HIGGS RATES AND NEW QUARKS

Elisabetta Furlan

Brookhaven National Laboratory

In collaboration with S. Dawson, I. Lewis

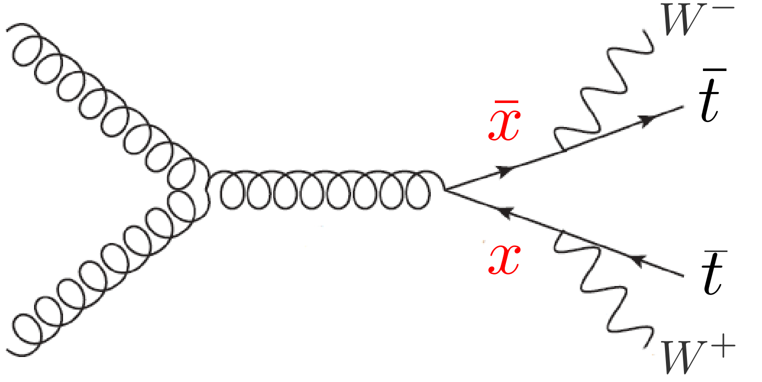
zpw 2013 the zurich phenomenology workshop Particle physics in the LHC era

MOTIVATION

- LHC experiments: “habemus Higgs!”

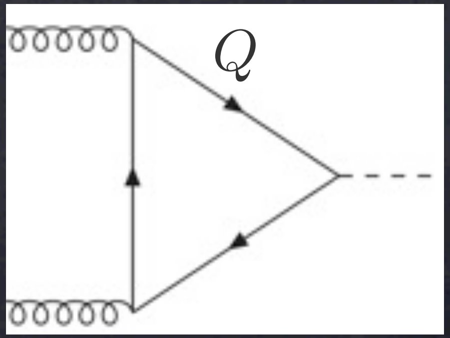
↕

- “a light fundamental scalar is not natural”: the hierarchy problem
- many extensions of the Standard Model introduce new particles that can alter the LHC phenomenology (supersymmetry, extra dimensions, little/composite Higgs models,...)



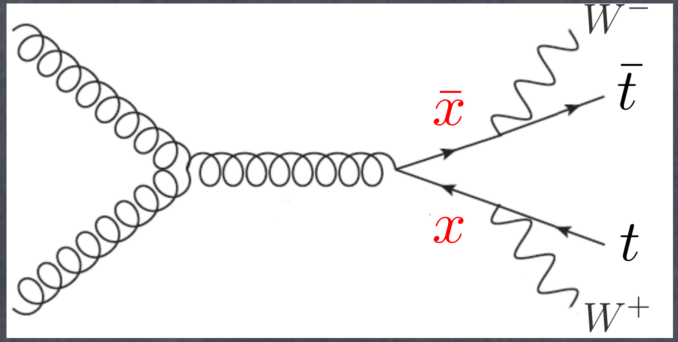
direct
production

loop
effects

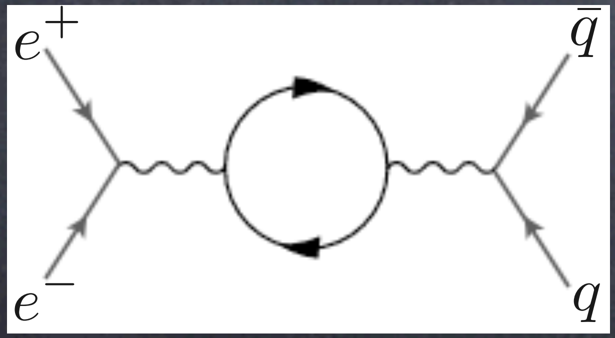


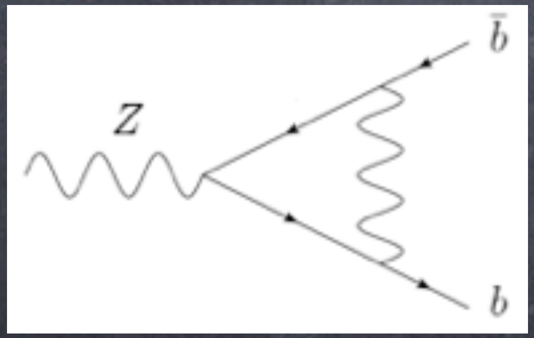
MOTIVATION

- constraints from
  - ➡ direct searches



  - ➡ effects on loop mediated processes (S, T, U parameters, $Z \to b\bar{b}$)





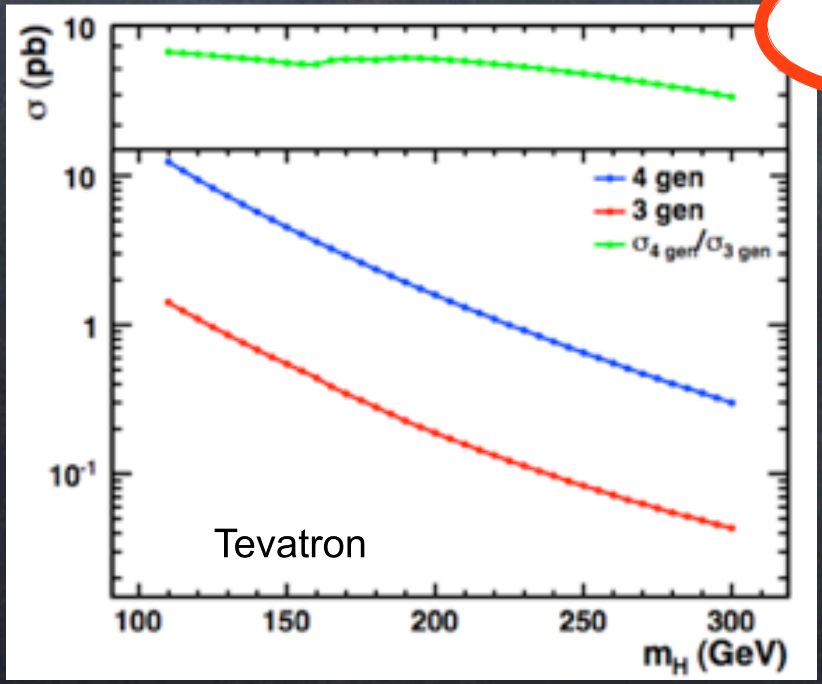
  - ➡ *measured Higgs rates!*

$$\frac{\sigma}{\sigma^{SM}} = \begin{cases} 1.4 \pm 0.3 \\ 0.87 \pm 0.23 \end{cases} \qquad \frac{\sigma_{H\to\gamma\gamma}}{\sigma^{SM}_{H\to\gamma\gamma}} = \begin{cases} 1.8 \pm 0.4 & \text{(ATLAS)} \\ 1.6 \pm 0.4 & \text{(CMS)} \end{cases}$$

MOTIVATION

- the new particles typically
  - couple to the Higgs boson
  - mix with the Standard Model top quark, modifying its coupling to the Higgs boson

➡ *can* significantly affect Higgs production and decays



SM4

MOTIVATION

- the new particles typically
  - ✦ couple to the Higgs boson
  - ✦ mix with the Standard Model top quark, modifying its coupling to the Higgs boson

➡ *can* significantly affect Higgs production and decays

➡ but.. do they *have to*?

