# Charged Higgs boson decays with NLO corrections in the NMSSM

[Thi Nhung Dao, Margarete Mühlleitner, Shruti Patel, KS, Eur.Phys.J.C 81 (2021) 4, 340]

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Charged Higgs@LHC, online

# Introduction

- Supersymmetry: hierarchy problem, gauge coupling unification, dark matter, etc.
- The current LHC experiment data:
    - No SUSY particles have been found.
    - The discovered Higgs boson (125 GeV) behaves very SM-like.

    →The properties will be precisely measured in the future collider experiments such as HL-LHC, ILC, CEPC, FCC-ee.

# Introduction

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      →The properties will be precisely measured in the future collider experiments such as HL-LHC, ILC, CEPC, FCC-ee.

- This requires that theoretical predictions are evaluated accurately.
    - SUSY loop corrections to observables for the Higgs boson may be significant.
    - Not only the discovered Higgs boson but also extra Higgs boson should be precisely calculated.
        - Direct searches at LHC
        - Discrimination of NP models when extra Higgs is discovered.

→ While there are a lot of works for the precise calculations in MSSM, we study next-to minimal supersymmetric model (NMSSM).

# Precise calculations of Higgs bosons

Many studies of precise calculations of Higgs bosons have been performed in the NMSSM.

- Higgs boson masses
  - ( Full 1-loop ) [G. Degrassi, P. Slavich, NPB 825 (2010)], etc.
  - ( $O(\alpha_t \alpha_S, \alpha_t^2)$ 2-loop ) [M. Mühlleitner, D. T. Nhung, H. Rzehak, K. Walz, JHEP05(2015)] [T.N. Dao, R. Gröber, M. Krause, M. Mühlleitner, H. Rzehak], etc.
  - ( $O((\alpha_t + \alpha_\lambda + \alpha_t)^2)$ 2-loop ) [T. N. Dao, M. Gabelmann, M. Mühlleitner, H. Rzehak, 2106.06990]

- Higgs boson decays
  - $H_i, A_i \to ff,\ VV$ ( Full 1-loop ) [F. Domingo, S. Heinemeyer, S. Paßehr, G. Weiglein, EPJC78(2018)]
  - $H_i \to H_j H_k$ ( Full 1-loop ) [D. T. Nhung, M. Muhlleitner, J. Streicher, K. Walz, JHEP11 (2013)] [G. Belanger, V. Bizouard, F. Boudjema, G. Chalons, PRD96 (2017)]
    ( $O(\alpha_t \alpha_S)$ 2-loop ) [M. Mühlleitner, D. T. Nhung, H. Ziesche, JHEP 12 (2015)]
  - $A_i \to \bar{\tilde{t}}\tilde{t}$ ( Full 1-loop ) [J. Baglio, C. Krauss, M. Muhlleitner, K. Walz, JHEP 10 (2015)]
  - All 2-body neutral Higgs decays, BRs [J. Baglio, T. N. Dao, M. Mühlleitner, 1907.12060]
  - $H_i^\pm \to WH_i$ ( Full 1-loop ) [T. N. Dao, L. Fritz, M. Krause, M. Muehlleitner, S. Patel, Eur.Phys.J. C80 (2020)]

→ Missing part for Higgs boson decays is charged Higgs boson decays.

- What is typical size of NLO corrections for each decay?

# Charged Higgs decays in the NMSSM

Charged Higgs decays in the NMSSM can be categorized as follows:

1. Decays into SM particles

$$H^+ \to q\bar{q}', \ \ (t\bar{b}, \ \ t\bar{s}, \ \ t\bar{d}, \dots)$$

$$H^+ \to \ell\nu, \ \ (\tau^+\nu, \ \ \mu^+\nu, \ \ e^+\nu, \ \ \dots)$$

$$H^+ \to W^+V \ \ (V = Z, \gamma)$$

2. Decays into extra Higgs bosons + W bosons

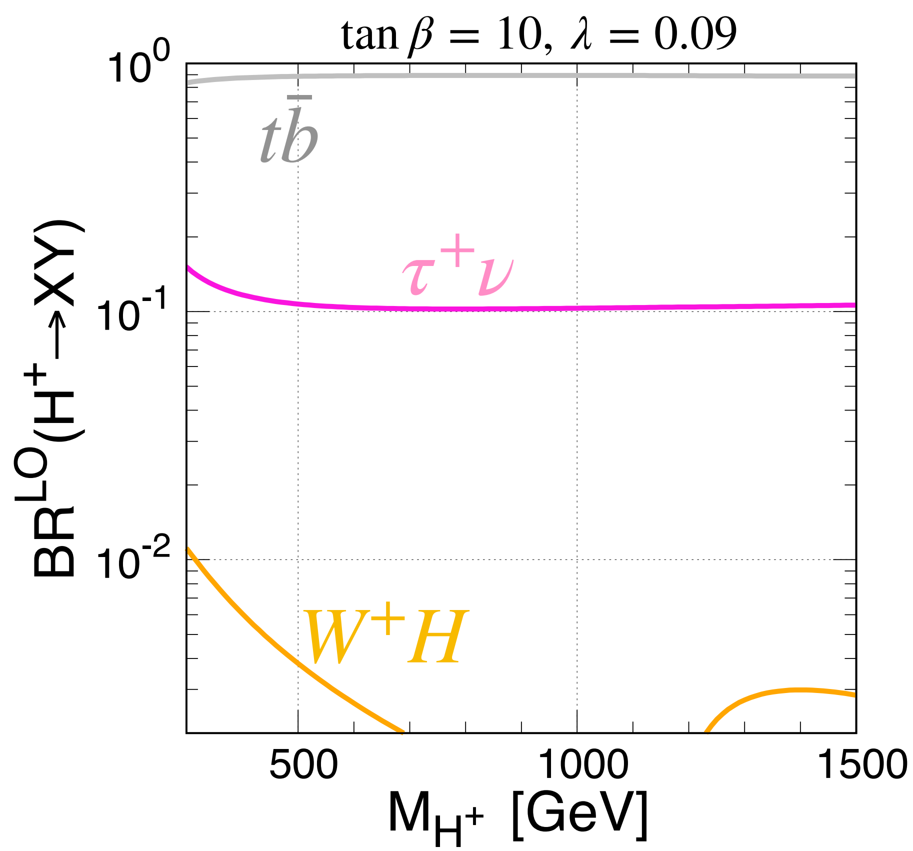
$$H^+ \to W^+H_i \ \ ( \ H_i : \text{ Neutral Higgs bosons})$$

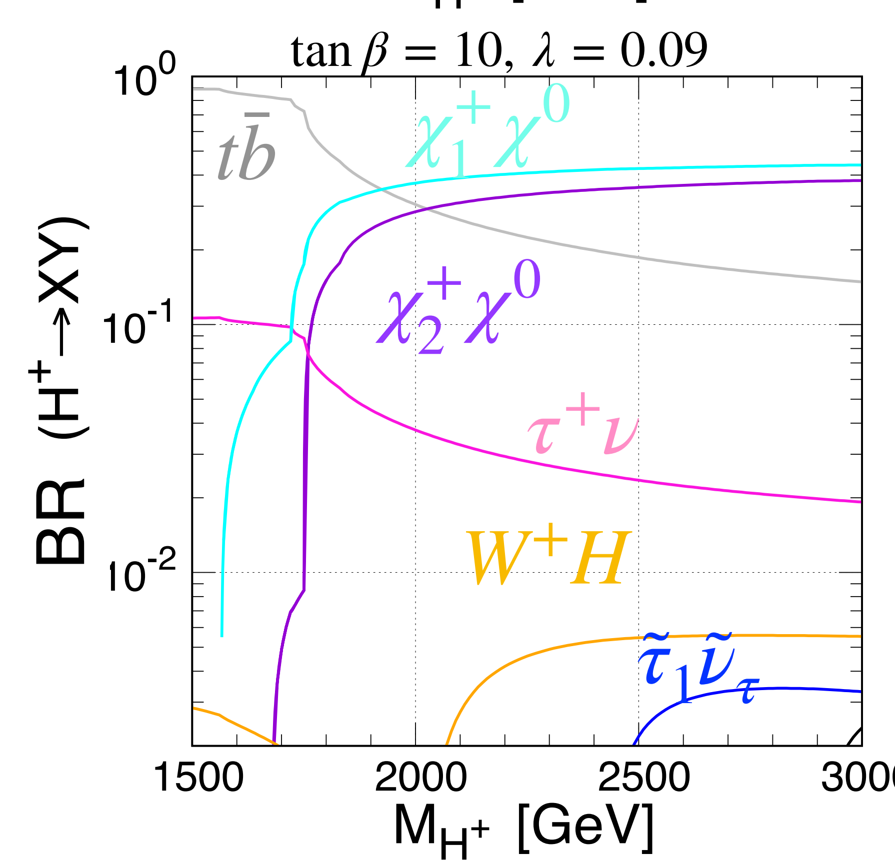
3. Decays into SUSY particles

$$H^+ \to \tilde{\chi}_i^0 \tilde{\chi}_j^+, \ \ (i = 1{,}2, \ j = 1{,}\dots 5)$$

$$H^+ \to \tilde{q}\bar{\tilde{q}}', \ \ (\tilde{t}\bar{\tilde{b}}, \dots)$$

$$H^+ \to \tilde{\ell}\tilde{\nu}, \ \ (\tilde{\tau}^+\tilde{\nu}, \ \dots)$$



# Renormalization

- Higgs potential: mixed OS-$\overline{\text{DR}}$ scheme. [K. Ender, T. Graf, M. Muhlleitner, H. Rzehak, PRD85(2012)] etc.

$$V_H = |\lambda|^2 |S|^2 \left(H_u^\dagger H_u + H_d^\dagger H_d\right) + \left|\lambda\left(H_u i\sigma_2 H_d\right) + \kappa S^2\right|^2 + \frac{1}{2}g_2^2 \left|H_u^\dagger H_d\right|^2 + \frac{1}{8}(g_1^2 + g_2^2)\left(H_u^\dagger H_u - H_d^\dagger H_d\right)^2$$
$$+ m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + m_S^2 |S|^2 + \left[A_\lambda \lambda \left(H_u i\sigma_2 H_d\right) S + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right]$$

