Complementarity of LHC and ILC

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Abstract. Two next-generation high-energy experiments, the Large Hadron Collider (LHC) and the e^+e^- International Linear Collider (ILC), are highly expected to unravel the new structure of matter and forces from the electroweak scale to the TeV scale. In this talk we give a compelling but rather descriptive review of the complementary role of LHC and ILC in drawing a comprehensive and high precision picture of the mechanism breaking the electroweak symmetries and generating mass, the unification of forces and the structure of spacetime. Supersymmetry is exploited in this description as a prototype scenario of the physics beyond the Standard Model.

PACS. 12.60.-i Models beyond the standard model – 12.60.Jv Supersymmetric models

1 Introduction

Particle physics has been very much successful in unraveling the basic laws of nature at the smallest accessible length scale and it has revealed a consistent picture, the Standard Model (SM), adequately describing the structure of matter and forces. However, many theoretical arguments and experimental observations strongly indicate that the model is incomplete and it should be embedded in a more fundamental theory, addressing a set of crucial questions to be approached experimentally at the TeV scale (Terascale): the mechanism of electroweak symmetry breaking (EWSB) and mass generation; the unification of forces, including gravity finally; and the structure of spacetime. This set of particle physics questions is intriguingly connected to the cosmology questions such as the nature of particles comprising cold dark matter (CDM) and the origin of the baryon asymmetry in the universe.

The next generation of high-energy accelerators will get access to the Terascale with a high expectation of providing decisive answers to these questions [1,2]. LHC with a c.m. energy of 14 TeV [3,4,5] will put the first springboard in 2008 for breakthrough discoveries in the EWSB sector and in the physics beyond the SM (BSM). However, the processes and the detections of new physics at LHC are extremely complicated. Therefore, a lepton facility with clean environments (and, if possible, with various facets) is required to complement this hadron machine in drawing a comprehensive and high-resolution picture of EWSB and of the BSM. ILC [6,7,8,9,10,11], which is now in the design phase, can be an excellent counterpart to LHC. The ILC energy of 500 GeV in the first phase and 1 TeV in the upgraded phase in the lepton sector is equivalent in many aspects to the higher LHC energy of about five TeV in the quark sector. Moreover, ILC covers one of the most crucial energy ranges including the characteristic EWSB scale ($v = 246$ GeV). [If the BSM scale revealed at LHC might be beyond the reach of ILC, it could be accessed later by a multi-TeV e^+e^- collider such as the Compact Linear Collider (CLIC) [12].]

There exist several world-wide studies of the LHC and ILC interplay [13,14]. In particular, the LHC/ILC Study Group, formed as a collaborative effort of the hadron and lepton collider experimental communities and theorists, has completed a very comprehensive working group report with many detailed studies of various conceivable BSM scenarios [13]. This talk will not cover all the topics unlike the report but it will give a compelling but descriptive review of the complementary role of LHC and ILC in drawing a model-independent and high-resolution picture of the new Terascale physics and revealing the fundamental theory at the scale close to the grand unification (GUT) or Planck scale. Supersymmetry (SUSY) will exclusively be considered as a BSM prototype concept in this description. For an excellent recent review for alternative scenarios, see, for example, Ref. [15].

2 Supersymmetric path

In supersymmetric theories a light Higgs boson is generated and the electroweak (EW) scale is stabilized naturally against the GUT/Planck-scale background. The presence of the supersymmetric particle spectrum is essential for a high-quality unification of the three SM gauge couplings at a high energy scale [16,17,18,19]. It offers a natural CDM candidate. Moreover, local SUSY provides a rationale for gravity by demanding the existence of massless spin-2 gravitons. In short, if realized in nature, SUSY will have an impact across all microscopic and cosmological scales.

There is no firm prediction yet for the SUSY mass scale. However, there are important direct constraints

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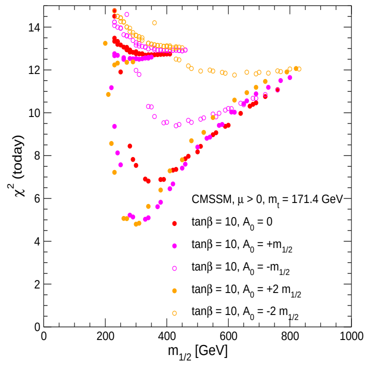

Fig. 1. The combined χ^2 function for electroweak precision observables and B-physics observables; Ref. [26].

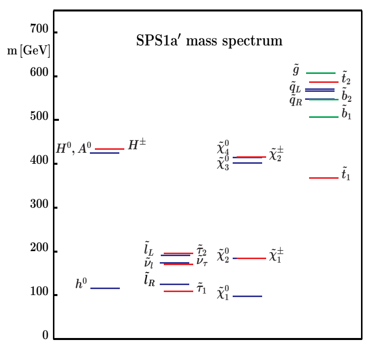

Fig. 2. Mass spectrum of supersymmetric particles and Higgs bosons in the reference point SPS1a′; Ref. [27].

on the mass scale due to the absence of sparticles at LEP and the Tevatron, and also indirect constraints from the LEP lower limit of 114 GeV on the Higgs mass [20], the reasonable agreement of SM calculations of $b \to s\gamma$ [21,22], the BNL measurement of the anomalous magnetic moment of the muon a_μ [23,24], and also from the measurement of the CDM density at WMAP [25]. As shown in Fig. 1, a global fit to precision EW and B-decay observables indicates a fairly low-mass spectrum for moderate values of the Higgs mixing parameter $\tan\beta$ in the constrained minimal supersymmetric SM (CMSSM) [26]. In the favorable case several non-colored supersymmetric particles such as lighter neutralinos and sleptons should be observed at ILC in the first phase with its c.m. energy of 500 GeV and even the heavier non-colored particles and the lighter top squark in the upgraded phase with its c.m. energy of 1 TeV. The spectrum corresponding to a parameter set with close to maximal possibility is depicted in Fig. 2. This spectrum had been chosen as a benchmark set for a minimal supergravity scenario in the SPS1a′ project [27].

