Higgs data does not rule out a sequential fourth generation fermion

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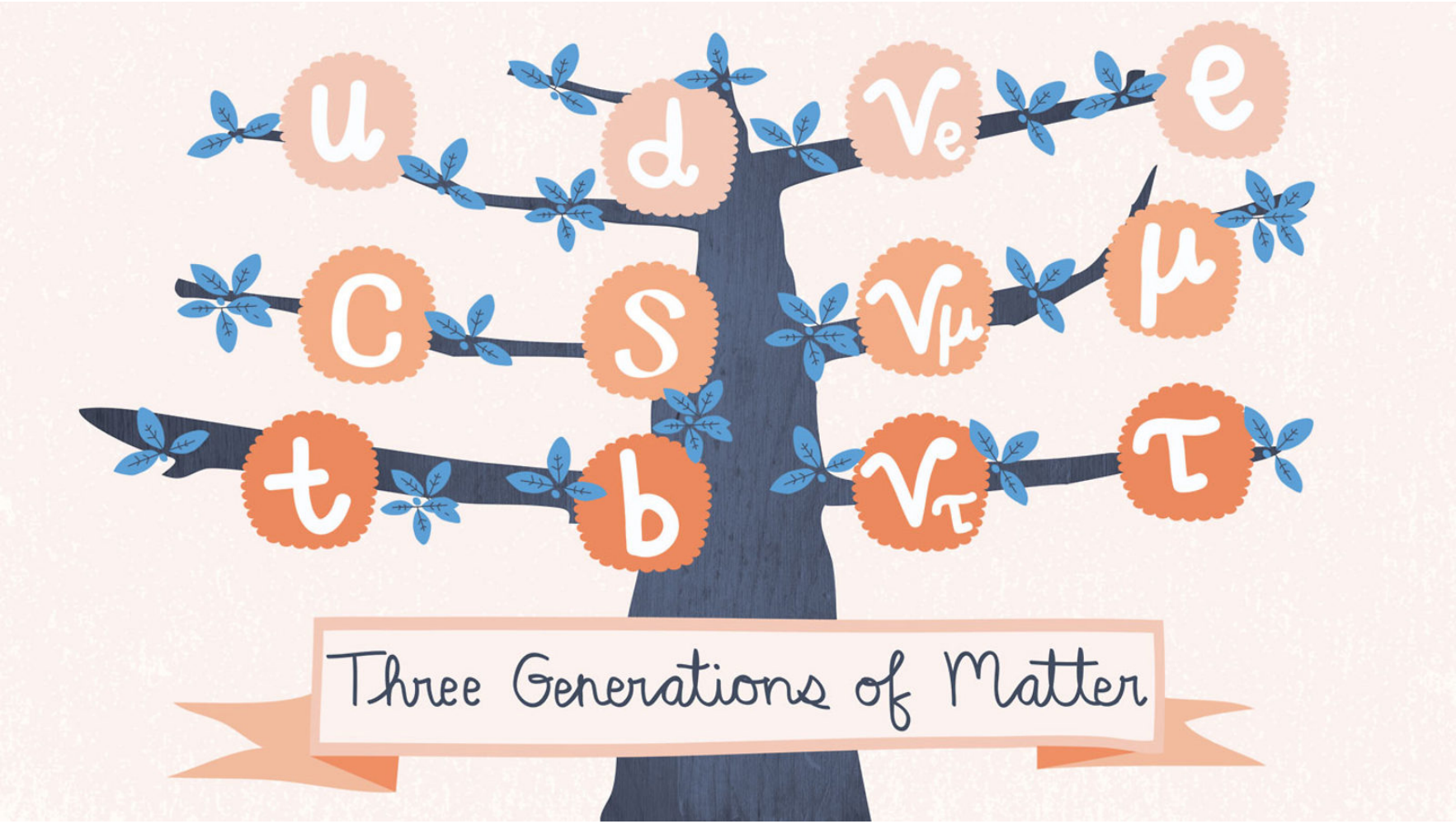
Phys. Rev. D97, 011701 (1707.03000)
With D. Das and A. Kundu

Why 3 generation?



