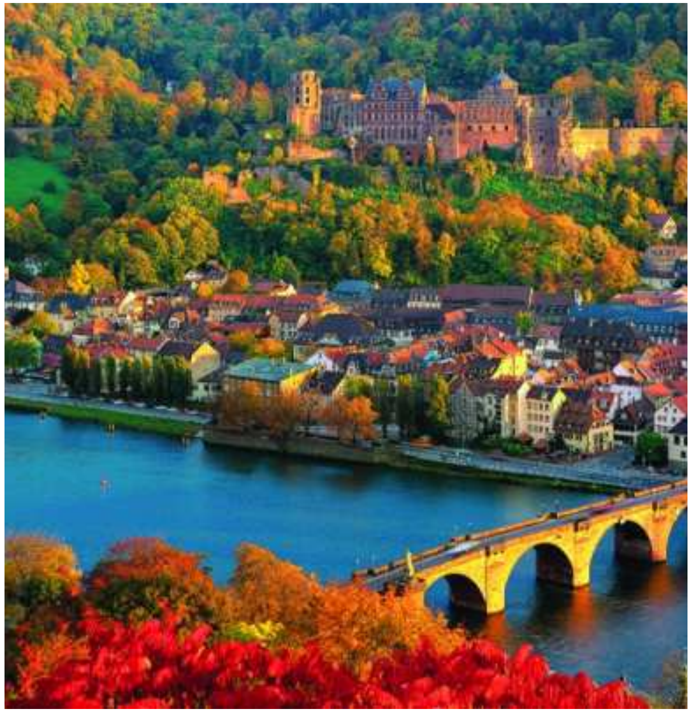
Supersymmetric Higgs Sectors

Milada Margarete Mühlleitner (KIT)

Higgs Couplings 2017
Heidelberg, 10 November 2017



Outline

◇ Introduction

◇ The Role of the Higgs Boson Mass

◇ Signatures

◇ CP violation

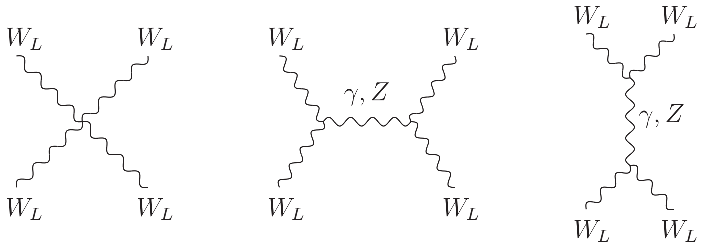
◇ Di-Higgs Production

◇ Distinction of Models based on Rates/Coupling Patterns

◇ Conclusions

$\mathcal{I}$ntroduction

- **Higgs Discovery $\rightsquigarrow$ New Era of Particle Physics**
  - Structurally completes the Standard Model
  - Self-consistent framework to describe physics up to the Planck scale



$$\mathcal{A} = \frac{G_F s}{8\sqrt{2}\pi}$$

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{D}$iscovery

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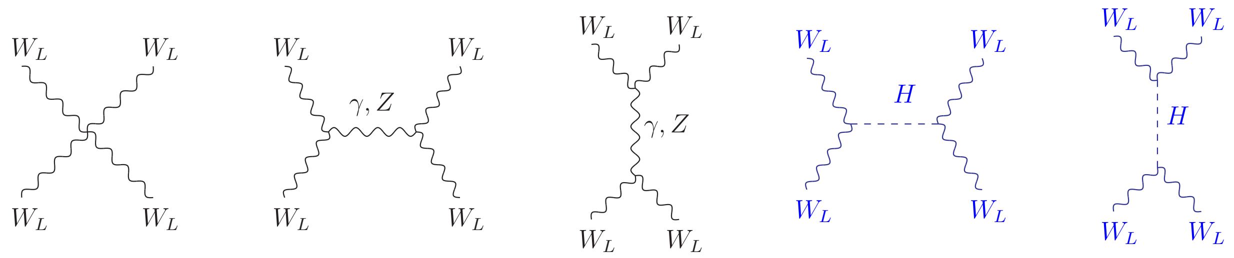

$$\mathcal{A} = \frac{G_F M_H^2}{8\sqrt{2}\pi}$$

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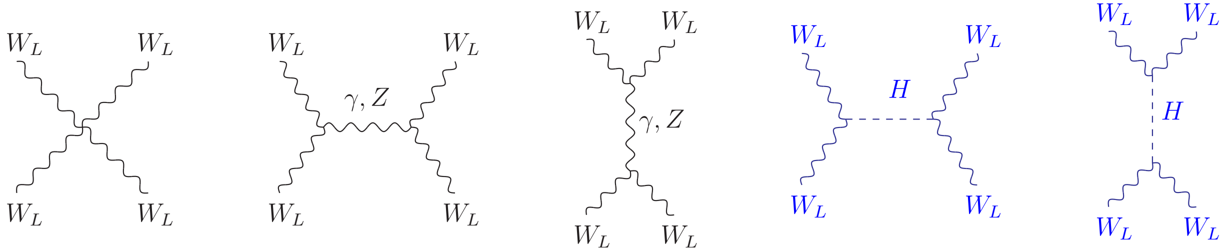
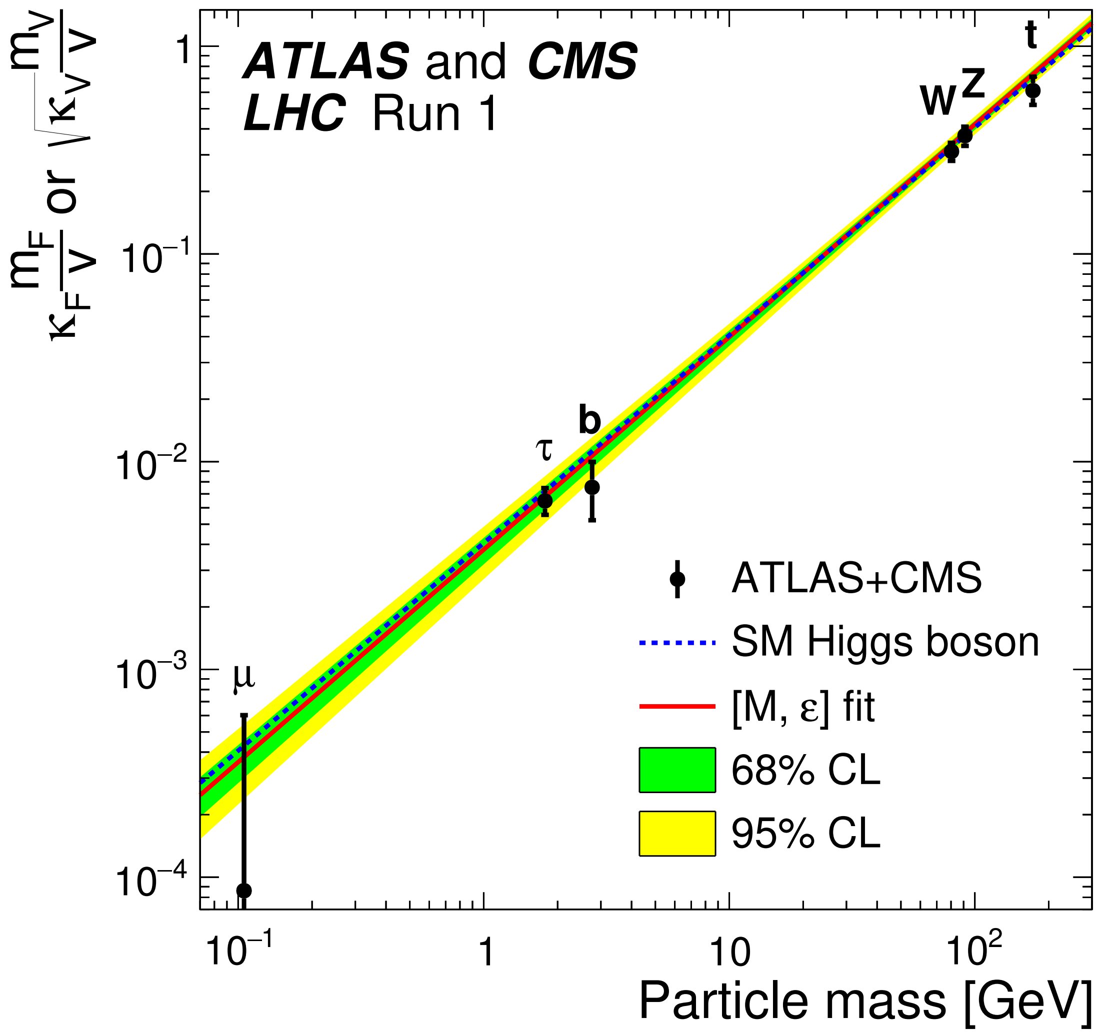


$$\mathcal{A} = \frac{G_F M_H^2}{8\sqrt{2}\pi}$$

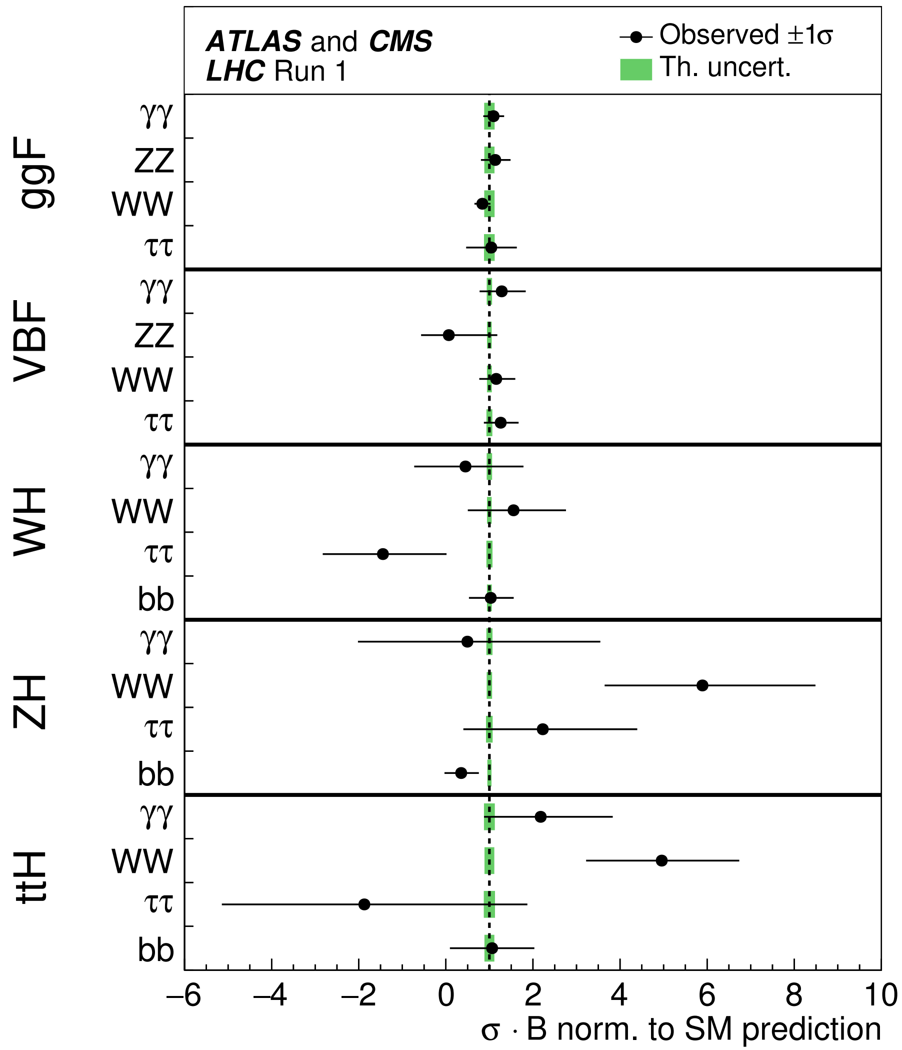
- **SM Higgs couplings:**
  - $g_{Hf\bar{f}} \sim \frac{m_f}{v}$ and $\sqrt{g_{HVV}} \sim \frac{m_V}{v}$

Higgs Boson Couplings to SM Particles

[ATLAS/CMS, JHEP08(2016)045]



Best Fit Values to Normalized Higgs Rates



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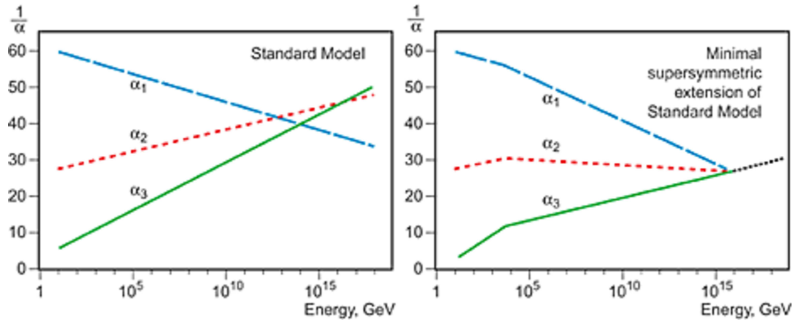

