HIGGS PRODUCTION IN MODELS WITH AN EXTENDED QUARK SECTOR

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in collaboration with Sally Dawson

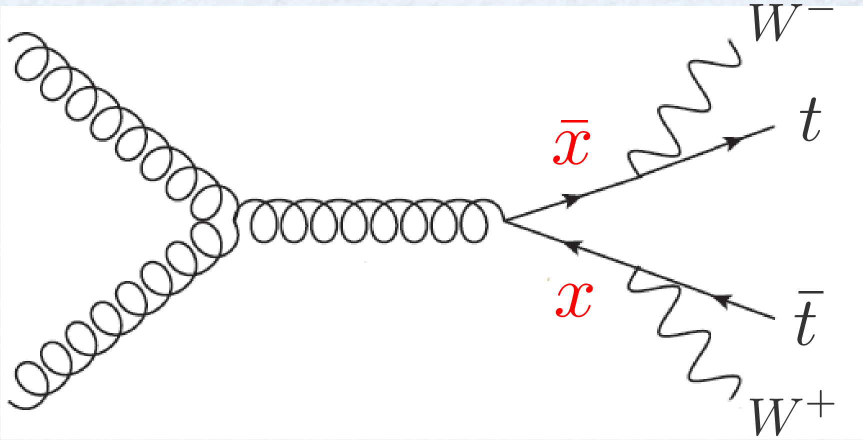
HP2^4, MPI Münuch, Sept 6 2012

MOTIVATION

- LHC experiments: *"habemus Higgs!"*

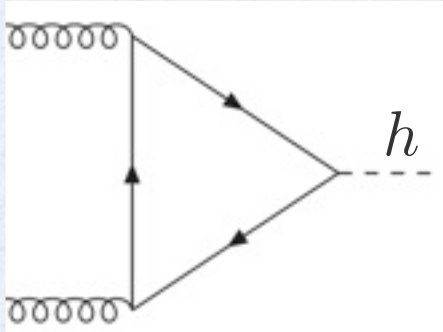
↕

- *"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



direct production

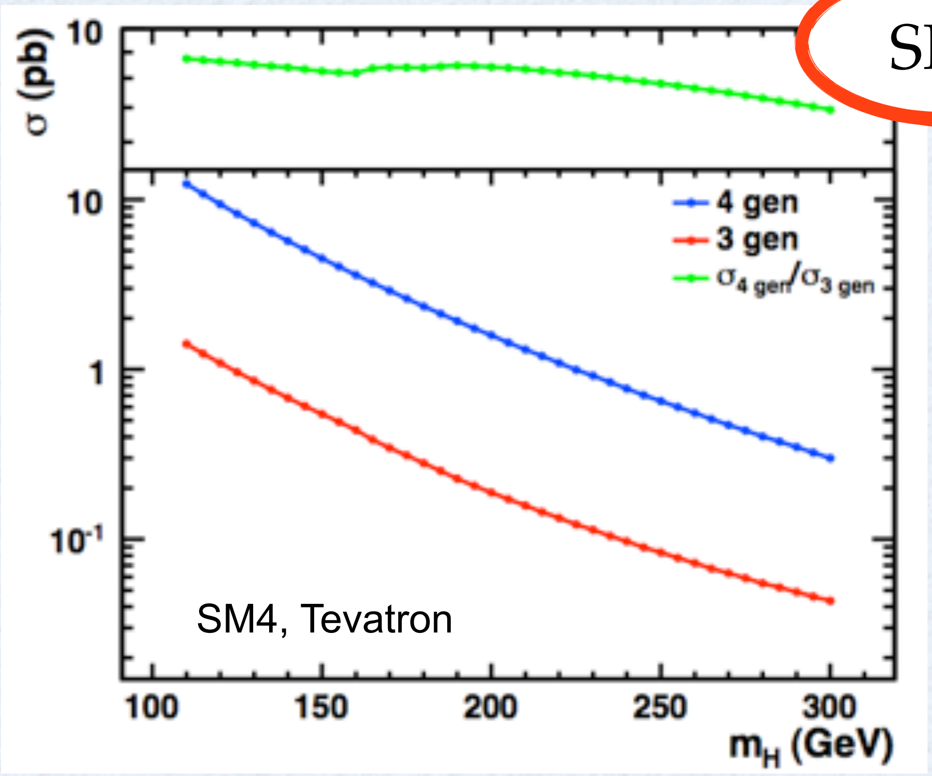
loop effects



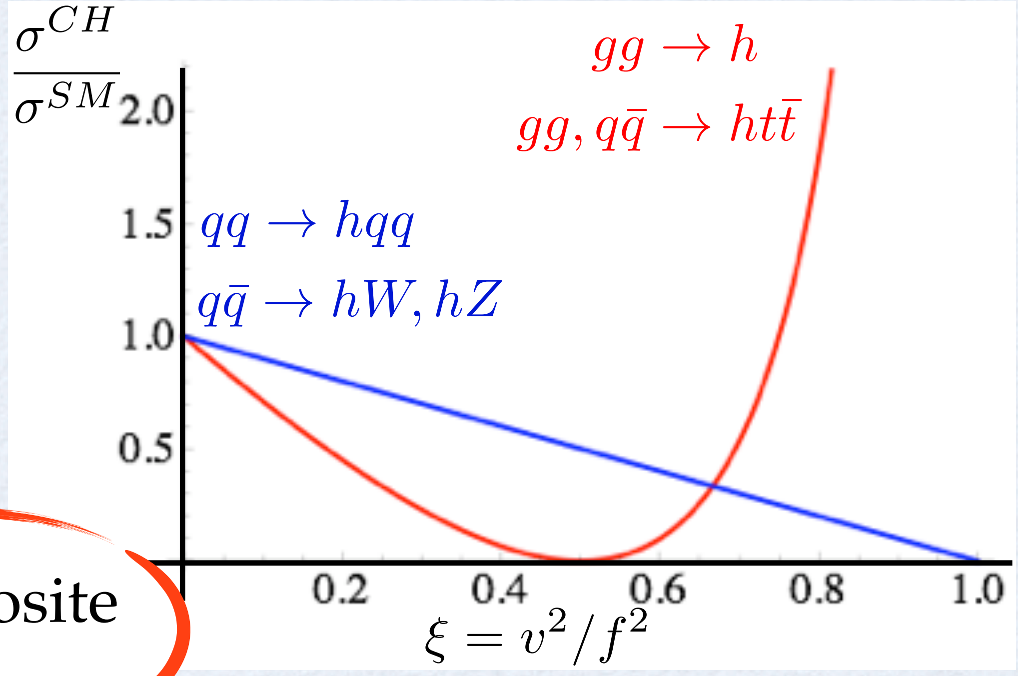
MOTIVATION

- 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



composite Higgs

MOTIVATION

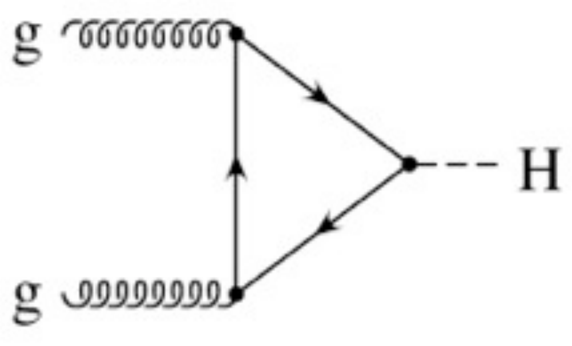
- the new particles typically
    - ✦ couple to the Higgs boson
    - ✦ mix with the Standard Model top quark, modifying its coupling to the Higgs boson

➡ *can* significantly affect Higgs production and decays

➡ but.. do they *have to*?

