Exploring top quark FCNC at hadron colliders in association with flavor physics

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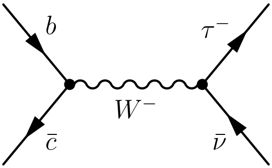
$B \to D^{(*)}\tau\nu$



$$\mathcal{R}(D) \equiv \mathcal{B}(B \to D\tau\nu)/\mathcal{B}(B \to D\ell\nu)$$

$$\mathcal{R}_{\text{exp}}(D) = 0.388 \pm 0.050 \qquad \text{BaBar + Belle}$$

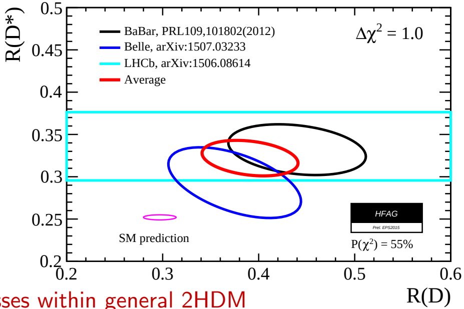
$$\mathcal{R}_{\text{SM}}(D) = 0.297 \pm 0.017 \qquad 2.2\sigma \to 1.7\sigma$$

$$\mathcal{R}(D^*) \equiv \mathcal{B}(B \to D^*\tau\nu)/\mathcal{B}(B \to D^*\ell\nu)$$

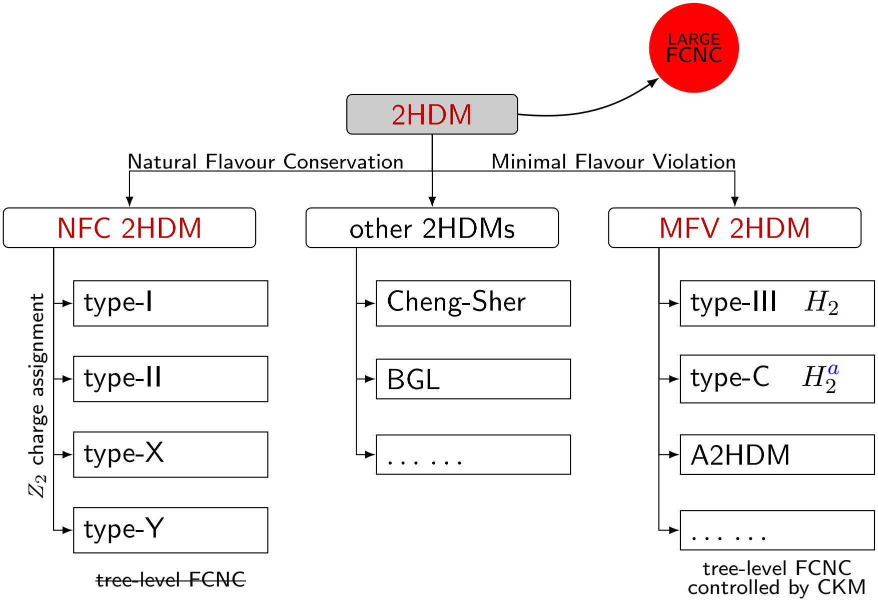
$$\mathcal{R}_{\text{exp}}(D^*) = 0.321 \pm 0.022 \qquad \text{BaBar + Belle + LHCb}$$

$$\mathcal{R}_{\text{SM}}(D^*) = 0.252 \pm 0.003 \qquad 2.7\sigma \to 3.0\sigma$$

- total discrepancy with SM: 3.9σ
- tree-level process
- SM: hadronic matrix elements
- exp: Belle II @ 50ab^{-1}
  $\sigma \approx 0.010$ for $R(D)$
  $\sigma \approx 0.005$ for $R(D^*)$
- BSM: two-Higgs doublet model



$B \to D^{(*)}\tau\nu$ and top-quark FCNC processes within general 2HDM


LARGE FCNC
2HDM
Natural Flavour Conservation
Minimal Flavour Violation
NFC 2HDM
other 2HDMs
MFV 2HDM
Z_2 charge assignment
type-I
type-II
type-X
type-Y
Cheng-Sher
BGL
... ...
type-III H_2
type-C H_2^a
A2HDM
... ...
tree-level FCNC
tree-level FCNC controlled by CKM

General 2HDM (2HDM type-III)

- Lagrangian (interaction basis)

$$-\mathcal{L}_Y = \bar{Q}_L(Y_1^d\Phi_1 + Y_2^d\Phi_2)d_R + \bar{Q}_L(Y_1^u\tilde{\Phi}_1 + Y_2^u\tilde{\Phi}_2)u_R + \bar{L}_L(Y_1^\ell\Phi_1 + Y_2^\ell\Phi_2)e_R$$

- Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \eta_1 + iG^0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\eta_2 + iA^0) \end{pmatrix}$$

- Mass eigenstate

$$\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H^0 \\ h^0 \end{pmatrix}$$

- Higgs spectrum: $H^0, h^0, A^0, H^\pm$

General 2HDM: Yukawa interaction

- Lagrangian (mass basis)

$$\mathcal{L}_{\rm Y} = \mathcal{L}_{\rm Y,\,SM} + \frac{1}{\sqrt{2}}\bar{d}\xi^d dH + \frac{1}{\sqrt{2}}\bar{u}\xi^u uH + \frac{1}{\sqrt{2}}\bar{\ell}\xi^\ell \ell H - \frac{i}{\sqrt{2}}\bar{d}\gamma_5\xi^d dA - \frac{i}{\sqrt{2}}\bar{u}\gamma_5\xi^u uA - \frac{i}{\sqrt{2}}\bar{\ell}\gamma_5\xi^\ell \ell A + \left[\bar{u}\Big(\xi^u V_{\rm CKM}P_L - V_{\rm CKM}\xi^d P_R\Big)dH^+ - \bar{\nu}\xi^\ell P_R \ell H^+ + h.c.\right]$$

