
Benchmarks for \mathcal{N} MSSM *Di-Higgs Boson Production*

Milada Margarete Mühlleitner (KIT)

Coll. with Steve King, Roman Nevzorov and Kathrin Walz

HH Subgroup Meeting

CERN

8 December 2014



The \mathcal{NMSSM} Higgs Sector

- **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: $\tilde{\chi}_i^0$ ($i = 1, \dots, 5$)

- **Significant changes of Higgs boson phenomenology**

Investigation of $\mathcal{N}MSSM$ Discovery Prospects - Scan

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

$$1 \leq \tan \beta \leq 30, \quad 0 \leq \lambda \leq 0.7, \quad -0.7 \leq \kappa \leq 0.7$$

with perturbativity requirement

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

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

$$-2 \text{ TeV} \leq A_\lambda \leq 2 \text{ TeV}, \quad -2 \text{ TeV} \leq A_\kappa \leq 2 \text{ TeV}, \quad -1 \text{ TeV} \leq \mu_{\text{eff}} \leq 1 \text{ TeV}$$

Remaining Parameters:

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

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

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

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

NMSSM Scan

- **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]

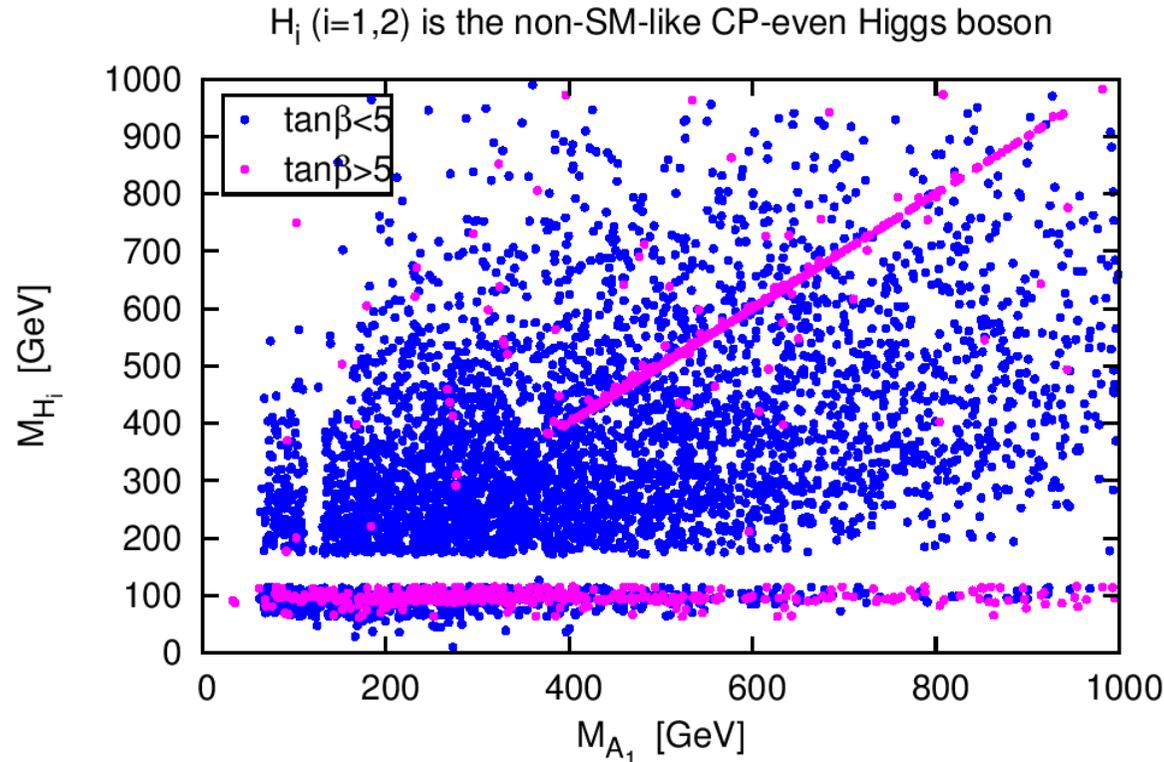
Experimental Signal Rates

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
$VH \rightarrow Vbb$	0.97	± 1.06
$H \rightarrow \tau\tau$	1.02	± 0.7
$H \rightarrow \gamma\gamma$	1.14	± 0.4
$H \rightarrow WW$	0.78	± 0.34
$H \rightarrow ZZ$	1.11	± 0.46

