimeter halo for events passing all other cuts.

Efficiency determination  The efficiency of the isolation cut was determined by the muon ID group [82] with the tag-and-probe method, similar to the way the muon ID and tracking efficiencies were determined (cf. section 5.2.2). The “tag” muon was required to have \( \sum_{\Delta R<0.5} p_{T}^{(track)} < 2.5 \text{ GeV} \) and \( \sum_{0.1<\Delta R<0.4} |E_{T}^{(cell)}| < 3.5 \text{ GeV} \). To ensure that the background from heavy flavor quark decays was negligible, the dimuon invariant mass \( M_{\mu\mu} \) was required to lie between 80 and 110 GeV. The dependence of the efficiency on the number of jets with an \( E_{T} > 15 \text{ GeV} \) is taken into account when applying the efficiency correction (see figure 5.8(a)). There is a small muon \( p_{T} \) dependence for \( p_{T} > 20 \text{ GeV}/c \) (see figure 5.8(b)) but it is well-modeled in Monte Carlo [82].

Remaining non-isolated background

An estimate of the remaining non-isolated background (mainly \( Z \rightarrow b\bar{b} \)) can be made by fitting the selected \( Z \) peak plus non-isolated background shapes to events
CHAPTER 5. EXPERIMENTAL ANALYSIS

Figure 5.8: Isolation efficiency for $Z \rightarrow \mu\mu$ data as a function of (a) the number of jets with $E_T > 15$ GeV and (b) muon $p_T$.

marginally passing the isolation cut, in the following way.

Figure 5.9(a) shows a fit (with the sum of two exponentials) to the invariant mass distribution of events in which both muons fail both isolation criteria. This is used to model the shape of the non-isolated background. It can be seen to fall more steeply with increasing dimuon mass than the Drell-Yan background.

The $Z$ peak shape is fitted on events where one muon passes both isolation criteria and one muon fails one isolation criterion (figure 5.9(b)). While the exponential background term has the same shape as for the non-isolated subsample, the $Z$ peak is wider and more shifted. (This is largely because of the $\sim 50\%$ of these events for which the second muon fails the calorimeter isolation but passes the track isolation. These might be due to the second muon radiating off a photon, which means the reconstructed muon track will ‘miss’ some of the muon’s energy. Figure 5.9(d) shows the invariant mass distribution for both subsamples.)

Figure 5.9(c) shows the mass distribution of events where one muon fails both isolation criteria and the other passes them both, fitted with the sum of the background and signal functions. By extrapolation, it can be seen that the amount of non-isolated background in the signal regions ($M \gtrsim 300$ GeV/$c^2$) is negligible.

5.4.4 Topology

- $\Delta z < 3$ cm

The distance between the tracks along the beam direction at the origin is required to be less than 3 cm. This is a loose cut (cf. figure 5.10(a)) to make sure the muons are coming from the same vertex. Figure 5.11 shows the invariant mass of events failing exclusively this cut. The efficiency of this cut measured on $Z$ events is $99.5 \pm 0.4\%$.

- $\Delta R(\phi, \eta) > 0.1$
5.4. EVENT SELECTION

Figure 5.9: Invariant dimuon mass for events in which (a) both muons fail both the calorimeter and track isolation cut (these events are not included in the final selection); (b) one muon passes both isolation cuts and the other fails either the calorimeter or track isolation cut; (c) one muon passes both isolation cuts and the other fails both isolation cuts. (d) shows the invariant mass for events as in (b) for which $M > 40$ GeV/c$^2$, separately for the events where the second muon fails the track isolation cut (dashed line) and the calorimeter isolation cut (solid line). (The events shown in (b), (c) and (d) are included in the selection.) The dotted line in figure (c) shows the fit of figure (a), while the solid line is the peak plus background line of figure (b).
Figure 5.10: (a) $\Delta z$, after all other cuts have been applied. (b) $\Delta R(\phi, \eta)$, after all other cuts have been applied. Both for events with $M > 40$ GeV/c$^2$.

