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

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1 Introduction

From the very beginning, the LHC has been designed as a discovery machine [1], to shed light on electroweak symmetry breaking and new physics beyond the Standard Model (SM) of electroweak and strong interactions. The recent discovery of the Higgs boson [2] is the first step in this direction, and a phantastic success for the LHC physics program. While tremendously important for the completion of the SM, it should however not be considered as the end of an chapter, but the opening of a new one.

Indeed, the SM with all its brilliant successes, leaves several fundamental question open. Most importantly, it does not explain the electroweak scale itself: why is the Higgs mass so light when one should expect that it be driven to the GUT or even the Planck scale by radiative corrections? Answers to this and related questions typically involve new phenomena at TeV energies — be it supersymmetric (SUSY) particles, new gauge groups and/or extended Higgs representations as e.g. in Little Higgs models, or the effect of extra space-time dimensions. **[add some arguments regarding the conceptual importance of the TeV scale]** For this reason, the LHC has been designed to reach $\mathcal{O}(1)$ TeV at the constituent level, implying a centre-of-mass energy of order 10–20 TeV at the parton level [1].

With the present runs at 7 TeV (in 2011) and 8 TeV (2012) we are but beginning this exciting journey. Nevertheless, the recent LHC results already provide important constraints on the simplest models of new physics, in particular on "vanilla" SUSY and very constrained modes, like the CMSSM. More general incarnations of SUSY, including theoretically well-motivated scenarios, are still little constrained. Major steps forwards can be expected at the second phase of LHC operation at $\sqrt{s} = 13$–14 TeV. **[Figure of SUSY production Xsections by M. Krämer et al.?]**

A clear indication that the SM misses out something fundamental is the existence of dark matter (DM) in the Universe, at least if we pursue the particle physics interpretation of DM. It is intriguing that models of new physics often invoke a new parity to get around some shortcomings of the model; this new parity makes the lightest new state stable and a natural DM candidate (needless to say this lightest state has to electrically and color neutral). The perhaps best example is R-parity in SUSY to avoid too rapid proton decay, leading to a stable lightest SUSY particle (LSP), which makes an excellent DM candidate. The LHC may thus turn out a DM factory, where the nature and interactions of the DM candidate may be studied in a controlled laboratory environment. A very distinct consequence of the DM paradigm is that any new state produced (cascade-)decays into the LSP, which escapes the detector without depositing any energy, thus leading to the typical *missing transverse energy (MET)* signature.

This motivates us in particular to consider new physics which manifests itself in MET signatures, which is precisely the topic of this working group report.

2 Searches at ATLAS and CMS

2.1 Strategy of the experimental searches

The first two years of LHC running have seen a very rapid, almost exponential growth of the accumulated luminosity, which happened in parallel with the work of understanding very complex and new detectors. A very broad palette of signatures has been proposed during the years of approach to the LHC for the discovery of SUSY. The strategy of the experiments has been to prioritize among these signatures the ones which would optimize the short term discovery potential in the complex experimental situation described above. The initial searches have therefore concentrated on signatures with the following characteristics:

- Cross-sections accessible with the progressively available luminosities.
- Reliance on robust signatures which were expected to be under good experimental control from the start of data-taking, like electrons, muons jets and $E_T^{\rm miss}$.
- Standard Model backgrounds easily reducible with simple experimental cuts and easy to predict, either through accurate theoretical prediction or the availability of well-defined control regions in data.
- Covering the broadest possible range of SUSY models.

While this strategy has been 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 the LHC searches.

From a simple perusal of a generic SUSY cross-section plot at 7 TeV, the first addressed signature must be the strong production of squarks and gluinos. Already with 1 fb^{-1} squarks and gluinos would be accessible to searches up to a mass of 1 TeV. In the framework of R-parity conserving SUSY, the cascade decays of heavy squark and gluinos will have a high $E_T^{\rm miss}$ from the undetected LSP and high-p_T jets, since the produced sparticles are coloured. Besides this extremely generic signature, the decays may typically include isolated electrons muons or photons. The loss in generality and of branching fraction by requiring these additional particles may be compensated by a strong reduction of the multi-jet backgrounds, where the $E_T^{\rm miss}$ is generated by instrumental effects and is difficult to predict. 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. Unfortunately none of these searches has shown a signal of new physics and the present status with 5 fb^{-1} can be summarised by saying that production of gluinos and squarks of the first two generations are excluded up to masses of 1.5 TeV in a very broad range of SUSY scenarios if the mass difference between the squark/gluino and the LSP is of order of a few hundred GeV, and if the decay pattern is relatively simple. While this scenario was progressively unveiling itself in the course of 2010, the LHC community has started addressing signatures which are not covered by the above mentioned searches.....

