[arXiv:2012.14889]

Precise calculations of charged Higgs boson decays in NMSSM

Kodai Sakurai (KIT)

Collaborators:

Thi Nhung Dao [A], Margarete Mühlleitner [B], Shruti Patel [B]

([A]: ICISE, Vietnam; [B]: KIT, Germany)

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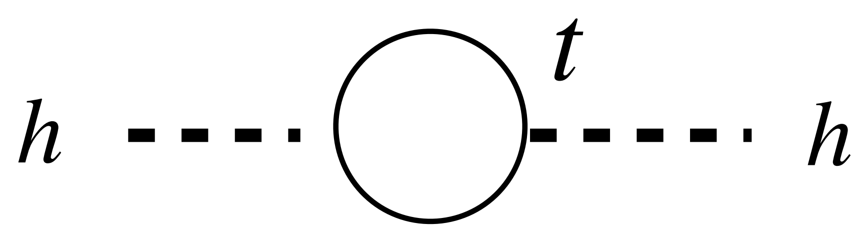
Hierarchy problem

Theoretical problems in the SM ⟷ This relates paradigm of BSM.

Loop corrections to mass of the Higgs boson in the SM:

$\Pi_{hh}^{1PI} =$ 

$+ \ldots \quad \sim -\frac{3y_t^2}{8\pi^2}\Lambda^2$

Quadratic divergence

If $\quad \Lambda^2 \simeq (M_p)^2 \sim (10^{19}\ \text{GeV})^2$

$$(125\ \text{GeV})^2 = m_h^2 + \Pi_{hh}^{1PI} \simeq m_h^2 - (10^{19}\ \text{GeV})^2$$

Fine tuning is required

Quadratic divergence only appears in the Higgs mass corrections:

$\Pi_{VV}^{1PI} \sim \log\Lambda^2$ (Gauge symmetry) $\qquad \Pi_{ff}^{1PI} \sim \log\Lambda^2$ (Chiral symmetry)

Symmetry solve the problem? → Supersymmetry (SUSY)

Indirect search of NP via precise calculations

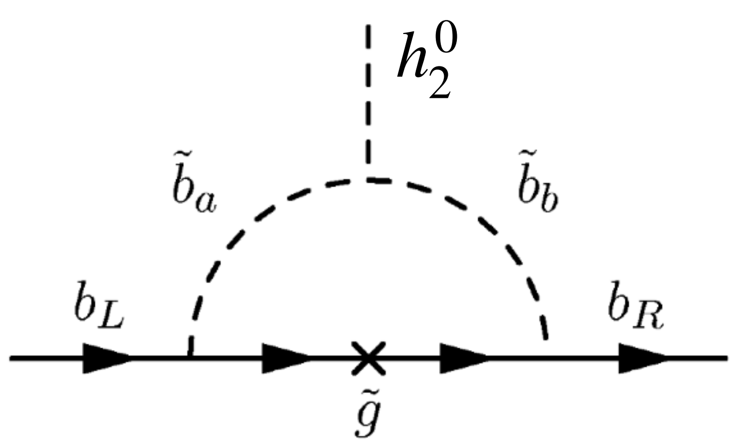
- No direct evidence of new particles

- In future collider experiments (HL-LHC, ILC, etc.), the discovered Higgs boson will be precisely measured.

→ It would be more important to focus on indirect searches of NP via precise measurement of Higgs bosons.

→ Precise calculations is necessary in oder to compare with precise measurement.

