acta physica slovaca vol. 52 No. 4, 199 – 206 **August 2002**

EXTRA GENERATIONS AND ELECTROWEAK PRECISION DATA[1]

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Received 15 June 2001, in final form 24 June 2002, accepted 25 June 2002

The latest electroweak precision data are analyzed assuming the existence of the fourth generation of leptons (N, E) and quarks (U, D), which are weakly mixed with the known three generations. If all four new particles are heavier than Z boson, quality of the fit for the one new generation is as good as for the Standard Model (SM). In the case of neutral leptons with masses around 50 GeV ("partially heavy extra generations") the minimum of χ^2 is between one and two extra generations. SM prediction of light higgs is no more valid if new generations exist.

PACS: 12.15.Lk, 12.60.-i

In this talk I will speak about modern status of electrowek precision data, see also [1, 2]. Though the content of my talk is rather far from the main topic of the conference I wish to stress that the central phenomena of the Renormalization Group, the growth of the fine structure constant at small distances, is very important for me: the value of $\alpha(M_Z) = 1/(128.9)$ determine numerical values of W- and Z-boson parameters.

Couple of years ago quality of Standard Model (SM) fit of precision electroweak data was exellent. We reanalyzed the non-decoupled New Physics in a form of additional heavy quark-lepton generations in paper [3] written at that time. We confirmed that in the case of all four new fermions (U and D quarks, neutral lepton N and charged lepton E) heavier than Z boson the radiative corrections to low-energy observables were large and the quality of the fit dropped down. As a result, such extension of the SM was excluded by the data. In particular we found that one heavy generation was excluded at 2.5 σ level. We also found that corrections due to existence of relatively light neutral lepton N ($m_N \approx 50$ GeV) and corrections due to heavy U, D and E could compensate each other and that the SM with additional "partially heavy" generation is allowed by presicion measurements.

From that time situation with the quality of the SM fit has been changed. At the time of Osaka Conference (summer 2000) the SM fit has become worse: $\chi^2/n_{d.o.f.} = 21/13$. The level at which one extra heavy generation was excluded went down to 2σ [4].
For the latest precision data (summer 2001) [5] the SM fit became even worse $\chi^2/n_{d.o.f.} = 24/13$. As for the fit of the SM with one additional heavy generation it became approximately of the same quality as for the SM.

[1]Invited talk at 5th Int. Conf. Renormalization Group 2002, Tatranská Štrba (Slovakia), March 2002
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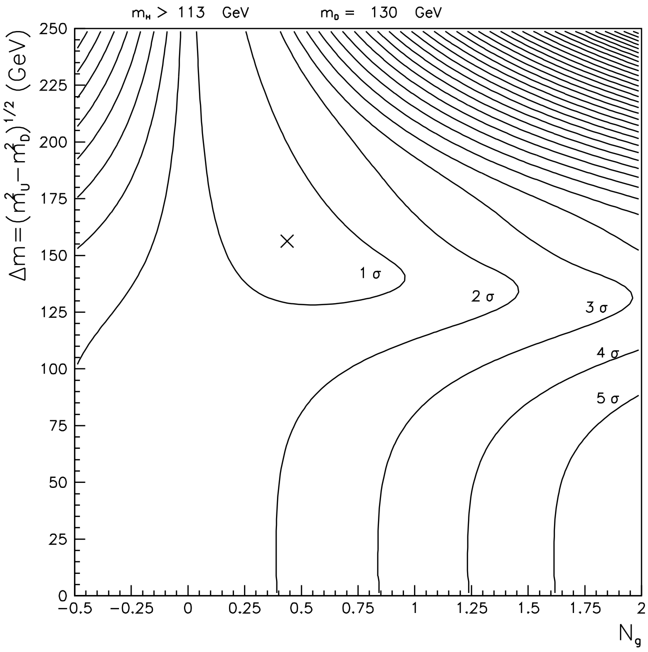

Fig. 1. Exclusion plot for heavy extra generations with the input: $m_D = m_E = 130$ GeV, $m_U = m_N$. χ^2 minimum shown by cross corresponds to $\chi^2/n_{d.o.f.} = 22.2/12$, $N_g = 0.4$, $\Delta m = 160$ GeV, $m_H = 116$ GeV. N_g is the number of extra generations. Borders of regions correspond to $\Delta\chi^2 = 1, 4, 9, 16$, etc.

