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WHERE IS THE HIGGS BOSON?* **

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The status of the Higgs boson search in the Standard Model and beyond is presented.

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1. Introduction

There are numerous "elementary particles" in nature, Review of Particle Properties AD 1998 lists about 1000 such particles [1]. The Standard Model describing these various particles together with their interactions introduces far less numerous fundamental objects:

spin $\frac{1}{2}\hbar$	leptons:	ν_e	ν_μ	ν_τ
		e	μ	τ
	quarks:	u	c	t
		d	s	b
spin $1\hbar$	gauge bosons:	γ, W, Z, g		

where quarks and gluons appear in, respectively, three and eight states with different colors, and in addition the corresponding antiparticles should be included.

It is difficult to imagine that also in future all these particles remain fundamental building blocks of matter. The appearance of fermions in the three generations has no explanation so far, masses of fundamental particles span a vast range from zero for photon and gluon to 80/90 GeV for other two gauge bosons W/Z, and from a few MeV up to 175 GeV for quarks (u,

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d and t), finally for leptons from 0.5 MeV (e) to 1.8 GeV (for τ). Do we understand this picture?

Today the most promising attempt to establish the origin of mass both for gauge bosons and fermions, and to explain the mass pattern, is based on *the idea that all particles and forces started out as massless quanta but somehow acquired their various masses because of their mutual interactions* [2]. It looks like a paradox that the key to the mass, being of a dynamical nature according to this conjecture, lies in the symmetry.

Two kinds of symmetries are studied in particle physics. From early days of particle physics a symmetry considerations were successfully applied to describe static properties of particles. To this purpose the global symmetries were involved. *A global symmetry ... merely happens to exist, there seems to be no compelling reason to think that things could not be other than they are. A local symmetry has a much more exalted status, because it is intimately connected with the basic forces of nature* [2]. Indeed the application of the local invariance or symmetry (gauge) principles to describe the interactions turned out to be one of the main achievement in the theory of elementary particles in the last 30 years.

The Standard Model, the theory which describes electromagnetic, weak and strong interactions is based on the local symmetry of the following form:

$$\mathrm{SU}(2)_{I_W} \times \mathrm{U}(1)_{Y_W} \times \mathrm{SU}(3)_c \,,$$

where the local (gauge) groups act on the weak isospin I_W, the weak hypercharge Y_W and the color c relevant for the strong interactions. The electric charge Q is related to the above "weak charges" as follows:

$$Q = I_W + \frac{Y_W}{2} \,.$$

Imposing the gauge symmetry we agree (temporarily!) to have W/Z gauge bosons mediating the electro-weak interactions to be massless and the fermions' masses will be zero as well (the corresponding mass terms in the Lagrangian density would violate the assumed symmetry).

The way to obtain a mass of gauge bosons W/Z, while preserving a local gauge symmetry, leads to the concept of the spontaneous symmetry breaking (or *the hidden symmetry*), which does not rely on the additional mass terms in the Lagrangian, but rather on the assumption that there exists a (scalar) field with a specific form of interaction, responsible for the mass of all the particles. *Mass then appears not as a result of emission and absorption of quanta of the scalar field, but as a result of the interaction with the classical part of the scalar field, which extends over all space* [4].

The spontaneous symmetry breaking, called the Higgs mechanism if applied to the local symmetry, is considered as an 'origin' of the mass of fermions and gauge bosons in the Standard Model. The existence of the Higgs scalar is expected to be the direct physical manifestation of this mechanism. Looking for a Higgs boson is therefore a challenge for the particle physics. Of course it is not obvious whether the source of mass lies within the Standard Model. Much more probably it requires a wider scenario beyond SM, presumably related to the unification of all fundamental forces (together with the gravity?).

2. Spontaneous symmetry breaking. Higgs mechanism

Let us consider a simple example showing how the Higgs mechanism works for a system containing a gauge boson A^μ. Here one introduces one complex scalar boson field Φ. The interaction with the gauge boson is described by the Lagrangian density with a local gauge group U(1) in the following form:

$$\mathcal{L} = (D_\mu \Phi)(D^\mu \Phi)^* + \mu^2 \Phi^* \Phi - \lambda(\Phi^* \Phi)^2 - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}\,, \tag{1}$$

where

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu\,. \tag{2}$$

The covariant derivative

$$D^\mu = \partial^\mu + igA^\mu \tag{3}$$

contains the term related to the interaction between the scalar and the gauge field with a coupling g. The considered Lagrangian density is manifestly symmetric under the local U(1) symmetry transformation.

The parameters in the potential part:

$$V = -\mu^2 \Phi^* \Phi + \lambda(\Phi^* \Phi)^2\,, \tag{4}$$

are both positive,

$$\mu^2 > 0 \qquad \text{and} \qquad \lambda > 0\,, \tag{5}$$

leading to the potential bounded from below. (Note that negative μ^2 would correspond to the conventional mass term for Φ.) The potential (4) has minima for

$$|\langle \Phi \rangle| = \frac{1}{\sqrt{2}} v = \sqrt{\frac{\mu^2}{2\lambda}}, \tag{6}$$

where v is called a vacuum expectation value. The example is shown in Fig. 1 for the one real field ϕ, where two minima appear. By choosing one of these minima as a true minimum of the energy, the symmetry of the physical system (the lowest (the vacuum) and higher excited states) is *spontaneously*

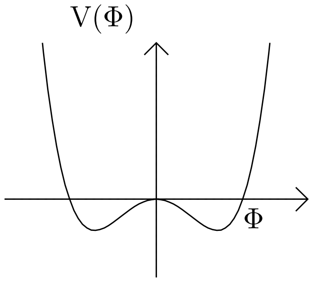


Fig. 1. The Higgs potential.

broken. To make the physical content of the theory more transparent the original field can be expressed by new real fields, ξ and h, with a zero vacuum expectation values, as in the standard quantum field approach:

$$\Phi(x) = \frac{e^{i\xi/v}}{\sqrt{2}}(v + h(x)), \tag{7}$$

and further by choosing a particular gauge with ξ=0 we get

$$\begin{aligned} \mathcal{L} &= \frac{1}{2}(\partial_\mu - igA_\mu)(v+h)(\partial^\mu + igA^\mu)(v+h) \\ &+ \frac{\mu^2}{2}(v+h)^2 - \frac{\lambda}{4}(v+h)^4 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \\ &= \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \mu^2\ hh + \frac{(gv)^2}{2}A^\mu A_\mu + g^2 v\ hA_\mu A^\mu + \ldots \end{aligned} \tag{8}$$

Interpreting the individual terms in the Lagrangian density $\mathcal{L}$ one can find that the considered theory contains:

- a mass term for the gauge boson $M = gv$,
- a neutral scalar boson h (a real field) with a mass $\sqrt{2}\mu$,
- the interaction terms $gM\ hA^\mu A_\mu$ with the coupling proportional to the mass of the gauge boson,
- the self interaction terms hhh, $hhhh$ *etc.*

By measuring the gauge boson mass one can determine the parameter v, provided there is independent constraint on the coupling g:

$$M = gv\,. \tag{9}$$

However, to obtain the mass of the Higgs boson we should know in the addition the self interaction, *i.e.* parameter λ, since

$$M_h = \sqrt{2\lambda} v\,. \tag{10}$$

Note that massless gauge boson has only two polarization states, so by adding one complex or equivalently two real fields we obtain enough independent components to describe one massive gauge boson with 3 polarization states and one neutral scalar particle h.

