$\mathcal{N}$MSSM $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{S}$earch at the $\mathcal{H}$igh-$\mathcal{E}$nergy $\mathcal{LHC}$

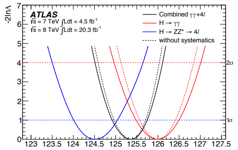
$\mathcal{M}$ilada $\mathcal{M}$argarete $\mathcal{M}$ühlleitner (KIT)
Coll. with Steve King, Roman Nevzorov and Kathrin Walz

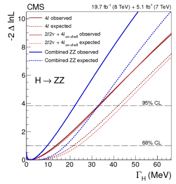
SUSY 2014
University of Manchester
21-26 July 2014

$\mathcal{I}$t is the $\mathcal{H}$iggs $\mathcal{B}$oson

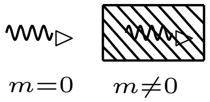
- **Investigation of properties of scalar particle:**

  * Mass m, Total Width Γ

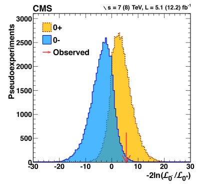


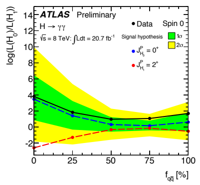


  * Couplings to SM particles $g_{HXX} \sim m_X$

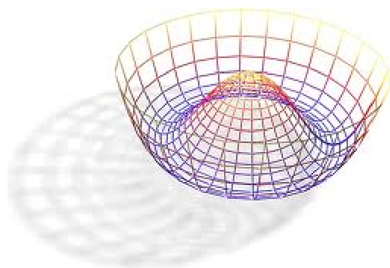


  * Spin and Parity Quantum Numbers J^P (CP violation?)

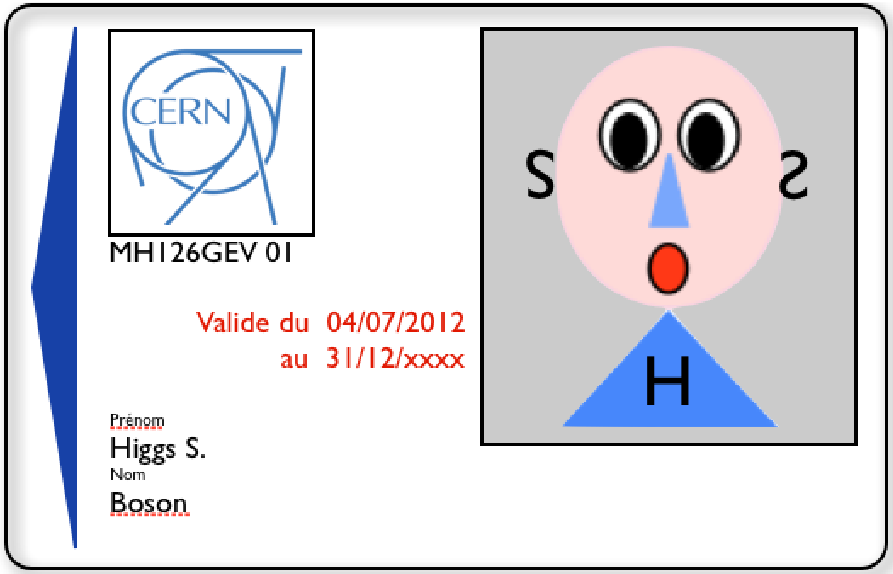




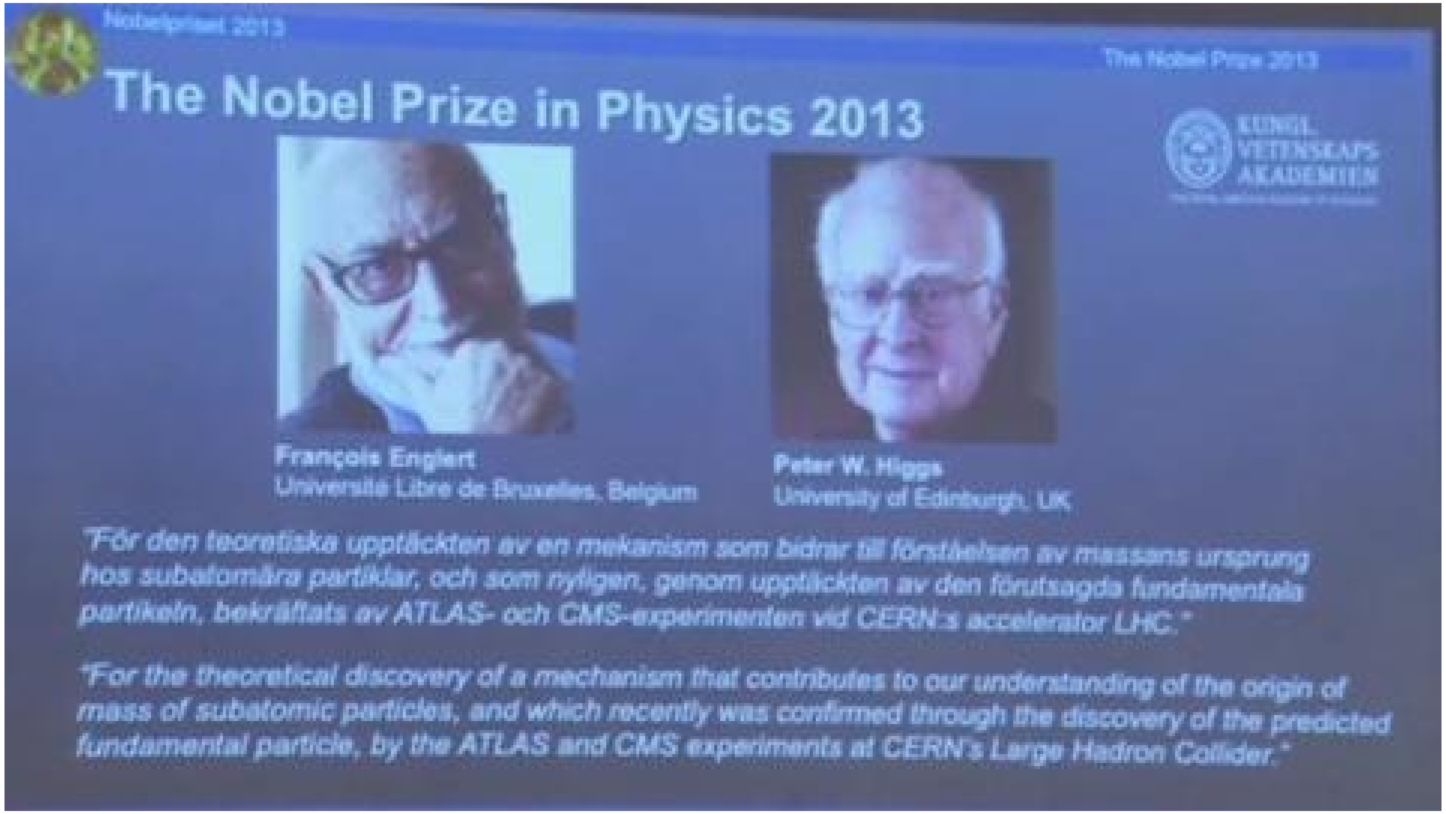
  * Trilinear and Quartic Higgs Self-Coupling $\rightsquigarrow$ Higgs Potential



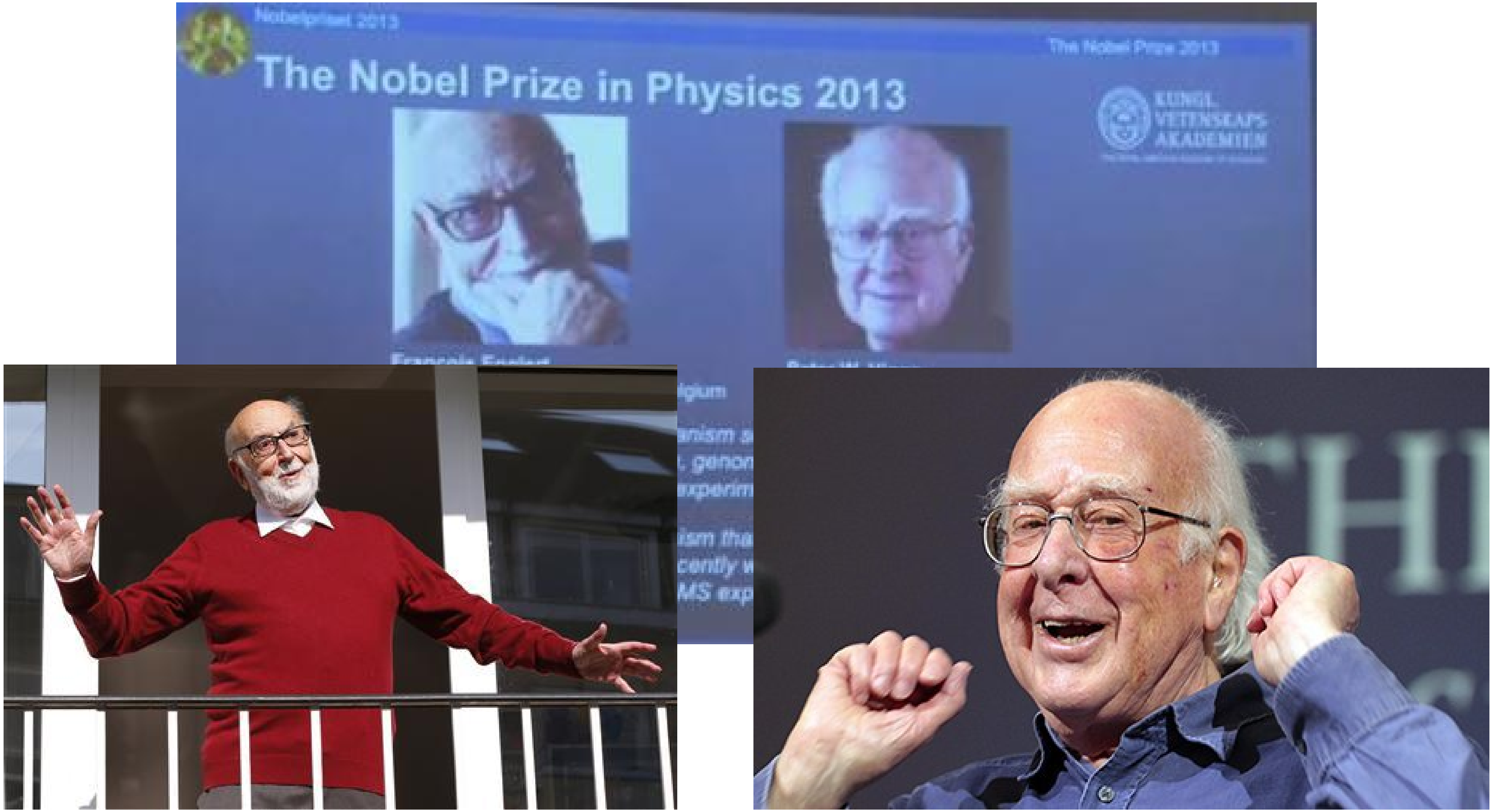
- **Investigation of properties of scalar particle:** $\rightsquigarrow$ Higgs Boson



$\mathcal{N}$obel $\mathcal{P}$rize in $\mathcal{P}$hysics 2013



$\mathcal{N}$obel $\mathcal{P}$rize in $\mathcal{P}$hysics 2013



After Higgs Discovery: Which Higgs Boson?

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

Lone Higgs

Simplest Higgs

Phantom Higgs

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**

NMSSM Higgs Mass and LHC Results

- **Vast literature on NMSSM Higgs of $\sim$ 125-126 GeV**

Hall eal; Ellwanger; Gunion eal; King,MMM,Nevzorov; Albornoz Vasquez eal; Cao eal; Gabrielli eal; Ellwanger, Hugonie; Kang eal; Cheung eal; Jeong eal; Hardy eal; Kim eal; Arvanitaki eal; Cheng eal; Bélanger eal; Kowalska eal; Badziak eal; Moretti eal: Choi eal; Munir eal; Barbieri eal; Beskidt eal; Berg eal; Gherghetta eal; Cerdeno eal; Das eal; Christensen eal; Bhattacherjee eal; Guo eal; ...

