# Implication of 2010 7 TeV CMS results on phenomenological MSSM

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**Abstract**

We discuss the implication of CMS results on phenomenological MSSM (pMSSM), which is a well-motivated generalization of supersymmetry (SUSY) that consists of 19 free parameters. We address the parameters sensitive to the recent CMS studies in a statistical consistent manner. The sensitivity of one as a function of others are studied here. The results provide new constraints on parameters, sensitive to hadronic as well as multilepton final states using 35 pb$^{-1}$ of integrated luminosity.

# 1 Introduction

With the extremely successful performence of both machine and detectors at $\sqrt{s} = 7$ TeV and good prospects to go soon into higher energies, the LHC is finally opening the window to the Terascale. Importantly, new insights are expected from the LHC data, most of all in the mechanism of electroweak (EW) symmetry breaking and, related to this, in the nature of new physics Beyond the Standard Model (BSM) stabilizing the EW scale.

A wealth of BSM theories has been put forth by the theoretical community and it is now up to experiments to test which, if any, of these theories are correct. The arguably best motivated, but certainly the best studied, such BSM theory is supersymmetry, SUSY for short. Indeed, searches for SUSY are among the primary objectives of the CMS collaboration. Here note that SUSY is exceedingly popular not only for its theoretical beauties but also because SUSY phenomenology is extremely rich, leading to a large variety of possible new signals at the LHC.

Over the years, it has become common practice to interpret collider results in terms of a strictly constrained parameterization of supersymmetry, namely the constrained minimal supersymmetric model (CMSSM). Though this setup has its practical implications, it lacks a sound theoretical motivation. In this work we would like to initiate an approach that uses a more generic, and theoretically more feasible expression of supersymmetry. We introduce here the phenomenological MSSM (pMSSM), studied recently by Berger et. al., which is a 19 parameter realization of SUSY defined at the SUSY scale $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ as an acceptably generic scenario for interpreting the early LHC results of 35pb$^{-1}$. We use results from the dijet $\alpha_T$ analysis, the opposite-sign dilepton analysis and the same-sign dilepton analysis to see the effects of these early observations on our knowledge on pMSSM.

We start the note with giving the motivation to go beyond CMSSM and to work with pMSSM, which is followed by the definition and parameterization of pMSSM. We then outline our analysis, giving details on the pMSSM points we have used, the detector simulation and the CMS analyses, and later describe the statistical method based on profile likelihoods used for coping with the 19 dimensional setup of pMSSM. This is followed by the results and conclusion.

# 2 Motivation for a generic MSSM setup

The majority of SUSY studies related to the interpretation of collider data focus on a very special setup: the so-called Constrained Minimal Supersymmetric Standard Model (CMSSM). This was justified in the preparation for discoveries, as the CMSSM having just a handful of new parameters is very predicive. However, the simple assumption of universality at the GUT scale lacks a sound theoretical motivation; the CMSSM should hence be regarded as a showcase model. When it comes to interpreting experimental results, on the one hand it is reasonable and interesting to do this within the CMSSM, because it provides an easy way to show performances, compare limits or reaches, etc. On the other hand, as said above, SUSY phenomenology is extremely rich and by far not exploited by the $(m_0, m_{1/2})$ plane.

Indeed perhaps the least understood aspect of SUSY is its breaking, which in turn determines the boundary conditions for the Lagrange parameters at some high scale. Again, theorists have come up with a long list of possible candidate scenarios, including supergravity (SUGRA), gauge mediation (GMSB), anomaly mediation (AMSB), gaugino mediation, radion mediation, etc.. They come in minimal (mSUGRA, mGMSB, ....) and less minimal (e.g., non-universal Higgs masses, NUHM, or non-universal gaugino masses) variants, as well as in general setups (general gauge mediation, ...). Moreover, there are models of compressed or split SUSY, GUT-inspired models, string-inspired models, and so on. Each of these possibilities features characteristic relations between fundamental parameters and hence characteristic mass spectra, decay patterns and properties of the dark matter candidate.

The CMSSM covers just a subset of this spectrum. To give some examples:

- The CMSSM assumes universal gaugino masses $M_1 = M_2 = M_3 \equiv m_{1/2}$ at the GUT scale, leading to
$$M_1 : M_2 : M_3 \approx 1 : 2 : 7 \text{ with } M_1 \approx 0.4\, m_{1/2} \tag{1}$$
at the EW scale, which is equivalent to $m_{\tilde{\chi}^0_2} \approx 2m_{\tilde{\chi}^0_1} \approx 0.8\, m_{1/2}$ and $m_{\tilde{g}} \approx 7m_{\tilde{\chi}^0_1} \approx 2.8\, m_{1/2}$. Other models can have very different relations between $M_1$, $M_2$, $M_3$, giving rise to the so-called "gaugino code" [1], which can be very useful for model discrimination. Besides, models with non-universal gaugino masses are quite natural [2] even within the SUGRA context, and they can have very low finetuning [3].
- Over most of the CMSSM parameter space $|\mu|^2 \gtrsim m^2_{1/2}$. The lightest neutralino is then mostly bino, the second-lightest mostly wino, and the heavier ones mostly higgsinos. Light higgsinos and large gaugino–higgsino mixing (mixed bino–higgsino dark matter) occur only in the focus point region, i.e. when squarks

and sleptons are very heavy. This has a strong impact on squark and gluino cascade decays, as well as on the part of parameter space that is compatible with dark matter constraints.

