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# *Higgs Physics Beyond the SM - the NMSSM*

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**ZPW2015**

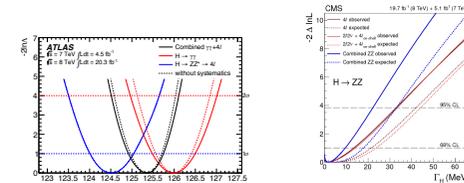
**The Flavour of New Physics**  
**7-9 January 2015**



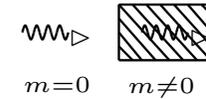
# It is the Higgs Boson

- Investigation of properties of scalar particle:

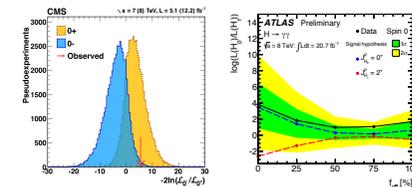
- Mass  $m$ , Total Width  $\Gamma$



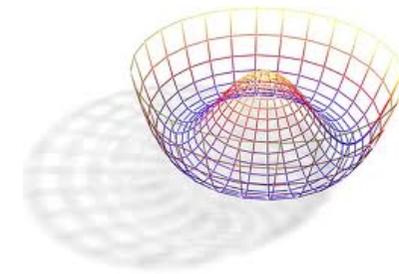
- Couplings to SM particles  $g_{HXX} \sim m_X$



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



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

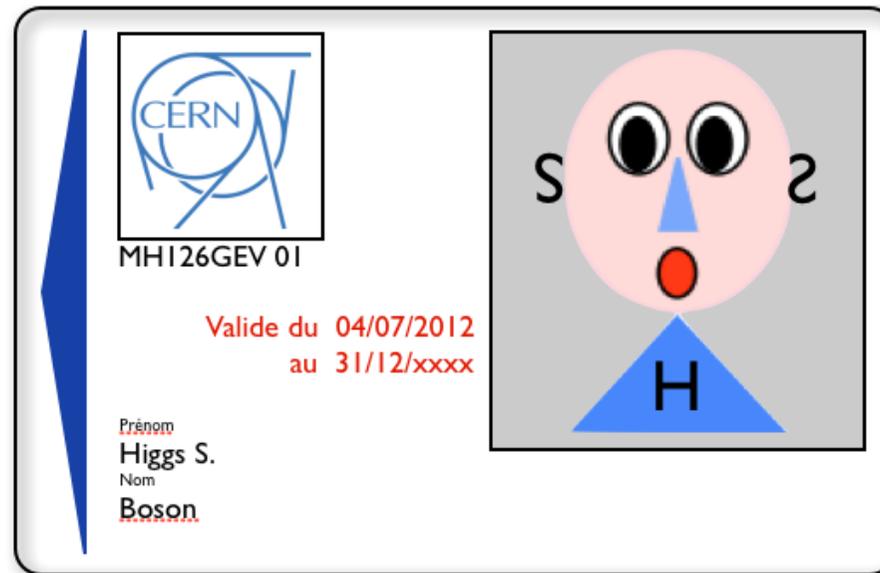


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# It is the Higgs Boson

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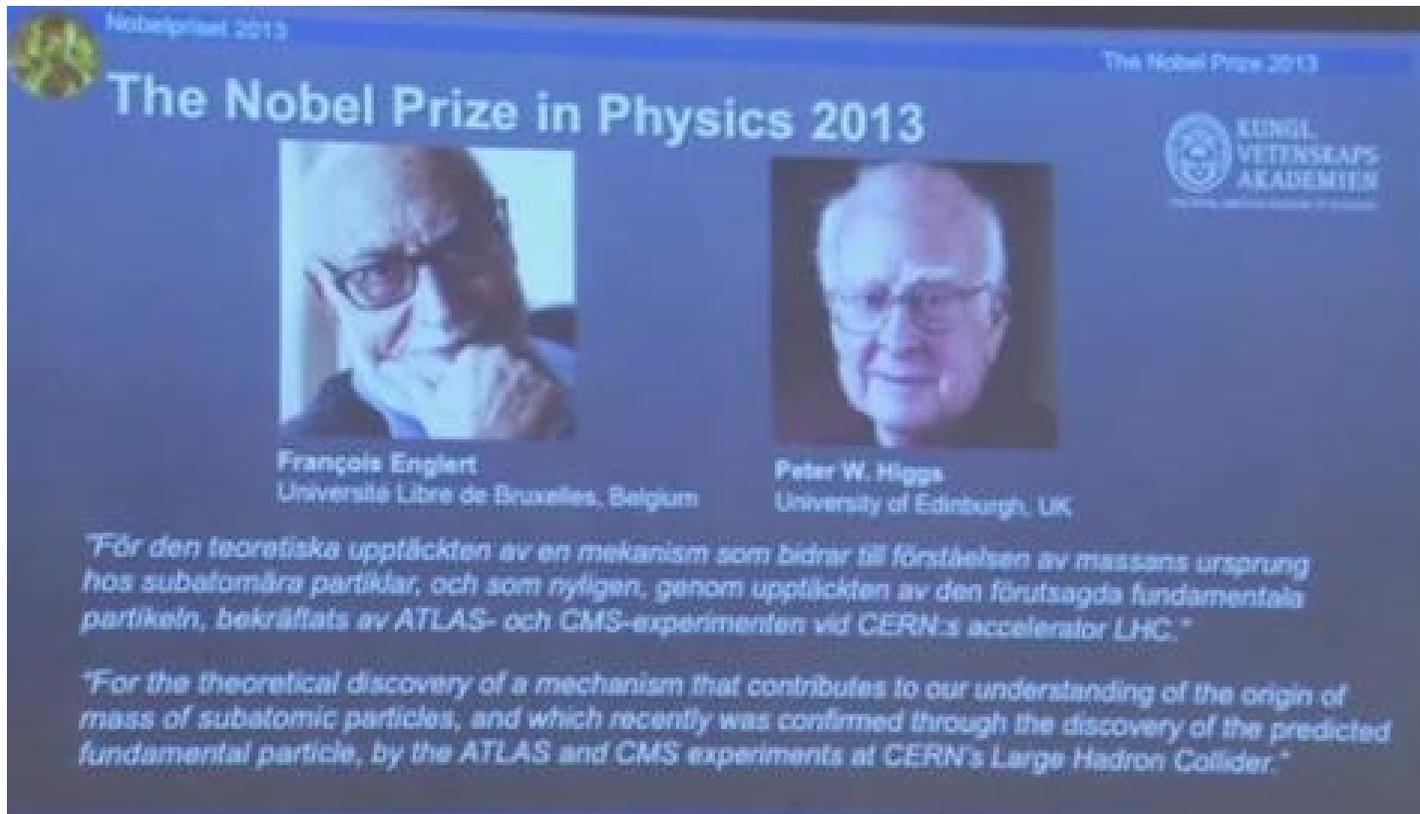
- Investigation of properties of scalar particle:  $\rightsquigarrow$  Higgs Boson



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# Nobel Prize in Physics 2013

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The slide features a blue background with the Nobel Prize logo in the top left and the text 'Nobelpriset 2013' and 'The Nobel Prize 2013' in the top corners. The main title 'The Nobel Prize in Physics 2013' is prominently displayed. Below the title are two portraits: François Englert on the left and Peter W. Higgs on the right. The Royal Swedish Academy of Sciences logo is in the top right. The award text is provided in both Swedish and English.

Nobelpriset 2013

The Nobel Prize 2013

## The Nobel Prize in Physics 2013



KONGL. VETENSKAPS AKADEMIEN

François Englert  
Université Libre de Bruxelles, Belgium

Peter W. Higgs  
University of Edinburgh, UK

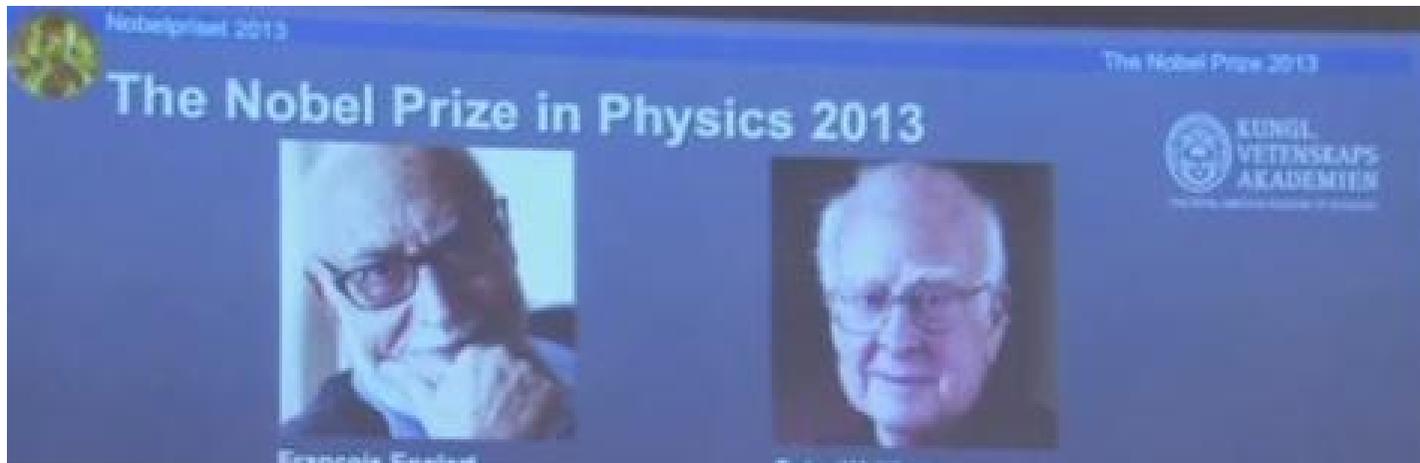
*"För den teoretiska upptäckten av en mekanism som bidrar till förståelsen av massans ursprung hos subatomära partiklar, och som nyligen, genom upptäckten av den förutsagda fundamentala partikeln, bekräftats av ATLAS- och CMS-experimenten vid CERN:s accelerator LHC."*

*"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."*

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# Nobel Prize in Physics 2013

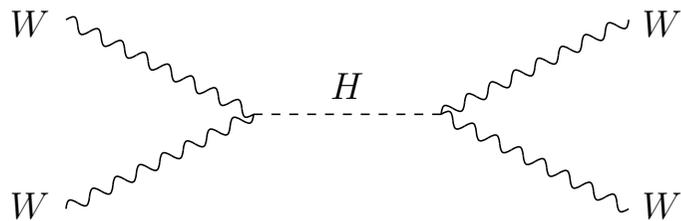
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# What is the Dynamical Origin of $\mathcal{EWSB}$ ?

Is the Higgs boson *Elementary* or *Composite*?

## Weakly coupled models

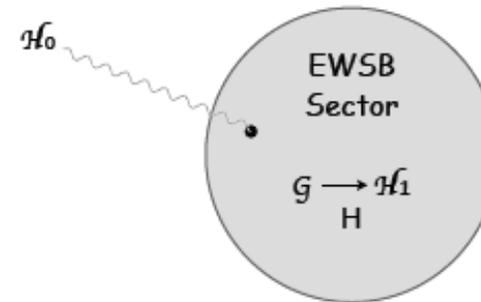


SM, SUSY, ...

