Search for SUSY in final states with Z bosons

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Abstract

A search for SUSY processes leading to final states with Z bosons is performed at a low mass point in the mSUGRA parameter space. The signature of such processes is studied using both a complete simulation of the CMS detector and a fast simulation. It is shown that the signal can be seen over the Standard Model background with high significance already at an integrated luminosity of $1 \, fb^{-1}$. The SUSY discovery potential is explored in the $m_\chi, m_{1/2}$ parameter space.
1 Introduction

Certain shortcomings of the Standard Model (SM) such as the hierarchy problem and the quadratic divergencies hint at the possibility of new physics which physicists aspire to explore at very high energy pp collisions at the Large Hadron Collider. A good candidate for solving such shortcomings is the minimal supersymmetric (SUSY) extension of SM known as MSSM [1],[2]. This scenario predicts supersymmetric fermionic and scalar partners to the currently known bosons and fermions, providing, thus, cancellation of quadratic divergencies which appear in loop corrections to the masses. For the detection of SUSY at CMS we work in the minimal Super Gravity (mSUGRA) frame where the soft breaking of the symmetry happens in the gravity hidden sector. In this model only five extra parameters are needed: the universal scalar mass $m_0$, the gaugino mass $m_{1/2}$, a universal trilinear scalar coupling $A_0$, the ratio of the Higgs fields’ vacuum expectation values $\tan(\beta)$ and the sign of the Higgsino mixing parameter $\text{sign}(\mu)$. For the detection of SUSY in this scenario we focus on processes leading to final states with Z bosons which can be easily detected in CMS due to the appreciable branching ratio of the Z boson decaying into an opposite sign same flavour (OSSF) lepton pair (LP). By lepton pair we mean $e^+ e^-$ or $\mu^+ \mu^-$. Final states with Z bosons are mainly produced by the decay of neutralinos and charginos which in turn are produced either directly from the pp collision or through the cascade decays of guinos and squarks. The decay chains finally end with the lightest supersymmetric particle (LSP) which is stable (assuming R-parity conservation) and escapes detection thus appearing as missing transverse energy (MET or $E_T^{miss}$). Therefore, the main signature of SUSY events ending in final states with Z bosons is large MET and an OSSF lepton pair. In this paper we use low mass point LM4 as a test point in order to explore the SUSY discovery potential of CMS through the above mentioned signature.

In the following section we describe in detail the characteristics of this test point and the topology of our signal. In section 3 we describe the reconstruction procedure for the signal and the background events and in section 5 we perform the selection of events. The reach of the analysis is studied in section 6 and the evaluation of the systematic uncertainties is performed in section 7. The final conclusions are given in section 8.

2 Signal Topology and relevant Background

LM4 was chosen as a test point for this study due to the enhanced production of Z bosons in SUSY cascades [3] and in particular due to the decay $\chi^0_2 \to Z + \chi^0_1$. LM4 is characterised by the following parameters: $m_0 = 210 \text{ GeV}$, $m_{1/2} = 285 \text{ GeV}$, $A_0 = 0$, $\text{sign}\mu = +1$, $\tan(\beta) = 10$ [3] The masses of the various sparticles at this point in the mSUGRA parameter space were calculated with ISAJET [4] and are displayed in Table 1.

<table>
<thead>
<tr>
<th>$\tilde{u}$</th>
<th>$\tilde{d}$</th>
<th>$\tilde{s}$</th>
<th>$\tilde{c}$</th>
<th>$\tilde{b}$</th>
<th>$b_{1/2}$</th>
<th>$\tilde{t}$</th>
<th>$\tilde{t}_{1/2}$</th>
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<tbody>
<tr>
<td>L</td>
<td>659.41</td>
<td>664.43</td>
<td>664.43</td>
<td>659.41</td>
<td>575.38</td>
<td>600.63</td>
<td>575.38</td>
</tr>
<tr>
<td>R</td>
<td>640.91</td>
<td>640.65</td>
<td>640.65</td>
<td>640.91</td>
<td>605.56</td>
<td>629.89</td>
<td>492.69</td>
</tr>
<tr>
<td>$\tilde{e}$</td>
<td>$\tilde{\mu}$</td>
<td>$\tilde{\tau}$</td>
<td>$\tilde{\tau}_{1/2}$</td>
<td>$\nu_e$</td>
<td>$\nu_\mu$</td>
<td>$\nu_\tau$</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>290.53</td>
<td>290.53</td>
<td>282.75</td>
<td>232.90</td>
<td>277.05</td>
<td>277.05</td>
<td>275.98</td>
</tr>
<tr>
<td>R</td>
<td>238.53</td>
<td>238.53</td>
<td>231.96</td>
<td>291.84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\chi^0_1$</td>
<td>$\chi^0_2$</td>
<td>$\chi^0_3$</td>
<td>$\chi^0_4$</td>
<td>$\chi^0_5$</td>
<td>$\chi^0_6$</td>
<td>$\chi^0_7$</td>
</tr>
<tr>
<td>L</td>
<td>695.05</td>
<td>110.29</td>
<td>210.24</td>
<td>384.68</td>
<td>403.73</td>
<td>210.39</td>
<td>402.98</td>
</tr>
<tr>
<td>R</td>
<td>114.00</td>
<td>467.87</td>
<td>466.62</td>
<td>474.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h0</td>
<td>H0</td>
<td>A0</td>
<td>H+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>146.00</td>
<td>467.87</td>
<td>466.62</td>
<td>474.29</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The inclusive SUSY production cross section (all processes leading into supersymmetric particles included) at LM4 are calculated with PYTHIA [5] at leading order (LO) and with PROSPINO [6] at leading order (LO) and at next to leading order (NLO) and are shown in Table 2.

