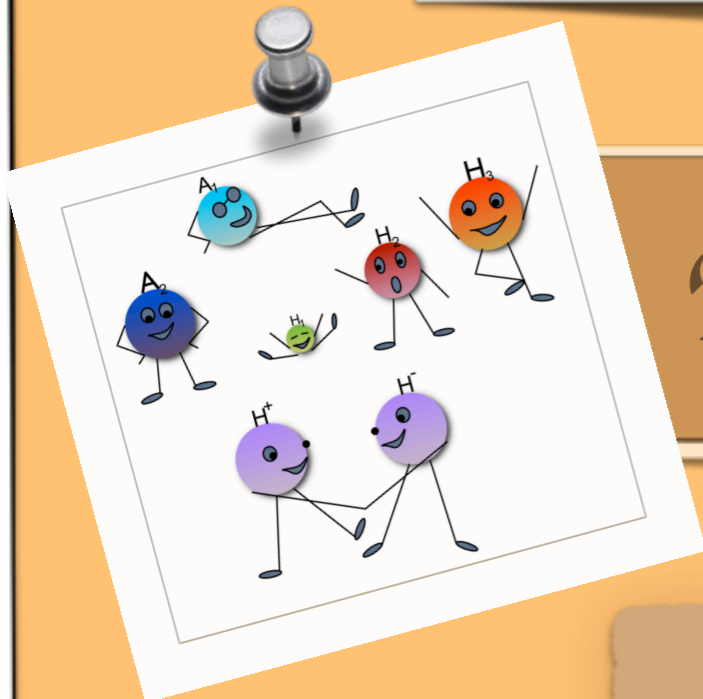


# The 17th Workshop of the LHC Higgs Working Group

## NMSSM Subgroup Updates



M. Margarete Mühlleitner (KIT)

Conveners:

ATLAS: Nikolaos Rompotis

CMS: Janek Bechtel

T: Ulrich Ellwanger, MM, Nausheen Shah

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# Topics

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Precision Physics

Phenomenology

Future Plans

A scenic view of a pond surrounded by lush green trees. The water is calm, reflecting the surrounding foliage. The sky is bright, and the overall atmosphere is peaceful and natural. A decorative box with a white border and a green background is positioned at the top center, containing the text "Precision Physics" in a yellow, cursive font.

*Precision Physics*

# Spectrum Calculations

- ♦ Next-to-MSSM (NMSSM): 2 complex Higgs doublets plus complex singlet field
- ♦ Enlarged Higgs and neutralino sector:

7 Higgs bosons:  $H_1, H_2, H_3, A_1, A_2, H^+, H^-$   
5 neutralinos:  $\tilde{\chi}_i^0$  ( $i = 1, \dots, 5$ )

also used conventions:  
 $h_{125}, H, h, A, a$   
or  
 $h_{SM}, H, h_s, A, a_s$

- ♦ MSSM and NMSSM masses computed from input parameters: predictive power of the MSSM, NMSSM and other extensions -> important experimental test to be passed

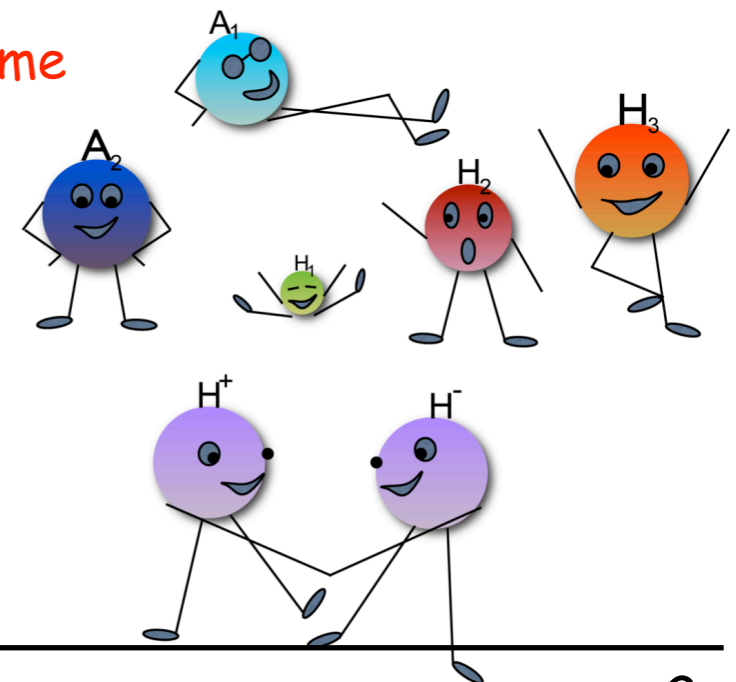
- ❖ Status MSSM spectrum calculations:

FO: up to 2-loop in on-shell (OS) and DR scheme, partial 3-loop in DR scheme

EFT: up to  $N^2LL$  (included in calculators),  $N^3LL$  (recently [Harlander et al., '18])

- ❖ Status NMSSM spectrum calculations:

up to 2-loop in mixed OS-DR scheme and in DR-scheme



taken from  
[Staub,Athron,  
Ellwanger,Gröber,  
MM,Slavich,  
Voigt,'15]

recent  
developments

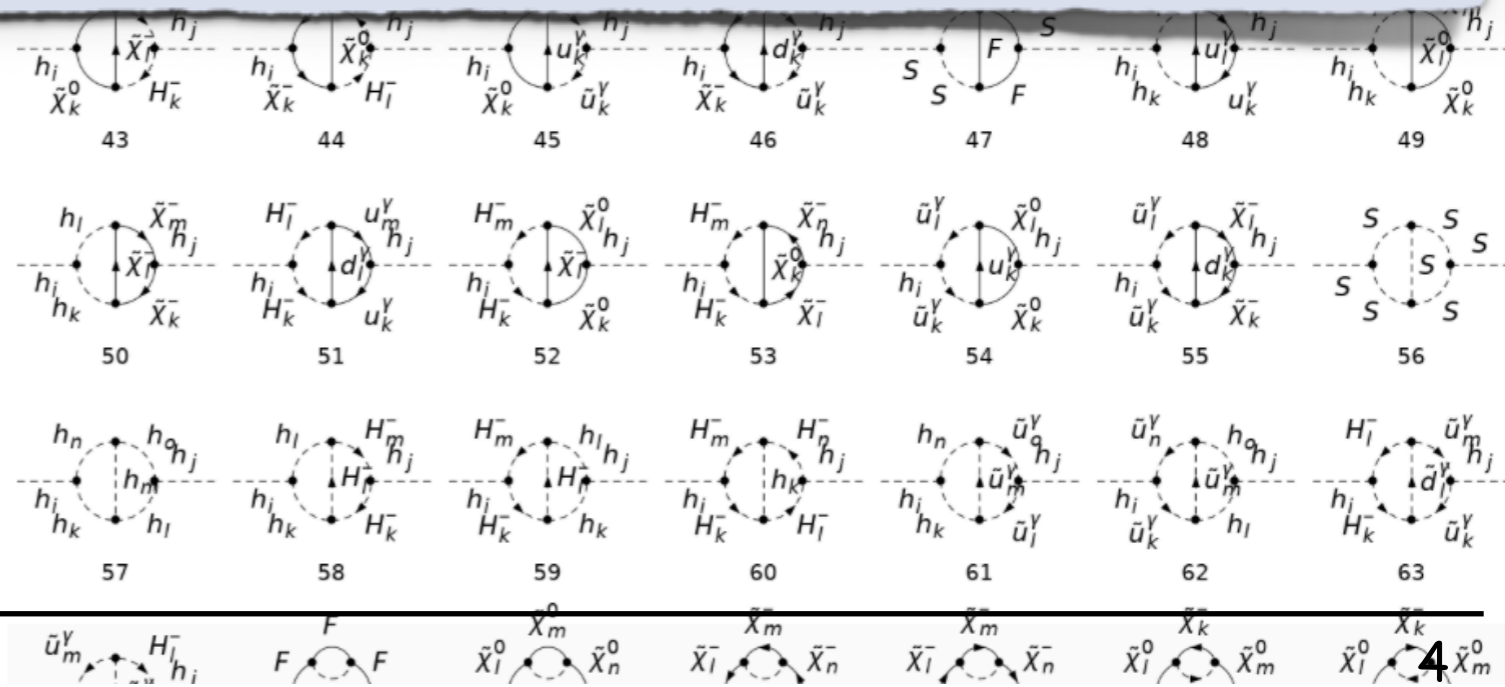
recent  
developments

	FlexibleSUSY	NMSSMCALCEW	NMSSMTools	SOFTSUSY	SPheno
Code					
type	using SARAH	stand alone	stand alone	stand alone	using SARAH
language	C++	Fortran 77 and 90	Fortran 77	C++	Fortran 90
Models					
No $Z_3$	✓	✗	✓	✓	✓
GUT model	✓	✗	✓	✓	✓
CPV	(✓)	✓	✓	✗	✓
Thresholds					
scale(s)	$M_Z$	$M_t, M_{SUSY}$	$M_t, M_{SUSY}$	$M_Z$	$M_Z$
EW parameters	full one-loop	OS definitions	full one-loop	full one-loop	full one-loop
Yukawas	full one-loop; two-loop QCD	one-loop (S)QCD; two-loop QCD	one-loop (S)QCD+Yukawa; two-loop QCD	full one-loop; two-loop QCD; optionally two-loop SQCD	full one-loop two-loop QCD
strong gauge	one-loop top+SUSY	—	—	one-loop top+SUSY	one-loop top+SUSY
Higgs mass calculation					
scheme	$\overline{DR}$	OS, $\overline{DR}$	$\overline{DR}$	$\overline{DR}$	$\overline{DR}$
one-loop	full	full	full	full	full
two-loop	$\alpha_s(\alpha_b + \alpha_t)$ + MSSM	$\alpha_s\alpha_t$ $\alpha_t^2$	$\alpha_s(\alpha_b + \alpha_t)$ + MSSM	$\alpha_s(\alpha_b + \alpha_t)$ + MSSM	$\alpha_s\alpha_i + \alpha_i\alpha_j$
SUSY masses					
one-loop	✓	✓	✓	✓	✓
momentum effects	✓	✗	✓ ( $\alpha_s, \alpha_t, \alpha_b$ only)	✓	✓
Other observables					
decays	✗	✓	via NMHDECAY	via NMHDECAY	✓
flavour, $g-2$	✗	✗	✓	✗	✓