MOTIVATION

- in the Standard Model (and in many of its extensions), the main Higgs production mechanism is gluon fusion



- at leading order

$$\sigma^{LO}_{gg\to h} \propto \left| \sum_q \frac{Y_q}{m_q}\left[\frac{2}{3} + \frac{7}{45}\frac{m_h^2}{4m_q^2} + \mathcal{O}\left(\frac{m_h^4}{(2m_q)^4}\right)\right]\right|^2 \qquad (2m_q > m_h)$$

- for heavy quarks with a Higgs coupling proportional to their mass, the leading contribution is independent on m_q

OUTLINE

- consider the case of vector isospin singlet/doublet
  - constraints from electroweak data on the mass of the new fermions and their mixing with the top quark
  - decoupling properties
  - effects on the Higgs production cross section
    - approximate result at leading order (analytical)
    - exact NNLO cross section

- "Gluon-fusion Higgs production at NNLO for a non-standard Higgs sector"

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

- ihixs

Anastasiou, Bülher, Herzog, Lazopoulos
JHEP 1112 (2011) 058

VECTOR SINGLET

- introduced for example in little / composite Higgs models

- the fermion mass terms are

$$-\mathcal{L}^{(s)} = \underbrace{\alpha \underline{\bar{q}_L} H \underline{d_R} + a \bar{q}_L \tilde{H} \underline{u_R}}_{-\mathcal{L}^{SM}} + \underbrace{b \bar{q}_L \tilde{H} U_R + c \bar{U}_L u_R + d \underline{\bar{U}_L U_R}}_{\text{mixing terms}} + \text{h.c.}$$

➡ the charge 2/3 mass eigenstates t, T are an admixture of u and U

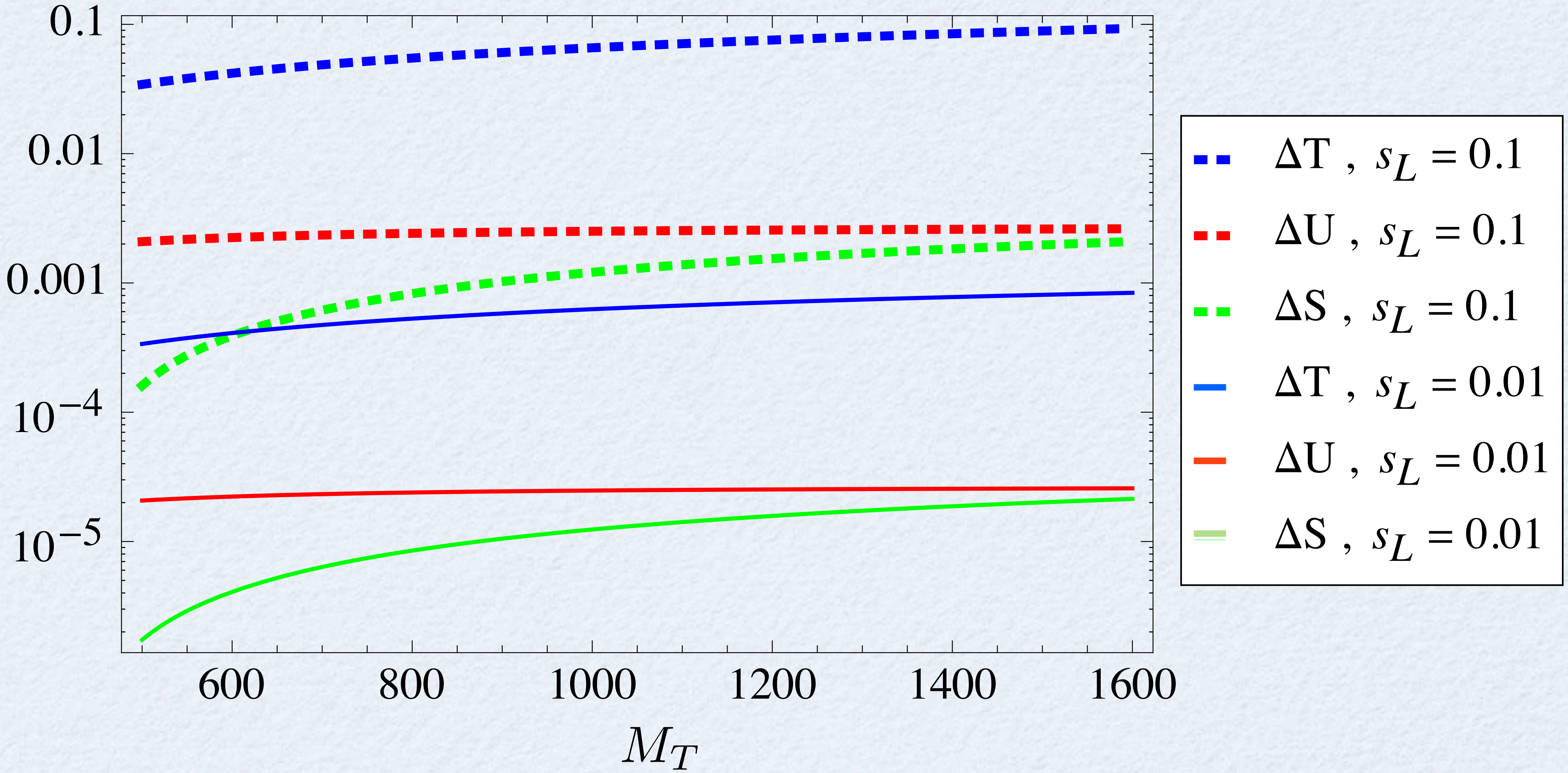
$$\begin{pmatrix} t_i \\ T_i \end{pmatrix} = \begin{pmatrix} c_i & -s_i \\ s_i & c_i \end{pmatrix} \begin{pmatrix} u_i \\ U_i \end{pmatrix}$$

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

➡ can redefine U_R so that $\theta_R = 0 \Rightarrow$ 4 independent parameters $(m_b, m_t, M_T, \theta_L)$

