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# *Di-Higgs Production in the $SM$ and $New Physics$ Extensions*

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7th RISE Collaboration Workshop  
'NonMinimalHiggs'  
Helsinki University, 27-29 May 2019



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## Outline

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- ◇ Motivation for Higgs pair production
- ◇ Higher-order corrections to Higgs pair production
  - \* Mass effects at NLO
- ◇ Di-Higgs production beyond the Standard Model
  - \* New physics effects
- ◇ Di-Higgs production in sample benchmark models
  - \* C2HDM and NMSSM
- ◇ Conclusions

Disclaimer: Main focus on own work

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# Motivation

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# Motivation Higgs Pair Production

- Higgs Discovery  $\rightsquigarrow$  New Era of Particle Physics

- Structurally completes SM, self-consistent framework to describe physics up to the Planck scale

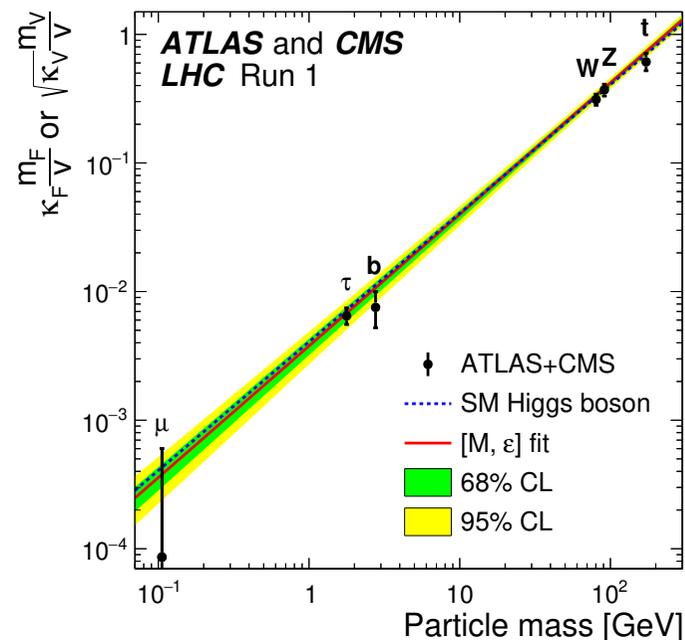
- SM Higgs couplings:

- $g_{Hf\bar{f}} \sim \frac{m_f}{v}$  and  $\sqrt{g_{HVV}} \sim \frac{m_V}{v}$

- Higgs self-coupling strength:

- still unknown

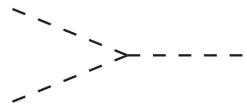
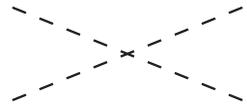
[ATLAS/CMS, JHEP08(2016)045]

