Working Group 3: NMSSM Subgroup

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Conveners

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LHCHXSWG Meeting

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Outline

- Benchmark points for Higgs pair production
- Benchmark planes
- Electroweak corrections to NMSSM Higgs boson decays

Benchmark Points for Higgs Pair Production

Based on ommon work by Philipp Basler, Ulrich Ellwanger, Margarete Mühlleitner

- **Higgs sector of the CP-conserving NMSSM:**
  - 3 neutral scalars H_i: the SM Higgs H_{SM}, an MSSM-like scalar H_{MSSM}, a mostly $SU(2)$ singlet-like scalar H_S
  - 2 neutral pseudoscalars A_j: an MSSM-like pseudoscalar A_{MSSM}, a mostly $SU(2)$ singlet-like pseudoscalar A_S

- **Trilinear Higgs couplings:**

  The (dimensionful) trilinear couplings $H_{\text{MSSM}} - H_S - H_{\text{SM}}$ and $A_{\text{MSSM}} - A_S - H_{\text{SM}}$ can be particularly large (since not suppressed by the $SU(2)$ symmetry)

- **Branching ratios:**

  BRs for $H_{\text{MSSM}} \to H_S + H_{\text{SM}}$ and $A_{\text{MSSM}} \to A_S + H_{\text{SM}}$ can be dominant

  (which would suppress the BRs into $\tau\tau$, used for standard searches of H_{MSSM} and A_{MSSM})

Benchmark Points for Higgs Pair Production

- **MSSM-like exclusion limits:** in the $M_A - \tan\beta$ plane do not hold in the NMSSM

- **Searches**

  $$ggF \to H_{\text{MSSM}}/A_{\text{MSSM}} \to H_S/A_S + H_{\text{SM}} \to xxxx \quad \text{with } xxxx = bbbb, bb\gamma\gamma, bb\tau\tau$$

  (possibly) more can be promising

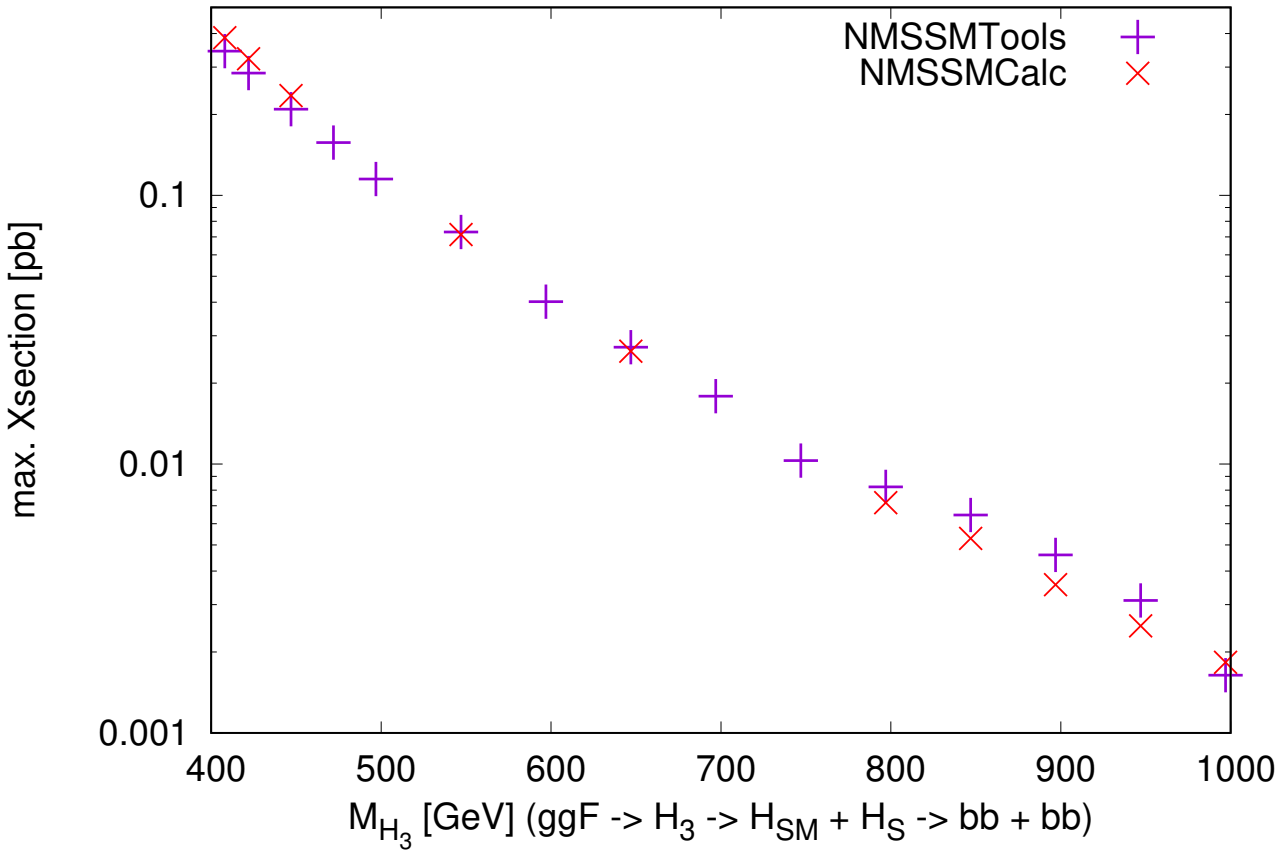
How large can these cross sections be within the viable parameter space of the NMSSM?
Benchmark points/planes are needed!