CONSTRAINTS: S, T, U

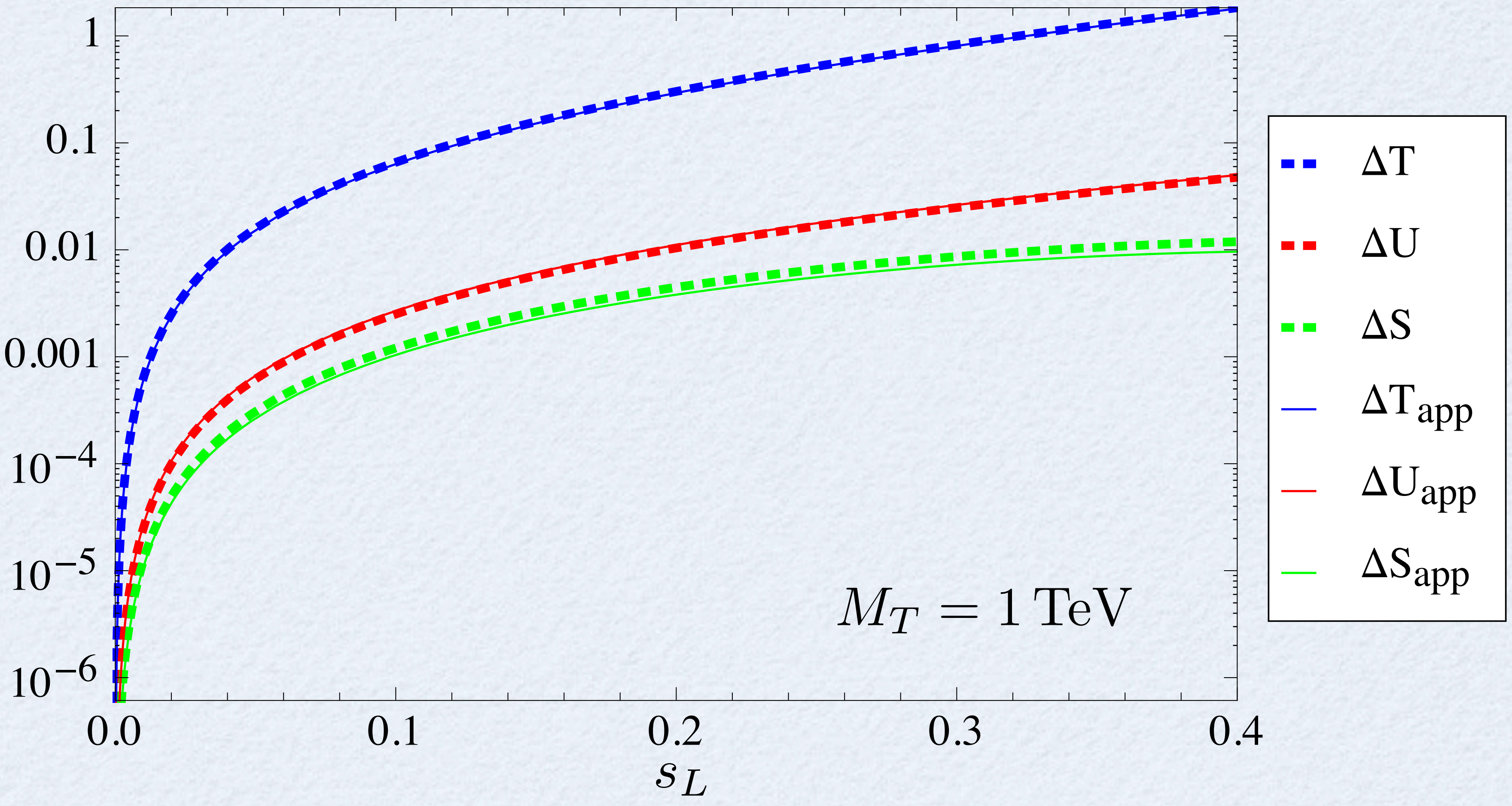
- Contribution to the Peskin - Takeuchi S, T, U parameters:



- Note that both ΔT , $\Delta S > 0$, but $\Delta T >> \Delta S$

CONSTRAINTS: S, T, U

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



$$\Bigg\} \quad m_b \to 0\,, \quad M_T >> m_t$$

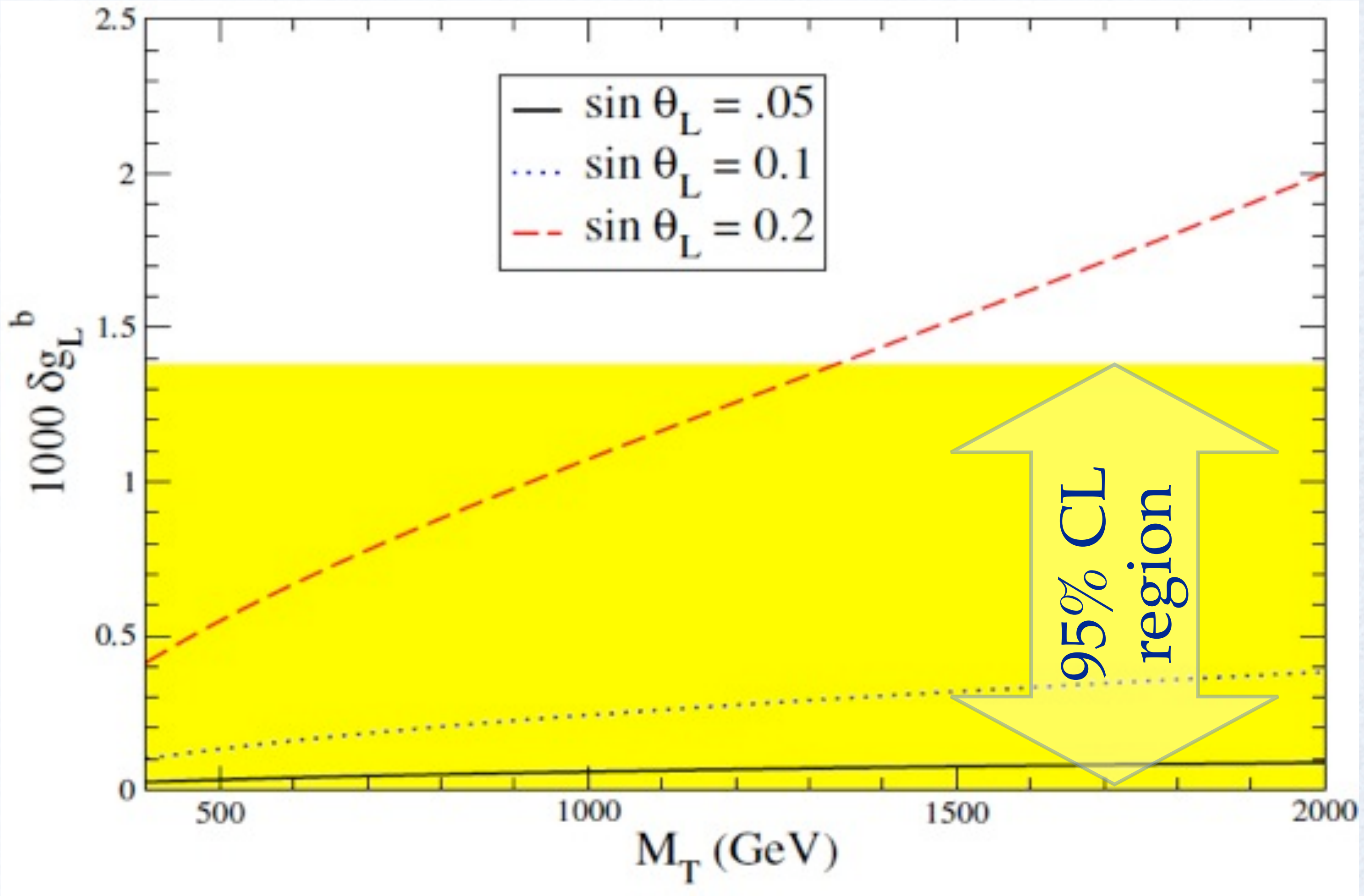
$$\Delta T_{app} = T_{SM}\boxed{s_L^2}\left(r s_L^2 + 2c_L^2 \log r - 1 - c_L^2\right) \qquad r = (M_T/m_t)^2$$