- **Compatibility of NMSSM Higgs mass with LHC Searches:**

$\star$ Upper mass bounds + corrections to the MSSM, NMSSM Higgs boson mass:

MSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$

NMSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$

$\Rightarrow M_H \approx 126$ requires:

MSSM: $\Delta m_h \approx 85$ GeV ($\tan\beta$ large) $\Rightarrow$ large corrections $\rightsquigarrow$ fine-tuning

NMSSM: $\Delta m_h \approx 55$ GeV ($\lambda = 0.7, \tan\beta = 2$)

$\Rightarrow$ NMSSM requires less fine-tuning

Hall,Pinner,Ruderman; Ellwanger; Arvanitaki,Villadoro; King,MMM,Nevzorov; Kang,Li,Li; Cao,Heng,Yang,Zhang,Zhu

$\mathcal{NMSSM}$ $\mathcal{H}$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 ATLAS-CONF-2012-011 and 2013-090, CMS-HIG-12-052

Degenerate NMSSM Higgs Scenario

King,Nevzorov,MMM,Walz

(Point ID 4617)	Scenario		
$M_{H_1}, M_{H_2}, M_{H_3}$	124.9 GeV	126.6 GeV	538 GeV
M_{A_1}, M_{A_2}	92 GeV	541 GeV	
$\|S_{H_1 h_s}\|^2, \|S_{H_2 h_s}\|^2$	0.69	0.29 (singlet admixture)	
$\mu_{\tau\tau},\ \mu_{bb}$	0.96	0.96	
$\mu_{ZZ},\ \mu_{WW},\ \mu_{\gamma\gamma}$	0.90	1.08	1.02
$\tan\beta,\ \lambda,\ \kappa$	1.93	0.67	0.13
$A_\lambda,\ A_\kappa,\ \mu_{\text{eff}}$	559 GeV	301 GeV	233 GeV
$A_t,\ A_b,\ A_\tau$	1062 GeV	349 GeV	-1753 GeV
$M_1,\ M_2,\ M_3$	887 GeV	265 GeV	1130 GeV
$M_{Q_3} = M_{t_R},\ M_{b_R}$	763 GeV	1 TeV	
$M_{L_3} = M_{\tau_R},\ M_{\text{SUSY}}$	700 GeV	1 TeV	

$M_{H^\pm} = 529$ GeV, $m_{\tilde{t}_1} = 694$ GeV, $m_{\tilde{t}_2} = 847$ GeV

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Largest H_3, A_2 BR: $H_3, A_2 \to t\bar{t},\ \tilde{\chi}_1^0\tilde{\chi}_1^0,\ \tilde{\chi}_1^+\tilde{\chi}_1^-,\ H_3 \to ZA_1,\ A_2 \to A_1 H_2$

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Resolve degenerate signal: double ratios of signal rates $\longleftarrow$ high luminosity [Gunion,Kraml,Jiang]

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$M_{L_3} = M_{\tau_R},\ M_{\text{SUSY}}$	700 GeV	1 TeV	

Resolve degenerate signal: test properties of event rate matrix ← high luminosity [Grossman,Surujon,Zupan]

$\mathcal{I}$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^{exp}_{XX} $(X = b, \tau, \gamma, W, Z)$: $|\mu^{\text{scan}}_{XX}(h) - \mu^{\text{exp}}_{XX}| \leq 2\sigma$
  * 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** $\Phi = H_i, A_j$

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

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

$\mathcal{N}$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

http://www.itp.kit.edu/∼maggie/NMSSMCALC

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:

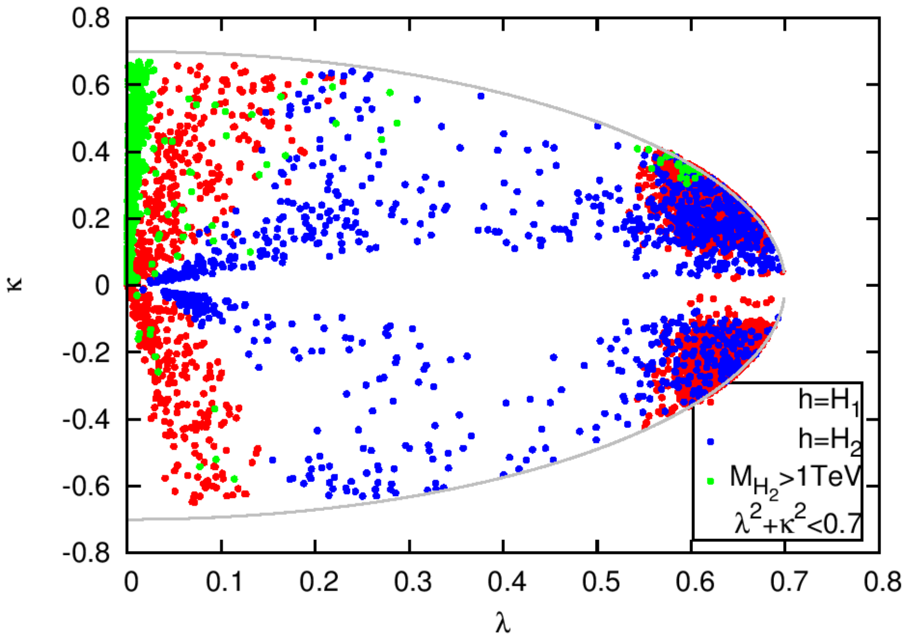
NMSSMCALC:	Julien Baglio, Ramona Gröber, Margarete Mühlleitner, Dao Thi Nhung, Heidi Rzehak, Michael Spira, Juraj Streicher and Kathrin Walz, in arXiv:1312.4788
One-Loop Masses:	K. Ender, T. Graf, M. Mühlleitner, H. Rzehak, in Phys. Rev. D85 (2012)075024
	T. Graf, R. Gröber, M. Mühlleitner, H. Rzehak, 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

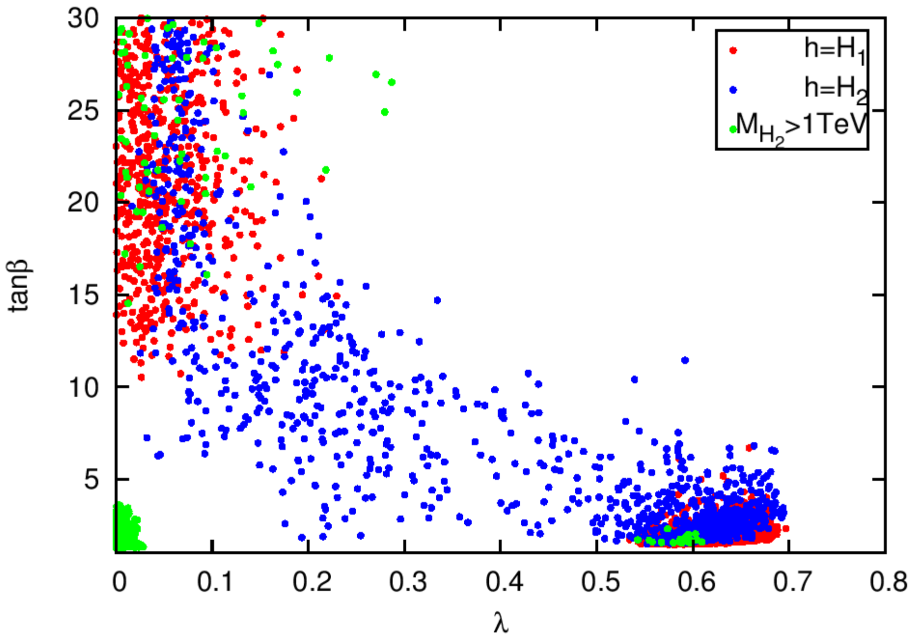
Informations on the Program:

- 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.

$\mathcal{D}$istributions of λ, κ and $\tan\beta$

King,MMM,Nevzorov,Walz



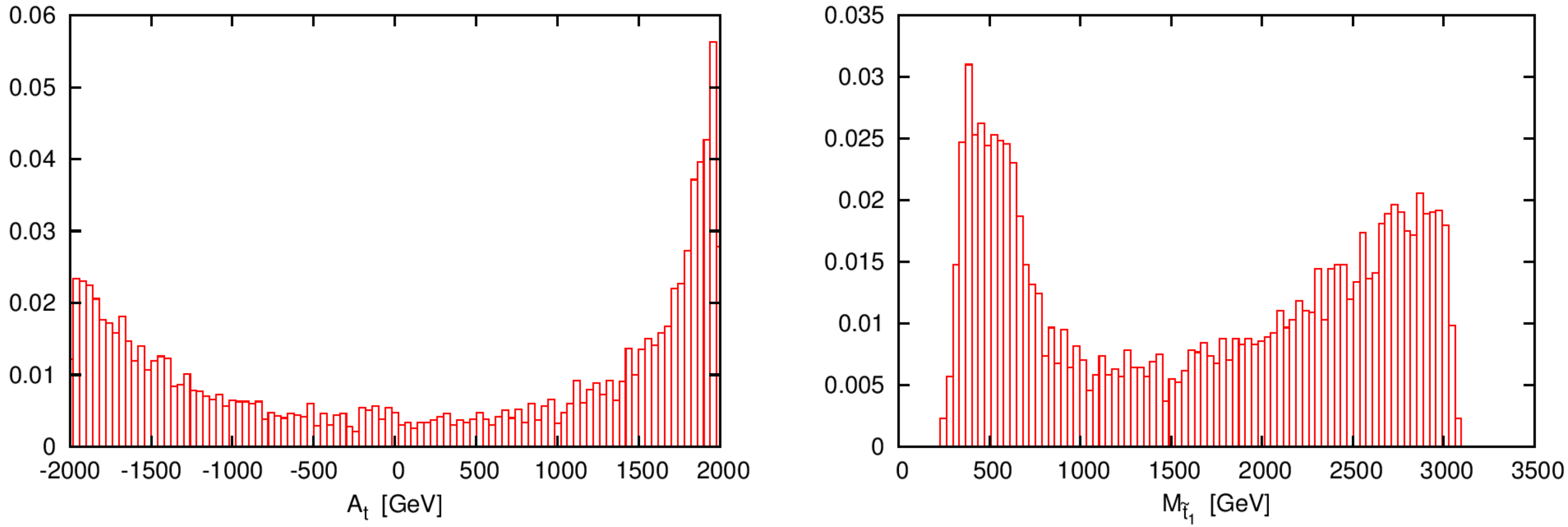


SM-like Higgs h around 126 GeV for $0.5 \lesssim \lambda \lesssim 0.7$, $\tan\beta \lesssim 5$ or $\lambda \lesssim 0.1$, $\tan\beta \gtrsim 10$

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{\lambda^2 v^2}{2} \sin^2 2\beta + \Delta m_h^2$$