- Turning to the sfermion sector, the slepton-mass parameters are to good approximation

$$m^2_{\tilde{R}} \approx m^2_0 + 0.15\, m^2_{1/2}\,, \qquad m^2_{\tilde{L}} \approx m^2_0 + 0.5\, m^2_{1/2}\,. \tag{2}$$

  Note that this implies that right-chiral states are alway lighter than the left-chiral ones. Combining Eqs. (1) and (2) we see that for small $m_0$ (but large enough to have a neutralino LSP) this leads to the typical mass pattern $m_{\tilde{\chi}^0_1} < m_{\tilde{e}_R} < m_{\tilde{\chi}^0_2} < m_{\tilde{e}_L}$. For the first two generations of squarks we have

$$m^2_{\tilde{U},\tilde{D}} \approx m^2_0 + K m^2_{1/2}\,, \qquad m^2_{\tilde{Q}} \approx m^2_0 + (K + 0.5) m^2_{1/2}\,, \tag{3}$$

  with $K \sim 4.5$ to $6.5$, and the dependence on $m_{1/2}$ dominated by the gluino contribution, i.e. by $M_3$. It is clear that any limit on or determination of $m_0$ is completely dominated by the slepton sector [4]. Non-universal scalar masses are heavily constrained by flavour-changing neutral currents (FCNC), at least for the first and second generations. For the third generation, the FCNC constraints are much less severe. One possibility to motivate universal mass parameters for sfermions is to embed them in a higher gauge group, like SO(10). But even then, non-universalities can occur through D-term contributions [5] and/or GUT-scale threshold corrections [6, 7]. Besides, there is no sound theoretical motivation for unifying the mass-squared terms of the Higgs fields, $m^2_{H_1}$ and $m^2_{H_2}$, with those of the other scalars. If this is given up $m^2_{H_{1,2}}$, or equivalently $\mu$ and $m_A$, become free parameters of the model [8] (cf. the discussion of the value of $\mu$ above).

- The assumption of scalar mass universality has another important implication, namely that the renormalization-group invariant quantity

$$S = \left(m^2_{H_2} + m^2_{H_1}\right) + \mathrm{Tr}\left(m^2_{\tilde{Q}} - 2m^2_{\tilde{U}} + m^2_{\tilde{D}} + m^2_{\tilde{R}} - m^2_{\tilde{L}}\right) \tag{4}$$

  vanishes. This so-called $S$-parameter, if non-zero, influences the running of the scalar mass parametres $M^2_\phi$ proportional to their hypercharge $Y_\phi$

$$16\pi^2 \frac{d}{dt} M^2_\phi = .... + \frac{6}{5} Y_\phi g^2_1 S\,. \tag{5}$$

  This can change the mass ordering of left- and right-chiral states or have an important influence on the Higgs sector. In the CMSSM however $S \equiv 0$.

From these considerations, which are just exemplary and by no means complete, it is clear that it is interesting and necessary to go beyond the naïve CMSSM. We need to search for SUSY without prejudice [9, 10], even more so as we have all the necessary knowledge and machinery at our disposal. In this context note that major efforts have recently been devoted to developing precise statistical tools for analyzing new physics at the LHC [11]. This includes sophisticated methods and tools for the investigation of multi-dimensional parameter spaces, as typical for SUSY models. Below we therefore lay out a program for the investigation of the general minimal supersymmetric Standard Model, the so-called *phenomenological MSSM* (pMSSM), with 19 free parameters.

# 3 Phenomenological MSSM (pMSSM)

Phenomenological MSSM is a model that makes no assumptions on the SUSY breaking mechanism. It is parametrized at the so-called "SUSY scale (i.e. the geometric mean of the two stop masses). At this low scale, SUSY is defined by over 120 parameters at its most generic form. However simplifying assumptions can be made without loosing much from the generality of the scenario. pMSSM construction stays within the CP-conserving MSSM (i.e. no new phases) with minimal flavor violation. Moreover, to help soften the impact of experimental constraints arising from the flavor sector, the first two generations of sfermions are taken to be degenerate. This results in the following 19-dimensional parameterization:

1. 10 scalar masses: $m_{\tilde{f}}$ (where $\tilde{f} = \tilde{Q}_L, \tilde{Q}_3, \tilde{L}_1, \tilde{L}_3, \tilde{u}_1, \tilde{d}_1, \tilde{u}_3, \tilde{d}_3, \tilde{e}_1$, and $\tilde{e}_3$),
2. 3 gaugino masses: $M_{1,2,3}$ (pertaining to U(1), SU(2), and SU(3), respectively),
3. 1 $\tan\beta$ parameter,

4. 3 trilinear couplings: $A_{b,t,\tau}$,

5. 1 pseudo-scalar Higgs mass: $m_A$.

6. 1 $\mu$ parameter.

The parameters $m_A$ and $\mu$ can be swapped for the Higgs mass parameters $m_{H_u}$ and $m_{H_d}$.

Berger et. al. performed a multi-dimensional scan to find out what regions in the pMSSM parameter space are consistent with theoretical and experimental constrains. They did a uniform random sampling of points from within the pMSSM subspace defined by the parameter ranges below

$$\begin{array}{rcl} 100\text{ GeV} \le & m_{\tilde{f}} & \le 1000\text{ GeV}, \\ 50\text{ GeV} \le & |M_{1,2}, \mu| & \le 1000\text{ GeV}, \\ 100\text{ GeV} \le & M_3 & \le 1000\text{ GeV}, \\ & |A_{b,t,\tau}| & \le 1000\text{ GeV}, \\ 1 \le & \tan\beta & \le 50, \\ 43.5\text{ GeV} \le & m_A & \le 1000\text{ GeV}, \end{array} \tag{6}$$

# 4 Current experimental and theoretical constraints

The most relevant constraints today are the [SUSY and Higgs] mass limits from LEP2 and the Tevatron, electroweak precision observables, the branching ratios of the decays $B \to X_s\gamma$ and $B_s \to \mu^+\mu^-$, the anomalous magnetic moment of the muon $(g-2)_\mu$, and the relic density of dark matter $\Omega h^2$. They are compiled in Table 1 (to be extended).