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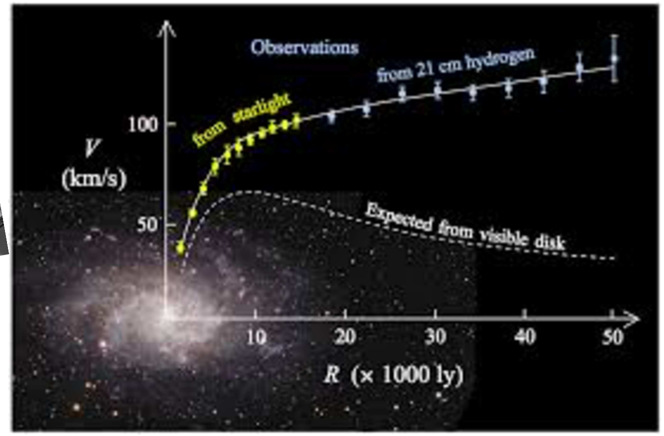
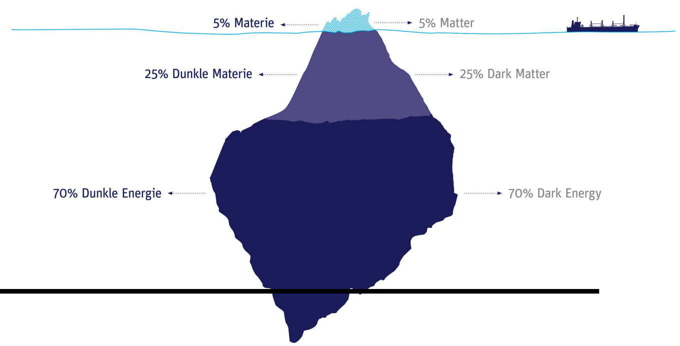
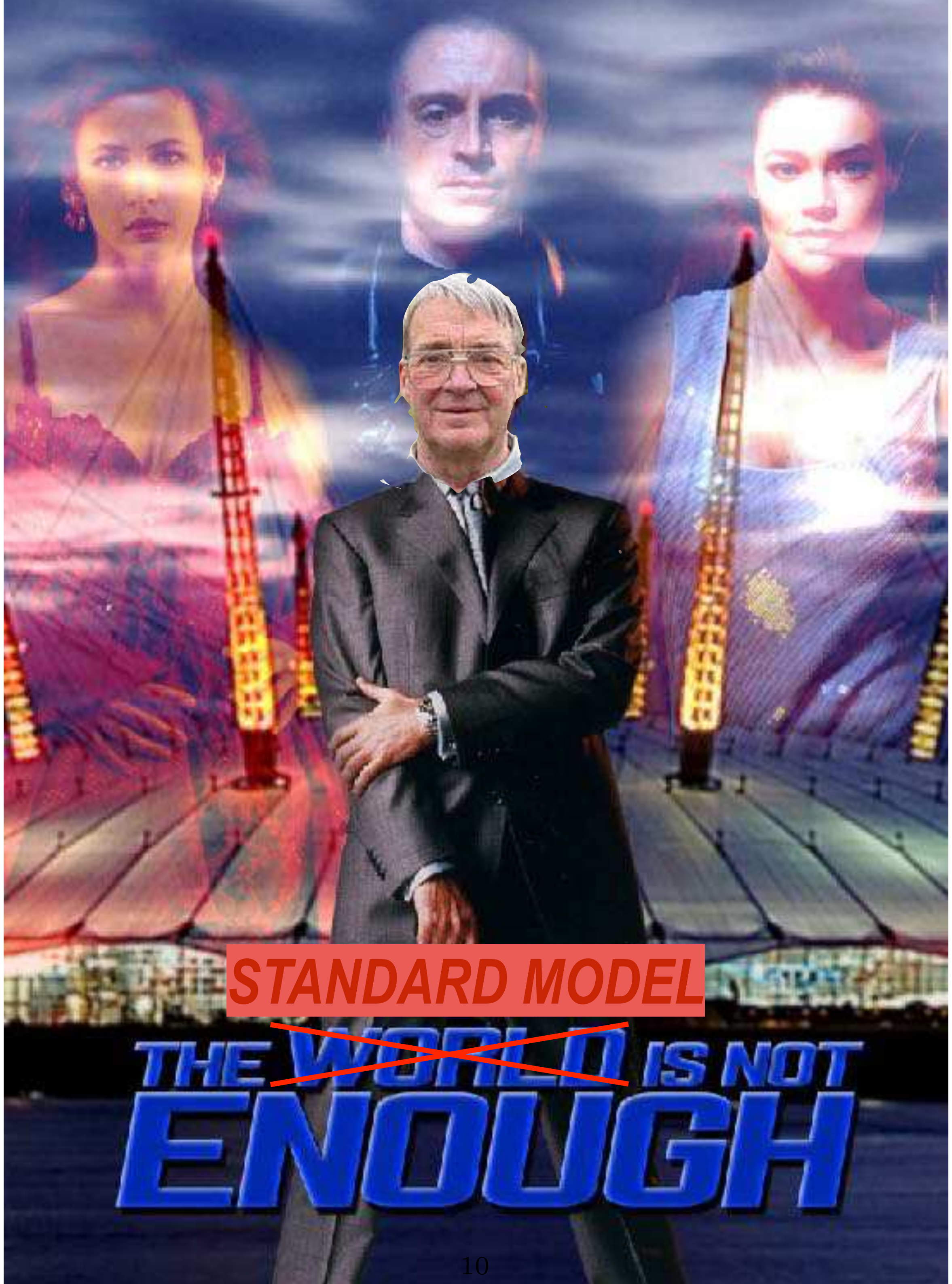


- **Discovered Higgs boson:**
  - $*$ Behaves very SM-like

- **Open Questions:**
  - $* \rightsquigarrow$ Standard Model is low-energy effective theory of more fundamental theory at some high scale




STANDARD MODEL
THE WORLD IS NOT
ENOUGH

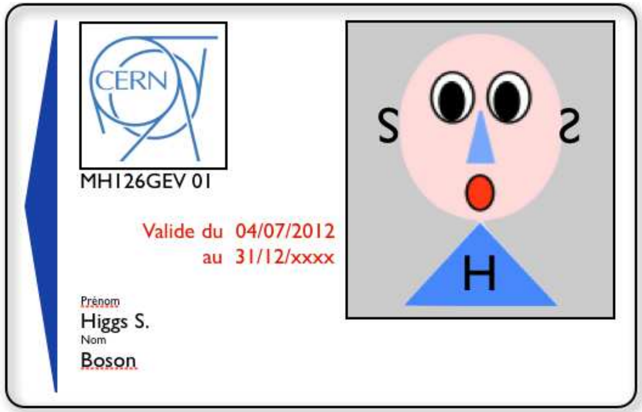
$\mathcal{W}$here is $\mathcal{N}$ew $\mathcal{P}$hysics?

- **Naturalness - just around the corner:** New physics stabilizes hierarchy
  - $*$ Supersymmetry: SUSY partners with different statistics, not too heavy to avoid new hierarchy
  - $*$ Extra Dimensions: hierarchy related to geometry of extra dim., fund. Planck scale $\mathcal{O}$(TeV)
  - $*$ Composite Higgs Models: Higgs composite; M_H =125 GeV requires top partners of $\mathcal{O}$ (TeV)

- **SUSY may hide very well:**
  - $*$ Compressed SUSY
  - $*$ Split SUSY
  - $*$ Long-lived SUSY
  - $*$ Invisible SUSY

Where is New Physics?

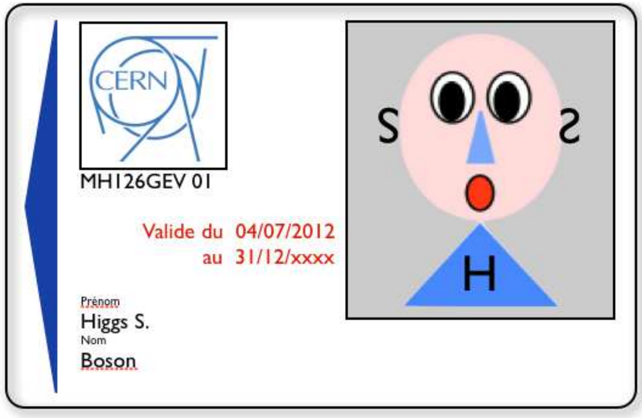
- **What we have:** Discovery of new scalar particle 4th July 2012



What can we learn from Higgs Physics in the Future?

$\mathcal{W}$here is $\mathcal{N}$ew $\mathcal{P}$hysics?

- **What we have:** Discovery of new scalar particle 4th July 2012



$\mathcal{W}$hat can we learn from $\mathcal{H}$iggs $\mathcal{P}$hysics in the $\mathcal{F}$uture?

- **How systematize approach not to miss any new physics sign?**
  - ∗ Effective Theory approach
  - ∗ Specific well-motivated models

Beyond SM Higgs Sectors

2Higgs-Doublet-Model

Multi-Higgs

CP-violating 2HDM

PortalHiggs

Next-2HDM

TwinHiggs

Singlet Extensions

LittlestHiggs

MSSM

3HDM

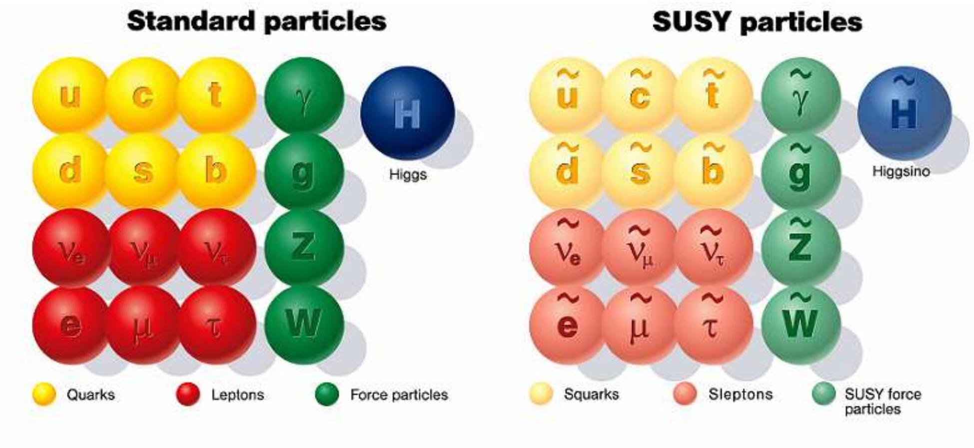
NMSSM

Georgi-Machachek

CompositeHiggs

Supersymmetry

Supersymmetry: relates fermions and bosons



Virtues of supersymmetry:

- ∗ solves hierarchy problem
- ∗ Higgs mechanism generated radiatively
- ∗ gauge coupling unification (MSSM)
- ∗ Cold Dark Matter candidate (← R-parity) ...

Consequences:

- ♢ new particles (*e.g.* running in the loops)
- ♢ extended Higgs sectors (scalar, pseudoscalar or no definite CP quantum number)
- ♢ couplings affected by mixing and loop effects, BRs by new non-SM decays

$\mathcal{T}$he $\mathcal{R}$ole of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{M}$ass

$\mathcal{T}$he $\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\stackrel{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-

Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;...

Higgs boson mass:

* SM: fundamental parameter, not given by theory
* Supersymmetry: calculable from input parameters - loop corrections Δm_h^2 are important!

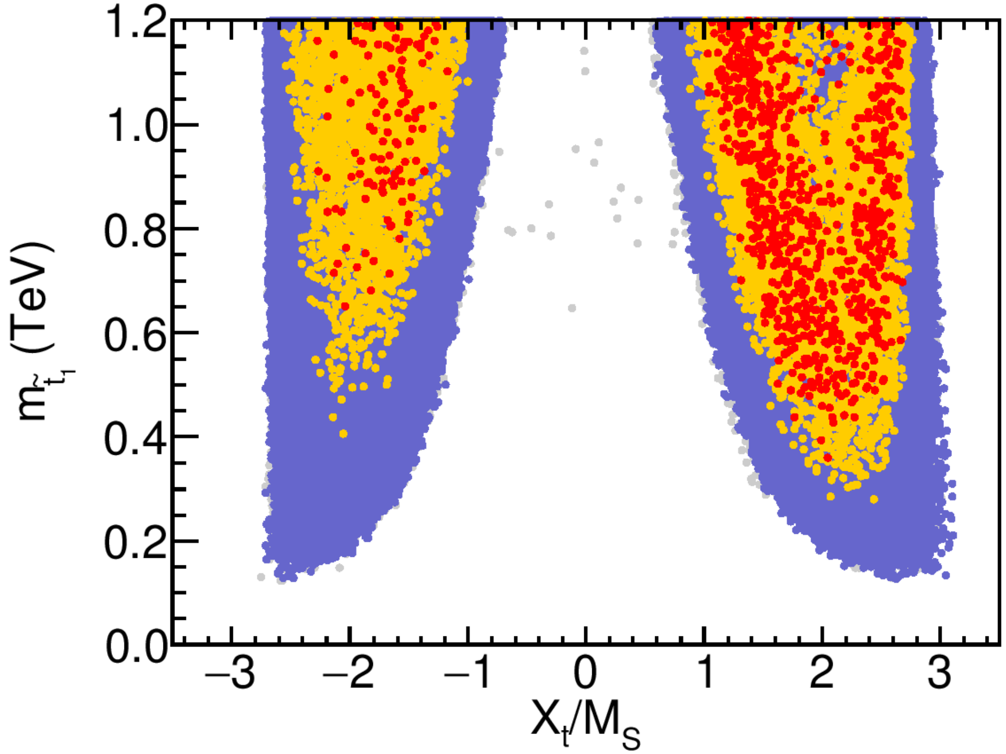
$$\text{MSSM:} \quad m_H^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_H^2 \leftarrow (85 \text{ GeV})^2 \, !$$

Present accuracy: [ATLAS, CMS, Phys Rev Lett 114 (2015) 191803]

$$M_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}$$

Points Compatible with Higgs Data

MSSM: see e.g. [Bechtle eal '16]



- **Large corrections** through large stop mixing X_t and/or large M_{SUSY}
  $\rightsquigarrow$ large logarithmic corrections $\rightsquigarrow$ resummation of logs needed

The Role of the Higgs Boson Mass

- **Why precision on Higgs boson mass?**
  - ∗ Self-consistency test of SM at quantum level (*e.g.:* Higgs loop corrections to W boson mass)
  - ∗ $M_H \leftrightarrow$ stability of the electroweak vacuum [Degrassi eal;Bednyakov eal]
  - ∗ Higgs mass uncertainty feeds back in uncertainty on Higgs observables
  - ∗ Test parameter relations in beyond-SM theories
    $\rightsquigarrow$ indirect constraint of viable BSM parameter space!

$\mathcal{M}$SSM $\mathcal{M}$ass $\mathcal{C}$odes on the $\mathcal{M}$arket

- **Fixed order codes**
  * SuSpect [Djouadi eal]
  * SPheno/SARAH [Porod, Staub; Staub]
  * SoftSUSY/FlexibleSUSY [Allanach eal; Athron eal]
  * H3m [Harlander eal; Kant eal]
- **EFT codes** (Log resummation through RGEs)
  * SusyHD [Vega,Villadoro]
  * MhEFT [Lee,Wagner]
  * HSSUSY [Athron eal]
- **Hybrid codes** RGEs)
  * FeynHiggs [Heinemeyer eal]
  * FlexibleEFTHiggs [Athron eal]

Example for Higgs Mass Calculation

Taken from P. Slavich, HDays '16

Simplified benchmark point: $\tan\beta = 20$, all SUSY masses = 1 TeV, X_t varied to maximize M_h

Public code	M_h [GeV]
SPheno 3.3.8	126.3
SuSpect 2.43	125.8
SoftSUSY 3.7.0	124.3
NMSSMTools 4.9.1	124.6
FeynHiggs 2.11.3	128.1
FeynHiggs 2.12.0	126.3

Same $\overline{DR}$ calculation of the Higgs mass, differences in determination of top Yukawa (SPheno, SuSpect, SoftSUSY, NMSSMTools)

OS calculation of Higgs mass (using running m_t at NNLO in loops) (FeynHiggs 2.11.3)

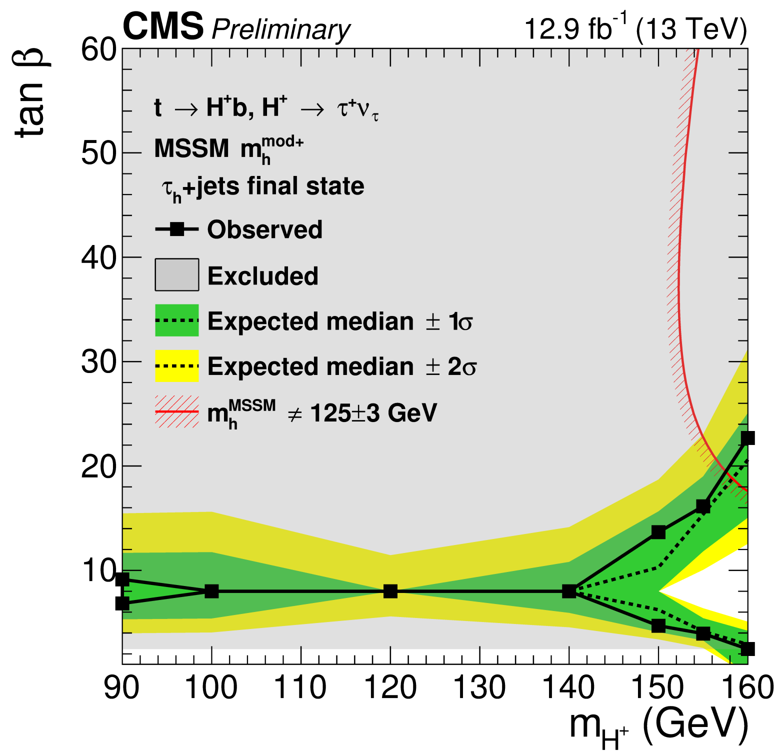
Including resummation plus EW effects in m_t (FeynHiggs 2.12.0)

All of these codes include full 1-loop + dominant (strong+Yukawa) 2-loop corrections to M_h

$\mathcal{L}$ow M_H $\mathcal{S}$cenario?

