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The Snowmass Point and Slopes[1]

Nabil Ghodbane[†], Hans-Ulrich Martyn[⋆]

[†] *DESY, Hamburg, Germany,* [⋆] *I. Physikalisches Institut der RWTH, Aachen, Germany*

Abstract

We report on the set of benchmark Snowmass Points and Slopes SUSY scenarios defined at Snowmass 2001 Workshop.

1 Introduction

Clearly the next and major project in High Energy Physics is the construction of a e^+e^- Linear Collider (LC) with a centre of mass energy in the sub-TeV range. A LC profits from its clean initial e^+e^- state, to complement the Large Hadron Collider (LHC) for the discovery and explanation of Supersymmetry (SUSY) regarded as one of the best motivated extensions of the Standard Model. Precision experiments at a high Luminosity e^+e^- LC, will provide essential informations about the SUSY particle mass spectrum, their decay widths and essential informations about the underlying SUSY breaking mechanism.

There are currently three world-wide Linear Collider projects [1, 2, 3, 4], namely TESLA which uses acceleration techniques based on superconductive cavities, JLC/NLC using warm cavities and CLIC, a two beam accelerator, which will extend the energy range up to 3 TeV. All these projects are designed with high luminosity of about $3.4\times10^{+34}/\mathrm{cm}^2/\mathrm{s}$.

2 The Snowmass Points and Slopes

The road-map for the establishment of the potential of a Linear Collider to research of Supersymmetry requires among other things a strategic approach to tackle the problem related to the large number of free parameters (over 100) once arbitrary soft supersymmetric-breaking parameters are allowed. At the Snowmass 2001 *Summer Study on the Future of Particle Physics*, a consensus was reached to define a set of SUSY models as benchmarks consistent with existing experimental constraints which are:

- the absence at LEP of supersymmetric particles with a mass less than 100 GeV,
- the agreement of $b \to s\gamma$ decay with the prediction of the Standard Model,
- the measurement of the anomalous magnetic momentum of the muon, $g_\mu - 2$,

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- the range allowed for relic cold dark matter and other cosmological data.

The Snowmass Points and Slopes (SPS) are a set of 9 typical to extreme benchmark points out of which six belong to the minimal SUGRA scenario, two to the GMSB scenario and one to the AMSB scenario for the possible SUSY breaking mechanism. In the next part of this section, we describe briefly the characteristics of the different benchmark points and we refer to [5] where the SPS points are discussed in more details. The different SPS benchmark mass spectra are summarized in table 1.

SPS 1: "typical" mSUGRA scenario

This scenario consists of a "typical" mSUGRA point with an intermediate value of $\tan\beta$ and a model line attached to it. This point lies in the "bulk" of the cosmological region. For the collider phenomenology in particular the τ-rich neutralino and chargino decays are important.

Point:

$$m_0 = 100\mathrm{GeV}, \mathrm{m}_{1/2} = 250\mathrm{GeV}, \mathrm{A}_0 = -100\mathrm{GeV}, \tan\beta = 10, \mu > 0.$$

Slope:

$$m_0 = -A_0 = 0.4\, m_{1/2},\ m_{1/2} \text{ varies.}$$

SPS 2: "focus point" scenario in mSUGRA

The benchmark point chosen for SPS 2 lies in the "focus point" region, where a too large relic abundance is avoided by an enhanced annihilation cross section of the LSP due to a sizable higgsino component. This scenario features relatively heavy squarks and sleptons, while the charginos and the neutralinos are fairly light and the gluino is lighter than the squarks.

Point:

$$m_0 = 1450\mathrm{GeV}, \mathrm{m}_{1/2} = 300\mathrm{GeV}, \mathrm{A}_0 = 0, \tan\beta = 10, \mu > 0.$$

Slope:

$$m_0 = 2\, m_{1/2} + 850\mathrm{GeV}, \mathrm{m}_{1/2} \text{ varies.}$$

SPS 3: model line into "coannihilation region" in mSUGRA

The model line of this scenario is directed into the "coannihilation region", where a sufficiently low relic abundance can arise from a rapid coannihilation between the LSP and the (almost mass degenerate) NSLP, which is usually the lighter $\tilde{\tau}$. Accordingly, an important feature in the collider phenomenology of this scenario is the very small slepton–neutralino mass difference.

Point:

$$m_0 = 90\mathrm{GeV}, \mathrm{m}_{1/2} = 400\mathrm{GeV}, \mathrm{A}_0 = 0, \tan\beta = 10, \mu > 0.$$

Slope:

$$m_0 = 0.25\, m_{1/2} - 10\mathrm{GeV}, \mathrm{m}_{1/2} \text{ varies.}$$

SPS 4: mSUGRA scenario with large $\tan\beta$

The large value of $\tan\beta$ in this scenario has an important impact on the phenomenology in the Higgs sector. The couplings of A, H to $b\bar{b}$ and $\tau^+\tau^-$ as well as the $H^{\pm}t\bar{b}$ couplings are significantly enhanced in this scenario, resulting in particular in large associated production cross sections for the heavy Higgs bosons.

Point:

$$m_0 = 400\mathrm{GeV}, \mathrm{m}_{1/2} = 300\mathrm{GeV}, \mathrm{A}_0 = 0, \tan\beta = 50, \mu > 0.$$

SPS 5: mSUGRA scenario with relatively light scalar top quark

This scenario is characterized by a large negative value of A_0, which allows consistency of the relatively low value of $\tan\beta$ with the constraints from the Higgs search at LEP.