Other important constraints, which we are not yet taking into account, come from $m_W$, $A_b^{\rm FB}$ and $\Delta M_b$.

| Observable | exp. constraint | ref. | add. theory error | ref. |
|---|---|---|---|---|
| $M_Z$ [GeV] | $91.1875 \pm 0.0021$ | [12] | – | |
| $M_t$ [GeV] | $173.3 \pm 1.1$ | [13] | – | |
| $m_b(m_b)^{\overline{\rm MS}}$ [GeV] | $4.19^{+0.18}_{-0.06}$ | [12] | – | |
| $\alpha_s(M_Z)^{\overline{\rm MS}}$ | $0.1184 \pm 0.0007$ | [12] | – | |
| | or $0.1176 \pm 0.002$ | [12] | – | |
| $m_h$ [GeV] | $\ge 114.4$ | [14] | $\pm 1.5$ | [15] |
| $\Delta a_\mu \times 10^{-10}$ | $e^+e^- : 29.6 \pm 8.1$ | [16] | $\pm 2$ | |
| | $\tau's : 15.7 \pm 8.2$ | [?] | | |
| $\mathrm{BR}(b \to s\gamma) \times 10^{-4}$ | $3.55 \pm 0.24_{\rm stat} \pm 0.09_{\rm sys}$ | [17] | ? | |
| $\mathrm{BR}(B_s \to \mu^+\mu^-)$ | $\le 3.6 \times 10^{-8}$ | [17] | ? | |
| $\Omega_{\rm DM}h^2$ | $0.1123 \pm 0.0035$ | [18] | ? | |
| SUSY masses | LEP2 limits | [19] | ? | |

Table 1: Important observables, to be used in the likelihood calculation.

# 5 Analysis

Outline of the analysis:

- Analysis

### 5.1 Event samples

### 5.2 Implementation of the three CMS analyses

### 5.3 Profile likelihood method for statistical interpretation

## 6 Statistical Formalism for multi-dimentional parameter space

## 7 Results

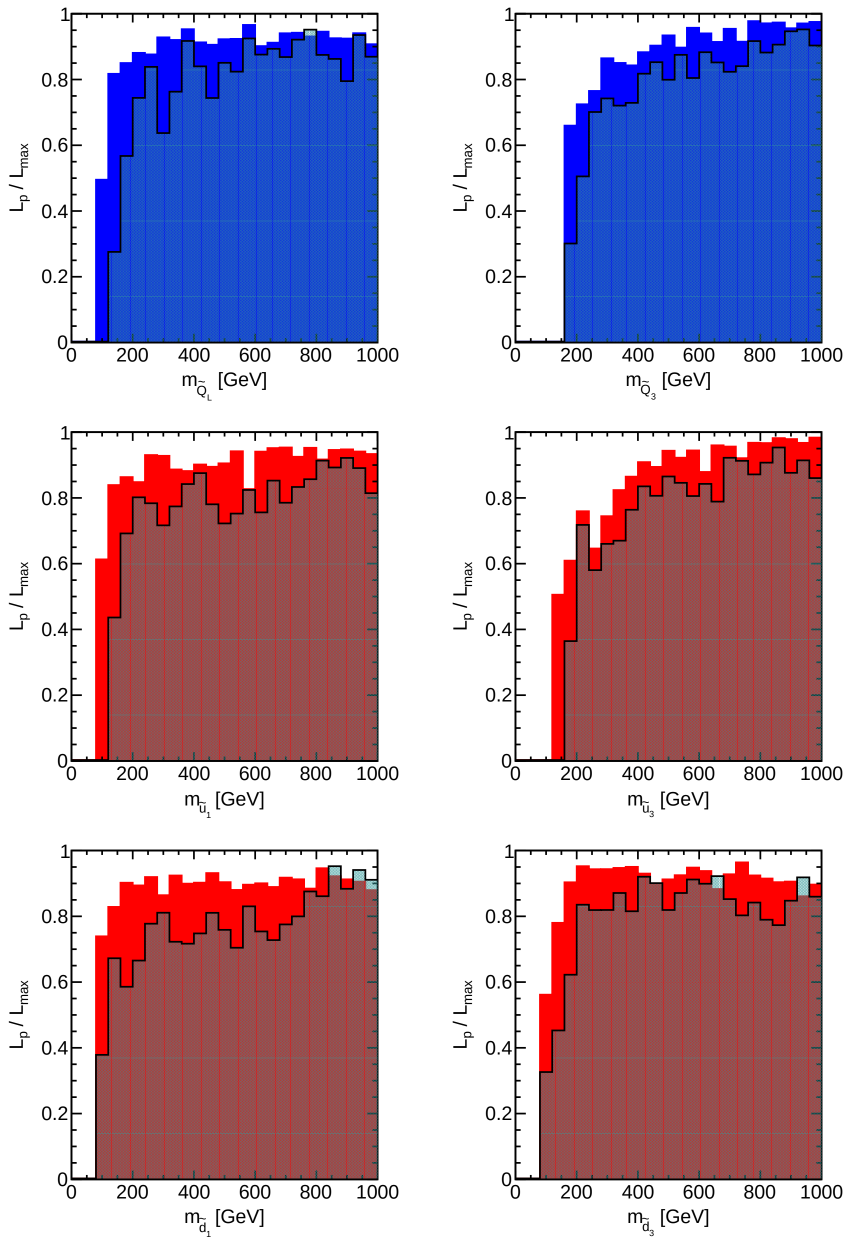


Figure 1: Squark mass parameters at the SUSY scale

## 8 Conclusion

We have studied

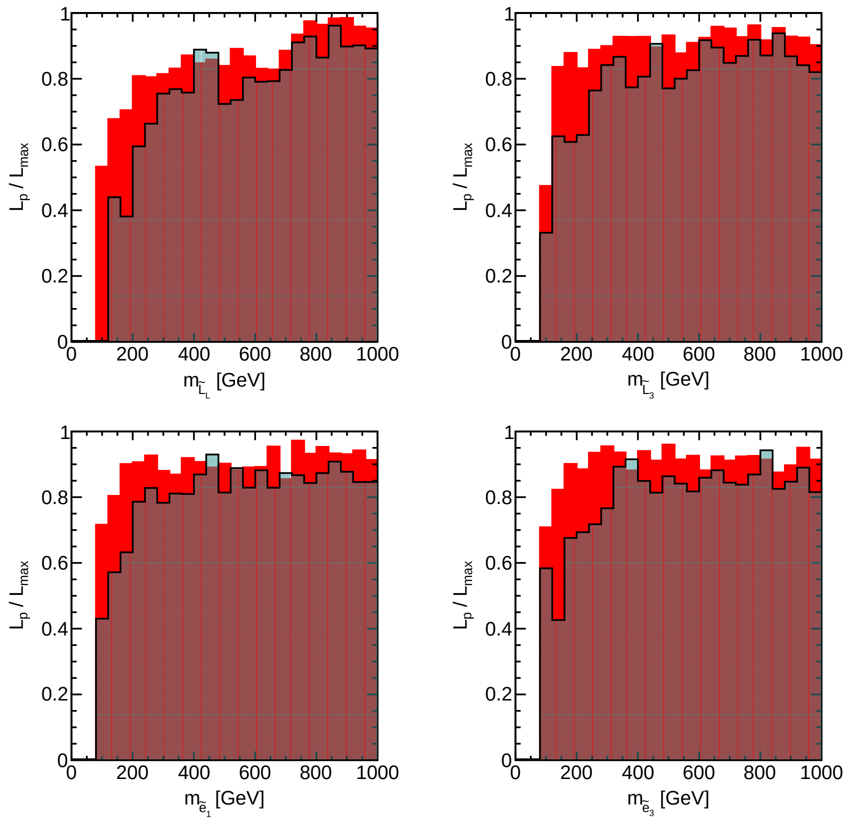


Figure 2: Slepton mass parameters at the SUSY scale

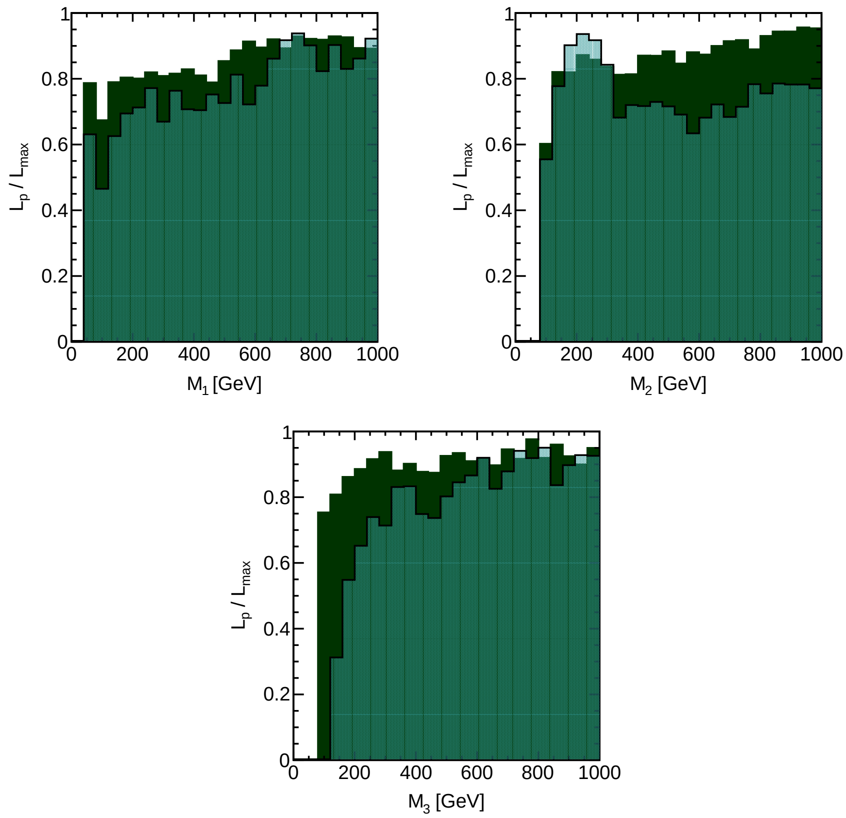


Figure 3: Gaugino mass parameters at the SUSY scale.

