Search for supersymmetry in hadronic final states with M_{T2}

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Abstract. We present the results of a search for physics beyond the Standard Model (BSM) using data of 1.1 fb^{-1} integrated luminosity collected by the CMS experiment at the LHC. Fully hadronic final states were selected based on the "stransverse" mass variable M_{T2} and interpreted in various models of supersymmetry (SUSY). Two complementary analyses were performed targeting different areas of the SUSY phase space. All backgrounds were estimated using both simulation and data-driven methods. As no excess of events over the expected background was observed exclusion limits were derived.

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1 Introduction

We describe a search [1] for physics beyond the Standard Model in pp collisions collected by the Compact Muon Solenoid (CMS) detector [2] at the Large Hadron Collider (LHC) at a centre-of-mass energy of 7 TeV. The results are based on a data sample of 1.1 fb^{-1} of integrated luminosity collected in 2011. We use the "stransverse mass" variable M_{T2} [3] to select new physics candidates out of fully hadronic events. We divide our search into two channels: one targets high squark and gluino masses with a high M_{T2} cut, the other heavy squarks and light gluinos with a medium M_{T2} cut but including a b-tag and high jet multiplicities.

In the following we describe the properties of M_{T2} in sec. 2, our analyis strategy and event selection in sec. 3, and the background estimation in sec. 4. In sec. 5 we state the results of our search, and draw a conclusion in sec. 6.

2 The search variable M_{T2}

The variable M_{T2} was introduced to measure the mass of primary pair-produced particles where both particles decay into detected and undetected particles (e.g. the lightest supersymmetric particle (LSP)). It is a generalization of the transverse mass m_T in case of two identical decay chains each containing unobserved particles. The variable M_{T2} is defined as

$$M_{T2}(m_\chi) = \min_{p_T^{\chi(1)} + p_T^{\chi(2)} = p_T^{miss}} \left[\max \left(m_T^{(1)}, m_T^{(2)} \right) \right], \qquad (1)$$

where m_T is the transverse mass of the visible system and the corresponding LSP χ of the decaying sparticle:

$$m_T^{(i)} = \sqrt{(m^{vis(i)})^2 + m_\chi^2 + 2 \left(E_T^{vis(i)} E_T^{\chi(i)} - \mathbf{p}_T^{vis(i)} \cdot \mathbf{p}_T^{\chi(i)} \right)}.$$

In this analysis the stransverse mass M_{T2} is not used for mass measurements but rather as a discovery variable [4].

In order to associate all visible decay products to the decay chains of the two sparticles we cluster the jets of an event into two "pseudojets" using a hemisphere algorithm

described in [5], Sect. 13.4. As seeds (inital axes) the direction of the two (massless) jets are chosen which have the largest invariant mass. We then associate a jet k to the pseudojet i rather j if the Lund distance is minimal:

$$(E_i - p_i cos\theta_{ik}) \frac{E_i}{(E_i + E_k)^2} \le (E_j - p_j cos\theta_{jk}) \frac{E_j}{(E_j + E_k)^2}.$$

2.1 Advantages of M_{T2}

In order to gain a better understanding of the behaviour of M_{T2} we take the case where we set all masses to zero and assume no initial-state radiation (ISR) or upstream transverse momentum[1]. In this simple case M_{T2} becomes

$$(M_{T2})^2 = 2 p_T^{vis(1)} p_T^{vis(2)} (1 + cos\phi_{12}), \qquad (2)$$

where $p_T^{vis(i)}$ is the transverse momentum of pseudojet i, and ϕ_{12} the angle between the two pseudojets in the transverse plane. It can be observed that for symmetric events ($p_T^{vis(1)} = p_T^{vis(2)}$) with large acoplanarity M_{T2} behaves like the missing transverse momentum (MET). Thus SUSY with expected large MET will accumulate in the high M_{T2} region. However, back-to-back systems or balanced events will populate the region with small M_{T2}. Thus M_{T2} is robust against QCD jet mismeasurements: Mismeasurements along one of the pseudojets results in $M_{T2} \approx 0$ GeV, while for asymmetric mismeasurements still $M_{T2} <$ MET.

