Unravelling an Extended Fermion Sector Through Higgs Physics

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Phys.Rev. D87 (2013) 014007, S. Dawson, E. Furlan, IL
arXiv:1406.3349, C-Y Chen, S. Dawson, IL

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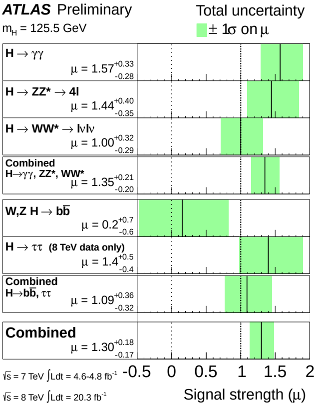
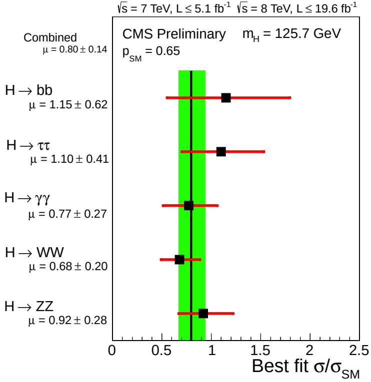
LHC After the Higgs

Santa Fe

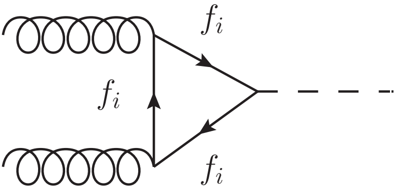
Now what?





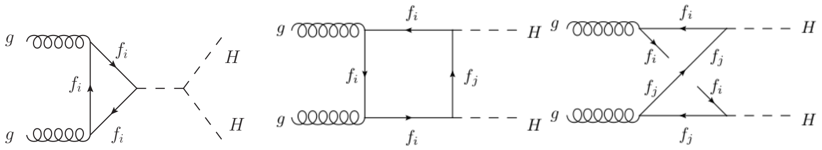
- Discovered a Higgs boson at $\sim$ 125 GeV, remarkably SM like properties.
- Era of precision Higgs physics fast approaching.
- Can we use these measurements to gain insight into new physics?
- In particular, if new heavy colored fermions, may expect Higgs production to be sensitive to physics of extended sector.

Single Higgs Production



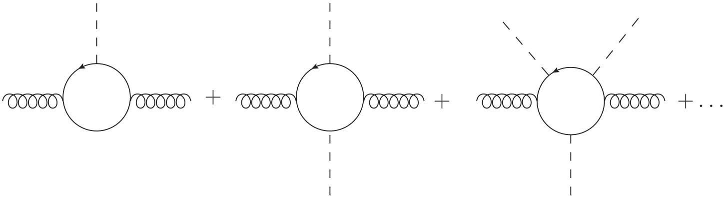
- Single Higgs production proceeds via triangle diagram:
  - Only sensitive flavor diagonal Higgs couplings.
  - Not enough information to probe structure of new sector.
- However, double Higgs production also includes a box diagram that may be sensitive to different couplings.

Double Higgs Production



- Double Higgs production proceeds through triangle and box diagrams.
- The box diagrams involve flavor off-diagonal couplings.
- Additionally, the *s*-channel diagram sensitive to Higgs trilinear coupling.
  - Directly probe structure of Higgs potential.
- Will focus on effects of heavy new colored fermions.
- However, flavor-off diagonal couplings not enough, to understand will analyze Low Energy Theorems (LET):
  - The limit in which the particles in the loops are much heavier than other energy scales of the process.

Low Energy Theorem in SM

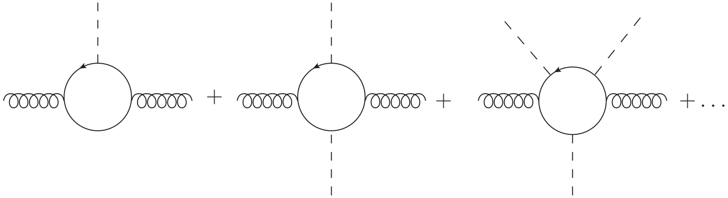


- In the limit $p_H \to 0$ Higgs coupling looks like a vev insertion (assume particles $m_i \gg m_H$)
- If masses proportional to vev, as in SM, have low energy theorem:

$$\lim_{p_H \to 0} \mathcal{M}(X+H) = \sum_i \frac{g_i}{v^0} m_i^0 \frac{\partial}{\partial m_i^0} \mathcal{M}(X)$$

  - X is some process with a Higgs.
- Apply many times find the effective operator: $\mathcal{O}_2 = \frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{a,\mu\nu} \log\left(\frac{\Phi^\dagger \Phi}{v^2}\right)$
  - Φ is the Higgs doublet.
- What if particles have other sources of mass?
- Notice the for gg fusion, the above LET looks like derivatives of the β-function.

Calculating LET



- In limit $p_H \to 0$, looks like QCD beta function corrections.
- Considering only colored fermions:

$$\mathcal{L} = -\frac{1}{4g_{\rm eff}^2(\mu)} G^a_{\mu\nu} G^{a,\mu\nu} = -\frac{1}{4g_s^2(\mu)} \left(1 - \frac{g_s^2(\mu)}{24\pi} \log\det \frac{\mathcal{M}^\dagger(\Phi)\mathcal{M}(\Phi)}{\mu^2}\right) G^a_{\mu\nu} G^{a,\mu\nu}$$

- $\mathcal{M}(\Phi)$ is the Higgs dependent mass matrix.
- Effective Lagrangian:

$$\mathcal{L}_{eff} = \frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{a,\mu\nu} \log\det \frac{\mathcal{M}^\dagger(\Phi)\mathcal{M}(\Phi)}{\mu^2}$$

Mass Dependence of LETs

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- Expand about $\Phi = (v+H)/\sqrt{2}$ to obtain effective Higgs interactions.
- In this formulation, can obtain LET with fermions in any mass basis.

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- Expand about $\Phi = (v+H)/\sqrt{2}$ to obtain effective Higgs interactions.
- In this formulation, can obtain LET with fermions in any mass basis.
- If particles get their mass only from Standard Model Higgs: $\mathcal{M}(\Phi) = \mathcal{M}(0)\Phi$:

$$\begin{aligned} \mathcal{L}_{eff} &= \frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{a,\mu\nu} \log\det \frac{\mathcal{M}^\dagger(\Phi)\mathcal{M}(\Phi)}{\mu^2} \\ &\to \frac{\alpha_s N}{24\pi} G^a_{\mu\nu} G^{a,\mu\nu} \log\left(\frac{\Phi^\dagger\Phi}{v^2}\right) \end{aligned}$$

  - $N =$ number of heavy particles.
- LET insensitive to couplings and masses of the new sector.
- Results in substantial deviation in Higgs production rate.
- To obtain results consistent with current data, new states need additional mass sources.
- Study vector-like fermions, such that have $SU(2)_L$ invariant Dirac mass.

Effective Operators

- Up to double Higgs production and for generic masses, $\mathcal{L}_{eff}$ generates two operators Pierce, Thaler, Wang JHEP 0705 (2007) 070:

$$\mathcal{O}_1 = \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a,\mu\nu} \frac{\Phi^\dagger \Phi}{v^2} \qquad \simeq \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a,\mu\nu} \left(\frac{H}{v} - \frac{H^2}{2v^2} \right)$$

$$\mathcal{O}_2 = \frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{a,\mu\nu} \log\left(\frac{\Phi^\dagger \Phi}{v^2} \right) \quad \simeq \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a,\mu\nu} \left(\frac{H}{v} + \frac{H^2}{2v^2} \right)$$

- Have effective Lagrangian:

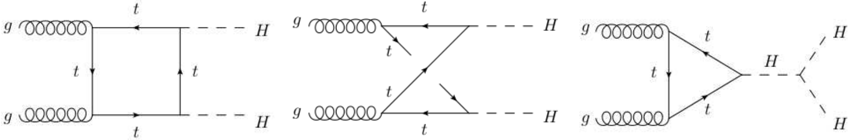
$$\mathcal{L} = c_1 \mathcal{O}_1 + c_2 \mathcal{O}_2 \simeq \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a,\mu\nu} \left[(c_1 + c_2) \frac{H}{v} + (c_1 - c_2) \frac{H^2}{2v^2} \right]$$

- Measuring both single and double Higgs rates can give insight into masses and couplings of colored particles in loops.

