Sparticle masses from transverse mass kinks at the LHC: The case of Yukawa unified SUSY GUTs

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We pose the question of the performance of the LHC in measuring actual SUSY spectra (or their lightest part) in the example of Yukawa-unified SUSY GUTs. We choose two spectra, representative of two scenarios of SUSY breaking terms, and note that both of them are characterized by short decay chains. We thus take the so-called m_{T2}-kink method as our key strategy – since it does not rely on the presence of long decay chains – and discuss a procedure allowing to determine the whole lightest part of the SUSY spectra.

SUSY GUTs with Yukawa Unification

Introduction

The main motivations for supersymmetric (SUSY) Grand Unified Theories (GUTs), and, in their context, for third-generation Yukawa unification (YU), are well known, and will not be repeated here (see e.g. [1]). Concerning YU, it will suffice to say that, within this hypothesis, the large hierarchy given by m_t/m_b is explained as a hierarchy in the vevs of the two Higgs doublets used to give masses to fermions (i.e. $\tan\beta \equiv v_U/v_D \gg 1$), thereby allowing the Y_t and Y_b couplings to be both of order 1.

The more strictly phenomenological aspects of YU within SUSY GUTs may instead be summarized in the following main facts. In [2], the predictive power of the YU hypothesis was used to estimate the top mass, given the measured bottom and tau masses. It was realized that the bottom and tau masses undergo EW-scale, radiative corrections, proportional to the 'wrong' vev $v_U = v_D \tan\beta$. Hence these corrections will be large for large $\tan\beta$. In ref. [3] an 'opposite' strategy was therefore proposed: rather than using YU to predict quark masses, use their measured values – m_t had also been measured meanwhile – to learn about the allowed parameter space for the model, and make predictions for the SUSY spectrum. In this context, assuming GUT-scale universalities for the soft SUSY-breaking terms, one preferred region emerges [3]

$$-A_0 \approx 2\, m_{16}, \quad \mu, m_{1/2} \ll m_{16}, \tag{1}$$

with A_0, m_{16} and $m_{1/2}$ the universal sfermion trilinear, sfermion bilinear and gaugino bilinear soft terms, respectively, and μ the higgsino mass parameter. Quite interestingly the same relations (1) emerge as fixed-point solution from the attempt to build SUSY models with radiatively-driven inverted scalar mass hierarchy (ISMH) [4], i.e. light third generation and heavy first and second generation sfermions. ISMH is an appealing possibility to relieve at one stroke the problem of fine tuning in the Higgs mass corrections, and of large flavor-changing neutral currents (FCNCs).

In more recent studies, SUSY GUTs with YU have been confronted with all the available low-energy data, using different techiques across the various studies, as well as different sets of low-energy data, and different assumed SUSY-breaking patterns. Our approach [5, 6, 7] has been to construct a χ^2 function out of EW observables, quark masses and FCNCs. This technique has the advantages of providing a global assessment of the model in a reparameterization-invariant way – what matters is the χ^2 minimum – and of exploiting at best the strong sensitivity of the high-energy parameters to the low-energy ones [8].

Two scenarios

From the findings of refs. [5, 6, 7], we picked up two representative scenarios. The two scenarios are as follows

S1: *SUSY GUTs with YU and universal GUT-scale soft terms [6]*[1]

The combined information from FCNCs favors values of $\tan\beta$ lower than O(50). Conversely, it is known [9] that m_b prefers $\tan\beta$ = O(50) – or else, close to 1, which is excluded by LEP. Hence this scenario is viable only advocating partial decoupling of the sfermion spectrum, the lightest mass exceeding 1 TeV. Relaxing $t - b - \tau$ YU to just $b - \tau$ YU allows to find a better compromise between the FCNC and m_b constraints, thereby somewhat lowering the lightest stop mass. Spectrum predictions are robust, and are summarized in the left column of table 1.

S2: *SUSY GUTs with YU and split trilinear soft terms at the GUT scale [7]*

With respect to scenario 1, trilinears are allowed to be split: $A_U \neq A_D$. Agreement with data clearly selects the region with large $\mu = \mathrm{O}(m_{16})$ and sizable $A_U - A_D$ splitting. In this region, the lightest stop (and the gluino) are required to be very close to their experimental bounds, i.e. are *very* light, and nonetheless all the FCNC tensions are relieved. Spectrum predictions are again robust, and are summarized in the right column of table 1.