3. Standard Model

We now summarize the situation of the Standard Model, actually of its electroweak sector (EW), where left-handed states of fermions constitute the $\mathrm{SU}(2)_{I_W}$ doublets, *e.g.* $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_{\mathrm{L}}$, while the right-handed states are $\mathrm{SU}(2)_{I_W}$ singlets. The neutrinos are massless in the standard version of the Standard Model, and the corresponding right-handed states are missing.

To generate masses of weak bosons, one introduces one complex scalar $\mathrm{SU}(2)_{I_W}$ doublet (with $Y_W = 1$) [4, 5]:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix},$$

which if a breakdown in the form $\mathrm{SU}(2)\times\mathrm{U}(1) \to \mathrm{U}_{em}$ is assumed, the vacuum carries the quantum numbers of the neutral component, $\langle\phi^0\rangle = v/\sqrt{2}$. The electroweak sector in SM is described by a covariant derivative:

$$D^\mu = \partial^\mu + ig\frac{\vec{\tau}}{2}\vec{W}^\mu + ig'\frac{Y_W}{2}B^\mu, \tag{11}$$

where the ratio of couplings g and g' is described by the Weinberg angle θ_W, $\tan\theta_W = g'/g$. The original vector gauge fields:

$$W_1^\mu, W_2^\mu \qquad \text{and} \qquad W_3^\mu, B^\mu \tag{12}$$

after mixing between the neutral fields, lead to following physical charged and neutral fields

$$W_\mu^+, W_\mu^- \qquad \text{and} \qquad Z_\mu, A_\mu\,, \tag{13}$$

with the corresponding particles known as $W^\pm$, Z bosons and the photon, γ. They mediate the so called charged (CC), neutral current (NC) processes and electromagnetic processes, respectively.

The mass formula for the W boson is as follows

$$M_W = \frac{gv}{2}\,, \tag{14}$$

and therefore the Fermi constant $G_{\rm F}$, measuring at low energy the strength of the CC weak interaction, can be directly related to the vacuum expectation value, giving

$$G_{\rm F} = \frac{g^2}{4\sqrt{2}M_W^2} \to v = \left(\sqrt{2}G_{\rm F}\right)^{-1/2} = 246 \text{ GeV}\,. \tag{15}$$

Note that generation of the masses for gauge bosons through the Higgs mechanism is such, that a simple relation between the gauge boson masses holds:

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1\,. \tag{16}$$

In addition to giving masses to the gauge bosons, the interaction of scalar field leads to masses of fermions. Namely, for $f_{\rm L}$ being a SU(2) doublet and f_R a SU(2) singlet, we get a mass term for the fermion f:

$$g_f[(\bar{f}_{\rm L}\Phi)f_{\rm R} + hc] \to \frac{g_f v}{\sqrt{2}}(\bar{f}f)\,. \tag{17}$$

Here g_f is the so called Yukawa coupling for fermion f. The parameter in front of the bracket in (20) for obvious reason should be interpreted as a mass of a fermion f, and therefore

$$m_f = \frac{g_f v}{\sqrt{2}}\,. \tag{18}$$

We conclude that the scalar field generates mass terms for fermions. However we note that the fermions' masses are not fixed by the parameters of the Higgs potential, nor the fermion mass pattern can be driven from the assumed mechanism.

The above expression shows also the way the scalar field couples to fermions, with

$$g_f = \frac{\sqrt{2}m_f}{v}\,, \tag{19}$$

i.e. with a coupling proportional to the fermion mass, similarly as for the Higgs boson coupling to the gauge bosons.

4. A need for a Higgs boson in SM: a high energy limit

Let us show now a different argument for introducing a new particle (scalar) into the SM spectrum of fundamental particles, with couplings to gauge bosons and fermions precisely as discussed above for the Higgs boson. The argument is based on a requirement that amplitudes for processes calculated in perturbation theory should not grow too fast at high energy. Following authors of [4] let us consider the process

$$e^+e^- \to \gamma\gamma \tag{20}$$

at very high energy. The differential cross section describes this process as a function of the CM energy $\sqrt{s}$ and the squared momentum transfer t, and

$$\frac{d\sigma}{dt} \sim \frac{\alpha^2}{s^2} \quad \text{for} \quad s \sim |t|\,, \tag{21}$$

which holds for the $s \to \infty$. Here α is the fine structure constant.

Let us now consider the corresponding process involving Z bosons:

$$e^+e^- \to ZZ\,. \tag{22}$$

Should one expect for very large energy $\sqrt{s} \gg M_Z$ the same kind of behaviour as for photons (24)?

First we observe that for the massive boson we have to include not only transverse but also longitudinal polarization. Therefore when calculating a cross section the sum over polarization states for Z appears:

$$\sum \varepsilon_\mu \varepsilon_\nu^* = -\frac{1}{3}\left(g_{\mu\nu} - \frac{k_\mu k_\nu}{M_Z^2}\right)\,, \tag{23}$$

with the high energy limit for the longitudinal polarization term

$$\frac{k_\mu}{M_Z} \sim \frac{k_0}{M_Z} \to \infty \quad \text{for} \quad k_0 \to \infty\,, \tag{24}$$

where k_0 is the Z energy. This behaviour of the polarization density leads to the following high energy behaviour for the cross section

$$\frac{d\sigma}{dt} \sim \frac{(g^2+g'^2)^2}{s^2}\frac{m_e^2 s}{M_Z^4}\,, \tag{25}$$

with the relevant couplings g and g'. This growth with energy is not accepted from point of view of unitarity. One can regularize this behaviour by adding to the Lagrangian density the contribution due to the particle H interaction in the form

$$\mathcal{L}_H = c_e H\bar{e}e + c_Z H Z^\mu Z_\mu\,. \tag{26}$$

This leads to the extra contribution to the ZZ production, see Fig. 2, with couplings c_e, c_Z adjusted to cancel the term (25), namely:

$$c_e c_Z = \frac{1}{2}(g^2+g'^2)m_e\,, \tag{27}$$

$$c_e = \frac{m_e}{v}\,, \tag{28}$$

$$c_Z = \frac{gM_Z}{\cos\theta_W} = \frac{(g^2+g'^2)v}{2}\,. \tag{29}$$

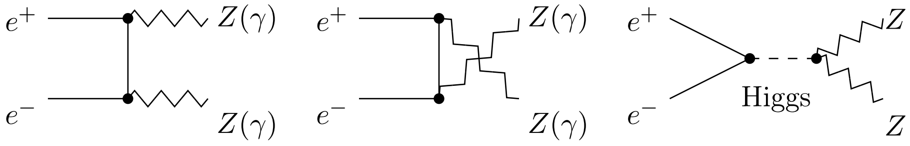


Fig. 2. The process $e^+e^- \to \gamma\gamma$, $e^+e^- \to ZZ$ and the Higgs boson contribution to $e^+e^- \to ZZ$.