→ Input parameters(12): $T_{H_1}, T_{H_2}, T_{H_3}, M_W, M_Z, \alpha_{\rm em}, \tan\beta, v_S, m_{H^\pm}, \lambda, \kappa, A_\kappa$

$T_{H_1}, T_{H_2}, T_{H_3}, M_{H^\pm}, M_Z, M_W, \alpha_{\rm em}$ → On-shell $\hat{T}_{H_i} = 0,\ \hat{\Sigma}_{VV}(M_V^2) = 0,\ \hat{\Gamma}_{\bar{f}f\gamma}(0) = 0$

$\tan\beta, v_S, \lambda, \kappa, A_\lambda, A_\kappa,$

(Wave function renormalization for $H_d, H_u, S$ ) → $\overline{\text{DR}}$

- Electroweakino sector: OS scheme or $\overline{\text{DR}}$ scheme [J. Baglio, T. N. Dao, M. Muhlleitner, EPJC 80 (2020) 10, 960]

$M_1, M_2$ : We have 7 OS conditions, i.e., $\Sigma_{ii}^{\chi^{\pm,0}}(m^2_{\chi_i^{\pm,0}}) = 0$

→ OS1 : $\chi_i^+ \sim \tilde{W}^+ : \text{OS},\ \chi_k^0 \sim \tilde{B} : \text{OS},$

OS2 : $\chi_i^0 \sim \tilde{W}^3 : \text{OS},\ \chi_k^0 \sim \tilde{B} : \text{OS},$

# Decay rates of charged Higgs bosons at NLO

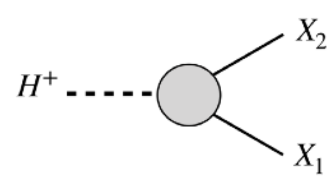
- We evaluated NLO EW (+SUSY EW) and NLO SUSY QCD corrections to the following processes:

$$H^{\pm} \to tb, \quad H^{\pm} \to \tau\nu, \quad H^{\pm} \to \chi_i^{+}\chi_j^{0}, \quad H^{+} \to \tilde{t}\tilde{b}, \quad H^{+} \to \tilde{\tau}\tilde{\nu}, \quad H^{+} \to WH_i$$

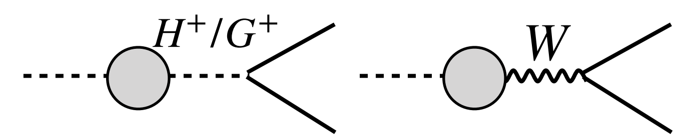
(i=1,2; j=1,…,5)

- Schematic formula for NLO decay rates

$$\Gamma(H^{\pm} \to X_1X_2) = (\text{Resummed factors}) \times \Gamma_{\rm LO}(H^{\pm} \to X_1X_2)$$
$$\times \left[1 + \Delta^{\rm QCD} + \Delta^{\rm SUSYQCD} + \Delta^{\rm (SUSY+)\,EW} + \Delta^{\rm H^+H^-} + \Delta^{\rm H^+G^-/W^-}\right]$$




+ (Real corrections)




(Resumed factors): $\Delta_b$ corrections ($H^+ \to tb$), Z factor ($H^+ \to W H_i$)

[M. Carena, D. Garcia, U. Nierste, C. E.M. Wagner, NPB 577(2000)], etc.

[K. E. Williams, G. Weiglein, Phys. Lett. B660 (2008)]

- resumed factors, $\Delta_{\rm QCD}$ are calculated by NMSSMCALC(EW).

[J. Baglio, T. N. Dao, M. Muhlleitner, EPJC 80 (2020) 10, 960]

# $\Delta_b$ corrections

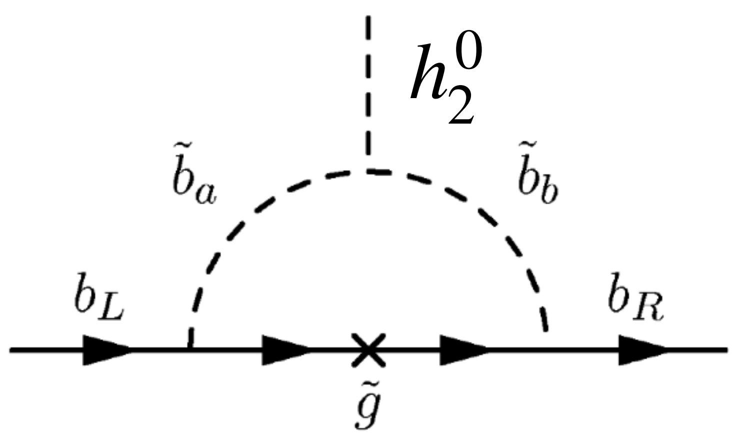
[M. Carena, D. Garcia, U. Nierste, C. Wagner, NPB577(2000)88, etc.]

For $H^{\pm} \to tb$, it is known that SUSY particles corrections to the bottom Yukawa coupling are significant in large $\tan\beta$ regime.

