# CMS and Constraining Supersymmetry

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**Abstract**

The Compact Muon Solenoid (CMS) is one of two general purpose detectors situated at the Large Hadron Collider (LHC). This experiment will give a window into physics at the TeV scale, beyond that of any current detector, opening opportunities for discovery of new physics. Among the possible discoveries is **Su**per**sy**mmetry (SUSY), many of these theories having a rich phenomenology at the TeV. The indicators for new physics at the TeV scale are discussed, in particular the outlook for SUSY, with emphasis on the need to constrain the parameter space for the Constrained Minimal Supersymmetric Model (CMSSM).

## 1 Introduction

The Large Hadron Collider (LHC) is currently the world's most energetic particle accelerator. Using proton-proton (pp) collisions it is capable of operating at a total centre-of-mass energy of 14TeV with a design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$[1] (though not all experiments at LHC will use this value). Located at the LHC are two large scale detectors (CMS and ATLAS), two medium scale (ALICE and LHCb), and two significantly smaller experiments (TOTEM and LHCf).

The Compact Muon Solenoid (CMS), a general purpose high luminosity detector at the LHC, is designed with the primary purpose of discovering new physics. With the LHC operating at the TeV scale, it is hoped that CMS (as well as the other experiments at the LHC) will confirm the existence of new physics at this energy scale, while also helping to constrain the parameter space of possible unified theories.

CMS started to take data in late 2009, with collision energies at the LHC at $\sqrt{s} = 0.9$TeV and $\sqrt{s} = 2.36$TeV[2]. The operating centre-of-mass energy for current and future data taking (until late 2011) will be $\sqrt{s} = 7$TeV, significantly higher than anything attained before.

One of the long term (and well publicised) goals of CMS is the discovery of the Higgs boson, whether this corresponds to the *standard model* (SM) Higgs or one arising from other theoretical models. There are also other observations that can be made during the earlier stages of running at the LHC that may indicate new physics. In early running the LHC will operate at an energy level of 7TeV (of a possible 14 TeV) but this still presents the opportuntity to observe a departure from the SM predictions. Initially some groups at CMS will be investigating and confirming current parameters of the standard model, with a particular focus on those that may provide evidence of deviations indicating new physics (NP). In particular, electroweak precision observables (EWPOs) will be studied (the cross-section for processes leading to these observables are mostly higher at the LHC centre-of-mass-energies[3]), namely the W and Z boson masses and cross-sections. The importance of these EWPOs, as well as the study of rare processes within the SM, that may indicate NP will be covered in more detail in section 4.

## 2 The standard model and indicators for new physics

The standard model, our current working model describing particle interactions, has stood up to significant investigation and includes predictions for some of the most precise measurements in all of physics (such as the anomalous magnetic dipole moment of the electron).

The SM originally arose out of, what is now, the standard method of constructing a field theory - starting out by writing down the most general Lagrangian that encompasses the symmetries that the a system observes. The SM describes three of the fundamental fields that define interactions that are observed in the universe, namely quantum chromodynamics (QCD, describing the strong force, embedding the symmetry group $SU(3)$) and electroweak (at low energies electroweak symmetry breaking results in quantum electrodynamics, describing electromagnetic interactions, symmetry group $U(1) \times SU(2)_L$). It is also normal in modern physics to consider a Higgs sector as part of the standard model. This sector is included as a complex spinor of the $SU(2)_L$ symmetry group. This was originally developed to explain how some of the gauge bosons (namely the W and Z) acquire mass[4]; postulating the existence of a Higgs field - with a non-zero vacuum expectation value - ultimately results in spontaneous breaking of the electroweak gauge symmetry introducing mass terms for the bosons in the lagrangian.

While the SM has been incredibly succesful, there also exist many indicators of physics beyond the standard model. While some of these are considered “small” corrections to the SM (i.e. the inclusion of massive neutrinos) and one is entirely absent from the theory (i.e. a description of gravity) there are other measurements that suggest deviations of observables within the scope of the SM, leading to the suggestion of new physics.

Two commonly cited observations that conflict strongly with the standard model are the existence of a relic cold dark matter density ($\Omega_{CDM}$) and the anomalous magnetic dipole moment of the muon (usually characterised by the parameter $a_\mu$ defined below in equation (1)). For $\Omega_{CDM}$, the issue is actually that the SM does not provide a candidate particle to account for *any* cold dark matter; whereas for the anomalous magnetic dipole moment of the muon the issue is that the SM prediction value differs significantly ($a_\mu^{\text{obs}} - a_\mu^{\text{SM}} > 3\sigma$) from the value observed[5].

