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**Abstract**

The hypothesis of small Higgs boson mass ($m_H \leq 2m_e$) is analyzed. It is indicated that in the analysis of LEP1 direct search results the soft and hard Higgs bremsstrahlung effects and the conversion of Higgs into photon due to Higgs–detector interaction were not regarded. Using ZFITTER programme we have evaluated the one–loop radiative corrections to several quantities measured in precision tests of Standard Model. We show that the very small Higgs mass hypothesis is consistent with this set of experimental data.

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We propose to reanalyze the Higgs mass problem in the limit of very small mass

$$m_H \leq 2m_e \tag{1}$$

which according to several experiments is excluded by experimental data [1]. After recalculation of most of theoretical predictions obtained in the framework of Standard Model (SM) and after the several discussions with experimentalists who carried out the above experiments we came to the conclusion that the authors of publications [1] disregarded the essential aspects of Higgs mass problem and consequently they had no full ground for exclusion of the existence of Higgs particles with mass in the interval (1) and in particular the Higgs mass close to zero.

First we point out some flaws in the direct search and low energy experimental analysis of light Higgs mass problem. Next we confront the light Higgs boson hypothesis with so called precision tests of SM.

In all direct search experiments at LEP the analysis was concentrated on the search of a trace of Higgs particles in the process

$$e^+e^- \to Z_0 \to H + Z_0^* \to H + f\bar{f} \tag{2}$$

where the fermion pair can be either leptons or quarks. The cross section was calculated using the Improved Born Approximation elaborated by Berends and Kleiss [2] and taking into account initial state radiative corrections [3]. Experimental searches for extremely light Higgs bosons ($m_H < 2m_e$) were based on the assumption that detectors are almost transparent for such particles. Then noninteracting, stable Higgs particle passes through the detector and the only signal of its presence is a missing energy and momentum of the rest of products of $Z_0$ decay. Putting proper experimental cuts on the background from neutrinos and nondetected photons one can estimate the number of events with missing energy and momentum in the process (2) [4]. This analysis predicts several events in the total statistics of $10^5$ $Z_0$ (with the background of the same order or without any background – depending on cuts). No such a signal was observed in experiments [1]. Hence the authors of [1] conclude that very light Higgs particle is excluded at 95% C.L.

However there are two essential problems in the above analysis which were not investigated in the satisfactory manner.

The first is the calculation of the cross section of process (2). As it was said this cross section was calculated using the Improved Born Approximation with initial state electromagnetic radiative corrections. However in the treatment of very light Higgs masses one should include also the bremsstrahlung Higgs diagrams describing the emission of additional Higgs particle from every initial, final and intermediate line.

It was calculated in [3] that the soft photon bremsstrahlung effect represents 50% of Born cross section. It was recently calculated that the hard photon bremsstrahlung is also significant [5]. Thus in the case of photon bremsstrahlung — taking into account the soft and hard bremsstrahlung effects — one can considerably change the cross section estimated without bremsstrahlung diagrams.

Now in the case of very light Higgs particles the Higgs bremsstrahlung corrections to the process (2) were not taken into account in the theoretical analysis of any of the considered experiment. No arguments were given that they are not important; on the contrary one can learn from the QED case that this effect can be large. Since in the process (2) light Higgs may have energy up to 45 GeV the hard bremsstrahlung effects should be also considered in the present case. Thus it seems that these potentially significant effects should be calculated before going to the final conclusions of experiments [1].

The second, and perhaps even more questionable point in the analysis of direct search experiment in the very light Higgs boson case is the assumption that Higgs particle does not interact with detector. It is generally assumed that very light Higgs particle produced in collision region leaves the detector without any direct signal. However, if for some reasons the interaction of Higgs particle with detector is sufficiently strong there exist an alternative scenario: Higgs particle penetrates detector and interacts somewhere within it producing photon or leptons, or hadrons. The event is probably registered as photonic or neutrino case or rejected by cut conditions. The crucial question is how strong should be the interaction of Higgs particle with detector in order that the above case would dominate the ordinary scenario with missing energy–momentum.