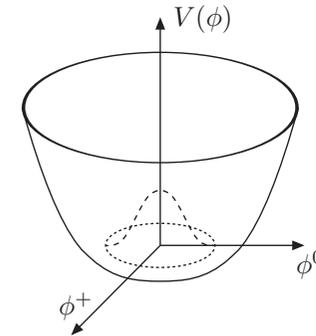


# Ultimate Test of the Higgs Mechanism

## 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:

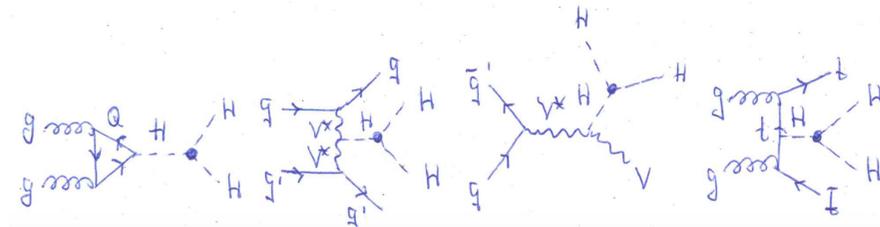
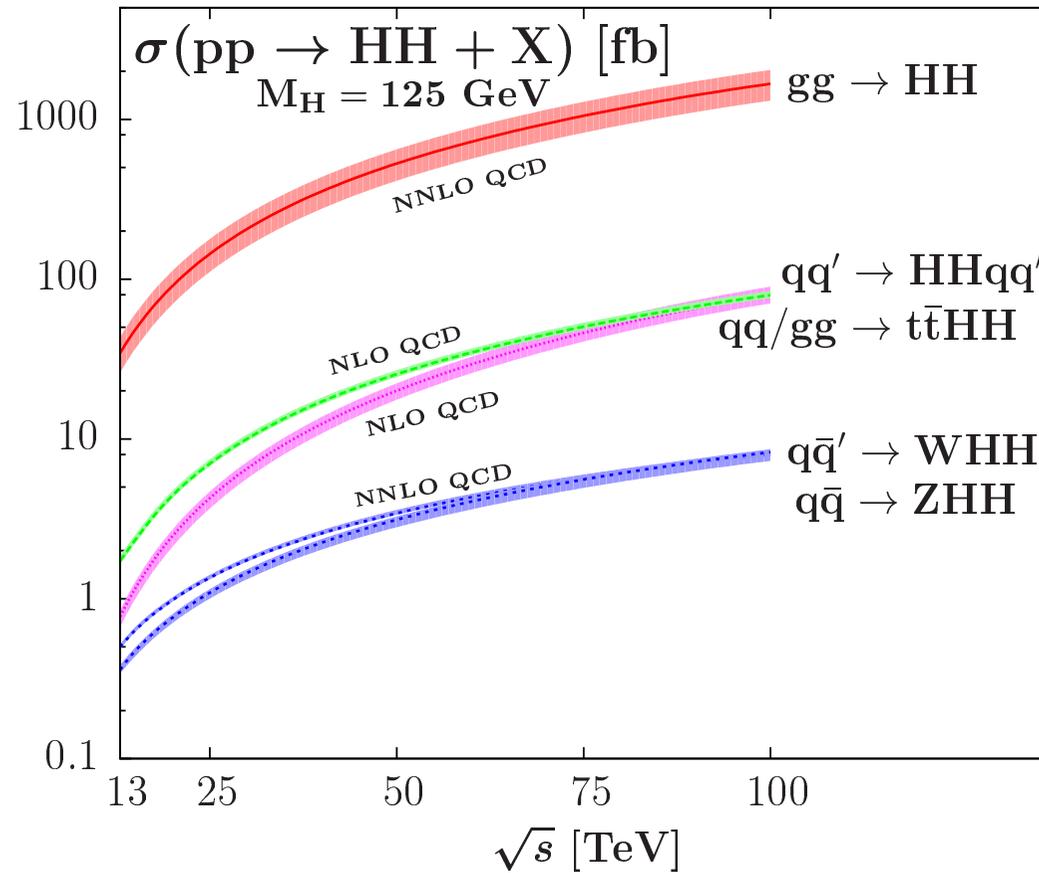
$\lambda_{HHH}$  via pair production

$\lambda_{HHHH}$  via triple production

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

# Double Higgs Production Processes

Baglio, Djouadi, Quevillon



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# Higher-Order Corrections

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## Main Production Channel at the $\mathcal{LHC}$

- **Gluon fusion:** loop induced, third generation dominant  $\rightsquigarrow t, b$



- virtual & real (N)NLO QCD corrections in large top mass limit (HTL):  $\sim 100\%$   
 [Dawson,Dittmaier,Spira], [de Florian,Mazzitelli], [Grigo,Melnikov,Steinhauser]
- Large top mass expansion:  $\sim \pm 10\%$  [Grigo,Hoff,Melnikov,Steinhauser]
- NLO mass effects @ NLO in real corrections:  $\sim -10\%$   
 [Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Torrielli,Vryonidou,Zaro]
- New expansion/extrapolation methods:
  - $1/m_t^2$  expansion & conformal mapping & Padé approximants [Grober,Maier,Rauh]
  - $p_T^2$  expansion [Bonciani,Degrassi,Giardino,Grober]
  - high-energy expansion [Davies,Mishima,Steinhauser,Wellmann]

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## Full NLO Calculation

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- Full NLO calculation: top only

Borowka, Greiner, Heinrich, Jones,  
Kerner, Schlenk, Schubert, Zirke

numerical integration, sector decomposition, tensor reduction, contour deformation

$$14\text{TeV: } (m_t = 173\text{GeV}) \quad \sigma_{\text{NLO}} = 32.91(10)_{-12.8\%}^{+13.8\%} \text{ fb}$$
$$\sigma_{\text{NLO}}^{\text{HTL}} = 38.75_{-15\%}^{+18\%} \text{ fb} \quad (\leftarrow \text{HPAIR})$$

⇒ -15% mass effects on top of LO

→ T

- Full NLO calculation: top only first independent cross-check

Baglio, Campanario, Glaus  
MM, Spira, Streicher

numerical integration, endpoint subtraction, no tensor reduction, Richardson extrapolation