Figure 5.11: Dimuon mass for events exclusively failing the cut on $\Delta z$, data (a) and Monte Carlo (b).
This cut mainly removes events where one muon is reconstructed twice. It is almost completely correlated with a number of other cuts; in the 136298 events passing the muon ID, track and isolation cuts, 14552 dimuon pairs fail the $\Delta R$ cut, but only 6 events fail it exclusively.

The muon pairs failing the $\Delta R$ cut are mainly non-isolated ones, and/or occur in events where a good muon pair is accompanied by a third muon that is very close to one of the other two. Of course the dimuon invariant mass of pairs failing this cut is much smaller than $M_Z$, so in the end it merely serves to ‘clean up’ the complement samples of the other cuts, and does not remove any signal events nor changes the normalization.

### 5.4.5 Cosmic muons

Another background comes from muons originating from cosmic showers, where the same muon is reconstructed as two muon-matched tracks as it traverses the detector. A cut on the difference between the scintillator hit times of both muons, in each layer respectively, removes most cosmic events. However, some cosmic events can pass this cut, since the loose muon definition allows one or more scintillator misses. In order to be able to keep the more efficient loose muon definition but remove all cosmic events from the selection, a tight cut on the polar angle between the muons is applied in addition to the cuts on the timing.

Since for a cosmic event the same muon is reconstructed twice, the two reconstructed muon objects should be exactly back-to-back. Muon pairs produced by a Drell-Yan type process will generally be back to back in the transverse plane, but not in the longitudinal plane, due to the boost of the parton-parton system. Therefore, a cut on the polar angle between the muons will tend to remove cosmic events but not signal events.
Figure 5.13: Time difference between (a) A-, (b) B- and (c) C-layer scintillator hits for events passing the cut on $\eta_1 + \eta_2$ and where both muons have a scintillator hit in that layer.

Specifically, a Gaussian distribution is fitted to the distribution of the sum over the pseudo-rapidities of the two muons, for events failing one of the timing requirements. Events within $\pm 5\sigma$ of this Gaussian are then rejected by this cut. Conversely, the timing cut is derived on events passing the cut on $\eta_1 + \eta_2$ by fitting a Gaussian to the time difference between scintillator hits of each muon in the same layer, and events outside $\pm 5\sigma$ are rejected. (This procedure is iterated between the two cuts, and the selection stabilizes after a few iterations.)

The cut on the polar angle is derived and applied separately for events with none, either or both of the muons having at least one hit in the silicon tracker respectively. The $\Delta t$ cuts are derived and applied independently for the difference between the times of scintillator hits in the A, B and C layer, for events where both muons have a scintillator hit in that layer.

Figures 5.12 shows the $\eta_1 + \eta_2$ distributions with the fits and cut values, while figures 5.13 shows the $\Delta t$ distributions with the fits and cut values.

In addition, each individual muon was required to pass the standard cosmic timing cut of $\pm 10$ ns in the A- and BC-layer (as part of the loose muon quality requirement). This cut is almost completely redundant with the cut on the time difference. It is applied anyway because the muon ID and tracking efficiency corrections were derived for muons passing this cut. Figure 5.14 shows the invariant mass distribution for events failing only this cut; its efficiency for $Z$ events is $98.1 \pm 0.4\%$.

Figure 5.15 shows the invariant mass distribution for events failing only the $\Delta t$ cuts; the efficiency of this cut for $Z$ events is consistent with 100%. Figure 5.16 shows the invariant mass distribution for events failing only the $\eta_1 + \eta_2$ cuts; the efficiency of this cut for $Z$ events is $99.0 \pm 0.3\%$.

Figure 5.17 shows the invariant mass distribution of events failing only (all) the anti-cosmic cuts; no $Z$ peak can be found in this sample.
5.4. EVENT SELECTION

Figure 5.14: Dimuon mass for events exclusively failing the cut on the individual muon scintillator hit times.

