

The rise and fall of the fourth quark-lepton generation

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The existence of the fourth quark-lepton generation is not excluded by the electroweak precision data. However, the recent results on the 126 GeV higgs boson production and decay do not allow an extra generation at least as far as the perturbation theory can be used.

1 Prehistory

In the course of 1974 November Revolution J/ψ particle was discovered, and soon it was understood that it consists of $c\bar{c}$ -quarks. In this way the second quark-lepton generation (ν_μ , μ , s , c) was completed. Two years later τ -lepton was found, and in 1978 $\Upsilon(b\bar{b})$ -meson was discovered as well. t -quark was found only in 1994, however, already in the 1980s people started to plan finding the particles of the next, fourth, quark-lepton generation. And the main question, of course, was: How heavy are U , D , and E ?

2 SLC, LEP

In the year 1989 e^+e^- colliders SLC and LEP started to work at $\sqrt{s} = M_Z$, and from the determination of Z invisible width it soon became clear that only three neutrino exist. According to the final data $\Gamma(\text{invisible}) = 499 \pm 1.5$ MeV, while according to the theory it equals $166 \cdot 3 = 498$ MeV, so there is no space for extra neutrinos. However the possibility of the heavy fourth generation neutrino with the mass $m_N > M_Z/2$ is not excluded.

3 Electroweak precision data

Since the fourth generation quarks and leptons contribute to the W - and Z -boson polarization operators and since these contributions do not decouple in the limit of heavy new generation (which is the essence of the electroweak theory and quite opposite to the case of QED, where, say, the top quark contribution to the anomalous magnetic moment of muon is suppressed as $(g - 2)_\mu \sim (m_\mu/m_t)^2$) one can get the constraints on the 4th generation from the precision measurements of M_W , m_t , and Z -boson parameters.

Indeed, in 1998 volume of the Review of Particle Properties Erler and Langacker wrote: “An extra generation is excluded at the 99.2% CL” [1]. The statement of the published in the year 2000 paper [2] is: “One extra generation is still allowed”.

The following two points were missed by Erler and Langacker:

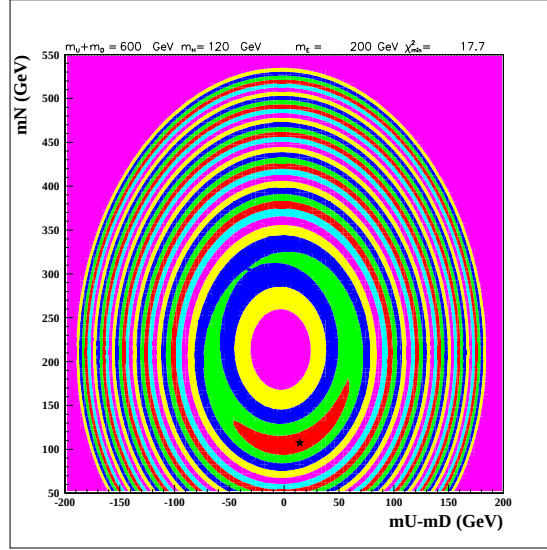


Figure 1: $M_H = 120$ GeV, $m_E = 200$ GeV, $m_U + m_D = 600$ GeV, $\chi^2/d.o.f. = 17.7/11$, the quality of fit is the same as in SM.

1. S, T, and U parametrization is valid only when the masses of all the new particles are much larger than M_Z ;
2. Instead of making a global fit they studied S, T, and U separately, while these quantities are correlated. The evolution of RPP analysis of extra quark-lepton generation in the years 1998 - 2010 is described in detail in paper [3].

The results of the fit of the electroweak precision observables in the presence of the fourth generation just before LHC started obtaining data are shown in Figures 1 and 2 [4]. Fig. 1 corresponds to the light higgs boson, $m_H = 120$ GeV, while Fig. 2 corresponds to heavy higgs, $m_H = 600$ GeV. In both cases the values of the fourth generation quark and lepton masses are determined, for which the quality of the fit is practically the same as for the Standard Model with three generations. In Figures 1 and 2 we put $m_E = 200$ GeV, $m_U + m_D = 600$ GeV, and the values of m_N and $m_U - m_D$ at which $\chi^2/d.o.f.$ is minimal (and the same as in SM) are shown by star.

4 LHC direct bounds

Since the search of heavy quarks is a relatively easy task for LHC; the first lower bounds on their masses appeared soon after the start of LHC. The last ATLAS bounds are: $m_{t'} > 656$ GeV at 95% CL if $t' \rightarrow Wb$ decay dominates [5] and $m_{b'} > 480$ GeV if $b' \rightarrow Wt$ decay dominates. CMS has similar bounds. These bounds push heavy quarks out of the perturbative unitarity domain: $m_{q'} < 500$ GeV, so if such quarks exist, their interaction with the higgs doublet is described by strong dynamics (let us remind that even for a top quark the coupling with higgs is not small: $\lambda_t = m_t/(\eta/\sqrt{2}) = 172/(246/\sqrt{2}) \approx 1$).

