SUPERSYMMETRY AT AND BEYOND THE LHC

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Prospects for SUSY discoveries and measurements at future colliders LHC and ILC are discussed. The problem of reconstructing the underlying theory and SUSY breaking mechanism is also addressed.

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1. Introduction

The Standard Model (SM) is very successful in describing the constituents of matter and their interactions at and below the electroweak scale. However, it does not address many important issues, like the mass generation and mass pattern, the unification of all forces (including gravity), the matter composition of our universe etc. These issues seem to point to new phenomena at a TeV scale which 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 the answers to these issues could have different origin, it is very tempting to contemplate supersymmetry (SUSY) as responsible for all of them. SUSY turned to be able to beautifully accommodate or explain (at least in the technical sense) some of the SM problems, e.g. it solves the hierarchy problem, explains the gauge coupling unification, provides the radiative electroweak symmetry breaking, provides a candidate for dark matter (DM), offers new ideas on matter-antimatter asymmetry of the universe etc. SUSY still lacks any direct experimental evidence, however, is not yet excluded either.

Discovering supersymmetry, the main candidate for a unified theory beyond the SM, is the challenge for world physics community experimenting at existing and future colliders. Many detailed phenomenological studies of SUSY at present and future colliders have been performed in the past. Here only some selected results are presented on the discovery potentials of the main two LHC detectors: ATLAS and CMS. Assuming that SUSY is discovered at LHC we will discuss how experi-
mentation at the ILC will help in revealing the details of the underlying model and address the question of reconstructing the fundamental SUSY parameters and the mechanism of SUSY breaking.

2. Supersymmetry searches at the LHC

At present the most restrictive limits on the SUSY parameter space come from negative results of SUSY searches at two colliders: Tevatron at Fermilab and HERA at DESY. Both machines perform beautifully and significant improvements (or discoveries) can be expected in near future until the LHC will start taking data.

The strongly interacting squarks and gluinos ($\tilde{q}$ and $\tilde{g}$), if they are in the TeV range, will be copiously produced at the LHC with production cross sections comparable to jet production with transverse momenta $p_t \sim$ SUSY masses (typically in the picobarn range). Direct production of weakly interacting sparticles has much lower rates. Squarks and gluinos will promptly decay into jets and lighter SUSY particles which will further decay. Generically one can expect in the final state high-$p_t$ jets and leptons, possibly large missing energy $\not{E}_T$, or displaced vertices etc. Since the LHC detectors are designed to detect these objects, 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 the LHC detectors ATLAS and CMS and we refer to technical design reports of both collaboration for more details.

2.1. Inclusive searches at LHC

Jets from squark and gluino decays will have large transverse momenta $p_t$ of the order of sparticle masses. If the lightest SUSY particle (LSP) is stable, as in scenarios with $R$-parity conserved, it will escape undetected giving large $\not{E}_T$. The SM background events from top quark, $W$ and $Z$ boson decays do not have such high-$p_t$ objects. A set of simple cuts can then be designed to enhance the signal over the background in inclusive “transverse” searches for SUSY particles. For example, in typical mSUGRA scenarios, requiring at least four jets with large $p_t$ and large

$$M_{\text{eff}} = \sum_{i=1,...,4} p_t^i + \not{E}_T$$

(1)
and selecting events spherical in the transverse plane (specific cuts 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 $p_t$ is then included in the definition of $M_{\text{eff}}$. The reach of inclusive searches at $10^{-1}$ fb is illustrated in Fig. I and squarks and gluinos with masses up to $\sim 2.5$ TeV can be found at LHC with 100 fb$^{-1}$. Monte Carlo studies have also shown that the position of the peak in $M_{\text{eff}}$ distribution correlates quite well with sparticle masses, namely $M_{\text{eff}} \sim \min(m_{\tilde{q}}, m_{\tilde{g}})$, providing a first estimate of the overall SUSY mass scale, Fig. I right panel.
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Recently the importance of including exact matrix element corrections to the previous parton shower estimate of the background has been emphasized. This may significantly change the background distribution in the signal region. This is particularly important in scenarios with sparticle masses degenerate in which the signal events are less “transverse”. As a result, the 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, in which the unification scale of the soft SUSY parameters can be much lower than the GUT scale, even of the order of the weak scale. 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. There are regions of parameters where the squark, slepton and gaugino masses are significantly degenerated. If \[ m_{\tilde{\chi}_0^1} \sim m_{\tilde{q}, \tilde{g}} / 2, \] the signal \( M_{\text{eff}} \) distribution becomes quite similar to that of the background. New ideas are needed to improve search strategies. For example, examining the pattern of events in the \( M_{\text{eff}} - E_t \) plane may help to discriminate signal from background better.