Figure 5.15: Dimuon mass for events exclusively failing $\Delta t$ cut, with both muons passing cuts on the individual muon scintillator hit times (scintillator hit times within $\pm10$ ns of beam crossing time).
CHAPTER 5. EXPERIMENTAL ANALYSIS

Figure 5.16: Dimuon mass for events exclusively failing $\eta_1 + \eta_2$ cut.

Figure 5.17: Dimuon mass, events exclusively failing both the timing and $\eta_1 + \eta_2$ cuts. (b) shows the region around the $Z$ peak.
5.4. EVENT SELECTION

5.4.6 Charge

While the signal event final state is expected to contain two oppositely charged muons, no cut on the charge of the muon is in fact applied. On the one hand, the expected remaining Standard Model like-sign background cross section is negligible at higher invariant dimuon mass relatively to the Drell-Yan cross section, while on the other hand the probability that the charge of the muon is wrongly reconstructed increases with the $p_T$ of the muon. To assess the efficiency of a possible charge cut on the selected events, one can look at the fraction of cosmic events (failing the $|\eta_1 + \eta_2|$ and scintillator timing cuts, see figure 5.17) that are opposite sign, as a function of the reconstructed dimuon mass. Since these muon objects are actually likely to be a single muon from a cosmic shower reconstructed twice, their charge should be opposite from each other. From figure 5.18(a), it can be seen that the fraction of correctly measured track curvatures drops for a reconstructed dimuon mass above $\sim 200 \text{ GeV}/c^2$.

The dimuon charge reconstruction efficiency for cosmic muons can be used to obtain an estimate of the expected number of like-sign events in the final sample, assuming that all cosmic events are in fact opposite-sign events. Figure 5.18(b) shows the invariant mass distribution of like-sign muon pairs in the final selected sample (round markers) as well as, per bin, the fraction of like-sign events in the cosmic sample times the number of selected events in that bin (crosses). These can be seen to (roughly) agree at high reconstructed dimuon mass. Of course, the charge reconstruction efficiency is possibly less good for (out-of-time) cosmic events than for events in the final selection.
which would mean that the number of expected like-sign events in the final selection should in fact be lower.

The total number of selected like-sign events with $M > 80 \text{ GeV}/c^2$ is $165 \pm 13$ whereas the estimated expected number is $216^{+473}_{-90}$.

5.4.7 More than 2 muons

In the case that an event has more than one dimuon pair (i.e., combination of two muons) which passes all the cuts, the two ‘most isolated’ muons are selected, i.e., the two muons for which the sum of the track halo and calorimeter halo (see section 5.4.3) is the smallest. This occurs in 45 events in the final sample, out of which 18 have two muon pairs passing all cuts (most of those have two reconstructed muons which do not pass the $\Delta R$ cut together and are likely to be one muon that was reconstructed twice), and 26 events have exactly 3 muon pairs passing all cuts (of which 24 have 3 muons passing all cuts).

Assuming this last signature comes from $\gamma^*/Z \rightarrow \mu^+\mu^-$ decays where a third muon comes from a heavy quark jet, the number of such events in the selected sample gives an upper limit for the expected number of selected $W \rightarrow \mu\nu$ events where the second muon comes from a heavy quark jet. Assuming that $>0$-jet branching fraction is the same for $Z$’s as for $W$’s and neglecting muon selection efficiency correlations,

\[
N(W) \lesssim \frac{\sigma(W \rightarrow \mu\nu)}{\sigma(Z \rightarrow \mu^+\mu^-)} \frac{N_{>1\mu\text{ pair}}}{P_{2\mu\text{ pair}}} \cdot \frac{2.416}{0.2416} \cdot 26/0.56 = 464 \pm 91 \text{ (stat.)}
\]

where $P_{2\mu\text{ pair}}$ is the conditional probability for the second muon in a $Z \rightarrow \mu^+\mu^-$ event to be identified (calculated on the $\gamma^*/Z$ Monte Carlo sample).

