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SUSY THEORY REVIEW*

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A brief review of SUSY physics in the advent of the LHC is presented.

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1. Introduction

The Standard Model (SM) provides a very good and economic description for all experimental data [1]. However, it does not pretend to answer a number of key physics questions, *e.g.*: What is the origin of mass? Is it the Higgs mechanism responsible, or its variants? What is the origin of matter–antimatter asymmetry? What are the properties of neutrinos? (neutrinos provide the first experimental evidence for physics beyond the SM). Do all forces, including gravity, unify? What is the nature of dark matter, dark energy? All these questions seem to point to new phenomena to be expected at a TeV scale. This expectation can experimentally be tested soon at the Large Hadron Collider (LHC) and in (hopefully) not too far a future at the International Linear Collider (ILC).

Although each of the above questions could have different answers, it is interesting to explore a possibility that supersymmetry (SUSY) is responsible for all of them. SUSY, being almost as old as the SM itself [2], was not invented or designed to solve some of the SM problems. It turned out however, that it can beautifully accommodate or explain (at least in the technical sense) some of the outstanding problems of the Standard Model, like the hierarchy problem, the gauge coupling unification, the radiative electroweak symmetry breaking. It predicts the heavy top quark, provides a perfect candidate for dark matter (DM), offers new ideas on matter–antimatter asymmetry of the Universe *etc.* Moreover, the unique mathematical nature of supersymmetric theories provides us a telescope to physics at the GUT/Planck scale where particle physics meets gravity.

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Discovering supersymmetry, the main candidate for a unified theory beyond the SM, is the challenge for world physics community experimenting at the LHC. We have to know which signatures of supersymmetry can be expected and how to extract them from the data obtained at the main two LHC detectors: ATLAS and CMS. The outcome of the LHC experiments, to my mind, will be by far more important than any other in the past since all future projects depend on the LHC discovery. This puts a huge responsibility on the LHC experiments to provide quick and reliable answers.

2. Structure of the MSSM

The minimal *exact* supersymmetric extension of the SM is uniquely defined: the particle content and couplings are fixed and no new parameters are introduced. Each SM particle has a partner with the same quantum numbers but with spin differing by 1/2 — called a spartner and denoted by a tilde over the symbol. Thus each SM fermion is accompanied by a scalar fermion (sfermion) and each gauge boson by a spin 1/2 gaugino. Moreover, self-consistency requires an even number of Higgs doublets. The minimal supersymmetric standard model (MSSM) employs two Higgs doublets with hypercharges $\pm 1/2$, accompanied by spin 1/2 Higgsinos. Supersymmetry requires that a particle and a corresponding sparticle have equal masses, *e.g.* $m_e = m_{\tilde{e}}$, and couplings, *e.g.* $g_{\gamma ee} = g_{\tilde{\gamma}\tilde{e}e}$ *etc.* The supersymmetric Lagrangian consists of the gauge invariant kinetic terms corresponding to the SU(3), SU(2) and U(1) gauge groups and the Yukawa terms and scalar potential derived from the superpotential

$$W = h_E H_1 L E^{\rm c} + h_D H_1 Q D^{\rm c} + h_U H_2 Q U^{\rm c} - \mu H_1 H_2 \,, \tag{1}$$

where color, SU(2) and generation indices are suppressed. Here L, $E^{\rm c}$, Q, $D^{\rm c}$, $U^{\rm c}$, H_i denote left-chiral superfields with self-obvious (s)particle content, h_i are corresponding Yukawa couplings and μ is the Higgs(ino) mass parameter. The first three terms are just supersymmetrized version of the SM Yukawa interactions.

In principle the superpotential can contain other terms

$$W_{\not R} = \lambda_{abd} L_a L_b E^{\rm c}_d + \lambda'_{abd} L_a Q_b D^{\rm c}_d + \epsilon_a L_a H_2 + \lambda''_{abd} U^{\rm c}_a D^{\rm c}_b D^{\rm c}_d \,, \tag{2}$$

with the generation indices a, b, d explicitly written. The first three terms generate lepton-number (L) and the last baryon-number (B) violating interactions in the Lagrangian. In the SM such interactions are forbidden by Lorentz invariance and particle content. In the SUSY version with scalar superpartners such interactions are fully consistent with all symmetries. Phenomenologically the presence of both L- and B-number violating interactions is disastrous since it leads to fast proton decay. The simplest, and most popular, solution is to suppress $W_{\not R}$ terms by imposing a symmetry, called R-parity [3], defined as

$$R = (-1)^{3B-L+2s} \,. \tag{3}$$

Imposing R-parity has important consequences: sparticles are created in pairs in particle collisions, among the decay products of a sparticle there is always a sparticle, and the lightest sparticle (LSP) is stable. This makes the LSP, in many SUSY models the lightest neutralino, a perfect candidate for the dark matter particle, which is one of the most attractive features of supersymmetric extension of the SM.