Point:

$$m_0 = 150\mathrm{GeV}, \mathrm{m}_{1/2} = 300\mathrm{GeV}, \mathrm{A}_0 = -1000, \tan\beta = 5, \mu > 0.$$

SPS 6: mSUGRA-like scenario with non-unified gaugino masses

In this scenario, the bino mass parameter M_1 is larger than in the usual mSUGRA models by a factor of 1.6. While a bino-like neutralino is still the LSP, the mass difference between the lightest chargino and the lightest two neutralinos and the sleptons is significantly reduced compared to the typical mSUGRA case. Neutralino, Chargino and slepton decays will feature less-energetic jets and leptons as a consequence.

Point:

$$\text{at GUT scale: } M_1 = 480\mathrm{GeV}, \mathrm{M}_2 = \mathrm{M}_3 = 300\mathrm{GeV} \tag{1}$$

$$m_0 = 150\mathrm{GeV}, \mathrm{m}_{1/2} = 300\mathrm{GeV}, \mathrm{A}_0 = 0, \tan\beta = 10, \mu > 0. \tag{2}$$

Slope:

$$M_3(\mathrm{GUT}) = M_2(\mathrm{GUT}), M_1(\mathrm{GUT}) = 1.6\, M_2(\mathrm{GUT}), m_0 = 0.5\, M_2(\mathrm{GUT}), M_2(\mathrm{GUT}) \text{ varies.}$$

SPS 7: GMSB scenario with $\tilde{\tau}$ NLSP

The NLSP in this GMSB scenario is the lighter stau, with allowed three body decays of right-handed selectrons and smuons into it. The decay of the NLSP into the Gravitino and the τ in this scenario can be chosen to be prompt, delayed or quasi-stable.

Point:

$$\Lambda = 40\mathrm{TeV}, \mathrm{M}_{\mathrm{mes}} = 80\mathrm{TeV}, \mathrm{N}_{\mathrm{mes}} = 3, \tan\beta = 15, \mu > 0.$$

Slope:

$$M_{\mathrm{mes}}/\Lambda = 2, \Lambda \text{ varies.}$$

SPS 8: GMSB scenario with neutralino NLSP

The NLSP in this scenario is the lightest neutralino. The second lightest neutralino has a significant branching ratio into h when kinematically allowed. The decay of the NLSP into the Gravitino (and a photon or a Z boson) in this scenario can be chosen to be prompt, delayed or quasi-stable.

Point:

$$\Lambda = 100\mathrm{TeV}, \mathrm{M}_{\mathrm{mes}} = 200\mathrm{TeV}, \mathrm{N}_{\mathrm{mes}} = 1, \tan\beta = 15, \mu > 0.$$

Slope:

$$M_{\mathrm{mes}}/\Lambda = 2, \Lambda \text{ varies.}$$

SPS 9: AMSB scenario

This scenario features a very small neutralino–Chargino mass difference, which is typical for AMSB scenarios. Accordingly, the LSP is a neutral wino and the NLSP a nearly degenerate charged wino. The NLSP decays to the LSP and a soft pion with a macroscopic decay length, as much as 10 cm.

Point:

$$m_0 = 450\text{GeV}, \mathrm{m}_{\mathrm{aux}} = 60\text{TeV}, \tan\beta = 10, \mu > 0.$$

Slope:

$$m_0 = 0.0075\, m_{\mathrm{aux}}, m_{\mathrm{aux}} \text{ varies.}$$

	mSUGRA scenario	m_0	$m_{1/2}$	A_0	$\tan\beta$	sign μ
SPS 1	typical point	100	250	-100	10	+
SPS 2	focus point region	1450	300	0	10	+
SPS 3	model line into coannihilation region	90	400	0	10	+
SPS 4	large $\tan\beta$	400	300	0	50	+
SPS 5	light stop	150	300	-1000	5	+
SPS 6	non-unified gaugino masses $M_1 = 480,\ M_2 = M_3 = 300$	150	300	0	10	+
	GMSB scenario	Λ	M_{mess}	N_{mess}	$\tan\beta$	sign μ
SPS 7	NLSP $= \tilde{\tau}_1$	40,000	80,000	3	15	+
SPS 8	NLSP $= \tilde{\chi}^0_1$	100,000	200,000	1	15	+
	AMSB scenario	m_0	$m_{3/2}$		$\tan\beta$	sign μ
SPS 9	small $\Delta m(\tilde{\chi}^+_1 - \tilde{\chi}^0_1)$	400	60,000		10	+

Table 1: The different benchmark models for the Snowmass Points and Slopes (SPS). The masses and scales are given in GeV. The top-quark mass for all SPS is $m_t = 175$ GeV.

3 Compilation of Susy Particle Spectra

Several sophisticated programs, with a high degree of flexibility in the choice of the model and the input parameters to deal with the supersymmetric spectrum for the different benchmark SPS points, are available. The most used ones are `ISASUSY` [7], `Suspect` [8], `SoftSusy` [9] and `Spheno` [10]. These codes have different features in general and have been compared in several studies [11]. The simulation of the supersymmetric events (hard production processes, parton showering, heavy particle decay, hadronization processes and hadron decays) uses one of the frequently used Monte Carlo generators:

- `ISAJET` [7], linked with `ISASUSY`, for the mass spectrum and decay branching ratios calculation.