For comparison, the expected number of selected $W$ events using the Monte Carlo simulation is 263. Since this background is difficult to predict theoretically, such a discrepancy is not unexpected. In either case, this background is expected to be small.

5.4.8 Final sample

The final data sample contains 94160 events, which is 1.2% of the number of events passing the data quality requirements. Table 5.4 shows the number of events passing each consecutive cut and complement sample size for cuts in the the final event selection. Figure 5.19 shows the reconstructed invariant mass for all dimuon pairs in selected events with a mass around the $Z$ peak. As in previous plots, the distribution is fitted around the $Z$ peak with the generator-level Breit-Wigner plus an exponential background term, convoluted with a non-central Gaussian. In the limit setting, the Monte Carlo normalization will be determined using the result of the kinematic fit, described below.

\footnote{Here and in figure 5.18(a) the statistical error corresponds with the shortest 68.3% Bayesian confidence interval given that the fraction of like-sign events has to lie between 0 and 1; see [84] for details.}
Table 5.4: The number of events passing each cut, starting from the 2MUhighpt skim. The last partition shows the final dimuon selection cuts; 119302 events fail at most one of these cuts; 118248 of those pass the nCFT cut, 118242 of those pass the $\Delta R$ cut as well; etc. The final selected sample passing all cuts contains 94160 events.
Figure 5.19: Reconstructed dimuon mass for events in final selection, data (a) and Monte Carlo (b).

5.5 Kinematic fit

In the final sample, the predominant remaining background in the signal regions ($M_{\mu\mu} \gtrsim 300$ GeV/c$^2$) comes from $Z \rightarrow \mu^+\mu^-$ events where one or both muons has a central track that has been reconstructed with a too high transverse momentum. This is caused by the fact that the track resolution is approximately Gaussian in $1/p_T$ rather than in $p_T$ while the cross section drops exponentially at invariant masses above the Z mass, in addition to possible non-Gaussian effects.

The total transverse energy in the event is expected to add up to zero. The leading order contribution to the hard scatter has two muons that are almost exactly back-to-back with little hadronic recoil in the event, but higher order corrections can lead to events where the dimuon system has a non-zero transverse $p_T$ (more in section 2.2).

The track momenta measurements are improved by a kinematic fit against the total recoil energy of the vector boson, as measured by the calorimeter. The reconstructed muon track polar angles are kept fixed in the fit, as little improvement over the track angle measurement can be expected.

Specifically, for each event the following function is minimized over the fitted muon using the MIGRAD method in MINUIT:

$$\chi^2(p_{T1}, p_{T2}) = \sum_{i=1,2} \left( \frac{1/p_T^{(\text{reco})}_i - 1/p_T^{(\text{reco})} \Delta (1/p_T^{(\text{reco})})}{\Delta p_T^{(Z)}(E_T)} \right)^2 + \left( \frac{p_T^{(Z)}(E_T) - |p_{T1} + p_{T2}|}{\Delta p_T^{(Z)}(E_T)} \right)^2$$

Here,
5.5. KINEMATIC FIT

\begin{align*}
\text{MC} & \quad \chi^2 / \nu = 347 / 32 \quad 0p \ 3.1 \pm -16.4 \quad 1p \ 0.03 \pm 1.08 \\
& \quad 2p \ 0.00057 \pm 0.00171 \quad 3p \ 0.0093 \pm 0.0551
\end{align*}

Figure 5.20: (a) Mean and (b) sigma of a Gaussian fit to the $Z p_T$ distribution per 3.2 GeV bin in the calorimeter missing transverse energy, fitted with the function in equations (5.4) and (5.5) respectively, ($\gamma^*/Z$ Monte Carlo).

