Chapter 8

Early SUSY Searches at CMS

8.1 Introduction

The previous chapter presented a study of the associated production of Z bosons with one or more jets. Apart from the obvious physics interest these processes are also helpful in commissioning of several reconstruction level variables and algorithms. Apart from the standard model processes, several SUSY models also contribute towards the production of Z bosons at CMS. This mainly happens through the decay chains of neutralinos and charginos which themselves may either be produced in primary interaction or may be produced via cascade decays of gluinos and squarks. The production of Z bosons in the decay chain of neutralinos is a direct implication of the gauge structure of SUSY and is realized whenever it is kinematically allowed, depending on the neutralino composition [96].

Current chapter presents the results for a study done using 36 $pb^{-1}$ of the data collected at CMS to search for possible presence of SUSY like signal in the final states having a lepton pair coming from the decays of Z boson. This is possible because of the appreciable branching ratio of Z boson to decay into an opposite sign and same flavor lepton pair. Along with the Z bosons the end-products of such decay chains include undetectable lightest SUSY particle (LSP), which is manifested as large missing transverse energy in the signal events. To the first order the most significant background for this channel is standard model Z+Jet(s) production. In such events while the Z boson momentum is ac-
accurately measured from its leptonic decay products, the imperfection in the measurement of jet energy scale leads to an instrumental missing $E_T$ mimicking the signal events. The ability to observe an excess of signal over the background therefore relies on the ability to predict this background. Also, there are several other standard model processes most notably $t\bar{t}$ production which can act as possible backgrounds, although they do not involve production of $Z$ boson. Such backgrounds can be easily estimated in a data driven way by using the side bands of the dilepton invariant mass distribution.

Estimation of the backgrounds containing a real $Z$ boson (predominantly $Z$+Jets) is done using Jet-Z (JZB) method which has been devised to predict the missing energy tail of this background [97]. This method exploits the principle of conservation of momentum which requires $Z$ boson to be exactly balanced by the the associated jet system under the ideal conditions. We define JZB as

$$JZB = | - \sum p_T - |p_T^Z|$$

(8.1)

where $p_T$ is the momentum of a particle reconstructed by particle flow, and $p_T^Z$ is the momentum of the $Z$ boson. The sum runs over the list of all the reconstructed particles except the two leptons coming from the decay of $Z$ boson. This variable has been shown to have strong discrimination power against the SM backgrounds in various SUSY scenarios [98]. The analysis presented in this chapter tries to explore the possible strategies for SUSY searches in the early operational phase of data collection at CMS.

### 8.2 Signal Characteristics

The analysis presented in this chapter has been performed using LM4 as a test point for this study due to enhanced production of $Z^0$ in SUSY cascades and in particular in the decay $\chi^0_2 \rightarrow Z^0 + \chi^0_1$ which has 100% branching ratio according to PYTHIA code. The LM4 point is characterised by following parameters: $m_0=210$ GeV, $m_{1/2}=285$ GeV, $A_0 = 0$, $sign\mu = +1$, $\tan\beta =10$. This low mass point has plenty production of gluinos
and squarks, former decay into squarks ($m_{gluino} > m_{squark}$), especially into the sbottoms (B.R = 21%) which then decay into $\tilde{\chi}_2^0$ (B.R=27%). We also have direct production of $\tilde{\chi}_2^0$ associated with other supersymmetric particles, so that in total about one third of all the SUSY decay chains involve $\tilde{\chi}_2^0$ leading to a total production cross section of about 7.1 pb to the leading order. As mentioned earlier $\tilde{\chi}_2^0 \rightarrow Z^0 + \tilde{\chi}_1^0$ and finally $Z^0 \rightarrow e^+ e^- \text{ or } \mu^+ \mu^-$ (B.R=6.7%). Thus the signal events are characterised by large missing $E_T$ due to undetectable LSP and an Opposite Sign Same Flavor (OSSF) lepton pair coming from the decay of $Z^0$ boson. Also we must note that $Z^0$ can be a part of other SUSY decay chains as well, so the inclusive $Z^0$ production cross section (via SUSY) amounts to about 0.475 pb. Among signal events thus about 45% come from $gluino + squark$ chain, 10% come from $gluino + gluino$ chain, 28% come from $squark + squark$ chain and rest 13% come from direct production of $\tilde{\chi}_2^0$. Our strategy for this analysis is as follows: We first explore the event yields for the signal and various standard model backgrounds using Monte Carlo samples and assuming 1 $fb^{-1}$ of the integrated luminosity. The characteristics of the various backgrounds studied in MC will then be used for presenting the possible methods of background estimation in an actual analysis of our kind. Finally we explore the commissioning and performance of our methods using the current 36 $pb^{-1}$ of luminosity integrated by CMS. As mentioned earlier, this signal has significant standard model backgrounds coming from $Z+Jet(s)$ production. Other major backgrounds are $t\bar{t}$, $W+Jet(s)$ productions, while the latter is easily suppressed by improving on the lepton identification former is one of the most important irreducible backgrounds. In addition to these we have also considered some minor backgrounds like $ZZ+Jet(s)$, $WW+Jet(s)$ and $ZW+Jet(s)$ production channels and evaluated the expected levels of contamination by them.
8.3 MC Samples and Event Skimming