At this low mass point we have abundant production of gluinos and squarks. Gluinos ($m_{\tilde{g}} > m_{\tilde{q}}$) decay into squarks and in particular into sbottoms with a 24% branching ratio (Br). Sbottoms then decay into $\chi^0_2$ with approximately 27% Br. We also have direct production of $\chi^0_2$ associated with another supersymmetric particle. In total, approximately 1/3 of the supersymmetric decay chains involve $\chi^0_2$ and the cross section for $\chi^0_2$ production is 7.1 pb (LO). At LM4 $\chi^0_2 \to Z + \chi^0_1$ (100% Br) and finally $Z \to e^- + e^+, \mu^- + \mu^+$ (6.7% Br). Therefore, the
signal events are characterized by large missing $E_T$ (due to the undetectable LSP) and an OSSF lepton pair coming from a Z boson. A Z boson is also the product of other supersymmetric chains and we have approximately a cross section of 7.9 pb for inclusive Z production due to SUSY at LM4. In this analysis we are going to focus on the $\chi^0_2$ chain. As already mentioned, the production cross section of $\chi^0_2$ (and therefore of the Z boson) is 7.1 pb and the decay Br of the Z into leptons is 6.7% thus the signal production cross section is 0.47 pb (LO). Approximately 45% of the signal come from the $\tilde{g} + \tilde{q}$ chain, 10% come from the $\tilde{g} + \tilde{g}$ chain, 28% come from the $\tilde{q} + \tilde{q}$ chain, 13% come from the direct production of $\chi^0_2$.

For this study 27000 signal events were generated using ISAJET interfaced to PYTHIA. The events were processed through the GEANT simulation of the CMS detector, reconstructed and analyzed using the standard CMS software [7], [8]. All possible SUSY processes were considered and no kinematic cuts were imposed at the generator level. Low luminosity pile-up was included.

Another 6000 signal events were produced independently, without pile-up using the same method as the standard CMS production. These events were used in the comparison between the full simulation of the CMS detector and the fast simulation [7], [8].

The main backgrounds for the detection of $\chi^0_2$ through the above decay are Standard Model backgrounds that involve the production of one or more Z bosons in association with jets and Standard Model backgrounds with large cross sections that may decay leptonically and involve large missing $E_T$ such as the production of two W bosons in association with jets and the production of $t\bar{t}$. The following backgrounds were studied: ZZ+jets, ZW+jets, WW+jets, $t\bar{t}$, Z+jets. All backgrounds (except the Z+jets) are inclusive backgrounds, i.e., the Z and the W bosons are not forced to decay leptonically. The production of the Z+jets sample has been done in various $P_T$ (Z) regions, where $P_T$ (Z) is the $P_T$ of the Z boson. We have studied two Z+jets samples that involve high $P_T$ (Z) (and so can give large missing $E_T$) and have large cross sections. In particular, we have studied the samples with 85 GeV $< P_T$ (Z) $<150$ GeV and with 150 GeV $< P_T$ (Z) $<250$ GeV. In addition, there will be also an amount of SUSY events which do not involve $\chi^0_2$ production but have large missing $E_T$ and an OSSF lepton pair with an invariant mass close to the Z invariant mass. These are events that come from supersymmetric chains and may or may not involve production of the Z boson. We are going to name these events (LM4 chains w/o $\chi^0_2$) as SUSY background, considering them as signal for SUSY detection and as irreducible background for the detection of $\chi^0_2$.

All background events include low luminosity pile-up. The LO and the NLO cross sections of the relevant processes are shown in Table 3. When CMS will start data taking we expect to have an integrated luminosity of 10 $fb^{-1}$ in approximately a year of running time.

### Table 2: Inclusive SUSY production cross section at LM4.

<table>
<thead>
<tr>
<th></th>
<th>PYTHIA</th>
<th>PROSPINO LO</th>
<th>PROSPINO NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$(pb)</td>
<td>18.9</td>
<td>19.4</td>
<td>26.7</td>
</tr>
</tbody>
</table>

### Table 3: Signal and background cross sections.

<table>
<thead>
<tr>
<th></th>
<th>LM4 chains with $\chi^0_2$</th>
<th>LM4 chains w/o $\chi^0_2$</th>
<th>ZZj</th>
<th>ZWj</th>
<th>WWj</th>
<th>$t\bar{t}$</th>
<th>$Zj$ 85 GeV</th>
<th>$Zj$ 150 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$(pb)LO</td>
<td>0.47</td>
<td>12.3</td>
<td>12.5</td>
<td>26.7</td>
<td>188</td>
<td>488</td>
<td>88.4</td>
<td>12.7</td>
</tr>
<tr>
<td>$\sigma$(pb)NLO</td>
<td>0.664</td>
<td>17.4</td>
<td>15.5</td>
<td>51.5</td>
<td>270</td>
<td>830</td>
<td>102</td>
<td>14.7</td>
</tr>
<tr>
<td>analyzed sample</td>
<td>27 K</td>
<td>58.6 K</td>
<td>479 K</td>
<td>277 K</td>
<td>463 K</td>
<td>950 K</td>
<td>47.3 K</td>
<td>16.7 K</td>
</tr>
</tbody>
</table>

