Implications of LHC results for TeV-scale physics: new physics with missing energy signatures

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1 Introduction

The LHC was built to explore the TeV energy scale, in order to unravel the mechanism of electroweak symmetry breaking (EWSB) and shed light on new physics beyond the Standard Model (SM) of electroweak and strong interactions. The recent discovery of a new particle, well consistent with being a Higgs boson,[1] is a triumph for the LHC physics program, and profoundly deepens our understanding of the universe. We are however still left with many fundamental questions open, and to address them it is imperative that the search for new physics continue, at the LHC and elsewhere. The recent LHC discovery is thus not to be considered as the end of a chapter, but rather as the opening of a new one.

Perhaps the most pressing issue is that the SM does not explain the value of the electroweak (EW) scale itself: Why is the Higgs boson so light when it is predicted to be driven to the scale of Grand Unified Theories (GUTs), or even the Planck scale, by radiative corrections? Either new physics appears at the EW scale, or the Higgs boson mass is fine tuned at the 10^{-32} level. This is the hierarchy problem. Another unresolved issue is the evidence from cosmological observations that 25% of the Universe consists of so-called Dark Matter (DM) — particles that are not present in the SM. These particles must be electrically and color neutral and make their presence known only through weak and gravitational interactions.

Answers to these (and related) questions typically involve new phenomena at TeV energies. Many new theories have been developed over the past decades, including Supersymmetry (SUSY), extended gauge groups and/or Higgs representations, and extra spatial dimensions. All of these models contain new particles or interactions that address the hierarchy problem. They can also exhibit symmetries that result in a stable new state with the natural properties of a DM candidate. These states can be produced at high-energy colliders either directly, or as the end result of a decay chain of a heavier new particle. High-energy colliders may thus turn out to be DM factories, where the properties and interactions of DM may be studied in a controlled laboratory environment. This opens fascinating opportunities for interplay between collider physics, astrophysics and cosmology. A very distinct consequence of the DM paradigm is that this lightest new state escapes the detector without depositing any energy, thus leading to the typical *missing transverse energy* ($E_T^{\rm miss}$) signature. This motivates the consideration of new physics that manifests itself in $E_T^{\rm miss}$ signatures, and is the topic of this Report.

Of the variety of new physics models, SUSY is arguably the most motivated and well-studied, particularly in the form of the minimal supersymmetric extension of the SM, the MSSM, which contains the minimal number of new particles. SUSY implies the existence of a super-partner for each SM particle. All super-partners are odd under a so-called R-parity, while all SM particles are even. If R-parity is a symmetry, as we assume here, the lightest SUSY particle (LSP) is stable and an excellent DM candidate. In this report, we focus on SUSY as the classic benchmark for LHC $E_T^{\rm miss}$ searches for new physics.

For SUSY to "naturally" solve the hierarchy problem, the super-partners, in particular those that are strongly coupled to the Higgs sector, should not be too heavy. Concretely, the lightest stop squark (top-quark partner) should be lighter than $\sim$700 GeV, and the gluino (gluon super-partner) lighter than $\sim$1500 GeV. Moreover, the higgsinos (the super-partners of the Higgs bosons) should not be too far from the EW scale.

With the LHC operations at 7–8 TeV in 2010–2012, we have just begun the exciting exploration of the TeV scale. Nevertheless, the recent LHC results already provide important constraints on the simplest models. More general and complex versions of SUSY, including many theoretically compelling scenarios, are thus emerging as new paradigms to guide the experimental searches. This Report documents the current status of searches for $E_T^{\rm miss}$ signatures at the LHC, and their implications for SUSY models and phenomenology. Section 2 describes the experimental strategies and findings. Section 3 delineates the theoretical landscape arising from these results, and reviews possible implications and prospects of the forthcoming LHC programme, as well as of future facilities (LHC upgrades and e^+e^- linear colliders

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[1] While the firm identification of this state as a Higgs boson is the main task of the future physics programme, for the sake of coherence we shall assume in this report, unless otherwise noted, that this is a Higgs boson (although not necessarily a SM one). Under this, very likely correct, assumption, the implications of current LHC results become more well defined in the context of reviewing the status and prospects of theories beyond the SM.

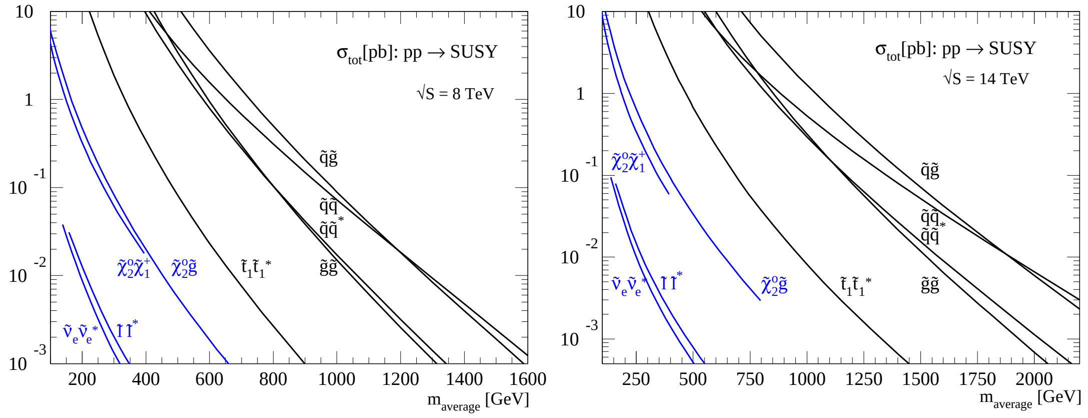

Fig. 1: SUSY production cross sections at the LHC with $\sqrt{s}$ = 8 TeV (left) and 14 TeV (right). The model parameters correspond to the CMSSM line 10.4, defined in ref. [1].

(LCs)). We shall not dwell on the discovery/precision potential of individual facilities, something which is done in greater detail in the reports of the various proposals, but rather illustrate their opportunities and challenges. Section 4 focuses on the implications of LHC results for DM searches. Section 5 summarizes our main conclusions.

2 Searches at ATLAS and CMS

2.1 Strategy of the experimental searches

The 2010-2012 LHC runs have seen a rapid growth of accumulated luminosity, happening in parallel with the work of understanding very complex and new detectors. A broad palette of SUSY-like signatures were proposed during the preparation of the LHC experimental program. The strategy of the experiments has been to prioritize among these in order to optimize the short term discovery potential. The initial searches have therefore concentrated on signatures with the following characteristics:

- Production cross-sections accessible with the progressively available luminosities.
- Reliance on robust signatures that were expected to be under good experimental control from the start of data-taking, such as electrons, muons, jets, and $E_T^{\rm miss}$.
- SM backgrounds easily reducible with simple experimental cuts and reliably predicted, either through accurate theoretical calculations or availability of well-defined control regions in data.
- Coverage of the broadest possible range of SUSY(-like) models.

While this strategy was adhered to in the course of 2010 and 2011, its detailed content has evolved, with lower and lower cross-section processes being addressed, and with more complex experimental signatures such as b-tagging becoming the staple of LHC searches.

The generic SUSY cross-sections presented in Fig. 1 show that the signature to address first must be the strong production of squarks and gluinos. Already with 1 fb^{-1}, squarks and gluinos are accessible to searches up to masses of $\sim$1 TeV. In the framework of R-parity conserving SUSY, the cascade decays of heavy squarks and gluinos typically have a high $E_T^{\rm miss}$ from the undetected LSP and high-p_T jets, the latter being abundant since the produced sparticles have color charge. In addition, the decays may typically include isolated electrons, muons or photons. The presence of these additional particles implies a strong reduction of the multi-jet backgrounds, and may increase the sensitivity to more specific SUSY scenarios.

