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Extra generations and discrepancies of electroweak precision data

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Abstract

It is shown that additional chiral generations are not excluded by the latest electroweak precision data if one assumes that there is no mixing with the known three generations. In the case of "heavy extra generations", when all four new particles are heavier than Z boson, quality of the fit for the one new generation is as good as for zero new generations (Standard Model). 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.

Two years ago in paper [1] we analyzed bounds from the electroweak precision data on the non-decoupled New Physics in a form of additional heavy quark–lepton generations. It was shown that while the case of all four new fermions (U and D quarks, neutral lepton N and charged lepton E) heavier than Z boson was excluded at 2.5σ level, existence of new generations with relatively light neutral lepton N ($m_N \approx 50$ GeV) was allowed. At that time quality of Standard Model (SM) fit of the data was very good, $\chi^2/n_{\text{d.o.f.}} = 15/14$. At the time of Osaka Conference, summer 2000, nothing radical happened but χ^2 became 21/13 and the level at which one extra heavy generation was excluded went down to 2σ [2]. However the latest precision data announced summer 2001 [3] has changed the situation: the fit is still bad, 24/13, but now the presence of one heavy generation does not make the fit worse as compared with SM.

In Table 1 the LEPTOP fit of summer 2001 data is presented. There are two significant changes in comparison with previous data presented in Table 2:

1. Due to precision measurement of the cross-section of e^+e^- annihilation into hadrons in the interval 2–5 GeV at BES the error in $\bar{\alpha} \equiv \alpha(M_Z)$ is now two times smaller. (Following Electroweak Working Group (EWWG) we use result [4] though other estimates can be found in the literature as well);
2. Central value of M_W is now bigger by a half of σ.

The latter is the main cause for the relaxation of the bound on heavy extra generations.

Exclusion plot for the number N_g of extra heavy generations is presented in Fig. 1.

To produce this plot we take $m_D = 130$ GeV—the Tevatron lower bound on new quark mass; we use

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Table 1
LEPTOP fit to electroweak observables. Year 2001. By italics we designate calculated (not measured) quantities

Source	Observable	Exp. data	LEPTOP fit	Pull
LEP I	Γ_Z [GeV]	2.4952(23)	2.4966(16)	−0.6
	σ_h [nb]	41.540(37)	41.480(14)	1.6
	A^l_{FB}	0.0171(10)	0.0165(3)	0.7
	R_l	20.767(25)	20.738(18)	1.1
	A_τ, A_e	0.1465(33)	0.1483(11)	−0.5
	R_b	0.2165(7)	0.2157(1)	1.2
	R_c	0.1719(31)	0.1723(1)	−0.1
	A^b_{FB}	0.0990(17)	0.1040(8)	−2.9
	A^c_{FB}	0.0685(34)	0.0743(6)	−1.7
	$s^2_l(Q_{FB})$	0.2324(12)	0.2314(1)	0.9
SLC	A_{LR}	0.1513(21)	0.1483(11)	1.4
	$s^2_l(A_{LR})$	*0.2310(3)*	*0.2314(1)*	−1.4
	A_b	0.9220(200)	0.9349(1)	−0.6
	A_c	0.6700(260)	0.6684(5)	0.1
LEP II, Tevatron	m_W [GeV]	80.451(33)	80.392(20)	1.8
	$s^2_W(m_W)$	*0.2216(6)*		
Tevatron	$s^2_W(\nu N)$	0.2255(21)	0.2230(3)	1.2
	$m_W(\nu N)$ [GeV]	*80.250(109)*		
	m_t [GeV]	174.3(5.1)	175.0(4.4)	−0.1
Fit	m_H [GeV]		79^{+47}_{-29}	
	$\hat{\alpha}_s$		0.1182(27)	
$e^+e^- \to$ hadrons	$\bar{\alpha}^{-1}$	128.936(49)	128.918(45)	0.4
	$\chi^2/n_{\text{d.o.f.}}$		23.8/13	

experimental 95% C.L. bound on higgs mass $m_H > 113$ GeV [3] 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); 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 ($N_g = 0$). In Ref. [5] one can find a statement that extra heavy generations are excluded by the precision electroweak data. However, analysis performed in [5] 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).