- **Low M_H scenario:** $M_H = 125$ GeV,
  $M_h \geq 65$ GeV ($\leftarrow$ avoid $H \to hh$) and reduced hZZ couplings ($\leftarrow$ avoid LEP bounds)

- **Tension w/ charged Higgs searches:**



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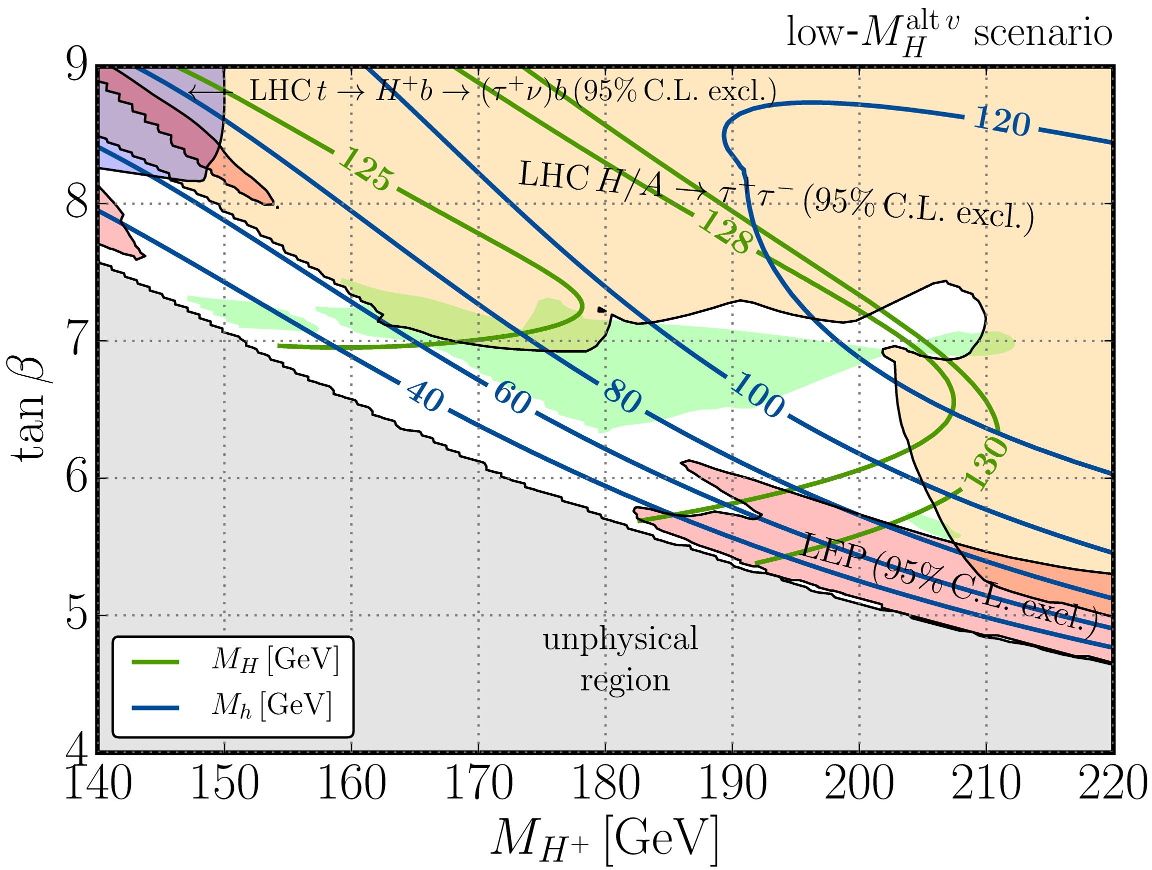
[Bechtle eal]

Small parameter space:
strongly under tension
from current searches

green:
compatible w/ the Higgs signal



The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **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 $\leadsto$

- **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: $\lambda\hat{S}\hat{H}_u\hat{H}_d$

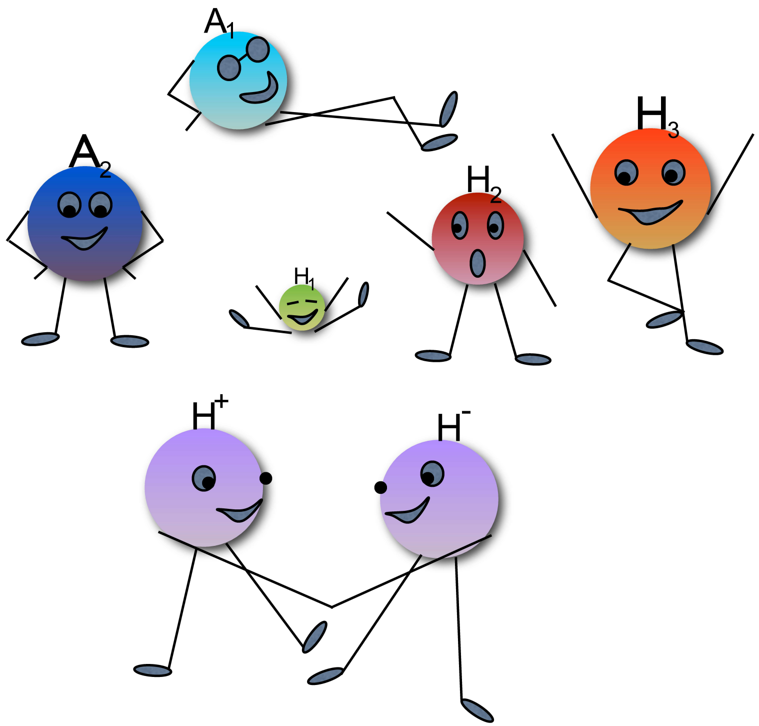
The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

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

- **Higgs mass eigenstates:**
  superpositions of doublet and singlet components $\leadsto$
  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)
  - $*$ $\leadsto$ invisible Higgs decays
  - $*$ tree-level CP violation ...



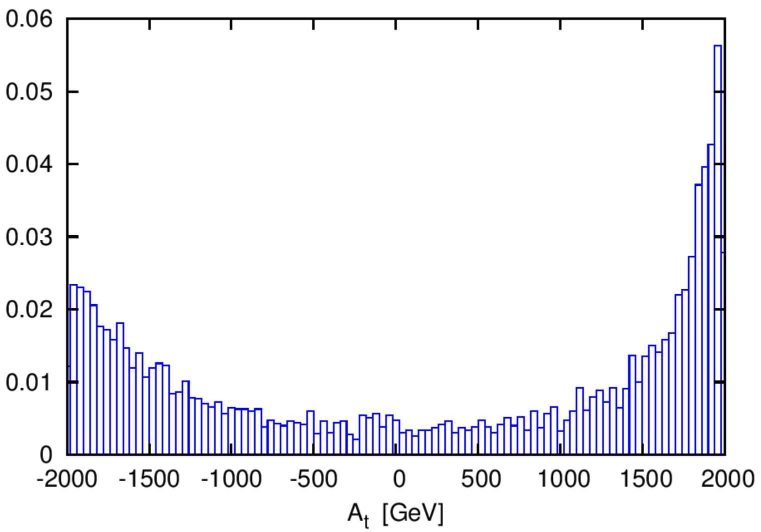
$\mathcal{N}$MSSM $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{M}$ass

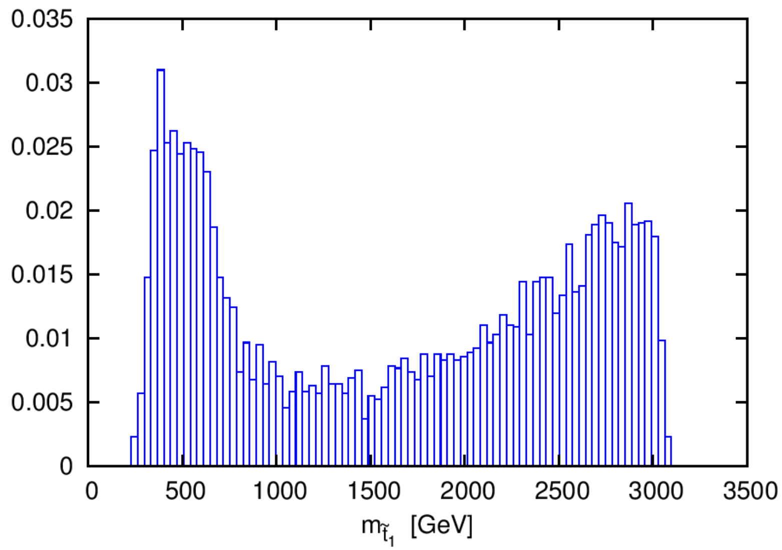
- **NMSSM Higgs boson masses given in terms of Higgs potential parameters**

- **Upper bound on Higgs mass:**

  $m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2 \quad \Rightarrow m_h = 125$ GeV requires less finetuning

King,MM,Nevzorov,Walz '14





Normalized A_t (top), $m_{\tilde{t}_1}$ distribution

NMSSM Mass Codes on the Market

	FlexibleSUSY	NMSSMCALC	NMSSMTools	SoftSUSY	SPheno
General					
type	using SARAH	stand alone	stand alone	stand alone	using SARAH
Language	C++	Fortran77/90	Fortran77	C++	Fortran90
Supported models besides general, scale-invariant NMSSM					
w/o $\mathbb{Z}_3$	✓	↯	✓	✓	✓
GUT models	✓	↯	✓	✓	✓
Corrections to Higgs mass ✍: in prep					
ren. scheme	$\overline{\text{DR}}$	OS, $\overline{\text{DR}}$	$\overline{\text{DR}}$	$\overline{\text{DR}}$	$\overline{\text{DR}}$
full 1-loop	✓	✓	✓	✓	✓
2-loop	$\alpha_s(\alpha_b+\alpha_t)$ +MSSM appr.	$\alpha_s\alpha_t$	$\alpha_s(\alpha_b+\alpha_t)$ +MSSM appr.	$\alpha_s(\alpha_b+\alpha_t)$ + MSSM appr.	$\alpha_i\alpha_j$, $i,j=s,t$ b,τ,λ,κ
CPV(1,2)-loop	(✓,↯)	(✓,✓)	(✍,↯)	(↯,↯)	(✓,✍)
Calculation of other observables					
1l SUSY masses	✓	↯	✓	✓	✓
decays	✍	✓	✓	w/ NMHDECAY	✓
flavour obs	↯	↯	✓	↯	✓

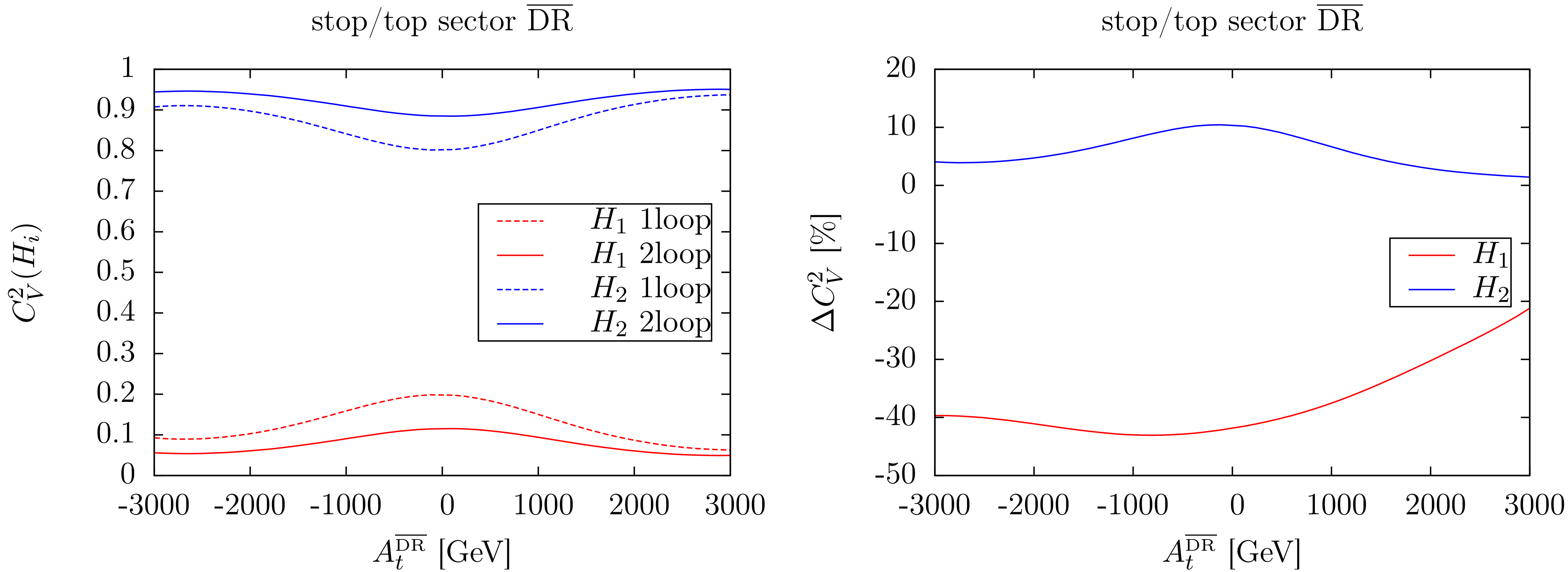
$\mathcal{N}$MSSM $\mathcal{M}$ass $\mathcal{C}$odes on the $\mathcal{M}$arket

- **Further recent computations:**
  - Real NMSSM: full 1-loop OS + MSSM appr. 2loop, `FeynHiggs`
  - Complex NMSSM: full 1-loop OS [Domingo,Drechsel,Paßehr]

- **Comparison of codes:**
  - $\overline{\text{DR}}$ codes [Staub eal]
  - OS codes (`NMSSMCALC`, `FeynHiggs`) [Drechsel eal]

$\mathcal{I}$mpact on $\mathcal{H}$iggs $\mathcal{C}$ouplings

MMM,Nhung,Rzehak,Walz '14

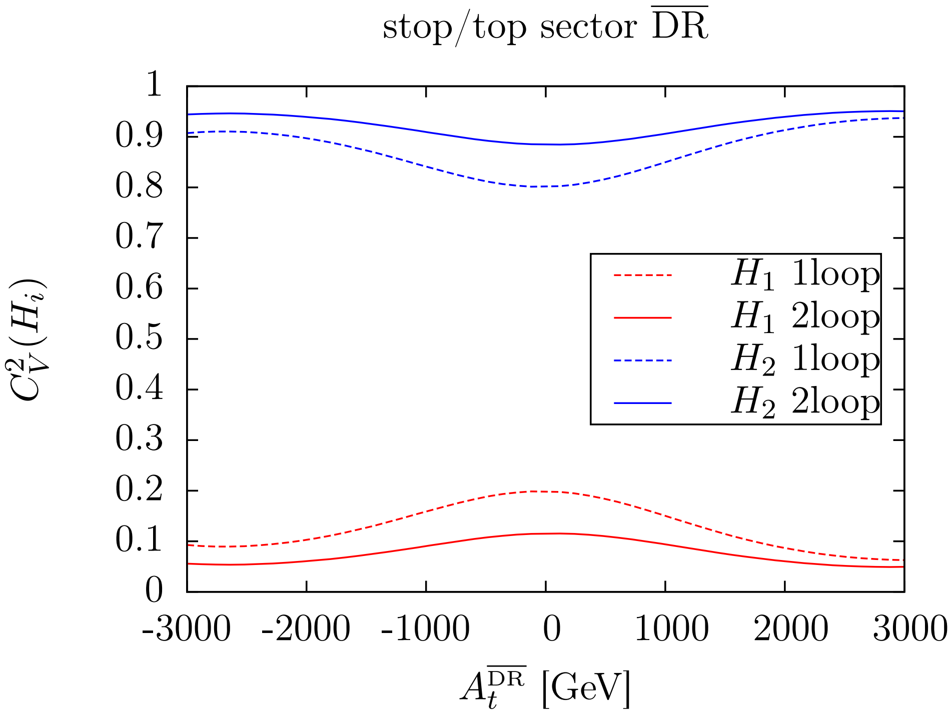


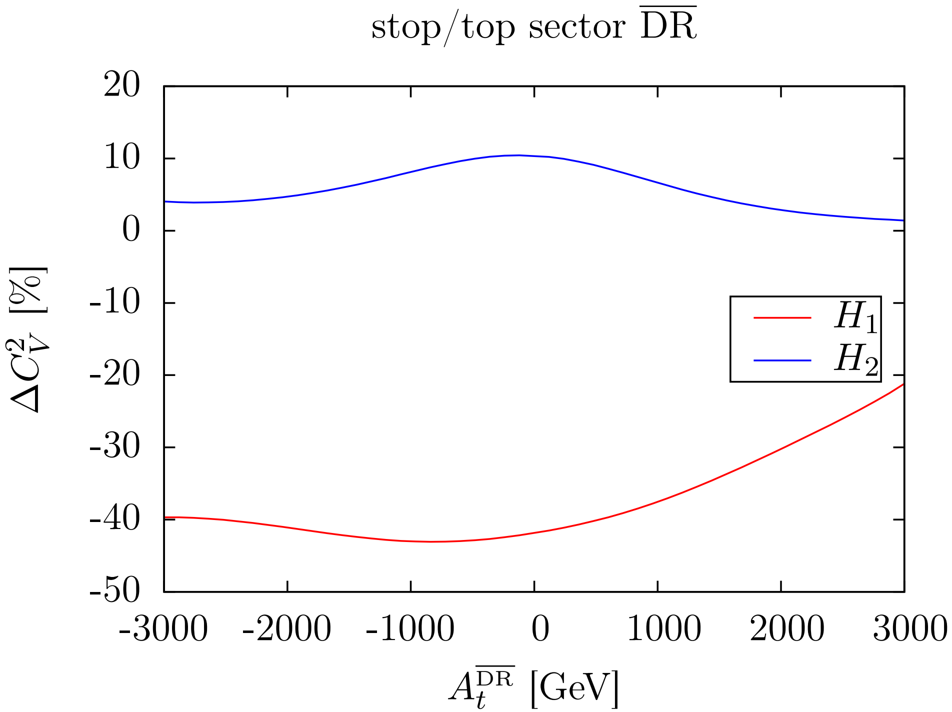
$* \; C_V(H_i) = \mathcal{R}^l_{i1}\cos\beta + \mathcal{R}^l_{i2}\sin\beta$

