NMSSM Higgs Boson Search at the High-Energy LHC

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NMSSM Kick-Off Meeting
LHC HXS WG3
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The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Next-to-Minimal Supersymmetric Extension of the SM: NMSSM**

  Fayet; Kaul eal; Barbieri eal; Dine eal; Nilles eal; Frere eal; Derendinger eal; Ellis eal;
  Drees; Ellwanger eal; Savoy; Elliott eal; Gunion eal; Franke eal; Maniatis; Djouadi eal; Mahmoudi eal; ...

- **SUSY Higgs Sector:** at least 2 complex Higgs doublets, NMSSM: plus complex singlet field $\rightsquigarrow$

- **Solution of the μ-problem:** μ must be of $\mathcal{O}$(EWSB scale) Kim,Nilles

  μ generated dynamically through the VEV of scalar component of an additional chiral superfield field $\hat{S}$: $\mu = \lambda\langle S\rangle$ from: $\lambda\hat{S}\hat{H}_u\hat{H}_d$

- **Enlarged Higgs and neutralino sector:** 2 complex Higgs doublets $\hat{H}_u, \hat{H}_d$, 1 complex singlet $\hat{S}$

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

- **Significant changes of Higgs boson phenomenology**

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{D}$iscovery at the $\mathcal{LHC}$

- **Present Status:**

  Higgs signal at 125 GeV

  No BSM Higgs discovered yet. True?

- **Could be that we already discovered NMSSM Higgs bosons!**

  Higgs signal at 125 GeV is built up by two degenerate Higgs bosons.

- **What about the MSSM?**

  Two light MSSM CP-even Higgs bosons $\Longleftrightarrow$ light CP-odd A, relatively light $H^\pm$

  light $M_{H^\pm}$ excluded CMS-HIG-12-052, ATLAS-CONF-2012-011 and 2013-090

$\mathcal{I}$nvestigation of $\mathcal{NMSSM}$ $\mathcal{D}$iscovery $\mathcal{P}$rospects - $\mathcal{S}$can

Mixing angle $\tan\beta$ and NMSSM couplings λ, κ:

$$1 \le \tan\beta \le 30 \, , \qquad 0 \le \lambda \le 0.7 \, , \qquad -0.7 \le \kappa \le 0.7$$

with perturbativity requirement

$$\sqrt{\lambda^2 + \kappa^2} \le 0.7$$

Soft SUSY breaking trilinear NMSSM couplings and μ_{eff}:

$$-2 \text{ TeV} \le A_\lambda \le 2 \text{ TeV} \, , \; -2 \text{ TeV} \le A_\kappa \le 2 \text{ TeV} \, , \; -1 \text{ TeV} \le \mu_{\text{eff}} \le 1 \text{ TeV}$$

Remaining Parameters:

$$-2 \text{ TeV} \le A_U, A_D, A_L \le 2 \text{ TeV}$$

$$600 \text{ GeV} \le M_{\tilde{t}_R} = M_{\tilde{Q}_3} \le 3 \text{ TeV} \, , \; 600 \text{ GeV} \le M_{\tilde{\tau}_R} = M_{\tilde{L}_3} \le 3 \text{ TeV} \, , \; M_{\tilde{b}_R} = 3 \text{ TeV}$$

$$M_{\tilde{u}_R,\tilde{c}_R} = M_{\tilde{d}_R,\tilde{s}_R} = M_{\tilde{Q}_{1,2}} = M_{\tilde{e}_R,\tilde{\mu}_R} = M_{\tilde{L}_{1,2}} = 3 \text{ TeV}$$

$$100 \text{ GeV} \le M_1 \le 1 \text{ TeV} \, , \; 200 \text{ GeV} \le M_2 \le 1 \text{ TeV} \, , \; 1.3 \text{ TeV} \le M_3 \le 3 \text{ TeV}$$

$\mathcal{NMSSM}$ $\mathcal{S}$can

- **Conditions on the parameter scan:**
  - ∗ At least one CP-even Higgs boson $H_i \equiv h$ with: $124\ \text{GeV} \lesssim M_h \lesssim 127\ \text{GeV}$
  - ∗ Compatibility with μ_{XX}^{exp} $(X = b, \tau, \gamma, W, Z)$: $|\mu_{XX}^{\text{scan}}(h) - \mu_{XX}^{\text{exp}}| \leq 2 \times 1\sigma$
  - ∗ Relic density $\Omega_c h^2$ below PLANCK result $(\Omega_c h^2)^{\text{NMSSM}} \leq 0.1187 \pm 0.0017$ [PLANCK]

Constraints from low-energy observables, from LEP, Tevatron and LHC searches [NMSSMTools]

- **Signal can be superposition of two Higgs boson rates close in mass: h and $\Phi = H_i, A_j$**

$$\mu_{XX}(h) \equiv R_\sigma(h)\, R_{XX}^{BR}(h) \;+ \sum_{\substack{\Phi \neq h \\ |M_\Phi - M_h| \leq \delta}} R_\sigma(\Phi)\, R_{XX}^{BR}(\Phi)\, F(M_h, M_\Phi, d_{XX})$$

δ : mass resolution in the respective XX final state

$F(M_h, M_\Phi, d_{XX})$: Gaussian weighting function

d_{XX}: experimental resolution of final state XX [NMSSMTools]