(Ex.) MSSM

Effective lagrangian for bottom Yukawa in gauge basis:

$$\mathcal{L}_{eff} = y_b h_1^0 b\bar{b} + \Delta y_b h_2^0 b\bar{b}\,.$$




After $h_1^0$ and $h_2^0$ acquire VEV,

$$\Rightarrow\; m_b = \frac{v_1}{\sqrt{2}}(y_b + \Delta y_b \tan\beta) \equiv \frac{y_b}{\sqrt{2}} v_1 (1 + \Delta m_b)$$

This modifies tree level $\bar{t}bH^+$ vertex relations:

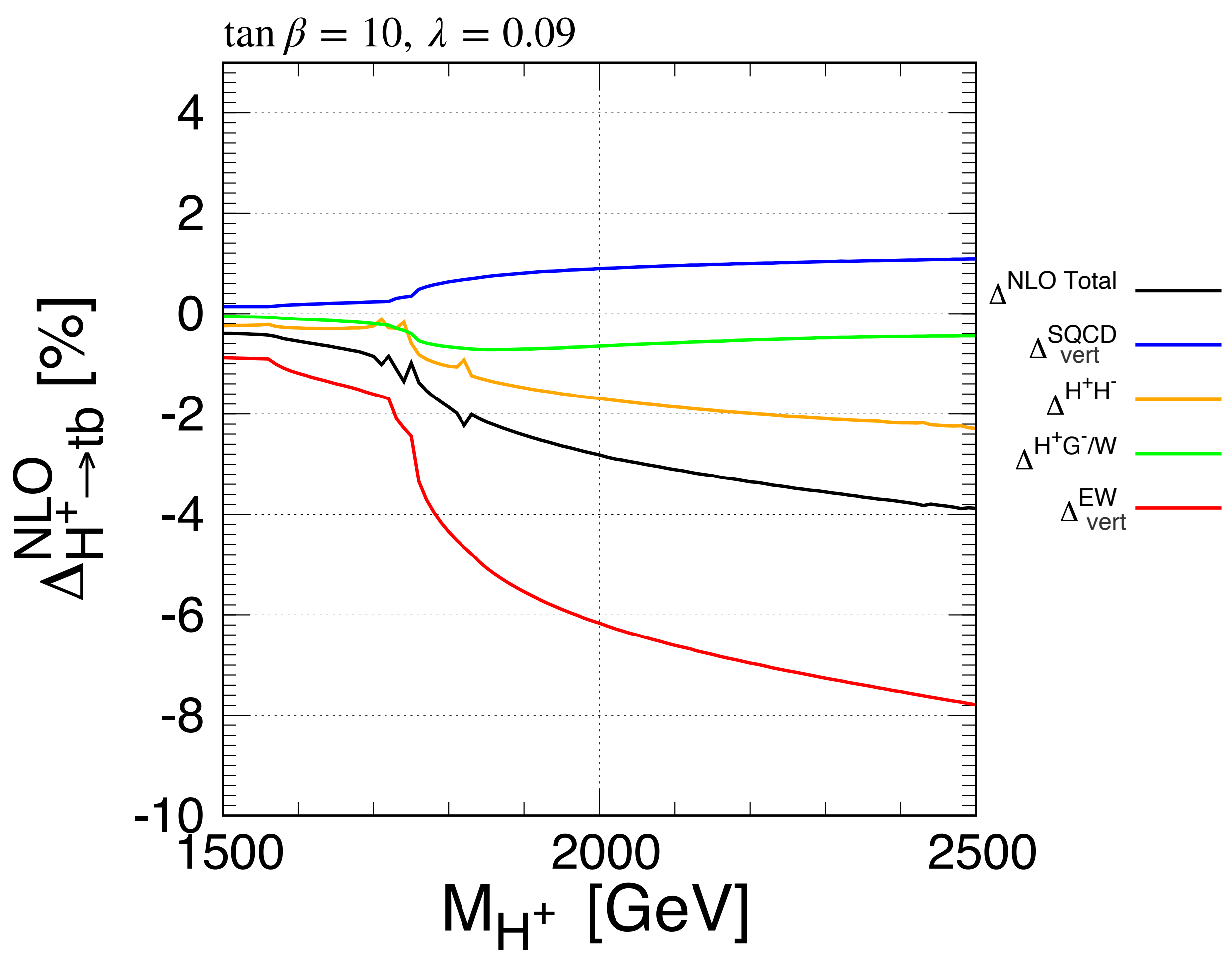
$$\bar{t}P_R bH^+ : \quad \frac{m_b}{v}\tan\beta \to \frac{m_b}{v}\tan\beta \frac{1}{1+\Delta m_b}$$

