Loop corrections to Higgs mass spectra and decay BRs in BSM

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Outline

Introduction

Higher-order corrections for the NMSSM Higgs masses

Higher-order corrections for the NMSSM Higgs decays

Outlook

From the SM to the (N)MSSM

- **SM Hierarchy problem:** Quantum corrections to Higgs mass m_H quadratically divergent in the SM $\Rightarrow$ m_H stabilized by SUSY, MSSM minimal SM extension, **2** Higgs doublets
- **But μ–problem:** $\mu \hat{H}_u \cdot \hat{H}_d$ term in the superpotential, μ SUSY-invariant but of the order of EW scale $\Rightarrow$ naturalness problem!
- **A solution:** effective μ–term generated dynamically $\Leftrightarrow$ **NMSSM**

NMSSM Superpotential

$$\mathcal{W} = \hat{u}_R^* y_u \left(\hat{Q} \cdot \hat{H}_u\right) - \hat{d}_R^* y_d \left(\hat{Q} \cdot \hat{H}_d\right) - \hat{e}_R^* y_e \left(\hat{L} \cdot \hat{H}_d\right) + \lambda \hat{S} \left(\hat{H}_u \cdot \hat{H}_d\right) + \frac{1}{3} \kappa \hat{S}^3$$

- **3+2 neutral Higgs** bosons, **2 charged Higgs** bosons, **4+1 neutralinos**
- Singlet field S gets a vacuum expectation value $\Rightarrow$ $\boldsymbol{\mu_{\rm eff} = \lambda v_s/\sqrt{2}}$
- Higgs sector less restricted in NMSSM compared to MSSM:

  upper bound on tree-level in the MSSM: $M_H \leq M_Z$
  $\Rightarrow$ large quantum corrections to get $M_H \simeq 125$ GeV

  Fine-tuning less important in the NMSSM, higher tree-level bound
  $M_H^2 \leq M_Z^2 \left(\cos(2\beta)^2 + \frac{\lambda^2}{g^2} \sin(2\beta)^2\right)$, $g^2 = (g_1^2 + g_2^2)/2$ [see Ellwanger, Hugonie, Teixeira, (2010)]

From the real NMSSM to the complex NMSSM

- **CP violation:** CKM matrix can explain CP violation in $K - \bar{K}$ system but not the baryon asymmetry in the Universe:

  amount of CP violation (from CKM) in the SM too small

  One solution

  CP violation enhanced with complex parameters

- **Richer Higgs spectrum:** complex parameters in the NMSSM $\Rightarrow$ CP violation at tree–level, all the Higgs bosons mix:

$$H_i = \sum_k S_{ik}\phi_k, \quad \phi = (h_d, h_u, s, a, a_s)$$

$$(S_{ik})\ 5 \times 5 \text{ matrix}$$

The scalar potential in the NMSSM

- From the superpotential to the scalar potential:

$$
\begin{aligned}
V =& |\lambda|^2 |S|^2 \left(H_u^\dagger H_u + H_d^\dagger H_d\right) + |\lambda \left(H_u^\intercal \epsilon H_d\right) + \kappa S^2|^2 + \frac{1}{2} g_2^2 |H_u^\dagger H_d|^2 \\
&+ \frac{1}{8}(g_1^2 + g_2^2)\left(H_u^\dagger H_u - H_d^\dagger H_d\right)^2 + m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + m_S^2 |S|^2 \\
&+ \left(\lambda A_\lambda \left(H_u^\intercal \epsilon H_d\right) S + \frac{1}{3}\kappa A_\kappa S^3 + \text{c.c}\right)
\end{aligned}
$$

- Higgs fields with phases:

$$
H_d = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d + h_d + \imath\, a_d \\ \sqrt{2}\, H_d^- \end{pmatrix} \qquad H_u = \frac{e^{\imath\,\phi_u}}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, H_u^+ \\ v_u + h_u + \imath\, a_u \end{pmatrix}
$$

$$
S = \frac{e^{\imath\,\phi_s}}{\sqrt{2}} \left(v_s + h_s + \imath\, a_s\right)
$$

$$
\tan\beta = \frac{v_u}{v_d}
$$

FCC target precision for Higgs decays

Exp error on $\Gamma(H \to xx) \Leftrightarrow$ expected precision on the (effective) SM-like coupling g^2_{Hxx} [FCC CDC Volume 1, EPJC 70 (2019) 474]

Partial width	FCC-ee target
$H \to b\bar{b}$	$\sim 0.6\%$
$H \to c\bar{c}$	$\sim 1.2\%$
$H \to \tau^+\tau^-$	$\sim 0.7\%$
$H \to \mu^+\mu^-$	$\sim 9.0\%$
$H \to gg$	$\sim 1.0\%$
$H \to \gamma\gamma$	$\sim 3.9\%$
$H \to WW \to 4f$	$\sim 0.4\%$
$H \to ZZ \to 4f$	$\sim 0.2\%$

$\Rightarrow$ Higher-order corrections mandatory! Define target for theory uncertainties

Higher-order corrections for the Higgs masses in the NMSSM

1-loop mass calculations: Ender, Graf, Mühlleitner, Rzehak, PRD 85 (2012) 075024; Graf, Gröber, Mühlleitner, Rzehak, Walz, JHEP 1210 (2012) 122

2-loop mass calculations: Mühlleitner, Nhung, Rzehak, Walz, JHEP 1505 (2015) 128; Dao, Gröber, Krause, Mühlleitner, Rzehak, JHEP 08 (2019) 114

Disclaimer of this talk

- I will only present results from my group there, in the framework of `NMSSMCALC`
- My apologies for the other calculators on the market, namely `FeynHiggs`, `FlexibleSUSY`, `FlexibleEFTHiggs`, `NMSSMTools`, `Spheno`, and `SOFTSUSY`
- See also [Drechsel, Gröber, Heinemeyer, Mühlleitner, Rzehak, Weiglein, EPJC 77 (2017) 366] for a comparison between some of them
- For a parallel approach to loop corrections to Higgs decays, see e.g. [Domingo, Heinemeyer, Paßer, Weiglein, EPJC 78 (2018) 942; Domingo, Paßer, EPJC 79 (2019) 905] $\Rightarrow$ see also Sven's talk!