### 3 Reconstruction of Events

For the reconstruction of the events the standard CMS algorithms were used [7],[8].
3.1 Electron reconstruction

When performing the event simulation there are many more electron candidates reconstructed than the ones generated because jet components such as $\pi$ can make a jet look like an electron. In Figure 1 we see the $P_T$ distribution of the generated and of the reconstructed electrons with $P_T > 17$ GeV and $|\eta| < 2.4$. Generated electrons are matched to reconstructed electrons by looking for reconstructed electrons with $|\phi_{rec} - \phi_{gen}| < 0.01$ and $|\eta_{rec} - \eta_{gen}| < 0.01$. The electron reconstruction efficiency obtained this way is $\sim 88\%$. The purity however of the reconstructed electron sample is very low $\sim 25\%$. In order to distinguish real electrons from electron look-alike background we perform the following cuts:

1. The ratio between the energy deposited by the electron in the hadronic and the electromagnetic calorimeter should be less than 0.02 ($E_{had}/E_{em} < 0.02$).

2. The ratio between the energy deposited in the electromagnetic calorimeter and the track momentum should be more than 0.9 ($E_{em}/P_{track} > 0.9$)

3. The ratio between the energy in the electromagnetic calorimeter and the track momentum should be such that $E_{em}/P_{track} < (1 + 0.02 E_{em}(\text{GeV}))$.

The matching between generated and reconstructed electrons after the previous requirements were applied gives electron reconstruction efficiency $74.5\%$. and reconstructed electron sample purity $93.8\%$.

![Figure 1: $P_T$ of generated (hatched) and reconstructed electrons before quality cuts.](image1)

![Figure 2: $P_T$ of generated (hatched) and reconstructed electrons after quality cuts.](image2)

In Figure 3 the electron $P_T$ resolution $\frac{P_T^{gen} - P_T^{rec}}{P_T^{rec}}$ is plotted. We see that we have an electron $P_T$ resolution of $\sim 2\%$ for the signal.

From the background samples the $t\bar{t}$ and $Z$+jets ($85 \text{ GeV} < P_T(Z) < 150 \text{ GeV}$) backgrounds were studied. For the $Z$+jets background the electron reconstruction efficiency and purity are the same as for the signal events. For the $t\bar{t}$ background both the electron reconstruction efficiency and the purity result somewhat smaller (efficiency=62.2%, purity=84.7%). For both backgrounds the electron $P_T$ resolution is $\sim 2.4\%$.

3.2 Muon reconstruction

In Figure 4 we plot the $P_T$ distribution of the generated and of the reconstructed muons in the signal sample with $P_T > 7$ GeV and $|\eta| < 2.4$ (current di-muon trigger requirements). Generated muons are again matched to reconstructed ones and the resulting muon reconstruction efficiency obtained this way is $\sim 96.9\%$ while the purity of the reconstructed muon sample is $\sim 92.2\%$. For the $Z$+jets background the muon reconstruction efficiency is $\sim 97.6\%$ and the purity of the muon sample is $\sim 98.4\%$ while for the $t\bar{t}$ muon sample we have an efficiency of $\sim 95.3\%$ and a purity of $\sim 91.0\%$. Considering that the purity of the signal and background samples is already adequate no further criteria will be imposed.
In Figure 5 the muon $P_t$ resolution for the signal is plotted. The slight shift in the reconstructed muon $P_t$ of $\sim 1.5\%$ is due to a very slight mismatch in the magnetic field that affected only the production of the signal sample using the full CMS detector simulation. Its effect on the final number of events after all analysis cuts is also very small ($\sim 1.5\%$). The fast simulation and the production of background events were not affected by such mismatch in the magnetic field. The reconstructed muon $P_t$ resolution is $\sim 1.2\%$ for the signal. Also for the $Z+\text{jets}$ ($85 \text{ GeV} < P_t(Z) < 150 \text{ GeV}$) and $t\bar{t}$ backgrounds the muon $P_t$ resolution is similar.

### 3.3 Missing Transverse Energy reconstruction

Within the CMS software, several algorithms can be used to reconstruct MET. In this note we have chosen the algorithm that gives the best accordance with the results of the fast simulation. The fast simulation is going to be used for the calculation of the reach of this analysis in the mSUGRA $m_0 - m_{1/2}$ parameter space and coherence between the two simulations is necessary to guarantee meaningful results. Figure 6 shows the MET distribution obtained using the full CMS detector simulation and the fast simulation. For this comparison, events generated without any pile-up were used. From Fig. 6 we note that there is good agreement between the MET estimation of the full CMS detector simulation and the fast simulation.
Figure 6: MET distribution for 6000 signal events using the complete (triangles, full line) and the fast (dots, dashed line) simulation.