Since not even a single SUSY particle has been found so far, sparticles cannot be degenerate in mass with corresponding particles and supersymmetry must be broken. However, no viable model of SUSY breaking within the MSSM itself can be constructed because none of the MSSM fields can have a non-zero vacuum expectation value needed for SUSY breaking without violating the gauge invariance. Instead, the most popular scenario is to invoke the so-called hidden sector where spontaneous supersymmetry breaking occurs and with the help of some messenger fields it is mediated to the visible sector generating in the MSSM Lagrangian terms that break SUSY explicitly. To maintain the cancellation of quadratic divergencies needed for solving the hierarchy problem, the SUSY breaking terms must be *soft*, *i.e.* of dimension less than 4. The most general form of soft terms includes gaugino ($\tilde{\lambda}_a$) and scalar (ϕ_i) masses (M_a, M_{ij}^2), and scalar bilinear (b_{ij}) and trilinear (A_{ijk}) couplings [4]

$$-\mathcal{L}_{\rm soft} = \frac{1}{2} M_a^2 \tilde{\lambda}_a \tilde{\lambda}_a + M_{ij}^2 \phi_i^\dagger \phi_j + b_{ij}\phi_i\phi_j + A_{ijk}\phi_i\phi_j\phi_k + \text{h.c.} \tag{4}$$

parameterized in total by 105 new parameters. The *unconstrained* MSSM is thus understood as an effective low-energy model defined by three assumptions: (a) minimal particle content, (b) R-parity conservation, (c) most general soft-supersymmetry breaking terms. The number of parameters could be further enlarged by relaxing (a) or (b), or reduced by constraining (c) with additional assumptions on SUSY breaking mechanism.

As the soft SUSY breaking is explicit, the Appelquist–Carazzone theorem applies to the superpartner spectrum. Thus, SUSY virtual effects disappear at least as an inverse of the SUSY breaking scale, $\mathcal{O}(1/M_{\rm SUSY})$, and can naturally be arranged compatible with the electroweak (EW) precision data. It is nevertheless interesting to note that global fits to EW and DM data [5], at least in the constrained MSSM (defined below), usually referred to as mSUGRA, point to a rather low values of SUSY breaking parameters [6], which interestingly enough are close to the benchmark point SPS1a of [7].

Together with the strong indication for a light Higgs boson it fuels hopes for a discovery of the Higgs boson(s) and (some of) supersymmetric particles at the LHC.

However, with that many new parameters it is hard to accept the unconstrained MSSM as a fundamental theory. Moreover, in most of the 105-parameter space the model exhibits phenomenologically bad features, like unsuppressed FCNC and CP-violating phenomena, color or charge breaking vacua *etc.* The MSSM is viable only in some regions of the parameter space with a certain degree of universality.

Since the gauge coupling unification suggests that physics might be simpler at or near the unification scale, renormalization-group equations (RGE) can be used to provide the link between low- and high-scale theories. In the *top–down* approach a plethora of theoretical scenarios of hidden sectors and mediation of SUSY-breaking has been examined, like gravity-, gauge-, anomaly-, mixed-, …, mediation. Then the RGE are used to derive the low-energy MSSM parameters. It turns out that phenomenological Lagrangian depends crucially only on gross features: which hidden-sector fields develop the largest F or D term vacuum expectation values, what is the mediation mechanism, what are dominant effects producing hidden-visible sector couplings: at tree level, or loop-induced *etc.* As a result, each scenario can be characterized by a handful of independent parameters which makes the phenomenological analyses of low-energy theory much simpler and more predictive. For example, the mSUGRA scenario mentioned above is defined by universal scalar (M_0) and gaugino ($M_{1/2}$) masses and universal trilinear (A_0) scalar couplings at some unification scale, while the universal bilinear parameter is traded for the ratio of the Higgs vacuum expectation values $\tan\beta = v_2/v_1$ from the condition of reproducing the correct mass of the Z-boson, and sign of the Higgsino-mass parameter μ.