2.2 Summary of latest results, incl. simplified-models interpretation

2 pages (Giacomo, Rick)

3 Interpretation of results and implications for specific models

3.1 Status of the Constrained MSSM

Matthew Dolan, Dumitru Ghilencea, Sven Heinemeyer, Michael Krämer, Leszek Roszkowski; partly revised by Sabine

Featuring just 4 parameters (plus a sign) the CMSSM [3] has become the showcase model for SUSY phenomenology. Indeed, as seen in the previous section, the experimental collaborations present most of the SUSY search results in the M_0 versus $M_{1/2}$ plane of the CMSSM, for fixed $\tan\beta$ and A_0.

Strong constraints on the CMSSM arise from interpreting cold dark matter in terms of the neutralino relic density, from flavour observables like $b \to s\gamma$ and $B_s \to \mu\mu$, and from $(g-2)_\mu$, where the Standard Model prediction deviates by about 3 σ from the experimental value. The best fits without LHC exclusions prefer a light SUSY spectrum with $M_0 \lesssim 100\,\mathrm{GeV}$ and $M_{1/2} \lesssim 400\,\mathrm{GeV}$ corresponding to sparticle masses at or below the TeV-scale. When current LHC exclusions from the jets and missing energy searches are included in the global fit, the SUSY mass spectrum is shifted into the multi-TeV range. Thus the description of the low-energy observables and the non-observation of SUSY at the LHC become increasingly incompatible with the CMSSM. Note, however, that the current LHC searches mostly constrain the masses of the strongly interacting SUSY particles, while $(g-2)_\mu$ and other low-energy observables are sensitive to the electroweak sparticle sector. In SUSY models with universal scalar and gaugino masses like 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 (NUHM1 or NUHM2), where the Higgs sector is partially decoupled from the squark and slepton sector.

A complementary analysis of supersymmetric models concerns the stability of the electroweak scale under quantum corrections (fine tuning Δ). The amount of fine tuning in the CMSSM, NUHM1, NUHM2 or NUGM (non-universal gaugino masses) reaches levels of order $\Delta \sim 500$ to 1000, for a Higgs mass $m_h \approx 125\,\mathrm{GeV}$ [4]. Note here that $\Delta \sim \exp(m_h)$, so there are rage variations in Δ with respect to the theoretical and experimental error in m_h. The level of fine-tuning can be much improved in extensions of the MSSM. For instance, models with an additional massive singlet (NMSSM with a superpotential mass term for the singlet) or massive extra $U(1)'$ can easily reduce Δ to what is usually regarded as "acceptable", i.e. $\Delta \sim 30$ or such.

[Be more concrete regarding the "increasing tension"; quantify it. Maybe add a χ^2 and/or a fine-tuning plot]

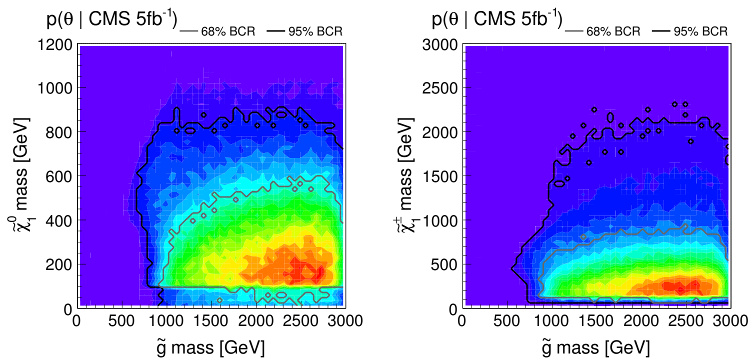

Fig. 1: Marginalized 2D posterior densities of gluino versus neutralino and of gluino versus chargino mass. The grey and black contours enclose the 68% and 95% Bayesian credible regions, respectively.

Phenomenological MSSM

Sabine, incorporating part of a contribution by S.S. AbdusSalam, B.C. Allanach, and F. Quevedo, and a paragraph by JoAnne

The simplifying assumption of universality at the GUT scale makes the CMSSM very predictive and a convenient showcase for SUSY phenomenology. Indeed, it is interesting to present limits within the CMSSM because it provides an easy way to show performances, compare limits or reaches, etc.. On the other hand, the interpretation of experimental results in the $(m_0, m_{1/2})$ plane risks imposing unwarranted constraints on SUSY, as many mass patterns and signatures that are possible *a priori* are not covered in the CMSSM.

It is thus important to ask what current LHC data tell us, and do not tell us, about SUSY in general, without relying on particular SUSY breaking schemes. While it is of course not possible to consider the MSSM in its full generality (105 parameters are clearly to much to scan over), a few plausible assumptions motivated by experiment let us reduce the dimensionality of the problem a lot. To be concrete, assuming that there are no new CP phases, the sfermion mass matrices and trilinear couplings are flavor-diagonal, the first two generations of sfermions are degenerate and their trilinear couplings are negligible. In addition, we assume that the LSP is the lightest neutralino, $\tilde{\chi}_1^0$. We thus arrive at a proxy for the MSSM characterized by 19 real, weak-scale parameters—the so-called phenomenological MSSM (pMSSM). 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. This can easily lead to atypical expectations for SUSY signals at the LHC.