4 Event Selection

4.1 Triggering

In the CMS experiment events are required to pass a global Level 1 (L1) and a global High Level Trigger (HLT) [9] to be recorded in the data. Moreover, the HLT paths that are relevant to the topology of the signal are the di-electron HLT and the di-muon HLT paths and these trigger requirements are going to be used in this analysis. The efficiency of these trigger conditions separately and combined (the OR of the two trigger conditions) is shown in Table 4 for the signal ($\chi_2^0 \rightarrow Z + \chi_1^0$, $Z \rightarrow e^- + e^+$, $\mu^- + \mu^+$) and for the SUSY background (i.e., LM4 decay chains without $\chi_2^0$) which is also considered part of the signal for the search of SUSY.

Table 4: HLT trigger path efficiency before and after reconstructing the Z boson invariant mass for the signal samples.

<table>
<thead>
<tr>
<th>Trigger description</th>
<th>LM4 with $\chi_2^0$</th>
<th>LM4 with no $\chi_2^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT di-electron</td>
<td>65.0%</td>
<td>54.1%</td>
</tr>
<tr>
<td>HLT di-muon</td>
<td>45.7%</td>
<td>55.4%</td>
</tr>
<tr>
<td>OR of 2 paths</td>
<td>92.2%</td>
<td>92.2%</td>
</tr>
</tbody>
</table>

In Table 5 we see the effect of requesting the OR of the two HLT paths on the number of events surviving the selection criteria explained in the following section. As seen from Table 5, choosing these particular two HLT paths does not reduce significantly the signal efficiency. We note that after imposing the Z boson mass requirement in the analysis, the efficiency the OR of the di-electron and the di-muon HLT trigger requirement is higher than 90%.

The effect of the trigger requirement on the signal and on the background samples is shown in Table 6. The overall efficiency of requiring a global L1 and a di-electron or a di-muon HLT condition on the number of signal events that pass the rest of the analysis cuts described in the next section is 96.5%.
Table 5: Effect of the OR of HLT di-electron and HLT di-muon trigger conditions on the signal samples (LM4 with $\chi_2^0$, i.e., $\chi_2^0 \rightarrow Z + \chi_1^0$, $Z \rightarrow e^+e^-$, $\mu^+\mu^-$ and LM4 without $\chi_2^0$) and on the background samples before and after the selection criteria described in section 4.2 for 10 $fb^{-1}$.

<table>
<thead>
<tr>
<th></th>
<th>LM4 with $\chi_2^0$</th>
<th>LM4 w/o $\chi_2^0$</th>
<th>ZZj</th>
<th>ZWj</th>
<th>WWj</th>
<th>$t\bar{t}$</th>
<th>$Zj$ 85 GeV &lt; $P_t(Z)$ &lt; 150 GeV</th>
<th>$Zj$ 150 GeV &lt; $P_t(Z)$ &lt; 250 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ NLO (pb)</td>
<td>0.664</td>
<td>17.4</td>
<td>15.5</td>
<td>51.5</td>
<td>270</td>
<td>830</td>
<td>102</td>
<td>14.7</td>
</tr>
<tr>
<td>10$fb^{-1}$ total events</td>
<td>6640</td>
<td>173.8 K</td>
<td>155 K</td>
<td>515 K</td>
<td>2.7 M</td>
<td>8.3 M</td>
<td>1.02 M</td>
<td>147 K</td>
</tr>
<tr>
<td>L1+HLT</td>
<td>6539</td>
<td>165 K</td>
<td>21.6 K</td>
<td>85.5 K</td>
<td>809 K</td>
<td>3800 K</td>
<td>602 K</td>
<td>118 K</td>
</tr>
<tr>
<td>L1+HLT+</td>
<td>6032</td>
<td>81.7 K</td>
<td>12.6 K</td>
<td>24.4 K</td>
<td>174 K</td>
<td>973 K</td>
<td>387 K</td>
<td>74.7 K</td>
</tr>
<tr>
<td>OR of the two trigger paths efficiency</td>
<td>92.2%</td>
<td>49.7%</td>
<td>58.4%</td>
<td>28.5%</td>
<td>21.5%</td>
<td>25.6%</td>
<td>64.3%</td>
<td>63.3%</td>
</tr>
<tr>
<td>OSSF LP+$M_{ll}$</td>
<td>3876</td>
<td>873</td>
<td>7339</td>
<td>12.1 K</td>
<td>2639</td>
<td>26.7 K</td>
<td>221 K</td>
<td>38.4 K</td>
</tr>
<tr>
<td>OSSF LP+$M_{ll}$+</td>
<td>3773</td>
<td>804</td>
<td>6999</td>
<td>11.5 K</td>
<td>2406</td>
<td>23.1 K</td>
<td>212 K</td>
<td>37.2 K</td>
</tr>
<tr>
<td>OR of the two trigger paths efficiency</td>
<td>97.3%</td>
<td>92.2%</td>
<td>95.4%</td>
<td>95.0%</td>
<td>91.2%</td>
<td>86.5%</td>
<td>96.1%</td>
<td>96.9%</td>
</tr>
<tr>
<td>$E_{miss}+\Delta \phi_{ll}$</td>
<td>1320</td>
<td>288</td>
<td>33</td>
<td>22</td>
<td>52</td>
<td>70</td>
<td>O(1)</td>
<td>44</td>
</tr>
<tr>
<td>$E_{miss}+\Delta \phi_{ll}$+</td>
<td>1289</td>
<td>264</td>
<td>31</td>
<td>22</td>
<td>47</td>
<td>61</td>
<td>O(1)</td>
<td>35</td>
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<tr>
<td>OR of the two trigger paths efficiency</td>
<td>97.6%</td>
<td>91.8%</td>
<td>96.0%</td>
<td>100%</td>
<td>88.9%</td>
<td>87.5%</td>
<td>N/A</td>
<td>80.0%</td>
</tr>
</tbody>
</table>