Mass Distributions

King, MMM, Nevzorov, Walz



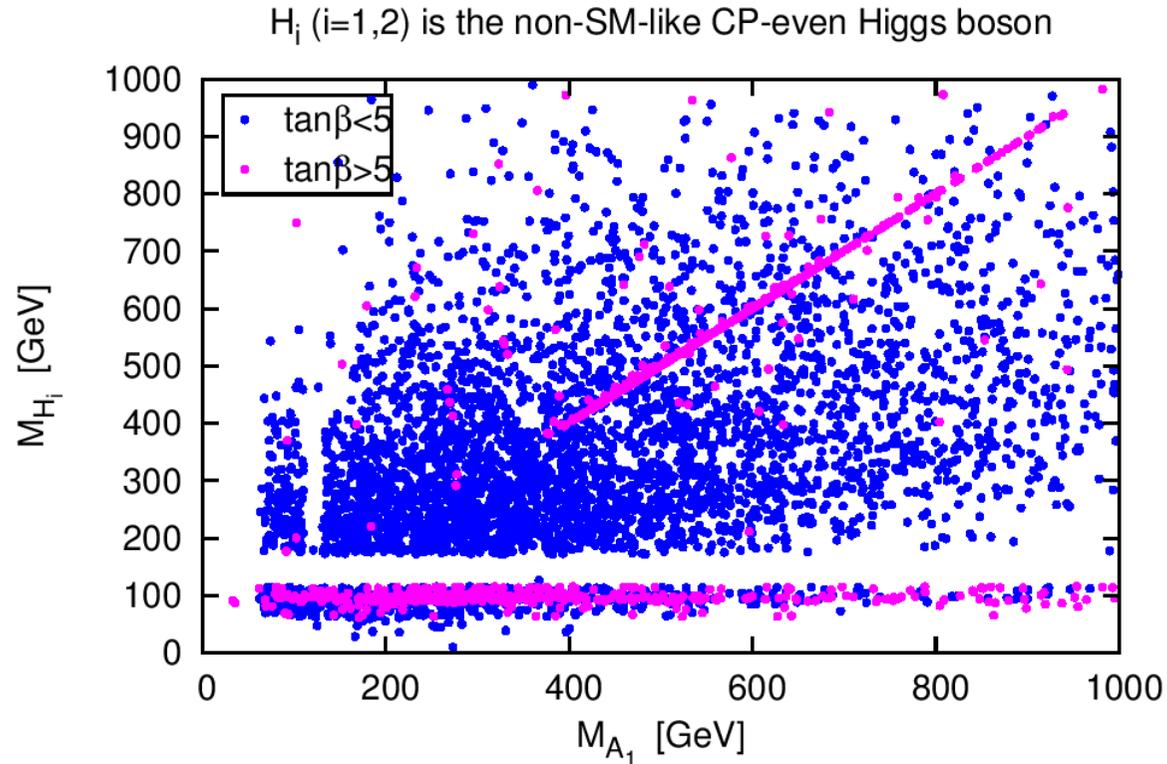
$M_{H_i} \lesssim 115$ GeV $\rightsquigarrow H_1$ non-SM-like; $M_{H_i} \gtrsim 180$ GeV $\rightsquigarrow H_2$ non-SM-like

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

Mass Distributions

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

Benchmarks for Higgs-to-Higgs Decays

- Higgs-to-Higgs Decays

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

- ▷ 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

Benchmarks for Higgs-to-Higgs Decays

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

A.1: CP-odd singlet close in mass to the SM-like Higgs, $M_{A_s} = 119$ GeV. Heavy Higgs boson masses around 341 and 347 GeV.

A.2: CP-odd singlet light, $M_{A_s} = 79$ GeV, heavy Higgs boson masses around 326 GeV.

Examples of rather light NMSSM Higgs spectrum \rightsquigarrow all can be discovered directly or in cascade decays; access to $\lambda_{HH_s H_s}, \lambda_{HH_s h}, \lambda_{AA_s h}, \lambda_{AA_s H}$

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

B.1: A_s light, $M_{A_s} = 73$ GeV, overall spectrum light: $M_H = 323$ GeV, $M_A = 312$ GeV.

B.2: A_s lighter than h , $M_{A_s} = 107$, overall spectrum heavier: $M_H = 556$ GeV, $M_A = 578$ GeV.

B.3: A_s heavier than h , $M_{A_s} = 133$ GeV; maximum masses: $M_H = 463$ GeV, $M_A = 457$ GeV.

B.1 unique!; B.2: H_s very singlet-like, challenging to find all Higgs bosons (only $\lambda_{HH_s h}, \lambda_{AA_s h}$ accessible); B.3: A_s very singlet-like ($\lambda_{HH_s h}, \lambda_{AA_s h}, \lambda_{AA_s H_s}$ accessible)

C) $H_1 = h, H_3 = H_s, \tan \beta$ large (not all accessible $\leftarrow M_{H_s} = 3.5$ TeV)

D) $H_2 = h$ decays into lighter Higgs pairs (D.1: $h \rightarrow H_s H_s, H_s$ very light!; D.2: $h \rightarrow A_s A_s$)