➡ *if* they do, can we use these effects to learn something about their properties?

MOTIVATION

- idea:

A. Pierce, J. Thaler, L.-T. Wang, JHEP 0705:070, 2007

  - ✦ up to dimension six, there are only two operators that describe the effective gluon-Higgs interaction

$$\begin{tikzcd} & \mathcal{L} = c_1\mathcal{O}_1 + c_2\mathcal{O}_2 \arrow[dl] \arrow[dr] & \\ \sim G^a_{\mu\nu}G^{a,\mu\nu}\Phi^\dagger\Phi & & \sim G^a_{\mu\nu}G^{a,\mu\nu}\log\left(\frac{\Phi^\dagger\Phi}{v^2}\right) \end{tikzcd}$$

- dimension 6
- not present in the SM

- only ggH operator present in the SM

MOTIVATION

- they contribute differently to Higgs single and pair production

$$\mathcal{O}_1 \propto G^a_{\mu\nu} G^{a,\mu\nu} \left(\frac{H}{v} + \frac{H^2}{2v^2} \right)$$

$$\mathcal{O}_2 \propto G^a_{\mu\nu} G^{a,\mu\nu} \left(\frac{H}{v} - \frac{H^2}{2v^2} \right)$$

➡ combine this two channels to gain insights on the effective gluon-Higgs operators that the new quarks introduce

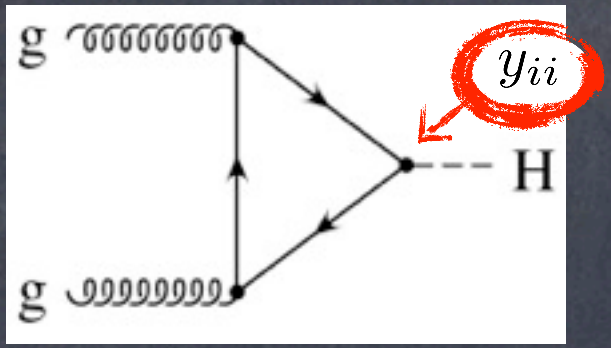
A. Pierce, J. Thaler, L.-T. Wang, JHEP 0705:070, 2007

OUTLINE

- single and pair Higgs production
  - approximate leading order results
- vector singlet
  - the model
  - experimental bounds
  - Higgs phenomenology
- chiral mirror families
  - the model
  - experimental bounds
  - Higgs phenomenology
- gluon-Higgs effective operators

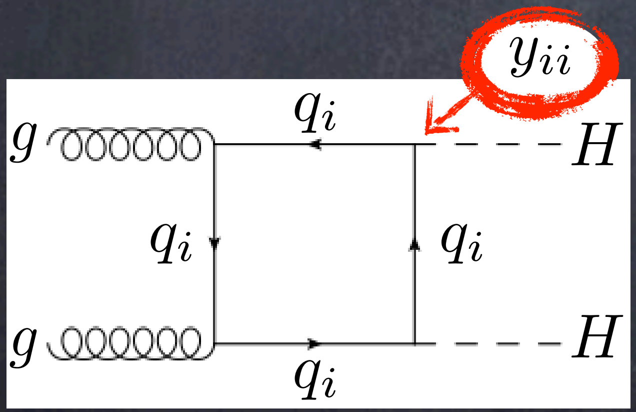
HIGGS PRODUCTION

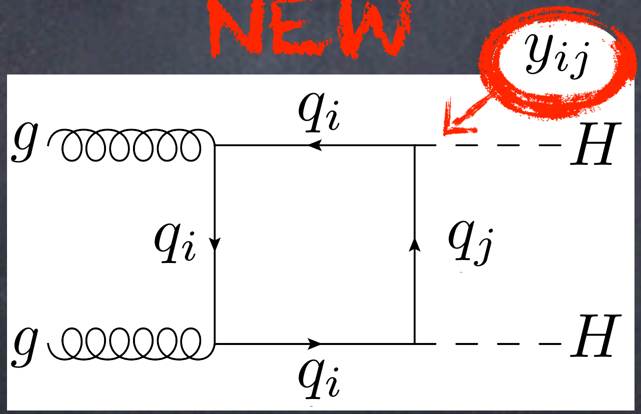
- main mechanism: gluon fusion

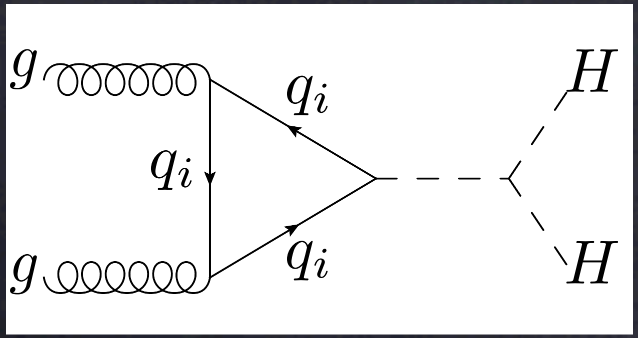


(in the SM
$y_{tt} = m_t$)

NEW

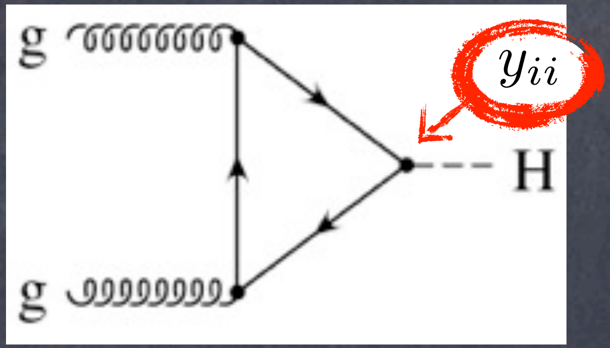






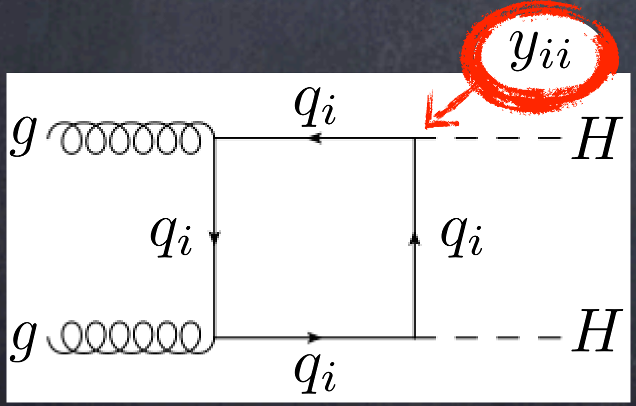
HIGGS PRODUCTION

- for heavy ($2m_q > m_H$) quarks

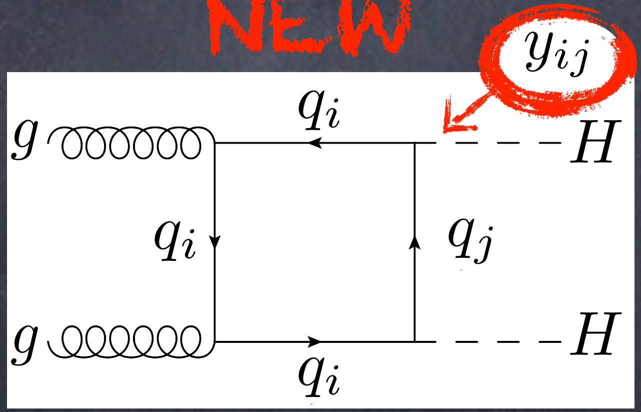


(in the SM $y_{tt} = m_t$)

