ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E2-97-17

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CONSISTENCY TEST OF THE STANDARD MODEL

Talk given at the IX Seminar «Gravitational Energy and Gravitational Waves», December 9 — 12, 1996, Dubna, Russia

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*Supported by the Polish Committee for Scientific Researches

1997

The introduction of the physical Higgs particle with nonzero mass regularizes some ultraviolet divergences of electroweak theories. It makes that the Standard Model (SM) and most of its extensions are perturbatively renormalizable. The physical mass of the Higgs particle m_H can be indirectly predicted by the theory: it can be derived from the precision measurements of observables that are sensitive to the radiative corrections dependent on m_H. Here m_H plays in fact a role of a UV regulator for bosonic contributions. The Higgs mass is a measurable physical constant, by definition. Consequently it must be the same when derived indirectly from the data of different experiments performed at different energy scales.

The regularizing role of m_H can be also played by the ultraviolet cutoff introduced in the models where the Higgs particle is absent [1, 2, 3]. The cutoff is an artificial element that we introduce to cover an incompleteness of the model or the imperfection of our calculational methods either it simply reduces a complicated task to a less complicated one. If we try to hide our ignorance in a simplest way we introduce one additional parameter - a cutoff Λ. We hope that this parameter can be the same for a class of similar phenomena. Predictivity of a model holds if the cutoff Λ is process independent for a restricted interaction energy region at least. It would be nice to have a universal cutoff valid for all phenomena below some energy scale but in principle it needs not to be the case. (We know this from the experience with QED [4].) Thus we have to admit that the cutoff is energy dependent.

In practice the energy dependence of Λ can be studied as follows: Predictions of a regularized model can be calculated for experiments performed in various energy regions. These predictions would depend on the cutoff Λ and inversely: the value of the appropriate cutoff derived from experimental data measured in different energy regions can be different. It makes that the cutoff becomes energy dependent in a sense.

As we have already mentioned, the UV cutoff Λ of electroweak models is closely connected with the Higgs mass of SM but, in contrast to the demanded and expected energy independence of m_H, we have to admit an energy dependence of Λ. This is the difference that makes a room for experimental tests and a comparison of the Standard Model and the models that admit an energy dependence of effective (or dynamical) UV regulator. The independence or dependence of the predicted Higgs mass on a set of observables that it has been derived from can be also seen as a sensitive selfconsistency check of the SM itself.

Thus the task is to derive the value of UV regulator (m_H or Λ) from at least two independent sets of data collected in experiments performed in different energy regions (to be more concrete: with different characteristic energy-momentum transfer of weak interactions). The close relation between m_H and the cutoff is an essential practical and logical element of the reasoning. It was shown [2, 1] that the results of an effective electroweak theory with the cutoff Λ can be reproduced approximately from the SM results when we replace m_H by Λ. The differences between the exact and the approximate results are small and are given by known expressions. Thus in practice, instead of studying directly the energy dependence of the cutoff Λ in a cut model, we can make use of the wealthy set of SM results. This fact is important also from the logical point of view. Any observed energy dependence of the regulator m_H can be clearly interpreted as a negative result of the self-check of the SM but will be admitted by theories without the physical Higgs boson. Of course if no energy dependence would be detected it will mean nothing for both classes of models. In this sense the proposed idea constitutes a kind of negative selfconsistency test of the SM.

The above consideration makes sense only if the Higgs particle is not found directly. LEP experiments put the direct limit $m_H > m_{min}$ on the mass of the physical Higgs boson. This direct search restriction cannot be valid longer if we admit reinterpretation of m_H. In fact the indirect LEP data are less restrictive than the direct search limit and prefer values of m_H even smaller than m_{min}. Thus in our considerations we have to ignore restrictions following from the direct Higgs search at LEP.

The problem of choice of a renolmalization scheme must be also treated carefully. It is convenient to use EW on-shell renormalization scheme in SM analysis. Then the theory is described by the parameter set consisting of α, α_s, m_Z, m_W, m_H and masses and mixing angles of fermions. Because W-meson mass m_W is known with relatively big experimental error it is practical to replace m_W by the precisely measured muon decay constant G_μ. This quantity can be calculated within the model and one obtains the famous relation

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G^\mu \sin^2\theta_W(1-\Delta r)} \tag{1}$$

where $\sin^2\theta_W = 1 - m_W^2/m_Z^2$ and Δr contains radiative corrections depending on all parameters of the theory including m_H and m_W. Equation (1) can be solved iteratively giving

$$m_W = m_W(\alpha, \alpha_s, m_Z, G_\mu, m_H, ...) \tag{2}$$

and we can replace m_W by G_μ in the parameter set of the model.