However, these bounds depend on the pattern of heavy quark decays and are not univer-

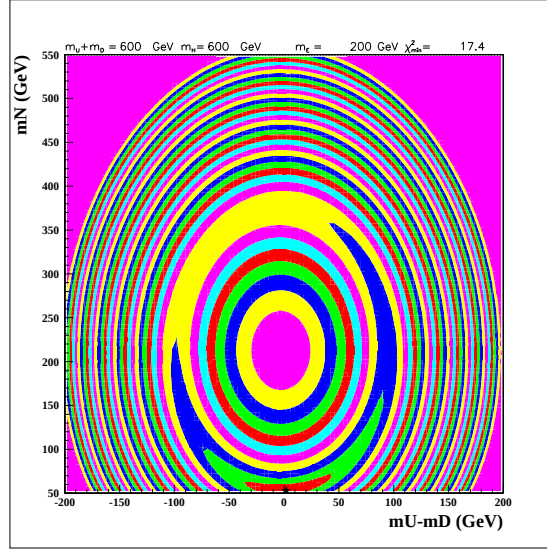


Figure 2: $M_H = 600\text{GeV}$, $m_E = 200\text{ GeV}$, $m_U + m_D = 600\text{ GeV}$, $\chi^2/d.o.f. = 18.4/11$, the quality of fit is the same as in SM.

sal. Much more interesting indirect bounds follow from higgs boson production and decay probabilities measured at LHC.

5 Higgs data

In the following Table the values of μ measured by ATLAS and CMS collaborations are given. μ is equal to the ratio of the measured product of the cross section of H production at LHC and branching ratio of H decay to a specific final state to the value of this product calculated in Standard Model. Thus, if there are no heavy quarks or any other kind of New Physics, μ equals one for any decay mode. The data in the Table are taken from papers [6, 7] and correspond to the summer 2013. $H \rightarrow b\bar{b}$ decay was observed only for the associative production of the higgs boson with Z - or W -boson.

Table

decay mode	ATLAS	CMS
$H \rightarrow \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \rightarrow ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
$H \rightarrow WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \rightarrow \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$VH \rightarrow Vb\bar{b}$	0.2 ± 0.5	1.00 ± 0.49

The values of $\mu_i \equiv (\sigma_H \cdot \text{Br}_i)_{\text{exp}} / (\sigma_H \cdot \text{Br}_i)_{\text{SM3}}$. A new ATLAS result is $\mu_{\tau\tau} = 1.4 \pm 0.5$.

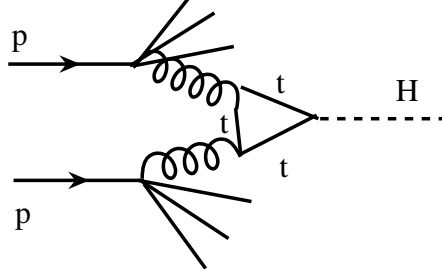


Figure 3: $t \rightarrow t, t', b'$. $\sigma(gg \rightarrow H)_{SM4} \approx 9\sigma(gg \rightarrow H)_{SM3}$.

The dominant diagram which describes the higgs boson production at LHC is shown in Fig. 3. In case of the fourth generation the amplitude triples since the contributions of heavy $U(t')$ and $D(b')$ quarks are the same as that of t -quark. As a result, the cross-section of H production in the case of 4 generations is nine times bigger than in the Standard Model:

$$\sigma(gg \rightarrow H)_{SM4} \approx 9\sigma(gg \rightarrow H)_{SM3} \quad (1)$$

Analogously the width of $H \rightarrow gg$ decay which in the Standard Model for $M_H = 126$ GeV is about 0.3 MeV in SM4 becomes 2.7 MeV. Taking into account that in the Standard Model $\Gamma_H \approx 4.2$ MeV, we get that the branching ratios of $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ decays in the case of SM4 are multiplied by factor $4.2/6.6 \approx 0.7$, which becomes 0.6 when the modification of other higgs decay probabilities are taken into account. However, the electroweak radiative corrections to the $H \rightarrow VV$ decay amplitude being enhanced by factor $(G_F m_{t',b'}^2)$ are big and according to [8] the factor 0.6 is changed to 0.2 (for $m_{t'} \approx 600$ GeV) when they are taken into account. It demonstrates that with such heavy new quarks we leave the domain of masses generated by Higgs mechanism where the perturbation theory is applicable. For the value of μ in case of $H \rightarrow WW^*, ZZ^*$ decays we get the enhancement by factor 2 in the case of the fourth generation. Such an enhancement is excluded by the experimental data from the Table. For the lighter fourth generation quarks the electroweak radiative corrections which diminish $H \rightarrow WW^*, ZZ^*$ decay widths are smaller, so exclusion will be even stronger.