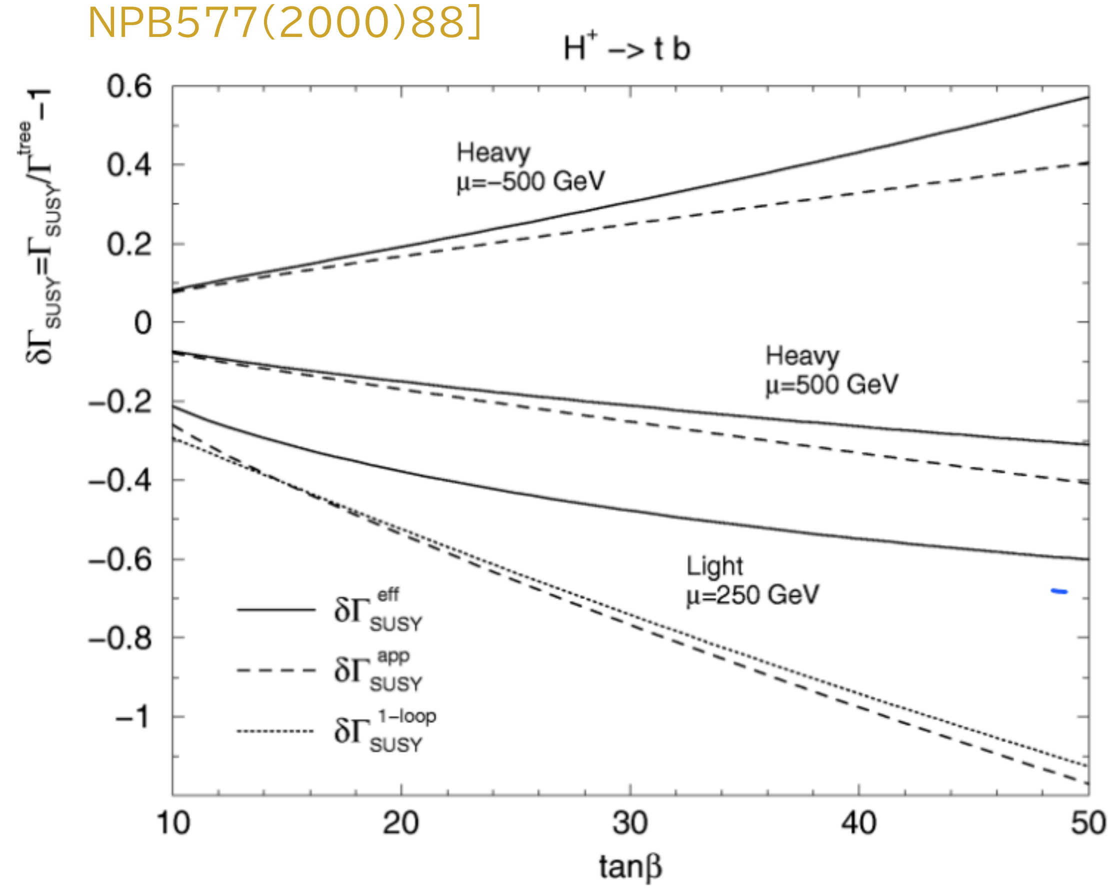
Ex.) Δ_b corrections to $H^+ \longrightarrow tb$ in MSSM



$$\bar{t}P_R bH^+ : \quad (y_b + \Delta y_b \tan\beta)$$

→ In case of *tanβ >> 1* 、 Δ_b correction can be large.

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



Next-to Minimal supersymmetric model (NMSSM) [1/2]

- NMSSM is a simplest extension of the MSSM with a singlet field:

$$\mathscr{L}_{\rm NMSSM} = \mathscr{L}_{\rm MSSM} + S$$

- There exist 5 neutralinos due to the new degree of freedom, singlino.

- μ problem can be solved in this model:

$$W_{\rm MSSM} \ni \underline{\mu H_u H_d}$$

NMSSM: $\mu_{\rm eff} \equiv \lambda < S > \ \leftarrow \lambda S H_u H_d$

- Constraint of mass of the Higgs boson may be easily satisfied than MSSM:

MSSM: $\left(m_{H_1}^{\rm tree}\right)^2 = M_Z^2 \cos 2\beta$

NMSSM: $\left(m_{H_1}^{\rm tree}\right)^2 = M_Z^2\left(\cos 2\beta + \underline{\frac{\lambda^2}{g_1^2 + g_2^2} \sin 2\beta}\right)$

Next-to Minimal supersymmetric model (NMSSM) [2/2]

