Mass Constraints on Fourth Generation of Standard Model Fermions

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***Abstract*— Current experimental bounds on fourth-generation, standard model fermion masses are revisited. Assuming a fourth generation, we cast uniformly distributed masses for four fermions and determine a probability density function based on consistency with the electroweak oblique parameters, S, T, and U, convoluting over Higgs masses. Recent Tevatron combination limit on Mh in the fourth generation scenario is used and a probability density function for the four fermions is obtained.**

I. Introduction

The Standard Model (SM) includes 12 fundamental quarks and leptons, accommodated into three generations. However the number of generations is not fixed by the theory. One extension could be a fourth generation of fermions in the SM (SM4) [1], with currently no strong experimental evidence in conflict or support with it. Also, electroweak precision data does not exclude entirely SM4 [2]. Assuming SM4 is a sequential repetition of the existing generation pattern and the extension maintains SM couplings with no new interactions that do not appear in the first three generations, the ggH0020coupling would be enhanced. We denote U, D for the fourth generation quarks, and N, E for the heavy neutral and charged leptons.

II. Existing Experimental mass constraints

A. Older Constraints

Precise measurements from LEP exclude a light fourth neutrino with mass $m(N) < m_Z/2$, where m_Z is the mass of the Z boson which gives the first constraint

$$m(U, D, N, E) > MZ/2 \tag{1}$$

There are constraints on the masses of fourth generation quarks based on various assumptions about the decay modes of these quarks. Previous searches for direct production of fourth generation quarks at the found $m(U) > 256$ GeV [3], assuming $U \rightarrow W\{q = d,s,b\}$. In 0.76 fb^{-1} of data, CDF searched via the chain

$$p\bar{p} \rightarrow U\bar{U} \rightarrow WqWq \rightarrow l\nu qqqq \tag{2}$$

by reconstructing top quark masses in top-like lepton + jet events and examined the distributions of this reconstructed mass with H_T, the scalar sum of the transverse momenta of all reconstructed objects in the event. From this the following constraint was set,

$$\min(m(U), m(D)) > 256 \text{ GeV} \tag{3}$$

The L3 experiment [4] has set limits on the leptonic side, giving 95% confidence level, CL, limits for 24 different scenarios, but we consider only 3. It may be that that the mixing angles are such that *N* or *E* can promptly decay to a W and a fermion of the first three generations, or it may be that the decay to produces a SM4 fermion. In the latter case, a sequential mass hierarchy (as in the third generation) or a mirror mass hierarchy ($m(D) > m(U)$ or $m(N) > m(E)$) need to be considered separately. The L3 results are summarized in Tables 1 and 2.

Decay mode	Model	Dirac	Majorana
$L^0 \rightarrow eW$	Sequential	101.3	89.5
	Vector	102.6	--
	Mirror	100.8	89.5
$L^0 \rightarrow \mu W$	Sequential	101.5	90.7
	Vector	102.7	--
	Mirror	101.0	90.7
$L^0 \rightarrow \tau W$	Sequential	90.3	80.5
	Vector	99.3	--
	Mirror	90.3	80.5

Table 1. 95% CL lower mass limits in GeV on N

Decay mode	Model	
$L^\pm \rightarrow \nu W$	Sequential	100.8
	Vector	101.2
	Mirror	100.5
$L^\pm \rightarrow L^0 W$	Sequential	101.9
	Vector	102.1
	Mirror	101.9
Stable	Sequential	102.6
	Vector	102.6
	Mirror	102.6

Table 2. 95% CL lower mass limits in GeV on E

The weakest constraints were taken,

$$m(N) > 90.3 \text{ GeV}, \; m(E) > 100.8 \text{ GeV} \tag{4}$$

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$\min(m(U), m(D)) > 256$ GeV

B. Updated Constraints

Recent searches by the CDF Collaboration [5, 6] have placed limits on SM4 quarks,

$$m(U) > 335\ GeV, m(D) > 338\ GeV \qquad (5)$$

We take the limit on the up-type heavy quark from (5), and by considering all scenarios of mixing among four SM generations [7], we use the limit $m(D) > 290$ GeV. The neutral lepton mass constraint is loosened by considering a Majorana coupling [4] and set $m(N) > 80.5$ GeV.

III. PRECISION DATA

The precision oblique parameters S, T, and U provide strong limitations to the parameters of SM4. We follow the work of He, Polonsky and Su [2]. In this form, the one-loop corrections to the oblique parameters are given by

$$\Delta S = \frac{N_c}{6\pi}\left\{\begin{array}{c} 2(3+4Y)x_1 + 2(3-4Y)x_2 - 2Y ln\frac{x_1}{x_2} \\ +\left[\left(\frac{3}{2}+2Y\right)x_1 + Y\right]G(x_1) \\ +\left[\left(\frac{3}{2}-2Y\right)x_2 - Y\right]G(x_2) \end{array}\right\}, \qquad (6)$$

$$\Delta T = \frac{N_c}{8\pi sin^2\theta_w cos^2\theta_w} F(x_1, x_2), \qquad (7)$$