2.2. Sparticle mass measurements

In R-parity conserving SUSY all sparticles decay into invisible LSP, so no mass peaks can be directly reconstructed. Nevertheless, it might be possible to identify particular decay chains and exploit the “endpoint method” to measure combinations of masses. A relatively clean channel, for example, 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

\[ \tilde{\chi}_i^0 \rightarrow \ell\ell \rightarrow \ell\ell\tilde{\chi}_1^0 \]  

(2)
The di-lepton mass distribution endpoints are functions of the masses of sparticles involved in the decay

\[ m_{\ell\ell}(3\text{-body}) = m_{\tilde{\nu}_i} - m_{\tilde{\nu}_1} \]  

\[ m_{\ell\ell}(2\text{-body}) = \sqrt{(m_{\tilde{\nu}_i}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\nu}_1}^2)}/m_{\tilde{\ell}} \]  

Requiring two isolated leptons in addition to multi-jet and $E_t$ cuts, like those described above, the signal events can be selected. If lepton flavor is conserved, contributions from two uncorrelated decays cancel in the combination of $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ sample giving a very clean signal and allowing a precise endpoint measurement. The shape of the distribution also helps to distinguish two-body from three-body decays.

Long decay chains, like

\[ \tilde{g} \to j j \tilde{g} \to \chi_2^0 j_1 j_2 \to \ell \ell j_1 j_2 \to \chi_1^0 \ell j_1 j_2 \]  

expected in some mSUGRA scenarios e.g. SPS1a\textsuperscript{11} allow more endpoint measurements. With two jets and two leptons in the final state it should be possible to measure the endpoints of invariant mass distributions $\ell\ell$, $\ell j$, like those shown in Fig. 2. Although these endpoints are smeared by jet reconstruction, hadronic resolution, and miss-assignment of the jets that come from squark decays, these endpoints should be measured at the level of 1%, i.e. determining mass relations to 1-2\%\textsuperscript{12}. In fact, with so many endpoints one can solve for the absolute values of the unknown masses of $\tilde{g}$, $\tilde{\nu}$, $\chi_2^0$, $\tilde{\ell}$ and $\chi_1^0$ within 5–10% accuracy. This is a general feature of the determination of sparticle masses when the LSP momentum cannot be measured directly. For this particular point, already $O(5)\%$ accuracy in the mass of sleptons and the lightest neutralino can provide a link to cosmology. Based in 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\%\textsuperscript{13}. For other scenarios, however, the expected accuracy can be much worse\textsuperscript{14}.

It is notable that via the above decay chain the LHC can access the heaviest neutralino $\chi_4^0$ which in the SPS1a\textsuperscript{1} scenario is too heavy to be produced at the 500 GeV $e^+e^-$ collider. The measured mass difference $m_{\chi_4^0} - m_{\chi_1^0}$, in the same decay
chain as in eq. (5), but with $\tilde{\chi}^0_4$ replacing $\tilde{\chi}^0_2$, would provide an important constraint on model parameters. If the measurements at the LHC and ILC could be combined the errors for the MSSM Lagrangian parameters would significantly be reduced.

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. An alternative “mass relation” method, which exploits the on-shell conditions for sparticle masses in the decay chains, allows to solve for the kinematics and reconstruct the SUSY masses as peaks in certain distributions. For example, in the cascade decay $q' \rightarrow j_1q' \rightarrow Z'j_1j_2 \rightarrow \ell'\ell_1j_1j_2 \rightarrow \gamma'\ell_3\ell_2j_1j_2$ (6) five on-shell conditions can be written for $g'$, $\tilde{q}$, $\tilde{\chi}^0_2$, $\tilde{\ell}$ and $\tilde{\chi}^0_1$ in terms of the measured momenta of leptons, jets and 4 unknown momentum components of the undetected neutralino. Each event, therefore, spans a 4-dim hypersurface in a 5-dim 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.