LHC and ILC can provide us with a perfectly combined tool for exploring SUSY [13]. The heavy colored supersymmetric particles, squarks and gluinos, can be discovered for masses up to 3 TeV with large rates at LHC. The properties of the potentially lighter non-colored particles, charginos, neutralinos, sleptons and Higgs bosons, can be studied very precisely at ILC by exploiting, in particular, beam polarizations. Once the properties of the light particles are determined precisely at ILC, the heavier particles produced at LHC can subsequently be studied in the cascade decays with much greater precision. Based on the coherent LHC and ILC analyses we can then take the following supersymmetric path by

- measuring the masses and mixings of the newly produced particles, their decay widths and branching ratios, their production cross sections, etc;
- verifying that there are indeed the superpartners of the SM particles by determining their spin and parity, gauge quantum numbers and their couplings;
- reconstructing the low energy Lagrangian with the smallest number of assumptions, i.e. as model independently as possible;
- and unraveling the fundamental SUSY breaking mechanism and shedding light on the physics at the very high energy (GUT or Planck) scale,

from the EW scale to GUT/Planck scale, on one side, for the reconstruction of the fundamental SUSY theory near the Planck scale and, on the other side, for the connection of particle physics with cosmology.

3 Higgs bosons

In SUSY theories the Higgs sector includes at least two iso-doublet scalar fields so that at least five more physical particles are predicted [28]. In the minimal supersymmetric SM (MSSM) the mass of the lightest neutral scalar Higgs particle h is bounded above to about 140 GeV, while the masses of the heavy neutral scalar and pseudoscalar Higgs bosons, H and A, and the charged Higgs bosons, $H^\pm$, may range from the EW scale to a multi-TeV scale. The upper bound on the lightest Higgs mass is relaxed to about 200 GeV in more general scenarios if the fields remain weakly interacting up to the Planck scale.

3.1 MSSM Higgs Bosons

While the light Higgs boson h can be detected at LHC in the full range of the M_A and $\tan\beta$ parameter space, the heavy Higgs bosons cannot be detected in a wedge centered around the medium mixing angle $\tan\beta \sim 7$ and opening from the masses of about 200 GeV up to higher values [3,29]. This region can however be covered considerably by ILC.

At ILC the search and study of the light Higgs boson h follows the pattern very similar to the SM Higgs boson in most of the parameter space and the heavy Higgs bosons are produced in mixed pairs at ILC: $e^+e^- \to HA$ and H^+H^-. Therefore, the wedge can be covered by pair production in e^+e^- collisions for masses $M_{H,A} \leq \sqrt{s}/2$, i.e., up to 500 GeV in the TeV phase of the ILC machine, cf. Fig. 3 [30]. Moreover, single production in photon-photon collisions, $\gamma\gamma \to H$ and A, can cover the wedge up to Higgs masses of

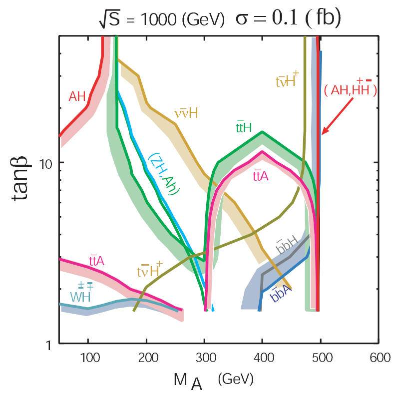

Fig. 3. Cross section contours of various heavy MSSM Higgs production processes in the $M_A/\tan\beta$ plane for $\sqrt{s} = 1$ TeV; Ref. [30].

800 GeV if a fraction of 80% of the total e^+e^- energy is transferred to the $\gamma\gamma$ system by Compton backscattering of laser light [31].

After the Higgs particles are discovered, it must experimentally be established that the Higgs mechanism is responsible indeed for breaking the electroweak symmetries and for generating the masses of the fundamental SM particles. This requires profiling the Higgs bosons precisely. First model-independent analyses of the properties can be performed at LHC by measuring the Higgs masses, the ratios of some Higgs couplings and the bounds on couplings [32].

However, the truly model-independent and high-resolution determination of the profile of the light Higgs boson h – the mass, the spin of the particle, its couplings and the trilinear self coupling – can be made at ILC with the clear signals of Higgs events above small backgrounds in the processes such as Higgs-strahlung, $e^+e^- \to Zh$, and WW fusion, $e^+e^- \to \bar{\nu}\nu h$, and in the process of double Higgs production, $e^+e^- \to Zhh$ and $\bar{\nu}\nu hh$ [28].

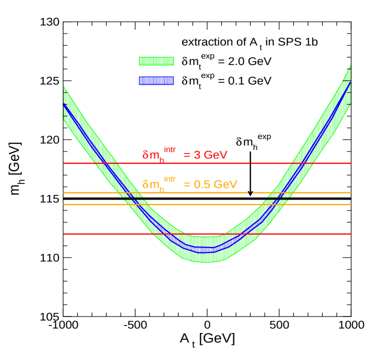

Fig. 4. Extracting the trilinear coupling A_t from radiative corrections to the light MSSM Higgs mass; Ref. [33].

Such high-precision measurements of the light Higgs mass can be exploited to determine parameters in the SUSY theory which are very difficult to measure directly. For instance, by evaluating quantum corrections, the top quark trilinear coupling A_t can be calculated from the Higgs mass, Fig. 4. For an error on the top quark mass of $\delta m_t = 100$ MeV and an error on the Higgs mass of $\delta m_h = 50$ MeV, A_t can be determined at an accuracy of about 10% [33].