- **Search for maximal cross sections** using `NMSSMCALC/NMSSMTools` imposing constraints from `HiggsBounds/HiggsSignals`, DM relic density/direct detection experiments, B-physics

  Production cross sections for $H_{\text{MSSM}}/A_{\text{MSSM}}$ decrease with their mass. BRs for the subsequent decays depend little on the mass of H_S/A_S.

Process $ggF \to H_{\text{MSSM}} \to H_S + H_{\text{SM}} \to bbbb,\ bb\tau\tau,\ \tau\tau bb$

Possible cross sections for $bbbb$ in the NMSSM as function of the mass of $H_3 \equiv H_{\text{MSSM}}$ for $M_{H_S} \sim 100 - 110$ GeV



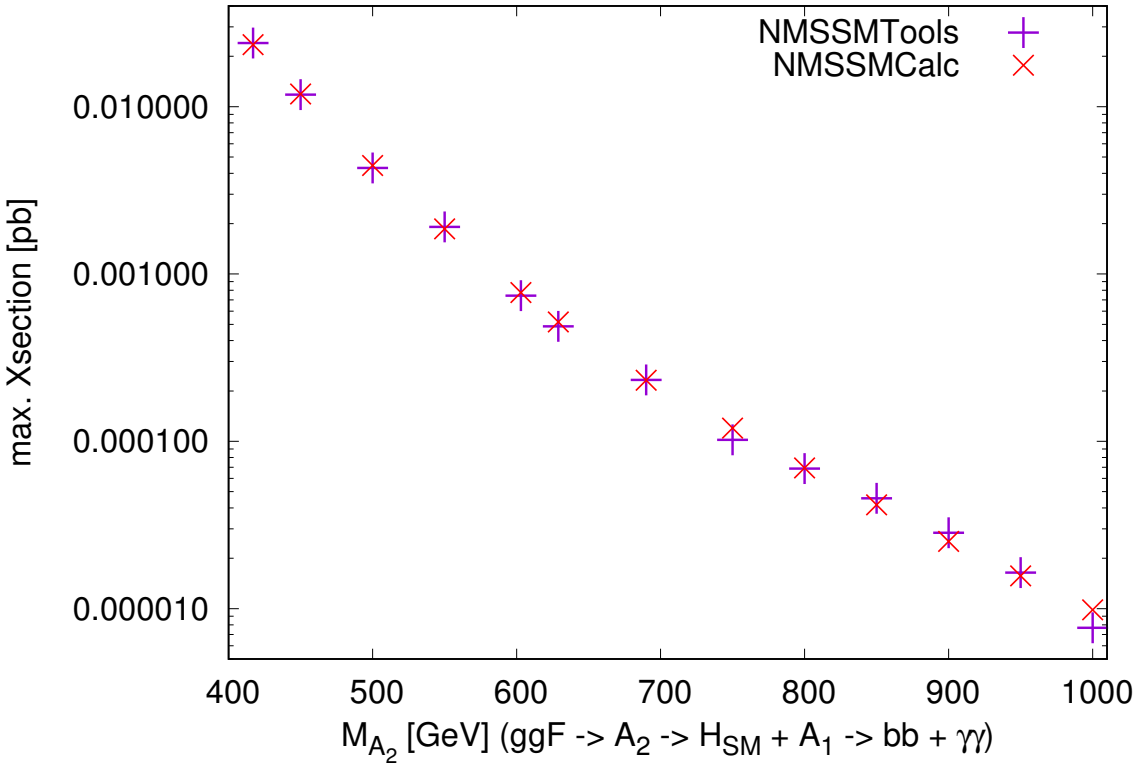
The largest possible cross sections for $bbbb$, $bb\tau\tau$, $\tau\tau bb$ are achieved for the same benchmark points as the branching ratios of H_{SM}, H_S into bb and $\tau\tau$ are always proportional to each other ($\sim 1 : 1/10$).