However, the top-down approach may be too restrictive: the phenomenologically viable region of the parameter space is larger than any RGE-derived region of the above scenarios. Moreover, our imagination of devising high-scale supersymmetry-breaking scenarios is certainly limited.

At present only the experimental limits on the parameter space can be used to gain some insight on the SUSY breaking. The non-discovery of SUSY and a light Higgs boson at LEP2 puts the solution of the naturalness problem in a subtle position: fine tuning of order of a few percent is required to reproduce the EW scale and evade experimental constraints. This problem, called the supersymmetric fine-tuning has attracted much attention [8] and is one of the main driving forces to go beyond the MSSM[1].

[1] For beyond MSSM review, see talk by S. Pokorski [9].

Once supersymmetry is discovered, we will have to face the problem of reconstructing the low-energy supersymmetry Lagrangian parameters from experimental measurements with minimum of theoretical assumptions. Only then in the *bottom–up* approach [10] we can attempt use the RGE as a telescope to explore the high-energy physics by exploiting the low-energy experimental input to the maximum extent possible.

3. Supersymmetry at LHC

If SUSY exists at the TeV scale, squarks and gluinos ($\tilde{q}$ and $\tilde{g}$), the strongly interacting superpartners of quarks and gluons, will be copiously produced at the LHC. Their production cross sections (typically in the picobarn range) are comparable to cross sections of jets with transverse momenta $p_{\rm t} \sim$ SUSY masses. Rates of directly produced weakly interacting sparticles are much lower. Squarks and gluinos will promptly decay into jets and lighter SUSY particles which will further decay. Their decay chains are model dependent, but generically one can expect in the final state high-$p_{\rm t}$ jets and leptons, possibly large missing energy $\not{E}_{\rm t}$, or displaced vertices *etc.* Since the LHC detectors are designed to detect jets, isolated leptons and photons, displaced vertices, measure energies and transverse momenta and missing transverse energy, they are well equipped to cover a broad spectrum of possible decay modes of SUSY particles. There have been many experimental analyses demonstrating the capabilities of LHC detectors ATLAS and CMS [11, 12]. It is impossible to give justice to all in my talk (and these proceedings) and I refer to [13] for more details. Below I present some selected examples.

3.1. Search for SUSY signals at LHC

Sparticle production in pp collisions at the LHC is dominated by $\tilde{q}$ and $\tilde{g}$. Leptonic decays may or may not be large but jets are always produced with transverse momenta $p_{\rm t}$ of the order of sparticle masses. If the LSP is stable, as in scenarios with R-parity conserved, it will escape undetected giving large $\not{E}_{\rm t}$. The SM background events from top quark, W and Z boson decays do not have such high-$p_{\rm t}$ objects.

Motivated by these observations, a set of simple cuts can be designed to enhance the signal over the background in inclusive "transverse" searches for SUSY particles. For example, it has been demonstrated [11] that in typical mSUGRA scenarios requiring at least four jets with large $p_{\rm t}^i$ and large

$$M_{\rm eff} = \sum_{i=1,...4} p_t^i + \not{E}_{\rm t} \qquad (5)$$

and selecting events spherical in the transverse plane, where specific lower cuts on $\not{E}_{\rm t}$, $p_{\rm t}^i$, $M_{\rm eff}$ and sphericity depend on details of the model, can be sufficient to discover new particles. To reduce the background further, hard, isolated lepton(s) may be required and their $p_{\rm t}$ is then included in the definition of $M_{\rm eff}$. Previous studies show that squarks and gluinos with masses up to ~ 2.5 TeV can be found at LHC with 100 fb^{-1}. Monte Carlo studies have also shown that the position of the peak in $M_{\rm eff}$ distribution correlates quite well with sparticle masses, namely $M_{\rm eff} \sim \min(m_{\tilde{q}}, m_{\tilde{g}})$, providing a first estimate of the overall SUSY mass scale.

While other R-parity conserving models of SUSY breaking are quite different, like the anomaly-mediation, the reach in $m_{\tilde{q}}, m_{\tilde{g}}$ is similar $\sim 2\,$TeV. It follows from the fact that the overall reach depends mainly on the production cross section as long as there are sufficiently large mass gaps between sparticle masses.