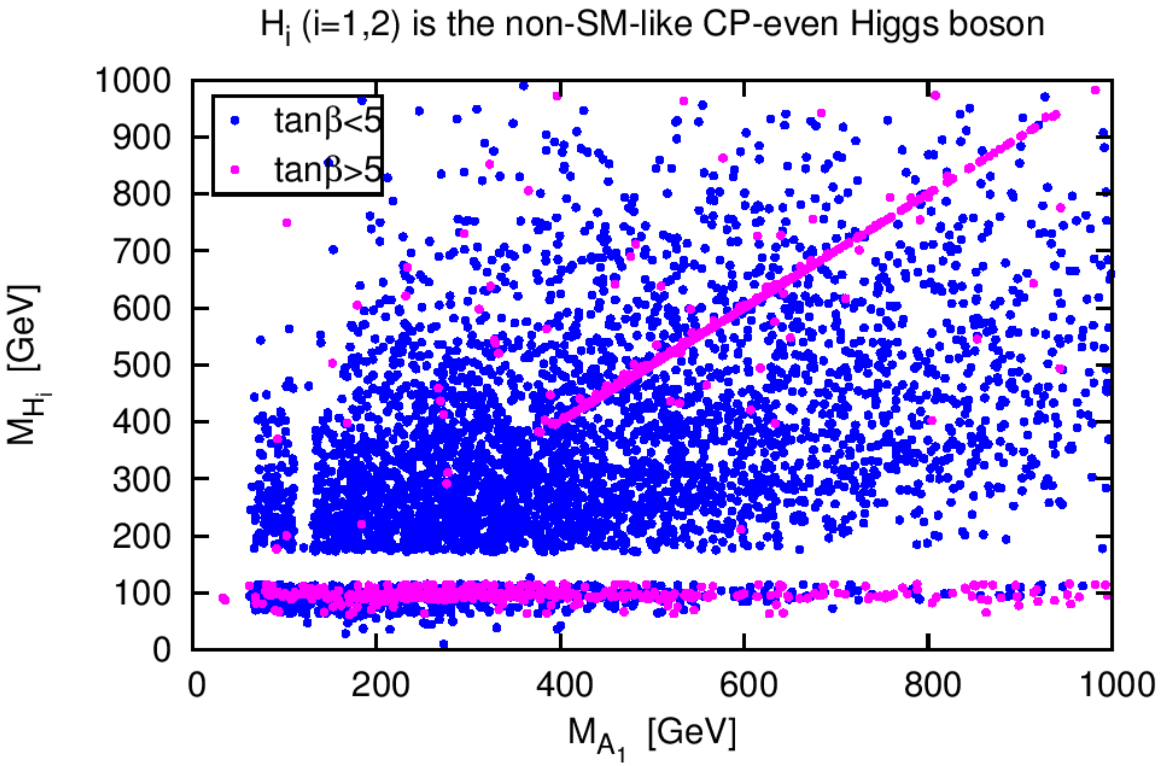
$\mathcal{E}$xperimental $\mathcal{S}$ignal $\mathcal{R}$ates

Based on: ATLAS-CONF-2013-034; CMS-PAS-HIG-13-005; combination à la Espinosa,MMM,Grojean,Trott

channel	best fit value	$2 \times 1\sigma$ error
$VH \to Vbb$	0.97	± 1.06
$H \to \tau\tau$	1.02	± 0.7
$H \to \gamma\gamma$	1.14	± 0.4
$H \to WW$	0.78	± 0.34
$H \to ZZ$	1.11	± 0.46

