Available on CMS information server **CMS CR 2004/041**

CMS Conference Report

17 September 2004

The CMS discovery potential of Supersymmetry within mSUGRA with same-sign di-muons

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Abstract

A detailed study of the same-sign muon signature within the mSUGRA model was performed. Selection criteria based on the missing transverse energy in the events and the jet and muon transverse momenta are applied to select the data sample. An excess of SUSY events over the Standard Model background processes can be statistically significant for many benchmark points for an integrated luminosity of less than $10\mathrm{fb}^{-1}$. The analysis shows that $m_{1/2}$ up to 650 GeV/c^2 can be reached at 5σ level with $10\mathrm{fb}^{-1}$. Full detailed detector simulation, trigger emulation and reconstruction were performed.

Presented at *Physics at LHC*, Vienna, Austria, July 13-17, 2004

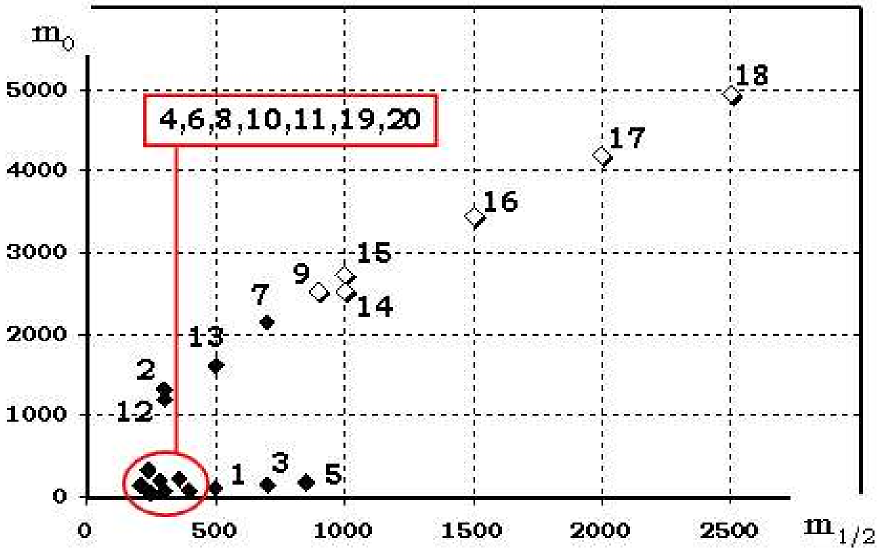

Figure 1: The mSUGRA benchmark points investigated in this analysis.

1 Introduction

There are several Supersymmetric (SUSY) extensions of the Standard Model (SM) theory. The mSUGRA, a GUT sub-model of the Minimal Supersymmetric Standard Model (MSSM) [1], is a popular simplification as it has only five parameters in comparison to more than 100 in MSSM. These five parameters are $m_0, m_{1/2}, \tan\beta, A_0, \mathrm{sign}(\mu)$.

In this study the following values of the parameters were used: $\mathrm{sign}(\mu) > 0$, $A_0 = 0$, $\tan\beta = 10, 20, 35$ and 20 $(m_{1/2}, m_0)$-points. All points were chosen so as to satisfy recent theoretical and experimental constraints [2].

The same-sign di-muon signature was chosen to evaluate the chances of discovering SUSY, since it is very clean, has high trigger efficiency and the background contamination is smaller than in the "multi-jets only" signature. A recent published theoretical study of that signature at the Tevatron can be found in Ref. [3].

The aim of the present work was to investigate the region in the mSUGRA parameter space accessible to CMS at the LHC start-up.

2 Simulation and Reconstruction

The points chosen for this analysis are shown in Fig. 1. Points 2, 11, 16, 19 are mSUGRA benchmark points taken from Ref. [4] (two of them, points 2 and 16, were modified for a top-quark mass of 175 GeV as used for all other points). All points shown on the plot by empty markers have a cross section too small for a target integrated luminosity of $10\mathrm{fb}^{-1}$ and are not considered in the study.

Coupling constants and cross sections in the Leading Order (LO) approximation for SUSY processes were calculated with ISASUGRA 7.69 [5]. Next-to-Leading Order (NLO) corrections were calculated with the PROSPINO program [6] and used in the analysis. The cross sections for the SM processes were calculated using PYTHIA 6.220 [7] and CompHEP 4.2p1 [8]. For several SM processes ($\mathrm{t\bar{t}}, \mathrm{ZZ}, \mathrm{Zb\bar{b}}$), the NLO correction are known and were used [9]. All events were generated with PYTHIA 6.220. Some preselection cuts were applied at generator level: events were kept if at least two same-sign muons with $P_T > 10$ GeV and $|\eta| < 2.5$. After the event generation, a GEANT-based simulation CMSIM [10], was performed.