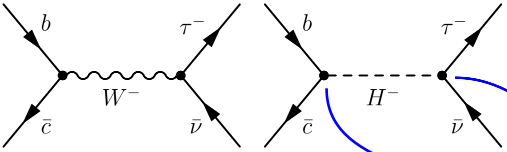
  - ▷ unitary and symmetric: $\xi \equiv \bar{Y}^{U,D,\ell} = (\bar{Y}^{U,D,\ell})^\dagger = (\bar{Y}^{U,D,\ell})^T$
  - ▷ decoupling limit (alignment limit): $\alpha = \pi/2 \Longleftarrow$ LHC Higgs data
  - ▷ Cheng-Sher ansatz: $\xi_{ij} = \lambda_{ij}\sqrt{2m_i m_j}/v, \qquad \lambda_{ij} \sim \mathcal{O}(1)$
  - ▷ small mass approximation: $m_u \approx m_d \approx m_s \approx 0$

- Yukawa coupling: control both charged and neutral currents

$$V\xi^d = \begin{pmatrix} 0 & 0 & V_{ub}\xi_{bb} \\ 0 & 0 & V_{cb}\xi_{bb} \\ 0 & 0 & V_{tb}\xi_{bb} \end{pmatrix}, \quad \xi^d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \xi_{bb} \end{pmatrix}, \quad \xi^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \xi_{cc} & \xi_{ct} \\ 0 & \xi_{ct} & \xi_{tt} \end{pmatrix},$$

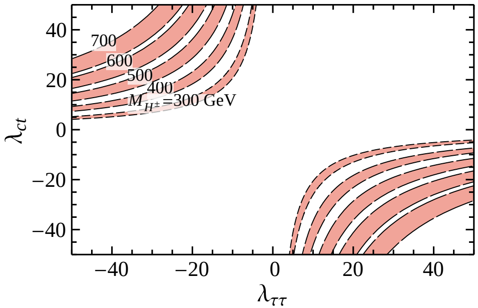
$$\xi^u V = \begin{pmatrix} 0 & 0 & 0 \\ V_{cd}\xi_{cc} + V_{td}\xi_{ct} & V_{cs}\xi_{cc} + V_{ts}\xi_{ct} & V_{tb}\xi_{ct} \\ V_{cd}\xi_{ct} + V_{td}\xi_{tt} & V_{cs}\xi_{ct} + V_{ts}\xi_{tt} & V_{cb}\xi_{ct} + V_{tb}\xi_{tt} \end{pmatrix}$$

$B \to D^{(*)}\tau\nu$ in general 2HDM



A. Crivellin, C.Greub, A.Kokulu, PRD, 2012

$\xi_{\tau\tau} P_L$



$$-\,(V\xi^D)_{23}P_R + (\xi^{U\dagger}V)_{23}P_L$$

$$= -\,(V_{cd}\xi_{db} + V_{cs}\xi_{sb} + V_{cb}\xi_{bb})P_R$$

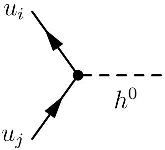
$$+\,(\xi^\dagger_{cu}V_{ub} + \xi^\dagger_{cc}V_{cb} + \xi^\dagger_{ct}V_{tb})P_L$$

$$\xi_{ct} = \lambda_{ct}\frac{\sqrt{2m_c m_t}}{v}, \quad \xi_{\tau\tau} = \lambda_{\tau\tau}\frac{\sqrt{2}m_\tau}{v}$$

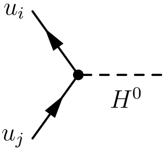
$$-750 < \frac{\lambda_{ct}\lambda_{\tau\tau}}{(m_{H^\pm}/500\,\mathrm{GeV})^2} < -575$$

① $\lambda_{\tau\tau} \gg 1$: $gg \to H/A \to \tau\tau$
② $\lambda_{\tau\tau} \ll 1$: $\lambda_{ct} \gg 1$

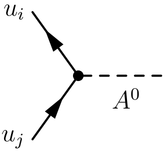
Higgs FCNC in general 2HDM



$\sim -\sin\alpha\lambda_u\delta_{ij} + \cancel{\cos\alpha\xi^U_{ij}}$ $\qquad$ $\cancel{t \to ch}$



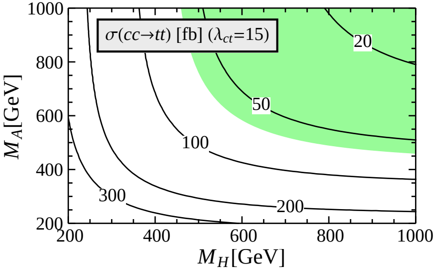
$\sim +\cancel{\cos\alpha\lambda_u\delta_{ij}} + \sin\alpha\xi^U_{ij}$ $\qquad$ $H \to t\bar{c}$

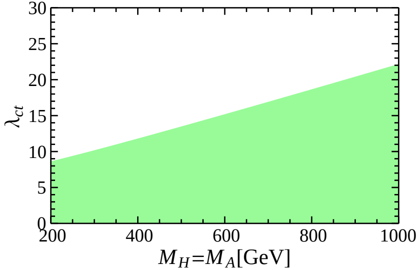


$\sim +\xi^U_{ij}$ $\qquad$ $A \to t\bar{c}$ or $t \to cA$

LHC Higgs data $\Longrightarrow$ decoupling limit $\alpha = \pi/2$

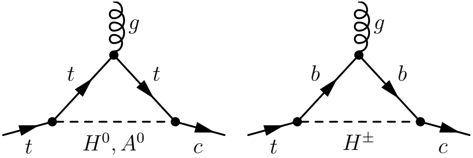
Higgs FCNC in general 2HDM: $cc \to tt$



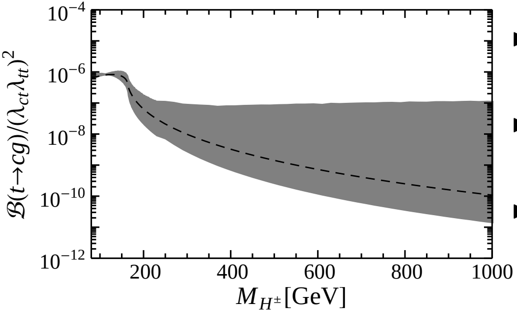


- tree-level u- and t- channel with exchange of H or A
- $\sigma(cc \to tt) \propto \lambda_{ct}^4$
- $\sigma(cc \to tt) = \int_\tau^1 dx \hat{\sigma}(xs) f_{cc}(x, \mu_F)$
  MSTW2008LO PDF
- processes with extra jet radiation are assumed to be subleading
- $\sigma(pp \to tt) < 62\,\mathrm{fb}$
  ATLAS 20.3 fb^{-1} @8 TeV
  largest in various helicity configuration of contact interaction models
- green region: allowed by exp