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

CONSTRAINTS: $Z \to b_L \bar{b}_L$

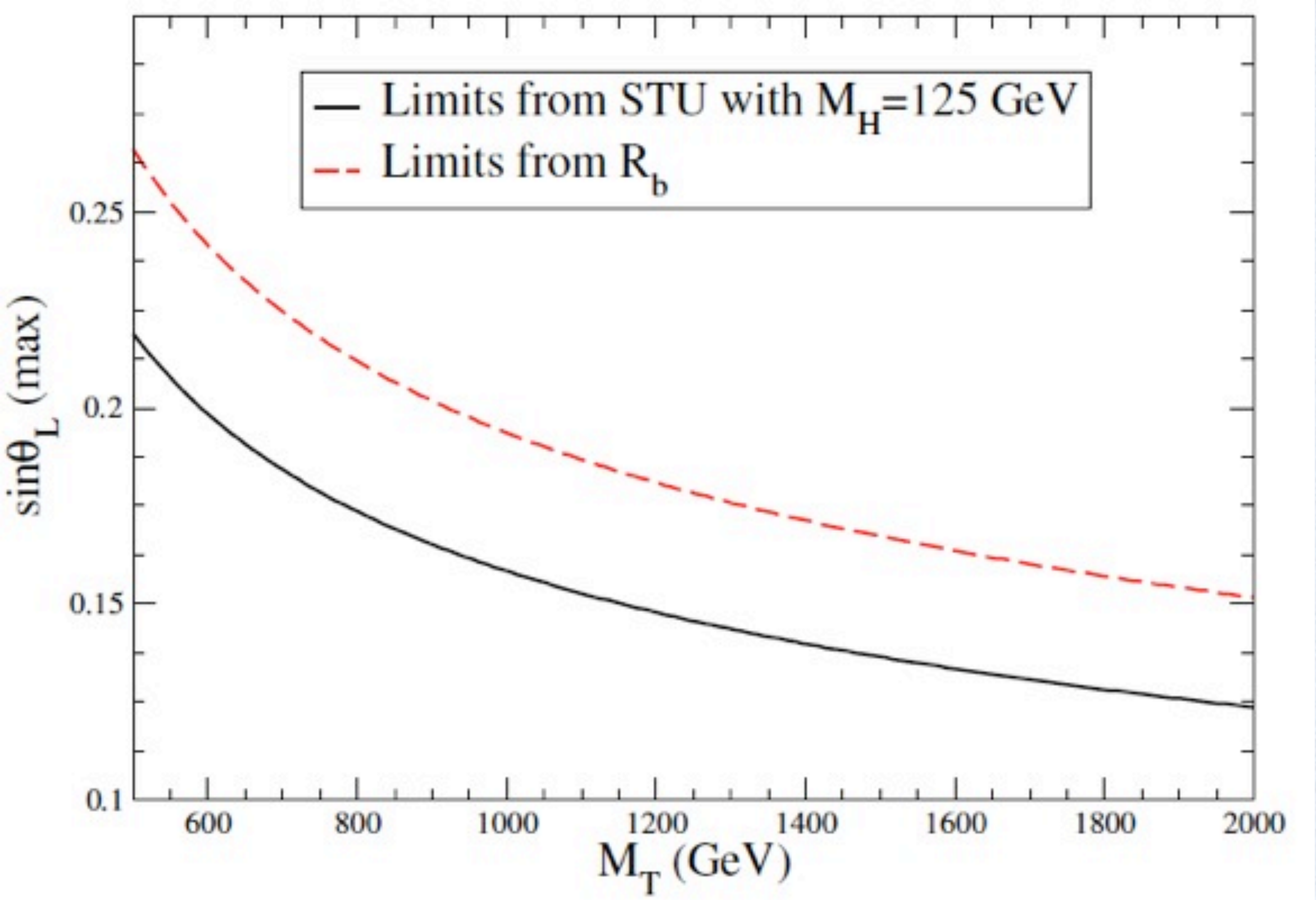
- In the approximation m_t , $M_T >> M_W$,

$$\delta g_b^L = \frac{G_F}{\sqrt{2}} \frac{m_t^2}{8\pi} s_L^2 \left(s_L^2 r - c_L^2 - 1 + 2c_L^2 \frac{r}{r-1} \log r \right)$$



COMBINED CONSTRAINTS

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



DECOUPLING

$$-\mathcal{L}^{(s)} = a\bar{q}_L\tilde{H}u_R + b\,\bar{q}_L\tilde{H}U_R + c\,\bar{U}_Lu_R + d\,\bar{U}_LU_R$$

- decoupling occurs for

$$c, d >> \frac{av}{\sqrt{2}}, \frac{bv}{\sqrt{2}} \text{ and } d >> c$$

- in this limit

$$M_T \sim d\,, \quad m_t \sim av/\sqrt{2}\,, \quad \boxed{s_L \sim v/M_T}$$

➡

$$\begin{aligned}
\Delta T &\sim T_{SM}\, s_L^2 \left(\boxed{r s_L^2} - 2 + \underline{2\log r}\right) \to 0\,, \qquad r = (M_T/m_t)^2 \\
\Delta S &\sim -\frac{N_c}{18\pi} s_L^2 \left(5 - \underline{2\log r}\right) \to 0\,, \\
\Delta U &\sim \frac{N_c}{18\pi} s_L^2\, 5 \to 0\,, \\
\delta g_b^L &\sim \frac{G_F}{\sqrt{2}} \frac{m_t^2}{8\,\pi^2} s_L^2 \left(\boxed{s_L^2 r} + \underline{2c_L^2 \frac{r}{r-1} \log r}\right) \to 0\,.
\end{aligned}$$

