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HIGGS PHYSICS AT e^+e^- LINEAR COLLIDERS *

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ABSTRACT

The Higgs sector in the Standard Model and supersymmetric theories can be explored in an ideal way at e^+e^- colliders. Operating in a first phase between 300 and 500 GeV, the detection of the Higgs particles in the important intermediate mass range is easy, and the profile of the particles, mass, quantum numbers and couplings, can be determined completely. Increasing the collider energy in a second phase to about 2 TeV, the entire range can be sweeped up to Higgs masses of more than 1 TeV.

1. Introduction

The Higgs mechanism is a cornerstone in the electroweak sector of the Standard Model [$\mathcal{SM}$]. The fundamental particles, leptons, quarks and gauge particles, acquire masses through the interaction with a scalar field [1]. To accommodate the well-established electromagnetic and weak phenomena, the mechanism requires the existence of at least one weak isodoublet scalar field. After absorbing three Goldstone modes to build up the longitudinal $W_L^\pm, Z_L$ states, one degree of freedom is left-over that corresponds to a real physical scalar particle. Even though the value of the Higgs mass cannot be predicted in the Standard Model, constraints can nevertheless be derived if we assume that the model can be extended up to a scale Λ before perturbation theory breaks down and new dynamical phenomena emerge [2]. In particular, if the Higgs mass is less than 200 GeV, the Standard Model can be extended up to the GUT scale of $\sim 10^{16}$ GeV with particles interacting weakly, a prerequisite to the renormalization of $\sin^2\vartheta_W$ from the symmetry value 3/8 down to ~ 0.2 at low energies. Since vacuum stability sets a lower limit of ~ 100 GeV to the Higgs mass for a top mass of ~ 140 GeV, a rather narrow window between 100 and 200 GeV is predicted for the Higgs mass as the theoretically most likely scenario in the Standard Model. Once the mass is fixed, the profile of the $\mathcal{SM}$ Higgs particle is determined completely. From the decay properties and the production cross sections, the quantum numbers of the Higgs particle and the couplings to matter and gauge particles, related to the nature of the Higgs mechanism *per se*, can be determined.

Supersymmetric theories provide a natural mechanism for retaining light Higgs particles in the background of high GUT energy scales [3]. In the minimal supersymmetric extension of the Standard Model [$\mathcal{MSSM}$], two isodoublet scalar fields must be introduced, leading to two $\mathcal{CP}$-even neutral bosons h^0 and H^0, a $\mathcal{CP}$-odd neutral boson A^0 and a pair of charged Higgs bosons $H^\pm$. The observed value of $\sin^2\vartheta_W$ has been predicted accurately in this theory [4]. The mass of the lightest Higgs boson h^0 is bound by the Z mass, modulo radiative corrections of a few tens of GeV [5]. [Triviality bounds similar to the $\mathcal{SM}$ Higgs sector suggest an upper limit of ~ 150 GeV for supersymmetric theories in general [6].] The masses of the heavy neutral and charged Higgs particles are expected in the range of the electroweak symmetry breaking scale. Apart from cascade decays, the main decay modes of the neutral Higgs particles are $b\bar{b}$ decays and to a much lesser extent $\tau^+\tau^-$ decays. [The gold-plated $ZZ\,\mathcal{SM}$ decays play a minor rôle.] $\mathcal{SUSY}$ Higgs particles can be generated through a variety of mechanisms at e^+e^- colliders, Higgs strahlung and fusion as well as pair production. Since these mechanisms are mutually complementary to each other, they allow us to cover the entire parameter range so that the supersymmetric Higgs sector can stringently be tested and thoroughly be explored at these colliders.

