Higgs data does not rule out a sequential fourth generation fermion

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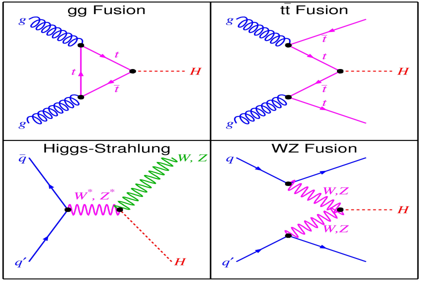
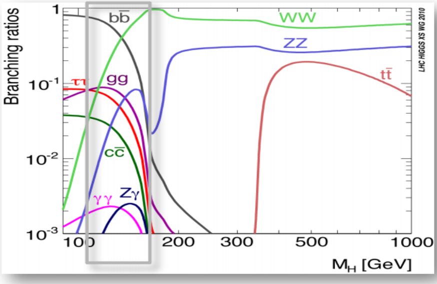
(With D. Das and A. Kundu)

A 125 GeV Higgs

- Production of Higgs at LHC in all four modes.
- LHC is sensitive to Higgs coupling to fermions and bosons and indirectly to gluons and photons.

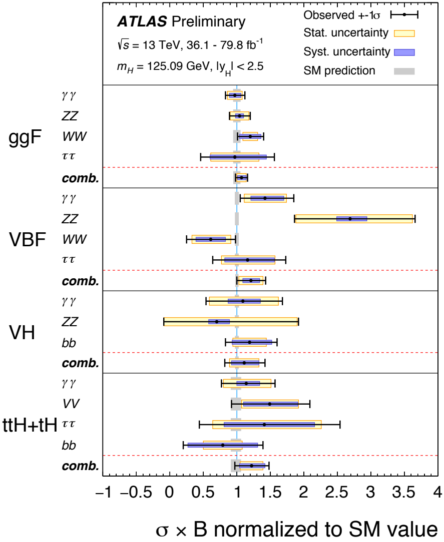




Higgs Signal Strengths

- Simultaneous fit of Higgs production cross section × Branching Ratio.
- Define signal strengths for production and branching ratio:

$$\boxed{\mu_i^f \equiv \frac{\sigma_i . BR^f}{(\sigma_i . BR^f)_{SM}}}$$



ATLAS-CONF-2018-031

The Deceased SM4

Inclusion of an additional fermion generation to the SM is constrained by several observables.

- Slayers:
  - Electroweak precision observables are affected via loop processes.
  - Flavor observables.
  - Direct searches for the production of the heavy fermions at the LHC and at Tevatron.
  - Higgs production and decay are affected via loop processes.
- Salvation:
  - Mass splitting in the fourth family.
  - Considerable CKM mixing with three generations can accommodate both Flavor and EWPO.
  - Stringent limits from direct searches pushes to non-perturbative regime. However, the results rely on specific decay patterns and thus the mass bounds can be relaxed.

No Savior from Higgs data.

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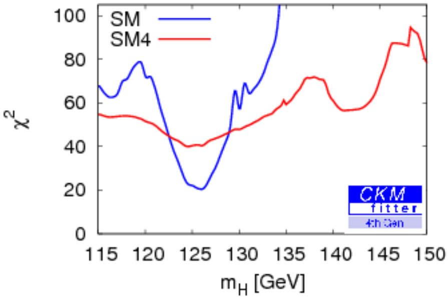
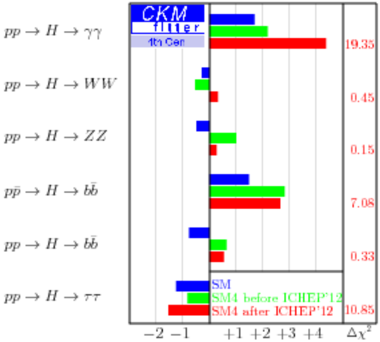
Effect in Higgs Production and Decay

- For a 125 GeV Higgs, the production cross section through gg fusion enhances by factor of 9.
-