The Deceased SM4

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

- 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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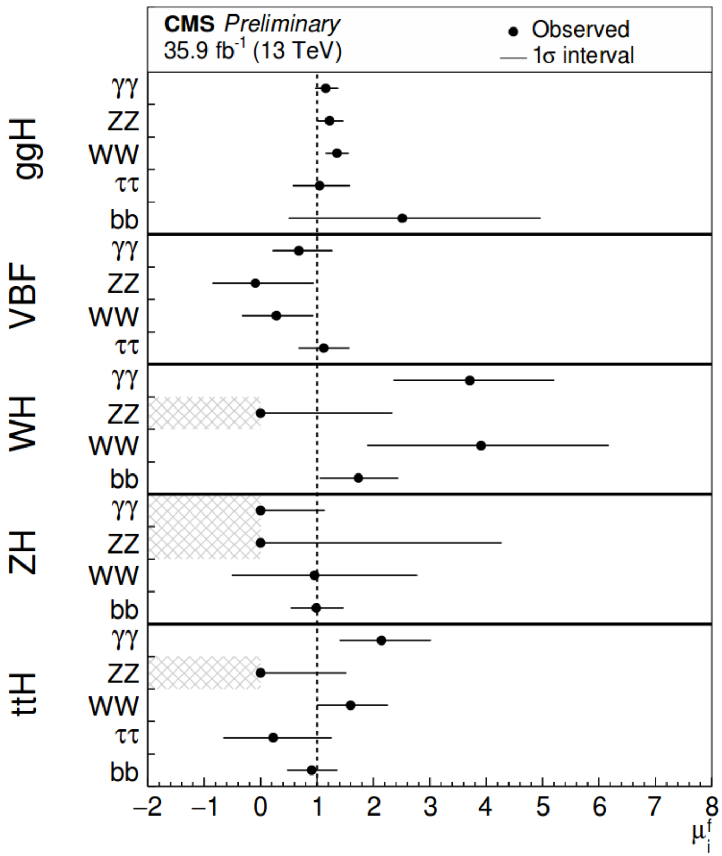
Latest Higgs Data

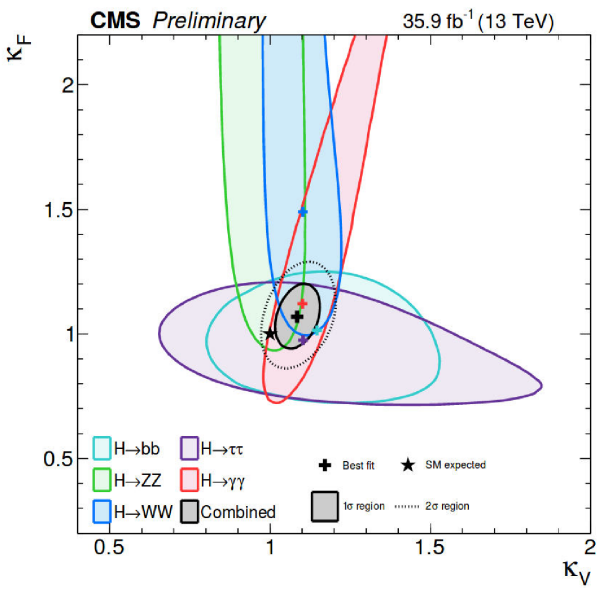
CMS Combination

CMS-PAS-HIG-17-031

NEW!



- Includes a wide range of H measurements using the full 2016 dataset
- Combined analysis sensitive to 22 out of 25 possible prod. x decay combinations