Benchmark $H_2 = h$, $H_1 = H_s$ and $\tan \beta$ small

A.1 (Point ID 3877)	Scenario		
$M_{H_1}, M_{H_2}, M_{H_3} = M_{H_s}, M_h, M_H$	90.3 GeV	126.8 GeV	341.3 GeV
$M_{A_1}, M_{A_2} = M_{A_s}, M_A$	118.5 GeV	346.7 GeV	
$ S_{H_1 h_s} ^2, P_{A_1 a_s} ^2$	0.97	0.94	
$\mu_{\tau\tau}, \mu_{bb}$	1.09	1.08	
$\mu_{ZZ}, \mu_{WW}, \mu_{\gamma\gamma}$	0.85	0.85	0.88
$\tan \beta, \lambda, \kappa$	1.66	0.64	0.11
$A_\lambda, A_\kappa, \mu_{\text{eff}}$	338.0 GeV	-71.2 GeV	162.8 GeV
A_t, A_b, A_τ	181.1 GeV	-1530.0 GeV	87.2 GeV
M_1, M_2, M_3	440.0 GeV	813.7 GeV	1710.2 GeV
$M_{Q_3} = M_{t_R}, M_{b_R}$	1827.5 GeV	3 TeV	
$M_{L_3} = M_{\tau_R}, M_{\text{SUSY}}$	1663.7 GeV	3 TeV	

$$\text{BR}(H \rightarrow H_s H_s) = 0.11 , \quad \text{BR}(H \rightarrow h H_s) = 0.12 , \quad \text{BR}(H \rightarrow Z A_s) = 0.25$$

$$\text{BR}(A \rightarrow h A_s) = 0.14 , \quad \text{BR}(A \rightarrow H_s A_s) = 0.085 , \quad \text{BR}(A \rightarrow Z H_s) = 0.047$$

A.1 (Point ID 3877)	Signal Rates
$\sigma(ggH)\text{BR}(H \rightarrow H_s H_s)$	458.74 fb
$\sigma(ggH)\text{BR}(H \rightarrow H_s H_s \rightarrow bb + bb)$	341.12 fb
$\sigma(ggH)\text{BR}(H \rightarrow H_s H_s \rightarrow bb + \tau\tau)$	68.34 fb
$\sigma(ggH)\text{BR}(H \rightarrow H_s H_s \rightarrow \tau\tau + \tau\tau)$	3.42 fb
$\sigma(ggH)\text{BR}(H \rightarrow H_s H_s \rightarrow bb + \gamma\gamma)$	0.92 fb
$\sigma(ggH)\text{BR}(H \rightarrow h H_s)$	505.60 fb
$\sigma(ggH)\text{BR}(H \rightarrow h H_s \rightarrow bb + bb)$	274.92 fb
$\sigma(ggH)\text{BR}(H \rightarrow h H_s \rightarrow bb + \tau\tau)$	56.46 fb
$\sigma(ggH)\text{BR}(H \rightarrow h H_s \rightarrow \tau\tau + \tau\tau)$	2.90 fb
$\sigma(ggH)\text{BR}(H \rightarrow h H_s \rightarrow bb + \gamma\gamma)$	1.34 fb
$\sigma(ggA)\text{BR}(A \rightarrow h A_s)$	472.37 fb
$\sigma(ggA)\text{BR}(A \rightarrow h A_s \rightarrow bb + bb)$	262.24 fb
$\sigma(ggA)\text{BR}(A \rightarrow h A_s \rightarrow \tau\tau + bb)$	55.00 fb
$\sigma(ggA)\text{BR}(A \rightarrow h A_s \rightarrow \tau\tau + \tau\tau)$	2.88 fb
$\sigma(ggA)\text{BR}(A \rightarrow h A_s \rightarrow WW + bb)$	85.39 fb
$\sigma(ggA)\text{BR}(A \rightarrow h A_s \rightarrow \gamma\gamma + bb)$	1.04 fb
$\sigma(ggA)\text{BR}(A \rightarrow H_s A_s)$	285.76 fb
$\sigma(ggA)\text{BR}(A \rightarrow H_s A_s \rightarrow bb + bb)$	216.95 fb
$\sigma(ggA)\text{BR}(A \rightarrow H_s A_s \rightarrow \tau\tau + bb)$	44.42 fb
$\sigma(ggA)\text{BR}(A \rightarrow H_s A_s \rightarrow \tau\tau + \tau\tau)$	2.27 fb
$\sigma(ggA)\text{BR}(A \rightarrow H_s A_s \rightarrow \gamma\gamma + bb)$	0.39 fb

Access to $\lambda_{HH_s H_s}$, $\lambda_{HH_s h}$, $\lambda_{AA_s h}$ and $\lambda_{AA_s H_s}$

Benchmark $H_1 = h$ 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

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

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

Benchmark $H_1 = h$ and $\tan \beta$ small

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

accessible:

$\lambda_{H_s A_s A_s}$

$\lambda_{H H_s h}$

$\lambda_{A A_s H_s}$

$\lambda_{A A_s h}$

Benchmark $H_1 = h$ and $\tan \beta$ small

B.1 (Point ID Poi2a)	Decay Rates
$\sigma(ggH_s)$	282.37 fb
$\sigma(ggH_s)\text{BR}(H_s \rightarrow A_s A_s)$	274.75 fb
$\sigma(ggH_s)\text{BR}(H_s \rightarrow A_s A_s \rightarrow b\bar{b} + b\bar{b})$	5.87 fb
$\sigma(ggH_s)\text{BR}(H_s \rightarrow A_s A_s \rightarrow \gamma\gamma + b\bar{b})$	67.33 fb
$\sigma(ggH_s)\text{BR}(H_s \rightarrow A_s A_s \rightarrow \gamma\gamma + \gamma\gamma)$	193.22 fb
$\sigma(ggH)$	3.166 pb
$\sigma(ggH)\text{BR}(H \rightarrow hH_s)$	1.609 pb
$\sigma(ggH)\text{BR}(H \rightarrow hH_s \rightarrow bb + \tau\tau)$	1.44 fb
$\sigma(ggH)\text{BR}(H \rightarrow hH_s \rightarrow h + A_s A_s \rightarrow bb + 4\gamma)$	712.47 fb
$\sigma(ggH)\text{BR}(H \rightarrow hH_s \rightarrow h + A_s A_s \rightarrow \gamma\gamma + 4b)$	248.02 fb
$\sigma(ggH)\text{BR}(H \rightarrow hH_s \rightarrow h + A_s A_s \rightarrow \tau\tau + 4\gamma)$	74.60 fb
$\sigma(ggH)\text{BR}(H \rightarrow hH_s \rightarrow h + A_s A_s \rightarrow \gamma\gamma + 4\tau)$	2.47 fb
$\sigma(ggH)\text{BR}(H \rightarrow hH_s \rightarrow h + A_s A_s \rightarrow 6\gamma)$	2.69 fb
$\sigma(ggH)\text{BR}(H \rightarrow hH_s \rightarrow h + A_s A_s \rightarrow \tau\tau + \gamma\gamma + b\bar{b})$	49.55 fb
$\sigma(ggH)\text{BR}(H \rightarrow A_s A_s)$	5.59 fb
$\sigma(ggH)\text{BR}(H \rightarrow A_s A_s \rightarrow 4\gamma)$	3.93 fb

Benchmark $H_2 = h$ and $h \rightarrow A_s A_s$

D.2 (Point ID 110)	Scenario		
M_{H_s}, M_h, M_H	112.0 GeV	126.3 GeV	1288.2 GeV
M_{A_s}, M_A	61.5 GeV	1287.4 GeV	
$ S_{H_1 h_s} ^2, P_{A_1 a_s} ^2$	0.63	1	
$\mu_{\tau\tau}, \mu_{bb}$	0.73	0.62	
$\mu_{ZZ}, \mu_{WW}, \mu_{\gamma\gamma}$	0.90	1.03	1.06
$\tan\beta, \lambda, \kappa$	6.36	0.47	0.14
$A_\lambda, A_\kappa, \mu_{\text{eff}}$	1217.1 GeV	19.6 GeV	195.3 GeV
A_t, A_b, A_τ	-1804.6 GeV	-1196.8 GeV	1704.8 GeV
M_1, M_2, M_3	417.2 GeV	237.5 GeV	2362.2 GeV
$M_{Q_3} = M_{t_R}, M_{b_R}$	967.8 GeV	3 TeV	
$M_{L_3} = M_{\tau_R}, M_{\text{SUSY}}$	2491.6 GeV	3 TeV	

$\lambda_{hA_s A_s}$ accessible

Production of H and A difficult (both down-component doublet-like)

D.2 (Point ID 110)	Signal Rates
$\sigma(ggh)$	27.37 pb
$\sigma(ggh)\text{BR}(h \rightarrow A_s A_s)$	1.85 pb
$\sigma(ggh)\text{BR}(h \rightarrow A_s A_s \rightarrow bb + bb)$	1.55 pb
$\sigma(ggh)\text{BR}(h \rightarrow A_s A_s \rightarrow \tau\tau + \tau\tau)$	12.36 fb
$\sigma(ggh)\text{BR}(h \rightarrow A_s A_s \rightarrow bb + \tau\tau)$	212.07 fb
$\sigma(ggh)\text{BR}(h \rightarrow A_s A_s \rightarrow bb + \gamma\gamma)$	0.34 fb

Benchmark $H_2 = h$ 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	
$\mu_{\tau\tau}, \mu_{bb}$	0.90	0.89	
$\mu_{ZZ}, \mu_{WW}, \mu_{\gamma\gamma}$	0.92	0.92	0.92
$\tan \beta, \lambda, \kappa$	3.37	0.64	0.20
$A_\lambda, A_\kappa, \mu_{\text{eff}}$	-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	
$M_{L_3} = M_{\tau_R}, M_{\text{SUSY}}$	2930.8 GeV	3 TeV	

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

$\lambda_{h H_s H_s}, \lambda_{H H_s h}$ accessible, $\lambda_{A A_s h}$ more difficult