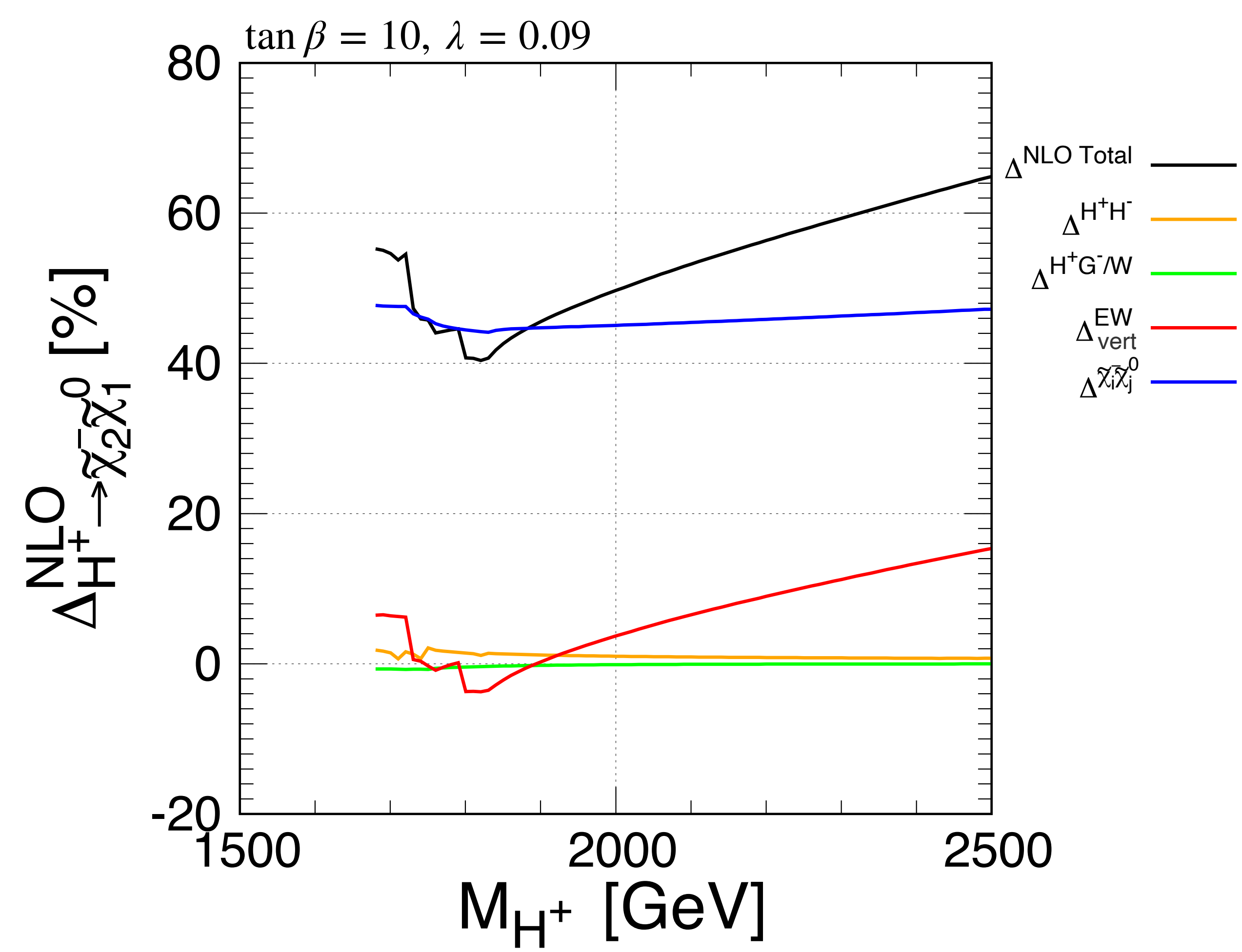
$\Delta m_b$ is proportional to $\tan\beta$ .

→ $\Delta m_b$ is significant if $\tan\beta \gg 1$ and this should be resummed.

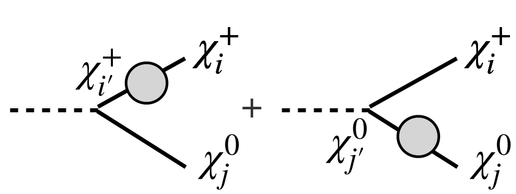
# Pure NLO corrections: $BR(H^+ \to tb)$, $BR(H^+ \to \tilde{W}^+\tilde{B})$

$$\Gamma(H^\pm \to X_1 X_2) = (\text{Resummed factors}) \times \Gamma_{\text{LO}}(H^\pm \to X_1 X_2)$$
$$\times \left[1 + \Delta^{\text{QCD}} + \Delta^{\text{SQCD}}_{\text{vert}} + \Delta^{\text{EW}}_{\text{vert}} + \Delta^{\text{H}^+\text{H}^-} + \Delta^{\text{H}^+\text{G}^-/\text{W}^-}\right]$$