Spectrum predictions			
S1, ref. [6]		S2, ref. [7]	
M_{h^0}	121	M_{h^0}	126
M_{H^0}	585	M_{H^0}	1109
M_A	586	M_A	1114
M_{H^+}	599	M_{H^+}	1115
$m_{\tilde{t}_1}$	783	$M_{\tilde{t}_1}$	192
$m_{\tilde{t}_2}$	1728	$m_{\tilde{t}_2}$	2656
$m_{\tilde{b}_1}$	1695	$m_{\tilde{b}_1}$	2634
$m_{\tilde{b}_2}$	2378	$m_{\tilde{b}_2}$	3759
$m_{\tilde{\tau}_1}$	3297	$m_{\tilde{\tau}_1}$	3489
$m_{\tilde{\chi}_1^0}$	59	$m_{\tilde{\chi}_1^0}$	53
$m_{\tilde{\chi}_2^0}$	118	$m_{\tilde{\chi}_2^0}$	104
$m_{\tilde{\chi}_1^+}$	117	$m_{\tilde{\chi}_1^+}$	104
$M_{\tilde{g}}$	470	$M_{\tilde{g}}$	399

Table 1: All masses are in units of GeV. Uppercase and lowercase masses stand for pole and respectively $\overline{\mathrm{DR}}$ masses.

From the table, it is evident that the main difference between the two scenarios is a stop respectively heavier and lighter than the gluino, whereas predictions are basically the same for $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^\pm_1$ and also $\tilde{g}$.

SUSY GUTs with YU at the LHC

At the 14 TeV LHC, the spectrum features described in the previous section imply that: *(1)* $\tilde{g} - \tilde{g}$ production is substantial in both scenarios (about 60 vs. 40% respectively); *(2)* $\tilde{t}_1 - \tilde{t}_1$ production is large (40% !) in scenario 2 (and basically zero in the other); *(3)* $\tilde{\chi}^\pm_1 - \tilde{\chi}^0_2$ associated

[1]Non-universality is allowed (and actually required) only for the Higgs soft terms (m_{H_u}, m_{H_d}).

production is also interesting in both scenarios (25 vs. 10%). Therefore, a suitable mass-determination strategy should be able to determine the masses of all these produced particles. In particular, noting that the $\tilde{g}$ and (for scenario 2) the $\tilde{t}_1$ are light, one can expect 2- or 3-steps decay chains, namely *short decay chains.* This points to the use of the M_{T2} variable as the main strategy for determining SUSY masses.

The M_{T2} event variable

The M_{T2} variable is best understood by shortly describing its precursor, the M_T variable. At the UA1 experiments, one could measure the W-boson mass from the decay mode $W \to \ell\nu$ by forming the variable [10]

$$M_T^2 = 2(E_T^\ell E_T^\nu - \vec{p}_T^\ell \vec{p}_T^\nu) \ .$$

Note in fact that $m_W^2 = (p_\ell + p_\nu)^2 = m_\ell^2 + m_\nu^2 + 2(E_T^\ell E_T^\nu \cosh(\eta_\ell - \eta_\nu) - \vec{p}_T^\ell \vec{p}_T^\nu) \geq M_T^2$, simply because $\cosh x \geq 1$. Here η: $\tanh \eta = p_z/E$ is the rapidity, in the usual HEP experimental definition. Therefore M_T provides, event by event, a lower bound on the m_W mass. The main point is that there are kinematical configurations whereby the bound is saturated, hence the endpoint of the m_T distribution equals (barring backgrounds) the m_W mass.

M_{T2} [11] is the two-decay-chains generalization of M_T. The event topology relevant for the applicability of M_{T2} is that of two produced particles Y_1 and Y_2 (e.g. $\tilde{g}\tilde{g}$) each decaying into a set of visible particles $V_{1,2}$, whose transverse invariant mass and transverse boost are supposed to be entirely reconstructed, plus an undetected particle (or set of particles), $\chi_{1,2}$. If the missing $\vec{p}_T$'s of the χ_i, $\vec{p}_T(\chi_i)$, were separately reconstructible, one could just construct two separate M_T variables. However, all one knows event by event is that $\vec{p}_T(\chi_1) + \vec{p}_T(\chi_2) =$ total $\vec{p}_T^{\rm miss}$, where the latter quantity can be inferred from the sum of the visible transverse momenta, because of momentum conservation. Therefore, the best one can say event by event is

$$M_{T2} \equiv \min_{\vec{p}_T(\chi_1)+\vec{p}_T(\chi_2)=\vec{p}_T^{\rm tot. miss}} \left\{ \max \left[M_T^2(\text{chain } 1), M_T^2(\text{chain } 2) \right] \right\} \leq m_Y^2 \ ,$$

where we have assumed mother particles $Y_1 = Y_2 = Y$, with mass m_Y.