Considering other processes of these types one can obtain couplings of scalar (Higgs) boson to other particles, all being proportional to the mass of the respective particle.

5. Search for the Higgs particle in SM

The Higgs particle is the only missing particle of the Standard Model. All properties of this particle but its mass are fixed by the Higgs potential. Theoretical constraints from vacuum stability place lower limit for the Higgs mass ~ 130 GeV while the requirement of applicability of the perturbation theory up to the unification scale gives upper limit ~ 180 GeV [7, 8].

But an experiment remains a decisive source of information on the spontaneous symmetry breaking. Direct searches, where one looks for a possible production of the Higgs particle, are being performed in e^+e^- colliders: LEP and SLC at the Z peak and above, in $p\bar{p}$ collider TEVATRON with a CM energy 1.8 TeV. In these experiments the Higgs mass up to 107 GeV [9] and 120 GeV [10, 11], respectively, can be found. In the near future the pp collider LHC will operate at 14 TeV with the coverage up to mass ~ 1 TeV [12]. There are plans to build e^+e^-, $e\gamma$ and $\gamma\gamma$ Linear Colliders (LC) [17], and maybe also Muon Colliders [18], where precise measurements of the properties of the SM Higgs boson can be performed.

Searches are based on the properties of the Higgs boson expected within SM, like the total decay width and the decay rates for the specific channels, see Fig. 3. It is obvious that the heavier the particle the larger branching ratio for the Higgs particle decay is expected.

The most important constraint at LEP I (at the so called Z-peak, *i.e.* at the CM energy $\sim M_Z$) arises therefore from the Bjorken process Fig. 4(a)

$$e^+e^- \to Z^* \to Z^* H_{\rm SM}. \tag{30}$$

At LEP II also W's and Z's fusion processes start to constrain the mass of the SM Higgs particle Fig. 4(b).

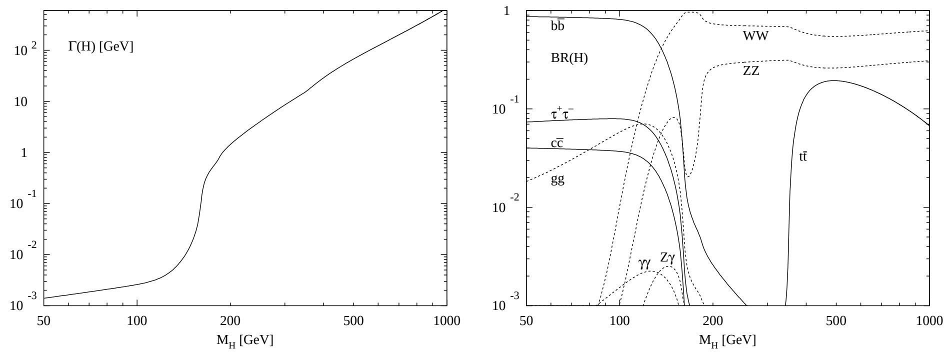
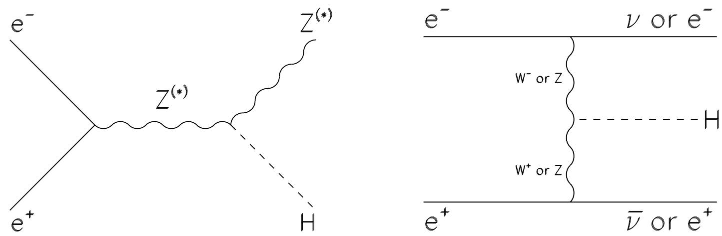


Fig. 3. Total decay width $\Gamma(H)$ in GeV and the main decay modes $BR(H)$ of the Standard Model Higgs boson (from [13]).



(a) (b)

Fig. 4. (a) — the Bjorken process; (b) — the fusion processes

The present combined 95 % C.L. limit for the mass of the Higgs boson from the direct search at LEP (up to the CM energy 183 GeV) is as follows [9, 14]

$$M_{H_{\rm SM}} > 89.8 \ \ {\rm GeV}. \tag{31}$$

In Fig. 5 the highest mass limit (93.6 GeV) from LEP II (at the energy 189 GeV) obtained by the OPAL group is presented [15].

The indirect analysis, where quantum effects due to the various fundamental particles of the SM are included, gives a hint that the Higgs boson mass is low. The indirect analysis based on all precision data as collected and analyzed in 1998, gives the SM Higgs mass (95% C.L.) [16]

$$M_{H_{\rm SM}} = 66^{+74}_{-39} \ \ {\rm GeV}\,. \tag{32}$$

One should stress a large sensitivity of the above limit to the mass of the t quark and the coupling constant of the strong interaction. A unique opportunity to see a Higgs boson as a resonance in the process $\mu^+\mu^- \to h \to f\bar{f}$ can appear at the muon collider [18]. The expected results are presented in

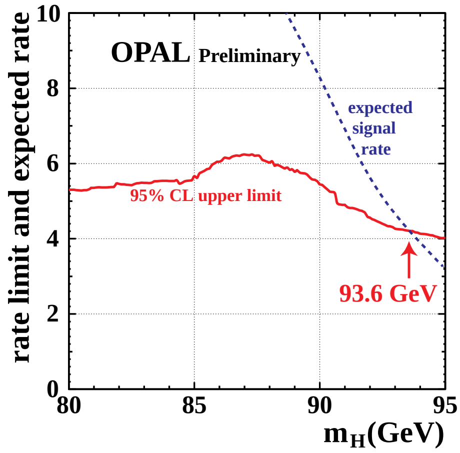


Fig. 5. Results from the LEP II (energy 189 GeV) obtained by the OPAL Collaboration giving the highest limit for the SM Higgs scalar [15].

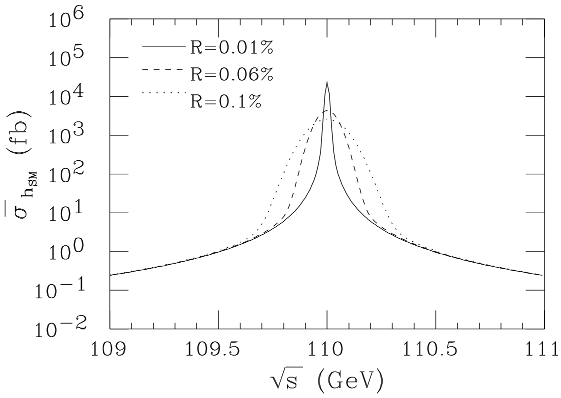


Fig. 6. The Higgs boson peak at Muon Collider, for three energy resolutions R. From [19].