$\mathcal{D}$istributions of A_t and $m_{\tilde{t}_1}$

King,MMM,Nevzorov,Walz



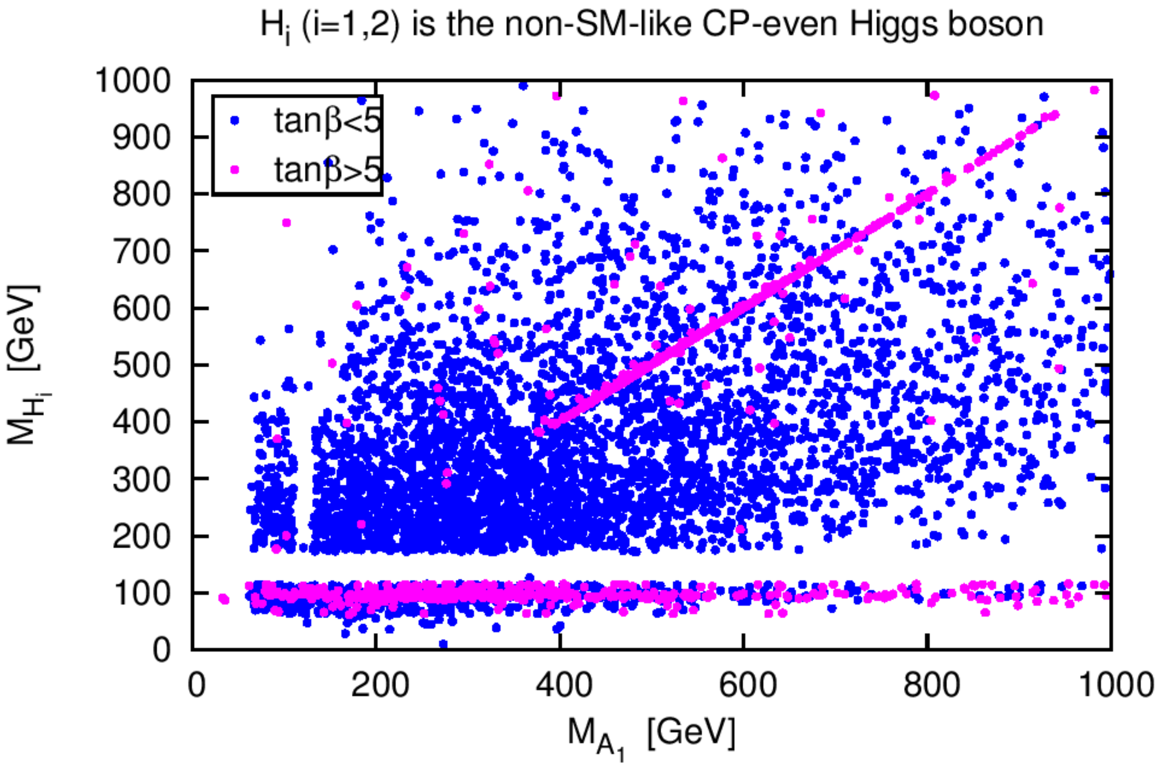
important Higgs mass corrections emerge from (s)top sector

larger (w/ resp to MSSM) tree-level SM-like Higgs mass $\rightsquigarrow$ lighter $m_{\tilde{t}_1}$ can be afforded

270 GeV $\lesssim m_{\tilde{t}_1} \lesssim 3.1$ GeV also $A_t = 0$ possible

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

King,MMM,Nevzorov,Walz



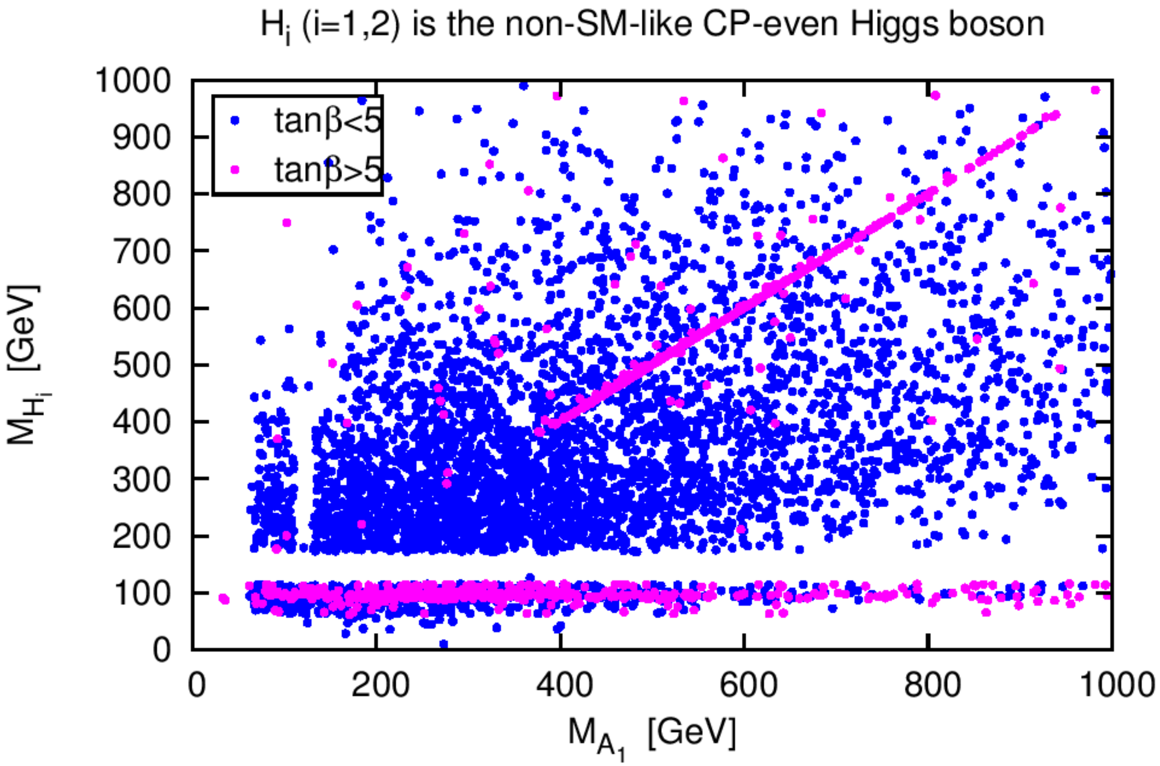
$M_{H_i} \lesssim 115$ GeV $\rightsquigarrow H_1$ non-SM-like; $M_{H_i} \gtrsim 180$ GeV $\rightsquigarrow H_2$ non-SM-like

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

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)

$\mathcal{E}$xperimental $\mathcal{S}$ituation

- CMS, CMS-HIG-12-004: σBR$(pp \to a \to \mu^+\mu^-)$, $5.5 \le m_{\mu\mu} \le 14$ GeV, excluded: $1.5 - 7.5$ pb at 95% CL ($\sqrt{s} = 7$ TeV, $\int \mathcal{L} = 1.3$ fb^{-1})

- ATLAS, ATLAS-CONF-2012-079: $H \to aa \to \gamma\gamma + \gamma\gamma$ for $M_H = 110 - 150$ GeV, $M_a = 100, 200, 400$ MeV; σ BR $= 0.1$ pb excluded in $115 - 140$ GeV, 0.2 pb outside ($\sqrt{s} = 7$ TeV, $\int \mathcal{L} = 4.9$ fb^{-1})

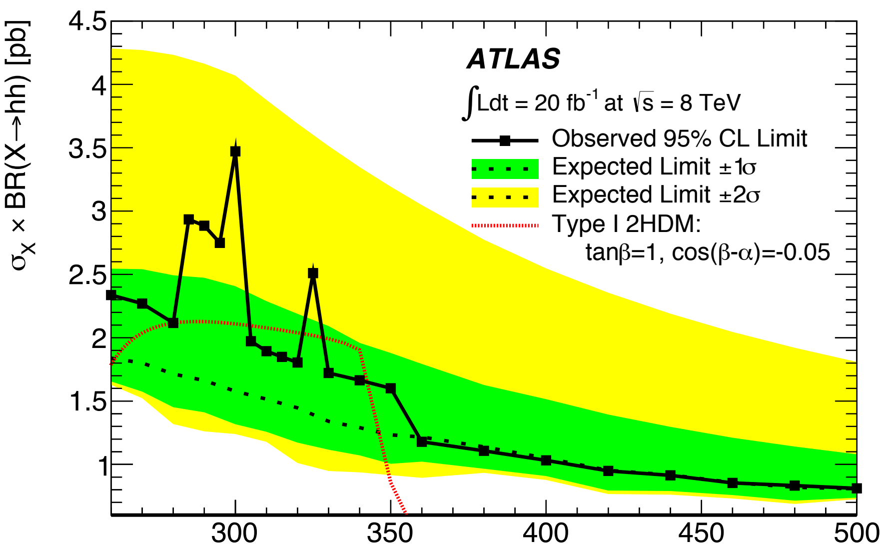
- CMS, CMS-PAS-HIG-13-032: $X \to HH \to (\gamma\gamma)(b\bar{b})$, $260 \le m_X \le 1100$ GeV, σ BR $\approx 0.4 - 4$ fb excluded at 95% CL ($\sqrt{s} = 8$ TeV, $\int \mathcal{L} = 19.7$ fb^{-1})

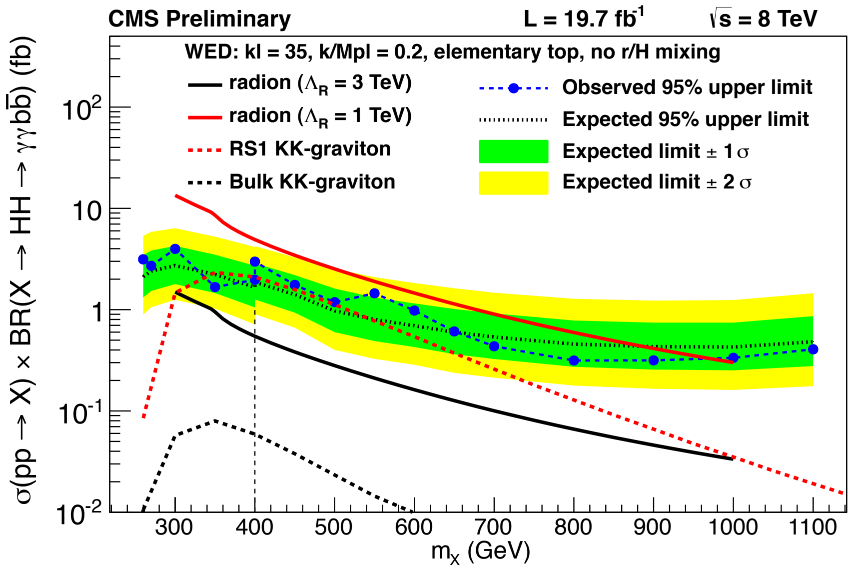
- ATLAS, 1406.5053: resonant and non-resonant pair production in $hh \to (\gamma\gamma)(b\bar{b})$, $260 \le m_h \le 500$ GeV (SM h),
  non-resonant σ BR $= 2.2$ pb upper limit,
  resonant σBR $= 0.8 - 3.5$ pb excluded at 95%CL ($\sqrt{s} = 8$ TeV, $\int \mathcal{L} = 20$ fb^{-1})

$\mathcal{E}$xperimental $\mathcal{S}$ituation

ATLAS, 1406.5053

CMS-PAS-HIG-13-032





$\mathcal{D}$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**

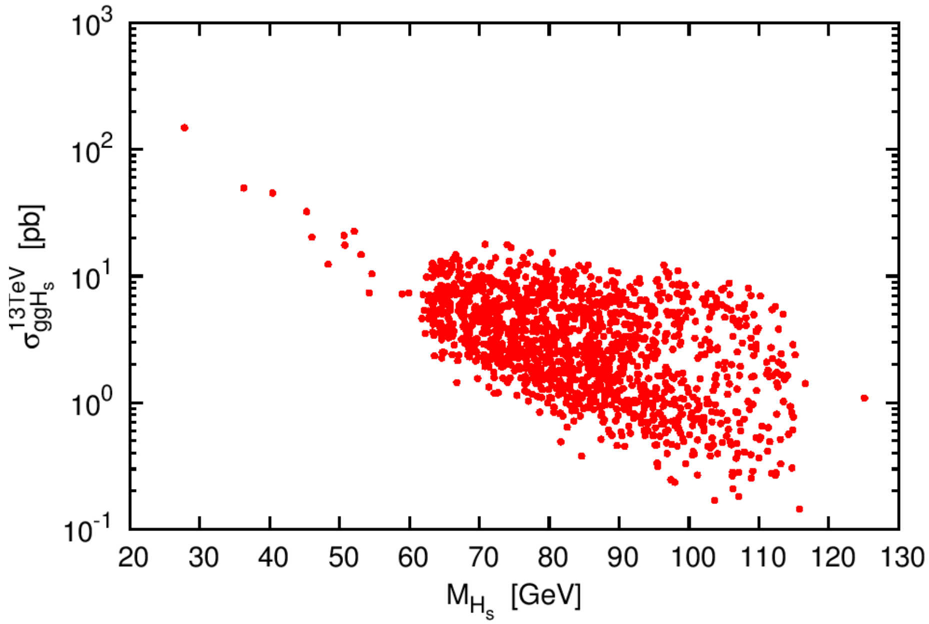
$230 \text{ GeV} \lesssim M_H, M_A \lesssim 530 \text{ GeV}\ ,\ 27 \text{ GeV} \lesssim M_{H_s} \lesssim 117 \text{ GeV}\ ,\ 29 \text{ GeV} \lesssim M_{A_s} \lesssim 300 \text{ GeV}$