SUSY Partner  $\sim 1$  TeV

New particles necessary to stabilise the Higgs boson mass

## Strongly-interacting dynamics



Composite Higgs

top partners  $\gtrsim 700$  GeV

Resonances for unitarity  
Higgs boson composite object

Cartoon from R.Contino [1005.4269]

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# Outline

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## ◇ Introduction

- \* NMSSM Higgs Sector
- \* NMSSM and 125 GeV mass

## ◇ NMSSM - higher order corrections

- \* to Higgs boson masses

## ◇ NMSSM phenomenology

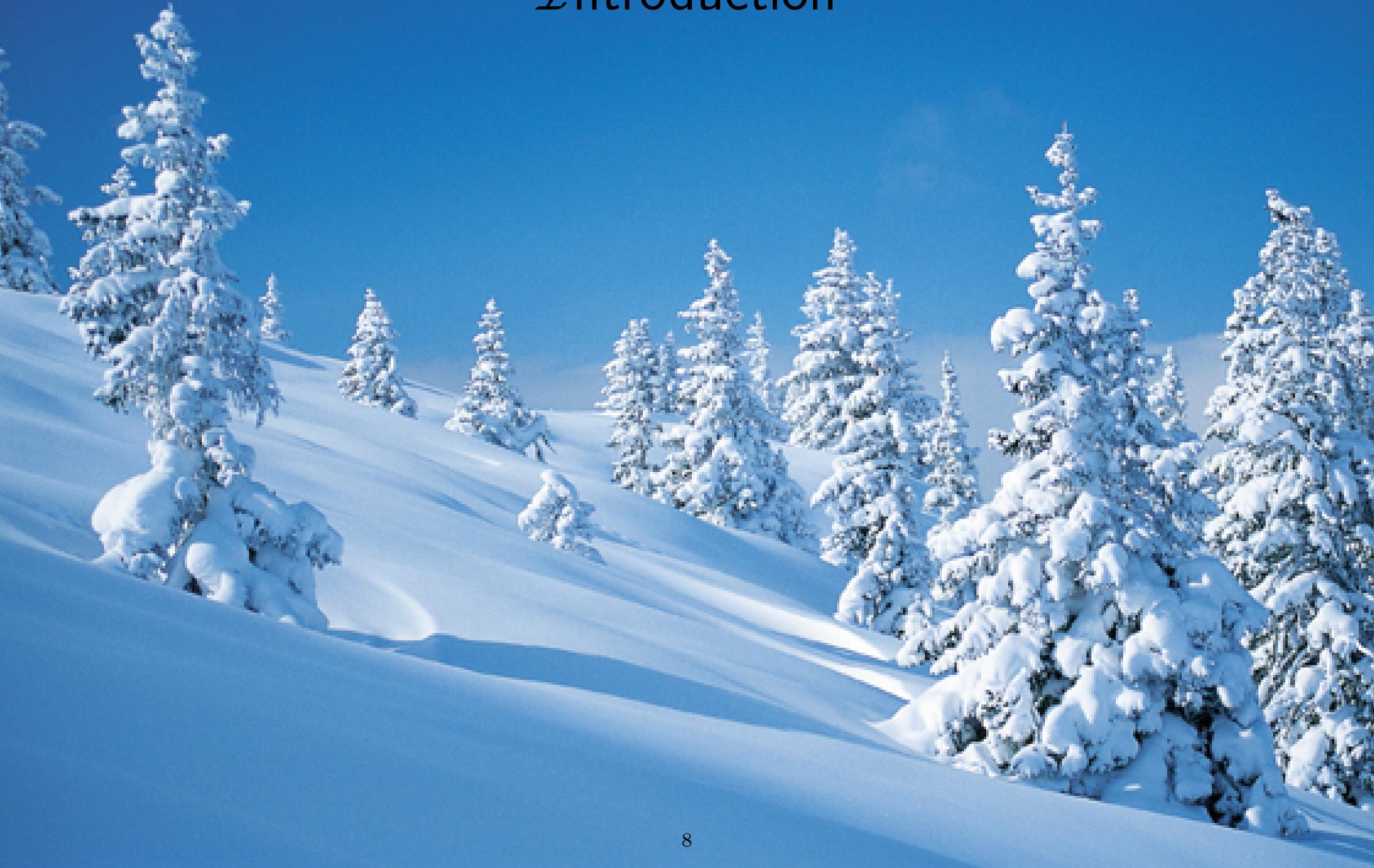
- \* NMSSM parameter scan and parameter distributions
- \* Natural NMSSM at LHC13
- \* Benchmarks for Higgs-to-Higgs decays

## ◇ Coupling measurements

- \* What we can learn

## ◇ Conclusions

# *I*ntroduction



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## Interpretation within *SUSY*: The *NMSSM* Higgs Sector

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- **Supersymmetric Higgs Sector:** SUSY & anomaly-free theory  $\Rightarrow$  2 complex Higgs doublets
- **Most economic version:** Minimal Supersymmetric Extension of the SM (MSSM):  
2 complex Higgs doublets
- **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; ...  
2 complex Higgs doublets plus one complex singlet field  $\rightsquigarrow$
- **Solution of the  $\mu$ -problem:**  $\mu$  must be of  $\mathcal{O}$ (EWSB scale) Kim, Nilles  
 $\mu$  generated dynamically through the VEV of scalar component of an  
additional chiral superfield field  $\hat{S}$ :  $\mu = \lambda \langle S \rangle$  from:  $\lambda \hat{S} \hat{H}_u \hat{H}_d$

# The $\mathcal{N}MSSM$ Higgs Sector

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

- **Higgs mass eigenstates:**

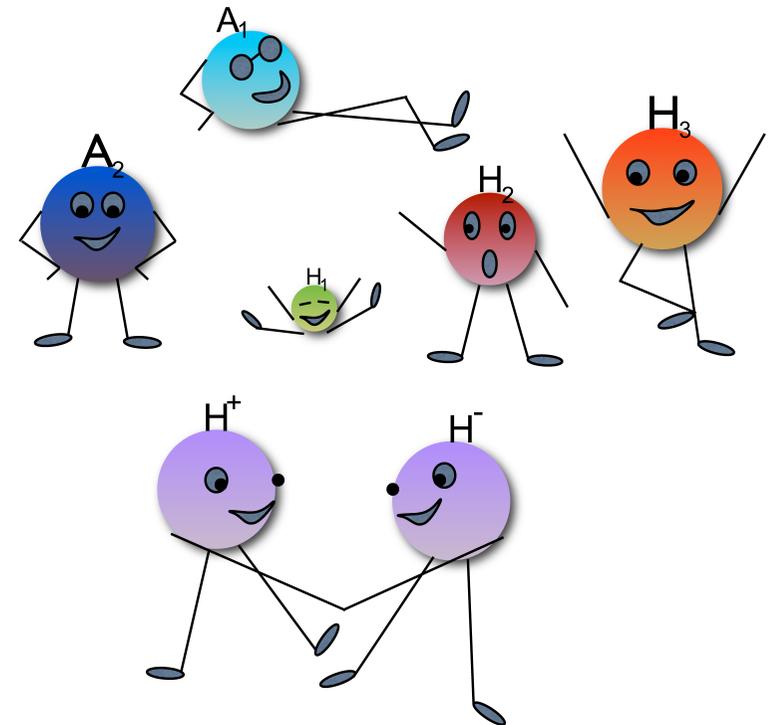
superpositions of doublet and singlet components  $\rightsquigarrow$

the more singlet-like

the smaller couplings to SM particles

- **Significant changes of Higgs boson phenomenology**

- \* light Higgses not excluded, Higgs-to-Higgs decays
- \* degenerate Higgs bosons around 125 GeV possible
- \* very light singlino-like lightest SUSY particle (LSP)
- \*  $\rightsquigarrow$  invisible Higgs decays
- \* tree-level CP violation ...



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# NMSSM Higgs Mass and LHC Results

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

Hall eal; Ellwanger; Gunion eal; King,MMM,Nezovorov; Alborno 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; Bhattacharjee eal; Guo eal; ...

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

★ Upper mass bounds + corrections to the MSSM, NMSSM Higgs boson mass:

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

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

$\Rightarrow M_H \approx 126$  requires:

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

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

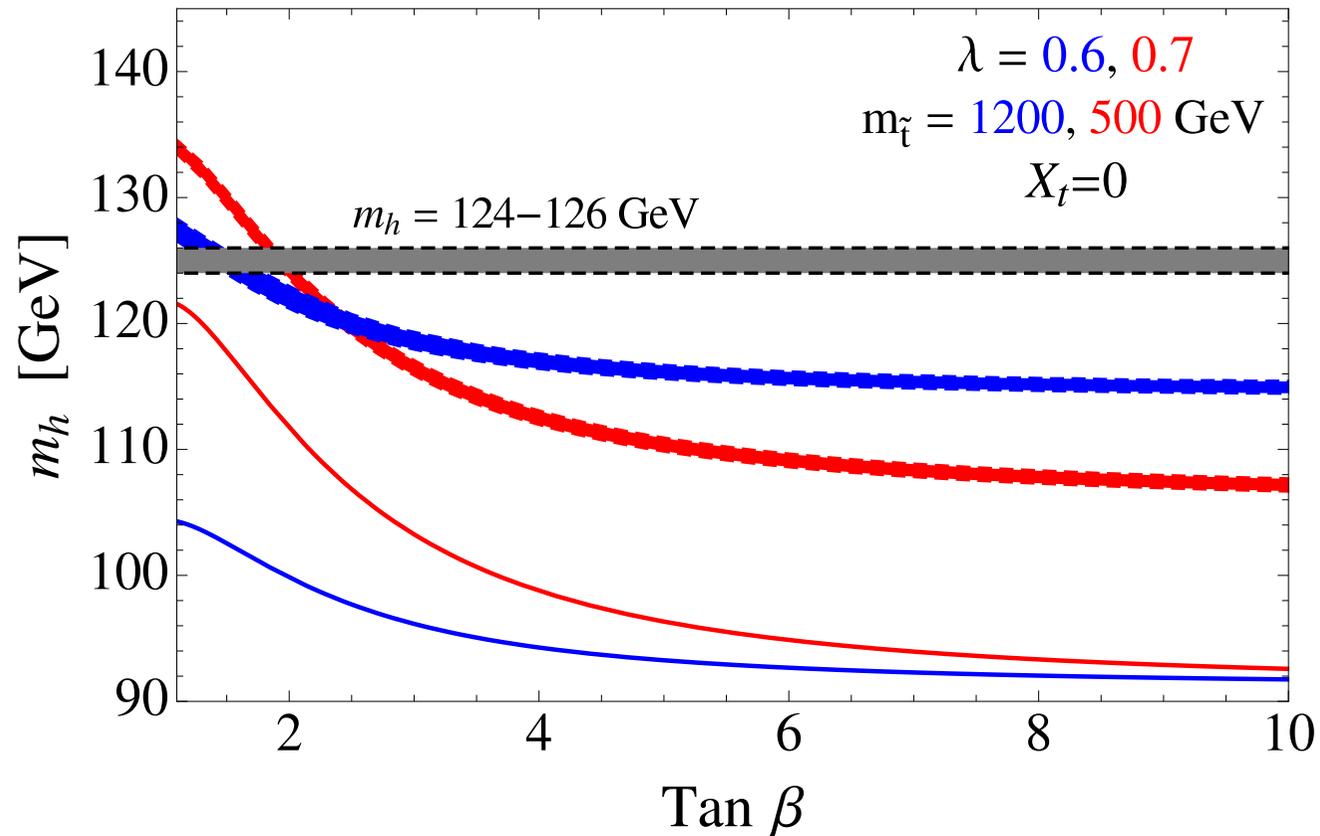
$\Rightarrow$  **NMSSM requires less fine-tuning**

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

# NMSSM Scalar Boson Mass in View of the LHC Results

Hall, Pinner, Ruderman 1112.2703

## NMSSM Higgs Mass



- ◇  $m_h$  maximized for small values of  $\tan \beta$
- ◇  $m_h \approx 124 - 126 \text{ GeV}$  can be achieved also for zero mixing  $X_t = 0$  and  $m_{\tilde{\tau}_1} \geq 500 \text{ GeV}$

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## *NMSSM Higgs Signal*

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- **SM-like scalar boson of  $\sim 125$  GeV**

Can be either  $H_1$  or  $H_2$  ( $H_1$  singlet like, suppressed SM couplings)

- **Could it be that we already discovered NMSSM Higgs bosons?**

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

- **What about the MSSM?**

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

light  $M_{H^\pm}$  excluded

ATLAS-CONF-2012-011 and 2013-090, CMS-HIG-12-052

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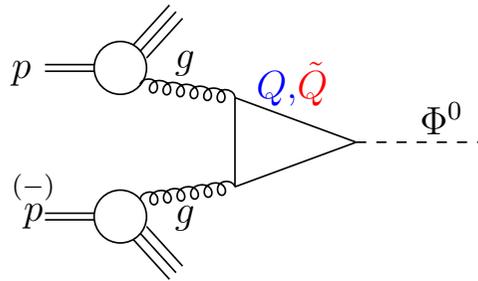
## Compatibility with $\mathcal{SM}$ -Like Higgs Signal

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- **SM-like NMSSM Higgs rate:**  $h = H_1$  or  $H_2$ ,  $M_h = M_{H^{\text{SM}}} \approx 125$  GeV

$$\mu_{XX}(h) = \frac{\sigma_{\text{prod}}(h) \text{BR}(h \rightarrow XX)}{\sigma_{\text{prod}}(H^{\text{SM}}) \text{BR}(H^{\text{SM}} \rightarrow XX)}$$

- **NMSSM  $h$  Production:** small  $\tan\beta$  favoured  $\rightsquigarrow$  gluon fusion dominant  $\sigma_{\text{prod}}$   
for SM-like production cxn:  $h$  must be up-type doublet-like  $\rightsquigarrow g_{htt} \approx g_{H^{\text{SM}}tt}$
- **Enhancement/suppression on the production side**