3 Analysis Strategy and Event Selection

In this analysis we have established two search channels in order to be sensitive to different regions in the SUSY phase space. One approach, the High M_{T2} analysis, targets events resulting from heavy sparticle production which is characterized by large MET and M_{T2}. The second approach, the Low M_{T2} analysis, is designed to be sensitive to the region where squarks are heavy and gluinos relatively light. Here

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[1] Upstream transverse momentum is the transverse momentum which is not clustered to the pseudojets (e.g. jets outside of acceptance).

gluino-gluino production is dominant, the gluinos giving rise to three-body decays with small MET. Also, as stops and sbottoms are expected to be relatively light, these events can be enriched with b-quarks. Thus the two strategies require two different sets of selection cuts stated in table 1.

Table 1. Event selection cuts which are specific to their strategies.

High M_{T2}	Low M_{T2}
at least 3 jets[2]	at least 4 jets
	at least 1 b-tag
$H_T > 600$ GeV[3]	$H_T > 650$ GeV
$M_{T2} > 400$ GeV	$M_{T2} > 150$ GeV

Besides this channel specific selection we also require:

- Lepton (e, μ) veto to reduce W+Jets and $t\bar{t}$ background.
- min $\Delta\phi$(MET, any jet) > 0.3 to reduce further QCD.
- $|\mathbf{MHT} - \mathbf{MET}| < 70$ GeV to minimize the influence of unclustered energy (e.g. ISR) to the M_{T2} shape[4].
- MET tail cleaning cuts (e.g. noise filters) to filter out events with unphysical MET.

For the selection of data we require the data to pass H_T trigger paths.

4 Background Estimation Strategy

For each type of background data-driven estimation methods have been designed: QCD is estimated from the bulk of the M_{T2} distribution as described in sec. 4.1. In order to reduce the effect of signal contamination and statistical fluctuations the electroweak and top background is estimated from an adjacent control region in M_{T2}. The prediction is taken from data in the control region scaled by Monte-Carlo (MC) ratio of the event yield in the signal region over the yield in the control region. Similarly the uncertainties are scaled by a MC ratio. The control region for High M_{T2} is defined as 200 GeV $< M_{T2} <$ 400 GeV, for Low M_{T2} it is defined as 100 GeV $< M_{T2} <$ 150 GeV.

4.1 QCD background estimation

The QCD estimation method is based on the two variables M_{T2} and $\Delta\phi_{\min} = \min\Delta\phi$(MET, any jet). These two variables are strongly correlated, but a factorization method can be applied if the functional form for the ratio $r(M_{T2}) = N(\Delta\phi_{\min} \geq 0.3)/N(\Delta\phi_{\min} \leq 0.2)$ is known. From simulation studies it has been found that for $M_{T2} > 50$ GeV the ratio falls exponantially:

$$r(M_{T2}) = \frac{N(\Delta\phi_{\min} \geq 0.3)}{N(\Delta\phi_{\min} \leq 0.2)} = \exp(a - b \cdot M_{T2}) + c \quad (3)$$

This behaviour was confirmed in data. The estimate has been performed by a fit from data in the QCD dominated region of 50 GeV $< M_{T2} <$ 80 GeV to extract the parameters a and b. In order to get also parameter c from data its value was fixed to the value of the ratio at $M_{T2} = 200$ GeV where the ratio still falls exponentially.

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[2] The jet selection requires $p_T > 20$ GeV, $|\eta| < 2.4$.

[3] H_T is the scalar sum of all jet-p_T.

[4] **MHT** is the negative vectorial sum of all jet-p_T.