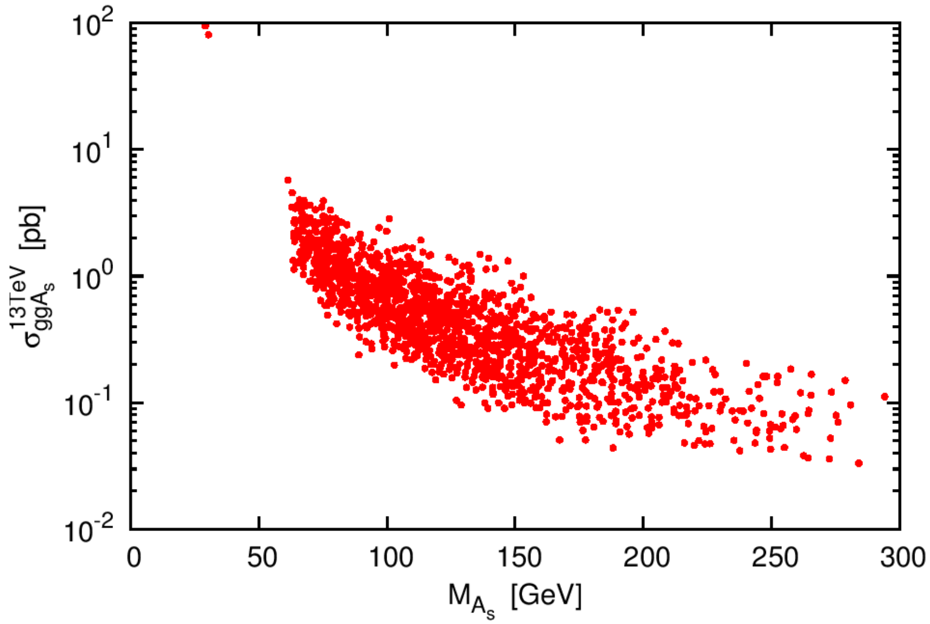
- **Production Cross Sections for H and A**

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

$\mathcal{P}$roduction $\mathcal{C}$ross $\mathcal{S}$ections for H_s, A_s

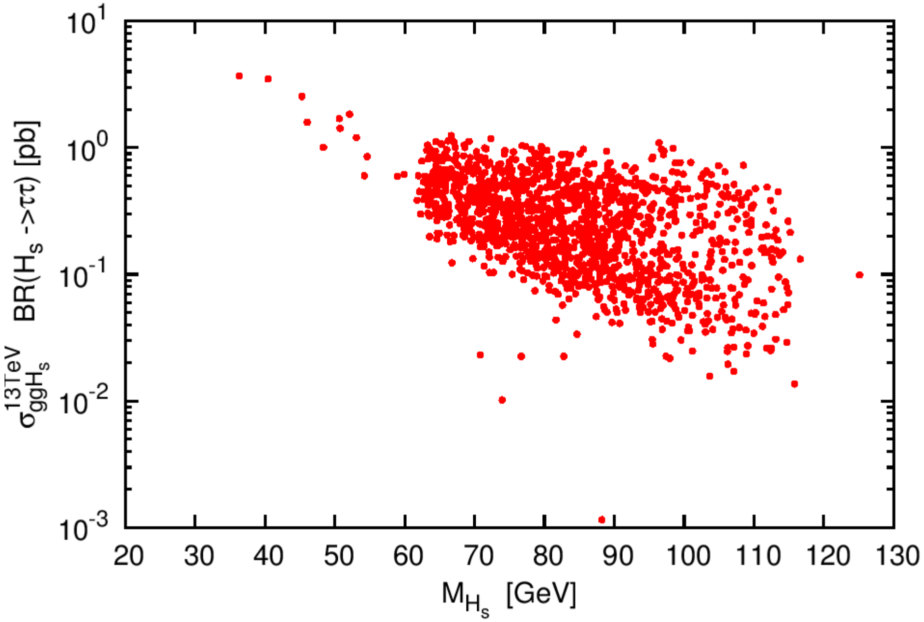
King,MMM,Nevzorov,Walz

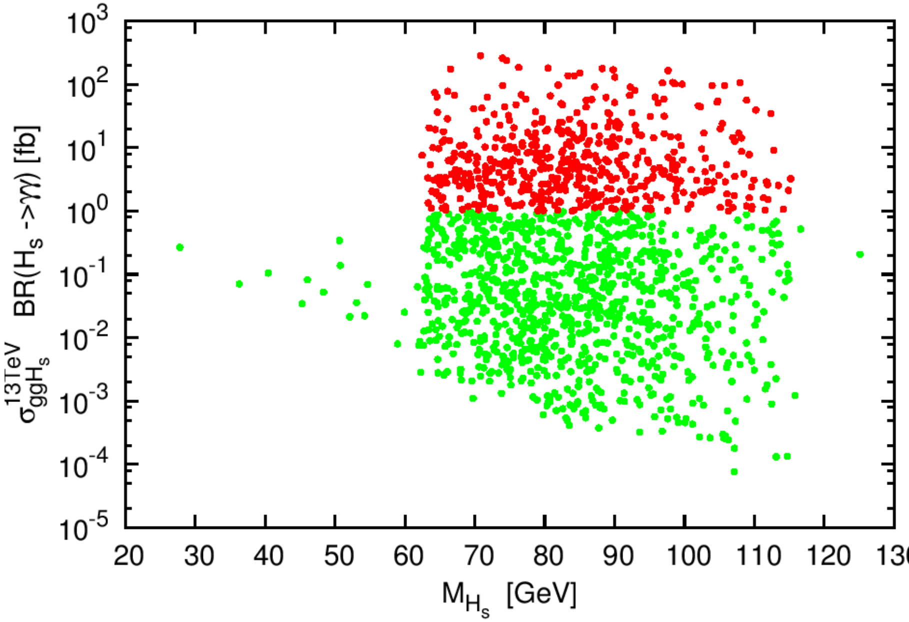


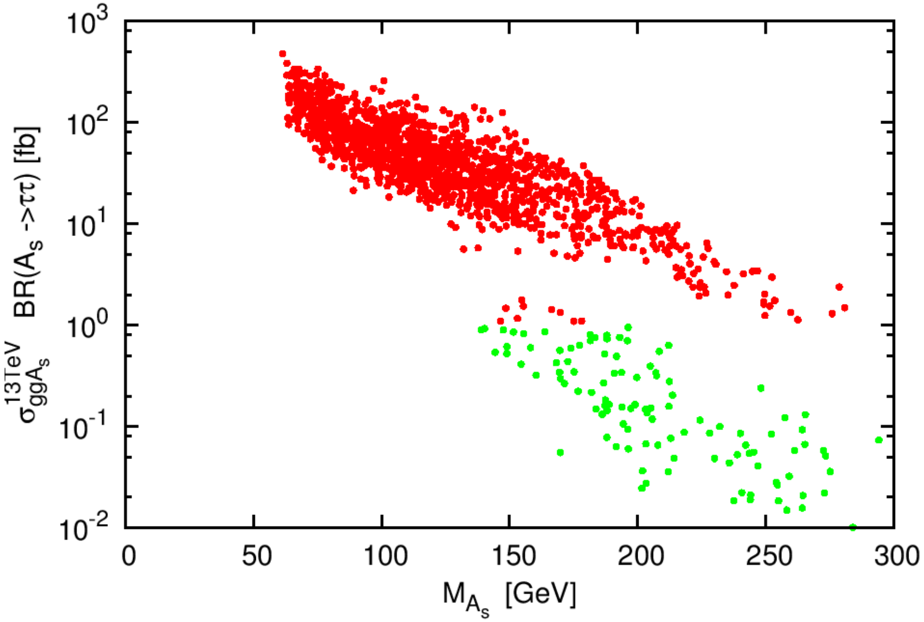


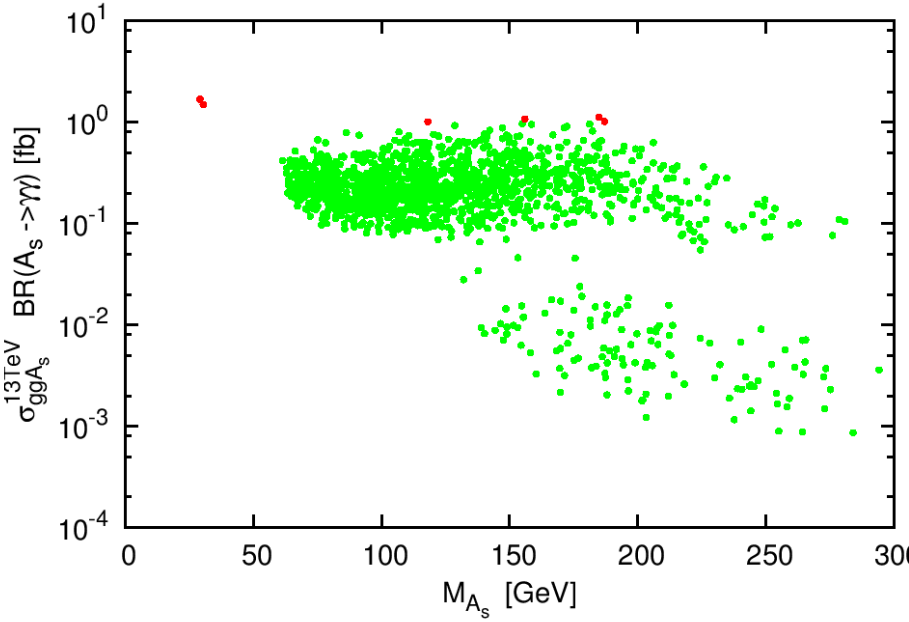
Signal Rates for H_s, A_s

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:**

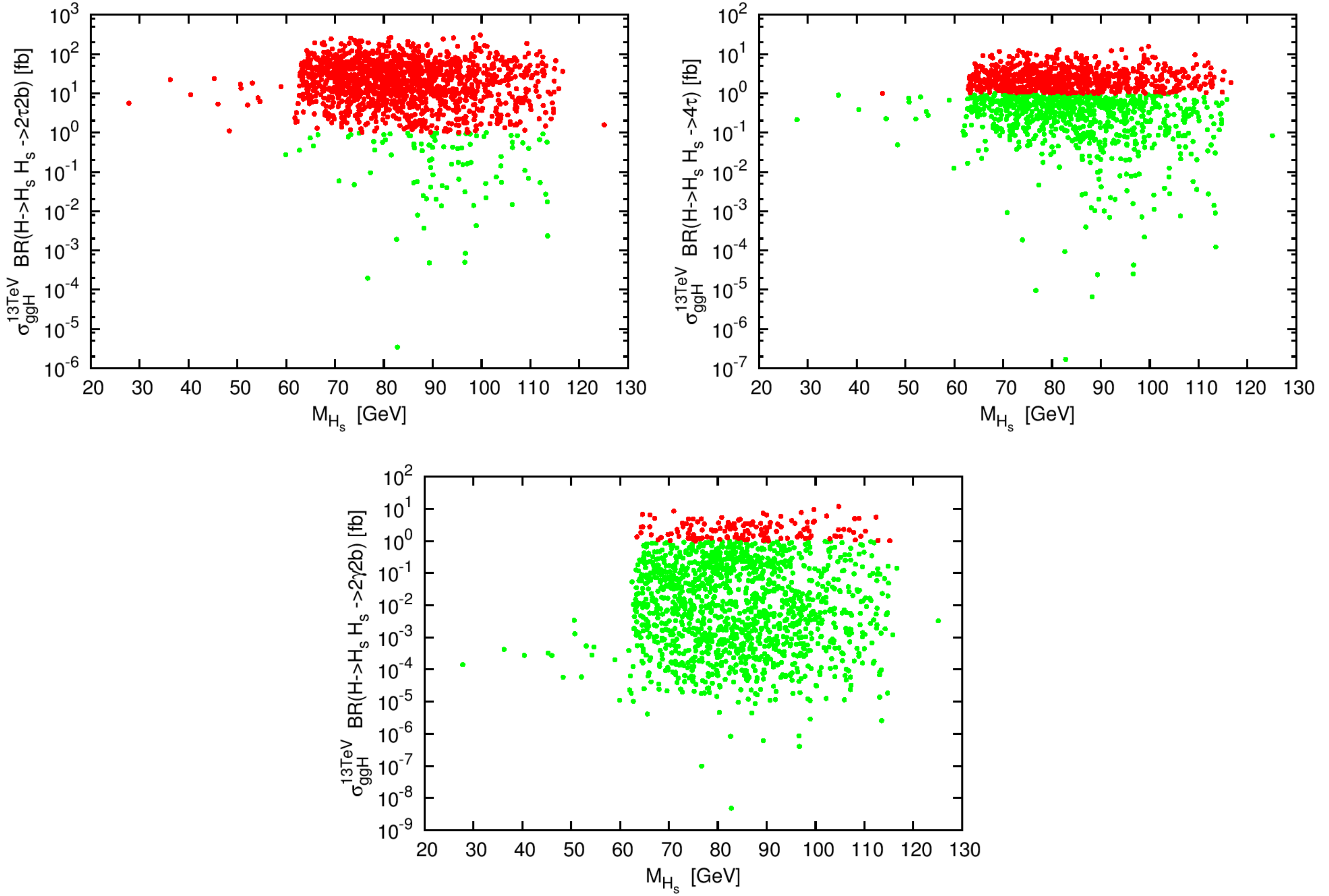
$$\sigma(gg \to \phi_i) \times BR(\phi_i \to \phi_j \phi_k) \times BR(\phi_j \to XX) \times BR(\phi_k \to YY)$$