- **Enhanced/suppressed gluon fusion production**

See e.g. King,MMM,Nezovorov,Walz

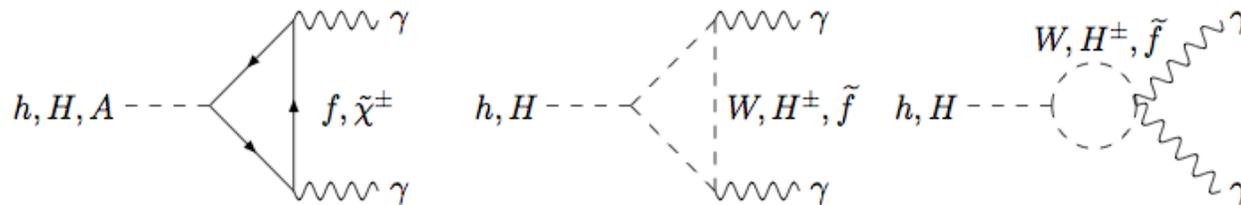
- \* Stop, sbottom loop contributions in  $gg \rightarrow H_i$  can enhance/suppress the production cxn for small/large mixing

## Compatibility with $\mathcal{SM}$ -Like Higgs Signal

- Branching ratios - e.g. into  $XX = \gamma\gamma$

$$BR(h \rightarrow \gamma\gamma) = \frac{\Gamma(h \rightarrow \gamma\gamma)}{(\Gamma_{b\bar{b}} + \Gamma_{WW} + \Gamma_{ZZ} + \dots + \Gamma_{\phi_i\phi_j} + \Gamma_{\chi_1^0\chi_1^0} + \dots)[h]}$$

- \*  $\Gamma_{b\bar{b}}$  dominant decay rate for 125 GeV SM-Higgs boson  $\rightsquigarrow BR(h \rightarrow XX)$  very sensitive to  $\Gamma_{b\bar{b}}$
- \* Suppression of  $\Gamma(h^{125 \text{ GeV}} \rightarrow b\bar{b})$  due to
  - Hall, Pinner, Ruderman; Ellwanger; King, MMM, Nevzorov;
  - Cao, Heng, Yang, Zhang, Zhu; Alborno-Vasquez, Belanger, Boehm, DaSilva, Richardson, Wymant
  - ◇ strong singlet-doublet mixing  $\rightsquigarrow$  reduced coupling to  $b\bar{b}$
  - ◇  $\Delta_b$  corrections to  $hb\bar{b}$  coupling Carena et al; Guasch et al; Noth, Spira; Mihaila, Reisser
- \* Enhanced  $\Gamma(h^{125 \text{ GeV}} \rightarrow \gamma\gamma)$  due to charged boson, chargino, stop loop contributions



- \*  $BR$  modifications due to Higgs-to-Higgs and/or Higgs-to-SUSY decays

# *Higgs Mass Corrections*



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## *NMSSM Higgs Boson Mass*

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- **NMSSM Higgs boson masses given in terms of Higgs potential parameters**
- **Higher order corrections:**
  - \* important to shift SM-like NMSSM Higgs boson mass to  $\sim 125$  GeV;
  - \* Higgs masses enter production c<sub>xn</sub>'s and BR's  $\rightsquigarrow$
  - \* need to be known at highest possible accuracy for proper interpretation of exp results, for distinction of Higgs sectors of different BSM models

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# NMSSM Higgs Boson Mass

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- Status of higher order corrections:

- \* Real NMSSM:

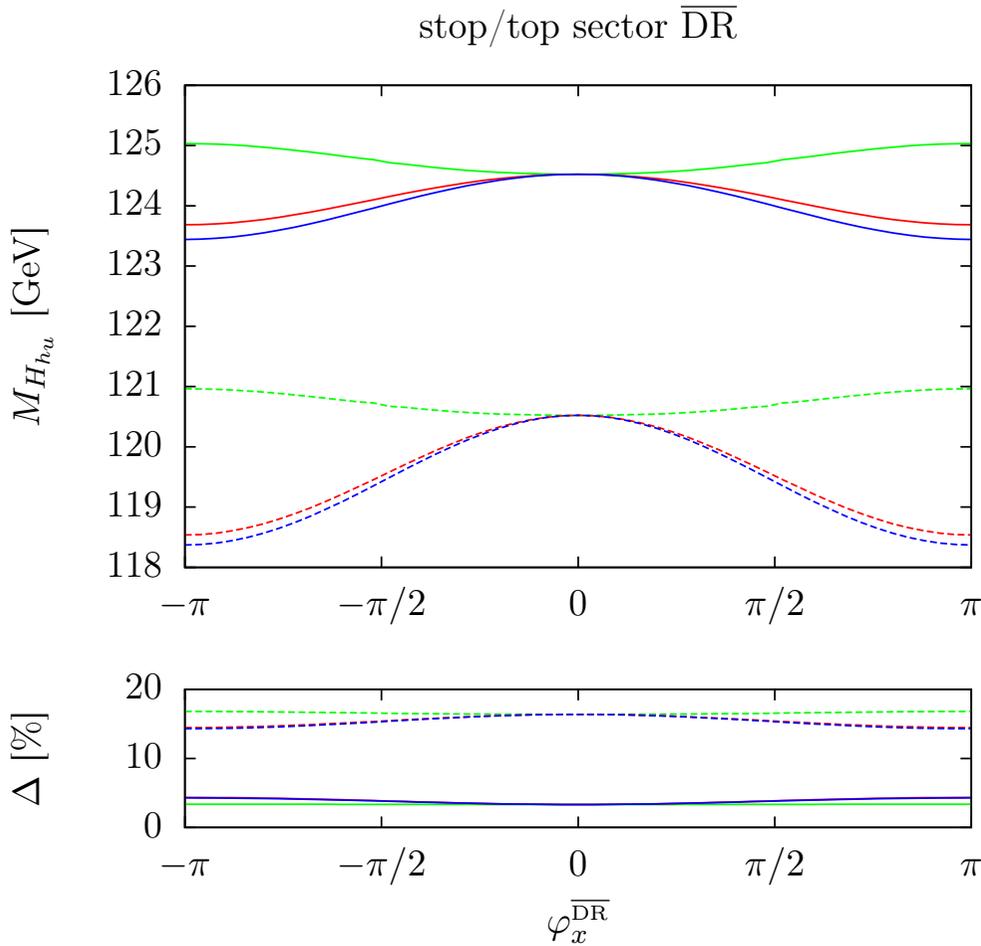
- ◇ leading one-loop [Ellwanger;Elliott et al; Pandita;Ellwanger,Hugonie]
- ◇ full one-loop in  $\overline{\text{DR}}$  scheme [Degrassi,Slavich;Staub et al]
- ◇ full one-loop in mixed  $\overline{\text{DR}}$ -OS scheme [Ender( $\rightarrow$ Walz),Graf,MMM,Rzehak]
- ◇  $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s)$   $\overline{\text{DR}}$  w/ zero external momentum [Degrassi,Slavich]
- ◇ first results beyond this [Goodsell et al]

- \* Complex NMSSM:

- ◇ various one-loop contributions in effective potential approach  
[Ham, Kim, Oh, Son; Ham, Oh, Son; Ham, Jeong, Oh; Funakubo, Tao; Ham, Kim, Oh, Son]
- ◇ full one-loop & leading two-loop in effective potential approach [Cheung, Hou, Lee, Senaha]
- ◇ full one-loop in diagrammatic approach [Graf, Grober, MMM, Rzehak, Walz]
- ◇  $\mathcal{O}(\alpha_t\alpha_s)$  mixed  $\overline{\text{DR}}$ -OS scheme w/ zero external momentum [MMM, Nhung, Rzehak, Walz]

# NMSSM Higgs Boson Mass 2-Loop Corrections

MMM, Nhung, Rzehak, Dao '14



dashed: one-loop, full: two-loop

variation of  $\varphi_{A_t}$

variation of  $\varphi_{M_3}$

variation of  $\varphi_\mu$

$$\Delta = |M_{H_{h_u}}^{(n)} - M_{H_{h_u}}^{(n-1)}| / M_{H_{h_u}}^{(n-1)}$$

dashed:  $n = 1$ , solid:  $n = 2$

difference in  $\overline{\text{DR}}$  and OS masses:

one-loop:  $\mathcal{O}(15 - 25\%)$

two-loop:  $\mathcal{O}(\lesssim 1.5\%)$

$$m_t^{pole} = 173.5 \text{ GeV}$$

$$m_t^{\overline{\text{DR}}} = 143.14 \text{ GeV at } Q = 1.25 \text{ TeV}$$

# $\mathcal{N}$ MSSM Higgs Phenomenology



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# *NMSSM Higgs Boson Phenomenology*

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- **Vast literature on NMSSM Higgs boson phenomenology:**

Arvanitaki,Villadoro; Ellwanger; Munir; King,MMM,Nezovorov,Walz; Gunion,Jiang,Kraml;  
Badziak,Olechowski,Pokorski; Munir,Roszkowski,Trojanowski; Kang,Li,Liu,Shu; Cerdeno,Ghosh,Park,Peiro;  
Beskidt,deBoer,Kazakov; Choi,Im,Jeong,Seo; Kozaczuk,Profumo; Barbieri,Buttazzo,Kannike,Sala,Tesi;  
Cao,Ding,Han,Yang,Zhu; Fan,Tao,Shen,Chen,Gascon-Shotkin,Lethuillier,Sgandurra; Huang,Liu,Wang,Yu;  
Belanger,Bizouard,Chalons; Buttazzo; Ellwanger,Hugonie; Ellwanger,Teixeira; Heng,Shang,Wan;  
Guo,Li,Williams; Bomark,Moretti,Munir,Roszkowski; Cao,Li,Shang,Wu,Zhang; ...

- **This Talk:**

*Discovery Prospects for NMSSM Higgs Bosons at the High-Energy Large Hadron Collider*

King,MMM,Nezovorov,Walz, Phys. Rev. D90 (2014) 9.

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

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Mixing angle  $\tan \beta$  and NMSSM couplings  $\lambda, \kappa$ :

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

with perturbativity requirement

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

Soft SUSY breaking trilinear NMSSM couplings and  $\mu_{\text{eff}}$ :

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

Remaining Parameters:

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

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

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

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

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## NMSSM Scan

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- **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  $\mu_{XX}^{\text{exp}}$  ( $X = b, \tau, \gamma, W, Z$ ):  $|\mu_{XX}^{\text{scan}}(h) - \mu_{XX}^{\text{exp}}| \leq 2 \times 1\sigma$
- \* 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  $\Phi = H_i, A_j$**

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

$\delta$  : 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]

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## Experimental Signal Rates

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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	$\pm 1.06$
$H \rightarrow \tau\tau$	1.02	$\pm 0.7$
$H \rightarrow \gamma\gamma$	1.14	$\pm 0.4$
$H \rightarrow WW$	0.78	$\pm 0.34$
$H \rightarrow ZZ$	1.11	$\pm 0.46$

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<http://www.itp.kit.edu/~maggie/NMSSMCALC>

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**NMSSMCALC**  
**Calculator of One-Loop and  $O(\alpha_t \alpha_s)$  Two-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 and  $O(\alpha_t \alpha_s)$  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 1.03 (5 January 2015) **NEW! Implementation of  $O(\alpha_t \alpha_s)$  mass corrections**