- Higgs potential

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

Additional terms from MSSM

- Higgs fields

$$H_u = e^{i\varphi_u}\begin{pmatrix} h_u^+ \\ \frac{1}{\sqrt{2}}(v_u + h_u + i a_u)\end{pmatrix}, \quad H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + h_d + i a_d) \\ h_d^- \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}} e^{i\varphi_s}(v_s + h_s + i a_s),$$

➡ Physical states: $H_1,\ H_2,\ H_3,\ A_1,\ A_2,\ H^\pm$

- Input parameters ($\tan\beta = v_u/v_d$)

Higgs sector (14) : $M_W, M_Z, \alpha_{\mathrm{em}}, \tan\beta, v_S, m_{H^+}, \lambda, \kappa, \mathrm{Re}A_\kappa, \varphi_X\ (X = S, u, \lambda, \kappa)$

Electroweakino sector(4) : $M_1,\ M_2,\ \varphi_{M_1},\ \varphi_{M_2}$

$$\mathscr{L}^{\mathrm{soft}} \ni -\frac{1}{2}(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}_j \tilde{W}_j + \mathrm{h.c.})$$

Masses and mixing matrices are determined by setting these parameters.

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)] [F. Staub, W. Porod, B. Herrmann,JHEP10(2010)], etc
  - ($O(\alpha_t \alpha_S)$ 2-loop) [M. Mühlleitner, D. T. Nhung, H. Rzehak, K. Walz, JHEP05(2015)] [M. D. Goodsell, K. Nickel,F. Staub, PRD91(2015)], etc
  - ($O(\alpha_t^2)$ 2-loop) [T.N. Dao, R. Gröber,M. Krause, M. Mühlleitner, H. Rzehak, JHEP08(2019)]
- Higgs boson decays
  - $H_i, A_i \to ff,\ VV$ (Full 1-loop) [F. Domingo, S. Heinemeyer, S. Paßehr, G. Weiglein, Eur.Phys.J.C78(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.

This talk

- We calculated NLO corrections to various charged Higgs bosons in the NMSSM.
- We investigated the impact of the NLO corrections for each decay process.

Open questions:

- What is typical size of NLO corrections for each decay?
- How does CPV effects change the NLO corrections?

Decay rates for charged Higgs (Leading order)

$H^+ \to tb$:

$$\lambda(x,y) = (1-x-y)^2 - 4xy$$

$$\Gamma(H^+ \to tb) = \frac{3M_{H^\pm}}{8\pi}|V_{tb}|^2 \lambda^{1/2}\left(\frac{M_t^2}{M_{H^\pm}^2}, \frac{M_b^2}{M_{H^\pm}^2}\right)\left[\left(1-\frac{M_t^2}{M_{H^\pm}^2}-\frac{M_b^2}{M_{H^\pm}^2}\right)\left(\frac{M_t^2}{v^2}\frac{1}{\tan^2\beta}+\frac{M_b^2}{v^2}\tan^2\beta\right)-4\frac{M_t^2M_b^2}{M_{H^\pm}^2v^2}\right]$$

→ Depending on value of *tanβ,* top Yukawa or bottom Yukawa can dominate.

$H^+ \to \chi_i^0\chi_j^+$: (CP conserving case) *U,V,N* : mixing matrix for electroweakinos

$$\Gamma(H^+ \to \chi_i^0\chi_j^+) = \frac{M_{H^\pm}}{16\pi}\lambda^{1/2}\left(\frac{M_{x_i^+}^2}{M_{H^\pm}^2}, \frac{M_{x_j^0}^2}{M_{H^\pm}^2}\right)\left[\left(1-\frac{M_{x_i^+}^2}{M_{H^\pm}^2}-\frac{M_{x_j^0}^2}{M_{H^\pm}^2}\right)\left(g_L^2+g_R^2\right)-4\frac{M_{x_i^+}M_{x_j^0}^2}{M_{H^\pm}^2}g_Lg_R\right]$$

$$g_R = -c_\beta\left[\frac{g_1}{\sqrt{2}}N_{i1}V_{j2}+\frac{g_2}{\sqrt{2}}\left(N_{i2}V_{j2}+\sqrt{2}N_{i4}V_{j1}\right)+\lambda N_{i5}V_{j2}\tan\beta\right]$$

$$g_L : g_R\ [U \to V,\ N_{i4} \to -N_{i3},\ \tan\beta -> -\cot\beta,\ c_\beta \to -s_\beta]$$