To see that we present in Fig. 1 the exclusion plot for the number N_g of extra heavy generations.

To produce this plot we take $m_D = 130$ GeV—the Tevatron lower bound on new quark mass; we use experimental 95% C.L. bound on higgs - mass $m_H > 113$ GeV [5] and vary $\Delta m = \sqrt{m_U^2 - m_D^2}$ and number of extra generations N_g. (In order to have two-dimensional plot we arbitrary assumed that $m_N = m_U$ and $m_E = m_D$; other choices do not change the obtained results drastically). We see that χ^2 minimum corresponds to unphysical point $N_g = 0.5$. For 170 GeV $< m_U <$ 200 GeV we get the same quality of fit in the case $N_g = 1$ as that for the SM ($N_g = 0$)[3].

Two heavy generations are excluded at more than 3σ level. Nevertheless, two and even three "partially heavy" generations are allowed when neutral fermions are relatively light, $m_N \simeq 55$ GeV (see Fig. 2)[4].

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[3]In ref. [6] one can find a statement that extra heavy generations are excluded by the recent precision electroweak data. However, analysis performed in [6] refers to upper and lower parts of Fig. 1, $\Delta m > 200$ GeV and $\Delta m = 0$, where the existence of new heavy generations is really strongly suppressed. This is not the case for the central part of Fig. 1 ($\Delta m \approx 150$ GeV).

[4]Using all existing LEP II statistics on the reactions $e^+e^- \to \gamma + \nu\bar{\nu}, \gamma + N\bar{N}$ in dedicated search (see [7]) one can exclude 3 "partially heavy" generations which contain such a light N at a level of 3σ (see [8]), while one or even two such generations may exist.

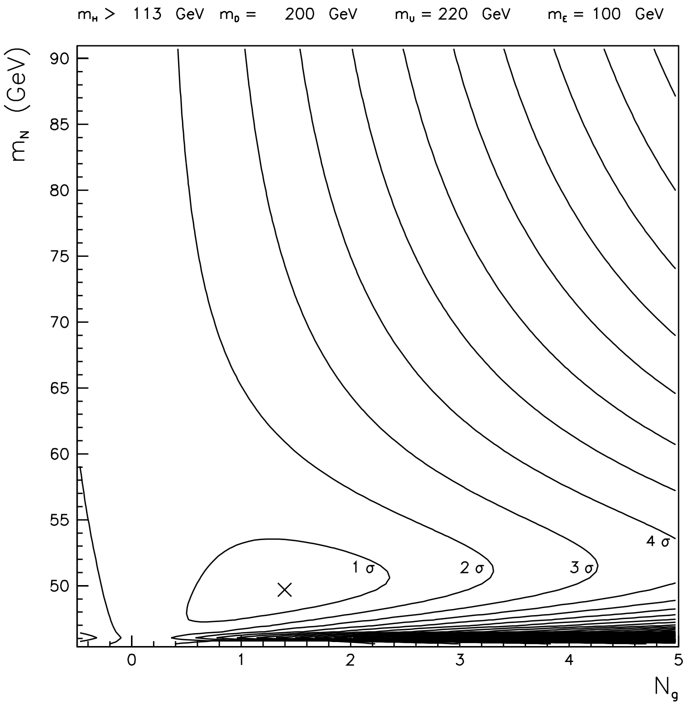

Fig. 2. Exclusion plot for the number of partially heavy extra generations with light neutral lepton N. On horizontal axis the number of extra generations N_g, on vertical axis—the mass of the neutral lepton m_N. The input: $m_U = 220$ GeV, $m_D = 200$ GeV, $m_E = 100$ GeV. At the minimum $\chi^2/n_{d.o.f.} = 21.6/12$, $N_g = 1.4$, $m_N = 50$ GeV, $m_H = 116$ GeV. According to LEP experimental data $m_N > 50$ GeV at 95% c.l. [7, 8].