$\mathcal{M}$ass $\mathcal{D}$istributions

King,MMM,Nevzorov,Walz



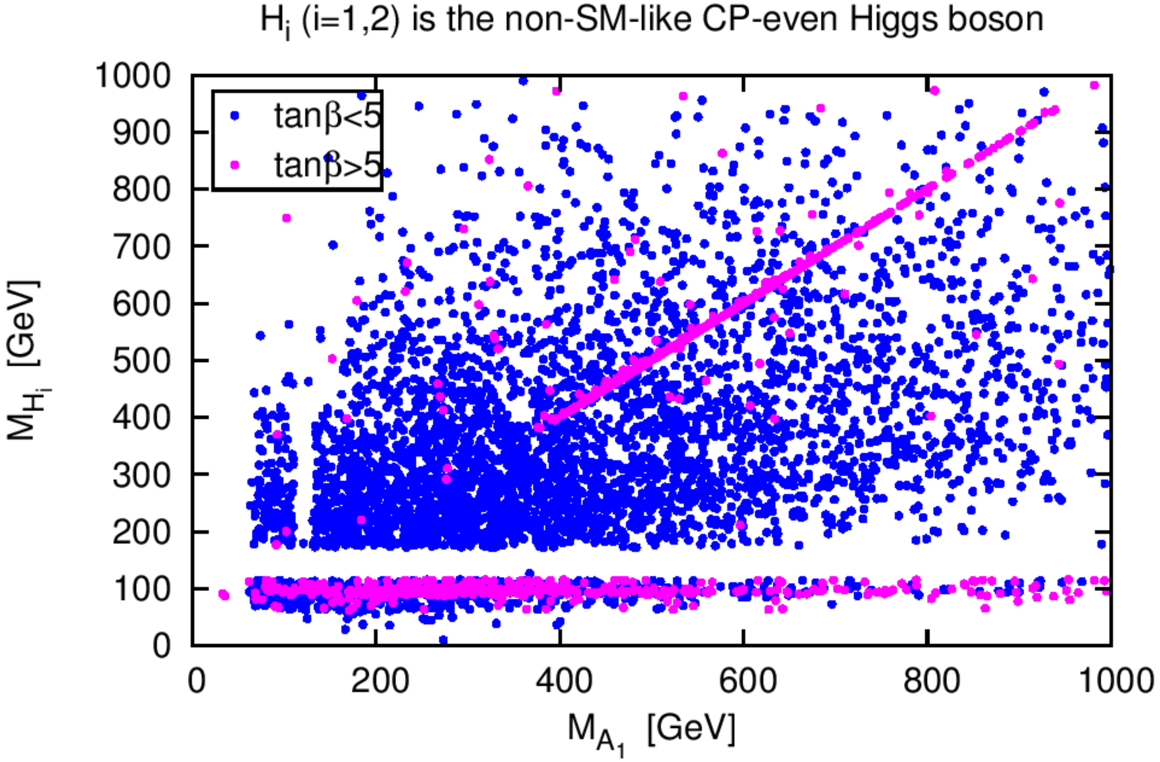
$M_{H_i} \lesssim 115$ GeV $\rightsquigarrow$ H_1 non-SM-like; $M_{H_i} \gtrsim 180$ GeV $\rightsquigarrow$ H_2 non-SM-like

Gaps at 115 GeV $\lesssim M_{H_i} \lesssim 180$ GeV and 115 GeV $\lesssim M_{A_1} \lesssim 130$ GeV due to LHC Higgs data

Very few points for $M_{H_i}, M_{A_1} \lesssim 62$ GeV $\leftarrow$ SM-like Higgs decays into H_i, A_1 $\rightsquigarrow$ reduced μ values

$\mathcal{M}$ass $\mathcal{D}$istributions

King,MMM,Nevzorov,Walz



$M_{H_i} \lesssim 115$ GeV $\rightsquigarrow H_1$ non-SM-like; $M_{H_i} \gtrsim 180$ GeV $\rightsquigarrow H_2$ non-SM-like

300 GeV $\lesssim M_{H_3}, M_{A_2} \lesssim \mathcal{O}$(TeV)

$\mathcal{D}$iscovery $\mathcal{P}$rospects in the $\mathcal{N}$atural $\mathcal{N}$MSSM

- **What scenario could be constrained at 13 TeV?**

- **Investigate prospects for subspace:** Natural NMSSM

$$0.6 \le \lambda \le 0.7\,,\ -0.3 \le \kappa \le 0.3\,,\ 1.5 \le \tan\beta \le 2.5\,,\ 100\text{ GeV} \le |\mu_{\text{eff}}| \le 185\text{ GeV}$$

- **Features of the NMSSM spectrum:**
  - ∗ SM-like Higgs boson: $H_2 \equiv h$
  - ∗ A_2, H_3 doublet-like
  - ∗ A_1, H_1 singlet-like

- **Convenient Notation**

$$H_2 = h\,, \quad H_3 = H\,, A_2 = A\,, \quad H_1 = H_s\,, A_1 = A_s$$

$\mathcal{D}$iscovery $\mathcal{P}$rospects in the $\mathcal{N}$atural $\mathcal{N}$MSSM

- **Tree-Level Mass Values** Nevzorov,Miller '04

$$M_H \approx M_A \approx M_{H^\pm} \approx \mu_{\text{eff}} \tan\beta$$

$$M_{A_s}^2 + 3M_{H_s}^2 \approx 12\left(\frac{\kappa}{\lambda}\mu_{\text{eff}}\right)^2 + \Delta$$

$\sqrt{\Delta} \approx 137$ GeV $\longleftarrow$ loop corrections

- **Loop-corrected Natural NMSSM Higgs Mass Values**

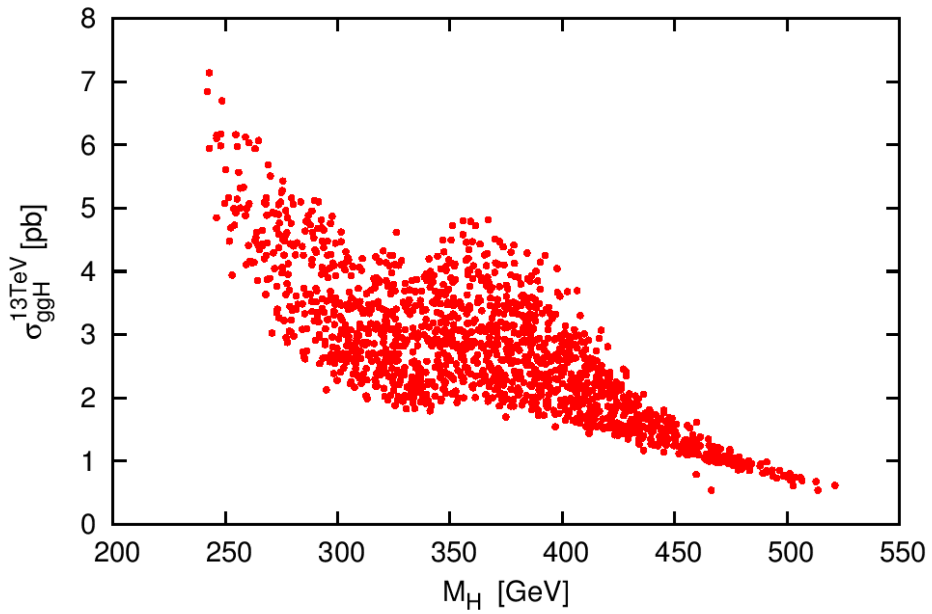
$230 \text{ GeV} \lesssim M_H, M_A \lesssim 530 \text{ GeV}\,,\ 27 \text{ GeV} \lesssim M_{H_s} \lesssim 117 \text{ GeV}\,,\ 29 \text{ GeV} \lesssim M_{A_s} \lesssim 300 \text{ GeV}$

