HIGGS RATES AND NEW QUARKS

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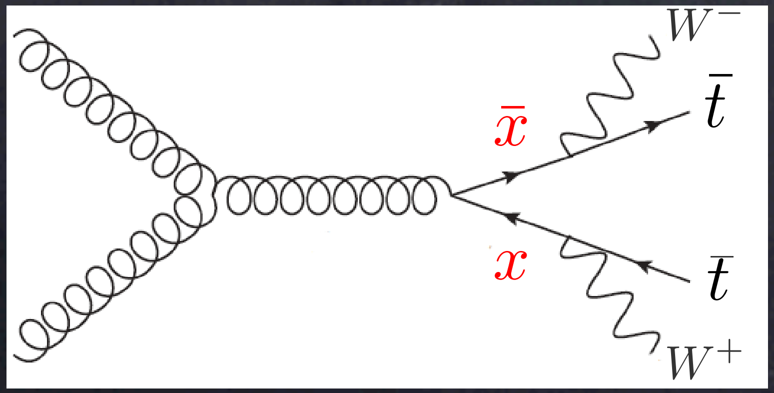
MOTIVATION

- LHC experiments: “habemus Higgs!”

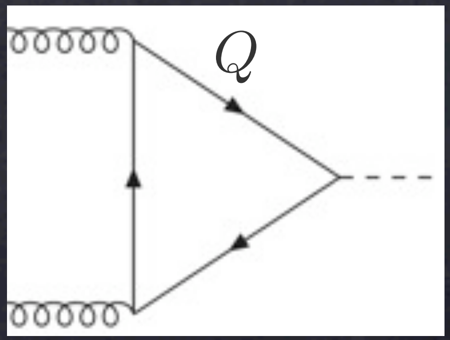
⇕

- “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,...)



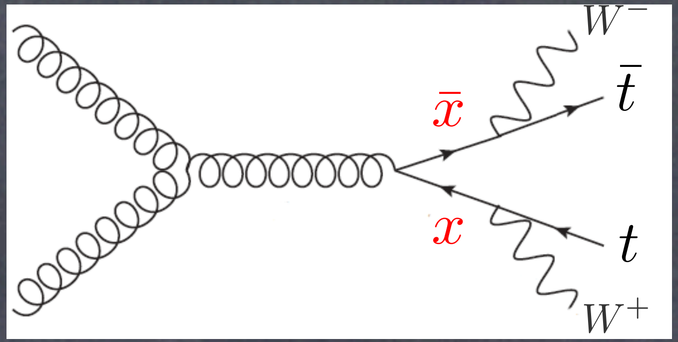
direct production

loop effects

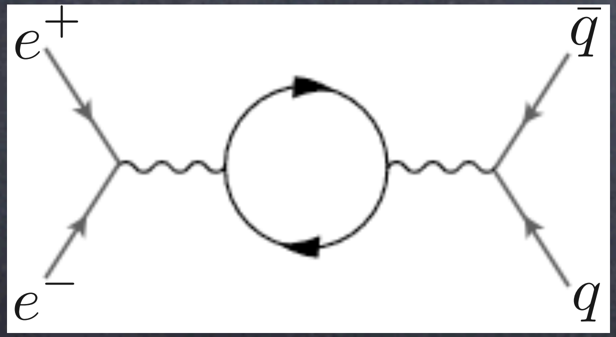


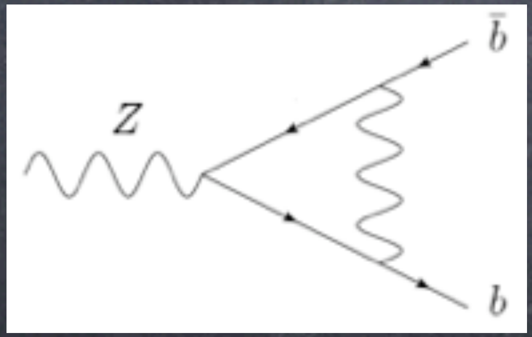
MOTIVATION

- constraints from
  - ➡ direct searches



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





  - ➡ *measured Higgs rates!*

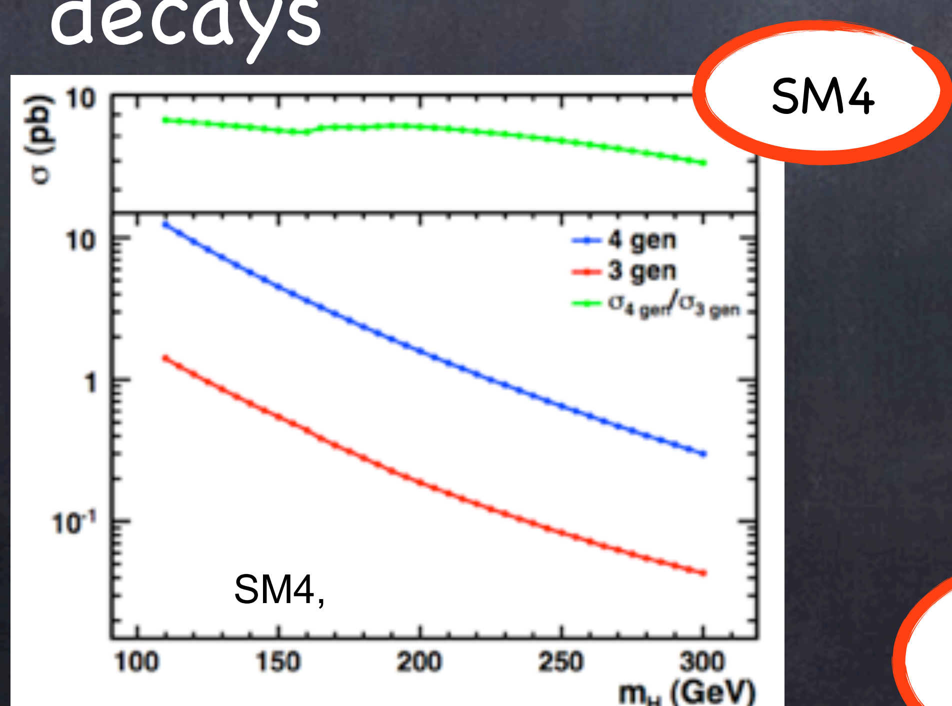
$$\frac{\sigma}{\sigma^{SM}} = \begin{cases} 1.4 \pm 0.3 \\ 0.88 \pm 0.21 \end{cases}$$

