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Search for a light Higgs boson in SUSY cascades

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Abstract

This note presents the potential of the CMS experiment to discover a light supersymmetric Higgs boson (h^0) produced at the end of a cascade of supersymmetric particles starting with the strong production of squarks ($\tilde{q}$) and gluinos ($\tilde{g}$). Because of this production mechanism, the events can be efficiently triggered using inclusive SUSY triggers such as jet+E_T^{miss}, and the dominant $h^0 \rightarrow b\bar{b}$ decay mode of the Higgs boson can be exploited. The Higgs mass can be extracted from the reconstructed di-b-jet effective mass distribution. The present investigation for the so-called LM5 test point has been done for 1, 3 and 10 fb^{-1}.

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1 Introduction

The main decay mode of the lightest MSSM Higgs boson (h^0) is the decay into a pair of bottom quarks $h^0 \rightarrow b\,\bar{b}$. Without additional particles in the final state, events containing the $b\bar{b}$ topology cannot be triggered due to overwhelming QCD backgrounds. Less favourable decay modes ($h^0 \rightarrow \gamma\gamma$, $h^0 \rightarrow \tau\tau$) are often used because they do allow to select the Higgs events online. Alternatively, associated production mechanisms can be considered in which additional particles are produced together with the Higgs boson; so the $b\bar{b}$ can be exploited. A classic example of this is the $t\bar{t}h^0$ process, which however suffers from a low cross section. Another example is the production of h^0 in the decays of neutralinos (mainly $\tilde{\chi}_2^0$). As the $\tilde{\chi}_2^0$ is a typical decay product of abundantly produced squarks and gluinos, the cross section can be very high [1], [2].

Following this ideas, this analysis focuses on the potential of the CMS experiment to discover a light MSSM Higgs boson decaying in a $b\bar{b}$ pair produced at the end of a cascade of supersymmetric particles starting with the strong interaction production mechanism of squarks ($\tilde{q}$) and gluinos ($\tilde{g}$).

As a case study, the analysis will focus on the full simulation of the LM5 test point. This mSUGRA point is defined by the following parameter choices: the common scalar mass m_0 is 230 GeV, the common gaugino mass $m_{1/2}$ is 360 GeV, the common trilinear coupling parameter $A_0 = 0$, the ratio of the vacuum expectation values of the neutral Higgs fields, tan β, is 10 and the sign of the Higgsino mixing parameter $sign(\mu)$ is positive. The NLO cross section for all SUSY processes at LM5 is 7.75 pb [3]. Table 1 shows the sparticle masses while table 2 gives relevant branching ratios for this particular mSUGRA point.

Table 1: Some sparticle masses at LM5.

Sparticle	Mass (GeV/c^2)
$\tilde{g}$	860
$\tilde{q}$	800
$\tilde{\chi}_2^0$	273
$\tilde{\chi}_1^0$	142
h^0	116

Table 2: Interesting branching ratios at LM5.

Decay	Branching ratio in %
$\tilde{g} \rightarrow \tilde{q} + q$	100
$\tilde{q} \rightarrow \tilde{\chi}_2^0 + q$	35
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h^0$	85
$h^0 \rightarrow b\bar{b}$	72
$\tilde{q} \rightarrow \tilde{\chi}_2^0 + q$ and $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h^0 \rightarrow \tilde{\chi}_1^0 + b\bar{b}$	21

All supersymmetric channels will be taken into account in the search for the Higgs boson. The final state will be characterized by at least two b-tagged jets, significant missing transverse energy (E_T^{miss}) which is due to the production of the lightest supersymmetric particle (LSP) and multiple hard jets. The main background will come from supersymmetric processes themselves, e.g. a lot of b quarks are produced in sbottom decays. Also Standard Model processes can produce multi-jet + E_T^{miss} final states and contribute to the background: top anti-top production ($t\bar{t}$), $W^{\pm}$+jets and Z^0+jets. Cuts on the missing energy (E_T^{miss}), on jet multiplicity and minimal jet energy will allow to keep them under control.

In section 2, the event generation, simulation and reconstruction will be presented, while section 3 covers the event selection and reconstruction efficiency, including trigger efficiency. Section 4 will present the method used to extract the Higgs boson mass from the invariant mass distribution obtained by the association of two reconstructed b-tagged jets. The main sources of systematic errors will be discussed in section 5. Finally, the signal observability and CMS discovery potential will be discussed in section 6.

2 Event generation, simulation and reconstruction

The generation of events at LM5 has been done with the Monte Carlo event generator ISAJET version 7.69[4] and PYTHIA version 6.225[5]. The simulation has been done with the Object oriented Simulation for CMS Analysis and Reconstruction (OSCAR) version 3_6_5 [6] , the digitisation including the low luminosity pile-up with the Object Oriented Reconstruction for CMS Analysis (ORCA) version 8_7_1 [7].

As the h^0 is searched through its $b\bar{b}$ decay and because its supersymmetric production mechanism implies a large E_T^{miss} and a large number of jets, the principal Standard Model backgrounds consist of processes with b jets, light jets and neutrinos in the final state. For this reason, the $t\bar{t}$, $W^{\pm}$+jets, the Z^0+jets and the dijet QCD backgrounds have been considered. All Standard Model backgrounds have been generated with PYTHIA 6.215, the detector simulation has been done with OSCAR_2_4_5 and the digitisation with ORCA_7_6_1.