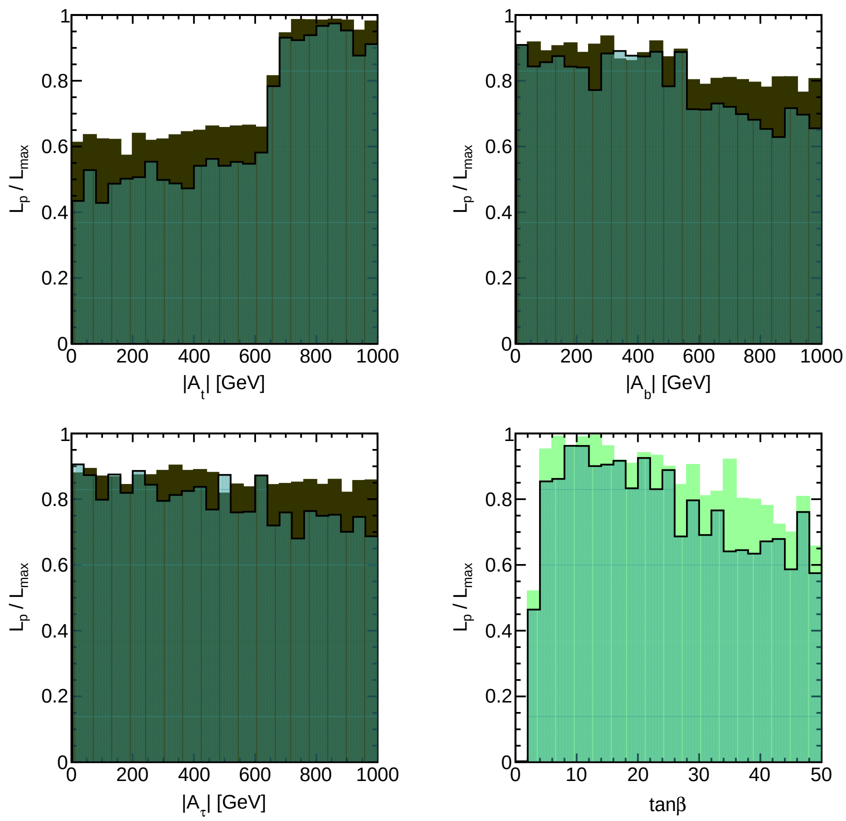


Figure 4: Trilinear couplings and $\tan\beta$ at the SUSY scale

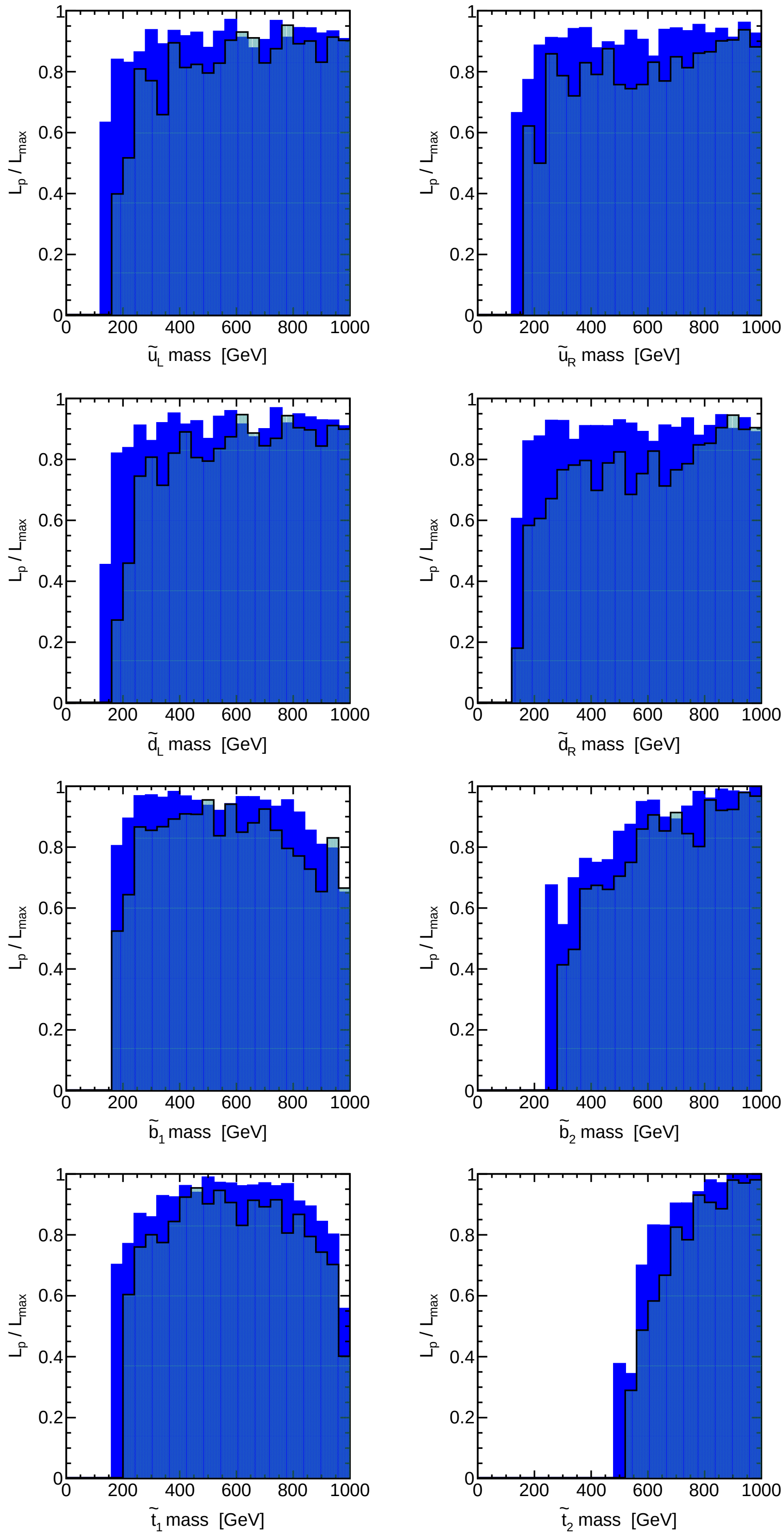


Figure 5: Squark masses.