NMSSM Higgs masses at the 1-loop order

- **LO Higgs masses:** diagonalizing the 3×3 CP-even $\mathcal{M}_S$ and the 3×3 CP-odd (+ Goldstone) $\mathcal{M}_A$ mass matrices give the LO masses $m_{H_1} < m_{H_2} < m_{H_3}$ and $m_{A_1} < m_{A_2}$

  sizable higher order corrections compulsory to obtain one SM-like H_i boson

- **1-loop corrections:** define input parameters, calculate renormalized self-energies in a mixed renormalization scheme

  - 7 parameters renormalized on-shell: $e,\ M_W,\ M_Z,\ M_{H^\pm},\ t_{h_u},\ t_{h_d},\ t_s$
  - 5 parameters renormalized $\overline{\text{DR}}$: $\tan\beta,\ \lambda,\ \kappa,\ A_k,\ v_s$

  - ▶ $\overline{\text{DR}}$ field renormalization constants for the Higgs fields

$$H_d = \left(1 + \frac{1}{2}\delta Z_d\right)\hat{H}_d \quad H_u = \left(1 + \frac{1}{2}\delta Z_u\right)\hat{H}_u \quad S = \left(1 + \frac{1}{2}\delta Z_s\right)\hat{S}$$

  - ▶ Tadpole condition: $\hat{T}_{h_{u/d/s}} = 0 \Rightarrow \delta t_{h_{u/d/s}} = T_{h_{u/d/s}}$

NMSSM Higgs masses at the 1-loop order

- **1-loop corrections:** with the renormalized self-energies $\hat{\Sigma}^{(1)}_{H_i H_j}(p^2)$ calculate the zeros of the 1-loop 2-point vertex matrix

$$\Gamma^{11}(p^2) = i \begin{pmatrix} p^2 - m^2_{H_1} + \hat{\Sigma}^{(1)}_{H_1 H_1}(p^2) & \hat{\Sigma}^{(1)}_{H_1 H_2}(p^2) & \hat{\Sigma}^{(1)}_{H_1 H_3}(p^2) \\ \hat{\Sigma}^{(1)}_{H_2 H_1}(p^2) & p^2 - m^2_{H_2} + \hat{\Sigma}^{(1)}_{H_2 H_2}(p^2) & \hat{\Sigma}^{(1)}_{H_2 H_3}(p^2) \\ \hat{\Sigma}^{(1)}_{H_3 H_1}(p^2) & \hat{\Sigma}^{(1)}_{H_3 H_2}(p^2) & p^2 - m^2_{H_3} + \hat{\Sigma}^{(1)}_{H_3 H_3}(p^2) \end{pmatrix}$$

Algorithm to calculate the masses

1. Set $p^2 = m^2_{H_1}$ in the self-energies $\hat{\Sigma}$
2. Solve $\det\hat{\Gamma}(p^2) = 0$
3. Extract the smallest root obtained m^2_{tmp}
4. Set $p^2 = m^2_{\text{tmp}}$ in the self-energies and back to 2. n times as long as $|m^2_{\text{tmp},n} - m^2_{\text{tmp},n-1}| > 10^{-9}$ (desired accuracy) $\Rightarrow$ get the 1-loop mass M_{H_1}
5. Start again at 1. with $m^2_{H_2}$, extract the next-to-smallest root, and so on

Complex parameters and renormalization

- **Many new phases in the complex NMSSM**, for the parameters M_1, M_2, A_t, etc

  In the Higgs sector: 6 phases ϕ_u, ϕ_S, ϕ_λ, ϕ_κ, ϕ_{A_λ}, and ϕ_{A_κ}

  At tree–level, only one relevant phase: only 3 combinations in the mass matrix

$$\Psi = \phi_\lambda - \phi_\kappa + \phi_u - 2\phi_s$$
$$\Psi_\lambda = \phi_\lambda + \phi_{A_\lambda} + \phi_u + \phi_s$$
$$\Psi_\kappa = \phi_\kappa + \phi_{A_\kappa} + 3\phi_s$$

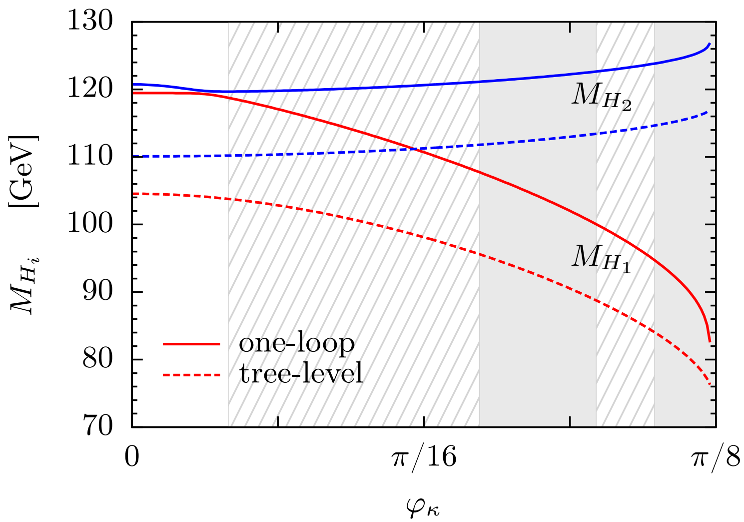
  Ψ_λ, Ψ_κ fixed by two tadpole conditions

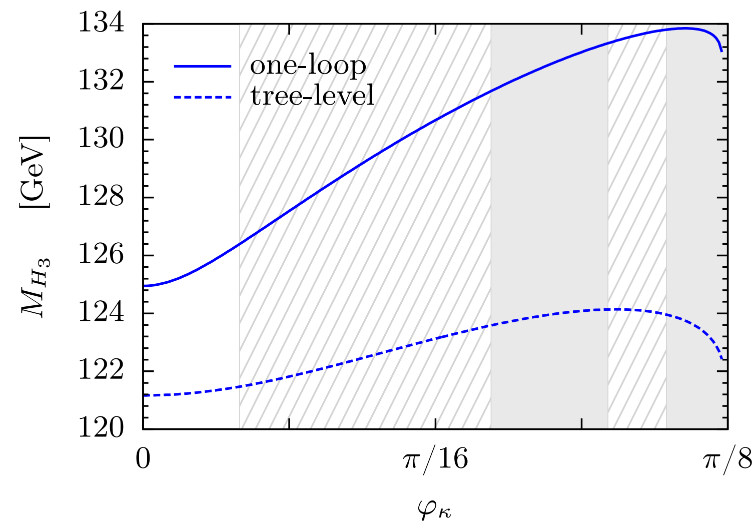
- **Renormalization in the Higgs sector:**
  - on–shell renormalization for e, M_W, M_Z, $M_{H^\pm}$
    $\overline{\mathrm{DR}}$ renormalization for $\tan\beta$, v_s, $|\lambda|$, $|\kappa|$, $|A_\kappa|$ and the phases
  - **vanishing phases counter–terms** but for two tadpole conditions t_a and t_{a_s}

Examplary results at the 1-loop order

Complex phases have sizable effects:

- **Tree–level CP violation ($\Psi \neq 0$):**



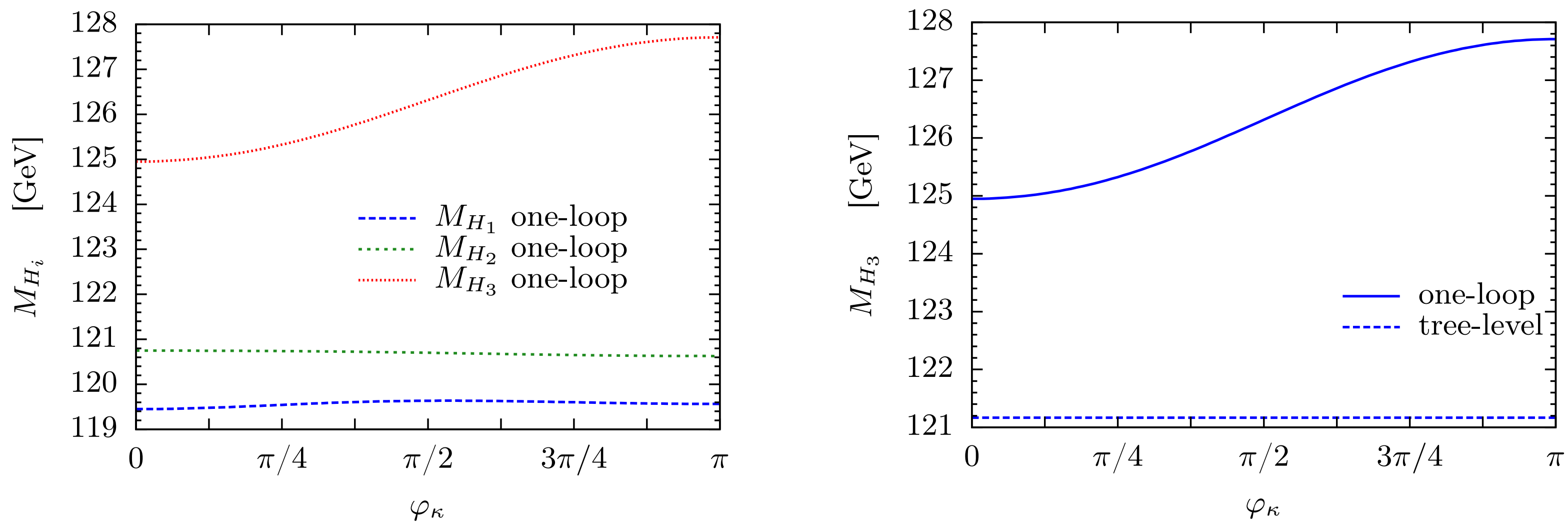


$|\lambda| = 0.72, \ |\kappa| = 0.2, \ \tan\beta = 3, \ v_s = 389 \text{ GeV}, \ |A_\kappa| = 27 \text{ GeV},$
$|A_\lambda| = 928 \text{ GeV}, \ A_t = -875 \text{ GeV}, \ A_b = A_l = -963 \text{ GeV}, \ M_{\text{SUSY}} = 1 \text{ TeV}$
$M_1 = 145 \text{ GeV}, \ M_2 = 200 \text{ GeV}, \ M_3 = 600 \text{ GeV}, \ Q = 300 \text{ GeV}$

Examplary results at the 1-loop order

Complex phases have sizable effects:

- **No tree–level CP violation ($\Psi = 0$), $\phi_\lambda = \phi_\kappa \neq 0$:**

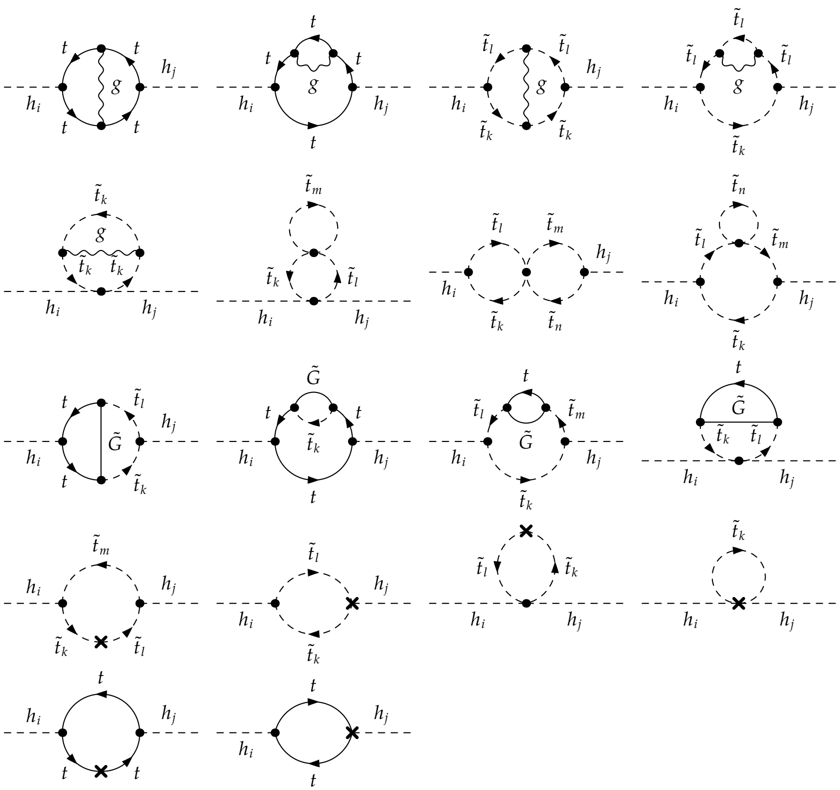


- One loop corrections have a sizable impact (restore some scenarios)
- No tree-level *CP* violation scenario: still slight impact of ϕ_κ over H_3 through its coupling to stops

2-loop effects in Higgs mass calculation

2-loop order $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ in the gaugeless limit and in the approximation of vanishing external momentum:

$$\hat{\Sigma}_{H_iH_j}(p^2) = \hat{\Sigma}^{(1)}_{H_iH_j}(p^2) + \hat{\Sigma}^{(2),\alpha_t\alpha_s}_{H_iH_j}(0) + \hat{\Sigma}^{(2),\alpha_t^2}_{H_iH_j}(0)$$