[Phys. Rev. Lett. 109 (2012) 241802]

New direction

- Sign of top Yukawa coupling is precisely measured.
- Sign of bottom Yukawa is hard to predict.
- Coupling modification factor, $\kappa = \lambda_{xxh}/\lambda_{xxh\,SM}$.
- In the SM, $\kappa_V = \kappa_u = \kappa_d = 1$. 'd' denotes down-type quark and charged leptons.
- The modification factor for the $gg \to h$ production cross section

$$R_{gg} \quad = \quad \frac{\left|\kappa_t F_{1/2}(\tau_t) + \sum_{f=t',b'} \kappa_f F_{1/2}(\tau_f)\right|^2}{\left|F_{1/2}(\tau_t)\right|^2} \tag{1}$$

- For chiral fermions much heavier than $m_h = 125$ GeV, the loop function, $F_{1/2}$ saturates to a constant value and the new physics (NP) contribution simply becomes proportional to $(\kappa_{t'} + \kappa_{b'})$. Clearly, in the SM-like limit $(\kappa_{t'} = \kappa_{b'} = 1)$, $R_{gg} = 9$.

New direction

- The current LHC data allows a *wrong-sign limit* as $\kappa_V = \kappa_u = -\kappa_d = 1$.
- In the *wrong-sign limit*, enhancement in the ggF channel can be controlled.
- Remember the additional 4G charged leptons that contributes to $h \to \gamma\gamma$ and $Z\gamma$.
- The NP contribution to the $h \to \gamma\gamma$ amplitude, in the heavy mass limit, is proportional to

$$\kappa_{\gamma\gamma} = \sum_{f=t',b',\tau'} Q_f^2 \, N_c^f \, \kappa_f \,, \qquad (2)$$

  One can easily check that $\kappa_{\gamma\gamma} = 0$ in the wrong sign limit.
- In the $h \to Z\gamma$ decay as well, the quantity

$$\kappa_{Z\gamma} = \sum_{f=t',b',\tau'} Q_f T_3^f N_c^f \kappa_f \,, \qquad (3)$$

  where T_3^f denotes the isospin projection of f_L, vanishes in the wrong sign limit leaving no trace of extra generations.

Realizing the Wrong-sign limit

- Not possible to acquire in the SM with one Higgs doublet ⇒ Problem with unitarity.
- A second Higgs doublet can ameliorate.
- Simplest possible BSM ⇒ Type-II 2HDM.

In the context of low energy SUSY: Wagner et al, Phys.Rev. D97 (2018) no.11, 115028.

Type-II 2HDM

- One Higgs doublet couples to the up-type quark and neutral leptons while the other higgs doublet to down type quark and charged leptons.
- The Higgs Potential

$$
\begin{aligned}
V \;=\;& m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - \left(m_{12}^2\phi_1^\dagger\phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\phi_1^\dagger\phi_1\right)^2 + \frac{\lambda_2}{2}\left(\phi_2^\dagger\phi_2\right)^2 \\
& +\lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) + \left\{\frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \text{h.c.}\right\}
\end{aligned}
$$

- Parameters $(m_h, m_H, m_A, m_{H^\pm}, \tan\beta, \alpha, m_{12}^2)$.
- After EWSB,

$$
\phi_1 = \begin{pmatrix} c_\beta G^+ - s_\beta H^+ \\ \frac{1}{\sqrt{2}}(c_\beta v - s_\alpha h + c_\alpha H + i(c_\beta G^0 - s_\beta A)) \end{pmatrix}
$$

$$
\phi_2 = \begin{pmatrix} s_\beta G^+ + c_\beta H^+ \\ \frac{1}{\sqrt{2}}(s_\beta v + c_\alpha h + s_\alpha H + i(s_\beta G^0 + c_\beta A)) \end{pmatrix}
$$

