Searches for supersymmetry with the CMS detector at the LHC

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Abstract. Supersymmetry may give rise to striking events that could be discovered early in LHC running. Search strategies based on the generic event signatures of high jet multiplicity and large missing transverse momentum, optionally including leptons and photons in the final state, are discussed. An important aspect of such searches is the commissioning of search variables with LHC data, and demonstrating a good understanding of the detector, which is covered in detail. Techniques for estimating the contributions from Standard Model background processes using data are presented. Finally prospects for a discovery are reviewed.

1. Introduction

The CMS experiment [1] will perform extensive studies to find proof of the existence of supersymmetric (SUSY) particles [2], the predicted partners of the known standard model (SM) particles. However, searches for SUSY particles are a highly non-trivial task, mostly due to the fact that the theoretical framework of SUSY allows for a broad range of different phenomenological features. These include different mass spectra with distinct individual decay channels or different cross sections and branching ratios. In spite of these difficulties the CMS collaboration decided to base the strategies for early searches [3] on generic event signatures comprised of high transverse momentum jets and large amounts of missing transverse energy (MET). Optionally, the signatures may also contain leptons and photons in the final state.

This strategy is motivated by several facts. First of all, the LHC is a proton-proton collision machine, for which the strong production of gluinos and squarks would be the dominant processes for SUSY production. Hence high transverse momentum jets originating from the decay of the colored SUSY particles in the hard scattering process are expected. Secondly, motivated by mSUGRA scenarios, the existence of an uncharged and weakly interacting lightest supersymmetric particle (LSP) is assumed. Under the assumption of R-parity conservation all decay chains containing SUSY particles should end with an LSP, thus being a potential source of a high excess of MET.

The strategy is supplemented with a set of mSUGRA scenarios [4] that are used as benchmark points for analyses (see Figure 1). These very well understood and not yet ruled out scenarios cover a large variety of distinct signatures. For this reason it is assumed that model dependent prejudices due to restrictions within the framework of mSUGRA are avoided as far as possible.
2. Commissioning of search variables with data

Backgrounds are expected to be orders of magnitude larger than any SUSY signal. A good understanding of the complex physics observables and control over backgrounds from SM processes hence are an inevitable experimental requirement. Careful commissioning of the search variables is therefore the key to success, especially the performance of the reconstruction of jets and MET.

2.1. Performance of jet reconstruction

For SUSY analyses jets are experimental signatures of the strong production of squarks and gluinos, which are produced in highly energetic hard scattering of partons in p-p collisions. A detailed understanding of the energy calibration and resolution of jets is of crucial importance and is a leading source of systematic uncertainty for any analyses with jets in the final state. The instrumentation of CMS allows the reconstruction of jets in four different ways [5], which combine information from individual sub-detectors to form the inputs to the jet clustering algorithm in

![Figure 1.](image1.png)

**Figure 1.** The low mass (LM) and high mass (HM) mSUGRA benchmark points used by CMS, depicted in the $m_0$-$m_{1/2}$-plane.

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**Figure 2.** Calorimeter (left) and PF (right) jet resolution for $0 \leq |\eta| \leq 1.4$ from QCD simulation and compared with the results from data.

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Contamination from beam halo, the filter efficiency is found to be 65% in a high-duty environment.

Figure 6a shows Calo activity parameterized by Monte Carlo sample.

Both analysis with multi jets and visible at the presently available level of data statistics. This feature is useful for various physics applications.

Figure 8 shows the calibrated ET distribution for events before the beam halo filter is applied and for events after noise cleaning and filtering.

Distribution of the calorimeter MET for dijet events from simulation and compared with data.

Different ways: calorimeter jets, Particle-Flow (PF) jets, Jet-Plus-Track jets, and track jets.

Calorimeter jets are reconstructed using information from the calorimeters only, by combining energy deposits in the electromagnetic and hadronic calorimeter cells into so-called calorimeter towers. The Particle Flow algorithm [6, 7] combines the information from all CMS sub-detectors to identify and reconstruct all particles in the event, namely muons, electrons, photons, charged hadrons and neutral hadrons. PF jets are then reconstructed from the resulting list of particles.

CMS has developed a factorized multi-step procedure for the jet energy calibration [8], comprising so-called offset, relative and absolute corrections. The offset correction aims to correct the jet energy for the excess unwanted energy due to electronics noise and pile-up. The relative correction removes variations in jet response due to the uniformity in $\eta$ of the detector. The absolute correction removes variations in jet response versus jet $p_T$. Figure 2 shows the jet energy resolution for calorimeter and PF jets after applying all correction steps. The good agreement between data and simulation confirms that the jet reconstruction is working properly.

2.2. Performance of MET reconstruction

MET is generally calculated as the magnitude of the negative vector sum of the momentum transverse to the beam axis of all final-state particles reconstructed in the detector. The instrumentation of CMS allows the reconstruction of MET in four different ways [9, 10, 11], which combine the information from the individual sub-detectors in different ways: calorimeter MET,
Particle-Flow (PF) MET, track-corrected (TC) MET, and MET calculated using reconstructed jets only.