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

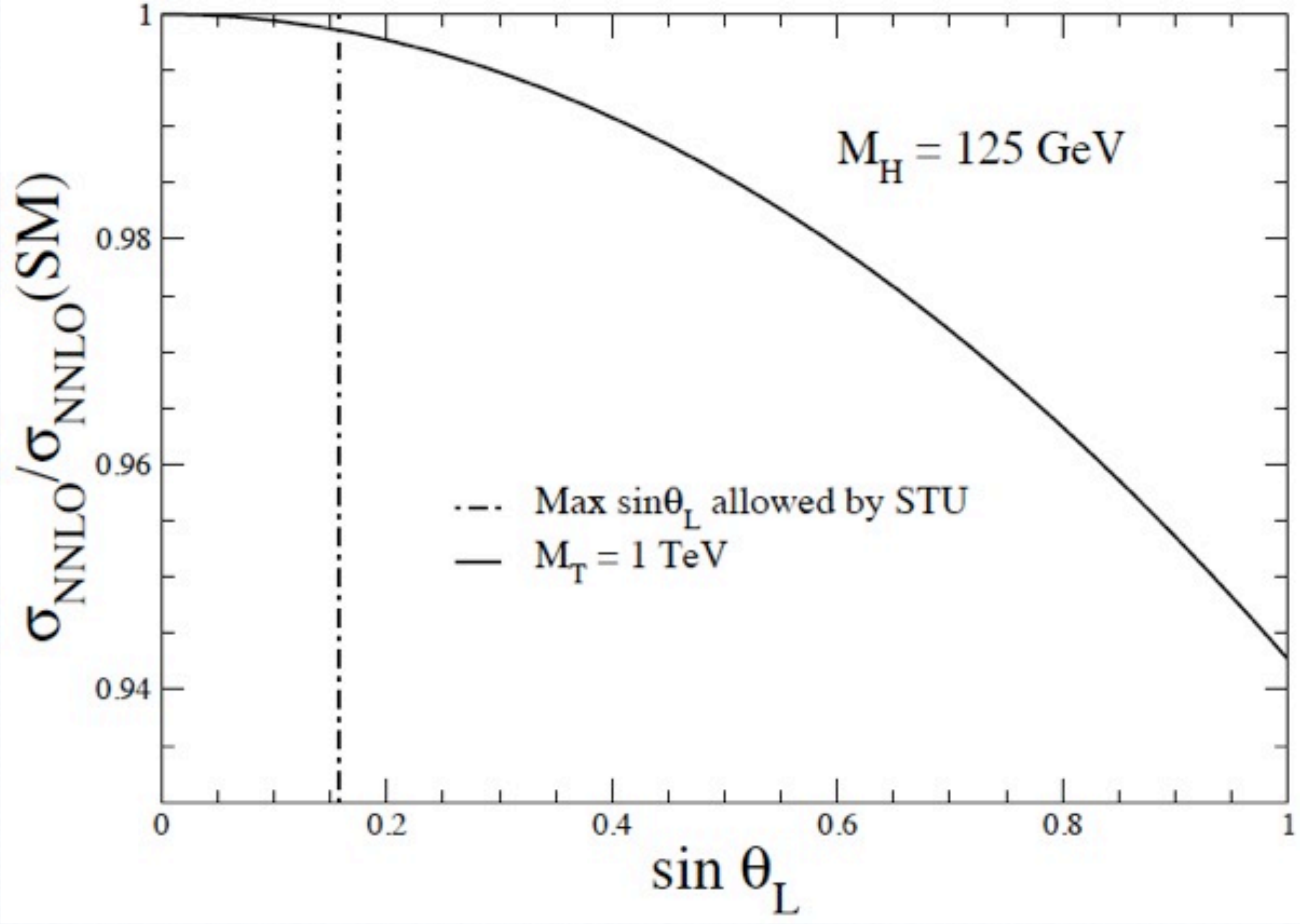
$$Y_t = c_L^2 \frac{m_t}{v} \quad , \; Y_T = s_L^2 \frac{M_T}{v}$$

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

$$\left. \frac{\sigma^{(s)}}{\sigma^{SM}} \right|_{LO} \approx 1 - \frac{7}{15} \frac{m_H^2}{4 m_t^2} s_L^2 \left(1 - \frac{m_t^2}{M_T^2} \right) \xrightarrow{\textbf{decoupling}} 1$$

HIGGS PRODUCTION

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



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Anastasiou et al., **JHEP 1112 (2011) 058**

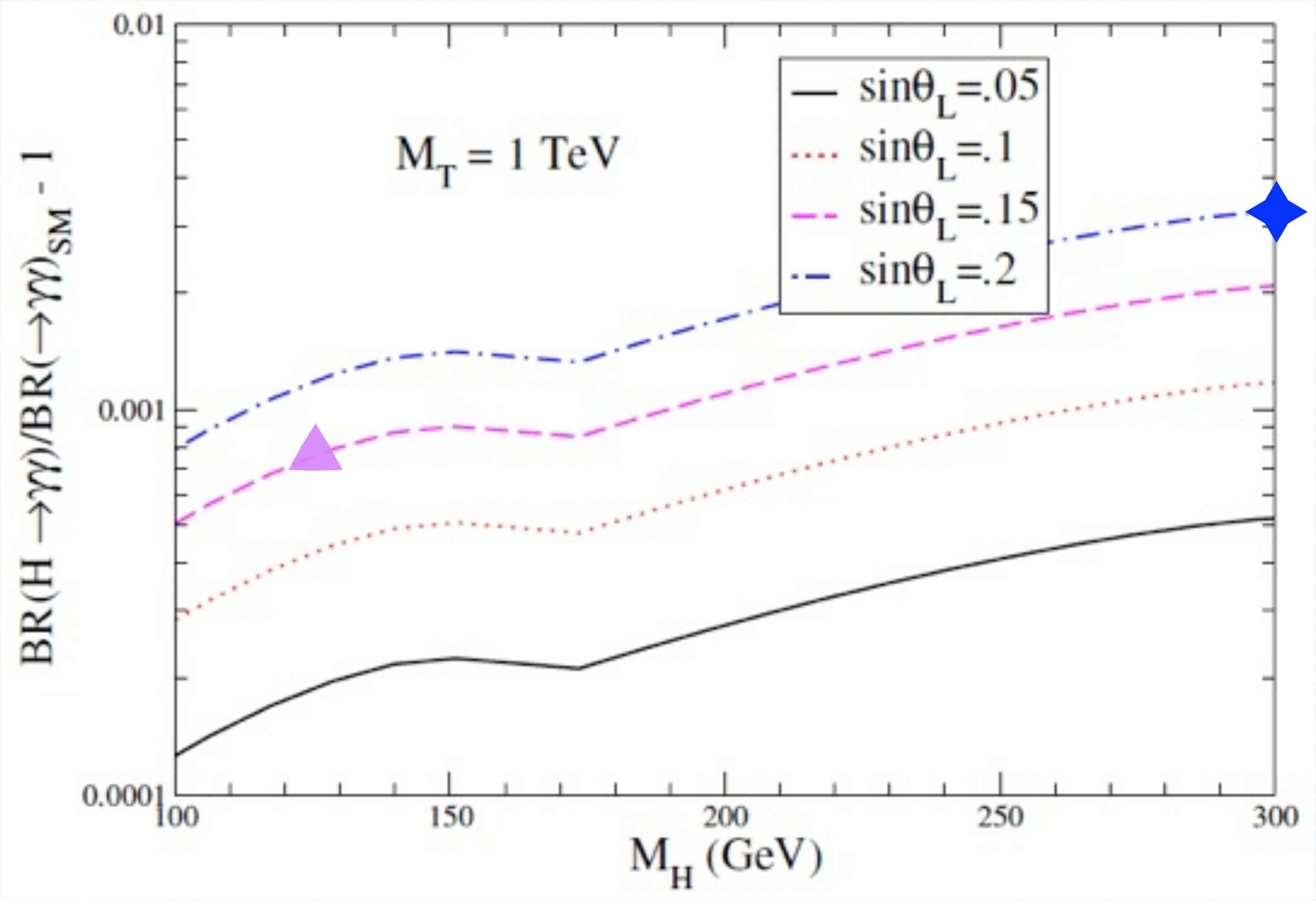
Based on

"Gluon-fusion Higgs production at NNLO for a non-standard Higgs sector",

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

HIGGS DECAYS

- the new top-partner also affects loop-mediated Higgs decays
- only small mixing angles allowed ⇨ below %-level effects