2.3. Proving it is SUSY

A generic signal of large $E_t$, as in the weak-scale SUSY, arises in almost any model with the lightest $O(100$ GeV) particle stable and neutral, as suggested by the dark matter of the universe. Therefore, we have to be able to distinguish the SUSY decay chain eq. (5) from, e.g., the cascade decay

$$g' \rightarrow j_1q' \rightarrow Z'j_1j_2 \rightarrow \ell'\ell_1j_1j_2 \rightarrow \gamma'\ell_3\ell_2j_1j_2$$

that arises in the universal extra-dimension model (UED). Here the primes denote the first excited Kaluza-Klein states of the corresponding SM particles. In both cases the final state is the same $\ell_1\ell_2j_1j_2$ with either the $\chi^0_1$ or the $\gamma'$ escaping detection. What differentiates the decays in eqs. (5,6) is the spins of intermediate states and the chiral structure of couplings. In contrast to the UED case, in many processes the SUSY particles are naturally polarized due to the chiral structure of the theory. For example, in the decay $\tilde{q}L \rightarrow \tilde{\chi}^0_2qL$, the $\tilde{\chi}^0_2$ is polarized as right-handed, opposite to $q_L$, because the $\tilde{q}\tilde{\chi}q$ Yukawa coupling flips chirality. The polarized neutralino further decays into either $\tilde{\ell}_R\ell^+$ or $\tilde{\ell}_R^\ast\ell^-$ with equal rates (because of the Majorana character of neutralinos), but due to the chiral nature of the Yukawa $\tilde{\ell}\chi\ell$ coupling, the $\ell^+$ is likely to fly in the neutralino direction in the squark rest frame, while the $\ell^-$ 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.

Although the charge asymmetry for $\tilde{q}L$ decay is just opposite, in $pp$ collisions more squarks than anti-squarks are expected and the $\tilde{\chi}^0_2$ production from squark decays
Fig. 3. Detector-level charge asymmetries with respect to the jet+lepton rescaled invariant mass, for UED-(left) and SUSY-like (right) mass spectra. Dashed: SUSY. Solid/red: UED.

is dominant. The amount of charge asymmetry in the $m(j\ell)$ is model dependent, Fig. 3, nevertheless it may allow resolving the fermionic nature of the neutralino from the vector nature of the $Z'$ and confirm the chiral structure of couplings [19][20].

2.4. The LHC 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. 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 [21]. In some favorable cases it might be possible to reconstruct the model. However, in many cases one is left with degenerate solutions, i.e. many models could fit the LHC data equally well [22].

This task can be greatly ameliorated by experimenting at the ILC where the experimental accuracies at the per-cent down to the per-mil level are expected [23].

3. SUSY studies at the ILC

If the superpartner masses (at least some of them) are in the TeV range, LHC will certainly see SUSY. Many different channels, in particular from squark and gluino decays will be explored and many interesting quantities measured, as discussed in the previous chapter. However, to achieve the ultimate goal of all experimental efforts to unravel the SUSY breaking mechanism and shed light on physics at high (GUT?, Planck?) scale, an $e^+e^-$ LC would be an indispensable tool [23]. First, the LC will provide independent checks of the LHC findings. Second, thanks to the LC unique features: clean environment, tunable collision energy, high luminosity, polarized incoming beams, and possibly $e^-e^-$, $e\gamma$ and $\gamma\gamma$ modes, it will offer precise measurements of masses, couplings, quantum numbers, mixing angles, CP phases etc. Last, but not least, it will provide additional experimental input to the LHC analyses, like the mass of the LSP. Coherent analyses of data from the LHC and LC would thus allow for a better, model independent reconstruction of low-energy SUSY parameters, and connect low-scale phenomenology with the high-scale physics [23].