The cross section of the relevant Standard Model processes are given in table 3.

The selection and analysis strategy has been developed using ORCA version 8_7_4. In order to optimise the reconstruction efficiency for the Higgs boson signature, two main algorithms have to be tuned : the jet reconstruction

Table 3: Cross section for the relevant processes.

Processes	Total cross section (pb)
All SUSY at LM5	7.75
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h^0 \rightarrow \tilde{\chi}_1^0 + b\bar{b}$	1.5
$t\bar{t}$ inclusive	830
Z^0+ jets	13 10^3
$W^{\pm}$+ jets	41 10^3
inclusive QCD dijet	819 10^6

algorithm (and the resulting calculation of the missing transverse energy) and the b-tagging algorithm. For the jet reconstruction, a cone algorithm with a cone size of 0.5 has been used. A jet calibration based on the γ+jet process and related backgrounds have been applied in order to correct the reconstructed jet energy for neutral particles and inefficiencies [8]. For the b-tagging, a b-tagging algorithm based on inclusive secondary vertex reconstruction in jets was used [9]. In the next section, their efficiencies and performances are discussed. In addition, the event selection is also presented.

3 Event selection and reconstruction efficiency

The first event selection is at the trigger level. The L1 and the high level (HLT) trigger efficiency for the signal has been studied. The results can be found in table 4.

The global L1 trigger efficiency is close to 100 %, the global HLT efficiency is around 96 %. The most efficient trigger paths are the E_T^{miss} and the b jet triggers. The E_T^{miss} trigger is efficient for all SUSY events as they produce a neutralino 1 ($\tilde{\chi}_1^0$), the Lightest Supersymmetric Particle (LSP). In order to have an easiest control during the first stage of the experiment running, it has been decided to use for this analysis only events accepted by the L1(Jet + E_T^{miss}) + HLT(Jet + E_T^{miss}) trigger. This particular trigger is already an important Standard Model background rejection tool, for example it rejects 97.8 % of the $t\bar{t}$ background and accepts 78.7 % of the signal events.

Table 4: Trigger path efficiency for the signal.

Trigger path	Efficiency in %
HLT(1 jet)	23.5
HLT(3 jets)	21.7
HLT(4 jets)	32.7
HLT(B jet)	77.4
L1 (Jet + E_T^{miss})	85.5
HLT (Jet + E_T^{miss})	83.0
L1 (Jet + E_T^{miss}) + HLT (Jet + E_T^{miss})	78.7
All L1 trigger path	99.9
All HLT trigger path	96.0

After these first trigger selections, the reconstruction itself is applied. Some initial requirements for all the samples are used in order to reject the Standard Model background events and to reduce the SUSY background:

- at least 4 jets with a transverse energy (E_T) above 30 GeV (see figures 1 and 2);
- at least 2 b-tagged jets with a transverse energy (E_T) above 30 GeV (see figures 3 and 4);
- a b-tagging quality estimator given by the b-tagging algorithm above 1.5.

3.1 Jet Reconstruction

The efficiency of the jet calibration has been tested and compared with the theoretical evolution of the calorimetric jet energy resolution as a function of the jet energy E. The energy behaviour can be roughly expressed as $100\ \%/\sqrt{E} + 4.5\ \%$ [10]. The result can be seen in figure 5. At low jet energy (below 100 GeV), the resolution is better for b jets than for other jets, while at higher jet energy, the resolution is found to be relatively stable at

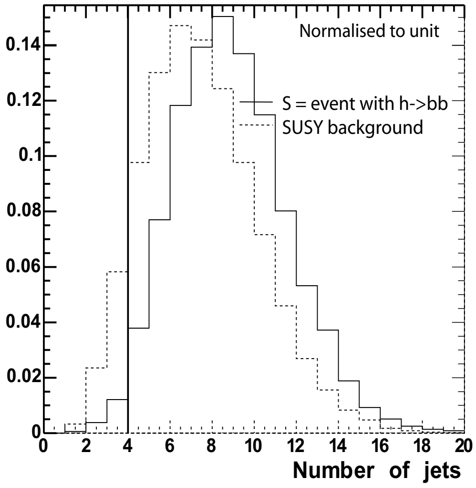

Figure 1: Distribution of the number of jets per event for SUSY events.

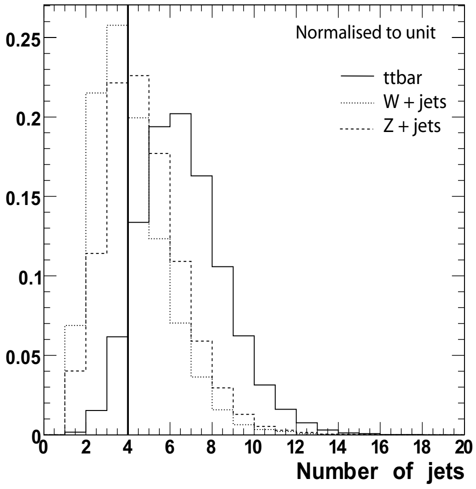

Figure 2: Distribution of the number of jets per event for Standard Model processes.