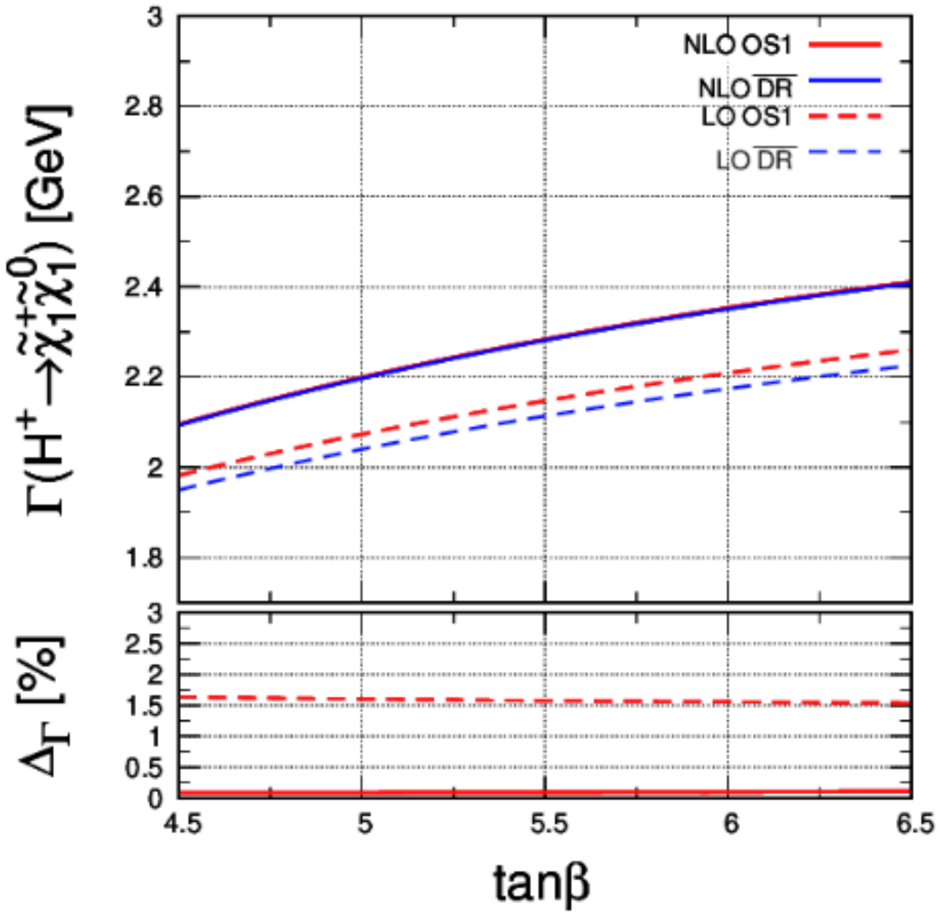



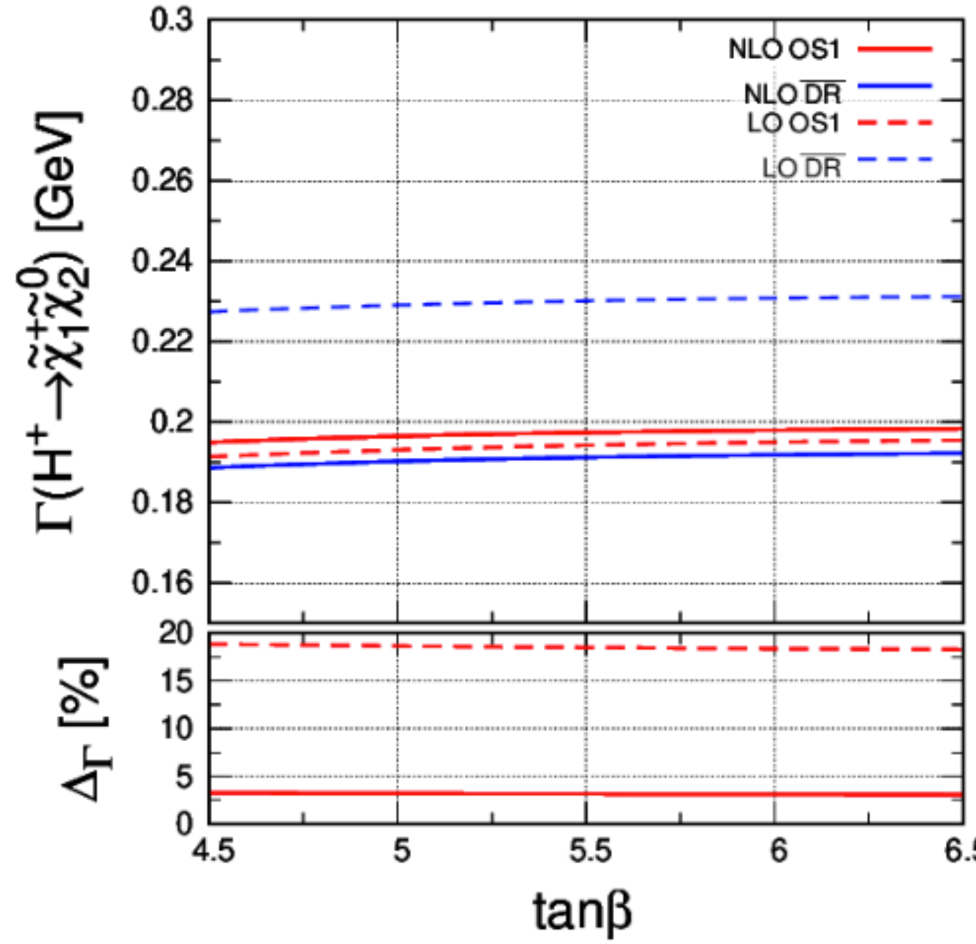

- For $H^+ \to tb$, EW corrections and SQCD corrections are destructive.
- For $H^\pm \to \tilde{\chi}^+_2 \tilde{\chi}^0_1$, WFRs for electroweakinos are significant. $\Delta^{\chi^+\chi^0} \sim$