- PYTHIA [12], reliable for all the Standard Model Processes simulation, it has been extended to the production and decay of SUSY and Higgs particles.

- SUSYGEN [13], extensively used for SUSY particle searches at LEP, it uses SUSPECT for the mass spectrum calculation and HDECAY [14] for the determination of the different partial widths associated to the Higgs particles.

In order to relate the high-energy SPS input parameters to the corresponding low-energy MSSM parameters, it was agreed that the standard should be ISAJET 7.58 . This arbitrary choice certainly does not imply that this program is superior to any of the other programs.

The spectrum and the partial decay widths of the different SUSY particles calculated using the same input parameters as generated by ISAJET 7.58 in comparison with results from the programs SUSYGEN 3.00/27 and PYTHIA 6.2/00 has been studied in detail in [6]. In general all three programs provide mass spectra which agree at the level of about 10%. However huge mass differences of up to factors of 2 or even more appears in SPS models with extreme parameters, e.g. high $m_0 >> m_{1/2}$ (SPS 2) or high $\tan\beta$ (SPS 4). Such extreme scenarios are very sensitive to large corrections for which these programs may not be prepared.

Another concern are the decay partial modes and branching ratios treated in the three programs with different sophistication. Some of them seem to be incomplete e.g. missing sfermion decays into gauge and Higgs bosons and missing chargino decays into Higgs (SUSYGEN) or missing Higgs decay into supersymmetric particles (PYTHIA). The different mass spectra as obtained with ISAJET are presented in table 2. In the next part of this section, we describe the main differences that we found, when comparing the three programs, namely: ISAJET 7.58, SUSYGEN 3.00/27 and PYTHIA 6.2/00. Theses discrepancies in the mass spectrum calculation for the three different generators is resumed in figures 1, 2, 3 and 4.

SPS 1 The spectra of this 'typical' mSUGRA scenario provided by the three programs are in remarkable agreement with each other to within a few percent. Also the decay modes are reasonably similar.

SPS 2 Most striking in this 'focus point' scenario with large $m_0 \gg m_{1/2}$ are the completely different neutralino and chargino mass spectra of all three programs. Factors of 2 with respect to some central value may easily occur. This is related to the derived values of μ which exhibit discrepancies of the same order, casting doubt on the calculations. The other sparticle masses are in reasonable agreement with each other. However, large controversies exist in the treatment of the decays. The heavy sleptons and squarks can decay via all charginos and neutralinos, which apparently do have completely different gaugino and higgsino ad-mixtures, thus leading to different χ's in the final states. This model as a whole needs certainly more care and a better theoretical understanding.

SPS 3 All spectra of this scenario which lies on a model line into the 'coannihilation region' are in good agreement with each other. The masses differ within a few up to ten percent, some branching ratios may need to be adjusted.

SPS 4 In general the mass spectra are consistent to within 10%. But due to the high $\tan\beta$ value larger discrepancies are observed for the third generation of sleptons and squarks and for the Higgs sector of PYTHIA. The original purpose of this parameter choice was to provide a model with relatively light Higgs bosons. At the time of the Snowmass meeting[1] a value of $m_A \simeq$ 310 GeV was supported by ISAJET 7.51 and `SuSpect` 2.0 (point d'Aix 3). Meanwhile the new release ISAJET 7.58 gives a considerably higher mass $m_A = 404$ GeV, probably a consequence of a new treatment of the Yukawa bottom coupling at two-loops in the RG evolution. Similarly, if `SuSpect` takes into account additional radiative corrections to all squarks and gauginos, one also gets a larger value of $m_A = 354$ GeV. Thus, in this parameter space with large $\tan\beta$ the Higgs spectrum depends sensitively on the details of higher order corrections. This also explains the lowish Higgs masses of PYTHIA, which uses a one-loop approximation.

SPS 5 The sparticle spectra of all three programs are in general agreement. But the scalar top $\tilde{t}_1$, which should be light in this scenario, is about 20% heavier in PYTHIA. This leads to quite different decay modes.

SPS 6 Very good agreement among the spectra is observed, since in this mSUGRA like scenario with non-unified gaugino masses the MSSM parameters calculated by ISAJET serve as input to SUSYGEN and PYTHIA. Slight discrepancies occur in the branching ratios.

SPS 7 & 8 Only ISAJET is able to generate genuine GMSB scenarios. Since the gravitino is incorporated, the MSSM parameters of SUSYGEN and PYTHIA are adjusted accordingly. PYTHIA does not offer to treat $\tilde{\tau}_1$ as NLSP (SPS 7). All the masses are in agreement by construction, except for discrepancies of 5 - 20% in the heavy Higgs sector of SUSYGEN; for the time being a more precise tuning appears problematic. Again there are some differences in the decay channels, most important are those of $\tilde{e}_R^-$ and $\tilde{\mu}_R^-$ decays in model SPS 7. The specified parameters do not fix the lifetime of the NLSP, which depends on the fundamental scale $\sqrt{F}$ of SUSY breaking. ISAJET allows to set this scale, such that finite decay length distributions $c\tau \sim F^2 \cdot m_{NLSP}^{-5}$ of the NLSP can be studied.