Higgs FCNC in general 2HDM: $t \to cg$



$\propto \lambda_{ct}\lambda_{tt}$



- dashed line:
  $m_{H^\pm} = m_A = m_H$
- dark region:
  $m_{H^\pm}, m_A, m_H$ constrained by $\Delta\rho$
- $\mathcal{B}(t \to cg)_{\text{exp}} < 1.6 \times 10^{-4}$
  single top production
  ATLAS 14.2 fb^{-1} @8 TeV

General 2HDM: experimental constraints

- 2HDM parameters

  $m_{H^\pm} \in [80, 1000]\,\mathrm{GeV}, \quad m_H \in [125, 1000]\,\mathrm{GeV}, \quad m_A \in [93, 1000]\,\mathrm{GeV}$

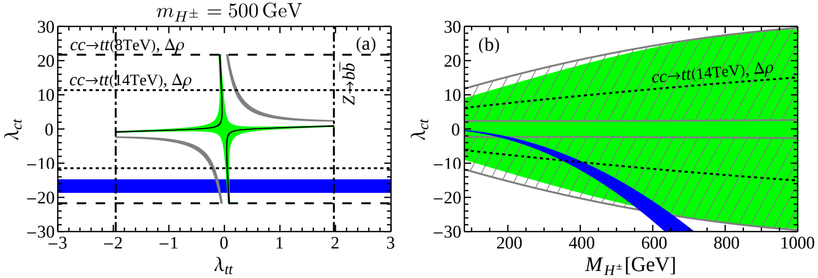
  $\lambda_{\tau\tau}, \lambda_{ct}, \lambda_{tt}, \lambda_{bb} \in [-50, +50] \qquad m_h = 125\,\mathrm{GeV}$

- Flavor physics
  - tree-level: $B \to D^{(*)}\tau\nu$, $B \to \tau\nu$
  - loop-level: $B \to X_s\gamma$ ($\Longrightarrow \lambda_{bb} \approx 0$), $B_s - \bar{B}_s$ mixing

- Electro-Weak precision measurement
  - $\Delta\rho$ ($\Longrightarrow |m_{H,A} - m_{H^\pm}|$), $Z \to b\bar{b}$

- Collider processes
  - $gg \to H/A \to \tau\tau$
  - $t \to cg$
  - $cc \to tt$

Parameter space: combined constraints ($\lambda_{\tau\tau} = 40$)

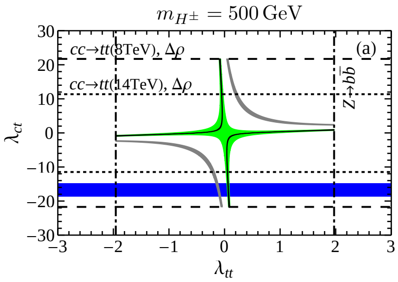


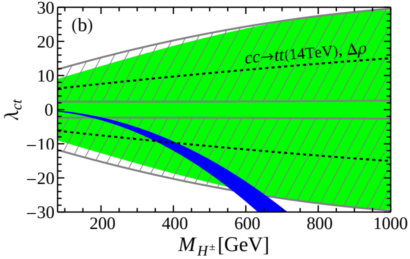
- $B \to D^{(*)}\tau\nu$, $\lambda_{\tau\tau} = 40$ is fixed
- Δm_s: fine-tuning $< 10\%$, bound on λ_{ct} as strong as $cc \to tt$
- Δm_s: fine-tuning $> 10\%$, $A_u \approx 0$
- Δm_s: fine-tuning $> 10\%$, $\mathrm{Re}C^{\mathrm{VLL}}_{1,WH} + \mathrm{Re}C^{\mathrm{VLL}}_{1,HH} \approx 0$, large $\mathrm{Im}M^s_{12}$

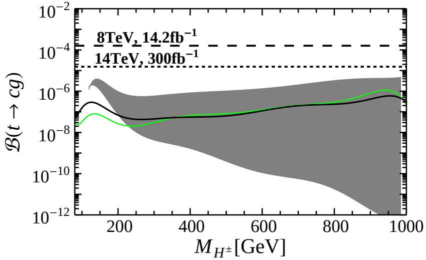
$$C^{\mathrm{VLL}}_{1,WH} \propto A_u, \qquad A_u = \left(\frac{V_{cs}}{V_{ts}}\sqrt{\frac{m_c}{m_t}}\lambda_{ct} + \lambda_{tt}\right)\left(\frac{V^*_{cb}}{V^*_{tb}}\sqrt{\frac{m_c}{m_t}}\lambda_{ct} + \lambda_{tt}\right)$$

$$C^{\mathrm{VLL}}_{1,HH} \propto A_u^2, \qquad \approx (0.004\lambda_{ct} + \lambda_{tt})[(-2.14 + 0.04i)\lambda_{ct} + \lambda_{tt}]$$