Figure 1 shows how three independent CMS analyses—the α_T hadronic the same-sign dilepton the opposite-sign dilepton analyses—currently constrain the gluino, chargino and neutralino masses [5]. The study has been done for the 1 fb^{-1} CMS results and has then been rescaled to 5 fb^{-1}. As can be seen, the sensitivity to the gluino mass corresponds to that found in the CMSSM only for light charginos and neutralinos. As the gluino:chargino (or gluino:neutralino) mass ratio decreases, one looses in sensitivity. For $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^\pm} \gtrsim$ 400–500 GeV, no gluino mass limit can be derived other than that the gluino must be heavier than the LSP. Analogous conclusions are found in studies of Simplified Models.

Interestingly, pMSSM points with low signal significance do not necessarily have low cross section. This is illustrated in Fig. 2 (*should be only the 5fbi plot*). As one can see, points that escape LHC detection can have cross sections as large as pb. In Fig. 2, about 2/3 of the points with large cross section but low signal significance have dominantly EW ino production with small χ_2^0–χ_1^0 mass splitting, so that the decay products are too soft to pass the analysis cuts, see sections **??** and 3.4. Another typical case, which also leads to soft jets, is small squark-neutralino mass difference. These class of events may be picked up by mono-photon or mono-jet plus MET searches, though the reach is still low, see section 3.8.

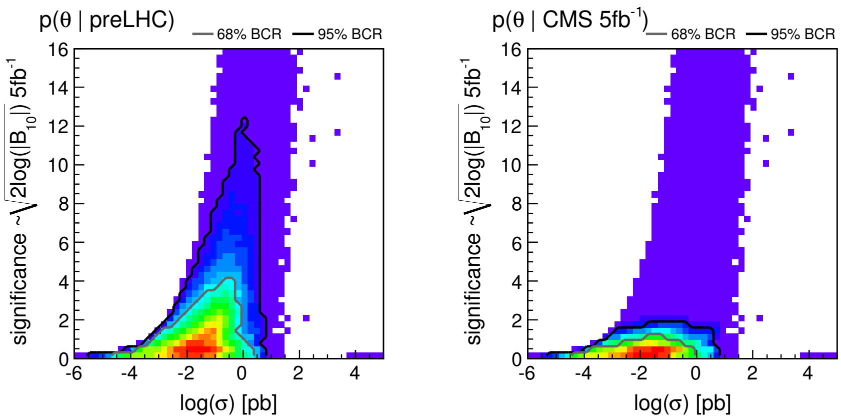

Fig. 2: Marginalized 2D posterior densities of signal significance versus total SUSY cross section, on the left before and on the right after taking the CMS searches into account. The grey and black contours enclose the 68% and 95% Bayesian credible regions, respectively.

from Ben et al:

A complementary analysis using ATLAS results comes to analogous conclusions. From the MCMC sampling based on pre-LHC (low-energy, flavor, LEP and Tevatron) constraints, about 43% of the sample points are ruled out by the LHC data but the general features of the posterior probability density functions remain approximately the same, i.e. the sparticle masses are prior independent except in the Higgs sector which remains approximately prior independent with sub-TeV stops. Imposing that the Higgs boson mass is 122-128 GeV; together with the ATLAS, CMS, LEP and Tevatron Higgs sector constraints using `HiggsBounds` & `FeynHiggs` about 75% of the posterior sample points are ruled out. All together 15% of the initial sample survives the 2011 full SUSY and Higgs search data set constraints.

The pre-LHC posterior samples have a significant volume of parameter space that would escape standard trigger-systems of the current LHC detectors. Probing such SUSY scenarios would require dedicated trigger-commissioning or a future linear collider. Other unprobed SUSY scenarios include those with squarks of a few TeV but with order 1 TeV neutralino and chargino masses. Such models would require an LHC run at energies greater than 14 TeV.

from JoAnne:

Natural sparticle spectra with a reasonable amount of fine-tuning, of order 1%, a Higgs mass in the 125 ± 2 GeV range, and are not excluded by LHC searches are possible within the pMSSM. In such scenarios, it is possible to accomodate gluinos and first/second generation squarks at higher masses while the lightest stop/sbottom squarks (as well as the electroweak gauginos) remain below a TeV. (**DO WE WANT A FIGURE OF SUCH A SPECTRA HERE???**) In these models, both charginos and 2 or 3 neutralinos tend to be lighter than the $\tilde{t}_1/\tilde{b}_1$, and hence the stop and sbottom have complicated decay patterns, with no single dominant decay channel, and several long cascade decays. If this indeed occurs in Nature, light stops/sbottoms may be difficult to observe at the LHC and will require more complex search strategies.