Questions

- How well can we measure double Higgs rate?
- How well do the LETs work?
- What type of colored fermions and couplings give deviations from SM-like single and double Higgs productions?
  - Singlet top partner.
  - Mirror fermion pair.
  - Vector-like quark pair with SM mixing.
- Given nearly SM-like single Higgs production cross section, can we get a significant enhancement in double Higgs production?

Standard Model DiHiggs production

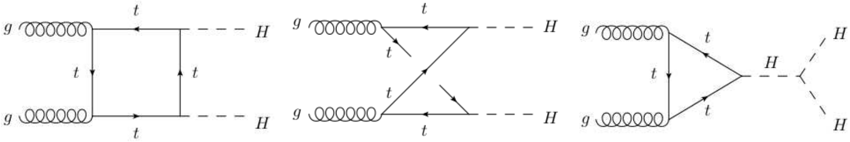


- Sensitive to Higgs trilinear coupling and possible new physics.
- Cross section of ~ 40.2 fb at 14 TeV at NNLO de Florian, Mazzitelli, PRL111 (2013) 201801
    - Top mass effects important for NLO K-factors Grigo, Hoff, Melnikov, Steinhauser, NPB875 (2013) 1
- Most likely most sensitive final state is $gg \to HH \to b\bar{b}\gamma\gamma$ Baur, Plehn, Rainwater, hep-ph/0310056
- In $b\bar{b}\gamma\gamma$ channel with 3 ab^{-1} (with NLO rate) Snowmass Higgs Working Group; Yao, 1308.6302:

	14 TeV	33 TeV	100 TeV
$S/\sqrt{B}$	2.3	6.2	15.0
Trilinear uncertainty	50%	20%	8%

- Maybe combine channels to increase LHC measurement to 30% Goertz, Papaefstathiou, Yang, Zurita, 1301.3492

Standard Model



- Parameterize amplitude for $g^{a,\mu}(p_1)g^{b,\nu}(p_2) \to H(p_3)H(p_4)$ Glover, van der Bij, NPB309 (1988) 282:

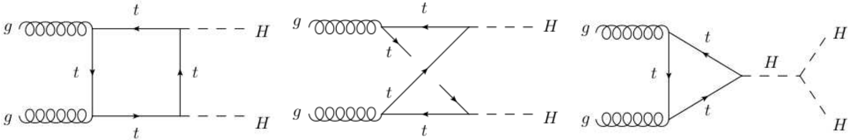
$$A^{\mu\nu}_{ab} = \frac{\alpha_s}{8\pi v^2}\delta_{ab}\left[P_1^{\mu\nu}(p_1,p_2)F_1(s,t,u,m_t^2) + P_2^{\mu\nu}(p_1,p_2,p_3)F_2(s,t,u,m_t^2)\right]$$

  - P_1 and P_2 are orthogonal spin-0 and spin-2 projectors.
- Partonic cross section:

$$\frac{d\hat{\sigma}(gg \to HH)}{dt} = \frac{\alpha_s^2}{2^{15}\pi^3 v^4}\frac{|F_1(s,t,u,m_t^2)|^2 + |F_2(s,t,u,m_t^2)|^2}{s^2}$$

- Can directly expand function in $1/m_t^2$ to see convergence of series.
- LET corresponds to LO piece.

Standard Model



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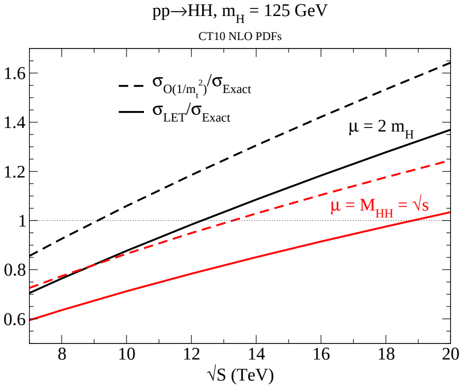
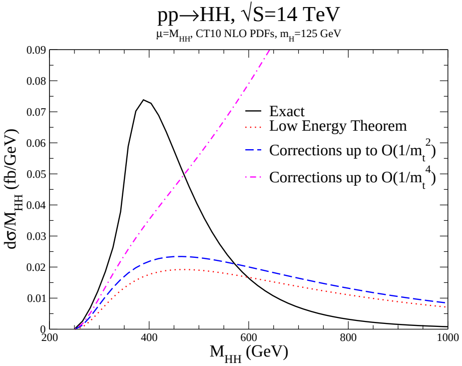
- In low energy limit $c_H = 1 \qquad c_{HH} = -1$:

$$F_1(s,t,u,m_t^2)\,|_{LET} \to \left(-\frac{4}{3} + \frac{4m_H^2}{s - m_H^2}\right)s \qquad F_2(s,t,u,m_t^2)\,|_{LET} \to 0$$

- At threshold $s = 4m_H$, $F_1 \to 0$.

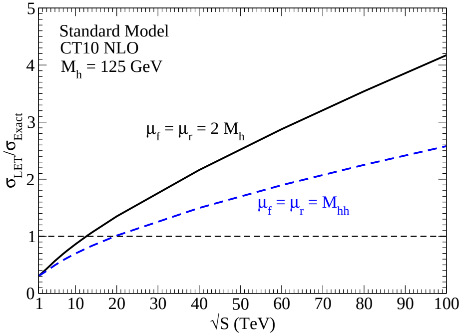
Accuracy of Expansion

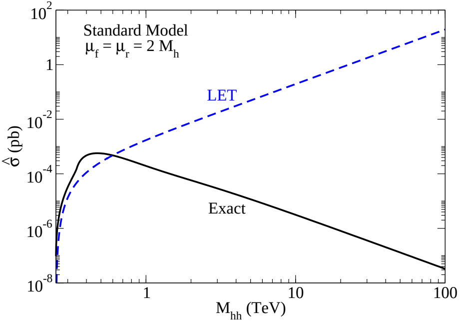




- LET appears to give good approximation to total cross section around 14 TeV.
- Distributions of M_{HH} are not convergent in the expansion.

Accuracy of Expansion





- Approximate answer at $\sim$ 14 TeV appears to be accident.
- Partonic cross section diverges.
- Hadronic cross section largely determined by where pdf suppressions cuts off partonic cross section.
- Never-the-less, will use LET to try to gain insight into physics of production cross sections.

Additional Heavy Quarks

- Will focus on additional heavy quarks running in loops.
- Current direct constraints depend on search strategy $T \to Ht$, $T \to Zt, T \to Wb$, etc.