Data digitization and reconstruction were performed with the ORCA [10] reconstruction package. Pile-up events were not taken into account in this study. The muon reconstruction was performed using an algorithm implemented for the CMS High-Level Triggers (HLT) [11] based on the Muon and Tracker sub-detector information. Jets were reconstructed with the Iterative Cone Algorithm with a cone size of 0.5[12]. Jet E_T corrections were applied and missing E_T was calculated as described in Ref. [11].

It was checked that all events satisfying the selection criteria passed both L1 and HLT muon triggers (single and di-muon triggers). Details on the trigger threshold and efficiencies can be found in Ref. [11].

3 Background processes

Several of the important backgrounds were studied in detail, while for several of the rare processes only an estimate was made based on the cross section and the branching ratio for the final state signature.

The cross sections and the number of generated and selected events for the important sources of backgrounds are listed in the Table 1. In all tb, tqb, $\bar{\mathrm{t}}\mathrm{b}$, $\bar{\mathrm{t}}\mathrm{qb}$ processes, the top quark was forced to decay to Wb and the W was forced to decay into a muon and neutrino. The muon from that decay chain was required to have $P_T > 10$ GeV and $|\eta| < 2.5$ at the CompHEP generation level. In the $\mathrm{Zb\bar{b}}$ process, the Z was allowed to be off-the-mass shell (Z/γ^*) and was forced to decay to $\mu^+\mu^-$. The invariant mass of the two muons from the initial Z/γ^* was required to be larger than 5 GeV/c^2 at the CompHEP generation level.

Table 1: Cross sections and numbers of events for the SM processes for which a detailed simulation was performed for an integrated luminosity of $10\mathrm{fb}^{-1}$. $N_{\mathrm{generated}}$ is the unweighted number of generated events, N_{selected} is the unweighted number of pre-selected events, N_1 is the number of events for an integrated luminosity of 10 fb^{-1}, N_2 is the number of events after pre-selection cuts (at least two same-sign muons with $P_T > 10$GeV/c.)

Process	$\sigma,\ pb$	$N_{\mathrm{generated}}$	N_{selected}	N1	N2
tb	0.212	18,999	1,000	2,120	112
tqb	5.17	28,730	1,000	51,700	1,798
$\bar{\mathrm{t}}\mathrm{b}$	0.129	13,588	745	1,290	71
$\bar{\mathrm{t}}\mathrm{qb}$	3.03	28,359	1,000	30,300	1,067
ZZ	18(NLO)	433,489	1,000	180,000	256
ZW	26.2	368,477	1,000	262,000	727
WW	26.2	894,923	41	702,000	39.7
$\mathrm{t\bar{t}}$	886(NLO)	931,380	15,000	8,860,000	142,691
Zbb	232(NLO)	359,352	2,000	2,320,000	12,924
All					160,000

In Table 2 the estimates of other potential background processes are shown. No detailed simulation was performed for these processes. An estimation was obtained from the process cross section (calculated with CompHEP) and the branching fraction into muons.

Table 2: Cross sections and event numbers for the SM processes for which only an estimate was obtained for an integrated luminosity of $10\mathrm{fb}^{-1}$. N_1 is the estimated number of events for integrated luminosity of 10 fb^{-1}, N_2 is the estimated number of events.

Process	$\sigma,\ pb$	N1	N2
WWW	0.129	1,290	< 15
ZWW	0.0979	979	< 10
ZZW	0.0305	305	< 3
ZZZ	0.00994	99.4	< 1
WWWW	0.000574	negl.	negl.
ZWWW	0.000706	negl.	negl.
ZZWW	0.000442	negl.	negl.
ZZZW	0.000572	negl.	negl.
ZZZZ	0.0000161	negl.	negl.
$\mathrm{t\bar{t}W}$	0.556	5,560	< 200
$\mathrm{t\bar{t}Z}$	0.65	6,500	< 200
$\mathrm{t\bar{t}WW}$	negl.	negl.	negl.
$\mathrm{t\bar{t}ZW}$	negl.	negl.	negl.
$\mathrm{t\bar{t}ZZ}$	negl.	negl.	negl.

The main conclusion here is that all but the $\mathrm{t\bar{t}W}$, $\mathrm{t\bar{t}Z}$ processes are negligible and they are neglected in this analysis. Both $\mathrm{t\bar{t}W}$ and $\mathrm{t\bar{t}Z}$ backgrounds need, however, further future investigation.

4 Selection and cut optimization

The distributions of kinematic variables such as missing E_T, jet E_T, muon P_T (as chosen for this study) are very different for SUSY and SM processes as shown in Fig. 2. Suitable cuts on these variables help reducing the SM background.