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

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

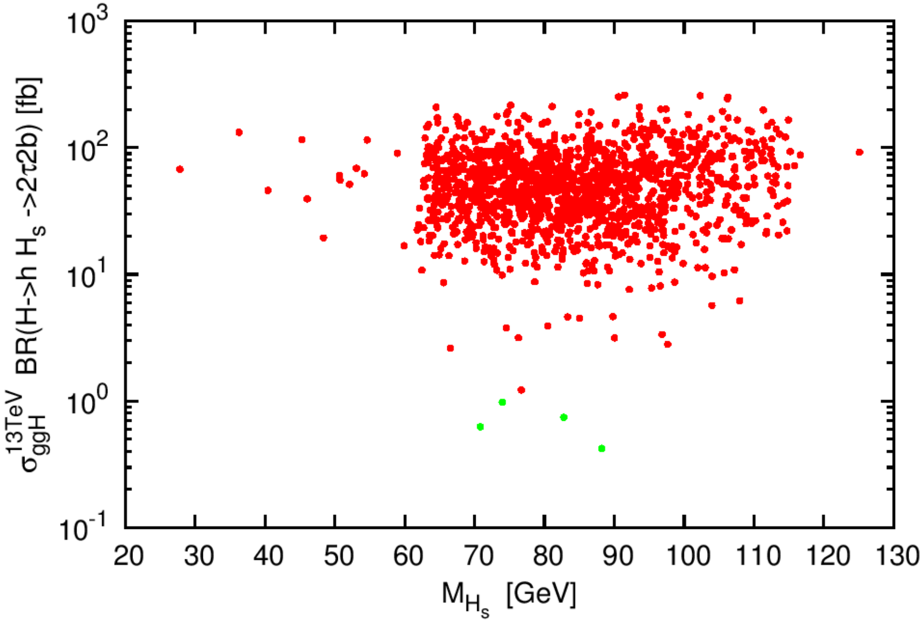
$$\sigma(gg \to H) BR(H \to H_s H_s \to (XX)(YY))$$