4.2 $Z \to \nu\nu$ background estimation

$Z \to \nu\nu$ is an irreducible background because the produced neutrinos leave the detector unmeasured and thus generate real MET. The number of $Z \to \nu\nu$+Jets events passing the event selection can be estimated from $W \to \mu\nu$+Jets via

$$N_{Z\nu\nu}(est) = W(\mu\nu) \cdot \frac{1}{\epsilon_{acc}\epsilon_{reco/iso}} \cdot R_{ZW} \quad (4)$$

where $W(\mu\nu)$ is the number of $W \to \mu\nu$ events passing the event selection with additionally requiring one muon, R_{ZW} is the ratio of $Z \to \nu\nu$ events to $W \to \mu\nu$ events, ϵ_{acc} is the acceptance, and $\epsilon_{reco/iso}$ is the combined reconstruction and isolation efficiency. In order to reduce the $t\bar{t}$ background in the $W \to \mu\nu$ selection a b-tag veto has been applied, while the residual $t\bar{t}$ background has been estimated from the b-tagged region. Furthermore $\epsilon_{reco/iso}$ has been calculated from Tag & Probe studies on $Z \to ll$ events while the acceptance and the ratio R_{ZW} are taken from MC.

4.3 W and Top background estimation

The background due to W and Top has two sources: Either a lepton (e, μ) from a W has been unobserved due to acceptance cuts, or has been "lost" due to failing either identification, isolation, or reconstruction criteria. The other source are W decays into neutrinos and taus which decay hadronically.

The number of events with a "lost" lepton has been estimated from the number of events with one lepton found in data. This number is then corrected for the probability to loose a lepton via the formula

$$N_{e,\mu}^{pass\ veto} = (N_{e,\mu}^{reco} - N_{e,\mu}^{bg})\frac{1 - \varepsilon_{e,\mu}}{\varepsilon_{e,\mu}}, \quad (5)$$

where $N_{e,\mu}^{reco}$ is the number of events containing a lepton, $N_{e,\mu}^{bg}$ is the expected background from processes other than W or Top, and $\varepsilon_{e,\mu}$ is the probability for a $W \to l\nu$ ($l = e, \mu$, or $\tau \to e, \mu$) passing all selection and reconstruction cuts.

The number of events with hadronic tau decays are taken from simulation and validated by data: The $W \to l\nu$ ($l = e, \mu, \tau$) kinematics in simulation has been validated in data with one muon. Furthermore, it has been shown that tau decays are well modelled in the simulation [6] justifying the use of simulation.

5 Results

The M_{T2} distributions for the High M_{T2} analysis and Low M_{T2} analysis are shown in Figs. 1 and 2, table 2 summarizes the results of the two analysis strategies. As no excess over background has been found limits have been set.

5.1 Exclusion Limits

First, model independent limits on $\sigma \times$ BR within our acceptance has been derived by computing a 95% upper limit on the number of events using a CL$_s$ formulation [7]. These
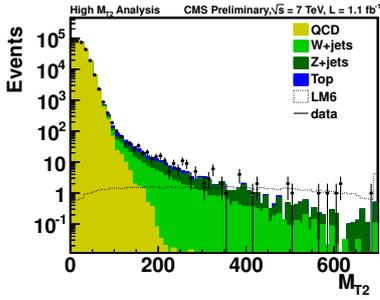
Fig. 1. M_{T2} distribution for the High M_{T2} analysis. The MC background is normalized to 1.1 fb^{-1}. A possible SUSY signal (LM6) is overlayed. Data are shown as dots on top of the background.
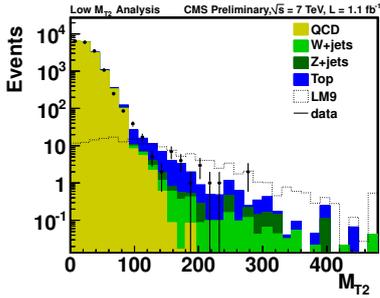

Fig. 2. M_{T2} distribution for the Low M_{T2} selection. The MC background is normalized to 1.1 fb^{-1}. A possible SUSY signal (LM9) is overlayed. Data are shown as dots on top of the background.