The situation is slightly different when we have to do with an effective theory without the physical Higgs particle in which m_H is not a mass of physical particle but can be a cutoff. Consider for example a generic quantity Σ describing an electroweak process proceeding with characteristic energy $E_{(1)}$.

$$\Sigma = \Sigma(\alpha, \alpha_s, m_Z, G_\mu, m_{H(1)}, ...). \tag{3}$$

Assume that in the considered model we can derive relation analogical to (2)

$$m_W = m_W(\alpha, \alpha_s, m_Z, G_\mu, m_{H(0)}, ...). \tag{4}$$

Relation (4) follows from the analysis of μ decay within the cut model. The characteristic energy for this process is μ meson mass $E_{(0)} = m_\mu \approx 0$. Thus $m_{H(1)}$ in (3) and $m_{H(0)}$ in (4) need not be the same as the values of cutoff in principle can be different for the processes with energies $E_{(1)}$ and $E_{(0)}$. This is the difference between the SM and models without the Higgs boson. We have to take into account this difference when we look for a supposed energy dependence of m_H or we can avoid this problem working with m_W as an input parameter. The last approach is also justified by growing accuracy of m_W measurements.

Currently the most precise EW data come from e^+e^- collider experiments. LEP and SLC provided us with a set of information about the physics near Z_0 peak with accuracy sensitive to EW radiative corrections. A limited information about the Higgs mass can be also derived from this data. Many other EW experiments were performed in the past [5] but none of them was accurate enough to give even qualitative information about m_H. New generation experiments are necessary both below and far above the energy of Z mass. We are to restrict ourselves only to low energy region in the present analysis.

Some of the quantities measured at Z_0 peak can be measured in principle for the whole e^+e^- energy collision range. These are cross sections and production asymmetries. Unfortunately most of them are almost insensitive to the value of the Higgs mass except the small region near the peak. For example it was known since the analysis of PETRA/PEP experiments that the forward–backward asymmetry is sensitive weaker than 0.2% for the variation of m_H from 10GeV to 1000GeV [6].

The exceptions are leptonic asymmetries, especially tau polarization A_{pol} and tau polarization forward–backward asymmetry $A_{pol}{}^{FB}$.

We have enumerated the energy dependence of these quantities for $m_H = 10GeV$ and $m_H = 1000GeV$. For this purpose we have used the old version 453 of ZFITTER package [7] that, according to its authors [8], can be applied for collision energies above b pair production threshold. We have modified this code introducing the experimental value of m_W as an input parameter instead of conventionally used G_μ for the reasons already discussed. This enlarges the error but in fact only qualitative results are interesting at the present stage. We have check that this modification has quantitatively observable but qualitatively unimportant consequences for the present analysis.

We have plotted our results in Figs. 1–6.

Fig. 1 (resp. 2) shows the energy dependence of A_{pol} (resp. $A_{pol}{}^{FB}$) for $m_H = 10GeV$ (dashed line) and $m_H = 1000GeV$ (solid line) in the energy range $\sqrt{s} < 100GeV$.

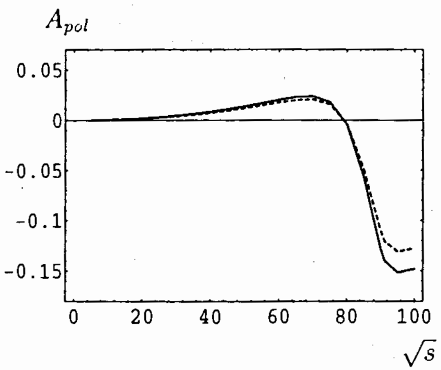

Fig. 1

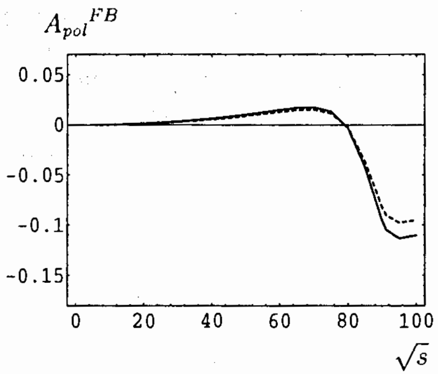

Fig. 2

The same but for the restricted energy range $\sqrt{s} < 60GeV$ is plotted in Fig. 3 (resp. 4).