$t \to cg$ in general 2HDM

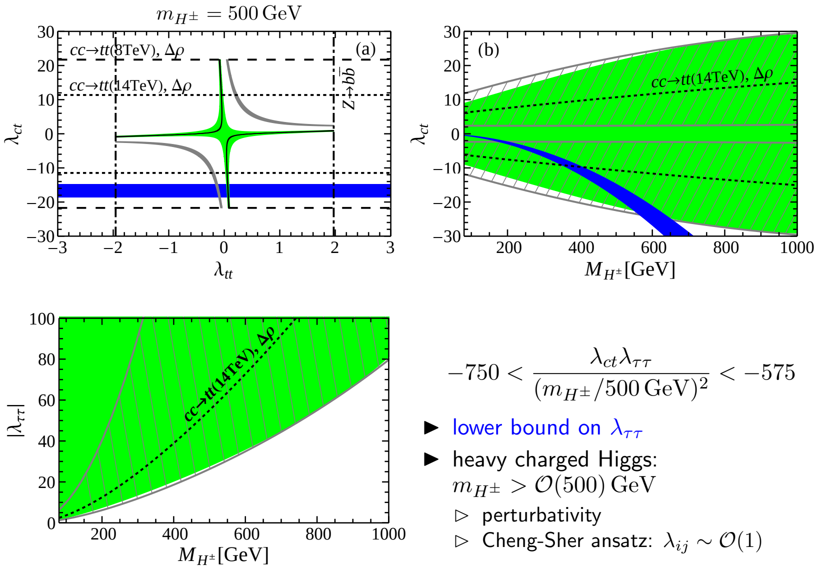






$$\lambda_{ct}\lambda_{tt} < \mathcal{O}(5) \quad ☹$$

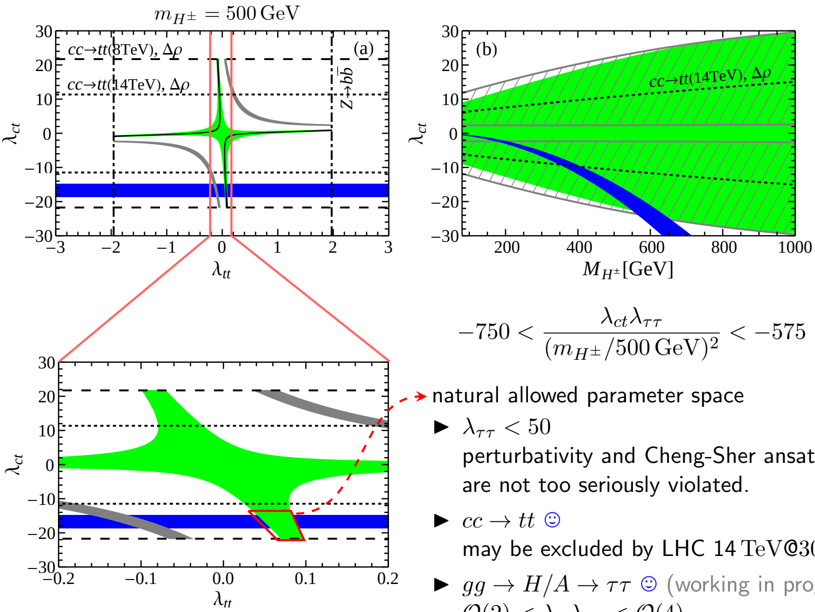
Parameter space: lower bound on $\lambda_{\tau\tau}$



$$-750 < \frac{\lambda_{ct}\lambda_{\tau\tau}}{(m_{H^\pm}/500\,\mathrm{GeV})^2} < -575$$

- lower bound on $\lambda_{\tau\tau}$
- heavy charged Higgs: $m_{H^\pm} > \mathcal{O}(500)\,\mathrm{GeV}$
  - ▷ perturbativity ☹
  - ▷ Cheng-Sher ansatz: $\lambda_{ij} \sim \mathcal{O}(1)$ ☹

Parameter space: natural region



$$-750 < \frac{\lambda_{ct}\lambda_{\tau\tau}}{(m_{H^\pm}/500\,\mathrm{GeV})^2} < -575$$

→ natural allowed parameter space

- $\lambda_{\tau\tau} < 50$
  perturbativity and Cheng-Sher ansatz are not too seriously violated.
- $cc \to tt$ ☺
  may be excluded by LHC 14 TeV@300 fb^{-1}
- $gg \to H/A \to \tau\tau$ ☺ (working in progress)
  $\mathcal{O}(2) < \lambda_{tt}\lambda_{\tau\tau} < \mathcal{O}(4)$

Conclusion

- The current $B \to D^{(*)}\tau\nu$ anomaly can be explained within the general two-Higgs doublet model under Cheng-Sher ansatz, which indicates large $\lambda_{\tau\tau}$ or λ_{ct} Yukawa coupling

$$\text{current } R(D^{(*)}) \text{ data} \Longrightarrow -750 < \frac{\lambda_{ct}\lambda_{\tau\tau}}{(m_{H^\pm}/500\,\text{GeV})^2} < -575$$

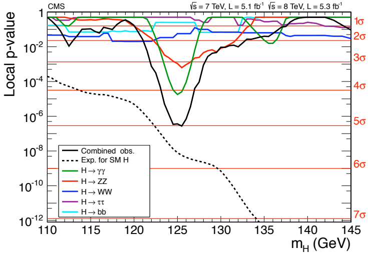
- We investigate various low and high energy processes and obtain allowed parameter space by the current exp data.

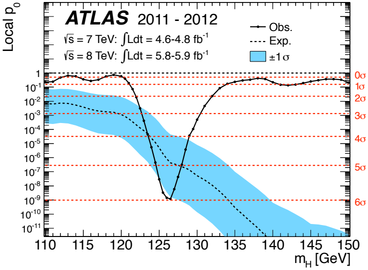
- We find the allowed parameter space can be probed at LHC by the following processes
  - $gg \to H/A \to \tau\tau$ ☺ $\Longleftarrow \mathcal{O}(2) < \lambda_{tt}\lambda_{\tau\tau} < \mathcal{O}(4)$
  - $t \to cg$ ☹ $\Longleftarrow \lambda_{ct}\lambda_{tt} < \mathcal{O}(5) \Longleftarrow B_s - \bar{B}_s$ mixing
  - $cc \to tt$ ☺ $\Longleftarrow \sigma(cc \to tt) \propto \lambda_{ct}^4$

Thank You !

Backup

Higgs discovery





- mass: $m_h = 126\,\mathrm{GeV}$ ☺
- spin ☺
- party ☺
- Yukawa coupling ☺
- gauge coupling ☺

Higgs After the Discovery

Question

This boson is the only one fundamental scalar just as the SM, or belongs to an extended scalar sector responsible to the electroweak symmetry breaking ?