→ $g_{L/R} \sim \lambda \quad (x_i^0 \sim \tilde{S}), \quad g_{L/R} \sim g_1 \text{ or } g_2 \quad (x_i^0 \sim \tilde{B},\ \tilde{W}^3,\ \tilde{H}_{u/d})$

Branching ratios for charged Higgs (Leading order)

Charged Higgs boson decays with the state of the art QCD corrections by using NMSSMCALCEW (w/o EW corrections)

- Definition of BRs

$$\mathrm{BR}(H^+ \to WH) = \sum_{i=1,...3} \mathrm{BR}(H^+ \to WH_i) + \sum_{i=1,2} \mathrm{BR}(H^+ \to WA_i)$$

$$\mathrm{BR}(H^+ \to \chi^+_{1/2}\chi^0) = \sum_{i=1,...,5} \mathrm{BR}(H^+ \to \chi^+_{1/2}\chi^0)$$

- Inputs

$$\tan\beta = 10,\ \lambda = 0.09$$

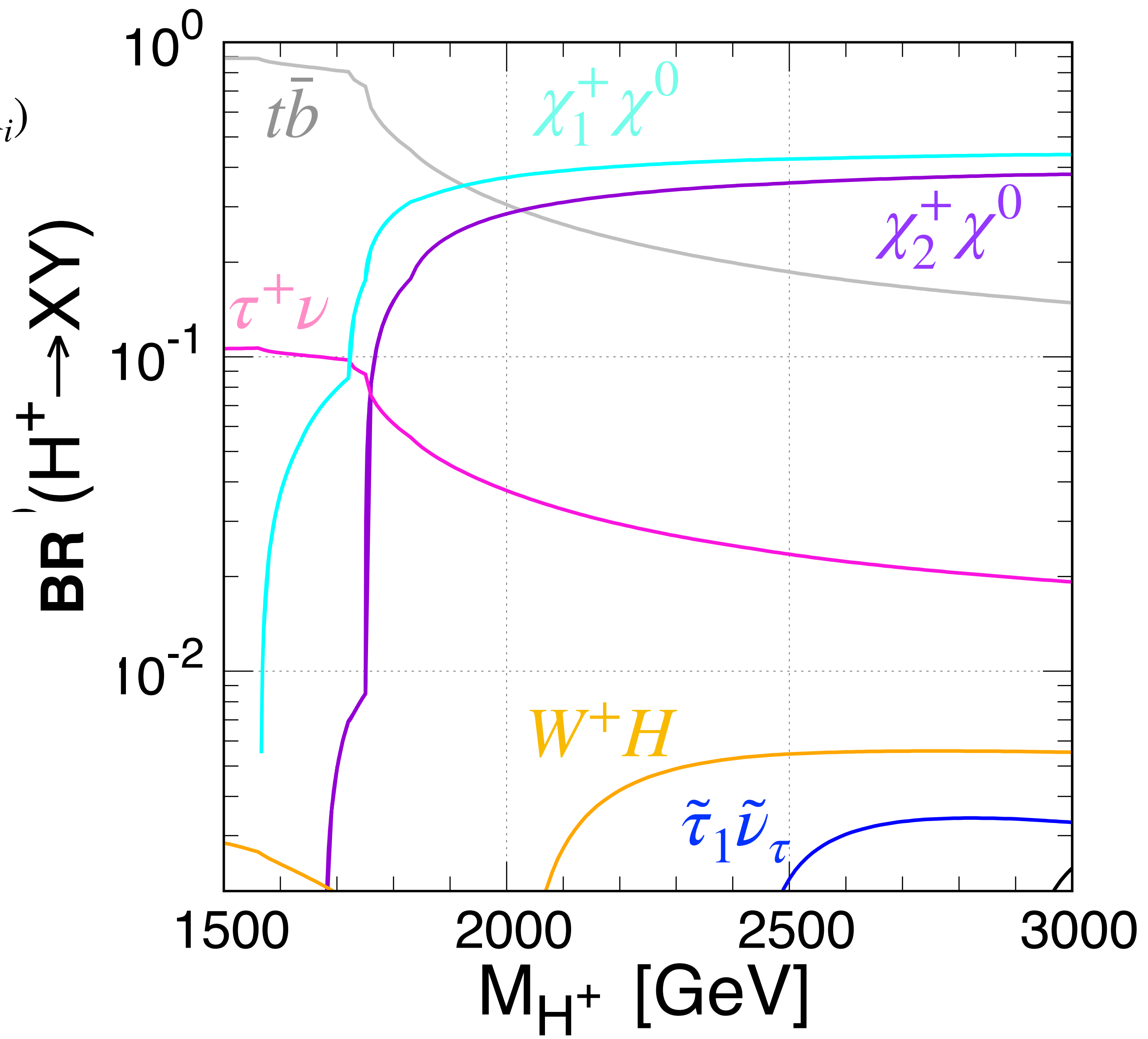
- Mass spectrum

$$m_{\chi^0_1} = 748\ \mathrm{GeV},\ m_{\chi^+_1} = 819\ \mathrm{GeV}$$

$$m_{\tilde{t}_1} = m_{\tilde{b}_1} = 1.4\ \mathrm{TeV}$$

$$m_{\tilde{\nu}_\tau} = 1.2\ \mathrm{TeV},\ \ m_{\tilde{\tau}_1} = 1.1\ \mathrm{TeV}$$