Process $ggF \to A_{\text{MSSM}} \to A_S + H_{\text{SM}} \to \gamma\gamma bb$

(Nearly) pure singlet-like pseudoscalar A_S has tiny tree-level couplings to SM particles but possibly a large coupling λ to charged higgsinos

$\to$ Higgsino-loop induced coupling of A_S to $\gamma\gamma$ can be dominant, imply BR($A_S \to \gamma\gamma$) up to $\sim 90\%$

$\to$ Astonishingly large (possible) cross section into $\gamma\gamma + bb$



Here $M_{A_S} \sim 147 - 180$ GeV; somewhat smaller possible cross sections for the full possible range $M_{A_S} \sim 1$ GeV $- (M_{A_{\text{MSSM}}} - 125$ GeV)

General Remarks

* The considered final states are the same as considered in searches for (resonant) Higgs pair production.
* However, these searches would miss the present scenarios if the singlet-like scalar/pseudoscalar masses differ considerably from 125 GeV.
* Here the signal depends on two unknown masses, the searches are slightly more involved compared to resonant SM Higgs pair production; proposals for searches involving sliding windows have been made in [U. Ellwanger, M. Rodriguez-Vazquez, 1707.08522].
* Similar processes would also be possible in non-SUSY extensions of the Higgs sector involving two Higgs doublets plus a singlet.

Benchmark Planes

- **MSSM Higgs sector:** at tree level described by M_A, $\tan\beta$
- **NMSSM Higgs sector:** at tree level described by (CP-conserving)

$$t_{h_u}, t_{h_d}, t_{h_s}, e, M_W^2, M_Z^2, \tan\beta, M_{H^\pm}^2/A_\lambda, \lambda, \kappa, v_s, A_\kappa$$

- complex relations between input parameters and masses/mixing angles diagonalizing mass — matrices ($\leftarrow$ enter the couplings)

- **How to get meaningful benchmark planes?:** not much progress; possible approaches

  * scan parameter space to get all possible results for given observable and plot its minimum/maximum values for one varying parameter
  * identify input parameters with largest impact on a given observable (not obvious)
  * restriction to NMSSM subspace where simple relations among masses/mixing angles and parameters hold or reduction of parameter space through reasonable assumptions
    ▷ 'Natural NMSSM' [King eal '14]
    ▷ GUT constraints; decoupling limit $m_{H_3} \approx m_{A_2} \approx m_{H^\pm}$ [Beskidt,de Boer '19]
    ▷ Alignment of the $H^{\rm SM}$ [Baum,Shah,Freese '19] ...
  * ... *input welcome!*