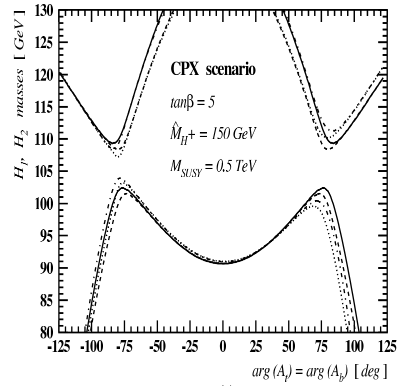

Fig. 5. Extracting the trilinear coupling A_t from radiative corrections to the light MSSM Higgs mass; Ref. [40].

3.2 CP violation in the MSSM Higgs sector

In the general MSSM [34], the gaugino mass parameters M_i $(i = 1, 2, 3)$, the higgsino mass parameter μ, and the trilinear couplings A_f can be complex so that they can induce explicit CP violation in various ways in the model. Their physical rephasing-invariant combinations affect sparticle masses and couplings through their mixing, induce CP violating mixing in the Higgs sector through radiative corrections, influence CP even observables such as cross sections and also lead to interesting CP odd asymmetries at colliders. As a result, although stringently constrained by low energy observables like electric dipole moments (EDMs), the non-trivial CP phases can significantly influence the collider phenomenology of Higgs and SUSY particles and also the properties of neutralino CDM [35,36,37].

Referring to the CPNSH report [35] for an extensive discussion of CP violation in supersymmetric theories, we simply mention here two examples of Higgs-sector CP violation. The lightest Higgs boson H_1 without definite CP parity can couple very weakly to the gauge bosons so that the state could have escaped detection at LEP2 [38] and the heavy Higgs states H and A can exhibit CP-violating resonant mixing phenomena when two states are degenerate in mass in the decoupling regime [39]. One example of the impact of the CP-violating Higgs mixing on the Higgs mass spectrum is shown in Fig. 5 as a function of the phase of the coupling A_t [40]. The other example for studying the CP-violating resonant mixing of two heavy neutral Higgs bosons is provided by $\gamma\gamma$-Higgs formation in polarized beams. As shown in Fig. 6, the CP violation due to resonant H/A mixing can directly be probed via the CP-odd asymmetry $A_{hel} = (\sigma_{++} - \sigma_{--})/(\sigma_{++} + \sigma_{--})$ constructed with circular photon polarization [39].

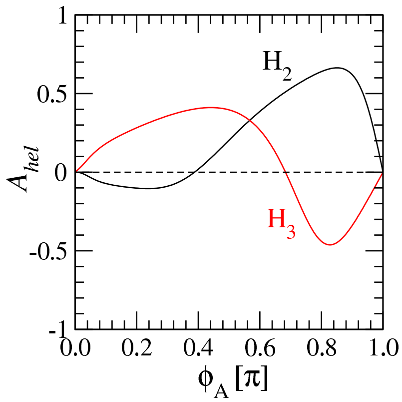

Fig. 6. The CP-odd asymmetry A_{hel} at the pole of H_2 and H_3 as a function of the rephasing invariant phase ϕ_A; Ref. [39].

3.3 Extended Higgs sector

A large variety of BSM theories such as GUT theories and string theories suggest extended gauge and Higgs sectors with additional gauge bosons and Higgs bosons beyond the minimal set of the MSSM [41,42,43,44,45].

For example, the next-to-MSSM (NMSSM), the simplest extension of the MSSM, introduces a complex iso-scalar field, generating a weak scale higgsino mass parameter μ. The NMSSM Higgs sector is thus extended to include an additional scalar and a pseudoscalar. In a large area of the parameter space the NMSSM Higgs sector reduces to the MSSM one but there is a possibility that one of the neutral Higgs particles, in general the lightest pseudoscalar A_1, is very light enough for the light scalar H_1 to decay into pairs of A_1 bosons subsequently decaying to b-quarks and τ leptons, with a large branching fraction. Nevertheless, a no-lose theorem for discovering at least one Higgs boson has been established for ILC. The situation is less clear for LHC [46], although the lightest scalar state H_1 may be detected at LHC via WH_1 and ZH production [47].

4 Supersymmetric particles

For illustration we adopt the parameters of the minimal supergravity reference point SPS1a′ [27]. It is characterized by the following values of the soft parameters at the GUT scale: $M_{1/2} = 250$ GeV, $M_0 = 70$ GeV, $A_0 = -300$ GeV, sign$(\mu) = +$ and $\tan\beta = 10$ where $M_{1/2}$, M_0, A_0 and μ denote the universal gaugino mass, the universal scalar mass, the universal trilinear coupling and the higgsino mass parameter. The modulus of the higgsino mass parameter is fixed by requiring radiative electroweak symmetry breaking [48, 49,50,51,52] so that $\mu = +396$ GeV. As shown by the sparticle and Higgs spectrum in Fig. 2, the squarks and gluinos can be studied very well at LHC and the non-colored charginos and neutralinos, sleptons and Higgs bosons can be analyzed partly at LHC and precisely at ILC operating at a c.m. energy up to 1 TeV.

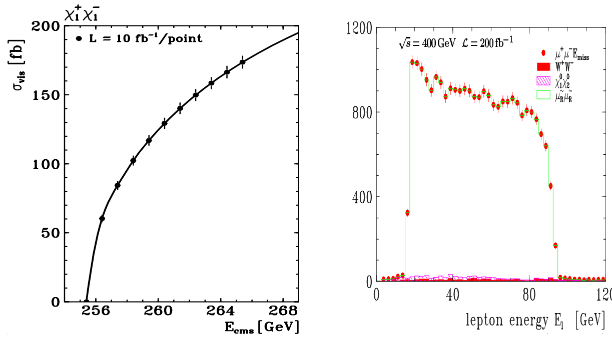

Fig. 7. Left: Mass measurement in chargino $\tilde{\chi}_1^+\tilde{\chi}_1^-$ pair production; Right: Smuon and neutralino edges in two-body smuon decays, $\tilde{\mu}_R^\pm \to \mu^\pm\tilde{\chi}_1^0$; Ref [54].