VECTOR DOUBLET

- introduced for example in composite Higgs models
- notation:

$$Q_L = \begin{pmatrix} \mathcal{T}_L \\ \mathcal{B}_L \end{pmatrix} \quad , \; Q_R = \begin{pmatrix} \mathcal{T}_R \\ \mathcal{B}_R \end{pmatrix}$$ vector doublet with Y=1/6

$t\ , T\ , b\ , B$ mass eigenstates of mass m_t, M_T, m_b, M_B

- Interaction Lagrangian:

$$-\mathcal{L}^{(d)} = -\mathcal{L}^{SM} + \beta \bar{Q}_L H d_R + B \bar{Q}_L \tilde{H} u_R + C \bar{Q}_L Q_R + \xcancel{D \bar{q}_L Q_R} + \text{h.c.}$$

$$= \begin{pmatrix} \bar{u}_L & \bar{\mathcal{T}}_L \end{pmatrix} M_t^0 \begin{pmatrix} u_R \\ \mathcal{T}_R \end{pmatrix} + \begin{pmatrix} \bar{d}_L & \bar{\mathcal{B}}_L \end{pmatrix} M_b^0 \begin{pmatrix} d_R \\ \mathcal{B}_R \end{pmatrix} + \text{h.c.}$$

VECTOR DOUBLET

- the left- and right-handed mass eigenstates of charge 2/3 and -1/3 are admixtures of $(u_L, \mathcal{T}_L)$,$(u_R, \mathcal{T}_R)$ and $(d_L, \mathcal{B}_L)$, $(d_R, \mathcal{B}_R)$
- parametrize the mixing through four angles,

$$\theta^t_L\,,\ \theta^t_R\,, \quad \theta^b_L\,,\ \theta^b_R$$

- eight physical parameters $\overset{?}{\Leftrightarrow}$ five parameters in the Lagrangian

$$-\mathcal{L}^{(d)} = -\mathcal{L}^{SM} + \beta \bar{Q}_L H d_R + B \bar{Q}_L \tilde{H} u_R + \underline{C \bar{Q}_L Q_R} + \cancel{D \bar{q}_L Q_R} + \text{h.c.}$$

$$\boxed{M^0_t(2,2) = M^0_b(2,2)} \qquad \boxed{\begin{aligned} M^0_t(1,2) &= 0 \\ M^0_b(1,2) &= 0 \end{aligned}}$$

VECTOR DOUBLET

- keep as physical parameters the four masses and the right mixing angle in the bottom sector
- θ_b^R is strongly constrained from $Z \to b\bar{b}$ observables, as it induces tree-level corrections to δg_b^R

$$\delta g_b^R = -\frac{1}{2}\sin^2\theta_b^R$$

- the oblique parameters are sensitive to the mass difference

$$\delta = M_T - M_B$$

of the heavy quarks $\Rightarrow$ they need to be almost degenerate

VECTOR DOUBLET

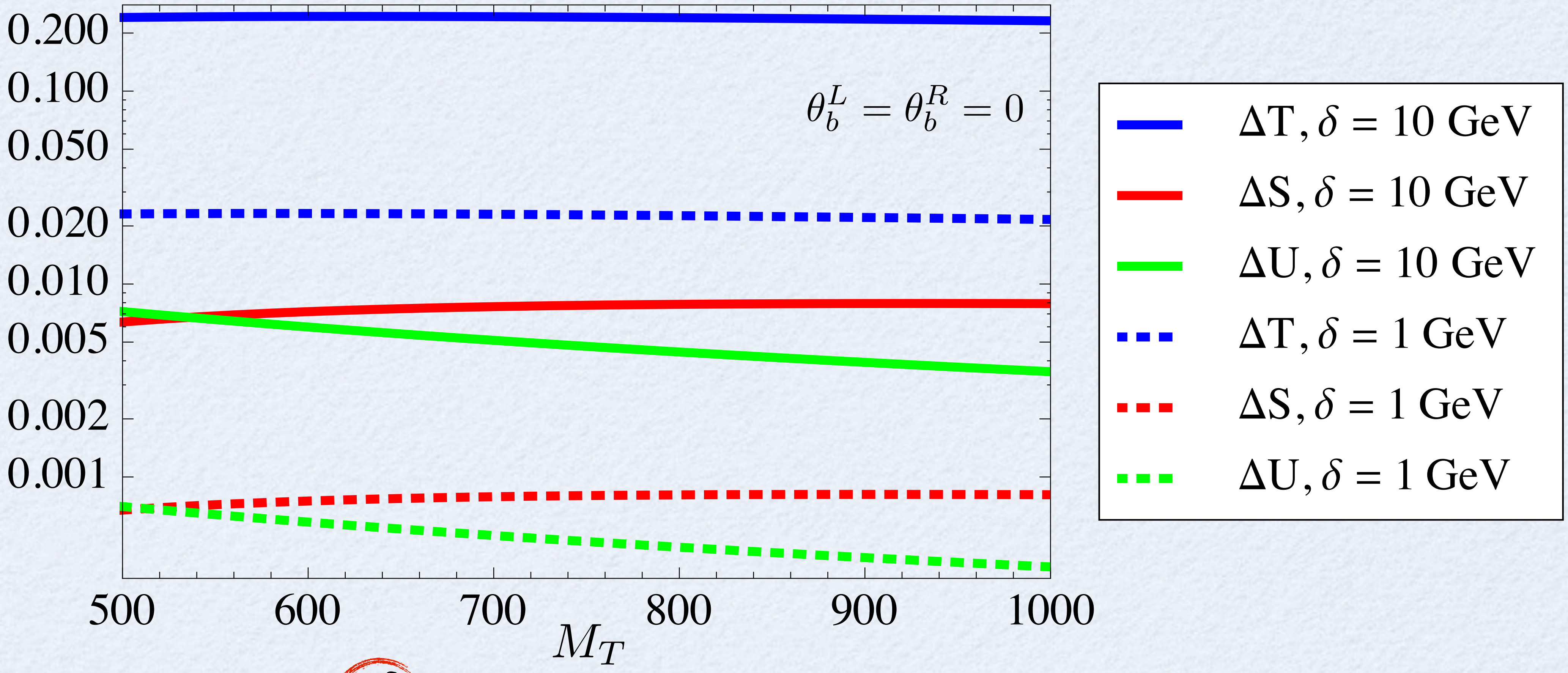
- for small mixing,

$$\sin^2\theta_L^{t,b} \sim \frac{m_{t,b}^2}{M_{T,B}^2}\sin^2\theta_R^{t,b}$$

⇨ the left mixing angles are suppressed by the heavy mass w.r.t. the right mixing angles

CONSTRAINTS: S, T, U

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



$$\Delta T_{app} = T_{SM}\boxed{\frac{4\delta}{M_T}}(2\log r - 3) \qquad (\theta_b^R = 0\,,\ m_b \to 0\,,\ r >> 1)$$