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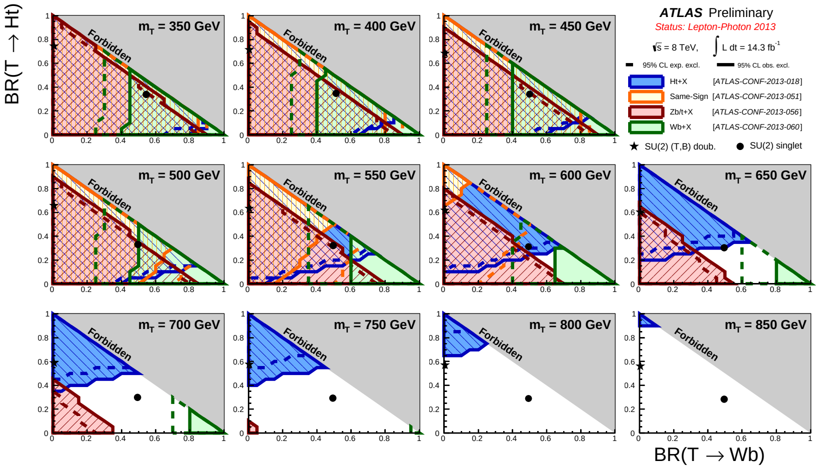

Singlet Top Partner

- Want new particle whose mass arises from some place besides the Higgs.
- Only concentrate on mixing with 3^{rd} generation SM quarks:

$$\psi_L = \begin{pmatrix} \mathcal{T}^1_L \\ \mathcal{B}^1_L \end{pmatrix}, \quad \mathcal{T}^1_R, \mathcal{B}^1_R$$

- Add vector-like singlet top quark: $\mathcal{T}^2_L, \mathcal{T}^2_R$
- Mass eigenstates: $\chi^t_{L,R} \equiv \begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} \equiv U^t_{L,R} \begin{pmatrix} \mathcal{T}^1_{L,R} \\ \mathcal{T}^2_{L,R} \end{pmatrix}$ $\quad b = \mathcal{B}^1$

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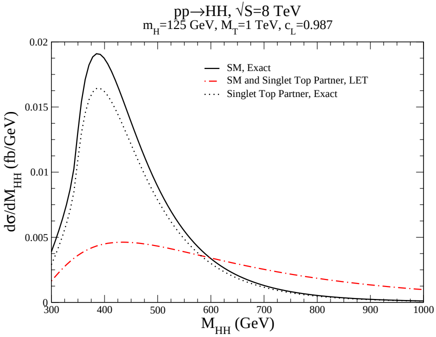
- Then have fermions mass terms:

$$-\mathcal{L}_{M,1} \quad = \quad \lambda_1 \overline{\psi}_L \Phi \mathcal{B}_R^1 + \lambda_2 \overline{\psi}_L \tilde{\Phi} \mathcal{T}_R^1 + \lambda_3 \overline{\psi}_L \tilde{\Phi} \mathcal{T}_R^2 + \lambda_4 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^1 + \lambda_5 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^2 + \text{h.c.}$$

  - $\tilde{\Phi} = i\sigma^2 \Phi^*$
- Note that by rotating $\mathcal{T}_R^2$ and $\mathcal{T}_R^2$, can eliminate $\overline{\mathcal{T}}_L^2 \mathcal{T}_R^1$.
- Choose to be m_t, M_T, θ_L

Singlet Top Partner



- $\cos\theta_L = 0.987$ is smallest allowed by electroweak precision measurements Dawson, Furlan, 1205.4733
- At most decreases SM double Higgs rate by $\sim 15\%$.
- The LET is exactly the same in two cases.

Low Energy Theorems, Again

- Why are the LETs exactly the same for the Standard Model and the Standard Model+Singlet Top Partner?
- Parameterize (using $\Phi = (v+H)/\sqrt{2}$):

$$\det \mathcal{M}(\Phi) = [1 + F_i(H/v)] \times P(\lambda_i, m_i, v)$$

  - λ_i, m_i are fermion couplings and masses

$$\begin{aligned} \mathcal{L}_{eff} &= \frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{a,\mu\nu} \log\det \frac{\mathcal{M}^\dagger(\Phi)\mathcal{M}(\Phi)}{\mu^2} \\ &\rightarrow \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a,\mu\nu} \log [1 + F_i(H/v)] \end{aligned}$$

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- If $F_i(H/v)$ is independent of fermion masses and couplings, then Higgs rates are insensitive to new fermion properties. Gillioz, Grober, Grojean, Muhlleitner, Salvioni, 1206.7120

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- Reproduce SM Higgs rate when $1+F_i(H/v) \propto 1+H/v$.
  - Need $F_i^{(n)}(0) = 0$ for $n \geq 2$ AND
  - $F_i'(0) = 1 + F_i(0)$
- Break one of those conditions can get Higgs rates different from SM.

Low Energy Theorems, Again

- Fermions mass terms:

$$-\mathcal{L}_{M,1} = \lambda_1 \overline{\psi}_L \Phi \mathcal{B}_R^1 + \lambda_2 \overline{\psi}_L \tilde{\Phi} \mathcal{T}_R^1 + \lambda_3 \overline{\psi}_L \tilde{\Phi} \mathcal{T}_R^2 + \lambda_4 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^1 + \lambda_5 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^2 + \text{h.c.}$$

- Higgs-dependent mass matrix:

$$\begin{aligned} \det M^t_{(1)}(H) &= \det \begin{pmatrix} \lambda_2 \frac{(H+v)}{\sqrt{2}} & \lambda_3 \frac{(H+v)}{\sqrt{2}} \\ \lambda_4 & \lambda_5 \end{pmatrix} \\ &= \left(1 + \frac{H}{v}\right) \det \begin{pmatrix} \lambda_2 \frac{v}{\sqrt{2}} & \lambda_3 \frac{v}{\sqrt{2}} \\ \lambda_4 & \lambda_5 \end{pmatrix} \\ &= (1 + F_i(H/v)) \times P(\lambda_i, m_i, v) \,. \end{aligned}$$

- $F_i(H/v) = H/v$
- $F_i'(0) = 1 + F_i(0)$

Low Energy Theorems, Again

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- $F_i(H/v) = H/v$
- $F_i'(0) = 1 + F_i(0)$
- Hence, in LET singlet top partner does not change effect Higgs production rates.
- LET breaks down, but maybe if can get large effect in LET can get large effect in exact result.

Mirror Fermions

- Introduce full generation of Mirror quarks with no SM-mixing. (Sorry for notation change, these are all non-SM quarks)

$$\psi_L^1 = \begin{pmatrix} \mathcal{T}_L^1 \\ \mathcal{B}_L^1 \end{pmatrix}, \ \mathcal{T}_R^1, \mathcal{B}_R^1; \qquad \psi_R^2 = \begin{pmatrix} \mathcal{T}_R^2 \\ \mathcal{B}_R^2 \end{pmatrix}, \ \mathcal{T}_L^2, \mathcal{B}_L^2$$

- Mass terms:

$$\begin{aligned} -\mathcal{L} &= \lambda_A \overline{\psi}_L^1 \Phi \mathcal{B}_R^1 + \lambda_B \overline{\psi}_L^1 \tilde{\Phi} \mathcal{T}_R^1 + \lambda_C \overline{\psi}_R^2 \Phi \mathcal{B}_L^2 + \lambda_D \overline{\psi}_R^2 \tilde{\Phi} \mathcal{T}_L^2 \\ &\quad + \lambda_E \overline{\psi}_L^1 \psi_R^2 + \lambda_F \overline{\mathcal{T}}_R^1 \mathcal{T}_L^2 + \lambda_G \overline{\mathcal{B}}_R^1 \mathcal{B}_L^2 + \text{h.c.} \end{aligned}$$

- Mass matrices:

$$\mathcal{M}_U = \begin{pmatrix} \lambda_B \frac{(H+v)}{\sqrt{2}} & \lambda_E \\ \lambda_F & \lambda_D \frac{(H+v)}{\sqrt{2}} \end{pmatrix}, \qquad \mathcal{M}_D = \begin{pmatrix} \lambda_A \frac{(H+v)}{\sqrt{2}} & \lambda_E \\ \lambda_G & \lambda_C \frac{(H+v)}{\sqrt{2}} \end{pmatrix}$$

- Can no longer factor out $H+v$ from determinant of mass matrices.