2. The Higgs Boson in the Standard Model

The main production mechanisms for Higgs particles in e^+e^- collisions are Higgs strahlung off the Z boson line [7]

$$e^+e^- \to (Z) \to Z + H$$

and the fusion process [8]

$$e^+e^- \to \bar{\nu}\nu(W^+W^-) \to \bar{\nu}\nu H$$

[Additional production processes include ZZ fusion [8] $e^+e^- \to e^+e^-(ZZ) \to e^+e^-H$, three-particle final states in e^+e^- annihilation [9] $e^+e^- \to W^+W^-H$ etc., $e\gamma$ scattering [10] $e\gamma \to \nu WH$ and $\gamma\gamma$ fusion [11] $\gamma\gamma \to H$ with the high energy photons generated by Compton back-scattering of laser light.] After reaching a maximum at $\sim m_Z + \sqrt{2}m_H$, the cross section for Higgs strahlung falls off with the energy $\sim s^{-1}$ so that this process is dominant for moderate values of $\sqrt{s}/m_H$ [12,

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13]. By contrast, the fusion cross section grows asymptotically $\sim m_W^{-2} log\, s/m_H^2$; this process is the most important source for Higgs particles at high energies [14]. The cross sections, shown in Fig.1 for c.m. energies $\sqrt{s} = 300$ and 500 GeV, are of order 100 fb each so that ~ 4,000 Higgs particles will be generated in the intermediate mass range for an integrated luminosity of $\int \mathcal{L} = 20$ fb^{-1} per year. Missing mass techniques in Higgs strahlung, refined by μ-vertexing to reject the ZZ background, provide a very efficient experimental method to detect the Higgs particle in the intermediate mass range, Fig. 2, or to rule out the particle in this range with certainty. In WW fusion the Higgs particles can be detected by collecting the hadronic decay products [16].

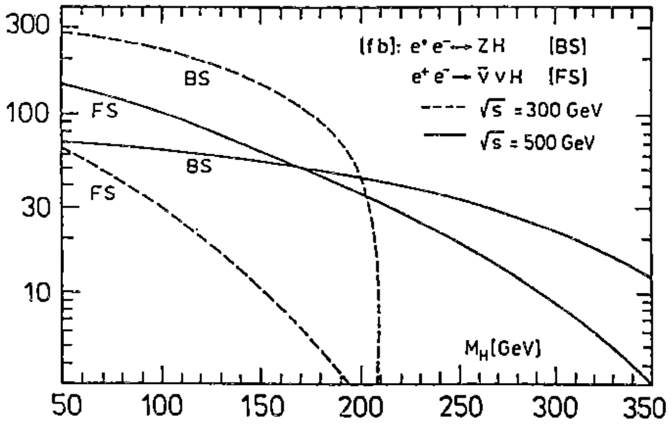

Figure 1: Production cross sections for Higgs strahlung and fusion in the Standard Model.

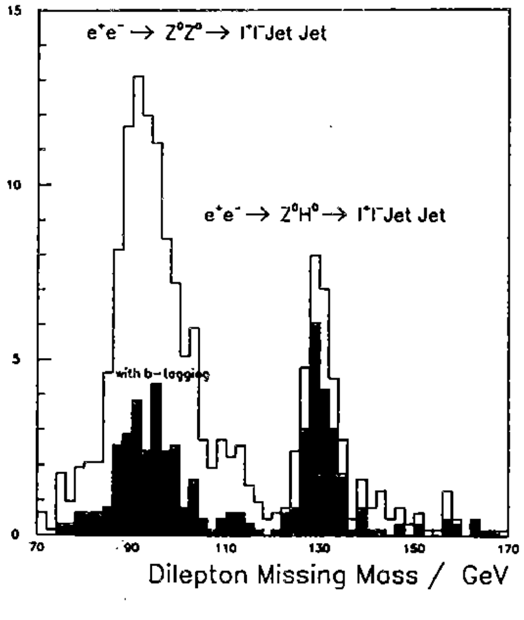

Figure 2: Missing mass distribution in Higgs strahl production; from Ref.[15].

The angular distribution of the Z/H bosons in the Higgs strahl process is sensitive to spin and parity of the Higgs particle [12]. For high energies the Z boson is produced in a state of longitudinal polarization — in accordance with the equivalence theorem — so that the angular distribution approaches asymptotically the $\sin^2 \vartheta$ law. By contrast, the production of a pseudoscalar particle would render the associated Z boson transversely polarized, with the angular distribution $1 + \cos^2 \vartheta$ independent of the energy, Fig.3.

