ASPECTS OF HIGGS PHYSICS AND PHYSICS BEYOND THE STANDARD MODEL
AT LHC AND $e^+e^-$ LINEAR COLLIDERS

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Recent developments in prospects of searching for Higgs particles and testing their properties at the LHC and at TeV $e^+e^-$ linear colliders are summarized. The discovery limits of supersymmetric particles at the LHC are presented and the accuracy is explored with which the fundamental SUSY parameters in the context of supergravity models can be determined at high-luminosity linear colliders. Finally, new discovery limits for gauge bosons in left-right symmetric models at the LHC are presented.

1 The physical basis

1. Recent results from high-precision measurements of electroweak observables at LEP, SLC and elsewhere strongly support the hypothesis that the electroweak symmetries are broken through the Higgs-mechanism and that a light fundamental Higgs boson is realized in Nature $^1$. Moreover, the perturbative expansion of the theory up to the GUT scale, backed by the observed value of the electroweak mixing angle, favors a Higgs mass in the intermediate range $M_H \lesssim 180$ GeV. This is the most difficult range to explore at the LHC, yet it is evident now that the lower part of this range can be covered in the $H \rightarrow \gamma\gamma$ decay channel $^2$ while the upper part is accessible in the four-lepton decay $H \rightarrow ZZ^* \rightarrow 4\ell^\pm$, both with high significance between $S = 8$ and 10.

Once Higgs bosons are discovered, their properties must be explored to establish the Higgs mechanism sui generis as the basic mechanism for the breaking of the electroweak symmetries. This program can be carried out in three consecutive steps. (i) The external quantum numbers $J^{PC}$ must be determined $^3$. (ii) The generating of vector-boson and fermion masses through the Higgs mechanism can be scrutinized by measuring the $HVV$ and $Hff$ couplings, *not a bene* the $Htt$ Yukawa coupling (of the heaviest matter particle in the Standard Model) to the Higgs particle. The bremsstrahlung of Higgs bosons in the process $e^+e^- \rightarrow t\bar{t}H$ offers a method for measuring this fundamental coupling directly $^4$. (iii) The Higgs potential which provides the operational basis for the Higgs mechanism, must finally be reconstructed. The strength and the form of the potential define the Higgs mass and the trilinear and quadrilinear self-couplings of the Higgs particle. The prediction for the trilinear coupling can be tested in Higgs-pair production at the LHC in the process $pp \rightarrow HH$, and at $e^+e^-$ colliders in Higgs-bremsstrahlung $e^+e^- \rightarrow ZHH$, for instance, where the Higgs pair is emitted in the decay of a virtual $H$ boson $^6$.

2. Extending the Standard Model to a supersymmetric theory provides a natural way to keep light fundamental Higgs bosons stable in the background of large GUT scales. The search for supersymmetric particles is therefore a very important endeavor at existing and future accelerators. The ultimate discovery limits, in the next two decades, of squarks and gluinos will be set by the LHC $^7$. TeV $e^+e^-$ linear colliders will play the same role in the non-colored sector for charginos/neutralinos and sleptons $^8$.

Moreover, the high-luminosity version of $e^+e^-$ colliders allows to carry out very accurate measurements of the sparticle properties $^8$. These measurements can be used to explore the structure of the basic supersymmetric theory, in particular the mechanism responsible for the breaking of supersymmetry. Since SUSY breaking mechanisms are (in general) generated at scales of the order of the Planck scale, these machines open windows to physics scenarios in which gravity is an integral part of the system. Thus, they prepare the basis for the unification of the four fundamental forces.