Let us assume that the production cross section for the process (2) and the number of events with Higgs particles was calculated properly. These calculations predict several events per detector for the considered statistics and experimental conditions discussed in [1]. Thus this what we ask about is the question how strong has to be the Higgs – detector interaction to convert these several Higgs events into electromagnetic or hadronic signal.

There are at least three channels in which Higgs particle can interact with detector. It can produce fermion pair in electromagnetic field of detector's atoms (Fig. 1(a)) analogously to Bethe–Heitler process. It can interact directly with nuclei producing some hadrons (Fig. 1(b)). Finally it can convert into photon via charged triangle interaction with detector (Fig. 1(c)).

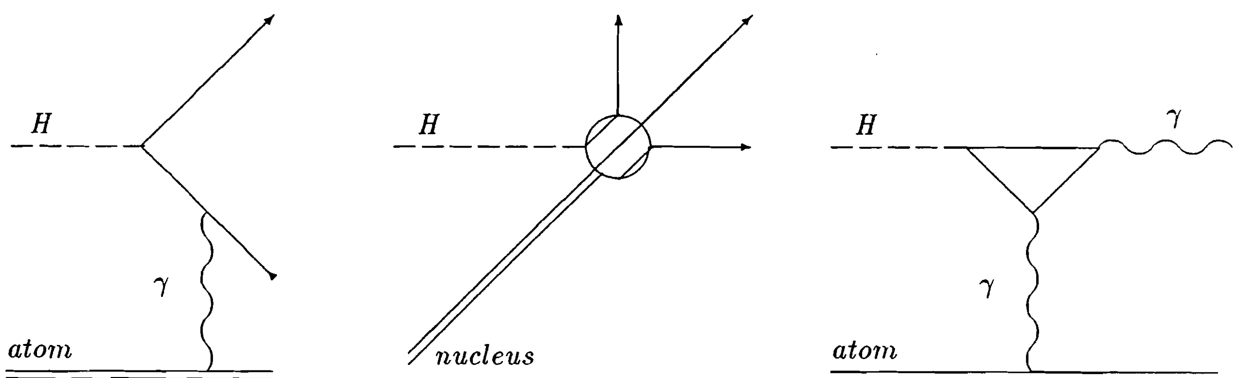


**Fig. 1(a)** **Fig. 1(b)** **Fig. 1(c)**

One can give some arguments that the first and the second channel in Fig. 1 give marginal contribution to cross section of process (2) [6]. However the third and probably most promising interaction channel is Higgs–photon conversion in the electromagnetic atomic field (Fig. 1(c)). One loop interaction in Fig. 1(c) is potentially large because it can proceed with zero momentum transfer (in the massless Higgs boson limit). In addition contributions from loops with all charged particles of the theory have to be included because they contribute independently of theirs masses – this is the same effect as in the case of Wilczek process [7]. $H\gamma\gamma^*$ vertex was calculated in [8]. However, because of the possibility of zero momentum transfer interaction, the cross–section is very sensitive to the choice of atomic formfactor – the situation seems to be more complicated than in the usual Bethe–Heitler production where Weizsacker–Williáms approximation works.

We conclude that the problem of Higgs boson – detector cross-section remains open and must be calculated carefully before going to the final claims.