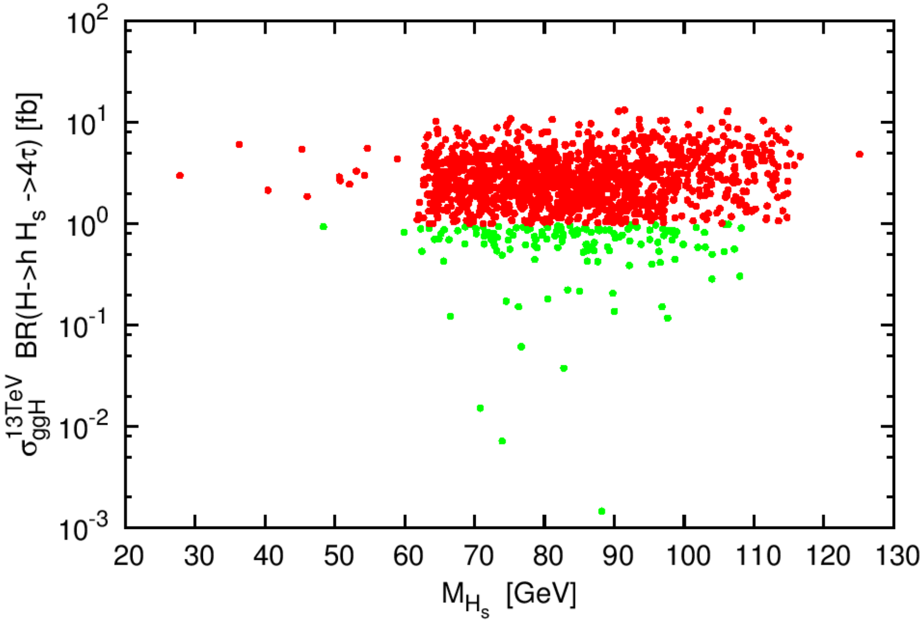
King, MMM, Nevzorov, Walz

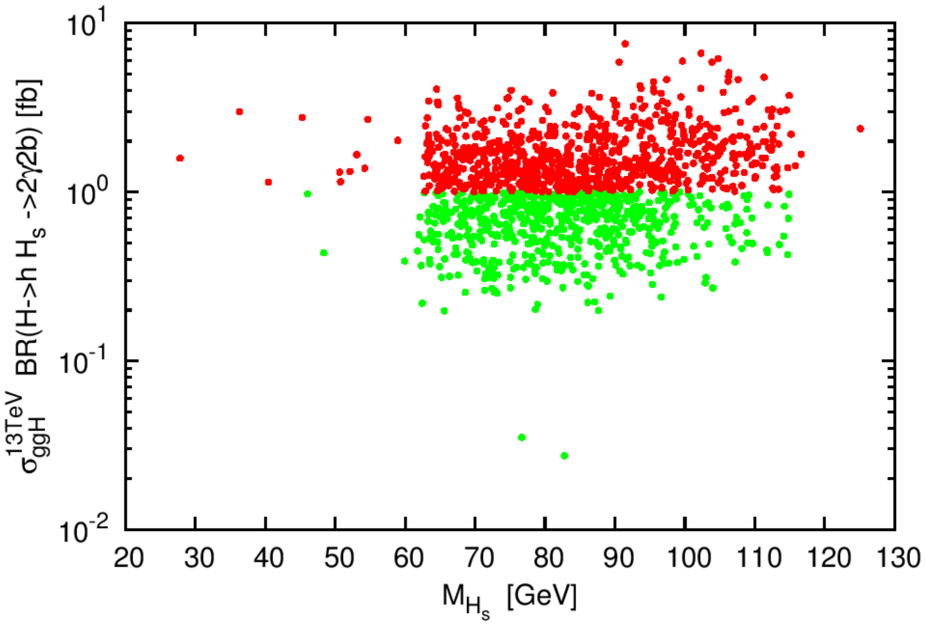


$\sigma(gg \to H)BR(H \to hH_s \to (XX)(YY))$

King, MMM, Nevzorov, Walz

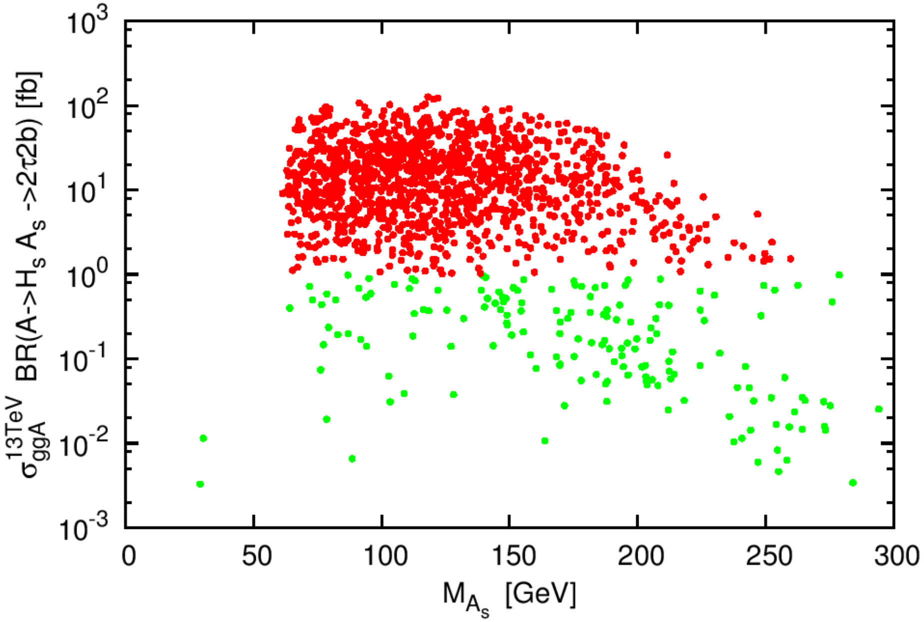


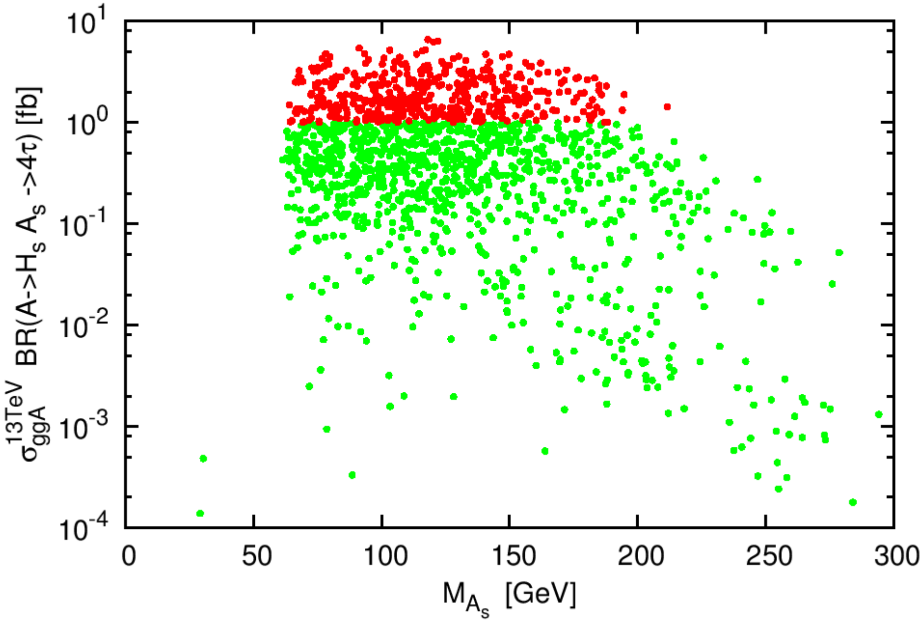


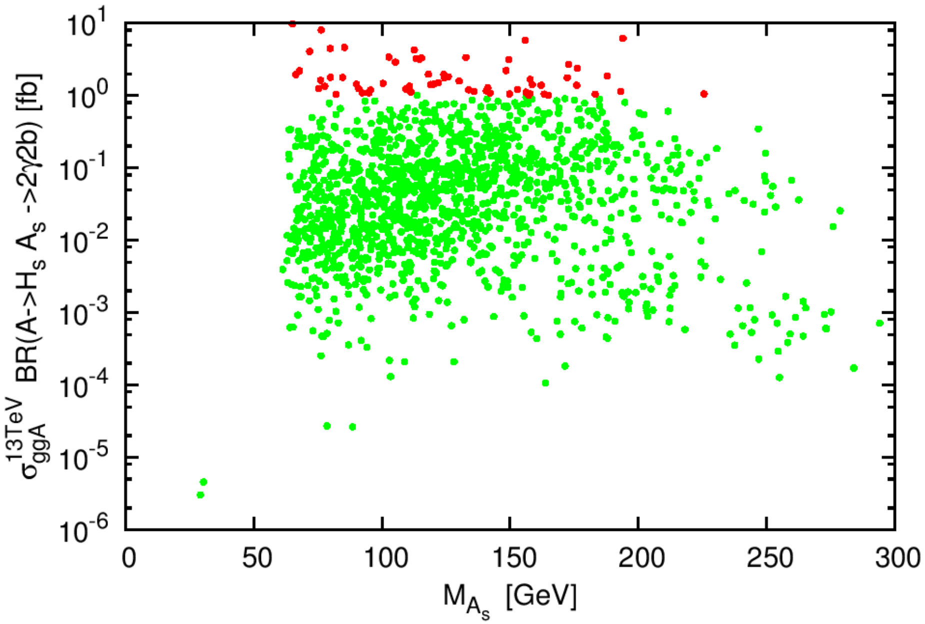


$\sigma(gg \to A)BR(A \to H_s A_s \to (XX)(YY))$

King, MMM, Nevzorov, Walz

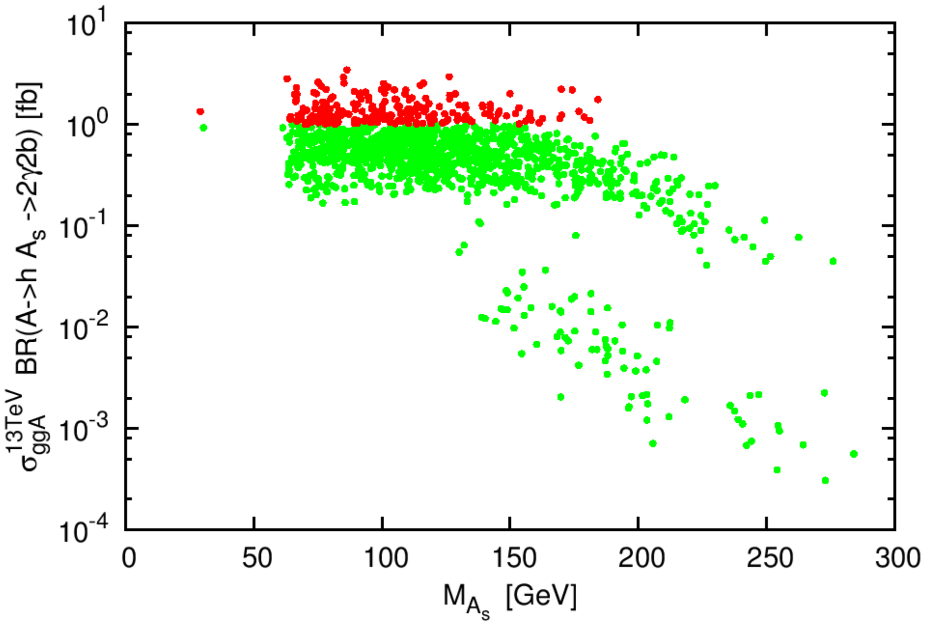






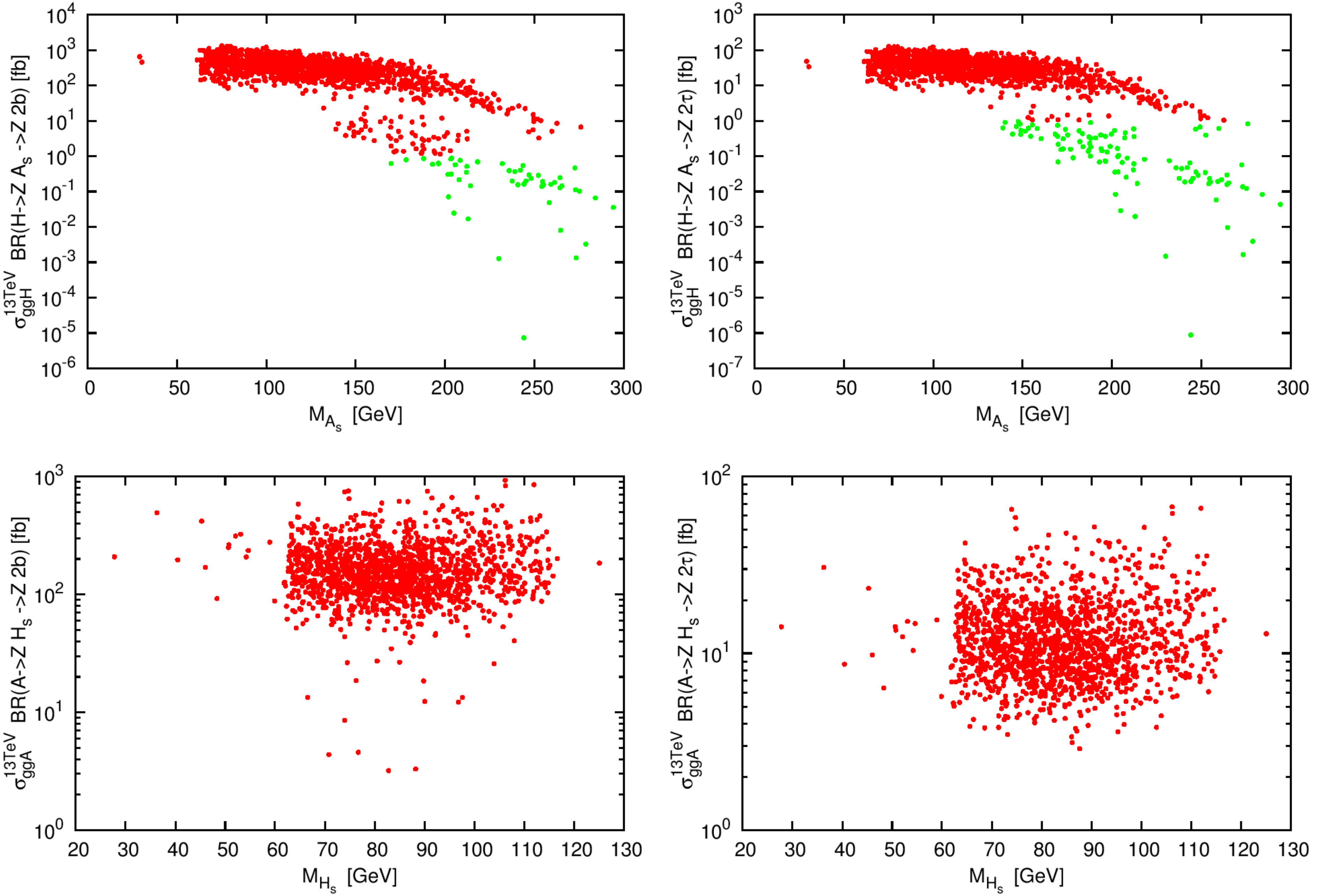
$\sigma(gg \to A) BR(A \to hA_s \to (XX)(YY))$

King,MMM,Nevzorov,Walz



$\sigma(H)BR(H \to ZA_s \to Z + (XX)),\ \sigma(A)BR(A \to ZH_s \to Z + (XX))$

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)

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

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

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	
$\lvert S_{H_2 h_s}\rvert^2, \lvert P_{A_1 a_s}\rvert^2$	0.90	1	
$\mu_{\tau\tau}$, μ_{bb}	1.54	1.01	
μ_{ZZ}, μ_{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

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

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

B.1 (Point ID Poi2a)	Decay Rates
$\sigma(ggH_s)$	282.37 fb
$\sigma(ggH_s)\text{BR}(H_s \to WW)$	5.09 fb
$\sigma(ggH_s)\text{BR}(H_s \to A_s A_s)$	274.75 fb
$\sigma(ggH_s)\text{BR}(H_s \to A_s A_s \to b\bar{b} + b\bar{b})$	5.87 fb
$\sigma(ggH_s)\text{BR}(H_s \to A_s A_s \to \gamma\gamma + b\bar{b})$	67.33 fb
$\sigma(ggH_s)\text{BR}(H_s \to A_s A_s \to \gamma\gamma + \gamma\gamma)$	193.22 fb
$\sigma(ggH)$	3.166 pb
$\sigma(ggH)\text{BR}(H \to WW)$	264.73 fb
$\sigma(ggH)\text{BR}(H \to ZZ)$	119.52 fb
$\sigma(ggH)\text{BR}(H \to b\bar{b})$	297.37 fb
$\sigma(ggH)\text{BR}(H \to \tau\tau)$	37.65 fb
$\sigma(ggH)\text{BR}(H \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$	383.33 fb
$\sigma(ggH)\text{BR}(H \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	403.14 fb
$\sigma(ggH)\text{BR}(H \to hH_s)$	1.609 pb
$\sigma(ggH)\text{BR}(H \to hH_s \to bb + \tau\tau)$	1.44 fb

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

B.1 (Point ID Poi2a)	Decay Rates
$\sigma(ggH)\mathrm{BR}(H \to hH_s \to h + A_sA_s \to bb + 4\gamma)$	712.47 fb
$\sigma(ggH)\mathrm{BR}(H \to hH_s \to h + A_sA_s \to \gamma\gamma + 4b)$	248.02 fb
$\sigma(ggH)\mathrm{BR}(H \to hH_s \to h + A_sA_s \to \tau\tau + 4\gamma)$	74.60 fb
$\sigma(ggH)\mathrm{BR}(H \to hH_s \to h + A_sA_s \to \gamma\gamma + 4\tau)$	2.47 fb
$\sigma(ggH)\mathrm{BR}(H \to hH_s \to h + A_sA_s \to 6\gamma)$	2.69 fb
$\sigma(ggH)\mathrm{BR}(H \to hH_s \to h + A_sA_s \to \tau\tau + \gamma\gamma + b\bar{b})$	49.55 fb
$\sigma(ggH)\mathrm{BR}(H \to A_sA_s)$	5.59 fb
$\sigma(ggH)\mathrm{BR}(H \to A_sA_s \to 4\gamma)$	3.93 fb
$\sigma(ggA_s)$	0.08 fb
$\sigma(ggA)$	2.51 pb
$\sigma(ggA)\mathrm{BR}(A \to \tau\tau)$	14.42 fb
$\sigma(ggA)\mathrm{BR}(A \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$	963.87 fb
$\sigma(ggA)\mathrm{BR}(A \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	273.57 fb
$\sigma(ggA)\mathrm{BR}(A \to H_sA_s)$	525.56 fb

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

B.1 (Point ID Poi2a)	Decay Rates
$\sigma(ggA)$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$(A \to hA_s)$	29.96 fb
$\sigma(ggA)$BR$(A \to hA_s \to \gamma\gamma + b\bar{b})$	16.25 fb
$\sigma(ggA)$BR$(A \to hA_s \to \gamma\gamma + \tau\tau)$	1.70 fb
$\sigma(ggA)$BR$(A \to hA_s \to b\bar{b} + b\bar{b})$	2.83 fb
$\sigma(ggA)$BR$(A \to ZH_s)$	554.38 fb
$\sigma(ggA)$BR$(A \to ZH_s \to bb + A_s A_s \to bb + 4\gamma)$	57.36 fb
$\sigma(ggA)$BR$(A \to ZH_s \to bb + A_s A_s \to 4b + \gamma\gamma)$	19.99 fb
$\sigma(ggA)$BR$(A \to ZH_s \to ZA_s A_s \to bb + \tau\tau + \gamma\gamma)$	6.35 fb
$\sigma(ggA)$BR$(A \to ZH_s \to ll/\tau\tau + A_s A_s \to ll/\tau\tau + 4\gamma)$	12.78 fb
$\sigma(ggA)$BR$(A \to ZH_s \to ll/\tau\tau + A_s A_s \to ll\tau\tau/4\tau + \gamma\gamma)$	0.42 fb

accessible:

$\lambda_{H_s A_s A_s}$

$\lambda_{H H_s h}$

$\lambda_{A A_s H_s}$

$\lambda_{A A_s h}$

$\mathcal{W}$hat if not all $\mathcal{H}$iggs $\mathcal{B}$osons can be discovered?

- **If not all NMSSM Higgs bosons are discovered:**

Scenario: 3 neutral Higgs bosons discovered, not all of them are scalar $\rightsquigarrow$

How tell NMSSM from the MSSM?