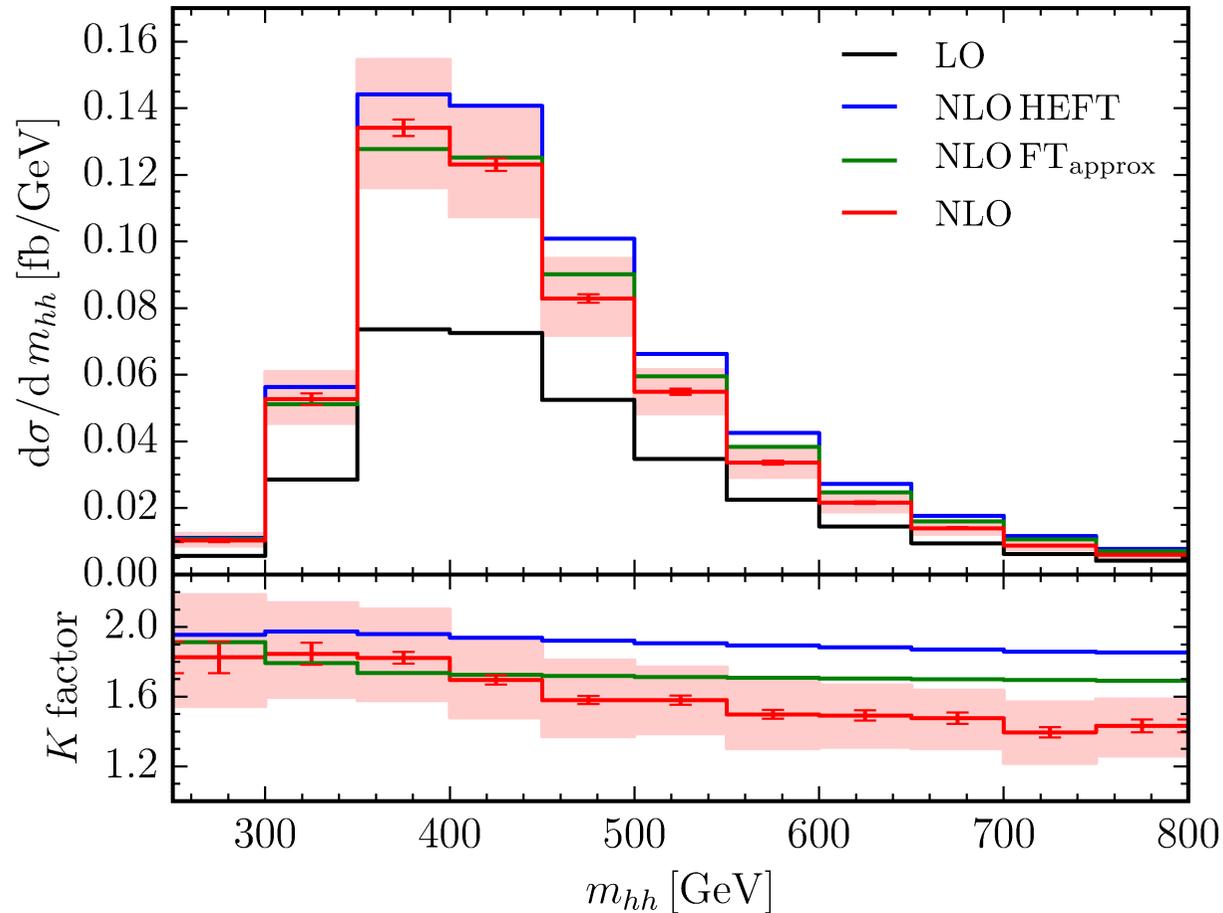
$$14\text{TeV: } (m_t = 172.5\text{GeV}) \quad \sigma_{\text{NLO}} = 32.78(7)_{-12.5\%}^{+13.5\%} \text{ fb}$$
$$\sigma_{\text{NLO}}^{\text{HTL}} = 38.66_{-15\%}^{+18\%} \text{ fb} \quad (\leftarrow \text{HPAIR})$$