The first results have therefore been from inclusive searches for events with $E_T^{\rm miss}$ and two or more jets, or $E_T^{\rm miss}$ plus jets plus leptons or photons. None of these searches has shown a signal of new physics so far, and the experiments are now working on increasing their generality. Generic low-mass signatures which may have been overlooked in the first round of searches are now being addressed. This is done

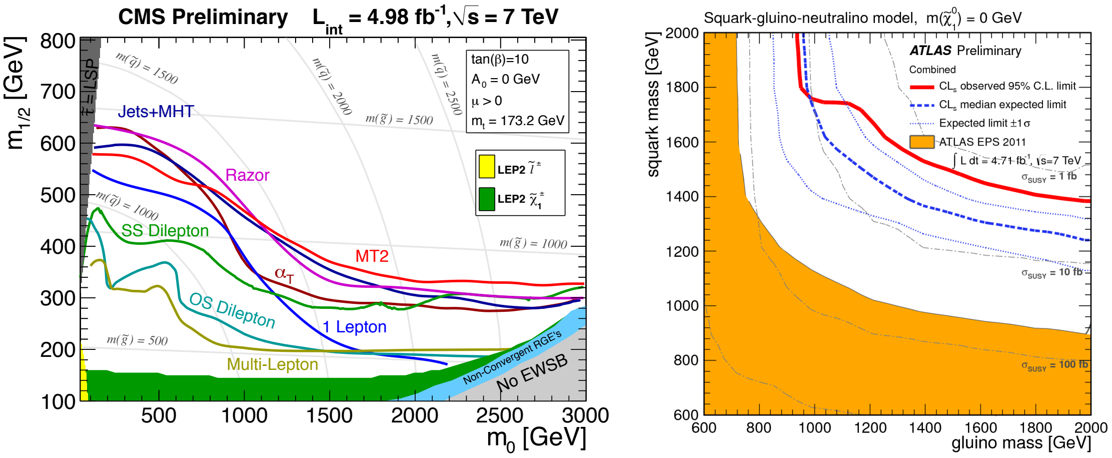

Fig. 2: Left: 95% CL exclusion in the $(m_0, m_{1/2})$ plane in the CMSSM from CMS; right: 95% CL exclusion in the $(m_{\tilde{q}}, m_{\tilde{g}})$ plane for a massless LSP from ATLAS.

e.g., by introducing new generic discriminant variables, incorporating additional signatures such as final states with multiple soft jets, or exploiting the production of hard jets from initial-state QCD radiation to cover situations where SUSY cascades yield little E_T^{miss} due to very compressed spectra.

In parallel, the LHC community has started to address more complex and exclusive signatures. A first step has been the extension of inclusive searches to final states including b-jets and hadronic tau decays, taking advantage of the excellent identification capability for these difficult experimental signatures achieved in the course of the year. These signatures address in particular the region of parameter space where sparticle cascades are dominated by 3rd generation squarks or sleptons.

With the rapid growth of the statistics, it has been possible to address lower cross-section processes, such as the direct production of 3rd generation squarks, and of sparticles with only EW couplings. These searches are ongoing, based on a detailed consideration of the possible decay chains for these 'simple' initial states, and the first results of a sustained effort in this direction, incorporating all of the 2011 statistics and in some cases part of the 2012 data, are becoming available.

2.2 Summary of the latest experimental results: SUSY interpretation

The null result of the searches described above have been interpreted by the ATLAS and CMS Collaborations as exclusion regions in various R-parity conserving, constrained SUSY models. We give a brief overview of the most relevant results as basis for the considerations in the following sections. The complete documentation can be found on the public result pages of the two experiments [2, 3]. Given the large number of parameters of generic SUSY models, two complementary approaches were used by the experiments.

The first approach is the exploration of very constrained models such as the CMSSM (described in the next section), where the full phenomenology descends from just a handful of parameters. An example are the exclusion curves provided by both ATLAS and CMS in the $(m_0, m_{1/2})$ plane of the CMSSM, on the basis of the inclusive multi-jet + E_T^{miss} + lepton analyses, as shown in the left panel in Fig. 2. A large part of the plane is excluded, corresponding to squark and gluino masses $\lesssim$ 1 TeV.

An alternative approach is to interpret the same analyses in terms of a small number of selected production and decay channels, often called "simplified models". Such models describe a set of benchmark topological signatures, parameterized in terms of sparticle masses and branching fractions to daughter sparticles. They can be used as an ingredient for the exploration of more general SUSY models. The results depend on the assumed setups, and ATLAS and CMS have adopted slightly different approaches and benchmarks.

Under the assumption that the 1st and 2nd generation squarks are degenerate and that the LSP

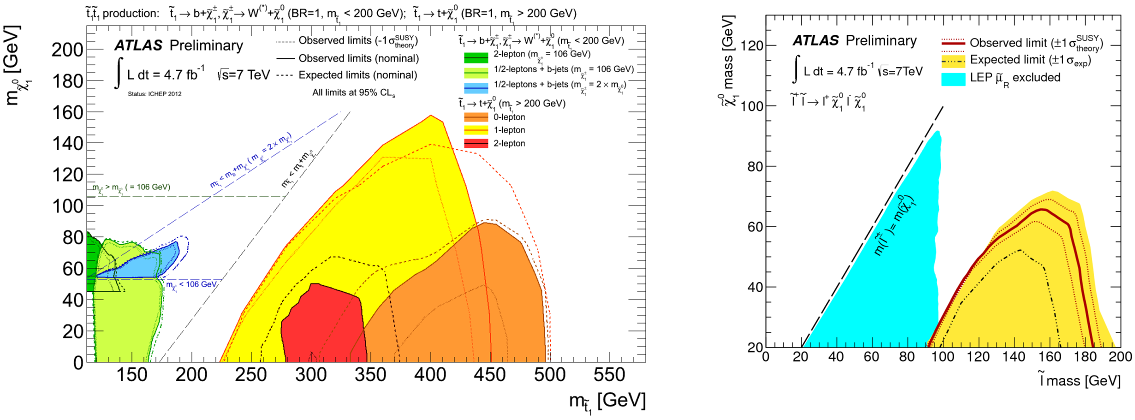

Fig. 3: Left: Summary plot of the ATLAS searches for the direct stop-pair production; right: 95% CL exclusion limit from ATLAS for direct production of sleptons.

is light, $m_{\tilde{\chi}_1^0} \lesssim 400$ GeV, light-generation squarks are excluded $\lesssim$ 1.4 GeV and gluinos are excluded $\lesssim$ 1 TeV, as shown in the right panel of Fig. 2. Relaxing either assumption dramatically changes this interpretation however, allowing either squark or gluino masses to be near 500 GeV in the case of a heavy LSP or if the first two generations are degenerate, the squark mass limits can degrade to 400–500 GeV.

An approach based on the study of simple decay chains has also been followed for 3rd generation squark and slepton searches. One benchmark used by ATLAS and CMS involves the pair production of gluinos, both of which are assumed to decay with 100% branching ratio to: $\tilde{g} \to t\tilde{t} \to tt\tilde{\chi}_1^0$ or $\tilde{g} \to b\tilde{b} \to bb\tilde{\chi}_1^0$. The final state therefore involves four top (or bottom) quarks and $E_T^{\rm miss}$. For final states having zero leptons, ATLAS and CMS exclude gluino masses $\lesssim$ 1100 GeV for LSP masses $\lesssim$ 400 GeV. For final states with one lepton, they exclude $m_{\tilde{g}} \lesssim$ 850 or 700 GeV, depending on a massless or heavy LSP of 150 GeV. For final states involving same-sign dileptons, $m_{\tilde{g}} \lesssim$ 900 GeV is excluded in the case of a LSP mass near 150 GeV, using about 3 fb^{-1} of data collected in 2012 at 8 TeV.