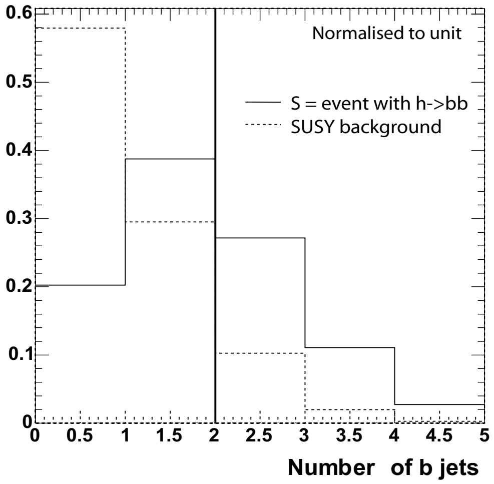

Figure 3: Distribution of the number of b jets per event for SUSY events.

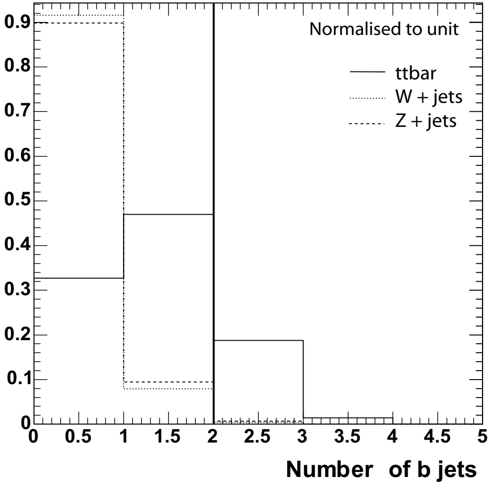

Figure 4: Distribution of the number of b jets per event for Standard Model processes.

the level of 10 to 15 %. However, the measured resolution is worse than the theoretical prediction over the full jet energy range, except for very low energies.

3.2 b-tagging

The evolution of the b-tagging efficiency as a function of the jet energy and η has been studied (see figures 6 and 7). The mean efficiency is found to be equal to 50 % with a global impurity of about 1.6 %, taking u,d,s quarks and gluons into account and 12 % taking c quarks into account (with a selection of b-tagged jets based on the b-tagging quality estimator S above 1.5). The mean b jet energy originating from the Higgs boson decay is approximately 70 GeV, corresponding to a b-tagging efficiency of about 50 % at this energy. This means that approximately 25 % of the signal events will be correctly identified with this algorithm.

3.3 Jet selection

Five interesting variables have been identified in order to improve the signal over background ratio, in particular for the most problematic $t\bar{t}$ background. They are constituted by the E_T^{miss}, the first, second and third highest jet p_t and the angle between the two b jets $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. There distributions can be found in figures 8 to 17.

In addition, two methods are used to select the b jets coming from the Higgs boson decay. First the Hemisphere separation technique in order to identify the jets associated with each initial squark and/or gluino. This novel

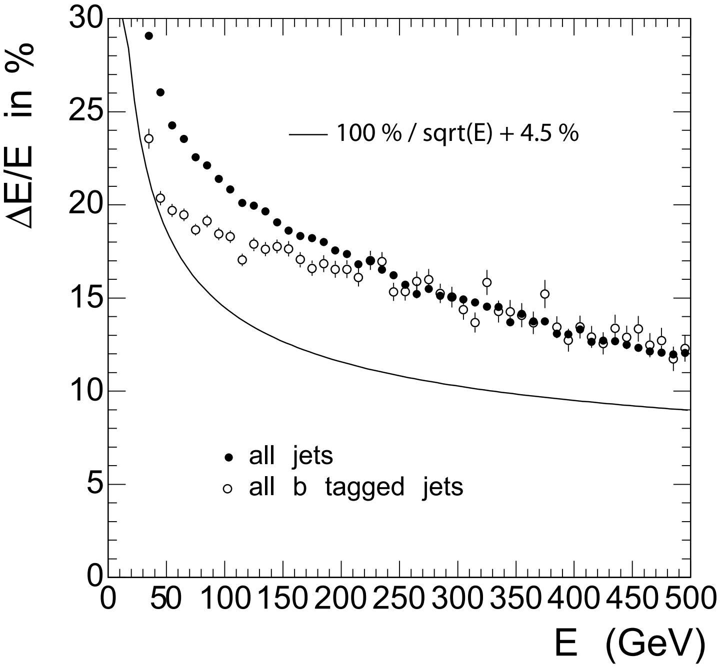

Figure 5: Jet energy resolution.

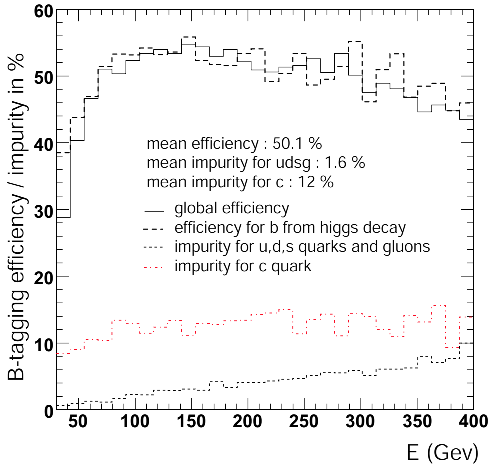

Figure 6: B-tagging efficiency / impurity as a function of the jet energy.