3. Recent experimental evidence that neutrinos are massive particles has renewed interest in grand unified theories such as $SO(10)$, which incorporate right-handed neutrino fields in a natural way. Even though the typical scales of gauge bosons associated with right-handed symmetries and heavy neutrino masses may likely be close to the GUT scale, it is nevertheless an interesting problem to search for new LR degrees of freedom $^9$, in particular at the LHC which defines the energy frontier of laboratory accelerators in the near future.
2 Higgs physics

2.1 The Higgs two-photon channel at the LHC

The SM Higgs boson in the lower part of the intermediate mass range $M_H \lesssim 150$ GeV, can be searched for at the LHC in the $H \rightarrow \gamma\gamma$ decay mode. The Higgs bosons are primarily produced in gluon-gluon fusion. However, the signal-to-background ratio improves from typical values of 8-12 to 8 if a cut is applied to the minimal transverse momentum, balanced by a recoiling gluon or quark jet. The size of signal and background cross section differs between the resonance values and the continuum estimates somewhat, it can nevertheless be concluded that a sufficient buffer does exist for the discovery of the SM Higgs boson in the $\gamma\gamma$ resonance channel at the LHC.

Even though theoretical refinements could change the estimates somewhat, it can nevertheless be concluded that a sufficient buffer does exist for the discovery of the SM Higgs boson in the $\gamma\gamma$ resonance channel at the LHC.

2.2 The parity of Higgs bosons

The external quantum numbers of the Higgs boson can be studied in production and decay processes. For heavy enough Higgs bosons, spin correlations in Higgs decays to top-quark pairs can be exploited to measure the parity of the couplings $\langle H|t\rangle = (|M_t/v|) [a + iγ\tilde{a}]$ (3) with the coefficient $a \neq 0$ describes the scalar component, the coefficient $\tilde{a} \neq 0$ the pseudoscalar component of the state. If both are non-zero, CP is violated in the interactions. The couplings determine the spin correlations between the final-state top and anti-top quark. Near threshold, the correlations are given by $\langle s_t s_{\bar{t}} \rangle = +1/4$ and $-3/4$ for scalar and pseudoscalar Higgs decay matrix elements, corresponding to spin triplets and singlets. The continuum prediction for the spin correlation in gg collisions at threshold is again $-3/4$. The correlation may be analyzed at the LHC through lepton-angular distributions in semileptonic t and $\bar{t}$ decays. The size of the angular correlations is given by $\langle \cos \theta^{\ell}_{+\ell^{-}} \rangle$. The statistical error with which $\langle \cos \theta^{\ell}_{+\ell^{-}} \rangle$ can be measured is estimated to be $\Delta = 0.001$ for $\int L = 100$ fb$^{-1}$. Thus, the small differences between the resonance values and the continuum are significant.

Table 1: Cross section at the LHC, branching ratio and acceptance for $H \rightarrow \gamma\gamma$ with $M_H = 100$ GeV, left column; background gluon cross sections for the same invariant $\gamma\gamma$ mass, right column.

<table>
<thead>
<tr>
<th>Signal $\sigma$</th>
<th>Backgrounds $d\sigma/dm_{\gamma\gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(pp \rightarrow H + X)$ 56.3 pb</td>
<td>quark annihil. 92 fb/GeV</td>
</tr>
<tr>
<td>BR($H \rightarrow \gamma\gamma$) $1.5 \times 10^{-3}$</td>
<td>gluon fusion 167</td>
</tr>
<tr>
<td>acceptance 51.9 %</td>
<td>isol. bremsstr. 120</td>
</tr>
<tr>
<td>$\sigma \times$ BR 86.2 fb</td>
<td>total 379 fb/GeV</td>
</tr>
</tbody>
</table>

Figure 1: The Higgs signal in the $\gamma\gamma$ channel for $\int L = 100$ fb$^{-1}$ before (a) and after (b) background subtraction.
2.3 The $Htt$ Yukawa coupling