Role of Precision Physics

Hadron Collider Phenomenology:

direct production of new particles $\rightarrow$ precision physics and indirect searches

- **Precision in theory predicions of Higgs observables indispensable:**
  - SM-like behaviour of discovered Higgs $\rightsquigarrow$ small indirect new physics effects
  - identification of underlying model $\leftarrow$ different new physics models lead to similar effects

The CP-Violating NMSSM Higgs Sector

- **Higgs Sector:** 2 Higgs doublets and 1 complex singlet

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

- **Higgs interaction states mix:** Mass term

$$\mathcal{L}^m_{\text{neutral}} = \frac{1}{2} \phi^T M_{\phi\phi} \phi \, , \quad \phi = (h_d, h_u, h_s, a_d, a_u, a_s)$$

mass eigentstates $h_1, ..., h_5$ with $m_{h_1} \leq ... \leq m_{h_5}$

- **Input parameters of the CP-violating Higgs sector:**

$$m^2_{H_d}, m^2_{H_u}, m^2_S, M^2_W, M^2_Z, e, \tan\beta, v_s, \varphi_s, \varphi_u, |\lambda|, \varphi_\lambda, |\kappa|, \varphi_\kappa, \Re A_\lambda, \Im A_\lambda, \Re A_\kappa, \Im A_\kappa$$

Status of the Mass Corrections

- **CP-conserving NMSSM:**
  - Full one-loop corrections, including momentum dependence
    [Ellwanger; Elliott eal; Pandita; Ellwanger,Hugonie; Degrassi,Slavich ($\overline{\text{DR}}$); Staub eal ($\overline{\text{DR}}$); Ender eal (mixed OS-$\overline{\text{DR}}$); Drechsel eal (mixed OS-$\overline{\text{DR}}$)]
  - Two-loop at $p^2 = 0$ at $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s)$ [Degrassi,Slavich] and beyond [Goodsell eal] ($\overline{\text{DR}}$)

- **CP-violating NMSSM:**
  - Full one-loop corrections, including momentum dependence
    [Ham eal; Cheung eal; Graf eal; MMM eal; Domingo eal]
  - Two-loop at $p^2 = 0$ at $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ [Nhung eal; Dao eal] for mixed OS-$\overline{\text{DR}}$ scheme and with OS or $\overline{\text{DR}}$ renormalization in the top/stop sector
    and automized ($\overline{\text{DR}}$) [Goodsell,Staub; Goodsell,Paßehr]

Codes for NMSSM Higgs Decays

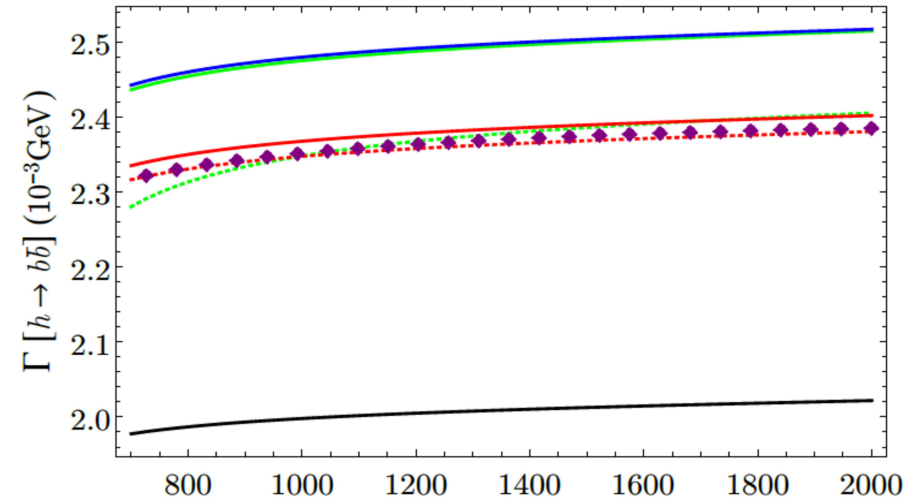
- **Decay Codes**
  - `NMSSMTools` - CP-conserving, recently CP-violating NMSSM [Ellwanger eal; Domingo] (includes dominant QCD corrections)
  - `NMSSMCALC` - CP-conserving and CP-violating NMSSM [Baglio eal] (includes dominant QCD and Δ_b corrections)
  - generic one-loop corrected two-body decays in the $\overline{\text{DR}}$ ($\overline{\text{MS}}$) scheme [Goodsell eal] implemented in `SPHENO` [Porod; Porod,Staub; Goodsell eal] and `SARAH` [Staub]
  - `SloopS` (not public) one-loop NMSSM Higgs decays [Bélanger eal]