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). Using all existing LEP II statistics on the reactions $e^+e^- \to \gamma + \nu\bar{\nu}, \gamma + N\overline{N}$ in dedicated search one can exclude 3 "partially heavy" generations which contain such a light N at a level of 3σ (see [6]), while one or even two such generations may exist.

The cause of disappearance of the suppression of extra heavy generations which existed in the early data is the contradiction in description of modern data on M_W and s_l^2 in the framework of SM. The point is that the higgs mass, a free parameter of the SM, has the following values being extracted from these observables:

$$(m_W)_{\text{LEPII,Tevatron,NuTeV}} = 80.428(32)\ \text{GeV}$$
$$\Rightarrow m_H = 50^{+50}_{-35}\ \text{GeV}, \tag{1}$$
$$(s_l^2)_{\text{LEPI,SLAC}} = 0.23140(15)$$
$$\Rightarrow m_H = 150^{+75}_{-50}\ \text{GeV}. \tag{2}$$

$N_g = 0.5$ reduces the contradiction between the two values of m_H. Nevertheless the resulting χ^2 does not improve drastically and this is due to another "defect" of precision data: the discrepancy between the average

Table 2
LEPTOP fit to electroweak observables. Year 2000

Source	Observable	Exp. data	LEPTOP fit	Pull
LEP I	Γ_Z [GeV]	2.4952(23)	2.4964(16)	−0.5
	σ_h [nb]	41.541(37)	41.479(15)	1.7
	A^l_{FB}	0.0171(10)	0.0164(3)	0.7
	R_l	20.767(25)	20.739(18)	1.1
	A_τ, A_e	0.1467(32)	0.1480(13)	−0.4
	R_b	0.2165(7)	0.2157(1)	1.2
	R_c	0.1709(34)	0.1723(1)	−0.4
	A^b_{FB}	0.0990(20)	0.1038(9)	−2.4
	A^c_{FB}	0.0689(35)	0.0742(7)	−1.5
	$s^2_l(Q_{FB})$	0.2321(10)	0.2314(2)	0.7
SLC	A_{LR}	0.1514(22)	0.1480(16)	1.5
	$s^2_l(A_{LR})$	*0.2310(3)*	*0.2314(2)*	−1.5
	A_b	0.9110(250)	0.9349(1)	−1.0
	A_c	0.6300(260)	0.6683(6)	−1.5
LEP II, Tevatron	m_W [GeV]	80.434(37)	80.397(23)	1.0
	$s^2_W(m_W)$	*0.2219(7)*		
Tevatron	$s^2_W(\nu N)$	0.2255(21)	0.2231(2)	1.1
	$m_W(\nu N)$ [GeV]	*80.250(109)*		
	m_t [GeV]	174.3(5.1)	174.0(4.2)	0.1
Fit	m_H [GeV]		55^{+45}_{-26}	
	$\hat{\alpha}_s$		0.1183(27)	
$e^+e^- \to$ hadrons	$\bar{\alpha}^{-1}$	128.878(90)	128.850(90)	0.3
	$\chi^2/n_{\text{d.o.f.}}$		21.4/13	

value of s^2_l extracted from pure leptonic measurements and its value from events with hadrons in final state [3]:

	s^2_l
Leptons	0.23113(21)
Hadrons	0.23230(29)

(3)

These 3.3σ difference is the root of poor quality of the SM fit. The value of hadronic contribution to s^2_l in (3) is dominated by very small uncertainty of the forward-backward asymmetry in reaction $e^+e^- \to Z \to b\bar{b}$. According to Table 1

$$\left(A^b_{FB}\right)_{\text{exp}} = 0.0990(17). \tag{4}$$

One can question whether such a good accuracy can be obtained in the analysis of hadronic jets production. Another value of A^b_{FB} can be obtained by multiplying measured at SLAC beauty asymmetry A_b and leptonic asymmetry A_l. Then

$$A^b_{FB} = \frac{3}{4} A_b A_l = 0.1038(25). \tag{5}$$

The number (5) differs from (4), but nicely coincides with the SM fit: 0.1040(8) (see Table 1).