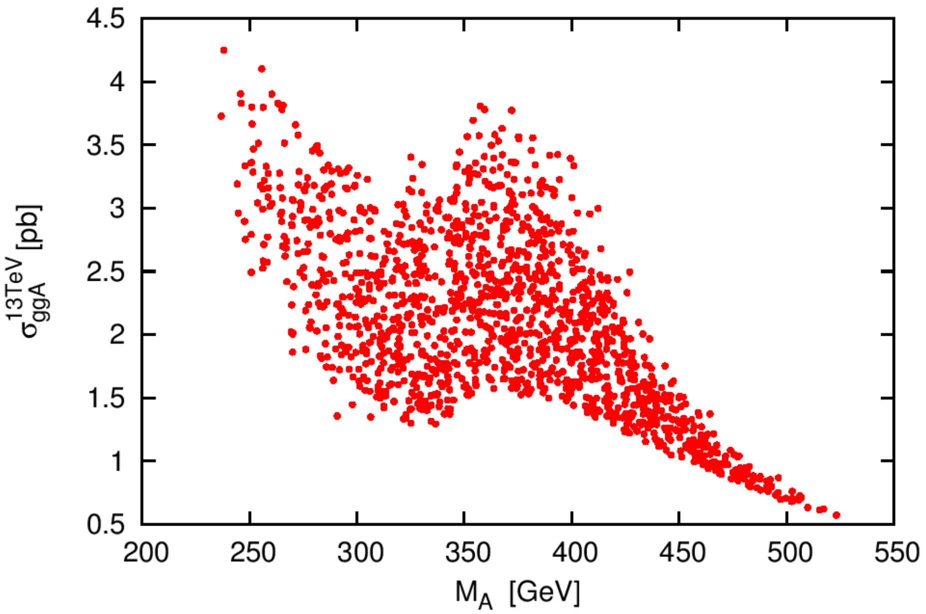
- **Production Cross Sections for H and A**

$$0.8 \text{ pb} \lesssim \sigma(gg \to H) \lesssim 7.5 \text{ pb}\,, \quad 0.6 \text{ pb} \lesssim \sigma(gg \to A) \lesssim 4.5 \text{ pb}$$