$$m_{H_2} = 1.1\ \mathrm{TeV},\ m_{A_1} = 1.9\ \mathrm{TeV}$$



→ $H^+ \to t\bar{b}$ is the main decay mode in $m_{H^+} \lesssim 2$ TeV.

→ $H^+ \to \chi_1^+\chi^0$ dominates in $2\ \mathrm{TeV} \lesssim m_{H^+}$.

Decay rates of charged Higgs bosons at NLO

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

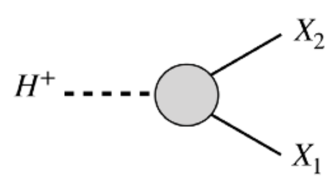
$$H^\pm \to tb, \quad H^\pm \to \tau\nu, \quad H^\pm \to \chi_i^+ \chi_j^0, \quad H^+ \to \tilde{t}\tilde{b}, \quad H^+ \to \tilde{\tau}\tilde{\nu}, \quad H^+ \to WH_i$$

(i=1,2; j=1,…,5)

- Schematic formula for NLO decay rates

$$\Gamma(H^\pm \to X_1 X_2) = (\text{Resummed factors}) \times \Gamma_{\mathrm{LO}}(H^\pm \to X_1 X_2)$$

$$\times \left[1 + \Delta_{\mathrm{QCD}} + \Delta_{\mathrm{SUSYQCD}} + \Delta_{\mathrm{(SUSY+)\ EW}} + \Delta^{\mathrm{ext.}}_{\mathrm{H^+H^-}} + \Delta^{\mathrm{ext.}}_{\mathrm{H^+G^-/W^-}}\right]$$



+ (Real corrections)