4.2 Selection procedure

A set of selection criteria is imposed in order to select the signal events and reject the Standard Model background. This set of criteria is suggested by the topology of the signal which contains two opposite sign same flavour leptons reconstructing to the $Z$ boson invariant mass and large MET due to the presence of two undetected $\chi_2^0$s. All criteria were chosen to maximize the final significance estimator $S_{c1} = N_{signal}/\sqrt{N_{bkg}}$ [11] for SUSY detection and for 10 $fb^{-1}$ integrated luminosity. The effect of the selection criteria on the signal and background samples can be seen in Table 6 for 10 $fb^{-1}$ integrated luminosity.

- **L1 and HLT triggering.** Events are required to pass the global L1 and to fire the di-electron or the di-muon path of the HLT trigger.

- **Presence of an opposite sign same flavour lepton pair.** We require that there is an $e^+e^-$ or $\mu^+\mu^-$ pair that satisfies L1 and HLT trigger $P_t$ requirements for each lepton. This means that muons should have $P_t > 7$ GeV to satisfy the di-muon trigger requirement and electrons should have $P_t > 17$ GeV to satisfy the di-electron trigger requirement. We also require that for each lepton $|\eta| < 2.4$.

- **Reconstruction of the $Z$ boson invariant mass.** We require the presence an OSSF lepton pair satisfying the previous requirements and with an invariant mass $M_{ll}$ such that 81 GeV < $M_{ll}$ < 96.5 GeV. The reconstructed masses for the $e^+e^-$ and the $\mu^+\mu^-$ pairs and the mass requirements are shown in Figure 7 and Figure 8 respectively. In the plots SUSY events not involving a $\chi_2^0$ are considered part of the signal. This cut reduces backgrounds not involving a $Z$ boson (such as $t\bar{t}$, WW+jets). It also reduces the contribution from SUSY events not involving a $\chi_2^0$.

- **MET > 230 GeV.** The MET distribution for events that survive all previous requirements is shown in Figure 11 for signal and background. We require a missing $E_T$ larger than 230 GeV. As mentioned before, this cut optimizes the significance of the signal over the background. This requirement significantly reduces all
SM backgrounds, especially the Z+jets production. Eventually, it reduces the signal and the contribution of the SUSY LM4 decay chains not involving a $\chi^0_2$ but it allows for enough signal events in order to maintain good statistics both for $1 \, fb^{-1}$ and for $10 \, fb^{-1}$.

- $\Delta\phi(ll) < 2.65$ rad. $\Delta\phi$ is the angle in the transverse plane between the two leptons of the lepton pair that reconstructs to the mass of the Z boson and is required to be less than 2.65 rad. In the unlikely event that there is more than one lepton pairs with $81 \, GeV < M_{ll} < 96.5 \, GeV$, we choose the one whose invariant mass is closer to the Z mass. This requirement targets the remainder of the $t\bar{t}$ and the WW+jets background events that survive from the MET requirement. For these backgrounds, the angle between the two leptons that accidentally reconstructed to the mass of the Z tends to be large. This happens because the two leptons come from the two distinct decay chains (one lepton from each W or t), thus they have large $\Delta\phi$. On the other hand, in the signal events both leptons come from one Z boson, which in addition tends to carry high $P_T$. Thus, in signal events the two leptons usually have small separation angle $\Delta\phi$. Figure 9 shows the $\Delta\phi$ distribution for the $t\bar{t}$ sample. Events with one same flavour opposite sign lepton pair are used, satisfying the first three selection criteria. Events are not required to pass the MET cut in order to have enough statistics to describe the $\Delta\phi$ behaviour of the $t\bar{t}$ sample. $\Delta\phi$ does not seem to depend on the MET of the event as seen in Figure 10 where we have plotted the profile distribution of the MET vs $\Delta\phi$ for the same $t\bar{t}$ sample. Figure 9 shows that the angle between the two leptons that accidentally reconstruct to the Z boson mass in the $t\bar{t}$ background tends to be large.

Figure 12 shows the $\Delta\phi$ distribution for signal and background events that pass all previous analysis requirements. The effect of this requirement and the final number of signal and background events is seen in Table 6.