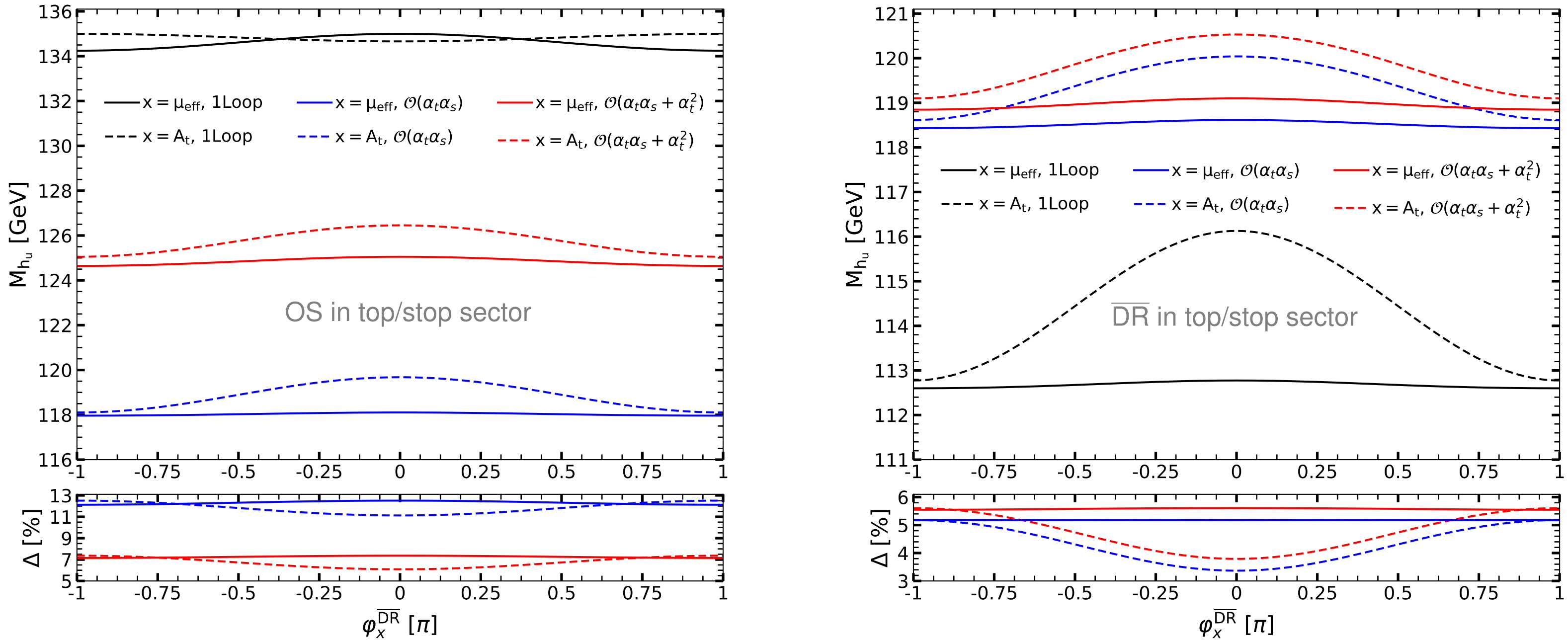


Set of parameters at 2-loop:

- OS renormalization for $M_{H^\pm}$, t_{h_i}, v (Higgs sector)
- $\overline{\text{DR}}$ renormalization for $\tan\beta$, v_s, $|\lambda|$, $|\kappa|$, Re A_κ, ϕ_λ, ϕ_κ, ϕ_u, ϕ_s (Higgs sector)
- OS or $\overline{\text{DR}}$ renormalization for m_t, $m_{\tilde{Q}_3}$, $m_{\tilde{t}_R}$, A_t (top/stop sector)

Examplary results at the 2-loop order

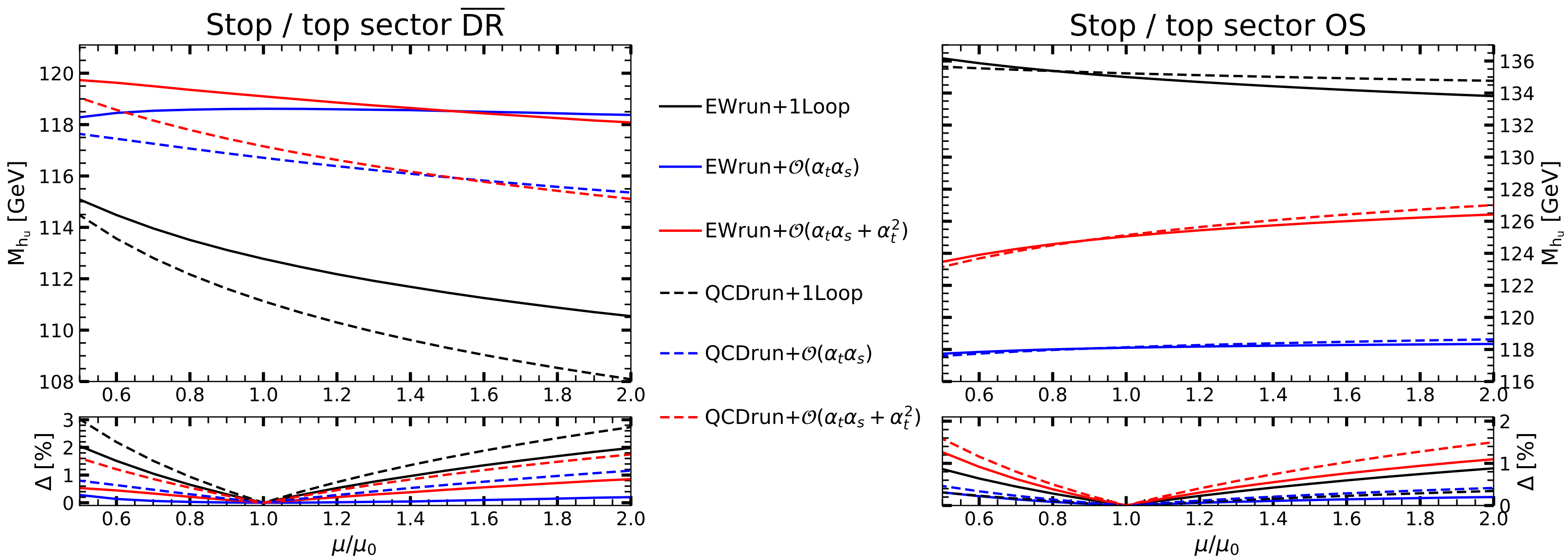
2-loop $\mathcal{O}(\alpha_s\alpha_t + \alpha_t^2)$ corrections of $\mathcal{O}(6\%)$ on top of 1-loop result:



$$|\lambda| = 0.301, \quad |\kappa| = 0.299, \quad \tan\beta = 4.44, \quad v_s = 981.962 \text{ GeV}, \quad \mathrm{Re}\,A_\kappa = -791 \text{ GeV},$$
$$m_{\tilde{t}_R} = 881 \text{ GeV}, \quad m_{\tilde{Q}_3} = 1226 \text{ GeV}, \quad \phi_{A_q} = \pi, \quad \phi_{A_l} = \phi_{M_i} = \phi_{\lambda,\kappa} = \phi_u = 0,$$
$$|M_1| = 644 \text{ GeV}, \quad |M_2| = 585 \text{ GeV}, \quad |M_3| = 1850 \text{ GeV}, \quad M_{H^\pm} = 898 \text{ GeV}$$

Discussion of the theoretical uncertainty

Intrinsic theoretical uncertainty due to
1. renormalization scheme choice; 2. renormalization scheme variation



- QCDrun $\equiv$ (OS $\to$ $\overline{\text{DR}}$ for $m_t(\mu_R = M_Z)$) & RGEs for $(\mu_R = M_Z \to \mu_R = \mu)$ at order $\mathcal{O}(\alpha_s + \alpha_s^2)$
- EWrun $\equiv$ (OS $\to$ $\overline{\text{DR}}$ for $m_t(\mu_R = M_Z)$) & RGEs for $(\mu_R = M_Z \to \mu_R = \mu)$ at order $\mathcal{O}(\alpha_s + \alpha_t + (\alpha_s + \alpha_t)^2)$
- Uncertainty of $\mathcal{O}(1\%)$ in each scheme choice, $\mathcal{O}(3-4\%)$ between $\neq$ schemes

Higher-order corrections for the Higgs decays in the NMSSM

Higgs decays and NMSSMCALC: **J.B.**, Gröber, Mühlleitner, Nhung, Rzehak, Spira, Streicher, Walz, CPC 185 (2014) 12

NLO SUSY-QCD+SUSY-EW corrections: **J.B.**, Krauss, Mühlleitner, Walz, JHEP 1510 (2015) 024; **J.B.**, Dao, Mühlleitner, arXiv:1907.12060