The event generation and the detector reconstruction was performed as a part of official Spring10 Monte Carlo production at center of mass energy $\sqrt{s} = 7$ TeV. The signal samples for LM1 benchmark point were generated using Pythia. The QCD multi-jet events, $t\bar{t}$, $Z/\gamma^* +$ Jets, $W+$Jets were generated using the Madgraph matrix element generator [80] and then parton shower, hadronisation are modelled in Pythia [55]. The simulation of detector response was done under ideal conditions without including the pileup. The PAT object creation was done with PF2PAT [99] machinery using CMSSW version CMSSW3.5.7. Then the trigger conditions (HLT) were applied, events were required to fire single muon HLT Mu9 path from 8E29 lean menu. The events passing the HLT are subjected to the skimming logic that requires presence of at least two particle flow muons with $p_T > 20$ GeV and $|\eta| < 2.3$. The distributions for diphoton invariant mass ($M_{\gamma\gamma}$) and transverse momentum ($p_T$) in the skimmed events are shown in figure 8.1. Also the multiplicity of particle flow jets and the missing transverse energy are shown in figure 8.2. Here the red curves represent the sum of all the standard model backgrounds, while the blue curves are for signal only.

8.4 Event Selection and Systematic Uncertainties

Most of the selected events belong to the standard model processes especially $Z+$Jet(s) production. So we apply the certain other criteria in order to reduce the background component. The selection criteria are listed below:

- Events must pass HLTMu9 trigger.
- Both muons must pass identification: $d_\eta < 0.2 \text{ cm}$
- Both muons must be isolated: $iso < 0.16$
- Dimuon Invariant Mass: $60 < M_{\mu\mu} < 120$. 


Figure 8.1: Distributions showing the invariant mass and $p_T$ of dimuon candidate signal and background events which pass the skimming criteria.

Figure 8.2: Distributions showing the jet multiplicity and pfMET variable in signal and background events which pass the skimming criteria.
- Event must have at least 4 particle flow jets with $p_T > 30$ GeV
- $p_{FMET} > 100$ GeV

The flow of the events for signal and background MC samples is shown in the table 8.1.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>LM4</th>
<th>Z.Jet</th>
<th>QCD</th>
<th>W.Jets</th>
<th>$t\bar{t}$</th>
<th>WW</th>
<th>WZ</th>
<th>ZZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skim</td>
<td>702</td>
<td>378099</td>
<td>224567</td>
<td>1405</td>
<td>2800</td>
<td>231</td>
<td>264</td>
<td>211</td>
</tr>
<tr>
<td>DiMu</td>
<td>219</td>
<td>273866</td>
<td>1651</td>
<td>16.9</td>
<td>618</td>
<td>149</td>
<td>150</td>
<td>127</td>
</tr>
<tr>
<td>Mass Wm</td>
<td>159</td>
<td>263837</td>
<td>90.7</td>
<td>0</td>
<td>278</td>
<td>68</td>
<td>134</td>
<td>115</td>
</tr>
<tr>
<td>$N_{jet} &gt; 3$</td>
<td>92</td>
<td>25354</td>
<td>18.4</td>
<td>0</td>
<td>144</td>
<td>1.1</td>
<td>29</td>
<td>16</td>
</tr>
<tr>
<td>$p_{FMET} &gt; 100$</td>
<td>71</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8.1: Flow of events across selection criteria, for the signal and background MC samples

The table above shows that $t\bar{t}$ is the most important irreducible background in final event selection. The $Z+Jet(s)$ appears to be firmly tamed by missing Et requirement. Rest of this section explores the sensitivity of yields towards various sources of systematic uncertainty.

**Jet Energy Scale Uncertainty:** The uncertainty in the absolute jet energy scale even after standard jet energy correction can be present due to several reasons like uncertainty in the correction factors or out of cone energy etc. The sensitivity of the yields towards this is determined by applying ±5 shifts to the PF jet energy scale. Figure 8.3 and table 8.2 summarize the affect of these shifts.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Expected</th>
<th>JES-5%</th>
<th>JES-5%</th>
<th>Δ N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>71 ± 8.4</td>
<td>70 ± 8.3</td>
<td>72 ± 8.4</td>
<td>1.4 %</td>
</tr>
<tr>
<td>Background</td>
<td>21 ± 4.5</td>
<td>20 ± 4.4</td>
<td>21 ± 4.5</td>
<td>4.5 %</td>
</tr>
</tbody>
</table>

Table 8.2: Effect of varying the jet energy scale on the expected number of signal and background events

**Modifying Jet $p_T$ Threshold:** We also explored the effect of changing the jet $p_T$ threshold. Details have been included in the table 8.3.
Figure 8.3: Distributions showing the effect of ±5% change in the jet energy scale.