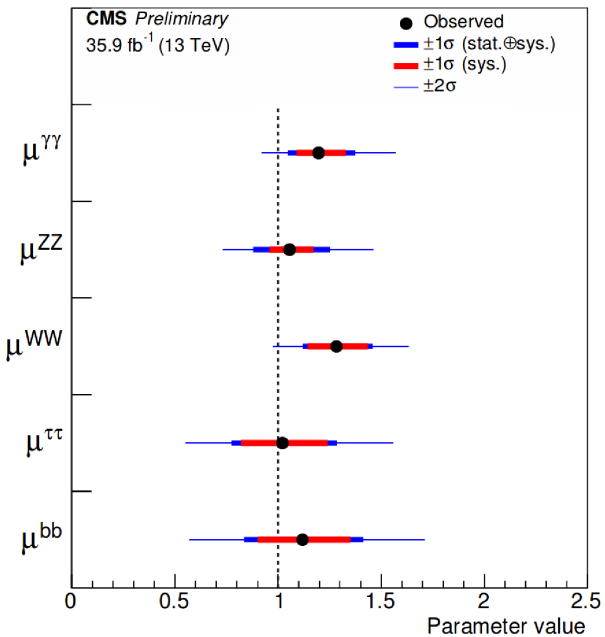


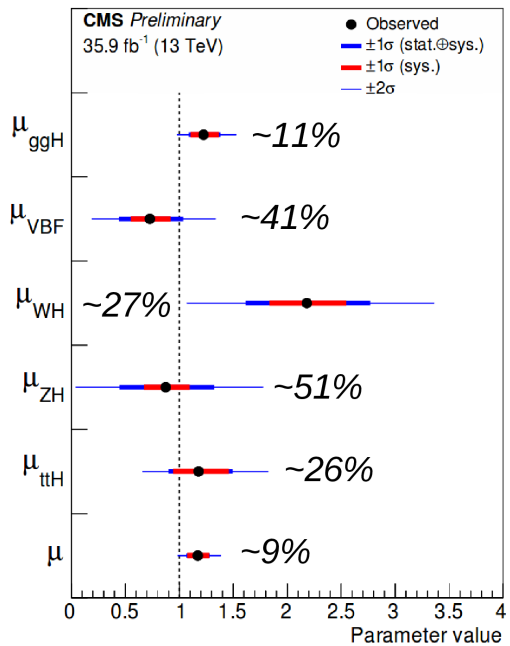
Latest Higgs Data

Production and Decay Modes

CMS-PAS-HIG-17-031

$$\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$$





Most precise measurement of gluon fusion, ttH, and total signal strength

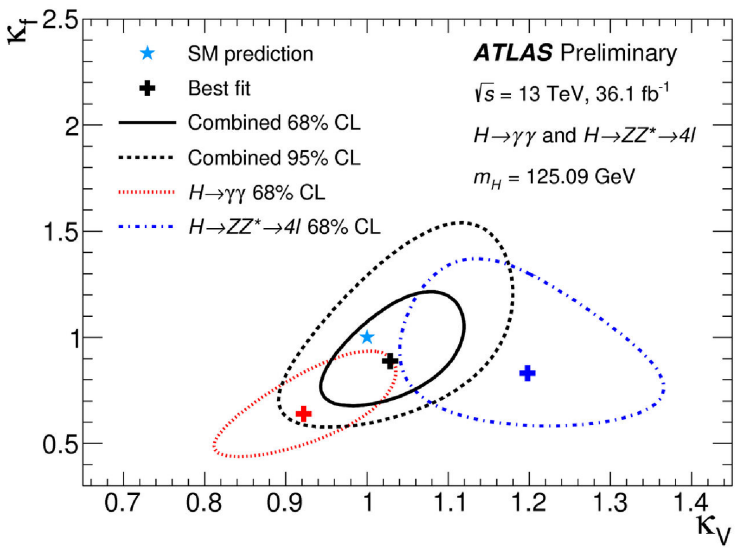
(ATLAS+CMS Run 1 combination: $\mu_{\text{ggH}} = 1.03^{+0.16}_{-0.14}$)

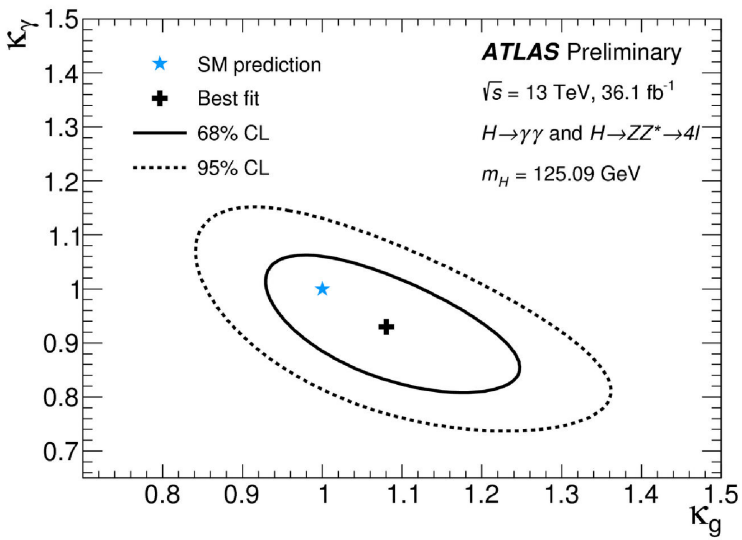
Latest Higgs Data

ATLAS Comb.: Higgs Couplings *ATLAS-CONF-2017-047*

- Results also interpreted in terms of Higgs couplings using the leading order inspired "κ-framework" model
- 2D regions found for κ_V vs. κ_F, and κ_g vs. κ_γ