3.2 Natural SUSY, light stops

to be done

3.3 Electroweak gauginos

Sabine, taken from arXiv:1201.5382

Within a large class of SUSY models, it is expected that pair production of strongly interacting sparticles—$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ production—constitutes the dominant SUSY production cross sections. The

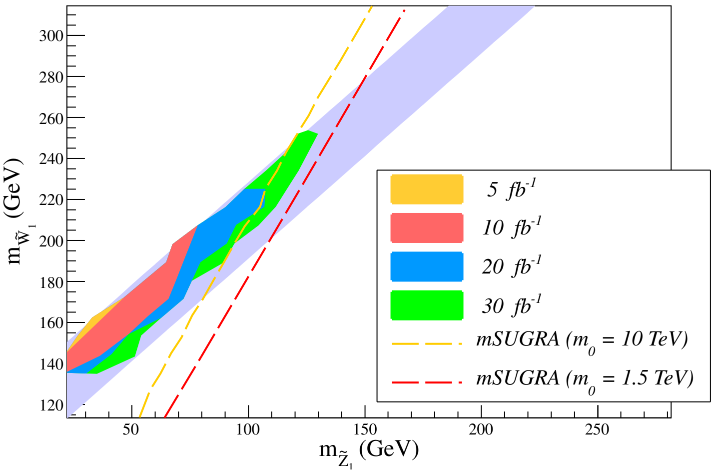

Fig. 3: 5σ discovery regions for various integrated luminosities at LHC7 in the $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ plane. We assume $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ and consider only $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production. The Higgs boson mass is assumed to be 128.5 GeV throughout the plane. The orange (red) line shows the mSUGRA line with $m_0 = 10$ TeV, $A_0 = -2m_0$, $tan\beta = 25$ and $\mu > 0$ ($m_0 = 1.5$ TeV, $A_0 = 0$, $\tan\beta = 45$ and $\mu > 0$).

gluinos and squarks are then expected to decay through a (possibly lengthy) cascade to lighter sparticles plus SM particles, until the decay chain terminates in the LSP. In models with universal gaugino masses, gluino-pair production is dominant for $m_{\tilde{g}} \lesssim 500$ GeV. For higher values of $m_{\tilde{g}}$, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production is dominant, followed by $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production. For LHC with $\sqrt{s} = 14$ TeV, $\tilde{g}\tilde{g}$ production remains dominant up to $m_{\tilde{g}} \sim 1$ TeV if squarks are very heavy. Since ATLAS and CMS already exclude $m_{\tilde{g}} \lesssim 550$ GeV when $m_{\tilde{q}}$ is large it may prove fruitful to probe electroweak gaugino pair production in the 2011 data but most of all in the 2012 LHC run.

Current analyses do not put independent constraints on the electroweak-ino masses if the gaugino mass unification condition is dropped. **[this is changing right now]** Moreover, the relative strengths of signals in various multilepton topologies (as well as the gluino mass reach if the parent-daughter mass difference is sufficiently small) depend sensitively on the $\tilde{g} - \tilde{\chi}_1^0$ and/or $\tilde{g} - \tilde{\chi}_1^\pm$ mass differences.

We remark that for 5 fb^{-1} of data, we would expect a 2σ effect over essentially the entire region where the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$ 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} of data will be required in order to establish a 5σ discovery. This may indeed be achieved in the 2012 run of the LHC. We note further that the SUSY signal events will contain a distinctive asymmetry of trilepton charges $+(+-)$ *vs.* $-(+-)$ (where the $(+-)$ pair reconstructs m_Z) that originates from the PDFs since LHC is a pp collider. In contrast, SM backgrounds from $t\bar{t}$ and $Zt\bar{t}$ (but not WZ) should have the number of $+(+-)$ events equal to $-(+-)$ events, up to statistical fluctuations. In addition, should a large enough data sample be accrued, the $p_T(Z)$ distribution should be well-suited for a $\tilde{\chi}_2^0$ mass extraction since the production and decay modes are single channel.

Figure 3 shows the 5σ discovery regions for various integrated luminosities at LHC7 in the $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ plane. **[will be updated to 8 TeV]** As can be seen, chargino masses up to ~ 170 GeV can already be probed with 5 fb^{-1}, if $m_{\tilde{\chi}_1^0} \lesssim 50$ GeV. As discussed above, for heavier $\tilde{\chi}_1^0$, the $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ mass gap reduces, resulting in softer m_T and $E_T^{\rm miss}$ distributions. Therefore the signal efficiency is reduced, requiring higher luminosities in order to achieve 5σ significance. This effect is seen throughout the $m_{\tilde{\chi}_1^\pm}$ vs. $m_{\tilde{\chi}_1^0}$ plane, rendering the narrow region close to $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim M_Z$, where the $\tilde{\chi}_1^0$ is produced at low p_T, inaccessible even for $\mathcal{L} = 30$ fb^{-1}. On the other hand, the region where $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \lesssim m_h$ results in boosted $\tilde{\chi}_1^0$s and can be easily probed until the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + h$ turns on, c.f. Fig. **??**. The 30 fb^{-1}