<table>
<thead>
<tr>
<th></th>
<th>Sample</th>
<th>&gt; 20</th>
<th>&gt; 30</th>
<th>&gt; 40</th>
<th>Δ N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td></td>
<td>71 ± 8.4</td>
<td>64 ± 8.0</td>
<td>57 ± 7.5</td>
<td>9.8%</td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td>21 ± 4.5</td>
<td>13 ± 3.6</td>
<td>9 ± 3.0</td>
<td>19.8%</td>
</tr>
</tbody>
</table>

Table 8.3: Effect of changing the definition of a jet by varying the minimum $p_T$ threshold.
Table 8.4: Flow of events for pythia Z+Jet(s) sample. The numbers have been rounded off to the nearest whole number.

**Z+Jet(s) Yields Using Pythia**: We have used the pythia sample generated in the bins of Z Boson $p_T$ in order to cross check the predictions for Z+Jet(s) yields in final selection. The flow of events in each $p_T$ bin is shown in the table 8.4.

### 8.5 Signal Searches With Data

The simple analysis presented in the previous sections was performed assuming 1 fb$^{-1}$ of the accumulated luminosity. This was done in order to study the characteristics of signal and various MC backgrounds and gain some insight into devising a possible strategy for searches using the present amount of data accumulated at CMS. We use the event selection criteria which are specially tailored for this early phase of the data taking. Hence they may be different from what we used to perform the MC study. This section presents the efforts using the real data collection at CMS in 2011 runs. The data sets used here are given in table 8.5. These samples are processed with CMSW version 3.8.4.patch2.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Sample name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>/EG/Run2010A-Sep17Reco-v2/RECO</td>
</tr>
<tr>
<td></td>
<td>/Electron/Run2010B-PromptReco-v2/RECO</td>
</tr>
<tr>
<td>Muons</td>
<td>/Mu/Run2010A-Sep17Reco-v2/RECO</td>
</tr>
<tr>
<td></td>
<td>/Mu/Run2010B-PromptReco-v2/RECO</td>
</tr>
</tbody>
</table>

Table 8.5: List of data samples and corresponding integrated luminosity used in the analysis.
cross-sections. We have used only the certified runs and luminosity sections as defined in:
Cert_132440-148058.7TeV.StreamExpress.Collisions10.JSON.txt The trigger decision is taken by logical “OR” between a large number of single and dilepton paths chosen to maximize the efficiency. The overlap between electron and muon trigger paths is removed after the full selection, based on the event, run and luminosity section numbers.

The triggered events are then subject to following preselection criteria:

- require at least one good primary vertex with n.d.o.f. $\geq 5$, $|z| < 24$ cm, $|\rho| < 2$ cm;
- require less than 10 tracks, or the fraction of tracks with high purity to be $> 25$%;

The preselected events are now used for the further analysis. We begin by listing the selection criteria used for the physics objects:

**Electrons** are selected from the `gsfElectron` collection with the following criteria:

- $p_T > 20$ GeV
- $|\eta| < 2.5$
- number of missing inner hits $\leq 1$
- $|d_0(\text{primary vertex})| < 0.04$ cm
- $|d_z(\text{primary vertex})| < 1.0$ cm
- simple cut-based electron ID.
- combined relative isolation $< 0.15$

**Muons** are selected from the `muons` collection with the following criteria:

- $p_T > 20$ GeV
- $|\eta| < 2.1$
• require that it be reconstructed as a global muon and a tracker muon

• global muon prompt tight requirement (normalised $\chi^2 < 10$, number of valid hits $> 0$)

• $\delta p_T/p_T < 0.1$ (bound on the track measurement error)

• number of valid tracker hits $\geq 11$

• at least one pixel hit

• number of muon chambers with matched segments $> 1$

• $|d_0(\text{primary vertex})| < 0.02 \text{ cm}$

• $|d_z(\text{primary vertex})| < 1.0 \text{ cm}$

• combined relative isolation $< 0.15$

The combined relative isolation for both lepton species is defined as the sum of ECAL, HCAL and tracker isolation in a cone of $\Delta R = 0.3$ around the lepton, divided by the lepton $p_T$. A $Z$ boson candidate is then formed with the leading lepton (highest $p_T$ lepton) and the second highest $p_T$ lepton with opposite charge.