# NMSSM Spectrum Calculators

## Remarks:

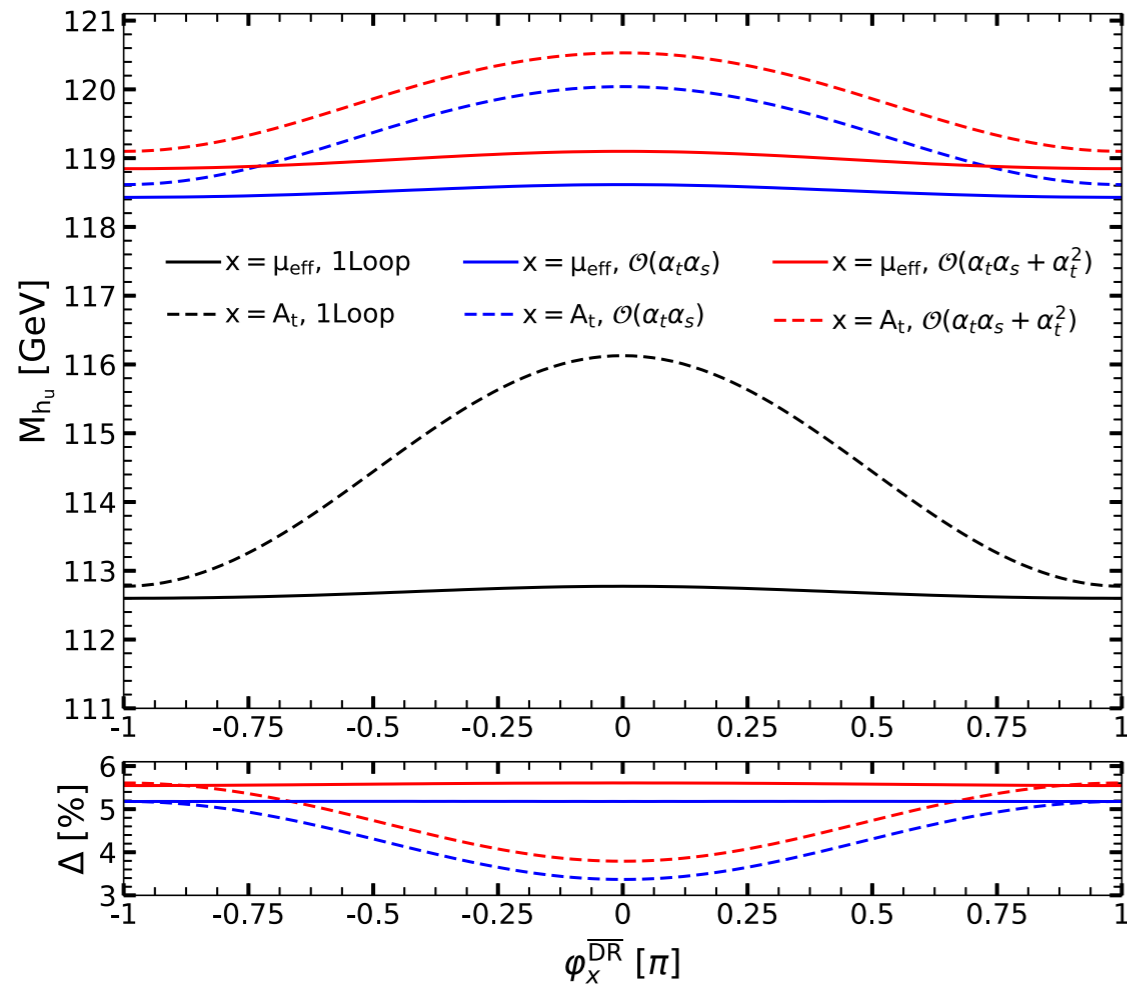
- comparison of codes in DR scheme: [Staub,Athron,Ellwanger,Gröber,MM,Slavich,Voigt,'15]  
FlexibleSUSY,NMSSMCALC,NMSSMTools,SOFTSUSY,SPheno
- comparison of codes in mixed OS-DR scheme: [Drechsel,Gröber,Heinemeyer,MM,Rzehak,Weiglein,'16]  
FeynHiggs, NMSSMCALC
- advances in FeynHiggs: [Drechsel,Galeta,Heinemeyer,Hollik,Liebler,Moortgat-Pick,Paßehr,Weiglein]  
real&complex NMSSM, GNMSSM: 1-loop in, 2-loop&resummation of HO log-effects only in  
MSSM limit, no public code yet
- **solution of Goldstone boson catastrophe** [Braathen,Goodsell,'16], [Braathen,Goodsell,Staub,'17]
- **OS masses CP-violating NMSSM, consistent description production/decay** [Domingo,Drechsel,Paßehr,'17]



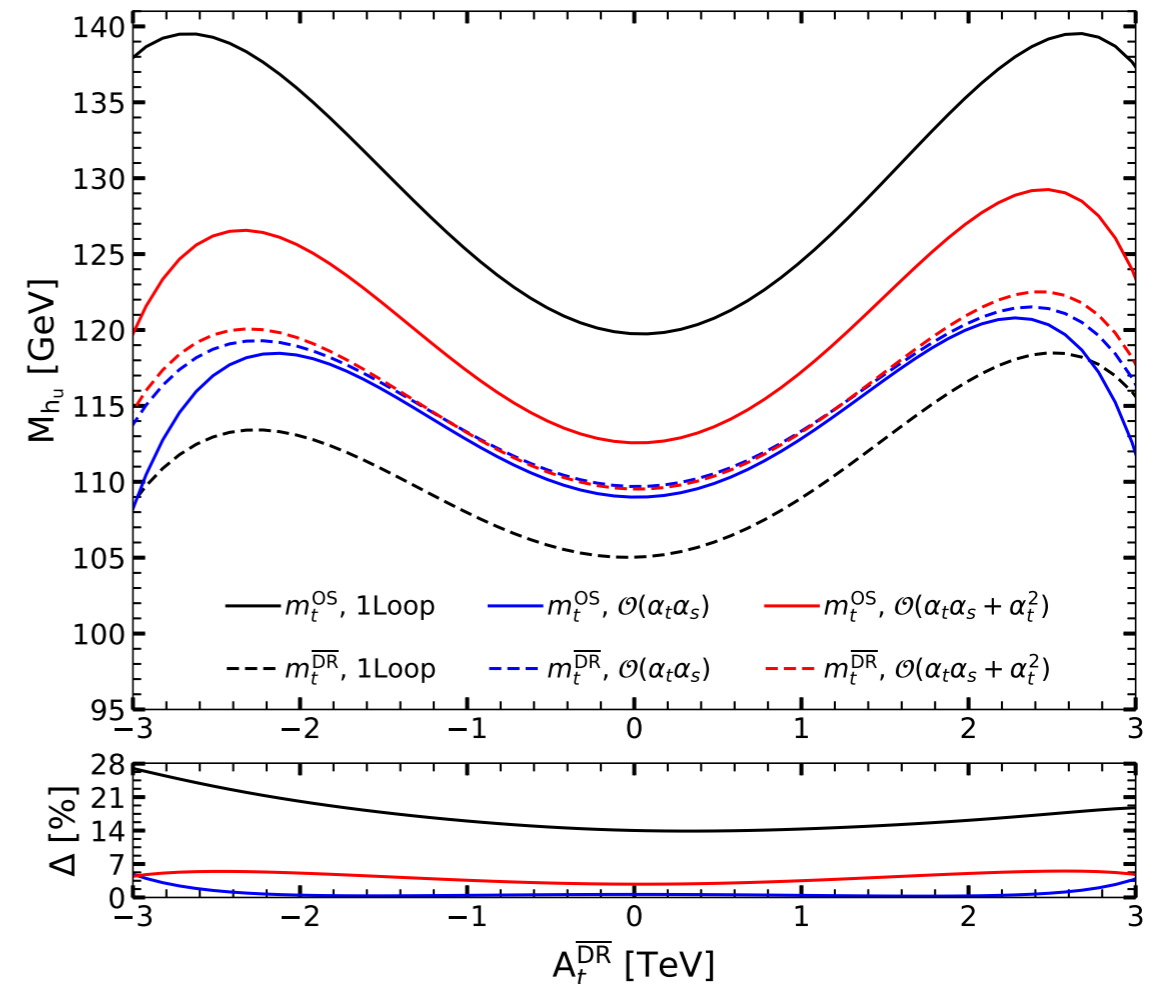
# Results for $O(\alpha_t^2)$ Corrections

[Dao,Gröber,Krause,MM,Rzehak, JHEP08 (2019) 114]

Size of relative corrections



Renormalization scheme dependence



\* tree-level CP-violating phase kept zero

$$* \Delta = \frac{|M_{h_u}^{(2,x)} - M_{h_u}^{(1)}|}{M_{h_u}^{(1)}} \text{ and } x = O(\alpha_t \alpha_s), O(\alpha_t \alpha_s + \alpha_t^2)$$

$$* \Delta = \frac{|M_{h_u}^{m_t(\overline{\text{DR}})} - M_{h_u}^{m_t(\text{OS})}|}{M_{h_u}^{m_t(\overline{\text{DR}})}}$$

# NMSSM (& Generic) Decay Calculators

- [SoftSUSY](#) [Allanach,Athron,Bednyakov,Tunstall,Voig,RuizdeAustri,Williams]: [MSSM & NMSSM](#); 1->2 tree-level Higgs into {Higgs/sparticles/SM} particles and Sparticles into {Higgs},  $h \rightarrow Vff$  at tree level, MSSM/NMSSM Higgs  $\rightarrow gg, qq$  at NLO QCD, MSSM  $\rightarrow \nu\nu, Z\nu$  at NLO QCD
- [NMSSMCALC](#) [Baglio,Gröber,MM,Nhung,Rzehak,Spira,Streicher,Walz]: [CP-conserving and CP-violating NMSSM](#) state-of-the-art HO QCD corrections from latest HDECAY version,  $\Delta_b, \Delta_s, \Delta_\tau$  corrections  $b, \tau, s$  final states, all relevant off-shell into  $WW/ZZ, ZH_i, WH^+, H_i H_j, tt$ ; also effective couplings output;  
[new: NMSSMCALCEW](#) [Baglio,Dao,MM,'19], see next slide
- [NMSSMTools](#) [Ellwanger,Hugonie]: [NMSSM](#); HO QCD corrections à la HDECAY, but no 3-body decays, new: updated QCD corrections to  $H \rightarrow gg$  from HDECAY [1801.09506]; constraints on reduced Higgs couplings in  $\kappa$  framework from ATLAS [1909.02845] CMS [1809.10733]; checks for DM relic density and regularly updated constraints on DM direct detection using MicrOmegas; computes also sparticle decays through generalization of SDECAY (MSSM) to NMSSM
- [SloopS](#) [Baro,Boudjema,Semenov]: [MSSM, NMSSM w/ complete one-loop corrections](#); renormalisation in non-linear gauge fixing; different renormalisation schemes; different  $\tan\beta$  definitions
- [SARAH/SPheno](#) [Goodsell,Liebler,Staub]: fully [generic implementation](#) of 2-body decay widths of fermions and scalars at full 1L, see [1703.09237] for details