SPS 9 An elementary treatment of AMSB scenarios is only possible in ISAJET. Using the corresponding MSSM parameters the appropriate spectra can be produced with SUSYGEN and PYTHIA. Again there are some inconsistent decay modes, e.g. $\tilde{e}_R^-$ and $\tilde{\mu}_R^-$ decays and, more important, the $\tilde{\chi}_1^\pm$ decays. The characteristic feature is the near degeneracy of the lightest chargino and neutralino masses, which critically determines the $\tilde{\chi}_1^\pm$ lifetime and decay modes. The present parameters give $\tau = 165$ ps ($c\tau = 50$ mm). The lifetime and proper branching ratios determine the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ search strategy and it is advisable to consult the literature[2].

4 Complementarity with LHC

We present in figure 5 a comparison of the number of different SUSY particles that may be observable at LHC and at a Linear Collider for the different SPS benchmark scenarios and

[2] J F Gunion, S Mrenna, Phys. Rev. D 64 (2001) 075002

Model	SPS 1	SPS 2	SPS 3	SPS 4	SPS 5	SPS 6	SPS 7	SPS 8	SPS 9
Masses									
h	114.0	115.7	117.0	115.4	119.8	114.8	113.6	114.8	114.8
H	394.1	1444.1	573.0	404.6	694.0	463.6	378.4	515.0	912.6
A	393.6	1443.0	572.4	404.4	693.9	463.0	377.9	514.5	911.7
$\mathrm{H}^{\pm}$	401.8	1446.2	578.3	416.3	698.5	470.1	386.7	521.2	915.8
$\tilde{\chi}^0_1$	96.1	79.5	160.6	118.7	119.5	189.4	161.7	137.2	175.5
$\tilde{\chi}^0_2$	176.8	135.3	297.0	218.1	226.3	217.9	260.1	252.3	549.0
$\tilde{\chi}^0_3$	358.8	140.8	512.9	383.9	642.8	399.3	306.3	404.0	874.4
$\tilde{\chi}^0_4$	377.8	269.4	529.6	401.1	653.0	420.0	379.9	426.3	876.0
$\tilde{\chi}^-_1$	176.4	104.0	296.9	218.1	226.3	215.3	256.3	252.0	175.7
$\tilde{\chi}^-_2$	378.2	269.0	529.5	402.3	652.7	418.9	379.5	426.5	877.2
$\tilde{g}$	595.2	784.4	914.3	721.1	710.3	708.5	926.1	820.5	1275.2
$\tilde{e}^-_L$, $\tilde{\mu}^-_L$	202.1	1456.3	287.1	448.4	256.3	264.9	261.5	356.6	319.7
$\tilde{e}^-_R$, $\tilde{\mu}^-_R$	143.0	1451.7	178.3	416.5	191.5	236.8	127.4	175.9	303.0
$\tilde{\nu}_e$, $\tilde{\nu}_\mu$	186.0	1454.2	276.0	441.2	244.5	252.8	249.1	347.6	309.7
$\tilde{\tau}^-_1$	133.2	1439.5	170.6	267.6	180.7	227.9	120.5	169.4	271.3
$\tilde{\tau}^-_2$	206.1	1450.4	289.2	414.9	257.9	269.6	263.4	357.6	322.5
$\tilde{\nu}_\tau$	185.1	1448.2	275.1	389.4	242.3	251.8	248.6	346.9	300.7
$\tilde{u}_L$, $\tilde{c}_L$	537.3	1532.7	816.6	730.2	641.8	639.1	859.7	1080.3	1218.1
$\tilde{u}_R$, $\tilde{c}_R$	520.5	1530.1	791.8	715.1	624.5	628.3	830.5	1033.2	1227.4
$\tilde{d}_L$,$\tilde{s}_R$	543.0	1534.7	820.4	734.6	646.4	644.0	863.3	1083.2	1220.7
$\tilde{d}_R$, $\tilde{s}_R$	520.1	1530.5	789.3	714.3	623.4	622.3	828.9	1029.3	1237.8
$\tilde{t}_1$	379.1	1003.9	623.8	530.6	220.7	476.2	779.1	957.7	1005.2
$\tilde{t}_2$	574.7	1307.4	819.5	695.9	644.7	660.7	863.0	1058.7	1128.8
$\tilde{b}_1$	491.9	1296.6	757.5	606.9	535.9	588.9	822.2	1021.9	1112.1
$\tilde{b}_2$	524.6	1520.1	791.4	706.4	623.0	624.5	843.4	1048.3	1232.9

Table 2: Proposed SPS benchmark points and mass spectra (in GeV), as calculated using `ISAJET 7.58`

for different centre of mass energies. We assume a total integrated Luminosity of 1/ab for the Linear Collider and 300/fb per experiment at LHC. We consider a signal to be observable if the minimal number of observed events per production channel is greater than 100 events. As it can be seen from figure 5, the scenario with a Linear Collider running at a centre of mass energy at 1 TeV, gives already essential information about the SUSY spectrum. The LC profits essentially from its clean e^+e^- initial state and the large delivered luminosity and enables then a precision study of the gaugino and the slepton sectors. It complements the LHC which is more sensitive to the squark and gluino production. With a higher centre of mass energy, 3 TeV, achievable by a technology à la CLIC (3 TeV), the squarks would be copiously produced and there too, precision measurements in combination with the results from the LHC, would allow to better understand how SUSY is realized in nature.