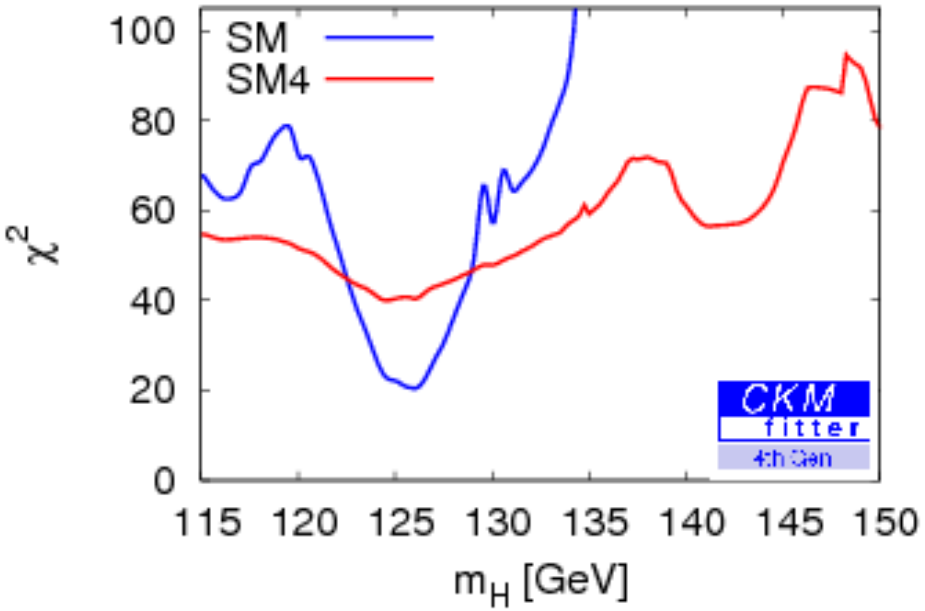
  ➔ Assuming no BSM contributions to total width

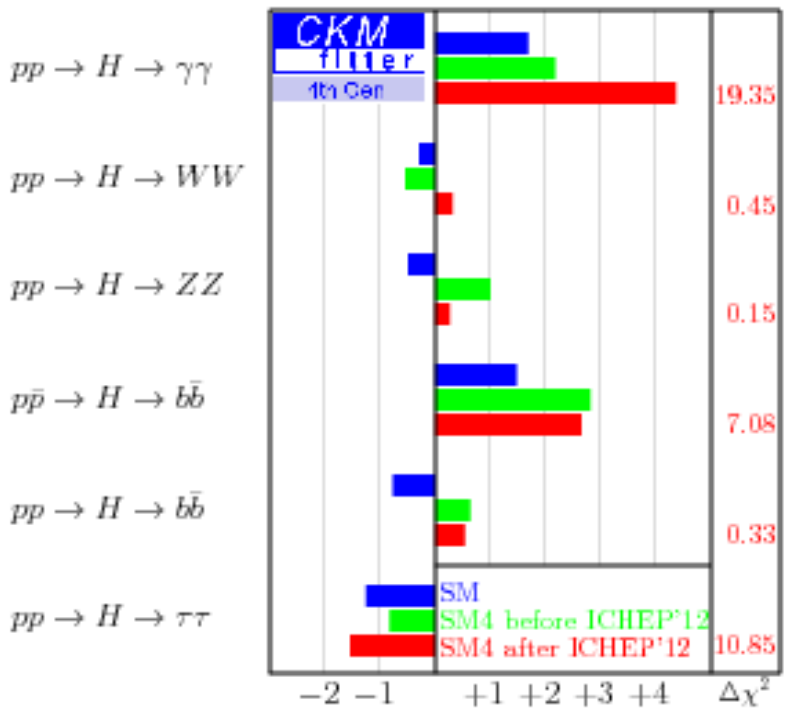




4G effect in Higgs Production and Decay

- 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

- 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

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

- 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 $(\kappa_{t'} = \kappa_{b'} = 1)$, $R_{gg} = 9$.
- Include extra charged lepton for anomaly cancellation that contribute to $h \to \gamma\gamma$ and $h \to Z\gamma$.
- The NP contribution to the $h \to \gamma\gamma$ amplitude, in the heavy mass limit

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

$N_c^f = 3$ for quarks and 1 for leptons.