# Recent Developments

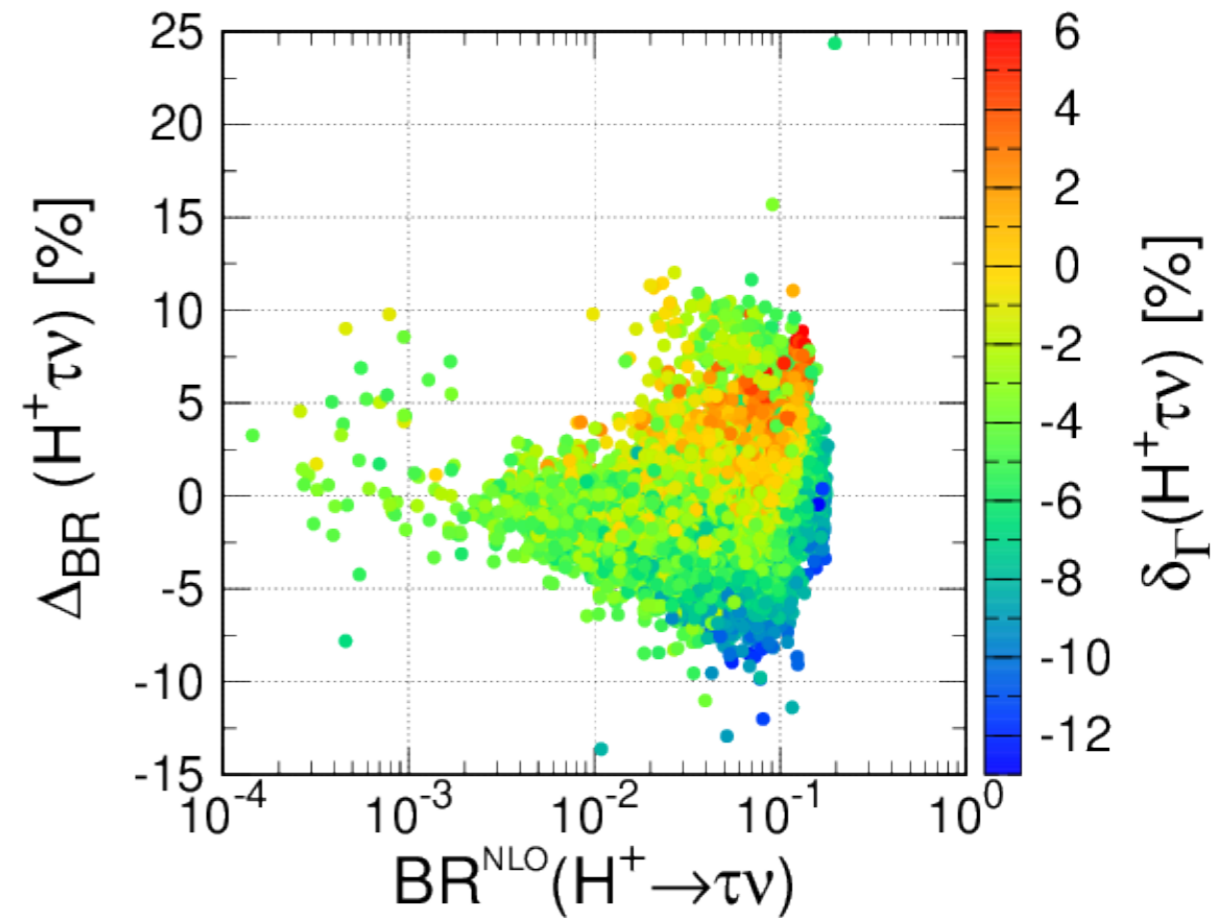
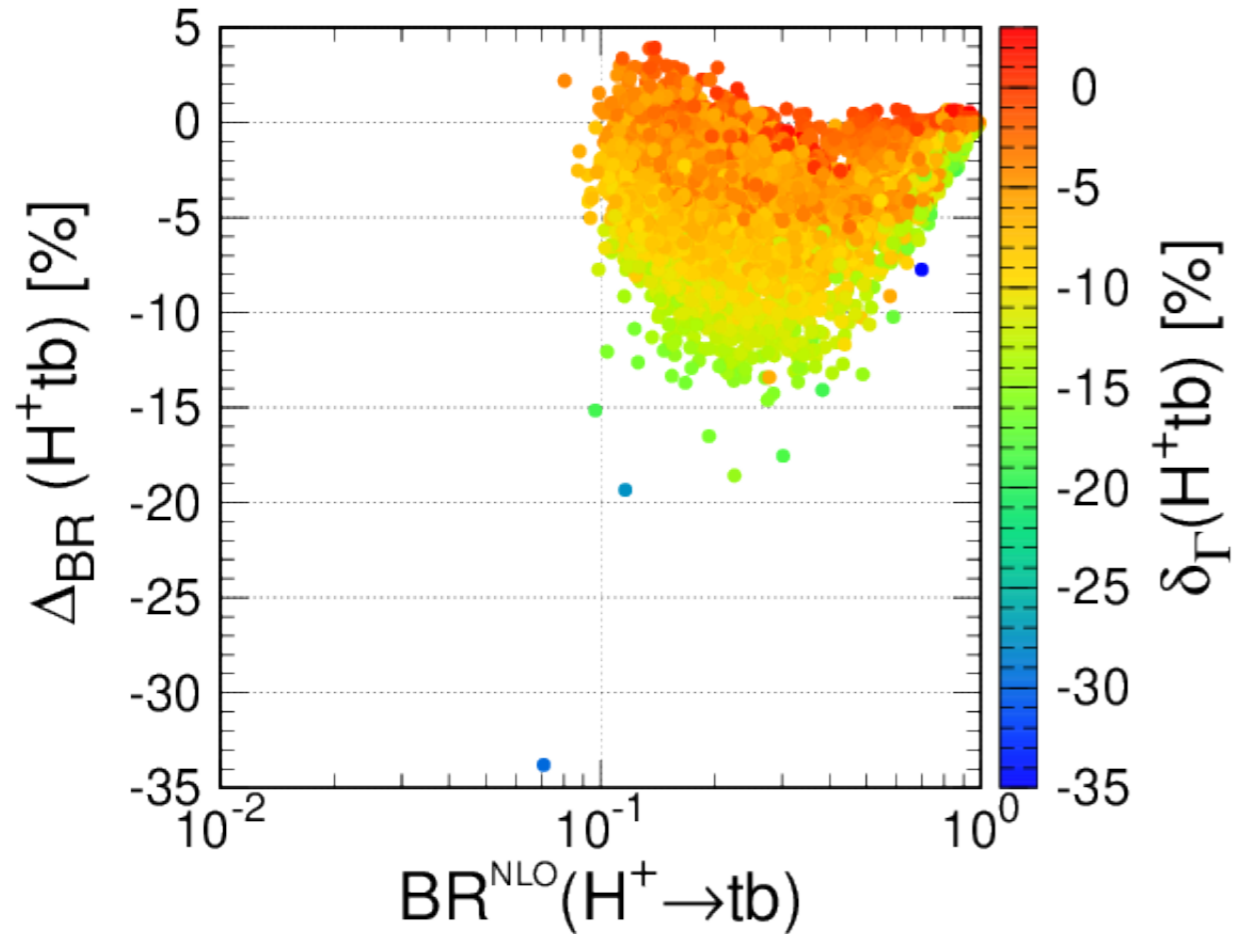
## Remarks:

- Full 1L to NMSSM Higgs decays in fermions and gauge bosons [Domingo,Paßehr,Weiglein,'18]
- EW corrections - effects on heavy NMSSM Higgs fermionic decays [Domingo,Paßehr,'19]
- Gauge dependence in 1L to  $H^+ \rightarrow W^+ H_i$  in NMSSM [Dao,Fritz,Krause,MM,Patel,'19]
- Investigation of possible solutions for the gauge-parameter violating problem in Higgs decays w/ (N)MSSM Higgs mixing effects [Domingo Paßehr,'20]
- **NMSSMCALCEW:** [Baglio,Dao,MM,'19]  
EW, SUSY-EW and SUSY-QCD corrections to neutral Higgs decays in the CP-conserving and CP-violating NMSSM consistently combined w/ QCD and  $\Delta b$ ; one-loop corrections to the electroweakino, stop and sbottom masses included in OS and DR scheme

# NEW: NMSSMCALCEW $H^\pm$ Decays

Preliminary

[Dao,MM,Patel,Sakurai]



$$\Delta_{\text{BR}}(H^\pm XX) = \frac{\text{BR}^{\text{NLO}}(H^\pm \rightarrow XX) - \text{BR}^{\text{LO}}(H^\pm \rightarrow XX)}{\max(\text{BR}^{\text{NLO}}(H^\pm \rightarrow XX), \text{BR}^{\text{LO}}(H^\pm \rightarrow XX))}$$

$$\delta_\Gamma(H^\pm X_i X_j) = \frac{\Gamma(H^\pm \rightarrow X_i X_j)^{\text{NLO}}}{\Gamma(H^\pm \rightarrow X_i X_j)^{\text{LO}}} - 1$$

A lush green forest with a stream in the foreground. The trees are tall and thin, with dense foliage. Sunlight filters through the leaves, creating a dappled light effect. A title box is overlaid on the top center of the image.