Mirror Fermions

- Focusing on up-type mass matrix:

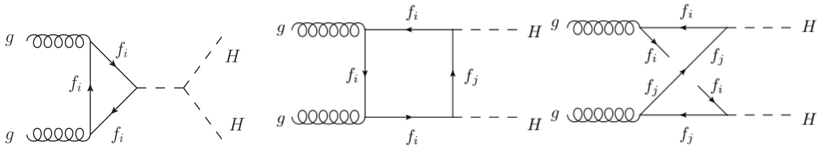
$$\begin{aligned} \det \mathcal{M}_U &= -\lambda_E\lambda_F\left(1-\frac{\lambda_B\lambda_D}{\lambda_E\lambda_F}\frac{v^2}{2}\left(1+\frac{H}{v}\right)^2\right) \\ &= (1+F_i(H/v))\times P(\lambda_i, m_i, v) \end{aligned}$$

- Check criteria if Higgs physics sensitive to new fermions:

$$\begin{aligned} F(H/v) &= -\frac{\lambda_B\lambda_D}{\lambda_E\lambda_F}\frac{v^2}{2}\left(1+\frac{H}{v}\right)^2 && \Rightarrow F''(0)\neq 0 \\ F'(H/v) &= -\frac{\lambda_B\lambda_D}{\lambda_E\lambda_F}v^2\left(1+\frac{H}{v}\right)\frac{H}{v} && \Rightarrow F'(0)=0\neq 1+F(0) \end{aligned}$$

- F depends on couplings and masses of Mirror Fermion sector.
- Mirror fermion sector can effect Higgs physics.
- Can we effect single and double Higgs rates differently?
  - $c_H = c_1 + c_2 \approx 1$ at SM value
  - $c_{HH} = c_1 - c_2$ different from SM value of -1

Mirror Fermions



- Triangle diagram LET amplitude relative to SM value (included SM contribution, and c are mass basis Higgs couplings normalized to v):

$$\frac{A_{gg\to H}}{A^{\rm SM}_{gg\to H}} \equiv 1+\Delta, \qquad \Delta = \frac{c_{T_1T_1}}{2M_{T_1}} + \frac{c_{T_2T_2}}{2M_{T_2}} + \frac{c_{B_1B_1}}{2M_{B_1}} + \frac{c_{B_2B_2}}{2M_{B_2}}$$

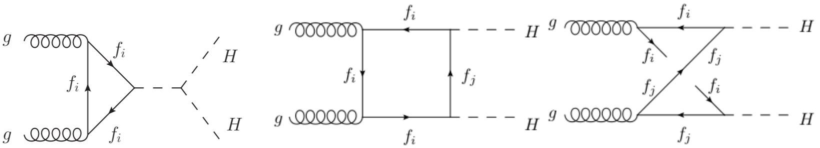
- Box diagram relative to SM:

$$\frac{A^{\rm box}_{gg\to HH}}{A^{\rm SM,box}_{gg\to HH}} \equiv 1+\Delta_{box}$$

$$\Delta_{box} = \frac{c^2_{T_1T_1}}{4M^2_{T_1}} + \frac{c^2_{T_2T_2}}{4M^2_{T_2}} + \frac{c^2_{B_1B_1}}{4M^2_{B_1}} + \frac{c^2_{B_2B_2}}{4M^2_{B_2}} + \frac{c_{T_1T_2}c_{T_2T_1}}{2M_{T_1}M_{T_2}} + \frac{c_{B_1B_2}c_{B_2B_1}}{2M_{B_1}M_{B_2}}$$

- Boxes sensitive to off-diagonal couplings of Higgs and new fermions.

Mirror Fermions



- Triangle diagram LET amplitude relative to SM value (included SM contribution, and c are mass basis Higgs couplings normalized to v):

$$\frac{A_{gg\to H}}{A^{\rm SM}_{gg\to H}} \equiv 1+\Delta, \qquad \Delta = \frac{c_{T_1T_1}}{2M_{T_1}} + \frac{c_{T_2T_2}}{2M_{T_2}} + \frac{c_{B_1B_1}}{2M_{B_1}} + \frac{c_{B_2B_2}}{2M_{B_2}}$$

- Box diagram relative to SM:

$$\frac{A^{\rm box}_{gg\to HH}}{A^{\rm SM,box}_{gg\to HH}} \equiv 1+\Delta_{box}$$

$$\Delta_{box} = \frac{c^2_{T_1T_1}}{4M^2_{T_1}} + \frac{c^2_{T_2T_2}}{4M^2_{T_2}} + \frac{c^2_{B_1B_1}}{4M^2_{B_1}} + \frac{c^2_{B_2B_2}}{4M^2_{B_2}} + \frac{c_{T_1T_2}c_{T_2T_1}}{2M_{T_1}M_{T_2}} + \frac{c_{B_1B_2}c_{B_2B_1}}{2M_{B_1}M_{B_2}}$$

- Boxes sensitive to off-diagonal couplings of Higgs and new fermions.
- LETs of single and double Higgs rates end up independent of absolute mass scale of heavy quarks, but sensitive mass difference.

Parameter Choice

- Original Lagrangian has 7 free parameters:

$$\mathcal{M}_U = \begin{pmatrix} \lambda_B \frac{H+v}{\sqrt{2}} & \lambda_E \\ \lambda_F & \lambda_D \frac{H+v}{\sqrt{2}} \end{pmatrix}, \qquad \mathcal{M}_D = \begin{pmatrix} \lambda_A \frac{H+v}{\sqrt{2}} & \lambda_E \\ \lambda_G & \lambda_C \frac{H+v}{\sqrt{2}} \end{pmatrix}$$

- Going to mass basis have 8 parameters:
  - 4 masses: $M_{T1}, M_{T2}, M_{B1}, M_{B2}$
  - 4 angles: $\theta^t_{L,R}, \theta^b_{L,R}$

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- Going to mass basis have 8 parameters:
  - 4 masses: $M_{T1}, M_{T2}, M_{B1}, M_{B2}$
  - 4 angles: $\theta^t_{L,R}, \theta^b_{L,R}$
- Since $\mathcal{M}_U$ and $\mathcal{M}_D$ have a common parameter, can remove one angle d.o.f.
- Can replace another angle with deviation from SM in single Higgs amplitude

$$\Delta = \frac{c_{T_1T_1}}{2M_{T_1}} + \frac{c_{T_2T_2}}{2M_{T_2}} + \frac{c_{B_1B_1}}{2M_{B_1}} + \frac{c_{B_2B_2}}{2M_{B_2}}$$

- Can then clearly see relative deviations in single and double Higgs rates.