Recently several groups [14] have emphasized importance of including exact matrix element corrections to the previous parton shower estimate of the background, which significantly change the background distribution in the signal region. This is even more critical if sparticle masses become degenerate because a reduced probability of events with high $p_{\rm t}$ jets is then expected as well as lower $M_{\rm eff}$ and $\not{E}_{\rm t}$ making them less "transverse". This means that standard SUSY cuts reduce the signal sample and SUSY discovery is more affected by the SM background. Such a scenario occurs, for example, in a string inspired model based on the flux compactification [15], dubbed the mixed modulus-anomaly mediation model [16]. Depending on the ratio of F-terms of the volume modulus field and the mSUGRA compensator field, the mass spectrum of SUSY particles changes smoothly from the mSUGRA-like to the anomaly-mediation-like. It is interesting that in this model the unification scale of the soft SUSY parameters can be much lower than the GUT scale, even of the order of the weak scale. There are regions of parameters where the squark, slepton and gaugino masses are significantly degenerated. If $m_{\tilde{\chi}^0_1} \gtrsim m_{\tilde{q},\tilde{g}}/2$, the signal $M_{\rm eff}$ distribution becomes quite similar to that of the background. However, it has been found [17] that the SUSY signal in the degenerate case exhibits a special universal pattern in $M_{\rm eff}$ and $\not{E}_{\rm t}$ plane which may help to identify the signal region and discriminate signal from background better.

3.2. Sparticle mass measurements

If R-parity is conserved, all SUSY particles decay into invisible LSP, so no mass peaks can be identified. Nevertheless, it might be possible to identify particular decay chains and exploit the "endpoint method" to measure combinations of masses [18]. For example, a relatively clean channel is provided by the three-body decay or, if the slepton can be on-shell, the cascade of two-body decays of the heavier neutralino

$$\tilde{\chi}^0_i \to (\tilde{\ell}\ell) \to \ell\ell\tilde{\chi}^0_1\,. \tag{6}$$

The dilepton mass distribution endpoints depend on the sparticle masses

$$m_{\ell\ell}(\text{3-body}) \;=\; m_{\tilde{\chi}_i^0} - m_{\tilde{\chi}_1^0}\,, \tag{7}$$

$$m_{\ell\ell}(\text{2-body}) \;=\; \frac{\sqrt{(m^2_{\tilde{\chi}_i^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m_{\tilde{\chi}_1^0})}}{m_{\tilde{\ell}}}\,. \tag{8}$$

The events can be searched for by requiring two isolated leptons in addition to multijet and $\not{E}_{\mathrm{t}}$ cuts like those described above. If lepton flavors are separately conserved, then contributions from two uncorrelated decays cancel in the combination of $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ giving a very clean signal and allowing a precise endpoint measurement. The shape of the distribution also allows us to distinguish two-body and three-body decays.

Long decay chains allow more endpoint measurements. For example, in the SPS1a mSUGRA scenario the following decay chain

$$\tilde{g} \to \; j_1\tilde{q} \to \tilde{\chi}_2^0 j_1 j_2 \to \tilde{\ell}\ell_1 j_1 j_2 \to \tilde{\chi}_1^0 \ell_1\ell_2 j_1 j_2 \tag{9}$$

can be exploited. With two jets and two leptons in the final state it should be possible to measure the endpoints of invariant mass distributions $\ell\ell$, $\ell\ell j^{\max}$, $\ell\ell j^{\min}$, ℓj. These endpoints are smeared by jet reconstruction, hadronic resolution, and mis-assignment of the jets that come from squark decays. Nevertheless, it has been shown [19] that for the integrated luminosity of $300\,\mathrm{fb}^{-1}$ these endpoints should be measured at the level of 1%, *i.e.* determining mass relations to 1–2%. In fact, with so many endpoints one can solve for the absolute values of the unknown masses of $\tilde{g}$, $\tilde{q}$, $\tilde{\chi}_2^0$, $\tilde{\ell}$ and $\tilde{\chi}_1^0$ within 5–10% accuracy. This is a general feature of the determination of sparticle masses when the LSP momentum cannot be measured directly. Nevertheless, $\mathcal{O}(5)$% accuracy in the mass of sleptons and the lightest neutralino provides a link to cosmology. With this information one can calculate the neutralino annihilation rate at the time of decoupling and estimate the amount of DM at the level of 7% [20].