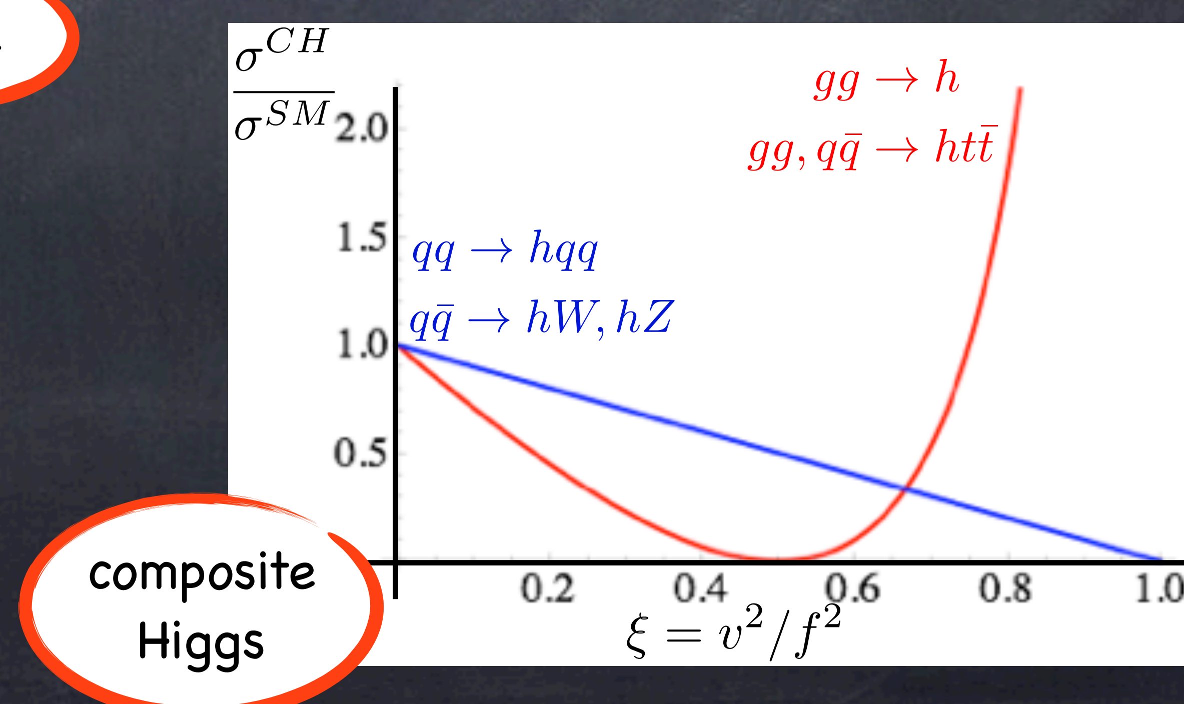
$$\frac{\sigma_{H\to\gamma\gamma}}{\sigma^{SM}_{H\to\gamma\gamma}} = \begin{cases} 1.7 \pm 0.3 & \text{(ATLAS)} \\ 0.8 \pm 0.3 & \\ 1.1 \pm 0.3 & \text{(CMS)} \end{cases}$$

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





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

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

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

    - dimension 6
    - not present in the SM

    - renormalizable (SM)

  - ✦ they are related to different mass generation mechanisms

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 nature of the mass of the new heavy quarks

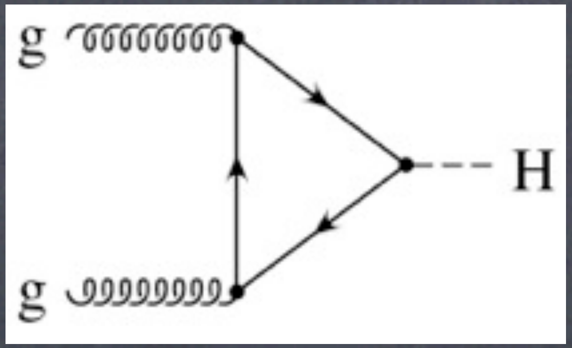
A. Pierce, J. Thaler, L.-T. Wang, JHEP 0705:070, 2007

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

SINGLE HIGGS PRODUCTION

- main mechanism: gluon fusion



- for heavy ($2m_q > m_H$) quarks, the leading order amplitude depends on the mass m_q and the Yukawa coupling y_{qq} as

$$A_{gg\to H} \propto \sum_q \frac{y_{qq}}{m_q}\left[\frac{2}{3} + \frac{7}{45}\frac{m_H^2}{4m_q^2} + \ldots\right]$$

➡ neglecting finite-mass effects,

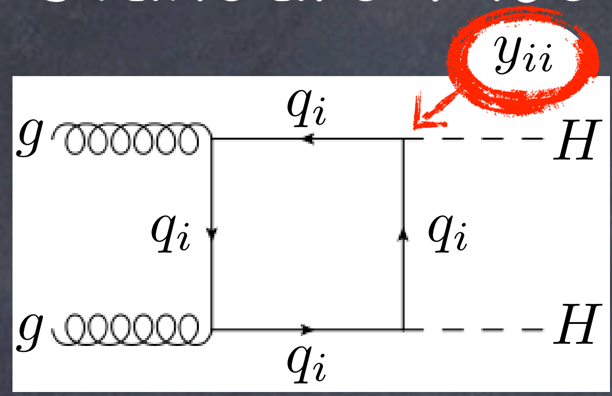
$$\frac{A_{gg\to H}}{A_{gg\to H}^{SM}} = \sum_q \frac{y_{qq}}{m_q}$$

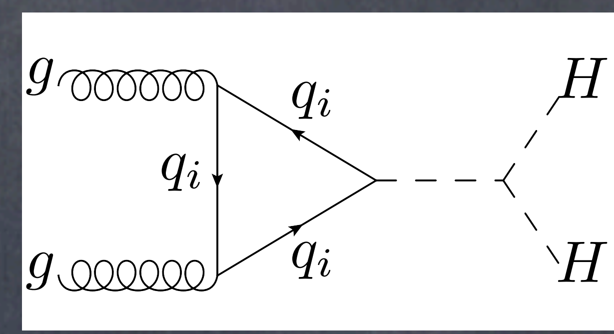
(In the SM $y_{tt} = m_t$)

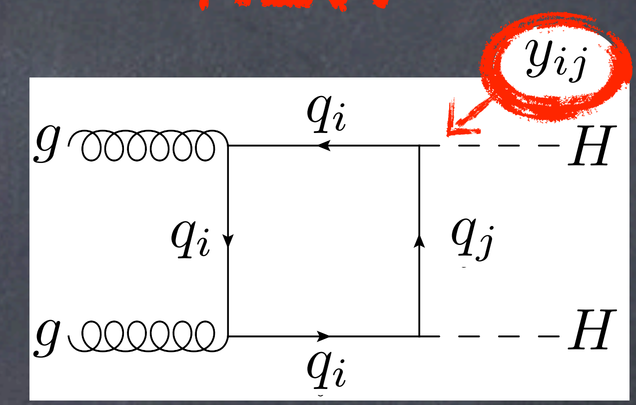
DOUBLE HIGGS PRODUCTION

- Standard Model like contributions

NEW







- at leading order, the amplitude is known with the full mass dependance

Glover, van der Bij, NPB309:282, 1988

- in the infinite quark mass approximation,

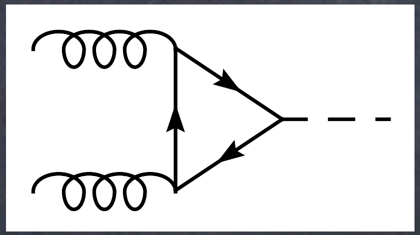
$$A^{box,ii}_{gg\to HH} \propto \frac{y_{ii}^2}{m_i^2} \qquad A^{tri}_{gg\to HH} \propto \frac{-3m_H^2}{s-m_H^2}\frac{y_{ii}}{m_i} \qquad A^{box,ij}_{gg\to HH} \propto \frac{y_{ij}^2}{m_i m_j}$$

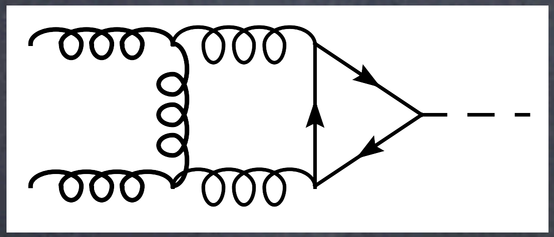
➡ neglecting finite-mass effects,

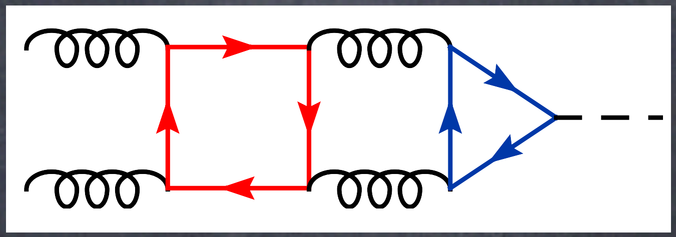
$$\frac{A^{box}_{gg\to HH}}{A^{box,SM}_{gg\to HH}} = \sum_{i,j} \frac{y_{ij}^2}{m_i m_j}$$