After the application of the above criteria for an integrated luminosity of $10 \, fb^{-1}$ we have $1553.0 \pm 33.2$ signal events and $196.5 \pm 40.3$ background events. The ratio of the signal events to the background events is 7.9. The significance estimator for SUSY detection is then

$$S_{cl\_SUSY} = \frac{N_{signal}}{\sqrt{N_{bg}}} = 111$$  \hspace{1cm} (1)

If a different significance estimator is used [11]:

$$S_{cl\_SUSY} = \sqrt{2 \ln(Q)} \hspace{0.5cm} \text{with} \hspace{0.5cm} Q = (1 + \frac{N_{signal}}{N_{bg}})N_{s}e^{N_{s}e}\exp(-N_{signal})$$  \hspace{1cm} (2)

we find that $S_{cl\_SUSY}$ is 67.
Figure 9: $\Delta\phi_{ll}$ distribution for $t\bar{t}$ background events that pass the first three requirements.

Figure 10: MET versus $\Delta\phi_{ll}$ profile distribution for $t\bar{t}$ background events that pass the first three requirements.

Figure 11: MET distribution for signal (shaded) and background events that have an OSSF lepton pair that reconstruct to the Z boson mass. SUSY events not involving a $\chi^0_2$ are considered part of the signal. The vertical line indicates the MET requirement.

Figure 12: $\Delta\phi_{ll}$ distribution for signal (shaded) and background events that pass all previous requirements. The value of the $\Delta\phi_{ll}$ cut is indicated by the vertical line and again SUSY events not involving a $\chi^0_2$ are considered part of the signal.
Table 6: Number of events for signal ($\chi^0_2 \rightarrow Z + \chi^0_1$, $Z \rightarrow e^- + e^+$, $\mu^- + \mu^+$) and background before and after selection criteria for 10 $fb^{-1}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>LM4 with $\chi^0_2$</th>
<th>LM4 w/o $\chi^0_2$</th>
<th>ZJ</th>
<th>ZWj</th>
<th>WWj</th>
<th>$t\bar{t}$</th>
<th>Zj 85 GeV</th>
<th>Zj 150 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ NLO (pb)</td>
<td>0.664</td>
<td>17.4</td>
<td>15.5</td>
<td>51.5</td>
<td>270</td>
<td>830</td>
<td>102</td>
<td>14.7</td>
</tr>
<tr>
<td>10^6 $fb^{-1}$</td>
<td>6640</td>
<td>173.8 K</td>
<td>155 K</td>
<td>515 K</td>
<td>2.7 M</td>
<td>8.3 M</td>
<td>1.02 M</td>
<td>147 K</td>
</tr>
<tr>
<td>L1+HLT,di-el</td>
<td>6032</td>
<td>81.7 K</td>
<td>12.6 K</td>
<td>24.4 K</td>
<td>174 K</td>
<td>973 K</td>
<td>387 K</td>
<td>74.7 K</td>
</tr>
<tr>
<td>di-muon</td>
<td>4489</td>
<td>7147</td>
<td>9124</td>
<td>14.7 K</td>
<td>26.3 K</td>
<td>268 K</td>
<td>281 K</td>
<td>49.5 K</td>
</tr>
<tr>
<td>OSSF LP</td>
<td>3773</td>
<td>804</td>
<td>6999</td>
<td>11.5 K</td>
<td>2406</td>
<td>23.1 K</td>
<td>212 K</td>
<td>37.2 K</td>
</tr>
<tr>
<td>$E_{miss}$</td>
<td>1420</td>
<td>306</td>
<td>32</td>
<td>24</td>
<td>70</td>
<td>149</td>
<td>O(1)</td>
<td>44</td>
</tr>
<tr>
<td>$\Delta\phi_{ll}$</td>
<td>1289</td>
<td>264</td>
<td>31</td>
<td>22</td>
<td>47</td>
<td>61</td>
<td>O(1)</td>
<td>35</td>
</tr>
</tbody>
</table>

From the sample which we considered as signal for SUSY detection, a large fraction (264 events) consists of SUSY events which do not involve $\chi^0_2$ production. If the aim is the discovery of $\chi^0_2$ in the mSUGRA scenario, then the SUSY events not involving $\chi^0_2$ production are considered part of the background.

We optimize the MET and $\Delta\phi(ll)$ requirements considering LM4 events not involving $\chi^0_2$ as background. With the optimized criteria, i.e., MET>215 GeV and $\Delta\phi(ll)<2.65$ rad, we obtain significances $S_{3\ell} = 60$ and $S_{CL} = 47$ for $\chi^0_2$ detection. The slight change in the MET requirement value reflects the fact that the LM4 events (subtracted now from the signal and added to the background) carry high MET. Figures 13 and 14 show the distributions of the reconstructed $e^+e^-$ and $\mu^+\mu^-$ invariant mass for events that come from $\chi^0_2$ SUSY chains and from background which includes both SM background and SUSY events with no $\chi^0_2$ production. Figure 11 shows the respective MET distributions for events that have an OSSF lepton pair that reconstructs to the Z boson mass. Figure 12 shows the respective $\Delta\phi_{ll}$ distribution for events that pass the MET>215 GeV requirement.