It is notable that the LHC can access the mass of the heaviest neutralino $\tilde{\chi}_4^0$ which in this model is too heavy to be produced at a 500 GeV e^+e^- collider. The measured mass difference $m_{\tilde{\chi}_4^0} - m_{\tilde{\chi}_1^0}$, in the same decay chain as in Eq. (9), but with $\tilde{\chi}_4^0$ replacing $\tilde{\chi}_2^0$, directly constrains the μ parameter. The errors for the MSSM Lagrangian parameters would significantly be reduced if the measurements at the LHC and ILC could be combined [21]. The LHC/ILC interplay is even more important in scenarios with heavy sparticles, like in the cosmology-motivated focus-point scenario in which only limited amount of complementary information from each collider alone can be exploited [22]. A comprehensive account of SUSY studies within the LHC/ILC context can be found in Ref. [23].

If the LSP mass could be measured at the ILC, then errors on the sparticle masses would be reduced significantly, to $\sim 1\%$ for squark and gluino masses (dominated by the 1% jet scaling error), and well below 1% level for weakly interacting sparticles in the SPS1a scenario [24]. In such a case the collider-based calculations of the DM could match the expected accuracy of the Planck probe [25] providing a strong consistency test of particle physics and cosmology.

The mass determination through the endpoint method has several shortcomings: the LSP momentum cannot be reconstructed except for a few very special points in the parameter space, only events near endpoints are used neglecting independent information contained in events away, and the selected events may contain contributions from several cascade decays causing additional systematic uncertainties. These problems can be ameliorated by using the "mass relation" method [26]. In this method the on-shell conditions for sparticle masses in the decay chain are used to solve for the kinematics and reconstruct the SUSY masses as peaks in certain distributions. For example, in the cascade decay Eq. (9) five on-shell conditions can be written for $\tilde{g}$, $\tilde{q}$, $\tilde{\chi}_2^0$, $\tilde{\ell}$ and $\tilde{\chi}_1^0$ in terms of the measured momenta of leptons, jets and the 4 unknown components of the undetected neutralino. Each event, therefore, spans a 4-dimension hypersurface in a 5-dimension mass space, and in principle 5 events would be enough to solve for masses of involved sparticles. Note that events need not be close to endpoints of the decay distributions, *i.e.* the method can be used even if the number of signal events is small.

3.3. Is it SUSY?

After careful calibration of LHC detectors and years of collecting data and determining masses of new particles, can we be sure that we see sparticles? Establishing SUSY at the LHC will require not only to discover new particles, to measure their masses, decay branching ratios, production cross sections, but also to verify that they are superpartners, *i.e.* to measure their spins and parities, gauge quantum numbers and couplings. A generic weak-scale SUSY signal of large $\not{E}_{\rm t}$ arises in almost any model with the lightest TeV-scale particle stable and neutral, as suggested by the dark matter of the Universe. Therefore, we should be able to distinguish the SUSY decay chain Eq. (9) from, *e.g.*, the cascade decay

$$g' \to \; j_1 q' \to Z' j_1 j_2 \to \ell' \ell_1 j_1 j_2 \to \gamma' \ell_1 \ell_2 j_1 j_2 \,, \tag{10}$$

that arises in the universal extra-dimension model (UED) [27]. Here the primes denote the first excited Kaluza–Klein states of the corresponding SM particles with the mass spectrum similar to the SUSY case. In both cases the final state is the same $\ell_1 \ell_2 j_1 j_2$ with either the $\tilde{\chi}_1^0$ or the γ' escaping detection.

What differentiates the decays in Eqs. (9), (10) is the spins of intermediate states and the chiral structure of couplings. Note that in contrast to the UED case the SUSY particles are naturally polarized in many processes. For example, in the sub-chain $\tilde{q}_{\rm L} \to \tilde{\chi}^0_2 q_{\rm L} \to \tilde{\ell}_{\rm R}\ell_{\rm R} q \to \tilde{\chi}^0_1 \ell\ell q$ the $\tilde{\chi}^0_2$ is polarized as right-handed, opposite to $q_{\rm L}$, because the $\tilde{q}\tilde{\chi}q$ Yukawa coupling flips chirality. The polarized neutralino further decays into either $\tilde{\ell}_{\rm R}\ell^+$ or $\tilde{\ell}^*_{\rm R}\ell^-$ with equal rates (because of the Majorana character of neutralinos). However, due to the chiral nature of the Yukawa $\tilde{\ell}\tilde{\chi}\ell$ coupling, the ℓ^+ is likely to fly in the neutralino direction in the squark rest frame, while the ℓ^- in the direction of the quark jet. The difference in the angular distribution is reflected as a charge asymmetry in the invariant mass distribution of the jet-lepton system [28].