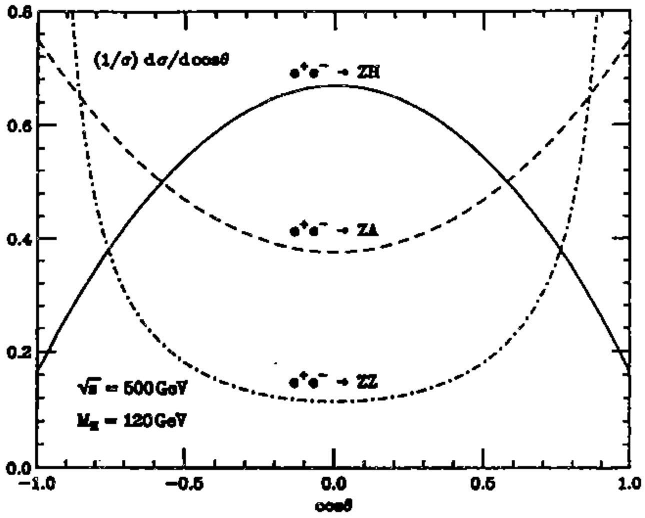

Figure 3: Angular distribution of the Higgs strahl process $e^+e^- \rightarrow ZH$, confronted with pseudoscalar particle production and ZZ background final states [12].

By measuring the couplings of the Higgs boson to gauge particles, leptons and quarks, it can experimentally be verified most directly that fundamental particles acquire masses through the interaction with the Higgs field. The HZZ and HWW couplings determine the magnitude of the cross section for Higgs strahlung and fusion. For Higgs masses below ~ 150 GeV, the measurement of the branching ratios for $b\bar{b}, \tau^+\tau^-, c\bar{c}$ and W^+W^- decays, Fig.4, will allow us to derive the ratios of the corresponding Yukawa couplings; by combining these ratios with measurements of the gauge boson couplings through the production cross sections, the absolute values of the coupling constants can be deduced. The Htt coupling, especially interesting because of the large top mass, can be determined indirectly from Higgs decays to gluons and photons, or equivalently from the $gg, \gamma\gamma \rightarrow H$ fusion processes at hadron and $\gamma\gamma$ colliders, which are mediated by top quark loops. The measurement of this Yukawa coupling can be performed directly if the Higgs mass is large enough for Higgs decays to top quark pairs [18], or if the mass is small enough $\lesssim 120$ GeV to allow for sufficiently large rates of the bremsstrahl processes e^+e^- or $\gamma\gamma \rightarrow t\bar{t}H$ [19].

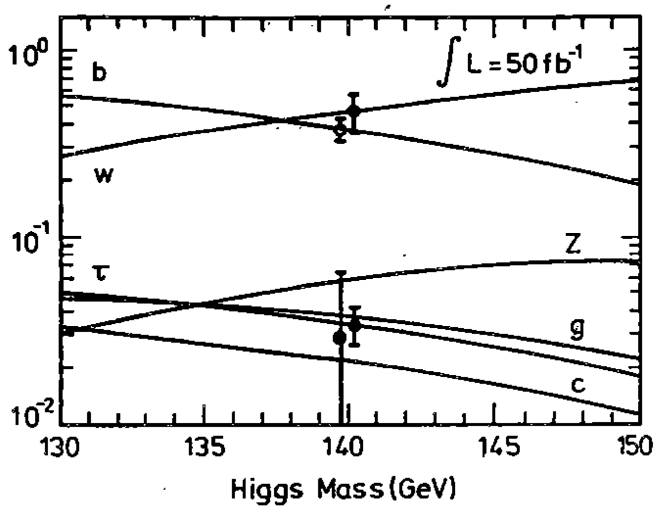

Figure 4: Measurement of the branching ratios for $\mathcal{SM}$ Higgs decays into $WW, b\bar{b}, \tau^+\tau^-$ and $c\bar{c}+gg$ final states, from Ref.[17].