The masses of the fundamental particles are generated in the Higgs mechanism by interactions with the non-zero Higgs field in the ground state. Within the Standard Model, the Yukawa couplings of the leptons and quarks with the Higgs particle are therefore uniquely determined by the particle masses:

$$g_{Hff} = M_f/v : v = (\sqrt{2} G_F)^{-1/2}$$

The measurement of these couplings provides a fundamental experimental test of the Higgs mechanism. Several methods have been proposed in the literature to test Yukawa couplings of the Higgs boson. Since the mass of the top quark is maximal within the fermion multiplets of the Standard Model, the $Htt$ coupling ranks among the most interesting predictions of the Higgs mechanism. This coupling can be tested indirectly by measuring the $H\gamma\gamma$ and $Hgg$ couplings, which are mediated by virtual top-quark loops. If the Higgs boson is very heavy, the decay mode $H \rightarrow tt$ can be exploited. On the other hand, if the Higgs boson is light, $M_H \sim 100 \ldots 200$ GeV, the radiation of Higgs bosons off top quarks lends itself as a basic mechanism for measuring the $Htt$ coupling. The prospects of operating $e^+e^-$ linear colliders at high luminosities render the radiation process

$$e^+e^- \rightarrow ttH$$

a suitable instrument to carry out this measurement.

The Higgs boson can be radiated off the final-state top quarks as well as off the intermediate $Z$ boson; due to the heavy top mass the first mechanism is by far leading. QCD rescattering corrections increase the cross section near the threshold while for high energies the positive contributions from gluon radiation are overwhelmed by negative $Htt$ vertex corrections. The two limits can be paraphrased by $K$ factors:

$$K_{\text{thr}} \approx 1 + \frac{\alpha_s}{\pi} \frac{64}{9} \sqrt{(s/2) - M_H^2}^2 - 4M_t^2$$

$$K_{\infty} \approx 1 - \frac{3\alpha_s}{\pi}$$

The complete cross section including Higgs emission from the $Z$ line, has been evaluated in Ref. 4. Characteristic values of the cross section are presented in Fig.2 for three $e^+e^-$ energy values $\sqrt{s} = 500$ GeV, 1 TeV and 2 TeV, as a function of the Higgs mass.

While the phase-space suppression is gradually lifted with rising energy, the lower part of the intermediate Higgs mass range is experimentally accessible already at high-luminosity $e^+e^-$ colliders for $\sqrt{s} = 500$ GeV; for $\sqrt{s} = 1$ TeV the entire intermediate Higgs mass range can be covered. For a typical size $\sigma \sim 1$ fb of the cross section, about $10^3$ events are generated when an integrated luminosity $\int L \sim 1$ ab$^{-1}$ is reached within two to three years of running. This should provide a sufficiently large sample for detailed experimental studies of this process. Since Higgs radiation from the top quarks is dominant, the sensitivity to the $Htt$ Yukawa coupling is nearly quadratic, $\sigma(e^+e^- \rightarrow t\bar{t}H) \propto g_{Htt}^2/4\pi$, thus being very high.

2.4 Higgs self-couplings

The electroweak symmetries are spontaneously broken in the Standard Model and related theories through a potential in the scalar sector for which the minimum is realized at a non-vanishing value of the fields,

$$V = \frac{\lambda}{2} \left| \varphi \right|^2 - \frac{\lambda}{2} \left| \varphi \right|^4$$

Expanding the field $\varphi$ about the ground-state value $\langle \varphi \rangle_0 = v/\sqrt{2}$, the physical Higgs mass $M_H = \sqrt{2\lambda} v$, and trilinear and quadrilinear self-couplings of the physical Higgs fields are generated:

$$V = \frac{1}{2} M_H^2 H^2 + \frac{1}{2} (M_H/v) H^3 + \frac{1}{8} (M_H/v^2) H^4$$

The fundamental Higgs potential can thus be reconstructed by measuring the trilinear and quadrilinear self-couplings of the Higgs boson.

The trilinear self-coupling of the Higgs boson determines the production of pairs of Higgs particles at $e^+e^-$ 

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*In TESLA designs, integrated luminosities of $\int L = 0.3$ ab$^{-1}$ and 0.5 ab$^{-1}$ per year are planned at c.m. energies $\sqrt{s} = 0.5$ TeV and 0.8 TeV, respectively.*
Figure 3: The cross sections for Higgs pair production at $e^+e^-$ colliders and at the LHC in various channels. The event rates on the first and second right scale correspond to integrated luminosities $\int\mathcal{L} = 2.5\,\text{ab}^{-1}$ and 500 fb$^{-1}$, respectively.