HIGGS PRODUCTION

- these approximate results are useful to understand the source of the (potential) deviations from the SM
- in our analysis we will use the "exact" cross section
  - ✦ for single Higgs production, through NNLO







Graudenz, Spira, Zerwas, PRL70, 1372 (1993)
Spira, Djouadi, Graudenz, Zerwas, NPB453, 17 (1995)

Harlander, Kilgore, PRL88, 201801 (2002)
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EF, **JHEP 1110 (2011) 115**

ihixs
Anastasiou, Bülher, Herzog, Lazopoulos

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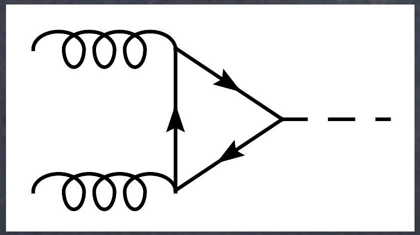

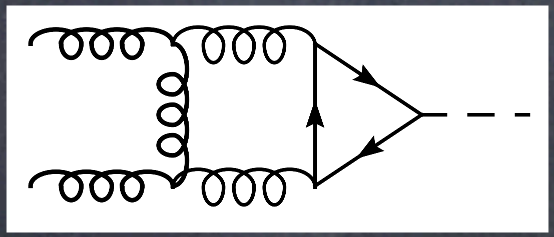

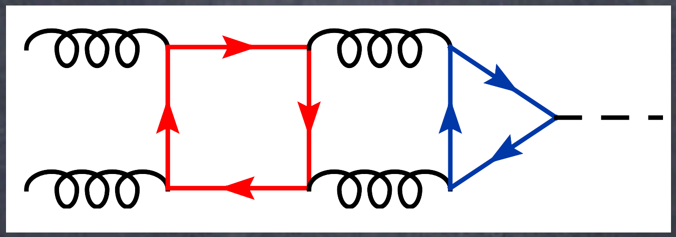

  - ✦ for double Higgs production, at LO with full mass dependence

Glover, van der Bij, NPB309:282, 1988

VECTOR SINGLET

- introduced for example in little Higgs and composite Higgs models
- notation

$$\psi_L = \begin{pmatrix} \mathcal{T}_L^1 \\ \mathcal{B}_L^1 \end{pmatrix} \quad , \mathcal{T}_R^1 \, , \mathcal{B}_R^1$$ SM-like chiral fermions

$\mathcal{T}_L^2 \, , \mathcal{T}_R^2$ vector singlet with Y=1/6

$t, T, b = \mathcal{B}^1$ mass eigenstates of mass m_t, M_T, m_b

- the fermion mass terms are

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

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

$$\begin{pmatrix} t_i \\ T_i \end{pmatrix} = \begin{pmatrix} c_i & -s_i \\ s_i & c_i \end{pmatrix} \begin{pmatrix} \mathcal{T}_i^1 \\ \mathcal{T}_i^2 \end{pmatrix}$$

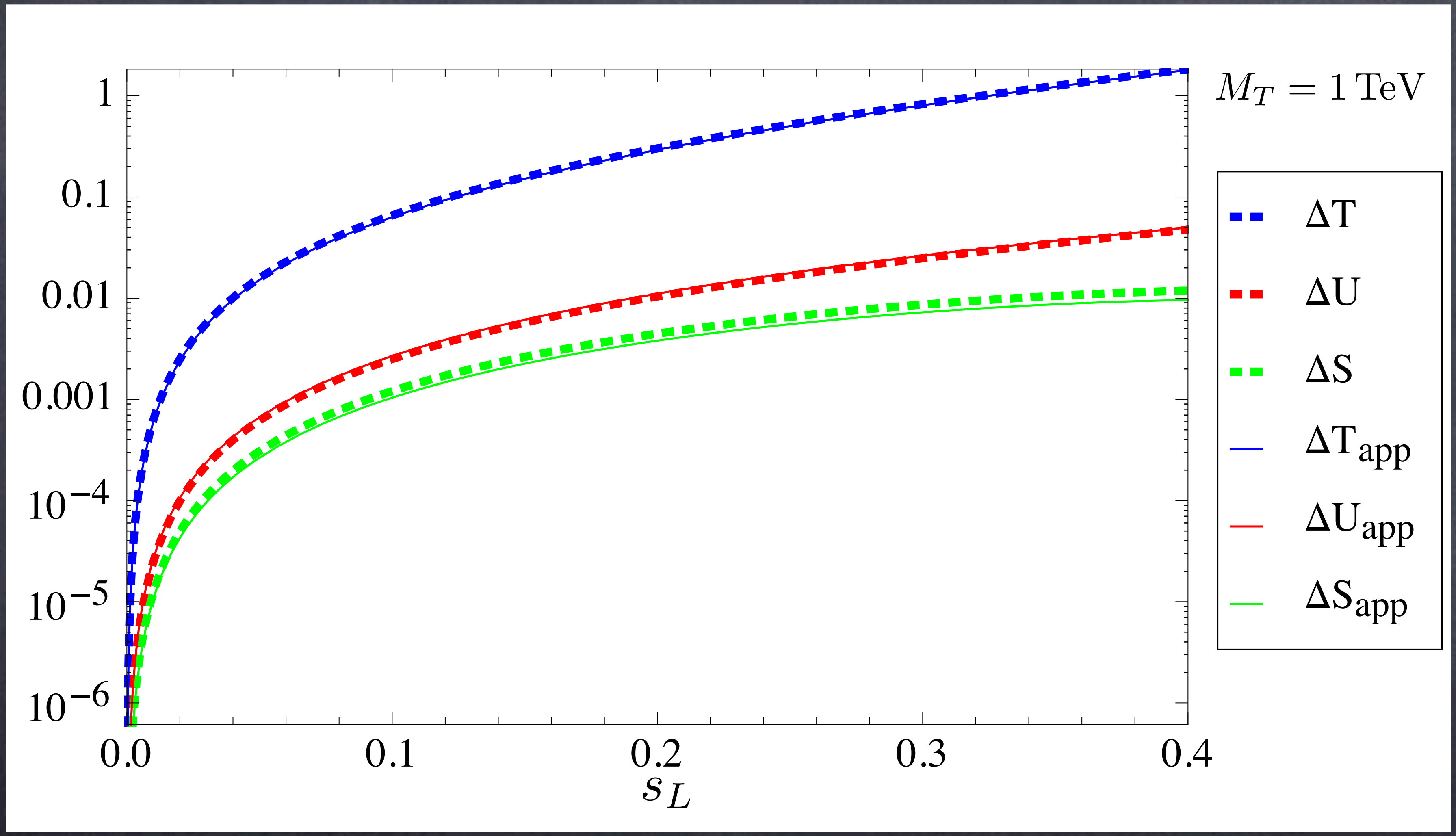
$$\begin{aligned} c_i &= \cos(\theta_i)\ , \\ s_i &= \sin(\theta_i) \end{aligned}$$

$$(i = L, R)$$

- the $\overline{\mathcal{T}}_L^2 \mathcal{T}_R^1$ term can be rotated away by a redefinition of the right handed fields
  ⇨ 4 independent parameters $(m_b, m_t, M_T, \theta_L)$