5 Conclusion

At the Snowmass Workshop a set of benchmark points and model lines within the mSUGRA, GMSB and AMSB scenarios for SUSY searches have been proposed as a guidance for experimental analyses at colliders. For each of these scenarios, the LHC and a Linear Collider measurements would provide crucial information to better describe the Physics beyond the Standard Model.

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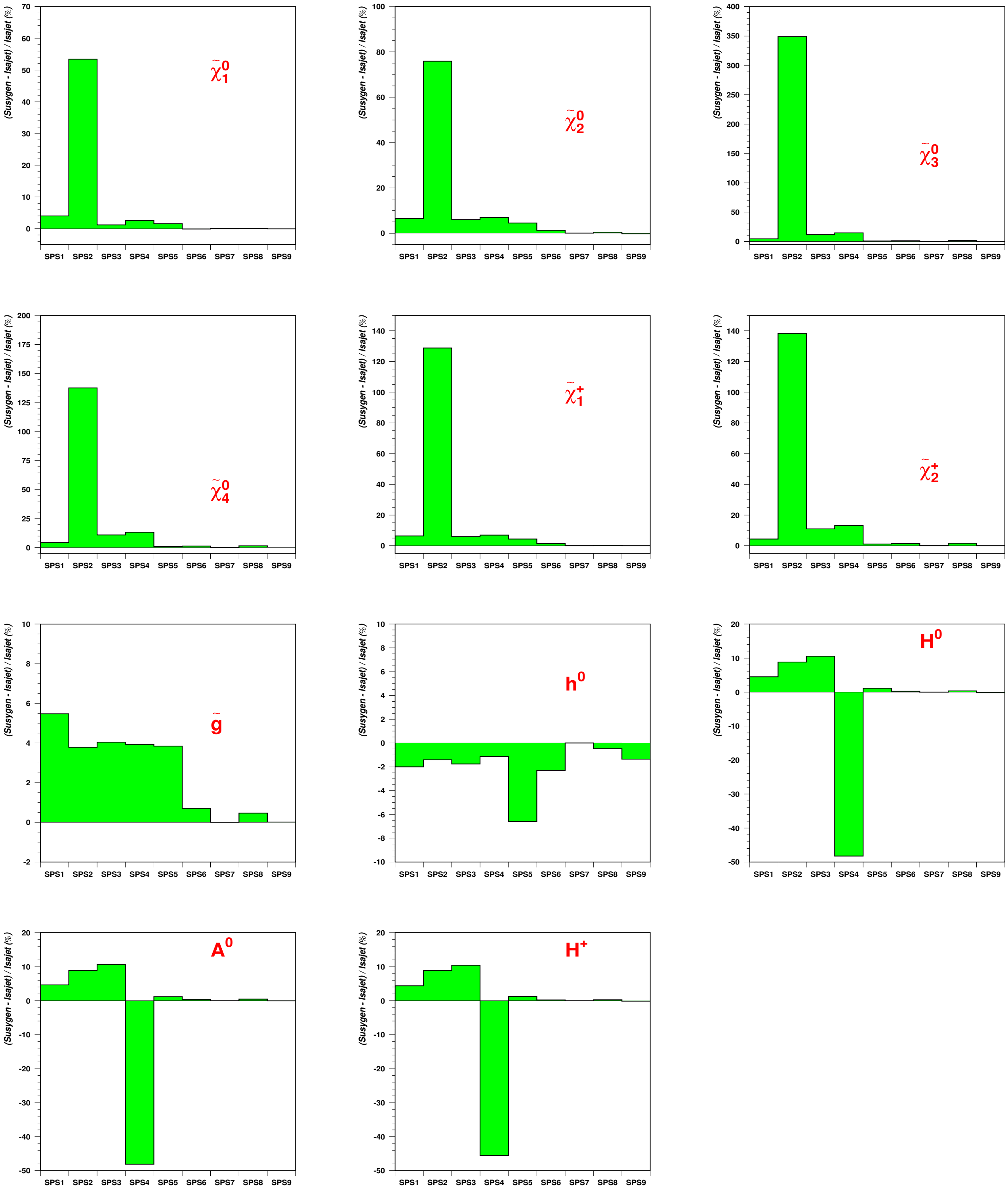

Figure 1: Discrepancies between `ISAJET 7.58` and `SUSYGEN 3.00/27` for the gaugino, gluino and higgsino mass spectrum calculation for the different SPS benchmark scenarios (plotted (Susygen - Isajet)/Isajet).