We see three main discrepancies in the existing data.

There is discrepancy between the average value of s_l^2 extracted from the pure leptonic measurements and its value from events with hadrons in final state [5]:

$$\begin{array}{ll} & s_l^2 \\ \text{Leptons} & 0.23113 \pm 0.00021 \\ \text{Hadrons} & 0.23230 \pm 0.00029 \end{array} \quad (1)$$

(2)

This 3.3 σ difference is one of the causes of poor quality of the SM fit.

The value of hadronic contribution to s_l^2 in (2) is dominated by very small uncertainty of the forward-backward asymmetry in reaction $e^+e^- \to Z \to b\bar{b}$, measured at LEP

$$(A_{FB}^b)_{\rm exp} = 0.0990 \pm 0.0017 \quad (3)$$

There is another discrepancy (indirect) between this LEP result and SLC data. Indeed the value of A^b_{FB} can be calculated by multiplying beauty asymmetry A_b and leptonic asymmetry A_l (both measured at SLAC). Then

$$A^b_{FB} = \frac{3}{4} A_b A_l = 0.1038 \pm 0.0025. \tag{4}$$

The number (4) differs from (3). Thus there is contradiction between LEP and SLC experimental data. Moreover SLC number nicely coincides with the SM fit: $(A^b_{FB})_{SM} = 0.1040(8)$ (see e.g. Table 1 from [1]).

Finally a new result for $s^2_W(\nu N)$ and hence for $m_W(\nu N)$ was published by NuTeV collaboration [9]:

$$s^2_W(\nu N) = 0.2277 \pm 0.0017\,,\; m_W(\nu N) = 80.140 \pm 0.080\,. \tag{5}$$

The new value of $m_W(\nu N)$ differs from m_W measured at LEP II and previously at Tevatron by 3.7 σ. With new NuTev result we get for the SM fit:

$$m_H = 86^{+51}_{-32} \text{ GeV}\,,\; \chi^2/n_{d.o.f.} = 30.3/13. \tag{6}$$

The previous consideration demonstrates that the accuracy of A^b_{FB} and new NuTeV data are under suspicion. Thus at that point we (following Chanowitz [10]) will exclude A^b_{FB} from data set. If we multiply experimental uncertainties of A^b_{FB} and A^c_{FB} (which are strongly correlated) by a factor 10 and do the same with new NuTeV data effectively excluding in this way them from the list, the quality of SM fit improves drastically: $\chi^2/n_{d.o.f.}$ shifts from 23.8/13 to 10.9/13.

However, a new problem arises after removing $A^{b,c}_{FB}$. It was known for a long time that the SM fit results in prediction of light higgs—the central value of its mass was below the direct lower limit by LEP II. For example in ref.([1]) we got from the SM fit that

$$m_H = 79^{+47}_{-29} \text{ GeV}\,, \tag{7}$$

It is slightly less than one sigma away from 114.1 GeV bound of LEPII. (The discrepancy is smaller in case of inclusion of the new NuTeV result, see Eq. (6)). Thus we have one sigma deviation of the predicted value of higgs mass from the direct LEPII bound. With our modification of experimental results on νN scattering and on $A^{b,c}_{FB}$ the SM fit gives :

$$m_H = 42^{+30}_{-18} \text{ GeV}\,, \tag{8}$$

with ecxellent $\chi^2/n_{d.o.f.} = 10.9/13$, but well below modern LEP II bound.

Fortunately there are ways to avoid this trouble. One possible way to raise the predicted value of m_H is to assume the existence of fourth generation of leptons and quarks [2, 11].

It was noticed in [11] that the predicted mass of the higgs could be as high as 500 GeV. That conclusion was based on a sample of 10.000 random inputs of masses of fourth generation leptons and quarks. In [2] we used our LEPTOP code [12] to find steep and flat directions in the five-dimensional parameter space: m_H, m_U, m_D, m_E, m_N. For each point in this space we performed three-parameter fit ($m_t, \alpha_s, \bar{\alpha}$) and calculated the χ^2 of the fit.