$* \; \Delta C_V^2 = [(C_V^2)^{\rm 2loop} - (C_V^2)^{\rm 1loop}]/(C_V^2)^{\rm 1loop}$

$\mathcal{I}$mpact on $\mathcal{H}$iggs $\mathcal{C}$ouplings

MMM,Nhung,Rzehak,Walz '14





Influence of 2-loop corrections on couplings sizeable

$\rightsquigarrow$ significant effects on phenomenology

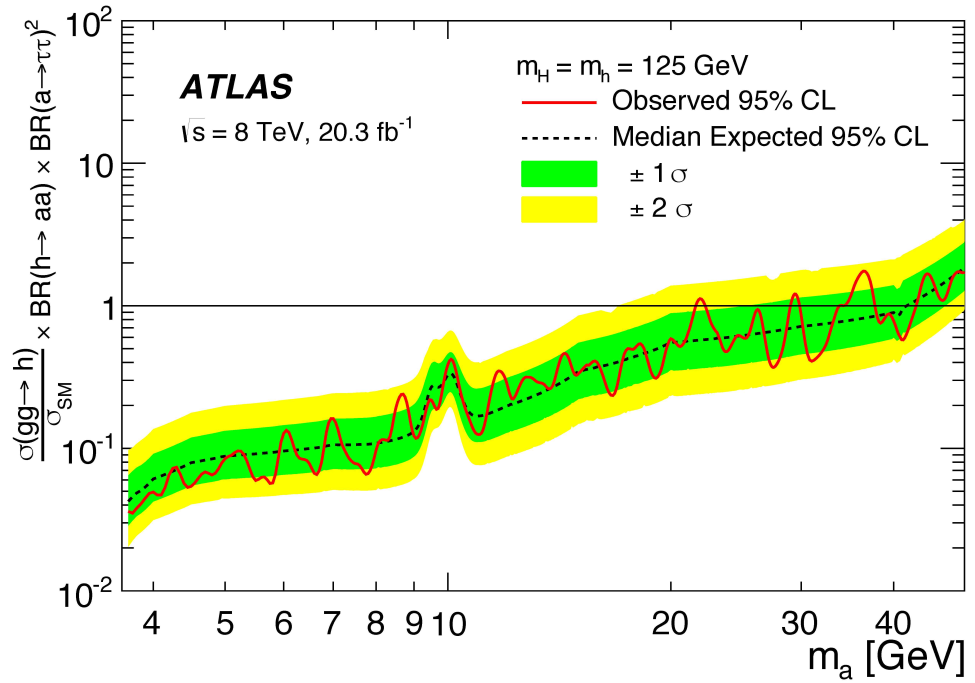
Signatures

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{P}$henomenology

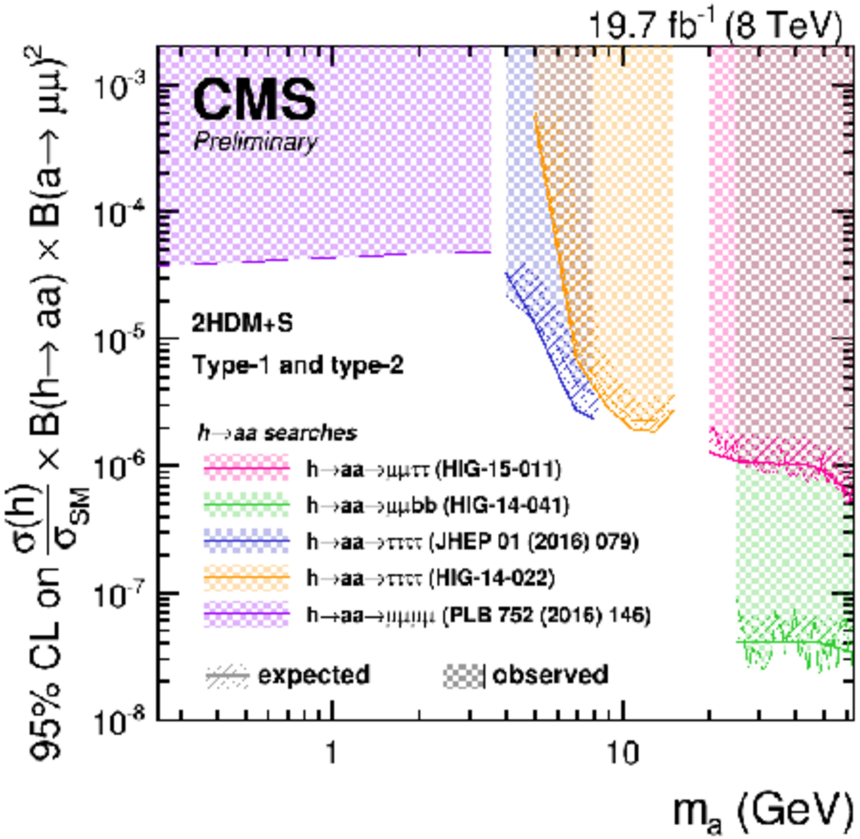
- **Neutral CP-Conserving NMSSM Higgs Spectrum:** H_1, H_2, H_3, A_1, A_2
  - SM-like Higgs boson h_{125}
  - Mostly MSSM-like Higgs bosons H, A
  - Mostly singlet-like Higgs bosons H_S, A_S, may be very light

- **NMSSM-specific phenomena:**
  - Second-lightest Higgs boson can be h_{125}; Higgs signal built up by 2 Higgs bosons possible
  - Branching ratios for $\phi_{\text{heavy}} \to \phi_{\text{light}} h_{\text{SM}}$ may be sizeable
  - Exotic decays of h_{125}: *e.g.* $h_{125} \to A_S A_S$
  - Higgs-to-Higgs and/or Higgs-to-gauge+Higgs decay cascades possible
  - Very light Higgs bosons possible; sizeable decays into light fermions below $2b$ threshold
  - Cascade decays into NMSSM-specific Higgs states H_S, A_S

[ATLAS Phys. Rev. D92 (2015) 052002]



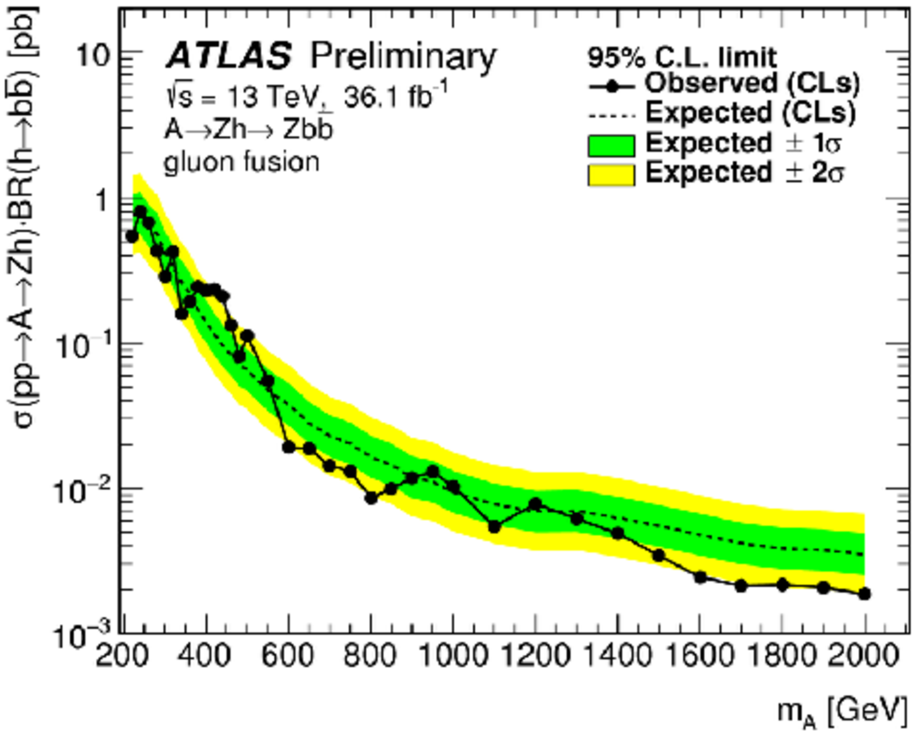
[CMS, 2HDM+singlet]

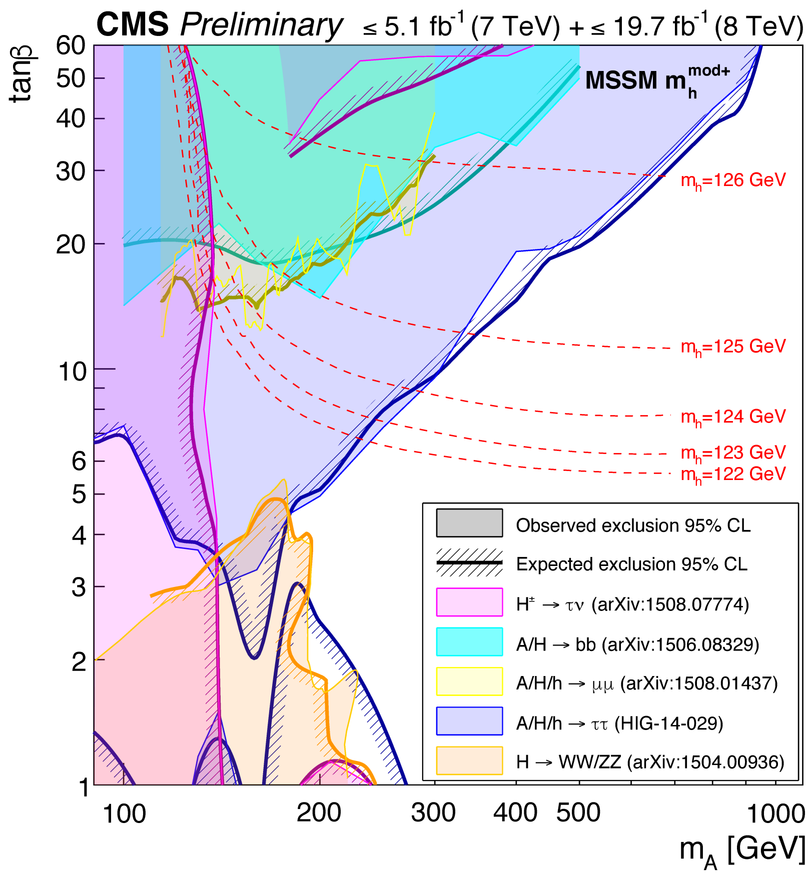


$\mathcal{H}$eavy $\mathcal{H}$iggs $\mathcal{S}$earches

[ATLAS-CONF-2017-065]

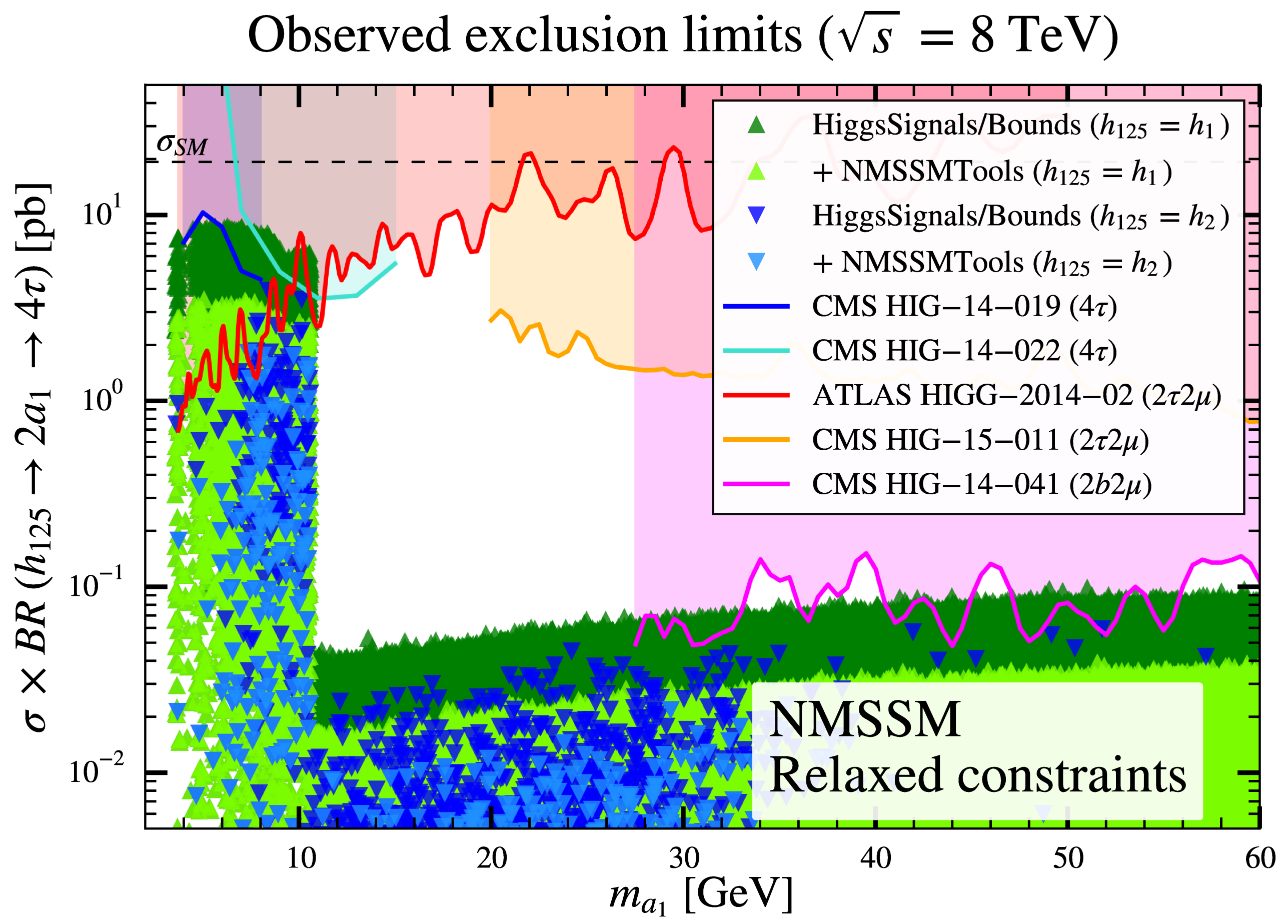
[CMS-PAS-HIG-16-007]