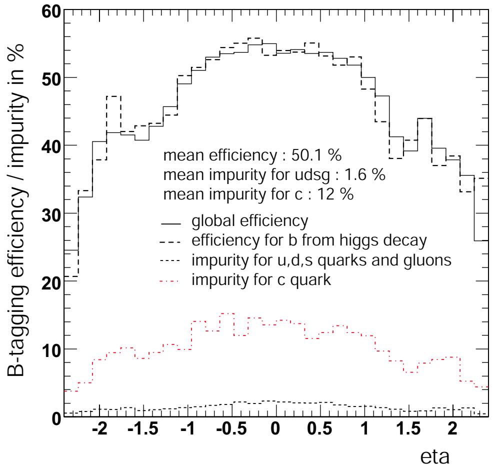

Figure 7: B-tagging efficiency / impurity as a function of the jet pseudo-rapidity (η).

method is proposed to collect the final state particles in two groups, called hemispheres, corresponding to the decay products of these two sparticles. This procedure is inspired by the reconstruction of the thrust or sphericity axis in e^+e^- collisions, except that in hadron collisions two separate axes need to be introduced per event. This algorithm consists of a recursive method going through the following steps: starting by computing two initial axes (called ”seeds”), associating the objects to one of these axes according to a certain criterion (hemisphere association method), recalculatig the axes as the sum of the momenta of all the connected objects and iterating the association until no objects switch from one group to the other.

After that, the b jet pairing should be done in each hemisphere separately reducing the number of combinations by a large factor. This method will play an important role for the so-called end-point reconstruction allowing the identification of the particles involved in the decay chain [11]. In addition, as the Higgs boson is relatively heavy, its decay products have an important boost leading to a small angle ΔR between the two b jets. Following this idea and as this method gives an efficiency of around 60 % and removes totally the combinatorial problem, it has been decided to select as the good one the b jet pair with the smallest ΔR value among those with a $\Delta R < 1.5$. This jet pairing method has approximately an efficiency of 40 % (40 % of the SUSY events containing a Higgs boson and passing the cuts will be correctly identified and selected).

The final selection criteria are :

- at least 4 jets above 30 GeV;
- at least 2 b jets above 30 GeV;
- $E_T^{miss} > 200$ GeV;
- highest jet p_t in event > 200 GeV;
- second highest jet p_t in event > 150 GeV;
- third highest jet p_t in event > 50 GeV;
- 2 b jets, with a b-tagging quality estimator > 1.5, found to be in the same hemisphere with the smallest ΔR among those with $\Delta R < 1.5$.

The cut set shown in tables 5 and 6, leads to a signal efficiency of about 8.1 % (which is a reasonnable number taking into account that only the requirement of two b-tagged jets has an efficiency of only 25 %). The global rejection factor for $t\bar{t}$ events, including the rejection made by the Jet + E_T^{miss} trigger, is close to 12 10^3. No Z+jets, W+jets nor QCD events from the full simulation sample pass the previously described series of cuts. The evolution of the number of QCD events as a function of the cuts is shown in table 7.

Table 5: Evolution of the number of events after various cuts starting with the proper initial cross sections.

Event type	Cuts				
	After trigger	Njets cuts	E_T^{miss}	Jet p_t cuts	ΔR + Jet pairing selection
SUSY events with Higgs boson	17 011	7 317	5 220	4204	1387
other SUSY events	61 492	8 140	6 269	4 905	940
$t\bar{t}$ inclusive	234 580	44 623	8 384	2 609	235
Z+jets	52 616	351	66	12	0
W+jets 8.1 10^7	3 504	1 100	296	0	

Table 6: Cut efficiency in %.

Event type	Cuts				
	After trigger	Njets cuts	E_T^{miss}	Jet p_t cuts	ΔR + Jet pairing selection
SUSY events with Higgs boson	100.	43.0	30.7	24.7	8.1
other SUSY events	100.	89.8	11.9	9.1	1.4
$t\bar{t}$ inclusive	100.	19.	3.6	1.1	0.1
Z+jets	100.	0.7	0.1	0.02	0.
W+jets	100.	0.004	0.001	0.0004	0.

As already said, when selection criteria are applied, no QCD events survive in the datasets, making an accurate background estimation impossible. In order to get a better estimation, a factorization procedure has been used. The total selection efficiency is factorized as the product of the selection without involving the b-tagging and the b-tagging efficiency. With this technique, one event from the [470;600] P̂t range, 2 from the [600;800] and 2 from [1000;1400] remain. Including the b-tagging efficiency and their respective weights compared to SUSY events, this means 0.25 events. Compared to the 235 $t\bar{t}$ events, the QCD background will be considered as negligible.

In the next section, the invariant mass distribution and the extraction of the Higgs boson mass will be discussed.

4 Invariant mass distribution and fitting procedure

The invariant mass distribution is reconstructed using the "best" ΔR combination of two b-tagged jets over the selected events. Among the 1387 events containing a Higgs boson decaying in a $b\bar{b}$ pair, 541 are correctly identified by the jet pairing method. The Higgs boson mass resolution is shown on figure 18.

Table 7: Cut efficiency for QCD events.