CONSTRAINTS

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



$m_b \to 0$, $M_T >> m_t$

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

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

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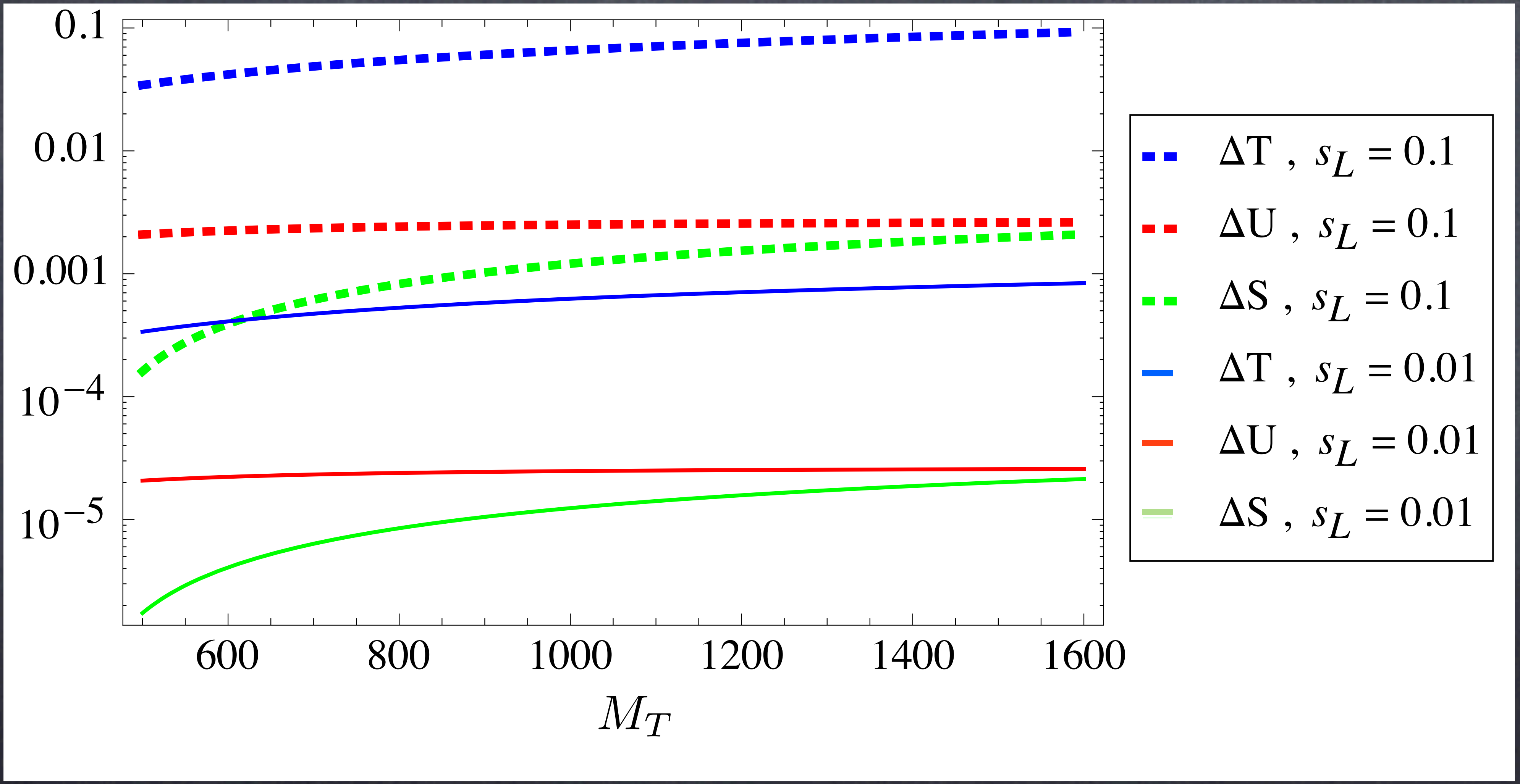

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DECOUPLING

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

- 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 $M_T \sim \lambda_5$, $m_t \sim \lambda_2 v/\sqrt{2}$, $s_L \sim \lambda_3 v / M_T$

➡ 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 (λ_3 constant)

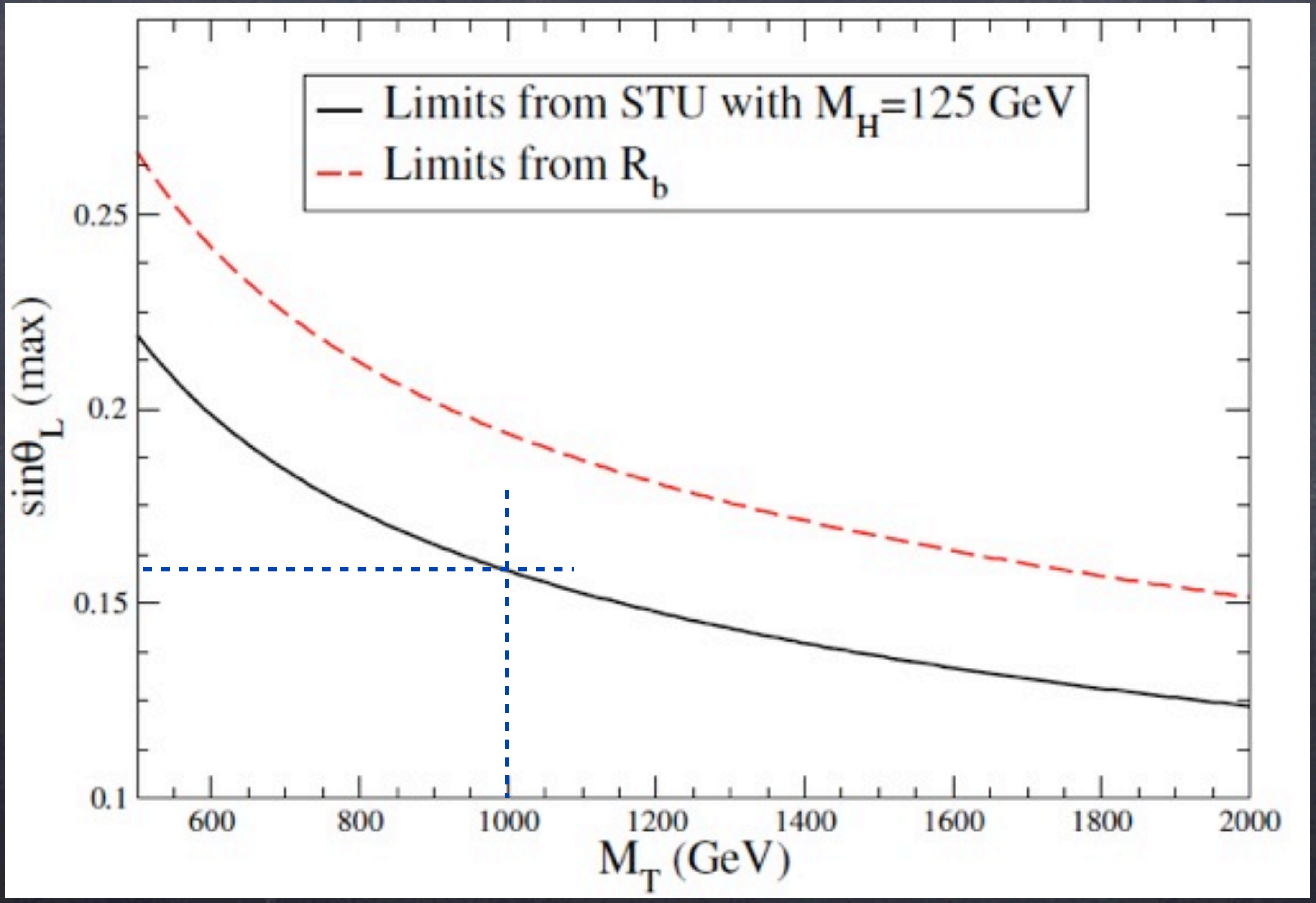
$$\Delta T \sim T_{SM}\, s_L^2 \left(r s_L^2 - 2 + 2 \log r \right) \to 0 \,,$$