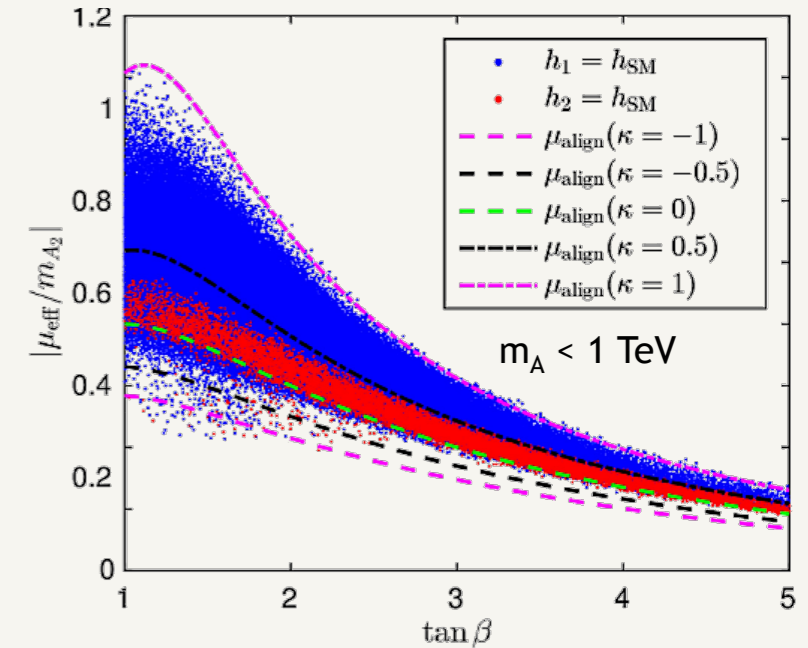
# *Phenomenology*

NMSSM SM-like  $h_{125}$

M. Carena, H. Haber, I. Low, NRS & C. Wagner, 2015

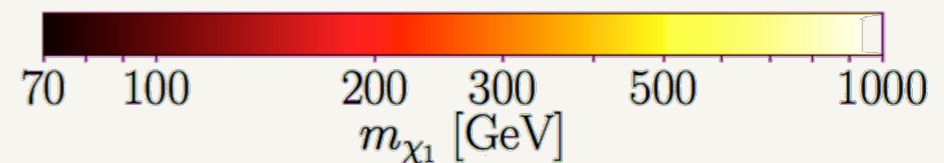
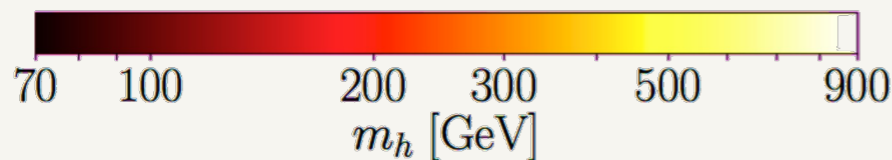
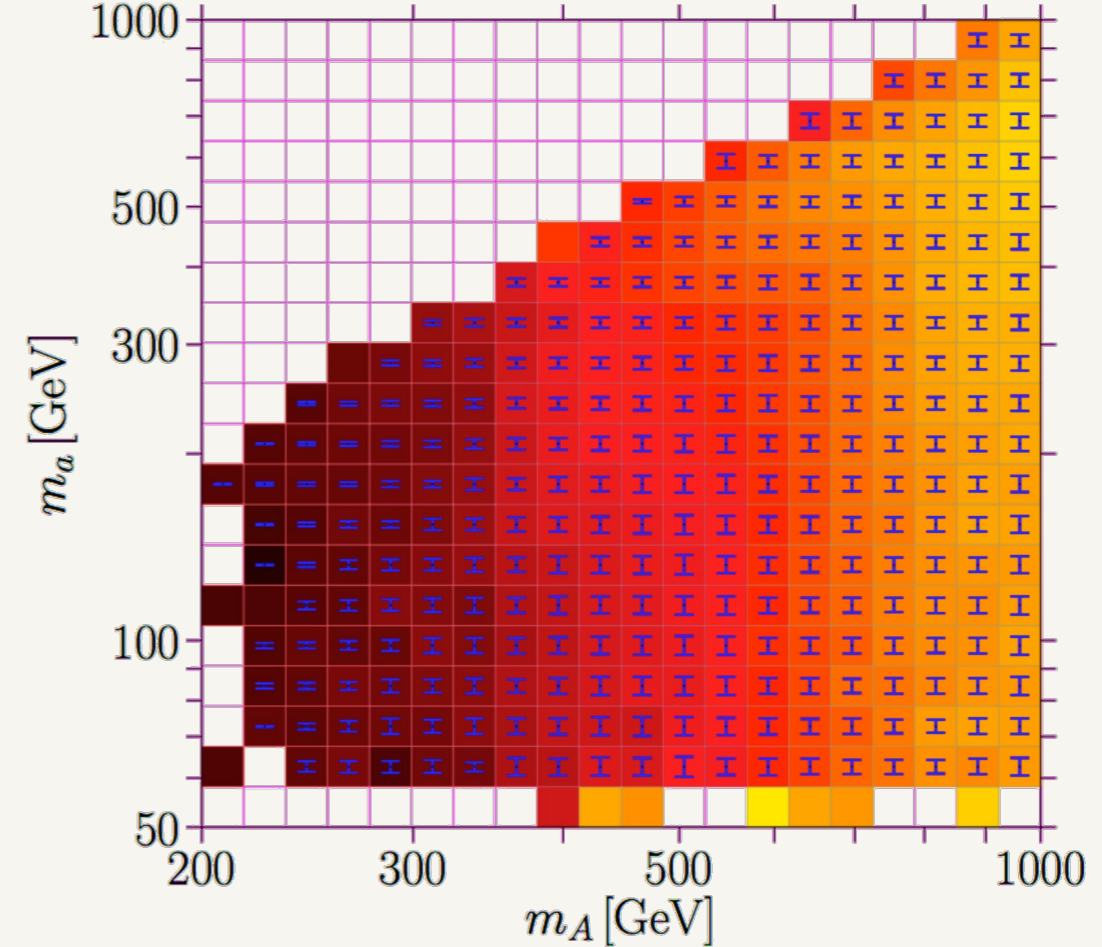
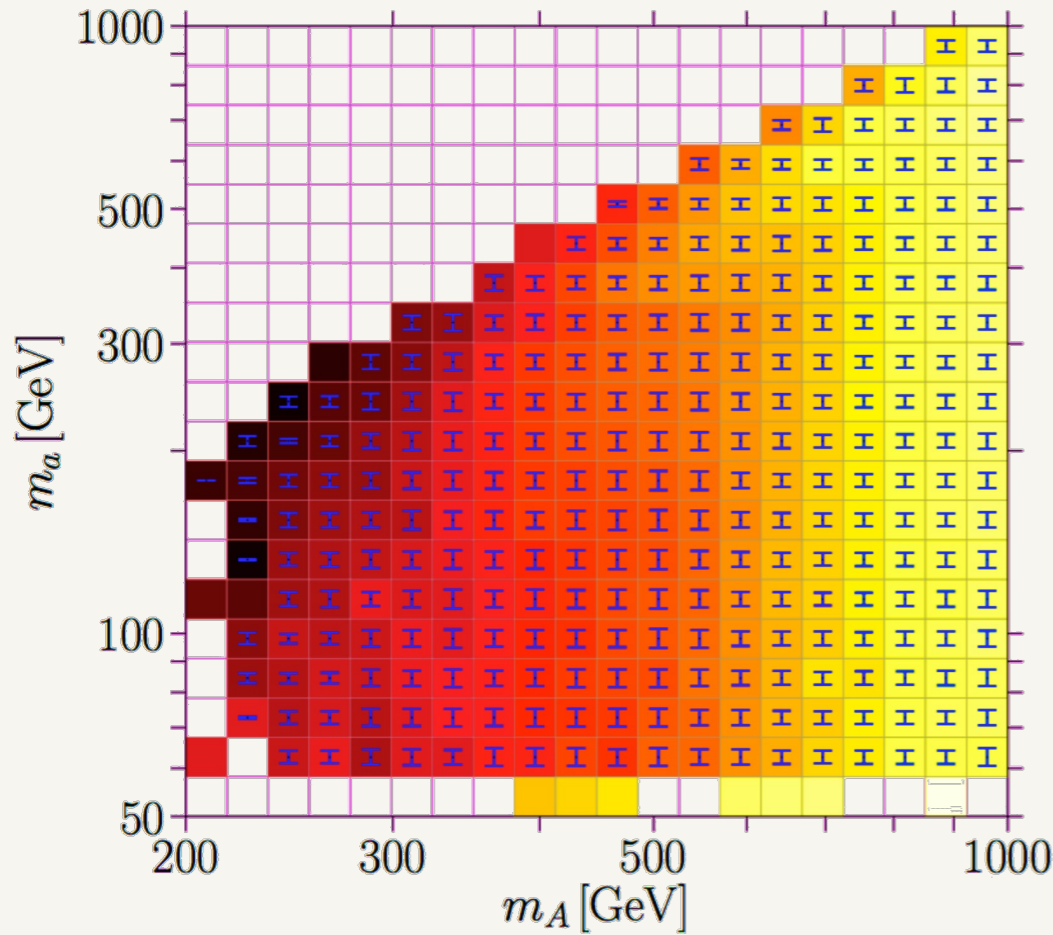
$$\lambda_{\text{alt}}^2 = \frac{m_h^2 - M_Z^2 c_{2\beta}}{v^2 s_\beta^2}$$

$$1 - \frac{m_A^2}{4\mu^2} s_{2\beta}^2 - \frac{\kappa}{2\lambda} s_{2\beta} = 0$$



NMSSMTools scans with consistent  $h_{125}$  phenomenology

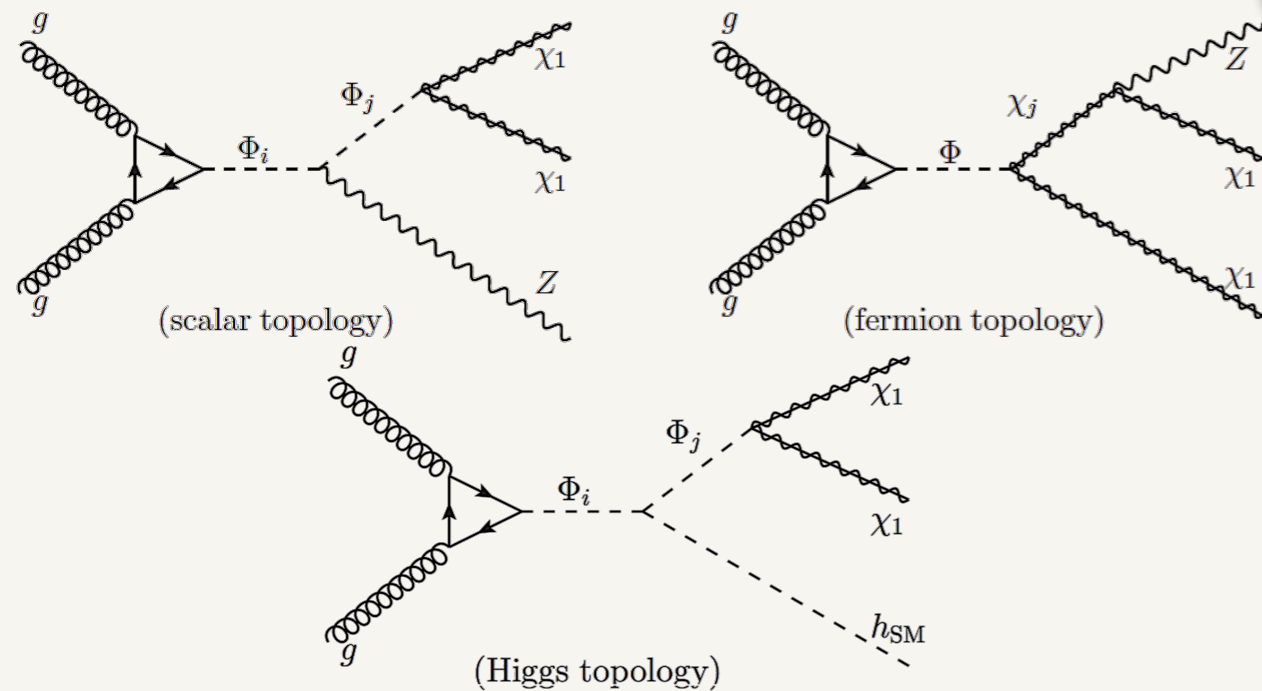
S. Baum, N.R.S., K. Freese, 2019



# 2HDM

$H_{NSM} \rightarrow H_{SM} H_{SM}$  or  $Z H_{SM}$   
suppressed due to alignment