$\hat{\mathrm{P}}$t range	Cuts After trigger	Njets cuts	E_T^{miss}	Jet p_t cuts	ΔR + Jet pairing selection
80 - 120	0	0	0	0	0
120 - 170	29	0	0	0	0
170 - 230	495	0	0	0	0
230 - 300	1 866	2	0	0	0
300 - 380	2 984	14	1	0	0
380 - 470	4 056	70	11	11	0
470 - 600	6 759	169	30	28	0
600 - 800	6 758	278	47	47	0
800 - 1000	5 602	447	83	81	0
1000 - 1400	3 761	447	103	102	0
1400 - 1800	570	110	33	32	0

The resulting invariant mass distribution is shown in figures 19 to 21 for the expected statistics equivalent to 1, 3 and 10 fb^{-1} of integrated luminosity with a clear peak around 116 GeV/c^2 associated with the Higgs boson decay. The main background is due to the remaining SUSY events and some $t\bar{t}$ events.

In order to extract the Higgs boson mass and to evaluate the signal significance a simple fit method has been developed. The signal is approximated by a gaussian G and the background is represented as a fifth order polynomial B with coefficients determined and then fixed by an off-peak fit. The global fit function F is then (the background and the signal function B and G have to be normalized):

$$F(\alpha, m_h, \sigma) = N\ [\ (1. - \alpha)\ B + \alpha\ G(m_h, \sigma)\ ] \tag{1}$$

where N is a normalisation factor (fixed by the number of entries in the invariant mass histogram) and alpha the fraction of signal in the global distribution.

The r.m.s. of the Higgs boson mass resolution distribution is 18.2 GeV (see figure 18) and has been used in order to fix the value of the σ parameter. This parameter will be estimated from real data with the measurement, for example, of the Z decay in a $b\bar{b}$ pair. The only free parameters in the global function F are then α and m_h the Higgs boson mass.

The results of the fit are shown in figures 19 to 21 and in table 8.

Table 8: Fit results.

Luminosity	1 fb^{-1}	3 fb^{-1}	10 fb^{-1}
χ^2/ndf	0.4	0.6	1.5
α	0.28 ± 0.08	0.28 ± 0.04	0.24 ± 0.02
m_h (GeV/c^2)	112.9 ± 6.6	118.0 ± 4.5	118.5 ± 2.6
Significance S_{CL}	4.5	7	11.5

The significance is extracted using the formula $S_{CL} = \sqrt{2[(ns + nb)\log(1 + \frac{ns}{nb}) - ns]}$, where ns stands for the number of signal events and nb for the number of background events and are directly estimated using the fitted value of α (the fraction of signal in the invariant mass histogram). A significance of 5 should be achieved with approximately 1.5 fb^{-1} luminosity (equivalent to approximately 2 months of data taking at low luminosity).

In the next section, the principal sources of systematic uncertainties will be discussed.

5 Systematics

The principal sources of systematic uncertainties for this analysis come from the jet calibration and tracker alignment as the result strongly relies on jet measurements and b-tagging. All these subjects will now be discussed in details.

The jet energy scale and E_T^{miss} uncertainties have been estimated assuming an uncertainty evolving linearly from ±15 % (±10 %) to ±5 % (±3 %) for low energy jet (below 50 GeV) and fixed at ±5 % (±3 %) for high energy jets have been assumed for the equivalent of 1 fb^{-1} (10 fb^{-1}) of integrated luminosity. As the E_T^{miss} is computed from the jets, a correction on the jet energy is automatically propagated to the E_T^{miss} estimation. For 1 fb^{-1} (10 fb^{-1}), the effect are about 15 % (7 %) on the SUSY event selection and 17 % (10 %) on the $t\bar{t}$ event rejection respectively. The impact on the Higgs boson mass measurement have been estimated to be ± 7.5 GeV/c^2 (± 5 GeV/c^2) and ±0.04 (±0.01) on α for 1 fb^{-1} (10 fb^{-1}) respectively.

Another systematic uncertainty is introduced by the misalignment of the tracker. Both the short and long term misalignment scenarios have been investigated. The short term misalignment corresponds to a displacement of the tracker (strips/pixels) = (100 μm / 10 μm), while the long term misalignment takes the following shift of the tracker (strips/pixels) = (20 μm / 10 μm) into account. The misalignment of the tracker reduces the track reconstruction resolution, which results in a reduced b-tagging efficiency and which in its turn causes a reduced signal event selection efficiency. As expected, the long term misalignment scenario results in a smaller signal selection efficiency reduction (∼10 %) compared to the case of an aligned detector as the short term misaligment case (∼17 %).

Finally, the systematics due to the choice of the background fit function has been estimated to be small by changing the background function to a third, fourth, sixth or a seventh order polynomial. The fitted Higgs boson mass is affected, in the worse case, by less than 1 % (from 112.9 to 111.4) and the fraction of signal α by 10 % (from 0.28 to 0.31). The mean variation (±0.3 GeV/c^2 on the Higgs boson mass and ±0.01 on α) has been used in order to estimate this systematic effect.

The final results including all the previously discussed systematics for a 1 fb^{-1} integrated luminosity are now:

- m_h = 112.9 ± 6.6 (stat) ± 7.5 (syst) GeV/c^2;
- α = 0.28 ± 0.08 (stat) ± 0.04 (syst).

In order to estimate the CMS reach for this particular signal, a mSUGRA phase space scan has been done. These results are presented in the next section.

6 CMS discovery potential

After establishing the visibility of the signal for the LM5 point, a scan was performed in the (m_0, $m_{1/2}$) plane in order to determine the region where a 5σ discovery could be made with 2, 10 and 30 fb^{-1}.