Jets are selected from corrected Particle Flow (PF) jets in the ak5PFJets collection, with the following criteria:

• $p_T > 30 \text{ GeV}$

• $|\eta| < 3.0$

• loose PF jet identification (all $\eta$):
  - at least 2 constituents
  - neutral EM fraction $< 0.99$
  - neutral hadronic fraction $< 0.99$
loose PF jet identification ($|\eta| < 2.4$ only):

- charged EM fraction < 0.99
- charged hadronic fraction > 0.0
- charge multiplicity > 0

Furthermore, we reject jets that are within a cone of $\Delta R < 0.1$ around any selected lepton (with $p_T > 10 GeV$), in order to avoid double counting of the energy (any lepton also forms a Particle Flow jet). Selected jets are then merely used for jet counting in the definition of the signal region.

Finally, MET is measured with Particle Flow missing energy. Kinematic distributions for selected leptons and jets, in MC and data, are given in figures 8.4, 8.5, 8.6, 8.7. We subsequently define the signal region (SR) as

- at least two selected jets;
- $|m(\ell\ell) - m(Z)| < 20$ GeV;
- $JZB > 50$ GeV

where $m(\ell\ell)$ is the invariant mass of the two lepton candidates, and $m(Z)$ is the $Z$ boson mass. $JZB$ is defined using particle flow information as

$$JZB = | - \vec{E}_T - p_T^{Z} | - |p_T^{\ell\ell}|,$$

and the 50 GeV selection corresponds to the region where $t\bar{t}$ starts to dominate. After this selection, the only relevant SM backgrounds are $Z+$Jet(s) and $t\bar{t}$ channels.

8.6 Background Estimation

For a final state with a $Z$ boson the background is naturally decomposed into two components:

- loose PF jet identification ($|\eta| < 2.4$ only):
  - charged EM fraction < 0.99
  - charged hadronic fraction > 0.0
  - charge multiplicity > 0
Figure 8.4: Kinematic distributions for selected electrons (top), muons (middle) (bottom). Plots on the left show the $p_T$ distributions; plots on the right show the distribution, for data (points) and sum of SM MC samples (histogram).
Figure 8.5: Kinematic distributions for $Z$ boson candidates in data (points) and $s$ SM MC samples (histogram). Left: $Z$ boson $p_T$ distribution, right: $Z$ mass distribution. Top: $Z$ boson from OS electron pairs; bottom: $Z$ boson from OS muon pairs.
Figure 8.6: Jet multiplicity in data (points) and sum of MC samples (histogram), (left) electrons and (right) muons.

- backgrounds with a real (visible) Z boson;
- background without a Z boson, but with an opposite-sign, same-flavor lepton (with invariant mass consistent with the Z mass). (This also includes events with a real Z boson decays into two neutrinos.)

As already mentioned, the first component (mainly Z+Jet(s)) is estimated using the $JZB < 0$, while Physics processes that do not contain a Z boson (mainly $t\bar{t}$) estimated using $e\mu$ pairs. This is schematically represented in table 8.6. ($H_1, H_2, H_3$)

Table 8.6: Schematic of the control samples ($H_1, H_2, H_3$) used to estimate the background event yield in the signal region $H_4$.

<table>
<thead>
<tr>
<th></th>
<th>$JZB &lt; 0$</th>
<th>$JZB &gt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu$ pairs</td>
<td>$H_1$</td>
<td>$H_2$</td>
</tr>
<tr>
<td>$ee$ or $\mu\mu$ pairs</td>
<td>$H_3$</td>
<td>$H_4$</td>
</tr>
</tbody>
</table>

the individual samples used to model the background in the signal region $H_4$. The data-driven background estimation is given by

$$E_B = H_3 \oplus R \times (H_2 \oplus H_1)$$
Figure 8.7: $JZB$ distributions in data (points) and sum of Monte Carlo samples (histogram). The upper plots compare the $JZB$ distribution with (left) and without (right) a requirement on the number of jets. The lower plots compare the $JZB$ distribution without (left) and with (right) a requirement on the number of primary vertices in data, after removing the invariant mass requirement.
where $\oplus(\ominus)$ denotes the addition (subtraction) of the corresponding binned distributions, and $R$ is the sideband normalization factor described below. The prediction is done in terms of a differential distribution of $|JZB|$. The estimated background shape $E_R$ can thus be compared with the distribution in the signal region $H_4$, while the region at low $JZB$, dominated by background, can be used to control the validity of the method. Finally, the actual position of the peak of the $JZB$ distribution is sensitive to the jet energy scale. In order to be robust against miscalibration of the jet energy scale, the position of the peak $\mu_{JZB}$ is used to define the zero of the $JZB$ distribution. $\mu_{JZB}$ is determined by a gaussian fit to the core of the $JZB$ distribution ($\pm 10$ GeV around the peak). The uncertainty on the determination of $\mu_{JZB}$ is propagated to the final result.