ATLAS and CMS have also performed searches for direct stop-pair production with the 2011 data corresponding to $\sim$5 fb^{-1} at 7 TeV, and have had a first look at a roughly equivalent amount of data from 2012 at 8 TeV. Both experiments interpreted their results for the simplified model topology $\tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)\,(\bar{t}\tilde{\chi}_1^0)$, and excluded $220 \lesssim m_{\tilde{t}_1} \lesssim 460$ GeV for very light LSPs. The excluded area in the $(m_{\tilde{t}_1},\, m_{\tilde{\chi}_1^0})$ plane from direct searches in ATLAS with 4.7fb^{-1} of integrated luminosity is shown in Fig. 3. For a stop lighter than the top quark, decaying to a final state including a b-quark, a real or virtual W and the LSP, dedicated searches were performed and exclude the range $110 \lesssim m_{\tilde{t}} \lesssim 165$ GeV for $m_{\tilde{\chi}_1^0} \lesssim 80$ GeV. The region $m_{\tilde{t}_1} \sim m_t$ is not yet covered.

Similarly, the two experiments have searched for the direct pair production of light sbottoms, assuming $\tilde{b}_1 \to b\tilde{\chi}_1^0$. The final state signature is then two b-jets plus $E_T^{\rm miss}$. Assuming a light LSP mass of about 50 GeV, sbottom squarks $\lesssim$ 550 GeV are excluded.

Besides performing searches for strongly produced sparticles, the two experiments have also looked for EW production of gauginos and sleptons in final states with two or more leptons and $E_T^{\rm miss}$. The ATLAS search in the two lepton mode excludes a region in the $(m_{\tilde{\ell}},\, m\tilde{\chi}_1^0)$ plane for slepton masses between 93 and 180 GeV with a massless $\tilde{\chi}_1^0$, see the right panel in Fig. 3. They also considered direct production of charginos, where the charginos decay into sneutrinos and leptons, yielding a limit between 120 and 330 GeV for the chargino, assuming a massless LSP. The tri-lepton signature, addressed both by ATLAS and CMS, is used in the search for direct associated production of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$. The exclusion extends up to $m_{\tilde{\chi}_1^\pm} \lesssim$500 GeV under the assumption that charginos and neutralinos decay 100% into sleptons. Searches for charginos and neutralinos decaying into W and Z bosons are ongoing and the first results from CMS are available, with exclusions just above the LEP bounds for a massless LSP. Additional constraints on the gaugino masses are obtained in search channels including jets and leptons, which are interpreted in terms of production of gluinos and squarks decaying into charginos.

Signatures including jets, $E_T^{\rm miss}$ and photons or τ's in the final state have been interpreted in the framework of models of General Gauge Mediation where the next-to-lighttest SUSY particle (NLSP) is respectively a $\tilde{\chi}_1^0$ or a $\tilde{\tau}$, yielding exclusion limits on the gluino mass of order 900–1000 GeV. The diphoton + $E_T^{\rm miss}$ signature was also used to set bounds in the parameter space of models with universal extra dimensions. Finally, $E_T^{\rm miss}$ signatures are also relevant for non-SUSY models. In particular, the experiments have studied models with additional large space-time dimensions, where the main signature is a high transverse momentum single jet or photon produced in association with $E_T^{\rm miss}$ from an undetected graviton. These searches have been used to place limits up to ~ 4 TeV on the D-dimensional Planck scale of the theory. The direct production of a generic DM particle would yield a similar signature, as described in detail in Sect. 4.

3 Interpretation and implications of the results

3.1 SUSY versus data: the theoretical landscape

The MSSM is described, in the case of the most general SUSY breaking (SSB), by 105 parameters. While most of these parameters are subject to very stringent experimental and theoretical constraints (coming from the lack of direct observation, from flavour physics observables, precision electroweak measurements, vacuum stability, etc.), the full exploration of the phenomenological implications of this large parameter space is an unfeasible task. Theoretical ideas on the possible nature of SSB, and the need to reduce the number of free parameters for practical purposes, have led in the course of the years to a variety of reference scenarios, defined by a small set of parameters.

Among these scenarios, the Constrained MSSM (CMSSM) has become the showcase model for SUSY phenomenology. It is based on the assumption of unification and equality, at the GUT scale, of several SSB parameters: a common mass m_0 for all scalar particles, a common mass $m_{1/2}$ for all fermionic partners of gauge bosons, a common mass A_0 to parameterize the trilinear couplings of scalar quarks and leptons, the ratio of Higgs vacuum expectation values $\tan\beta$, and the sign of the parameter μ defining the mixing among the two Higgs doublets, sign(μ). The renormalization group evolution of these parameters from the GUT scale to the EW scale, with the constraint of a realistic breaking of EW symmetry, leads to the low-energy spectrum and interactions of all SUSY particles. The GUT-scale relations result in highly constrained correlations among the EW scale physical observables, giving rise to a high predictive power, and exposing the model to possible falsification when confronted against the data. As discussed in Sect. 3.2.1, the main outcome of the current LHC searches for SUSY and for the Higgs boson is to have established a strong tension between experimental data and the CMSSM predictions, to the point that the CMSSM paradigm is now hardly tenable. New scenarios are therefore emerging as alternative benchmarks for the SUSY searches and their interpretation.

On one side we find the so-called phenomenological MSSM (pMSSM), where no specific prejudice is introduced regarding the nature of SSB or the pattern of unification at the GUT scale, and well motivated assumptions reduce the MSSM to a proxy characterized by 19 (for a neutralino LSP) or 20 (for a gravitino LSP) real, weak-scale parameters. This allows us to examine the LHC results in a more general fashion, without imposing unwarranted constraints on SUSY, and considering mass patterns and signatures not covered by the CMSSM, as discussed in Sect. 3.2.2.

On the other side, we have specific models driven by alternative perspectives on the relation between SUSY and the issue of EWSB. Among these, we shall focus on the so-called "natural SUSY" scenarios, on the next-to-minimal SUSY extension of the SM (NMSSM), and on scenarios with extended gauge symmetries. Many other scenarios exist, but we do not consider them here because either they do not add new features, or they are strongly disfavoured by $m_h \approx 125$ GeV. The latter is notably the case for gauge-mediated SSB and anomaly-mediated SSB, at least in their minimal versions.

Naturalness provides a useful measure of how well SUSY solves the weak hierarchy problem. Indeed, natural EWSB is the leading motivation for why we might expect to discover superpartners at the LHC. The naturalness requirement is encapsulated by the following tree-level relation in the MSSM (given for simplicity in the large $\tan\beta$ limit):

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2 \,. \tag{1}$$

If the superpartners are too heavy, the contributions to the right-hand side must be tuned against each other to achieve electroweak symmetry breaking at the observed energy scale. We can learn from this which superparticles are required to be light, *i.e.*, it defines the minimal spectrum for Natural SUSY. The higgsinos should not be too heavy because their mass is controlled by μ, and the stop and gluino masses, contributing to $m_{H_u}^2$ at one and two-loop order, respectively, must also not be too heavy. In particular, the gluino should be not much heavier than 1.5 TeV, and the lightest stop-squark should be lighter than ∼700 GeV. By isospin, the lightest sbottom-squark is also required to be light. The remaining superpartner spectrum, including the squarks of the first two generations, are not relevant for naturalness and can be much heavier than the present LHC reach.

Naturalness in SUSY has been under pressure for quite some time by $m_h > 114$ GeV from LEP2, and a Higgs mass of 125 GeV makes this issue even more acute. We are thus confronted with the so-called "Little Hierarchy Problem": large stop masses, $m_{\tilde{t}} > 1$ TeV, or maximal stop mixing are required to raise m_h with radiative corrections and these feed into $m_{H_u}^2$ in Eq. (1), leading to fine-tuning. A more direct test of naturalness comes from searches for a natural spectrum. It is hence crucial to search for and determine the limits on the higgsinos, stops, left-handed sbottom and gluino.

If we abandon the criterium of naturalness (resorting *e.g.*, to arguments of anthropic principle) but preserve the other motivations for weak-scale SUSY, *i.e.* , gauge coupling unification and a thermal dark matter candidate, we arrive at what is known as "Split SUSY". In this class of models, all scalars apart from the light Higgs are super-heavy, and the only accessible new states are the fermionic super-partners. Such a scenario is quite challenging for LHC analyses.