$\rightsquigarrow$ exploit sum rules

- **Unitarity requirement leads to sum rules for Higgs-gauge and Higgs-Yukawa couplings:**

Englert,Freitas,MMM,Plehn,Rauch,Spira,Walz, 1403.7191

$$\frac{G_{H_iVV}}{g_{H^{\rm SM}VV}} \equiv g_{H_iVV} = (\mathcal{R}^S_{i1}\cos\beta + \mathcal{R}^S_{i2}\sin\beta)$$

$$\frac{G_{H_itt}}{g_{H^{\rm SM}tt}} \equiv g_{H_itt} = \frac{\mathcal{R}^S_{i2}}{\sin\beta}\,, \quad \frac{G_{H_ibb}}{g_{H^{\rm SM}bb}} \equiv g_{H_ibb} = \frac{\mathcal{R}^S_{i1}}{\cos\beta}$$

$\mathcal{W}$hat if not all $\mathcal{H}$iggs $\mathcal{B}$osons can be discovered?

- **If not all NMSSM Higgs bosons are discovered:**

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- **Unitarity requirement leads to sum rules for Higgs-gauge and Higgs-Yukawa couplings:**

Englert,Freitas,MMM,Plehn,Rauch,Spira,Walz, 1403.7191

[couplings normalized to SM couplings]

$$\sum_{i=1}^{3} g^2_{H_i VV} = 1$$

$$\frac{1}{\sum_{i=1}^{3} g^2_{H_i tt}} + \frac{1}{\sum_{i=1}^{3} g^2_{H_i bb}} = 1$$

Scenario: MSSM: sum rules fulfilled – NMSSM: deviation from sum rule

- **Example benchmark scenario D.2**

D.2 (Point ID 110)	**Scenario**		
$M_{H_1}, M_{H_2}, M_{H_3} \equiv M_{H_s}, M_h, M_H$	112.0 GeV	126.3 GeV	1288.2 GeV
$M_{A_s}, M_A = M_{A_1}, M_{A_2}$	61.5 GeV	1287.4 GeV	
$\lvert S_{H_1 h_s}\rvert^2, \lvert P_{A_1 a_s}\rvert^2$	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
$A_\lambda,\ A_\kappa,\ \mu_{\rm eff}$	1217.1 GeV	19.6 GeV	195.3 GeV
$A_t,\ A_b,\ A_\tau$	-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	
$M_{L_3} = M_{\tau_R},\ M_{\rm SUSY}$	2491.6 GeV	3 TeV	

$\sigma(gg \to H) = 0.46$ fb , $\sigma(bbH) = 0.82$ fb , $\sigma(gg \to A) = 0.72$ fb , $\sigma(bbA) = 0.82$ fb

$\mathcal{C}$oupling $\mathcal{S}$um $\mathcal{R}$ules

- H, A **difficult to produce** $\rightsquigarrow$ exploit sum rules

$$\sum_{i=1}^{2} g^2_{H_i VV} \approx 1$$

$$\frac{1}{\sum_{i=1}^{2} g^2_{H_i tt}} + \frac{1}{\sum_{i=1}^{2} g^2_{H_i bb}} = 1.85$$

Non-discovered H has large MSSM H_d component $\rightsquigarrow$

Significant deviation in Higgs-fermion coupling sum rule

(H_u component taken by SM-like $H_2 \equiv h$ for sufficient cxn in gluon fusion)

At high-energy LHC: Higgs-fermion couplings measurable at $\mathcal{O}(10-20\%)$

CMS, 1307.7135; ATLAS, 1307.7292, Snowmass 1310.8361

$\mathcal{C}$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**
  - ⋆ good discovery prospects at high-enery LHC
  - ⋆ direct production or production in Higgs-to-Higgs and/or Higgs-to-Higgs+Gauge Boson
  - ⋆ Higgs-to-Higgs $\rightsquigarrow$ measurement of trilinear Higgs self-couplings
- **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
  - ⋆ exploit coupling measurements to distinguish NMSSM from MSSM if not all Higgses discovered

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

Thank You For Your Attention!

D.2 (Point ID 110)	Signal Rates
$\sigma(ggh)$	27.37 pb
$\sigma(ggh)\text{BR}(h \to A_s A_s)$	1.85 pb
$\sigma(ggh)\text{BR}(h \to A_s A_s \to bb + bb)$	1.55 pb
$\sigma(ggh)\text{BR}(h \to A_s A_s \to \tau\tau + \tau\tau)$	12.36 fb
$\sigma(ggh)\text{BR}(h \to A_s A_s \to bb + \tau\tau)$	212.07 fb
$\sigma(ggh)\text{BR}(h \to A_s A_s \to bb + \gamma\gamma)$	0.34 fb
$\sigma(ggH_s)$	17.25 pb
$\sigma(ggH_s)\text{BR}(H_s \to b\bar{b})$	14.64 pb
$\sigma(ggH_s)\text{BR}(H_s \to \tau\tau)$	1.50 pb
$\sigma(ggH_s)\text{BR}(H_s \to \gamma\gamma)$	13.93 fb
$\sigma(ggH_s)\text{BR}(H_s \to ZZ)$	23.90 fb
$\sigma(ggH_s)\text{BR}(H_s \to WW)$	401.21 fb
$\sigma(ggH_s)\text{BR}(H_s \to \mu\mu)$	5.33 fb
$\sigma(ggH_s)\text{BR}(H_s \to Z\gamma)$	4.15 fb
$\sigma(ggA_s)$	1.13 pb
$\sigma(ggA_s)\text{BR}(A_s \to b\bar{b})$	1.03 pb
$\sigma(ggA_s)\text{BR}(A_s \to \tau\tau)$	92.46 fb
$\sigma(ggH)$, $\sigma(bbH)$	0.46 fb, 0.82 fb
$\sigma(ggA)$, $\sigma(bbA)$	0.72 fb, 0.82 fb

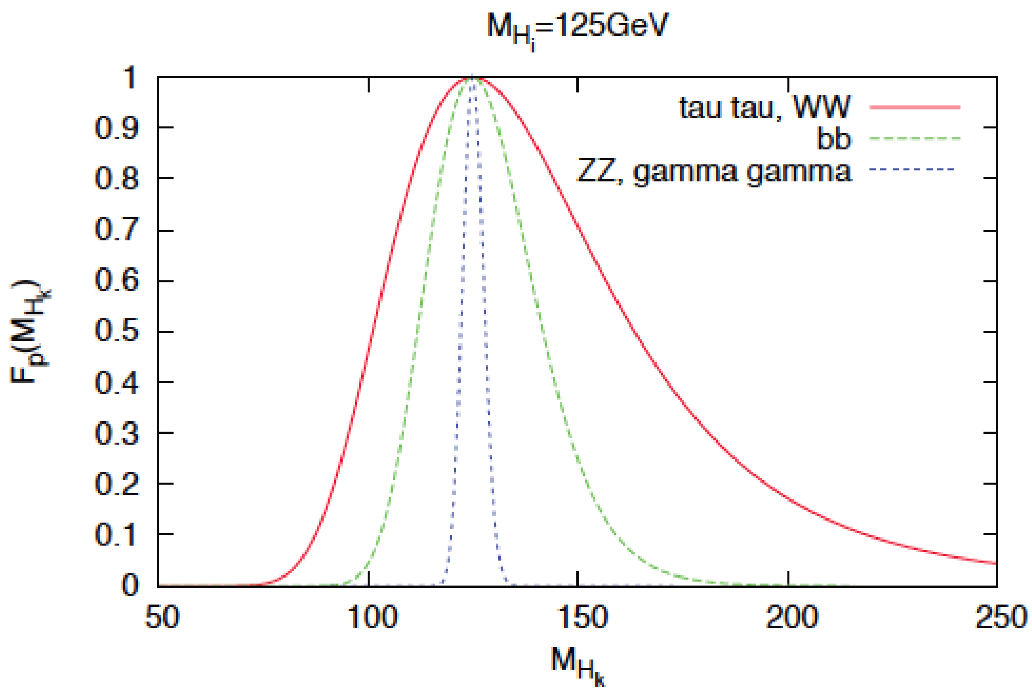
$\mathcal{S}$uperposition of $\mathcal{S}$ignal $\mathcal{R}$ates

$$R_{pp,H_i} = \frac{\sigma_{\text{incl}}^{\text{NMSSM}}}{\sigma_{\text{incl}}^{\text{SM}}} \cdot \frac{\text{BR}(H_i \to pp)^{\text{NMSSM}}}{\text{BR}(H_i \to pp)^{\text{SM}}} \qquad \text{with} \quad i = 1..5.$$

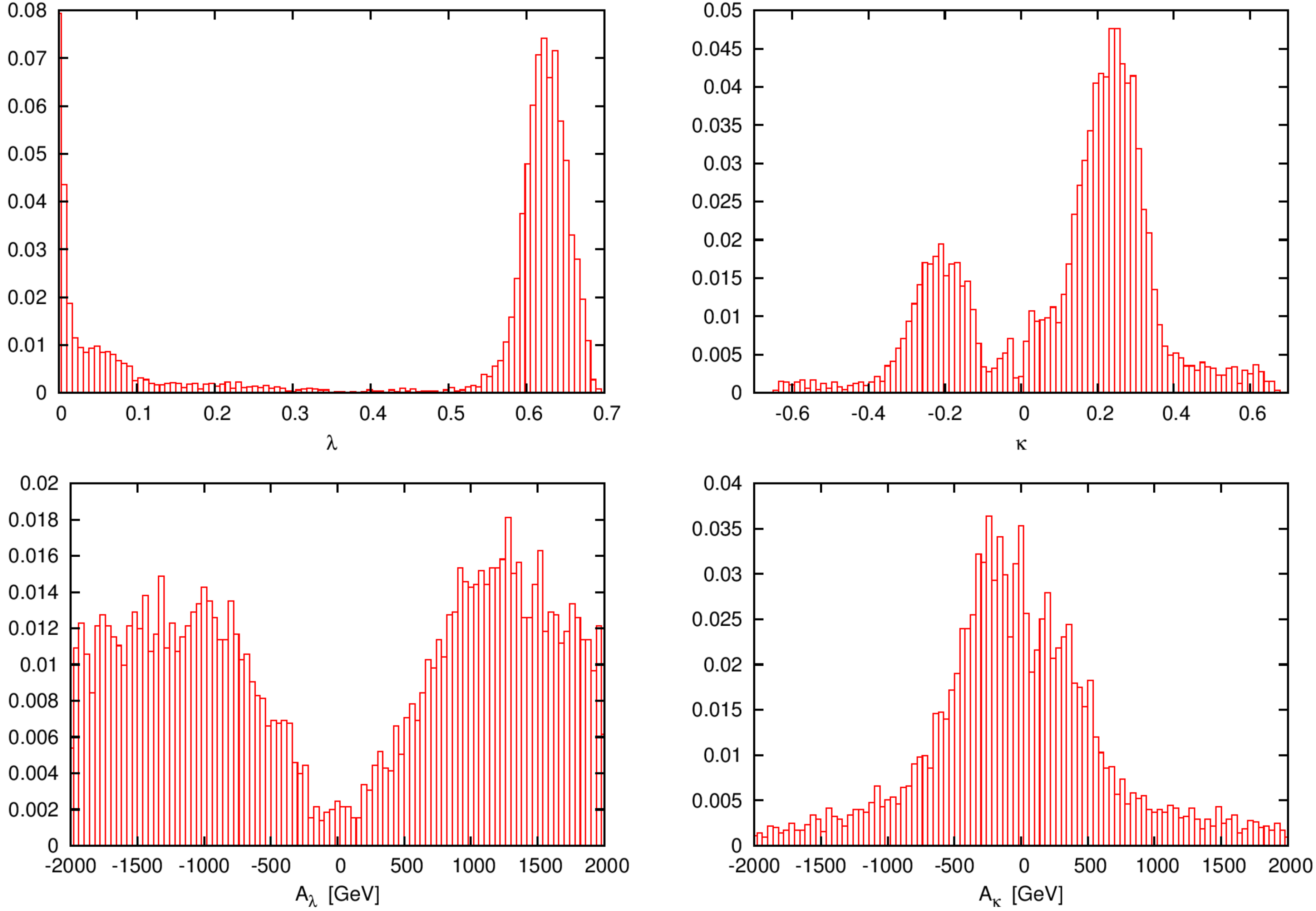
$$R_{pp,H_i}^{\text{combined}} = \sum_{k=1}^{5} R_{pp,H_k} \cdot \underbrace{\exp\left(\frac{-(M_{H_k} - M_{H_i})^2}{2\,(d_p \cdot M_{H_k})^2}\right)}_{F_p(M_{H_k})}$$