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

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

CONSTRAINTS

- In the singlet model, the strongest constraints come from the oblique parameters



HIGGS PRODUCTION

- mixing with the singlet reduces the coupling of the top-like quark to the Higgs and yields a coupling to the Higgs also for the heavy top partner

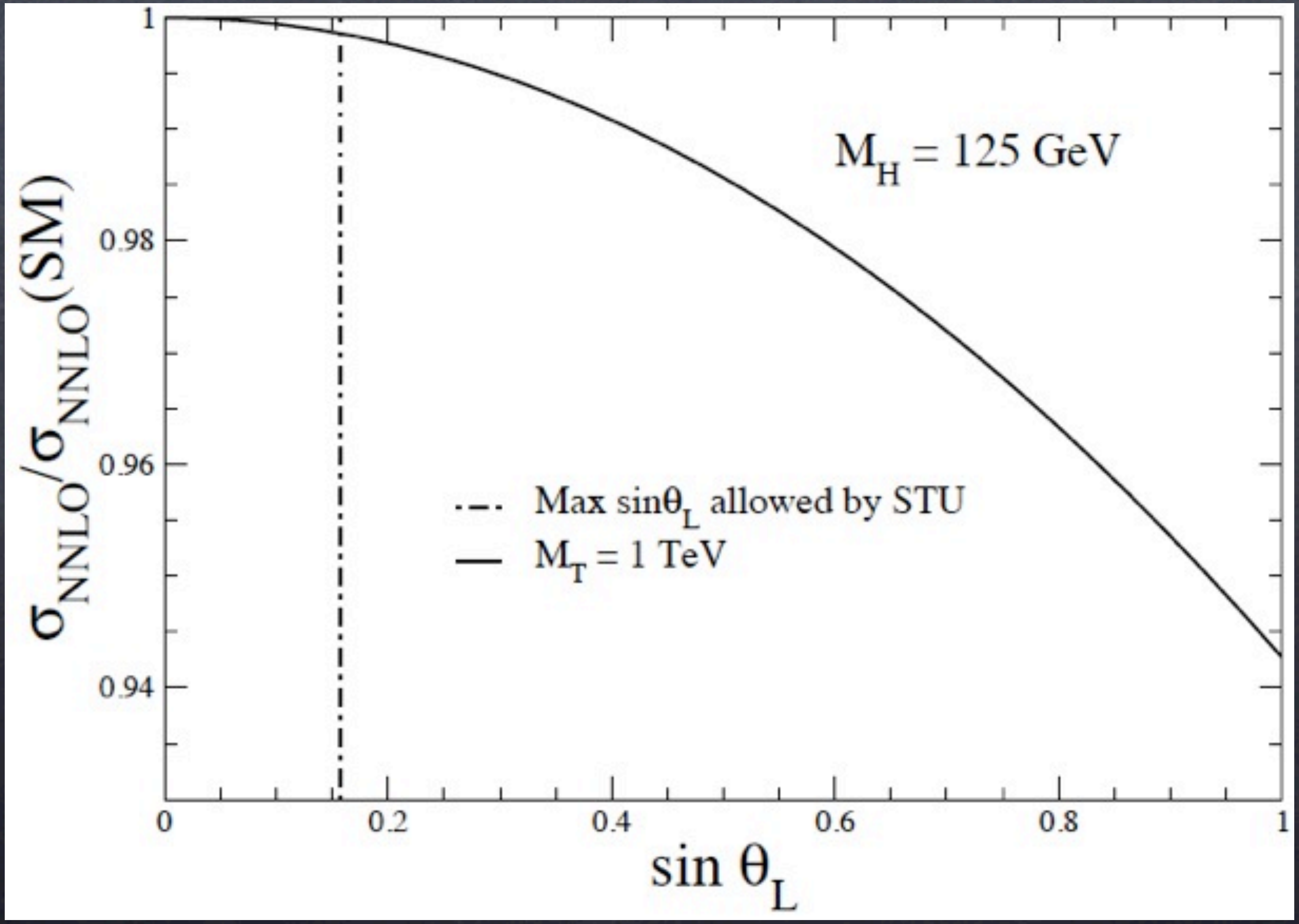
$$Y_{tt} = c_L^2 \frac{m_t}{v} \quad , \; Y_{TT} = s_L^2 \frac{M_T}{v}$$
$$Y_{Tt} = s_L c_L \frac{m_t}{v} \quad , \; Y_{tT} = s_L c_L \frac{M_T}{v}$$

- the Higgs production cross section is suppressed with respect to the Standard Model

$$\frac{\sigma^{(s)}_{gg\to H}}{\sigma^{SM}_{gg\to H}} \approx 1 - \frac{7}{15}\frac{m_H^2}{4m_t^2} s_L^2 \left(1 - \frac{m_t^2}{M_T^2}\right) \xrightarrow{\text{decoupling}} 1$$

HIGGS PRODUCTION

- potentially large effect, but electroweak observables require a small mixing angle ⇨ at most some few % effect