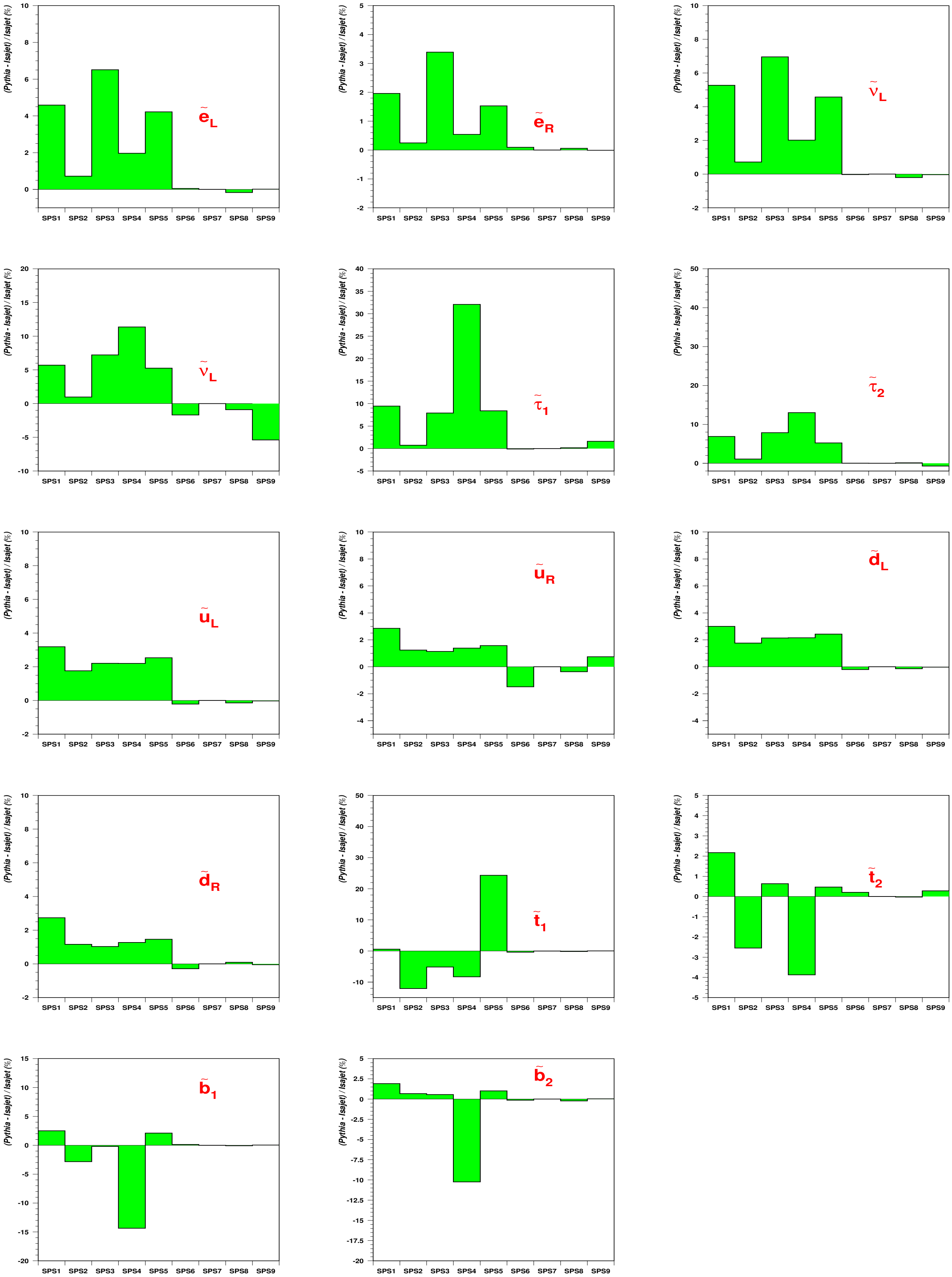

Figure 2: Discrepancies between `ISAJET 7.58` and `SUSYGEN 3.00/27` for the sfermion mass spectrum calculation for the different SPS benchmark scenarios (plotted (Susygen - Isajet)/Isajet).