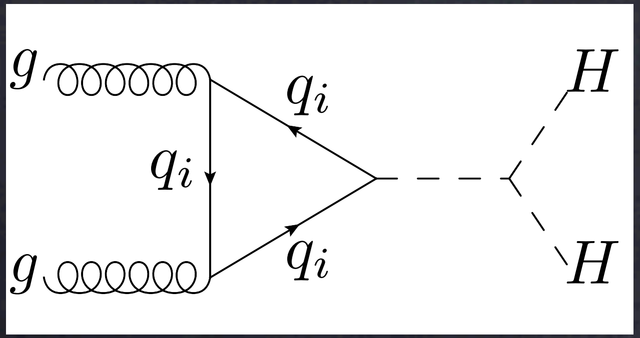
$$\frac{A_{gg\to H}}{A^{SM}_{gg\to H}} = \sum_i \frac{y_{ii}}{m_i}$$



NEW



$$\frac{A^{box}_{gg\to HH}}{A^{box,SM}_{gg\to HH}} = \sum_{i,j} \frac{y_{ij}^2}{m_i m_j}$$



VECTOR SINGLET

- introduced for example in little Higgs and composite Higgs models

- the fermion mass terms are

$$-\mathcal{L}_M^S = \underbrace{\lambda_1 \overline{\psi}_L H \mathcal{B}_R^1 + \lambda_2 \overline{\psi}_L \tilde{H} \mathcal{T}_R^1}_{-\mathcal{L}_M^{SM}} + \lambda_3 \overline{\psi}_L \tilde{H} \mathcal{T}_R^2 + \lambda_4 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^1 + \lambda_5 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^2 + \mathrm{h.c.}$$

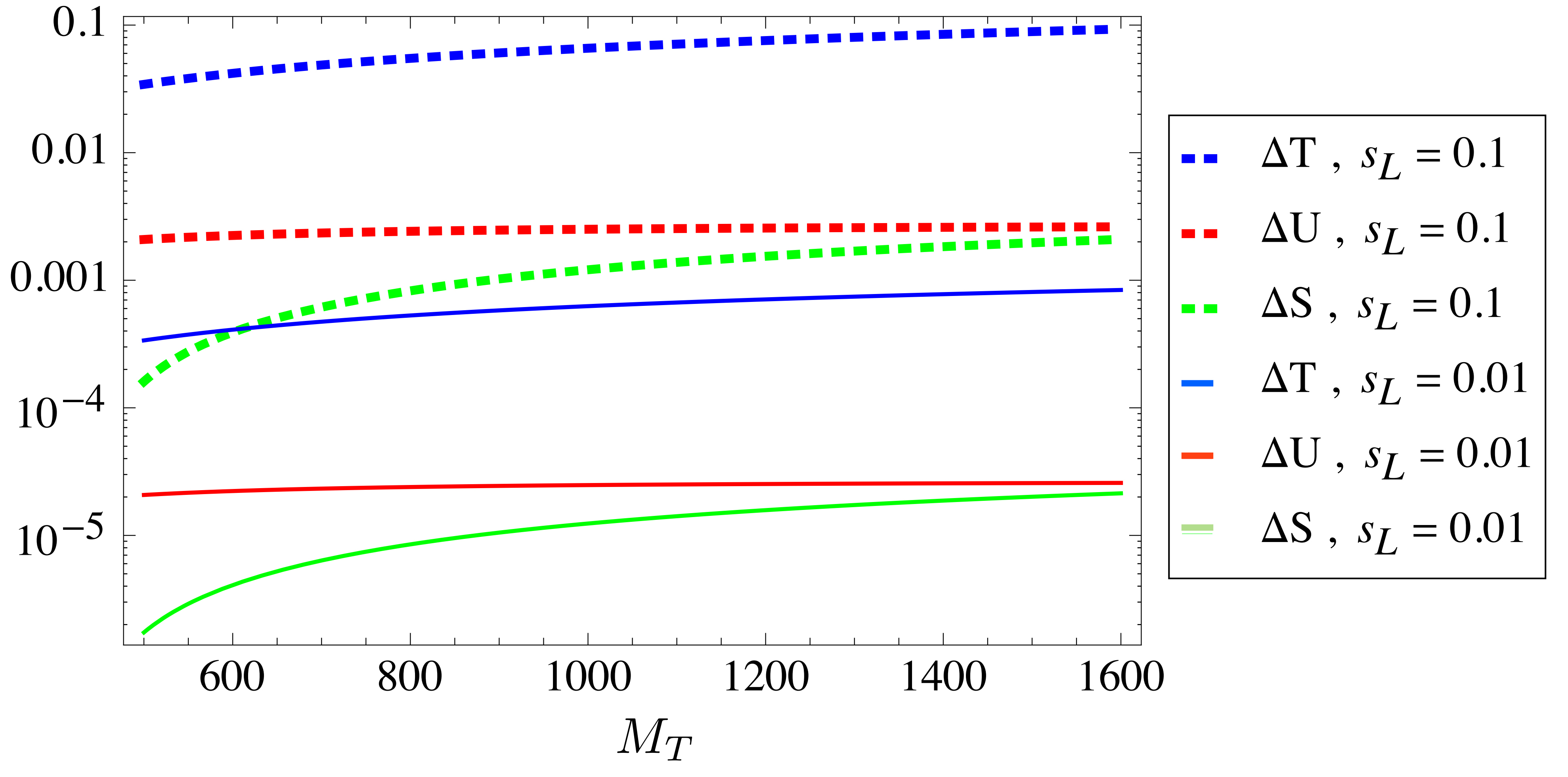
- the charge 2/3 mass eigenstates t, T are an admixture of $\mathcal{T}^1$ and $\mathcal{T}^2$,

$$\begin{pmatrix} t_i \\ T_i \end{pmatrix} = \begin{pmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{pmatrix} \begin{pmatrix} \mathcal{T}_i^1 \\ \mathcal{T}_i^2 \end{pmatrix} \qquad (i = L, R)$$