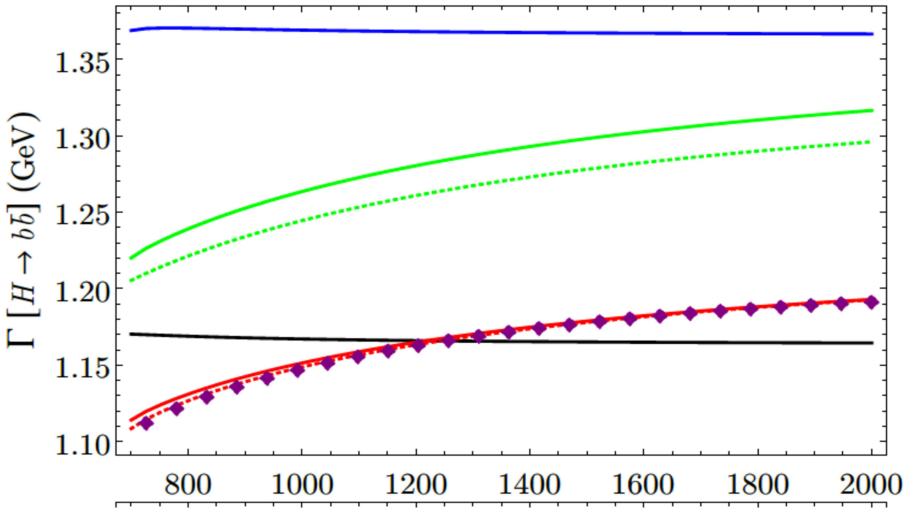
- **New Developments:**
  - `FeynHiggs` group: Full one-loop decay widths of neutral Higgs bosons into SM particles including leading QCD corrections in the CP-violating NMSSM [Domingo,Heinemeyer,Paßehr,Weiglein '18; Domingo,Paßehr '19]
  - `NMSSMCALCEW`: Full (SUSY-)EW corrections to neutral Higgs bosons in the CP-violating NMSSM into SM and SUSY particle final states combined with existing (SUSY-)QCD corrections in `NMSSMCALC` [Baglio,Dao,MMM]