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

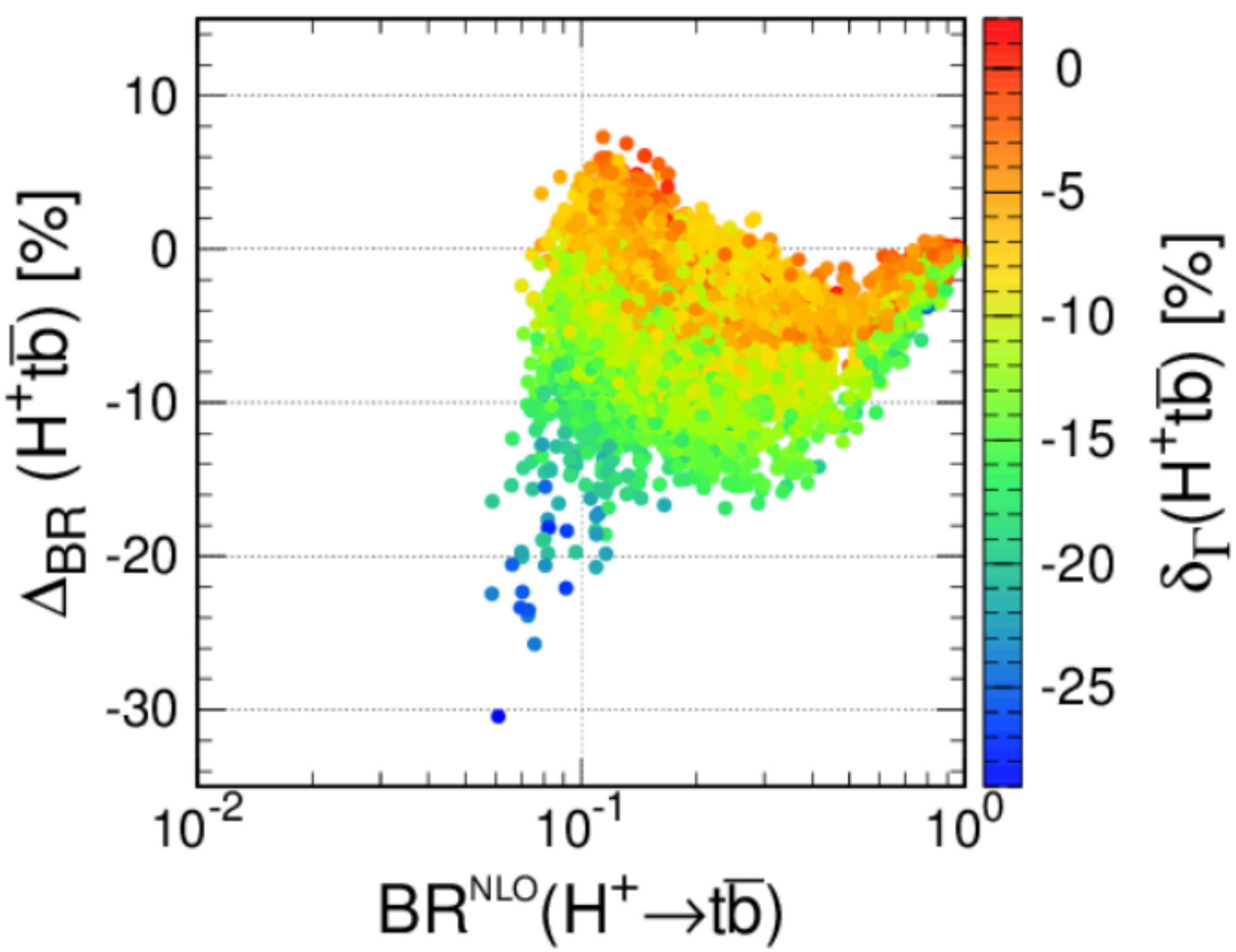
[M. Carena, D. Garcia, U. Nierste, C. E.M. Wagner, NPB 577(2000)], etc.