3. The Supersymmetric Higgs Sector

Decays of Higgs particles in supersymmetric theories can be catalogued in three classes [20]. (i) Neutral Higgs particles decay primarily into $b\bar{b}$ and $\tau^+\tau^-$ pairs among the $\mathcal{SM}$ particles (with branching ratios of order 90 and 10 %, respectively) since the couplings to down–type fermions are generally enhanced over the up–type fermions. Charged Higgs particles decay preferentially into $\tau\nu_\tau$ pairs and tb pairs if kinematically possible. (ii) For small tgβ in particular, one of the mixing parameters in the $\mathcal{MSSM}$ Higgs sector, cascade decays like $H^0 \to h^0h^0$ etc. can play a major rôle with branching ratios up to ~ 50 %. (iii) Among the supersymmetric channels, decays into gauginos/higgsinos, $\chi_i^0\chi_j^0$, $\chi_i^+\chi_j^-$ etc., are most likely to occur since the non–colored states are presumably the lowest–mass states in the $\mathcal{SUSY}$ sector. If allowed kinematically, the branching ratios for these decays can range from a few to nearly 100 %. In particular, invisible decays into the lightest supersymmetric particle, $h^0 \to \chi_1^0\chi_1^0$, could be very important [20, 21]. These modes are nevertheless easy to detect at e^+e^- colliders by missing mass techniques.

The main production mechanisms of neutral Higgs bosons at e^+e^- colliders are the standard Higgs strahlung/fusion processes as well as pair production [20],

$$\begin{aligned} e^+e^- &\to (Z) \to Z + h^0/H^0 \\ e^+e^- &\to (Z) \to A^0 + h^0/H^0 \\ e^+e^- &\to \bar{\nu}\nu(WW) \to \bar{\nu}\nu + h^0/H^0 \end{aligned}$$

The pseudoscalar Higgs boson A^0 does not couple to gauge bosons directly. The cross sections

$$\begin{array}{ll} \sigma(Zh^0) \sim \sin^2(\beta-\alpha) & \sigma(A^0h^0) \sim \cos^2(\beta-\alpha) \\ \sigma(ZH^0) \sim \cos^2(\beta-\alpha) & \sigma(A^0H^0) \sim \sin^2(\beta-\alpha) \end{array}$$

are mutually complementary to each other, with the overall size set by the $\mathcal{SM}$ cross section, Fig.5. As a result, the lightest neutral Higgs particle h^0 will be produced with certainty. Moreover, since the processes $e^+e^- \to Z + h^0/H^0$ sweep the entire $\mathcal{MSSM}$ parameter space, the discovery of at least one Higgs particle is possible by missing mass techniques even if the main decay modes are invisible.

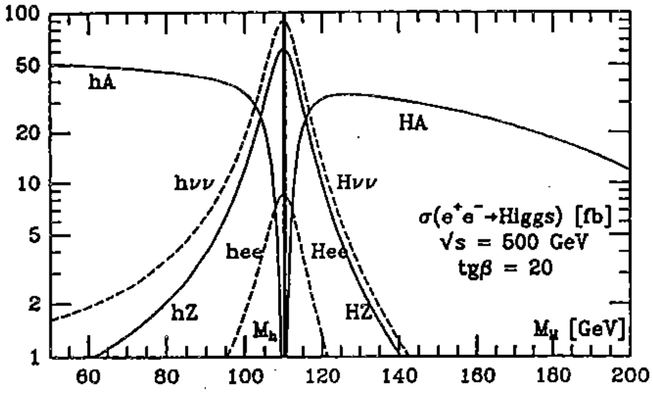

Figure 5: Production cross sections of the $\mathcal{SUSY}$ neutral Higgs bosons in e^+e^- collisions as a function of the mass [in GeV] for $tg\beta = 20$; Ref.[20].

Charged Higgs bosons can be identified in top decays at $pp/p\bar{p}$ and e^+e^- colliders,

$$t \to b + H^+$$

if the H^+ boson is light enough. Since the preferred decay mode $H^+ \to \tau^+\nu_\tau$ breaks e, μ *vs.* τ universality, the particle can be searched for down to branching ratios of order 1% [22]. If the Higgs mass is larger than the top mass, the only clean channel available is pair production in e^+e^- collisions,

$$e^+e^- \to H^+ + H^-$$

leading preferentially to $(t\bar{b})(\bar{t}b)$ final states. In these modes, charged Higgs particles can be detected with masses up to the beam energy [23].