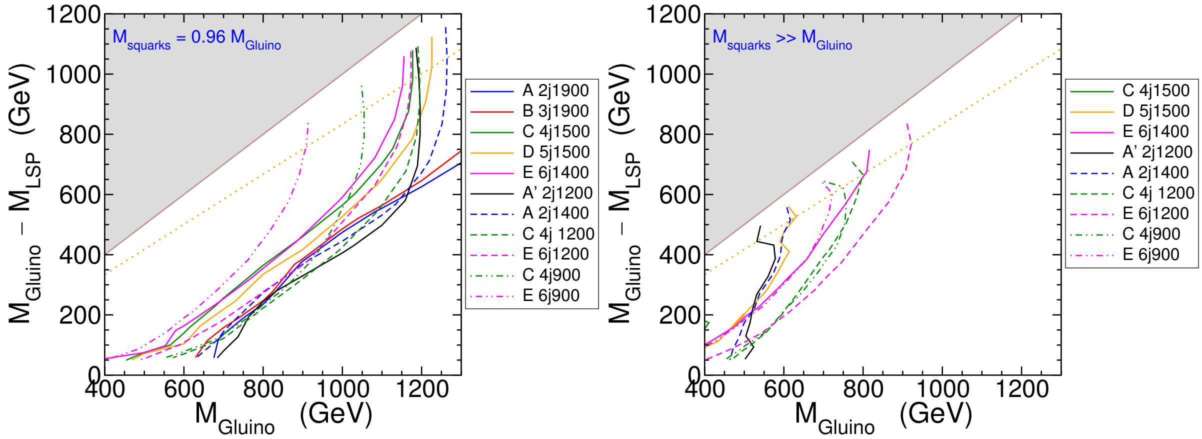

Fig. 4: Exclusion contours for compressed SUSY models, estimated based on limits on new physics contributions to ATLAS signal regions for 4.7 fb^{-1} at $\sqrt{s} = 7$ TeV.

reach extends up to $m_{\tilde{\chi}_1^\pm} \sim 250$ GeV, for $m_{\tilde{\chi}_1^0} \lesssim 130$ GeV, covering almost all of the kinematically allowed region for the mSUGRA line with $m_0 = 10$ TeV, $A_0 = -2m_0$. We also show in Fig. 3 a second mSUGRA line with $m_0 = 1.5$ TeV, $A_0 = 0$, $\tan\beta = 45$ and $\mu > 0$. For these choice of parameters the $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ mass difference is reduced, due to a small (positive) A_0 value and smaller squark masses. As a result, all of the region where the $WZ + E_T^{\rm miss}$ channel is open falls into the inaccessible region at high $m_{\tilde{\chi}_1^0}$. However, $m_h \sim 125$ GeV now excludes values of $A_0 \sim 0$ in mSUGRA.

[just a start to have something, needs to be worked over; also, discuss LC potential]

3.4 Compressed spectra

S.P. Martin, J. Tattersall

The LHC exclusion reach in mass for supersymmetry is greatly reduced if the superpartner spectrum is compressed compared to the usual mSUGRA assumptions. 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 passed far less often. In evaluating the reach of compressed SUSY models, radiation of extra QCD jets from the nominal hard scattering event is important.

In ref. [6], several model lines of compressed SUSY were proposed and the reach of ATLAS signal regions with up to 1 fb^{-1} at $\sqrt{s} = 7$ TeV was evaluated. The models were defined in terms of a “compression parameter” c, with the bino and wino mass parameters at the TeV scale related to the gluino mass by $M_1 = M_{\tilde{g}}(1 + 5c)/6$ and $M_2 = M_{\tilde{g}}(1 + 2c)/3$. Thus $c = 0$ corresponds approximately to the mSUGRA scenario, while $c = 1$ is the limit of total compression with degenerate gauginos. One version of this model framework had light squarks, with mass $0.96 M_{\tilde{g}}$, and a heavy squark version took the squarks to be almost decoupled, with mass $M_{\tilde{g}} + 1000$ GeV. One of the lessons learned from this analysis is that while all distributions both 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 MSUGRA or simplified models with large mass splittings can be extremely inefficient for compressed SUSY, particularly if $m_{\rm eff}$ cuts are taken too high.

The estimated exclusion curves corresponding to the ATLAS signal regions at 4.7 fb^{-1} are shown in Figure 4 for the two classes of models discussed above. 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.