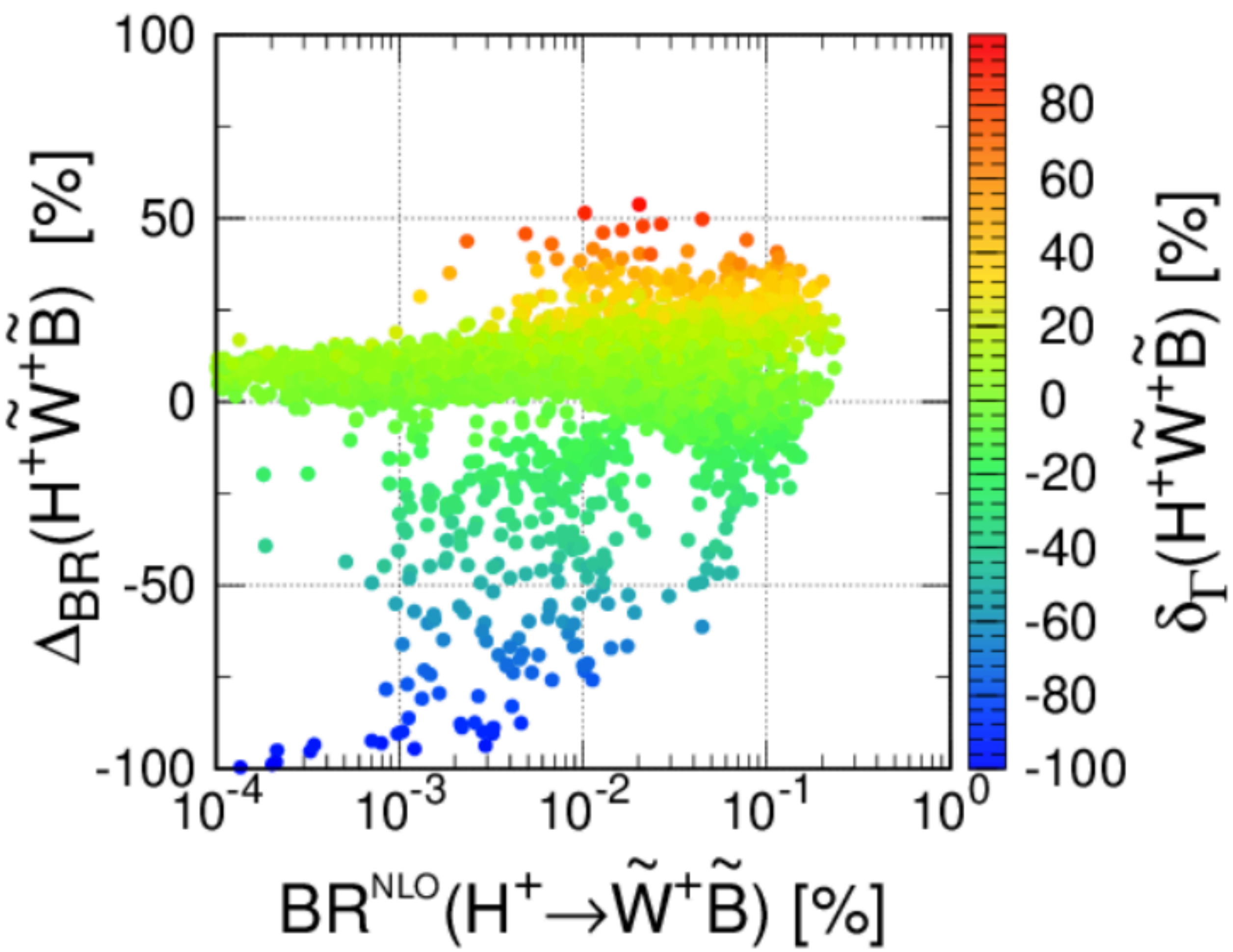
- Resumed factors, Δ_{QCD} are calculated by NMSSMCALC(EW)
- New ingredients are $\Delta_{\mathrm{SUSYQCD}} + \Delta_{\mathrm{(SUSY+)\ EW}} + \Delta^{\mathrm{ext.}}_{\mathrm{H^+H^-}} + \Delta^{\mathrm{ext.}}_{\mathrm{H^+G^-/W^-}}$.