+S



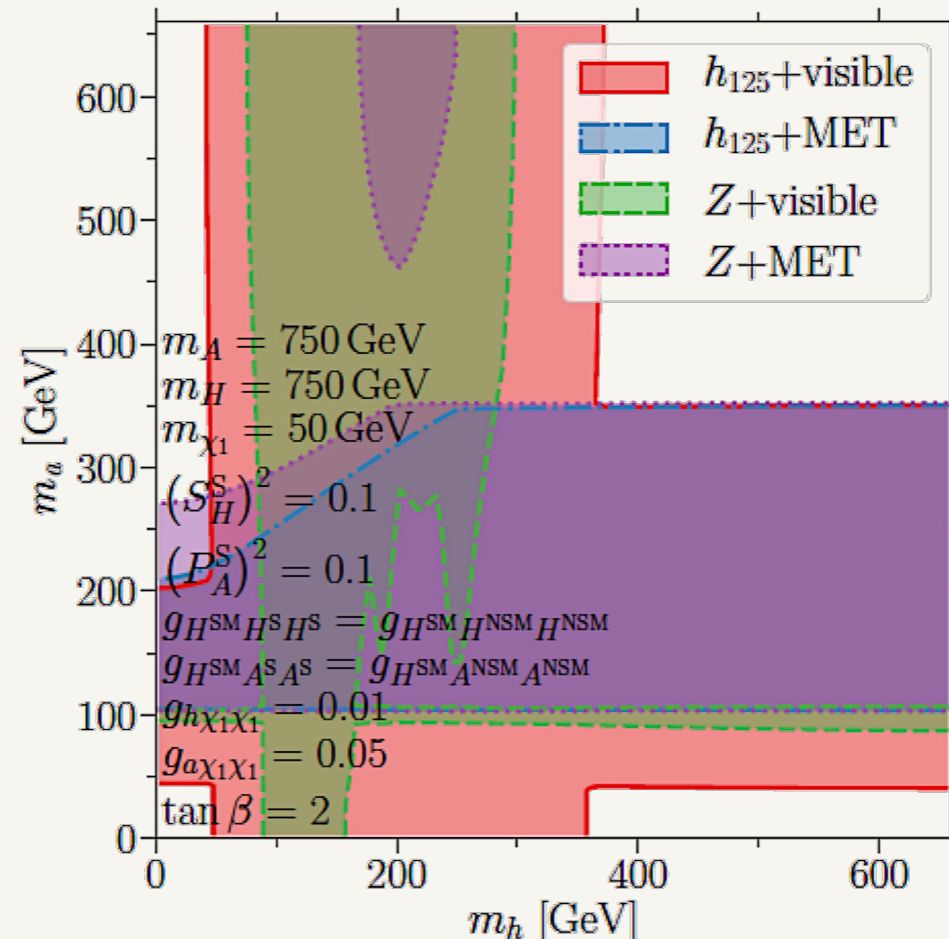
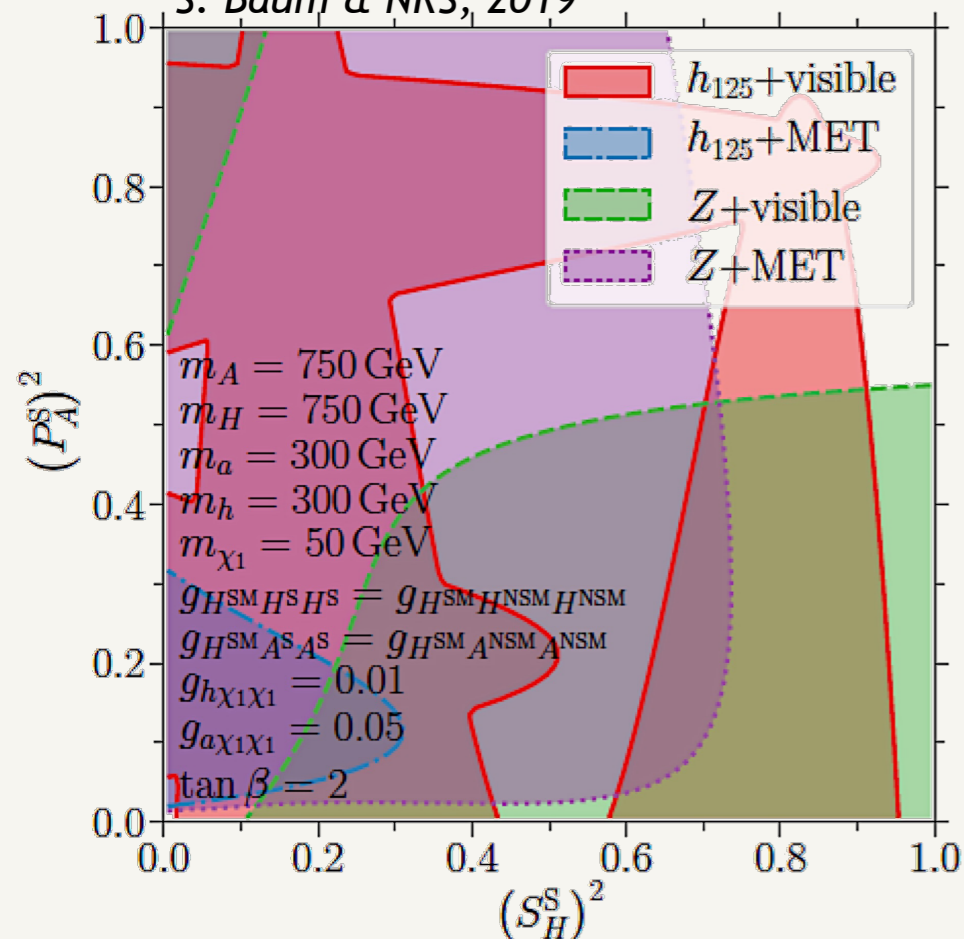
Interesting *cascade* decays due to presence of additional Higgs bosons:

Eg:  $H_{NSM} \rightarrow h_S H_{SM}$  or  $H_{NSM} \rightarrow a_S Z$

Visible (SM) and invisible decays of  $h_S/a_S$

S. Baum & NRS, 2018

S. Baum & NRS, 2019



Future reach of the different Higgs Cascade search modes at the LHC with  $L = 3000 \text{ fb}^{-1}$  of data.

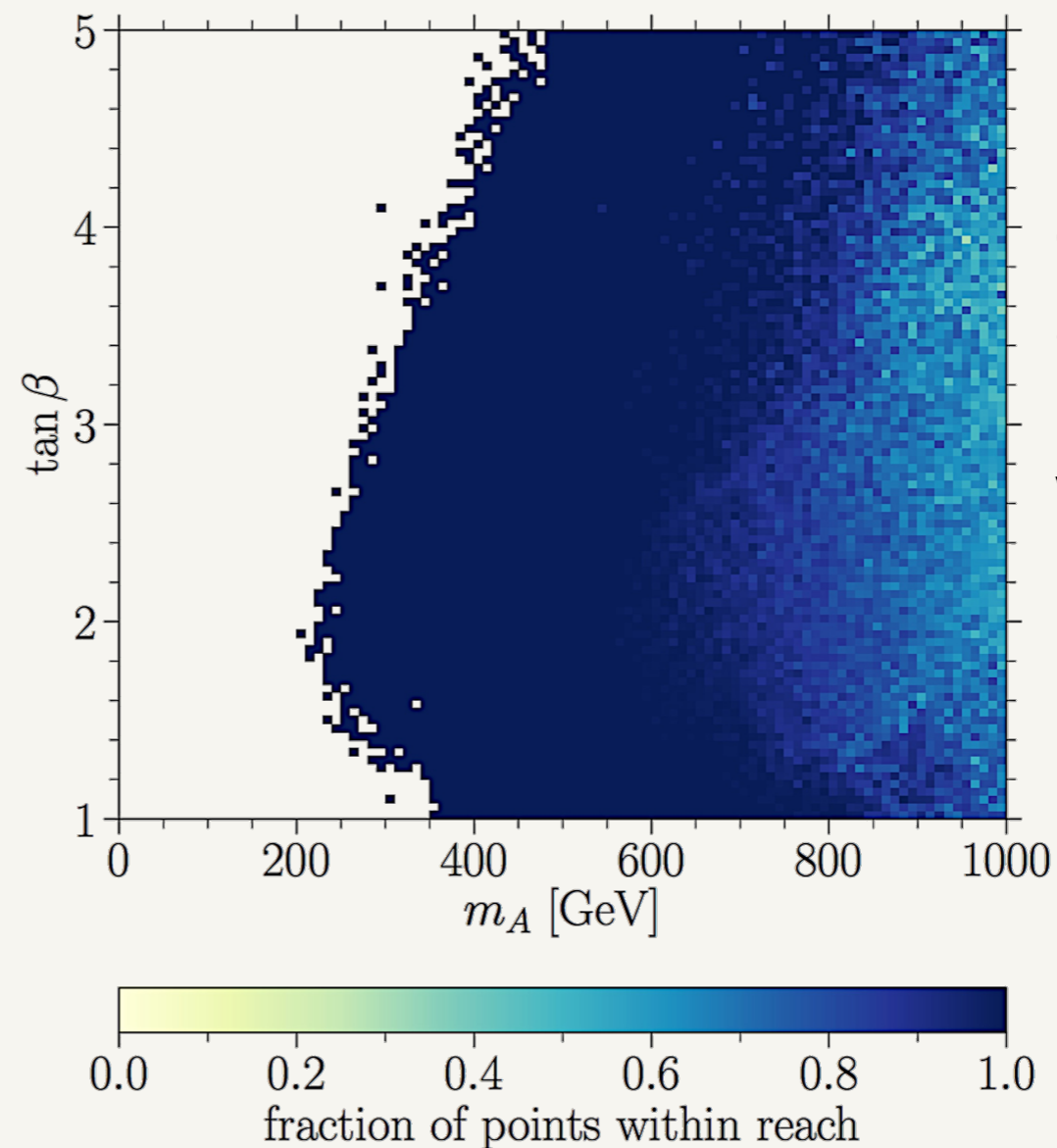
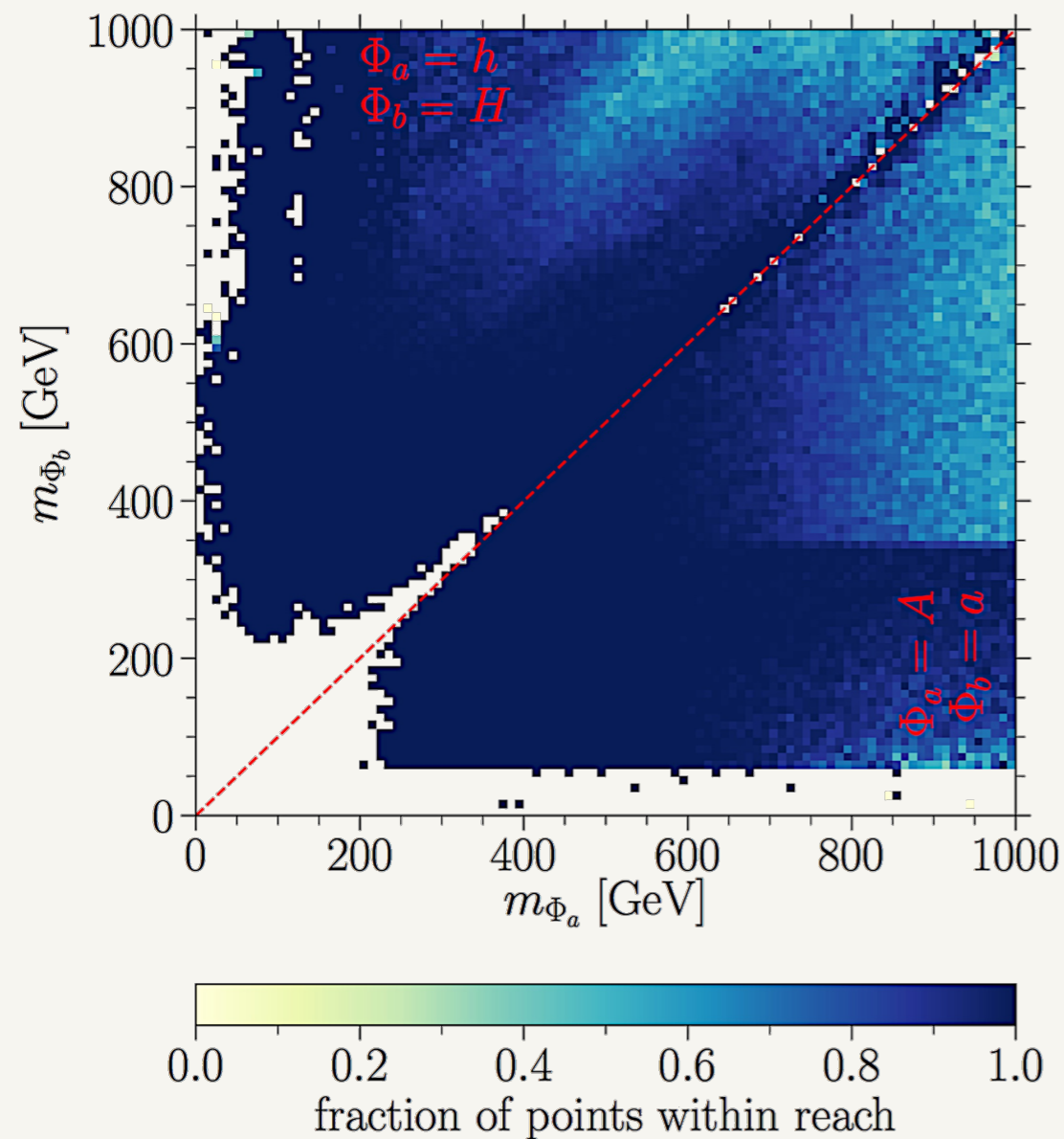