Table 2. Expected yield in the signal region from Standard Model (SM) background in simulation and from data-driven background predictions, as well as data yield for both analysis strategies.

	SM-MC	Background prediction	Data
High M_{T2}	10.6	12.6 ± 1.3 (stat) ± 3.5 (syst)	12
Low M_{T2}	14.3	10.6 ± 1.9 (stat) ± 4.8 (syst)	19

Table 3. Observed and expected limits on $\sigma \times$ BR within the acceptance ot the two analysis strategies.

	$\sigma \times$ BR (pb)	
	observed limit	expected limit
High M_{T2}	0.010	0.011
Low M_{T2}	0.020	0.014

limits are shown in table 3. Exclusion limits at 95% C.L. have been determined in the mSUGRA/CMSSM (m$_0$, m$_{1/2}$) plane. The results are shown in fig. 3 for A$_0 = 0, \mu > 0$ and $\tan\beta = 10$ combining the High and Low MT2 selections by taking the best expected limit in each point. Besides the exclusion in the mSUGRA/CMSSM plane the results are interpreted in a so-called Simplified Models topology. This is a simple signal model with exactly one decay mode which is only constrained by the kinematics and the masses of the participating particles. The Low M_{T2} analysis is interpreted in a model where gluinos are pair produced and each gluino decays into two b-quarks and a neutralino, the LSP. The limits on the model cross sections and the signal efficiencies are shown in fig. 4.
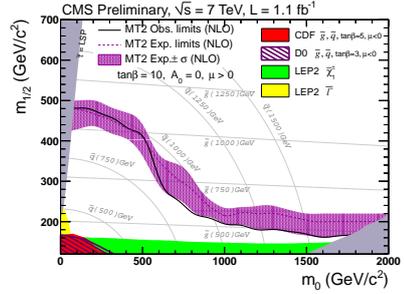

Fig. 3. Combined exclusion limit in the mSUGRA/CMSSM (m$_0$, m$_{1/2}$) plane with $\tan\beta = 10$.
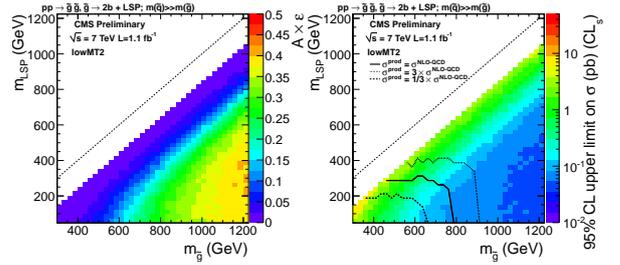

Fig. 4. Model $pp \rightarrow \tilde{g}\tilde{g}$, $\tilde{g} \rightarrow bb\tilde{\chi}^0$ for the Low M_{T2} selection as a function of the mass parameters m$_{\text{LSP}}$ and m$_{\tilde{g}}$: Signal efficiencies (left), 95% CL upper limit on cross section of the model (right).

6 Conclusion

We conducted a search for supersymmetry in hadronic final states using the M_{T2} variable calculated from massless pseudojets. A data set containing 1.1 fb^{-1} of integrated luminosity in $\sqrt{s} = 7$ TeV pp collisions recorded by the CMS detector during the 2011 LHC run was analyzed. Two complementary analyses were performed to probe a larger SUSY phase space. In both analyses the tail of the M_{T2} is sensitive to a possible SUSY signal. As no evidence for a signal was found, we set upper limits on the cross section times branching ratio within our acceptance. Exclusions limits were established in the mSUGRA/CMSSM parameter space, as well as in a Simplified Model topology.

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