- 4 independent parameters $(m_b, m_t, M_T, \theta_L)$

CONSTRAINTS

- Contribution to the Peskin-Takeuchi S, T, U parameters



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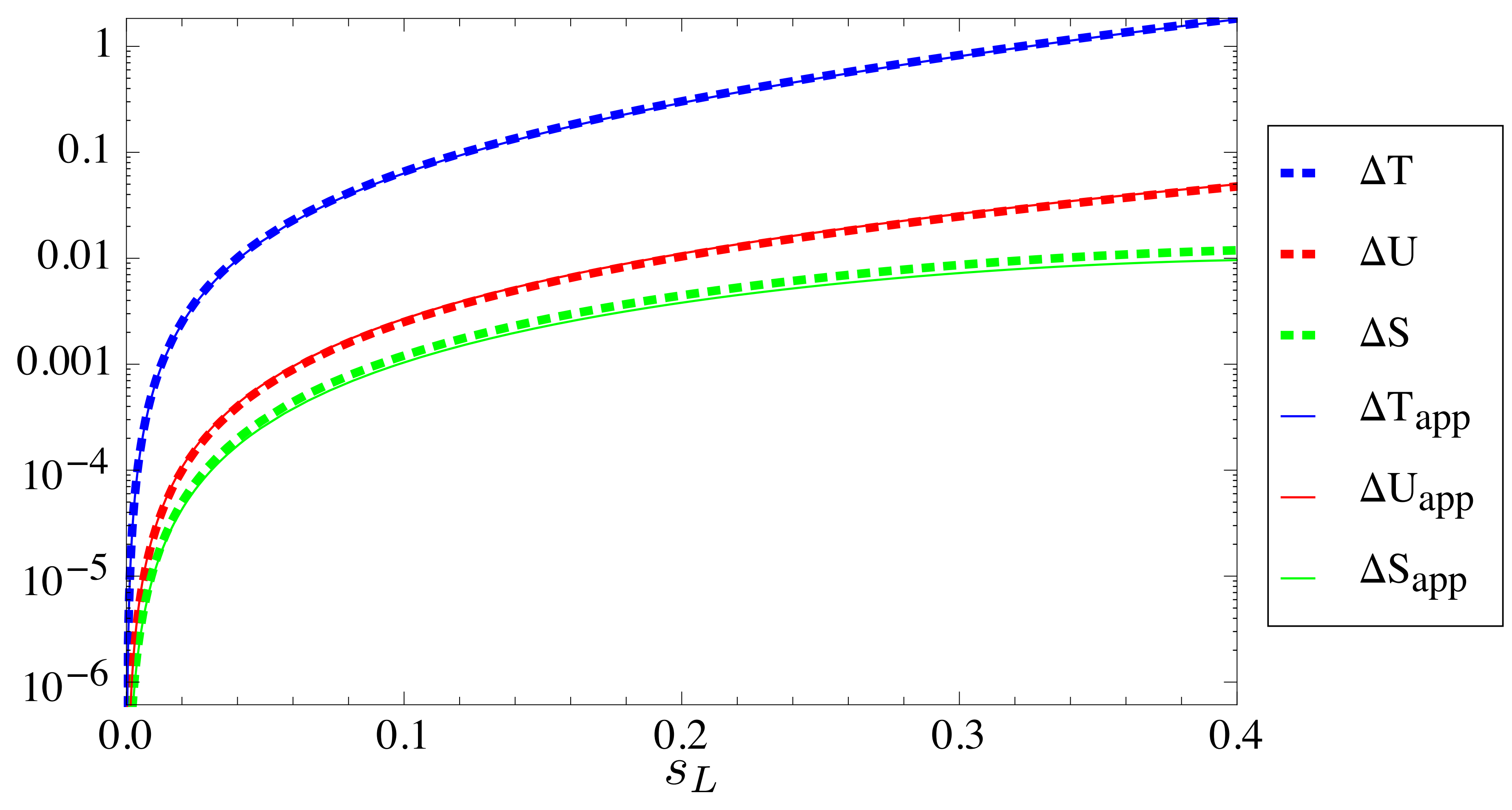


$$\left.\begin{matrix} m_b \to 0 \,, \\ M_T >> m_t \end{matrix}\right\}$$

$$\Delta T_{app} = T_{SM} \enclose{circle}{s_L^2} (r s_L^2 + 2 c_L^2 \log r - 1 - c_L^2) \qquad r = (M_T/m_t)^2$$

$$\Delta S_{app} = -\frac{N_c}{18\pi} \enclose{circle}{s_L^2} [\log r \, (1 - 3c_L^2) + 5 c_L^2] \qquad \Delta U_{app} = \frac{N_c}{18\pi} \enclose{circle}{s_L^2} (3 s_L^2 \log r + 5 c_L^2)$$

DECOUPLING

$$-\mathcal{L}_M^S = \lambda_1 \overline{\psi}_L H \mathcal{B}_R^1 + \lambda_2 \overline{\psi}_L \tilde{H} \mathcal{T}_R^1 + \lambda_3 \overline{\psi}_L \tilde{H} \mathcal{T}_R^2 + \lambda_4 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^1 + \lambda_5 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^2 + \mathrm{h.c.}$$

- decoupling occurs for

$$\lambda_4, \lambda_5 \gg \frac{\lambda_2 v}{\sqrt{2}}, \frac{\lambda_3 v}{\sqrt{2}} \qquad \text{and} \qquad \lambda_5 \gg \lambda_4$$

- in this limit $M_T \sim \lambda_5$, $m_t \sim \lambda_2 v/\sqrt{2}$, $\boxed{s_L \sim \lambda_3 v/M_T}$
  - ➡ if $M_T \to \infty$ and s_L is kept fixed, $\lambda_3 \to \infty$ and the singlet does not decouple!
  - ➡ in the decoupling limit