Figure 13: Reconstructed invariant mass of $e^+e^-$ pairs for the background and for the signal (shaded) events. Only events with $\chi^0_2$ production are considered signal. The vertical lines indicate the imposed mass requirement

Figure 14: Reconstructed invariant mass of $\mu^+\mu^-$ pairs for the background and for the signal (shaded) events. Again, only events with $\chi^0_2$ production are considered signal and the vertical lines indicate the imposed mass requirement
Figure 15: MET for background (line) and signal (shaded) events with an OSSF lepton pair that reconstructs to the Z boson mass. SUSY events not involving $\chi_2^0$ production are considered part of the background. The vertical line indicates the MET requirement that optimizes $\chi_2^0$ detection at LM4.

Figure 16: $\Delta\phi_{ll}$ distribution for OSSF lepton pairs that reconstruct to the Z boson mass for background (black line) and signal (shaded) events with MET $>$ 215 GeV. SUSY events not involving $\chi_2^0$ production are considered part of the background. The vertical line indicates the $\Delta\phi_{ll}$ requirement that optimizes $\chi_2^0$ detection at LM4.

For 1 fb$^{-1}$ integrated luminosity we have used estimator $S_{cL}$ (Eqn. 2). When looking for SUSY detection the optimization yields again MET $>$ 215 GeV, $\Delta\phi_{ll} < 2.65$ rad resulting in $S_{cL,SUSY} = 21$, while in the case of a search for $\chi_0^0$ production, the optimization yields MET $>$ 200 GeV, $\Delta\phi_{ll} < 2.75$ rad and $S_{cL} = 15$. This optimization (MET $>$ 200 GeV, $\Delta\phi_{ll} < 2.75$ rad) results again to $S_{cL,SUSY} \sim 21$.

5 Reach of the analysis

Point LM4 is used as a benchmark in order to plan the analysis that may reveal new physics in the mSUGRA scenario. Keeping $A_0 = 0$, $\sin\mu = +1$ and $\tan(\beta) = 10$, we scanned the mSUGRA $m_0$, $m_{1/2}$ parameter space in order to see if the above analysis can reveal new physics. 192 points were investigated. The test points were taken at high density in the area where the Z boson has a high production cross section (especially due to the decay $\chi_2^0 \rightarrow Z + \chi_0^0$). This is an almost horizontal band in the $m_0 - m_{1/2}$ plane between $m_{1/2} \sim 240$ GeV and $m_{1/2} \sim 320$ GeV. There were also points taken at higher and lower $m_{1/2}$ values, because, due to SUSY processes, there is an excess of lepton pairs which may reconstruct to the Z boson mass. For each point 2000 events were produced with an OSSF lepton pair close to the mass of the Z. The events were generated interfacing ISAJET with PYTHIA and they were simulated and analyzed using the fast simulation of CMS. Since the aim is the discovery of new physics the SUSY background events (SUSY events that do not involve $\chi_0^0$ production) are considered part of the signal and can not be at this point distinguished from the SUSY events involving $\chi_0^0$ production. An average 96.5% efficiency was taken in the final signal events in order to simulate the effect of the global L1 and the HLT trigger requirement. The LO cross section was used for SUSY processes since the K-factors were not computed at each point. This is a conservative approach since the background is estimated with NLO accuracy. In the case of 10 fb$^{-1}$ integrated luminosity we have used the values MET $>$ 230 GeV and $\Delta\phi(ll) < 2.65$ rad which optimize the significance for SUSY discovery at LM4. In the case of 1 fb$^{-1}$ integrated luminosity we have used the significance estimator $S_{cL}$ (Eqn. 2) and the values MET $>$ 215 GeV and $\Delta\phi(ll) < 2.65$ rad which optimize the significance for SUSY discovery at LM4 for 1 fb$^{-1}$. Figure 19 shows the resulting 5 $\sigma$ significance contours for integrated luminosities of 10 fb$^{-1}$ and 1 fb$^{-1}$.

6 Systematics

Systematic errors arise from the calculation of the significance of the signal and these are mainly due to our imperfect knowledge of the detector and of the background. When data taking starts we can gain a lot of information that can help control some of the uncertainties. In the mean time, and from our present knowledge, we can estimate
some of the most relevant uncertainties. These are the uncertainties relevant to the experimental selection (or better rejection) of the background events and the uncertainties in the theoretical calculation of the background cross section and the uncertainty in the measurement of the luminosity. For the theoretical uncertainties in the NLO cross sections of the leading background (t\bar{t}) we estimate that we have 2.5% uncertainty due to PDF [12] and a 5% due to scale variation [13]. The uncertainty in the luminosity is taken \( \sim 5\% \) according to [8] which introduces a \( \sim 5\% \) uncertainty in the number of the background events.