⇒ -15% mass effects on top of LO

→ T

# NLO $gg \rightarrow HH$ with Full Mass Dependence

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

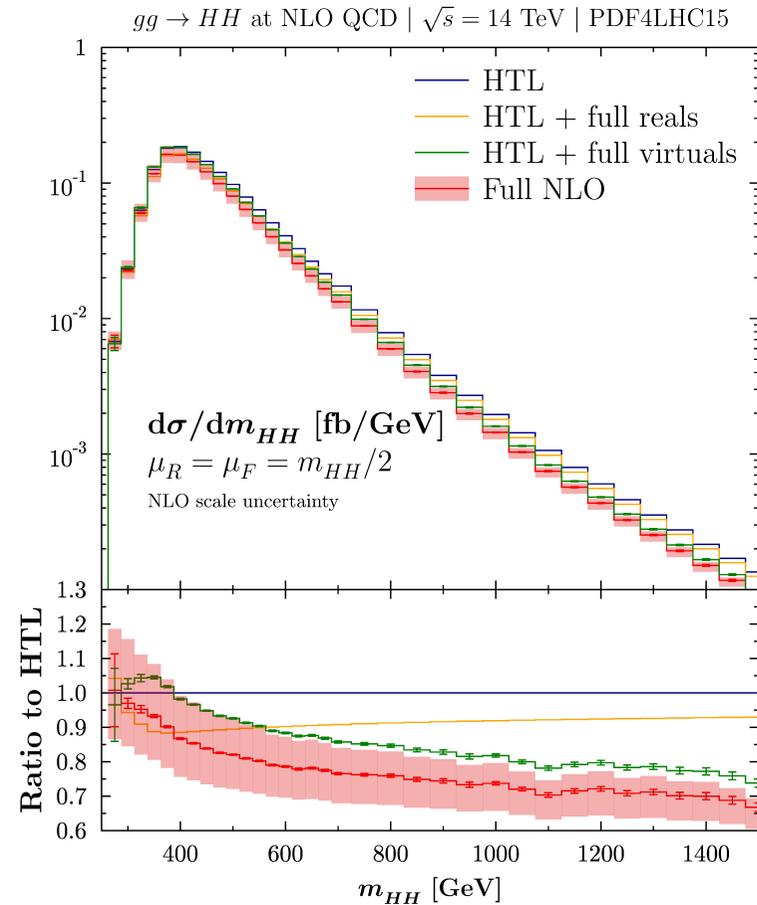
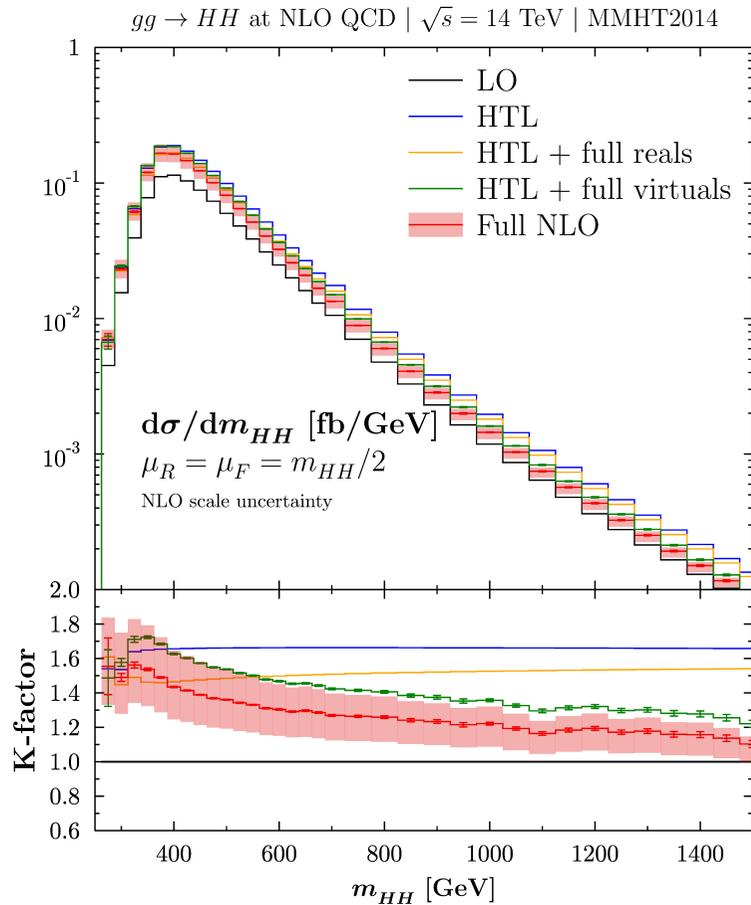


Red: full result w/ mass dependence; blue/green approximations; scale variation:  $\mu = (0.5...2)m_{hh}/2$

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

# NLO $gg \rightarrow HH$ with Full Mass Dependence

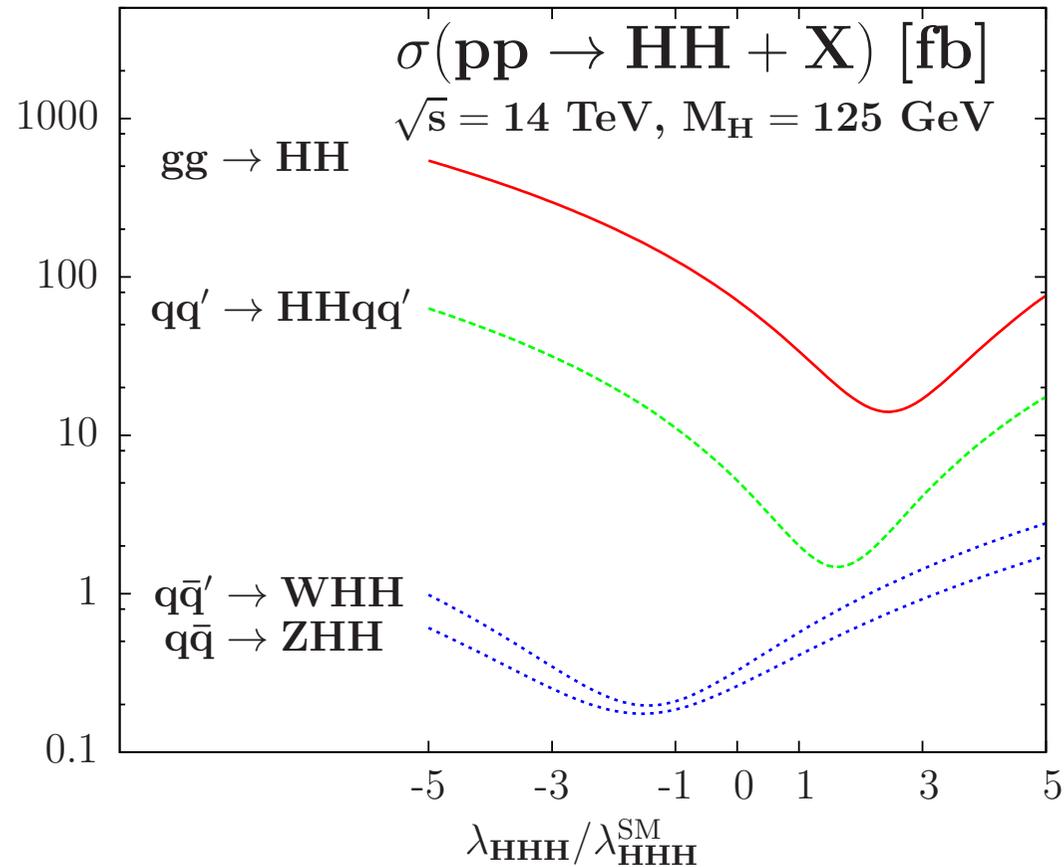
Baglio,Campanario.Glauss,MM,Streicher,Spira '18