In the rest of this Section we shall present more details on the status of the CMSSM, pMSSM and NMSSM scenarios, and discuss the prospects and challenges for the observation at the LHC and at LCs of stops, charginos, neutralinos, and of squarks and gluinos in presence of small mass splittings.

3.2 Status of specific models

3.2.1 Constrained MSSM

The CMSSM has been a primary target of the experimental searches, with stringent limits being set in the $(m_0, m_{1/2})$ plane, see Fig. 2. Additional indirect constraints on the CMSSM arise from interpreting the neutralino LSP as DM, from flavour observables such as $b \to s\gamma$ and $B_s \to \mu\mu$, and from the muon anomalous magnetic moment, $(g-2)_\mu$, where the SM prediction deviates by about $3\,\sigma$ from the experimental value. The best fits, excluding LHC results, prefer a light SUSY spectrum with $m_0 \lesssim 100\,\mathrm{GeV}$ and $m_{1/2} \lesssim 400\,\mathrm{GeV}$, corresponding to sparticle masses below the TeV scale. These fits are mostly driven by the need for light charginos and sneutrinos to contribute to $(g-2)_\mu$.

When current LHC results from the jets + E_T^{miss} searches are included in the global fit, the SUSY mass spectrum is shifted above the TeV range. Thus the non-observation of SUSY at the LHC makes the CMSSM as inadequate as the SM in explaining the observed anomalies in the low-energy observables. Note, however, that the current LHC searches mostly constrain the masses of squarks and gluinos, while $(g-2)_\mu$ and other low-energy observables are sensitive to the EW sparticle sector. In SUSY models with universal scalar and gaugino masses as in the CMSSM, these two sectors are tightly connected, resulting in an increasing tension between low-energy observables and the LHC search limits, which would not necessarily be present in more general SUSY scenarios.

The measurement of the light Higgs boson mass provides a significant constraint on SUSY. Within the global CMSSM fit, the light Higgs scalar is SM-like, with a preferred mass around $m_h \approx 120\,\mathrm{GeV}$. A light Higgs with mass around 125 GeV is difficult to accommodate within the CMSSM, although this is considerably weakened by the 2–3 GeV theoretical uncertainty in the calculation of m_h in the MSSM. Higgs masses near 125 GeV can more easily be accommodated in models with non-universal Higgs soft terms (NUHM), where the Higgs sector is partially decoupled from the squark and slepton sector.

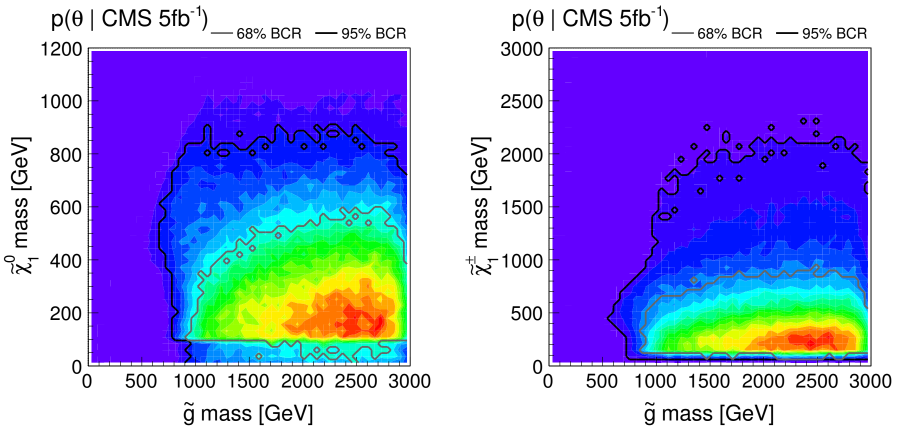

Fig. 4: Marginalized 2D posterior densities of gluino versus neutralino and of gluino versus chargino mass. The grey and black contours enclose the 68% and 95% Bayesian credible regions, respectively.

The amount of fine-tuning is severe in the CMSSM or NUHM models, of the level of per-mil for $m_h \approx 125\,\mathrm{GeV}$ [4], while generally at most $\mathcal{O}(1\%)$ tuning is regarded as "acceptable". Note here that the fine-tuning depends exponentially on m_h, so it has large variations with respect to the theoretical and experimental errors in m_h. The level of fine-tuning can be much improved in extensions of the MSSM that can increase the effective quartic Higgs coupling (see also Sections 3.2.3 and 3.2.4).

3.2.2 Phenomenological MSSM

In the pMSSM, one considers the full R-parity conserving MSSM and imposes: (i) CP conservation, (ii) minimal flavor violation at the electroweak scale, (iii) degeneracy of the first and second generations of sfermion masses (in order to address flavor issues), and (iv) negligible Yukawa couplings and A-terms for the first and second generation sparticles. In addition, it is assumed that the LSP is the lightest neutralino $\tilde{\chi}^0_1$, or a gravitino.

The pMSSM leads to a much broader set of predictions for the properties of the SUSY partners as well as for a number of experimental observables than those found in any of the conventional SUSY breaking scenarios such as the CMSSM, and can easily lead to atypical expectations for SUSY signals at the LHC. Several groups have performed scans of the 19(20)-dimensional pMSSM parameter space, subjecting the model points to constraints from the global data set on heavy flavor physics, precision electroweak observables, collider searches, and (in part) cosmological considerations.

Figure 4 shows how three independent CMS analyses — the α_T hadronic, the same-sign dilepton, and the opposite-sign dilepton analyses — currently constrain the gluino, chargino and neutralino masses [5]. The study has been performed for the 7 TeV 1 fb^{-1} CMS results and has been rescaled to 5 fb^{-1}. The sensitivity to the gluino mass corresponds to that found in the CMSSM only for light charginos and neutralinos. As the gluino-to-chargino (or gluino-to-neutralino) mass ratio decreases, the sensitivity is reduced. For $m_{\tilde{\chi}^0_1}$, $m_{\tilde{\chi}^\pm_1} \gtrsim$ 400–500 GeV, a gluino mass limit cannot be obtained from the data, other than that the gluino must be heavier than the LSP. Complementary analyses using ATLAS results arrive at analogous conclusions.

Interestingly, pMSSM points that currently escape LHC detection do not necessarily have a low production rate. Indeed, pMSSM points with low signal significance can still have cross sections as large as $\sim$1 pb. A large fraction of these points have large "EW-ino" (gaugino or higgsino) production with small $\tilde{\chi}^0_2$–$\tilde{\chi}^0_1$ mass splitting, so that the decay products are too soft to pass the analysis cuts. Another typical case that also leads to soft jets, is a small squark–neutralino mass difference. This class of events may be picked up at the LHC by mono-photon or mono-jet plus E_T^{miss} searches, *cf.* Sect. 3.3.3. The standard LHC SUSY searches will increasingly cover such difficult scenarios as the LHC energy and luminosity increase. In general, however, such scenarios are best explored at LCs, provided the relevant sparticles are within kinematic reach.

We also note that natural pMSSM spectra with a reasonable of fine-tuning, of order 1%, and $m_h = 125 \pm 2$ are not excluded by LHC searches [6]. In such scenarios, gluinos and first/second generation squarks have masses well above 1 TeV, while the $\tilde{t}_1$ and $\tilde{b}_1$ (as well as the EW-inos) remain well below a TeV. In models of this type, both charginos and 2 or 3 of the neutralinos tend to be lighter than the $\tilde{t}_1$ or $\tilde{b}_1$. The stops and sbottoms thus have complicated decay patterns, with no single dominant decay channel, and a choice of several long cascade decays. If this pattern occurs in Nature, light stop and sbottom squarks may be difficult to observe at the LHC and will require more complex search strategies, or searches at a LC.

Finally, we recall that, while the LHC analyses are starting to put independent constraints on slepton masses, see Fig. 3, this is still limited to $m_{\tilde{\chi}_1^0} \lesssim 80$ GeV. Light sleptons within the reach of a 500 GeV LC (preferred by $(g-2)_\mu$ at least for low $\tan\beta$) are thus still a viable option.

