A New Technique for Finding the Underlying Model Parameters in GMSB.

Ehud Duchovni \(^1\) and Peter Renkel \(^2\)

Particle Physics Department,  
Weizmann Institute of Science, Rehovot 76100, Israel

Abstract

A new, model dependent way of uncovering some of the values of the underlying GMSB parameters is proposed. This method is faster than the existing procedures and once enough luminosity is available, can be used to check the consistency of the model.

\(^1\)ehud.duchovni@weizmann.ac.il  
\(^2\)Renkel@wisemail.weizmann.ac.il
1 Introduction

This note assumes that after a short run at LHC one will find out that nature is supersymmetric and follows the Gauge-Mediated SuperSymmetry Breaking (GMSB) scheme. At that point one will face the task of uncovering the value of the underlying model parameters. In the simplified version of such a model 6 such parameters exist [1], namely:

\[ \Lambda, M, \tan\beta, N, \text{sign}(\mu), \kappa \]

For simplicity sake it is assumed here that \( N=1 \). This assumption gives rise to the lightest possible mass spectrum of SUSY particles for a given \( M \) and \( \Lambda \). The case of \( N > 1 \) will be discussed in a future note.

The value of \( M \) has marginal effect on the phenomenology which will be discussed below because it enters only through the logarithmic running of the masses in the renormalization group equations, and will therefore, be ignored hereafter. The sign of \( \mu \) has also a small effect and will be only briefly treated. \( \kappa \) controls the way in which the LSP, namely the Gravitino couples to the other particles, in particular to the NLSP. It is assumed here to be small. In case it is large it will be determined by measuring the lifetime of the NLSP. The value of \( \Lambda \) will be determined directly from the production cross section of SUSY events (Figure 1) and due to its triviality will not be further discussed here.

The parameter which is at the focus of the present study is \( \tan\beta \). \( \tan\beta \) is traditionally [2] determined using the mass of the Higgs boson and to a lesser extent by the mass of the 3rd generation sparticles. However, if nature is indeed supersymmetric, the Higgs boson mass is expected to be at most 130 GeV. In this mass range the discovery and the mass determination of the Higgs boson require relatively high luminosity (the cross-section times branching ratio of a 130 GeV Higgs boson to a \( ZZ^* \) and later to a 4-lepton final state is only \( \approx 3 fb \)). Mass reconstruction is also a non-trivial task. Only a small fraction of the produced events are suitable for mass reconstruction. Consequently one will be able to determine \( \tan\beta \) with a reasonable accuracy only after collecting a significant amount of data.

The method which is proposed in the present study is based on the fact that the mass of the \( \tilde{\tau} \) lepton depends on the value of \( \tan\beta \). For low \( \tan\beta \) the \( \tilde{\tau} \) lepton is relatively
Figure 1: Total SUSY cross-section as a function of Λ value.

heavy \(^3\) and it decays into the NLSP, namely to the \(\chi_1^0\). For high values of \(\tan\beta\) the \(\tilde{\tau}\) lepton becomes lighter and eventually it becomes the NLSP (Figure 2). This change in the \(\tilde{\tau}\) lepton mass leads to a change in the average number of \(\tilde{\tau}\) leptons in SUSY events. The \(\tilde{\tau}\) lepton decay gives rise to a final state that contains a \(\tau\) lepton. Hence, it is argued here that one does not need to reconstruct and measure the mass of the \(\tilde{\tau}\) lepton, rather, one can determine \(\tan\beta\) by simply counting the number of \(\tau\) leptons as well as electrons and muons in SUSY events.

2 Description of the technique

One may divide the relevant \(\tan\beta\) interval into 3 distinctive regions. The first one, the low \(\tan\beta\) region, is characterized by a light \(\chi_1^0\) (whose mass is independent of \(\tan\beta\)) which is the NLSP and a relatively heavy \(\tilde{\tau}\) lepton (whose mass depends on \(\tan\beta\)). In this region one expects to see a large number of isolated energetic photons which are the result of the only possible \(\chi_1^0\) decay mode, namely, \(\chi_1^0 \rightarrow \gamma \tilde{G}\). One would also expect to see relatively sizable number of isolated energetic \(\tau\) leptons. These \(\tau\) leptons can originate from two main sources: the decay \(\tilde{\tau} \rightarrow \chi_1^0 \tau\) which gives rise to relatively