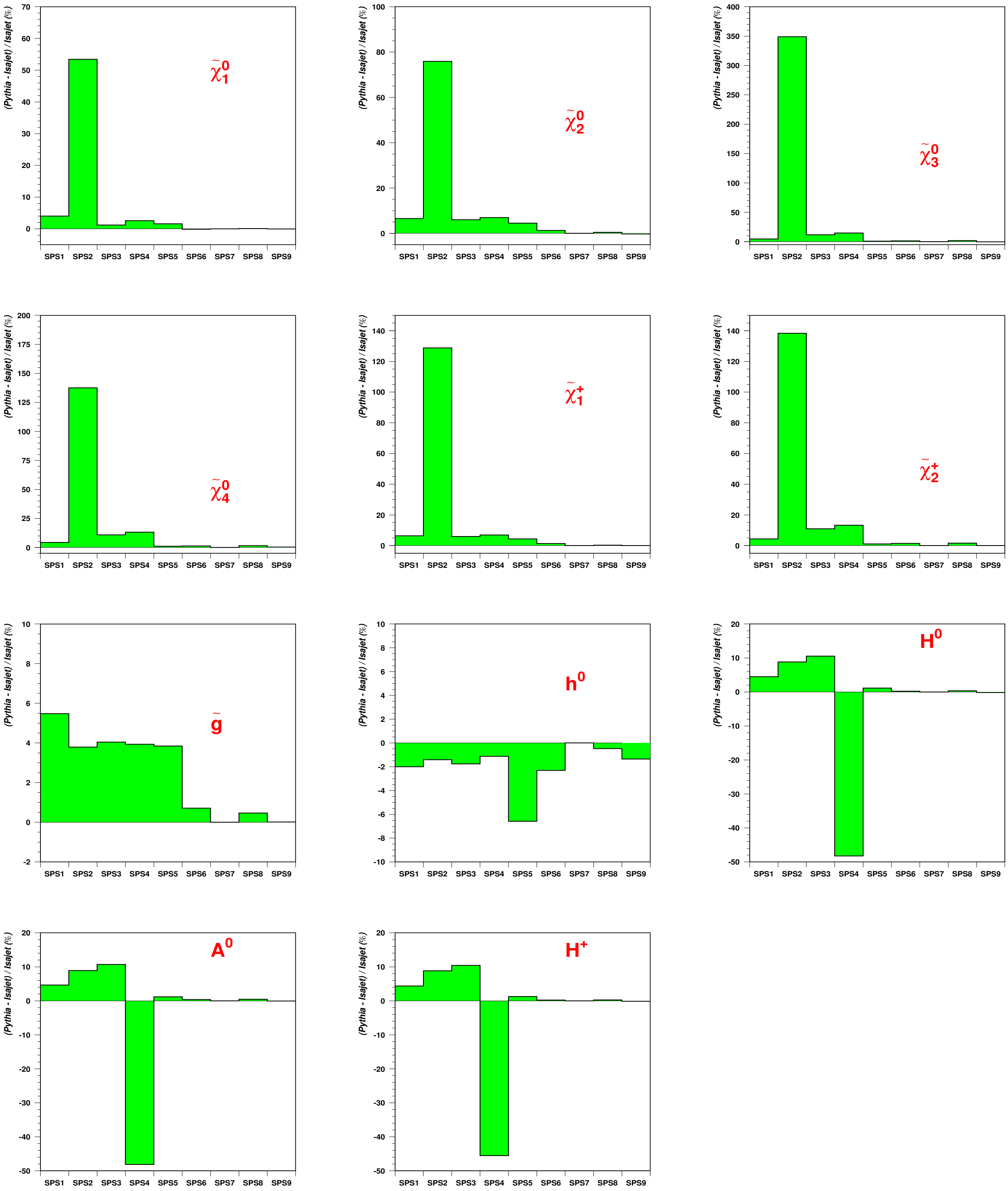

Figure 3: Discrepancies between `ISAJET 7.58` and `PYTHIA 6.2/00` for the gaugino, gluino and higgsino mass spectrum calculation for the different SPS benchmark scenarios (plotted (Pythia - Isajet)/Isajet).