Although the charge asymmetry for $\tilde{q}^*_{\rm L}$ decay is just opposite, in pp collisions more squarks than anti-squarks are expected and the $\tilde{\chi}^0_2$ production from squark decays is dominant. The charge asymmetry in the $m(j\ell)$ remains allowing to resolve the fermionic nature of the neutralino from the vector nature of the Z' and confirm the chiral structure of couplings [29]. Certainly, new ideas to exploit specific features of SUSY at the LHC, for example how to measure the jet charge, are very much welcome.

4. The inverse problem

The LHC experiments in the supersymmetric particle sector offer not only the discovery potential but also many high precision measurements of masses and couplings [11, 12]. The next step towards establishing SUSY is the reconstruction of low-energy SUSY breaking Lagrangian parameters without assuming a specific scenario. This is a highly non-trivial task, as stressed recently in [30]. This task will be greatly ameliorated by experimenting at the ILC where the experimental accuracies at the per-cent down to the per-mill level are expected [31]. The ultimate goal of all experimental efforts will be to unravel the SUSY breaking mechanism shedding light on physics at high (GUT?, Planck?) scale.

The expected high experimental accuracies at the LHC/ILC should be matched from the theoretical side [32]. This calls for a well defined theoretical framework for the calculational schemes in perturbation theory as well as for the input parameters. Motivated by the experience in analyzing data at the former e^+e^- colliders LEP and SLC, the SPA Convention and Project [24] has been proposed. It provides: a convention for high-precision theoretical calculations, a program repository of numerical codes, a list of tasks needed further improvements and a SUSY reference point SPS1a$'$ as a test-bed.

The SPA Convention and Project is a joint inter-regional effort that could serve as a forum to discuss future improvements on both experimental and theoretical sides to exploit fully the physics potential of LHC, and ILC. The current status of the project is documented on the routinely updated web-page `http://spa.desy.de/spa/`

4.1. SPA Convention

Building on vast experience in SUSY calculations and data simulations and analyses, the SPA Convention consists of the following propositions:

- The masses of the SUSY particles and Higgs bosons are defined as pole masses.
- All SUSY Lagrangian parameters, mass parameters and couplings, including $\tan\beta$, are given in the $\overline{DR}$ scheme at the scale $\tilde{M} = 1\,\mathrm{TeV}$.
- Gaugino/Higgsino and scalar mass matrices, rotation matrices and the corresponding angles are defined in the $\overline{DR}$ scheme at $\tilde{M}$, except for the Higgs system in which the mixing matrix is defined in the on-shell scheme, the scale parameter chosen as the light Higgs mass.
- The Standard Model input parameters of the gauge sector are chosen as G_F, α, M_Z and $\alpha_{\mathrm{s}}^{\overline{MS}}(M_Z)$. All lepton masses are defined on-shell. The t quark mass is defined on-shell; the b, c quark masses are introduced in $\overline{MS}$ at the scale of the masses themselves while taken at a renormalization scale of $2\,\mathrm{GeV}$ for the light u, d, s quarks.
- Decay widths, branching ratios and production cross sections are calculated for the set of parameters specified above.

4.2. Program repository

The repository contains links to codes grouped in several categories: scheme translation tools for definitions and relations between on-shell, $\overline{DR}$ and $\overline{MS}$ parameters; spectrum calculators from the Lagrangian parameters; calculators of various observables: decay tables, cross sections, low-energy observables, cold dark matter relics, cross sections for CDM particle searches; event generators; analysis programs to extract the Lagrangian parameters from experimental data; RGE codes; as well as some auxiliary programs and libraries.

The responsibility for developing codes and maintaining them up to the current theoretical state-of-the-art precision rests with the authors. The SLHA [33] convention is recommended for communication between the codes.

4.3. The test-bed: Reference Point SPS1a′

The SPA Convention and Project is set up to cover general SUSY scenarios. However, to perform first checks of its internal consistency and to explore the potential of such coherent data analyses a MSSM Reference Point SPS1a′ has been proposed as a testing ground. Of course, in future the SPA has to be tested in more complicated scenarios.

The roots defining the Point SPS1a′ are the mSUGRA parameters $M_{1/2} = 250\,\text{GeV}$, $M_0 = 70\,\text{GeV}$, $A_0 = -300\,\text{GeV}$ defined at the GUT scale, and $\tan\beta(\tilde{M}) = 10$, $\mu > 0$. The point is close to the original Snowmass point SPS1a [7] and to point B' of [34].