Table 1. Accuracies for representative mass measurements of SUSY particles in individual LHC, ILC and coherent LHC/ILC analyses for the point SPS1a′ [mass units in GeV]; Ref. [27].

Particles	Mass	"LHC"	"ILC"	"LHC+ILC"
h^0	116.0	0.25	0.05	0.05
H^0	425.0		1.5	1.5
$\tilde{\chi}_1^0$	97.7	4.8	0.05	0.05
$\tilde{\chi}_2^0$	183.9	4.7	1.2	0.08
$\tilde{\chi}_4^0$	413.9	5.1	3-5	2.5
$\tilde{\chi}_1^\pm$	183.7		0.55	0.55
$\tilde{e}_R$	125.3	4.8	0.05	0.05
$\tilde{e}_L$	189.9	5.0	0.18	0.18
$\tilde{\tau}_1$	107.9	5-8	0.24	0.24
$\tilde{q}_R$	547.2	7-12	-	5-11
$\tilde{q}_L$	564.7	8.7	-	4.9
$\tilde{t}_1$	366.5		1.9	1.9
$\tilde{b}_1$	506.3	7.5	-	5.7
$\tilde{g}$	607.1	8.0	-	6.5

4.1 Properties of supersymmetric particles

At LHC, the masses can be obtained by analyzing edge effects in the cascade decay spectra, cf. Ref. [53]. An ideal chain is a sequence of two-body decays: $\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}_R \ell q \to \tilde{\chi}_1^0 \ell\ell q$. The kinematic edges and thresholds predicted in the invariant mass distributions of the two leptons and the jet determine the masses in a model independent way. The determined four particle masses are used subsequently as input for other decay chains like $\tilde{g} \to \tilde{b}_1 b \to \tilde{\chi}_2^0 bb$ and the shorter chains $\tilde{q}_R \to q\tilde{\chi}_1^0$ and $\tilde{\chi}_4^0 \to \tilde{\ell}\ell$. However, there are residual ambiguities and the strong correlations between the heavier masses and the lightest supersymmetric particle (LSP).

At ILC very precise mass values can be extracted from threshold scans and decay spectra [54]. The excitation curves for chargino $\tilde{\chi}_{1,2}^\pm$ production in S-waves rise steeply with the velocity of the particles near threshold and they are thus very sensitive to the mass values, the left panel of Fig. 7. The same holds true for mixed chiral selectron pairs in $e^+e^- \to \tilde{e}_R^+\tilde{e}_L^-$ and for diagonal pairs in $e^-e^- \to \tilde{e}_R^-\tilde{e}_R^-, \tilde{e}_L^-\tilde{e}_L^-$ [55,56]. Other scalar fermions as well as neutralinos are produced in P-waves with a less steep threshold behavior proportional to the third power of the velocity. An important information on the mass of the LSP such as the lightest neutralino $\tilde{\chi}_1^0$ can be obtained from the sharp edges of two-body decay spectra such as $\tilde{\ell}_R \to \ell\tilde{\chi}_1^0$, the right panel of Fig. 7 [54]. The accuracy in the measurement of the LSP mass can be improved at ILC by two orders of magnitude compared with LHC; Tab. 1.

The values of typical mass parameters and their related measurement errors are presented in Tab. 1: "LHC" from LHC analyses and "ILC" from ILC analyses. The fourth column "LHC+ILC" represents the corresponding errors if the experimental analyses are performed coherently [27].

Determining the spin of new particles is an important method to clarify the nature of the particles and the underlying theory. This determination is crucial to distinguish the supersymmetric interpretation of new particles from other models. The measurement of the spins in particle cascades at LHC is quite involved [57,58,59]. In contrast spin measurement at ILC is straightforward [60,61]. The $\sin^2\theta$ law for the angular distribution in the production of sleptons (for selectrons close to threshold) is a unique signature of the fundamental spin-zero character; the P-wave onset of the excitation curve is a necessary but not sufficient condition; Fig. 8. In contrast, neither the onset of the excitation curves near threshold nor the angular distribution in the production processes provide unique signals of the spin of charginos and neutralinos. However, decay angular distributions of polarized charginos/neutralinos could provide an unambiguous determination of the spin-1/2 character of the particles albeit at the expense of more involved experimental analyses [61]. [Quantum interference among helicity amplitudes, reflected on azimuthal angle distributions, may also be used to determine spin in a model-independent way [62].]

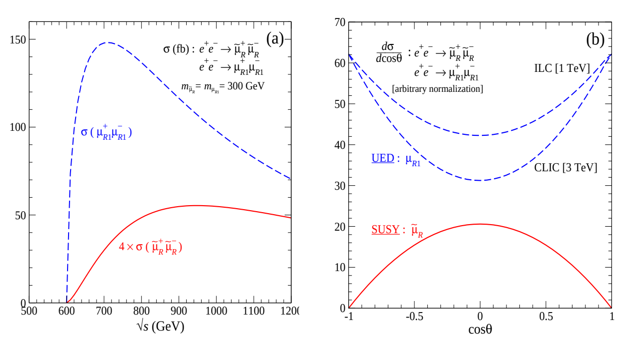

Fig. 8. The threshold excitation (a) and the angular distribution (b) in the case of smuons in the MSSM and the first Kaluza-Klein muons in an adopted model of universal extra dimensions in pair production at ILC; For details, see Ref. [61].

Mixing parameters must be extracted from measurements of cross sections and polarization asymmetries. In the production of charginos and neutralinos, both diagonal and mixed pairs can be exploited: $e^+e^- \to \tilde{\chi}_i^+\tilde{\chi}_j^-$ $[i,j=1,2]$ [63,64,65] and $\tilde{\chi}_i^0\tilde{\chi}_j^0$ $[i,j=1,..,4]$ [66]. The production cross sections for charginos are binomials in $\cos 2\phi_{L,R}$ where $\phi_{L,R}$ are the mixing angles rotating current to mass eigenstates. Using polarized electron and positron beams, the mixings can be determined in a model-independent way, Fig. 9. The same procedures can be applied to determine the mixings in the sfermion sector [67,68,69]. The production cross sections for stop particle pairs, $e^+e^- \to \tilde{t}_i\tilde{t}_j^*$ $[i,j=1,2]$, depend on the stop mixing angle $\theta_{\tilde{t}}$ which can be determined with high accuracy by use of polarized electron beams [69].