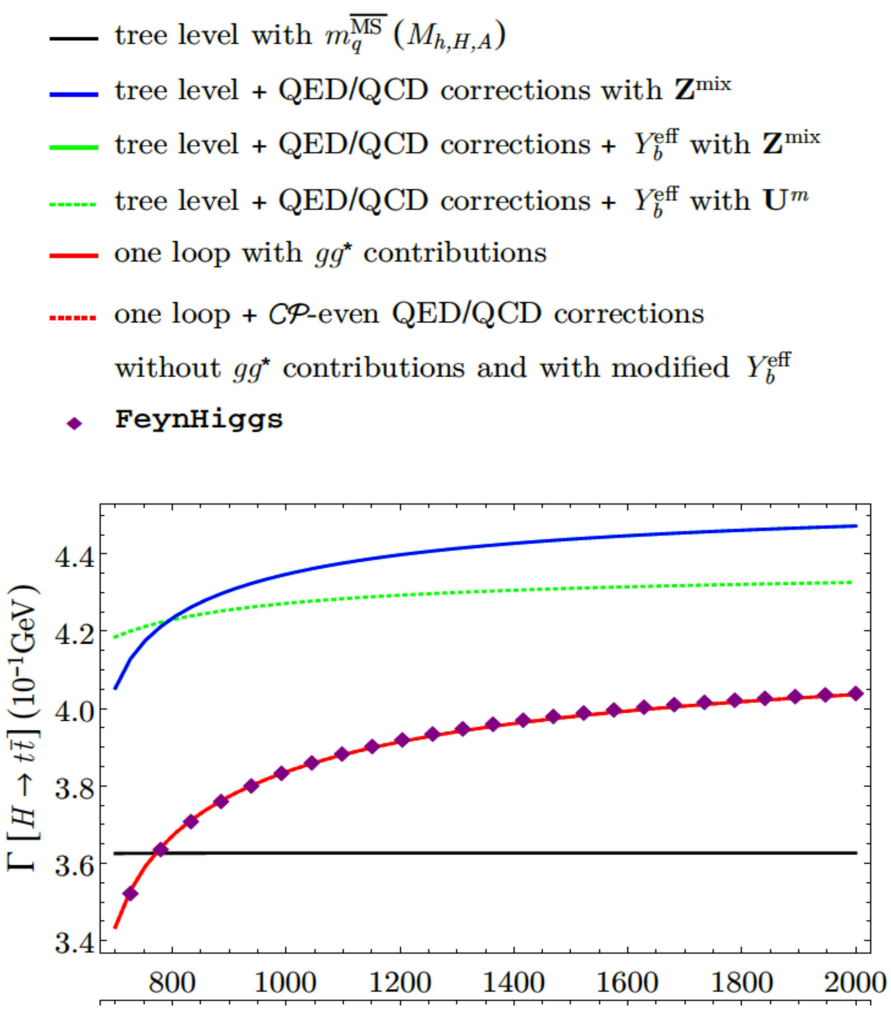
FeynHiggs *Approach*

- **Features:** [Domingo eal, Eur. Phys. J. **C78** (2018) no. 11, 942]
  - external Higgs fields, mixing effects consistently taken into account [Domingo eal; Fuchs,Weiglein]
    self-energies include full one-loop and leading $\mathcal{O}(\alpha_t\alpha_s, \alpha_t^2)$ two-loop corrs. in MSSM approx.
  - fermionic decay channels supplemented by higher-order QCD corrections (also Δ_b corrections)
  - radiatively induced bosonic decay modes include higher-order QCD corrections
  - tree-level estimate of off-shell decay widths into WW/ZZ, full one-loop above threshold
  - discussion of remaining theoretical uncertainties

Comparison with FeynHiggs [Domingo eal]







The Code NMSSMCALCEW

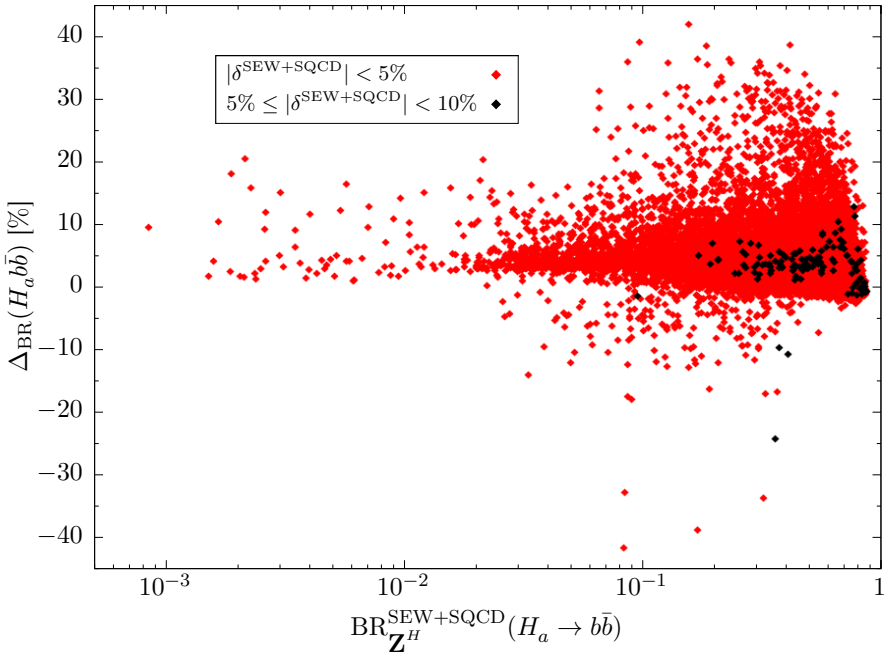
- **Features:** [Baglio, Dao, MMM, arXiv:1907.12060]
  - external Higgs fields, mixing effects consistently taken into account [Domingo eal; Fuchs,Weiglein] self-energies include full one-loop and $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ two-loop corrections [Ender eal; Graf eal; Nhung eal; Dao eal]
  - Complete NLO (SUSY-)electroweak corrections to neutral Higgs decays of the CP-violating NMSSM into on-shell SM final states, gauge plus Higgs boson, Higgs pairs, chargino and neutralino pairs, squarks
  - Combined with (SUSY-)QCD corrections where applicable, Δ_b corrections taken into account
  - radiatively induced bosonic decay modes include higher-order QCD corrections
  - one-loop corrections to the chargino, neutralino, stop and sbottom masses for different renormalization schemes: OS and $\overline{\text{DR}}$