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

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

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



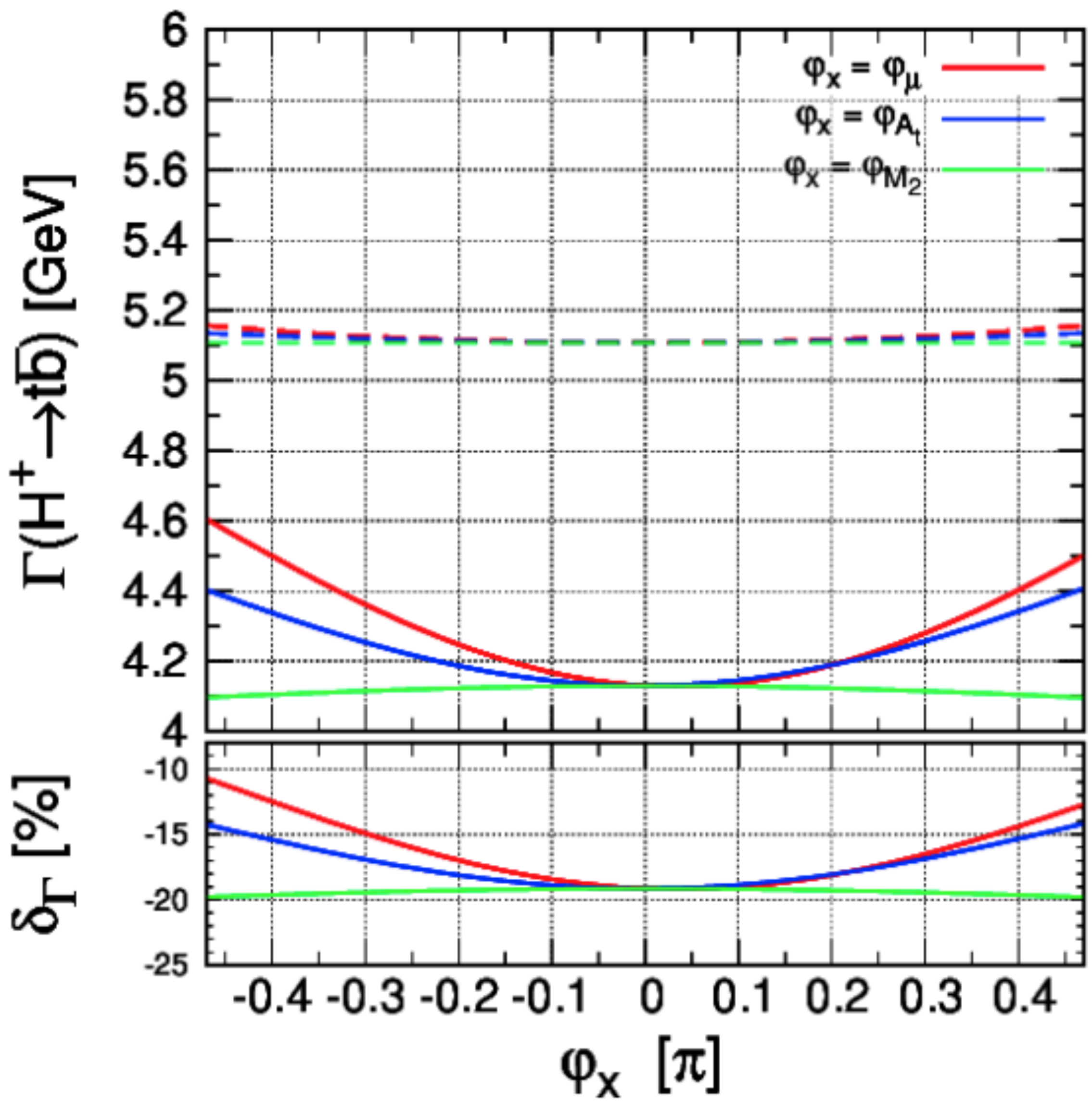


- For $H^+ \to tb$, maximum size of NLO corrections is ~ -30%.
- For $H^+ \to \tilde{W}^+ \tilde{B}$, large corrections, $|\Delta_{BR}|$~100%, can appear.

Effect of CP violation

Ex.) $H^+ \to tb$

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



- Phase of $\mu_{\rm eff}, A_t, M_2$ is varied.
- At LO, slight phase dependence appear for $\mu_{\rm eff}, A_t$.
- At NLO, decay rates charges match compared with those of LO.

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.

- 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%.

  - CPV effect : NLO corrections can deviate from those of CP conserving case.