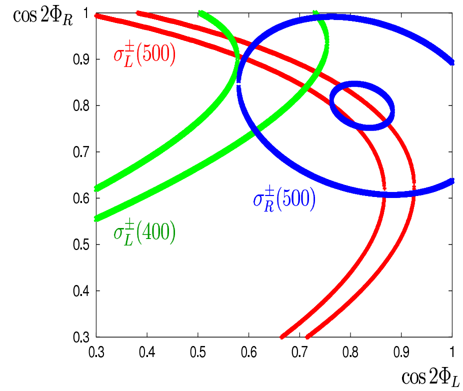

Fig. 9. Contours for the $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ production cross section for polarized $e^\pm$ beams at $\sqrt{s} = 400$ and 500 GeV; Ref. [65].

SUSY predicts the identity of Yukawa and gauge couplings among supersymmetric partners for gauge bosons and gauginos, and for fermions and their scalar partners. On one hand the fundamental $\mathrm{SU(3)}_C$ relation can be studied experimentally at LHC through pair production of squarks partly mediated by gluino t-channel exchanges [70,71]. On the other hand the $\mathrm{SU(2)}_L$ and $\mathrm{U(1)}_Y$ relations can be confirmed experimentally at ILC through pair production of charginos and neutralinos which is partly mediated by the exchange of sneutrinos and selectrons in the t-channel [66], as well as selectron and sneutrino production which is partly mediated by neutralino and chargino exchanges [56]. The separation of the electroweak SU(2) and U(1) couplings is also possible if polarized electron beams are available. Of course the analysis for confirming the identity of Yukawa and gauge couplings should be performed by taking into account the prior measurements of the masses and/or mixing parameters of the particles exchanged in the t-channel.

4.2 Fundamental theory

Combining the information from LHC on the generally heavy colored particles with the information from

Table 2. Excerpt of extracted SUSY Lagrangian mass and Higgs parameters at the Terascale in the reference point SPS1a′ [mass units in GeV]; Ref. [27].

Parameter	SPS1a′ value	Fit error [exp]
M_1	103.3	0.1
M_2	193.2	0.1
M_3	571.7	7.8
μ	396.0	1.1
M_{L_1}	181.0	0.2
M_{E_1}	115.7	0.4
M_{L_3}	179.3	1.2
M_{Q_1}	525.8	5.2
M_{D_1}	505.0	17.3
M_{Q_3}	471.4	4.9
m_A	372.0	0.8
A_t	-565.1	24.6
$\tan\beta$	10.0	0.2

ILC on the generally lighter non-colored particle sector (and later from CLIC on heavier states) will generate a model-independent and high-precision picture of SUSY at the Terascale. The picture may subsequently serve as a solid platform for the reconstruction of the fundamental SUSY theory at a high scale, potentially close to the Planck scale, and for the analysis of the microscopic mechanism of SUSY breaking [72,73]. The experimental accuracies expected at the percent down to the per-mil level must be matched on the theoretical side. This demands a well-defined framework for the calculational schemes in perturbation theory as well as for the input parameters like a recently proposed scheme called Supersymmetry Parameter Analysis (SPA) [27].

If SPS1a′ or a similar SUSY parameter set is realized in nature, various channels can be exploited to extract the basic Terascale SUSY parameters at LHC and ILC. The data analysis performed coherently for LHC and ILC is shown to give rise to a very precise picture of the supersymmetric particle spectrum. Running global analysis programs with the whole set of data enables us to coherently extract the Lagrangian parameters in the optimal way after including the available radiative corrections [74,75,76, 77,78]. The present quality of such an analysis can be judged from the results shown in Tab. 2.

Based on the parameters extracted at the Terascale we can reconstruct the fundamental SUSY theory and the related microscopic picture of the SUSY breaking mechanism [72]. The experimental information is exploited to the maximum extent possible in the bottom-up approach in which the extrapolation from the Terascale to the GUT/Planck scale is performed by the renormalization group (RGE) evolution of all parameters, with the GUT scale defined by the unification point of the two electroweak couplings.

Typical examples for the evolution of the gaugino and scalar mass parameters are presented in Fig. 10. While the determination of the high-scale parameters in the gaugino and higgsino sector, as well as in the

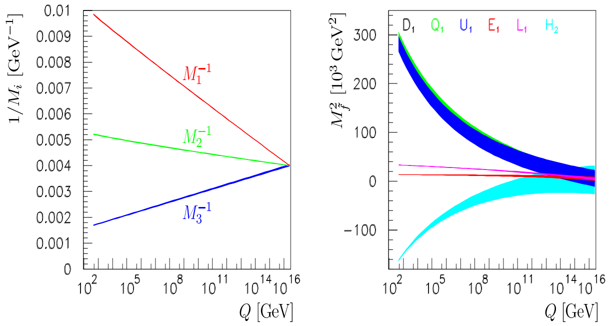

Fig. 10. Running of the gaugino and scalar mass parameters as a function of the scale Q in SPS1a′. Only experimental errors are taken into account; theoretical errors are assumed to be reduced to the same size in the future; Ref. [72].

non-colored slepton sector, is very precise, the picture of the colored scalar and Higgs sectors is still coarse so that considerable efforts should be made to refine it considerably. If the structure of the theory at the GUT scale was known a priori and merely the experimental determination of the high scale parameters were lacking, then the top down-approach would lead to a very precise parametric picture at the Terascale.