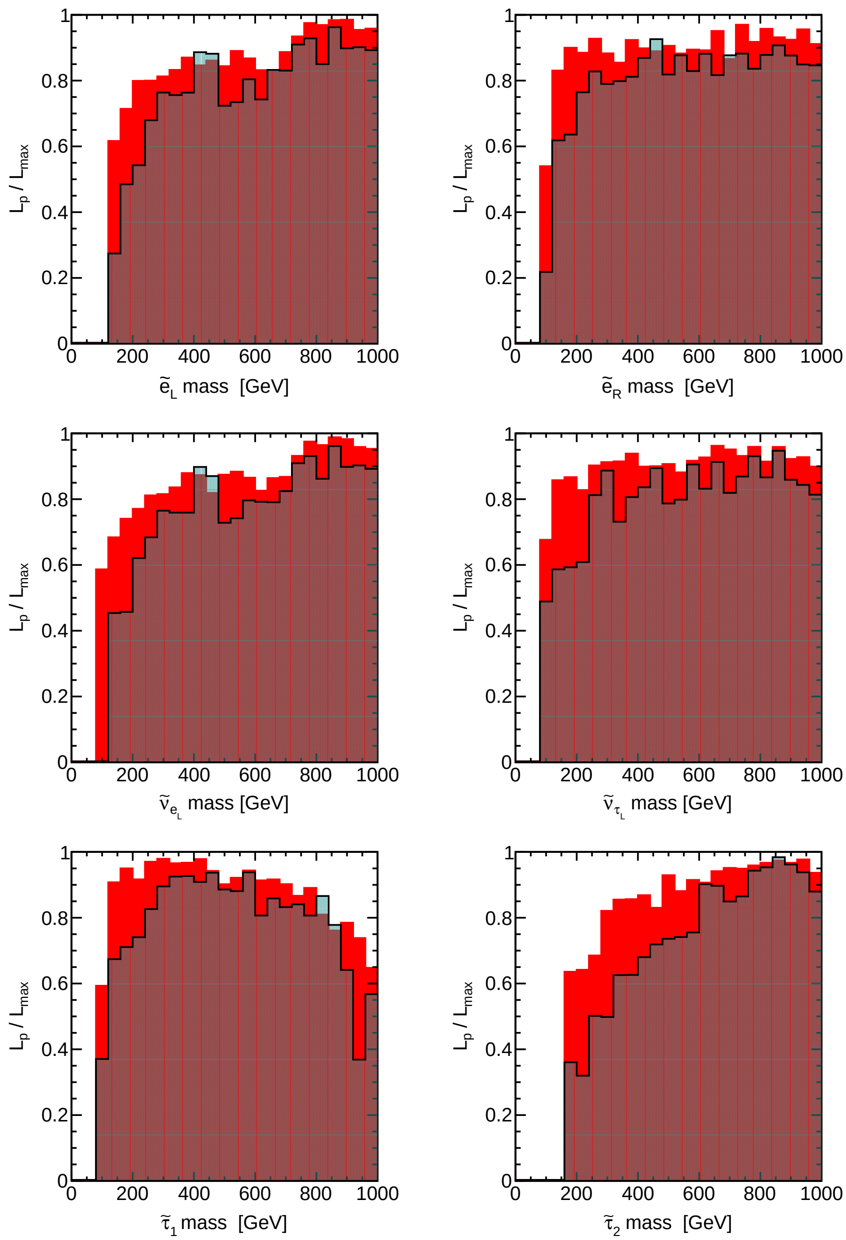


Figure 6: Slepton masses.

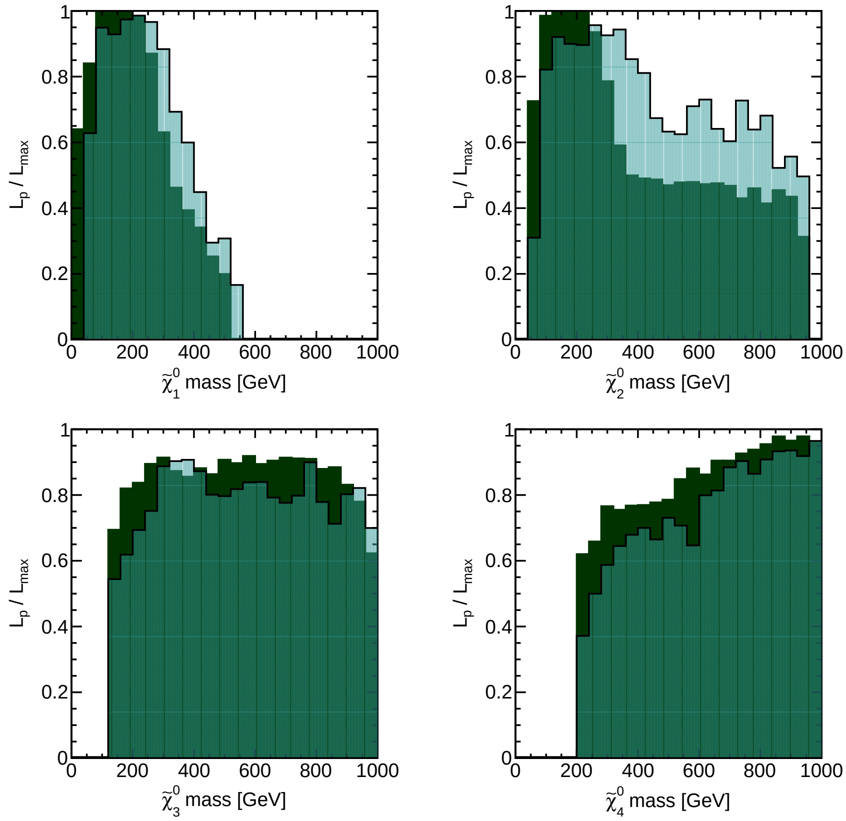


Figure 7: Neutralino masses.