- independent cross-check; completely different methods; no fixed masses
- first uncertainty estimate due to scheme and scale choice of top-quark mass

## Dependence on Higgs Self-Coupling

Baglio, Djouadi, Gröber, MM, Quevillon, Spira



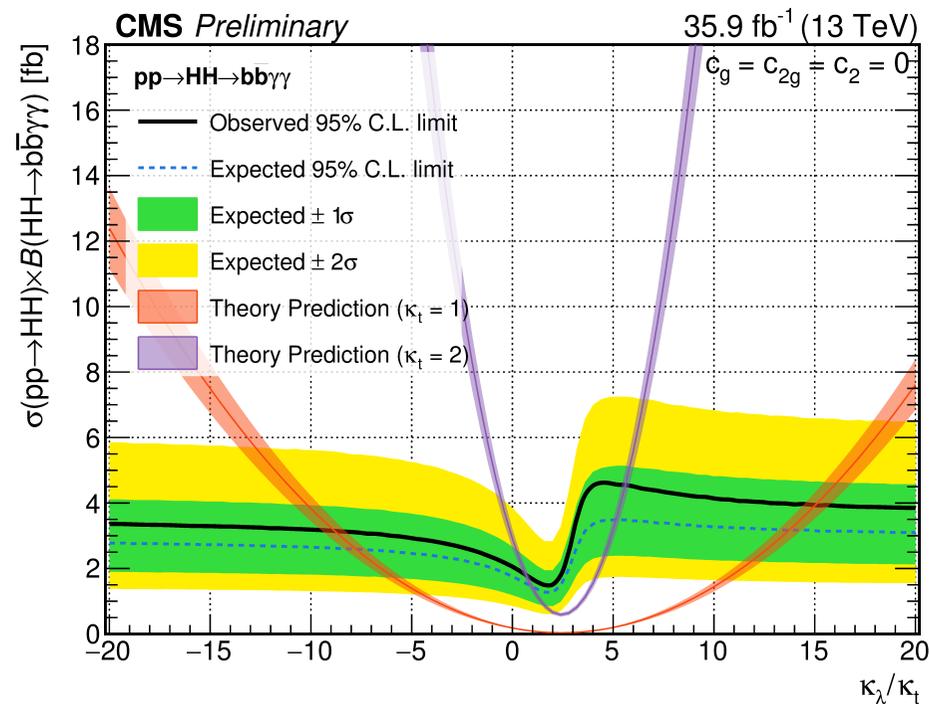
- threshold region sensitive to  $\lambda$ ; large  $M_{HH}$  sensitive to New Physics
- $gg \rightarrow HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$ ; decreasing with  $M_{HH}^2$

# Challenge *Di-Higgs Production*

- **Small signal + large QCD background**  $\rightsquigarrow$  **Experimental challenge!**

$$\mathcal{O}(\pm(15 - 20)\lambda_{HHH}^{\text{SM}}) \quad [\text{ATLAS,CMS}]$$

[CMS-PAS-HIG-17-008]



- **Prospects in  $b\bar{b}\gamma\gamma$  final state:**  $-0.8 < \lambda_{hhh}/\lambda_{hhh}^{\text{SM}} < 7.7$

[ATL-PHYS-PUB-2017-001]