Colliders and at the LHC$^6$. Several subprocesses are relevant in this context:

$$e^+e^- \rightarrow HH + X :$$
- double Higgs-strahlung $e^+e^- \rightarrow Z + HH$
- $WW$ fusion $e^+e^- \rightarrow \tau_+\tau_- + HH$
- $pp \rightarrow HH + X :$
  - double Higgs-strahlung $q\bar{q} \rightarrow W/Z + HH$
  - $WW/ZZ$ fusion $q\bar{q} \rightarrow q\bar{q} + HH$
  - gluon fusion $gg \rightarrow HH$

In all subprocesses, the two Higgs bosons can either be emitted from the $W/Z$ lines of the first two subprocesses and the $t$ line of the third subprocess, or from the splitting of a virtual Higgs boson $H_{\text{virt}}$ generated, for instance, in Higgs-strahlung $e^+e^- \rightarrow Z + H_{\text{virt}}$ followed by $H_{\text{virt}} \rightarrow HH$.

The size of the cross sections for the different channels is illustrated in Figs.3a/b. Since all the processes are of higher order in the electroweak coupling, the cross sections are small, posing severe background problems at the LHC, and requiring very high luminosities at $e^+e^-$ linear colliders. The sensitivity to the trilinear coupling $\lambda_{HHH}$ is indicated by arrows which point to the variation of the cross sections if the coupling is modified, ad hoc, from 1/2 to $2 \times \lambda_{HHH}$. The shifts are distinctly larger than the statistical fluctuations.

3 Supersymmetry

There are strong indications that the Standard Model is embedded in a supersymmetric theory. Besides the doubling of the basic Higgs doublet, SUSY doubles the spectrum of the SM particles in the minimal supersymmetric extension of the Standard Model (MSSM). The SM leptons and quarks are associated with scalar sleptons and squarks; the gluons with spin-$\frac{1}{2}$ gluinos; the partners of the electroweak gauge bosons and Higgs bosons mix to form two charginos and four neutralinos. The LHC is the machine proper to search for colored squarks and gluinos while lepton colliders are suitable machines to discover the non-strongly interacting particles, charginos/neutralinos and sleptons.

Apart from variants, essentially two scenarios have been developed to induce the breaking of supersymmetry: mSUGRA and gauge-mediated supersymmetry breaking. Most phenomenological analyses have been performed so far in the minimal supergravity model mSUGRA. In this approach, the breaking is triggered by gluino condensation in a shadow-world, transferred by gravitational interactions to the eigen-world. Soft SUSY breaking terms are generated this way near Planck scale distances. Evolving the universal gaugino and scalar mass parameters from the GUT scale down to the low electroweak scale, the mass parameters split eventually, generating the Higgs mechanism when the mass parameter (squared) in the Higgs sector becomes negative. This scenario is described by five parameters, with masses and couplings being universal at the GUT scale: the scalar mass $M_0$; the gaugino mass $M_1/2$; the trilinear coupling $A_0$; $\tan\beta$, the ratio of the VEVs in the Higgs sector; and $\text{sgn}(\mu)$, the sign of the higgsino parameter. The more than one hundred phenomenological SUSY parameters at the electroweak scale can all be expressed in terms of those five fundamental parameters, leading to many relations for testing the scheme.

3.1 Ultimate discovery limits at the LHC

Sparticles can be searched for at the LHC in a variety of channels. While the classical signature of squark and gluino production is the observation of $\text{"multi-jets + } E_{\text{miss}}\text{"}$, the search for isolated leptons, together eventually with combinations of the other signatures, have proven extremely successful, too$^7$:

$$pp \rightarrow \text{sparticles} \rightarrow \text{lepton(s) + (jets) + } E_{\text{miss}}$$

(10)

This set of signatures can be applied to the search of squarks/gluinos, charginos/neutralinos, and sleptons.
a) Squarks and gluinos