For compressed spectra where the gluino and/or squarks are quasi-degenerate (1–100 GeV mass splitting) with the LSP, LSPs recoiling against initial state radiation (ISR) may also give sensitive sensi-

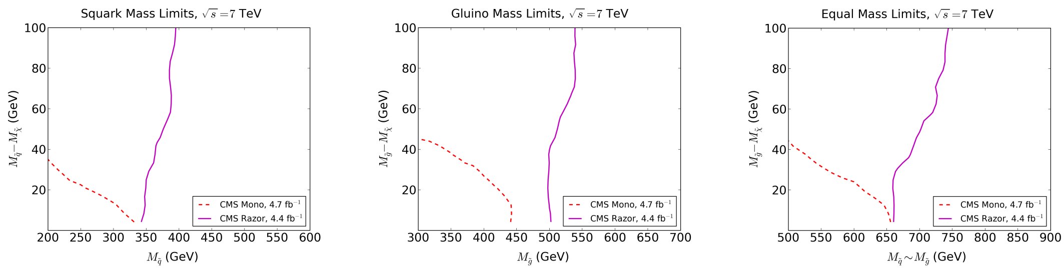

Fig. 5: Exclusion contours for compressed SUSY models......

tive signals. Here, it is vital that the ISR is understood and possible uncertainties in the predictions are evaluated. Both MLM [**?**] (with Pythia 6 [**?**]) and CKKW- L [**?**, **?**] (with Pythia 8 [**?**]) matching are used in order to give a precise prediction whilst avoiding issues with double counting radiation. In addition, the scale of matching and parton shower properties are varied to accurately determine the theoretical uncertainties in the kinematic distributions. In order to place the most stringent bounds on the model, all current LHC SUSY and monojet analyses are employed. We find that the most constraining limits come from the CMS Razor [**?**] and CMS monojet [**?**] searches. For a scenario of squarks degenerate with the LSP and decoupled gluinos we find $M_{\tilde{q}} > 340$ GeV. Moving to gluinos degenerate with the LSP and decoupled squarks, $M_{\tilde{g}} > 500$ GeV. Finally, with equal mass squarks and gluinos degenerate with the LSP, $M_{\tilde{q}} \sim M_{\tilde{g}} > 650$ GeV [**?**].

[add a comment on LHC potential with 13-14 TeV, hi-lumi and implications for a LC]

3.5 Higgsino LSP: Hidden SUSY

H. Baer

Rather light higgsino states appear in supersymmetric models with low fine-tuning in the electroweak sector, and in fact the μ parameter itself has been suggested as a measure of fine-tuning. In this latter case, values of $|\mu| \sim M_Z$ are expected, while LEP2 searches for charginos expect $|\mu| \gtrsim 100$ GeV. Low values of $\mu \sim 100 - 200$ GeV thus appear "natural". In this case, the $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ states are all relatively light with mass $\lesssim 250$ GeV, and dominantly higgsino-like. The remaining sparticles may well be heavy and inaccessible to LHC searches. A second attractive feature of light higgsinos is that the lightest neutralino—if it is the LSP—has a standard thermal abundance well below WMAP-measured values, with $\Omega_{\chi}^{std}h^2 \sim 0.007$. Then, in appealing cosmological scenarios such as those containing TeV-scale scalar fields such as moduli, or in scenarios with mixed axion-$\tilde{\chi}_1^0$ cold dark matter, the neutralino abundance can be easily pushed up into the measured range. It is also possible to tune Peccei-Quinn parameters such that the WIMP abundance remains tiny, while the bulk of CDM is comprised of axions.

At LHC8, or even at LHC14, gluino and squark production may be suppressed by large values of $m_{\tilde{g}}$ and especially $m_{\tilde{q}}$. The $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production reactions are then dominant, but are difficult to detect at LHC due to the small $\tilde{\chi}_1^{\pm}$–$\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$–$\tilde{\chi}_1^0$ mass gaps, which lead to very soft visible particle production. The reaction $pp \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ may lead to tightly collimated OS/SF dilepton pairs, although calculations of signal and background after simple cuts indicate these occur at unobservable levels. Trileptons from $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production are also difficult to see due to the soft spectrum of isolated leptons. The light higgsino possibility should motivate experimentalists to push for di- and tri-muon analyses at the very lowest levels of $p_T(\mu)$ which are possible.

[add comment on LC potential]

3.6 Next-to-minimal MSSM

G. Belanger, J.F. Gunion, U. Ellwanger

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) is the simplest supersymmetric extension of the Standard Model 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 Standard Model-like CP-even Higgs boson. Consequently it is more natural in the NMSSM to find a Higgs boson with a mass near 125 GeV than in the MSSM; large radiative corrections involving heavy scalar top quarks as in the MSSM are not required. This has direct consequences for the search for supersymmetry at the LHC. Moreover in the NMSSM, the cross section times di-photon branching ratio for the SM-like Higgs can be enhanced, especially at low values of $\tan\beta$.