Trilinear Higgs couplings: Nhung, Mühlleitner, Streicher, Walz, JHEP 1311 (2013) 181; Mühlleitner, Nhung, Ziesche, JHEP 1512 (2015) 034

Electron dipole moments: King, Mühlleitner, Nevzorov, Walz, Nucl.Phys.B 901 (2015) 526

NMSSMCALC 3.0: The Higgs sector in the NMSSM

2-loop Higgs boson masses in the NMSSM, allowing for complex parameters

+

calculation of the Higgs boson decay widths in the NMSSM

based on the latest version of HDECAY

[Djouadi, Kalinowski, Spira, CPC 108 (1998) 56; Djouadi, Mühlleitner, Spira, Acta Phys.Polon. B38 (2007) 635; Djouadi, Kalinowski, Mühlleitner, Spira, CPC 238 (2019) 214]

- Real or complex parameters
- $\mathcal{O}(\alpha_t \alpha_s + \alpha_t^2)$ 2-loop masses, electric dipole moments
- Decay widths and branching ratios including dominant higher order QCD corrections
- Off-shell decays into VV^*, $H_i V^*$, tt^*, bt^*
- Dominant SUSY corrections in the decays into quarks and leptons: implemented with effective Δ_b-Yukawa couplings calculated in the NMSSM

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2-loop Higgs boson masses in the NMSSM, allowing for complex parameters

+

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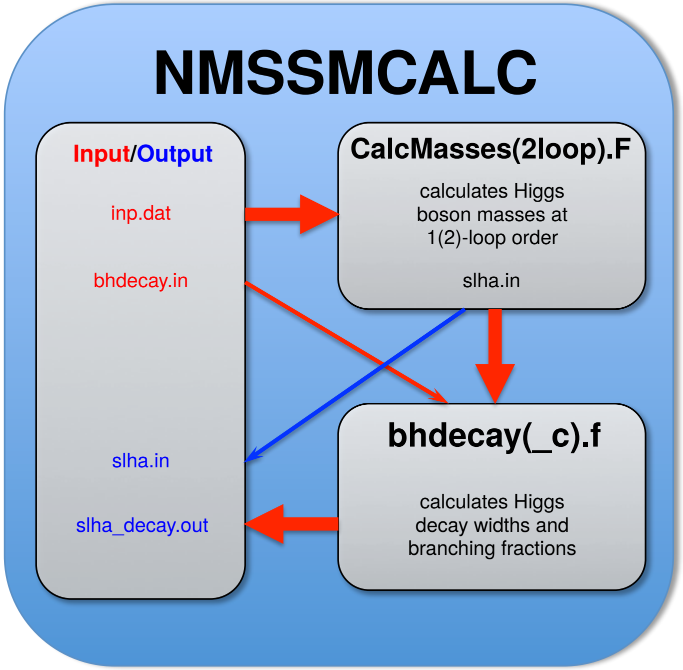

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Current status of mass calculation in NMSSMCALC:

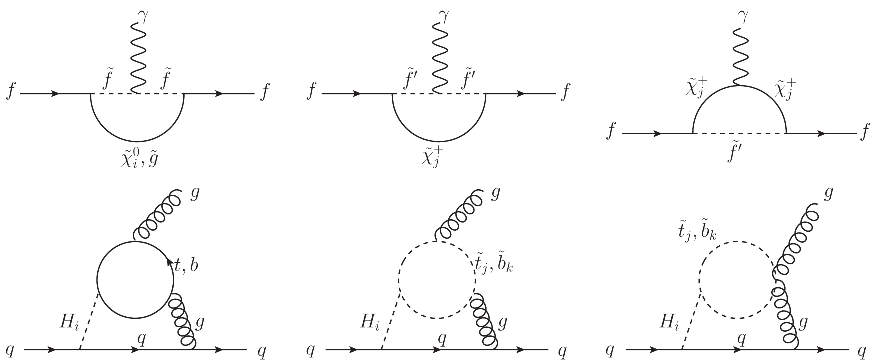
- 2-point 1-loop integrals with complex momentum
  $\Rightarrow$ no instabilities due to threshold singularities
- approximate 2-loop order for the calculation of the Higgs spectrum with $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ corrections

To download NMSSMCALC:

https://www.itp.kit.edu/~maggie/NMSSMCALC

Inclusion of electric dipole moments

CP-violating effects enhance the (chromo-)electric dipole moments (EDM), predicted to be very small in the SM, and not yet observed



Exp upper bounds:

- Electron EDM $\lesssim 10^{-29} e$.cm
  [ACME, Nature 562 (2018) 355]
- Thallium EDM $\lesssim 9 \times 10^{-25} e$.cm
  [Regan et al, PRL 88 (2002) 071805]
- Neutron EDM $\lesssim 3 \times 10^{-26} e$.cm
  [Baker et al, PRL 97 (2006) 131801]
- Mercury EDM $\lesssim 3.1 \times 10^{-29} e$.cm
  [Griffith et al, PRL 102 (2009) 101601]