$h_{125} \to A_S A_S \to ...$

[Aggleton eal, 2016]

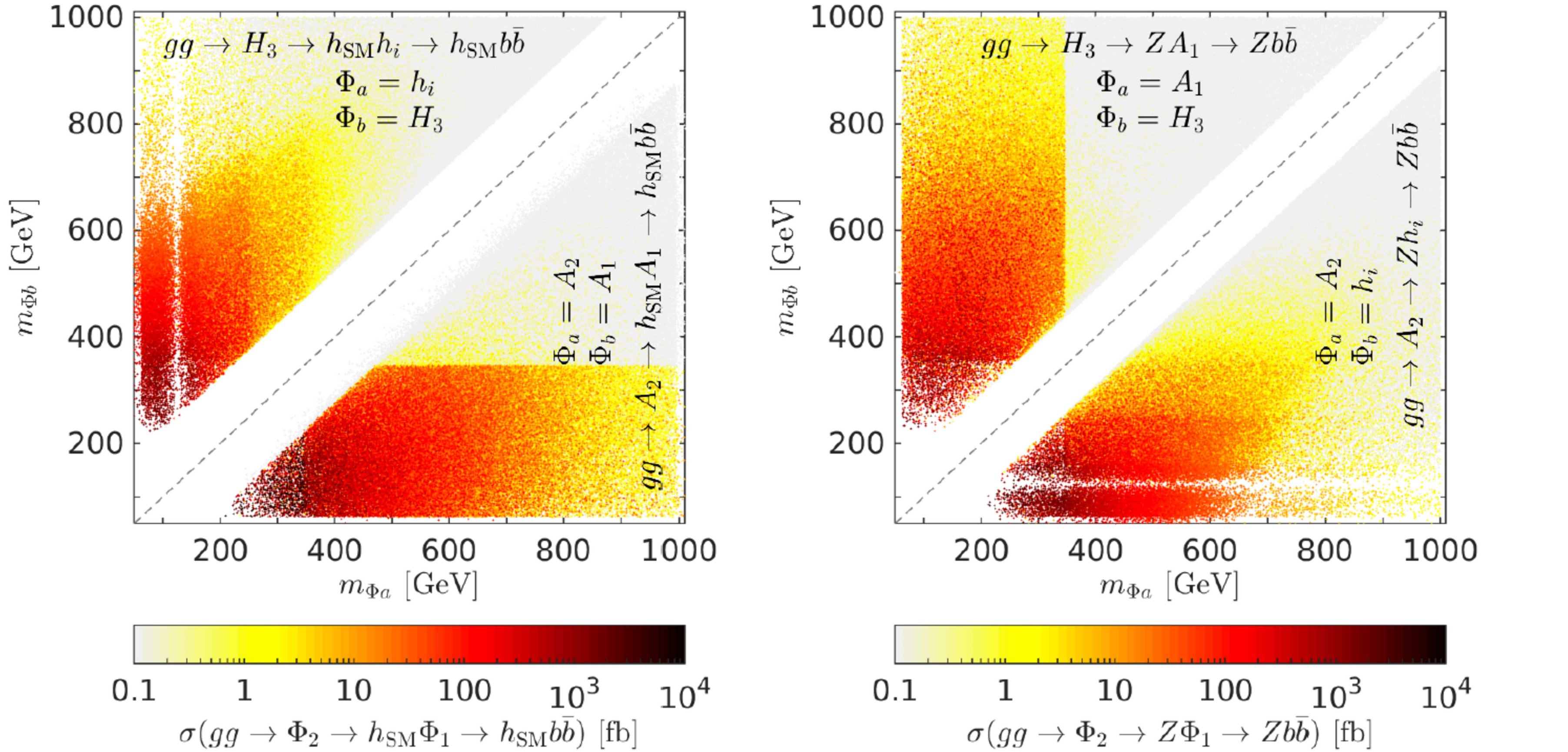


- Green/blue points viable in the NMSSM after NMSSMTools (light) or HiggsSignals/Higgsbounds constraints (dark)

$\mathcal{N}$MSSM-specific $\mathcal{C}$hannels beyond $\mathcal{M}$SSM

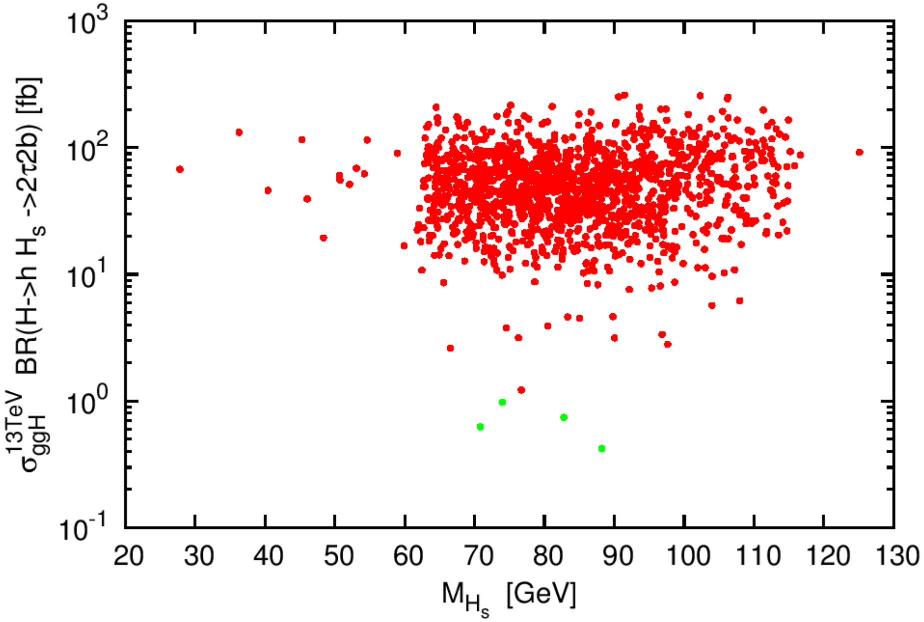
[Baum eal, 2017]

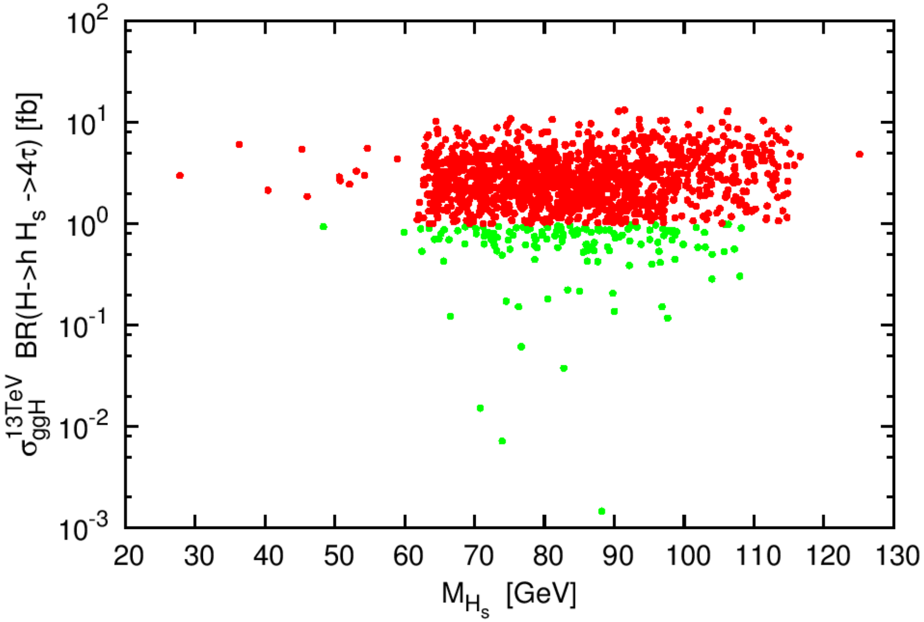
- NMSSM scenarios w/ large values of λ (coupling the doublet and singlet fields)
- $gg \to \Phi_i^* \to \Phi_k Z$, $\Phi_i^* \to \Phi_j \Phi_k$ $(j \neq k)$, $\Phi_i^* \to h_{125}\tilde{\chi}_1\tilde{\chi}_1$, $\Phi_i^* \to \Phi_k/Z\tilde{\chi}_1\tilde{\chi}_1$

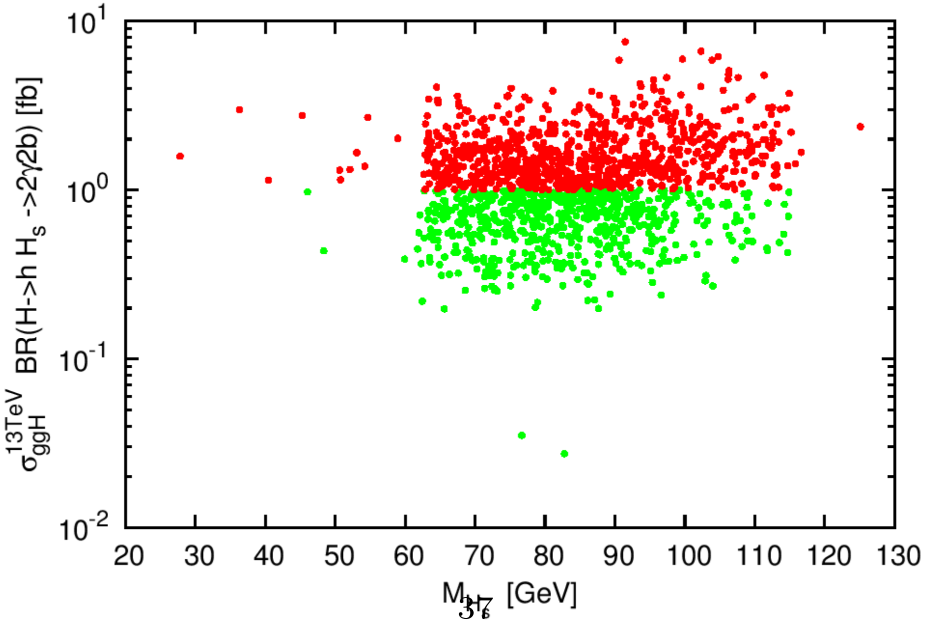


$\sigma(gg \to H)BR(H \to hH_s \to (XX)(YY))$

King,MMM,Nevzorov,Walz







$\mathcal{N}$MSSM-specific $\mathcal{H}$iggs $\mathcal{B}$osons from $\mathcal{S}$particle $\mathcal{D}$ecays

- **Scenario w/ singlino-like LSP:** Sparticle decay into LSP only if sole decay mode

- **Last decay in a decay chain:** NLSP $\rightarrow$ LSP + X can lead to very small E_T^{miss} if

  a) M_{LSP} is small (few GeV)

  a) $M_{\text{NLSP}} \approx M_{\text{LSP}} + M_X$

  $\rightsquigarrow$ most energy into X and very little E_T^{miss}

$\rightsquigarrow$ scenario evades lower limits on squark, gluino, stop, ... masses

X could be h_{125}, H_S or A_S, which are pair produced

- **LHCHXSWG benchmarks:** [Ellwanger, Teixeira]

  (i) $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h_{125}$: $\tilde{q}, \tilde{g}$ production, Jets+$\underbrace{h_{125} + h_{125}}_{\rightarrow bb+\tau\tau}$: 14 fb

  (ii) $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + H_S$: ($M_{H_S} = 82$ GeV) $\tilde{q}, \tilde{g}$ production, Jets+$\underbrace{H_S + H_S}_{\rightarrow bb+\tau\tau}$: 272 fb

$\mathcal{C}$P $\mathcal{V}$iolation

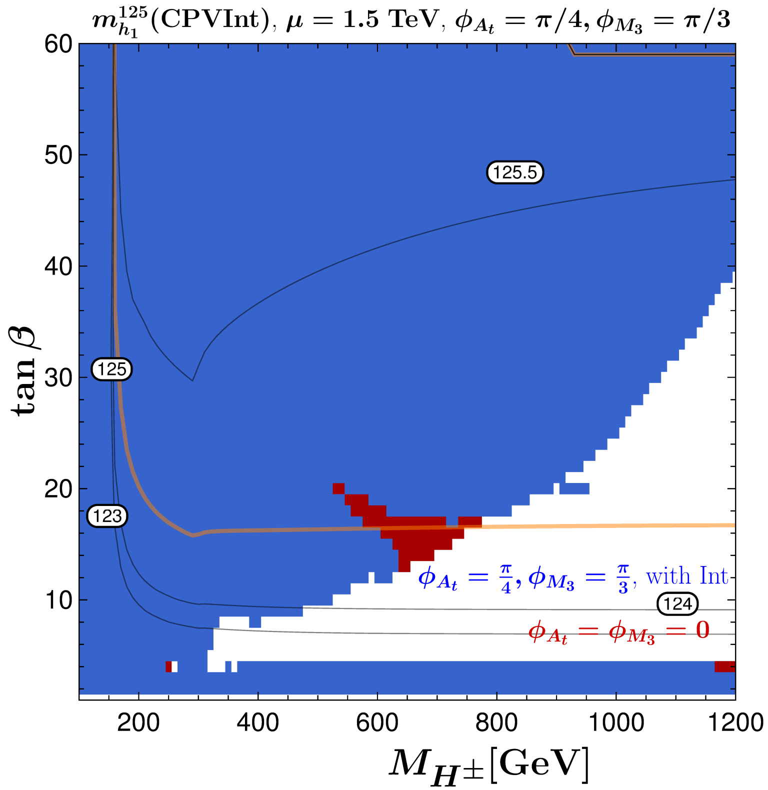
$\mathcal{CP}$ $\mathcal{V}$iolation

- **CP violation in the Higgs sector:**
  - ◇ Immediate sign of BSM physics
  - ◇ One of the three Sakharov conditions for EW baryogenesis
- **Sakharov Conditions:**
  - ∗ (i) B number violaton (sphaleron processes)
  - ∗ (ii) C or CP violation
  - ∗ (iii) Out-of-equilibrium or CPT violation
- **CP violation in SUSY Higgs sectors:**
  - ◇ MSSM: no Born level CP violation, CP violation is loop-induced
  - ◇ NMSSM: CP-violating phase at Born level
- **EDM measurements:** strongly constrain possible amount of CP violation

$\mathcal{C}$P $\mathcal{V}$iolation in the $\mathcal{M}$SSM

- **CP violation in the Higgs sector:**
  - ◇ Mixing of h, H, A through higher order effects $\rightsquigarrow$ H_i mass eigenstates
  - ◇ $\leftarrow$ CP-violating phases in higgsino parameter μ, gaugino masses M_i or trilinear couplings A_f
- **CP-violating effects on exclusion limits:** [Liebler,Patel,Weiglein; Fuchs,Weiglein]

[Liebler,Patel,Weiglein]



$\mathcal{CP}$ $\mathcal{V}$iolation in the $\mathcal{N}$MSSM $\mathcal{H}$iggs $\mathcal{S}$ector