D.1 (Point ID 5416)	Signal Rates
$\sigma(ggh)$	44.28 pb
$\sigma(ggh)\text{BR}(h \rightarrow H_s H_s)$	4.22 pb
$\sigma(ggh)\text{BR}(h \rightarrow H_s H_s \rightarrow \tau\tau + \tau\tau)$	3.58 pb
$\sigma(ggh)\text{BR}(h \rightarrow H_s H_s \rightarrow \tau\tau + \mu\mu)$	31.64 fb
$\sigma(ggH)$	38.72 fb
$\sigma(ggH)\text{BR}(H \rightarrow t\bar{t})$	9.80 fb
$\sigma(ggH)\text{BR}(H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	5.73 fb
$\sigma(ggH)\text{BR}(H \rightarrow h H_s)$	8.08 fb
$\sigma(ggH)\text{BR}(H \rightarrow h H_s \rightarrow b\bar{b} + \tau\tau)$	4.26 fb
$\sigma(ggH)\text{BR}(H \rightarrow h H_s \rightarrow \tau\tau + \tau\tau)$	0.45 fb
$\sigma(ggA)$	41.26 fb
$\sigma(ggA)\text{BR}(A \rightarrow t\bar{t})$	11.24 fb
$\sigma(ggA)\text{BR}(A \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	5.94 fb
$\sigma(ggA)\text{BR}(A \rightarrow h A_s)$	4.95 fb
$\sigma(ggA)\text{BR}(A \rightarrow h A_s \rightarrow b\bar{b} + b\bar{b})$	1.15 fb
$\sigma(ggA)\text{BR}(A \rightarrow h A_s \rightarrow b\bar{b} + \tau\tau)$	0.26 fb
$\sigma(ggA)\text{BR}(A \rightarrow Z H_s)$	7.78 fb
$\sigma(ggA)\text{BR}(A \rightarrow Z H_s \rightarrow b\bar{b} + \tau\tau)$	1.08 fb

Conclusions

- **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