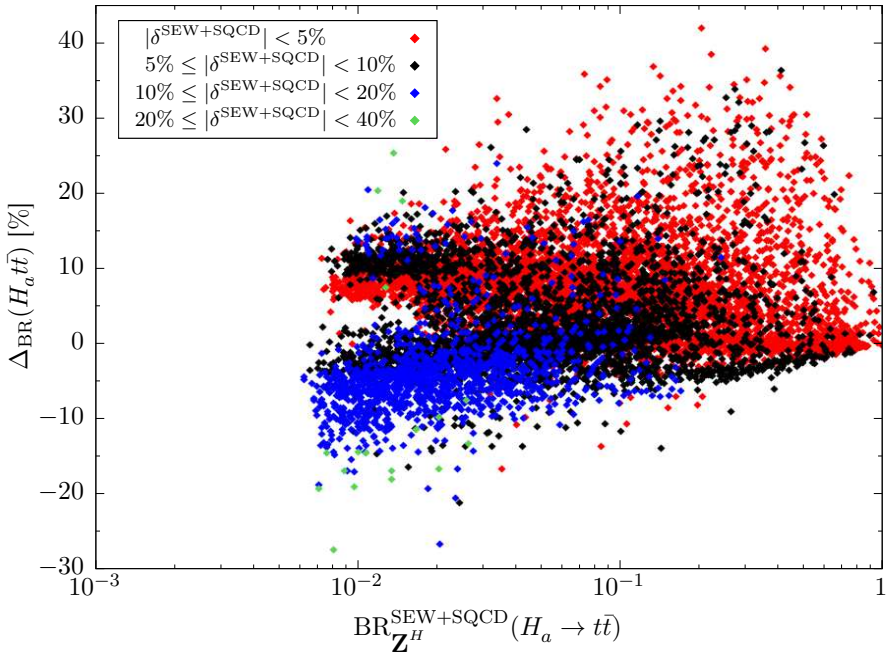
- **Program Code:** available at

  https://www.itp.kit.edu/∼maggie/NMSSMCALCEW/

NMSSMCALCEW: $\mathcal{F}$ermionic $\mathcal{D}$ecays

NMSSMCALCEW [Baglio,Dao,MMM]