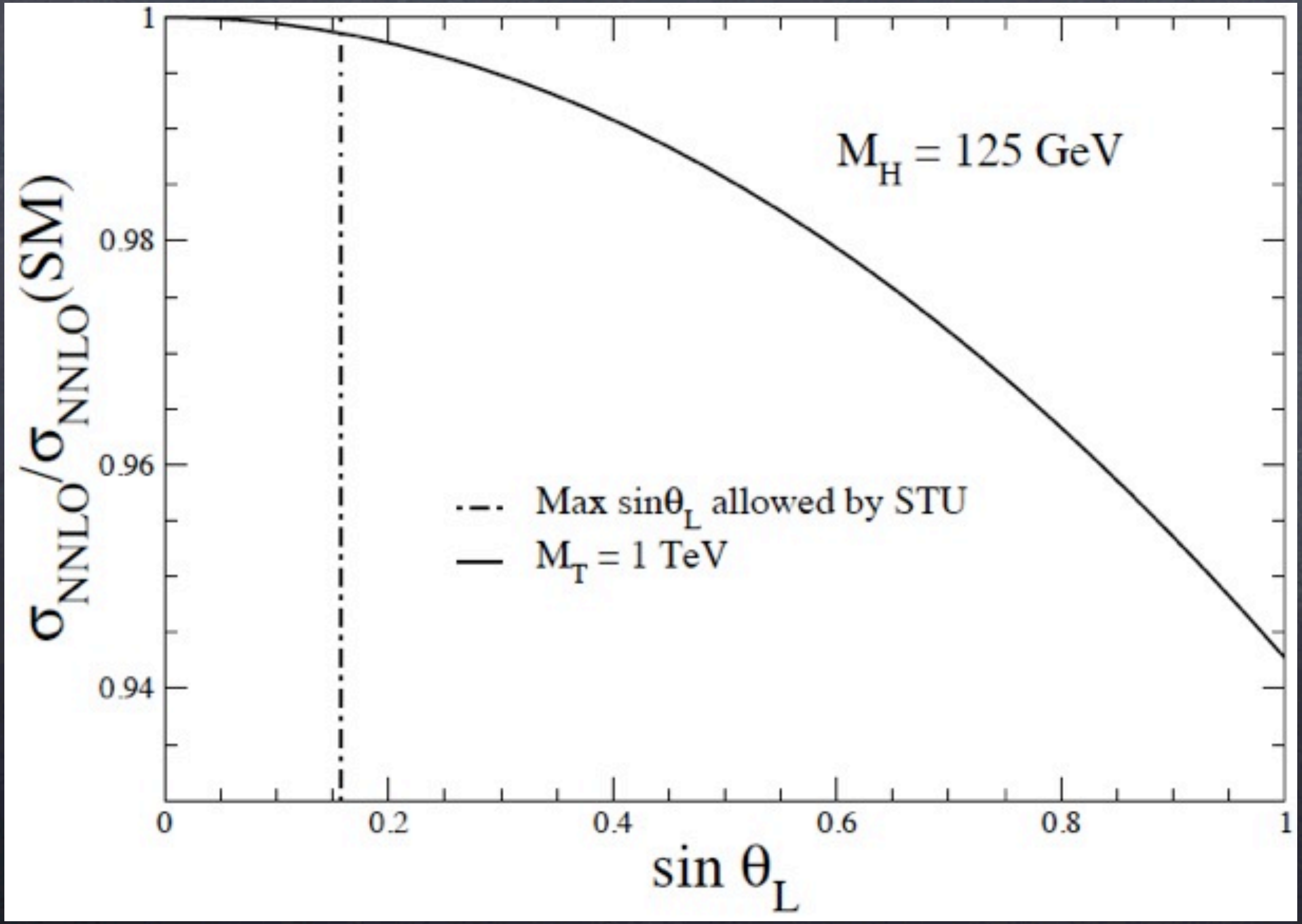
$$\Delta T \sim T_{SM}\, s_L^2 \left(\boxed{r s_L^2} - 2 + \underline{2 \log r}\right) \to 0 \, ,$$

$$\Delta S \sim -\frac{N_c}{18\pi} s_L^2 \left(5 - \underline{2 \log r}\right) \to 0 \, .$$

$$r = (M_T/m_t)^2$$

HIGGS PRODUCTION

- electroweak observables require a small mixing angle ⇨ at most some few % effect