Implemented in `NMSSMCALC` at the 2-loop level, new switch in Block MODSEL

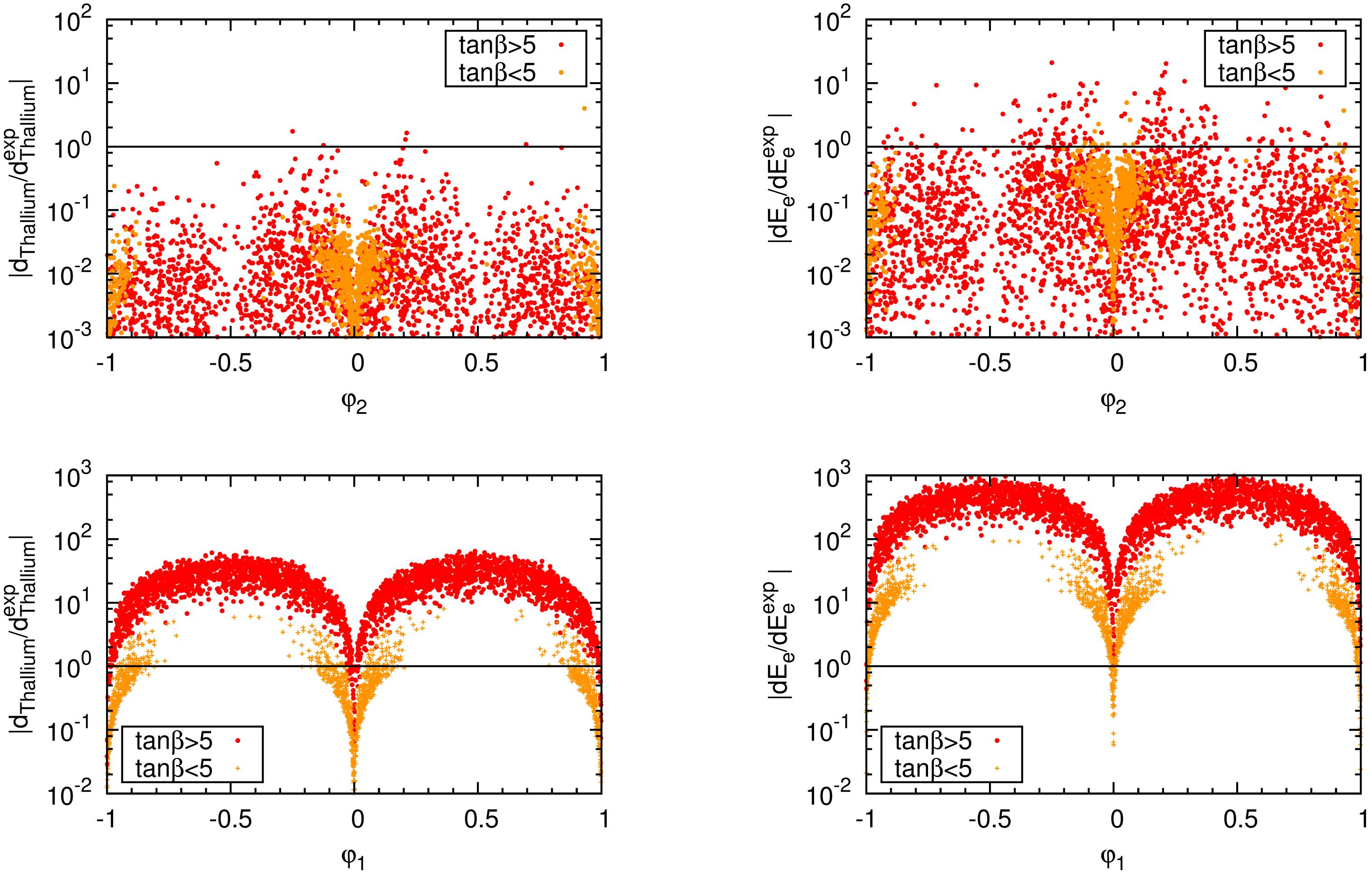
[King, Mühlleitner, Nevzorov, Walz, Nucl.Phys.B 901 (2015) 526]

```
Block MODSEL
  3  1   # NMSSM
  5  2   # CP violation
  10 1   # EDMs: 0, no EDMs); 1, with EDMs); 2, EDMs individual contributions
```

Output with results rescaled to exp upper-bound

Impact of EDMs constraints

Still a sizable portion of NMSSM phases allowed by EDMs constraints



$\phi_2 = \phi_\kappa + 3\phi_s$, specific NMSSM phase $\phi_1 = \phi_\lambda + \phi_s + \phi_u$, MSSM-like phase

NMSSMCALCEW: NLO Higgs decay widths

New in 2019: Extension of NMSSMCALC to include the complete NLO SUSY-QCD and SUSY-EW corrections to neutral Higgs decay widths:

- $\Gamma(H_i \to f\bar{f})$: decay to fermions at 1-loop SUSY-QCD, SUSY-EW, running masses for the quarks
- $\Gamma(H_i \to W^+W^-, ZZ)$: (improved) tree-level for off-shell decays to massive SM gauge bosons, 1-loop SUSY-EW for on-shell decays of heavy Higgs bosons
- $\Gamma(H_i \to ZH_j, H_jH_k)$: Higgs-to-Higgs and Higgs+Z decays at 1-loop NLO SUSY-EW
- $\Gamma(H_i \to \tilde{f}_i\tilde{f}_j)$: decay to sfermions at 1-loop SUSY-QCD, SUSY-EW
- $\Gamma(H_i \to \tilde{\chi}_i\tilde{\chi}_j, \tilde{\chi}_i^+\tilde{\chi}_j^-)$: decay to neutralinos and charginos at 1-loop SUSY-EW

To download NMSSMCALCEW:
https://www.itp.kit.edu/~maggie/NMSSMCALCEW

Some technical details

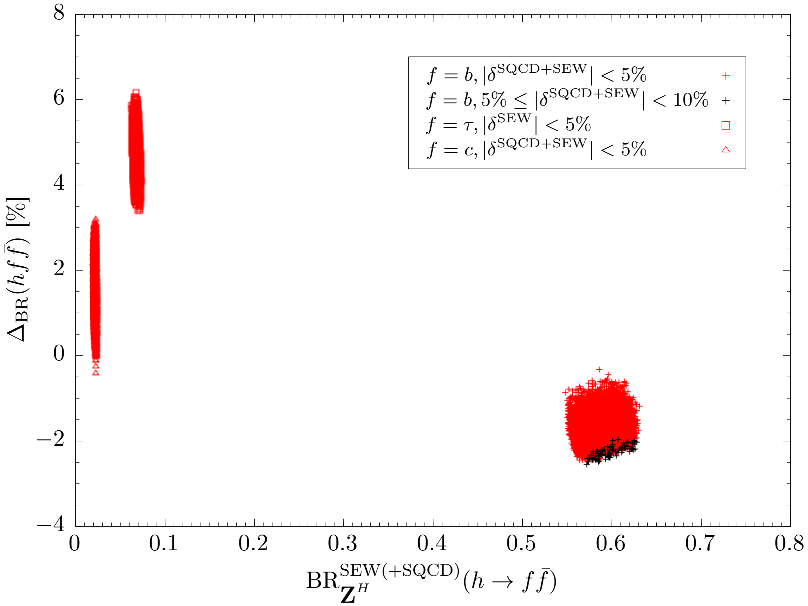
- Loop corrections to squark, neutralinos, and weakino masses needed, 2 descriptions for the wave-function renormalization (WFR):
  - EMT description [see e.g. Espriu, Manzano, Talavera, PRD 66 (2002) 07600]: 2 $\neq$ WFR for ingoing and outgoing states
    - no mixing self-energies, absorptive part of loop functions included ✔
    - no hermiticity of the Lagrangian ✗
  - Denner description [Denner, Fort.Phys. 41 (1993) 307]: only 1 common WFR
    - hermiticity of the Lagrangian ✔
    - absorptive part of the loop functions must be removed ✗
- Z-Goldstone boson mixing $\delta\mathcal{M}_{GZ,mix}$ dealt with Slavnov-Taylor identities adapted to loop-corrected masses [Nhung, Mühlleitner, Streicher, Walz, JHEP 11 (2013) 181; Domingo, Heinemeyer, Paßer, Weiglein, EPJC 78 (2018) 942]