Wrong-sign limit in Type-II 2HDM

- The Higgs coupling modification factors are

$$\begin{aligned}
\kappa_V &= \sin(\beta-\alpha)\,, \quad (V = W, Z) \\
\kappa_u &= \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\,, \quad \text{(for up type quarks)} \\
\kappa_d &= \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\,, \quad \text{(for down type quarks and charged}
\end{aligned}$$

- The Wrong-sign limit reaches at

$$\cos(\beta-\alpha) = \frac{2}{\tan\beta}\,, \quad \text{with, } \tan\beta \gg 2$$

- If one demands $\kappa_u = -\kappa_d$ only,

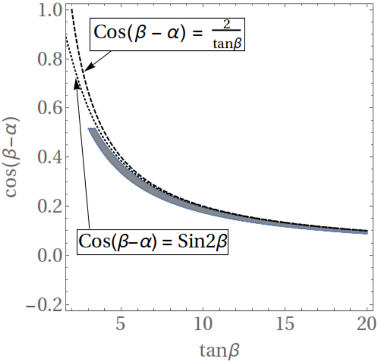
$$\cos(\beta-\alpha) = \sin 2\beta\,.$$

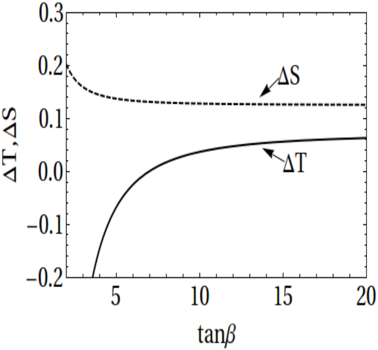
which is the same as above for large $\tan\beta$.

The undying 4G chiral fermions

- Charged scalar mass has to be > 500 GeV from $b \to s\gamma$.
- Additional scalars and fermions contribute to oblique parameters and one should verify $\Delta T = (0.08 \pm 0.12), \Delta S = 0.05 \pm 0.10$.
- Recent direct search bound $m_{q'} > 700\text{GeV}$ depending on decay channel.
- For a benchmark point,

$$m_{t'} = 550 \text{ GeV}\,,\ m_{b'} = 510 \text{ GeV}\,,\ m_{\tau'} = 400 \text{ GeV}\,,\ m_{\nu'} = 200 \text{ GeV}\,,$$
$$m_H = 400 \text{ GeV}\,,\ m_A = 810 \text{ GeV}\,,\ m_{H+} = 600 \text{ GeV}\,.$$





Conclusion

- The 4G chiral fermions are severely disfavored from Higgs data in the SM.
- We invoke the *Wrong-sign limit* to cancel the additional fermion contribution in Higgs production.
- The limit can only be achieved with an additional Higgs doublet.
- We show that such limit can be realized in a Type-II 2HDM in accordance with electroweak precision constraints.
- Lower bound on $\tan\beta$.


Thank you

Backup

$\boxed{BACKUPs}$

T parameter

The scalar contribution to T parameter [Branco et al.' 2011]

$$
\begin{aligned}
\mathrm{T}_{\mathrm{Scalar}} \quad = \quad & \frac{1}{16\pi \sin^2\theta_w M_W^2}\Big[\sin^2(\beta-\alpha) F_T\left(m_{H^+}^2, m_H^2\right) + \cos^2(\beta-\alpha) F_T\left(m_{H^+}^2, m_H^2\right) + F_T\left(m_{H^+}^2, m_A^2\right) \\
& -\cos^2(\beta-\alpha) F_T\left(m_h^2, m_A^2\right) - \sin^2(\beta-\alpha) F_T\left(m_A^2, m_H^2\right) + \\
& 3\left\{\cos^2(\beta-\alpha)\left(F_T\left(M_Z^2, m_H^2\right) - F_T\left(M_W^2, m_H^2\right)\right) + \sin^2(\beta-\alpha)\left(F_T\left(M_Z^2, m_h^2\right) - F_T\left(M_W^2, m_h^2\right)\right) \\
& -3\left\{F_T\left(M_Z^2, m_h^2\right) - F_T\left(M_W^2, m_h^2\right)\right\}\Big];
\end{aligned}
$$