8.6.1 Determining Efficiency Ratio: $\frac{\epsilon_e}{\epsilon_\mu}$

In flavor symmetric processes the number of $e^+e^-$ pairs is two times that of $e^+e^-$ and $\mu^+\mu^-$, up to differences in reconstruction and triggering efficiencies. This is shown in figure 8.8. The ratio $R$ of opposite-sign same-flavor (OSSF) lepton pairs to opposite-sign opposite-flavor (OSOF) pairs defined in Eq. 8.2 is equal to

$$R = \frac{1}{\epsilon_e / \epsilon_\mu},$$

where $\epsilon_e$ and $\epsilon_\mu$ are the selection efficiencies. Uncertainties in the estimation of the true value of $\epsilon_e / \epsilon_\mu$ cancel out in the determination of $R$. When the difference in reconstruction efficiencies is small, $\epsilon_e / \epsilon_\mu \approx 2$. For leptons with $p_T > 20$ GeV we expect $R \approx 1$. We estimate the efficiencies ratios using the tag-and-probe measurements, described in Sect. 8.8. We find $\epsilon_e / \epsilon_\mu = 0.946 \pm 0.005$ in data and $\epsilon_e / \epsilon_\mu = 0.969 \pm 0.007$ in MC simulation. Substituting these values in Eq. 8.3 we get $R_{\text{data}} = 1.002 \pm 0.005$ and $R_{\text{MC}} = 1.0010 \pm 0.0007$, justifying the use of $R = 1$. 

8.6.1 Determining Efficiency Ratio: $\frac{\epsilon_e}{\epsilon_\mu}$
Figure 8.8: Shape comparison of the $JZB$ distribution in the $ee$ and $\mu\mu$ final states with that in the $e\mu$ final state, in $t\bar{t}$ MC simulation.

8.6.2 Analysis closure test in MC

The analysis steps described above are first applied in a mixture of MC simulation samples (see Table ??). The corresponding predicted and observed $JZB$ distributions are shown in Figure 8.9. The Gaussian fit to the core of the $JZB$ distribution gives a value for the peak position of $\mu_{JZB} = -1.6 \pm 0.9$, with width $\sigma_{JZB} = 9.2 \pm 1.6$.

The background prediction agrees well with the observed distribution. Based on the remaining discrepancy, a conservative systematic error of $+20\%$ to $-40\%$ is assigned (see Figure 8.9 right). The mean of the ratio between the two distributions is determined from a first-order polynomial fit and found to be $0.93 \pm 0.02$. This indicates a slight overprediction of the background which originates from the jet energy response: the probability for an undermeasurement is higher than the probability of an overmeasurement of the jet energy. This effect is below $10\%$ and it keeps the method on the conservative side. An attempt to correct for it is made. The comparison of the observed and predicted distributions at $JZB < 20$ can thus be used to assess the systematic uncertainty and validate the method directly on data, as will be shown in Section 8.7. In order to demonstrate
Figure 8.9: Closure test in MC simulation comparing background prediction (red histogram) and the observed SM background distribution in the $JZB > 0$ region (left plot). Ratio of observed to predicted number of events in bins of $JZB$ (right plot). The red line shows the mean of this ratio, the solid blue line shows the position of unity the dashed lines show the assigned systematic error.

The robustness of the method against signal contamination in the $JZB < 0$ region, closure test is repeated in a MC sample where the SUSY LM4 signal has been mixed into the SM processes (figure 8.10). The cross-section of the LM4 benchmark point has been scaled by $\times 20$ for the purpose of illustration. The background prediction is slightly raised due to signal contamination in the $JZB < 0$ region. However, the excess of events in the predicted background is still clearly visible.

8.7 Results

The analysis steps are then performed on the CMS data sample. The $JZB$ distributions in the $ee$ and $\mu\mu$ sample, and in the $e\mu$ sample are shown in figure 8.11. A Gaussian interpolation in the $[-10, 10]$ $GeV$ range of the $ee + \mu\mu$ $JZB$ distribution in figure is performed to find the position $\mu_{JZB}$ of the $JZB$ peak in data. We find $\mu_{JZB} = -1.3 \pm 1.4 GeV$, in good agreement with the value found in MC simulation. The width
the distribution, $\sigma_{JZB} = 13.9 \pm 3.3$, is slightly higher due predominantly to pileup effects.

Figure 8.12 (left) shows the comparison between background prediction and observed event yield in the $JZB > 0$ region. The two distributions agree within errors. The ratio of observed to predicted number of events is shown in the right plot of figure 8.12. The agreement is especially good in the low $JZB$ region, which confirms the validity of the method. The mean of the ratio is found to be $0.83 \pm 0.07$, in agreement with that of MC simulation (see figure 8.9).