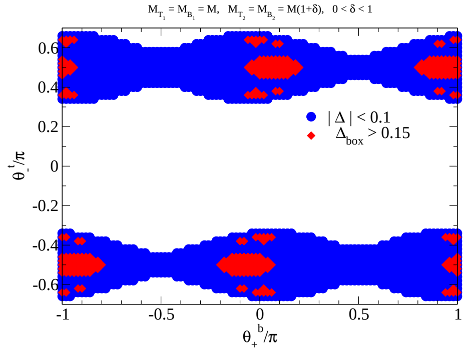
Parameter Choice

- For simplicity and to avoid large corrections to oblique parameters assume equal masses for doublets of heavy quarks:

$$M_{T1} = M_{B1} = M \quad M_{T2} = M_{B2} = M(1+\delta)$$

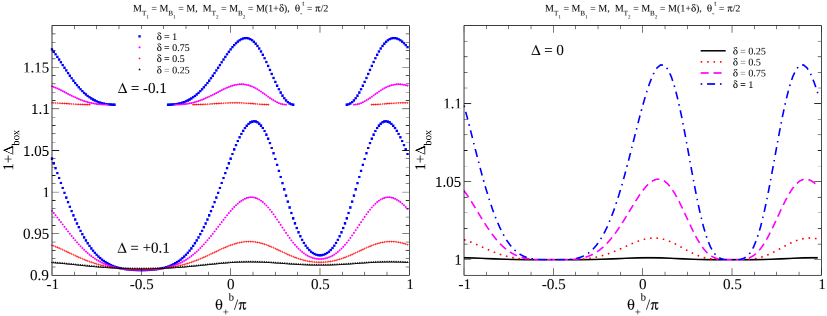
- After these choices have 5 free parameters:
  - M: Heavy mass (which LETs are independent of)
  - δ: mass difference
  - Δ: Deviation from SM single Higgs amplitude.
  - θ^t_-, θ^b_+
- To make equations simpler, have defined $\theta^{t,b}_\pm = \theta^{t,b}_L \pm \theta^{t,b}_R$
- Will also introduce Δ_{box}, the deviation in the double Higgs amplitude.

Parameter Scan



- Forced into the limit $\theta_-^{t,b} \sim \pi/2$
- Δ : deviation from SM single Higgs amplitude

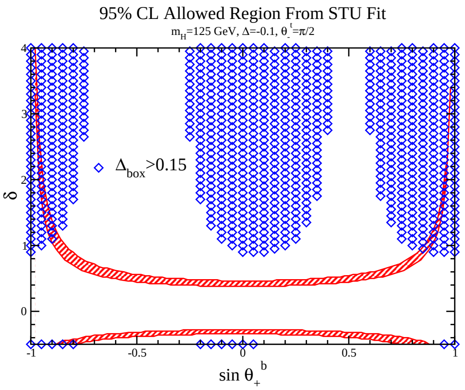
Deviation in Two Higgs Amplitude



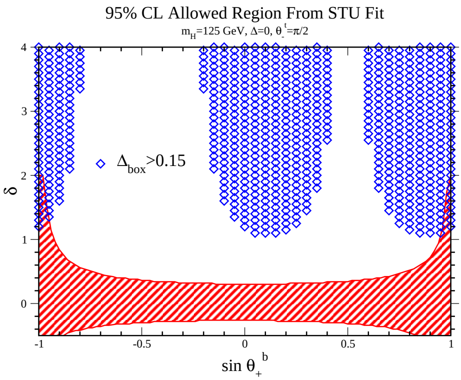
Blue:	$\delta = 1$
Magenta:	$\delta = 0.75$
Red:	$\delta = 0.5$
Black:	$\delta = 0.25$

- Δ : deviation from SM single Higgs amplitude.
- δ : mass separation between M_{B_2}, M_{T_2} and M_{B_3}, B_{T_3}
- Double Higgs coupling does not increase from $\delta = 0$.

Oblique Parameter Constraints



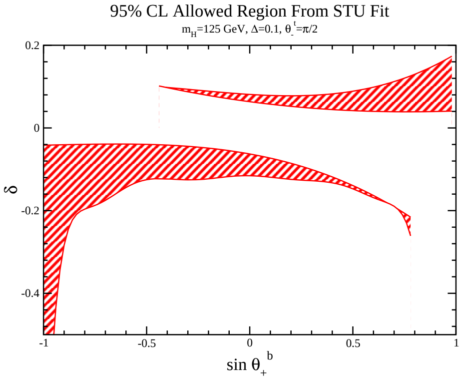
$\Delta = -0.1$



$\Delta = 0$

- Red shaded region allowed by oblique parameters.
- Δ : deviation from SM single Higgs amplitude.
- δ : mass separation between M_{B_2}, M_{T_2} and M_{B_3}, B_{T_3}
- EW precision eliminates most of region with large deviation.
- $M = 800$ GeV $\quad \theta^t_- = \pi/2$

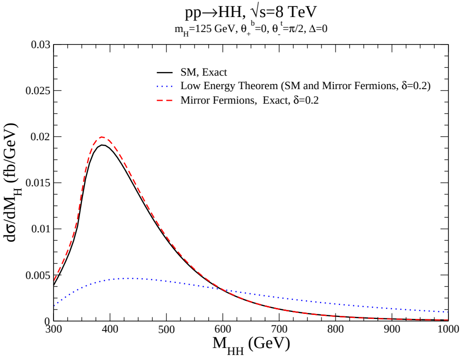
Oblique Parameters Constraints



$\Delta = 0.1$

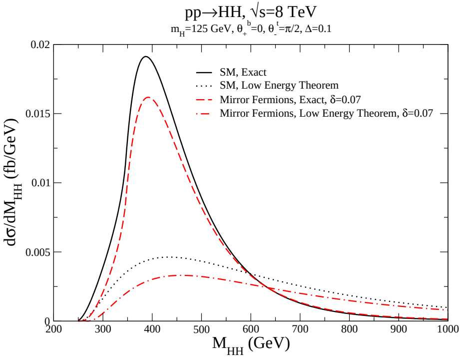
- Red shaded region allowed by oblique parameters.
- Eliminated region with large deviation.

DiHiggs Rate



$\Delta = 0, \delta = 0.2$

Negligible effect on DiHiggs rate.

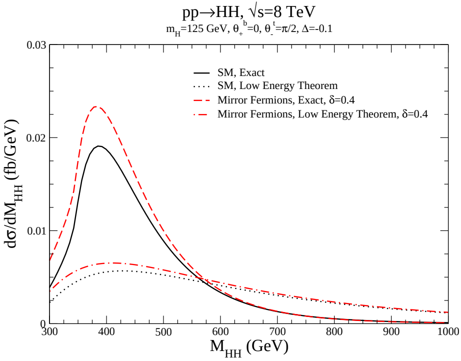


$\Delta = +0.1, \delta = 0.07$

Decreases the DiHiggs rate.

- Δ : deviation from SM single Higgs amplitude.
- δ : mass separation between M_{B_2}, M_{T_2} and M_{B_3}, B_{T_3}
- $\theta_+^b = 0 \quad \theta_-^t = \pi/2 \quad M = 800$ GeV

DiHiggs Rate



- $\Delta = -0.1, \delta = 0.4$
- $\theta_+^b = 0 \quad \theta_-^t = \pi/2 \quad M = 800$ GeV
- Increases the DiHiggs rate by $\sim 15\%$
- Δ : deviation from SM single Higgs amplitude.
- δ : mass separation between M_{B_2}, M_{T_2} and M_{B_3}, B_{T_3}

Vector Fermions with SM Mixing

- Finally, will analyze the addition of a heavy vector fermion generation that mixes with 3^{rd} generation SM quarks.
- Matter content:
  - Heavy vector-like quark doublets and singlets: $Q = \begin{pmatrix} T \\ B \end{pmatrix}, U, D$
  - 3^{rd} generation quarks: $q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}, t_R, b_R$
- Same as Mirror fermion case with SM Higgs mixing added.