An intense R&D process and physics studies since 1992 has lead to world-wide consensus that the next high energy machine after the LHC should be an International Linear Collider (ILC). Planning, designing and funding the ILC requires
global participation and global organization. Therefore the Global Design Effort for the ILC, headed by Barry Barish, has been established with the goal of preparing the project to be ready for approval around 2010 and beginning construction around 2012. Recently released the Reference Design Report defines the ILC baseline as follows:

- CM energy adjustable from 200 to 500 GeV, and at $M_Z$ for calibration,
- integrated luminosity of at least 500 fb$^{-1}$ in first 4 years,
- beam energy stability and precision below 1%,
- electron beam polarization of at least 80%,
- upgradeability to CM energy of 1 TeV.

The choice of options, like GigaZ (high luminosity run at $M_Z$), positron polarization, $e^+e^-$, $e\gamma$ or $\gamma\gamma$, will depend on LHC+ILC physics results.

Many detailed physics calculations and simulations have been performed and presented during numerous ECF, ACA and ALCPG workshops and LCWS conferences. Below only some highlights are presented.

3.1. Mass measurements

At the ILC two methods can be used to measure sparticle masses: threshold scans or in continuum. The shape of the production cross section near threshold is sensitive to the masses and quantum numbers. For first 2 generations, where $R$-$L$ mixing can be neglected for example, $\tilde{\mu}^+_L\tilde{\mu}^-_L$, $\tilde{\mu}^+_R\tilde{\mu}^-_R$, $\tilde{e}^+_L\tilde{e}^-_L$ and $\tilde{e}^+_R\tilde{e}^-_R$ pairs are excited in P-wave characterized by a slow rise of the cross section $\sigma \sim \beta^3$ with slepton velocity $\beta$. On the other hand, in $e^+_L\tilde{e}^-_L / e^-_RE^+_R$ and $e^-_L\tilde{e}^+_L / e^-_RE^-_R$ sleptons are excited in S-wave giving steep rise of the cross sections $\sigma \sim \beta$. Simulations for the SPS1a point show that the $\tilde{e}_R$ mass can be determined to 2 per mil; the resolution deteriorates by a factor of $\sim 2$ for $\tilde{\mu}^+_R\tilde{\mu}^-_R$ production. For $e^-_R\tilde{e}^-_R \rightarrow \tilde{e}^-_R\tilde{e}^-_R$ the fast rise of the cross section allows to gain a factor $\sim 4$ in precision already at a tenth of the luminosity if the $e^+e^-$ case.

![Cross sections at threshold for the reactions](image)

Above the threshold, slepton masses can be obtained from the endpoint energies of leptons coming from slepton decays. In the case of two-body decays, $\ell^- \rightarrow \ell^- \tilde{\chi}_i^0$ and $\tilde{\nu}_\ell \rightarrow \ell^- \tilde{\chi}_i^+$ the lepton energy spectrum is flat with endpoints (the minimum
$E_\pm$ and maximum $E_\pm$ energies) given by

$$E_\pm = \frac{1}{2} \sqrt{s} (1 \pm \beta)(1 - m_\chi^2/m_\ell^2)$$  \hspace{1cm} (7)

Unlike at the LHC, the knowledge of the collision energy allows not only an accurate determination of the mass of the primary slepton but also the secondary neutralino/chargino. One finds that $m_{\tilde{e}_R}$, $m_{\tilde{\mu}_R}$ and $m_{\tilde{\chi}_1^0}$ can be measured to 0.1 to 0.18 GeV, i.e. 2 per mil in selectron and smuon production processes.\(^{30}\) The $\tilde{\mu}_L$ is more difficult to detect because of large background from WW pairs and SUSY cascades. However, high luminosity allows one to select the rare decay modes $\tilde{\mu}_L \rightarrow \mu \tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$ leading to a unique, background free signature $\mu^+ \mu^- 4\ell^\pm \not{E}_T$. The achievable mass resolution for $m_{\tilde{\mu}_L}$ and $m_{\tilde{\chi}_2^0}$ is of the order 4 per mil.\(^{31}\)