New direction

- Sign of top Yukawa coupling is precisely measured but the sign of bottom Yukawa is hard to predict.
- 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.
- Note that the additional 4G charged leptons makes $\kappa_{\gamma\gamma} = 0$ in this limit.
- Even for $Z\gamma$ amplitude,

$$\kappa_{Z\gamma} \quad = \quad \sum_{f=t',b',\tau'} Q_f^2 T_3^f N_c^f \kappa_f \tag{3}$$

  T_3^f is the isospin projection, vanishes in the same limit.
- Therefore, in the *wrong-sign limit*, the chiral fermion generation remain perfectly **hidden** from the Higgs data leaving no trace of extra generation.

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.
- Possible BSM ⇒ Type-II 2HDM. Ferreira et al 1410.1926

Recent study in the context of low energy SUSY
N. M. Coyle, B. Li and C. E. M. Wagner – 1802.09122 .

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

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

- 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,

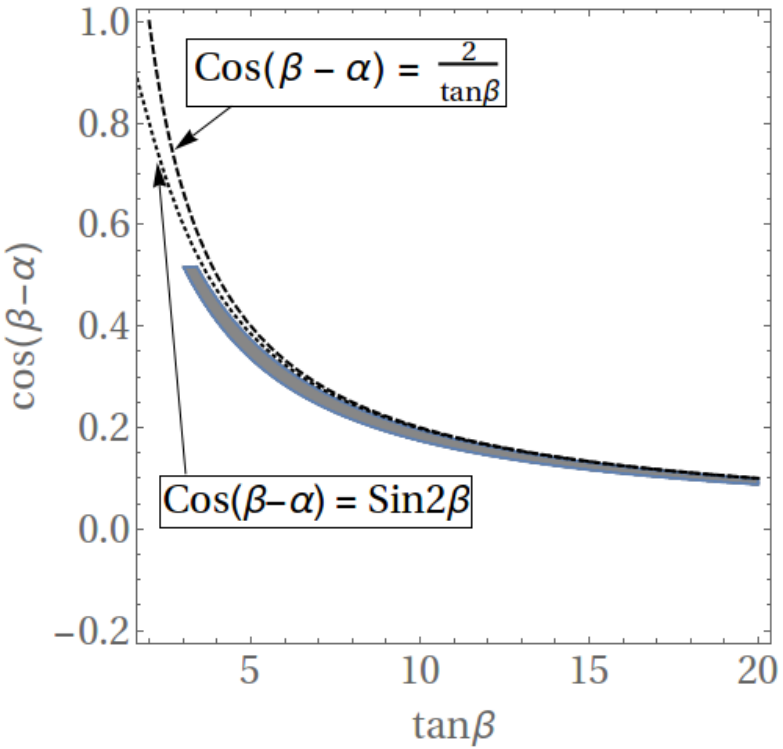
$$\cos(\beta-\alpha)=\sin 2\beta\,.$$

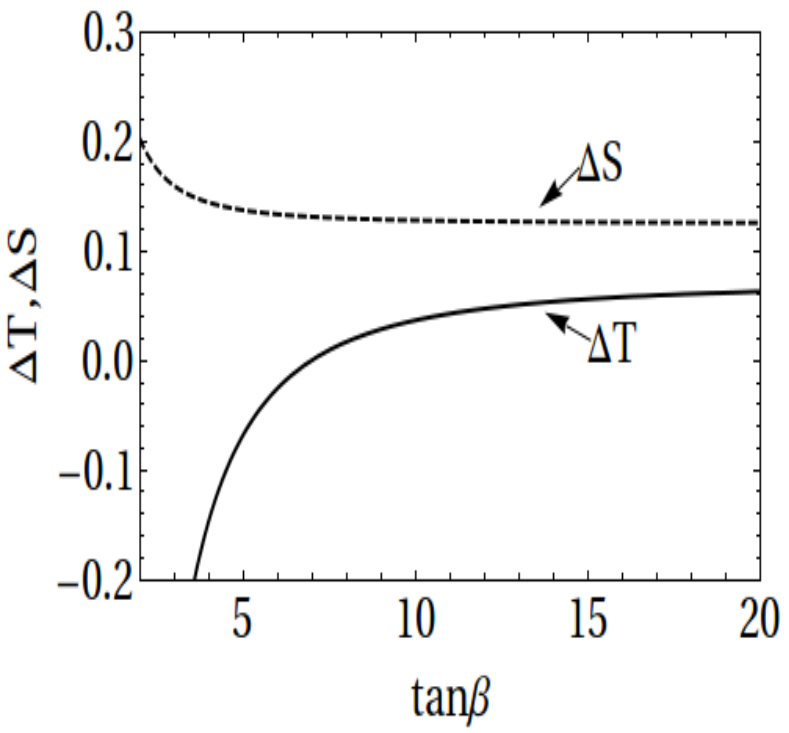
which is the same as above for large $\tan\beta$.