Squark and gluino masses can be expressed in terms of the fundamental parameters by two simple approximate relations (for moderate values of $\tan\beta$) in the mSUGRA scenario:

$$M_{\tilde{g}} \approx \sqrt{M_0^2 + 6M_{1/2}^2}$$  \hspace{1cm} (11)
$$M_{\tilde{g}} \approx 2.5 M_{1/2}$$  \hspace{1cm} (12)

Depending on the relative magnitude of $M_{\tilde{q}}$ vs. $M_{\tilde{q}}$, the SUSY particles first decay via mutual cascades, before leptonic channels become relevant, e.g.

$$pp \rightarrow \tilde{q} \tilde{q}/\tilde{g} \tilde{q}/\tilde{q}\tilde{q}$$

As shown in Fig.4, ultimate discovery limits $^7$ of

$$M_{\tilde{q}} \lesssim 2 \text{ to } 2.5 \text{ TeV}$$  \hspace{1cm} (13)
$$M_{\tilde{g}} \lesssim 2 \text{ to } 2.5 \text{ TeV}$$  \hspace{1cm} (14)

depth in the TeV range, can be reached for leptonic signatures. Similar bounds are found if the parameters $\tan\beta$, $A_0$ and $\mu$ are altered.

b) Charginos/neutralinos and sleptons

The mSUGRA mass relations (for the lightest members of the two species) can be cast in the form:

$$M_{\tilde{\chi}_i^\pm} \approx 0.5 M_{1/2} \quad M_{\tilde{\chi}_j^0} \approx M_{1/2}$$

and

$$M_{\tilde{\chi}_i^0} = M_0^2 + 0.15 M_{1/2}^2 - \frac{\tan^2\beta}{2} M_{1/2}^2 \cos 2\beta$$
$$M_{\tilde{\chi}_j^0} = M_0^2 + 0.52 M_{1/2}^2 - \frac{1}{2}(1 - 2\tan^2\beta) M_{1/2}^2 \cos 2\beta$$
$$M_{\tilde{\chi}_k^0} = M_0^2 + 0.52 M_{1/2}^2 + \frac{1}{2} M_{1/2}^2 \cos 2\beta$$

Apart from cascade decays, these particles can be generated through the Drell-Yan mechanism:

$$pp \rightarrow \tilde{\chi}_i \tilde{\chi}_j \quad \text{and} \quad \tilde{\ell}\tilde{\ell}$$

in quark-antiquark collisions leading eventually to clean non-jetty events. From the abundant leptonic decay states, bounds $^7$ of

charginos/neutralinos: $M_{\chi_1^\pm} \lesssim 180 \text{ GeV}$
sleptons: $M_{\tilde{\ell}_i} \lesssim 350 \text{ GeV}$

can be set in the high-luminosity runs at LHC.

The mass limits accessible in the Drell-Yan mechanism can be doubled if suitable cascade decays are realized in the SUSY models.

3.2 Discovery limits and ultimate precision at LC

Discovery limits for spin-$\frac{1}{2}$ $\chi$ states and spin-0 $\tilde{\ell}, \tilde{\nu}_i$ states in $e^+e^-$ linear colliders coincide nearly with the kinematical limits, i.e.

$$M_{\tilde{\chi}_1^\pm} \lesssim \sqrt{s}/2 \quad \text{etc.}$$
$$M_{\tilde{\ell},\tilde{\nu}_i} \lesssim \sqrt{s}/2 \quad \text{etc.}$$

Thus, in a 2 TeV collider, chargino/neutralino and slepton masses up to $\sim 1 \text{ TeV}$ [and in some unpaired $\tilde{\chi}_i \tilde{\chi}_j$ channels even beyond] can be observed.

However, the second target of $e^+e^-$ linear colliders is the measurement to high precision of the phenomenological SUSY mass parameters etc. This is possible in a high-luminosity machine, such as TESLA, which allows to perform many threshold scans consecutively. Anticipating $^8$ about 50 pb$^{-1}$ for the high-precision mass measurement at spin-$\frac{1}{2}$ thresholds which rise steeply $\sim \beta$, and about 100 pb$^{-1}$ for spin-0 thresholds which rise more slowly $\sim \beta^3$, more than a dozen independent channels can be analyzed if a total luminosity $\int L \sim 1.5 \text{ ab}^{-1}$ can be provided by the machine.