Mass terms

- Define basis $\chi^t_{L,R} \equiv (t,T,U)_{L,R}$, $\chi^b_{L,R} \equiv (b,B,D)$
- The mass and Yukawa interactions are then:

$$-L_{Y'} = \overline{\chi}^t_L M^{(t)}(h)\chi^t_R + \overline{\chi}^b_L M^{(b)}(h)\chi^b_R + h.c.,$$

- Higgs-dependent mass matrices:

$$M^{(t)}(H) = \begin{pmatrix} \lambda_t\left(\frac{H+v}{\sqrt{2}}\right) & M_4 & \lambda_7\left(\frac{H+v}{\sqrt{2}}\right) \\ \lambda_9\left(\frac{H+v}{\sqrt{2}}\right) & M & \lambda_1\left(\frac{H+v}{\sqrt{2}}\right) \\ M_5 & \lambda_3\left(\frac{H+v}{\sqrt{2}}\right) & M_U \end{pmatrix}$$

$$M^{(b)}(H) = \begin{pmatrix} \lambda_b\left(\frac{H+v}{\sqrt{2}}\right) & M_4 & \lambda_8\left(\frac{H+v}{\sqrt{2}}\right) \\ \lambda_{10}\left(\frac{H+v}{\sqrt{2}}\right) & M & \lambda_2\left(\frac{H+v}{\sqrt{2}}\right) \\ M_6 & \lambda_{11}\left(\frac{H+v}{\sqrt{2}}\right) & M_D \end{pmatrix},$$

- Three up-type quarks (T_1,T_2,T_3) and three down-type quarks (B_1,B_2,B_3).
- Clear Higgs dependence does not factorize from coupling and mass dependence in determinant.

Top quark LET

- Integrating out only the three heavy top quarks the Hgg coupling is:

$$L^{(t)}_{hgg} = \frac{\alpha_s}{12\pi}\frac{h}{v}\left[1 + 2\lambda_3 v^2\left(\frac{\lambda_1\lambda_t - \lambda_7\lambda_9}{X}\right)\right] G^{A,\mu\nu}G^A_{\mu\nu}\,,$$

- The $HHgg$ coupling is:

$$L^{(t)}_{hhgg} = -\frac{\alpha_s}{24\pi}\frac{h^2}{v^2}\left\{1 - \left[\frac{2\lambda_3 v^2(\lambda_1\lambda_t - \lambda_7\lambda_9)}{X} - \left(\frac{2\lambda_3 v^2(\lambda_1\lambda_t - \lambda_7\lambda_9))}{X}\right)^2\right]\right\} G^{A,\mu\nu}G^A_{\mu\nu}$$

  - $X \equiv -\frac{v}{2\sqrt{2}}\det M^{(t)}(0)$
- Violet: Heavy-light coupling   Red: Heavy-heavy coupling   Blue: Light-light coupling
- Deviations from SM only depend on one coupling combination, with opposite signs for single and double Higgs coupling.

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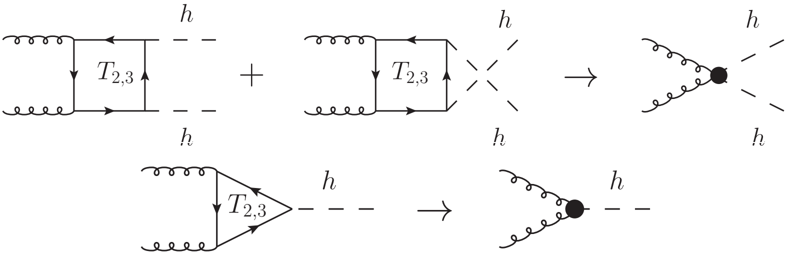
  - $X \equiv -\frac{v}{2\sqrt{2}}\det M^{(t)}(0)$
- Violet: Heavy-light coupling Red: Heavy-heavy coupling Blue: Light-light coupling
- Deviations from SM only depend on one coupling combination, with opposite signs for single and double Higgs coupling.
- For $\lambda_3 = 0$ have no deviation:

$$\det M^{(t)}(H)\Big|_{\lambda_3=0} = -\frac{H+v}{2\sqrt{2}}X\Big|_{\lambda_3=0}\,.$$

- Need to seriously break the LET.

Top and bottom EFT

- Integrate out heavy states, have usual LET operators:



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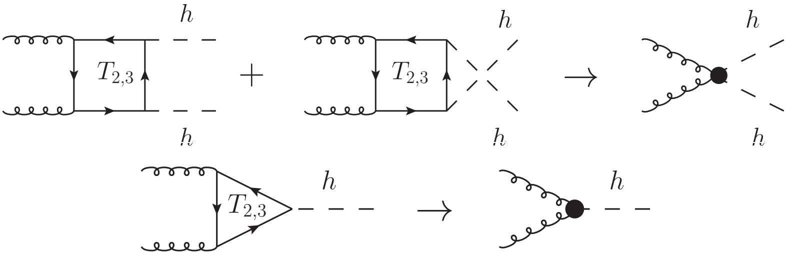
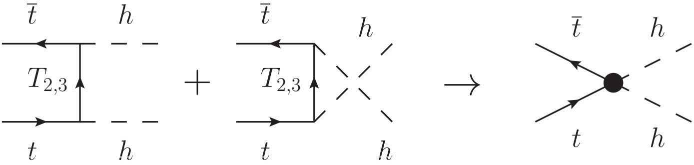


- Have new operator from SM-heavy mixing:



- This new operator can break the LETs Gillioz, Grober, Grojean, Muhlleitner, Salvioni, 1206.7120

Top and bottom EFT

- Integrating out heavy states to $O(1/M^2)$:

$$L_{eff} = -m_t\bar{t}t - Y_t\bar{t}th + c_{2h}^{(t)}\bar{t}th^2 - m_b\bar{b}b - Y_b\bar{b}bh + c_{2h}^{(b)}\bar{b}bh^2 + \frac{c_g\alpha_s}{12\pi v}G^{A,\mu\nu}G_A^{\mu\nu}h - \frac{c_{gg}\alpha_s}{24\pi v^2}G^{A,\mu\nu}G_A^{\mu\nu}h^2$$

- Have shift in Yukawa couplings:

$$\sqrt{2}Y_t = \sqrt{2}\frac{m_t}{v} + \frac{v^2}{MM_U}\lambda_3\lambda_7\lambda_9 - \lambda_t\frac{v^2}{2}\left(\frac{\lambda_7^2}{M_U^2} + \frac{\lambda_9^2}{M^2}\right) \equiv \sqrt{2}\frac{m_t}{v}(1+\delta_t)$$

$$\sqrt{2}Y_b \equiv \sqrt{2}\frac{m_b}{v}(1+\delta_b)$$

- Four point interactions: $c_{2h}^{(t)} = -\frac{3}{2}\frac{m_t\delta_t}{v^2} \qquad c_{2h}^{(b)} = -\frac{3}{2}\frac{m_b\delta_b}{v^2}$
- Effective Higgs-gluon couplings:

$$c_g = -c_{gg} = v^2\left[-\frac{\lambda_1\lambda_3}{MM_U} - \frac{\lambda_2\lambda_{11}}{MM_D} + \frac{1}{2}\left(\frac{\lambda_7^2}{M_U^2} + \frac{\lambda_8{}^2}{M_D^2} + \frac{\lambda_9^2+\lambda_{10}^2}{M^2}\right)\right]$$

Top and bottom EFT

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$$L_{eff} = -m_t\bar{t}t - Y_t\bar{t}th + c_{2h}^{(t)}\bar{t}th^2 - m_b\bar{b}b - Y_b\bar{b}bh + c_{2h}^{(b)}\bar{b}bh^2 + \frac{c_g\alpha_s}{12\pi v}G^{A,\mu\nu}G_A^{\mu\nu}h - \frac{c_{gg}\alpha_s}{24\pi v^2}G^{A,\mu\nu}G_A^{\mu\nu}h^2$$

- Have shift in Yukawa couplings:

$$\sqrt{2}Y_t = \sqrt{2}\frac{m_t}{v} + \frac{v^2}{MM_U}\lambda_3\lambda_7\lambda_9 - \lambda_t\frac{v^2}{2}\left(\frac{\lambda_7^2}{M_U^2} + \frac{\lambda_9^2}{M^2}\right)$$

$$\equiv \sqrt{2}\frac{m_t}{v}(1+\delta_t)$$

$$\sqrt{2}Y_b \equiv \sqrt{2}\frac{m_b}{v}(1+\delta_b)$$

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- Only three independent parameters: δ_t, δ_b, c_g

Mass Hierarchies

- Although LETs and top and bottom EFT have few parameters, full theory still consists of 16 free parameters.
- Want to compare how well the different effective Lagrangians reproduce the full theory.
- Will consider different hierarchies of the parameters to simplify parameter space.
- Already have natural hierarchy $m_t \ll M_{T_2}, M_{T_3}$ and $m_b \ll M_{B_2}, M_{B_3}$.