**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 Comput. Phys. Commun. 185 \(2014\) 12](#)

**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](#)

**$O(\alpha_t \alpha_s)$  Mass Corrections:** [M. Mühlleitner, D.T. Nhung, H. Rzehak, K. Walz, in arXiv:1412.0918](#)

**HDECAY:** [A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun. 108 \(1998\) 56](#)

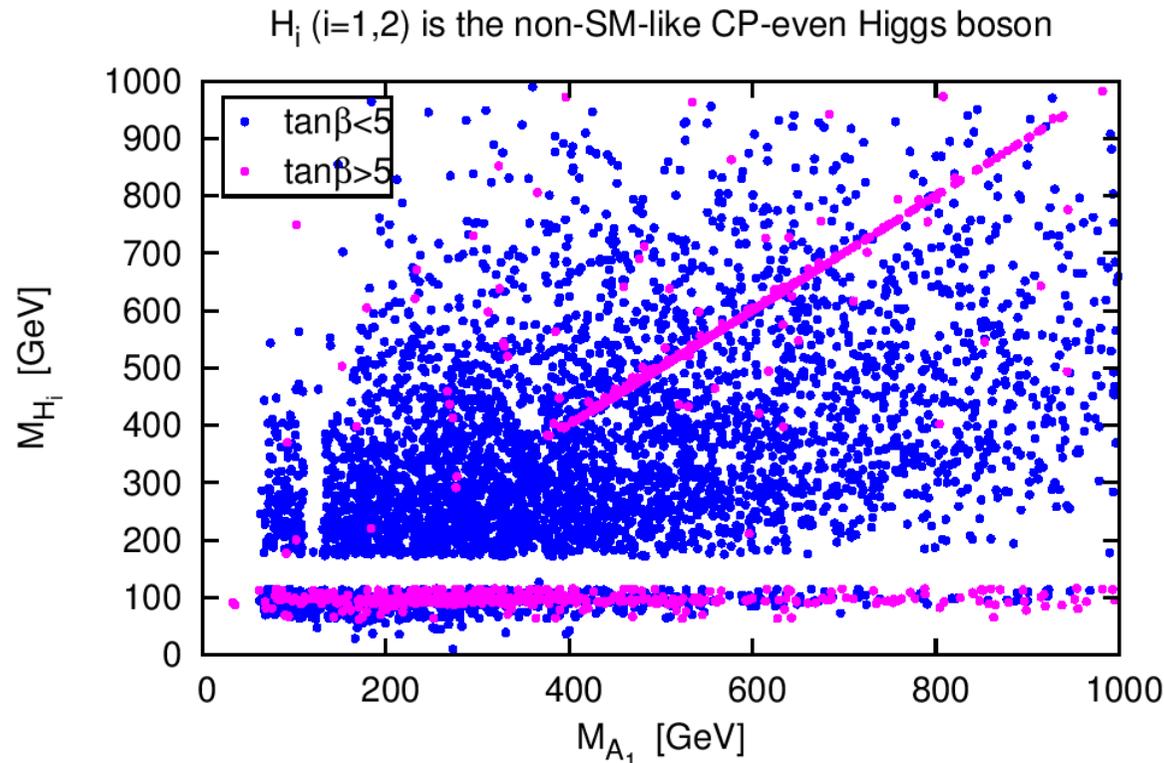
**An update of HDECAY:** [A. Djouadi, J. Kalinowski, Margarete Mühlleitner, M. Spira, in arXiv:1003.1643](#)

**Informations on the Program:**

- Short explanations on the program are given [here](#).

# Mass Distributions

King, MMM, Nevzorov, Walz



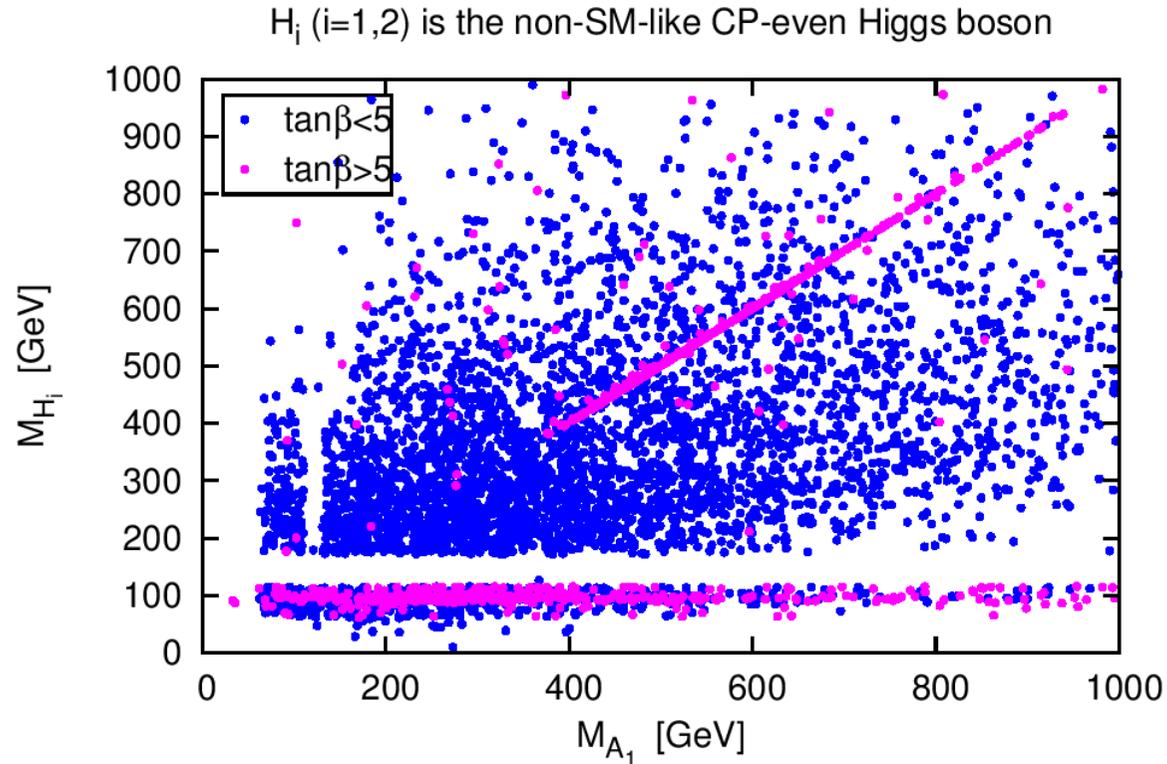
$M_{H_i} \lesssim 115$  GeV  $\rightsquigarrow H_1$  non-SM-like;  $M_{H_i} \gtrsim 180$  GeV  $\rightsquigarrow H_2$  non-SM-like

Gaps at  $115$  GeV  $\lesssim M_{H_i} \lesssim 180$  GeV and  $115$  GeV  $\lesssim M_{A_1} \lesssim 130$  GeV due to LHC 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  $\mu$  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  $\lesssim M_{H_3}$ ,  $M_{A_2} \lesssim \mathcal{O}(\text{TeV})$

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## Experimental Situation

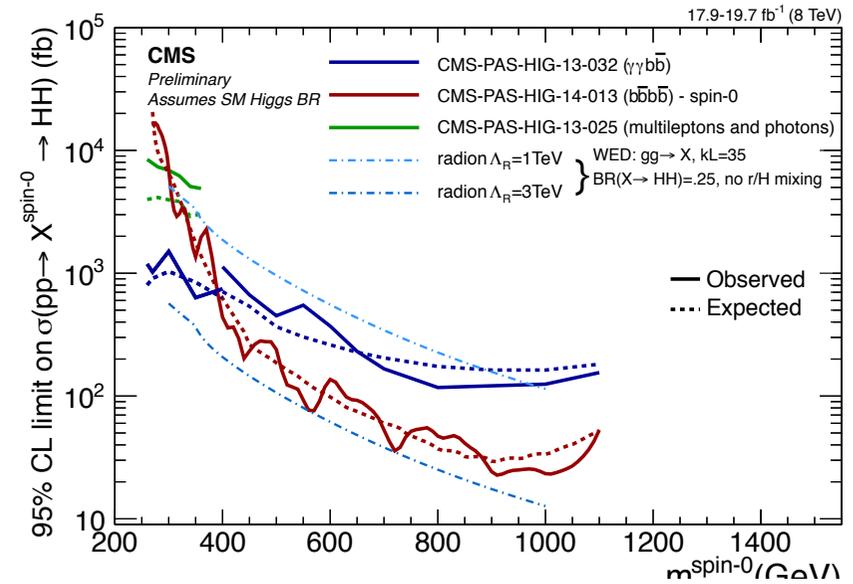
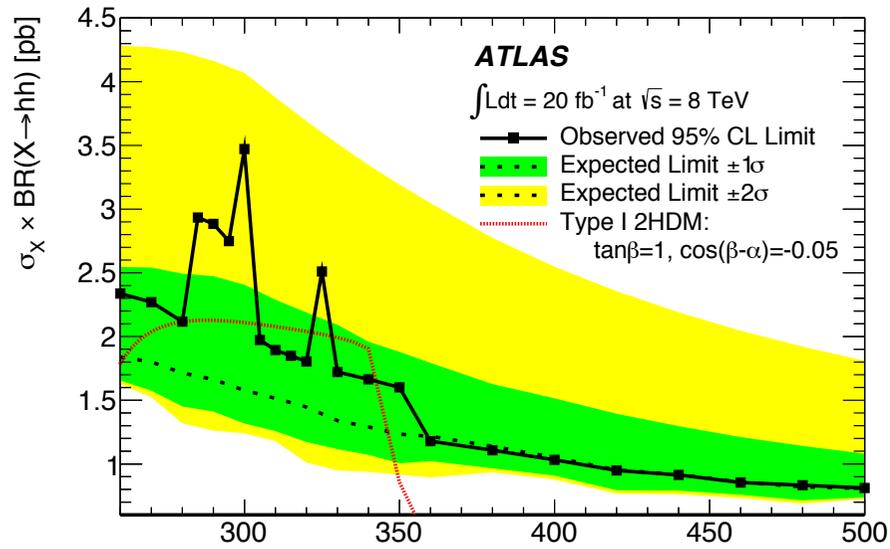
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- ▷ CMS, CMS-HIG-12-004:  $\sigma\text{BR}(pp \rightarrow a \rightarrow \mu^+\mu^-)$ ,  $5.5 \leq m_{\mu\mu} \leq 14$  GeV,  
excluded: 1.5 – 7.5 pb at 95% CL ( $\sqrt{s} = 7$  TeV,  $\int \mathcal{L} = 1.3$  fb $^{-1}$ )
- ▷ ATLAS, ATLAS-CONF-2012-079:  $H \rightarrow aa \rightarrow \gamma\gamma + \gamma\gamma$  for  $M_H = 110 - 150$  GeV,  
 $M_a = 100, 200, 400$  MeV;  $\sigma\text{BR} = 0.1$  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:  $X \rightarrow HH \rightarrow (\gamma\gamma)(b\bar{b})$ ,  $260 \leq m_X \leq 1100$  GeV,  
 $\sigma\text{BR} \approx 0.4 - 4$  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  $hh \rightarrow (\gamma\gamma)(b\bar{b})$ ,  
 $260 \leq m_h \leq 500$  GeV (SM  $h$ ),  
non-resonant  $\sigma\text{BR} = 2.2$  pb upper limit,  
resonant  $\sigma\text{BR} = 0.8 - 3.5$  pb excluded at 95%CL ( $\sqrt{s} = 8$  TeV,  $\int \mathcal{L} = 20$  fb $^{-1}$ )
- ▷ CMS, CMS-PAS-HIG-14-013:  $X \rightarrow HH \rightarrow (b\bar{b})(b\bar{b})$ ,  $270 \leq m_X \leq 1100$  GeV,  $m_H = 125$  GeV

# Experimental Situation

ATLAS, 1406.5053

CMS-PAS-HIG-13-032, 14-013, 13-025



---

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

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- 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

