The rise and fall of the fourth quark-lepton generation

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Prehistory

1974, $J/\psi(c\bar{c})$ discovery, "November Revolution"
c quark - the last member of the 2nd family (c, s, μ, ν_μ)

1976, τ-lepton, 1978; $\Upsilon(b\bar{b})$
the 3rd family
1994 - t-quark, but already in the 1980s - why only 3 generations? where is the fourth generation? Special conference in mid 1980s on the 4th generation.

How heavy are U, D, E?

1989: SLC, LEP

Z invisible width:

$$\Gamma(\text{invisible}) = 499 \pm 1.5\text{MeV}$$

Theory: $166 * 3 = 498$ - no space for extra neutrinos;
$n_g = 3$ - the only discovery made at SLC and LEP.

BUT: $m_N > M_Z/2$

Electroweak precision data

Since the fourh generation quarks and leptons contribute to the W and Z polarization operators
and since these contributions do not decouple in the limit of heavy new generation (the essence of electroweak theory; opposite to the case of QED, where $(g-2)_\mu \sim (m_\mu/m_t)^2$)
one can get constraints on the 4th generation from the precision measurements of M_W, m_t and Z-boson parameters.

Indeed: RPP, 2000 year edition, Erler, Langacker:
"An extra generation is excluded at the 99.6%CL (97%) by the analysis based on S,T and U parametrization of New Physics contributions into electroweak observables."

The same 2000 year, Maltoni, Novikov, Okun, Rozanov, Vysotsky:
"One extra generation is still allowed".

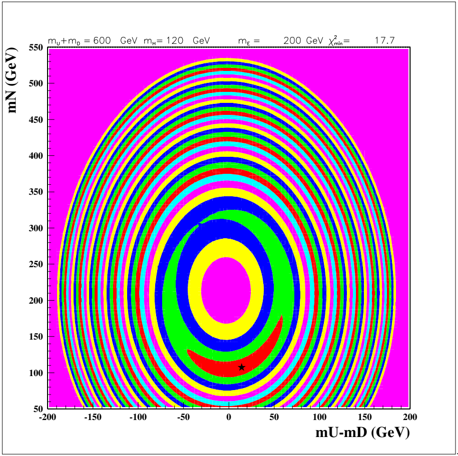
What was missed by Erler and Langacker

Comment for specialists:

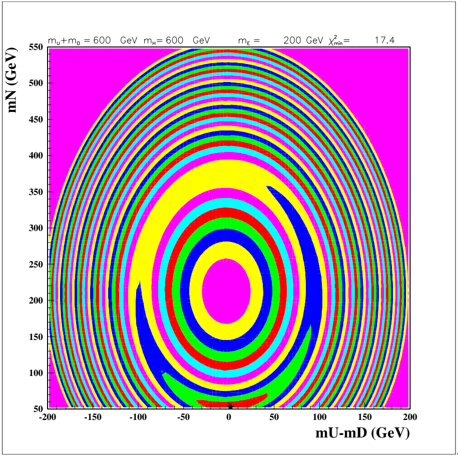
1. S, T and U are applicable only for $M >> M_Z$;
2. Instead of making global fit they studied S, T and U separately, while they are correlated.

Alexander Lenz, CERN-PH-TH/2012 - detailed description of 1998-2010 PDG extra generation story.

What we had before LHC



$M_H = 120$ 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.



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

LHC direct bounds

ATLAS: $m_{t'} > 656$ GeV at 95% CL ($t't' \longrightarrow WbWb$, Phys. Lett. B 718 (2013) 1284);
$m_{b'} > 480$ GeV ($b'b' \longrightarrow WtWt$).
CMS has similar bounds.

These bounds push heavy quarks out from the perturbative unitarity domain: $m_{q'} < 500$ GeV, strong dynamics.

$$\lambda_t = m_t/(\eta/\sqrt{2}) = 172/(246/\sqrt{2}) \approx 1$$

However these bounds depend on the pattern of heavy quarks decay and are not universal.

Much more interesting bounds follow from higgs boson production and decays.

Higgs data, $\mu \equiv \sigma/\sigma_{SM}$

ATLAS - conf - 2013 - 034

$H \longrightarrow \gamma\gamma : \quad 1.6 \pm 0.3$

$H \longrightarrow ZZ : \quad 1.5 \pm 0.4$

$H \longrightarrow WW : \quad 1.0 \pm 0.3$

$H \longrightarrow \tau\tau : \quad 0.8 \pm 0.7$

$VH \longrightarrow Vbb : \quad -0.4 \pm 1.0$

CMS-PAS-HIG-13-005, 13-012

$H \longrightarrow \gamma\gamma : \quad 0.77 \pm 0.27$

$H \longrightarrow ZZ : \quad 0.92 \pm 0.28$

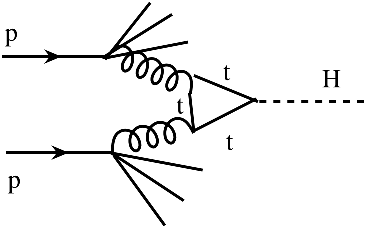
$H \longrightarrow WW : \quad 0.68 \pm 0.20$

$H \longrightarrow \tau\tau : \quad 1.10 \pm 0.41$

$VH \longrightarrow Vbb : \quad 1.00 \pm 0.49$

I am grateful to Ilya Tsukerman for proper references.