One of the implications of a Higgs with a mass of 125 GeV for SUSY searches within the context of the NMSSM is that light scalar top quarks are natural. Indeed for low $\tan\beta$—motivated by the NMSSM-specific contributions to the Higgs mass — the top Yukawa coupling is relatively large, leading to small scalar top quark masses at the weak scale through the running implied by the renormalization group. Thus scalar top searches at the LHC provide a crucial test for the model. Light scalar top quarks imply complicated decay cascades of gluinos and scalar up/down quarks leading to many jets, leptons and less missing transverse energy; signatures for direct scalar top quark pair production with scalar top quark masses slightly above the top quark mass are very difficult to distinguish from the top quark background. Hence, corresponding (constrained) versions of the NMSSM are much less tested at present than constrained versions of the MSSM, and remain a challenge for the future.

Another implication of a a CP-even SM-like Higgs with mass of order 125 GeV for the NMSSM with universal scalar squared masses and A parameters for the squarks/sleptons (but not the scalar Higgs masses squared) and universal gaugino masses is rather heavy coloured particles. Once all relevant experimental constraints are imposed (from B physics, relic density of dark matter, and muon anomalous moment) 1st and 2nd generation squarks and the gluino were found to have masses between about 1.7 TeV and 2.3 TeV. Hence, the LHC needs sensitivity to quite high 1st and 2nd generation squark and gluino masses.

The NMSSM 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.

In the supersymmetric sector the most distinctive feature of the NMSSM is that the singlino can well be the lightest supersymmetric particle, and the singlino-like LSP appears at the end of every sparticle decay cascade. The additional cascade $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + X$ will reduce the missing energy and will provide additional jets or leptons. 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 $\mathcal{O}(10\ GeV)$ LSP compatible with dark matter constraints — can also modify the final states in sparticle cascade decays.

Finally, also nearly Standard Model-like Higgs bosons can have a non-negligible decay branching fraction into (invisible) neutralinos in the NMSSM which is not excluded by present searches, but potentially observable in searches for missing transverse energy and Higgs production via $t\bar{t}H$ production, vector boson fusion or ZH production.

3.7 SUSY models with extended gauge symmetries

W. Porod

In the MSSM one imposses R-parity 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 $SO(10)$ as shows for example the following breaking chain

$$\begin{aligned} SO(10) &\rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ &\rightarrow SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi \end{aligned} \quad (1)$$

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. One can show that the existence of an additional gauge group at the TeV scale is consistent with all current data mit den Rechnungenimplying that an additional heavy vector boson Z' could exist with a mass of a few TeV.

In the context of supersymmetry such models have an additional appealing feauture in view of Higgs physics. Current LHC data hint for a Higgs boson with a mass $m_h \simeq 125$ GeV. Within the MSSM this is difficult to explain in the framework of unified models as huge radiative corrections are required to explain such a mass. The source of the required size for these corrections is the tree-level constraint $m_h \leq m_Z$. In models with extended gauge symmetries this bound is not valid anymore as there are additional D-term contributions to the Higgs mass.

At the LHC new gauge bosons and supersymmetric particles are searched for by both, ATLAS and CMS. This searches are done however without a combination of both elements and, thus, the following features are not taken into account in the interpretation of the existing data:

- The current searches for a Z' look for resonances in various two-lepton and/or two-quark distributions. For the calculation of the corresponding widths only decays into SM-particles are considered. However, there are several effects which have to be taken into account and which can lead to a shift of the bounds: (i) there are additional decay channels open, e.g. right-handed neutrinos or supersymmetric particles. Supersymmetric final states can enhance the width by 30 per-cent after taking into account the existing experimental bounds on their masses. This is important as the peak cross section of the resonance scales like Γ_{tot}^{-2} and thus, it gets reduced if additional states are present. (ii) Within GUT models the relation of the additional gauge coupling to the known SM couplings depends on the particle content of the model if unification is assumed. (iii) In addition, the correct treatment of gauge kinetic mixing plays an important role as can be seen from the left plot in figure 6.
- 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 $\tilde{\chi}_1^0 \rightarrow l^\pm \tilde{l}^\mp \rightarrow l^\pm W^\mp \tilde{\nu}$ are possible. Moreover, in such scenarios parameter regions exist where all neutralinos and charginos are heavier than squarks implying that only decays of the form $\tilde{q} \rightarrow q\nu\tilde{\nu}$ or $\tilde{q} \rightarrow q' l \tilde{\nu}$ are open with a quite different p_T spectrum of the resulting jet compared to the case of two-body decays.
- The supersymmetric partner of the Z' can be lighter than the Z' itself with a mass of a few hunderd GeV. In such cases the R-squarks do not only decay into the a quark and the bino-like neutralino but also into the extra gaugino with a branching ratios of up to 30 per-cent for the latter. The resulting final states contain several leptons and jets which in the MSSM is usual the signal of a L-squark. The same holds also for sleptons.