- **Possibility of CP violation in the tree-level Higgs sector**

- **Several sources of CP violation:**
  - CP-violating parameters $\lambda, \kappa, A_\lambda, A_\kappa$
  - CP-violating vacuum expectation values $v_s e^{i\varphi_s}$, $v_u e^{i\varphi_u}$

- **Only one possible phase combination at tree level**

$$\varphi_2 - \varphi_1 \quad \text{with} \quad \begin{array}{rcl} \varphi_1 & = & \varphi_\lambda + \varphi_s + \varphi_u \\ \varphi_2 & = & \varphi_\kappa + 3\varphi_s \end{array}$$

[after exploiting the tadpole conditions]

- **At higher order in Higgs masses:** φ_1 and φ_2 not related any more
  - φ_1 and φ_2 independent in neutralino sector, φ_1 in chargino and up-type squark sector
  - $\leadsto$ φ_1 and φ_2 independent phases

Constraints from EDMs

- **Included constraints on CP-violating phases from:** [King,MMM,Nevzorov,Walz,1508.03255]

$$\begin{aligned}
\text{Electron EDM} &: \quad \sim 1 \cdot 10^{-28} e\,\text{cm} \\
\text{Thallium EDM} &: \quad \sim 9 \cdot 10^{-25} e\,\text{cm} \\
\text{Neutron EDM} &: \quad \sim 3 \cdot 10^{-26} e\,\text{cm} \\
\text{Mercury EDM} &: \quad \sim 3.1 \cdot 10^{-29} e\,\text{cm} \;,
\end{aligned}$$

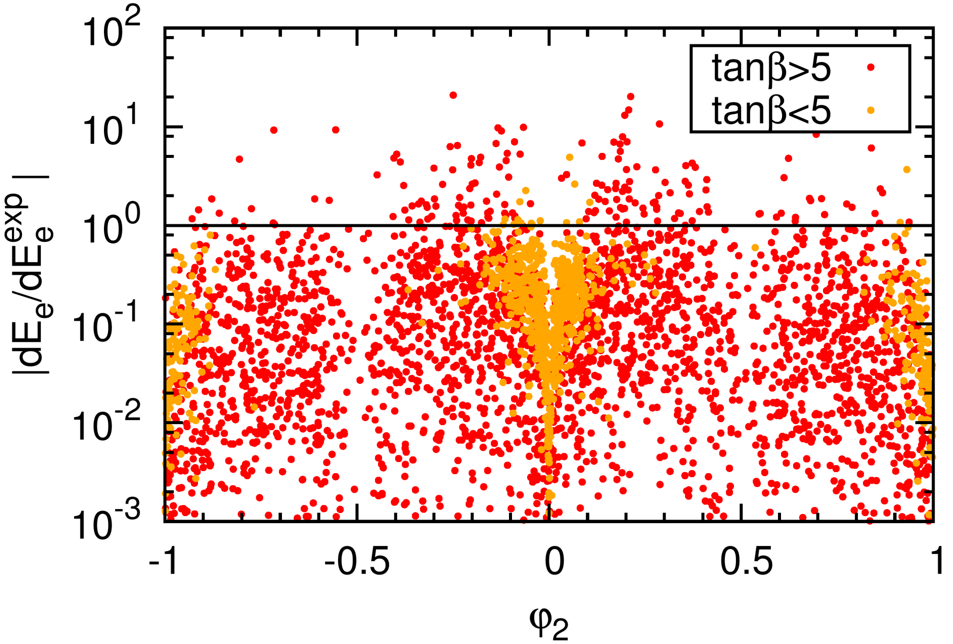
- **Most stringent constraint from:** electron EDM

- **Computation of EDMs in the NMSSM** implemented in `NMSSMCALC`

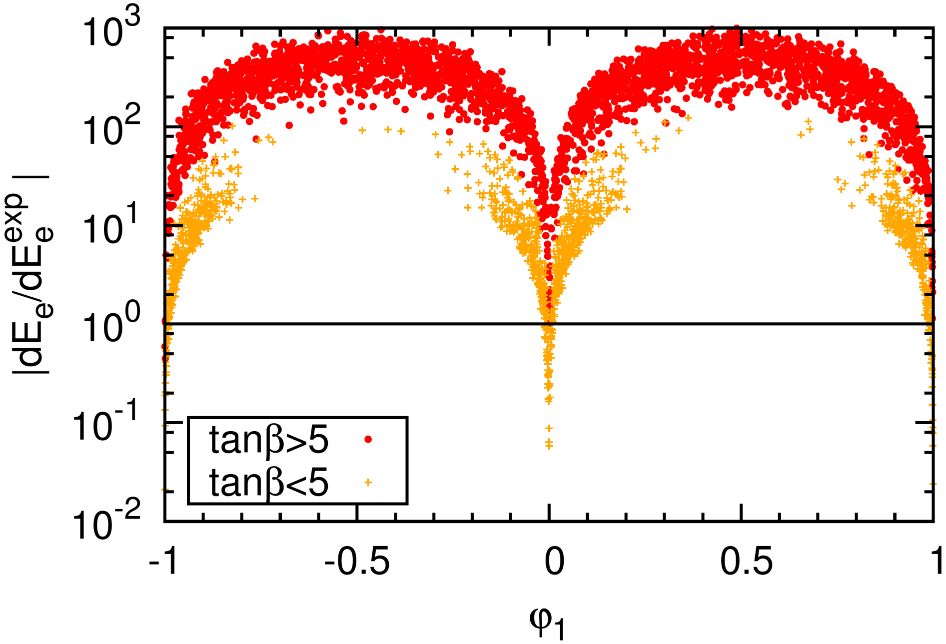
  [Baglio,Gröber,MMM,Nhung,Rzehak,Spira,Streicher,Walz; King,MMM,Nevzorov,Walz]

$\mathcal{MSSM}/\mathcal{N}$MSSM $\mathcal{C}$ompatibility with $\mathcal{C}$onstraints from $\mathcal{EDM}$s

[King,MM,Nevzorov,Walz]



'NMSSM-type CP violation'



'NMSSM-type and MSSM-type CP violation'

CP-violating angles of the NMSSM Higgs sector: $\varphi_1 = \varphi_\lambda + \varphi_s + \varphi_u$

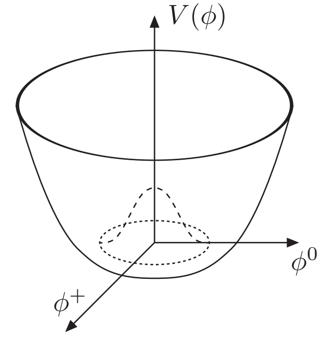
$\varphi_2 = \varphi_\kappa + 3\varphi_s$ [See also Domingo '15]

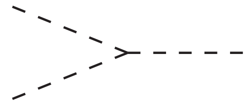
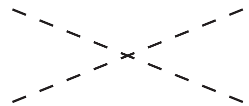
$\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction

Determination of the Scalar Boson Self-Couplings

The EWSB potential:

$$V(H) = \frac{1}{2!}\lambda_{HH}H^2 + \frac{1}{3!}\lambda_{HHH}H^3 + \frac{1}{4!}\lambda_{HHHH}H^4$$



Trilinear coupling	$\lambda_{HHH} = 3\frac{M_H^2}{v}$	
Quartic coupling	$\lambda_{HHHH} = 3\frac{M_H^2}{v^2}$	

Measurement of the scalar boson self-couplings
and
Reconstruction of the EWSB potential

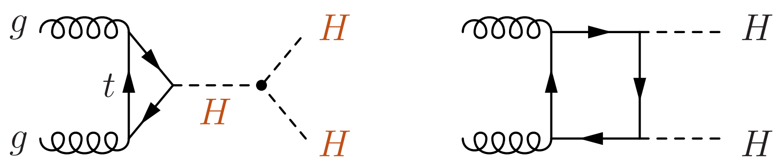
} Experimental verification Of the scalar sector of the EWSB mechanism

Determination of the scalar boson self-couplings at colliders:

$\boldsymbol{\lambda_{HHH}}$ via pair production
$\boldsymbol{\lambda_{HHHH}}$ via triple production

radiation off W/Z, $t\bar{t}$, WW/ZZ fusion, gg fusion

Gluon fusion - dominant process

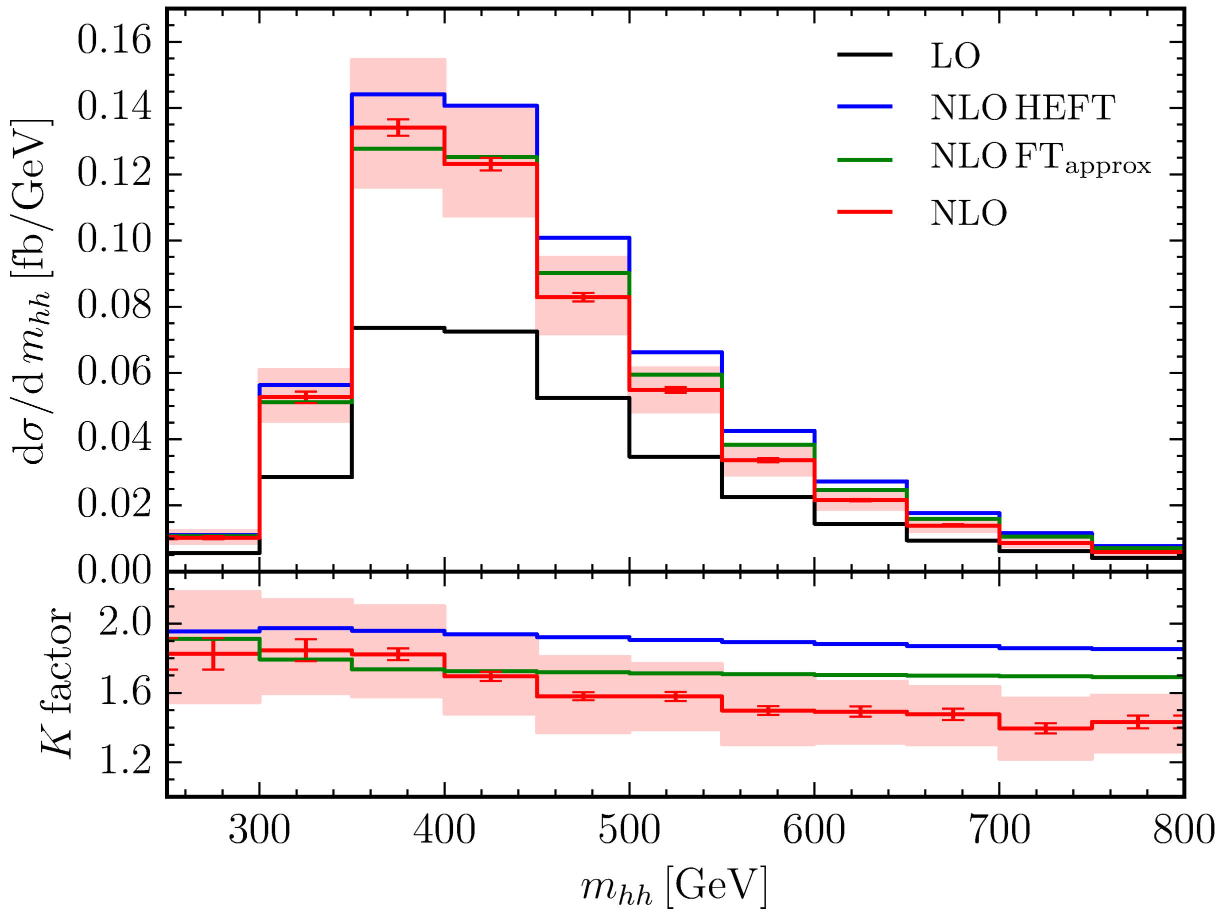


SM HH cross section small:

$$\sigma^{\text{NLO}}_{gg\to HH} = 32.91^{+13.6\%}_{-12.6\%}\ \text{fb @14 TeV}$$ [Borowka eal '16]

NLO $gg \to HH$ with $\mathcal{F}$ull $\mathcal{M}$ass $\mathcal{D}$ependence

Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Schubert,Zirke, Phys.Rev.Lett. 117 (2016) 1



Red: full result w/ mass dependence; blue/green approximations; scale variation: $\mu = (0.5...2)m_{hh}/2$

See also [Borowka eal, JHEP 1610(2016)107]

Challenge Di-Higgs Production

- **Small signal + large QCD background $\rightsquigarrow$ Experimental challenge!**
  $\mathcal{O}(\pm(15-20)\lambda_{HHH}^{\text{SM}})$ [ATLAS,CMS]

- **Theory Goals:**

∗ Provide precise predictions for di-Higgs production: total cross section and distributions!

∗ Observables sensitive to trilinear Higgs self-coupling and/or new couplings ← vast literature

Phenomenological studies: Englert eal;Degrassi eal;Chang eal;Nakamura eal;Huang eal;Papaefstathiou,Sakurai;Baglio,Weiland;Cao eal;Bishara eal;Moyoti eal;Bizon eal;Charanjit eal;Banerjee eal;Bian,Chen;Tao eal;Kling eal;Shi-Ping eal;Gorbahn,Haisch;Degrassi eal;Degrande eal;Zhao eal;Biswas eal;Gao eal;Boos eal;Kanemura eal;Gounaris,Renard;Nakamuroa,Baglio;Baglio,Weiland;Dicus eal;Zhou eal;Behr eal;Huang eal;Wen-Juan eal;Castilla-Valdez eal;Fuks eal;Zhemchugov;Batell eal;Kumar eal;Han eal;Dall'Osso eal;He eal;Dolan eal;Lu eal;Mohsen eal;Osland eal;Kotwal eal;Wu eal;Dawson eal;Shen eal;Ellwanger;Li eal;Edelhaeuser eal;Azatov eal;Zhang eal;Martin-Lozano eal;Liu eal;Chen eal;Barr eal;Chadkar eal:Berger,Zhang;Wardrobe eal;Gröber eal;Goertz eal;Englert eal;Slawinska eal;Yang eal;Liu eal;Bhattacherjee eal;de Lima eal;Contino eal;Nishiwaki eal;Wao;No eal;Li,Voloshin;Heng eal;Efrati,Nir;Barradas-Guevara eal;Kribs eal;Yue eal;Moretti eal;Kilian eal;Hespel eal;Grigo eal;de Florian eal;Borowka eal;Frederix eal;Agostini eal;Moyoti eal;...]