If SPS1a′, or a SUSY scenario with mass scales similar to this point, is realized in nature, a plethora of interesting channels can be exploited to extract the basic supersymmetry parameters when combining experimental information from mass distributions at LHC with measurements of decay spectra and threshold excitation curves at an e^+e^- collider with energy up to 1 TeV. Recently global analysis programs have become available [35] in which the whole set of data, masses, cross sections, branching ratios *etc.*, is exploited coherently to extract the Lagrangian parameters in the optimal way after including the available radiative corrections.

4.4. Future developments

Although current SPA studies are very encouraging, much additional work both on the theoretical as well as on the experimental side will be needed to achieve the SPA goals. In particular:

— The present level of theoretical calculations still does not match the expected experimental precision, particularly in coherent LHC+ILC analyses.

— There is no complete proof that $\overline{DR}$ scheme preserves supersymmetry and gauge invariance in all cases.

— A limited set of observables included in experimental analyses by no means exhausts the opportunities which data at LHC and at ILC are expected to provide. Most experimental analyses do not include the theoretical errors which must be improved considerably before matching the experimental standards.

— Astrophysical data play an increasingly important role in confronting supersymmetry with experiments. On the one hand the relic DM abundance imposes crucial limits on supersymmetric scenarios, on the other, the comprehensive parameter analysis of high-energy experiments should provide insight into the nature of the cold dark matter particles.

— The parameter set SPS1a′ chosen for a first study provides a benchmark for developing and testing the tools needed for a successful analysis of future SUSY data. However, neither this specific point nor the MSSM itself may be the correct model for low-scale SUSY. While versions of mSUGRA and of gaugino mediation have also been analyzed in some detail, the analyses have to be extended systematically to other possibilities. In particular, CP violation, R-parity violation, flavor violation, NMSSM and extended gauge groups are among scenarios which might be realized in the SUSY sector. The SPA conventions are general enough to cover all these scenarios.

5. Summary

Much progress has been achieved during last years. At the beginning the LHC has been considered merely as a discovery machine. However, over the years many techniques have been developed for extracting masses and couplings, and in some cases the Lagrangian parameters. Many experimental analyses are still based on lowest-order expressions. On the theory side many higher-order calculations have been completed and implemented in numerical codes. New theoretical ideas are popping up that deserve experimental analyses. To complete the task of exploring all masses and couplings of SUSY particles is probably impossible by the LHC alone. Nevertheless, even after the start of the ILC, the measurements at the LHC are useful to understand the nature of SUSY. We still need new ideas and techniques to explore fully the opportunities offered to us by the LHC. The SPA Convention and Project should prove very useful in streamlining discussions and comparisons of different calculations and experimental analyses.

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REFERENCES

[1] ALEPH, DELPHI, L3, OPAL and SLD Collaborations and LEPEW, SLDEW and SLD Heavy Flavour Working Groups, *Phys. Rep.* **427**, 257 (2006). See also J.D. Lykken, *Acta Phys. Pol. B* **38**, 325 (2007) these proceedings.

[2] Yu.A. Golfand, E.P. Likhtman, *JETP Lett.* **13**, 323 (1971); [*Pisma Zh. Eksp. Teor. Fiz.* **13**, 452 (1971)]; D.V. Volkov, V.P. Akulov, *JETP Lett.* **16**, 438 (1972); [*Pisma Zh. Eksp. Teor. Fiz.* **16**, 621 (1972)]. J. Wess, B. Zumino, *Phys. Lett.* **B49**, 52 (1974).

[3] P. Fayet, *Phys. Lett.* **B69**, 489 (1977); G.R. Farrar, P. Fayet, *Phys. Lett.* **B76**, 575 (1978).

[4] L. Girardello, M.T. Grisaru, *Nucl. Phys.* **B194**, 65 (1982).

[5] C.L. Bennett *et al.*, *Astrophys. J. Suppl.* **148**, 1 (2003); D.N. Spergel *et al.*, (WMAP Collaboration), *Astrophys. J. Suppl.* **148**, 175 (2003); D.N. Spergel *et al.*, `astro-ph/0603449`.

[6] J.R. Ellis, S. Heinemeyer, K.A. Olive, G. Weiglein, *J. High Energy Phys.* **0605**, 005 (2006).

[7] B.C. Allanach *et al.*, *Eur. Phys. J.* **C25**, 113 (2002).

[8] J. Espinosa, *Acta Phys. Pol. B* **38**, 565 (2007), these proceedings.

[9] S. Pokorski, talk given at this Conference.