Possible Answer

Two-Higgs Doublet Model (2HDM)

General 2HDM: Yukawa interaction

- Lagrangian (mass basis)

$$-\mathcal{L}_Y = (\bar{u}, \bar{d}) M^q \begin{pmatrix} u \\ d \end{pmatrix} + (\bar{\nu}, \bar{e}) M^\ell \begin{pmatrix} \nu \\ e \end{pmatrix}$$

- Quark sector

$$M^q = M_m + M_H^d + M_H^n + M_G$$
$$M_H^d = \frac{1}{\sqrt{2}} \begin{pmatrix} \lambda_u \eta_1 & 0 \\ 0 & \lambda_d \eta_1 \end{pmatrix}$$
$$M_H^n = \begin{pmatrix} \frac{1}{\sqrt{2}}\eta_2(\bar{Y}^U P_R + \bar{Y}^{U\dagger} P_L) - \frac{i}{\sqrt{2}} A^0 (\bar{Y}^U P_R - \bar{Y}^{U\dagger} P_L), & H^+(V\bar{Y}^D P_R - \bar{Y}^{U\dagger} V P_L) \\ H^-(-V^\dagger \bar{Y}^U P_R + \bar{Y}^{D\dagger} V^\dagger P_L), & \frac{1}{\sqrt{2}}\eta_2(\bar{Y}^D P_R + \bar{Y}^{D\dagger} P_L) + \frac{i}{\sqrt{2}} A^0 (\bar{Y}^D P_R - \bar{Y}^{D\dagger} P_L) \end{pmatrix}$$

- Lepton sector

$$M^\ell = M_e + M_H^d + M_H^n + M_G$$
$$M_H^d = \frac{1}{\sqrt{2}} \lambda_e \eta_1$$
$$M_H^n = \begin{pmatrix} 0 & H^+ \bar{Y}_2^\ell P_R \\ H^- \bar{Y}_2^{\ell\dagger} P_L & \frac{1}{\sqrt{2}}\eta_2(\bar{Y}_2^\ell P_R + \bar{Y}_2^{\ell\dagger} P_L) + \frac{i}{\sqrt{2}} A^0 (\bar{Y}_2^\ell P_R - \bar{Y}_2^{\ell\dagger} P_L) \end{pmatrix}$$

General 2HDM: assumption on the Yukawa coupling

1. unitary and symmetric

$$\xi \equiv \bar{Y}^{U,D,\ell} = (\bar{Y}^{U,D,\ell})^\dagger = (\bar{Y}^{U,D,\ell})^T$$

2. Cheng-Sher ansatz

$$\xi_{ij} = \lambda_{ij} \frac{\sqrt{2 m_i m_j}}{v} \qquad \lambda_{ij} \sim \mathcal{O}(1)$$

3. small mass approximation

$$m_u = m_d = m_s = 0$$

General 2HDM: assumption on the Yukawa coupling

- couplings with neutral Higgs h, H, A

$$\xi^D = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \xi_{bb} \end{pmatrix} \qquad \xi^U = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \xi_{cc} & \xi_{ct} \\ 0 & \xi_{ct} & \xi_{tt} \end{pmatrix}$$

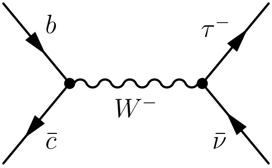
- couplings with charged Higgs $H^\pm$

$$V\xi^D = \begin{pmatrix} 0 & 0 & V_{ub}\xi_{bb} \\ 0 & 0 & V_{cb}\xi_{bb} \\ 0 & 0 & V_{tb}\xi_{bb} \end{pmatrix}$$

$$\xi^U V = \begin{pmatrix} 0 & 0 & 0 \\ V_{cd}\xi_{cc} + V_{td}\xi_{ct} & V_{cs}\xi_{cc} + V_{ts}\xi_{ct} & V_{tb}\xi_{ct} \\ V_{cd}\xi_{ct} + V_{td}\xi_{tt} & V_{cs}\xi_{ct} + V_{ts}\xi_{tt} & V_{cb}\xi_{ct} + V_{tb}\xi_{tt} \end{pmatrix}$$

- connection charged and neutral

Basic Idea: $B \to D^{(*)}\tau\nu$



$$\mathcal{R}(D) \equiv \mathcal{B}(B \to D\tau\nu)/\mathcal{B}(B \to D\ell\nu)$$

$\mathcal{R}_{\text{exp}}(D) = 0.391 \pm 0.050$ BaBar + Belle

$\mathcal{R}_{\text{SM}}(D) = 0.297 \pm 0.017$ $2.2\sigma \to 1.7\sigma$

$$\mathcal{R}(D^*) \equiv \mathcal{B}(B \to D^*\tau\nu)/\mathcal{B}(B \to D^*\ell\nu)$$

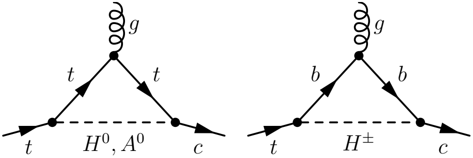
$\mathcal{R}_{\text{exp}}(D^*) = 0.322 \pm 0.022$ BaBar + Belle + LHCb

$\mathcal{R}_{\text{SM}}(D^*) = 0.252 \pm 0.003$ $2.7\sigma \to 3.0\sigma$

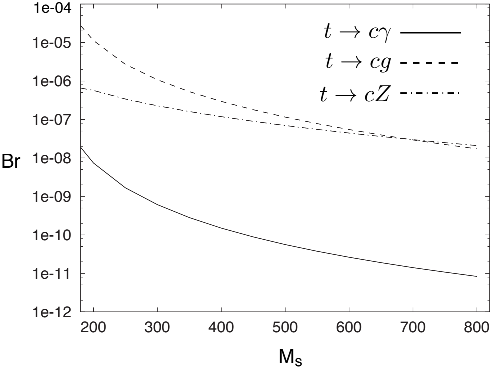
- total discrepancy with SM: 3.9σ
- SM: hadronic matrix elements
- BSM: A widely studied possibility is 2HDM, since the charged Higgs couples proportionally to the masses of the fermions involved in the interaction.