The $\Omega_{CDM}$ problem for the SM requires an extension that provides a new particle (or particles) to act as a candidate for CDM, whereas to understand the extension required to solve the disparity in predicted and observed $a_\mu$ it is necessary to understand what contributes to this parameter.

The anomalous magnetic dipole moment for any particle is calculated from the loop corrections to the magnetic moment of that particle arising from the coupling of it to other particles (as shown in [6]). In the standard model the anomalous magnetic moment of a particle is characterised by $g - 2$, usually expressed as the parameter $a_\mu$,

$$a_\mu = \frac{g-2}{2} \tag{1}$$

with $g$ defined from $\mu$, the magnetic moment,

$$\mu = g\frac{e\hbar}{2m_\mu}\frac{S}{\hbar}. \tag{2}$$

Because these loop corrections arise from any particle with a non-zero coupling to the muon, $a_\mu$ is sensitive to contributions from any new physics particles that fulfil this criterion. This implies there exists some particle(s) whose contribution corrects this discrepancy.

While the observations discussed indicate the existence of particles beyond the standard model, they are not the only observations to suggest this is the case. Arguments based on the construction of the SM suggest that new physics should come into play at the TeV scale.

## 2.1 The hierarchy problem and fine-tuning

Within the Higgs sector, when the radiative corrections to the Higgs mass are calculated, quadratic divergences emerge. To end up with a “low mass” Higgs boson one of two things must occur: either there is an incredibly high degree of fine-tuning necessary in the parameters of the standard model, or these divergences are cancelled out by another group of particles that the SM does not account for. In essence, to solve this discrepancy one must choose some point in the energy scale at which the SM breaks down[7] denoted $Q_L$. Assuming the SM is the correct description of all physics up to and including the Planck scale (if this point, $Q_L$, is aribitrarily high this results in a non-interacting theory at low energies[8]), this would suggest there is some more fundamental theory describing behavior at and above the Planck scale. This leaves two important problems, firstly that it is necessary to fine tune the parameters of the SM to a high degree, secondly the rather scientifically unsatisfying notion (because of the necessity of fine tuning) that there is simply no new physics until the planck scale. Since we already observe discrepancies between what the SM would predict and observed behaviour it would seem necessary to choose $Q_L$ at a point *below* the Planck scale. For this to correctly resolve the divergence problem new physics must be introduced at this scale ($Q_L$) that cancels the radiative correction terms. For this to have a discernible effect it must occur at $\sim$ TeV scale (although being more precise on this value is not possible through this arugment) or else the corrections would be suppressed too greatly.

# 3 Supersymmetry

While the arguments above lend strength to the suggestion of new physics occuring around the TeV scale, they particularly suggest models based on supersymmetry (SUSY) which provide a solution to each of these problems. Not only do some SUSY theories resolve the quadrative divergences in the Higgs sector (by the introduction of a new set of fermions), they also provide a plausible CDM candidate (in the form of a neutral, weakly interacting, stable particle), naturally break electroweak symmetry at low energies, as well as providing the mechanism for unification of gauge coupling constants at the GUT scale[9].

## 3.1 Unbroken supersymmetry

Supersymmetry arises from the suggestion that there is another symmetry observed by physics at higher energies. The foundation of supersymmetry is the prediction of scalar partners to each of the SM fermions, and spin-$\frac{1}{2}$ partners to the SM gauge bosons; i.e. each particle has a superpartner (a sparticle) that is identical in mass and quantum numbers other than by differing by half a unit of spin. Also within SUSY, lepton and baryon number are not considered to be strictly conserved[10]. Given that the sparticles have identical mass to their SM counterparts it is expected that they would have been observed if SUSY was an unbroken symmetry.

## 3.2 Breaking supersymmetry

Since no observation of sparticles has been made to date, SUSY (if correct) must be a broken symmetry, allowing for the sparticles to have radically different masses from their SM partners. The various SUSY models proposed each implement a different mechanism of supersymmetry breaking. This lack of constraint in the symmetry breaking machanism leads to, what can be, very different parameters for various implementations of SUSY.