First, an effective cross section ($\sigma \times BR(h0)$) was used (calculated with the PROSPINO next-to-leading order calculation program [3] and the ISASUGRA program included in the ISAJET package [4]) to obtain an estimate of the reach. Using this first estimate, 40 points were chosen for which the full spectrum was calculated and a fast simulation was performed with the CMS FAst MOnte-Carlo Simulation program FAMOS [12]. The same selection criteria as for LM5 point were applied, and the number of Higgs boson signal and background events was determined; the same significance definition (S_{CL}) was used in order to determine the 5-sigma contours. Comparing the ORCA/FAMOS results at LM5, the significances obtained with both programs were found to agree well.

The result of the scan is displayed in the reach plot in Figure 22. Although for 1 fb^{-1} the sensitivity remains below 5σ everywhere, a sizeable region of the (m_0, $m_{1/2}$) plane, up to 1100 (1600) GeV in m_0 and 600 (650) GeV in $m_{1/2}$, can be covered with 10 (30) fb^{-1}. The plot assumes $\tan\beta$ = 10, A_0=0, and a positive sign of μ.

7 Conclusion

In this note, a method to search for a light Higgs boson produced at the end of a SUSY cascade has been presented. The selection criteria are based on a large E_T^{miss} and an important jet multiplicity. For the LM5 point under study, including systematics due to the jet energy scale, E_T^{miss}, tracker misalignment and fit, the final result on the Higgs boson mass is 112.9 ± $6.6(stat)$ ± $7.5(syst)$ GeV/c^2 with a statistics expected to be the equivalent of 1 fb^{-1} of integrated luminosity for a generated 116 GeV/c^2 Higgs boson. It is expected that a signal with 5 sigma significance can be extracted after a few months, running at low luminosity.

A sizeable region of the mSUGRA (m_0, $m_{1/2}$) plane, up to 1100 (1600) GeV in m_0 and 600 (650) GeV in $m_{1/2}$, can be covered with 10 (30) fb^{-1}.

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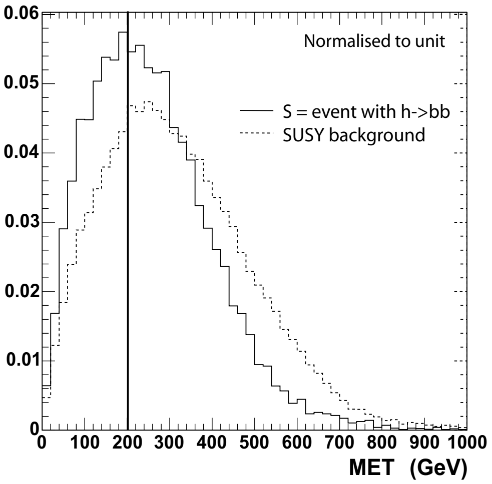

Figure 8: E_T^{miss} distribution for SUSY events.

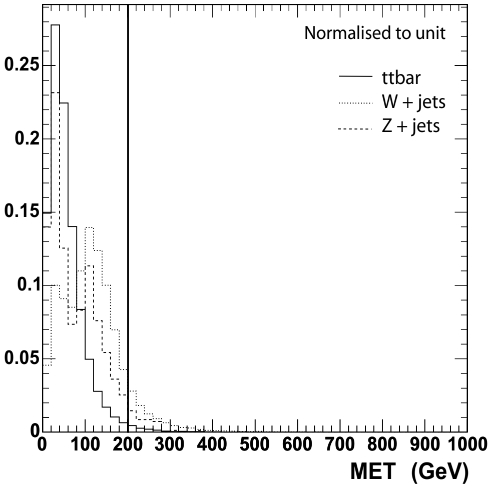

Figure 9: E_T^{miss} distribution for Standard Model processes.

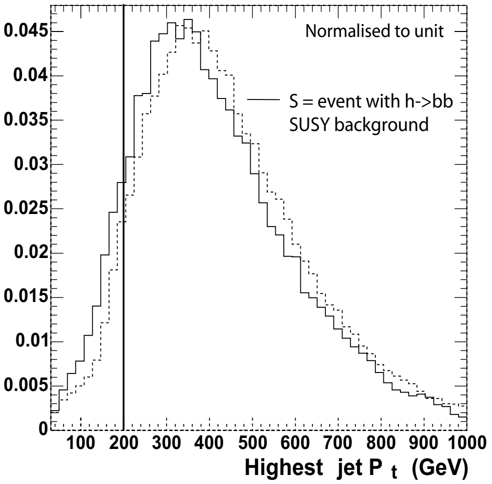

Figure 10: Distribution of the highest jet p_t in SUSY events.

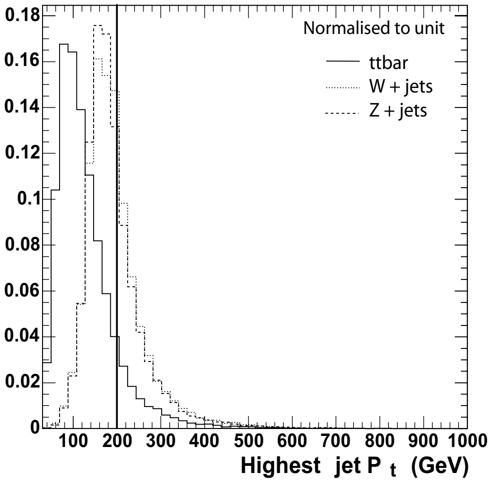

Figure 11: Distribution of the highest jet p_t for Standard Model processes.