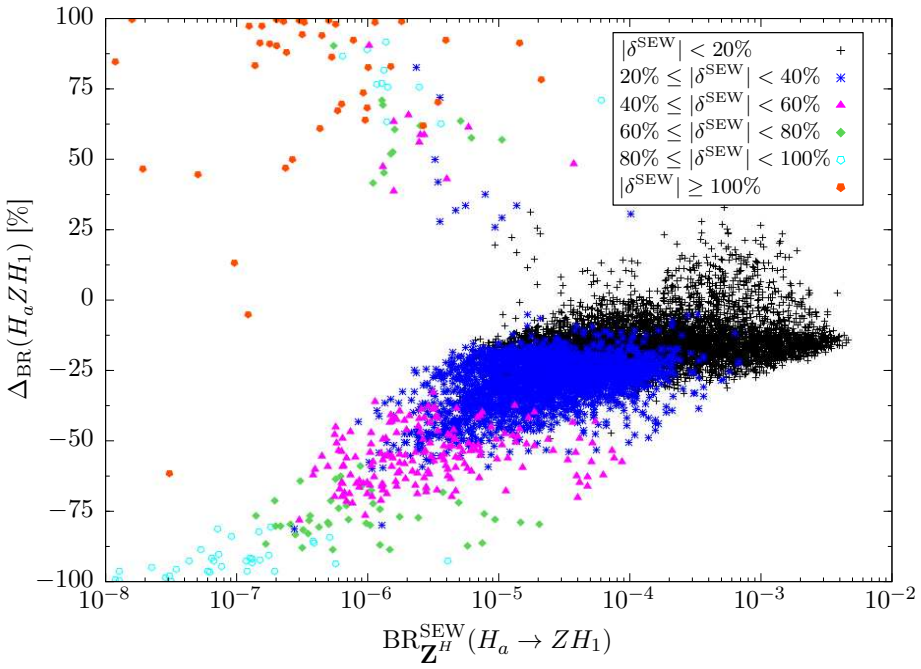


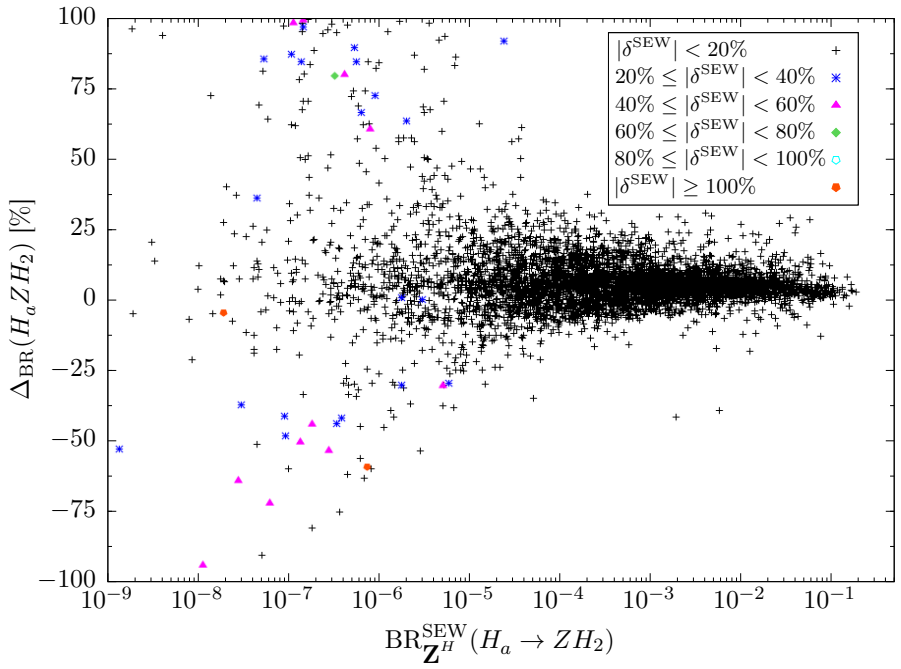


Points from scan in the NMSSM parameter space, check for compatibility with Higgs data [HiggsBounds,HiggsSignals]; $\Delta_{\rm BR}$ quantifies relative difference between NMSSMCALC and NMSSMCALCEW; δ quantifies relative vertex corrections

NMSSMCALCEW: $\mathcal{D}$ecays in $\mathcal{Z}$ plus $\mathcal{H}$iggs

NMSSMCALCEW [Baglio,Dao,MMM]





Points from scan in the NMSSM parameter space, check for compatibility with Higgs data [HiggsBounds,HiggsSignals]; H_1 SM-like, $H_2 \equiv H_{h_s}$

Thank You For Your Attention!