▷ NFC 2HDM ☹
▷ MFV 2HDM ☹
▷ General 2HDM ☺

$t \to cg$ in general 2HDM



$\sim \xi^U_{ct}\xi^U_{tt}$



$M_S = m_{A^0} = m_{H^0} = m_{H^+} = 700\,\text{GeV}$

$$\mathcal{B}(t \to cg) = \left(\frac{\xi^U_{ct}}{0.06}\frac{\xi^U_{tt}}{0.7}\right)^2 \times 10^{-7}$$

$$\approx (\xi^U_{tt})^2 \times 10^{-3} \qquad (\xi^U_{ct} = 5)$$

$$\mathcal{B}(t \to cg)_{\text{exp}} < 1.6 \times 10^{-4}$$

D.Atwood, L.Reina, A.Soni, PRD,1997

Parameter space: $R(D)$ and $R(D^*)$

- Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = C_{\text{VLL}}\mathcal{O}_{\text{VLL}} + C_{\text{SRL}}\mathcal{O}_{\text{SRL}} + C_{\text{SLL}}\mathcal{O}_{\text{SLL}}$$

- Operator

$$\mathcal{O}_{\text{VLL}} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) \qquad C_{\text{VLL}}^{\text{SM}} = \frac{4G_F V_{cb}}{\sqrt{2}}$$

$$\mathcal{O}_{\text{SRL}} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau) \qquad C_{\text{SRL}}^{\text{SM}} = 0$$

$$\mathcal{O}_{\text{SLL}} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau) \qquad C_{\text{SLL}}^{\text{SM}} = 0$$

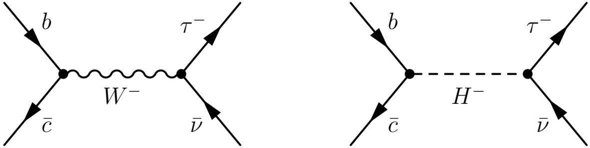
- in the case of no NP effects on $\mathcal{O}_{\text{VLL}}$

$$R(D) = R_{\text{SM}}(D)\left(1 + 1.5\text{Re}\left[\frac{C_{\text{SRL}} + C_{\text{SLL}}}{C_{\text{VLL}}^{\text{SM}}}\right] + 1.0\left|\frac{C_{\text{SRL}} + C_{\text{SLL}}}{C_{\text{VLL}}^{\text{SM}}}\right|^2\right)$$

$$R(D^*) = R_{\text{SM}}(D^*)\left(1 + 0.12\text{Re}\left[\frac{C_{\text{SRL}} - C_{\text{SLL}}}{C_{\text{VLL}}^{\text{SM}}}\right] + 0.05\left|\frac{C_{\text{SRL}} - C_{\text{SLL}}}{C_{\text{VLL}}^{\text{SM}}}\right|^2\right)$$

Parameter space: $R(D)$ and $R(D^*)$

- Feynman diagram



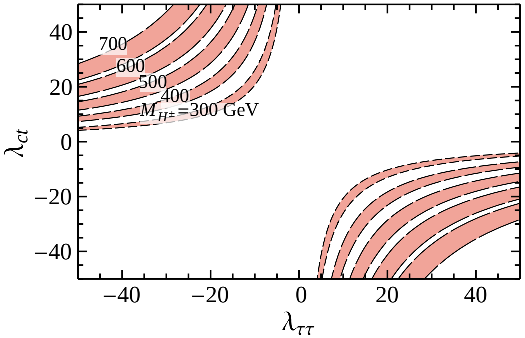
- Relevant Yukawa interaction

$$-\Delta\mathcal{L}_Y = -V_{tb}\xi_{ct}\bar{c}P_L bH^+ + V_{cb}\xi_{bb}\bar{c}P_R bH^+ + \xi_{\tau\tau}\bar{\nu}_\tau P_R \tau H^+ + h.c.$$

- G2HDM contributions

$$C_{\mathrm{VLL}}^{\mathrm{G2HDM}} = 0 \qquad C_{\mathrm{SRL}}^{\mathrm{G2HDM}} = -\frac{V_{cb}\xi_{bb}\xi_{\tau\tau}}{m_{H^\pm}^2} \qquad C_{\mathrm{SLL}}^{\mathrm{G2HDM}} = \frac{V_{tb}\xi_{ct}\xi_{\tau\tau}}{m_{H^\pm}^2}$$

Parameter space: $R(D)$ and $R(D^*)$



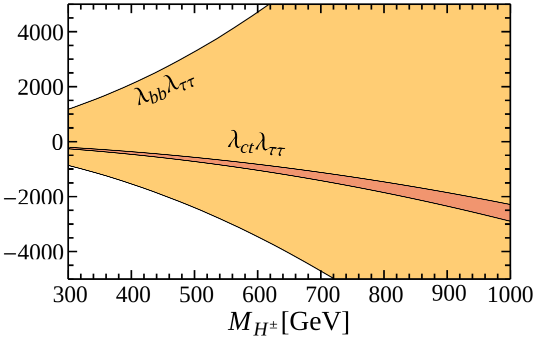
- $\lambda_{ct} \sim \mathcal{O}(10)$
- $\lambda_{\tau\tau} \gg 1$: $H/A \to \tau\tau$
- $\lambda_{\tau\tau} \ll 1$: $t \to cg$?

Parameter space: $B \to \tau\nu$

- Effective Hamiltonian: similar to $B \to D^{(*)}\tau\nu$
- G2HDM contributions

$$C_{\rm VLL}^{\rm G2HDM} = 0 \qquad C_{\rm SRL}^{\rm G2HDM} = 0 \qquad C_{\rm SLL}^{\rm G2HDM} = \frac{V_{ub}\xi_{bb}\xi_{\tau\tau}}{m_{H^\pm}^2}$$

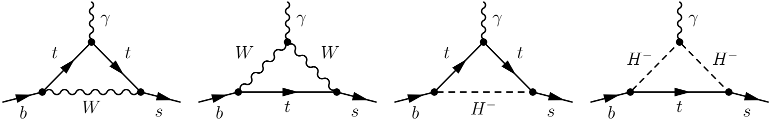
Parameter space: tree-level flavor processes



$$-0.0030 < \frac{\lambda_{ct}\lambda_{\tau\tau}}{m_{H^\pm}^2} < -0.0023$$

Parameter space: $B \to X_s\gamma$

- Feynman Diagram



- Relevant Yukawa interaction

$$-\Delta\mathcal{L}_Y = +V_{tb}\bar{t}(\xi_{bb}P_R - (\xi_{tt} + V_{cb}/V_{tb}\xi_{ct})P_L)bH^+ - \bar{t}(V_{cs}\xi_{ct} + V_{ts}\xi_{tt})P_L s H^+$$

- Branching ratio

$$\mathcal{B}(B \to X_s\gamma) \times 10^{-4} = (3.36 \pm 0.23) - 8.22 C_7^{\rm NP} - 1.99 C_8^{\rm NP}$$