It turns out that the $\chi^2_{\min}$ depends weakly on $m_U + m_D$ and m_H, while its dependence on $m_U - m_D$, m_E and m_N is strong. Therefore to present the result of the complete analysis of the Summer 2001 precision data it is enough to have a few two-dimensional plots. In Figs. 3 and

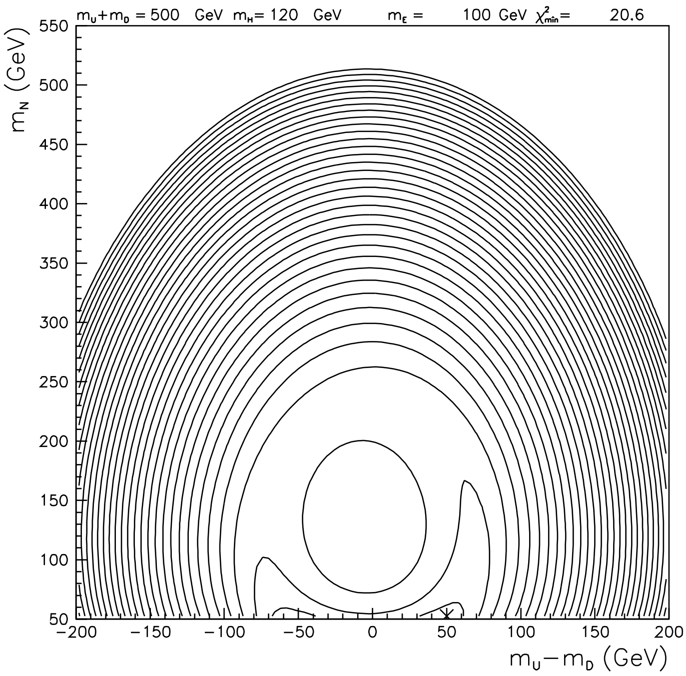

Fig. 3. Exclusion plot on the plane $m_N, m_U - m_D$ for fixed values of $m_H = 120$ GeV, and $m_E = 100$ GeV. $\chi^2_{\rm min}$ shown by two crosses corresponds to $\chi^2/n_{d.o.f.} = 20.6/12$. (The left-hand cross is slightly below $m_N = 50$ GeV.) The plot was based on the old NuTeV data. The new NuTeV data preserve the pattern of the plot, but lead to $\chi^2_{\rm min}/n_{d.o.f.} = 27.7/12$. If A^b_{FB} and A^c_{FB} uncertainties are multiplied by factor 10 we get $\chi^2_{\rm min}/n_{d.o.f.} = 19.1/12$ for new NuTeV, and $\chi^2_{\rm min}/n_{d.o.f.} = 11.3/12$ for old NuTeV.

4 we show $\chi^2_{\rm min}$ (crosses) and constant χ^2 lines corresponding to $\Delta\chi^2 = 1, 4, 9, 16, ...$ on the plane $m_N, m_U - m_D$ for fixed values of $m_U + m_D = 500$ GeV, $m_H = 120$ (Fig. 3) and 500 GeV (Fig. 4) and $m_E = 100$ GeV.

The above choice of masses is based on a large number of fits covering a broad space of parameters: 300 GeV $< m_U + m_D <$ 800 GeV; 0 GeV $< m_U - m_D <$ 400 GeV; 100 GeV $< m_E <$ 500 GeV; 50 GeV $< m_N <$ 500 GeV; 120 GeV $< m_H <$ 500 GeV. Concerning quarks, $m_U + m_D$ is bounded from below by direct searches limit, while from above by triviality arguments. Since χ^2 dependence on $m_U + m_D$ is very weak, our choice of intermediate value $m_U + m_D = 500$ GeV represents a typical, almost general case. For this choice $|m_U - m_D|$ can not be larger than ~ 200 GeV because of the mentioned above direct searches bound.

Concerning charged lepton, its mass is taken above LEP II bound. We present fits at two values of m_E (100 GeV and 300 GeV) and one can see how fit is worsening with m_E going up.