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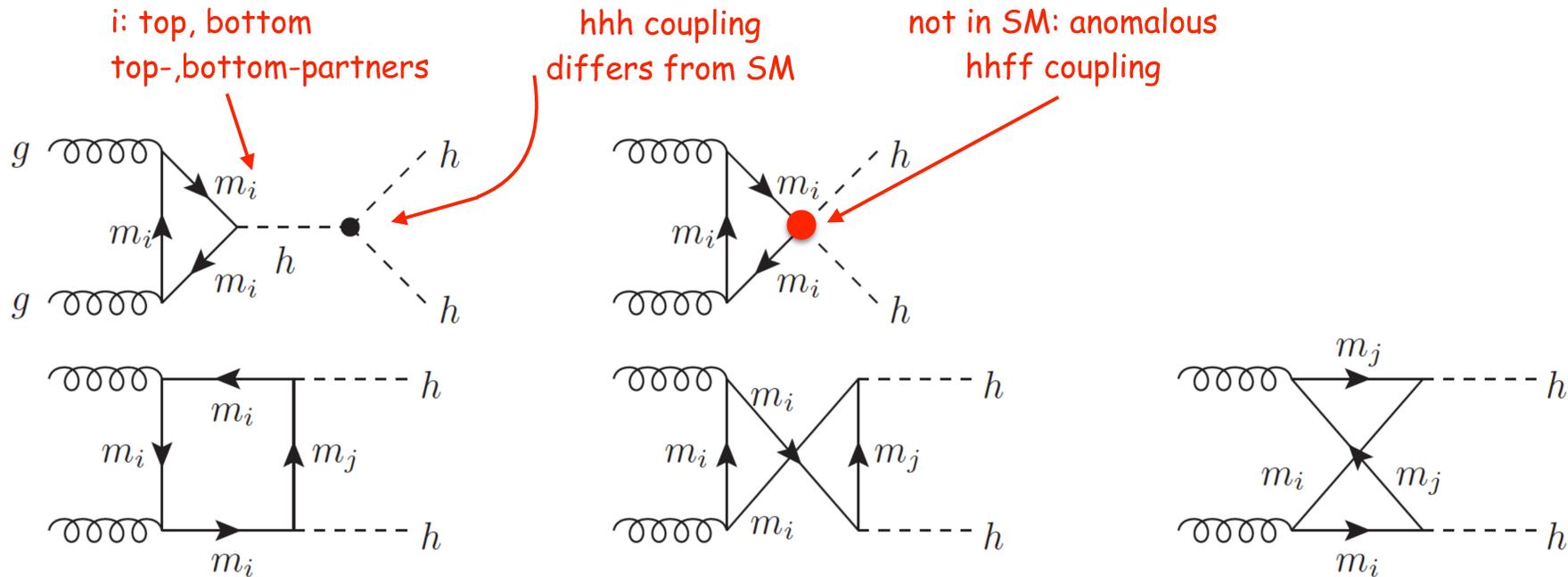
# *BSM Higgs Pair Production*

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## Di-Higgs Production Beyond the SM

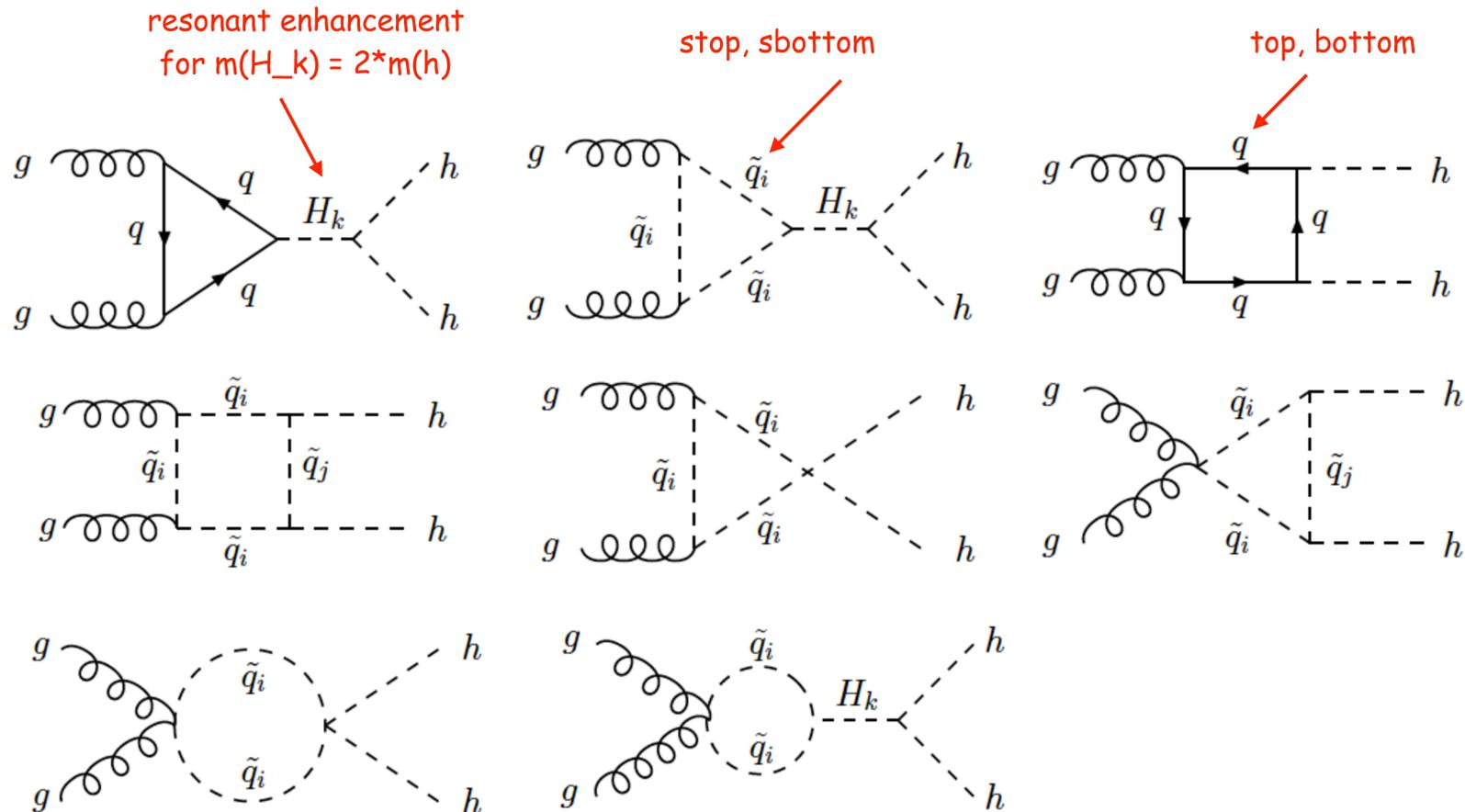
- **Beyond SM HH production:** Cross sections can be considerably larger: ex.: composite Higgs
  - \* different  $\lambda_{3H}$ ; \* novel couplings; \* novel particles in the loop; \* resonant enhancement