Many authors have also tried to derive limitations on Higgs mass from hadron physics by investigating the processes like

$$K \to \pi H, \quad \eta \to \pi H, \quad \eta' \to \eta H, \quad J/\Psi \to H\gamma \quad \Upsilon \to H\gamma \quad \Sigma^o \to \Lambda H, \qquad (3)$$

etc..[7] and from nuclear physics [9]. However all these limits suffer from a fundamental theoretical uncertainty. In spite of many years of intensive work and efforts of many people there is no generally accepted theory leading from a fundamental high energy physics model to a calculable unambiguous model of low energy hadronic and nuclear interactions. The reason seems to be clear: the strong coupling constant in low energy region is large. For instance for the process $K \to \pi H$ the $\sqrt{s}$ is comparable with $\Lambda_{QCD}$: in this region in $\overline{MS}$ renormalization scheme $\alpha(s) = 2\pi(\beta_o ln\frac{s}{\Lambda^2})^{-1}$ is very large and hence it is very difficult to use perturbative arguments to justify any calculations. The satisfactory description of process (3) in the language of Standard Model would also require the knowledge of hadron wave function expressed in terms of quarks and gluons. As it is known the reliable representation for hadrons does not exist up to now and there is seven proposals in the literature for hadron wave functions which lead to drastically different physical predictions [10].

In addition, because of the problems listed above a part of analysis of experiments (3) was based on the simplest, extrapolated from high energy region assumptions concerning Higgs – hadron interaction. It was assumed in these analysis that Higgs particle couples effectively to hadrons or nuclei in the same way as to the constituent quarks with effective coupling constant $\frac{m_{HADRON}}{< H >}$, $< H >= 246GeV$, but of course this assumption was never tested and it was not derived in SM framework [11].

Hence conclusions on exclusion of small Higgs mass on the basis of analysis of hadronic decays (3) is not reliable.

Now we present the theoretical analysis of the influence of the light Higgs boson hypothesis on first order radiative corrections to the typical experiments at LEP.

In order to demonstrate that the perturbative calculations in SM do not exclude very small Higgs mass we present contour plots of theoretical predictions dependent on Higgs and top mass for four typical quantities used in so called "precision tests" of the Standard Model. The predictions were evaluated using ZFITTER fortran code [12] based on *on–shell* electro–weak radiative correction analysis of Bardin *et al.* [13][14][15]. Weak boson box diagrams corrections and all second order QED corrections were included as well as three loop QCD correction factors of Gorishny, Kataev and Larin [16]. We have assumed $m_Z = 91.187GeV$ [17] and strong coupling constant $\alpha_S = 0.12$.

The first quantity is the weak mixing angle expressed by $sin^2\theta_W$ (defined by weak bosons masses ratio according to Sirlin [18]). We see in Fig. 2(a) the contour plot of SM predictions for $sin^2\theta_W$ plotted as a function of Higgs and top masses. The theoretical expression does not contain "bare" logarithms of $m_H$ and consequently the SM prediction is a regular function of $m_H$ even in the zero Higgs mass limit. The theoretical curve depends on Higgs mass changing logarithmically from 1keV to over 1TeV (on x axis) and on top quark mass changing linearly from 80 to 270GeV (on y axis). The solid lines represent central experimental values and regions within one standard deviation are indicated by gray color. We have used the value $sin^2\theta_W = 0.2273 \pm 0.0052$ from UA1 and CDF [19]. We see that the light Higgs hypothesis is consistent with experimental data. In this limit we get from experimental cut the estimate

$$m_t = 120 \pm 45 GeV. \tag{4}$$

The error reflects mostly our ignorance of W mass. The solid curve of experimental cut growths in the $m_H, m_t$ plane from $m_t = 120GeV$ for $m_H = 0$ to $m_t = 165GeV$ for $m_H = 1TeV$.