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- Tree-Level Mass Values

Nevezorov, Miller '04

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

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

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

- 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  $A$

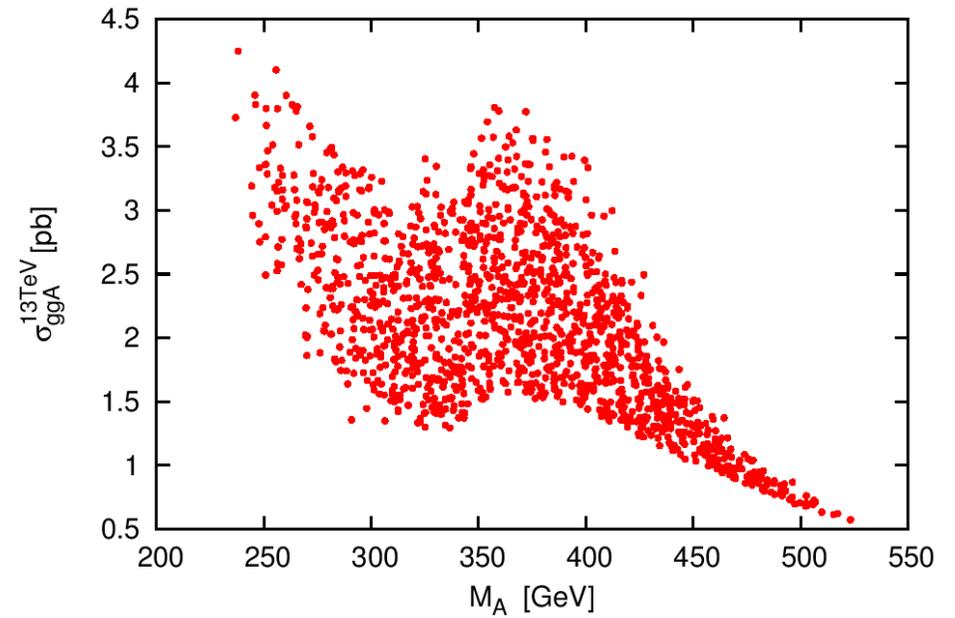
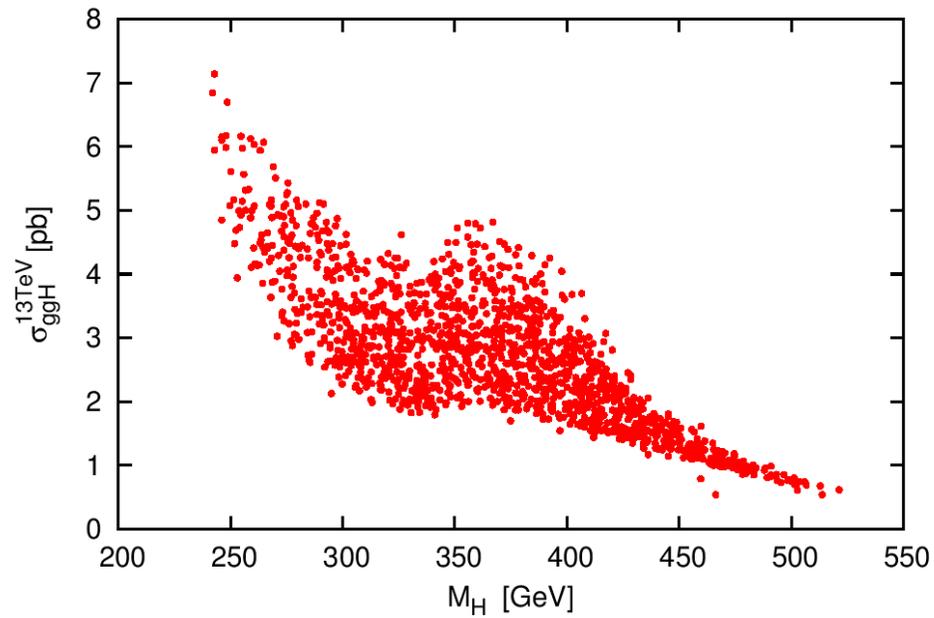
$$0.8 \text{ pb} \lesssim \sigma(gg \rightarrow H) \lesssim 7.5 \text{ pb}, \quad 0.6 \text{ pb} \lesssim \sigma(gg \rightarrow A) \lesssim 4.5 \text{ pb}$$

---

# Production Cross Sections for $H, A$

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King, MMM, Nevzorov, Walz



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## Alternative Production Channels

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

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

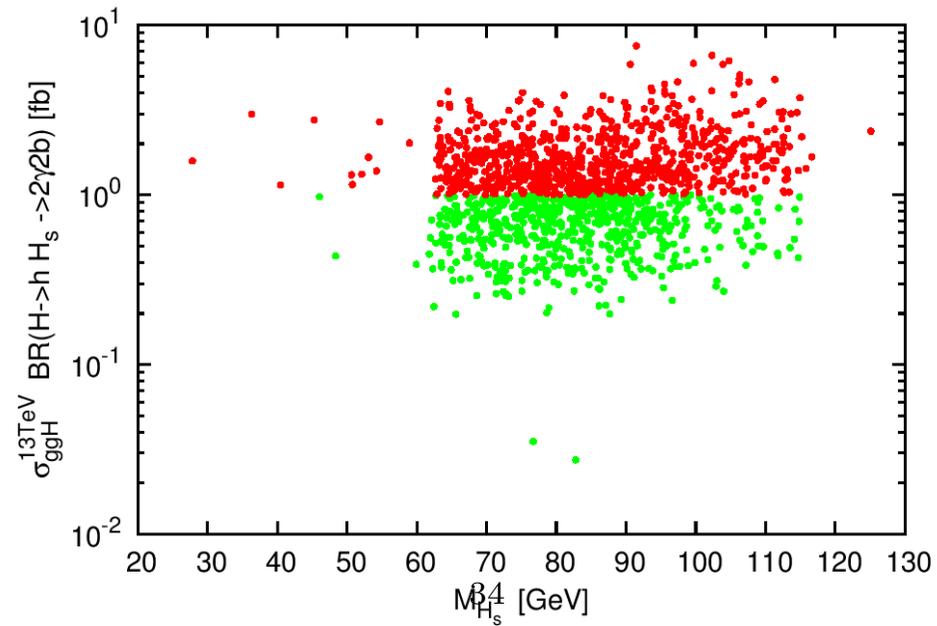
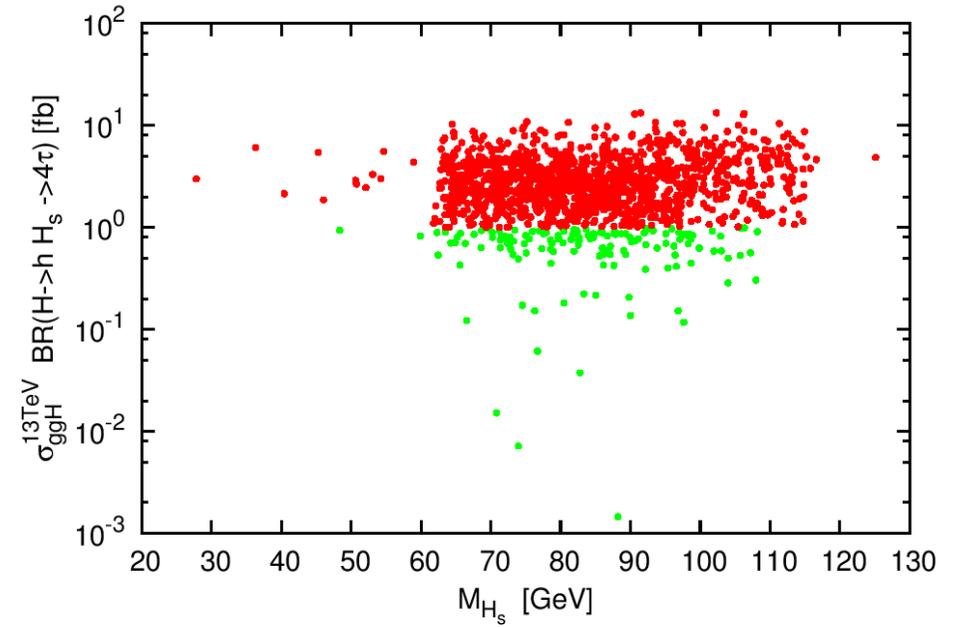
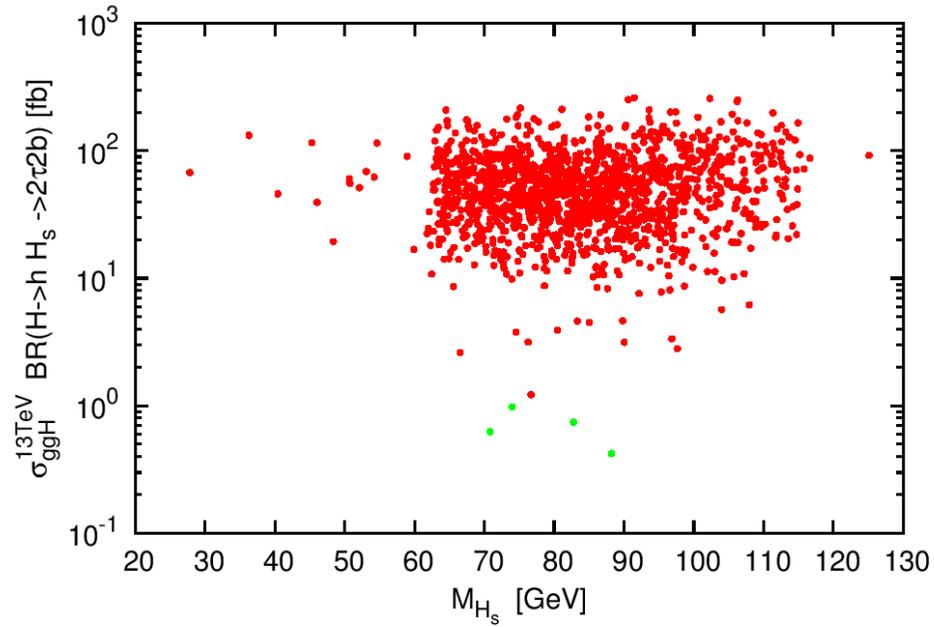
$$\sigma(gg \rightarrow \phi_i) \times BR(\phi_i \rightarrow \phi_j \phi_k) \times BR(\phi_j \rightarrow XX) \times BR(\phi_k \rightarrow YY)$$

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

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

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

King, MMM, Nevzorov, Walz



---

## Discovery Prospects in the Natural NMSSM

---

- 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  $\sigma_{\text{prod}}$  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)

$$H \rightarrow H_s H_s, H \rightarrow h H_s, A \rightarrow H_s A_s, A \rightarrow h A_s, \dots$$

$$H \rightarrow Z A_s, A \rightarrow Z H_s$$

LHC13: Natural NMSSM Scenario confirmed or strongly constrained

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## 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  $\phi_i$  discovery if  $\sigma_{\text{prod}}$  large enough and BR into lighter Higgs pairs dominates
- ▷ For lighter  $\phi_j, \phi_k$  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

## 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
$A_t, A_b, A_\tau$	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:

$$\lambda_{H_s A_s A_s}$$

$$\lambda_{HH_s h}$$

$$\lambda_{AA_s H_s}$$

$$\lambda_{AA_s h}$$

# Higgs Couplings



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## What if not all Higgs Bosons can be discovered?

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- 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

$$\frac{G_{H_i VV}}{g_{H^{SM} VV}} \equiv g_{H_i VV} = (\mathcal{R}_{i1}^S \cos \beta + \mathcal{R}_{i2}^S \sin \beta)$$

$$\frac{G_{H_i tt}}{g_{H^{SM} tt}} \equiv g_{H_i tt} = \frac{\mathcal{R}_{i2}^S}{\sin \beta}, \quad \frac{G_{H_i bb}}{g_{H^{SM} bb}} \equiv g_{H_i bb} = \frac{\mathcal{R}_{i1}^S}{\cos \beta}$$

---

## What if not all Higgs Bosons can be 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]

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

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

## Coupling Sum Rules

- 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	
$ 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
$A_t, A_b, A_\tau$	-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	
$M_{L_3} = M_{\tau_R}, M_{\text{SUSY}}$	2491.6 GeV	3 TeV	

$$\sigma(gg \rightarrow H) = 0.46 \text{ fb} , \sigma(bbH) = 0.82 \text{ fb} , \quad \sigma(gg \rightarrow A) = 0.72 \text{ fb} , \sigma(bbA) = 0.82 \text{ fb}$$

---

## Coupling Sum Rules

---

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

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

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

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 ctn 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

# Conclusions



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## Conclusions

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- **NMSSM Higgs sector compatible w/ LHC data**

- ★ SM-like Higgs can be  $H_1$  or  $H_2$ ; degenerate Higgs signal at  $\sim 125$  GeV possible
- ★ Higgs bosons below 100 GeV not excluded

- **Natural NMSSM**

- ★ good discovery prospects at high-energy 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,  $\cancel{E}_T$  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!*