This weighting factor depends on the mass difference and on a factor d_p which is decay specific:

p	$\tau\tau$	WW	bb	ZZ	$\gamma\gamma$
d_p	0.2	0.2	0.1	0.02	0.02

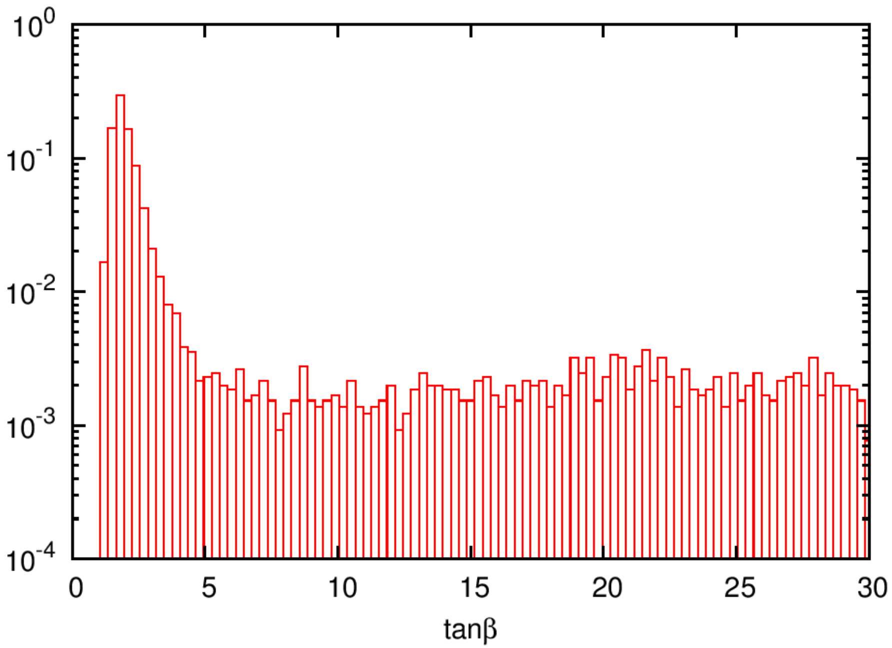


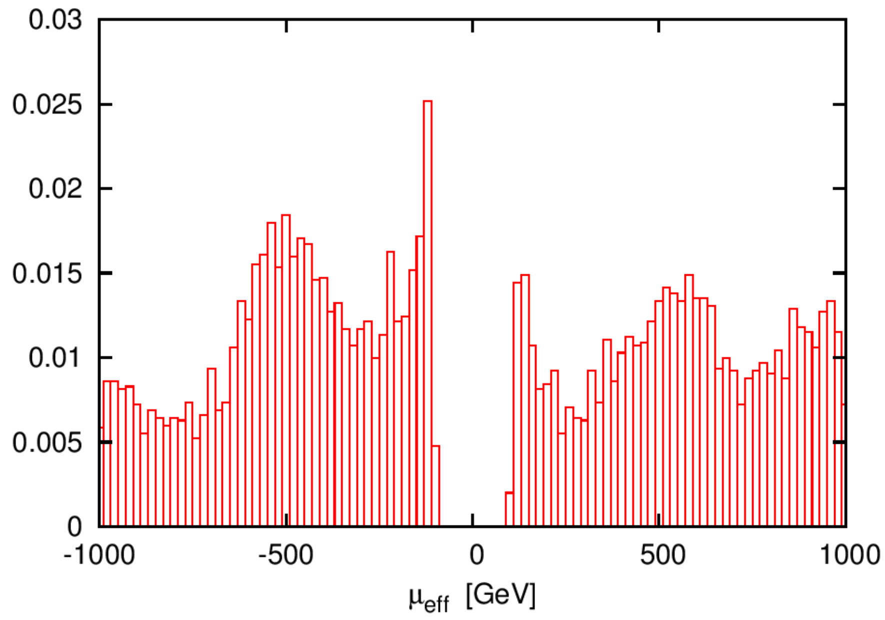
$\mathcal{D}$istributions of λ, κ A_λ and A_κ



$\mathcal{D}$istributions of $\tan\beta$ and μ_{eff}

King,MMM,Nevzorov,Walz





$|\mu_{\text{eff}}| \lesssim 100$ GeV excluded due to lower chargino mass bounds

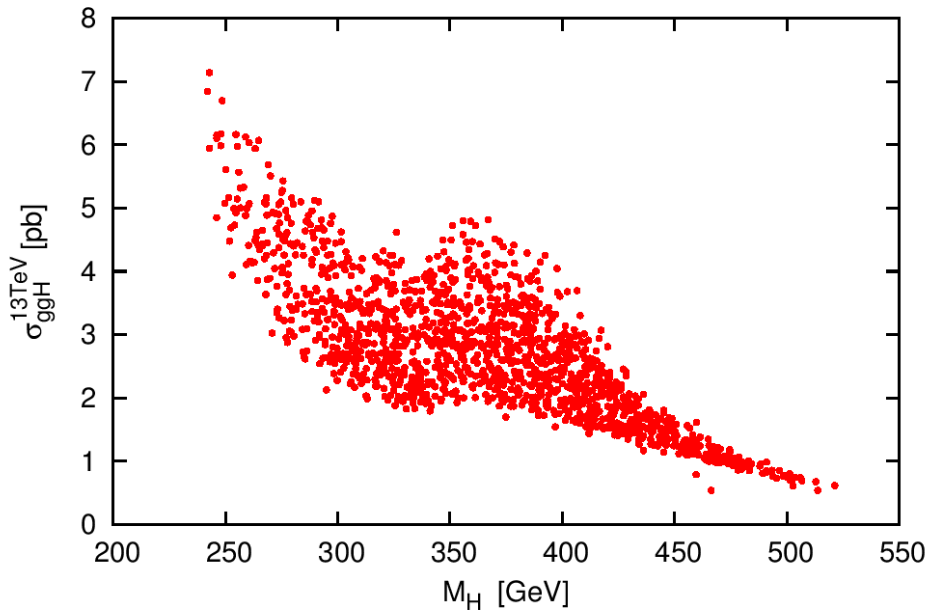
Singlet-/Doublet Character of the NMSSM Higgs Bosons

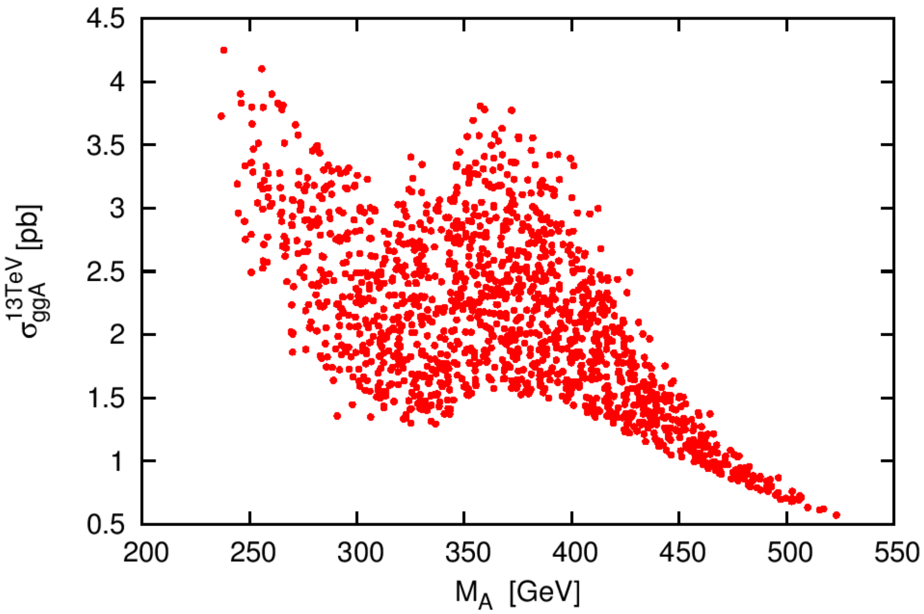
King,Nevzorov,MMM,Walz

$\tan\beta < 5$	$H_{i=1}$ 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

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

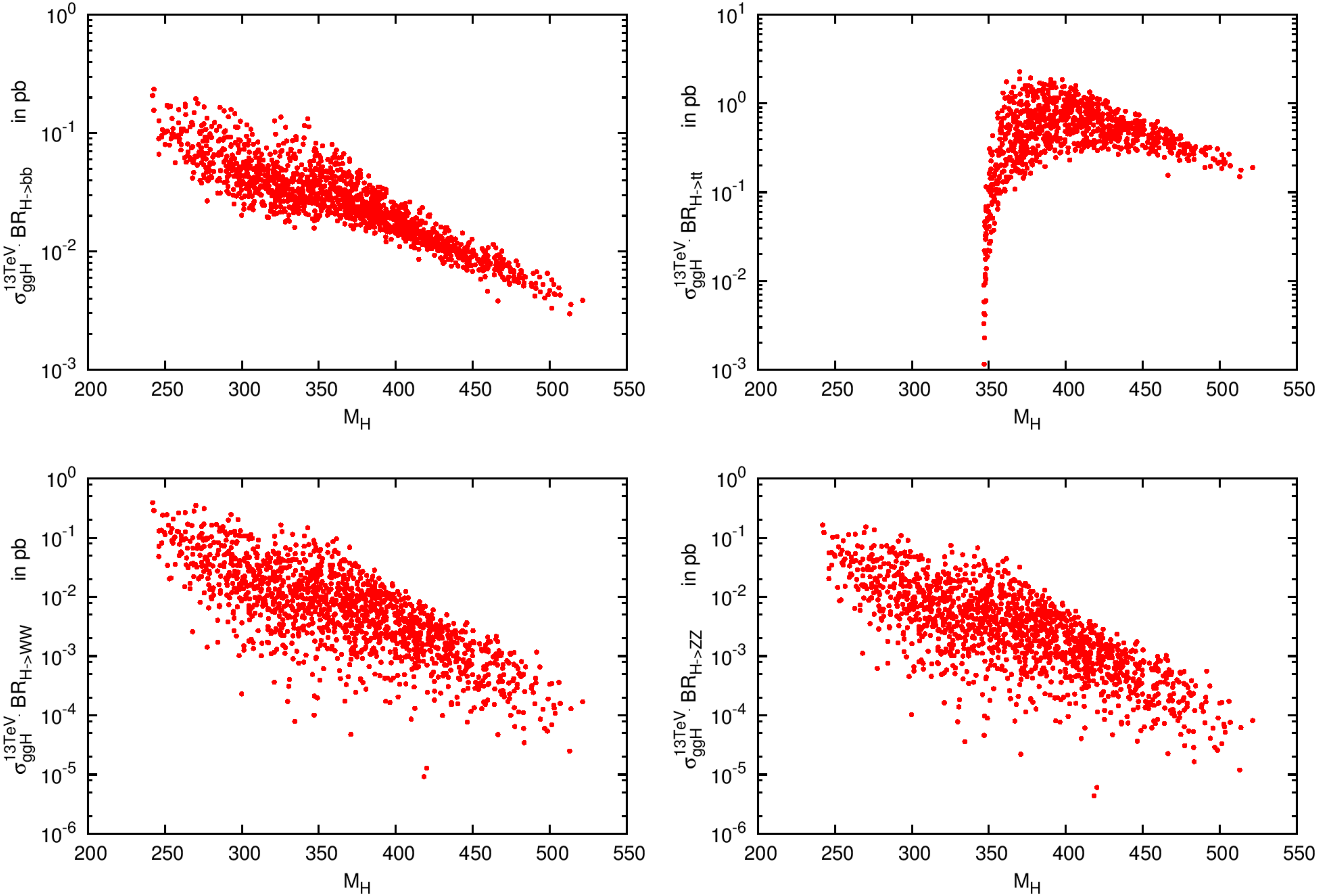
King,MMM,Nevzorov,Walz





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

King,MMM,Nevzorov,Walz



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

King,MMM,Nevzorov,Walz