Fig. 6 for mass of SM Higgs boson equal to 110 GeV [19]. Note, that since the expected Higgs boson width is small (Fig. 3(a)), the line shape will be given by the energy resolution.

6. Open problems of the Standard Model

Although the Standard Model nearly perfectly, below two standard deviations, describes the existing data there are still open problems which are not satisfactorily solved in the SM [7]. Large number of free parameters, the lack of explanation for the existence of the generations of fermions, the lack of explanation of the mass pattern for fermions (scales and mixing among them) can not satisfy particle physicists.

As follows from the discussion in Sec. 5 the indirect Higgs boson mass bound (32) means that the SM may be extrapolated up to energies around the Planck scale $M_{\rm Pl} = 10^{19}$ GeV, where the quantum-gravity effects are expected to appear [7,8]. But the smallness of the electroweak scale $v \ll M_{\rm Pl}$ seems then to be a problem (a "hierarchy" problem), which is related to the fact that quantum corrections to v^2 will contain term $\sim M_{\rm Pl}^2$, strongly modifying the mass of the gauge boson and destroying the hierarchy of scales.

The well known quadratic divergence which appears in the Higgs boson mass squared due to the SM particle loop corrections is another face of this problem. Thus, it is not "natural" to have a light Higgs boson in SM. The replacement of an elementary Higgs boson by a bound state might cure this problem. More promising seems to be solution based on supersymmetry where additional particles (superpartners) contribute in a way, which guarantees a cancellation of the divergencies. Note, that "naturalness" leads to a scale $\mathcal{O}$ 1 TeV for mass of superparticles.

The unification of gauge coupling constants cannot be obtained in the SM, pointing once more to a need of larger framework, *e.g.* supersymmetry.

It is a curiosity of the SM that (some) of these questions will persist even after the Higgs boson will have been discovered [7].

A recent experimental evidence for the massive neutrinos leads to the additional questions — note that although the degrees of freedom of the Standard Model permit neutrino masses, a larger theoretical context is needed in order to understand it, see [7, 20].

7. Beyond the Standard Model

No doubt, the most important ideas leading beyond SM are related to supersymmetry. The minimal version of such model is called the Minimal Supersymmetric Standard Model (MSSM). *MSSM, mainly theoretically advocated, is competitive to the SM in describing the data with about the same quality in global fits* [7] (see also [21]).

The unification of supersymmetric gauge theories with quantum gravity within a superstring approach looks also appealing. A unification of gauge couplings is a feature intrinsic to the theory. Recently it has been speculated that the characteristic quantum-gravity scale could be as low as the weak scale [22]. If this is the case, one loses the original motivation for supersymmetry, based on the hierarchy problem. *Supersymmetry may still be desirable as a necessary ingredient of string theory, but it could be broken at the string level and not be present in the effective low-energy field theory* [22].

Other suggestions are going towards the possibility of a non-supersymmetric 1 TeV Grand Unification Theories [23]. It seems that there are good reasons to discuss the extensions of the SM without supersymmetry. Interestingly enough the minimal non-supersymmetric model Two Higgs Doublet Model II (2HDM) can also properly describe the low energy data even with one very light neutral Higgs boson [24, 25].

8. Two Higgs doublet extensions of SM

One of the minimal extension of the Standard Model is the approach where instead of one, two complex scalar doublets of SU(2) (with $Y_W = 1$) are introduced [5]

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}.$$

The potential is usually parametrized as [5]

$$\begin{aligned} V(\Phi_1,\Phi_2) \; = \; & \lambda_1 \left(\Phi_1^\dagger\Phi_1 - v_1^2\right)^2 + \lambda_2(\Phi_2^\dagger\Phi_2 - v_2^2)^2 \\ & +\lambda_3 \left[(\Phi_1^\dagger\Phi_1 - v_1^2) + (\Phi_2^\dagger\Phi_2 - v_2^2)\right]^2 \\ & +\lambda_4 \left[(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - (\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2)\right] \\ & +\lambda_5 \left[\mathrm{Re}(\Phi_1^\dagger\Phi_2) - v_1 v_2 \cos\xi\right]^2 \\ & +\lambda_6 \left[\mathrm{Re}(\Phi_1^\dagger\Phi_2) - v_1 v_2 \sin\xi\right]^2 , \end{aligned} \tag{33}$$

where the parameter $\xi = 0$ guarantees a CP conservation. Below only this case will be discussed.

After spontaneous symmetry breaking two vacuum expectation values appear

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}, \quad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix} ,$$

with

$$v^2 = v_1^2 + v_2^2 \quad \text{and} \quad M_W = \frac{gv}{2} . \tag{34}$$

In the model with two (in fact any) scalar doublets (and singlets) large corrections to the ρ parameter are naturally avoided. There are few patterns how the new fields may couple to fermions in order to avoid in addition the flavour changing neutral currents (FCNC). Four models are considered in the literature (see *e.g.* [5, 26]): in Model I only Φ_2 couples to all fermions, in Model II — Φ_2 couples to the up quarks and Φ_1 to the down quarks and the charged leptons, Model III — Φ_2 couples to the up quarks and the charged leptons and Φ_1 to the down quarks, finally Model IV - Φ_2 couples to the quarks and Φ_1 to the leptons. The Higgs sector of the MSSM has a structure of Model II, therefore below I will concentrate only on this model. First the common features of and limits for the Higgs sector in the Model II will be presented (Sec. 8.1 and 8.2). In Sec. 9 the results specific for the supersymmetric version of the Model II, ie. MSSM, will be given, while in Sec. 10 the non-supersymmetric approach, 2HDM, will be discussed.

8.1. Model II

This model may explain a large ratio between the top quark t and the bottom quark b mass by relating it to the large ratio of the vacuum expectation values [27]:

$$\tan\beta = \frac{v_2}{v_1}\,. \tag{35}$$

The neutral Higgs fields may mix among themselves, this mixing is parametrized by the parameter α. The content of the Higgs sector of the Model II in terms of physical parameters can be described as follows (for the CP conservation)

$$M_h,\ \ M_H,\ \ M_A,\ \ M_{H^\pm}\ \ \text{and}\ \ \tan\beta,\ \alpha,\ \lambda_5,$$

where h, H are the neutral scalars (CP-even particles, by definiton $M_h \leq M_H$), A is a CP-odd particle (often called a pseudoscalar) and $H^\pm$ denotes charged Higgs scalars.

Parameters $\tan\beta$ and α govern the corresponding couplings of Higgs bosons to themselves and to gauge bosons and fermions. The SM couplings of the h to fermions, $(-igm_f/2M_W)$ are modified by multiplicative factors which differ for the two fermion isospins. For example for bottom and top quarks we get:

$$hb\bar{b}:\quad \frac{-\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\,, \tag{36}$$

$$ht\bar{t}:\quad \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \frac{1}{\tan\beta}\cos(\beta-\alpha)\,. \tag{37}$$

The h couples to ZZ with the SM factor $(igM_Z/\cos\theta_W\ g^{\mu\nu})$ times

$$hZZ:\quad \sin(\beta-\alpha)\,. \tag{38}$$

One can see that for $\sin(\beta-\alpha) = 1$ the Higgs boson h behaves in the general Model II Higgs boson as in the SM, while for small $\sin(\beta-\alpha)$ a large differences between two approaches may appear.