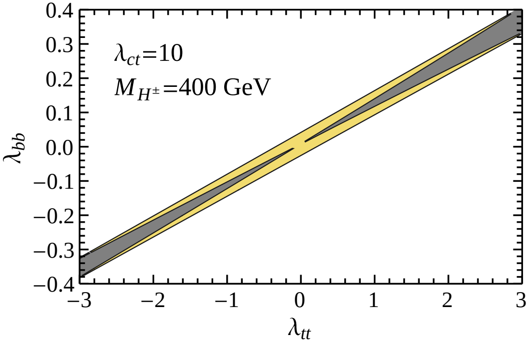
- G2HDM contributions

$$C_{7,8}^{\rm 2HDM} = \frac{1}{3}\lambda_s^* F_{7,8}^{(1)}(x_W) - \kappa_s^* F_{7,8}^{(2)}(x_W)$$

$$\lambda_s = \left(\frac{V_{cs}}{V_{ts}}\sqrt{\frac{m_c}{m_t}}\lambda_{ct} + \lambda_{tt}\right)\left(\frac{V_{cb}^*}{V_{tb}^*}\sqrt{\frac{m_c}{m_t}}\lambda_{ct} + \lambda_{tt}\right) \approx (0.004\lambda_{ct} + \lambda_{tt})[(-2.14 + 0.04i)\lambda_{ct} + \lambda_{tt}]$$

$$\kappa_s = \left(\frac{V_{cs}}{V_{ts}}\sqrt{\frac{m_c}{m_t}}\lambda_{ct} + \lambda_{tt}\right)\lambda_{bb} \approx \lambda_{bb}[(-2.14 + 0.04i)\lambda_{ct} + \lambda_{tt}]$$

Parameter space: $B \to X_s\gamma$



$\lambda_{bb} < \mathcal{O}(0.1)$

Parameter space: $B_s - \bar{B}_s$ mixing

- Effective Hamiltonian in the SM

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{16\pi^2} M_W (V_{tb}^* V_{ts})^2 C_1^{\text{VLL}}(\mu) Q_1^{\text{VLL}} + h.c.$$

- Four-quark operators

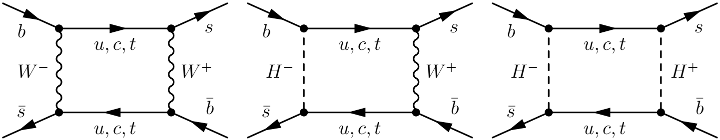
$$Q_1^{\text{VLL}} = (\bar{b}^\alpha \gamma_\mu P_L s^\alpha)(\bar{b}^\beta \gamma^\mu P_L s^\beta)$$

- off-diagonal matrix element

$$\begin{aligned} M_{12} &= \frac{1}{2M_{B_s}} \langle \bar{B}_s | \mathcal{H}_{\text{eff}} | B_s \rangle \\ &= \frac{1}{2M_{B_s}} \frac{G_F}{16\pi^2} M_W^2 (V_{tb}^* V_{ts})^2 C_1^{\text{VLL}}(\mu) \langle \bar{B}_s | Q_1^{\text{VLL}} | B_s \rangle (\mu) \end{aligned}$$

Parameter space: $B_s - \bar{B}_s$ mixing

- Feynman Diagram



- Relevant Yukawa interaction

$$-\Delta\mathcal{L}_Y = +V_{tb}\bar{t}(\xi_{bb}P_R - (\xi_{tt} + V_{cb}/V_{tb}\xi_{ct})P_L)bH^+ - \bar{t}(V_{cs}\xi_{ct} + V_{ts}\xi_{tt})P_L sH^+$$

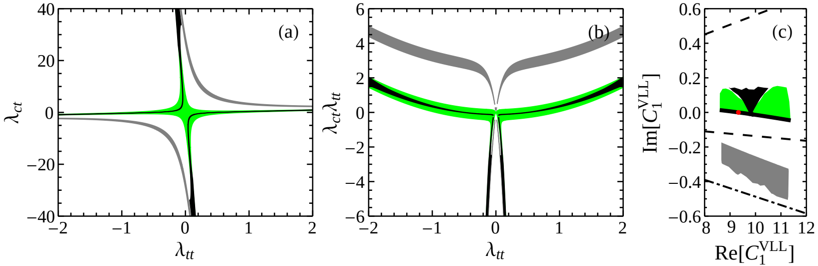
- G2HDM contributions

$$C_1^{\mathrm{VLL}}(WH) = +2\lambda_s x_W x_{H^\pm}\left(+\frac{-4+x_W}{(x_{H^\pm}-1)(x_W-1)} + \frac{(x_W - 4x_{H^\pm})\log x_{H^\pm}}{(x_{H^\pm}-1)^2(x_{H^\pm}-x_W)} + \frac{3x_W \log x_W}{(x_W-1)^2(x_{H^\pm}-x_W)}\right)$$

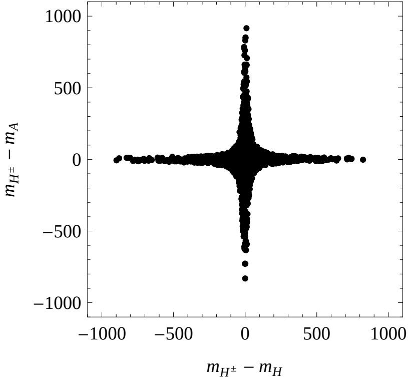
$$C_1^{\mathrm{VLL}}(HH) = +\lambda_s^2 x_W x_{H^\pm}\left(+\frac{x_{H^\pm}+1}{(x_{H^\pm}-1)^2} - \frac{2x_{H^\pm}\log x_{H^\pm}}{(x_{H^\pm}-1)^3}\right)$$

$$C_1^{\mathrm{SRR}}(HH) = +4\kappa_s^2 x_{H^\pm}^2\left(\frac{m_b^2}{m_W^2}\right)\left(+\frac{2}{(x_{H^\pm}-1)^2} - \frac{(x_{H^\pm}+1)\log x_{H^\pm}}{(x_{H^\pm}-1)^3}\right)$$

Parameter space: $B_s - \bar{B}_s$ mixing



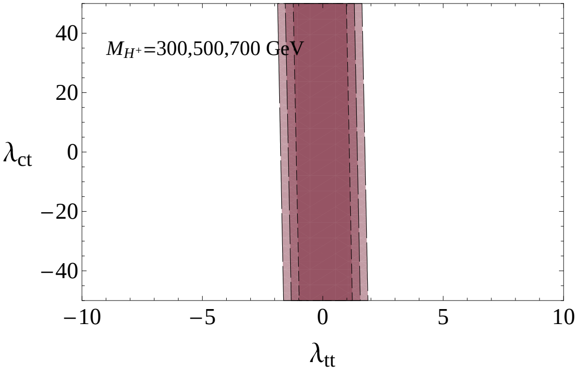
Parameter space: oblique parameter T



- $80\,\mathrm{GeV} < m_{H^\pm} < 1000\,\mathrm{GeV}$
- $m_h < m_H < 1000\,\mathrm{GeV}$
- $1\,\mathrm{GeV} < m_A < 1000\,\mathrm{GeV}$

Higgs mass splittings are highly bounded.