[10] G.A. Blair, W. Porod, P.M. Zerwas, *Phys. Rev.* **D63**, 017703 (2001); *Eur. Phys. J.* **C27**, 263 (2003); B.C. Allanach, D. Grellscheid, F. Quevedo, *J. High Energy Phys.* **0205**, 048 (2002); G.L. Kane, J. Lykken, S. Mrenna, B.D. Nelson, L.T. Wang, T.T. Wang, *Phys. Rev.* **D67**, 045008 (2003).

[11] ATLAS Collaboration, CERN-LHCC-99-14/15 (1999).

[12] CMS Collaboration, CERN-LHCC-2006-021 (2006).

[13] M. Spiropulu, talk given at this Conference.

[14] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau, A.D. Polosa, *J. High Energy Phys.* **0307**, 001 (2003); T. Plehn, D. Rainwater, P. Skands, `hep-ph/0510144`; S. Asai, talk presented at TeV4LHV, Oct. 20–22, 2005.

[15] S. Kachru, R. Kallosh, A. Linde, S.P. Trivedi, *Phys. Rev.* **D68**, 046005 (2003).

[16] K. Choi, K.S. Jeong, K.I. Okumura, *J. High Energy Phys.* **0509**, 039 (2005); A. Falkowski, O. Lebedev, Y. Mambrini, *J. High Energy Phys.* **0511**, 034 (2005).

[17] K. Kawagoe, M.M. Nojiri, `hep-ph/0606104`.

[18] I. Hinchliffe *et al.*, *Phys. Rev.* **D55**, 5520 (1997).

[19] B.K. Gjelsten, D.J. Miller, P. Osland, *J. High Energy Phys.* **0412**, 003 (2004).

[20] M.M. Nojiri, G. Polesello, D.R. Tovey, *J. High Energy Phys.* **0603**, 063 (2006).

[21] K. Desch, J. Kalinowski, G. Moortgat-Pick, M.M. Nojiri, G. Polesello, *J. High Energy Phys.* **0402**, 035 (2004).

[22] K. Desch, J. Kalinowski, G. Moortgat-Pick, K. Rolbiecki, W.J. Stirling, `hep-ph/0607104`.

[23] G. Weiglein *et al.* [LHC/LC Study Group], `hep-ph/0410364`.

[24] J.A. Aguilar-Saavedra *et al.*, *Eur. Phys. J.* **C46**, 43 (2006).

[25] B.C. Allanach, G. Belanger, F. Boudjema, A. Pukhov, *J. High Energy Phys.* **0412**, 020 (2004).

[26] M.M. Nojiri, G. Polesello, D.R. Tovey, `hep-ph/0312317`; K. Kawagoe, M.M. Nojiri, G. Polesello, *Phys. Rev.* **D71**, 035008 (2005).

[27] H.C. Cheng, K.T. Matchev, M. Schmaltz, *Phys. Rev.* **D66**, 056006 (2002).

[28] A.J. Barr, *Phys. Lett.* **B596**, 205 (2004).

[29] J.M. Smillie, B.R. Webber, *J. High Energy Phys.* **0510**, 069 (2005); C. Athanasiou, C.G. Lester, J.M. Smillie, B.R. Webber, *J. High Energy Phys.* **0608**, 055 (2006); L.T. Wang, I. Yavin, `hep-ph/0605296`.

[30] N. Arkani-Hamed, G.L. Kane, J. Thaler, L.T. Wang, *J. High Energy Phys.* **0608**, 070 (2006).

[31] J.A. Aguilar-Saavedra *et al.*, TESLA Technical Design Report, DESY 01-011 hep-ph/0106315; T. Abe *et al.* [American LC WG], in Proceedings of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001, SLAC-R-570 hep-ex/0106055-58; T. Abe *et al.*, [Asian LC WG], KEK-Report–2001-011, hep-ph/0109166.

[32] J. Kalinowski, Proceedings of International Conference on Supersymmetry and Unification of Fundamental Interaction, SUSY02 (Hamburg 2002), hep-ph/0212388.

[33] P. Skands *et al.*, *J. High Energy Phys.* **0407**, 036 (2004).

[34] M. Battaglia *et al.*, *Eur. Phys. J.* **C33**, 273 (2004).

[35] P. Bechtle, K. Desch, P. Wienemann, *Comput. Phys. Commun.* **174**, 47 (2006); R. Lafaye, T. Plehn, D. Zerwas, hep-ph/0404282.