It turns out the sleptons can be significantly lighter than squarks in such models even if one assummes mSUGRA inspired boundary conditions. An interesting aspect of the first item is that sleptons can be produced in a Drell-Yan like process via the Z' even if they have a mass of several hundred GeV. As an example we show the reach of 14 TeV LHC with an integrated luminosity of 300 fb^{-1} in figure 6.

A detailed study of the Z' properties will be necessary to determine (i) its nature, in particular to determine its couplings to SM-fermions, and (ii) its couplings to neutralinos and charginos to give a first insight in their nature. In the latter case the corresponding branching ratios are at most a few per-cent in most of the parameter space the large luminosity option is required. The full properties can then be explored at a multi-TeV collider like CLIC.

In these class of models the nature of the electroweak particles, sleptons, sneutrinos and neutralinos, can be quite different from the usual CMSSM expectations even if one assumes universal boundary conditions at the GUT scale, see e.g. [7, 8] and refs. therein. The jet and lepton distributions resulting from SUSY cascade decays are hardly sensitive to the nature of these particles. Here detailed investigations at an e^+e^- linear collider like ILC or CLIC will be necessary for their determination. This knowledge is a vital ingredient to determine the underlying SUSY parameters and, thus, the mechanism of SUSY breaking.

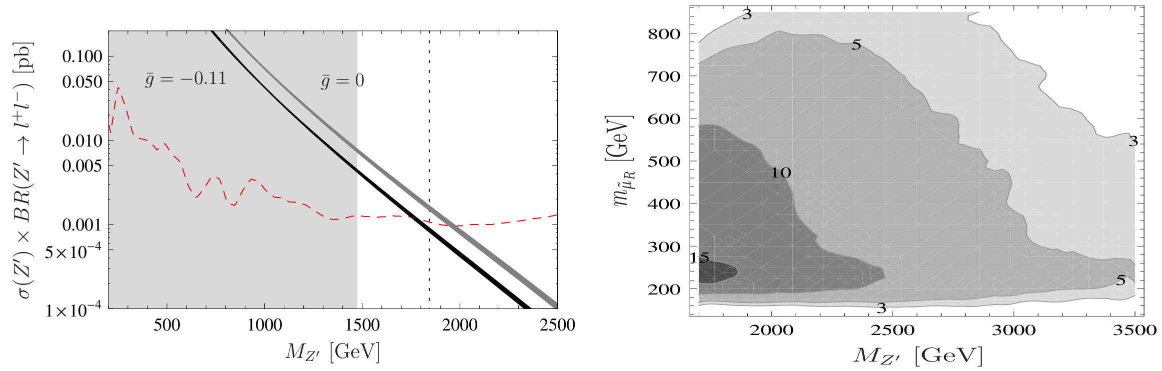

Fig. 6: Left plot: limits on the mass of a Z_{B-L} with ($\bar{g} = -0.11$) and without($\bar{g} = 0$) the effect of gauge kinetic taking into. Right plot: LHC reach for $\tilde{\mu}$ searches via a Z' at 14 TeV and $\mathcal{L} = 100$ fb^{-1}. For the SUSY background we have fixed the remaining parameters using $m_0 = 600$ GeV, $M_{1/2} = 600$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\tan\beta' = 1.07$, $\mu > 0$ and $\mu' > 0$. Taken from [8].

3.8 Mono-photon and mono-jet plus MET

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The lack of any hint of Supersymmetry in missing energy and hard objects is firing the interest for compressed spectrum scenarios characterized by close-by masses. Leading-order strong production of squarks would not be captured by the standard searches, and a lower limit on squark masses is unavailable.

Nevertheless, compressed Supersymmetry is sensitive to searches for a jet or a photon recoiling against missing energy. The hard jet or photon would come from initial or final state radiation. One can re-interpret these searches as a bound on the squark mass in the compressed scenario, and a conservative bound can be obtained assuming one single squark in kinematic reach. Current photon plus missing energy searches leads to a bound of 150 (110) GeV for up (down) type squarks in this conservative scenario. Similarly, jet plus missing energy would lead to a bound of 180 GeV.

The monophoton and monojet searches have been interpreted in terms of large extra-dimensions, where the Kaluza-Klein graviton is produced in association with a photon or jet, and escapes detection and of Dark Matter effective operators. For light dark matter particles, the constraints on the dark matter-nucleon scattering cross sections obtained by CMS are more stringent than the ones extracted from direct detection experiments.

[maybe rather incorporate this (the mono-photon part) into the compressed spectra section]

3.9 Dark matter

to be done, according to Monday parallel session contributions and discussions

4 Summary and conclusions

5 References

Use `wg2report.bib` file and BibTex-style for bibliography. Keep the bibliography to a bare minimum, to save space.

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