The chargino masses can be measured very precisely at threshold: simulations for the reaction $e^+_R e^-_L \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \ell^+ \nu \chi_0^0 q \bar{q}$ show that the mass resolution is excellent of $\mathcal{O}(50$ MeV), degrading to the per mil level for the higher $\tilde{\chi}_2^\pm$ state. Above threshold, from the di-jet energy distribution in $\tilde{\chi}_2^\pm \rightarrow q \bar{q}' \tilde{\chi}_1^0$ one expects a mass resolution of $\delta m_{\tilde{\chi}_1^0} = 0.2$ GeV, while the di-jet mass distributions constrains the $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass splitting to about 100 MeV. Similarly, the di-lepton energy and mass distributions in the reaction $e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow 4\ell^\pm \not{E}_T$ can be used to determine $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ masses to about 2 per mil.\(^{31}\) Higher resolution of order 100 MeV for $m_{\tilde{\chi}_2^0}$ can be obtained from a threshold scan of $e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$, heavier states $\tilde{\chi}_3^0$ and $\tilde{\chi}_4^0$, if accessible, can still be resolved with a resolution of a few hundred MeV.

### 3.2. Couplings and mixings

The $L-R$ mixing for the third generation can be non-negligible due to the large Yukawa coupling making the $\tilde{t}$, $\tilde{t}$ and $\tilde{b}$ systems very interesting to study to determine their mixing and chiral quantum numbers. Likewise, we would like to determine the gaugino and higgsino composition of charginos and neutralinos. Equally important is to verify the SUSY mass relations and exact equality (at tree level) of gauge couplings and their supersymmetric Yukawas. For all these measurements the ability of having both beams, positrons and electrons, polarised turns to be crucial, since for many measurements even 100% electron polarisation is insufficient.

The couplings and mixing angles can be extracted from production cross sections measured with polarized beams. For example, experimental analyses of stop quarks with small stop-neutralino mass difference, motivated by the stop-neutralino co-annihilation DM scenario, are very demanding. Nevertheless, the stop parameters can be determined precise enough, Fig. 5(left), and precisions for the dark matter predictions comparable to that from direct WMAP measurements in the region down to mass differences $\sim \mathcal{O}(5$ GeV) can be achieved.\(^{32}\)

The Yukawa couplings of scalar fermions can precisely be determined by measuring the production cross-sections with polarized beams. For example, in the electroweak sector, the relation between the hypercharge $U(1)_Y$ coupling $g_1$ and the $SU(2)_L$ coupling $g_2$ and the corresponding Yukawa couplings $\hat{g}_1$ and $\hat{g}_2$ can accu-
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Fig. 5. Power of polarization – bounds on: (left) light stop mass $m_{\tilde{t}_1}$ and stop mixing angle $\theta_t$ from $\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1^*)$; (center) on $Y_L = \hat{g}_2/g_2$ and $Y_R = \hat{g}_1/g_1$ from neutralino pair–production with polarized beams. (right) $\Phi_1$ dependence of the CP–odd asymmetry $A_{CP}$.

3.3. Looking beyond the ILC kinematic reach

The precision measurements offered by the ILC allow us to infer indirect information on heavy states not directly accessible. As an illustration we consider two examples.

The first example concerns an interesting scenarios in which scalar sparticle sector is heavy while the gaugino masses are kept relatively small, like in the cosmology-motivated focus-point scenario. Precision analyses of cross sections for light chargino production and forward–backward asymmetries of decay leptons at the first stage of the ILC, Fig. 6 (left), together with mass information on $\tilde{\chi}_2^0$ and squarks from the LHC, show that the underlying fundamental gaugino/higgsino MSSM parameters and constrains on the heavy, kinematically inaccessible sparticles with masses $\mathcal{O}(2 \text{ TeV})$, can be obtained nevertheless.

If the second top squark $\tilde{t}_2$ is too heavy for the ILC, and due to huge background invisible at the LHC, the precise measurement of the Higgs boson mass $m_h$ at ILC together with measurements from the LHC can be used to obtain indirect limits on $m_{\tilde{t}_2}$, Fig. 6. Both examples again demonstrate the power of the LHC/ILC...
interplay, since neither of these colliders alone can provide sufficient data needed to
determine the SUSY parameters in such difficult scenarios.