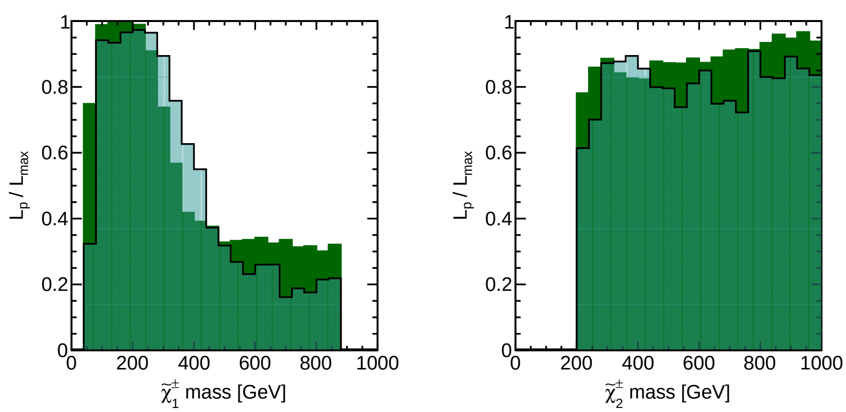


Figure 8: Chargino masses

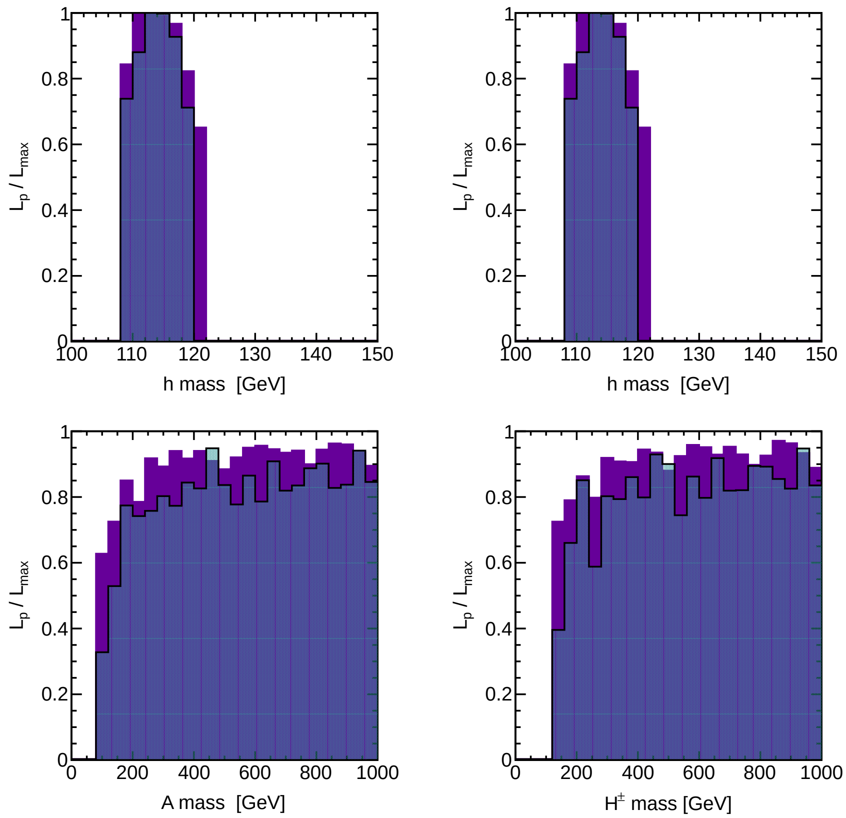


Figure 9: Higgs masses

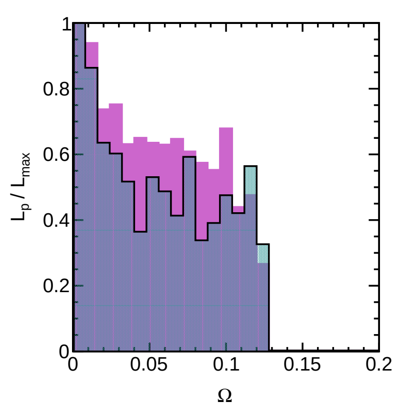


Figure 10: Lightest neutralino dark matter relic density.

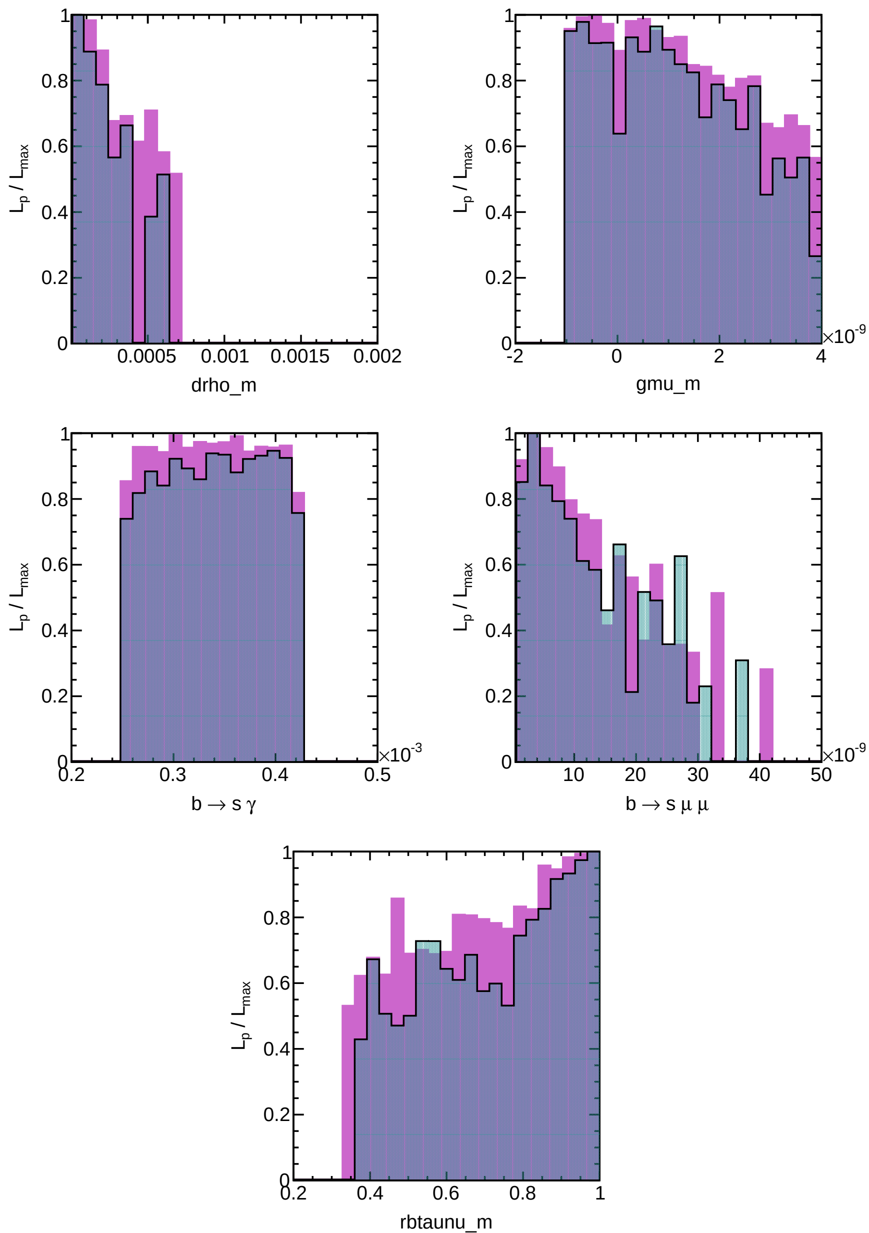


Figure 11: Predictions for weak scale observables as calculated by micromegas.