The number of signal and the background events in the signal region is obtained by integrating the differential $JZB$ shapes above $> 50$ GeV. The final estimates on data are summarized in table 8.7. An additional uncertainty is assigned the background prediction from the uncertainty on $\mu$, which is mainly due to limited statistics. This uncertainty is estimated by repeating the background predictions with $\mu$ varied by $\pm \sigma$. We find an uncertainty of $\pm 2.0^{-1.7}$ and quote it separately from the systematic uncertainty, because it is expected to scale down with luminosity.
Figure 8.11: The $JZB$ distribution in the $ee$ and $\mu\mu$ data sample, and in the $e\mu$ $e\tau$ samples.

Figure 8.12: The $JZB$ distribution in the $ee$ and $\mu\mu$ sample, and the $e\mu$ sample (left). Ratio of observed to predicted number of events in bins of $JZB$ (right).

Table 8.7: Total number of events observed in the signal region ($JZB > 50$ GeV), data, and corresponding background prediction and MC expectation.

<table>
<thead>
<tr>
<th>Observed events</th>
<th>Background prediction</th>
<th>MC expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$9^{+4.1}<em>{-2.9}$(stat)$^{+2.0}</em>{-1.7}$(peak)$^{+1.8}_{-3.6}$(sys)</td>
<td>$5.2 \pm 0.2$ (MC stat)</td>
</tr>
</tbody>
</table>
8.8 Limits on physics beyond the standard model

Using bayesian inference [100] and a profile likelihood model for the nuisance parameters (uncertainty on the number of background events), a 95% C.L. upper limit of 5.6 is set on the number of signal events. This limit is independent of any choice of model. More information is needed, however, in order to confront specific models to our results. In this section we provide additional information on our selection efficiency, including statistical and systematic uncertainties. This information is model-dependent; we provide it for three scenarios: $H$, LM4 and LM8.

8.8.1 Acceptance and selection efficiencies

Our acceptance is defined by two opposite-sign same-flavor leptons ($e^+e^-, \mu^+\mu^-$) with $p_T > 20\text{GeV}$ and $|\eta| < 2.4 (2.5)$ for muons (electrons). The dilepton invariant mass is restricted to the $Z$ boson mass with a window of $20\text{GeV}$. We define $J_{ZB}$ as $| - \sum \vec{p}_T| - |\vec{p}_{T,Z}|$, where the sum is over all visible particles in the event, except the two leptons from the $Z$, and require $J_{ZB} > 50\text{GeV}$. We further require two jets with $p_T > 30\text{GeV}$. For the trigger efficiency, we rely on studies made for the $H$ cross-section [101] and the OS dilepton searches in CMS [102]. The trigger efficiency for two leptons of $p_T > 20\text{GeV}$ is typically higher than 99%, with up to 8% efficiency loss in the rare case of dimuon events where both muons have $|\eta| > 2.4$. This can also be seen in the comparison between data and MC simulation, which has no trigger requirement applied. We therefore assume 100% efficiency and assign a 2% systematic uncertainty to cover the efficiency loss. The lepton selection efficiency is determined using a tag-and-probe method on $Z$+Jet(s) events, in MC simulation and data, as shown in figure 8.13 and summarized in table 8.8. We observe good agreement between data and MC simulation, and assign a 2% systematic uncertainty on efficiencies determined from full MC simulation to account for the difference. The isolation efficiency is part of the selection efficiency and depends strongly on the hadronic activity in the event. In order to quantify this effect, we estimate the selection efficiency.
Table 8.8: Average lepton selection efficiencies determined using a tag-and-probe method on data and Z+Jet(s) MC simulation.

<table>
<thead>
<tr>
<th>Source</th>
<th>data</th>
<th>Z+Jet(s) MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>0.909 ± 0.004</td>
<td>0.933 ± 0.0005</td>
</tr>
<tr>
<td>Muons</td>
<td>0.961 ± 0.003</td>
<td>0.963 ± 0.0003</td>
</tr>
</tbody>
</table>

Figure 8.13: Lepton selection efficiencies determined using a tag-and-probe method on data and Z+Jet(s) MC simulation, in bins of (top) $p_T$ and (bottom) $|\eta|$, for (left) electrons and (right) muons.
in $t\bar{t}$, LM4 and LM8 MC simulation, and compare it to that in $Z+$Jet(s) MC simulation (figure 8.14). In order to determine the effect of the dilepton mass requirement, we first compare the corresponding MC selection efficiency with different requirements on the number of selected jets, as shown in table 8.9. No dependence on the number of jets is observed. The same comparison is then performed in data, with and without correcting for contamination from $t\bar{t}$ processes (by $e\mu$ subtraction). The total efficiency is found to be
Table 8.9: Ratio of the number of events with $|m(\ell\ell) - M_Z| < 20 GeV$ to the number of events with $m(\ell\ell) > 30 GeV$ for data ($L \approx 34 \text{ pb}^{-1}$) and Z+Jet(s) MC simulation ($L \approx 352 \text{ pb}^{-1}$). The numbers corrected for $t\bar{t}$ contamination is also quoted.