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 $m_{q'} > 700$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

$BACKUPs$

T parameter

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

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

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

$$
\mathrm{T}_{\mathrm{Fermion}} \quad = \quad \frac{1}{8\pi \sin^2\theta_W \cos^2\theta_W}\left[3F_T\left(\frac{m_{t'}^2}{M_Z^2}, \frac{m_{b'}^2}{M_Z^2}\right) + F_T\left(\frac{m_{E'}^2}{M_Z^2}, \frac{m_{N'}^2}{M_Z^2}\right)\right]; \tag{6}
$$

$$
\Delta T \quad = \quad \mathrm{T}_{\mathrm{Scalar}} + \mathrm{T}_{\mathrm{Fermion}}\,. \tag{7}
$$

$$
\text{with,} \qquad F_T(x,y) = \begin{cases} \frac{x+y}{2} - \frac{xy}{x-y}\ln\left(\frac{x}{y}\right) & x \neq y\,, \\ 0 & x = y\,. \end{cases}
$$

S parameter

$$
\begin{aligned}
{}^{\mathrm{S}}\mathrm{Scalar} &= \frac{1}{24\pi}\Big[(\sin^2\theta_w-\cos^2\theta_w)^2 G_S\left(\frac{m_{H+}^2}{M_Z^2},\frac{m_{H+}^2}{M_Z^2}\right)+\cos(\beta-\alpha)^2 G_S\left(\frac{m_h^2}{M_Z^2},\frac{m_A^2}{M_Z^2}\right)+ \\
&\quad \sin(\beta-\alpha)^2 G_S\left(\frac{m_A^2}{M_Z^2},\frac{m_H^2}{M_Z^2}\right)+\cos(\beta-\alpha)^2 G_S'\left(\frac{m_H^2}{M_Z^2}\right)+\sin(\beta-\alpha)^2 G_S'\left(\frac{m_h^2}{M_Z^2}\right) \\
&\quad -G_S'\left(\frac{m_h^2}{M_Z^2}\right)+\ln\left(\frac{m_H^2}{m_{H+}^2}\right)\Big]; \qquad (8)
\end{aligned}
$$

$$
{}^{\mathrm{S}}\mathrm{Fermion} = \frac{3}{6\pi}\left[1-2\left(\frac{1}{6}\right)\ln\left(\frac{m_{t'}^2}{m_{b'}^2}\right)\right]+\frac{1}{6\pi}\left[1-2\left(\frac{-1}{2}\right)\ln\left(\frac{m_{N'}^2}{m_{E'}^2}\right)\right]; \qquad (9)
$$

$$
\Delta S = {}^{\mathrm{S}}\mathrm{Scalar}+{}^{\mathrm{S}}\mathrm{Fermion}\,. \qquad (10)
$$

$$
G_S(x,y) = \begin{cases} -\frac{16}{3}+5(x+y)-2(x-y)^2+3\left(\frac{x^2+y^2}{x-y}-x^2+y^2+\frac{(x-y)^3}{3}\right)\ln\left(\frac{x}{y}\right) & \\ \quad +(1-2(x+y)+(x-y)^2)F_S(x+y-1,1-2(x+y)+(x-y)^2) & x\neq y\,, \\ -\frac{16}{3}+8(x+y)+(1-2(x+y))F_S(x+y-1,1-2(x+y)) & x=y\,. \end{cases} \qquad (11)
$$

$$
G_S'(x) = -\frac{79}{3}+9x-2x^2+\left(-10+18x-6x^2+x^3-9\frac{x+1}{x-1}\right)\ln(x)+(12-4x+x^2)F_S(x,x^2-4x)\,. \qquad (12)
$$

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