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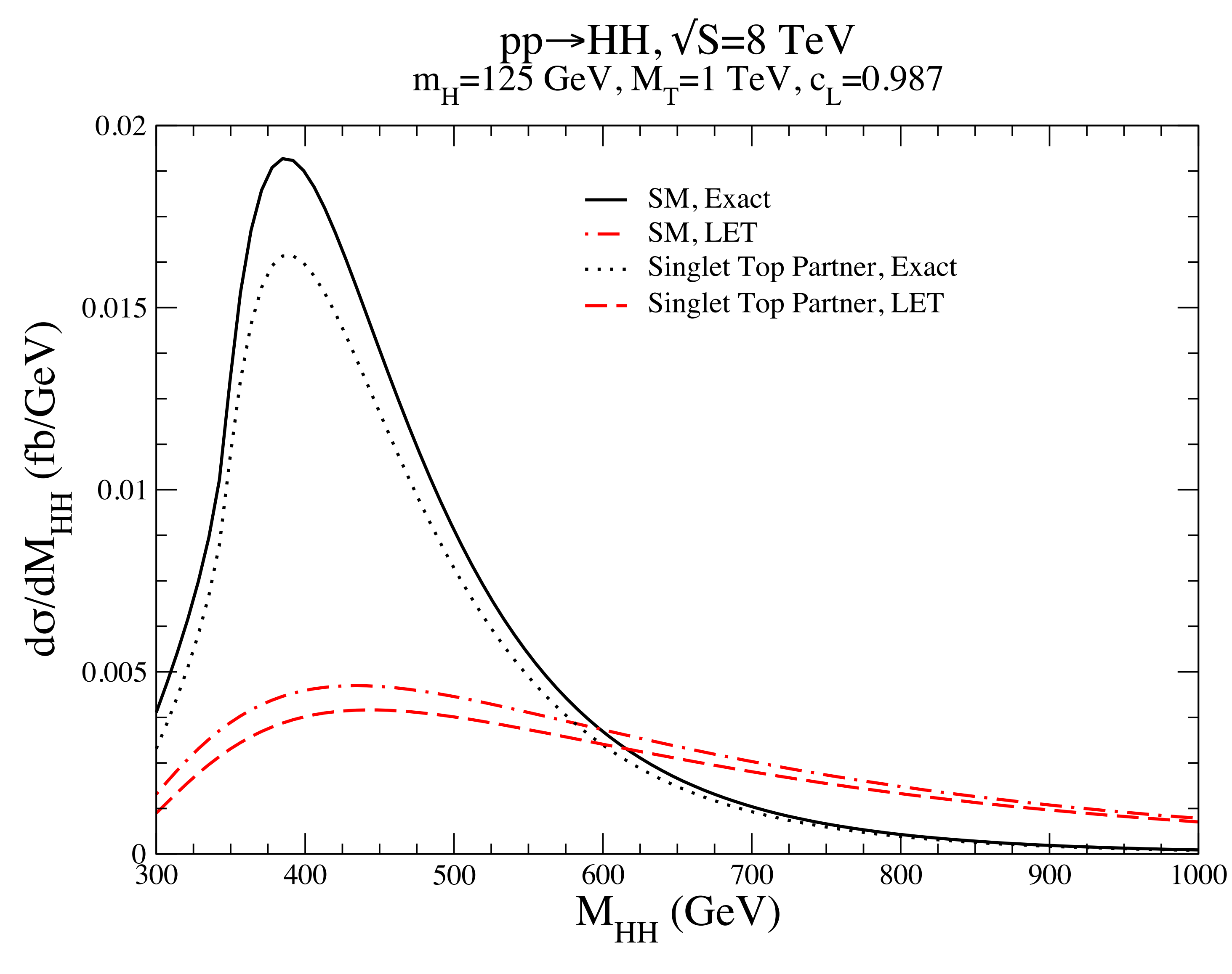
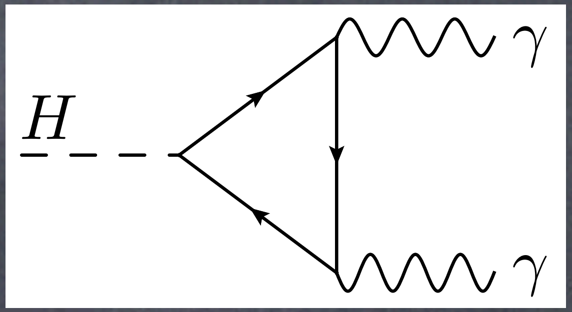
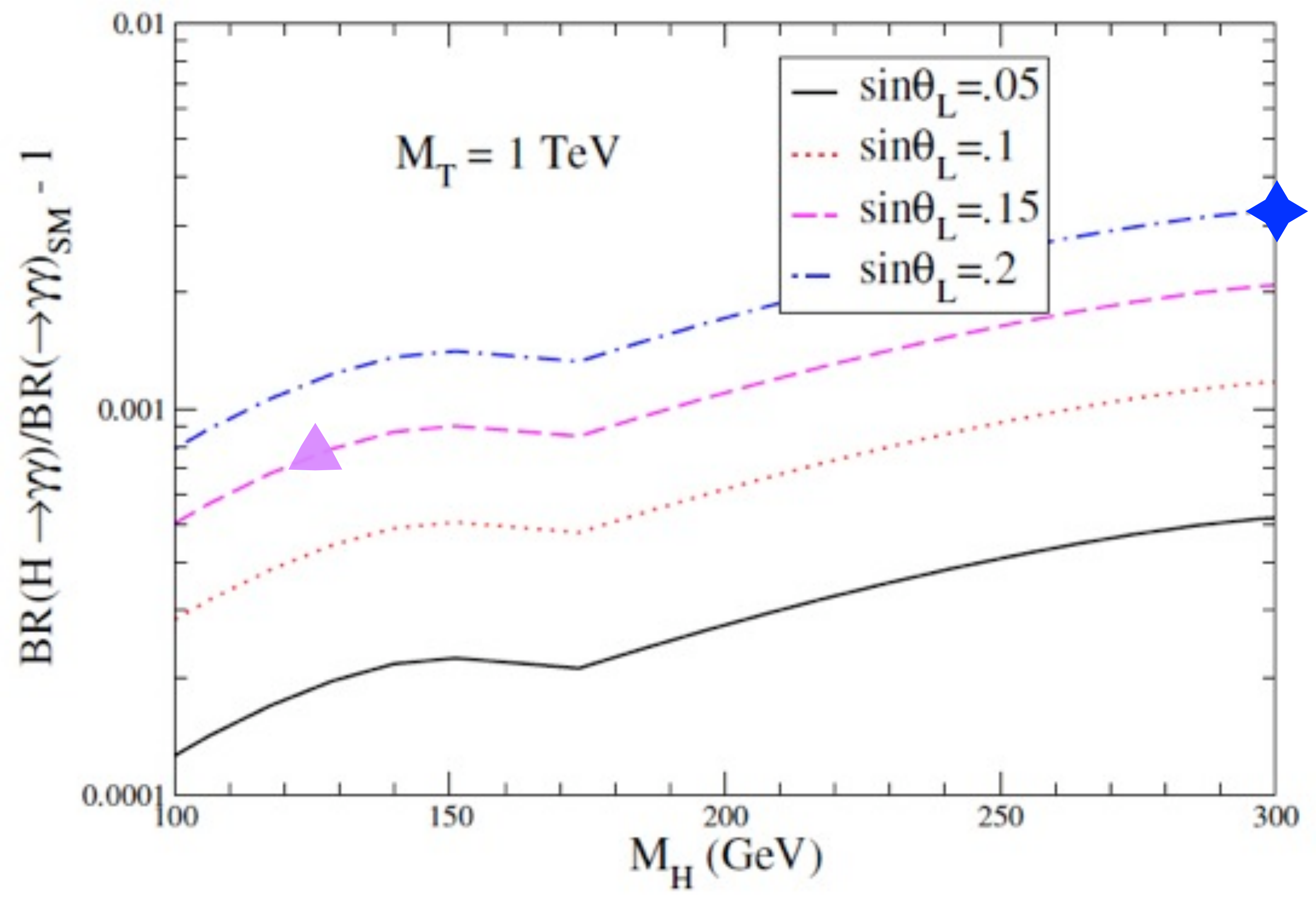


HIGGS DECAYS

- 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

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

- assume no mixing with the Standard Model t, b quarks,

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

MIRROR QUARKS

- mass terms:

$$\mathcal{M}_U = \begin{pmatrix} \lambda_B \frac{v}{\sqrt{2}} & \lambda_E \\ \lambda_F & \lambda_D \frac{v}{\sqrt{2}} \end{pmatrix} \begin{matrix} \overline{\mathcal{T}}_L^1 \\ \overline{\mathcal{T}}_L^2 \end{matrix} \qquad \mathcal{M}_D = \begin{pmatrix} \lambda_A \frac{v}{\sqrt{2}} & \lambda_E \\ \lambda_G & \lambda_C \frac{v}{\sqrt{2}} \end{pmatrix} \begin{matrix} \overline{\mathcal{B}}_L^1 \\ \overline{\mathcal{B}}_L^2 \end{matrix}$$

$$\mathcal{T}_R^1 \quad \mathcal{T}_R^2 \qquad\qquad \mathcal{B}_R^1 \quad \mathcal{B}_R^2$$

- the mass eigenstates $T_1, T_2; B_1, B_2$ are obtained though unitary rotations ⇨ need four rotation angles

- for simplicity assume

$$M_{T_1} = M_{B_1} = M \; , M_{T_2} = M_{B_2} = M(1+\delta)$$

➡ six parameters, $M, \delta, \theta_\pm^t, \theta_\pm^b \; (\theta_L^q = \theta_L^q \pm \theta_R^q)$.

➡ one condition, $\mathcal{M}_{U,12} = \mathcal{M}_{D,12}$

HIGGS PRODUCTION

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

?