- **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, \cancel{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!



Discovery Prospects in the \mathcal{N} atural \mathcal{N} MSSM

- What scenario could be constrained at 13 TeV?

- Investigate prospects for subspace: Natural NMSSM

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

- 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

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

Discovery Prospects in the Natural NMSSM

- Tree-Level Mass Values

Nevezorov, Miller '04

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

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

$\sqrt{\Delta} \approx 137 \text{ GeV}$ ← loop corrections

- Loop-corrected Natural NMSSM Higgs Mass Values

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

- Production Cross Sections for H and A

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

Alternative Production Channels

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

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

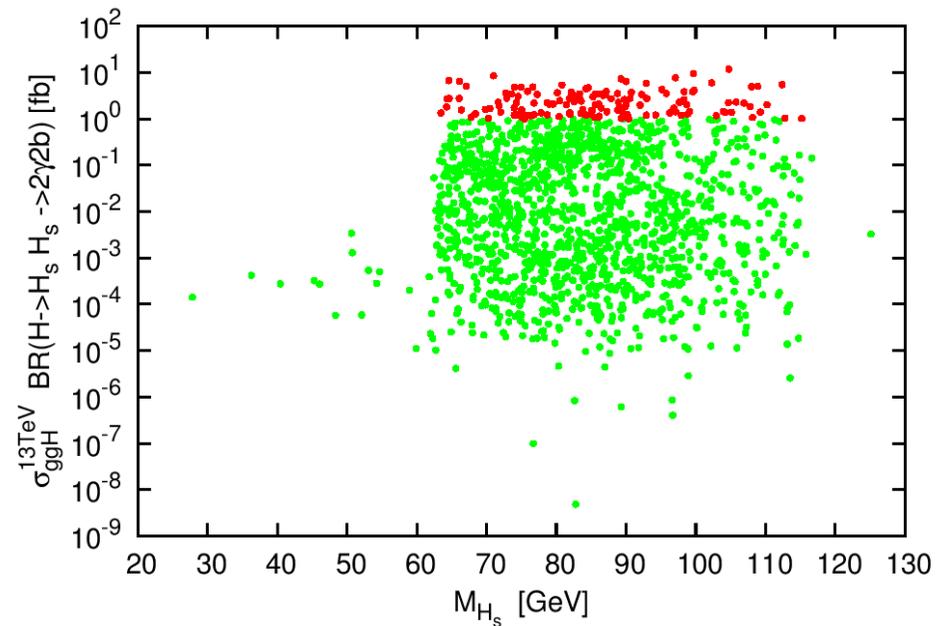
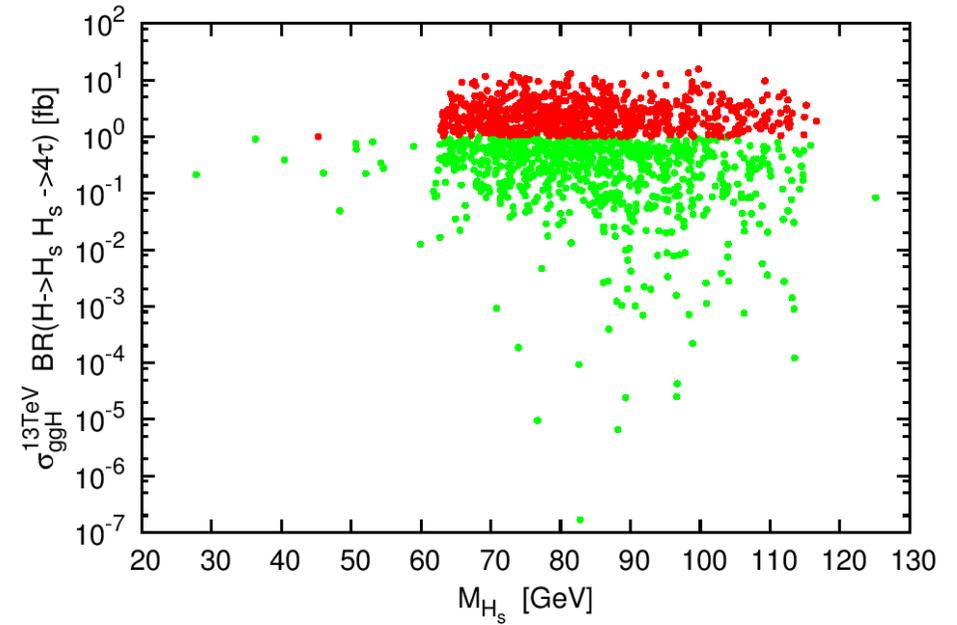
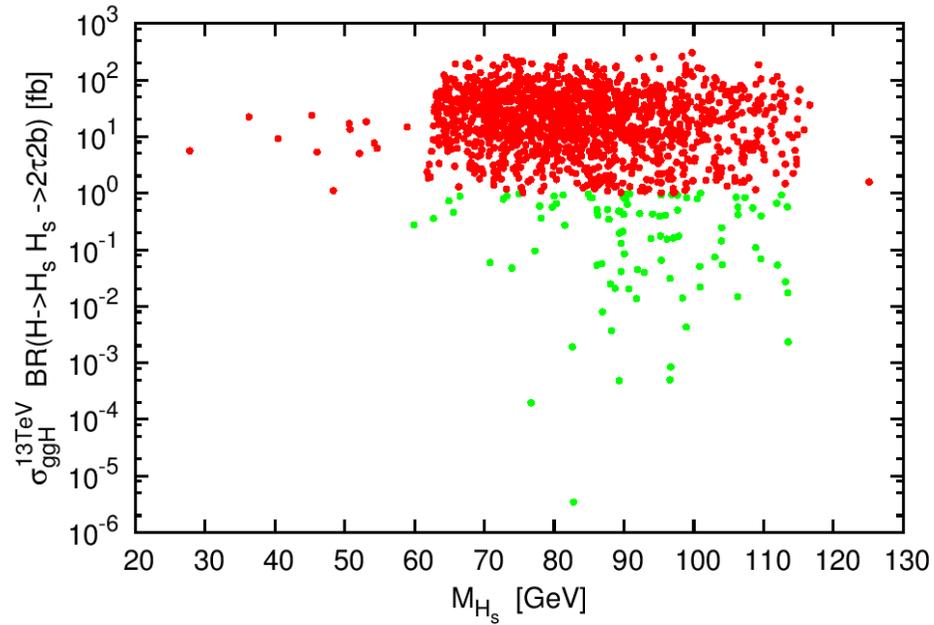
$$\sigma(gg \rightarrow \phi_i) \times BR(\phi_i \rightarrow \phi_j \phi_k) \times BR(\phi_j \rightarrow XX) \times BR(\phi_k \rightarrow YY)$$