$\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{B}$eyond the $\mathcal{S}$M

- **Beyond SM HH production:** Cross sections can be considerably larger ($\leftarrow$ larger λ_{3H}; novel couplings; resonant enhancement)

  For higher order corrections to beyond-SM Higgs pair production, see: [Dawson,Dittmaier,Spira; Agostini,Degrassi,Gröber,Slavich; Dawson,Lewis; Gröber,MM,Spira,Streicher; Gröber,MM,Spira; Hespel,Lopez-Val,Vryonidou; Moyoti eal]

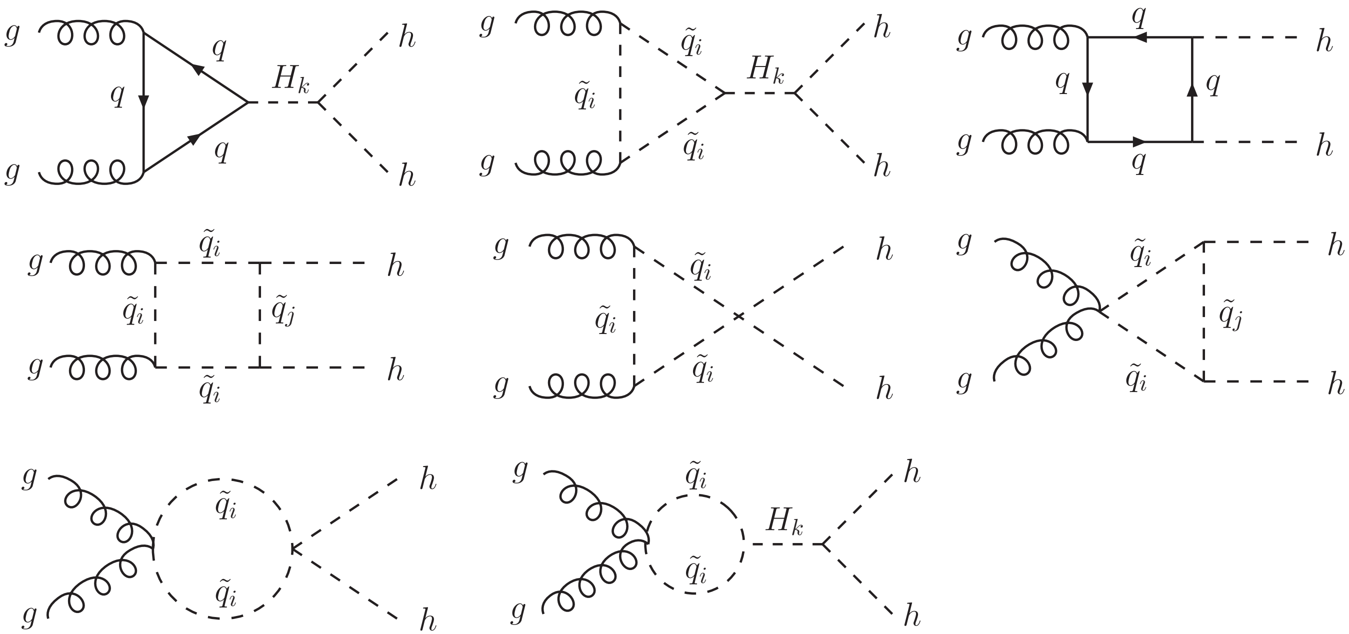
- **How large can λ_{3H} be?** $\lambda_{3H} = \kappa_\lambda \lambda_{3H}^{\mathrm{SM}}$

  - $|\kappa_\lambda| \leq 6$ [Di Luzio, Grober, Spannowsky, 1704.02311]
  - $|\kappa_\lambda| \leq 6$ [Di Vita, Grojean, Panico, Riembau, Vantalon, 1704.01953]
  - $\kappa_\lambda \leq 5/3$ [Kurup, Perelstein, 1704.03381]
  - $|\kappa_\lambda| \leq 10$ [Falkowski, Rattazzi]

$\mathcal{N}$MSSM $\mathcal{H}$iggs $\mathcal{P}$air $\mathcal{P}$roduction

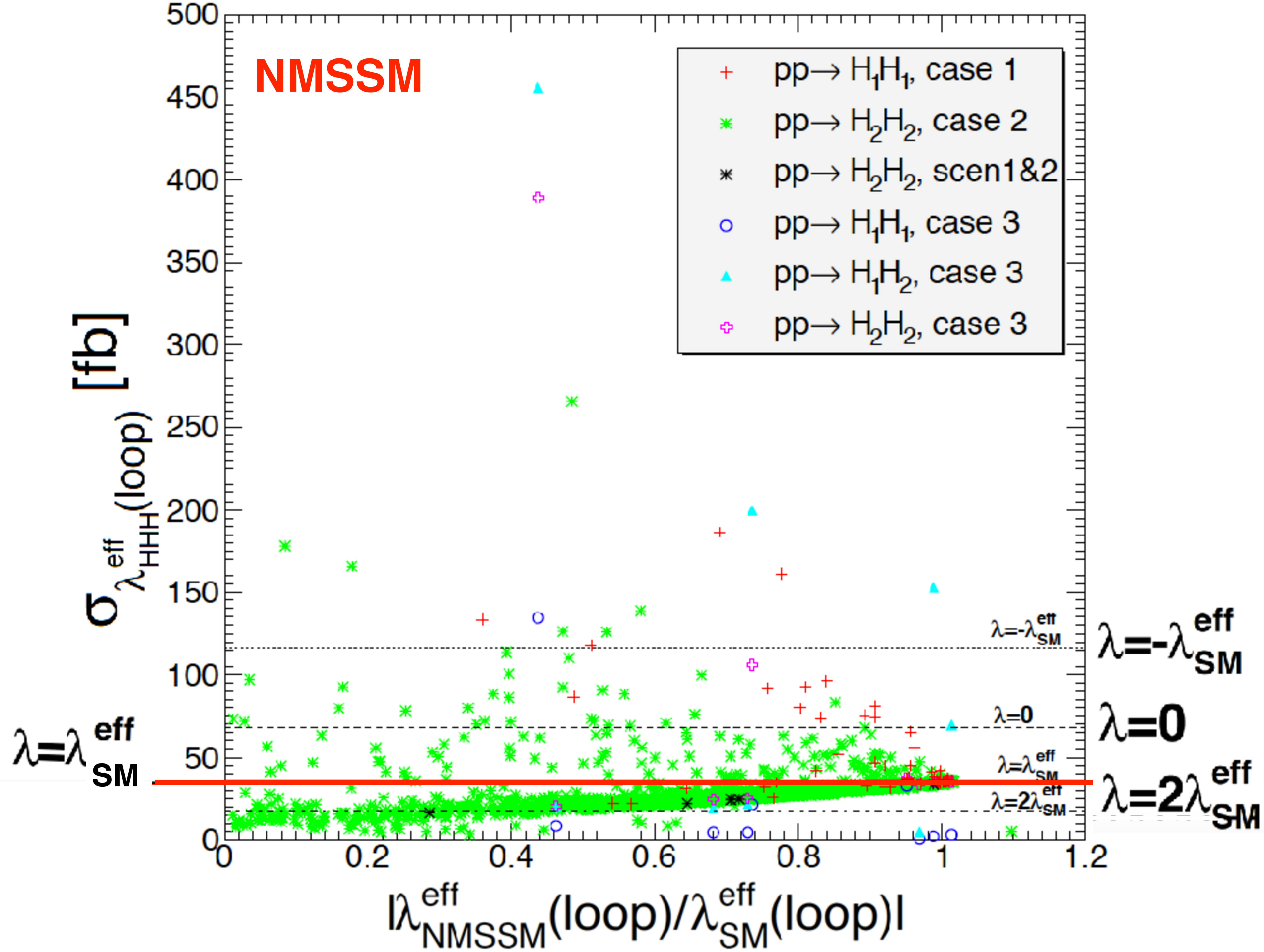
- **Dominant process at LHC:** $gg \to \phi_i \phi_k$ HO: Agostini,Degrassi,Gröber,Slavich

  $\phi_i, \phi_k = 1, ..., 5$



$\mathcal{N}$MSSM $\mathcal{H}$iggs $\mathcal{P}$air $\mathcal{P}$roduction in Gluon Fusion

Dao,MM,Streicher,Walz



Higher order corrections: Agostini,Degrassi,Gröber,Slavich

$\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{B}$eyond the $\mathcal{S}$M

- **Expect the unexpected:**

$*$ Higgs-to-Higgs cascade decays in multi-Higgs models (not possible in MSSM!) $\leadsto$
Exotic multi-fermion and/or multi-photon final states

$*$ Example benchmark point BP7_P2 [King,MM,Nevzorov,Walz]

$gg \to A_2 \to H_s A_1 \to A_1 A_1 A_1 \to bb + 4\gamma$ 13.12fb

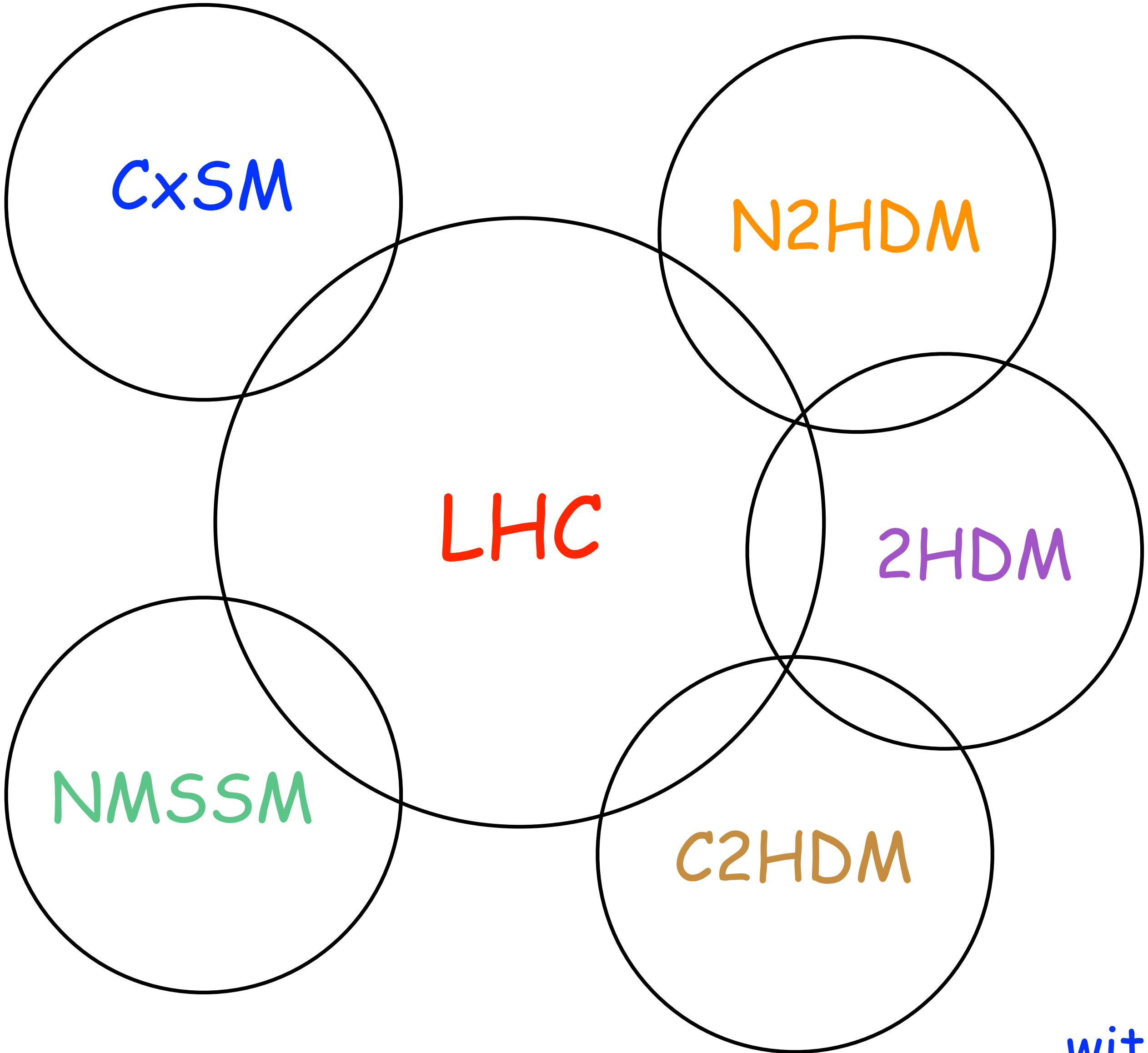
$gg \to A_2 \to H_s A_1 \to A_1 A_1 A_1 \to 4b + 2\gamma$ 84.78fb

$\mathcal{C}$an we distinguish $\mathcal{M}$odels through $\mathcal{H}$iggs $\mathcal{P}$roduction?

Some of the simplest non-SUSY models and the NMSSM

How can we distinguish them ....

.... if a scalar is found.



.... with precision measurements.

$\mathcal{T}$he $\mathcal{M}$odels

	CxSM	2HDM	C2HDM	N2HDM
Model	SM+complex singlet	2 Higgs doublets	CP-violating 2HDM	2HDM+real singlet
Particle content	3 CP-even $H_{1,2,3}$ (broken phase)	2 CP-even h,H 1 CP-odd A charged $H^\pm$	3 CP-mixed $H_{1,2,3}$ charged $H^\pm$	3 CP-even $H_{1,2,3}$ 1 CP-odd A charged $H^\pm$
Motivation	minimal model for DM & baryogenesis benchmark for Higgs-to-Higgs decays	additional sources for for CP-violation; DM candidate (inert 2HDM) benchmark for MSSM	2HDM benefits + explicit CP violation in the Higgs sector	benchmark model for the NMSSM DM candidate

- **The $\mathcal{N}$MSSM:** 3 CP-even $H_{1,2,3}$, 2 CP-odd $A_{1,2}$, charged $H^\pm$

$\mathcal{T}$he $\mathcal{M}$odels

	CxSM	2HDM	C2HDM	N2HDM
Model	SM+complex singlet	2 Higgs doublets	CP-violating 2HDM	2HDM+real singlet
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- **The $\mathcal{N}$MSSM:** 3 CP-even $H_{1,2,3}$, 2 CP-odd $A_{1,2}$, charged $H^\pm$
- Comparison of the NMSSM, CxSM, N2HDM, C2HDM

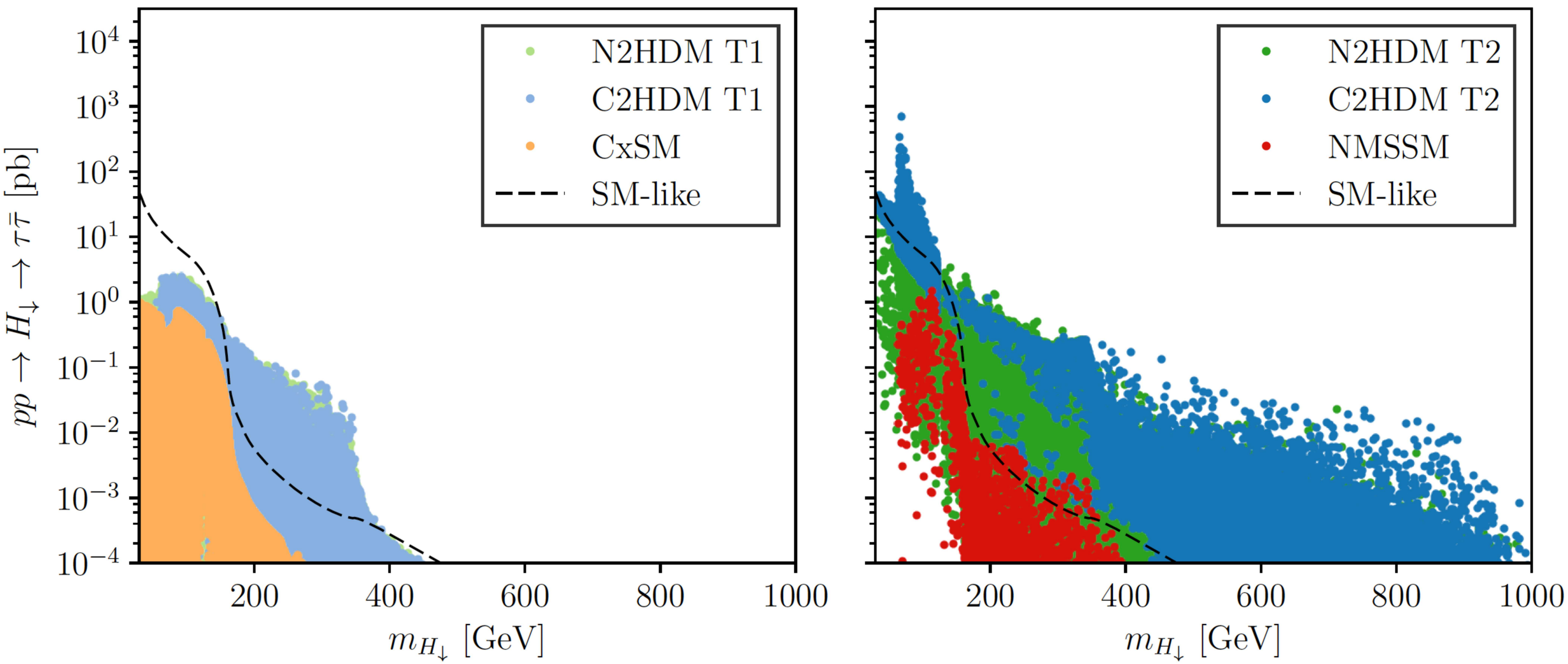
$\mathcal{E}$xample: $\mathcal{D}$ecay $\mathcal{R}$ates in τ $\mathcal{F}$inal $\mathcal{S}$tates

$H_{\downarrow/\uparrow}$: lighter/heavier of the non-SM-like H_i [MM,Sampaio,Santos,Wittbrodt '17]

Comments: - Includes latest bound on $M_{H^\pm}$(2HDM II) > 580 GeV [Misiak,Steinhauser '17]

- Experiments: Test 70-80 GeV mass region to probe type II C2HDM and N2HDM

included limits: [CMS-PAS-HIG-16-037] 90 GeV...3.2 TeV; [ATLAS-CONF-2016-085] 200 GeV...1.2 TeV



$\mathcal{C}$oupling $\mathcal{P}$atterns

- **Precise measurement of couplings:** See also: [Englert eal '14;Gupta,Rzehak,Wells '12,'13]
  - $*$ Deviations from SM $\leftarrow$ indirect hint of new physics
  - $*$ Coupling pattern can reveal the underlying model and the scale of new physics!