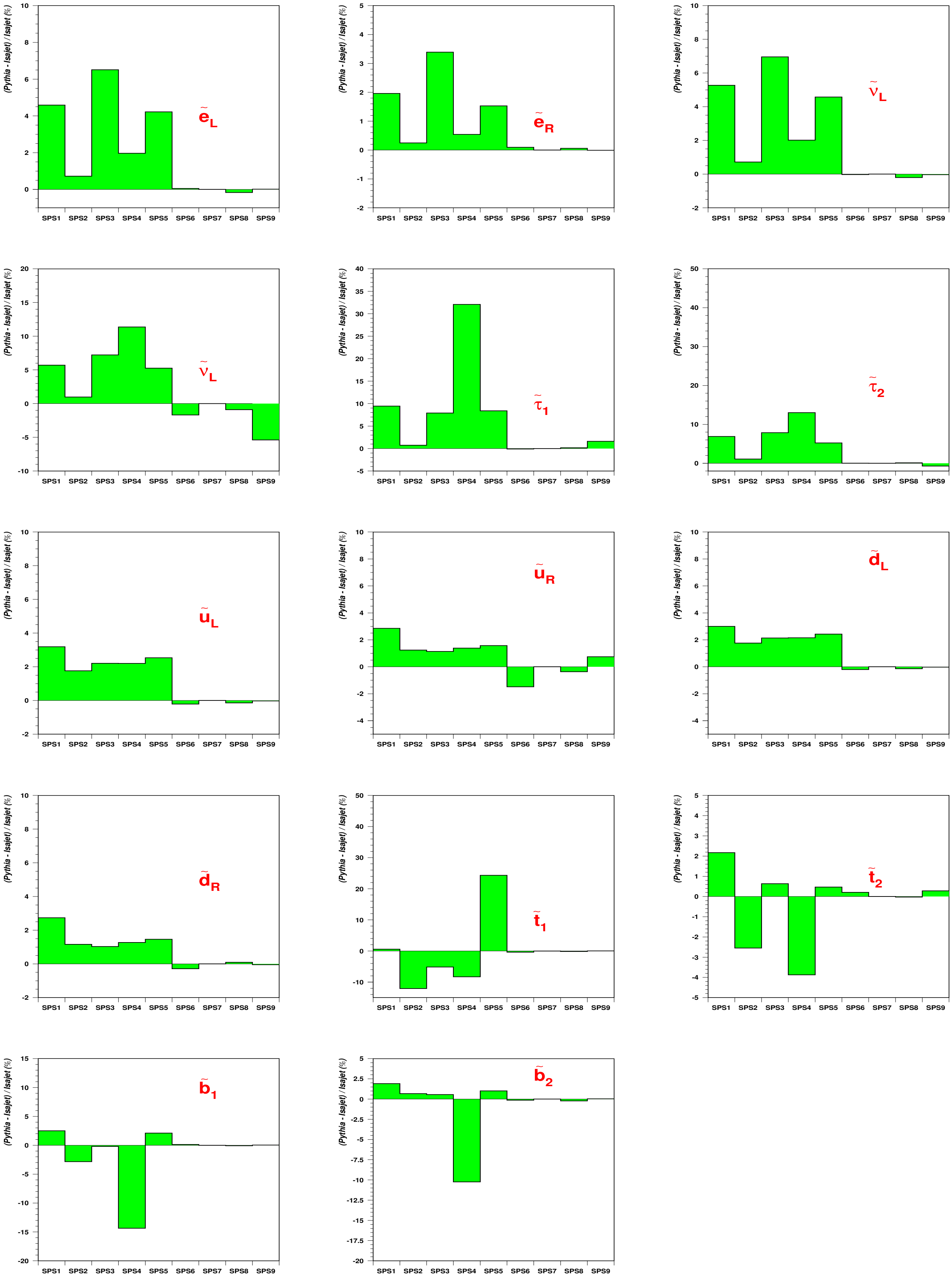

Figure 4: Discrepancies between `ISAJET 7.58` and `PYTHIA 6.2/00` for the sfermion mass spectrum calculation for the different SPS benchmark scenarios (plotted (PYTHIA - ISAJET)/ISAJET).

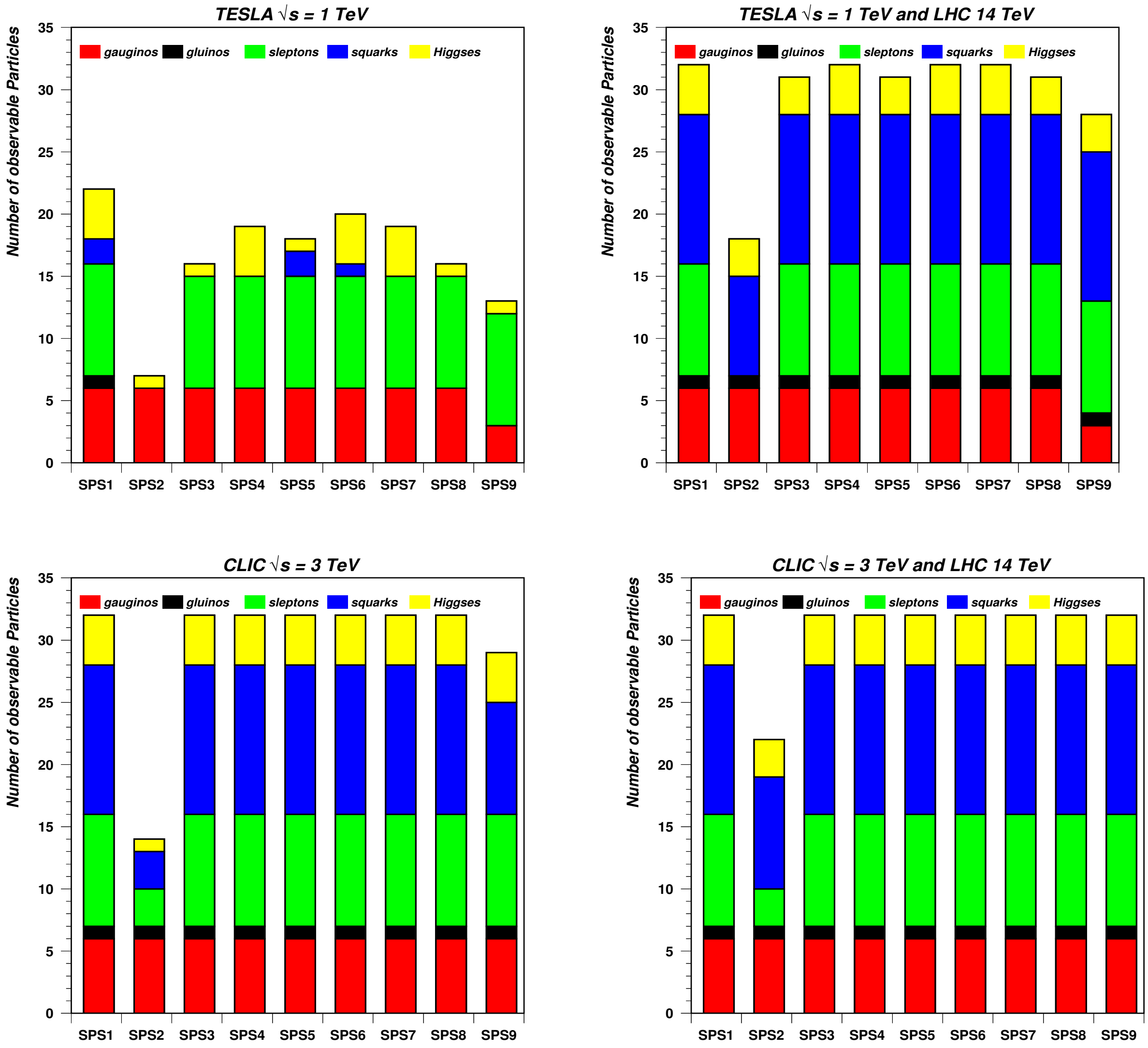

Figure 5: The number of SUSY particles detectable at a Linear Collider for different scenarios and how it combines with the LHC.