So far, we have only considered the MSSM, in particular the parameter set SPS1a′, as a benchmark scenario for judging the coherent capabilities of LHC and ILC experiments 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. Various extended models have therefore to be investigated. In particular, models which incorporate the right-handed neutrino sector to accommodate the complex structure observed in the neutrino sector must be scrutinized in a systematic way [79]. Furthermore, CP violation, R-party violation [80], flavor violation [81], NMSSM [82,83] and/or extended gauge groups [45,84] are among the paths that nature may have taken. It is, therefore, strongly recommended that the analysis conventions and methods be so general that they can be applied to all those BSM scenarios as well.

4.3 SUSY dark matter

Since there is no proper CDM particle candidate in the SM, the presence of the CDM is a clear evidence for physics beyond the SM. In SUSY theories with R-parity the LSP is absolutely stable and represents a good CDM candidate [25]. In particular, the lightest neutralino is considered to be the prime candidate, but other interesting possibilities are the axino and the gravitino.

In certain areas of the SUSY parameter space with the $\tilde{\chi}_1^0$ relic density in the range required by WMAP, SUSY particles can be produced abundantly at LHC and ILC. However, to determine the predicted WMAP relic density, we must have detailed knowledge not only of the LSP properties but also of all other particles contributing to the LSP pair annihilation cross section. To quantify the prospects for determining the neutralino CDM relic density at ILC as well as LHC, and the connection of ILC with cosmology, four benchmark mSUGRA scenarios called LCC points and compatible with WMAP data have been proposed [85]. The ILC measurements at $\sqrt{s} = 0.5$ TeV and 1 TeV for various sparticle masses and mixings in the scenarios, taking into account LHC data, are compared to those which can be obtained using LHC data (after a qualitative identification of the model). As can be seen in Fig. 11 for two LCC points, the LCC1 "bulk" point and the LCC2 "focus-point" point, the gain in sensitivity by combining LHC and ILC is spectacular.

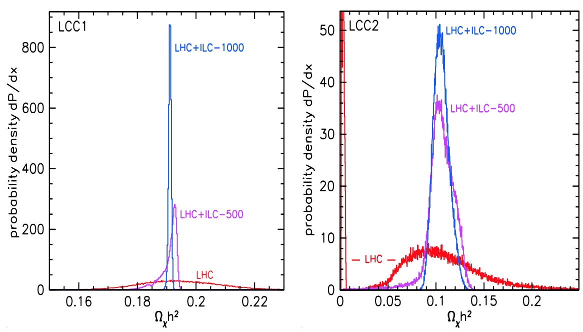

Fig. 11. Probability distribution of predictions of $\Omega_\chi h^2$ for the LCC1 "bulk" point and the LCC2 "focus-point" point from measurements at ILC with $\sqrt{s} = 0.5$ and 1 TeV, and LHC (after qualitative identification of the model); Ref. [85]

In supergravity models the gravitino $\tilde{G}$ itself may be the LSP, building up the dominant CDM component [86,87,88,89]. In such a scenario, with a gravitino mass in the range of 100 GeV, the lifetime of the next-to-LSP (NLSP) can become macroscopic as the gravitino coupling is only of gravitational strength. The lifetime of the NLSP $\tilde{\tau}$ can extend up to several months, suggesting special experimental efforts to catch the long-lived $\tilde{\tau}$'s and to measure their lifetime [90,91,92,93]. Tau slepton pair production at ILC determines the $\tilde{\tau}$ mass and the observation of the τ energy in the $\tilde{\tau}$ decay determines the gravitino mass. The measurement of the lifetime can subsequently be exploited to determine the Planck scale, a unique opportunity in a laboratory experiment.

5 Conclusions

The next generation of high energy experiments, LHC and ILC (and also CLIC later), will usher us into the Terascale, opening a new territory which is highly expected to be full of ground-breaking discoveries. The physics programme of both LHC and ILC in exploring this microscopic world will be very rich with their unique characteristics depending on the BSM physics scenario realized in nature. Furthermore, as demonstrated by dedicated studies using the SUSY models, the physics potential of LHC and ILC can significantly be extended by coherent or/and "concurrent" running of both machines.

In summary, the LHC and ILC experiments with different advantages and capabilities can contribute coherently and complementarily to solutions of key questions in particle physics and cosmology. Eventually both experiments can provide us with a comprehensive and high-resolution picture not only of SUSY but also of any alternative scenario, serving as a telescope to unification of matter and interactions, and connection of particle physics and cosmology.

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References

1. F. Wilczek, arXiv:0708.4236 [hep-ph] and talk at this conference.
2. J. Ellis, arXiv:0710.4959 [hep-ph] and talk at this conference.
3. L. Evans, talk at this conference.
4. ATLAS TDR, CERN/LHCC/99/15.
5. CMS TDR, CERN/LHCC/2006-021.
6. H. Murayama and M. E. Peskin, Ann. Rev. Nucl. Part. Sci. **46** (1996) 533 [arXiv:hep-ex/9606003].
7. E. Accomando *et al.* [ECFA/DESY LC Physics Working Group], Phys. Rept. **299** (1998) 1 [arXiv:hep-ph/9705442].
8. K. Abe *et al.* [ACFA Linear Collider Working Group], arXiv:hep-ph/0109166.
9. T. Abe *et al.* [American Linear Collider Working Group], arXiv:hep-ex/0106055, hep-ex/0106056, hep-ex/0106057 and hep-ex/0106058.
10. J. A. Aguilar-Saavedra *et al.* [ECFA/DESY LC Physics Working Group], arXiv:hep-ph/0106315.
11. W. Kilian and P. M. Zerwas, arXiv:hep-ph/0601217.
12. E. Accomando *et al.* [CLIC Physics Working Group], arXiv:hep-ph/0412251.
13. G. Weiglein *et al.* [LHC/LC Study Group], Phys. Rept. **426** (2006) 47 [arXiv:hep-ph/0410364].
14. A. Djouadi, J. Lykken, K. Monig, Y. Okada, M. J. Oreglia and S. Yamashita, arXiv:0709.1893 [hep-ph].
15. H. C. Cheng, arXiv:0710.3407 [hep-ph] and talk at this conference.
16. U. Amaldi, W. de Boer and H. Furstenau, Phys. Lett. B **260** (1991) 447.
17. J. R. Ellis, S. Kelley and D. V. Nanopoulos, Phys. Lett. B **260** (1991) 131.
18. C. Giunti, C. W. Kim and U. W. Lee, Mod. Phys. Lett. A **6** (1991) 1745.
19. P. Langacker and M. x. Luo, Phys. Rev. D **44** (1991) 817.