For the coupling of the pseudoscalar A to fermions, the corresponding factors, with the normalization as for h in the SM, are

$$Ab\bar{b}: \quad -i\gamma_5 \tan\beta\,; \quad At\bar{t}: \quad -i\gamma_5 \frac{1}{\tan\beta}\,. \tag{39}$$

The AZZ, AWW couplings are absent in the considered model, as a results of CP conservation [5].

For large $\tan\beta$ couplings of h and A to the down quarks and the charged leptons are strongly enhanced while those to the up quarks are suppressed. The situation is reversed for low $\tan\beta$.

From a requirement of the perturbativity of the calculation the value of $\tan\beta$ is restricted to lay between 0.2 and 200 [28].

Below the constraints which are valid for both the supersymmetric and non-supersymmetric versions of Model II will be presented.

8.2. Basic searches

At LEP the basic Higgs boson searches in the neutral sector of the Model II are based on the following processes:

- the Bjorken process $e^+e^- \to Z^*h$,
- the pair production $e^+e^- \to Ah$,
- the Yukawa process $e^+e^- \to f\bar{f}h(A)$,

where the corresponding Higgs couplings can be measured directly.

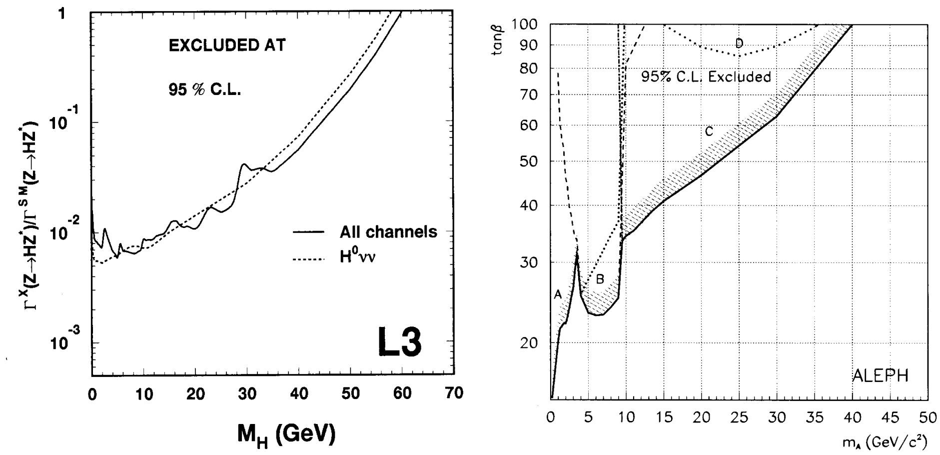
The cross section for the Bjorken process is given by $\sigma(e^+e^- \to Z^*h) = \sin^2(\beta-\alpha)\sigma_{\rm SM}(e^+e^- \to Z^*h)$; therefore by measuring it one can constrain the h coupling to gauge boson (see Eq. (38) and Fig. 7(a), and also Fig. 5). On the other hand the pair production cross section is proportional to $\cos^2(\beta-\alpha)$.

The strength of the pseudoscalar coupling to the down-type fermions, $\tan\beta$, was studied at LEP I by the ALEPH group in the Yukawa process $e^+e^- \to Z \to \bar{f}fA$ [30], for results see Fig. 7(b).

For charged Higgs boson mass there are constraints from the direct search performed at LEP for the process $Z \to H^+H^-$. The 95% C.L. limit, deriven from four LEP experiments, for the CM energy up to 183 GeV, is [9]

$$M_{H^\pm} \geq 59 \text{ GeV}\,.$$

If the charged Higgs boson is lighter than 170 GeV, the t quark may decay into charged Higgs boson and b quark. In such a case in addition to the LEP limit, the limit for $M_{H^\pm}$ as a function of $\tan\beta$ can be obtained from



(a) (b)

Fig. 7. (a) — the experimental limits on $\sin^2(\beta-\alpha)$ from L3 [29], (b) — the present limits for $\tan\beta$ versus mass M_A from the Yukawa process $e^+e^- \to \bar{f}fA$ at LEP I [30].

the TEVATRON data [31]. The resulting exclusion region in the mass $M_{H^\pm}$ and $\tan\beta$ plane is presented in Fig. 8. Note, however that the EW and QCD (strong interaction) corrections may invalidate this analysis in Model II as it was pointed out recently [32].

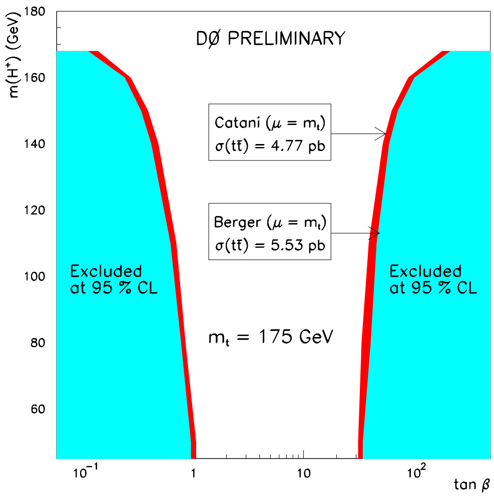


Fig. 8. The exclusion plot for the mass of the charged Higgs boson as function of $\tan\beta$ [31].

The process $Z \to h(A)\gamma$, proceeding via loop diagram, may be of an importance as it has been shown in a recent study [33], see below Sec. 10. There is a sensitivity here not only to the $h(A)$ couplings to fermions and gauge boson W (for h), but also to the trilinear coupling hH^+H^- (λ_5) and the mass of $H^\pm$.

Below we shortly present specific constraints of the two versions of the Model II, the supersymmetric MSSM and non-supersymmetric 2HDM. We will see how much phenomenological consequences differ in these two approaches. The most striking difference is that much lighter Higgs bosons are allowed by the same data in the 2HDM than in the MSSM case.

There are many excellent reviews on the status of Higgs particle searches in the MSSM model (see *e.g.* [34]), therefore below only the main results obtained in this model will be collected. In the following section (Sec. 10) non-supersymmetric version of the Model II, *i.e.* 2HDM, will be disccused in detail.

9. MSSM

Supersymmetry relates fermions and bosons in such a way that for each fermion there exists "its" boson and vice versa (supersymmetric partners). The supersymmetry has to be broken — otherwise exactly equal masses of both kinds of particles are expected, contrary to the observed spectrum of particles.