3.4. \(e^- e^-\), \(e\gamma\) and \(\gamma\gamma\) options

Compton back-scattering of the laser light on electron beam(s) opens a possibility of
converting the \(e^- e^-\) collider to an \(e\gamma\) and \(\gamma\gamma\) collider with energies and luminosities
comparable to those of \(e^+ e^-\) collider\(^{11}\). If realized, these options may open new
discovery channels. Again I will take two specific examples to illustrate the point.

If the mass difference between the lightest neutralino and the selectron is a few
hundred GeV, it may happen that chargino pair production at the ILC is possible,
while selectron pair production is kinematically forbidden. However, \(m_{\tilde{\chi}^0_1} + m_{\tilde{e}}\) can
still be below 90% of the centre-of-mass energy, so that the process \(e\gamma \rightarrow \tilde{\chi}^0_1 \tilde{e}^-\)
is possible at an \(e\gamma\) collider. If the photon energy were known, the selectron and
neutralino masses could be determined from the endpoints of the decay electron
distribution, like in \(e^+ e^-\) collisions. Although the variable photon energy smears
the endpoints, simulations have shown \(^{42}\) that with the \(m_{\tilde{\chi}^0_1}\) determined in
\(e^+ e^-\) running, the selectron mass can be reconstructed from the position of the
lower edge.

\(\gamma\gamma\) collider offers a unique possibility of producing as \(s\)-channel resonances neutral
Higgs bosons \(H, A\) that are both too heavy to be produced in associated \(HA\) or
\(ZH\) processes at \(e^+ e^-\) collider and lay in the so called “LHC-wedge” of intermediate
values of \(\tan\beta\), to which the LHC is blind. Results of a simulation for the combined
\(\gamma\gamma \rightarrow H, A \rightarrow b\bar{b}\) analyses are shown in Fig. 7 \(^{43}\) (the \(H\) and \(A\) bosons are almost
mass-degenerate). Other decay modes \((WW, ZZ, t\bar{t})\) can provide a means to
determine the Higgs-boson CP properties \(^{44}\), and the \(\tau\)-fusion process, \(\gamma\gamma \rightarrow \tau\tau H, A\), can
serve to measure \(\tan\beta\) \(^{45}\), the parameter that is notoriously difficult to determine
experimentally.

3.5. Beyond the ILC

It is expected that higher energy colliders will be needed to help unravel the multi-
TeV physics left unveiled either by the LHC or by the ILC. Further progress in
particle physics may require clean experiments at a linear \(e^+ e^-\) collider at multi-
TeV energies, like CLIC \(^{46}\), which would be an ideal machine to complement the
the LHC and ILC physics program. Simulations for CLIC concentrated on such scenarios with sparticles beyond the LHC and ILC reach.

Fig. 8 (left) shows simulations of the muon energy spectrum from a 1150 GeV selectron decaying to a muon and a 660 GeV LSP neutralino. The endpoints are clearly seen allowing the selectron and neutralino mass determination. Likewise, in Fig. 8 (middle) the di-muon invariant mass distribution from $\tilde{\chi}_2^0 \rightarrow \mu^+\mu^-\chi^0_1$ exhibits a pronounced edge which, together with results from selectron decay make a measurement of $m_{\tilde{\chi}_2^0}$ possible.

In more distant future a muon collider with extremely good beam energy resolution will provide a tool to explore Higgs (and Higgs-like objects) by direct $s$-channel fusion because of enhanced couplings of muons to Higgs bosons, much like the LEP explored the $Z$. Right panel of Fig. 8 demonstrates how well two almost mass-degenerate Higgs bosons $H$ and $A$ can be resolved.

### 4. Reconstructing the underlying SUSY model

The expected high experimental accuracies at the LHC/ILC could not be fully exploited if not matched from the theoretical side. 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, and building on vast experience in SUSY calculations and data simulations and analyses, the Supersymmetry Parameter Analysis
(SPA) Convention and Project has been proposed. It recommends a convention for high-precision theoretical calculations, and provides 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 web-page [http://spa.desy.de/spa/](http://spa.desy.de/spa/).