In such an experimental program, the masses can be determined at the per-mille level $^8$:

$$M_{\tilde{\chi}_1^\pm} = 138 \text{ GeV} \pm 100 \text{ MeV}$$
$$M_{\tilde{\mu}_i} = 132 \text{ GeV} \pm 300 \text{ MeV} \quad \text{etc.}$$

Based on these measurements, the fundamental mSUGRA parameters can be extracted with very high accuracy $^{11}$; for example,
\[ \tan \beta = 3 \pm 0.01 \quad M_0 = 100 \text{ GeV} \pm 120 \text{ MeV} \]
\[ A_0 = 0 \pm 5 \text{ GeV} \quad M_{1/2} = 200 \text{ GeV} \pm 130 \text{ MeV} \]

These high-precision measurements at the per-mille level will allow us to test stringently scenarios of supersymmetry breaking. Since these mechanisms are generated at the GUT/Planck scale, eventually involving gravity, high-luminosity \( e^+ e^- \) linear colliders appear indispensable facilities for opening windows to physics scales where gravity plays an integral role, thus providing a bridge to the unification of all four forces.

4 Left-right symmetric gauge theories

Left-right symmetric gauge theories connect the right-chiral leptons, charged and neutral, and the right-chiral quarks by the absorption or emission of \( W_R^\pm \) gauge bosons. Moreover, neutral gauge bosons \( \nu^\pm \) exist in these scenarios, heavier than the \( W_R^\pm \) by the ratio \( (2 \cos^2 \theta_w / \cos 2\theta_w)^{1/2} \approx 1.7 \). The left and right degrees of freedom mix in general to form mass eigenstates \( W, W' \) and \( Z, Z' \); however, these mixing effects will in general be neglected.

To generate a spectrum of very light and very heavy neutrinos, a see-saw mechanism may be operative which is driven by large Majorana masses associated with the right-handed neutrinos. The light as well as the heavy mass eigenstates are Majorana neutrinos \( \nu \) and \( N \), marked by a family index each.

The gauge bosons \( W_R^\pm \) and \( Z' \) can be produced in the Drell-Yan mechanism:

\[
pp \rightarrow W_R \quad \text{and} \quad Z' \tag{15}
\]

The \( W_R \) bosons are produced in collisions of right-handed quarks and left-handed antiquarks. Similarly \( Z' \), yet also in quark/antiquark beams with reverse handedness. The particles decay into right/left-handed quarks/antiquarks following the same rule, yet also to charged leptons and heavy neutrinos, if kinematically possible:

\[
W_R^- \rightarrow q\bar{q}' \quad \text{and} \quad N_\ell \ell^- \quad \text{and} \quad Z' \rightarrow q\bar{q} \quad \text{and} \quad \ell^+\ell^- \oplus N_\ell N_\ell
\]

The quark decays dominate strongly. The Majorana neutrinos \( N \) decay, if mixing effects are neglected, into charged leptons of either sign with equal probability,

\[
N_\ell \rightarrow \ell^\pm + jj \tag{16}
\]

where a right-handed quark current is coupled to the right-handed lepton current by virtual \( W_R \) exchange.

The signatures of the events\(^9\) are spectacular isolated leptons \( \ell^\pm \) plus two jets, clustering at the \( N_\ell = (\ell jj) \) mass, and a second charged lepton, clustering together with \( N_\ell \) at the \( W_R = (\ell jj) \) mass. Similarly the \( Z' \) chains. As expected, the \( W_R \) channel provides the highest discovery limit\(^9\), shown in Table 2.

Thus, left-right symmetric phenomena can be probed at the LHC in the multi-TeV mass range, in the gauge-boson as well as the neutrino sector.

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References

1. D. Karlen, these proceedings.
7. L. Rurua [CMS], Contribution to ICHEP98; see also Discovery Potential for Supersymmetry at CMS, CMS Note 1998/006.