$\mathcal{P}$roduction $\mathcal{C}$ross $\mathcal{S}$ections for H, A

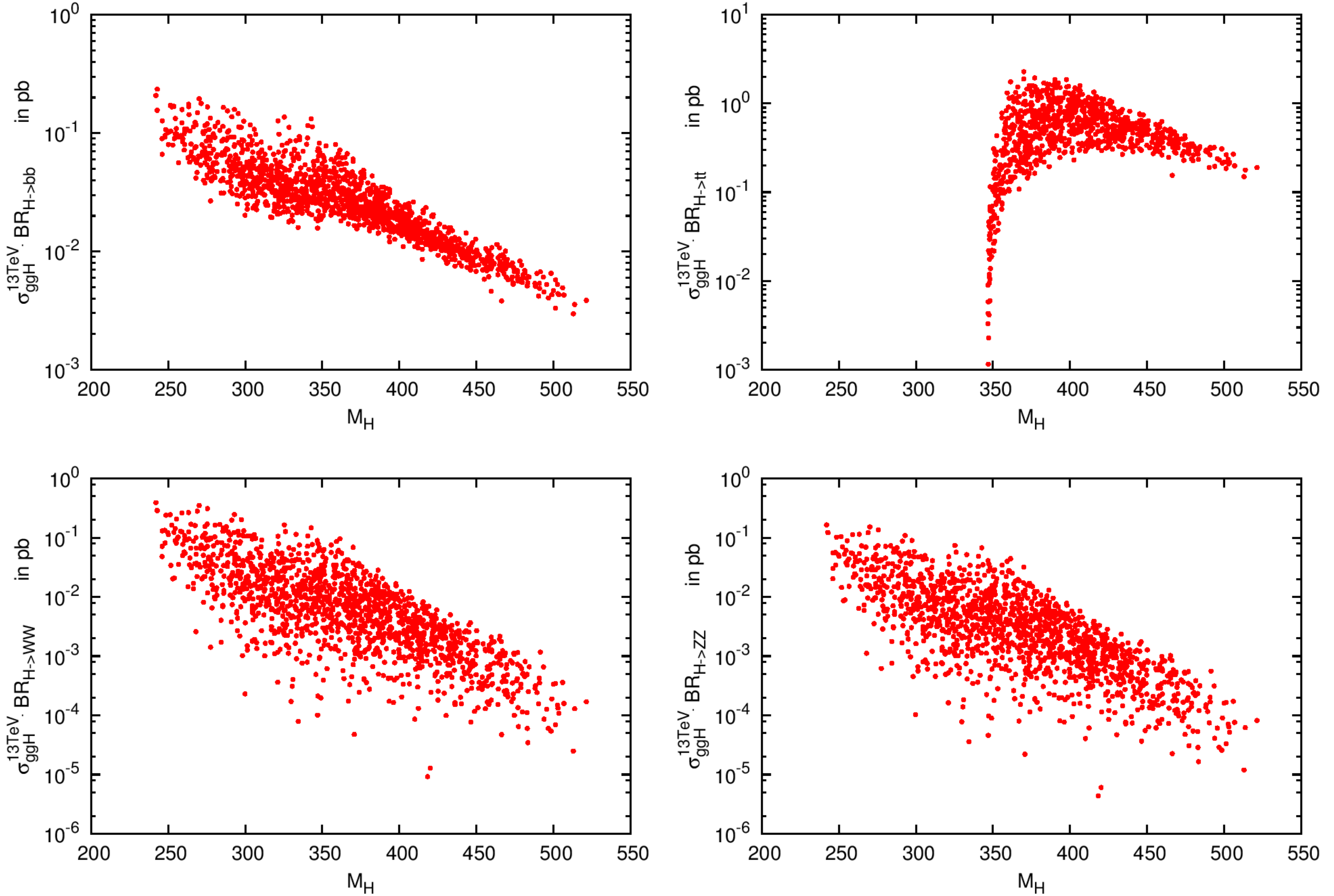
King,MMM,Nevzorov,Walz





$\mathcal{S}$ignal $\mathcal{R}$ates for H

King,MMM,Nevzorov,Walz



$\mathcal{A}$lternative $\mathcal{P}$roduction $\mathcal{C}$hannels

- **Small direct production rates:** $\rightsquigarrow$ alternative production channels

- **Higgs-to-Higgs Decays:**

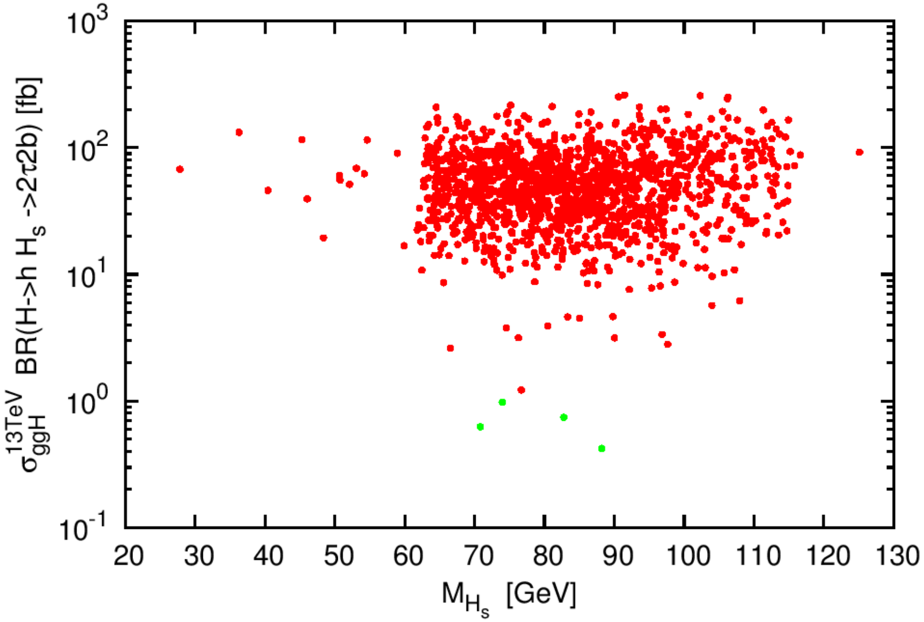
$$\sigma(gg \to \phi_i) \times BR(\phi_i \to \phi_j \phi_k) \times BR(\phi_j \to XX) \times BR(\phi_k \to YY)$$