# Di-Higgs Production Beyond the SM

- **Beyond SM HH production:** Cross sections can be considerably larger: ex.: NMSSM

\* different  $\lambda_{3H}$ ; \* novel couplings; \* novel particles in the loop; \* resonant enhancement



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## Di-Higgs Production Beyond the SM

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

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

- Expect the unexpected:

- \* Higgs-to-Higgs cascade decays in non-minimal Higgs sectors  $\rightsquigarrow$   
Exotic multi-fermion and/or multi-photon final states

- \* Example NMSSM benchmark point BP7\_P2

[King, MM, Nevzorov, Walz]

$$gg \rightarrow A_2 \rightarrow H_s A_1 \rightarrow A_1 A_1 A_1 \rightarrow bb + 4\gamma \quad 13.12\text{fb}$$

$$gg \rightarrow A_2 \rightarrow H_s A_1 \rightarrow A_1 A_1 A_1 \rightarrow 4b + 2\gamma \quad 84.78\text{fb}$$

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## Higher-Order Corrections - Beyond the SM

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- **Higher-order corrections to  $\sigma_{hh}$ :**

- for higher-order corrections for BSM Higgs pair production, see  
[Dawson,Dittmaier,Spira; Agostini,Degrassi,Gröber,Slavich; Dawson,Lewis;  
Gröber,MM,Spira,Streicher; Gröber,MM,Spira; Hespel,Lopez-Val,Vryonidou; Moyotieal; ...]
- available in large loop particle mass limit
- $K$ -factor typically of  $\mathcal{O}(1.5 - 2)$
- new physics effects on  $K$ -factors in general small
- new physics effects on absolute cross section large

- **Higher-order corrections to triple Higgs couplings: and Higgs-to-Higgs decays**

[Hollik,Penaranda; Dobadoeal; Arhrib eal; Aoki eal; Kanemura eal; Senaha; Spira,Brucherseifer;  
Nhung,MM,Streicher,Walz; MM,Nhung,Ziesche; Krause,Santos,MM,Ziesche; Braatheneal; ...]

implementation in tools: H-COUP  
2HDECAY

[Kanemura,Kikuchi,Sakurai,Yagyu]  
[Krause,MM,Spira]

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## New Tool 2HDECAY

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- **2HDECAY:**

[Krause,MM,Spira '18]

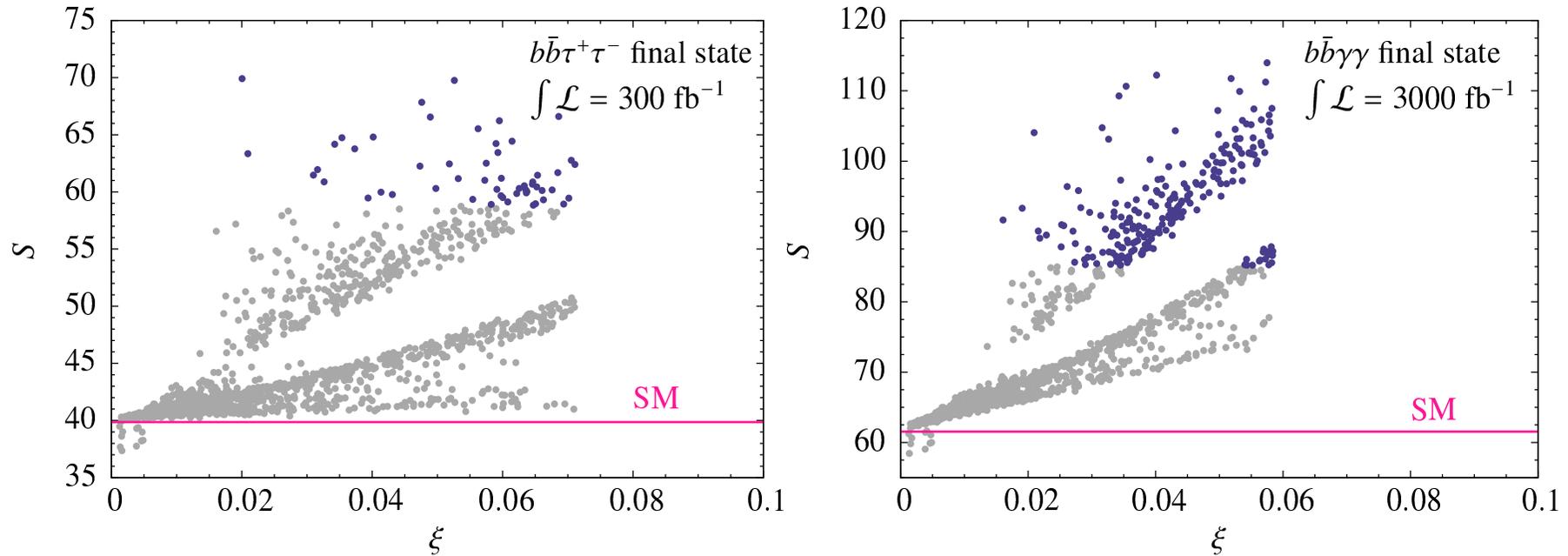
A tool for the electroweak one-loop corrections to Higgs decays in the 2HDM including the state-of-the-art QCD corrections