There is a possibility to diminish $Br(H \rightarrow WW^*, ZZ^*)$ by choosing $M_H/2 > m_N > M_Z/2$, which makes $H \rightarrow NN$ a dominant higgs decay mode (N is a neutral lepton of the fourth generation). From the ATLAS search of $ZH \rightarrow l^+l^- + \text{invisible}$ decay mode the 95% CL upper bound $Br(H \rightarrow \text{invisible}) < 0.65$ follows [9]. According to CMS $Br(H \rightarrow \text{invisible}) < 0.52$. Thus, for light N the values of μ for visible final states can be diminished by factor 2 and for $H \rightarrow WW^*$ and ZZ^* decay modes μ approaches its SM3 values. Up to now we present the result of the 4th generation electroweak loop corrections for the moderate values of the masses of new leptons. If their masses approach 600 GeV, then factor 0.2 in the suppression of $Br(H \rightarrow VV^*)$ becomes 0.15 [10] and the value of μ approaches its value for the 3 generation case.

6 $H \rightarrow \gamma\gamma$

In SM3 this decay is described by two one-loop diagrams shown in Fig. 4. In the limit $M_H \ll 2m_t, 2M_W$ for the decay amplitude we have:

$$A_3 \sim 7 - 4/3 * 3 * (2/3)^2 = 7 - 16/9 . \quad (2)$$

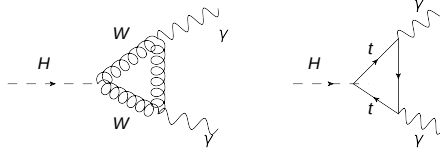


Figure 4: $H \rightarrow 2\gamma$ decay in SM3.

The numbers 7 and 16/9 are one-loop QED β - function coefficients; the signs correspond to asymptotic freedom and zero charge behavior, respectively. Number 7 for the first time appears in 1965 paper of V.S. Vanyashin and M.V. Terentiev [11]. Nowadays it could be derived from the following equation:

$$7 = 22/3 - 1/6 - 1/6 , \quad 22/3 = 11/3 * 2 , \quad (3)$$

where the factors 1/6 originate from the higgs doublet contribution into running of SU(2) and U(1) couplings g and g' , while 22/3 is a vector boson contribution into the running of g .

For $M_W = 80.4$ GeV 7 should be substituted by 8.3, while 16/9 has 3% accuracy for $m_t = 172$ GeV. So, in SM3 $A_3 \sim 8.3 - 16/9 = 6.5$, while in the case of the fourth generation a strong compensation occurs:

$$A_4 \sim 8.3 - 16/9 - 16/9 - 4/9 - 4/3 = 3.0 \quad (4)$$

and taking into account the enhancement of $gg \rightarrow H$ production cross-section and the modification of Higgs decay probabilities (mainly the enhancement of $H \rightarrow gg$ decay), we obtain the same $\sigma * Br(H \rightarrow 2\gamma)$ as in SM3:

$$\mu_{2\gamma} = 9 * 0.6 * (3/6.5)^2 \approx 1.2 . \quad (5)$$

But the electroweak radiative corrections greatly diminish $\sigma * Br(H \rightarrow 2\gamma)$; according to [8] it equals 1/3 of SM3 result or even less, while the average of ATLAS and CMS data is 1.2 ± 0.2 , so the 4th generation is excluded at 4-5 σ level. It would be good to calculate 3 loop electroweak corrections to the $\Gamma(H \rightarrow 2\gamma)$ in the case of the fourth generation.

7 $H \rightarrow \tau\tau, H \rightarrow b\bar{b}$

μ for the $(\tau\tau)$ mode at tree level equals approximately

$$\mu_{\tau\tau} \approx 9 \text{ (from } H \text{ production cross section)} * 0.6 \text{ (enhancement of } H \text{ width in SM4)} \approx 5 , \quad (6)$$

and the electroweak loop corrections make the decay width larger by 30% [8]. The experimental data exclude this huge enhancement.

The consideration differs for $H \rightarrow b\bar{b}$ mode: it is seen only in the associative higgs boson production $VH \rightarrow Vb\bar{b}$, which unlike gluon fusion is not enhanced in the 4th generation case, and there is no contradiction with the LHC experimental data.

8 Conclusions

- LHC data on 126 GeV higgs boson production and decays exclude the Standard Model with the sequential fourth generation in the perturbative domain: too small $gg \rightarrow H \rightarrow \gamma\gamma$ probability, too big $gg \rightarrow H \rightarrow \tau\tau$ probability;
- If we are out of the perturbative domain ($m_4 \sim 1$ TeV) extra generation cannot be excluded, but we are unable to understand why all the experimentally measured μ 's are close to one and SM3 works so well;
- In two higgs doublets model the fourth generation is still allowed [12];
- Since the vector generation has $SU(2) \times U(1)$ invariant masses it is not excluded by higgs data.

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