\(^3\)since only the \(\tilde{\tau}_1\) lepton is relevant in the present study the subscript ‘1’ was omitted.
Figure 2: Mass dependence on $\tan\beta$. The solid black line represents the mass of the $\chi^0_1$, the dotted red line that of the $\tilde{\tau}$ lepton, the dashed-dotted green line represents the mass of the $e_R$ and $\tilde{\mu}_R$ which are degenerated, the dashed blue line that of the $\chi^{\pm}_1$, the upper solid light blue line is for the $\chi^0_2$ and the brown dashed-dotted line represents the mass of the $\tilde{\tau}_2$. The masses here are plotted for the case of $\Lambda = 75 \text{ TeV}$, $M=250 \text{ TeV}$ and positive $\mu$. 
soft $\tau$ leptons due to the small $\tilde{\tau} - \chi_0^0$ mass difference, and the decay $\chi_2^0 \rightarrow \tilde{\tau}\tau$ which gives rise to a harder spectrum of $\tau$ leptons. The low $\tan\beta$ region extends over a very large region of $\tan\beta$ and the determination of the value of $\tan\beta$ inside this region will be the main issue of this study.

The other extreme case: the high $\tan\beta$ region, is characterized by a light $\tilde{\tau}$ lepton which is the NLSP and a somewhat heavier $\chi_1^0$. In this region one expects to see a large number of isolated energetic $\tau$ leptons and no isolated energetic photons. Here one would have an additional source for hard $\tau$ leptons, namely, the $\tilde{\tau} \rightarrow \tau\tilde{G}$ decay. This region, in principle, can extend up to $\tan\beta$ of about 50. However, for moderate values of $\Lambda$ the mass of the $\tilde{\tau}$ lepton drops, for high $\tan\beta$, below the LEP limit of 86.9 GeV. Consequently, the range of $\tan\beta$ covered by this region is quite limited.

The intermediate region is the region in which the mass difference between the $\tilde{\tau}$ lepton and the $\chi_1^0$ is smaller than the mass of the $\tau$ lepton and one cannot decay to the other. In this region both the number of isolated photons and $\tau$ leptons are 'frozen'. For the case in hand of $\Lambda = 75$ TeV this happens for $\tan\beta$ between 32.8 and 34.6.

The main features of the events, namely the average number of isolated energetic photons and $\tau$ leptons as a function of $\tan\beta$ is shown in Figure 3 for a machine luminosity of 1 $fb^{-1}$, $\Lambda = 75$ TeV and $M = 250$ TeV. The number of $\tau$ leptons in the figure is computed after applying a $p_t$ cut of 15 GeV on visible $\tau$ lepton decay products and without any detector simulation. These results show that by a simple photon and $\tau$ leptons counting experiment one will, in principle, be able to determine which is the relevant region of $\tan\beta$: In the low $\tan\beta$ one would see a large number of photons and a sizable amount of $\tau$ leptons. In the intermediate region the number of photons will drop significantly but one will still be able to see a few hundred photons per $fb^{-1}$. One will see, in addition, a large number of $\tau$ leptons. In the high $\tan\beta$ region one will observe a very large number of $\tau$ leptons and no isolated photons coming from $\chi_1^0$.