Note that: *(1)* an event topology consisting of two decay chains, each with a final particle escaping detection, is actually a very useful one, for many Standard Model extensions (e.g. all those with a conserved Z_2 symmetry); *(2)* the inclusion of only transverse momentum components makes M_{T2} very suitable for hadron colliders, where the boost along the beam axis is unknown anyway; *(3)* at variance with the $W \to \ell\nu$ case, the missing-particle mass m_χ is not zero, it is not negligible, and it is unknown. Therefore M_{T2} is actually a function of trial values for m_χ. This functional dependence can actually be turned into an advantage. In fact, it was realized [12] that the maximum over the events of $M_{T2}(m_\chi)$ has a 'kink' (a discontinuity in the first derivative) at $\{m_Y^{\rm phys},\ m_\chi^{\rm phys}\}$. Hence the kink location permits a simultaneous measurement of both the Y and the χ masses!

Application to SUSY GUTs with YU

From the previous ideas, one can set up a strategy [13] to determine the whole lightest part of the SUSY spectrum for the two scenarios in table 1. This strategy can then be tested on events simulated at the 14 TeV LHC, including detector effects, in order to understand to which extent it is effective with real data. For the full analysis, the reader is referred to ref. [13]. The main results are also reported in table 2.

Here we will only shortly describe an example. Consider $\tilde{g}\tilde{g}$ production in scenario 2, followed by the decay chain

$$\tilde{g} \to W b\, \tilde{t}_1 \quad \text{with} \quad \tilde{t}_1 \to b\, \tilde{\chi}_1^{\pm} \quad \text{and} \quad \tilde{\chi}_1^{\pm} \to \ell\, \nu_\ell\, \tilde{\chi}_1^0 \ .$$

In 100/fb of data, one expects about 1.1 million such events. In the channel shown here, the mother particle, Y, is the gluino, and the escaping one, χ, is actually not only the $\tilde{\chi}_1^0$, but the $\tilde{\chi}_1^0$ plus the ν. For the event selection, one may: *(1)* trigger on $2W + 4b -$ jets $+ 2\ell + p_T^{\rm miss}$; *(2)* apply suitable kinematical cuts on the obtained event sample, and a suitable jet-pairing scheme, in order to tame the combinatoric error (see [13] for details). Thereafter, one can *(3)* take *the whole $\tilde{\chi}_1^{\pm}$-initiated decay chain* as the escaping particle and construct M_{T2} accordingly. Plotting the maximum over the events of this M_{T2} shows indeed a discontinuity at the physical $m_{\tilde{g}} - m_{\tilde{\chi}_1^{\pm}}$ masses, whose fitted values are reported in table 2.

With the $\tilde{g}$ and $\tilde{\chi}_1^{\pm}$ masses determined this way, one can determine the $\tilde{t}_1, \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ masses using simple endpoint methods. E.g., from $\tilde{t}_1\tilde{t}_1$, with $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{\pm} \to qq'\tilde{\chi}_1^0$, one may determine $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ from the endpoint of $M_{T,bqq'}$ and $m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0}$ from the endpoint of $M_{T,qq'}$. A similar strategy can be worked out for scenario 1, with the caveat that, in this case, the $\tilde{t}_1$ is too heavy to be produced in non-negligible amounts, and its mass cannot be determined.

	Mass	Result (GeV)
S2	$m_{\tilde{g}}$	395 ± 16
	$m_{\tilde{\chi}_1^{\pm}}$	109 ± 17
	$m_{\tilde{\chi}_1^0}$	57 ± 17
	$m_{\tilde{\chi}_2^0}$	107 ± 18
	$m_{\tilde{t}_1}$	206 ± 17
S1	$m_{\tilde{g}}$	456 ± 15
	$m_{\tilde{\chi}_1^{\pm}}$	144 ± 20
	$m_{\tilde{\chi}_1^0}$	66 ± 16
	$m_{\tilde{\chi}_2^0}$	126 ± 16

Table 2: Mass determinations within our strategy, to be compared with table 1.

As demonstrated in the analysis (see [13]) and shown in table 2, our strategy allows to determine all of the lightest part of the SUSY spectra within 20 GeV of error.

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