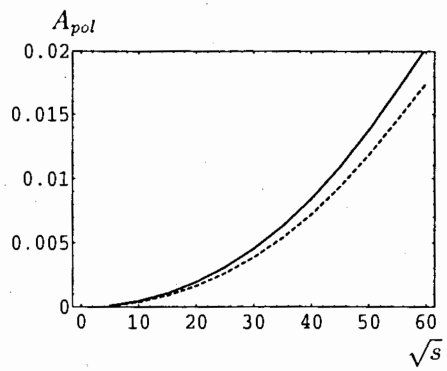

Fig. 3

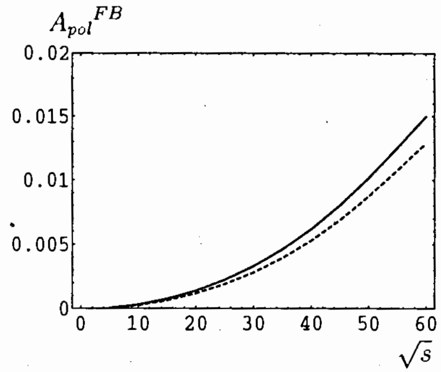

Fig. 4

We see that the relative sensitivity to the value of the Higgs mass remains at the same level and is bigger than ~15% although the considered quantities rapidly decrease when the energy decreases. This fact is shown in Fig. 5 (resp. 6) where the difference to the mean value ratio $\mathcal{R}A = \frac{A[1000]-A[10]}{\frac{1}{2}(A[1000]+A[10])}$ is plotted.

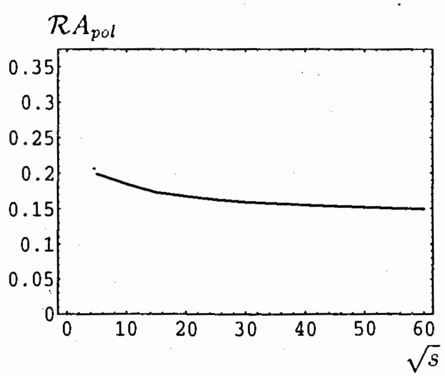

Fig. 5

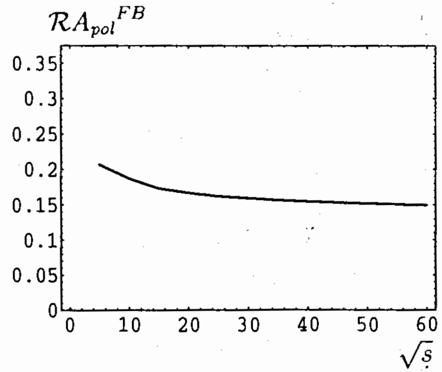

Fig. 6

One can try to estimate the tau pair production sample that is necessary to observe such effect and to derive an information about m_H from it. This estimation can be deduced from only statistical considerations. Let quantity $A \ll 1$ be constructed from two independently counted numbers of events N_1 and N_2 as the ratio

$$A = \frac{N_1 - N_2}{N_1 + N_2}. \tag{5}$$

Statistical error of A may be estimated by

$$\Delta A \approx \frac{\sqrt{N}}{N} \tag{6}$$

where $N = N_1 + N_2$. Taking into account the fact that sensitivity of A to the value of m_H is of order of 15% we demand that

$$\Delta A/A < 0.1 \ . \tag{7}$$

Both considered quantities A_{pol} and ${A_{pol}}^{FB}$ are of the order or bigger than 0.001 for collision energies $\sqrt{s} \sim 10 GeV$. It is easy to obtain from (6) and (7) that the event sample necessary for deriving conclusions concerning m_H from measurements of tau polarization and tau polarization forward–backward asymmetry is of the order of $N_\tau = 10^8$. This corresponds to the expected yearly sample at b-factory of luminosity of the order of $10^{34} cm^{-2}s^{-1}$. The estimation is very rough and does not include many practical and theoretical problems. However it provides an information about required technical conditions that must be fulfilled to study low energy electroweak phenomena at the level sensitive to the Higgs sector content of the theory.

We have proposed a framework for a negative selfconsistency test of the Standard Model. It follows from the trivial observation that the models with an effective or dynamical ultraviolet cutoff are less restrictive than the models with the physical Higgs particle. We have suggested experimental conditions that allow for testing the restrictions following from the interpretation of UV regulator as a mass of physical particle. The derived conclusions will be valid for extensions of the SM that predicts the existence of a massive physical scalar boson playing the part of the Higgs boson.

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Received by Publishing Department
on January 24, 1997.