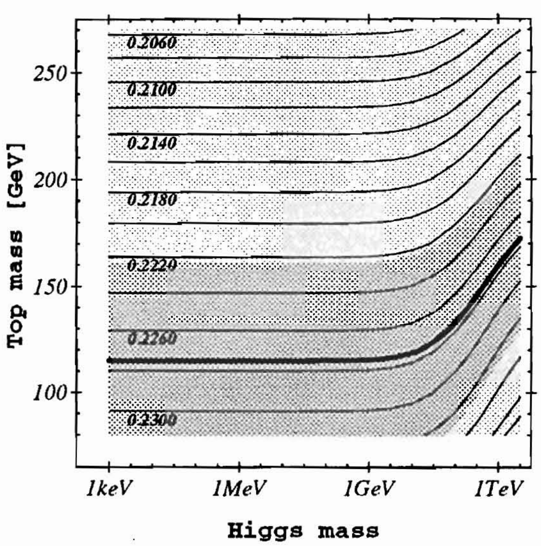


**Fig. 2(a)** (*contour plot*)
Weak mixing angle $sin^2\theta_W(m_H, m_t)$

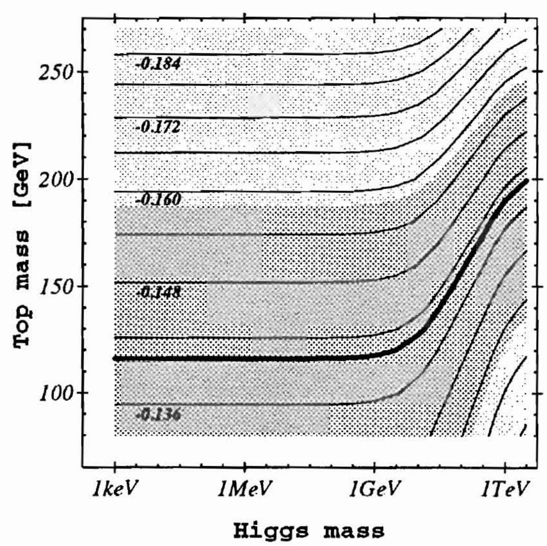


**Fig. 2(b)** (*contour plot*)
$\tau$ helicity polarization asymmetry
$P_\tau(m_H, m_t)$

The second quantity is the helicity polarization asymmetry $P_\tau$ of tau lepton pair production in $e^+e^-$ collision at $Z^0$ peak. We give in Fig 2(b) the contour plot of SM predictions for $P_\tau$. We see again that the very light Higgs mass is not excluded by data.

We have carried out the same analysis for four other quantities measured in LEP1 experiments namely for forward–backward asymmetry $A^0_{FB}(m_H, m_t)$, tau polarization forward-backward asymmetry $P^{FB}_\tau(m_H, m_t)$, peak cross–section $\sigma^0_{had}(m_H, m_t)$ and the hadron to lepton production width $R(m_H, m_t)$ in the interval $1keV \leq m_H \leq 1GeV$, $80GeV \leq m_t \leq 270GeV$ and we have reached the same conclusion: the very low Higgs mass is not excluded by the above experimental data [6].

We wish to stress however that there are physical quantities which do depend in the small Higgs mass limit on the term $c \ln m_H$ (with a relatively large factor $c$) which sharply decreases.

The example of such quantities represent the electron $\Gamma_e(m_H, m_t)$ and hadron $\Gamma_{had}(m_H, m_t)$ pair production widths in $e^+e^-$ collision at $Z^0$ peak. We present in Fig. 3(a) the contour plot for $\Gamma_e$ width and in Fig. 3(b) the contour plot for $\Gamma_{had}$ width.