As mentioned above, the low $\tan\beta$ region extends for $\Lambda=75$ TeV and positive $\mu$ from $\tan\beta \approx 2$ till $\tan\beta \approx 32.7$. This is a very large region and one would like to be able to determine $\tan\beta$ inside this region. The number of photons is absolutely flat and offers no clue for $\tan\beta$ determination, but the number of $\tau$ leptons shows some dependence on $\tan\beta$ and a measurement of $N_{\tau}$ will allow one to determine $\tan\beta$ value inside this region. The number of $\tau$ leptons increases initially as $\tan\beta$ increases since heavy gauginos prefer decaying into $\tilde{\tau}$ due to the drop in its mass compared to the
Figure 3: The expected average number of isolated energetic photons and $\tau$ leptons as a function of $\tan\beta$. The number of $\tau$ leptons is shown after applying a $p_t$ cut of 15 GeV (full black curve) on its visible decay products (no detector simulation). The number of photons (blue dotted) was computed with the same $p_t$ cut. The numbers were computed assuming luminosity of $1 \, fb^{-1}$, $\Lambda = 75 \, TeV$, $M = 250 \, TeV$ and positive $\mu$. 
mass of the other slepton. This effect is then balanced and overcome by the effect of the $p_t$ cut of the $\tau$ lepton, as the resulting $\tau$ leptons at high $\tan\beta$ values are softer due to the smaller mass difference between the $\tilde{\tau}$ and the $\chi^0_1$. The resulting shape of the $N_\tau$ curve shows that the determination of $\tan\beta$ in this way will suffer from a low-high ambiguity. One may exploit the $\tau$ lepton momentum distribution to resolve this ambiguity but a higher sensitivity to $\tan\beta$ can be achieved by counting the number of light leptons, namely, electrons and muons which is shown in Figure 4. At low values of $\tan\beta$ the $\tilde{\tau}$ lepton is relatively heavy and consequently its production in gaugino decays is as likely as the production of light leptons. At higher values of $\tan\beta$ the $\tilde{\tau}$ lepton becomes lighter and its production in those decay is preferred. As a result the number of prompt light leptons (not from $\tau$ lepton decay) is dropping. This is clearly shown in Figure 4.

3 Results Using Fast Simulation

The fast Atlas detector simulation program was used in order to estimate the sensitivity of the procedure which was outlined above under semi-realistic conditions. In addition to the expected degradation of the sensitivity due to detector simulation the effects of possible background sources were also taken into account. Signal events were simulated using the Isajet MC program. QCD, $W^\pm$ and $W^\pm$+jets, $Z^0$ and $Z^0$+jets as well as $t\bar{t}$ events were also simulated using Isajet and the same detector simulation program. The isolation of SUSY events was based on the presence of isolated photons in the final state, namely on two simple requirements:

1. at least one isolated photon \(^4\) with $p_T > 15\ GeV$;

2. $E_T^{miss} > 100\ GeV$.

these simple cuts reduced the SM background to a negligible level. The hadronic $\tau$ leptons are identified using the Weizmann algorithm \([5]\). In this algorithm one starts with jets. A jet is accepted as a $\tau$ if it fulfills the following requirements:

1. there is 1 charged track with $p_{T\text{track}} > 5\ GeV$ in a cone $\Delta R < 0.07$, $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$, around the jet axis;

\(^4\)an isolated photon is defined as an electromagnetic cluster with $E_T > 15 GeV$ in $|\eta| < 2.5$ range, separated from the closest jet by $\Delta R > 0.4$ and from the closest lepton by $\Delta R > 0.15$ and surrounded by a $\Delta R > 0.2$ cone in which less than 10 GeV were recorded in the calorimeter.
Figure 4: The dependence of the number of light leptons (electrons and muons) on the value of $\tan\beta$. The black (dashed) curve is for the total number of lepton and at high values of $\tan\beta$ is dominated by leptons coming from $\tau$ lepton decays. The blue (solid) curve represents the leptons that do not come from $\tau$ lepton decays (mostly from slepton and gaugino decays). The plot is done with equivalent luminosity of 1 fb$^{-1}$. 
2. an isolation fraction, i.e. fraction of transverse energy in a ring \(0.2 < \Delta R < 0.4\) around the jet axis, is smaller than 0.1;

3. \(p_T\) of the jet (non-calibrated) is greater then 15 GeV;

4. number of the hit cells within a jet cone of \(\Delta R < 0.4\) is smaller than six.

The number of identified \(\tau\) leptons and light leptons is shown in Figure 5 for a luminosity of 4 \(fb^{-1}\) for the case of positive \(\mu\) (a) and negative \(\mu\) (b). The drop in the number of leptons at low values of \(\tan\beta\) for the negative \(\mu\) case results from the rise in the \(\chi_0^0\) and \(\chi_1^\pm\) mass in this region, which is absent in the \(\mu > 0\) case. By simply counting the number of \(\tau\) leptons and light leptons one can extract the value of \(\tan\beta\) with a small statistical error as shown in Figures 6 and 7, in which the error on the reconstructed \(\tan\beta\) is shown as a function of the input value of \(\tan\beta\) (statistical errors only). One can also see that the number of light leptons differs significantly between the positive and negative \(\mu\) scenarios as long as \(\tan\beta < 15\). Hence, light lepton counting will allow a determination of the sign of \(\mu\) in this region. Finally, the error on \(\tan\beta\) was evaluated using the present procedure under the conditions specified in [2], namely, a luminosity of 10 \(fb^{-1}\), \(M=500\) TeV and \(\Lambda= 90\) TeV. The evaluation of the value of \(\tan\beta\) in two independent ways will provide an important consistency check. The performance of both methods is compared in Figure 8 with the attainable performance based on mass reconstruction and the present method is shown to perform much better.