- $p_{T_i}^{(\text{reco})}$ is the reconstructed track $p_T$ of the $i$-th muon,
- $\vec{p}_{T1} + \vec{p}_{T2}$ denotes the vector sum over the vectors with length $p_{T1,2}$ in the direction of the reconstructed muon $\vec{p}_{T1,2}$,
- $\Delta(1/p_{T_i}^{(\text{reco})})$ is the resolution on $1/p_{T_i}^{(\text{reco})}$ as a function of $1/p_{T_i}^{(\text{reco})}$,
- $p_{T}^{(Z)}(\not\!E_T)$ is the $p_T$ of the vector boson as a function of the missing transverse energy
- $\Delta p_{T}^{(Z)}(\not\!E_T)$ is the resolution on this quantity, as a function of the missing transverse energy

5.5.1 Recoil parameterization

To estimate the recoil, the transverse calorimeter energy in the event is measured by adding vectorially the energy in calorimeter cells. Energy deposited in cells in the coarse hadronic (CH) layer of the calorimeter is not added, because energy in those cells is mostly from noise. An exception is made if a CH cell overlaps with a “good” reconstructed jet\footnote{“good”/”bad”: jet ID criteria aimed at removing jets that are due to noise, ”hot cells” etc., and reflect the noise characteristics and geometry of the detector. For details of jet reconstruction, jet quality and correction, see \cite{85}}. The calorimeter cell energy is corrected for the electromagnetic energy scale for cells which are part of reconstructed photons and electrons, and for
the jet energy scale for cells in “good” jets. “Bad” jets are removed and their energy
is not added to the total.
To account for the energy loss of the muons, the energy deposited in a 0.1 cone in
\( R(\phi, \eta) \) around each muon was subtracted.
The correlation of the corrected missing transverse energy in the calorimeter, \( \not{E}_T \),
with the true (generator-level) vector boson transverse momentum \( p_T^{(Z)} \) is derived
for the same Monte-Carlo samples that are used to simulate the \( \gamma^*/Z \) background.
These have zero-bias overlay and are reweighted to match the \( Z \) \( p_T \) distribution in
\( Z \to e^+e^- \) data (see section 4.2). The dependence on the missing transverse energy
of the mean \( p_T^{(Z)}(\not{E}_T) \) and one standard deviation width \( \Delta p_T^{(Z)}(\not{E}_T) \) is parameterized
with suitably chosen functions, namely,
\[
p_T^{(Z)}(\not{E}_T) = p_0 + p_1 \not{E}_T + (p_2 \cdot \not{E}_T + p_3)^{-1} \tag{5.4}
\]
\[
\Delta p_T^{(Z)}(\not{E}_T) = \frac{p_0 \not{E}_T}{\sqrt{1 + p_1 \not{E}_T + p_2 \not{E}_T^2}} + p_3 + p_4 \cdot \not{E}_T \tag{5.5}
\]
which are fitted to the mean and width of Gaussian distributions fitted to the \( p_T^{(Z)} \)
distribution for each 3.2 GeV bin in \( \not{E}_T \), as shown in figure 5.20.

### 5.5.2 Track resolution parameterization

The track \( p_T \)-resolution as reproduced by the ‘smeared’ simulation was parameterized
as a function of \( p_T \). Different parameterizations were used for muons without SMT
hits, central muons with SMT hits and forward/backward muons with SMT hits, and
for each of these again for Monte Carlo smeared to match the pre-shutdown and post-
shutdown data (see section 5.3). Figure 5.25 on page 92 (at the end of this chapter)
shows the used parameterizations.

### 5.5.3 Results of the kinematic fit

Figure 5.26 on page 93 shows the kinematic fit pull distributions on \( \gamma^*/Z \) Monte
Carlo. From the fact that these distributions are close to being normal, it can be
inferred that the uncertainties were reasonably well modeled and that the constraint
is close to being Gaussian.

Figures 5.27 show the difference of the true (generated) vector boson mass with the
reconstructed mass and with the fitted mass, respectively, again for \( \gamma^*/Z \) Monte
Carlo. It can be seen that the number of events with a severely overestimated dimuon
mass is reduced significantly after the fit.