For specific benchmarks in the 2HDM+S & NMSSM,  
see S.Baum,N.R.Shah, 1904.10810

NMSSM: 2HDM+S + SUSY

# Heavy Higgs Direct Searches & Cascades!

S. Baum, NRS & K. Freese, 2019



Optimistic assumptions:  
~90% probed  
with 3000 fb<sup>-1</sup>

$$(\max[\mu_{\text{Curr. Lim.}}^{<37 \text{ fb}^{-1}} (\text{conventional})] > 0.01 \text{ or } \max[\mu_{\text{Proj.}}^{3000 \text{ fb}^{-1}} (\text{Higgs cascades})] > 0.1)$$



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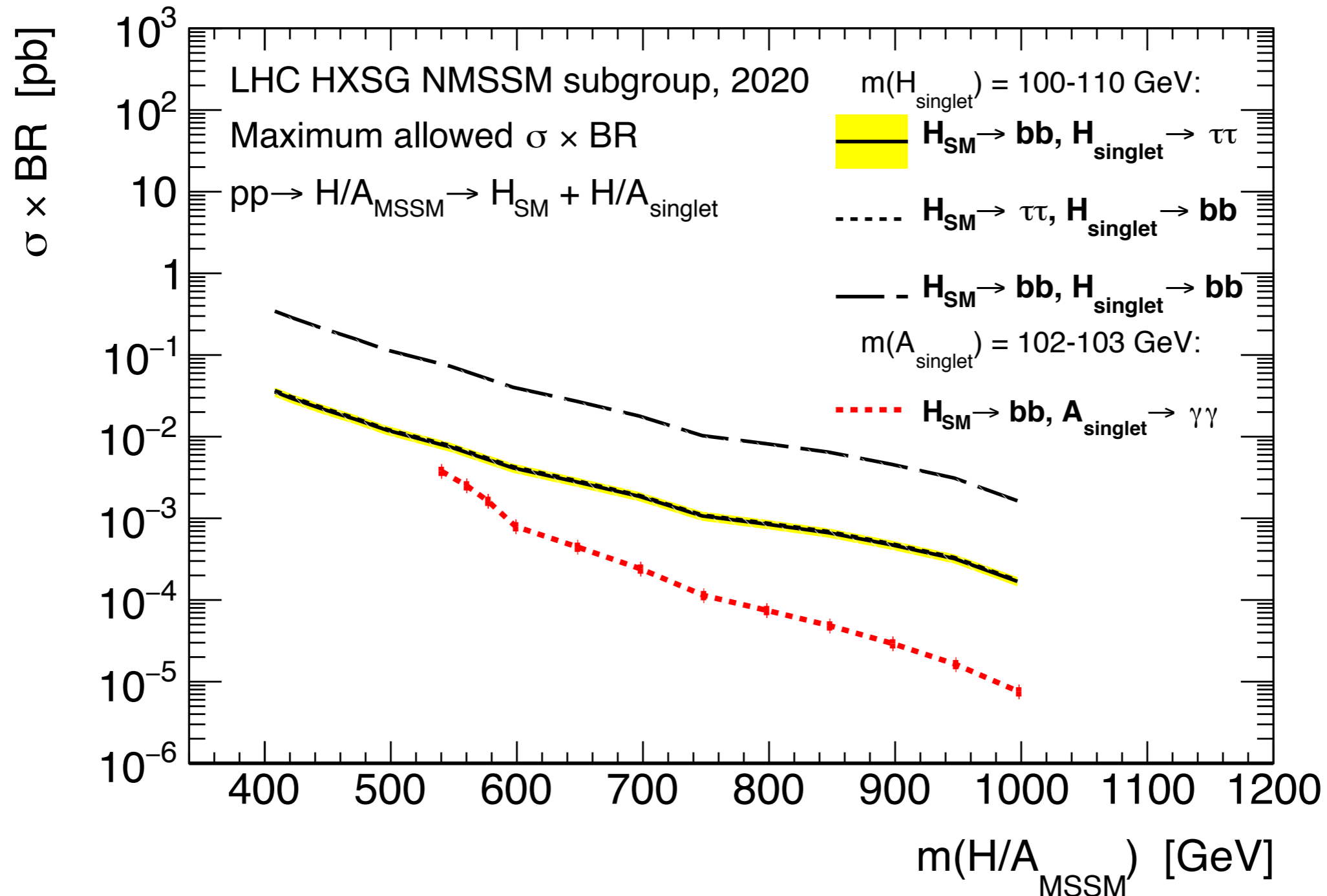
# Benchmark Lines Higgs Pair and Z+Higgs

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- **Non-degenerate masses** of NMSSM-specific mostly singlet-like scalar and pseudoscalar Higgs,  $H_s, A_s$ , not constrained by present BSM searches if couplings to SM particles are very small
- **Their production** is possible in  $H_{MSSM}$  and  $A_{MSSM}$  decays
- **Trilinear Higgs couplings:**  
The (dimensional) trilinear couplings  $H_{MSSM}-H_s-H_{SM}$  and  $A_{MSSM}-A_s-H_{SM}$  can be particularly large (since not suppressed by the  $SU(2)$  symmetry)
- **Branching ratios:**  
BRs for  $H_{MSSM} \rightarrow H_s + H_{SM}$  and  $A_{MSSM} \rightarrow A_s + H_{SM}$  can be large, even dominant  
(which would suppress the BRs into  $\tau\tau$ , used for standard searches of  $H_{MSSM}$ ,  $A_{MSSM}$ )
- **Search for maximal cross sections**  
 $gg \rightarrow H_{MSSM} \rightarrow H_s + H_{SM} \rightarrow (bb)(bb) / (bb)(\tau\tau) + (\tau\tau)(bb)$  and  $gg \rightarrow A_{MSSM} \rightarrow A_s + H_{SM} \rightarrow (\gamma\gamma)(bb)$   
using [NMSSMCALC/NMSSMTools](#) imposing experimental constraints