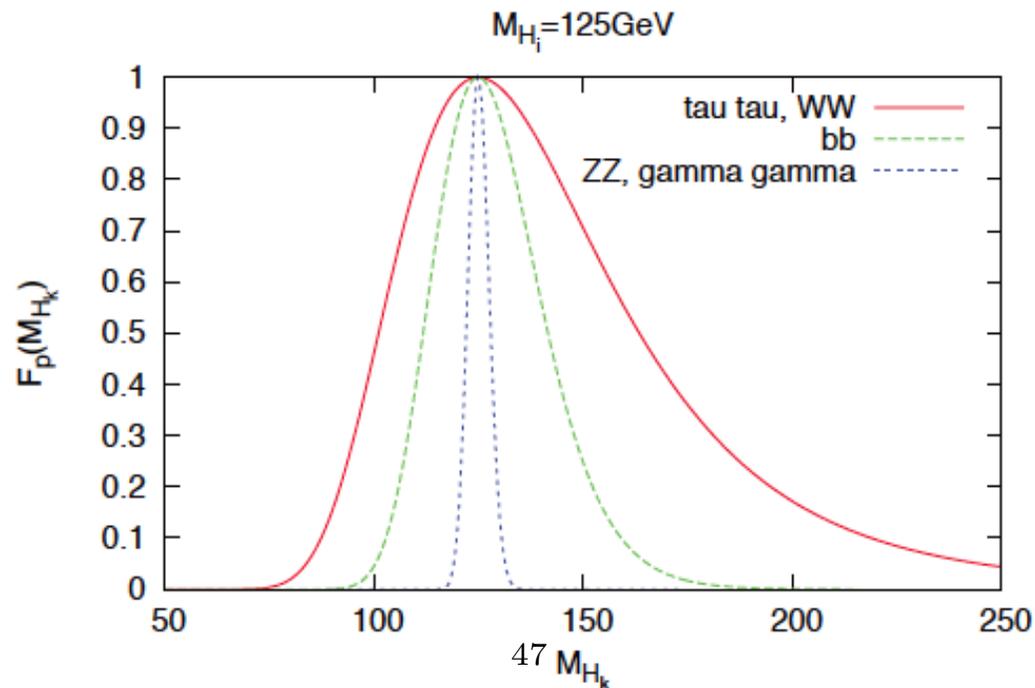
## Superposition of Signal Rates

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

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

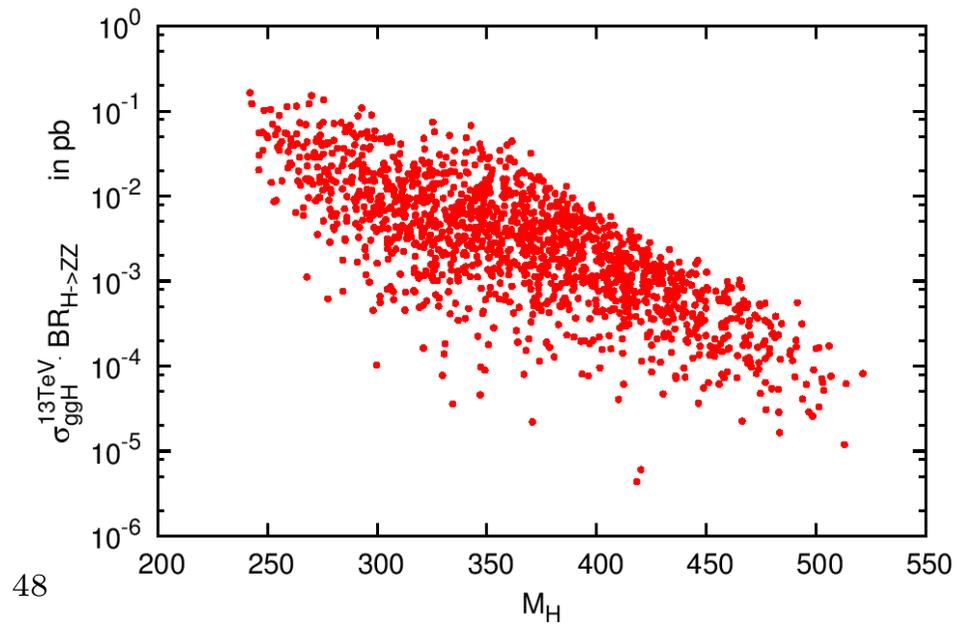
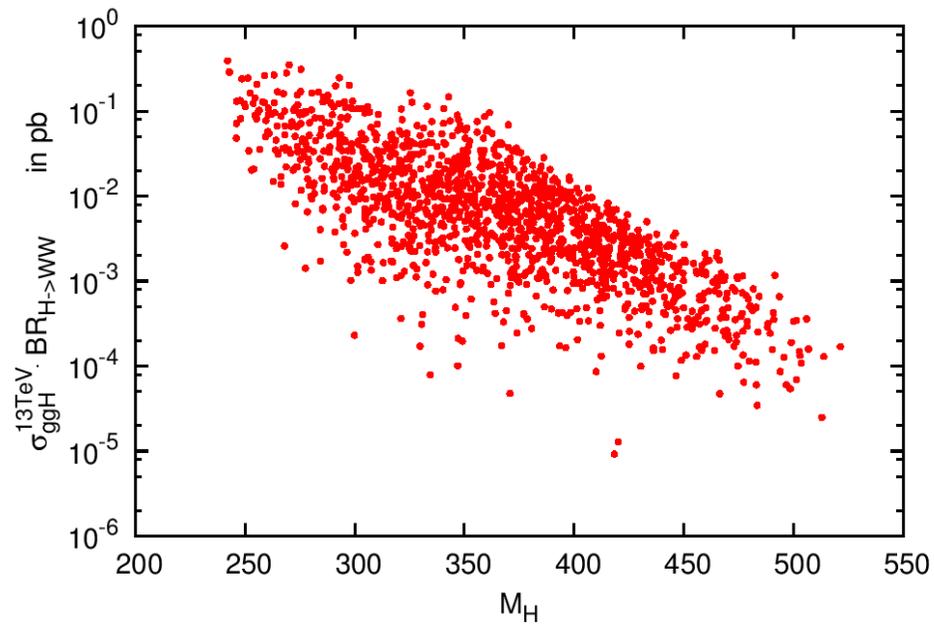
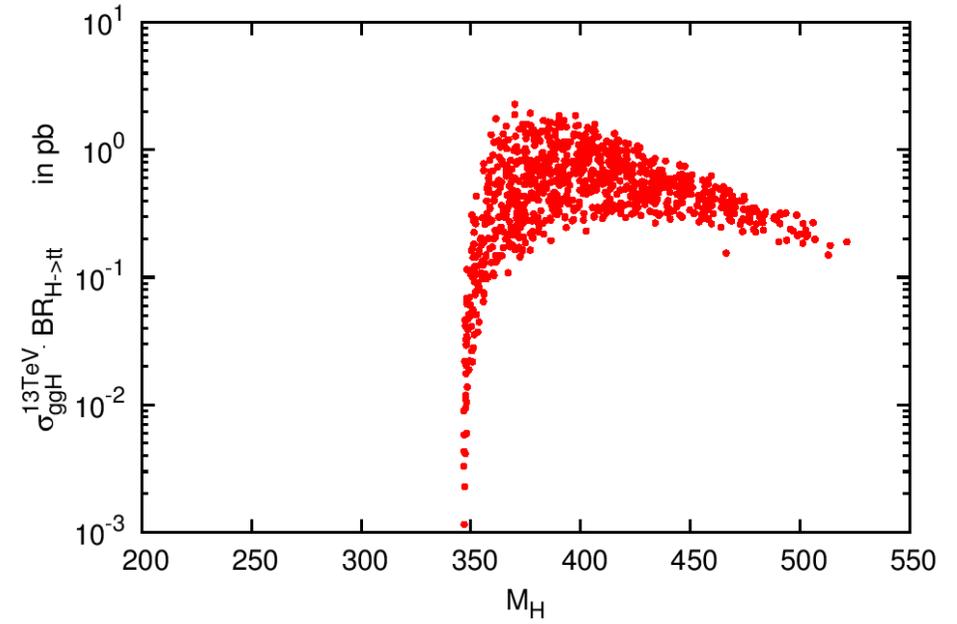
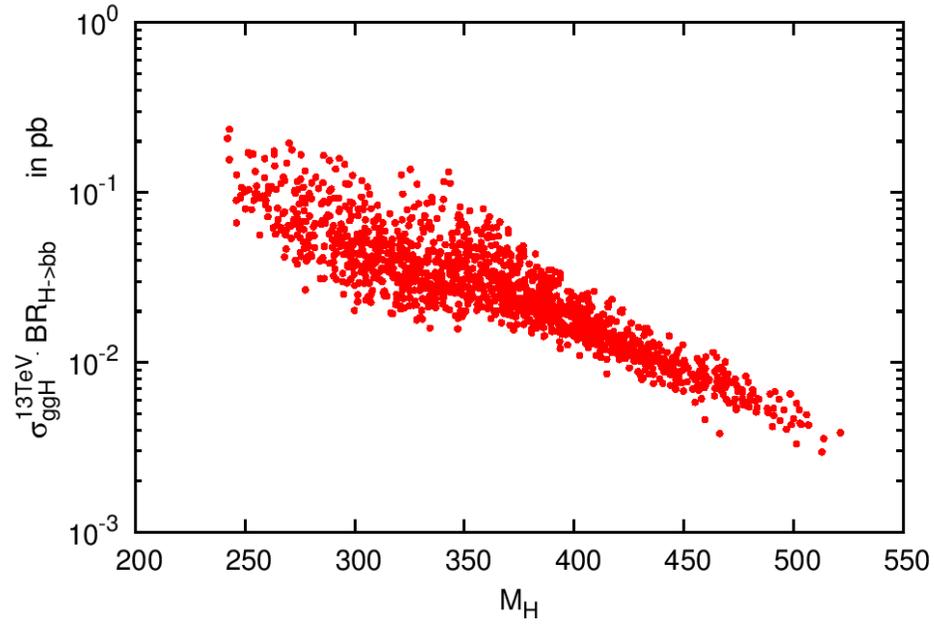
This weighting factor depends on the mass difference and on a factor  $d_p$  which is decay specific:

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



# Signal Rates for $H$

King, MMM, Nevzorov, Walz



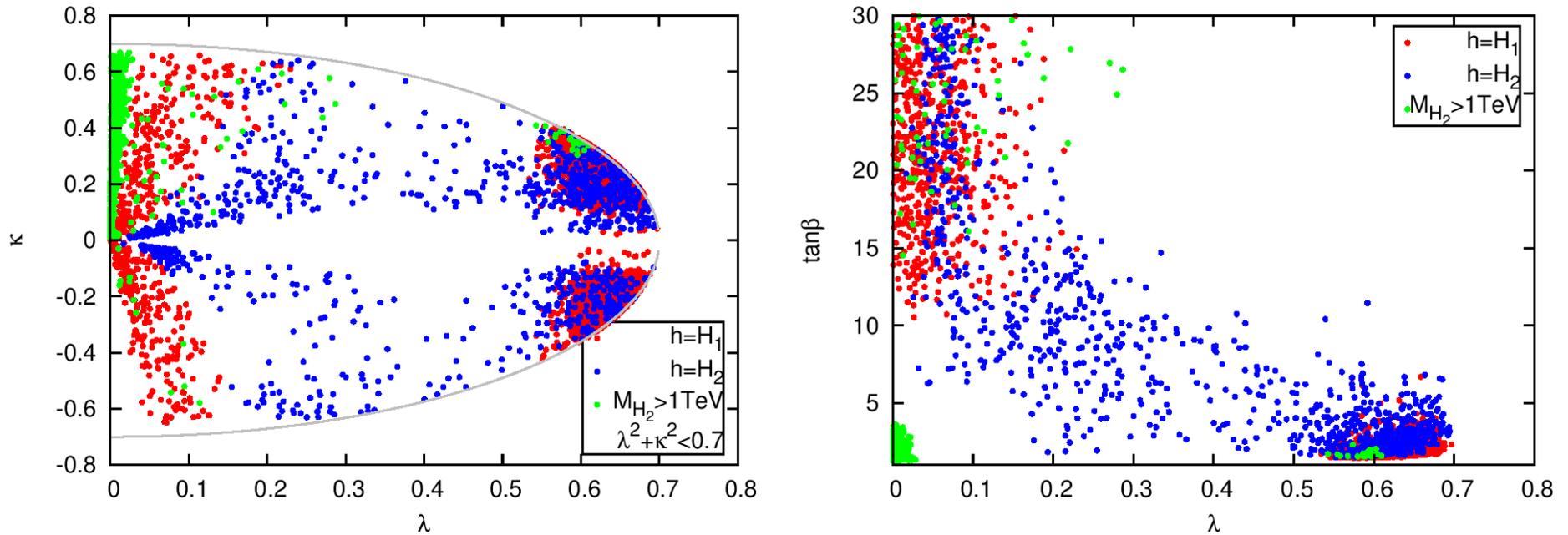
# Singlet-/Doublet Character of the $\mathcal{NMSSM}$ Higgs Bosons

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

# Distributions of $\lambda$ , $\kappa$ and $\tan\beta$

King, MMM, Nevzorov, Walz



SM-like Higgs  $h$  around 125 GeV for  $0.5 \lesssim \lambda \lesssim 0.7$ ,  $\tan\beta \lesssim 5$  or  $\lambda \lesssim 0.1$ ,  $\tan\beta \gtrsim 10$