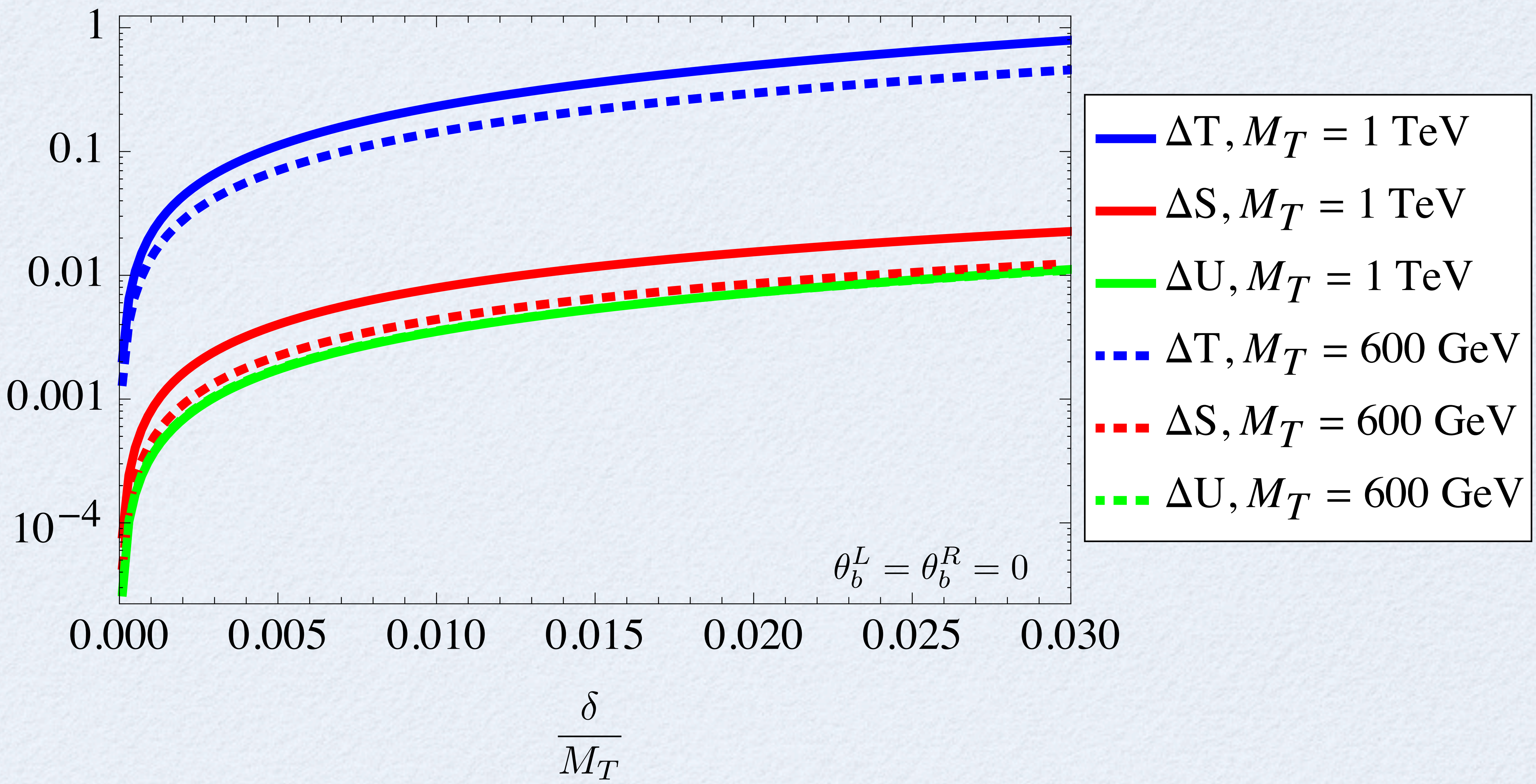
$$\Delta S_{app} = \frac{N_c}{9\pi}\boxed{\frac{\delta}{M_T}}[4\log r - 7] \quad , \qquad \Delta U_{app} = \frac{N_c}{18\pi}\boxed{\frac{3\delta}{M_T}}$$

$$\delta = M_T - M_B$$

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

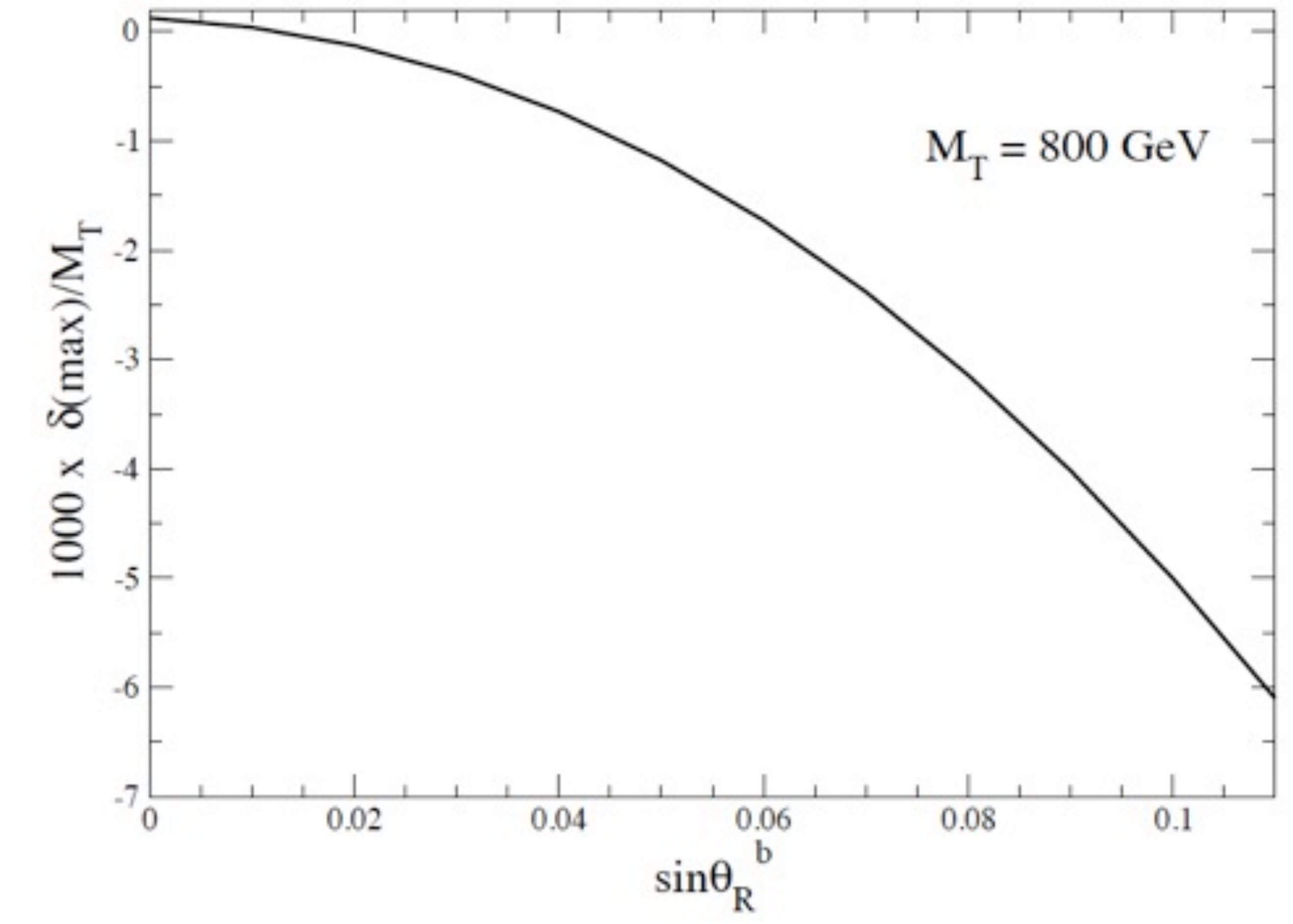
DECOUPLING

- we observe decoupling for $\frac{\delta}{M_T} \to 0$



CONSTRAINTS: $Z \to b_L \bar{b}_L$

- in the doublet model, the most stringent constraints on the parameter space come from the $Z \to b\bar{b}$ observables