After the gauge symmetry is broken spontaneously the MSSM Higgs sector arises in a form of the discussed above Model II with five Higgs bosons. In the MSSM there appear supersymmetric relations between parameters of the model, leaving only two of them as independent parameters at the tree level, *e.g.* M_A and $\tan\beta$. Therefore tight constraints from the data on the Higgs boson masses are expected (with a surprisingly weak dependence on the other sectors of supersymmetric particles). Below we list the present constraints on the Higgs sector in MSSM.

9.1. Constraints on the Higgs sector in the MSSM

In supersymmetry the strength of the Higgs self coupling is related to the gauge coupling, leading to the bound on the mass of the lightest scalar h, namely

$$M_h \leq 135 \text{ GeV}\,, \tag{40}$$

for large $\tan\beta$ ([7,35]).

From the direct search discussed above (Bjorken process, and the pair production at LEP, see Sec. 8.2) the analysis in the MSSM framework leads to the present 95% C.L. limits (for the CM energies up to 183 GeV) [9, 14]

$$M_h \geq 77 \text{ GeV} \quad \text{and} \quad M_A \geq 78 \text{ GeV}\,,$$

for

$$\tan\beta \leq 0.8 \quad \text{or} \quad \tan\beta \geq 2.1.$$

In Fig. 9(a), (b) the OPAL limits for the neutral pseudoscalar and scalar based on LEP data (with the CM energy 183 GeV) are shown for $\tan\beta$ as a function of M_A and M_h.

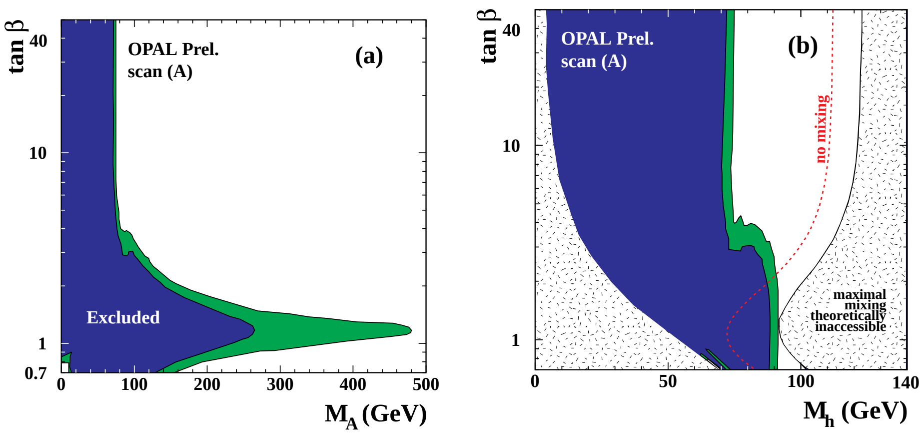


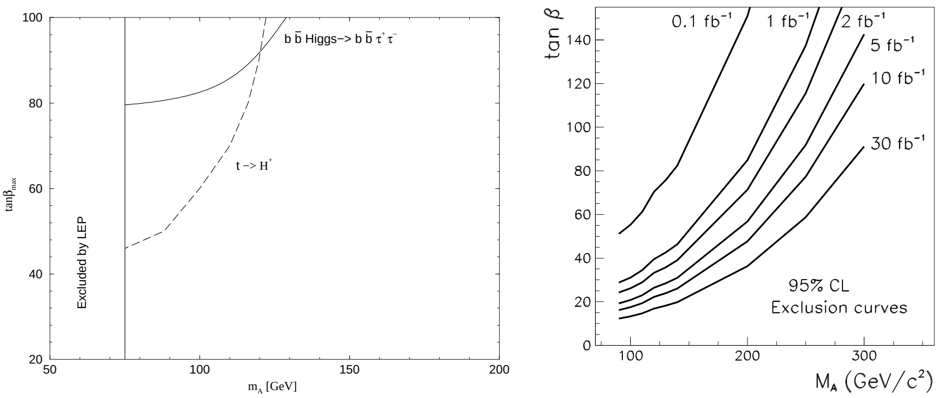
Fig. 9. The OPAL limits based on the LEP data at the CM energy 183 GeV for (a) — $\tan\beta$ versus mass M_A, (b) — $\tan\beta$ versus mass M_h [15].

The TEVATRON allows to constrain the neutral Higgs sector as well. The maximal allowed $\tan\beta$ as a function of the M_A from present data (Run I), and expected for Run II are presented in Fig. 10(a) and (b), respectively. (See also [36]).

The allowed mass region for neutral Higgs bosons (M_h, M_A) in the MSSM is shown in Fig. 11. The important mass relation exists in the MSSM between pseudoscalar and charged Higgs bosons. The charged mass Higgs has to satisfy (at the tree level) the relation

$$M^2_{H^\pm} = M^2_W + M^2_A\,. \tag{41}$$

Therefore we conclude that both neutral and charged Higgs bosons with masses below, roughly, 80 GeV are excluded in the MSSM. The coverage of future searches of the Higgs bosons in the MSSM is summarized in Fig. 12(a), where the potential of different experiments is displayed and in Fig. 12(b), where the role of different channels at LHC is shown [40, 41].



(a) (b)

Fig. 10. (a) — the present 95% C.L. limits for $\tan\beta$ as a function of M_A in MSSM from the TEVATRON (I) data [38]. (b) — similar limits (based on $p\bar{p} \to b\bar{b}A$) expected for the TEVATRON (II) for different luminosities [39].

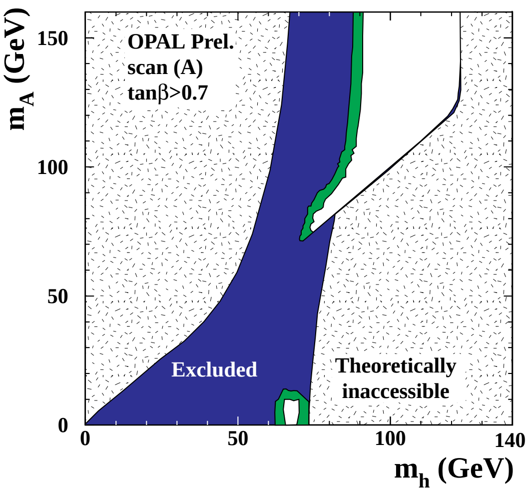
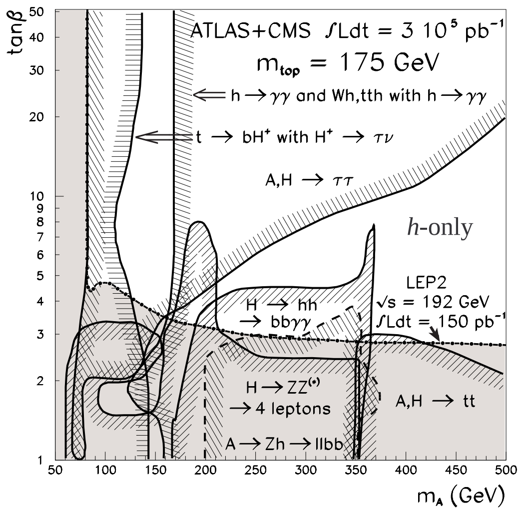


Fig. 11. The limits for Higgs boson masses M_A versus M_h from OPAL analysis obtained in MSSM [15].