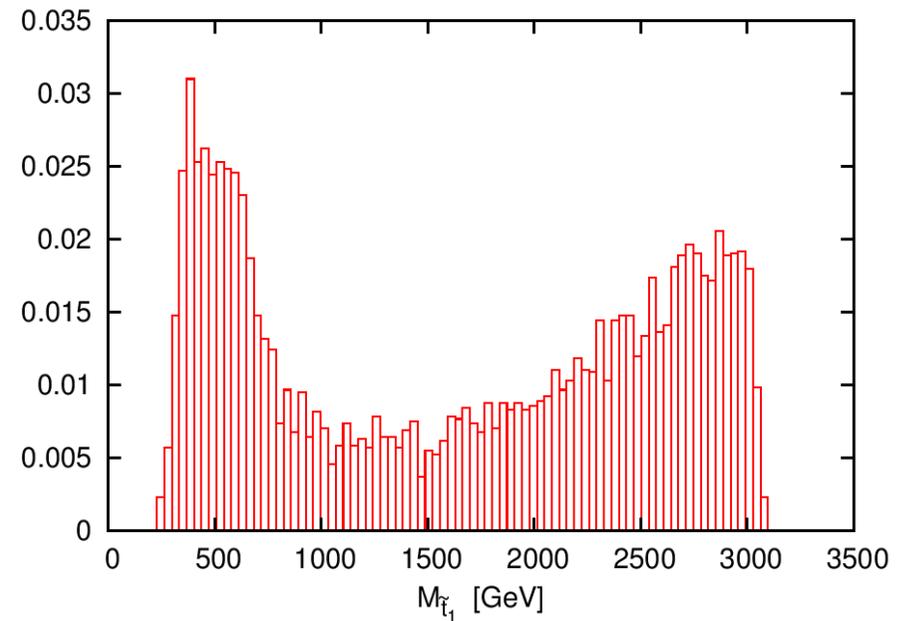
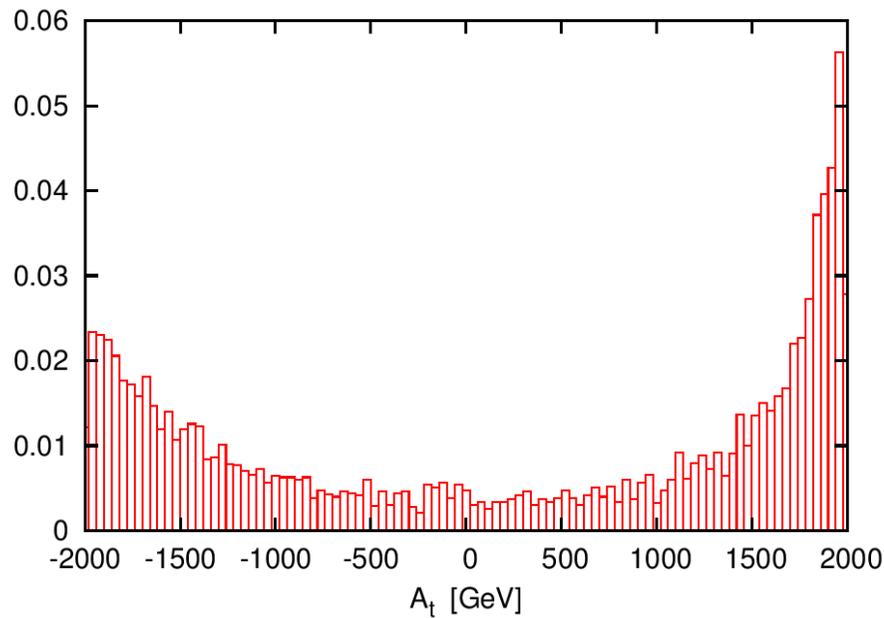
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{\lambda^2 v^2}{2} \sin^2 2\beta + \Delta m_h^2$$

---

## Distributions 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

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

---

## Intermezzo - What about Light Stops?

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- **Fine-tuning** reduced for light stop
- **SUSY searches:** stops can still be much lighter than 1st and 2nd generation squarks
- **Scenario:**
  - ◇  $\tilde{\chi}_1^0$  is lightest SUSY particle (LSP)
  - ◇  $\tilde{t}_1$  is next-to-lightest SUSY particle (NLSP)
  - ◇  $m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_W + m_b$
- **Stop Decays:**

Flavour violating (FV) 2-body decays:  $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0, u\tilde{\chi}_1^0$ , 4-body decay:  $\tilde{\chi}_1^0 d_i f \bar{f}'$
- **Many sources of flavour violation in MSSM**  $\rightsquigarrow$  FV 2-body decay can take place at tree-level
- **FV strongly constrained by experiment**  $\rightsquigarrow$  flavour protection needed

---

# Flavour Protection

---

- **Flavour protection by**

- ◇ **Minimal flavour violation:** all flavour violation due to the Yukawas,  $m_{\text{soft}}$  and  $A_f$  chosen flavour universal
- ◇ **Reduced flavour symmetries:**  $m_{\text{soft}}$  and  $A_f$  of 3rd generation chosen differently from 1st and 2nd generation

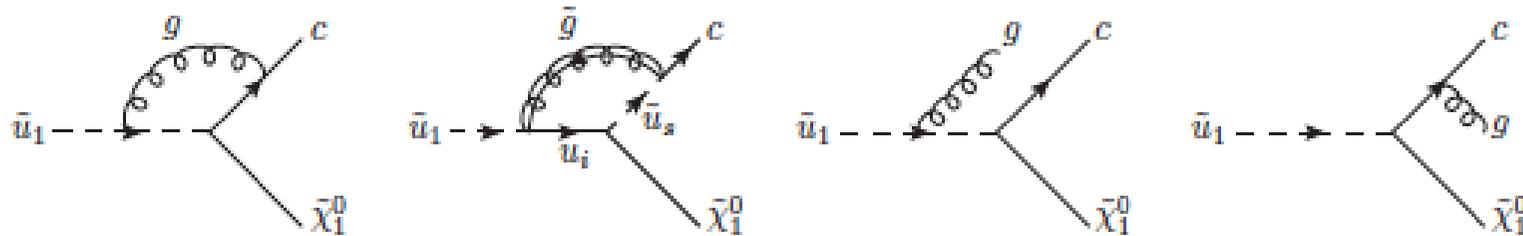
- **Investigated scenarios inspired by:**

- ◇  **$U(3)$ :**  $m_{\tilde{t}_R}$  and  $A_t$  chosen differently from other flavour universal  $m_{\tilde{q}}$  and  $A_q$
- ◇  **$U(2)$ :**  $m_{\tilde{Q}_3}$ ,  $m_{\tilde{t}_R}$  and  $A_t$  chosen differently from other flavour universal  $m_{\tilde{q}}$  and  $A_q$

Flavour off-diagonal terms induced by RGE running.

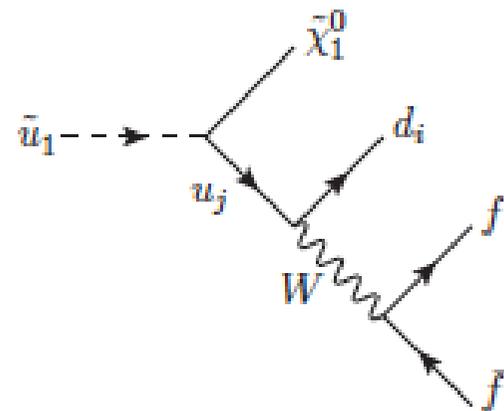
## The 2- and 4-Body Decays

- SUSY-QCD corrections to 2-body decays :  $\tilde{u}_1 \rightarrow c\tilde{\chi}_1^0, u\tilde{\chi}_1^0$ 
[Grober,MMM,Popenda,Wlotzka; Aebischer,Crivellin,Greub]



- Stop 4-body decays:
[Boehm,Djouadi,Mambrini;Grober,MMM,Popenda,Wlotzka]

$\tilde{u}_1 \rightarrow \tilde{\chi}_1^0 d_i f \bar{f}'$  with  $d_i = b, s, d$  and  $f, f' = b, s, d, c, u, \tau, \mu, e, \nu_\tau, \nu_\mu, \nu_e$ , w/ flavour-violation  
 full mass dependence of third generation fermions



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## Scan Over Parameter Space

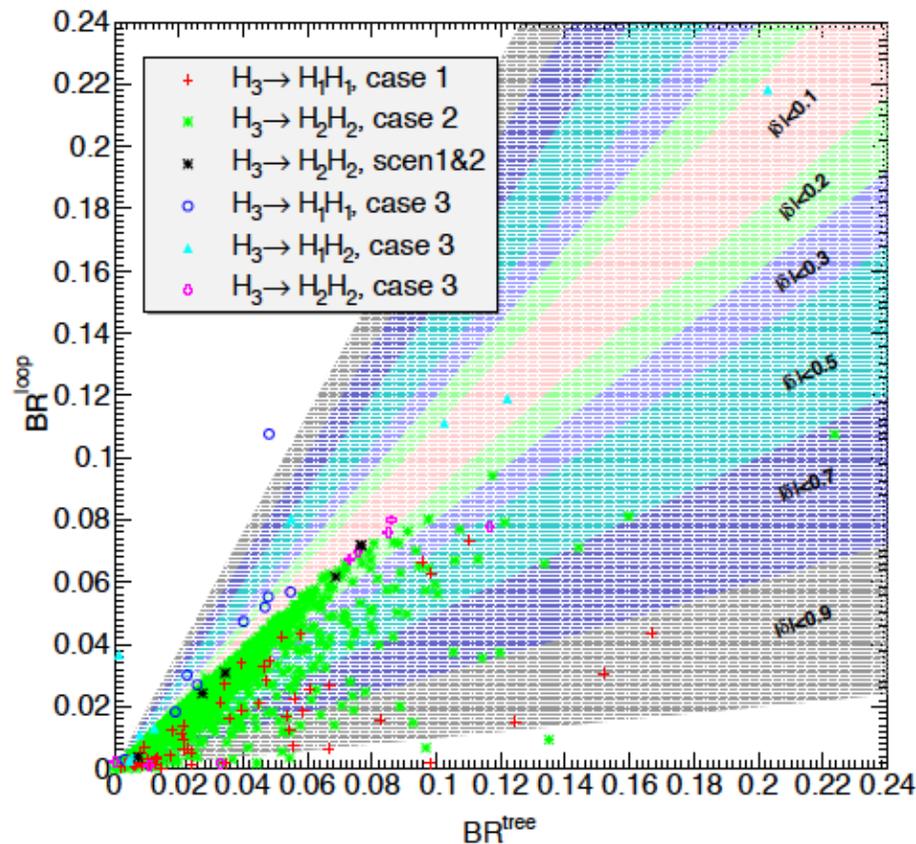
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- ◇ Spectrum generated with SPHENO Porod,Staub
- ◇ Decays implemented in SUSY-HIT Djouadi,MMM,Spira;Grober,MMM,Popenda,Wlotzka
- **Checked constraints:**
  - ◇ Higgs results: checked with HiggsBounds and HiggsSignals Bechtle,Heinemeyer,Stal,Stefaniak,Weiglein,Williams  
For Higgs branching ratios: HDECAY Djouadi,Kalinowski,MMM,Spira
  - ◇ Relic density  $\Omega_c h^2 < 0.12$  [Planck Coll.] with SuperIsoRelic Arbey,Mahmoudi
  - ◇ Some  $B$  flavour observables with SuperIsoRelic
  - ◇ Sparticle masses chosen large enough to evade LHC exclusion limits