Hierarchy 1

- $\lambda_i v \ll M_4, M_5 \ll M, M_U, M_D$

$$M^{(t)}(H) = \begin{pmatrix} \lambda_t(\frac{H+v}{\sqrt{2}}) & M_4 & \lambda_7(\frac{H+v}{\sqrt{2}}) \\ \lambda_9(\frac{H+v}{\sqrt{2}}) & M & \lambda_1(\frac{H+v}{\sqrt{2}}) \\ M_5 & \lambda_3(\frac{H+v}{\sqrt{2}}) & M_U \end{pmatrix}$$

$$M^{(b)}(H) = \begin{pmatrix} \lambda_b(\frac{H+v}{\sqrt{2}}) & M_4 & \lambda_8(\frac{H+v}{\sqrt{2}}) \\ \lambda_{10}(\frac{H+v}{\sqrt{2}}) & M & \lambda_2(\frac{H+v}{\sqrt{2}}) \\ M_6 & \lambda_{11}(\frac{H+v}{\sqrt{2}}) & M_D \end{pmatrix},$$

- Use mixing angles that scale as

$$\theta \sim \frac{\lambda_i v}{M_4} \sim \frac{\lambda_i v}{M_5} \sim \frac{M_4}{M} \sim \frac{M_5}{M} \qquad \theta^2 \sim \frac{\lambda_i v}{M} \sim \frac{\lambda_i v}{M_U} \sim \frac{\lambda_i v}{M_D}$$

- Count $\lambda_i \sim O(1)$.

Hierarchy 1

- Left and right mixing matrices for transformation $t, T, U \to T_1, T_2, T_3$.

$$V_L^t = \begin{pmatrix} 1-\frac{1}{2}\theta_L^{D2} & -\theta_L^D & -\theta_L^{S2} \\ \theta_L^D & 1-\frac{1}{2}\theta_L^{D2} & \theta_L^{H2} \\ \theta_L^{S2} & -\theta_L^{H2} & 1 \end{pmatrix} \qquad V_R^t = \begin{pmatrix} 1-\theta_R^{S2} & -\theta_R^{D2} & -\theta_R^S \\ \theta_R^{D2} & 1 & -\theta_R^{H2} \\ \theta_R^S & \theta_R^{H2} & 1-\frac{\theta_R^{S2}}{2} \end{pmatrix}$$

- t is SM 3^{rd} generation, T is part of vector-fermion doublet, U is vector-fermion singlet.
- θ^D parameterizes mixing between 3^{rd} generation and vector-fermion doublet.
- θ^S parameterizes mixing between 3^{rd} generation and vector-fermion singlet.
- θ^H is mixing between vector-fermion doublet and singlet.

Hierarchy 1

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- t is SM 3^{rd} generation, T is part of vector-fermion doublet, U is vector-fermion singlet.
- θ^D parameterizes mixing between 3^{rd} generation and vector-fermion doublet.
- θ^S parameterizes mixing between 3^{rd} generation and vector-fermion singlet.
- θ^H is mixing between vector-fermion doublet and singlet.
- Solve for EFT parameters to $\mathcal{O}(\theta^2)$:

$$Y_t = \frac{m_t}{v} \quad Y_b = \frac{m_b}{v}$$
$$c_{2h}^{(t)} = c_{2h}^{(b)} = c_g = -c_{gg} = 0$$

- New operators go to zero, and Yukawas revert to the SM.
- From this approach can see result without doing full calculation.

Hierarchy 2

- $M_4, M_5 \ll \lambda_i v \ll M, M_U, M_D$ (before assumed $\lambda_i v \ll M_4, M_5 \ll M, M_U, M_D$.)

$$M^{(t)}(H) = \begin{pmatrix} \lambda_t(\frac{H+v}{\sqrt{2}}) & M_4 & \lambda_7(\frac{H+v}{\sqrt{2}}) \\ \lambda_9(\frac{H+v}{\sqrt{2}}) & M & \lambda_1(\frac{H+v}{\sqrt{2}}) \\ M_5 & \lambda_3(\frac{H+v}{\sqrt{2}}) & M_U \end{pmatrix}$$

$$M^{(b)}(H) = \begin{pmatrix} \lambda_b(\frac{H+v}{\sqrt{2}}) & M_4 & \lambda_8(\frac{H+v}{\sqrt{2}}) \\ \lambda_{10}(\frac{H+v}{\sqrt{2}}) & M & \lambda_2(\frac{H+v}{\sqrt{2}}) \\ M_6 & \lambda_{11}(\frac{H+v}{\sqrt{2}}) & M_D \end{pmatrix},$$

- Use mixing angles that scale as

$$\theta \sim \frac{M_{4,5}}{\lambda_i v} \sim \frac{\lambda_i v}{M} \quad \text{and} \quad \theta^2 \sim \frac{M_{4,5}}{M}$$

Hierarchy 2

- Left and right mixing matrices for transformation $t, T, U \to T_1, T_2, T_3$.

$$V_L^t = \begin{pmatrix} 1-\frac{1}{2}\theta_L^{S\,2} & -\theta_L^{D\,2} & -\theta_L^S \\ \theta_L^{D\,2}+\theta_L^H\theta_L^S & 1-\frac{1}{2}\theta_L^{H\,2} & \theta_L^H \\ \theta_L^S & -\theta_L^H & 1-\frac{1}{2}\left(\theta_L^{S\,2}+\theta_L^{H\,2}\right) \end{pmatrix}$$

$$V_R^t = \begin{pmatrix} 1-\frac{1}{2}\theta_R^{D\,2} & -\theta_R^D & -\theta_R^{S\,2} \\ \theta_R^D & 1-\frac{1}{2}\left(\theta_R^{D\,2}+\theta_R^{H\,2}\right) & -\theta_R^H \\ \theta_R^D\theta_R^H+\theta_R^{S\,2} & \theta_R^H & 1-\frac{1}{2}\theta_R^{H\,2} \end{pmatrix}.$$

- t is SM 3^{rd} generation, T is part of vector-fermion doublet, U is vector-fermion singlet.
- θ^D parameterizes mixing between 3^{rd} generation and vector-fermion doublet.
- θ^S parameterizes mixing between 3^{rd} generation and vector-fermion singlet.
- θ^H is mixing between vector-fermion doublet and singlet.
- Structure of mixing matrices now different.