4 Systematics

Simple particle counting is sensitive to uncertainties in the luminosity measurement as well as to the uncertainties of the identification efficiency and purity of the relevant counted object. The uncertainty in the determination of the luminosity might be fairly large and might lead to large systematic error in the determination of \(\tan\beta\). However, since the proposed procedure is valid in the framework of a given model which gives rise to a constant number of photons which does not depend on the value of \(\tan\beta\), one would be able to replace the uncertainty on the luminosity by the statistical error on the number of observed photons, which is expected to be small due to the abundance of photons. This 'photon-recalibration' will render the luminosity error negligible.
Figure 5: The number of expected $\tau$ leptons (dotted black curve) and light leptons (red solid curve) for different values of $\tan\beta$ as predicted using fast simulation for an luminosity of $4\ fb^{-1}$. A cut of $p_t > 15\ GeV$ visible transverse momentum of the $\tau$ lepton and light leptons has been applied. a) is drawn for the positive $\mu$ scenario and b) for the negative case.
Figure 6: The final attainable accuracy on $\tan\beta$ determination for various possible $\tan\beta$ values. The errors are statistical only and evaluated for luminosity of $4 \text{ fb}^{-1}$. The plot is done for the $\mu > 0$ case. The shaded light-blue region represents the final result. Note that no ambiguity is left.

Figure 7: The final attainable accuracy on $\tan\beta$ determination for various possible $\tan\beta$ values. The errors are statistical only and evaluated for luminosity of $4 \text{ fb}^{-1}$. The plot is done for the $\mu < 0$ case. Note that no ambiguity is left.
Figure 8: A comparison between the present procedure (yellow band) and the one based on mass reconstruction [2] (red arrow bar at \( \tan \beta = 5 \)). The present procedure gives a much lower error (\( \pm 0.25 \) compared to \( \pm 1.3 \)) for the same luminosity (10 \( fb^{-1} \)).

Figure 9: Effect of 1% systematic error on both the detection efficiency of light and \( \tau \) leptons. Comparing the uncertainty in this plot, which is done for positive \( \mu \) with Figure 6 shows the relatively small effect of such systematic uncertainty.
The identification efficiency of electrons, muons and $\tau$ leptons and the purity of these samples should be understood, once $\approx 1fb^{-1}$ has been collected, at a level of 1% or better. This can be done by studying the large number of $Z^0$ and other SM processes. In order to evaluate the sensitivity of the present proposed procedure to identification uncertainties a 1% shift in both light and $\tau$ lepton identification was introduced and the value of $\tan\beta$ was recomputed and is shown in Figure 9. As can be seen by comparing this to the result shown in Figure 3 in which no systematic error is introduce, the effect of 1% systematic error in the identification efficiency is quite limited.

5 Conclusion

A simple electron, muon and $\tau$ leptons as well as photons counting is shown to provide a fairly accurate determination of $\tan\beta$ in N=1 SUSY GMSB case. The proposed technique does not depend on the measurement of the Higgs boson or $\tilde{\tau}$ mass and hence, can be carried out with low luminosity, well before the Higgs boson mass can be measured. The attainable accuracy is significantly better than the one obtained by the conventional way [2] of using Higgs boson mass and by explicitly reconstructing the $\tilde{\tau}$ lepton.

References

[1] e.g. S. Dimopoulos, S. Thomas and J. D. Wells, Nucl.Phys.B488:39-91,1997, hep-ph/9609434.

[2] ATLAS TDR, CERN LHCC/99-14 vol II.

[3] LEP SUSY working group web-page:

http://lepsusy.web.cern.ch/lepsusy/www/gmsb_summer02/lepgmsb.html

[4] ISAJET 7.69 A Monte-Carlo Event Generator, Frank E. Paige, Serban D. Protopopescu, Howard Baer and Xerxes Tata, hep-ph/0312045

[5] E. Gross and L. Zivkovic, note in preparation.