20. J. Alcaraz *et al.* [ALEPH Collaboration], arXiv:hep-ex/0612034.
21. M. Misiak *et al.*, Phys. Rev. Lett. **98** (2007) 022002 [arXiv:hep-ph/0609232].
22. T. Becher and M. Neubert, Phys. Rev. Lett. **98** (2007) 022003 [arXiv:hep-ph/0610067].
23. A. Czarnecki, talk at this conference.
24. S. Heinemeyer, arXiv:0710.3022 [hep-ph].
25. K. A. Olive, arXiv:0709.3303 [hep-ph] and talk at this conference.
26. J. R. Ellis, S. Heinemeyer, K. A. Olive, A. M. Weber and G. Weiglein, JHEP **0708** (2007) 083 [arXiv:0706.0652 [hep-ph]]; G. Weiglein, arXiv:0711.0200 [hep-ph] and talk at this conference.
27. J. A. Aguilar-Saavedra *et al.*, Eur. Phys. J. C **46** (2006) 43 [arXiv:hep-ph/0511344].
28. For a review, see, for example, A. Djouadi, talk at this conference.
29. S. Heinemeyer, talk at this conference.
30. S. Kiyoura, S. Kanemura, K. Odagiri, Y. Okada, E. Senaha, S. Yamashita and Y. Yasui, arXiv:hep-ph/0301172.
31. M. M. Muhlleitner, M. Kramer, M. Spira and P. M. Zerwas, Phys. Lett. B **508** (2001) 311 [arXiv:hep-ph/0101083].
32. M. Duhrssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein and D. Zeppenfeld, Phys. Rev. D **70** (2004) 113009 [arXiv:hep-ph/0406323].
33. S. Heinemeyer, W. Hollik and G. Weiglein, Phys. Rept. **425** (2006) 265 [arXiv:hep-ph/0412214].
34. For a review of the general MSSM, see,e.g., D. J. H. Chung, L. L. Everett, G. L. Kane, S. F. King, J. D. Lykken and L. T. Wang, Phys. Rept. **407** (2005) 1 [arXiv:hep-ph/0312378].
35. E. Accomando *et al.*, arXiv:hep-ph/0608079.
36. T. Ibrahim and P. Nath, arXiv:0705.2008 [hep-ph].
37. S. Kraml, arXiv:0710.5117 [hep-ph] and talk at this conference.
38. S. Schael *et al.* [ALEPH Collaboration], Eur. Phys. J. C **47** (2006) 547 [arXiv:hep-ex/0602042].
39. S. Y. Choi, J. Kalinowski, Y. Liao and P. M. Zerwas, Eur. Phys. J. C **40** (2005) 555 [arXiv:hep-ph/0407347].
40. M. S. Carena, J. R. Ellis, A. Pilaftsis and C. E. M. Wagner, Nucl. Phys. B **625** (2002) 345 [arXiv:hep-ph/0111245].
41. D. J. Miller, R. Nevzorov and P. M. Zerwas, Nucl. Phys. B **681** (2004) 3 [arXiv:hep-ph/0304049].
42. U. Ellwanger, J. F. Gunion and C. Hugonie, JHEP **0502** (2005) 066 [arXiv:hep-ph/0406215].
43. R. Dermisek and J. F. Gunion, Phys. Rev. Lett. **95** (2005) 041801 [arXiv:hep-ph/0502105].
44. V. Barger, P. Langacker, H. S. Lee and G. Shaughnessy, Phys. Rev. D **73** (2006) 115010 [arXiv:hep-ph/0603247].
45. S. F. King, S. Moretti and R. Nevzorov, Phys. Rev. D **73** (2006) 035009 [arXiv:hep-ph/0510419].
46. U. Ellwanger, J. F. Gunion and C. Hugonie, JHEP **0507** (2005) 041 [arXiv:hep-ph/0503203].
47. K. m. Cheung, J. Song and Q. S. Yan, arXiv:0710.1997 [hep-ph] and K. m. Cheung, talk at this conference.
48. K. Inoue, A. Kakuto, H. Komatsu and S. Takeshita, Prog. Theor. Phys. **68** (1982) 927 [Erratum-ibid. **70** (1983) 330]; **71** (1984) 413.
49. L. E. Ibanez and G. G. Ross, Phys. Lett. B **110** (1982) 215.
50. L. E. Ibanez, Phys. Lett. B **118** (1982) 73.
51. J. R. Ellis, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. B **121** (1983) 123.
52. L. Alvarez-Gaume, J. Polchinski and M. B. Wise, Nucl. Phys. B **221** (1983) 495.
53. B. K. Gjelsten, D. J. Miller and P. Osland, JHEP **0412** (2004) 003 [arXiv:hep-ph/0410303]; JHEP **0506** (2005) 015 [arXiv:hep-ph/0501033].
54. H. U. Martyn, arXiv:hep-ph/0302024.
55. J. L. Feng and M. E. Peskin, Phys. Rev. D **64** (2001) 115002 [arXiv:hep-ph/0105100].
56. A. Freitas, A. von Manteuffel and P. M. Zerwas, Eur. Phys. J. C **34** (2004) 487 [arXiv:hep-ph/0310182]; Eur. Phys. J. C **40** (2005) 435 [arXiv:hep-ph/0408341].
57. A. J. Barr, Phys. Lett. B **596** (2004) 205 [arXiv:hep-ph/0405052].
58. A. Datta, K. Kong and K. T. Matchev, Phys. Rev. D **72** (2005) 096006 [Erratum-ibid. D **72** (2005) 119901] [arXiv:hep-ph/0509246].
59. C. Athanasiou, C. G. Lester, J. M. Smillie and B. R. Webber, JHEP **0608** (2006) 055 [arXiv:hep-ph/0605286]; arXiv:hep-ph/0606212.
60. M. Battaglia, A. Datta, A. De Roeck, K. Kong and K. T. Matchev, JHEP **0507** (2005) 033 [arXiv:hep-ph/0502041].
61. S. Y. Choi, K. Hagiwara, H. U. Martyn, K. Mawatari and P. M. Zerwas, Eur. Phys. J. C **51** (2007) 753 [arXiv:hep-ph/0612301]; P. M. Zerwas, talk at this conference.
62. M. R. Buckley, H. Murayama, W. Klemm and V. Rentala, arXiv:0711.0364 [hep-ph].
63. S. Y. Choi, A. Djouadi, H. S. Song and P. M. Zerwas, Eur. Phys. J. C **8** (1999) 669 [arXiv:hep-ph/9812236].
64. S. Y. Choi, A. Djouadi, M. Guchait, J. Kalinowski, H. S. Song and P. M. Zerwas, Eur. Phys. J. C **14** (2000) 535 [arXiv:hep-ph/0002033].
65. K. Desch, J. Kalinowski, G. A. Moortgat-Pick, M. M. Nojiri and G. Polesello, JHEP **0402** (2004) 035 [arXiv:hep-ph/0312069].
66. S. Y. Choi, J. Kalinowski, G. A. Moortgat-Pick and P. M. Zerwas, Eur. Phys. J. C **22** (2001) 563 [Addendum-ibid. C **23** (2002) 769] [arXiv:hep-ph/0108117].
67. M. M. Nojiri, K. Fujii and T. Tsukamoto, Phys. Rev. D **54** (1996) 6756 [arXiv:hep-ph/9606370].
68. E. Boos, H. U. Martyn, G. A. Moortgat-Pick, M. Sachwitz, A. Sherstnev and P. M. Zerwas, Eur. Phys. J. C **30** (2003) 395 [arXiv:hep-ph/0303110].
69. A. Finch, H. Nowak and A. Sopczak, arXiv:hep-ph/0211140.
70. A. Freitas and P. Z. Skands, JHEP **0609** (2006) 043 [arXiv:hep-ph/0606121].
71. A. Freitas, P. Z. Skands, M. Spira and P. M. Zerwas, JHEP **0707** (2007) 025 [arXiv:hep-ph/0703160]; A. Freitas, talk at this conference.
72. G. A. Blair, W. Porod and P. M. Zerwas, Eur. Phys. J. C **27** (2003) 263 [arXiv:hep-ph/0210058].
73. S. Raby, arXiv:0710.2891 [hep-ph] and talk at this conference.
74. B. Allanach, talk at this conference.
75. R. Lafaye, T. Plehn and D. Zerwas, arXiv:hep-ph/0404282.