Hierarchy 2

- Solve for EFT parameters to $\mathcal{O}(\theta^2)$:

$$
\begin{aligned}
Y_t &= \frac{m_t}{v}\left(1-\theta_R^{Dt\,2}-\theta_L^{St\,2}\right) \qquad c_{2h}^{(t)} = \frac{3m_t}{2v^2}\left(\theta_R^{Dt\,2}+\theta_L^{St\,2}\right)\\
Y_b &= \frac{m_b}{v}\left(1-\theta_R^{Db\,2}-\theta_L^{Sb\,2}\right) \qquad c_{2h}^{(b)} = \frac{3m_b}{2v^2}\left(\theta_R^{Db\,2}+\theta_L^{Sb\,2}\right)\\
c_g = -c_{gg} &= (2\theta_L^{Ht\,2}+\theta_L^{St\,2})+(2\theta_R^{Ht\,2}+\theta_R^{Dt\,2})+2\frac{M_{T_2}^2+M_{T_3}^2}{M_{T_2}M_{T_3}}\theta_L^{Ht}\theta_R^{Ht}\\
&\quad +(2\theta_L^{Hb\,2}+\theta_L^{Sb\,2})+(2\theta_R^{Hb\,2}+\theta_R^{Db}2)+2\frac{M_{B_2}^2+M_{B_3}^2}{M_{B_2}M_{B_3}}\theta_L^{Hb}\theta_R^{Hb}
\end{aligned}
$$

- Possible to get deviations from SM rates.
  - $c_{2h}^{(t)}$ is the coefficient for $\bar{t}th^2$
  - c_g and c_{gg} are coefficients of $hG^{a\mu\nu}G^a_{\mu\nu}$ and $h^2G^{a\mu\nu}G^a_{\mu\nu}$
- Shift in Yukawa terms depend on same parameters at $\bar{t}th^2$ and $\bar{b}bh^2$ coefficients.
- If $M_{B_2}=M_{B_3}$ and $M_{T_2}=M_{T_3}$ find $c_g>0>c_{gg}$.
  - Box diagram dominates, so decreases double Higgs rate.
- Need θ_L^H and θ_R^H opposite signs for $c_{gg}>0$.

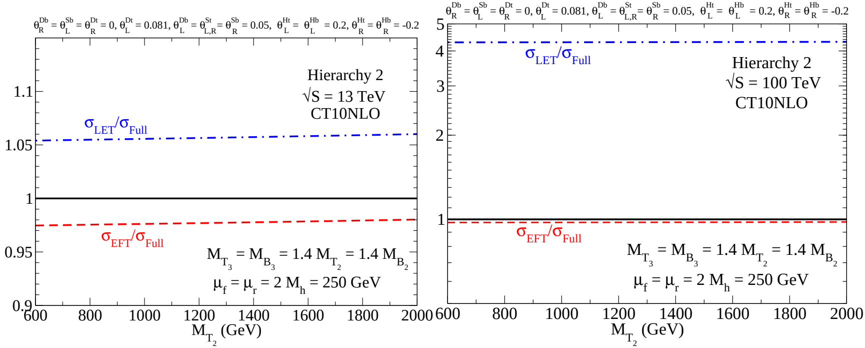
Electroweak Precision

- Mixing between vector-fermions and SM introduces deviations in EW gauge boson couplings.
- To prevent flavor changing neutral currents, eliminate mixing between states with different EW quantum number:
  - No mixing between vector-fermion doublet and right-handed SM quarks:
    $$\theta_R^{Dt} = \theta_R^{Db} = 0$$
  - No mixing between vector-fermion singlet and left-handed SM quarks:
    $$\theta_L^{St} \simeq \theta_L^{Sb} = 0.$$
  - Also allow small θ_L^{St} so that $c_{2h}^{(t)} \neq 0$.
- Assumptions allow for $Z \to b\bar{b}$ to be the SM value, and there are no flavor-changing neutral currents between the light and heavy quarks.

Electroweak Precision

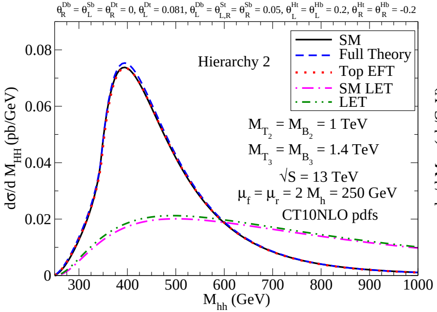
- Mixing between vector-fermions and SM introduces deviations in EW gauge boson couplings.
- To prevent flavor changing neutral currents, eliminate mixing between states with different EW quantum number:
    - No mixing between vector-fermion doublet and right-handed SM quarks:
    $$\theta_R^{Dt} = \theta_R^{Db} = 0$$
    - No mixing between vector-fermion singlet and left-handed SM quarks:
    $$\theta_L^{St} \simeq \theta_L^{Sb} = 0.$$
    - Also allow small θ_L^{St} so that $c_{2h}^{(t)} \neq 0$.
- Assumptions allow for $Z \to b\bar{b}$ to be the SM value, and there are no flavor-changing neutral currents between the light and heavy quarks.
- With assumption $\theta_L^{Dt} = \theta_L^{Db}$, isospin violation in the heavy-light mixing is eliminated.
- Oblique parameters only constrain θ^H, and constraints are the same as in Mirror fermion case.

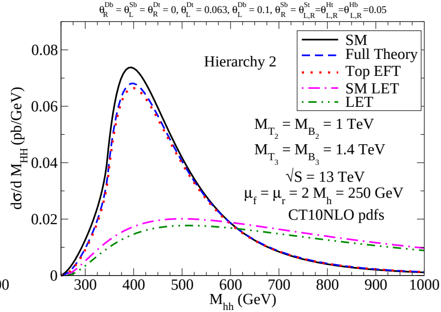
DiHiggs Total Cross Section



- As shown before, LET diverges at $\sqrt{S} = 100$ TeV.
- EFT closely approximates exact cross section at 13 and 100 TeV.

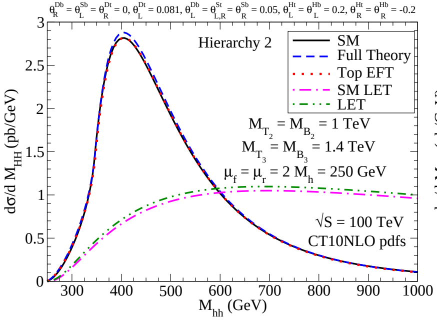
DiHiggs Invariant Mass Distributions 13 TeV

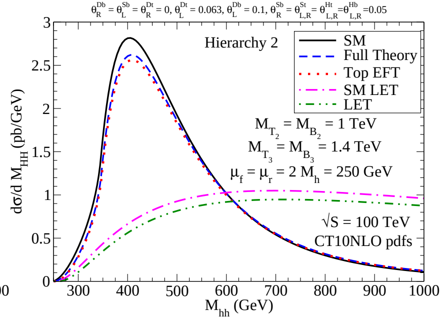




- LET does not reproduce distrubution.
- EFT closely follows exact distribution.

DiHiggs Invariant Mass Distribution 100 TeV





- LET does not reproduce distrubution.
- EFT closely follows exact distribution even at 100 TeV.

Conclusions

- Current rates for single Higgs production definitively rule out the simple addition of a new chiral generation.
- New colored particles need additional mass sources beyond the SM Higgs.
- By measuring both single and double Higgs production, can possibly shed light on mass the mass generating mechanism of new colored particles.
- Studied the effects of new heavy vector-like quarks on single and double Higgs rates.
- Singlet top quark:
  - After taking into consideration EW precision measurement, singlet top quark decreased the double Higgs production bye $\sim 15\%$
  - The low energy theorem was unchanged from the SM.
- Mirror Fermions:
  - Found that can at most increase DiHiggs rate by 17% while suppressing the low energy theorem triangle amplitude by 10%

Conclusions

- Mixing between SM and new vector-quark generation:
  - LET badly diverges from exact cross section at 100 TeV.
  - In addition to low energy theorem, integrating out just the heavy partners introduces a new EFT containing top and bottom quarks.
  - Although many coupling, in addition to the top and bottom quark masses, EFT only depends on 3 independent parameters.
  - The new EFT closely reproduces both invariant mass distributions and cross section of full theory.
- May be other possible avenues to increase double Higgs rate:
  - Can have new resonances that could increase double Higgs rate by $\sim 60 - 70$ times Baglio, Eberhardt, Nierste, Wiebusch, 1403.1264
  - Also possible to have color octet-scalars reproduce SM single Higgs rate within 25% and have factor of two increase in double Higgs Kribs, Martin, PRD86 095023 (2012)