While MET is an important observable not only for SUSY searches, it is also one of the most complex observables. Its reconstruction is very sensitive to various detector malfunctions, particles impinging poorly-instrumented regions of the detector, cosmic-ray particles, and beam-halo particles. Especially in the extreme tails of the distribution these effects may result in an artificial MET. This is demonstrated by Figure 3 that shows for the case of the calorimeter MET the importance of noise cleaning, i.e. the removal of noisy channels from the computation of the MET, and filtering, i.e. the removal of a complete event. Thus, great care is required to understand the MET distribution as measured by the detector (see Figure 4). Figure 5 shows the resulting Gaussian core resolution of the calorimeter MET, the PF MET and the TC MET, after correcting for all before mentioned unwanted sources of artificial MET. Both TC MET and PF MET show improvements in the resolution compared to the calorimeter only MET, and the PF MET yields the smallest MET resolution.

3. Treatment of backgrounds in SUSY searches

Searches for SUSY with MET depend on a good understanding of the extreme tails of the MET distribution, since the cross sections of the background channels are assumed to be orders of magnitude larger than any SUSY signal. Especially the cross section of QCD is not predicted with high enough precision and key topological and kinematical features such as number of jets, angular distributions or momentum spectra are difficult to model in simulations. Electroweak backgrounds (e.g. W+jets, Z+jets, t¯t) present similar challenges, even though they are not as harsh as those for QCD. Therefore backgrounds will be determined using data-driven methods whenever possible, with multiple methods for cross-checks.

3.1. Suppression of backgrounds

QCD events in which the hadronic activity is mis-measured are a significant source of artificial MET. Such events, where the observed MET is primarily due to jet resolution effects rather than to real missing momentum carried by unobserved particles, have to be carefully suppressed. To this end a variety of kinematical variables or information from complementary detector systems can be used.

![Figure 6. Comparison of the distribution of α_T between data (black) and simulation (yellow) for different values of H_T for multi-jet events (≥3 jets).](image-url)
As an example [3] for the suppression of background, the variable \( \alpha_T \) [12, 13] is discussed here. It is a dimensionless quantity that characterizes the overall transverse momentum balance of the event by using the ratios of magnitudes of transverse momenta:

\[
\alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - MHT^2}}
\]

where

\[
H_T = \sum_{j} p_{T,j}, \quad \Delta H_T = \min_{j} (p_{T,pseudoj 1} - p_{T,pseudoj 2}), \quad MHT = |\sum_{j} -\vec{p}_{T,j}|.
\]

The partition of the multi-jet system into two pseudo-jets can be performed in multiple ways. For the computation of \( \alpha_T \) typically the configuration with the minimal \( \Delta H_T \) of all possible partitions is chosen.

Like the MET, \( \alpha_T \) is a powerful discriminator against QCD background. While QCD background is not the only or even the dominant background in the jets+MET search, it is perhaps the most challenging to control due to the above mentioned problems with predicting QCD precisely. For the suppression of other backgrounds, such as W+jets or tt, other methods have to be applied.

Figure 6 shows that in practice, QCD background is largely confined to the region with \( \alpha_T \leq 0.55 \). Figure 7 demonstrates that the suppression, i.e. the fraction of events with \( \alpha_T \leq 0.55 \), even improves with increasing values of \( H_T \). This is not only true for carefully reconstructed data from di-jet events (blue), but also for artificially degraded data using photon-triggered events dominated by mis-identified jets (green), events with emulated jet loss (red) or momentum-smeared jets (violet). In all these cases an exponential trend is confirmed. Thanks to the reliability and robustness of the method, this behavior can even be used to calculate limits on the suppression rate for higher \( H_T \)-bins.

3.2. **Background estimation**

Even though variables like \( \alpha_T \) provide a good handle on the suppression of background channels, the remaining background still has to be quantified using supplementary measurements and methods. In this section two examples [3] are presented.

Both examples make use of control samples in which no genuine MET is present to make predictions for the background at high values of MET, where SUSY signals might be observed. The control samples are divided into bins of number of jets and \( H_T \) and for each bin the shape of the MET spectrum – the so-called MET template – is reconstructed. Figure 8 shows such a set of
templates extracted from a multi-jet QCD sample. For a given signal channel the corresponding
distributions of the number jets and $H_T$ are measured. To obtain a background estimate the
control sample’s MET templates are weighted accordingly to these distributions.

The before mentioned MET templates extracted from the multi-jet QCD sample were used
to perform a consistency test in the $\gamma$+jets+MET channel. Since the kinematical effects are
expected to get diluted, the templates from the multi-jet sample should give a good estimate
for artificial MET. Figure 9 confirms this assumption. For the region with MET $\geq$ 15 GeV the
prediction of 12.5 events and the observation of 11 events is statistically consistent.