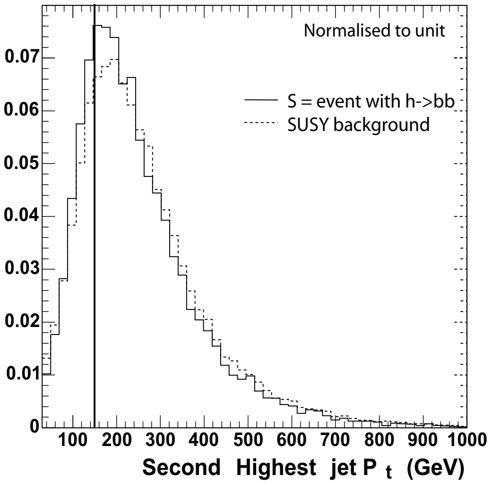

Figure 12: Distribution of the second highest jet p_t in SUSY events.

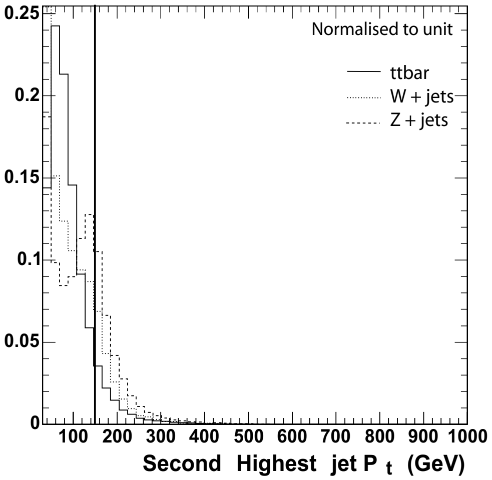

Figure 13: Distribution of the second highest jet p_t for Standard Model processes.

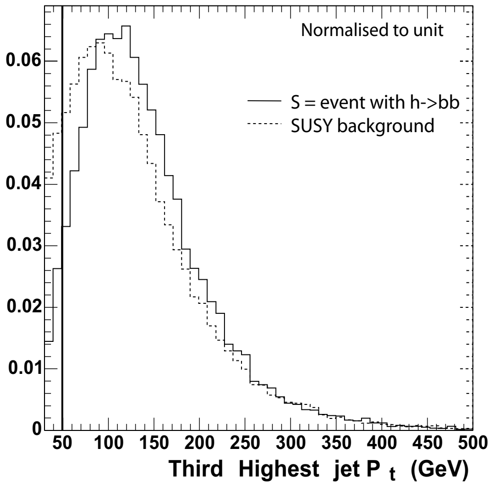

Figure 14: Distribution of the third highest jet p_t in SUSY events.

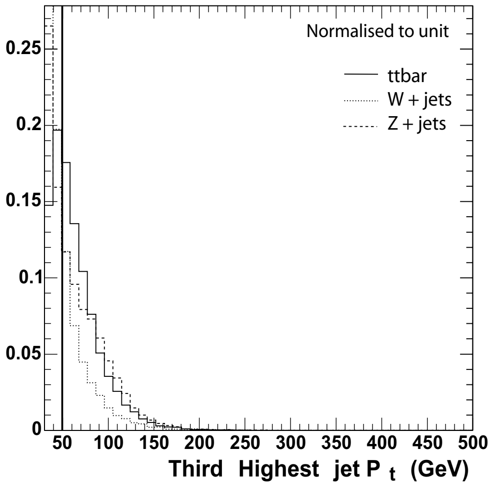

Figure 15: Distribution of the third highest jet p_t for Standard Model processes.

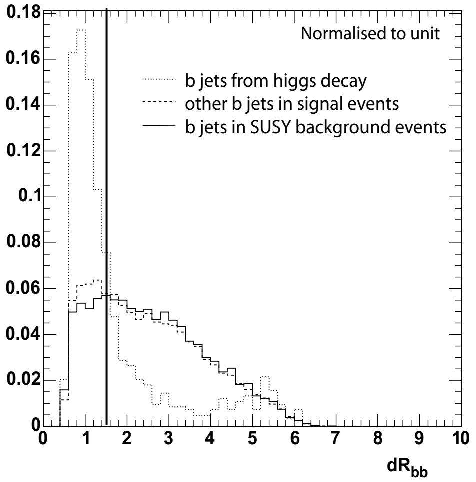

Figure 16: ΔR distribution for SUSY events.

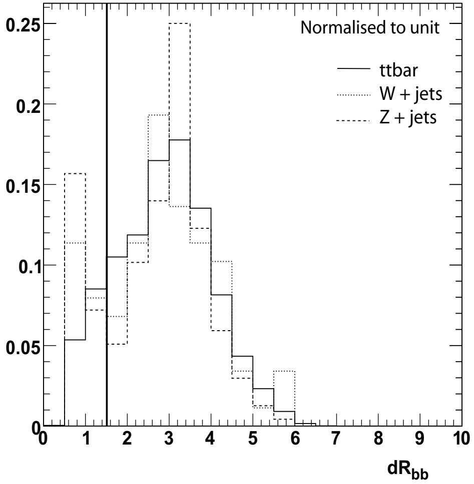

Figure 17: ΔR distribution for Standard Model processes.