The experimental uncertainties refer to quantities used for the rejection of the background events and these are mainly the lepton \( P_t \) resolution and the MET estimation. The lepton \( P_t \) resolution is estimated to be \( \sim 3\% \) [14] [15]. This affects also the measurement of \( \Delta\phi \) and results in a systematic uncertainty of 2.7% in the number of background events. The systematic error related to MET follows the systematic uncertainty of the Jet Energy Scale (JES). MET consists of a high \( P_t \) component (jets of high \( P_t \)) and a low \( P_t \) component (jets of low \( P_t \), unclustered towers). High \( P_t \) components have a JES systematic uncertainty of \( \sim 3\% \) [16], while low \( P_t \) components have a JES systematic uncertainty that varies between 10% and 3% depending on the \( P_t \) [17]. This results to an average MET systematic uncertainty of 5%. This MET uncertainty has been applied to the background samples. In order to have better statistics this uncertainty was applied in the background samples that has passed the trigger requirements and have one OSSF lepton pair with reconstructed invariant mass \( M_{\ell\ell} > 30 \text{ GeV} \). Figure 17 shows the MET distribution for the case of \( t\bar{t} \) events with an OSSF lepton pair with \( M_{\ell\ell} > 30 \text{ GeV} \). In order to understand if there is a correlation between the lepton invariant mass and the MET, we plot the profile distribution of MET versus the lepton invariant mass of \( \mu^+\mu^- \) pairs in Figure 18. No obvious dependence is seen.

We calculate the uncertainty as \( \frac{\Delta N^+ - \Delta N^-}{2} \) where \( \Delta N^+ \) (\( \Delta N^- \)) is the difference in the number of events when the MET is overestimated (underestimated) by 5%. This uncertainty is estimated to be \( \sim 20\% \) of the \( t\bar{t} \) background. The effect of the MET uncertainty was similar also to the rest of the background samples. Adding quadratically the uncertainties we find a \( \sim 9.5\% \) uncertainty in the number of background events. This uncertainty is applied in order to recompute the significance estimators.

For the 10 \( fb^{-1} \) case we have used the significance estimator \( S_{cl} = \frac{N_r}{\sqrt{(N_b + \Delta N_b^2)}} \) and the resulting significance for SUSY detection at LM4 for 10 \( fb^{-1} \) (MET>230 GeV, \( \Delta\phi < 2.65 \text{ rad} \)) considering systematics is \( S_{cl,SUSY} = 6.7 \). Due to the uncertainty the reach is also reduced.

For the 1 \( fb^{-1} \) case, there is not available code that calculates the significance estimator \( S_{cl} \) taking into account experimental uncertainties. Therefore, for the calculation of the reach we have used the significance estimator \( S_{cP} \) [18], which for event counting gives similar results to \( S_{cl} \). The significance \( S_{cP} \) gives the probability from Poisson distribution with mean \( N_b \) to observe equal or greater than \( N_{0_{be}} \) events, converted to equivalent number of \( \sigma_s \) of a Gaussian distribution. The code that calculates \( S_{cP} \) takes into account experimental uncertainties. For large values of \( S_{cP} \) (\( S_{cP} > 6.2 \)) there are technical problems in the calculation of \( S_{cP} \), thus, estimator \( S_{cl2} \) [19],[20] is used.

Figure 17: MET distribution for \( t\bar{t} \) events with one OSSF lepton pair with \( M_{\ell\ell} > 30 \text{ GeV} \).

Figure 18: Profile distribution of MET vs \( M_{\ell\ell} \) of \( \mu^+\mu^- \) pairs for \( t\bar{t} \) events.
which is calculated with the following formula taking into account experimental uncertainties:

\[
S_{c12} = 2 \times (\sqrt{N_b + N_a} - \sqrt{N_b}) \times \text{factor}, \quad \text{where} \quad \text{factor} = \frac{\sqrt{N_b}}{\sqrt{N_b + \Delta N^2_b}}
\]  

(3)

The resulting significance at LM4 for \(1 \text{ fb}^{-1}\) is \(S_{c12, \text{SUSY}} = 16\). The 5 \(\sigma\) significance contours when taking into account systematic uncertainties are shown for integrated luminosities of \(10 \text{ fb}^{-1}\) and \(1 \text{ fb}^{-1}\) in Figure 20.

Figure 19: The 5 \(\sigma\) significance contours for integrated luminosities of \(1 \text{ fb}^{-1}\) (dashed line) and \(10 \text{ fb}^{-1}\) (full line) in the region where the decay \(\chi^0_2 \rightarrow Z + \chi^0_1\) takes place. The extensions at higher and lower \(m_{1/2}\) where the Z is off-shell are indicated as dotted and short dashed lines.

![Figure 19](image19)

Figure 20: The 5 \(\sigma\) significance contours for integrated luminosities of \(1 \text{ fb}^{-1}\) (dashed line) and \(10 \text{ fb}^{-1}\) (full line) taking into account systematic uncertainties in the region where the decay \(\chi^0_2 \rightarrow Z + \chi^0_1\) takes place. The extensions at higher and lower \(m_{1/2}\) where the Z is off-shell are indicated as dotted and short dashed lines.

![Figure 20](image20)

### 7 Conclusions

In this note we have performed a study to evaluate the capability to discover SUSY with the CMS detector from SUSY processes leading to final states with Z bosons. The study was performed using the low mass point LM4. This SUSY signature was studied using the full CMS detector simulation and a fast simulation. The signal is clearly visible over the Standard Model background already at an integrated luminosity of \(1 \text{ fb}^{-1}\). The SUSY discovery potential was also explored in the \(m_0, m_{1/2}\) parameter space.
8 Acknowledgments

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