A similar example is shown in Figure 10, where the template method was used to estimate
the background MET distribution in the di-photon+MET channel, coming from electrons and
jets misidentified as photons. A kinematically similar QCD control sample was used, in which fake
photon candidates were selected by inverting the isolation criteria. The templates were
then re-weighted according to the photon $p_T$-spectrum. For the region with MET $\geq$ 20 GeV the
prediction of 4.2±1.5 events and the observation of 4 events is again statistically consistent.

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**Figure 8.** MET templates reconstructed from a multi-jet sample.

**Figure 9.** Consistency test for MET templates in the $\gamma$+jets channel.

**Figure 10.** Consistency test for MET templates in the di-photon channel.
yields in the calculations used for our projections were obtained assuming NLO cross sections. For this exercise, the MSSM Higgs boson parameter space beyond the current Tevatron limits. Both of the channels discussed here—uall-flavor hadronic and like-sign dileptons—should be able to yield interesting sensitivities well before 4 fb⁻¹.

The Higgs boson search sensitivity at the center-of-mass energy of 0 TeV for an integrated luminosity of 4 fb⁻¹ is discussed in this Section. The projections are based on rescaling of the earlier published results at 47 TeV at 0 TeV cross sections were computed as follows, gluon-gluon fusion at the LEP excluded regions are based on searches for

Due to the generic nature of these requirements, the all-hadronic search typically has the highest sensitivity plots at 100 pb⁻¹, whereas for 1 fb⁻¹, the cuts are tightened to $H_T \geq 400$ GeV and MHT $\geq 225$ GeV/c are demanded, whereas for 1 fb⁻¹, the cuts are tightened to $H_T \geq 500$ GeV and MHT $\geq 250$ GeV/c. Other cuts are used to help ensure the reliability of the quantities used in these selection procedures. Due to the generic nature of these requirements, the all-hadronic search typically has the highest efficiency of all early CMS searches over the mSUGRA parameter space. Figure 11 shows the

Figure 11. Estimated 95% confidence level exclusion limits for the all-hadronic SUSY search,

4. Early data SUSY searches

The two searches discussed here are representative of the CMS SUSY search program [12, 13, 14, 15]. Here we give a brief sketch of how these analyses are performed.

In the all-hadronic search, events with isolated muons or electrons above a certain momentum threshold (10 GeV/c for muons and 15 GeV/c for electrons) are vetoed, so the search is nearly statistically independent from the leptonic searches. At least three jets with a $p_T \geq 50$ GeV/c are required. The angle of the missing momentum vector is required to point away from the leading jets, since fluctuations in the jet-energy measurement can lead to artificial MHT. For the sensitivity plots at 100 pb⁻¹ values of $H_T \geq 400$ GeV and MHT $\geq 225$ GeV/c are demanded, whereas for 1 fb⁻¹, the cuts are tightened to $H_T \geq 500$ GeV and MHT $\geq 250$ GeV/c. Other cuts are used to help ensure the reliability of the quantities used in these selection procedures. Due to the generic nature of these requirements, the all-hadronic search typically has the highest efficiency of all early CMS searches over the mSUGRA parameter space. Figure 11 shows the

Figure 12. Estimated 95% confidence level exclusion limits for the like-sign di-lepton SUSY search. The expected SM background at 100 pb⁻¹ (1 fb⁻¹) is 0.4 (4.0) events; an observed yield of 1 event (4 events) for setting these exclusion limits is assumed.
corresponding 95% confidence level contour lines.

The like-sign di-lepton analysis is performed in the three channels $\mu^\pm \mu^\pm$, $\mu^\pm e^\mp$ and $e^\pm e^\pm$, with the requirement of two like-sign, isolated leptons above minimum $p_T$-thresholds (both leptons with $p_T \geq 10$ GeV/c and at least one with $p_T \geq 20$ GeV). A minimum of three jets above $p_T \geq 30$ GeV/c is required, and the jets must satisfy $H_T \geq 200$ GeV. Additionally, $M_{H_T} \geq 80$ GeV/c is demanded. Figure 11 shows the corresponding 95% confidence level contour lines.

These results indicate that in the 7 TeV run, CMS should have sensitivity to regions of SUSY (mSUGRA) parameter space beyond the currently existing limits. Both of the channels discussed here should be able to yield interesting sensitivities well before 1 fb$^{-1}$.

5. Conclusion and Outlook
Jets and missing transverse energy play a key role for early SUSY searches at the LHC. The CMS Collaboration has put a lot of effort into the accurate reconstruction of these observables. Both are by now well understood, as confirmed by the good agreement seen in the comparison between data and simulation. A good understanding of backgrounds from the SM is another prerequisite for SUSY searches. Methods for suppressing these backgrounds and data-driven techniques for estimating what remains have been developed. By now, these methods have been successfully tested and validated with data.

Due to the excellent performance of CMS and the LHC, the data collected so far ($\approx 42$ pb$^{-1}$) will allow to draw new conclusions about the existence of SUSY very soon. Also, as more data will arrive in the near future, plenty of new results are expected.

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