$$\Delta U = -\frac{N_c}{2\pi}\left\{\begin{array}{c} \frac{x_1+x_2}{2} + \frac{(x_1-x_2)^2}{3} + \left[\frac{(x_1-x_2)^3}{6} - \frac{1}{2}\frac{x_1^2+x_2^2}{x_1-x_2}\right] ln\frac{x_1}{x_2} \\ + \frac{x_1-1}{6} f(x_1,x_1) + \frac{x_2-1}{6} f(x_2,x_2) \\ + \left[\frac{1}{3} - \frac{x_1+x_2}{6} - \frac{(x_1-x_2)^2}{6}\right] f(x_1,x_2) \end{array}\right\}, \qquad (8)$$

where $x_i = (m_i / m_Z)^2$ with i = 1 (2), the color factor $N_C = 3$ (1), and the weak isospin Y = 1/6 (-1/2) for quarks (leptons). The functions *f*, F, G are

$$f(x_1,x_2) = \begin{cases} -2\sqrt{\Delta}\left[\arctan\frac{x_1-x_2+1}{\sqrt{\Delta}} - \arctan\frac{x_1-x_2-1}{\sqrt{\Delta}}\right] & (\Delta > 0), \\ 0 & (\Delta = 0), \\ \sqrt{-\Delta}\ln\frac{x_1+x_2-1+\sqrt{-\Delta}}{x_1+x_2-1-\sqrt{-\Delta}} & (\Delta < 0), \end{cases}$$

$$\Delta = 2(x_1+x_2) - (x_1-x_2)^2 - 1,$$

$$F(x_1,x_2) = \frac{x_1+x_2}{2} - \frac{x_1 x_2}{x_1-x_2}\ln\frac{x_1}{x_2},$$

$$G(x) = -4\sqrt{4x-1}\arctan\frac{1}{\sqrt{4x-1}} \qquad (9)$$

Using the Global Analysis of Particle Properties (GAPP) [8], we run a fit to the Higgs boson mass with S,T, and U fixed to zero and obtain $ln(M_H) = 4.43$ in agreement with the Particle Data Group. We then float S, T, and U and obtain correlation values of 88.3% between S and T, -37.0% between S and U, and -58.7% between T and U. Values for dependence of S, T, and U upon $ln(M_H)$ were obtained by repeating the fit of S, T, and U while fixing $ln(M_H)$.

IV. ANALYSIS AND RESULTS

We repeat the He, Polonsky, and Su analysis by selecting only those events from a uniform distribution in all four fermion masses that ranges from the lower limits to 300 GeV that are within a 2σ bound on S, T, and U. We extend the HPS analysis by removing the 2σ bound selection and instead weighing according to the probability density function for the electroweak parameters and integrating over a plausible p.d.f. of M_H, truncated reflecting current direct search bounds [9] and show the results in Fig 1-3.

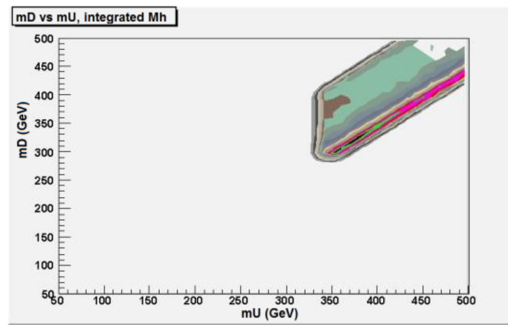

Fig 1. Quark mass distribution plot, weighted by p.d.f. of electroweak parameters after integration over M_H from 114.4 GeV on up and excluding $131 < M_H < 204$.

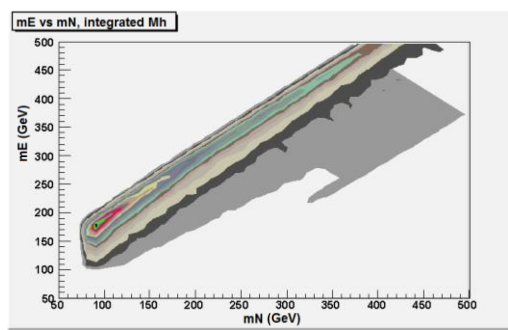

Fig 2. Lepton mass distribution plot.

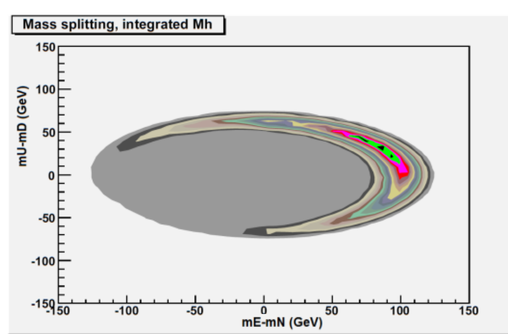

Fig 3. Mass splitting for integration over M_H.

V. Conclusion

It is interesting to note the tendency towards a normal mass hierarchy, with the charged lepton more massive than the neutral one and the up-type quark more massive than the down-type quark, which appeared in the HPS analysis remains, but is not definitive in all scenarios. The mass splitting in the lepton sector is related to the mass splitting in the quark sector in the standard model case.

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