4.1. **SPA Convention**

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 $\overline{\text{DR}}$ scheme at the scale $\tilde{M} = 1 \text{ TeV}$.
- Gaugino/higgsino and scalar mass matrices, rotation matrices and the corresponding angles are defined in the $\overline{\text{DR}}$ 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 $G_F$, $\alpha$, $M_Z$ and $\alpha_{\text{MS}}(M_Z)$. All lepton masses are defined on-shell. The $t$ quark mass is defined on-shell; the $b$, $c$ quark masses are introduced in $\overline{\text{MS}}$ at the scale of the masses themselves while taken at a renormalization scale of 2 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; 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 convention is recommended for communication between the codes.

4.3. **The test-bed: Ref. Point SPS1a’**

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. The roots defining $\text{SPS}1a'$ are the mSUGRA parameters $M_{1/2} = 250$ GeV, $M_0 = 70$ GeV, $A_0 = -300$ GeV at the GUT scale, and $\tan \beta (\tilde{M}) = 10$, $\mu > 0$. The point is close to the original Snowmass point $\text{SPS}1a$ \cite{28} and to point $B'$ of \cite{49}. Recently global analysis programs have become available 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.

The parameter set $\text{SPS}1a'$ 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. Other scenarios might be realized in the SUSY sector and the SPA convention is general enough to cover them.

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.