<table>
<thead>
<tr>
<th>#(jets)</th>
<th>data (raw)</th>
<th>data (c/r subtr.)</th>
<th>Z+Jet(s) MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 0</td>
<td>$23728/25251$ (94%)</td>
<td>$23678/25072$ (94%)</td>
<td>$25445/26625$ (95%)</td>
</tr>
<tr>
<td>≥ 1</td>
<td>$3019/3878$ (93%)</td>
<td>$3529/3794$ (95%)</td>
<td>$3420/36110$ (95%)</td>
</tr>
<tr>
<td>≥ 2</td>
<td>$774/1289$ (91%)</td>
<td>$688/1170$ (95%)</td>
<td>$574/1152$ (94%)</td>
</tr>
</tbody>
</table>

of the order of 95%, without significant differences between data and MC simulation. The uncertainty in the hadronic energy scale affects distributions for $JZB$ and jet multiplicity. The effect on the jet selection is estimated by varying the jet energy scale by a conservative ±5% [103] and taking the variation in the selection efficiency as a systematic uncertainty. This uncertainty covers the scale uncertainty (when comparing to generator information), as well as differences in data and MC simulation, from which we estimate the number of selected signal events. The resulting uncertainties on the $t\bar{t}$, LM1 and LM8 scenarios are 0.2%, 1.2%, and 1.2%, respectively. The effect of the energy scale uncertainty on the $JZB$ selection is estimated by varying our $JZB$ selection by ±5%, as found in $E_T$ resolution studies, since it is fully correlated with $E_T$. The $JZB$ selection efficiency is shown in figure 8.15 for all scenarios and the $JZB$ response in figure 8.16. The average response is ~92% and it does not depend strongly on the scenario. The $JZB$ distribution is also affected by pileup events, as shown in figure 8.7. Since pileup is the main contributor to the width of the $JZB$ distribution, we use the 50% difference between $\sigma_{JZB}$ in data and MC simulation to quantify this effect on the $JZB$ selection efficiency, using a gaussian model for the $JZB$ resolution. The MC $JZB$ resolution function is first interpolated with a complementary error function. The fitted function is then smeared by 50% and the difference between the two functions is taken as a systematic uncertainty. This is illustrated on figure 8.17. The resulting systematic uncertainties are 39.0%, 5.4%, and 6.9% on $t\bar{t}$, LM1 and LM8, respectively. Also the systematic error on the luminosity is calculated to be 11%.
Figure 8.15: $J_{ZB}$ selection efficiency estimated in MC simulation of $Z$+Jet(s), $t\bar{t}$, $L1$ and LM8. The blue line shows the position of the selection cut.

Figure 8.16: $J_{ZB}$ response estimated in LM4 and LM8 MC simulation. The red line is the result of a linear fit.
Figure 8.17: Estimate of the systematic uncertainty due to pile-up. The solid red line is a fit to the JZB resolution function and the dashed line is the result of the smearing of the fitted function. The vertical blue line shows the cut value.

8.8.2 Upper limit on \((\sigma \times BR \times \text{acceptance})\) in two benchmark scenarios

The systematic uncertainties on efficiencies determined in MC simulation are summarized in table 8.10. The selection efficiencies for the three scenarios are listed in table 8.11, together with the statistical uncertainties and the systematic uncertainties discussed above. Using the above information, we set upper limits on \((\sigma \times BR \times \text{acceptance})\) for the two CMSSM benchmark points LM4 and LM8. The results are shown in table 8.11.

Table 8.10: Summary of systematic uncertainties on efficiencies on MC simulation scenarios.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
<th>t(\bar{t})</th>
<th>LM4</th>
<th>LM8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency</td>
<td>2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton selection efficiency</td>
<td>2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilepton mass selection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.2%</td>
<td>1.2%</td>
<td>1.2%</td>
<td></td>
</tr>
<tr>
<td>JZB scale uncertainty</td>
<td>8.0%</td>
<td>1.1%</td>
<td>1.4%</td>
<td></td>
</tr>
<tr>
<td>Pile-up</td>
<td>39.0%</td>
<td>5.4%</td>
<td>6.9%</td>
<td></td>
</tr>
</tbody>
</table>
Table 8.11: Final selection efficiencies with total statistical and systematic errors, and corresponding upper limits on $(\sigma \times BR \times \text{acceptance})$ for $t\bar{t}$, LM1 and LM8 scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Efficiency [%]</th>
<th>Upper limit [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM1</td>
<td>$93.3 \pm 0.6\text{(stat)} \pm 5.9\text{(syst)}$</td>
<td>0.18</td>
</tr>
<tr>
<td>LM8</td>
<td>$91.3 \pm 0.7\text{(stat)} \pm 7.0\text{(syst)}$</td>
<td>0.19</td>
</tr>
</tbody>
</table>