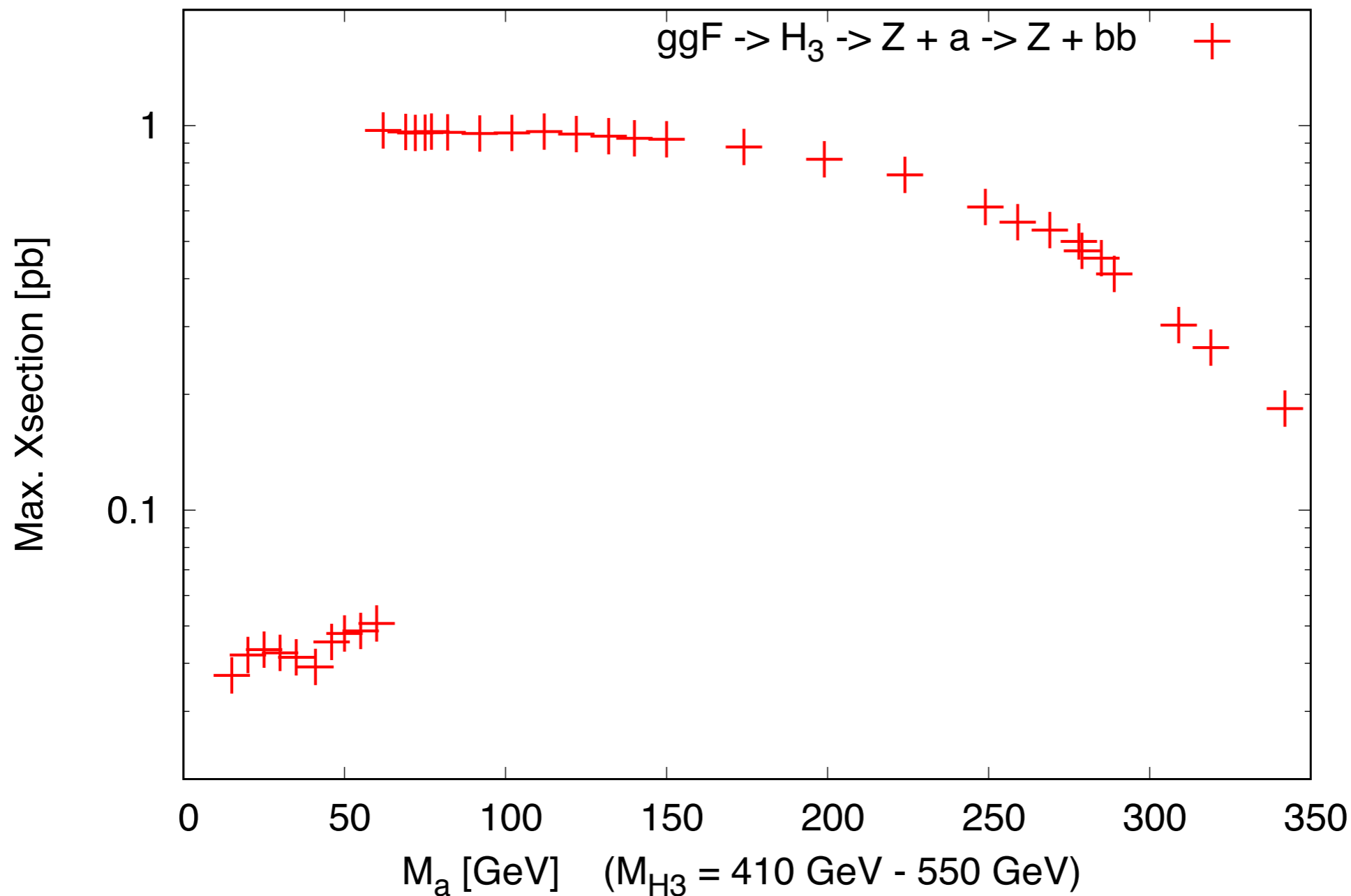
# Benchmark Lines SM+Singlet Higgs Pair Production

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/NMSSMBenchmarksMarch2020>





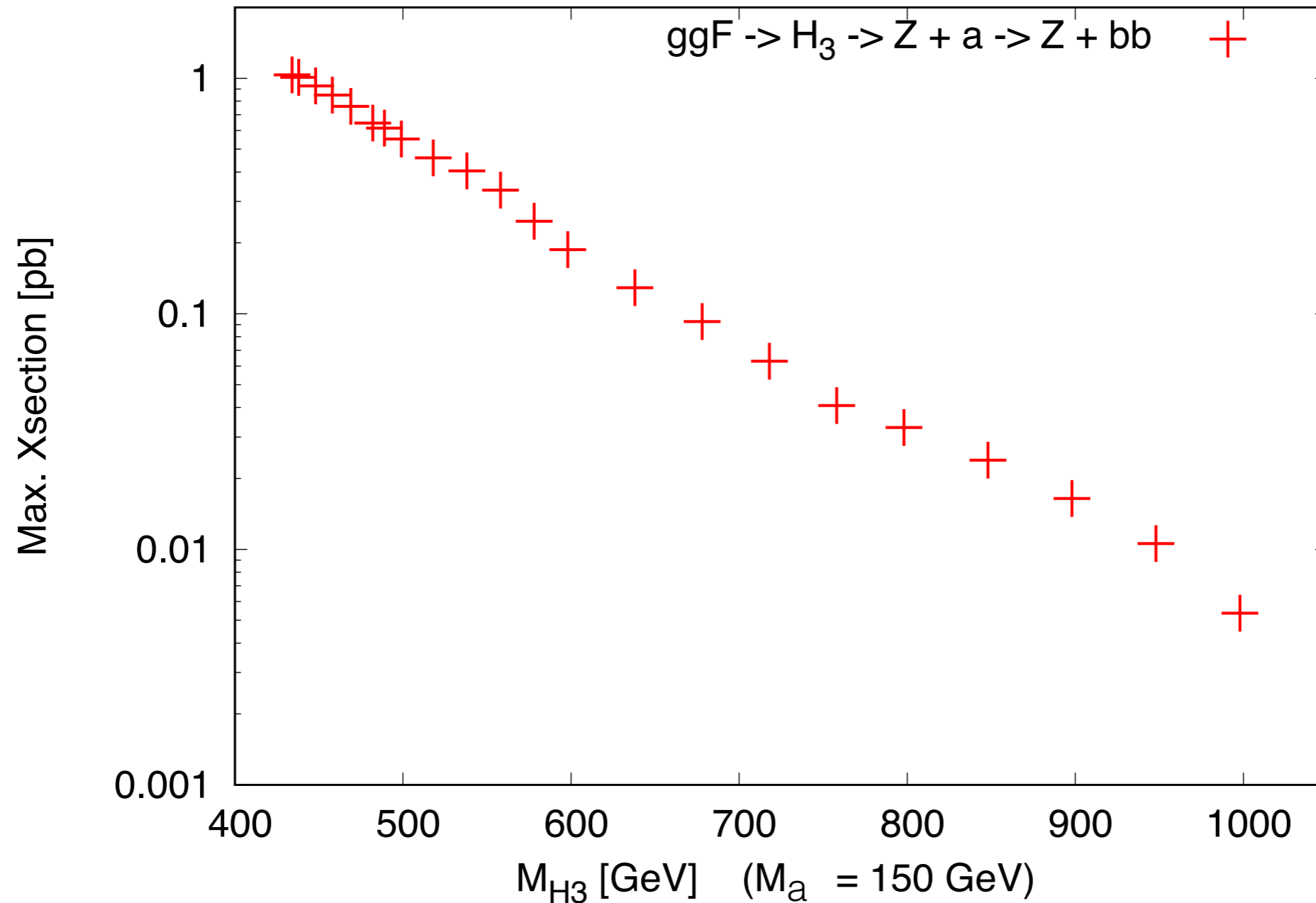
# Benchmark Lines SM+Gauge Boson Production



- generalises benchmark points [MM,Nevzorov,King,Walz,'14], [Baum,Shah,Freese,'19]
- includes experimental constraints, DM relic density required to be smaller than measured value
- cxn drop for  $m_a \leq 62.5$  GeV due to experimental constraints on BR(H<sub>SM</sub> $\rightarrow$ aa)

# Benchmark Lines SM+Gauge Boson Production

[Ellwanger]



- generalises benchmark points [MM,Nevzorov,King,Walz,'14], [Baum,Shah,Freese,'19]
- includes experimental constraints, DM relic density required to be smaller than measured value

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# Outlook

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- Benchmark Lines:  
Extend benchmark lines to different mass combinations and different final states  
(input from experimentalists required)
- Benchmark and Exclusion Regions:  
Exact alignment and  $h_{125}$  mass imposes tree-level relations between parameters in the NMSSM =>  
Define NMSSM benchmarks in the CP-odd mass plane denoted by misalignment and/or singlet mixing;  
this could be similar to MSSM  $m_A$ - $\tan\beta$  plane, benchmarks  $m_{hmax}$  etc.
- Relic density impact on Higgs cascades:  
Branching ratios for NMSSM-specific Higgs decays like  $H_{SM} \rightarrow aa$ ,  $H \rightarrow H_{SM} + H_{singlet}$ ,  $A \rightarrow Z + H_{SM}$  are  
proportional to NMSSM-specific coupling  $\lambda$  (MSSM limit:  $\lambda \rightarrow 0$ ). For relic density equal to or below  
observed value,  $\lambda$  cannot be too small, otherwise no singlino-like LSP annihilation into SM particles.  
=> For given BSM Higgs masses, lower bounds for the corresponding  $cxn \cdot BRs$  which will be studied
- Precision Calculations (spectrum and decay): ongoing

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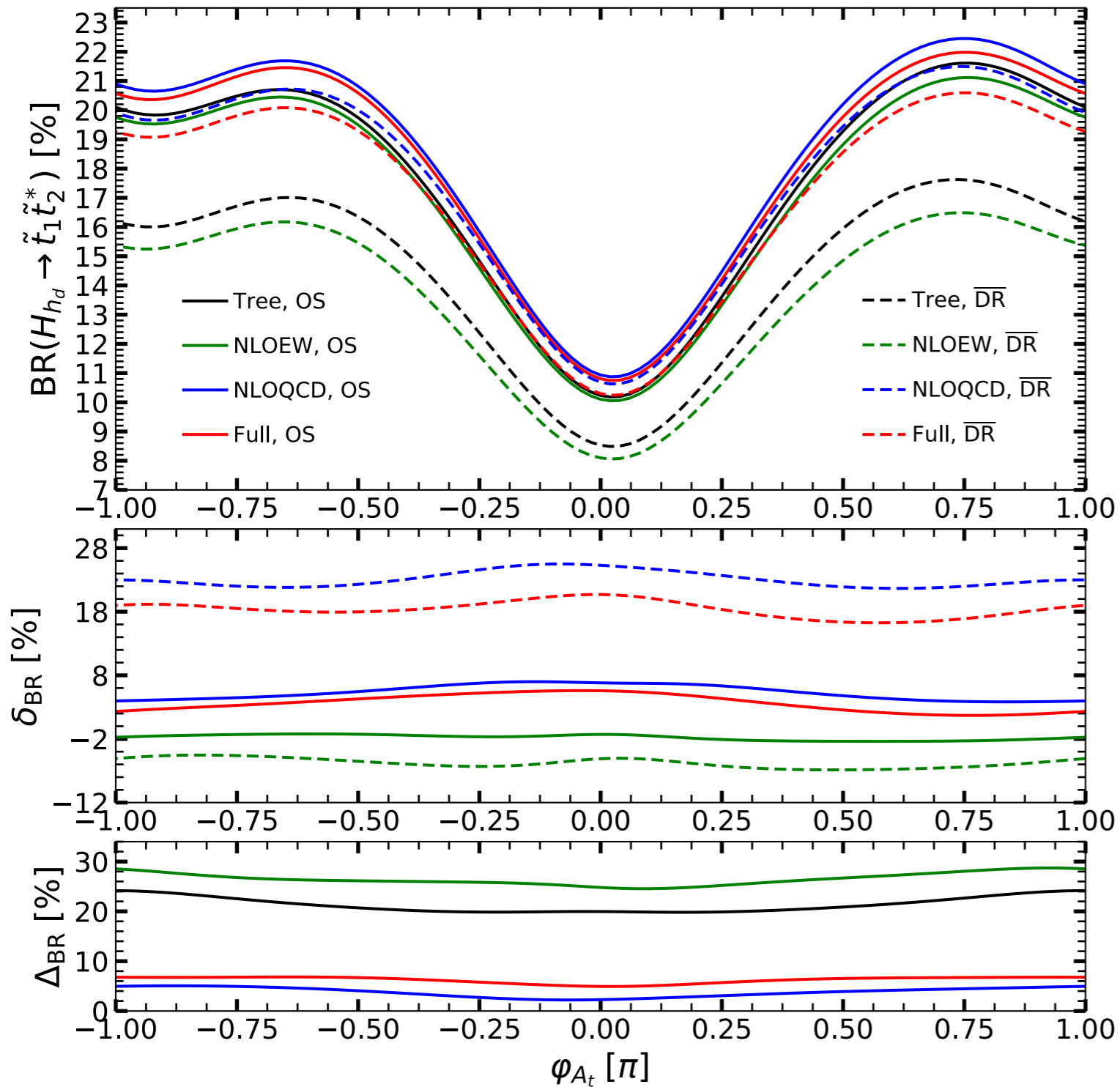
*Thank you for your attention*