- **Coupling Sums:** Example Higgs couplings to gauge bosons $V = Z, W$, normalized to SM

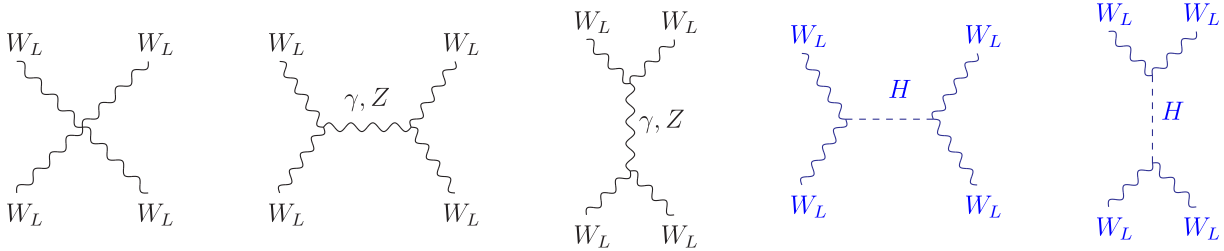
$$\Pi_{VV}^{(n)} = \sum_{j=1}^{n} |c(H_j VV)|^2$$

- **If sum extends over all Higgs bosons that couple to VV** $\rightsquigarrow \Pi_{VV} = 1$ ($\leftarrow$ unitarity)

$\Pi_{VV}^{(2)} = 1$ for MSSM, 2HDM

$\Pi_{VV}^{(3)} = 1$ for CxSM, C2HDM, N2HDM, NMSSM

- **Higgs Discovery $\rightsquigarrow$ New Era of Particle Physics**
  - Structurally completes the Standard Model
  - Self-consistent framework to describe physics up to the Planck scale



$$\mathcal{A} = \frac{G_F M_H^2}{8\sqrt{2}\pi}$$

- **SM Higgs couplings:**
  - $g_{Hf\bar{f}} \sim \frac{m_f}{v}$ and $\sqrt{g_{HVV}} \sim \frac{m_V}{v}$

$\mathcal{C}$oupling $\mathcal{P}$atterns

- **Precise measurement of couplings:** See also: [Englert eal '14;Gupta,Rzehak,Wells '12,'13]
  - ∗ Deviations from SM ← indirect hint of new physics
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$$\Pi_{VV}^{(2)} = 1 \quad \text{for MSSM, 2HDM}$$

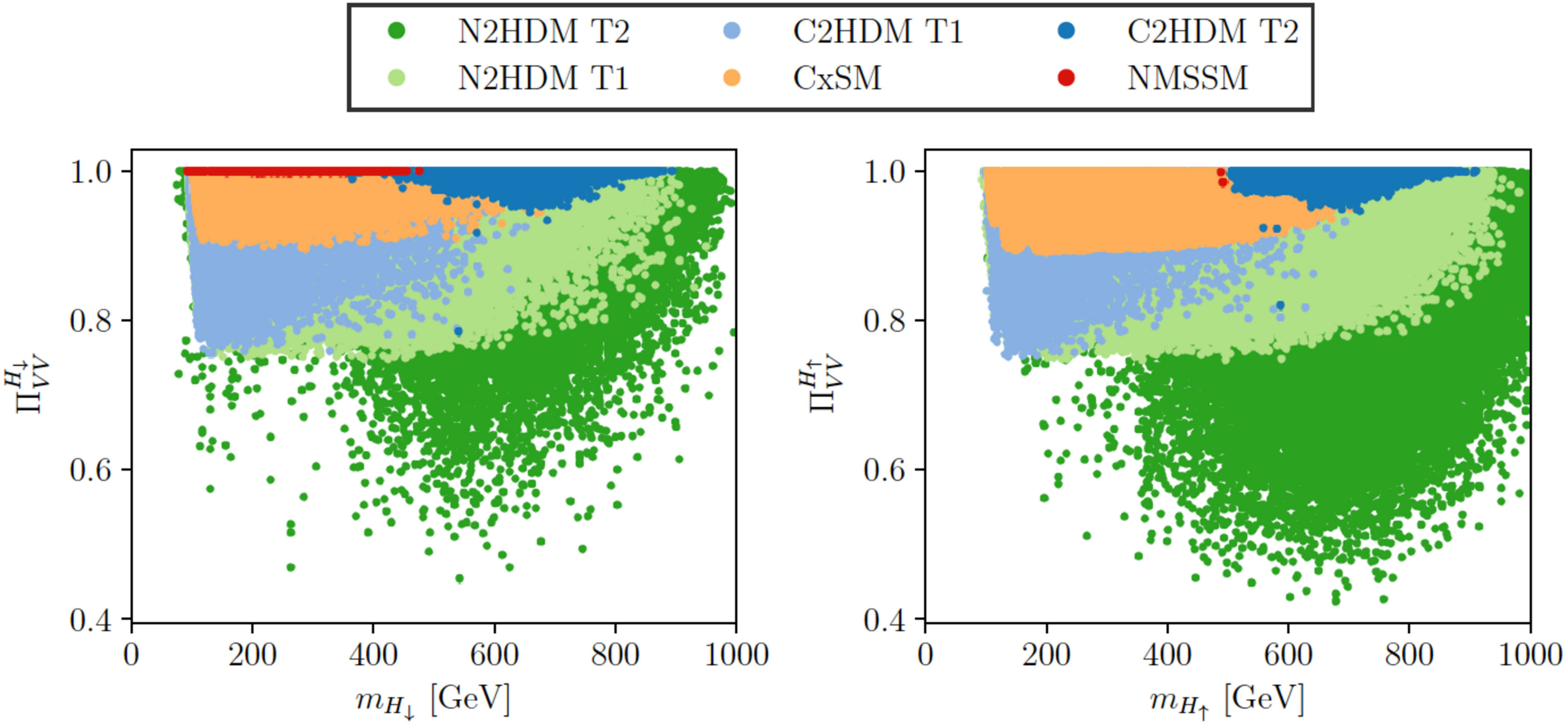
$$\Pi_{VV}^{(3)} = 1 \quad \text{for CxSM, C2HDM, N2HDM, NMSSM}$$

$\mathcal{G}$auge $\mathcal{C}$oupling $\mathcal{S}$ums

[MM,Sampaio,Santos,Wittbrodt '17]

Comments: - We assume that we have found h_{125} and *only* $H_\downarrow$ (left) *or* $H_\uparrow$ (right)

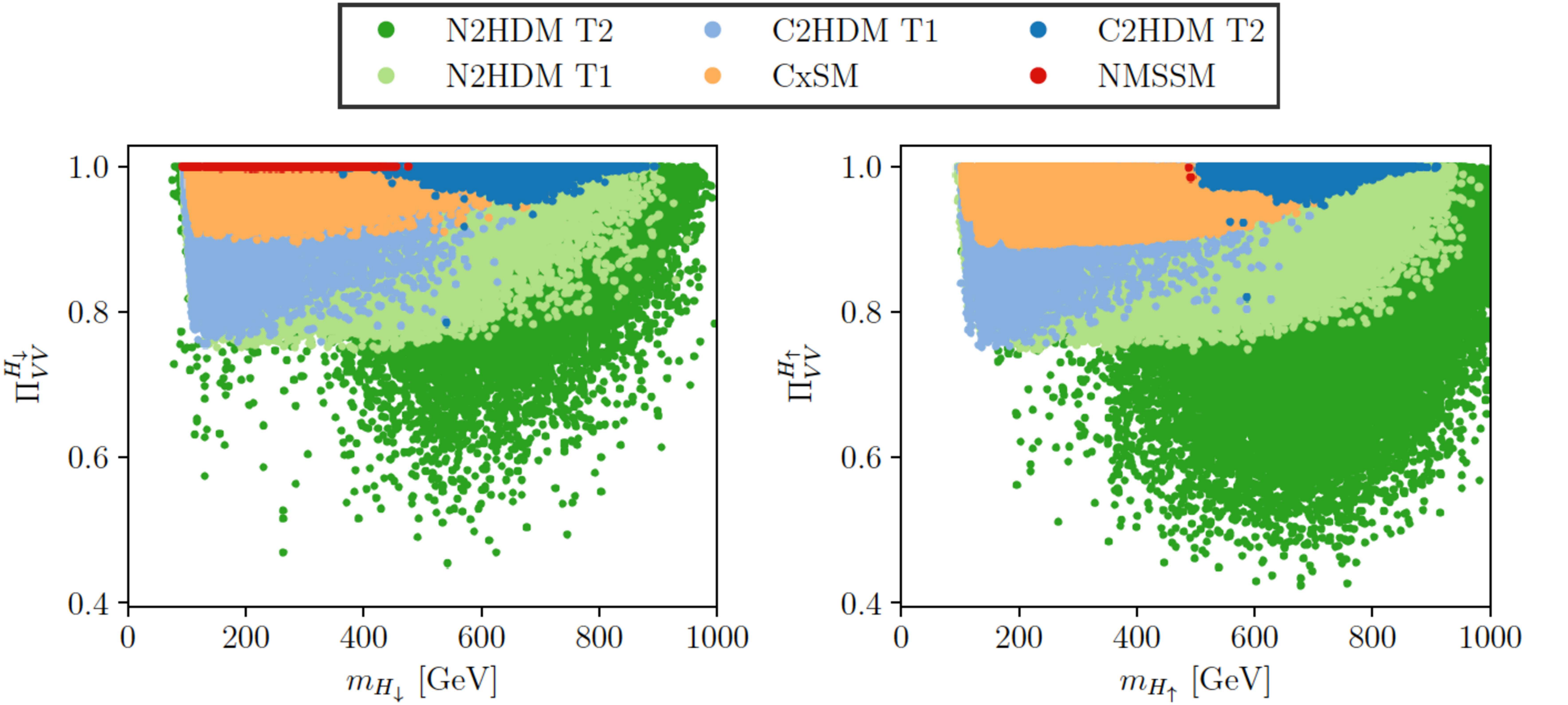
- All models contain alignment/SM-limit $\rightsquigarrow \Pi_{VV} = 1$: here not distinguishable from 2HDM, MSSM



Gauge Coupling Sums

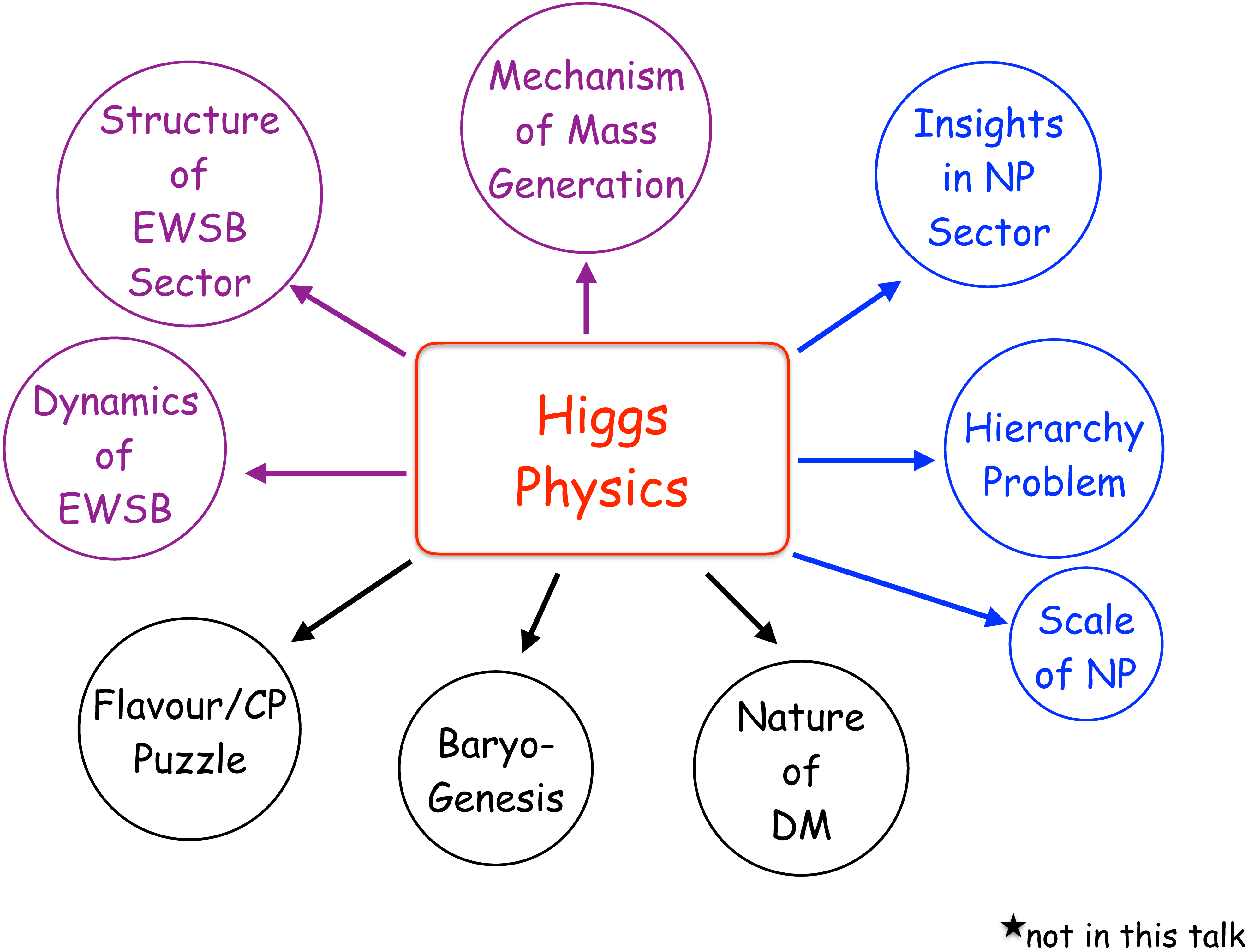
[MM,Sampaio,Santos,Wittbrodt '17]

<u>Comments:</u> - larger deviations for C2HDM II $\leftarrow$ wrong-sign regime
- NMSSM: very constrained $\leftarrow$ SUSY relations
- N2HDM II: largest deviations $\leftarrow$ no SUSY relations, large # of parameters



Higgs Physics
The answer to
life, the universe
and everything?

Not quite,
but


Structure of EWSB Sector
Mechanism of Mass Generation
Insights in NP Sector
Dynamics of EWSB
Higgs Physics
Hierarchy Problem
Scale of NP
Flavour/CP Puzzle
Baryo-Genesis
Nature of DM
★not in this talk

Thank You For Your Attention!