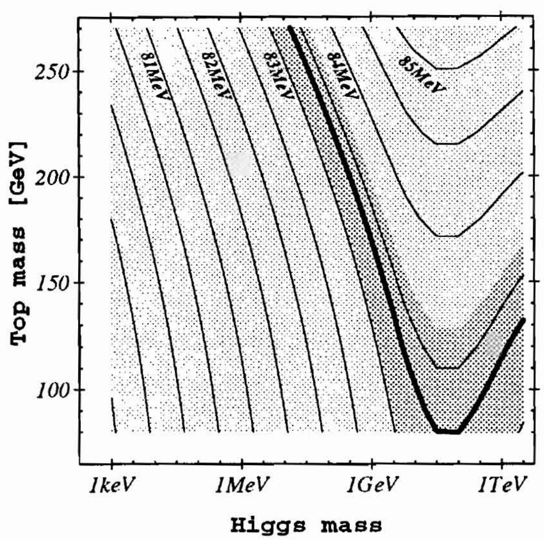


**Fig. 3(a)** *(contour plot)*
$e^+e^-$ production width $\Gamma_e(m_H, m_t)$

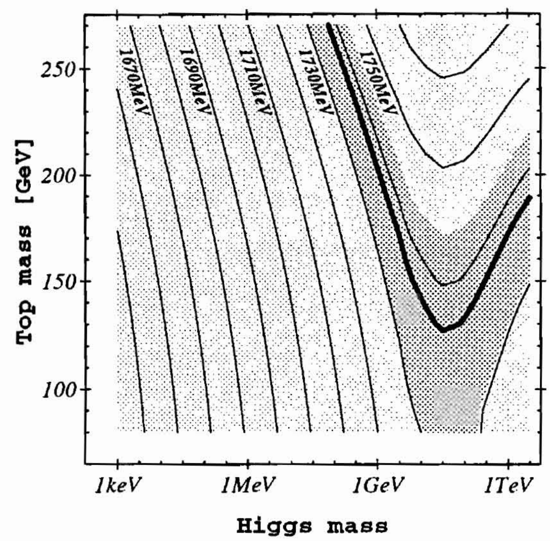


**Fig. 3(b)** *(contour plot)*
Hadron production width $\Gamma_{had}(m_H, m_t)$

We see that if $m_H \to 0$ the contour lines sharply changes. We have observed the same phenomenon for some other quantities, e.g. for all partial widths. The reason is clear: theoretical predictions obtained in renormalization scheme used by the authors of ZFITTER (and in most of other renormalization schemes used in the literature) are valid only in the case of massive Higgs fields. For instance in ZFITTER programme it was assumed already at the stage of regularization, that scalar loops do not produce infrared singularities (see [13]). Consequently the obtained expressions contain logarithms of scalar mass and explode in the massless limit due to infrared singularities. In our case such contribution is contained in $\Delta\rho$ radiative correction, namely in $Z_F(-1)$ term of (A.1) in ref. [15] given explicitly by eqs. (A.5) of ref. [14]. Collecting all expressions we can write

$$\rho = 1 + \Delta\rho = 1 + \frac{\alpha}{4\pi}\frac{1}{\sin^2\theta_W \cos^2\theta_W} \ln\frac{m_H}{m_Z} + (regular\ terms). \qquad (5)$$

The quantity $\rho$ appears as the multiplicative factor in one–loop expressions of production widths at $Z^0$ peak and enters to some other related measurable quantities. We have plotted in Fig. 4 the correction $\Delta\rho(m_H)$ (solid line) as well as its regular (dotted line) and logarithmically exploding term (dashed line). We see that the last one dominates the full expression for $\Delta\rho$ for Higgs mass smaller than several GeV.