5. Summary

Much progress has been achieved in preparing the physics programme for new machines. 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 deserve experimental analyses. However, the task of exploring all masses and couplings of SUSY particles is probably impossible by the LHC alone. The ILC will extend the discovery reach, in particular in the electroweak sector, and greatly improve on precision SUSY measurements. We still need new ideas and techniques to explore fully the opportunities offered to us by the LHC and ILC. 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, \textit{Precision electroweak measurements on the Z resonance}, Phys. Rept. \textbf{427} (2006) 257. See also talk of J. D. Lykken, these Proceedings [arXiv:hep-ph/0609274].
2. Yu. A. Golfand and E. P. Likhtman, JETP Lett. \textbf{13} (1971) 323 [Pisma Zh. Eksp.
2. D. V. Volkov and V. P. Akulov, JETP Lett. 16 (1972) 438
Pisma Zh. Eksp. Teor. Fiz. 16 (1972) 621. J. Wess and B. Zumino, Phys. Lett. B 49 (1974) 52.
3. [http://www-cdf.fnal.gov/physics/exotic/exotic.html]
4. ATLAS Collab., ATLAS Detector and physics performance technical design report,
  CERN-LHCC-99-14/15 (1999).
5. CMS Collab., CMS Physics Technical Design Report, CERN-LHCC-2006-021 (2006).
6. M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. D. Polosa, JHEP 0307 (2003) 001.
  T. Plehn, D. Rainwater and P. Skands, Phys. Lett. B 645, 217 (2007) [arXiv:hep-ph/0510144].
  S. Asai, talk at 4th TEV4LHV, Oct. 20-22, 2005.
7. B. K. Gjelsten, D. J. Miller and P. Osland, JHEP 0412 (2004) 003.
8. K. Kawagoe and M. M. Nojiri, Phys. Rev. D 74, 115011 (2006) [arXiv:hep-ph/0606104].
9. K. Desch, J. Kalinowski, G. Moortgat-Pick, M. M. Nojiri and G. Polesello, JHEP 0402 (2004) 035.
10. M. M. Nojiri, G. Polesello and D. R. Tovey, JHEP 0603 (2006) 063.
11. A. Falkowski, O. Lebedev and Y. Mambrini, JHEP 0511 (2005) 034.
12. B. K. Gjelsten, D. J. Miller and P. Oslan, JHEP 0412 (2004) 003.
13. M. M. Nojiri, G. Polesello and D. R. Tovey, JHEP 0603 (2006) 063.
14. E. A. Baltz, M. Battaglia, M. E. Peskin and T. Wizinsky, Phys. Rev. D 74 (2006) 103521
  [arXiv:hep-ph/0612317]. K. Kawagoe, M. M. Nojiri and G. Polesello, Phys. Rev. D 71 (2005) 035008.
15. H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D 66 (2002) 056006.
16. A. J. Barr, Phys. Lett. B 596 (2004) 205.
17. J. M. Smillie and B. R. Webber, JHEP 0510 (2005) 069.
18. C. Athanasiou, C. G. Lester, J. M. Smillie and B. R. Webber, JHEP 0608 (2006) 055.
19. L. T. Wang and I. Yavin, JHEP 0704, 032 (2007) [arXiv:hep-ph/0605296].
20. P. M. Zerwas et al., [LHC/LC Study Group], Phys. Rept. 426, 47 (2006) [arXiv:hep-ph/0410364].
21. N. Arkani-Hamed, G. L. Kane, J. Thaler and L. T. Wang, JHEP 0608 (2006) 070.
22. J. A. Aguilar-Saavedra et al., TESLA Technical Design Report, DESY 01-011 and
  [arXiv: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 and [arXiv:hep-ex/0106055-58]. T. Abe et al. [Asian LC WG], KEK-
  Report-2001-011 and [arXiv:hep-ph/0109166].
23. G. Weiglein et al. [LHC/LC Study Group], Phys. Rept. 426, 47 (2006) [arXiv:hep-ph/0410364].
28. B. C. Allanach et al., Eur. Phys. J. C 25 (2002) 113.
29. A. Freitas et al., arXiv:hep-ph/0211108; A. Freitas, Ph.D. thesis, Hamburg (2002), DESY THESIS-2002-023.
30. H. U. Martyn, arXiv:hep-ph/0406123.
31. H. U. Martyn, arXiv:hep-ph/0302024.
32. G. A. Moortgat-Pick et al., arXiv:hep-ph/0507011.
33. M. Carena, A. Finch, A. Freitas, C. Milstene, H. Nowak and A. Sopczak, Phys. Rev. D 72 (2005) 115008.
34. 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].
35. J.A. Aguilar–Saavedra, Phys. Lett. B596 (2004) 247.
36. J.A. Aguilar–Saavedra and A.M. Teixeira, Nucl. Phys. B675 (2003) 70; J.A. Aguilar–Saavedra, LC–TH–2003–098 [hep-ph/0312140].
37. S. Y. Choi, B. C. Chung, J. Kalinowski, Y. G. Kim and K. Rolbiecki, Eur. Phys. J. C 46 (2006) 511.
38. J. L. Feng, K. T. Matchev and T. Moroi, Phys. Rev. D 61 (2000) 075005; J. L. Feng and F. Wilczek, Phys. Lett. B 631 (2005) 170.
39. K. Desch, J. Kalinowski, G. Moortgat-Pick, K. Rolbiecki and W. J. Stirling, JHEP 0612, 007 (2006) [arXiv:hep-ph/0607104].
40. S. Heinemeyer, S. Kraml, W. Porod and G. Weiglein, JHEP 0309 (2003) 075.
41. For a review and references see e.g. V. I. Telnov, Acta Phys. Polon. B 37 (2006) 1049.
42. I. Alvarez Illan and K. Monig, DESY LC note LC-PHSM-2005-002.
43. P. Niezurawski, A. F. Zarnecki and M. Krawczyk, Acta Phys. Polon. B 37 (2006) 1187;
44. P. Niezurawski, A. F. Zarnecki and M. Krawczyk, Acta Phys. Polon. B 36 (2005) 833.
45. S. Y. Choi et al, Phys. Lett. B 606 (2005) 164.
46. E. Accomando et al. [CLIC Physics Working Group], arXiv:hep-ph/0412251.
47. M. M. Alsharoa et al. [Muon Collider/Neutrino Factory Collaboration], Phys. Rev. ST Accel. Beams 6 (2003) 081001.
48. P. Skands et al., JHEP 0407 (2004) 036.
49. M. Battaglia et al., Eur. Phys. J. C 33 (2004) 273.
50. P. Bechtle, K. Desch and P. Wienemann, Comput. Phys. Commun. 174 (2006) 47; R. Lafaye, T. Plehn and D. Zerwas, arXiv:hep-ph/0404282.