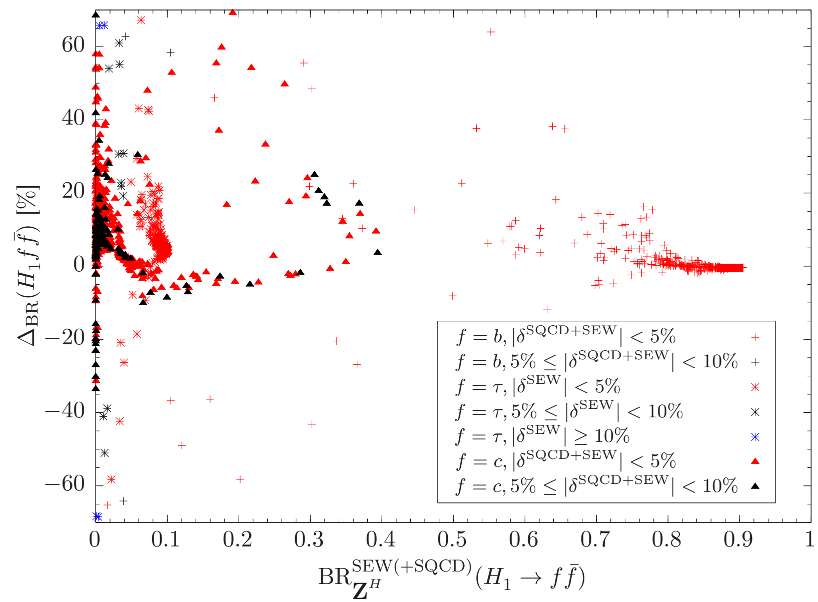
$$M_Z\hat{\Sigma}_{h_i,G}(M_{h_i}^2) + \imath M_{h_i}^2\hat{\Sigma}_{h_i,Z}(p^2) = 0$$

- Real corrections including $\Gamma(H_i \to W^+W^-\gamma)$ to ensure IR-finiteness, but loop-corrected Higgs masses used in the amplitude $\Rightarrow$ gauge-invariance not enforced, see [Dao, Fritz, Krause, Mühlleitner, Patel, arXiv:1911.07197] for a detailed discussion

Decays into SM fermions

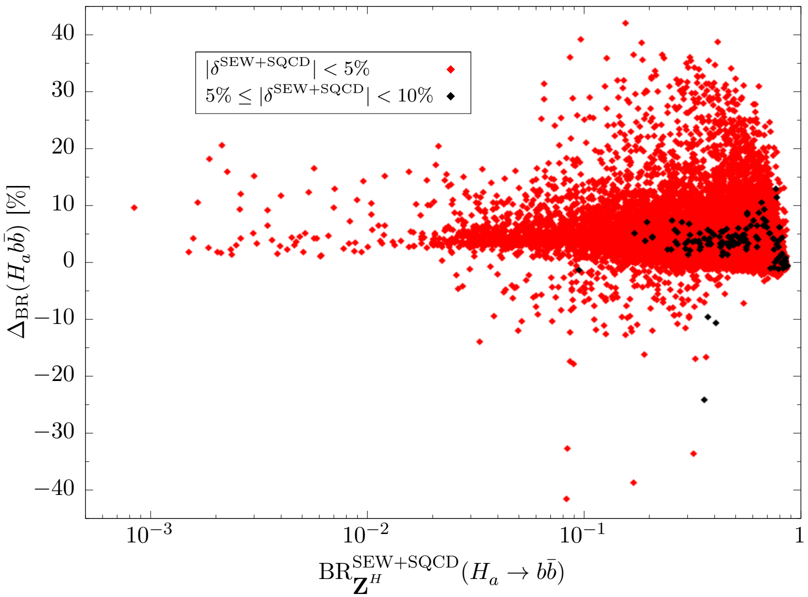
Random scan of the NMSSM parameter space, δ 1-loop vertex correction, $\Delta_{\rm BR}(H_i XY)$ comparison to `NMSSMCALC` 3.0 for $\mathrm{BR}(H_i \to XY)$

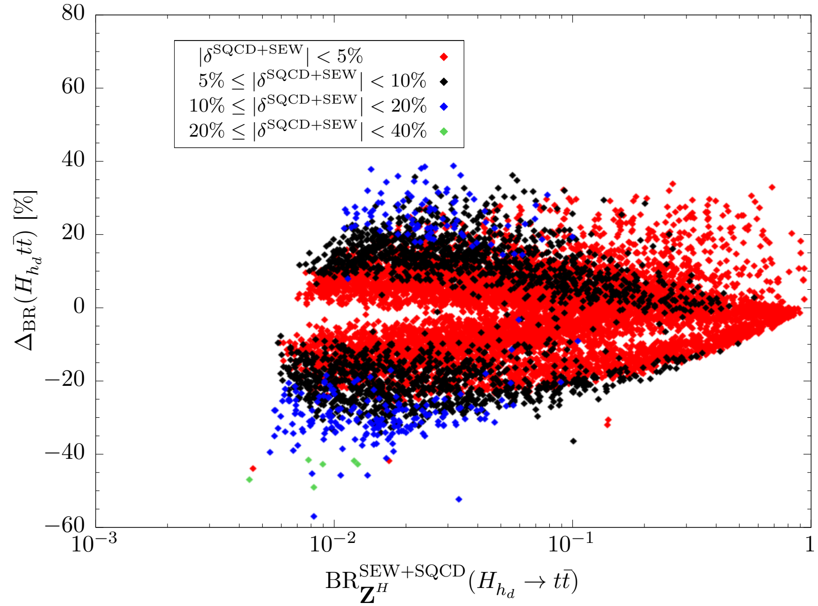




- New implementation (with full WFR factor $\mathbf{Z}^H$ and NLO amplitudes) close to `NMSSMCALC` 3.0 (with unitary Higgs mixing matrix) for SM-like Higgs boson h
- Vertex corrections at most $\mathcal{O}(10\%)$ for SM-like state h
- Same mostly true for singlet-like H_1 boson, $\Delta_{\rm BR}(H_1)$ mostly below 30%