The most commonly considered supersymmetric model is the Minimal Supersymmetric Standard Model (MSSM) as it both presents the favourable aspects of SUSY (as discussed above) as well as potential for discovery at the LHC, see section 4). A result of the symmetry breaking in the MSSM is five physical Higgs bosons ($h^0$,$H^0$,$A^0$,$H^{\pm}$) arising from the two Higgs doublets (see Fig 2).

The MSSM is defined by the multiplicative conservation of a new quantum number, which is *not* a standard requirements of all SUSY models, R-parity,

$$R \equiv (-1)^{3(B-L)+s} \tag{3}$$

where B and L are the baryon and lepton number, respectively, and s is the spin of the particle. This is to make the low-energy behaviour of the theory consistent with current phenomenology (such as the lower limits on proton lifetime). This conservation law has immediate implications as all SM particles have $R = +1$, and sparticles in the MSSM have $R = -1$ indicative of two behaviours - baryon and lepton number are not exactly conserved and all sparticles are produced in pairs from SM particles. Given that R-parity is conserved within the MSSM framework this suggests these pair-produced sparticles will decay until they reach the Lightest Supersymmetric Particle (LSP, the previously mentioned candidate for CDM). This result was the original motivation for the conservation of R-parity, resulting in processes as in Fig 1.

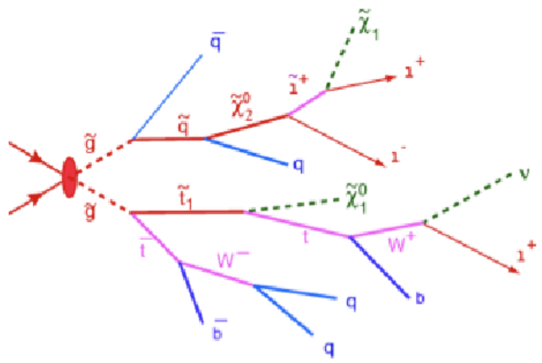


Figure 1: An example R-parity conserving MSSM process. The neutralinos, $\tilde{\chi}_0^1$ would escape without being detected.

### 3.3 Parameters in the MSSM

One of the problems of the SM is the necessity of fine tuning to fit the model to observations. Specifically, the SM is defined by 19 free parameters, demonstrating that there is some underlying behaviour that is not currently understood. In moving to a theory to correct or replace the SM it is required that at least some of this underlying behaviour becomes apparent. In actuality, the transition to the MSSM results in the need for 105 parameters to properly constrain the model. While being in the same unsatisfying position as the SM (namely that the properties of the theory are exceptionally "free"), this number of free parameters makes tracking and constraining the paramater space of the MSSM exceptionally computationally challenging. This has led to the need for more constrained models based on the MSSM to be implemented.

### 3.4 The Constrained Minimal Supersymmetric Model

The Constrained Minimal Supersymmetric Model (CMSSM) reduces the number of parameters by enforcing universality at a scale *below* renormalisation, in turn reducing the parameters to the scalar mass $m_0$, the gaugino mass $m_{\frac{1}{2}}$, the trilinear couplings $A_0$, $\tan\beta$ (where $\beta$ is the ratio of the two neutral Higgs field vacuum expectation values) and finally the sign of $\mu$ the Higgs mixing parameter[11]. The universality condition states that all of the scalar masses of squarks and sleptons are equal to $m_0$, the gaugino masses are equal to $m_{\frac{1}{2}}$, and the trilinear couplings are related by $A_0$ to the Yukawa couplings[12]. There are even more constrained models, for example minimal supergravity with only 3 parameters and a sign (mSUGRA), but the general behaviour and signals covered here would not change that significantly.

| (s)particles$_{\mathbf{h}}$ | spin |
|---|---|
| $[u,d,c,s,t,b]_{L,R}$ $[e,\mu,\tau]_{L,R}$ $[\nu_{e,\mu,\tau}]_L$ | $\frac{1}{2}$ |
| $[\tilde{u},\tilde{d},\tilde{c},\tilde{s},\tilde{t},\tilde{b}]_{L,R}$ $[\tilde{e},\tilde{\mu},\tilde{\tau}]_{L,R}$ $[\tilde{\nu}_{e,\mu,\tau}]_L$ | 0 |
| $g$ $(W^{\pm},H^{\pm})$ $(\gamma,H_1^0,H_2^0)$ | 1 / 0 |
| $\tilde{g}$ $\tilde{\chi}_{1,2}^{\pm}$ $\tilde{\chi}_{1,2,3,4}^0$ | $\frac{1}{2}$ |