The fermion contribution to T-parameter [Dighe et al.' 2012]

$$
\begin{aligned}
\mathrm{T}_{\mathrm{Fermion}} \quad &= \quad \frac{1}{8\pi \sin^2\theta_W \cos^2\theta_W}\left[3F_T\left(\frac{m_{t'}^2}{M_Z^2}, \frac{m_{b'}^2}{M_Z^2}\right) + F_T\left(\frac{m_{E'}^2}{M_Z^2}, \frac{m_{N'}^2}{M_Z^2}\right)\right]; && (6) \\
\Delta T \quad &= \quad \mathrm{T}_{\mathrm{Scalar}} + \mathrm{T}_{\mathrm{Fermion}}\,. && (7) \\
\text{with,} \quad & \quad F_T(x, y) = \begin{cases} \frac{x+y}{2} - \frac{xy}{x-y}\ln\left(\frac{x}{y}\right) & x \neq y\,, \\ 0 & x = y\,. \end{cases}
\end{aligned}
$$

S parameter

$$
\begin{aligned}
S_{\text{Scalar}} &= \frac{1}{24\pi}\Bigg[(\sin^2\theta_w - \cos^2\theta_w)^2 G_S\left(\frac{m_{H+}^2}{M_Z^2}, \frac{m_{H+}^2}{M_Z^2}\right) + \cos(\beta-\alpha)^2 G_S\left(\frac{m_h^2}{M_Z^2}, \frac{m_A^2}{M_Z^2}\right) + \\
&\quad \sin(\beta-\alpha)^2 G_S\left(\frac{m_A^2}{M_Z^2}, \frac{m_H^2}{M_Z^2}\right) + \cos(\beta-\alpha)^2 G'_S\left(\frac{m_H^2}{M_Z^2}\right) + \sin(\beta-\alpha)^2 G'_S\left(\frac{m_h^2}{M_Z^2}\right) \\
&\quad - G'_S\left(\frac{m_h^2}{M_Z^2}\right) + \ln\left(\frac{m_H^2}{m_{H+}^2}\right)\Bigg]; \qquad (8) \\
S_{\text{Fermion}} &= \frac{3}{6\pi}\left[1 - 2\left(\frac{1}{6}\right)\ln\left(\frac{m_{t'}^2}{m_{b'}^2}\right)\right] + \frac{1}{6\pi}\left[1 - 2\left(\frac{-1}{2}\right)\ln\left(\frac{m_{N'}^2}{m_{E'}^2}\right)\right]; \qquad (9) \\
\Delta S &= S_{\text{Scalar}} + S_{\text{Fermion}} . \qquad (10) \\
G_S(x,y) &= \begin{cases} -\frac{16}{3} + 5(x+y) - 2(x-y)^2 + 3\left(\frac{x^2+y^2}{x-y} - x^2 + y^2 + \frac{(x-y)^3}{3}\right)\ln\left(\frac{x}{y}\right) & \\ \quad +(1-2(x+y)+(x-y)^2)F_S(x+y-1, 1-2(x+y)+(x-y)^2) & x \neq y , \\ -\frac{16}{3} + 8(x+y) + (1-2(x+y))F_S(x+y-1, 1-2(x+y)) & x = y . \end{cases} \qquad (11) \\
G'_S(x) &= -\frac{79}{3} + 9x - 2x^2 + \left(-10 + 18x - 6x^2 + x^3 - 9\frac{x+1}{x-1}\right)\ln(x) + (12 - 4x + x^2)F_S(x, x^2 - 4x) . \qquad (12)
\end{aligned}
$$

$$
F_S(z,w) = \begin{cases} \sqrt{w}\ln\left|\frac{z-\sqrt{w}}{z+\sqrt{w}}\right| & w > 0 , \\ 0 & w = 0 , \\ 2\sqrt{-w}\arctan\left(\frac{\sqrt{-w}}{z}\right) & w < 0 . \end{cases}
$$