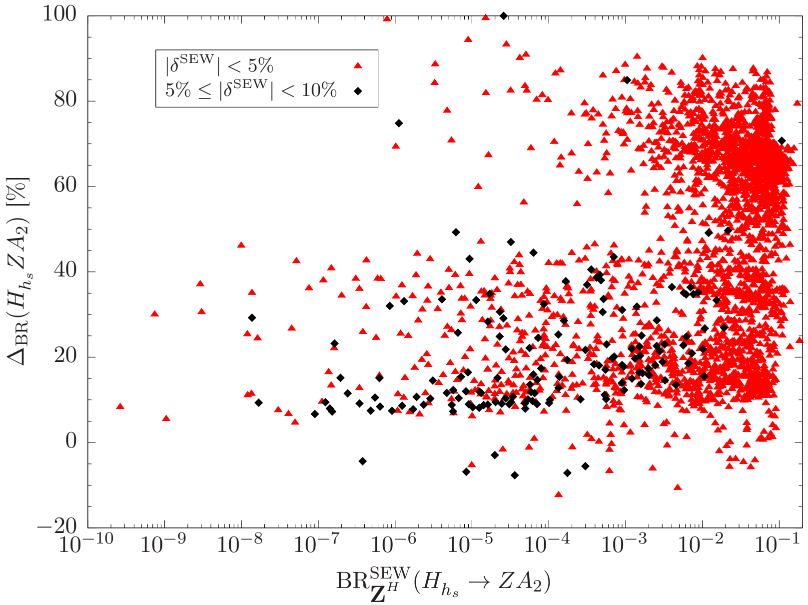
Decays into SM fermions

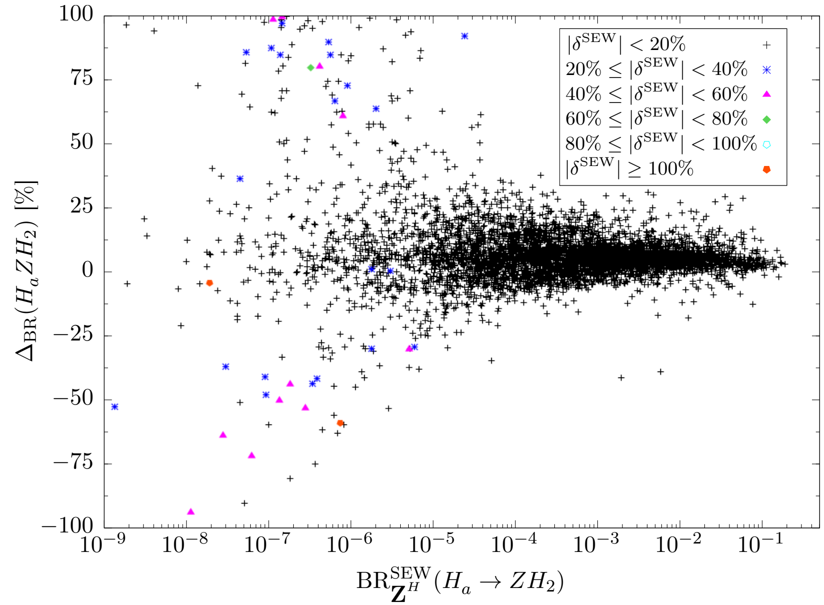




- $|\Delta_{\mathrm{BR}}(H_a b\bar{b})|$ and $|\Delta_{\mathrm{BR}}(H_{h_d} t\bar{t})|$ mostly below 40%
- Vertex corrections can reach 40% for the H_{h_d} state

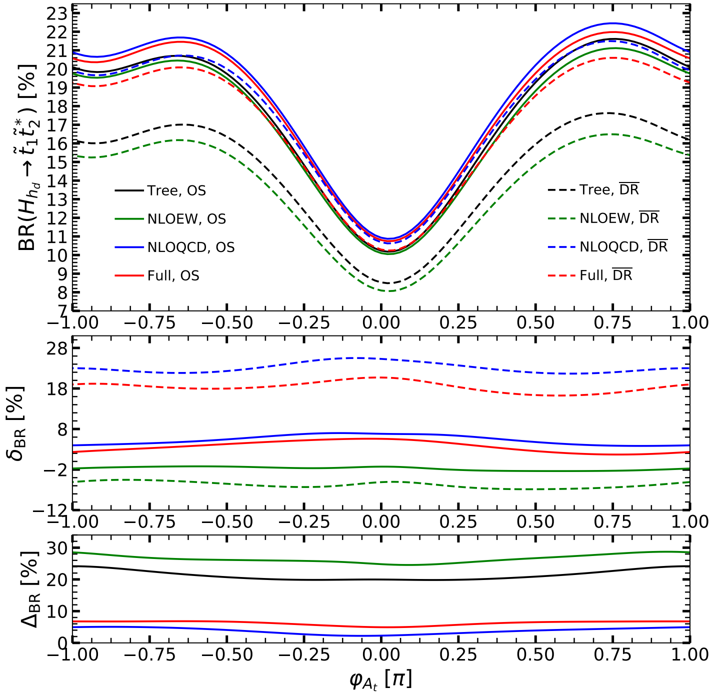
Decays into Higgs+Z boson

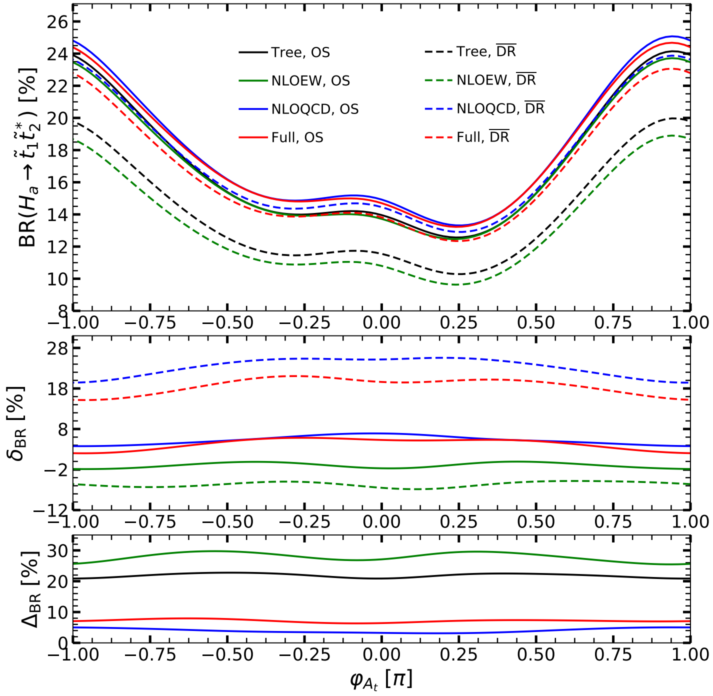




- Many points with large BR($H_{h_s} \to ZA_2$), A_2 doublet-like
- $|\Delta(H_{h_s}ZA2)|$ up to 80% while $|\delta| < 10\%$ $\Rightarrow$ corrections here driven by $\mathbf{Z}^H$ factor
- $|\Delta(H_aZH_2)|$ mostly below 25% (H_2 singlet-like), vertex corrections can reach 100% $\Rightarrow$ large corrections for very small BRs where 1-loop squared are also taken into account

Decays into a squark pair





- $\delta_{\mathrm{BR}} \equiv$ vertex correction, $\Delta_{\mathrm{BR}} \equiv$ difference between OS and $\overline{\mathrm{DR}}$
- SUSY-EW corrections negative, SUSY-QCD corrections positive, cancelation between the two of them
- vertex corrections larger in $\overline{\mathrm{DR}}$ than in OS
- strong decrease of Δ_{BR} when both EW and QCD taken into account!

Conclusions and outlook

In view of the HL-LHC and FCC programs, plenty of room for improvement!

- **2-loop mass calculation:**
  - **2-loop $\mathcal{O}(\alpha_s\alpha_t + \alpha_t^2)$ corrections in the gaugeless limit at zero momentum current state-of-the-art in the mixed renormalization scheme**;
    agreement with other codes when taking into account $\neq$ input setup
    [see e.g. Staub et al, CPC 202 (2016) 113; Goodsell, Staub, EPJC 77 (2017) 46]
  - **For the future: 2-loop terms $\mathcal{O}(\alpha_s\alpha_b + \alpha_t\alpha_b)$ to be done for the complex NMSSM** (known in the real NMSSM, see `FeynHiggs 3`)
- **NLO decay widths: Inclusion of NLO SUSY-(QCD+)EW corrections in the complex NMSSM for all neutral Higgs decays now known!**
  $\rightarrow$ For the future: corrections for charged Higgs decays
- Uncertainties on the decay BRs: reaching FCC precision for the SM-like Higgs boson at the percent level, $\mathcal{O}(10-30\%)$ for the BSM Higgs states
  $\Rightarrow$ room for improvement in the precision of the Higgs decay widths