To summarize: *If M_h exceeds 130* GeV [1], *the MSSM is inconsistent. If M_h is below 130* GeV, *the MSSM is viable, but is the Higgs boson the MSSM Higgs? Discovery of only one Higgs boson is insufficient to establish the MSSM* [40].

[1] in [7, 35] the limit 135 GeV is given

	complete coverage	partial coverage
LEP-2		h^0 $m_{h^0} \leq 95$ GeV $h^0, A^0, H^0, H^{Ñ}$ possible
TeV-33		h^0 $m_{h^0} \leq 120$ GeV
LHC		at least one MSSM Higgs boson
NLC-500	h^0	$A^0, H^0, H^{Ñ}$ $m_A < \frac{1}{2}\sqrt{s}$
NLC-500 (γγ)	h^0	A^0, H^0 $m_A < 0.8\sqrt{s}$
FMC-500	h^0	A^0, H^0 $m_A < \sqrt{s}$



(a) (b)

Fig. 12. (a) — the coverage of the parameter space in the MSSM by future colliders: LEP II, TEVATRON (Run II), Next Linear Colliders at CM energy 500 GeV (also with the $\gamma\gamma$ collider option) and the First Muon Collider at the same energy [40], (b) — the potential of LHC for testing MSSM [41].

10. 2HDM

The non-supersymmetric version of the Model II, 2HDM, has a Higgs sector the same as MSSM but the relations among parameters imposed by the supersymmetry are missing[2]. In contrast to the MSSM, each parameter has to be constrained independently.

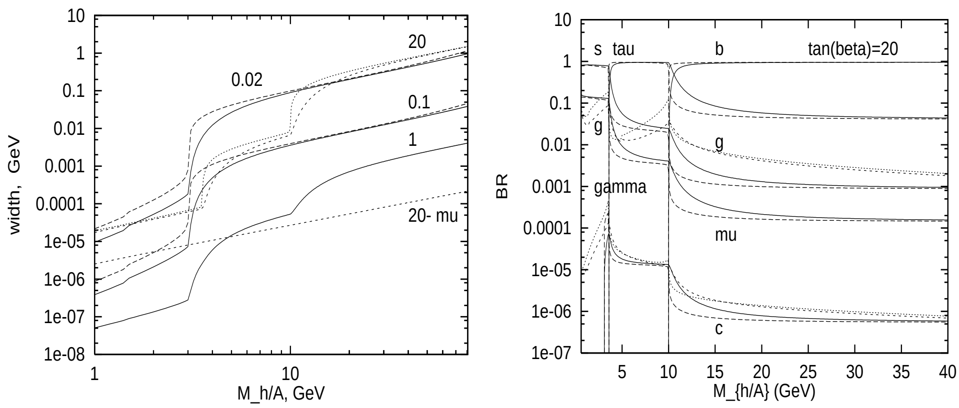
The requirements of vacuum stability and validity of perturbation theory suggests that 2HDM can not be valid up to the unification scale [42]. This is exactly what is expected if 2HDM is treated as a low energy realization of some more fundamental theory.

10.1. Search for Higgs bosons in 2HDM

The basic searches are being performed at LEP (see Sec. 8.2). In addition some limits can be derived from the present measurements of the anomalous magnetic moment for muon, $(g-2)_\mu$, [43a,c] [3].

Direct searches are based on the expected Higgs boson decay width and the branching ratios, as shown in Fig. 13 for low and large $\tan\beta$.

[2] Also the additional particles besides the Higgs bosons are not considered.
[3] Similar analysis in the MSSM can be performed as well.



(a) (b)

Fig. 13. (a) — the total width for h and A for $\tan\beta = 0.1$, 1 and 20 in the 2HDM. For comparison results for $\tan\beta = 0.02$, and the muonic partial decay width for $\tan\beta$=20 are shown [44], (b) — the branching ratio for $\tan\beta = 20$ is presented for A and h (with $\beta = \alpha$) [33a].

Combining the data from the Bjorken process and the pair production leads to the exclusion mass region presented in Fig. 14. This is to be compared to Fig. 11, where similar exclusion plot is obtained in the MSSM framework. The main conclusion is that in the 2HDM a neutral Higgs particle lighter than in SM and in MSSM is allowed, provided the other Higgs particles are heavy enough, $M_h + M_A \geq 50$ GeV. This is also in agreement with recent results from the global fit to the precision EW data obtained in the 2HDM [25].

Two scenarios are worth to be studied here:

→ with a (very) light scalar h

→ with a (very) light pseudoscalar A.

Note that the limit on the coupling of A to b quark and leptons (μ and τ) is given by the measurement of the Yukawa process, see Fig. 7(b) for results. Even a very light pseudoscalar can couple with a large strength, $\tan\beta \sim$ 10–20. For a comparison with the MSSM limit see Fig. 9.

The direct search of a charged Higgs boson leads to results as discussed above in Sec. 8.2. The indirect limit on the mass of a charged Higgs boson arises from the process $b \to s\gamma$. This process is mediated by loops and therefore it is a probe of the Standard Model and of its possible extension. In the context of the 2HDM for $\tan\beta$ larger than 2 [45] one gets a bound

$$M_{H^\pm} \geq 165 \text{ GeV}$$

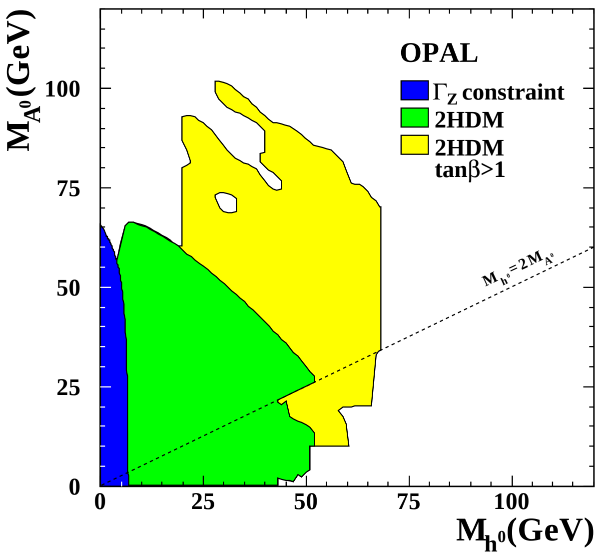


Fig. 14. The limits for Higgs boson masses M_A versus M_h from OPAL analysis obtained in the 2HDM [37].

which is not valid in MSSM. Note, that this limit still allows (in 2HDM!) for the decay of t quark to the charged Higgs boson and b-quark.