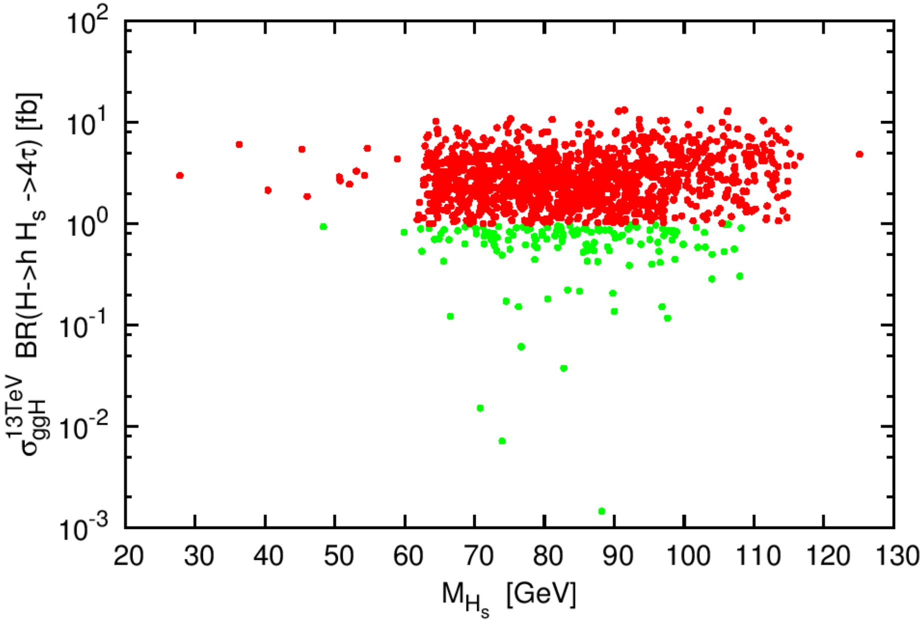
- **Higgs-to-Higgs+Gauge-Boson Decays:**

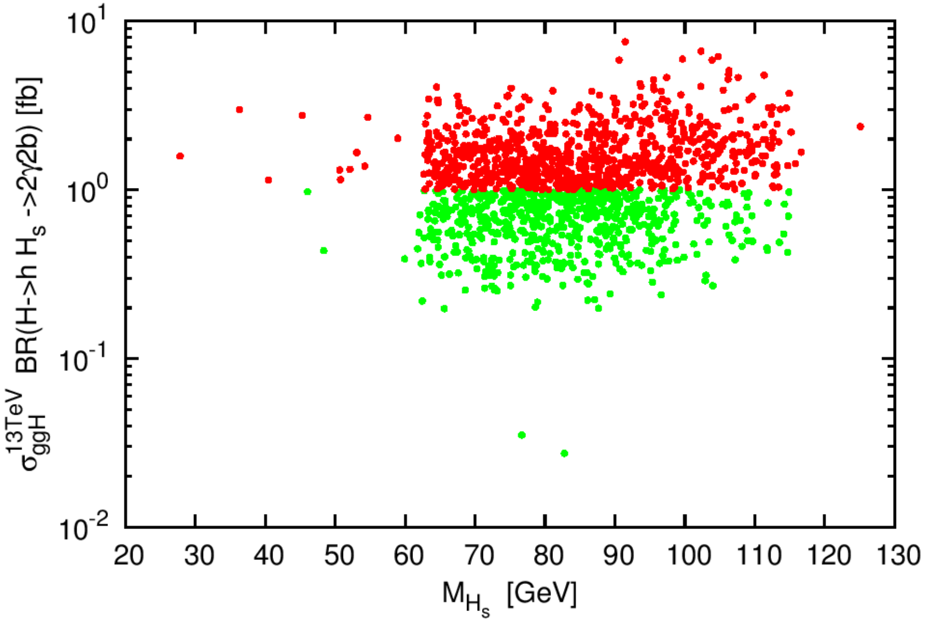
$$\sigma(gg \to H) \times BR(H \to ZA_s) \;, \quad \sigma(gg \to A) \times BR(A \to ZH_s)$$

$$\sigma(gg \to H)BR(H \to hH_s \to (XX)(YY))$$

King,MMM,Nevzorov,Walz







$\mathcal{D}$iscovery $\mathcal{P}$rospects in the $\mathcal{N}$atural $\mathcal{N}$MSSM

- **Heavy Higgs bosons H and A**

  With masses $\lesssim 530$ GeV light enough to be discovered directly

- **Singlet-like Higgs bosons H_s and A_s**

  cross sections large enough for direct discovery

  or: if σ_{prod} too small $\rightsquigarrow$ discovery via Higgs-to-Higgs or Higgs-to-Gauge&Higgs decays

  (also from decays of SUSY particles might be alternative; not discussed here)

$$H \to H_s H_s \; , \; H \to h H_s \; , \; A \to H_s A_s \; , \; A \to h A_s \; , \ldots$$

$$H \to Z A_s \; , A \to Z H_s$$

LHC13: Natural NMSSM Scenario confirmed or strongly constrained

$\mathcal{B}$enchmarks for $\mathcal{H}$iggs-to-$\mathcal{H}$iggs $\mathcal{D}$ecays

- **Higgs-to-Higgs Decays**

$$\sigma(gg \to \phi_i) \times BR(\phi_i \to \phi_j \phi_k) \times BR(\phi_j \to XX) \times BR(\phi_k \to YY)$$

▷ Interesting for heavier ϕ_i discovery if σ_{prod} large enough and BR into lighter Higgs pairs dominates

▷ For lighter ϕ_j, ϕ_k interesting production if direct prod strongly suppressed due to singlet nature