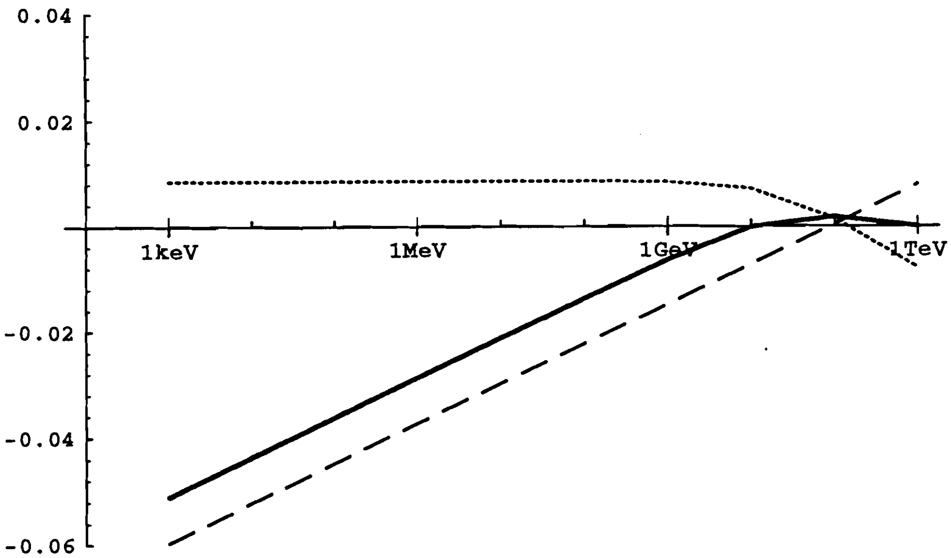


**Fig. 4** One–loop correction $\Delta\rho(m_H)$ (*solid line*), its regular component (*dotted line*) and logarithmic component (*dashed line*); $m_t = 110 GeV$.

The source of this logarithmic term (in the considered renormalization scheme) is the scalar loop contribution to renormalization of $Z$ boson wave function. The effect of such exploding of some quantities has of course no physical meaning. It means only that the chosen (in the process of renormalization) method of perturbative expansion taylored to the expected rather large Higgs mass is improper in case of light mass limit and, due to infrared divergences, this method leads to big radiative corrections such as $\Delta\rho$ described above.

There is a serious problem how to decide starting from which value of the Higgs mass we can believe in one loop corrected expressions? The first and simplest idea is to check how big are the corrections in comparison with the tree expression. We have calculated that the one loop corrections do not exceed several percent in the whole region plotted in Figure 3(a-b). However our calculations suggest that something wrong occurs somewhere around $m_H = 50 GeV$. Indeed as we can see from Fig. 3(a) and 3(b) starting down from the Higgs mass value around $m_H = 50 GeV$ the central value solid curves for $\Gamma_e$ and $\Gamma_{had}$ sharply increase due to the logarithmic term shown in Fig. 4 which we know about that it is asymptotically incorrect. We think that this is a serious reason to doubt in one–loop predictions for Higgs mass smaller than several dozens GeV obtained in so far considered renormalization schemes.

We have to mention that this artificial effect described above was totally ignored by many authors of so called "global fits" to data (see, e.g., [20], [21]). In fact they found some "minima" at Higgs mass between $10 GeV$ and $100 GeV$ depending on the chosen set of analyzed quantities and data. In our opinion this is a spurious effect implied by large unphysical logarithmic term (see Fig. 4).

If we want to extract a reliable predictions in the frame–work of existing calculational scheme we should select out the physical quantities which either do not depend on exploding logarithmic term (like $sin^2\theta_W$) or quantities which very weakly depend on singular term (like $P_T$ plotted in Fig. 2(b) or some other asymmetries and widths ratios discussed e.g. in our previous work [6]). Comparing results of our calculations with experimental data we found in [6] our predictions for the top quark mass in the very light Higgs boson limit:

$$m_t = 110 \pm 35 GeV. \tag{6}$$

Since the above results were surprising for us and other people we have decided to repeat our analysis also in $\overline{MS}$ renormalization scheme. Using the computer programmes provided for us by G. Degrassi [22] we have obtained the similar conclusions.

Summarizing we stress again that the calculational programme codes utilized for analysis of Higgs mass dependence problem had build in the supposition that Higgs mass is far away from massless limit. Hence these programmes – by construction – cannot be utilized for analysis of light Higgs mass problem as it was unfortunately done in several works [1].

In order to give the reliable analysis of light Higgs mass problem there must be satisfied three conditions:

$1^0$ The soft and hard bremsstrahlung Higgs effects must be taken into account.

$2^0$ The conversion of Higgs bosons into photons due to Higgs–detector interaction must be regarded.

$3^0$ The selected renormalization scheme must be valid for entire Higgs mass interval $0 \leq m_H \leq 1TeV$.

We have given in [6] a natural cosmological arguments that Higgs mass may be close to zero.

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