3.2.3 Next-to-minimal MSSM

The NMSSM is the simplest SUSY extension of the SM with a scale invariant superpotential: The Higgs/higgsino mass term $\mu H_u H_d$ in the superpotential of the MSSM is replaced by a coupling $\lambda S H_u H_d$ to a gauge singlet superfield S. This coupling leads to additional tree-level contributions to the mass of the SM-like Higgs. Consequently it is more natural in the NMSSM to find a Higgs mass near 125 GeV than in the MSSM; large radiative corrections involving heavy stops as in the MSSM are not required.

Indeed for low $\tan\beta$—motivated by NMSSM-specific contributions to the Higgs mass—the top Yukawa coupling is relatively large, leading to small $\tilde{t}$ masses at the weak scale through renormalization group running. Thus searches for light stops provide a crucial test for the model. Light stops imply complicated decay cascades of gluinos, leading to many jets, leptons and less E_T^{miss}; signatures for direct stop production with $m_{\tilde{t}_1}$ slightly above the top quark mass are very difficult to distinguish from the top quark background. The corresponding (constrained) versions of the NMSSM are thus much less tested at present than constrained versions of the MSSM, and remain a challenge for the future or for a LC. In this context it is interesting to note that in NUHM versions of the NMSSM, requiring an ≈125 GeV Higgs along with imposition of all other experimental constraints, including $(g-2)_\mu$, leads to 1st/2nd generation squark and gluino masses of ∼1.7–2.3 TeV, which might only be probed at the 14 TeV LHC.

Furthermore in the NMSSM, the cross section times di-photon branching ratio for the SM-like Higgs can be enhanced, especially at low values of $\tan\beta$ [7]. If the enhanced Higgs signal persists, it would provide support for the NMSSM. The NMSSM moreover contains new particles in addition to the MSSM: a Higgs scalar and pseudoscalar and the fermionic component of the gauge singlet superfield S, the singlino. These new particles can lead to new Higgs and SUSY signatures at the LHC as well as weaken the limits from standard searches. It is also possible that the two scalar Higgses of the NMSSM are quasi-degenerate and both contribute to an enhanced $\gamma\gamma$ signal at 125 GeV [8].

The most distinctive feature of the NMSSM is that the singlino can easily be the LSP, leading to an additional decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + X$ at the end of every sparticle decay cascade. This reduces the E_T^{miss} and provides additional jets or leptons [9]. In a constrained version of the NMSSM, it was found that the efficiencies could be reduced by up to 30% thus weakening the present lower bounds on $m_{1/2}$ obtained in the CMSSM by a factor 0.9–0.75. SUSY searches with a singlino-like LSP thus require improving the efficiencies in multijet or multilepton channels. The presence of a new light singlet Higgs state, which is well motivated in NMSSM models with a $\mathcal{O}(10\ \mathrm{GeV})$ LSP compatible with DM constraints, can also modify the final states in sparticle cascade decays.

3.2.4 SUSY models with extended gauge symmetries

In the MSSM, R-parity is imposed by hand as a discrete symmetry to prevent the appearance of terms that would lead to too rapid proton decay. A possible way to explain the origin of R-parity is an extended gauge sector containing $B-L$ as a generator, such as $SO(10)$.[2] The existence of an additional gauge

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[2] The requirement of $U(1)_{B-L}$ being anomaly free implies the existence of right-handed neutrinos beside the usual SM fermions; these new states can in turn be used to explain current neutrino data via the seesaw mechanism.

group at the TeV scale is consistent with all current data, implying that an additional heavy vector boson Z' could exist with a mass of a few TeV. An appealing feature of SUSY models with extended gauge symmetries is that the tree-level constraint $m_h \leq m_Z$ of the MSSM, requiring huge radiative corrections in order to achieve $m_h = 125$ GeV, is alleviated by additional D-term contributions to the Higgs mass.

At the LHC, both ATLAS and CMS search for new gauge bosons and SUSY particles. Up to recently, these searches have been performed without a combination of both elements: the conventional Z' searches look for resonances in di-lepton and/or di-quark distributions, with only decays into SM-particles being considered in the calculation of the corresponding widths. This is important because the peak cross section of the resonance scales like $\Gamma_{\rm tot}^{-2}$. Decays into SUSY final states can enhance the width by about 30%, thus significantly reducing the Z' rate. Other effects that may impact the current search limits are the relation of the additional gauge coupling to the known SM couplings, which depends on the particle content of the model, and the correct treatment of gauge kinetic mixing [10].

The SUSY partner of the right-handed neutrino, the R-sneutrino, can be the LSP and is a potential dark matter candidate. This implies changes in the SUSY cascade decays and the corresponding signatures. This holds in particular if the lightest neutralino is heavier than at least one charged slepton as then decays such as $\tilde{\chi}_1^0 \to l^\pm \tilde{l}^\mp \to l^\pm W^\mp \tilde{\nu}$ are possible. The supersymmetric partner of the Z' can be lighter than the Z' itself with a mass of a few hundred GeV. In such cases, the $\tilde{q}_R$ not only decay into a quark and the bino-like neutralino, but also into the extra gaugino with a branching ratio of up to 30%. With the extra gaugino decaying further to the LSP, the resulting final states contain several additional leptons and/or jets, which in the MSSM would be interpreted as the signal of a $\tilde{q}_L$ decay.

Regarding sleptons, an interesting aspect is that they can be produced in a Drell-Yan like process via the Z', even if they have a mass of several hundred GeV. This can considerably extend the reach of the 14 TeV LHC for direct slepton production.

3.3 Specific signatures

3.3.1 Light stops

ATLAS and CMS have begun to place limits on direct stop production, thus constraining models in which gluinos are very heavy but stops are light. The direct limits on the $\tilde{t}_1$ mass are however still below 500 GeV and have numerous gaps, especially in the region $m_{\tilde{t}_1} \sim m_t$, for $m_{\tilde{\chi}_1^0} > 100$ GeV, and for large branching fractions of $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$. It remains very plausible that the $\tilde{t}_1$ has a mass below 250 GeV. Different ideas to improve the LHC reach for stops in both, the high mass region and the compressed region, have been proposed very recently. All sensitivities quoted below are for 20 fb^{-1} at 8 TeV.

For the high mass region, variations of M_{T2} in the semileptonic channel may be used as a discriminating kinematical variable, whose distribution has an endpoint for background but not for signal. For $m_{\tilde{\chi}_1^0} \lesssim 100$ GeV, this may give a sensitivity to $\tilde{t}$ masses up to 700 GeV [11] . Top tagging techniques to search for boosted tops from stop decays may also be exploited. Considering the fully hadronic channel and requiring large $E_T^{\rm miss}$ and a top-tagged fat jet, the backgrounds may be significantly reduced, and $m_{\tilde{t}_1} \lesssim 650$ GeV may be probed as long as one is not in the compressed regime [12].

For the compressed region, differences between signal and background in the shape of the $E_T^{\rm miss}$ distribution (for fully hadronic stop decays) and the W transverse mass distribution (for the semileptonic stop decays) may be exploited [13]. This provides a powerful handle for at background dominated regions such as those with moderate $E_T^{\rm miss}$, where signals from compressed spectra are concentrated. The estimated reach is $m_{\tilde{t}} \lesssim 300$ GeV even for the very compressed case with $m_{\tilde{t}} \approx m_{\tilde{\chi}_1^0} + m_t$.

Finally, one may use the fact that $t\bar{t}$ pairs produced from regular SM processes have spin correlations, which are absent for $t\bar{t}$ pairs from $\tilde{t}$ decays. Moreover, u- and t-channel processes enhance the probability that SM $t\bar{t}$ pairs are produced with large rapidity differences relative to $t\bar{t}$ from $\tilde{t}$ decays. Based on the distributions of $\Delta\phi(\ell^+\ell^-)$ and $\Delta\eta(\ell^+\ell^-)$ in the dileptonic channel, $\tilde{t}$'s around 200 GeV decaying to a top and a massless LSP may be excluded at the 3σ level [14].