# Impact for scheme difference for charged Higgs decays

[T. N. Dao, M. Mühlleitner, S. Patel, KS]




- Scheme difference is defined by $\Delta_\Gamma \equiv \left| \frac{\Gamma^{\mathrm{OS1}} - \Gamma^{\mathrm{DR}}}{\Gamma^{\mathrm{OS1}}} \right|$.

$$\Delta_\Gamma^{1-\mathrm{loop}}(H^+ \to \chi_1^+ \chi_1^0) \sim 0\,\%\,, \quad \Delta_\Gamma^{1-\mathrm{loop}}(H^+ \to \chi_1^+ \chi_2^0) \sim 2.5\,\%\,,$$

→ We can see that theoretical error becomes small by including 1-loop corrections.

# Scan analysis for NLO corrections

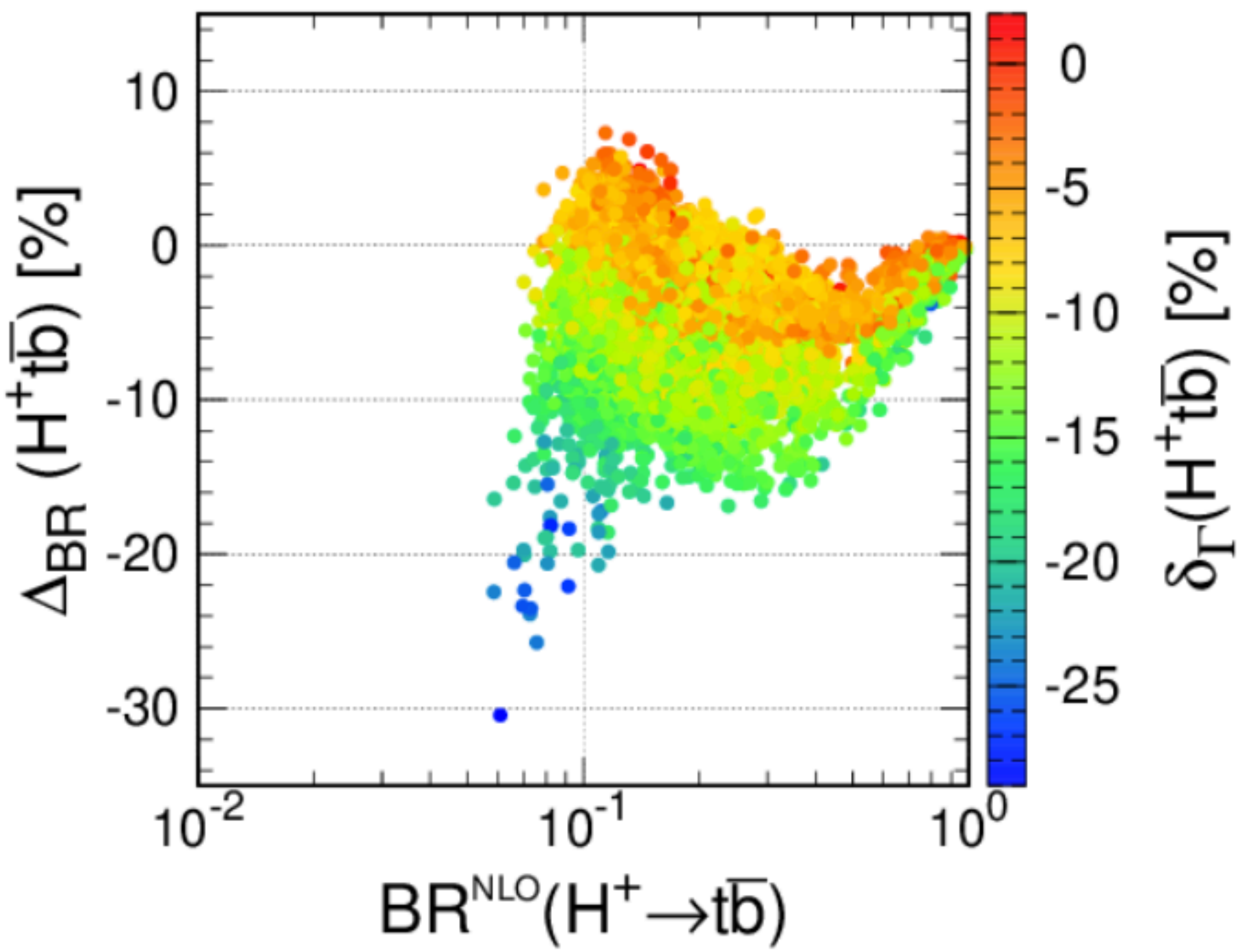
Scan range:

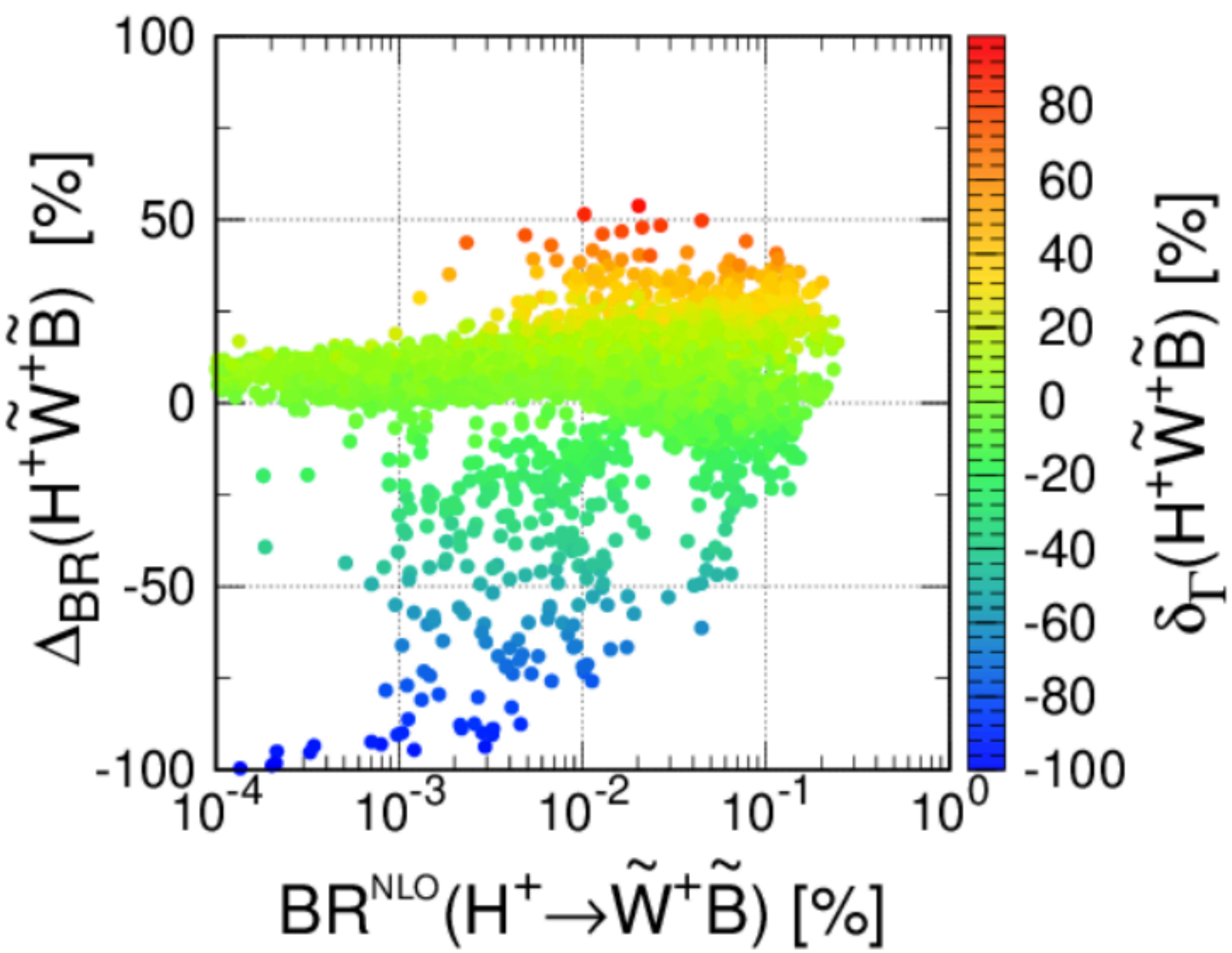
$$0.5\ \text{TeV} < m_{H^+} < 3\text{TeV},\ 1 < t_\beta < 20,\ 0 < \lambda, |\kappa| < 0.7,$$

also, soft breaking parameters, A terms are scanned.

$$\Delta_{\rm BR} = \frac{\text{BR}^{\text{NLO}} - \text{BR}^{\text{LO}}}{\max(\text{BR}^{\text{NLO}}, \text{BR}^{\text{LO}})}, \quad \delta_\Gamma = \frac{\Gamma^{\text{NLO}}}{\Gamma^{\text{LO}}} - 1$$

[T. N. Dao, M. Mühlleitner, S. Patel, KS]




- For $H^+ \to tb$, maximum size of NLO corrections is ~ -30%.
- For $H^+ \to \tilde{W}^+\tilde{B}$, large corrections, $|\Delta_{BR}|$~100%, can appear.

# Summary

- The Higgs boson will be precisely measured at the future collider experiments, such as the HL-LHC and the ILC.

  → This means that the theoretical predictions should also accurately evaluated not only for the discovered Higgs bosons but also extra Higgs bosons.

- We study NLO (SUSY +)EW and SUSY QCD corrections for various charged Higgs bosons decays in the complex NMSSM.

  - $H^+ \to tb$ : maximally ~|30%| NLO corrections are obtained.
  - $H^+ \to \tilde{W}^+\tilde{B}$ : large corrections due to mixing of electroweakinos can be found in BR<1%.