Let us assume following Chanowitz [8] that A^b_{FB} has larger uncertainty than given in Eq. (4) and look to what consequences with respect to extra generations this hypothesis will lead.[1] If we multiply experimental uncertainties of A^b_{FB} and A^c_{FB}, which are strongly correlated, by a factor 10, the quality of SM fit improves drastically: $\chi^2/n_{\text{d.o.f.}}$ shifts from 23.8/13 to 10.9/13 and simultaneously one heavy extra generation becomes excluded at the level of 2.5σ (see Fig. 3).

[1] Another way to resolve situation with A^b_{FB} is to assume that there exist New Physics contributions to $Zb\bar{b}$ couplings g^b_V and g^b_A. Since in the expression for A^b_{FB} the corrections to g^b_V and g^b_A are multiplied by small factor g^e_V they should be large, so they must appear at the tree level. Also $Z \to b\bar{b}$ width proportional to $(g^b_A)^2 + (g^b_V)^2$ should not noticeably change since $R_b \equiv \Gamma_{Z\to b\bar{b}}/\Gamma_Z$ is at present in good agreement with SM fit, see Table 1. In recent paper [9] inclusion of additional bottom-like heavy quarks with vector currents is suggested to resolve the discrepancy (3).

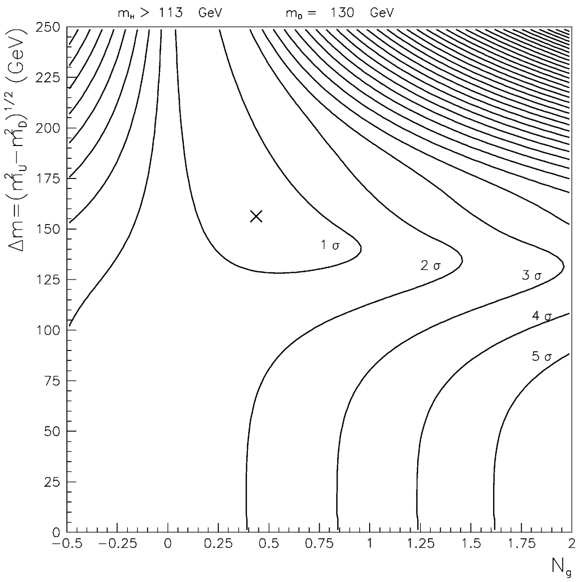

Fig. 1. Exclusion plot for heavy extra generations with the input: $m_D = m_E = 130$ GeV, $m_U = m_N$. χ^2 minimum shown by cross corresponds to $\chi^2/n_{\mathrm{d.o.f.}} = 22.2/12$, $N_g = 0.4$, $\Delta m = 160$ GeV, $m_H = 116$ GeV. N_g is the number of extra generations. Borders of regions show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