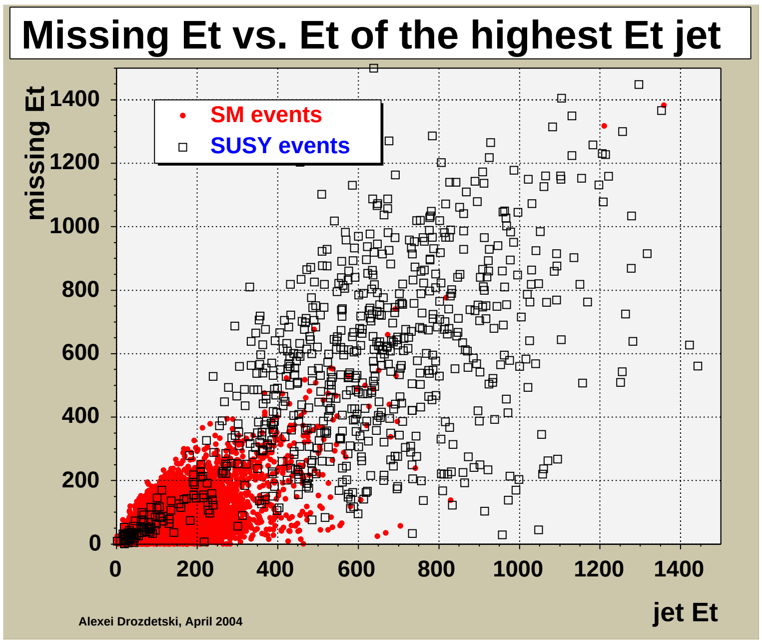

Figure 2: Missing transverse energy vs. jet E_T for SUSY (open squares) and SM events (points) after full simulation and reconstruction.

A set of five variables (missing E_T, E_{T,jet_1}, E_{T,jet_3}, P_{T,μ_1}, P_{T,μ_2}) was chosen. For each variable a set of possible selection cuts was defined. A combination of selection variables and cuts was performed leading to different sets of cuts. The significance, the signal-over-background ratio and the number of expected events for $10\mathrm{fb}^{-1}$ were calculated for each set of cuts. Only the two sets of cuts shown in the Table 3 were finally chosen to be applied in the analysis, since they cover all mSUGRA points with significance greater than five.

Table 3: Chosen cut sets. E_{T,jet_1} is the E_T of the leading jet (maximum E_T) (GeV), E_{T,jet_3} is the E_T of the third highest E_T jet (GeV), P_{T,μ_1} and P_{T,μ_2} are the two highest P_T values of the same-sign muons (GeV).

set	miss. E_T, GeV	E_{T,jet_1}, GeV	E_{T,jet_3}, GeV	P_{T,μ_1}, GeV	P_{T,μ_2}, GeV
1	>200	>0	>170	>20	>10
2	>100	>300	>100	>10	>10

5 SUSY points characteristics

For each mSUGRA point, the LO cross section was calculated as well as the number of events for an integrated luminosity of 10 fb^{-1}. NLO corrections were applied for all mSUGRA points and corrected values were used for this analysis.

Two other parameters were calculated for each mSUGRA point: the statistical significance and the signal-over-background ratio. The significance was calculated using the following expression [13]: $S_{12} = 2(\sqrt{N_S + N_B} - \sqrt{N_B})$, where N_B is the total number of background events and N_S is the number of signal events for each point in the $(m_{1/2}, m_0)$-plane.

Six points (# 9, 14-18) were excluded from the analysis because of the small cross section.

6 Results

Details concerning the expected number of signal and background events as well as the significance at each point studied are listed in the Table 4.

Table 4: The mSUGRA benchmark points: significance values, the signal-over-background ratio and expected "final" number of events after all cuts. The errors quoted on $N_{\rm set1,set2}$ account for Monte Carlo statistics only. The indices, set1 and set2, are for cut sets # 1 and 2 respectively, and the "SM" row gives the expected number of the SM background events after all cuts for all considered processes.

	$N_{\rm set1}$	$S_{12,\rm set1}$	$S/B_{\rm set1}$	$N_{\rm set2}$	$S_{12,\rm set2}$	$S/B_{\rm set2}$
SM	69.5±6.0			432±8.8		
1	95.9±6.7	9.05	1.38	184±9.3	8.06	0.43
2	282±20	20.8	4.06	560±29	21.4	1.3
3	17.7±1.1	2	0.25	30.4±1.4	1.44	0.07
4	365±73	25	5.26	1590±152	48.4	3.7
5	6.54±0.37	0.77	0.094	9.6±0.45	0.46	0.002
6	277±35	20.6	4.0	1030±67	35	2.4
7	6.7±0.35	0.78	0.096	8.31±0.39	0.4	0.019
8	188±17	15.5	2.71	530±28	20.5	1.2
10	515±78	31.7	7.41	1950±151	56.1	4.5
11	137±11	12.1	1.98	322±18	13.4	0.75
12	409±30	27.1	5.89	781±42	28.1	1.8
13	58.8±3.3	6	0.85	86.9±4	4	0.2
19	377±59	26.5	5.43	1220±106	39.8	2.8
20	279±36	20.6	4.01	996±67	34	2.3