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# NMSSMCALCEW

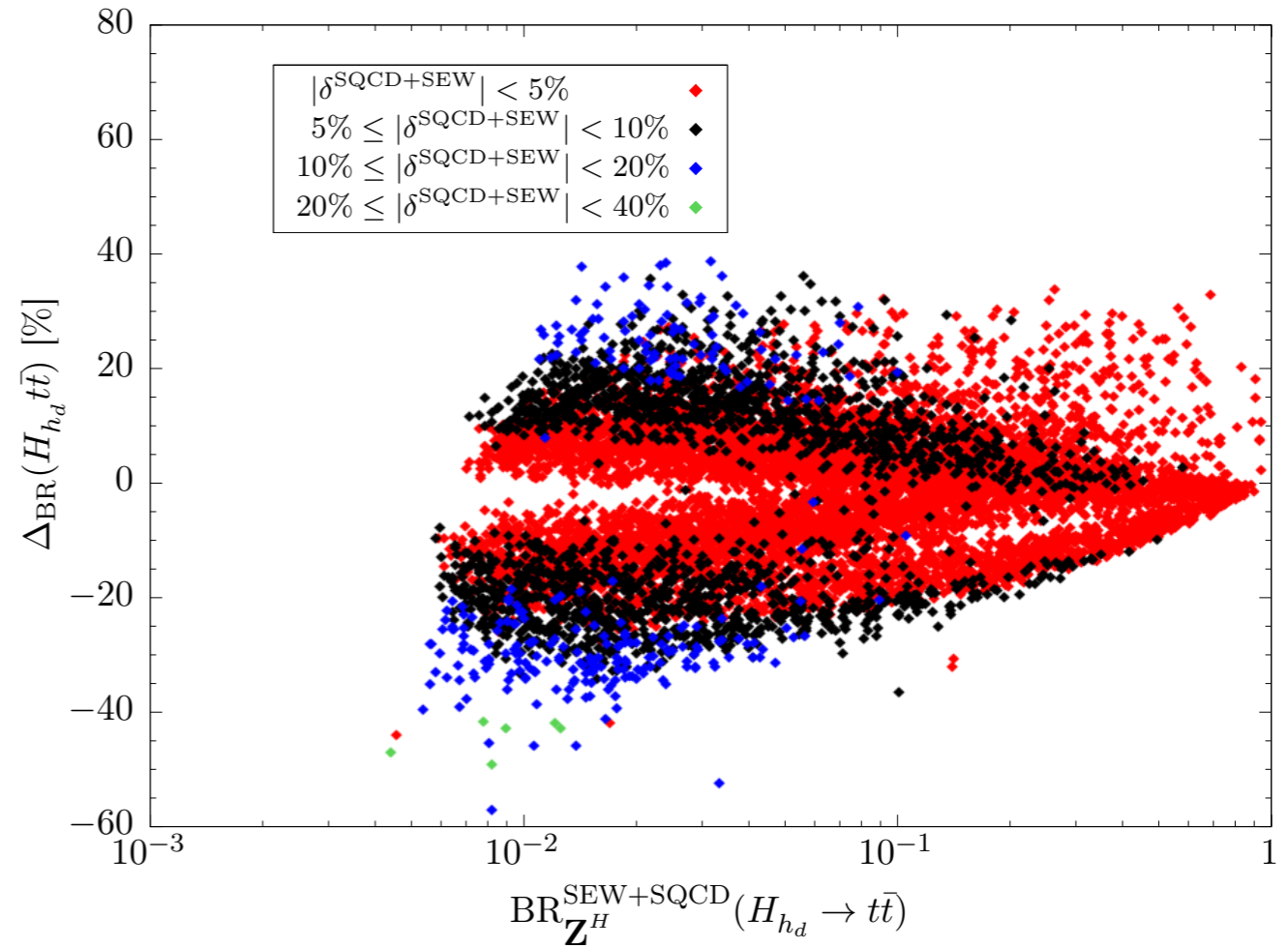
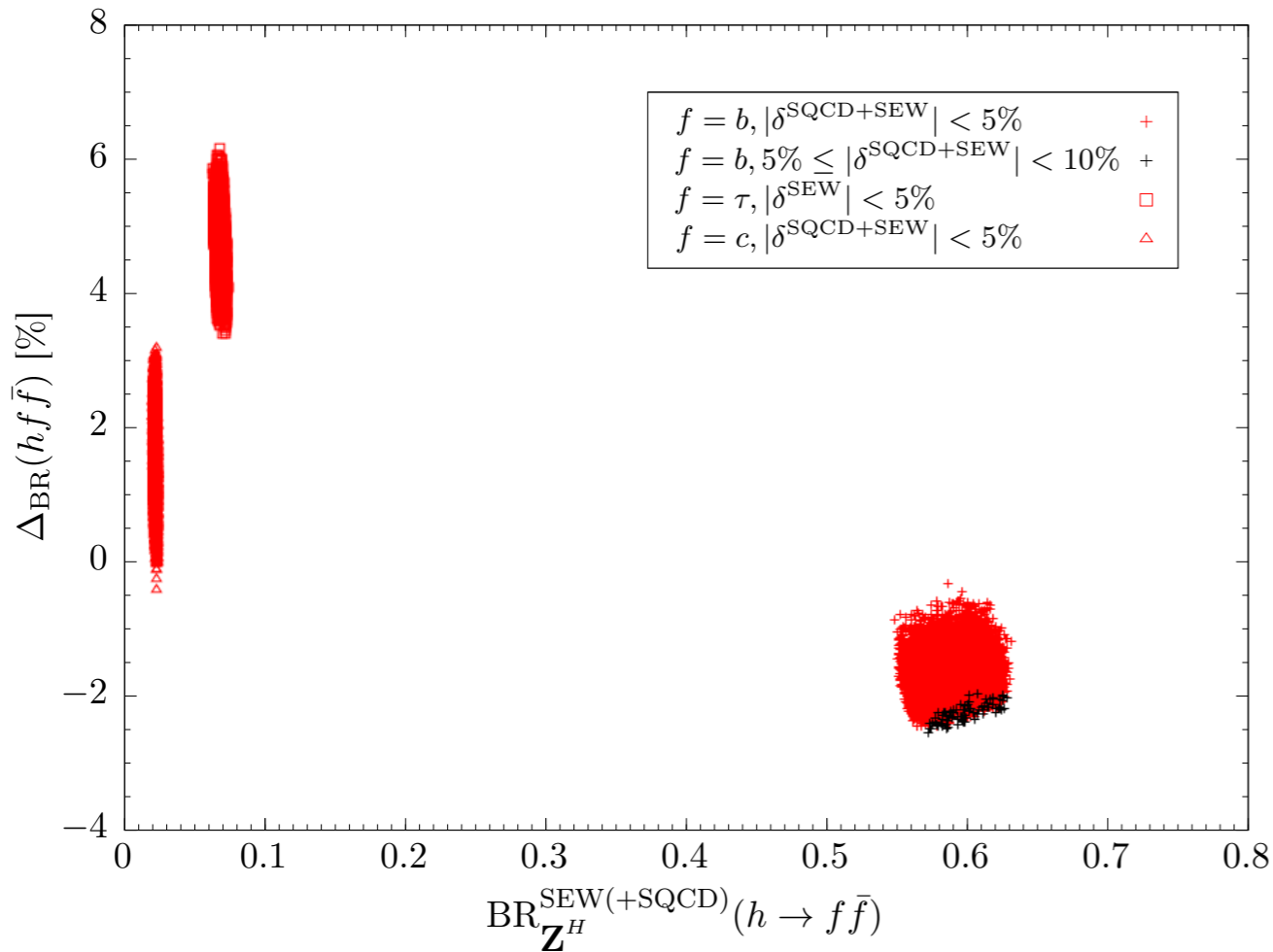
[Baglio, Dao, MM, EPJC 80(2020) 10,960]



$$\delta_{BR} = \frac{BR_{Z^H}^{EW/QCD/EW+QCD} - BR_{Z^H}^{tree}}{BR_{Z^H}^{Tree}}$$

# NMSSMCALCEW

[Baglio, Dao, MM, EPJC 80(2020) 10,960]



$$\Delta_{\text{BR}}(H_i X_j X_k) = \frac{\text{BR}_{\mathbf{Z}^H}^{\text{SEW}(+\text{SQCD})}(H_i \rightarrow X_j X_k) - \text{BR}_{\mathcal{R}^l}^{\text{tree}}(H_i \rightarrow X_j X_k)}{\max(\text{BR}_{\mathbf{Z}^H}^{\text{SEW}(+\text{SQCD})}(H_i \rightarrow X_j X_k), \text{BR}_{\mathcal{R}^l}^{\text{tree}}(H_i \rightarrow X_j X_k))}$$

# NMSSM Spectrum Calculators

- FlexibleSUSY [Athron,Bach,Harries,Kotlarski,Kwasnitza,Park,Stöckinger,Voigt,Ziebell]: DR, FO & hybrid, through FlexibleEFTHiggs
- NMSSMCALC [Baglio,Dao,Gröber,MM,Rzehak,Spira,Streicher,Walz]: FO, real & complex NMSSM, DR and mixed OS-DR
- NMSSMTools [Ellwanger,Gunion,Hugonie]: FO, DR scheme
- SOFTSUSY [Allanach,Athron,Bednyakov,Tunstall,Voig,RuizdeAustri,Williams]: FO, DR scheme
- SPheno [Porod,Staub]: FO, DR scheme