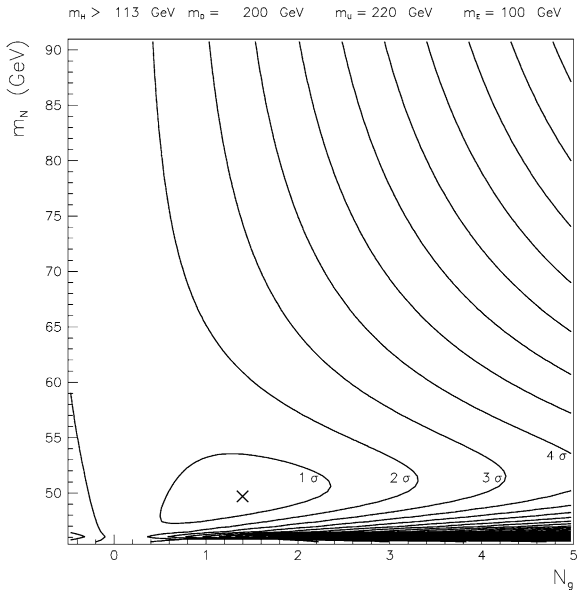

Fig. 2. Exclusion plot for the number of partially heavy extra generations with light neutral lepton N. On horizontal axis the number of extra generations N_g, on vertical axis—the mass of the neutral lepton m_N. The input: $m_U = 220$ GeV, $m_D = 200$ GeV, $m_E = 100$ GeV. At the minimum $\chi^2/n_{\mathrm{d.o.f.}} = 21.6/12$, $N_g = 1.4$, $m_N = 50$ GeV, $m_H = 116$ GeV. The spectacular behaviour of lines at the bottom of this figure as well as Fig. 4 is caused by the threshold singularity. This singularity must manifest itself also in the Z lineshape. We have not studied it because according to experimental data by LEP Collaborations on the emission of initial state bremsstrahlung photon $m_N > 50$ GeV at 95% C.L. [6,7] and the effect at such distance above threshold is not prominent.

However, a serious problem arises: it is just A_{FB}^b given by Eq. (4) which pushes m_H to larger values. With our modification of experimental results on A_{FB}^b and A_{FB}^c the SM fit gives:

$$m_H = 42^{+30}_{-18}\ \text{GeV}, \tag{6}$$

well below modern LEP II bound: $m_H > 113$ GeV, a substantial trouble for the SM. In case the constraint $m_H > 113$ GeV is imposed, we get: $m_H = 116^{+15}_{-2}$ GeV, $\chi^2/n_{\mathrm{d.o.f.}} = 14.5/14$. What concerns partially heavy extra generations, they nicely fit the data even with ten times enlarged uncertainties of A_{FB}^b and A_{FB}^c, see Fig. 4. At both minima in this figure $\chi^2/n_{\mathrm{d.o.f.}} \simeq 13/12$, while $m_H \simeq 116$ GeV due to the imposed constraint $m_H > 113$ GeV. Without this constraint m_H drops to ~ 40 GeV, while $\chi^2/n_{\mathrm{d.o.f.}} \simeq 10.1/11$ at $N_g = 0.9$, $m_N = 53$ GeV. (The various values of $n_{\mathrm{d.o.f.}}$ stems from unconstrained or constrained value of m_H and to additional parameters m_N and N_g in case of New Physics.)

In the recent paper [10] it was noted that SUSY extension of Standard Model with light sneutrinos with masses in the range 55–80 GeV is allowed by precision data and pushes higgs mass to larger values. (A_{FB}^b was neglected there as well). This might be a strong indication in favor of light SUSY particles.

The presence of new particles is important for production and decay of higgs. New heavy quarks considerably enhance higgs production at Tevatron and LHC through gluon fusion which should help to discover this particle [11]. If the decay of higgs into a pair of neutral leptons is kinematically allowed it will dominate, so that a moderately heavy higgs will decay invisibly [12]. At LEP II the invisibly decaying higgs is excluded almost at the same level as the SM higgs by missing mass method [13]. Contrary to that the LHC will look for visible decay modes of higgs. If the branching ratios of the latter are small the search will be not easy.

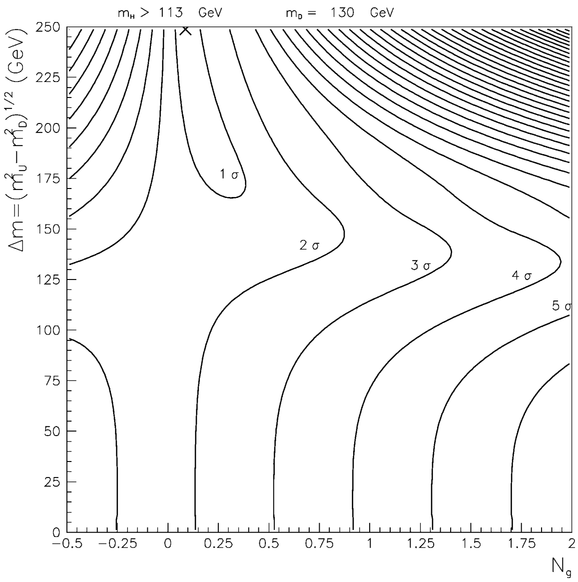

Fig. 3. Exclusion plot for heavy extra generations with 10 times enlarged errors in A^b_{FB} and A^c_{FB} with the input $m_D = m_E = 130$ GeV, $m_U = m_N$. χ^2 minimum is at the upper border of the figure, where $\chi^2/n_{\text{d.o.f.}} = 11.8/12$, $N_g = 0.1$, $\Delta m = 248$ GeV, $m_H = 116$ GeV.