$$\delta g_b^L = \frac{G_F}{\sqrt{2}} \frac{m_t^2}{8\pi} \frac{\delta}{M_T} \left(\log r - 4 + 3 \frac{\log r - 2}{r} \right)$$

HIGGS PRODUCTION

- the new quarks couple to the Higgs because of their mixing with the SM-like quarks

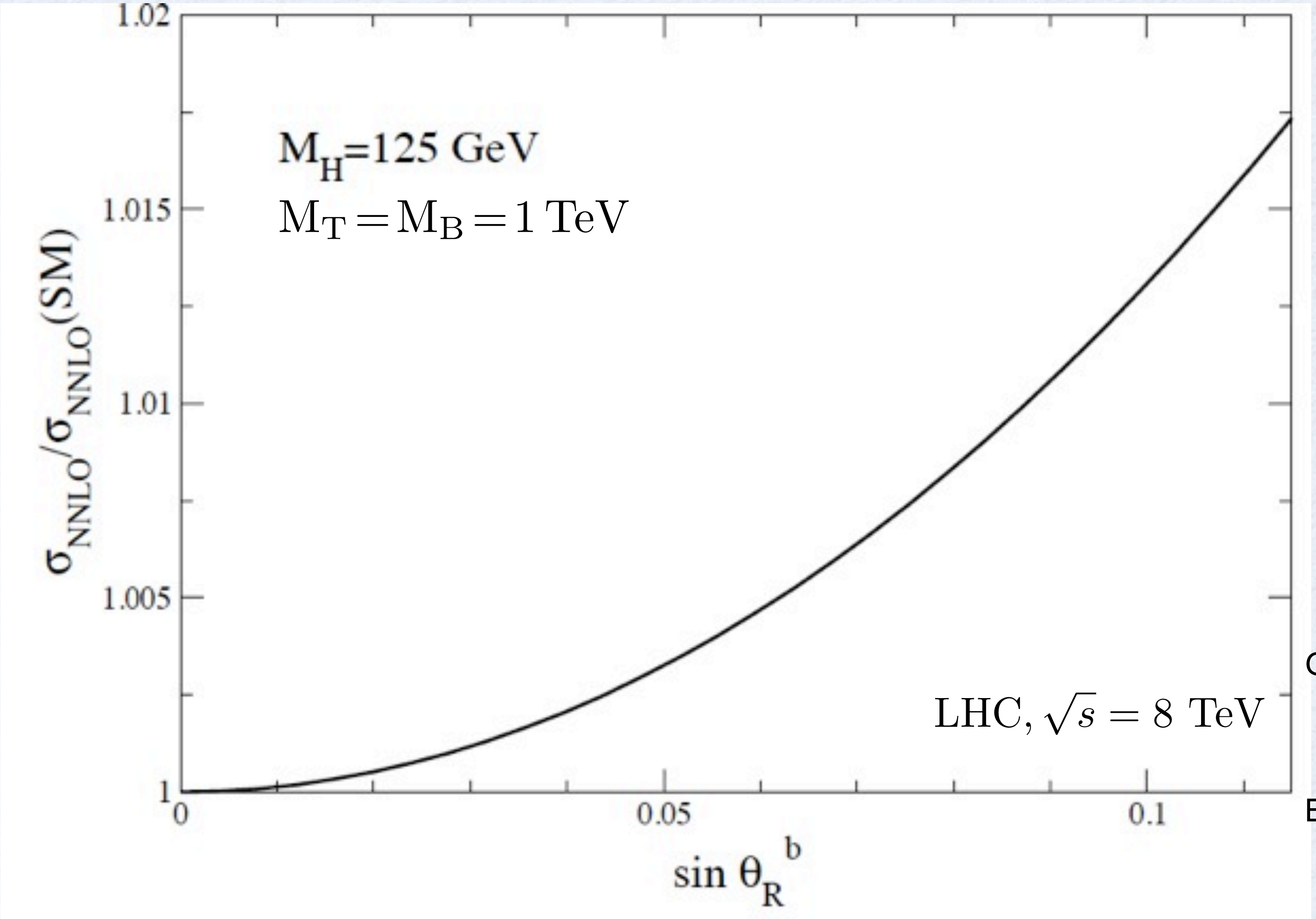
- $$Y_t = \frac{m_t}{v}\cos^2\theta_R^t \quad , \; Y_T = \frac{M_T}{v}\sin^2\theta_R^t$$
  $$Y_b = \frac{m_b}{v}\cos^2\theta_R^b \quad , \; Y_B = \frac{M_B}{v}\sin^2\theta_R^b$$

- for small mixing and mass splitting,

$$\left.\frac{\sigma^{(d)}}{\sigma^{SM}}\right|_{LO} \approx \left(1+\sin^2\theta_R^b\right)^2 < 1.03$$

HIGGS PRODUCTION

- potentially large effect, but $Z \to b\bar{b}$ observables require a small mixing angle ⇨ at most some few % effect



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Anastasiou et al., **JHEP 1112 (2011) 058**

Based on
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CONCLUSIONS

Vector singlet

- the strongest constraints on the parameter space come from the Peskin-Takeuchi parameters
- yields a positive contribution both to S and T, but

$$\Delta T >> \Delta S$$

- reduces the Higgs production cross section
    - ➡ the fit to electroweak precision observables forces this reduction to be small
    - ➡ Higgs production and decays will look the same as in the Standard Model
- decouples for $M_T \to \infty$ only if the mixing angle scales as M_T^{-1}

CONCLUSIONS

Vector doublet

- mixing in the bottom sector is strongly constrained by δg_b^R
- oblique parameters require the two heavy quarks to be almost degenerate in mass
- the mixing of the left-handed quarks is suppressed with respect to the mixing of the right-handed quarks by the heavy scale,

$$\sin^2\theta_L^q \sim \frac{m_q^2}{M_Q^2}\sin^2\theta_R^q \qquad , \; q = t, b$$

CONCLUSIONS

Vector doublet

- because of the small mixings and mass splitting allowed, deviations from the Standard Model Higgs rates are not observable
- the heavy quarks decouple for

$$\frac{M_T - M_B}{M_T} \to 0$$