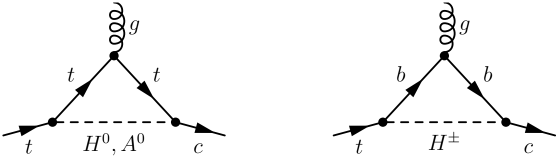
Parameter space: $R(Z \to b\bar{b})$



$|\lambda_{tt}| < 2$

$t \to cg$ in 2HDM

- Feynman diagram



- Relevant Yukawa interaction

$$
\begin{aligned}
-\Delta\mathcal{L}_Y = &+ \frac{1}{\sqrt{2}} c_\alpha \xi_{ct} \bar{c} t h + \frac{1}{\sqrt{2}} s_\alpha \xi_{ct} \bar{c} t H - \frac{i}{\sqrt{2}} \xi_{ct} \bar{c} \gamma_5 t A + h.c. \\
&+ \frac{1}{\sqrt{2}} (-s_\alpha \lambda_t + c_\alpha \xi_{tt}) \bar{t} t h - \frac{i}{\sqrt{2}} \xi_{tt} \bar{t} \gamma_5 t A \\
&+ \frac{1}{\sqrt{2}} (+c_\alpha \lambda_t + s_\alpha \xi_{tt}) \bar{t} t H \\
&+ V_{tb} \bar{t} (\xi_{bb} P_R - (\xi_{tt} + V_{cb}/V_{tb} \xi_{ct}) P_L) b H^+ + h.c.
\end{aligned}
$$

$t \to cg$ in 2HDM

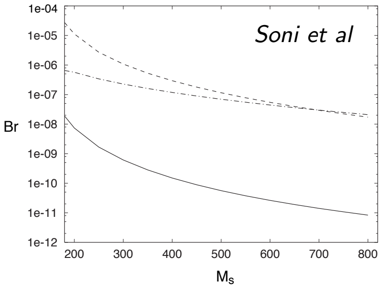
- tcg form factor

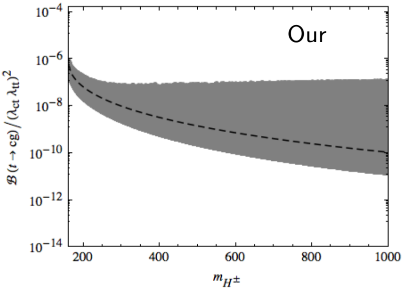
$$\mathcal{L} = \frac{1}{16\pi^2}\bar{c}\left(A\gamma^\mu + B\gamma^\mu\gamma_5 + iC\sigma^{\mu\nu}\frac{q_\nu}{m_t} + iD\sigma^{\mu\nu}\frac{q_\nu}{m_t}\gamma_5 - A\frac{m_t}{q^2}q^\mu + B\frac{m_t}{q^2}\gamma_5 q^\mu\right) t g^a_\mu T^q$$

- Decay width

$$\Gamma(t \to cg) = \frac{1}{(16\pi^2)^2}\frac{1}{8\pi}m_t C_F(|C|^2 + |D|^2)$$

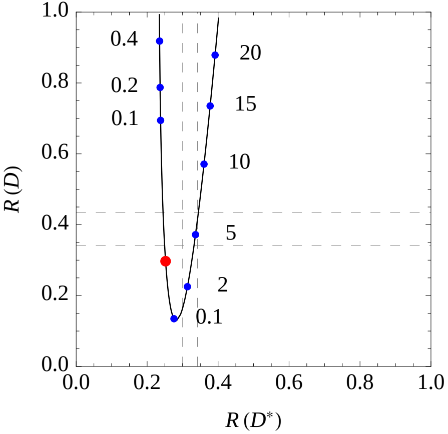
- Same expressions but different numerical results ☹



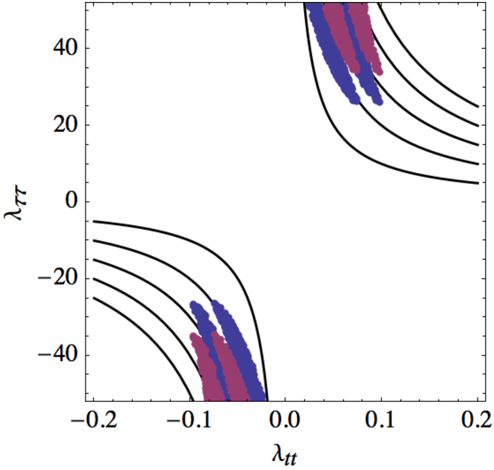


$cc \to tt$ in 2HDM

- t-channel tree-level process mediated with H and A



combined allowed region: $(\lambda_{tt}, \lambda_{\tau\tau})$ plane



Lines: $\lambda_{tt}\lambda_{\tau\tau} = 1 \ldots 5$

fine tuning measure

$$\Delta = \frac{\max(\delta Q_i)}{Q}$$

H.Baer, V.Barger, P.Huang, A.Mustafayev, X.Tata, PRL, 2012

future LHC sensitivity

assuming the statistical error is dominant
S.Jung, J.D.Wells, PRD 2014
A.Djouadi, L.Maiani, A.Polosa, J.Quevillon, V.Riquer, JHEP, 2015

$$\frac{(\text{significance})_i}{(\text{significance})_j} = \sqrt{\frac{\sigma_{S_i}\mathcal{L}_i}{\sigma_{S_j}\mathcal{L}_j}}$$