The existence of opposite parity states in two–doublet Higgs models demands a discriminating measurement of this external quantum number. The only known way in practice is presumably the spin asymmetry in the Higgs fusion by linearly polarized photon beams [24, 25]. The production amplitudes are characteristically different,

$$
\begin{aligned}
\mathcal{M}(\gamma\gamma \to h^0/H^0[0^+]) &\sim \vec{\varepsilon}_1 \cdot \vec{\varepsilon}_2 \\
\mathcal{M}(\gamma\gamma \to A^0[0^-]) &\sim \vec{\varepsilon}_1 \times \vec{\varepsilon}_2
\end{aligned}
$$

so that beams of parallel/perpendicular spins can generate only $0^+/0^-$ states, respectively. The linear spin polarization is transferred in Compton back–scattering of polarized laser light to the photon beam up to ~ 30% for the maximum γ energy [26]. The measured asymmetry,

$$A(0^+) = -A(0^-) = \frac{d\sigma^{\parallel} - d\sigma^{\perp}}{d\sigma^{\parallel} + d\sigma^{\perp}}$$

[of opposite sign for 0^+ and 0^- states] is therefore predicted to reach a maximum of ~ 11% at the upper end of the luminosity spectrum, Fig.6.

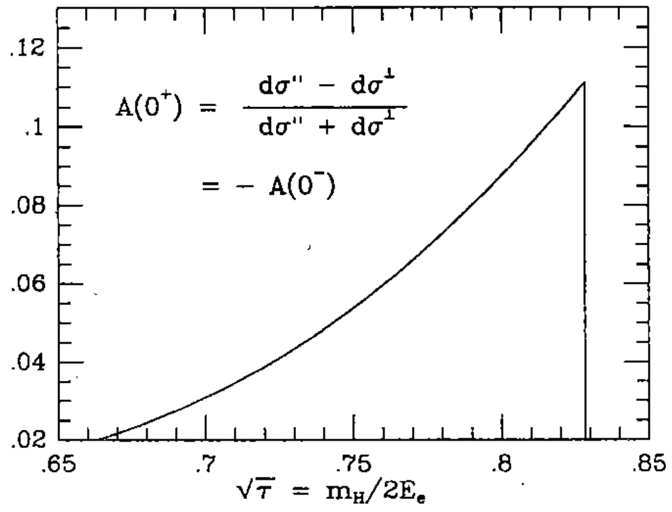

Figure 6: Polarization asymmetry for the production of scalar and pseudoscalar Higgs particles in $\gamma\gamma$ fusion, with photons generated by Compton back–scattering of linearly polarized laser light; Ref.[25].

$\mathcal{MSSM}$ *vs.* $\mathcal{SM}$

If for a given tgβ the mass of the lightest neutral Higgs particle approaches its maximum value, the masses of the $H^0/A^0/H^{\pm}$ bosons move to infinity. As a result, these particles decouple from the system and the properties of the h^0 Higgs boson become $\mathcal{SM}$ like. The $\mathcal{SUSY}$ Higgs sector can therefore be discriminated from the $\mathcal{SM}$ Higgs sector only in the low mass range [20, 16], (i) if for a given top mass the h^0 mass is smaller than the bound derived from vacuum stability in the $\mathcal{SM}$ [27]; (ii) if for $m(H^0/A^0/H^{\pm})$ less than the beam energy several Higgs states can be observed; or (iii) if the decay branching ratios, for $b\bar{b}$ in particular, and the production cross sections are sufficiently different from the $\mathcal{SM}$ prediction, *i.e.* for m_A less than ~ 250 GeV.

4. Conclusions

e^+e^- linear colliders with energies between 300 and 500 GeV are ideal instruments to search for the Standard Model Higgs boson in the theoretically very important intermediate mass range. The profile of the particle can be scanned completely; the external $\mathcal{J}^{PC} = 0^{++}$ quantum numbers can be determined as well as the couplings to the fundamental matter and gauge particles, intimately related to the Higgs phenomenon *per se*.

The same characteristics apply to the Higgs sector in the supersymmetric extension of the Standard Model. The lightest neutral Higgs particle can be found with certainty, the other neutral and charged Higgs states can be searched for masses up to the beam energy. Anticipating the operation of linear colliders in the second phase with c.m. energies up to ~ 2 TeV, it is clear that also the entire $\mathcal{SUSY}$ Higgs sector can thoroughly be explored in these machines. Laser generated polarized $\gamma\gamma$ collisions will be important for measurements of the parity of the Higgs particles. While the minimal version of the Higgs sector in supersymmetric theories has been elaborated at great detail, the essential elements of these patterns transfer to more baroque $\mathcal{SUSY}$ realizations in general.

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