EF, **JHEP 1110 (2011) 115**

ihixs
Anastasiou, Bülher,
Herzog, Lazopoulos

HIGGS PRODUCTION

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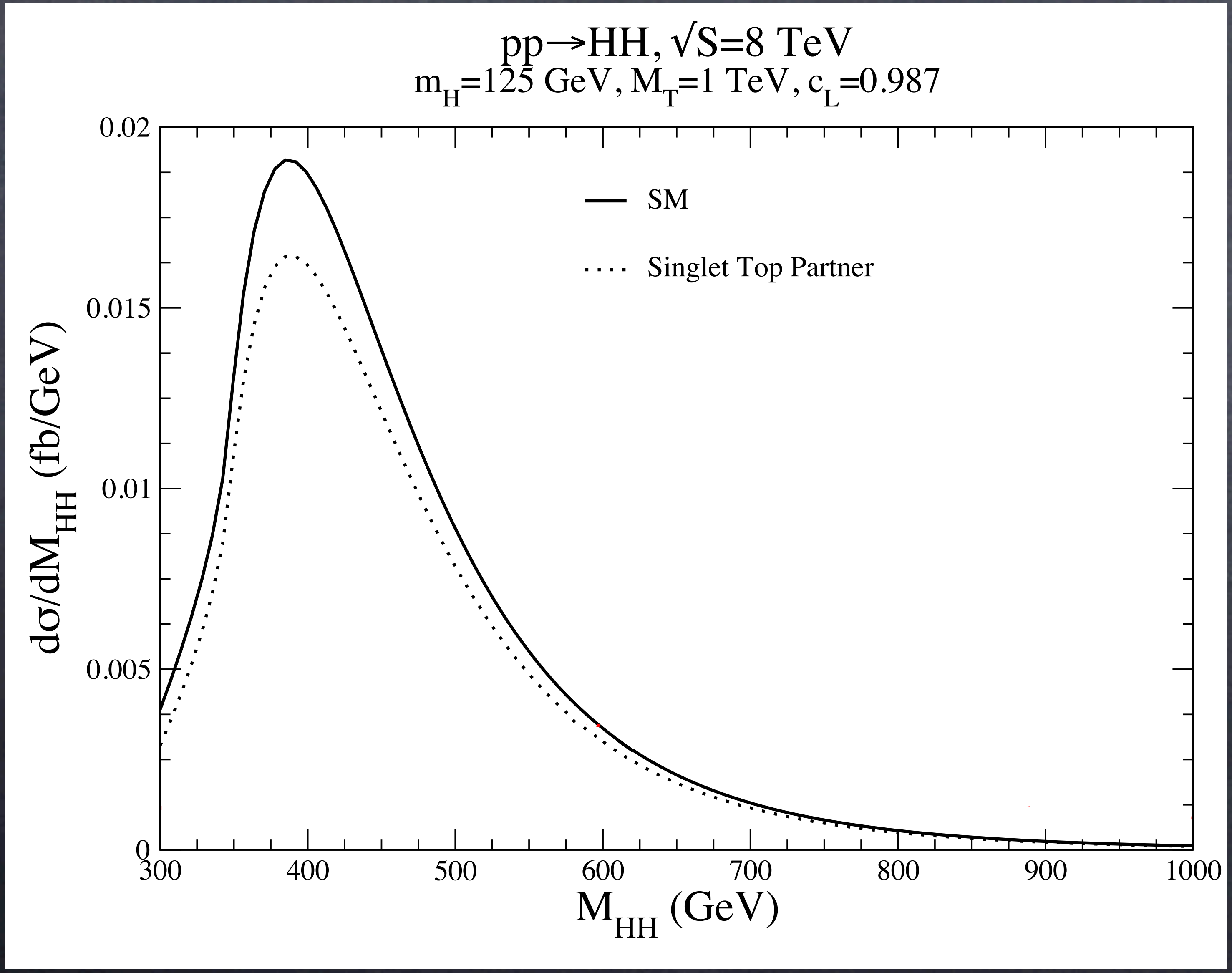
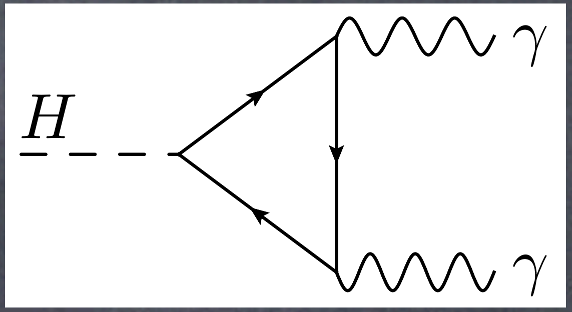
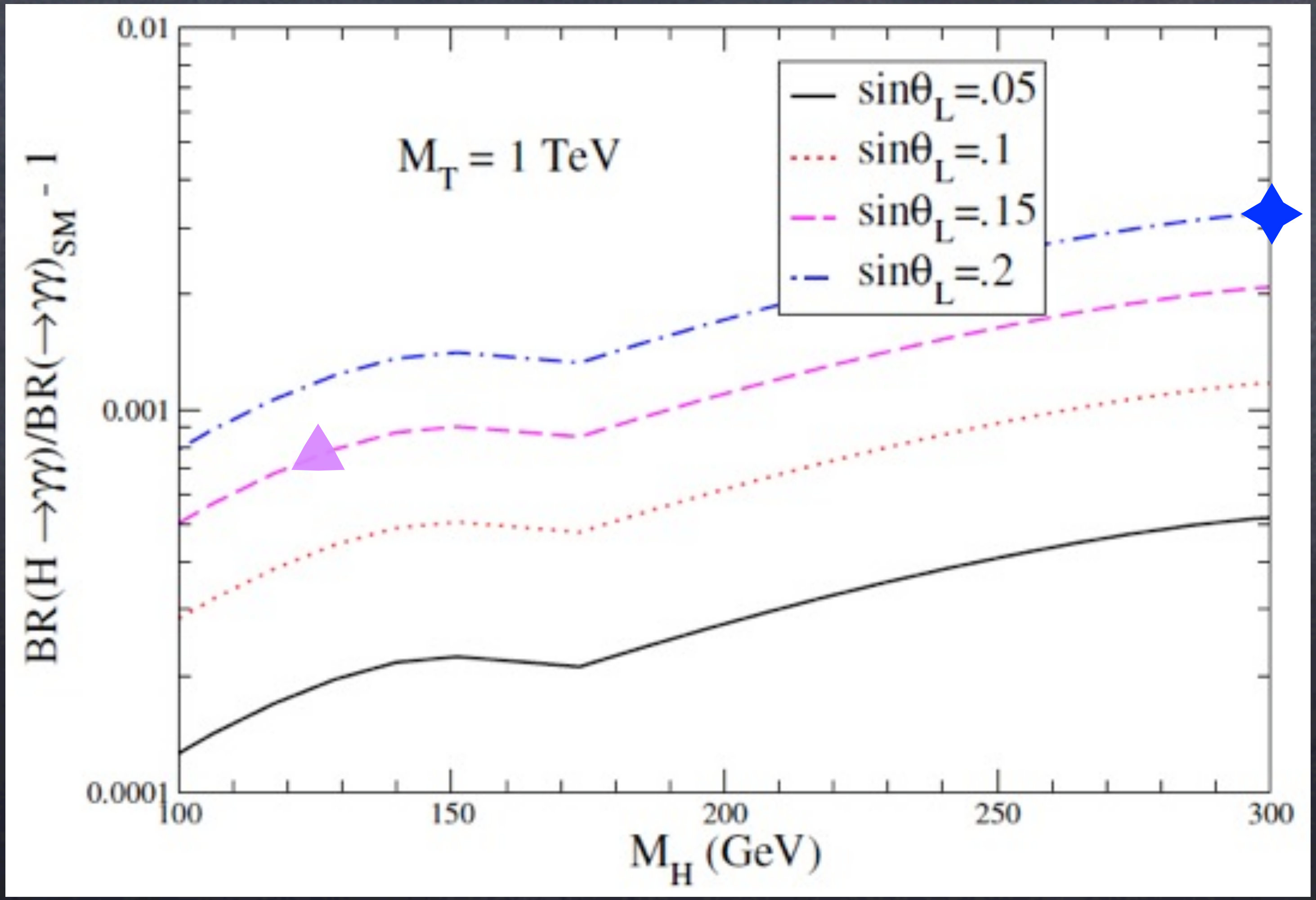


HIGGS DECAYS

- the top partner also affects loop mediated decays



- only small mixing allowed ⇨ below-% effects



MIRROR QUARKS

- four additional heavy quarks, $\mathcal{T}^{1,2}$ (charge 2/3), $\mathcal{B}^{1,2}$(charge -1/3), in the SU(2)$_L$ representations

$$\underbrace{\psi_L^1 = \begin{pmatrix}\mathcal{T}_L^1\\ \mathcal{B}_L^1\end{pmatrix}\,,\ \ \mathcal{T}_R^1\,,\mathcal{B}_R^1\,;}_{\text{as Standard Model families}} \qquad \underbrace{\psi_R^2 = \begin{pmatrix}\mathcal{T}_R^2\\ \mathcal{B}_R^2\end{pmatrix}\,,\ \ \mathcal{T}_L^2\,,\mathcal{B}_L^2\,.}_{\text{left} \longleftrightarrow \text{right}}$$

- for simplicity assume
  - ➡ no mixing with the Standard Model t, b quarks
  - ➡ $M_{T_1} = M_{B_1} = M\ , M_{T_2} = M_{B_2} = M(1+\delta)$