- 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

Fix

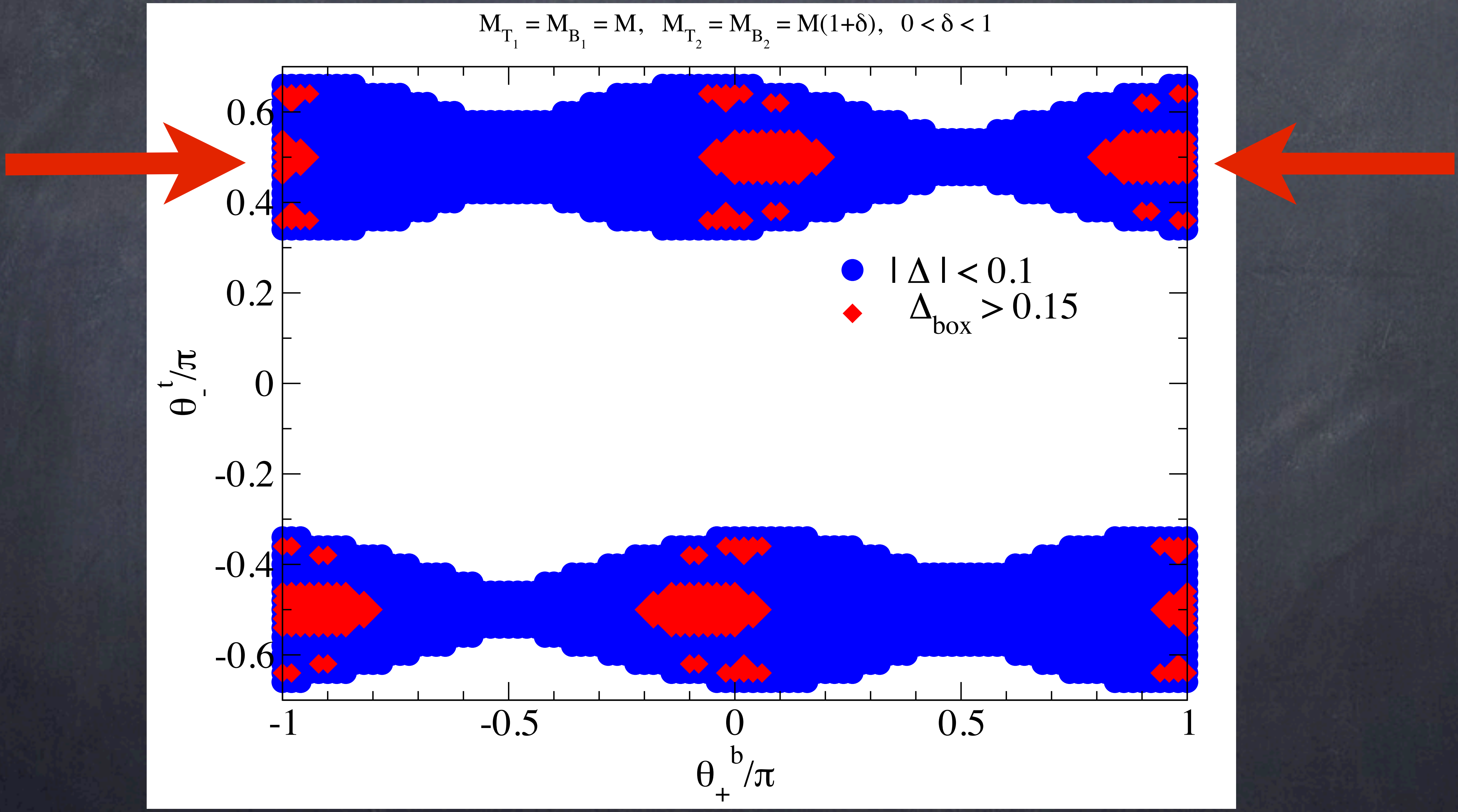
- mass splitting δ between the two quark mirror families
- fractional difference Δ from the Standard Model single Higgs amplitude

$$A_{gg\to H} \equiv A^{SM}_{gg\to H}\,(1 + \Delta)$$

$$\Rightarrow \quad (2+\delta)\sin\theta^t_- + \delta \sin\theta^t_+ = (2+\delta)\sin\theta^b_- + \delta\sin\theta^b_+$$

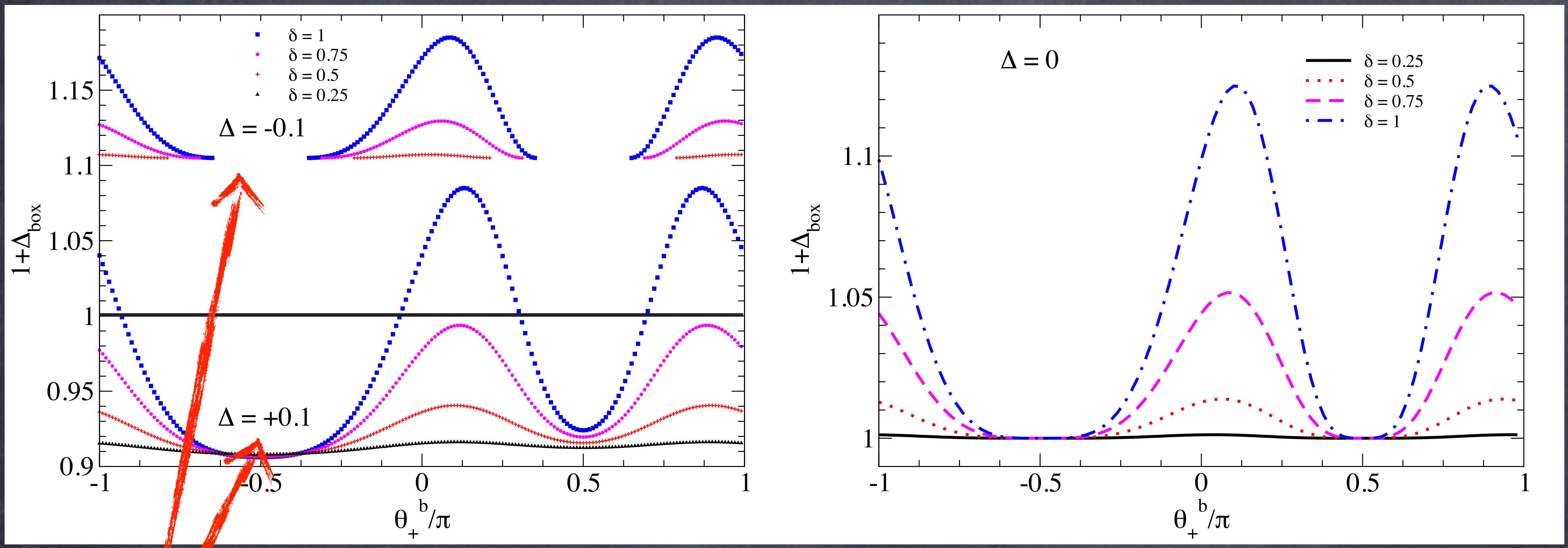
$$\Rightarrow \quad \sin\theta^b_- = \frac{1}{2+\delta}\left\{ \frac{(4-\Delta)(1+\delta)}{(2+\delta)\sin\theta^t_- - \delta\sin\theta^b_+} - \delta\sin\theta^b_+ \right\}$$