In order to compare the fit pull on data and on Monte Carlo, we can compare the
distribution of the following quantity,
\[
\frac{p_T,\text{ reco} - p_T,\text{ fit}}{\sqrt{\sigma_{\text{fit}}^2 - \Delta^2(p_T)}}
\]
Figure 5.22: Binned likelihood fit on the dimuon $Z$ resonance for events after final selection, after the kinematic fit, for data (a) and Monte Carlo (b).

Figure 5.21: Pull difference distributions for central (a, d) and forward (b, e) muons with SMT hits, and muons without SMT hits (c, f). Data (open circles) and Standard Model Monte Carlo (line) with muon resolutions ‘smeared’ to match pre-shutdown (a-c) and post-shutdown (d-f) data.
where $p_T, \text{fit/reco}$ are the measured muon $p_T$ before and after the fit respectively, $\sigma_{\text{fit}}$ is the fit error and $\Delta(p_T)$ is the track $p_T$ resolution. Figures 5.21 on the previous page show the distributions in data and Monte Carlo; they can be seen to agree quite well.

Figures 5.22 show a binned likelihood fit to the $Z$ peak for data and Monte-Carlo after the kinematic fit. The number of counted $Z$ decays and normalization are indicated as well. It can be seen that the overall mass resolution at the $Z$ peak is slightly improved. In addition, the number of $Z$ decays as counted with the fit is slightly increased after the fit as well.

There is a small difference of 1.25% between the Monte Carlo normalization before and after the fit, which is likely due to remaining differences in the track and calorimeter energy resolutions in data and Monte Carlo. This is added as an additional systematic uncertainty on the background prediction (see section 5.4.1).

Finally, figure 5.23 shows the full mass distribution after the fit. As expected, the (absolute) agreement between data and Monte Carlo is much better after the fit, because the dependence on the knowledge of the track resolution is reduced. Accordingly, the systematic uncertainty on the Standard Model background due to the track resolution uncertainty is also reduced (see figure 5.4(b)).

Figure 5.24 shows the ratio of data events over the expected number of background events, before and after the fit, with the systematic uncertainties on the expected background taken into account (for a description of the systematic uncertainties, see section 6.2.2). The difference between data and prediction in the 280 GeV/$c^2$ bin is $1.5\sigma(\text{stat. + syst.})$ after the fit.
Figure 5.24: Ratio of the number of data events to the number of background Monte Carlo events in a bin, as a function of the (reconstructed or fitted) dimuon invariant mass. The dashed line solid line shows the result before the fit, the solid line the result after the kinematic fit. The gray band represents the systematic plus statistical uncertainty on the ratio (the uncertainty on the last bin exceeds the axis limits).
Figure 5.25: Sigma of a Gaussian fit to the true muon 1/\(p_T\) per bin in the central track reconstructed 1/\(p_T\) for central (a, d) and forward (b, e) muons with SMT hits, and muons without SMT hits (c, f). The plots are for Monte Carlo events with the muon resolutions ‘smear’ed’ to match pre-shutdown (a-c) and post-shutdown (d-f) data.
5.5. KINEMATIC FIT

Figure 5.26: Fit pull distributions for central (a, d) and forward (b, e) muons with SMT hits, and muons without SMT hits (c, f). $\gamma^*/Z$ Monte Carlo with muon resolutions ‘smeared’ to match pre-shutdown (a-c) and post-shutdown (d-f) data.
Figure 5.27: Difference of the generated vector boson mass with the reconstructed (closed squares) and with the fitted (open circles) dimuon mass respectively for events with both muons without SMT hits (c, f), or the forward (b, e) muon with with at least one selected central (a, d) or the forward (b, e) muon with SMT hits, smeared to match pre-shutdown (a-c) and post-shutdown (d-f) data. Errors are due to Monte Carlo statistics only.