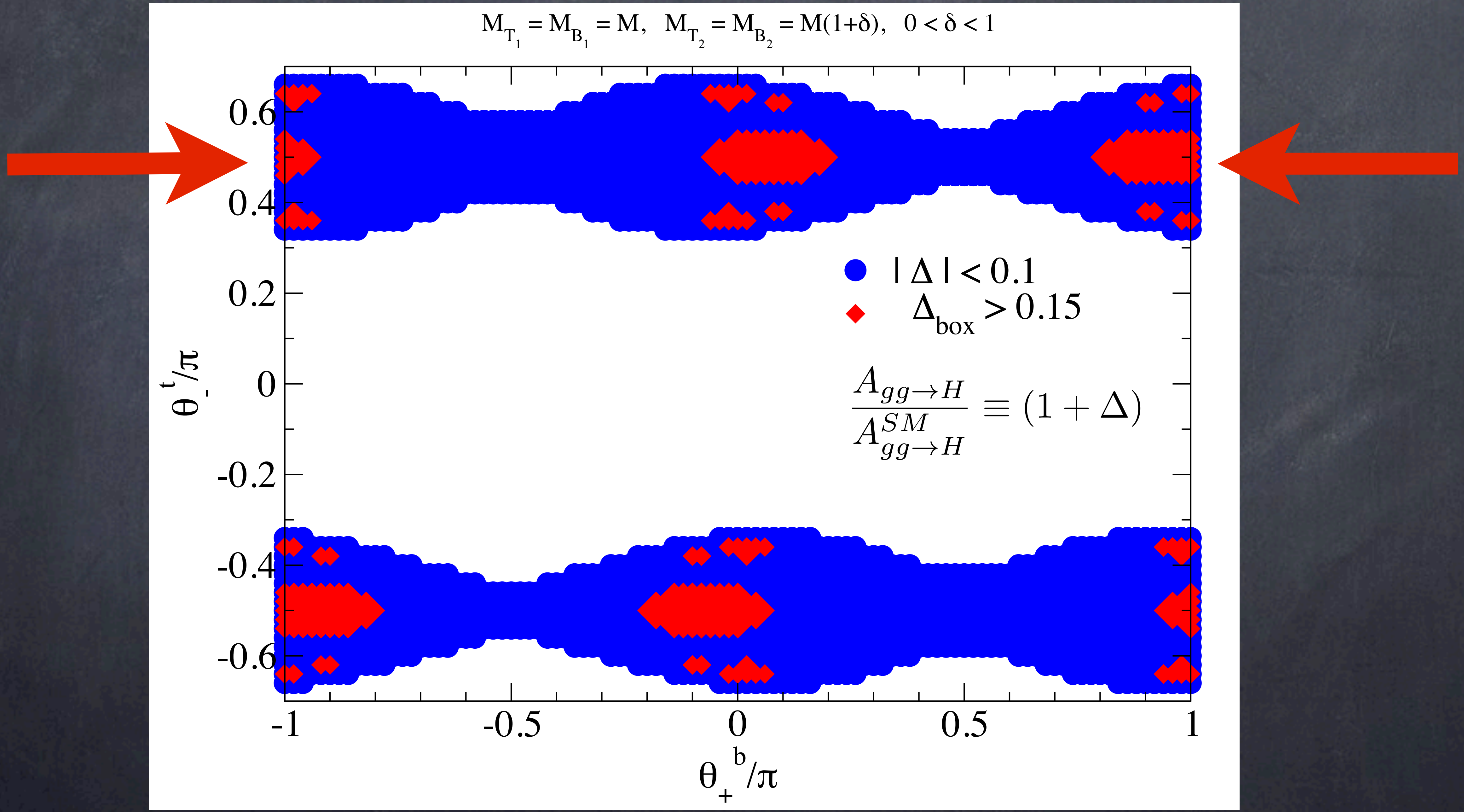
HIGGS PRODUCTION

- are large deviations from the Standard Model double Higgs rate compatible with
  - the measured single Higgs production cross section
  - electroweak bounds

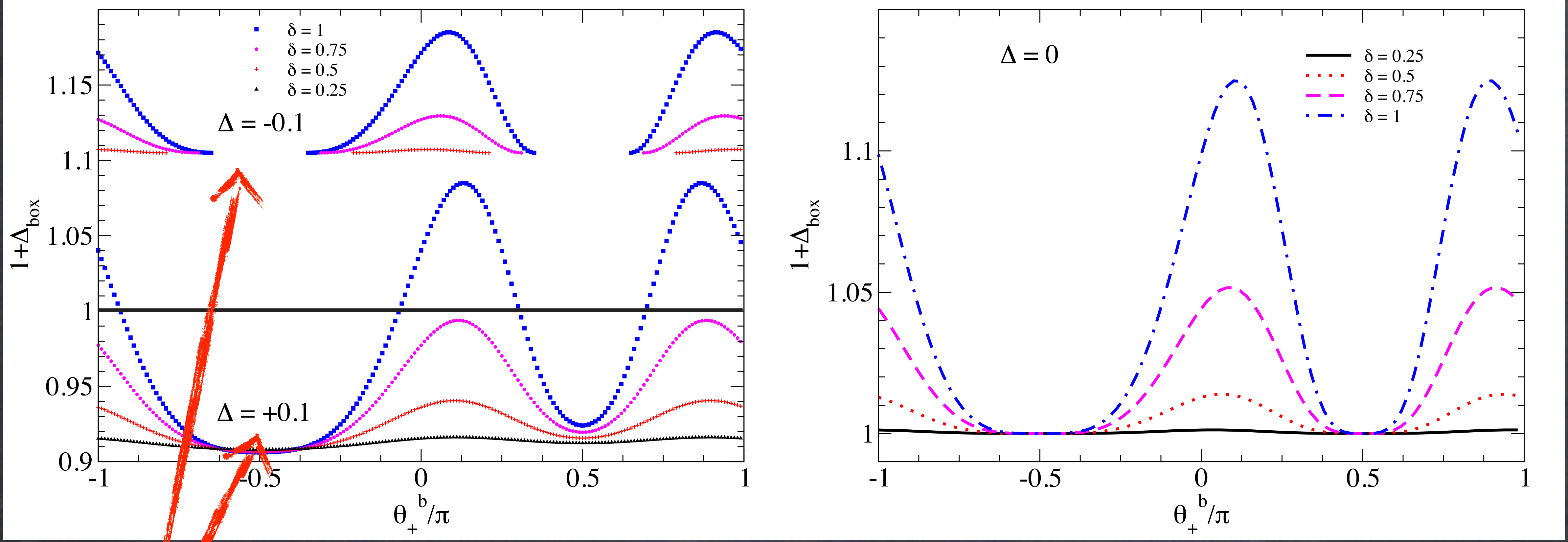
?

- e.g., can we have a 15% or larger enhancement in the double Higgs amplitude (from the box contributions) while keeping single Higgs within 10% from the Standard Model?