- **Benchmarks for Higgs-to-Higgs Decays**

A) $H_2 = h, H_1 = H_s, \tan\beta$ small, light spectrum $\lesssim 350$ GeV

B) $H_1 = h, H_2 = H_s, \tan\beta$ small

C) $H_1 = h, H_3 = H_s, \tan\beta$ large

D) $H_2 = h$ decays into lighter Higgs pairs

$\mathcal{B}$enchmark $H_1 = h$ and $\tan\beta$ small

B.1 (Point ID Poi2a)	Scenario		
M_h, M_{H_s}, M_H	124.6 GeV	181.7 GeV	322.6 GeV
M_{A_s}, M_A	72.5 GeV	311.7 GeV	
$\|S_{H_2 h_s}\|^2, \|P_{A_1 a_s}\|^2$	0.90	1	
$\mu_{\tau\tau}, \mu_{bb}$	1.54	1.01	
$\mu_{ZZ}, \mu_{WW}, \mu_{\gamma\gamma}$	0.93	0.93	1.54
$\tan\beta, \lambda, \kappa$	1.9	0.628	0.354
$A_\lambda, A_\kappa, \mu_{\text{eff}}$	251.2 GeV	53.8 GeV	158.9 GeV
M_1, M_2, M_3	890 GeV	576 GeV	1919 GeV
A_t, A_b, A_τ	1555 GeV	-1006 GeV	-840 GeV
$M_{Q_3} = M_{t_R}, M_{L_3} = M_{\tau_R}$, other SSB parameters	1075 GeV	540 GeV	3 TeV

$\text{BR}(A_s \to \gamma\gamma) = 0.84$, $\text{BR}(H_s \to A_s A_s) = 0.97$, $\text{BR}(H \to h H_s) = 0.51$

$\text{BR}(A \to H_s A_s) = 0.21$, $\text{BR}(A \to h A_s) = 0.012$

$\mathcal{B}$enchmark $H_1 = h$ and $\tan\beta$ small

B.1 (Point ID Poi2a)	Decay Rates
$\sigma(ggA_s)$	0.08 fb
$\sigma(ggA)$BR$(A \to H_s A_s)$	525.56 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to 6\gamma)$	301.58 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to bb + 4\gamma)$	157.64 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to 4b + \gamma\gamma)$	27.47 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to \tau\tau + 4\gamma)$	14.99 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to \tau\tau + bb + \gamma\gamma)$	5.22 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to 4\tau + \gamma\gamma)$	0.25 fb
$\sigma(ggA)$BR$(A \to h A_s)$	29.96 fb
$\sigma(ggA)$BR$(A \to h A_s \to \gamma\gamma + b\bar{b})$	16.25 fb
$\sigma(ggA)$BR$(A \to h A_s \to \gamma\gamma + \tau\tau)$	1.70 fb
$\sigma(ggA)$BR$(A \to h A_s \to b\bar{b} + b\bar{b})$	2.83 fb

accessible:

$\lambda_{H_s A_s A_s}$

$\lambda_{H H_s h}$

$\lambda_{A A_s H_s}$

$\lambda_{A A_s h}$

$\mathcal{B}$enchmark $H_2 = h$ and $h \rightarrow H_s H_s$ ($\tan\beta$ small)

D.1 (Point ID 5416)	Scenario		
M_{H_s}, M_h, M_H	9.6 GeV	124.2 GeV	793.4 GeV
M_{A_s}, M_A	273.2 GeV	792.2 GeV	
$\|S_{H_1 h_s}\|^2$, $\|P_{A_1 A_s}\|^2$	0.98	0.99	
$\mu_{\tau\tau}$, μ_{bb}	0.90	0.89	
μ_{ZZ}, μ_{WW}, $\mu_{\gamma\gamma}$	0.92	0.92	0.92
$\tan\beta$, λ, κ	3.37	0.64	0.20
A_λ, A_κ, μ_{eff}	-709.0 GeV	297.3 GeV	-222.4 GeV
A_t, A_b, A_τ	-1075.3 GeV	-1973.1 GeV	-143.7 GeV
M_1, M_2, M_3	307.7 GeV	789.8 GeV	2933.1 GeV
$M_{Q_3} = M_{t_R}$, M_{b_R}	2931.3 GeV	3 TeV	
$M_{L_3} = M_{\tau_R}$, M_{SUSY}	2930.8 GeV	3 TeV	

BR$(h \rightarrow H_s H_s) = 0.1$, BR$(H_s \rightarrow \tau\tau) = 0.9$ and BR$(H \rightarrow h H_s) = 0.21$