Figure 2: The minimal supersymmetric standard model (s)particles, $h$ signifying handedness, $H_{1/2}^0$ are the Higgs doublets

# 4 Searches for supersymmetry

Now that SUSY models have been constructed that have reasonable numbers of parameters, and still have embedded the overall behaviour of SUSY models, it is important that direct and indirect observable effects of these models are defined. These observables, as expected, cover a broad range of physics (cosmological values, b-physics, electroweak precision measurements, etc.) and in some cases are exceptionally sensitive to new physics. A large sample of the more commonly considered observables can be found in [13]. While these observables cover wide areas and allow us to constrain our parameter space, some direct observations arise out of the phenomenology associated with SUSY models, namely missing transverse energy in an event (missing $E_T$, see section 4.1) and same sign dileption events (see section 4.3).

## 4.1 Missing $E_T$

This is a particularly promising channel to search for signals of SUSY models (that is pp $\rightarrow$ jets$+ME_T$), but *only* those derived from the MSSM or others that enforce R-parity conservation. Because of this conservation law, as discussed, sparticles in the MSSM can only be pair-produced from SM particles, and decay until the LSP is reached (see Fig 1, which is usually a neutralino, $\tilde{\chi}_1^0$. These particles escape the detector, so would manifest themselves as missing transverse energy. This is an attractive feature of these models, as this must occur for *all* R-parity conserving models, allowing any other analysis to be combined with missing $\mathrm{E_T}$. The missing energy should correspond to a particular range of possible masses for the sparticles escaping the detector and therefore can be related to the indirect constraints on the sparticle masses from other experiments and observations.

Figure 3 clearly shows that as the event's missing $E_T$ (roughly characterised by $\alpha_t$ in this case) increases the SM background falls off, leaving a strong SUSY signal in this parameter.

## 4.2 Opposite sign dilepton events

A particularly well studied possible neutralino decay to leptons and the LSP is $\tilde{\chi}_2^0 \rightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$. Combining this signal with a study of missing $E_T$ theory predicts a linear rise, with energy, of the invariant mass spectrum of the leptons that abruptly cuts off at the kinematic limit characterized by the mass difference between the two neutralinos. This edge gives a distinct direct observable to SUSY, the position of this edge can be theoretically calculated with relatively high precision[14].

## 4.3 Same sign dilepton events

While in the SM a large number of events are only allowed with leptons being produced in $\ell^{\pm}\ell^{\mp}$ pairs (e.g. $Zbb \rightarrow llbb$, $t\bar{t}$ events, $WW+$ jets, etc.[15]) there is a much greater cross-section for processes resulting in same sign ($\ell^{\pm}\ell^{\pm}$) lepton production in SUSY (similar to the event in Fig 1). This attribute makes the same sign dilepon signal a comparatively low-background channel (with the main background arising from QCD dijet production, top quark production, and electroweak boson production[16]).

# 5 CMS and supersymmetry

## 5.1 Electromagnetic calorimeter (ECAL)

Because the three main inclusive signals for SUSY require very reliable identification of leptons, and the main *direct* sign for SUSY comes from the invariant mass spectrum of the leptons, $M_{\ell\ell}$, produced (section 4.2), the ECAL plays a crucial role. The ECAL of CMS is constructed from high density scintillating crystals ($\mathrm{PbW0_4}$) which are fast (scintillation decay time is of the same order of magnitude as the bunch crossing time of the LHC) and radiation hard. This gives it two appealing properties - short radiation length and a small Molire radius[18] resulting in a fine granularity. The ECAL pseudorapidity coverage is $|\eta| < 3.0$. The combination of these properties make the ECAL a particularly appropriate section of the detector for understanding the final states of the events associated with SUSY.

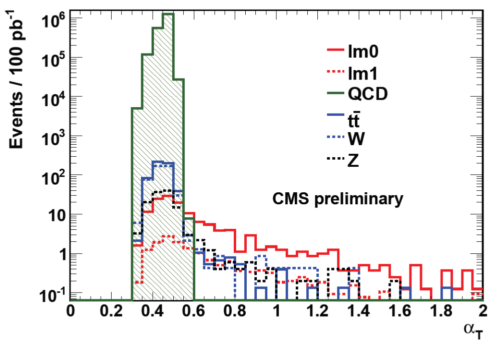


Figure 3: Standard model backgrounds shown against the supersymmetry signal ($lm0$ and $lm1$) in an n-jet event for varying $\alpha_t$[17], which embeds the *balance* of the jets in the event, i.e. for a completely balanced event $\alpha_t = 0.5$ and one would expect either no missing energy or (for a dijet event) equal loss. Cutting on $\alpha_t > 0.6$ in this situation would elimate the majority of the background (QCD).