Overall, a combination of dedicated searches targeting different regions of phase space, and using advanced techniques as explained above, will be necessary to cover the entire range of Natural SUSY

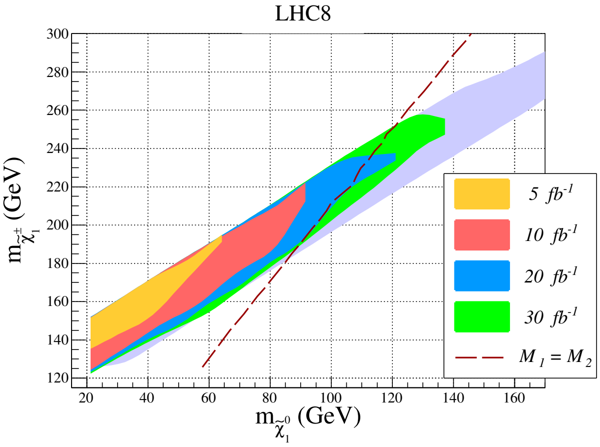

Fig. 5: 5σ discovery regions for various integrated luminosities at the 8 TeV LHC run in the $m_{\tilde{\chi}^{\pm}_1} - m_{\tilde{\chi}^0_1}$ plane. We assume $m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^{\pm}_1}$ and consider only $\tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2$ production. The dashed red line shows the case of universal gaugino mass ($M_1 = M_2$ at the GUT scale).

models at the LHC. In addition to the stop mass, a determination of the stop mixing and trilinear Higgs coupling is crucial information for testing EWSB and for explaining $m_h \approx 125$ GeV in SUSY models. At a LC, the measurement of polarized cross sections would allow a direct determination of the $(\tilde{t}_L, \tilde{t}_R)$ mixing angle with an accuracy of a few degrees.

3.3.2 Electroweak Inos

If squarks are very heavy, electroweak $\tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2$ production (and to some extent by $\tilde{\chi}^{+}_1 \tilde{\chi}^{-}_1$ production) may compete with gluino-pair production. It may hence prove fruitful to directly probe EW-ino pair production in the 2011 and 2012 data. Figure 5 shows the expected 5σ discovery regions in the WZ+$E_T^{\rm miss}$ channel for various integrated luminosities at LHC8 in the $(m_{\tilde{\chi}^{\pm}_1}, m_{\tilde{\chi}^0_1})$ plane. As can be seen, chargino masses up to ~ 190 GeV can already be probed with 5 fb^{-1}, if $m_{\tilde{\chi}^0_1} \lesssim 65$ GeV. For heavier $\tilde{\chi}^0_1$ (or lighter $\tilde{\chi}^{\pm}_1$), the $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ mass gap reduces, resulting in softer m_T and $E_T^{\rm miss}$ distributions and a reduced signal efficiency. This effect is seen throughout the $(m_{\tilde{\chi}^{\pm}_1}, m_{\tilde{\chi}^0_1})$ plane, rendering the narrow region near $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} \sim m_Z$, where the $\tilde{\chi}^0_1$ is produced at low p_T, inaccessible even for $\mathcal{L} = 30$ fb^{-1}. Even smaller $\tilde{\chi}^0_2 - \tilde{\chi}^0_1$ mass differences are expected in higgsino-LSP scenarios, making this case particularly difficult to resolve at the LHC [15].

The region where $m_Z < m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} \lesssim m_h$ results in boosted $\tilde{\chi}^0_1$'s can be easily probed until the decay $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 + h$ turns on. The 30 fb^{-1} reach extends up to $m_{\tilde{\chi}^{\pm}_1} \sim 255$ GeV, for $m_{\tilde{\chi}^0_1} \lesssim 135$ GeV, covering almost all of the kinematically allowed region for universal gaugino masses. We also remark, that for 5 fb^{-1} of data, we would expect a $\sim 2\sigma$ effect over essentially the entire region where the decay $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 Z$ dominates. Therefore, the LHC experiments already have accumulated enough luminosity to probe this entire region at $\sim 95\%$ C.L. However, in the happy circumstance that some excess is seen in the data, $\sim 20 - 30$ fb^{-1} will be required in order to establish a 5σ discovery. This could be achieved in the 2012 run of the LHC.

On the other hand, if $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} > m_h$, then $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 + h$ is the dominant decay mode, and the analysis of EW-ino production has to wait for the 14 TeV LHC run [16]. With 100 fb^{-1} of integrated luminosity, the searches should become sensitive to chargino masses $m_{\tilde{\chi}^{\pm}_1} \lesssim 550$ GeV at 14 TeV.

The optimal machine to study the neutralino–chargino system would be a future LC. Using threshold scans, polarized beams, and possibly exploiting signatures with ISR photons, it should be possible to disentangle gaugino–higgsino (and, in the NMSSM, singlino) mixing and determine the underlying parameters to within a few percent.

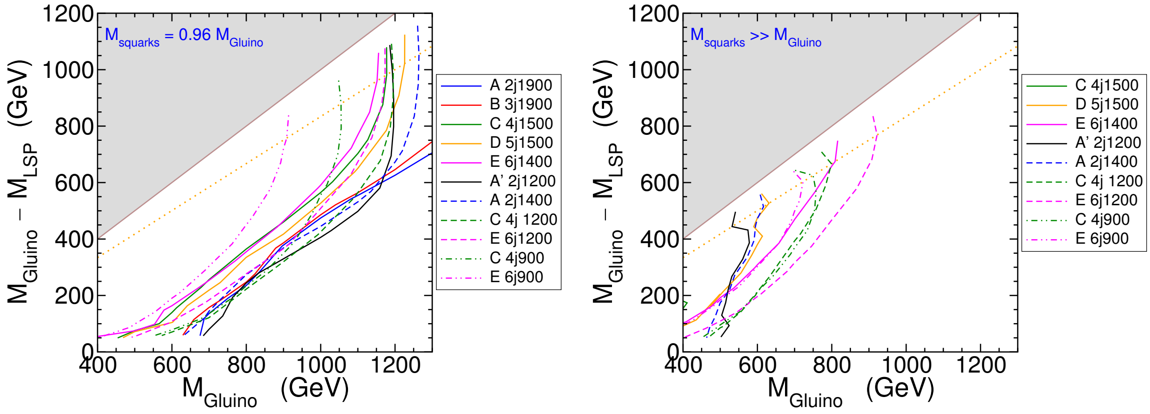

Fig. 6: Exclusion contours for compressed SUSY models, estimated based on limits on new physics contributions to ATLAS signal regions for 4.7 fb^{-1} at $\sqrt{s} = 7$ TeV.

3.3.3 Compressed spectra

The LHC discovery potential is greatly reduced if the SUSY spectrum is compressed. If the mass difference between the strongly interacting superpartners (gluino and squarks) and the LSP is small, then the amount of visible energy in each event is reduced, and cuts on the p_T of the leading jet(s), $E_T^{\rm miss}$, and $m_{\rm eff}$ or H_T will be less efficient. In evaluating the reach of compressed SUSY models, radiation of extra QCD jets from the nominal hard scattering event could provide an important extra handle.

Model lines of compressed SUSY can be defined in terms of a "compression parameter" c, with the bino and wino masses related to the gluino mass by $M_1 = m_{\tilde{g}}(1 + 5c)/6$ and $M_2 = m_{\tilde{g}}(1 + 2c)/3$ [17]. Thus $c = 0$ corresponds approximately to the CMSSM scenario, while $c = 1$ is the limit of total compression with degenerate gauginos. Figure 6 shows the estimated exclusion curves corresponding to the ATLAS signal regions at 4.7 fb^{-1} for two versions of this model framework: one with light squarks of mass $0.96 m_{\tilde{g}}$, and another with almost decoupled squarks with mass $m_{\tilde{g}} + 1000$ GeV. One sees that for high compression (lower in the plots), gluino masses as light as about 700 GeV (for light squarks) and 500 GeV (for heavy squarks) are still viable, of course pending further results from $\sqrt{s} = 8$ TeV running. One of the lessons learned from this analysis is that while all distributions become very soft in the compressed limit, $m_{\rm eff}$ does so faster than $E_T^{\rm miss}$. Therefore, signal regions that are optimized to extend the frontier of CMSSM or simplified models with large mass splittings can be extremely inefficient for compressed SUSY, particularly if $m_{\rm eff}$ cuts are taken too high.