H production cross section



$$t \longrightarrow t, t', b'$$

$$\sigma(gg \longrightarrow H)_{SM4} \approx 9\sigma(gg \longrightarrow H)_{SM3}$$

$H \to VV$ decay rates

Mainly because of $H \longrightarrow gg$ enhancement:

$$Br(H \longrightarrow ZZ^*, WW^*)_{SM4} \approx 0.6 Br(H \longrightarrow ZZ^*, WW^*)_{SM3}$$

Taking into account EW loop corrections $(G_F m_{t'}^2)$ (Passarino, Denner,... arXiv:1111.6395):

$$0.6 \longrightarrow 0.2$$

and for $H \longrightarrow ZZ^*, WW^*$

$$\sigma * Br(SM4) \approx 2\sigma * Br(SM3),$$

which is definetly excluded by CMS data on higgs production (slide #9).

light N

There is a possibility to diminish

$$Br(H \longrightarrow ZZ^*, WW^*)_{SM4}$$

by choosing

$$M_H/2 > m_N > M_Z/2$$

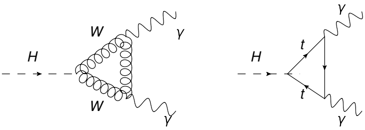
since $H \to NN$ becomes a dominant H decay mode.

From the ATLAS study of $ZH \to ll+$invisible
95% CL upper bound $Br(H \to$invisible$) < 0.65$ follows
(ATLAS-CONF-2013-011).
So, we can make $Br(H \longrightarrow \text{visible})$ up to three times smaller than in SM3.

$m_{\nu'}, m_{l'} \approx 600$GeV

Up to now we present the result of the 4th generation loop corrections for moderate values of the masses of new leptons. If their masses approach 600 GeV then factor 0.2 in the suppression of $H \longrightarrow VV$ decays becomes 0.15, and the product $\sigma * Br$ approaches its value for the 3 generation case (Djouadi, Lenz, arXiv 1204.1252).

$H \to \gamma\gamma, SM$



$$A \sim 7 - 4/3 * 3 * (2/3)^2 = 7 - 16/9,$$

in the limit $M_H << 2M_W, 2m_t$.
These 7 and 16/9 are the QED β - function coefficients; the signs correspond to asymptotic freedom and zero charge behavior respectively.

"7" for the first time appears in the 1965 paper of M.V.Terentiev and V.S.Vanyashin.
Now: $7 = 22/3 - 1/6 - 1/6$, $22/3 = 11/3 * 2$, factors 1/6 originate from the higgs doublet contributions into running of g and g'.

$H \to \gamma\gamma$, 4 generations

For $M_W = 80.4$ GeV 7 should be substituted by 8.3, while for $m_t = 172$GeV 16/9 has 3% accuracy.
So, SM: $A \sim 8.3 - 16/9 = 6.5$

4 gen: $A \sim 8.3 - 16/9 - 16/9 - 4/9 - 4/3 = 3.0$

and taking into account the enhancement of the $H \longrightarrow gg$ decay in 4 gen case $(0.6 * 9 = 5.4)$ we obtain the same $\sigma * Br$ as in Standard Model.

BUT
(2) loop corrections in case of 4 generations greatly diminish $\sigma * Br(H \to 2\gamma)$; according to Denner et al, arXiv: 1111.6395 it equals $1/3$ of 3 generations result (or even less), while the average of ATLAS and CMS data is 1.2 ± 0.2, so the 4th generation is excluded at $4 - 5\sigma$ level. Would be good to calculate 3 loops.

$H \to \tau\tau, bb$

$\sigma * Br$ for $\tau\tau$ mode at tree level equals approximately 9 (H production) * 0.6(enhancement of H decay into gluons) ≈ 5 and electroweak loop corrections make the decay width larger by 30%. The experimental data on $H \to \tau\tau$ (slide $\#$9) exclude this huge enhancement (though light N helps to avoid the contradiction it is excluded by $H \to \gamma\gamma$).

Consideration differs for bb mode: it is seen only in associative higgs boson production $VH \to Vbb$, which unlike gluon fusion is not enhanced in the 4th generation case, and there is no contradiction with the LHC experimental data.

Conclusions

- LHC data on 126 GeV Higgs boson production and decays exclude Standard Model with the sequential fourth generation in perturbation domain: too small $gg \longrightarrow H \longrightarrow \gamma\gamma$, too big $gg \longrightarrow H \longrightarrow \tau\tau$.

- If we are out of perturbative domain ($m4 \sim 1$TeV) extra generation can not be excluded, but we loose the understanding of why all μ's are close to 1 and SM3 works so well.

- In two Higgs doublets model the fourth generation is still allowed (e.g. Geller, Bar-Shalom, Eilam, Soni, arXiv:1209.4081).

- Vector generation has $SU(2) * U(1)$ invariant masses - so, not excluded by higgs data.