HIGGS PRODUCTION



➡ Fix $\theta_-^t = \frac{\pi}{2}$

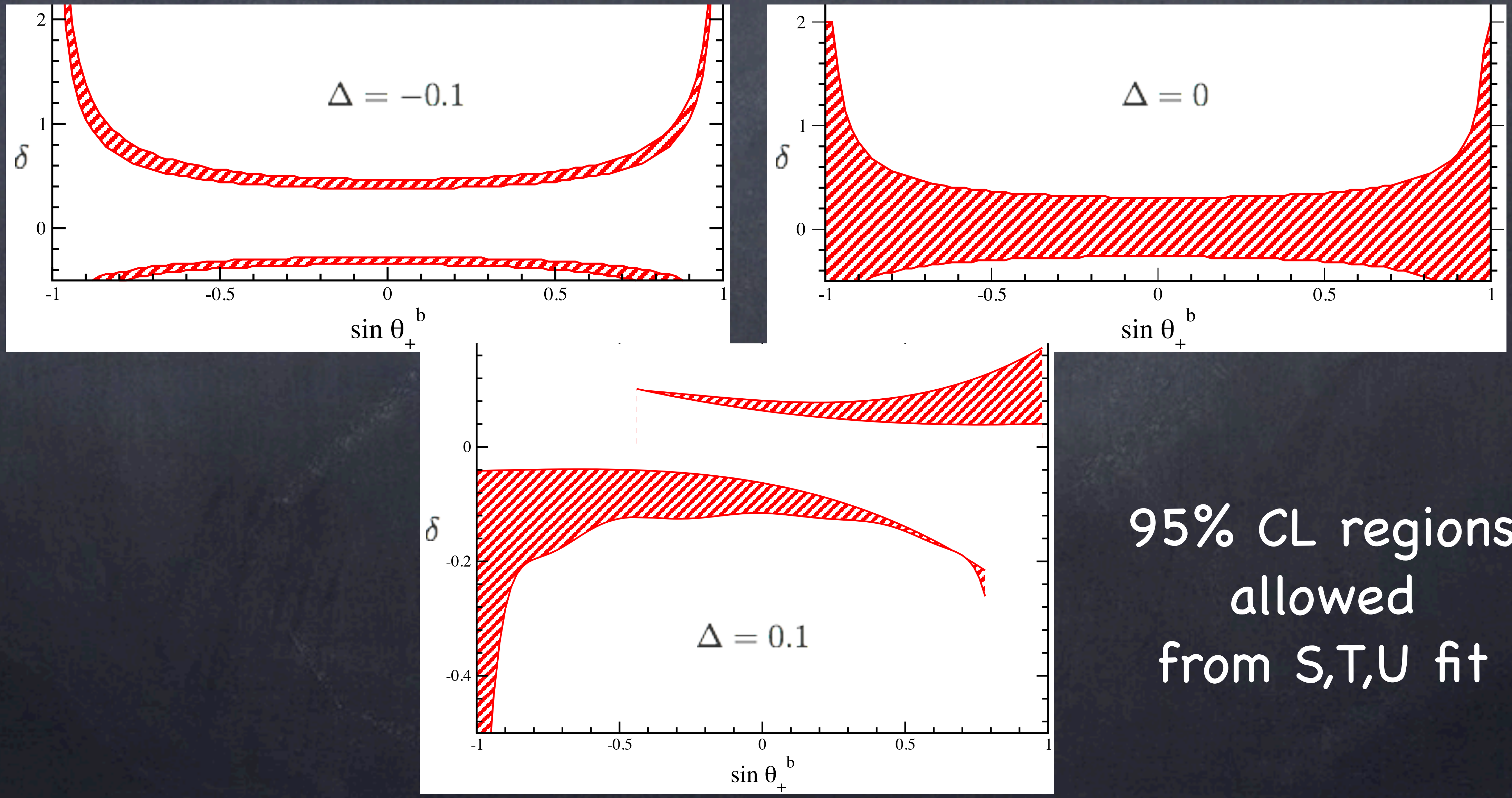
HIGGS PRODUCTION



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

FORGOT ANYTHING?

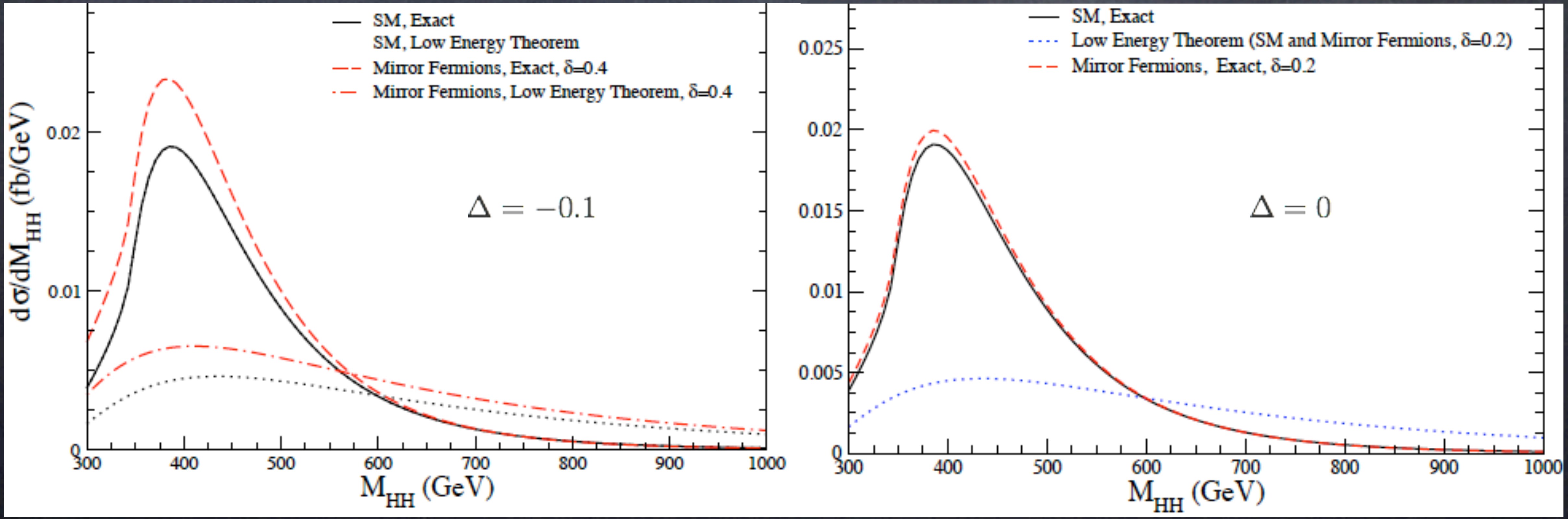
- the mirror quarks also contribute to the self energies of the electroweak gauge bosons ⇨ bounds from the S, T, U parameters



95% CL regions allowed from S,T,U fit

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



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)

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

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

- ✦ dimension 6
- ✦ not present in the SM

➡ $c_1^{SM} = 0\,,\ c_2^{SM} = 1$

- ✦ renormalizable

GLUON-HIGGS OPERATORS

- $\mathcal{O}_1, \mathcal{O}_2$ contribute differently to Higgs single and pair production,

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

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

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

- in the singlet model $c_1 = 0$ ⇨ as Standard Model

GLUON-HIGGS OPERATORS

- in the mirror fermion model

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

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

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

- require single Higgs close to Standard Model

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

➡ need large c_1 ⇨ $\beta_q \simeq 1$ ⇨ either massless or infinitely heavy quarks!

CONCLUSIONS

vector singlet

- its mixing with the top quark strongly constrained by S, T, U ⇨ forced almost to decouple
- decoupling: $M_T \to \infty, s_L \sim v M_T^{-1}$
- 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 the $H \to \gamma\gamma$ branching ratio 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
  - ➡ double Higgs cross section and distributions also become close (within 20%) to the Standard Model ones
  - ➡ the Higgs branching ratio into photons is within 10% the Standard Model prediction

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 or infinitely heavy quarks!