In the limit of complete compression, hard QCD radiation must be present in order to pass the relevant cut on $m_{\rm eff}$ or H_T. Therefore, one may expect that a monojet signal where a single hard QCD jet recoils against missing energy could yield an effective search strategy. This possibility was investigated and compared with all other hadronic SUSY searches, with particular attention to a careful treatment of uncertainties in the QCD prediction [18]. Three simplified scenarios were investigated: 1) first and second generation squarks quasi-degenerate with the LSP and all other particles removed from the spectrum; 2) the reversed case with the gluino quasi-degenerate with the LSP; and 3) the first two generations of squarks placed in between the gluino and LSP. In all scenarios, the mass splitting between the LSP and the coloured states is varied from 1 to 100 GeV.

In the limit of degeneracy the CMS monojet and CMS Razor searches both provide competitive limits, see Fig. 7. The limit found for scenario 1 is $m_{\tilde{q}} > 340$ GeV whilst for scenario 2 it is $m_{\tilde{g}} > 500$ GeV. For scenario 3, $m_{\tilde{q}} \sim m_{\tilde{g}} > 650$ GeV. However, as soon as the degeneracy is broken and the mass splitting between the coloured states and LSP is increased, the monojet search loses efficiency due to the presence of a third jet with $p_T > 30$ GeV, which is vetoed in the cut flow. In contrast, the CMS Razor search remains stable and the bounds actually improve with increased mass splitting. It should also be noted that these results are in good agreement with the ATLAS searches mentioned above.

This exercise shows that a promising way forward in inclusive searches is the analysis of shapes

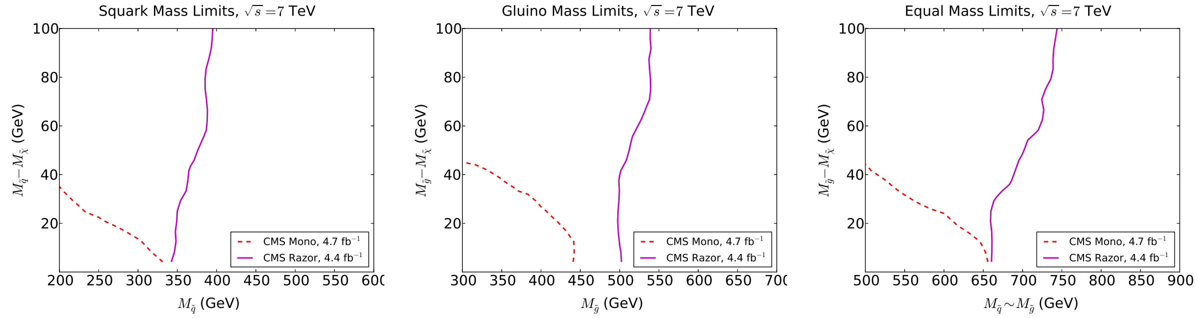

Fig. 7: Exclusion contours for compressed SUSY models, estimated based on limits on new physics contributions to the CMS Razor (4.4 fb^{-1}) and CMS monojet (4.7 fb^{-1}) searches at $\sqrt{s} = 7$ TeV.

of relevant kinematic distributions, as compared to event counting in the tails of the distributions. The consideration of larger intervals in the distributions of discriminant variables allows the implementation of looser selections, thus enhancing the sensitivity to compressed spectra.

Compressed SUSY is also sensitive to searches for an initial or final state photon recoiling against missing energy. One can re-interpret these searches as a bound on the squark mass in the compressed scenario. Assuming a single squark is in kinematic reach, current mono-photon plus $E_T^{\rm miss}$ searches lead to a conservative bound of 150 (110) GeV for up (down)-type squarks [19].

4 Dark Matter

If DM consists of a new weakly interacting massive particle (WIMP), originating from new physics beyond the SM, this opens intriguing opportunities for the interplay between collider physics, astrophysics and cosmology. In particular, in this case DM may be produced and studied at colliders in cascade decays of other new states and/or directly in association with an initial-state photon or gluon (mono-photon or mono-jet searches). The properties of the DM candidate may thus be determined precisely in a controlled laboratory environment. This would allow to predict the cross sections relevant for the relic density calculation and for direct and indirect DM detection, thus providing important consistency checks with astrophysical measurements.

Here note that the calculation of the relic density relies on important assumptions about the history of the Early Universe,[3] and different cosmological scenarios can lead to results which differ by several orders of magnitude from the standard picture. Similarly, direct and indirect DM detection constraints rely on several assumptions. In the case of direct detection, important uncertainties arise, *e.g.*, from the local DM density and velocity distribution, while indirect detection rates heavily depend on the propagation model. Therefore, even if the detection of a WIMP signal would allow determination of the DM mass, the determination of the cross section would be subject to large astrophysical uncertainties. Measurements at colliders, on the other hand, would make it possible to determine (or at least constrain) these cross sections without suffering from astrophysical uncertainties.

Collider experiments cannot determine, however, whether a particle that escapes as $E_T^{\rm miss}$ is indeed stable on cosmological time-scales. Therefore any DM candidate put forth by collider searches needs to be confirmed by a corroborating signal, agreeing in mass and cross section, from (in)direct DM detection.

4.1 Neutralino dark matter

Within the MSSM, the best thermal DM candidate is the neutralino LSP. There are only a few mechanisms that provide the correct amount of neutralino annihilation, so that $\Omega h^2 \approx 0.1$: annihilation of a bino LSP into fermion pairs through t-channel sfermion exchange in case of very light sparticles; annihilation of a mixed bino-Higgsino or bino-wino LSP into gauge boson pairs through t-channel chargino

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[3] Most importantly that i) that the initial temperature after inflation was high enough to fully thermalize the LSP and ii) the entropy per co-moving volume was constant after freeze-out.

and neutralino exchange, and into top-quark pairs through s-channel annihilation; and finally annihilation near a Higgs resonance (the so-called Higgs funnel). Furthermore, co-annihilation processes with sparticles that are close in mass with the LSP may bring Ωh^2 into the desired range. In particular, co-annihilation with light sfermions can help to reduce the relic density of a bino-like LSP. Note that coannihilation generically occurs when there is a small mass gap between the LSP and the next-to-lightest SUSY particle (NLSP). In scenarios with a higgsino or wino LSP, however, one has a mass-degenerate triplet of higgsinos or winos, and coannihilations are so efficient that Ωh^2 becomes too small, unless the LSP has a mass of order TeV. In the case that Ωh^2 is too low one would need, for instance, a significant contribution from non-thermal production.

It becomes clear that masses and couplings of all relevant sparticles must be measured with high precision to reconstruct the relic density and direct and indirect DM detection cross sections. Roughly speaking, $\lesssim 1\%$ accuracy in the key parameter(s) of any process relevant for the $\tilde{\chi}_1^0$ annihilation (and reliable bounds on the other parameters) is necessary to achieve $\sim 10\%$ precision for the inferred Ωh^2. At the LHC, this may be achieved in some favorable cases. A reliable determination of the DM properties however clearly requires precision measurements at a LC.

An interesting option in the context of the NMSSM is singlino (or mixed singlino–higgsino) DM. The decay width of the higgsino to the singlino is of the order of 100 MeV. The pattern of final states is rich, and the measurement of branching ratios can give additional information on the Higgs sector. The decay products are quite soft, however, and likely invisible under standard LHC trigger constraints. Whether or not these decays can be seen at the LHC, a LC would be needed for a complete study. The singlino annihilation cross section, which determines its thermal DM density, depends on the singlino–higgsino mixing angle. This could be measured at a LC by measurement of the higgsino width using a threshold scan, or by precision measurements of the neutralino system exploiting beam polarization.