$\lambda_{hH_sH_s}$, λ_{HH_sh} accessible, λ_{AA_sh} more difficult

D.1 (Point ID 5416)	Signal Rates
$\sigma(ggh)$	44.28 pb
$\sigma(ggh)$BR$(h \to H_s H_s)$	4.22 pb
$\sigma(ggh)$BR$(h \to H_s H_s \to \tau\tau + \tau\tau)$	3.58 pb
$\sigma(ggh)$BR$(h \to H_s H_s \to \tau\tau + \mu\mu)$	31.64 fb
$\sigma(ggH)$	38.72 fb
$\sigma(ggH)$BR$(H \to t\bar{t})$	9.80 fb
$\sigma(ggH)$BR$(H \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	5.73 fb
$\sigma(ggH)$BR$(H \to hH_s)$	8.08 fb
$\sigma(ggH)$BR$(H \to hH_s \to b\bar{b} + \tau\tau)$	4.26 fb
$\sigma(ggH)$BR$(H \to hH_s \to \tau\tau + \tau\tau)$	0.45 fb
$\sigma(ggA)$	41.26 fb
$\sigma(ggA)$BR$(A \to t\bar{t})$	11.24 fb
$\sigma(ggA)$BR$(A \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	5.94 fb
$\sigma(ggA)$BR$(A \to hA_s)$	4.95 fb
$\sigma(ggA)$BR$(A \to hA_s \to b\bar{b} + b\bar{b})$	1.15 fb
$\sigma(ggA)$BR$(A \to hA_s \to b\bar{b} + \tau\tau)$	0.26 fb
$\sigma(ggH_s)$	439.80 pb
$\sigma(ggH_s)$BR$(H_s \to \mu\mu)$	1.79 pb
$\sigma(ggH_s)$BR$(H_s \to \tau\tau)$	405.09 pb
$\sigma(ggH_s)$BR$(H_s \to c\bar{c})$	5.17 pb
$\sigma(ggH_s)$BR$(H_s \to s\bar{s})$	7.24 pb
$\sigma(ggH_s)$BR$(H_s \to \gamma\gamma)$	7.95 fb

$\mathcal{N}$MSSM$\mathcal{C}$ALC

- **Comparison of Branching Ratios and Decay Widths with:** `NMSSMCALC`

  Baglio,Gröber,MMM,Nhung,Rzehak,Spira,Streicher,Walz [arXiv:1312.4788]

- **NMSSMCALC:** Fortran package for the calculation in the real & complex NMSSM of the
  - ⋆ loop-corrected NMSSM Higgs boson masses at one-loop

    masses and self-couplings at two-loop: implementation about to be finished
  - ⋆ NMSSM Higgs boson decay widths and branching ratios

- **Input and output files** feature the SUSY Les Houches Accord (SLHA) Skands eal; Allanach eal

- **Decay Widths:** extension of `HDECAY` to the NMSSM Djouadi,Kalinowski,MM,Spira
  - ⋆ include dominant higher order QCD corrections
  - ⋆ down-type leptons: HO SUSY-EW, down-type quarks: SUSY-QCD, bottoms: SUSY-QCD&EW
  - ⋆ off-shell decays into VV $(V = Z, W)$, V+Higgs, Higgs pair, $t\bar{t}$; $H^+ \to t\bar{b}$
  - ⋆ real NMSSM: SUSY-QCD to decays into stop, sbottom pairs

NMSSMCALC
Calculator of One-Loop Higgs Mass Corrections and of Higgs Decay Widths in the CP-conserving and the CP-violating NMSSM

The program package NMSSMCALC calculates the one-loop corrected Higgs boson masses and the Higgs decay widths and branching ratios within the CP-conserving and the CP-violating NMSSM. The decay calculator is based on an extension of the program HDECAY 6.10 now.

Released by: Julien Baglio, Ramona Gröber, Margarete Mühlleitner, Dao Thi Nhung, Heidi Rzehak, Michael Spira, Juraj Streicher and Kathrin Walz
Program: NMSSMCALC version 1.02

When you use this program, please cite the following references:

NMSSMCALC:	Julien Baglio, Ramona Gröber, Margarete Mühlleitner, Dao Thi Nhung, Heidi Rzehak, Michael Spira, Juraj Streicher and Kathrin Walz, in arXiv:1312.4788
One-Loop Masses:	K. Ender, T. Graf, M. Mühlleitner, H. Rzehak, in Phys. Rev. D85 (2012)075024
	T. Graf, R. Gröber, M. Mühlleitner, H. Rzehak, K. Walz, in JHEP 1210 (2012) 122
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications, send an E-mail to nmssmcalc@itp.kit.edu.

$\mathcal{C}$onclusions

- **NMSSM Higgs sector compatible w/ LHC data**
  - ⋆ SM-like Higgs can be H_1 or H_2; degenerate Higgs signal at 126 GeV possible
  - ⋆ Higgs bosons below 100 GeV not excluded
- **Natural NMSSM**
  - ⋆ May be tested or excluded at LHC13
- **Benchmark Scenarios**
  - ⋆ cross sections in Higgs-to-Higgs decays can be large
  - ⋆ $\rightsquigarrow$ discovery channels and/or trilinear Higgs coupling measurements
  - ⋆ exotic multi-photon, multi-fermion final states, $\not{E}_T$ final states possible

Be prepared for (exotic) signals in low- & high-mass regions in order not to miss BSM Higgs sectors

Thank You For Your Attention!

Singlet-/Doublet Character of the NMSSM Higgs Bosons

King, Nevzorov, MMM, Walz

$\tan\beta < 5$	$H_{i=1}$ SM-like	$H_{i=2}$ SM-like
$H_{j=1,2\neq i}$	singlet	singlet- up to almost doublet
H_3	doublet	doublet
A_1	mostly singlet (few doublet)	mostly singlet (few doublet)
A_2	mostly doublet (few singlet)	mostly doublet (few singlet)

$\tan\beta \geq 5$	$H_{i=1}$ SM-like	$H_{i=2}$ SM-like
$H_{j=1,2\neq i}$	mostly doublet	singlet- up to almost doublet
H_3	singlet (few doublet)	doublet
A_1	doublet or singlet (for small M_{A_1})	doublet or singlet (for small M_{A_1})
A_2	singlet or doublet	singlet or doublet