Concerning the value of m_H, we vary it from the lower LEP II limit up to triviality bound and since the dependence of observables on m_H is flat, one can get χ^2 behavior from two limiting points: m_H =120 and 500 GeV.

For $m_E = 100$ GeV we have the minimum of χ^2 at $m_N \simeq 50$ GeV and:

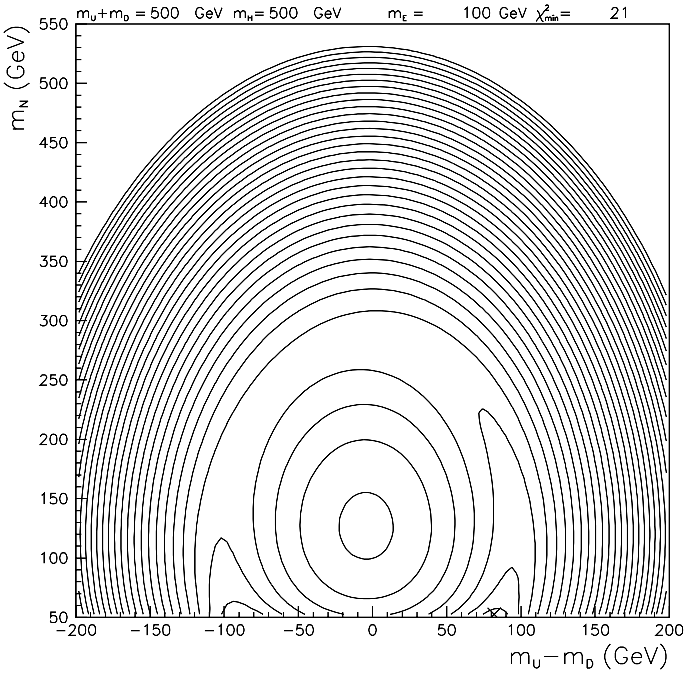

Fig. 4. Exclusion plot on the plane $m_N, m_U - m_D$ for fixed values of $m_H = 500$ GeV, and $m_E = 100$ GeV. $\chi^2_{\rm min}$ shown by two crosses corresponds to $\chi^2/n_{d.o.f.} = 21.4/12$. (The left-hand cross is slightly below $m_N = 50$ GeV.) The plot was based on the old NuTeV data. The new NuTeV data preserve the pattern of the plot, but lead to $\chi^2_{\rm min}/n_{d.o.f.} = 28.3/12$. If A^b_{FB} and A^c_{FB} uncertainties are multiplied by a factor 10, we get $\chi^2_{\rm min}/n_{d.o.f.} = 21.2/12$ for new NuTeV, and $\chi^2_{\rm min}/n_{d.o.f.} = 13/12$ for old NuTeV.

for $m_H = 120$ GeV: $|m_U - m_D| \sim 50$ GeV, $\chi^2_{\rm min}/n_{d.o.f.} = 20.6/12$
for $m_H = 300$ GeV: $|m_U - m_D| \sim 75$ GeV, $\chi^2_{\rm min}/n_{d.o.f.} = 20.8/12$
for $m_H = 500$ GeV: $|m_U - m_D| \sim 85$ GeV, $\chi^2_{\rm min}/n_{d.o.f.} = 21.4/12$

Thus we have two lines ($m_U > m_D$ and $m_U < m_D$) in the ($m_U - m_D, m_H$) space that correspond to the best fit of data. Along these lines the quality of the fit is only slightly better for light higgs ($m_H \sim 120$ GeV) than for the heavy one ($m_H \sim$ 300–500 GeV).

For $m_E = 300$ GeV we have the minimum of χ^2 at $m_U - m_D \simeq 25$ GeV and:

for $m_H = 120$ GeV: $m_N \sim 200$ GeV, $\chi^2_{\rm min}/n_{d.o.f.} = 23.0/12$
for $m_H = 300$ GeV: $m_N \sim 170$ GeV, $\chi^2_{\rm min}/n_{d.o.f.} = 24.0/12$
for $m_H = 500$ GeV: $m_N \sim 150$ GeV, $\chi^2_{\rm min}/n_{d.o.f.} = 24.4/12$

Thus, the best fit of the data corresponds to the light $m_E \simeq 100$ GeV and $m_N \simeq 50$ GeV. The significance of light m_N (around 50 GeV) was first stressed in [3]. Increase of m_E leads to the increase of m_N and to fast worsening of $\chi^2_{\rm min}$.