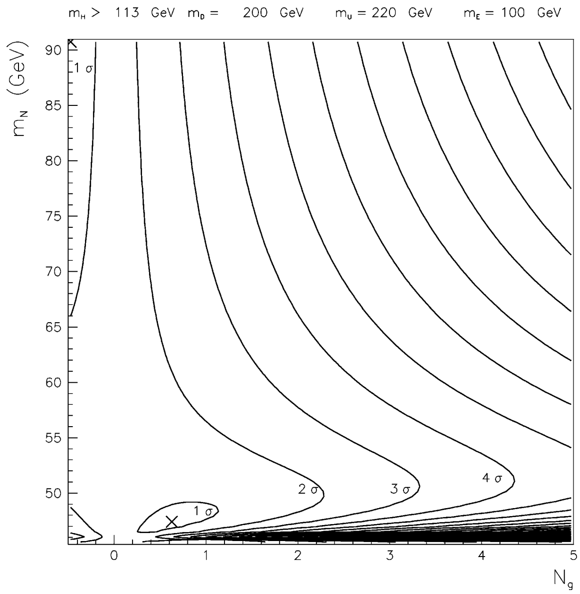

Fig. 4. Exclusion plot for partially heavy extra generations with 10 times enlarged errors in A^b_{FB} and A^c_{FB} with the input $m_D = 200$ GeV, $m_U = 220$ GeV, $m_E = 100$ GeV. Two local χ^2 minima are shown. At the first minimum $\chi^2/n_{\text{d.o.f.}} = 12.4/12$, $N_g = -0.5$, $m_N = 90$ GeV, $m_H = 116$ GeV (see upper left corner of the plot). At the second minimum $\chi^2/n_{\text{d.o.f.}} = 13.1/12$, $N_g = 0.6$, $m_N = 48$ GeV, $m_H = 116$ GeV.

Note added

After this Letter had been completed a new result for $s^2_W(\nu N)$ and hence for $m_W(\nu N)$ was published by NuTeV Collaboration [14]:

$$s^2_W(\nu N) = 0.2277(17),$$

$$m_W(\nu N) = 80.140(80).$$

The new value of $m_W(\nu N)$ differs from m_W measured by LEP II and Tevatron by 3.7σ and leads to a pull of 2.8 instead of 1.2 (see Table 1) aggravating the discrepancy. Using the same procedure as for Table 1 we get:

$$m_H = 86^{+51}_{-32}\ \text{GeV},$$

$$\chi^2/n_{\text{d.o.f.}} = 30.3/13.$$

The influence of the new NuTeV data on the limits on extra generations, as well as the change of LEPTOP code accounting for the new NuTeV procedure of extracting $s^2_W(\nu N)$ will be discussed elsewhere.

We are grateful to V. Rubakov for providing Ref. [14].

As a response to the appearance of this Letter on hep/ph H.-J. He kindly brought to our attention Ref. [15], in which the problem of extra generations has been considered in a framework of the models with two and one higgs doublets. In latter case the results of Ref. [15] could be compared with ours. According to Ref. [15], the 500 GeV higgs, if accompanied by fourth generation, does not contradict the electroweak precision data. In order to check this statement we made special LEPTOP runs assuming $m_H = 500$ GeV and $N_g = 1$. We found that for certain fixed values of quark and lepton masses the χ^2 of the fits with heavy higgs is even better than in the SM. For example, for $m_N = 55$ GeV, $m_E = 200$ GeV, $m_U = 130$ GeV, $m_D = 130$ GeV, and $m_H = 500$ GeV $\chi^2/n_{\text{d.o.f.}} = 20.3/14$ which should be compared with $\chi^2/n_{\text{d.o.f.}} = 23.8/13$ from Table 1. Let us note that we do not use S, T, U parametrization of oblique corrections which is well suited for heavy fermions but not for light ones (with masses of the order of M_Z).

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