With the above limits valid in 2HDM in mind we can discuss now new results from the analysis of the $Z \to h(A) + \gamma$ process, measurements of which were performed recently at the Z-peak by all four LEP experiments. The measured branching ratio is 10^{-6} to 10^{-5} [33, 46]. In the SM the scalar production is due to the W and fermion loop contributions (with a strong domination of the W-loop). The data lay above the SM prediction.

In the 2HDM the $Z \to h + \gamma$ proceeds via loops with W and fermions (with different couplings depending on the parameters α and β (Eqs (43) and (44))), and in addition via a charged Higgs boson loop. For the pseudoscalar production only fermion loops contribute. The results are given Fig. 15 in the form of the 95 % C.L. exclusion plot for $\tan\beta$ versus M_h or M_A.

An interesting opportunity to look for a light neutral Higgs bosons is due to the photoproduction processes at the ep HERA collider [47]. Here the Higgs boson production with masses below 40-50 GeV is dominated by subprocesses due to the partonic content of the photon [48, 49]. In particular the process, where the gluonic content of the photon, denoted as g^γ, interacts with the gluon from the proton, g^p, producing h or A:

$$g^\gamma g^p \to h(A), \tag{42}$$

with subsequent $h(A)$ decay into τ pairs was studied in detail. We found that

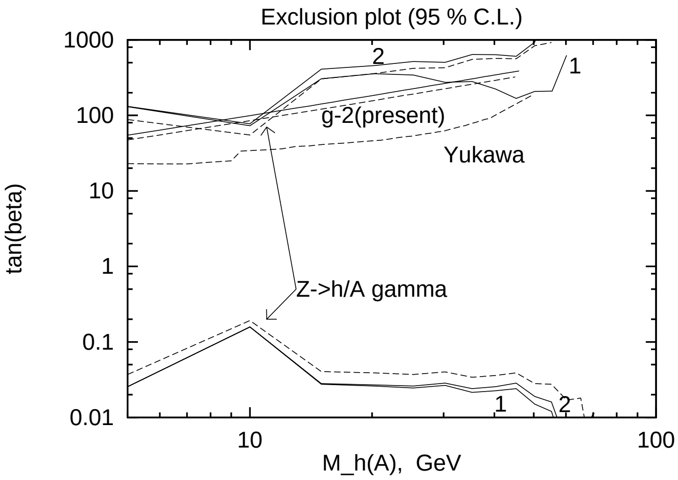


Fig. 15. The present limits for $\tan\beta$ versus mass M_h (solid lines) or M_A (dashed lines) from the analysis of $Z \to h(A) + \gamma$ process at LEP I, compared to constraints from the g-2 for muon data [42a,c] and the Yukawa process $e^+e^- \to \bar{f}fA$ at LEP I [30]. The regions above the upper and below the lower curves are excluded. For the scalar production experimental limits on $\sin(\beta - \alpha)$ from L3 [29] are included and two masses of the charged Higgs boson are assumed: 1) 54.5 GeV and 2) 300 GeV. From [33a].

for this channel one can, at least in principle, get rid of a serious background due to $\gamma g^p \to \tau^+\tau^-$. (For the $b\bar{b}$ final state the background is too large.) The potential of the HERA collider to search for a light Higgs boson is larger than it follows from this analysis, since in addition there are other subprocesses which contribute. On the other hand the SM Higgs search is hopeless at HERA due to the very small rate for mass above 60 GeV.

The potential of futures searches of a very light neutral Higgs boson in the context of 2HDM is presented in Fig. 16. Here the expected limits for the $\tan\beta$ versus Higgs boson mass from a new measurement on $g-2$ for muon at BNL are presented together with a possible exclusion based on the gluon-gluon fusion into h or A (Eq. (42)) at HERA. Results based on the neutral Higgs boson production in $\gamma\gamma$ collision (with $h(A)$ decaying into muons) at low energy LC [4], and the possible results from the process $Z \to A\gamma$ measured at the LC running at the Z-peak are also given.

[4] The very low energy $\gamma\gamma$ collider has been suggested some time ago as a test machine for the NLC [50]. The potential of such a collider in searching for a light neutral Higgs boson in 2HDM was studied in [51]

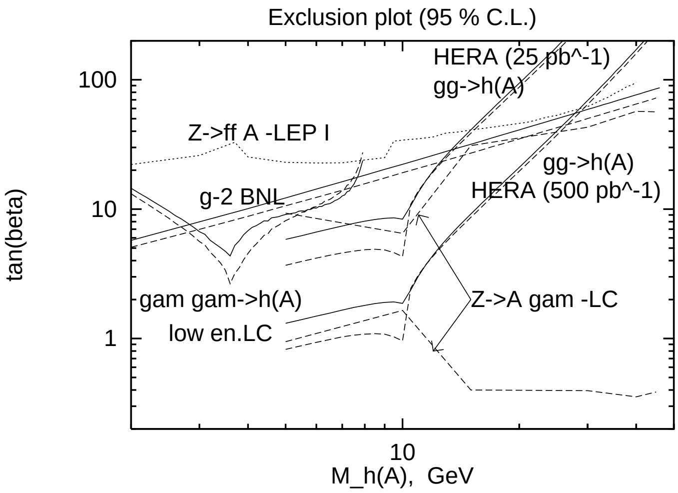


Fig. 16. The potential of the future data on $g-2$ for muon [42c], the HERA measurement (the integrated luminosity 25 and 500 pb^{-1}), and the Linear Collider running at low energy $\sqrt{s}_{ee} = 10$ GeV (with 10 fb^{-1}) and at Z-peak (with 20 fb^{-1}). For the reference the results from the Yukawa process $Z \to \bar{f}fA$ at LEP I are shown. From [33b].

11. Future colliders

LEP is still collecting data, now at the CM energy 189 GeV. The upgrading of the existing colliders TEVATRON and HERA will allow to extend the direct searches of the Higgs boson(s) in the SM, MSSM and 2HDM. Also a new high precision measurement of $g-2$ for muon at BNL may provide crucial, although indirect, source of information on the Higgs sector.

The new hadronic collider LHC will cover a large part of parameter space of the SM and MSSM. After the discovery of the Higgs boson, the determination of its properties will be of highest priority. New generation of the e^+e^- Linear Colliders with energy 300–500 GeV are considered to be an ideal laboratory for discovering and studying the intermediate-mass Higgs boson.

The Linear Colliders running as γe and $\gamma\gamma$ Linear Colliders, with high energy photon beams, offer excellent probe of the $Zh\gamma$, $ZA\gamma$ and $\gamma\gamma h$ or $\gamma\gamma A$ couplings. All these couplings are of great importance for testing the structure of the Standard Model and of the MSSM or 2HDM. The Muon Collider can run at the Higgs boson-peak offering a unique chance to study properties of the Higgs boson.

12. Conclusion and outlook

No Higgs boson has been discovered so far. Both in the SM and the MSSM there are hints that scalar Higgs h should be light, while in the 2HDM one neutral Higgs boson h or A may be light (even very light). So, there is a good chance to learn more about the origin of the spontaneous symmetry breaking in the EW sector in near future.

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