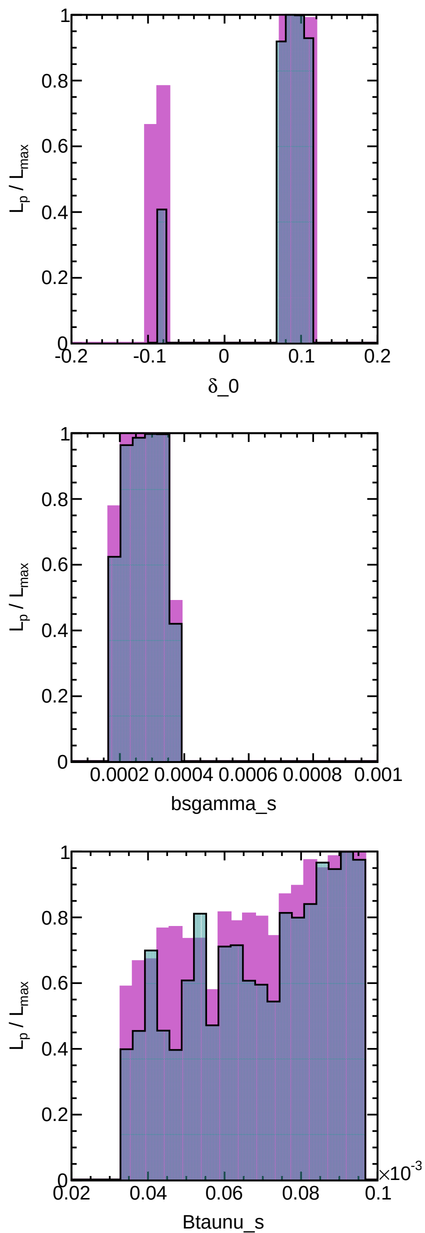


Figure 12: Predictions for weak scale observables as calculated by superiso - I

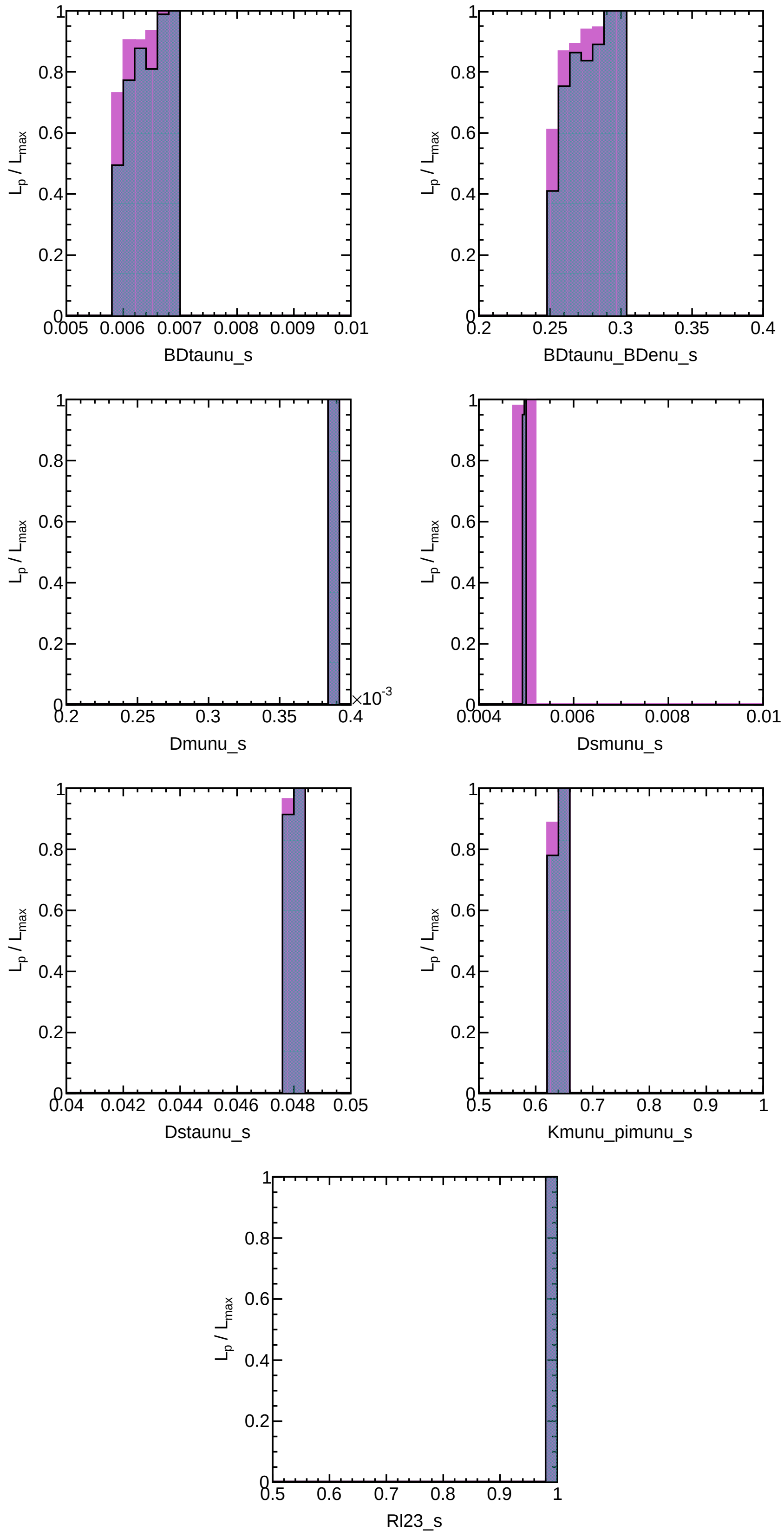


Figure 13: Predictions for weak scale observables as calculated by superiso - II

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