The number of points out of reach (significance less than five) for $10{\rm fb}^{-1}$ varies from nine to ten. For the benchmark mSUGRA points with significance greater than five the signal to background ratios are greater than 0.4 (the excess of SUSY events over the SM is greater than 40%).

Figure 3 shows which mSUGRA points have a significance greater than five when plotted in ($m_{1/2}$,m_0)-plane. An approximate sensitive area for $10{\rm fb}^{-1}$ is well defined on the $m_{1/2}$ parameter axis. In order to put bounds also on m_0 more mSUGRA benchmark points with $m_{1/2} < 650$ GeV and $m_0 > 1500$ GeV should be investigated.

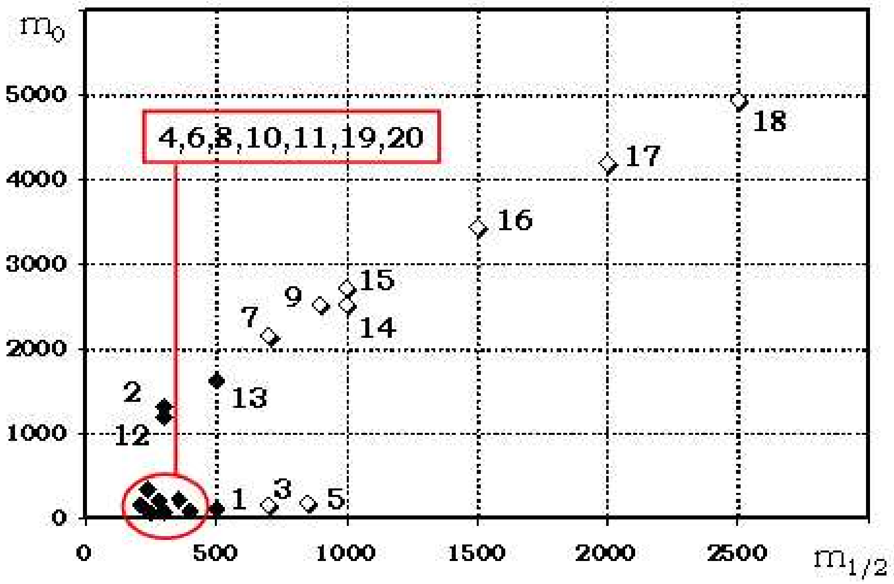

Figure 3: The black points in the $(m_{1/2}, m_0)$-plane have significance greater than five. The white points are not reacheable.

7 First estimate of systematic effects

The stability of the significance as a function of the uncertainty on the signal acceptance and the background normalization was verified. A correlated variation of the SM event number ($+30\%$) and expected number of SUSY events (-30%) was applied. As a result (Table 5) the significance of only one mSUGRA point (# 13) drops below the discovery level.

Table 5: mSUGRA benchmark points: results after the variation for cuts set #1 and 2.

	S_{12}, set#1	S/B, set#1	S_{12}, set#2	S/B, set#2
1	6.09	0.743	5.15	0.23
2	14.9	2.19	14.4	0.7
3	1.26	0.137	0.889	0.038
4	18.2	2.83	34.5	2
5	0.476	0.0507	0.283	0.012
6	14.7	2.15	24.3	1.3
7	0.425	0.0516	0.245	0.01
8	10.8	1.46	13.7	0.66
10	23.5	3.99	40.5	2.4
11	8.31	1.07	8.71	0.4
12	19.8	3.17	19.2	0.97
13	3.93	0.456	2.5	0.11
19	18.6	2.93	27.9	1.5
20	14.8	2.16	23.6	1.2

8 Summary

A detailed study of the same-sign muon signature arising from 20 different points in the mSUGRA model was performed. The region in the $(m_{1/2}, m_0)$-plane with $m_{1/2} < 650$ GeV$/c^2$ is accessible by the CMS at 5σ level at the LHC start-up (10fb^{-1}).

9 Acknowledgments

We would like to thank Salavat Abdullin, Andreas Birkedal, Nancy Marinelli, Konstantin Matchev, Luc Pape, Albert De Roeck, Alexander Sherstnev, Michael Spira, Grzegorz Wrochna, for their special help and contributions to the analysis.

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