76. P. Bechtle, K. Desch and P. Wienemann, Comput. Phys. Commun. **174** (2006) 47 [arXiv:hep-ph/0412012].
77. P. Bechtle, K. Desch, W. Porod and P. Wienemann, Eur. Phys. J. C **46** (2006) 533 [arXiv:hep-ph/0511006]; P. Bechtle, talk at this conference.
78. R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, arXiv:0709.3985 [hep-ph]; M. Rauch, R. Lafaye, T. Plehn and D. Zerwas, arXiv:0710.2822 [hep-ph].
79. A. Freitas, W. Porod and P. M. Zerwas, Phys. Rev. D **72** (2005) 115002 [arXiv:hep-ph/0509056].
80. R. Barbier *et al.*, Phys. Rept. **420** (2005) 1 [arXiv:hep-ph/0406039].
81. A. Masiero, talk at this conference; G. W. S. Hou, arXiv:0710.5424 [hep-ex] and talk at this conference.
82. U. Ellwanger, M. Rausch de Traubenberg and C. A. Savoy, Phys. Lett. B **315** (1993) 331 [arXiv:hep-ph/9307322].
83. S. Y. Choi, D. J. Miller and P. M. Zerwas, Nucl. Phys. B **711** (2005) 83 [arXiv:hep-ph/0407209].
84. S. Y. Choi, H. E. Haber, J. Kalinowski and P. M. Zerwas, Nucl. Phys. B **778** (2007) 85 [arXiv:hep-ph/0612218].
85. E. A. Baltz, M. Battaglia, M. E. Peskin and T. Wizansky, Phys. Rev. D **74** (2006) 103521 [arXiv:hep-ph/0602187].
86. H. Pagels and J. R. Primack, Phys. Rev. Lett. **48** (1982) 223.
87. M. Y. Khlopov and A. D. Linde, Phys. Lett. B **138** (1984) 265.
88. J. R. Ellis, J. E. Kim and D. V. Nanopoulos, Phys. Lett. B **145** (1984) 181.
89. M. Bolz, W. Buchmuller and M. Plumacher, Phys. Lett. B **443** (1998) 209 [arXiv:hep-ph/9809381].
90. W. Buchmuller, K. Hamaguchi, M. Ratz and T. Yanagida, arXiv:hep-ph/0403203.
91. J. L. Feng, S. Su and F. Takayama, Phys. Rev. D **70** (2004) 075019 [arXiv:hep-ph/0404231].
92. K. Hamaguchi, M. M. Nojiri and A. de Roeck, JHEP **0703** (2007) 046 [arXiv:hep-ph/0612060].
93. H. U. Martyn, arXiv:0709.1030 [hep-ph] and talk at this conference; Eur. Phys. J. C **48** (2006) 15 [arXiv:hep-ph/0605257].