4.2 Effective theory descriptions of WIMP interactions

While the details of a given WIMP model are usually involved and depend sensitively on the nature of the particles which mediate interactions between WIMPs and the SM particles, a relevant simplification takes place when the mediating particles, of mass M_*, are heavy compared to the momentum transfer of the processes of interest. In this limit, the mediators never appear on-shell in processes, and their effects are well approximated by an effective field theory (EFT) containing contact interactions between the WIMP and the SM fields. The EFT offers the possibility to capture classes of similar models in a common framework, and to compare different kinds of WIMP searches in a consistent language which allows one to highlight the strengths and weaknesses of each one.

Any interaction coupling WIMPs to quarks or gluons allows WIMPs to be produced at hadron colliders. Since they escape undetected from a typical detector, the strategy is to look for events containing additional hadronic (or electromagnetic) radiation from which the presence of the WIMPs can be inferred due to an imbalance in the transverse momentum of the visible particles, *i.e.*, E_T^{miss}. Since a typical event contains one jet (or one γ) as well as the undetected WIMPs, this signature is known as a "mono-jet" (or "mono-photon") search. The null results of LHC searches so far allow one to place upper limits on the value of M_* for each operator that mediates WIMP–SM interactions.

The EFT approach allows one to directly compare searches at colliders with those from direct and indirect detection of DM. Figure 8 shows the constraints from ATLAS and CMS mono-photon data on the direct detection plane, for both spin-dependent and spin-independent interactions. As can be seen, for spin-dependent interactions, the constraints from colliders are stronger than those from the direct DM detection experiments. In case of spin-independent interactions, the LHC mono-photon (and mono-jet) searches cover in particular the very light DM region with mass below a few GeV, where the direct DM detection experiments loose sensitivity. Analogously, one may map the collider constraints onto the plane of indirect detection, including production of gamma rays, and anti-protons. In both cases, there is a high degree of complementarity between collider, direct, and indirect searches; together the three provide a much more complete picture of WIMP interactions than can be achieved with one search strategy alone.

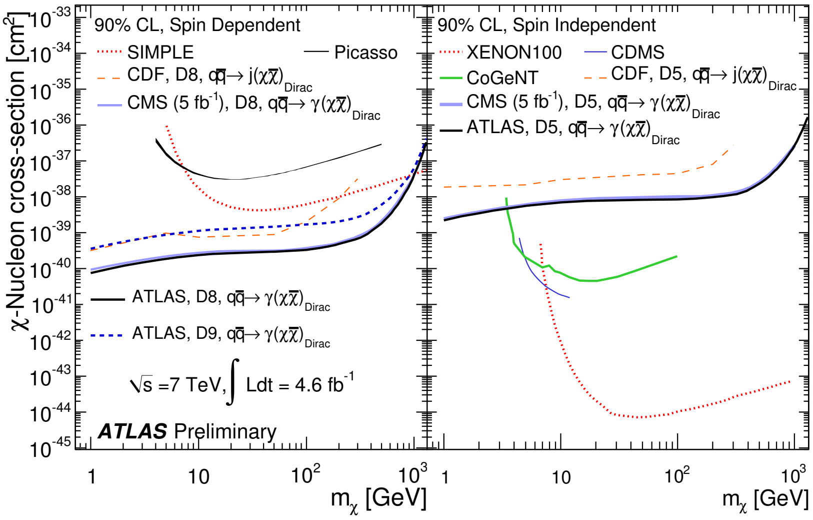

Fig. 8: 90% confidence level upper limits on the nucleon-WIMP cross section as a function of $\mathrm{M}_\star$ for spin-dependent (left) and spin-independent (right) interactions. The ATLAS and CMS results are compared with previous CDF results and with limits from direct WIMP detection experiments.

5 Summary and conclusions

Natural stablization of the electroweak scale requires new phenomena at TeV energies. The underlying theories, including Supersymmetry, naturally contain light, stable DM candidates that can be readily produced at high-energy colliders (in particular in the decays of heavier new states) and escape the detectors unobserved. This results in the experimental signature of missing transverse energy. Numerous E_T^{miss}-based searches have been carried out with the 2010–12 LHC data. The first rounds of analyses focused on the golden signature of jets+E_T^{miss}. High rates would arise from the strong production of new colored particles, such as squarks and gluinos, cascade-decaying to the DM candidate and SM particles. Searches have placed strong restrictions on simplified or constrained models of SUSY, with squarks and gluinos in this case being excluded up to ∼1.4 TeV (for $m_{\tilde{q}} \sim m_{\tilde{g}}$). When the implications of a 125 GeV Higgs boson are folded in, such simple models become very unnatural, or fine-tuned, and no longer address the stabilization of the EW scale. The null results of the LHC have thus shown that Nature has not chosen this simplest path for Supersymmetry.

The next round of LHC searches is concentrating on more complicated E_T^{miss}-based scenarios. In particular, dedicated searches for light stops and for EW gauginos and higgsinos will provide important tests of "natural" models. Other searches, designed to close analysis gaps such as compressed spectra, will also be an important focus for the analysis of the 8 TeV data sample.

Less theoretically constrained and/or extended SUSY scenarios remain viable and predict natural spectra that are in full agreement with the present data, including a 125 GeV Higgs boson. Theoretical work is now focused in this area, including models with light stops that have complicated decay patterns, or models with compressed SUSY spectra. Such models easily accommodate the LHC data and do not yet exclude the possibility of SUSY particles lying in the kinematic range of a 500 GeV LC.

In short, while the simplest SUSY models are becoming less favored by the data, natural SUSY at the weak scale is still viable in seemingly more complex models. A first signal of such models is still possible at the 8 TeV run, but resolving these scenarios likely requires the full 300 fb^{-1} at 14 TeV. The discovery of SUSY would give additional physics opportunities at the LCs, allowing for precision measurements of all SUSY particles that are within kinematic reach.

It is well understood that, if SUSY particles can be produced at a LC, we can learn much from studying them [20, 21]. By measuring EW production cross sections using polarized beams, we can not only unambiguously determine the quantum numbers of the new particles, but we can also recognize that they are mixed states, measure the mixing angles, and determine the underlying SSB parameters. These measurements can address crucial questions such as the detailed dynamics of EWSB, the mechanism of SUSY breaking, and the suitability of the DM candidate to explain the observed cosmic density of DM.

Likewise, the discovery of Supersymmetry at the LHC would also motivate the high luminosity phase of the LHC, extending the reach for $\tilde{q}$ and $\tilde{g}$ to beyond 3 TeV, for $\tilde{t}/\tilde{b}$ to about 1.6 TeV, and for EW-inos to about 1.1 TeV. Detailed studies of kinematic distributions with high statistics would enable many important studies of the properties of the SUSY (and extra Higgs) particles. All these ingredients would be required to start addressing the new big question for the field, namely what is the origin and nature of SUSY breaking, and possibly yield valuable information on physics at even higher energy scales, such as tests of GUT models.

Last but not least let us note that all the above prospects and the exciting roadmap necessitate constant development of methods and tools for theoretical calculations and interpretation studies. On the theory side, predictions of higher-order cross sections, branching ratios and kinematic distributions with an increased precision for the SM, Higgs and new physics processes is a crucial task. Improving Monte Carlo tools has also become critical since the growing complexity of the upcoming experimental searches requires more extensive usage of Monte Carlo events in the analyses, particularly in background estimation. Interpretation studies also demand Monte Carlo tools capable of generating signals for a diverse range of new physics models.

A systematic presentation of the experimental results, as well as creation of common sample databases and analyses platforms will help to enable a more effective usage of our valuable time and computing resources. Finally, a robust interpretation depends on devising novel, sophisticated statistical techniques that can be reliably used in multi-parameter model spaces. Dedicated studies deliberately address all these needs and lead to creation of advanced methods and tools.

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