We demonstrate that inclusion of one extra generation improves the quality of the fit (compare $\chi^2/n_{d.o.f.} = 23.8/13$ for the SM from [2] and $\chi^2_{\rm min}/n_{d.o.f.} = 20.6/12$ from Fig. 3), but it remains pretty poor. If one multiplies experimental errors of A^b_{FB} and A^c_{FB} by a factor 10, one gets good quality of SM fit [2, 10] but with extremely light higgs, having only a small (few percent) likelihood to be consistent with the lower limit from direct searches. The fourth generation allows to have higgs as heavy as 500 GeV with a perfect quality of the fit: $\chi^2_{\min}/n_{d.o.f.} = 13/12$, if one uses old NuTeV data (see caption of Fig. 4). Captions of Figs. 3 and 4 reflect also the recent change in NuTeV data (from $m_W = 80.26 \pm 0.11$ GeV [13] to $m_W = 80.14 \pm 0.08$ GeV [9]) which results in drastic worsening of the fit even in the presence of the fourth generation.

To qualitatively understand the dependence of $m_U - m_D$ on m_H in the case of $m_E = 100$ GeV at $\chi^2_{\min}$ let us recall how radiative corrections to the ratio m_W/m_Z and to g_A and $R = g_V/g_A$ (the axial and the ratio of vector and axial couplings of Z-boson to charged leptons) depend on these quantities [14]:

$$\delta V^i \approx \left[- \begin{pmatrix} \frac{11}{9}s^2 \\ s^2 \\ s^2 + \frac{1}{9} \end{pmatrix} \ln\left(\frac{m_H}{m_Z}\right)^2 + \frac{4}{3}\frac{(m_U - m_D)^2}{m_Z^2} + \begin{pmatrix} \frac{16}{9}s^2 \frac{m_U - m_D}{m_U + m_D} \\ 0 \\ \frac{2}{9}\frac{m_U - m_D}{m_U + m_D} \end{pmatrix} \right] \quad (9)$$

where $i = m, A, R$, while $s^2 \simeq 0.23$. Corrections to other observables can be calculated in terms of δV^i. In the vicinity of $\chi^2_{\min}$ the third term in brackets is much smaller than the second one. Hence the smallness of the left-right asymmetry of the plots of Figs. 1, 2. Since $\frac{11}{9}s^2 \approx s^2 + \frac{1}{9} \approx s^2$, the increase of m_H is compensated by increase of $|m_U - m_D|$ and we have a valley of $\chi^2_{\min}$.

In conclusion I'd like to make two remarks.

1) Note that the often used parameters S, T, U (introduced in [15]) are not adequate for the above analysis, because they assume that all particles of the fourth generation are much heavier than m_Z, while in our case the best fit corresponds to $m_N \sim m_Z/2$. In the paper [11] modified definitions of S and U were used in order to deal with new particles with masses comparable to m_Z. However, both original and modified definitions of S, T and U take into account radiative corrections from the "light" 4th neutrino only approximately, while the threshold effects, that are so important for $m_N \simeq 50$ GeV, can be adequately described in the framework of functions V^i as it was done in ref. [1, 2].

2) Note that in the framework of SUSY with three generations radiative corrections due to loops with superpartners also shift upward the mass of the higgs in the case of not too heavy squarks (300–400 GeV, see Table 1 in [16]) or light sneutrinos (55–80 GeV, see [17]).

Acknowledgement: I am grateful to the organizers of 5th International Conference RENORMALIZATION GROUP 2002 for their hospitality and for opportunity to visit such a beautiful place. I am also grateful to V. A. Novikov, L. B. Okun, and A. N. Rozanov for fruitful discussions.

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