### 5.2 Hadronic calorimeter (HCAL)

Events at the LHC are proton-proton collisions, as such all signal events that have been discussed originate from jets. While these do not form the identifying part of the event (i.e. the detection of two same sign leptons in the ECAL), it is essential to accurately reconstruct the entire event, particularly given that missing $E_T$ is a key parameter in all SUSY searches. The HCAL at CMS has a similar coverage to that of the ECAL, although near $|\eta| = 3$ the angular uncertainty doubles (compared to that of the HCAL for $|\eta| < 3$).

### 5.3 Tracker

At the closest point to the beam pipe, the inner tracking system has exceptionally high granularity (due to the high luminosity and short bunch crossing) to be able to reconstruct the trajectories of the particles produced. The particular requirements made of the tracker in CMS are that it has a good lifetime (∼10 years) and uses the minimum amount of material (to limit scattering[18]). These motivated the design of the active part of the tracker to comprise entirely of silicon detector technology. The performance of the tracker gives more than 95% reconstruction efficiency with transverse momentum resolution of 1-2%[19].

### 5.4 Muon Chambers

The muon system in CMS plays a key role for SUSY detection. Since this is the best part of the detector to make measurements of any muon final states it is important for all inclusive lepton based searches. The muon system has been a key part in the design of CMS, as it is essential for many signal channels across a wide range of physics (i.e. SM Higgs, etc.) not just those with final state muons. It has been designed to accurately reconstruct the muon momentum over the entire range of energies available at the LHC, as well as having a spatial and directional resolution of 200$\mu$m and 1mrad[19] respectively.

## 6 Conclusion

Supersymmetry appears to be a prime candidate for a possible explanation to the current observed deviations from the standard model. As well as having good theoretical motivation SUSY provides a rich phenomenology with well defined behaviours and channels. While it suffers from the same (even greater) problem with free parameters that is seen in the SM, constraining SUSY has resulted in a model that can realistically be tested at CMS. Although it is not guaranteed that SUSY does become apparent at these energy scales, CMS is in a prime position to observe even relatively small deviations from the SM, especially when combined with indrect results from other experiments at the LHC. It is

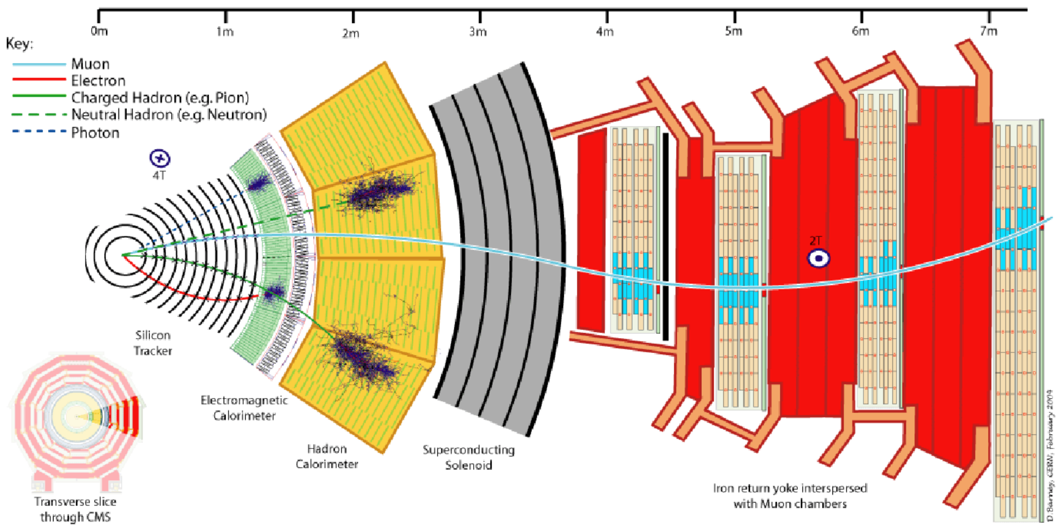


Figure 4: A transverse slice of the CMS detector

essential that in preparation for the data analysis to come, the various models are well understood and a framework is developed to allow discrimination between the various flavours of supersymmetry.

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