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

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

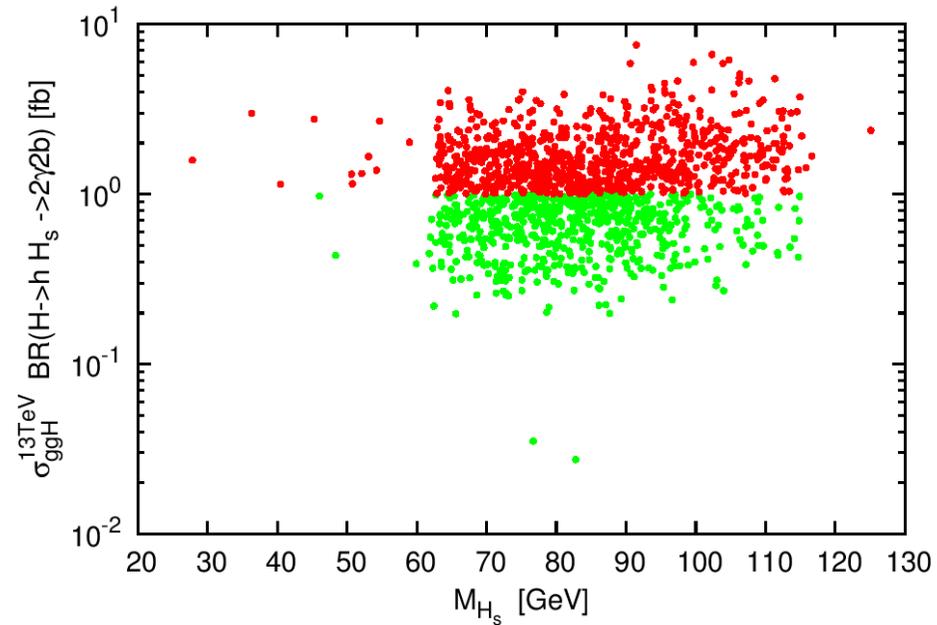
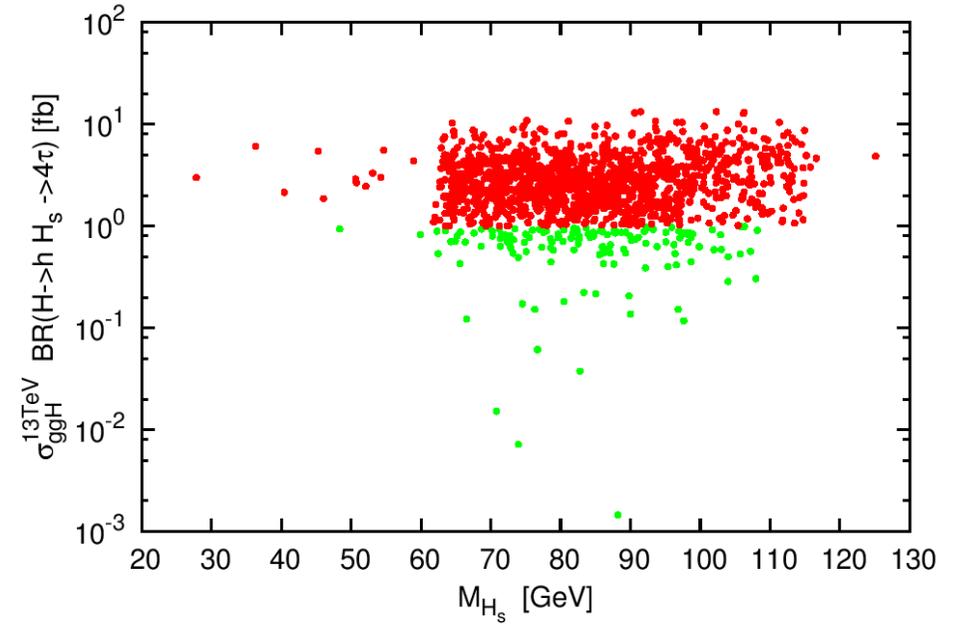
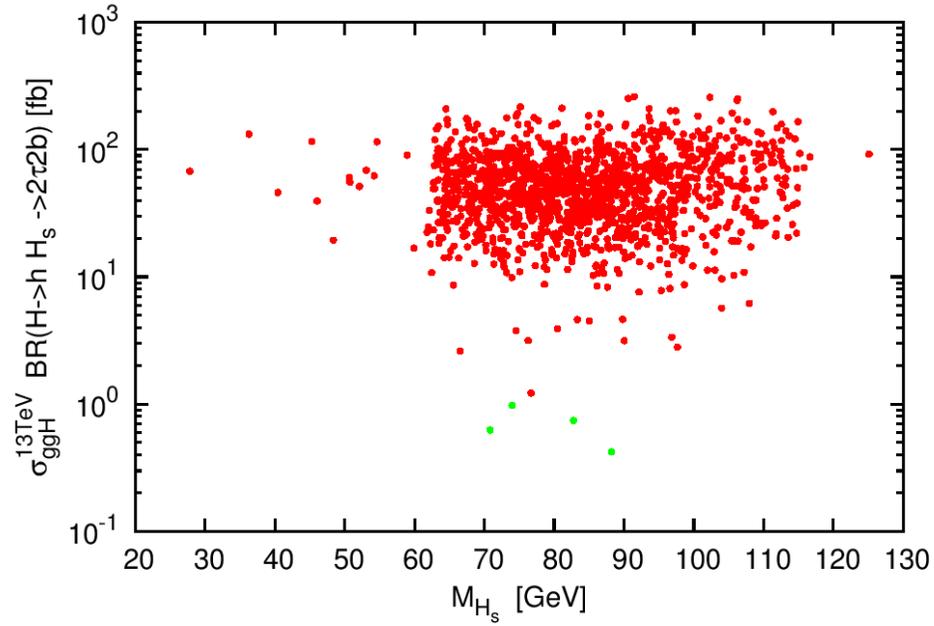
$$\sigma(gg \rightarrow H)BR(H \rightarrow H_s H_s \rightarrow (XX)(YY))$$