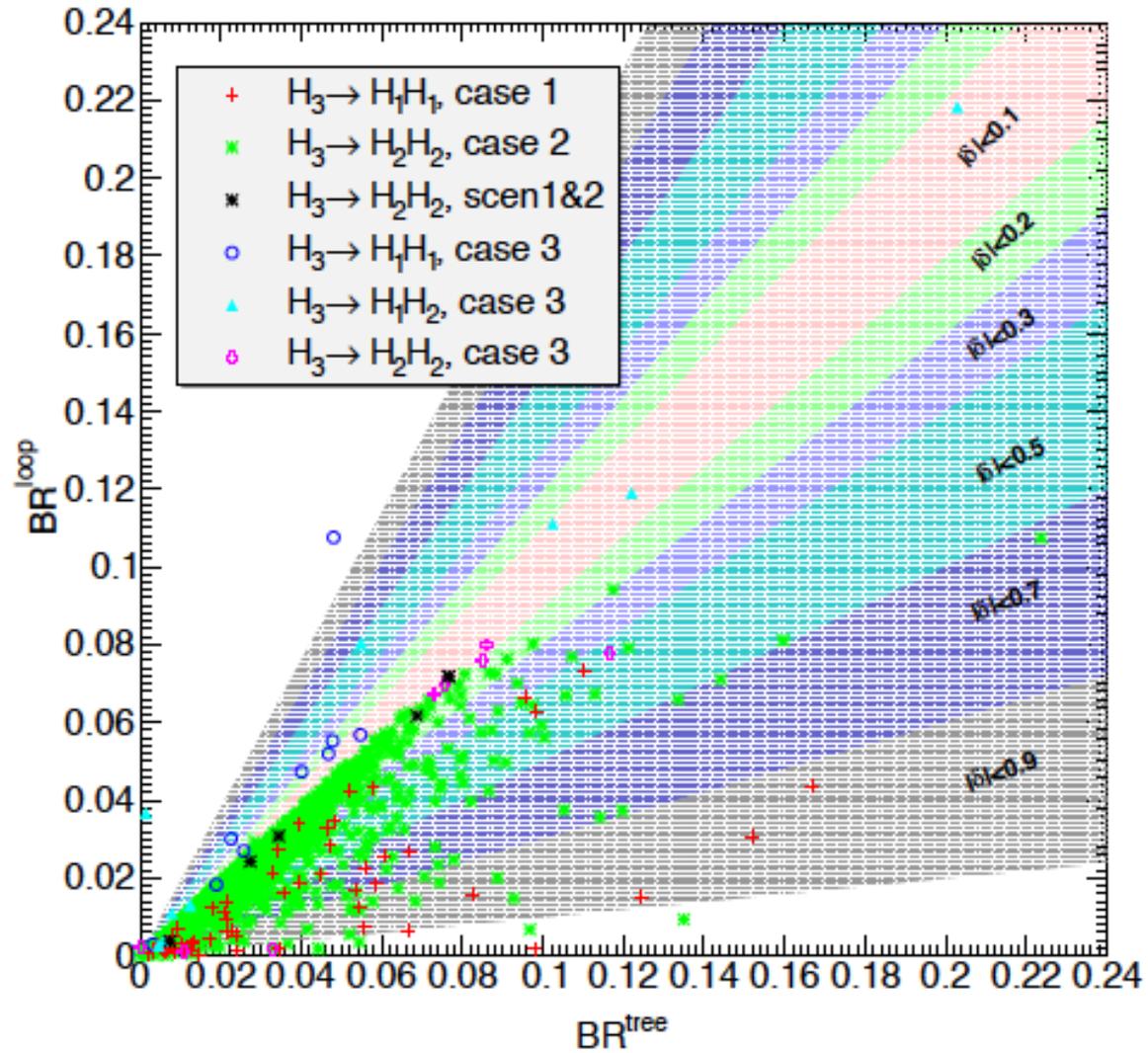
## Loop Corrected Trilinear Higgs Self-Coupling

- **Higgs mass and self-couplings:** determined from Higgs potential  $\rightsquigarrow$  consistent description of Higgs sector at higher order requires loop corrections to masses **and** self-couplings  
 $\Rightarrow$  determination of higher order corrections to trilinear Higgs self-couplings

Dao,MMM,Streicher,Walz '13



$$\delta \equiv \frac{BR^{\text{loop}} - BR^{\text{tree}}}{BR^{\text{tree}}}$$



$$\delta \equiv \frac{BR^{\text{loop}} - BR^{\text{tree}}}{BR^{\text{tree}}}$$

---

# NMSSMCALC

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- **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 up to  $\mathcal{O}(\alpha_t \alpha_s)$

- ★ 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,  $t\bar{t}$ ;  $H^+ \rightarrow t\bar{b}$

- ★ real NMSSM: SUSY-QCD to decays into stop, sbottom pairs

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## Addendum - What about Light Stops?

---

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- **SUSY searches:** stops can still be much lighter than 1st and 2nd generation squarks
- **Scenario:**
  - ◇  $\tilde{\chi}_1^0$  is lightest SUSY particle (LSP)
  - ◇  $\tilde{t}_1$  is next-to-lightest SUSY particle (NLSP)
  - ◇  $m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_W + m_b$
- **Stop Decays:**

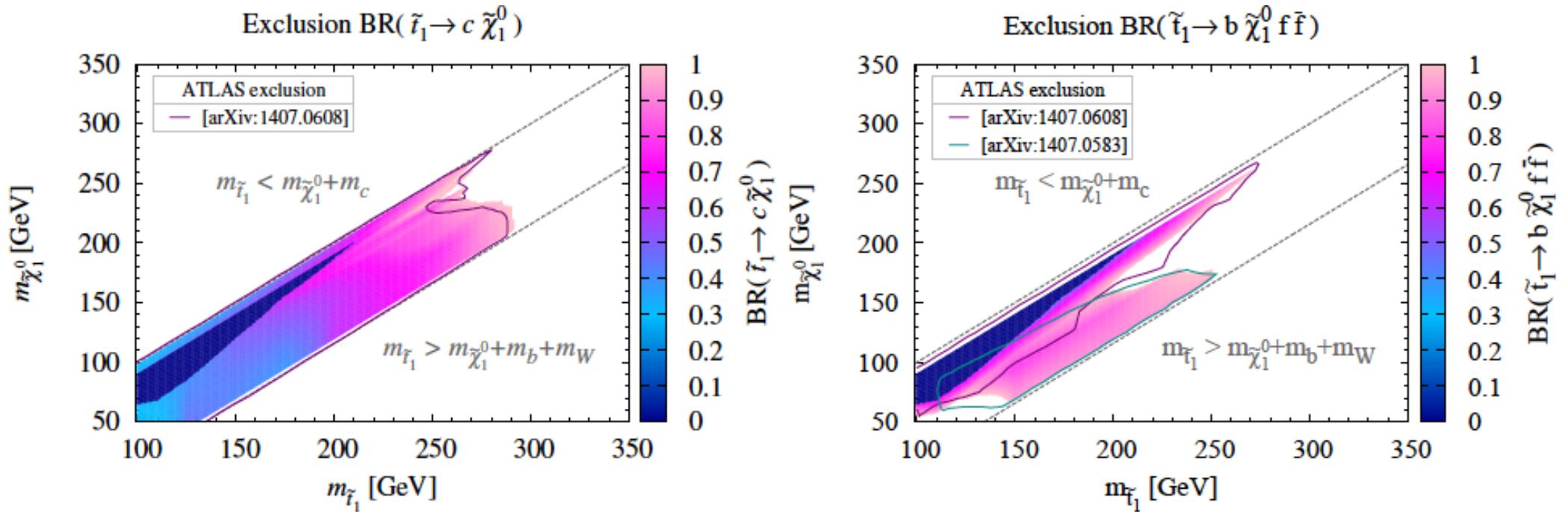
Flavour violating (FV) 2-body decays:  $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0, u\tilde{\chi}_1^0$ , 4-body decay:  $\tilde{\chi}_1^0 d_i f \bar{f}'$
- **Many sources of flavour violation in MSSM**  $\rightsquigarrow$  FV 2-body decay can take place at tree-level
- **FV strongly constrained by experiment**  $\rightsquigarrow$  flavour protection needed
- **Flavour protection by:** minimal flavour violation or reduced flavour symmetries

## Stop Exclusion Limits

- Exclusions assume BRs of 100% in either decay into  $c\tilde{\chi}_1^0$  [ATLAS-CONF-2013-068, ATLAS 1407.0608, CMS-PAS-SUS-13-009] or 4-body decay [ATLAS 1407.0583]

- Reinterpretation for different BRs:

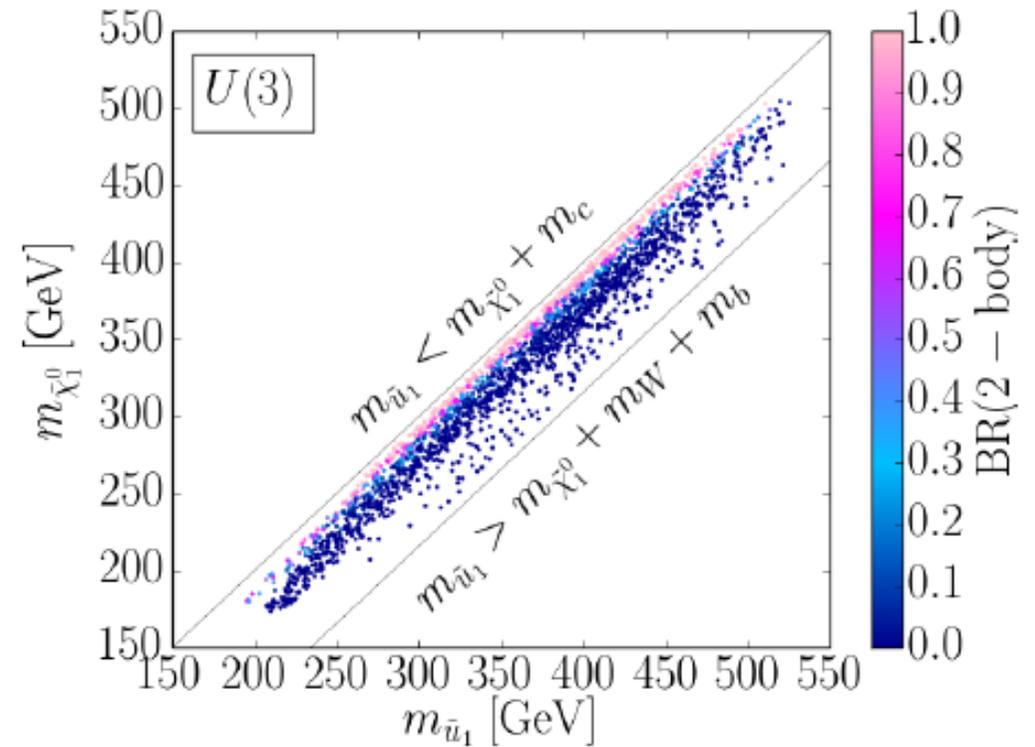
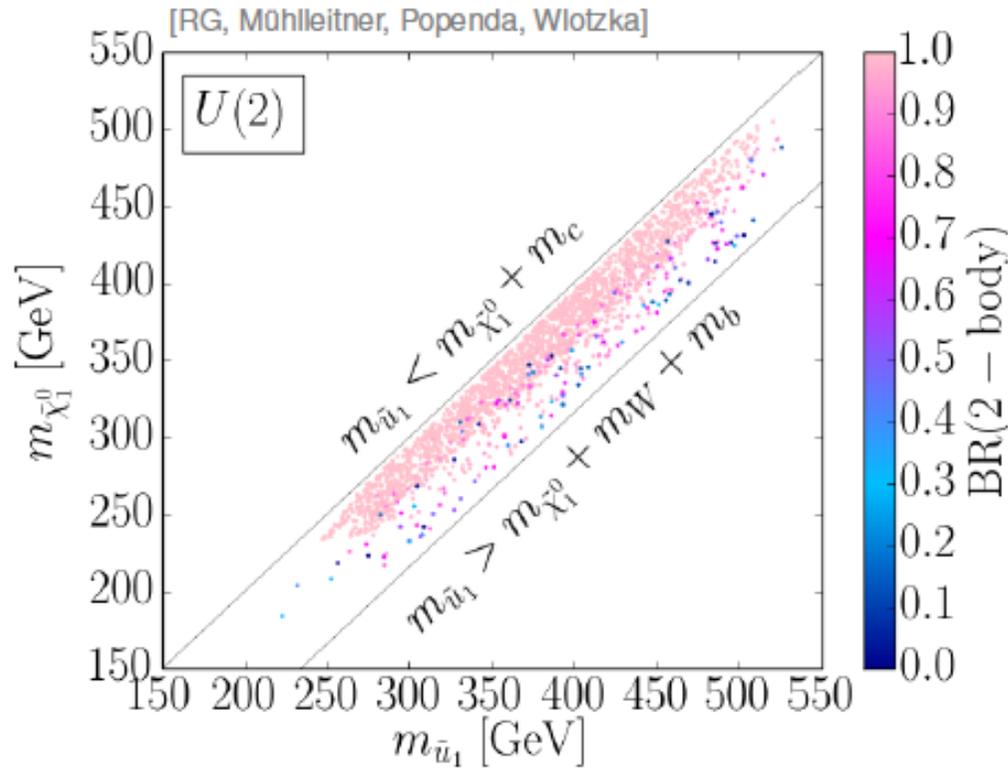
Grober, MMM, Popena, Wlotzka



BRs with values above associated colour are excluded  
 For BRs < 1 the exclusion limits become weaker

# Stop Branching Ratios

Grober, MMM, Popena, Wlotzka



assumption of BRs of 100% not valid in large parts of the parameter space

↪ lower mass points are not excluded yet if BR is reduces