HIGGS PRODUCTION



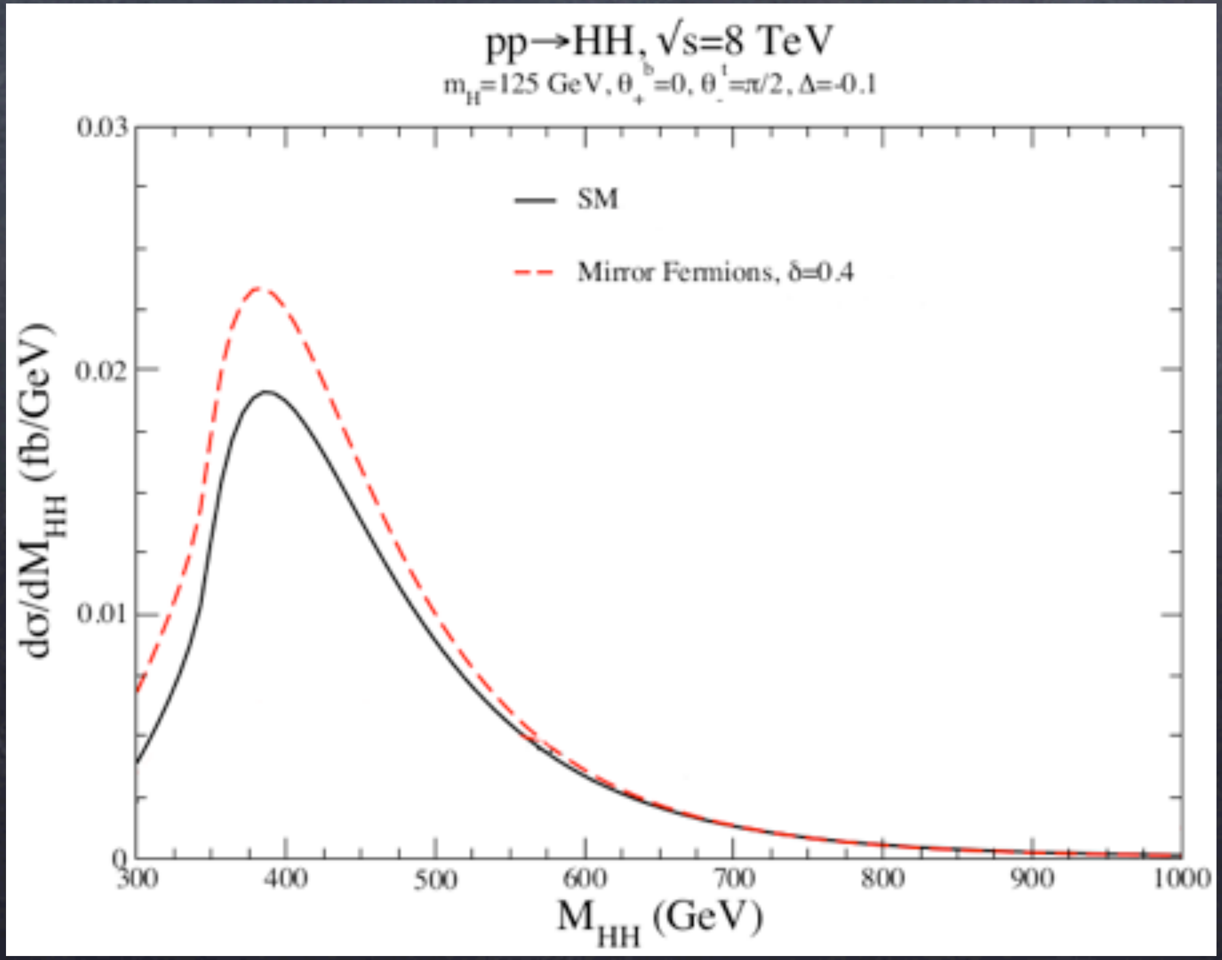
HIGGS PRODUCTION



$$\boxed{\Delta_{box} \simeq -\Delta}\left[1-\delta^2\cos^2\theta_+^b+\mathcal{O}(\delta^3)\right]\boxed{+\,\delta^4\cos^4\theta_+^b}\left[\frac{1}{2}-\delta(1-\sin\theta_+^b)\right]$$

DOUBLE HIGGS PRODUCTION

- electroweak and single Higgs constraints do not allow for significant changes in double Higgs production
  - ✦ the largest enhancement is below 20% (for $\Delta = -0.1$)
  - ✦ small effects on the differential distributions



$\Delta = 0$

HIGGS DECAYS

- the bounds from electroweak observables allow for large suppressions (up to -90%) or enhancements (up to +10%) in $H \to \gamma\gamma$!

  but..

- for a single Higgs rate within 10% the Standard Model value these deviations are reduced to $\pm$10% !

GLUON-HIGGS OPERATORS

- effective Lagrangian for gluon-Higgs interactions (up to dim. 6 operators)

$$\mathcal{L} = c_1 \mathcal{O}_1 + c_2 \mathcal{O}_2$$

$$\sim G^a_{\mu\nu} G^{a,\mu\nu} \Phi^\dagger \Phi \qquad\qquad \sim G^a_{\mu\nu} G^{a,\mu\nu} \log\left(\frac{\Phi^\dagger \Phi}{v^2}\right)$$

- in the Standard Model $c_1^{SM} = 0 \, , \, c_2^{SM} = 1$
- $\mathcal{O}_1, \mathcal{O}_2$ contribute differently to Higgs single and pair production,

$$\mathcal{O}_1 \propto G^a_{\mu\nu} G^{a,\mu\nu} \left(\frac{H}{v} + \frac{H^2}{2v^2}\right) \quad , \quad \mathcal{O}_2 \propto G^a_{\mu\nu} G^{a,\mu\nu} \left(\frac{H}{v} - \frac{H^2}{2v^2}\right)$$

➡ $c_H \equiv c_1 + c_2 \quad , \quad c_{HH} \equiv c_1 - c_2$

GLUON-HIGGS OPERATORS

- in the singlet model $c_1 = 0 \, , c_2 = 1$ ⇨ as the SM!

- in the mirror fermion model

$$c_1^{t,b} = \frac{-2\beta_{t,b}}{(1-\beta_{t,b})^2} \xrightarrow{\beta_{t,b}=0} c_1^{SM} = 0$$

$$\beta_q \sim \frac{\text{Dirac couplings}}{\text{Yukawa couplings}} \xrightarrow[\text{from EWSB}]{\text{mass entirely}} 0$$

$$c_2^t = \textcircled{1} + \frac{2}{(1-\beta_t)^2} \qquad c_2^b = \frac{2}{(1-\beta_b)^2}$$

- require single Higgs close to Standard Model

$$c_H \to c_H^{SM}(1+\Delta) = 1+\Delta \quad ⇨ \quad c_{HH} \to 2c_1 - (1+\Delta)$$

➡ need large c_1 ⇨ either massless quarks or nonperturbative Higgs couplings!

CONCLUSIONS

vector singlet

- its mixing with the top quark strongly constrained by S, T, U ⇨ forced almost to decouple
- would yield reduced Higgs production rates
- electroweak bounds allow only for a few % effect in single Higgs production, and at most a 15% effect in double Higgs
- enhancement in $H \to \gamma\gamma$ below % level

➡ same phenomenology as the Standard Model

CONCLUSIONS

mirror fermions

- electroweak bounds allow for large enhancement/ suppression in Higgs rates
- require single Higgs rate to be close to the measured one
  - ➡ both double Higgs production and $H \to \gamma\gamma$ become undistinguishable from the Standard Model

CONCLUSIONS

connection to the effective gluon-Higgs operators

- singlet model: only the Standard Model like operator $\mathcal{O}_2$ is induced
- mirror fermion model
  - ➡ large deviations in Higgs pair production require large c_1
  - ➡ only possible for massless quarks or nonperturbative Yukawa couplings