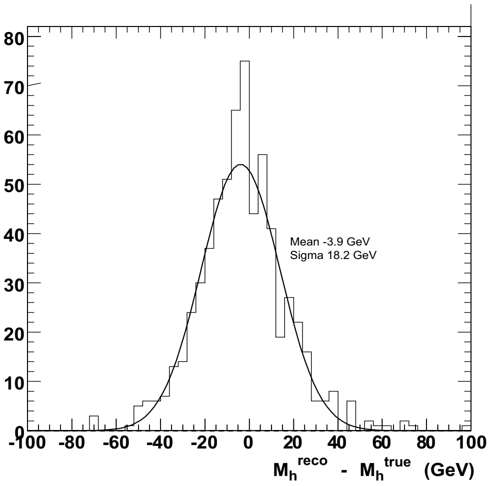

Figure 18: Higgs boson mass resolution.

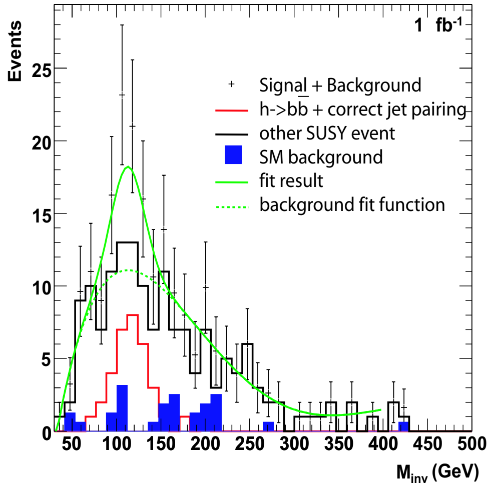

Figure 19: Invariant mass distribution and global fit for 1 fb^{-1}.

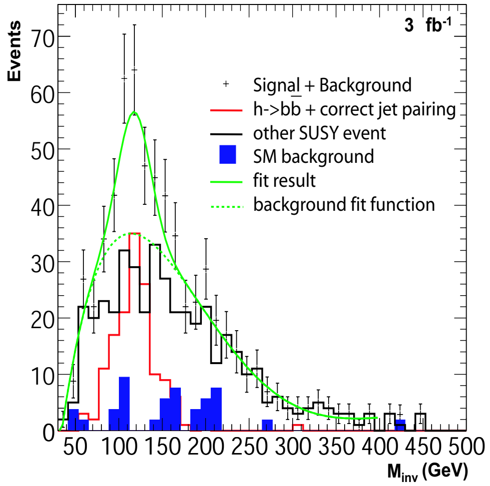

Figure 20: Invariant mass distribution and global fit for 3 fb^{-1}.

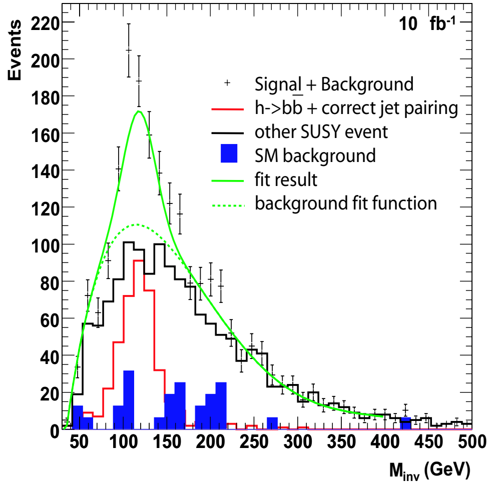

Figure 21: Invariant mass distribution and global fit for 10 fb^{-1}.

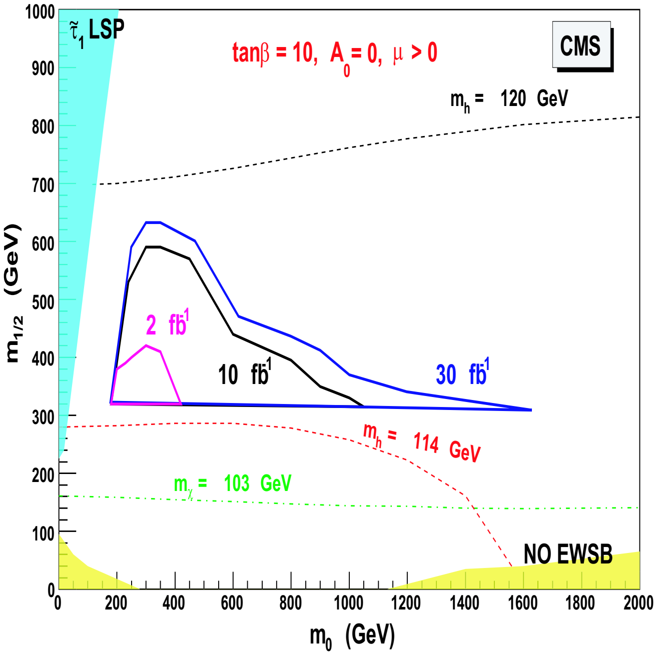

Figure 22: Higgs boson discovery reach in SUSY cascades for 2, 10 and 30 fb^{-1}.