King, MMM, Nevzorov, Walz



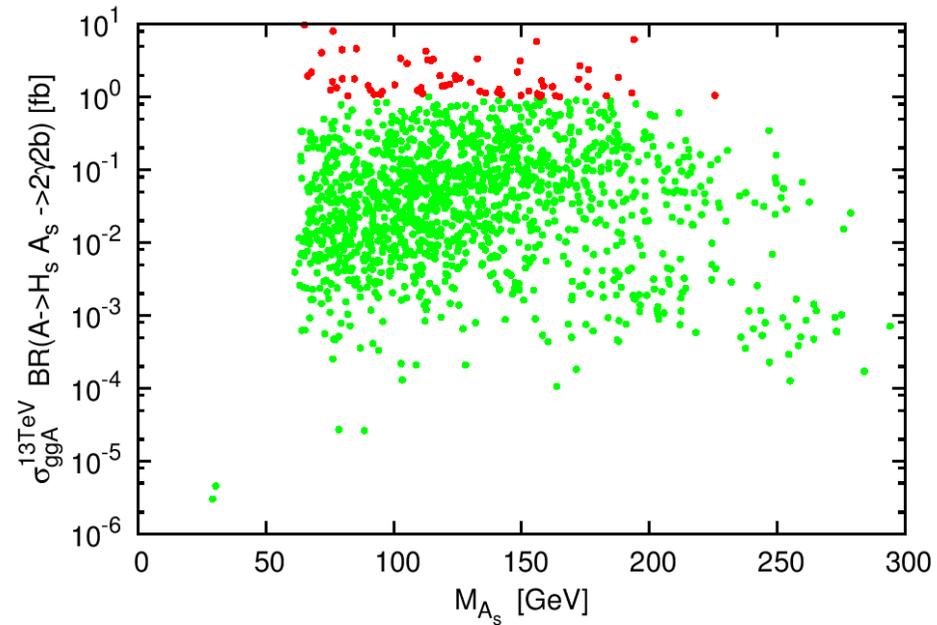
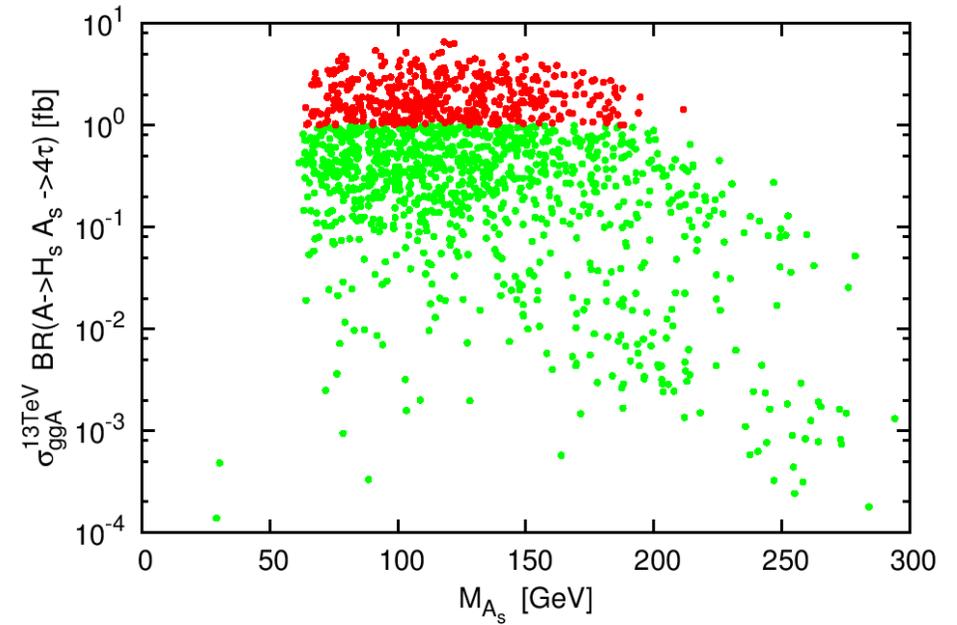
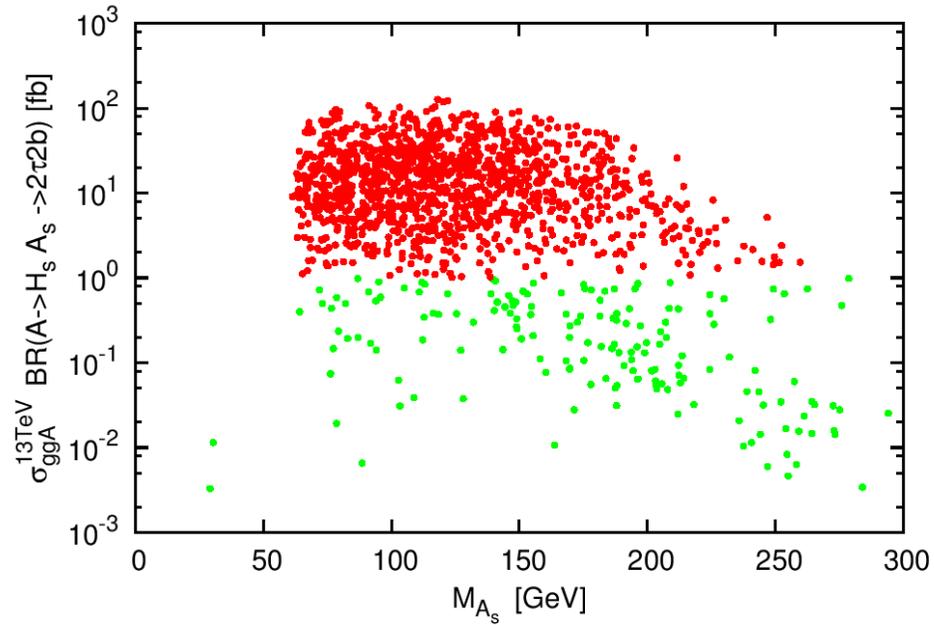
$$\sigma(gg \rightarrow H)BR(H \rightarrow hH_s \rightarrow (XX)(YY))$$

King, MMM, Nevzorov, Walz



$$\sigma(gg \rightarrow A)BR(A \rightarrow H_s A_s \rightarrow (XX)(YY))$$

King, MMM, Nevzorov, Walz



$$\sigma(gg \rightarrow A)BR(A \rightarrow hA_s \rightarrow (XX)(YY))$$

King,MMM,Nezvorov,Walz