8.9 NMSSM

The considerations of the naturalness suggest that the entire physical picture at the TeV scale is not fully represented by a single Higgs boson. Rather we expect new physics which may affect the phenomenology of the higgs sector. The Minimal Supersymmetric Model (MSSM) is the leading candidate for the new physics beyond standard model and has a pair of the Higgs doublets with very constrained set of the interactions. The Higgs quartic couplings related to the gauge coupling via supersymmetry, predict a standard model like Higgs with mass not very far from $M_Z$ if the vev value is not fine tuned. But to get above the LEP2 limits on the Higgs mass, even in the MSSM the vev must be fine tuned to be a few percent of the its natural value. This has motivated several extensions to the MSSM Higgs sector to push the Higgs boson above the LEP2 limits. The current survey has been performed in the framework of the NMSSM (Next to Minimal Standard Model) though the analysis is not limited to this particular model only. We here consider a higgs boson that predominantly decays into a pair of the light pseudoscalars (axions), which themselves are kinematically limited to decay into a pair of the tau leptons each. Thus we get final state with four tau leptons where each pair is collimated.

8.9.1 What is NMSSM?

One of the most attractive supersymmetric models is the Next to Minimal Supersymmetric Standard Model (NMSSM) which extends the MSSM by the introduction of just one singlet superfield $S$. When the scalar component of $S$ acquires a TeV scale vacuum expectation value the superpotential term $S H_u H_d$ generates an effective $H_u$
Higgs interaction for the Higgs doublet superfields. Such a term is essential for acceptable phenomenology. No other SUSY model generates this crucial component of the superpotential in as natural a fashion. Thus, the phenomenological implications of the NMSSM at future accelerators should be considered very seriously. One aspect of this is the fact that the $h, H, A, H$ Higgs sector of the MSSM is extended so that there are three CP-even Higgs bosons ($h_1, h_2, h_3$, $m_{h_1} < m_{h_2} < m_{h_3}$), two CP-odd Higgs bosons ($a_1, a_2$, $m_{a_1} < m_{a_2}$) and a charged Higgs pair ($h^\pm$). At the LHC the Higgs bosons are produced via gluon fusion mechanism centrally. This Higgs boson will give rise to two back to back $a^0$ each with a large boost factor. As a result the decay products of the $a^0$ will be collimated. An observation of this signature challenging. First the Higgs bosons are predominantly produced by small $p_T$. Their decays will be isotropically distributed throughout the detector and with four body decays the probability that some particles will be lost is non-negligible. Second in the leptonic decays of the taus a large fraction of the energy is carried in the neutrinos resulting in the soft leptons.

8.9.2 NMSSM Searches in Tri-Lepton Channel

The trilepton channel is one with very little standard model background. Here at least three of the final state taus decay leptonically. We must be careful that these three leptons will be somewhat softer than the those expected from the traditional SUSY signatures. The leptons will have energies of the order 10 GeV roughly. Also since these events contain a substantial number of the neutrinos the Higgs boson mass can not be reconstructed. So this channel is marked by presence of rather substantial amount of the missing energy. The significant standard model backgrounds are form the $t\bar{t}W^\pm$ and $\gamma W^\pm$ which also have large missing energy from the neutrino in the $W^\pm$ decay.

The trilepton Higgs decays make 12.7% of the total branching fraction of the four tau events. There are two challenges in observing this signal: the third lepton is typically soft, all the three leptons must lie with in the geometric acceptance of the detector.
8.10 Summary

We have examined the feasibility of a possible SUSY discovery in the channel $Z + \text{jets} + \not{E}_T$ at CMS. The preliminary study of signal characteristics and background issues was done using Monte Carlo samples. The experience gained therein was used to perform the signal searches using the data collected at CMS. We developed and a novel method for background estimation and presented the first results. Excellent agreement between predicted and measured distributions are observed, both in data and in MC simulation. The results are currently dominated by statistical uncertainties in our search region. Additional information for the confrontation of our results with BSM models was given, and we set upper limits on two benchmark CMSSM scenarios. Finally we have surveyed the possibility of observing possible signature for NMSSM higgs boson in four tau channel. The associated final states were found to be rich in very soft leotons. But we must also take care that the particle identification and missing $E_T$ calculation are still in the commissionig stage. Hence we conclude that this channel must be revisited once we have more data and the various reconstruction algorithms are better commissioned.