- **Webpage:** <https://github.com/marcel-krause/2HDECAY>

- **Features:**

- \* Full EW one-loop corrections to all 2-body (not-loop induced) 2HDM Higgs decays
- \* Combination with state-of-the-art QCD corrections implemented in HDECAY [Djouadi,Kalinowski,MM,Spira]
- \* Different renormalization schemes implemented [Krause,Lorenz,MM,Santos,Ziesche; Krause,Santos,MM,Ziesche; Altenkamp,Dittmaier,Lang,Rzehak,Denner]
- \* Separate output of EW corrections to tree-level partial widths
- \* Consistent parameter conversion for comparison of different renormalization schemes

# New Physics First in Higgs Pair Production? [Gröber,MM,Spira '16]



- **MCHM10**: minimal composite Higgs model with heavy top and bottom partners;  
cxn at NLO QCD

Blue points - Signal events  $S$ :  $S_{SM} + 3\sqrt{S_{SM}} \leq S$  or  $S_{SM} - 3\sqrt{S_{SM}} \geq S$

Assumption: Deviations of Higgs couplings to SM particles  $<$  projected experimental sensitivity

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## C2HDM Higgs Pair Production

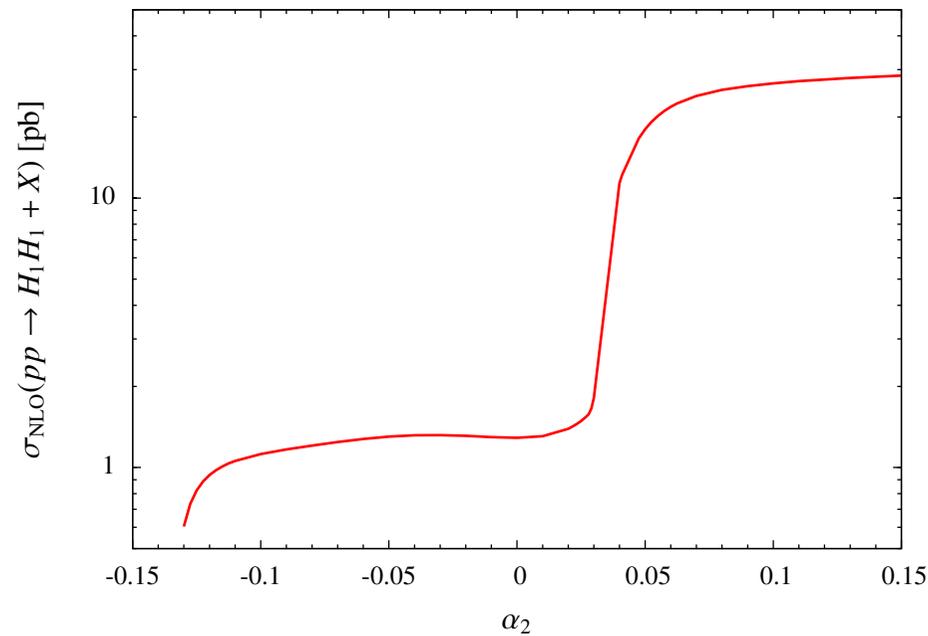
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- 3 CP-mixed neutral scalars in C2HDM:

Resonant heavy Higgs production possible  $\rightsquigarrow$  strong increase of  $\sigma_{\text{NLO}}$

$\alpha_2$  CP mixing angle;  $\sigma_{\text{NLO}}$  at NLO QCD

Gröber, MMM, Spira '17



For recent works on di-Higgs production in 2HDMs, see also e.g.  
[Kon, Nagura, Ueda, Yagyu; Babu, Jana]

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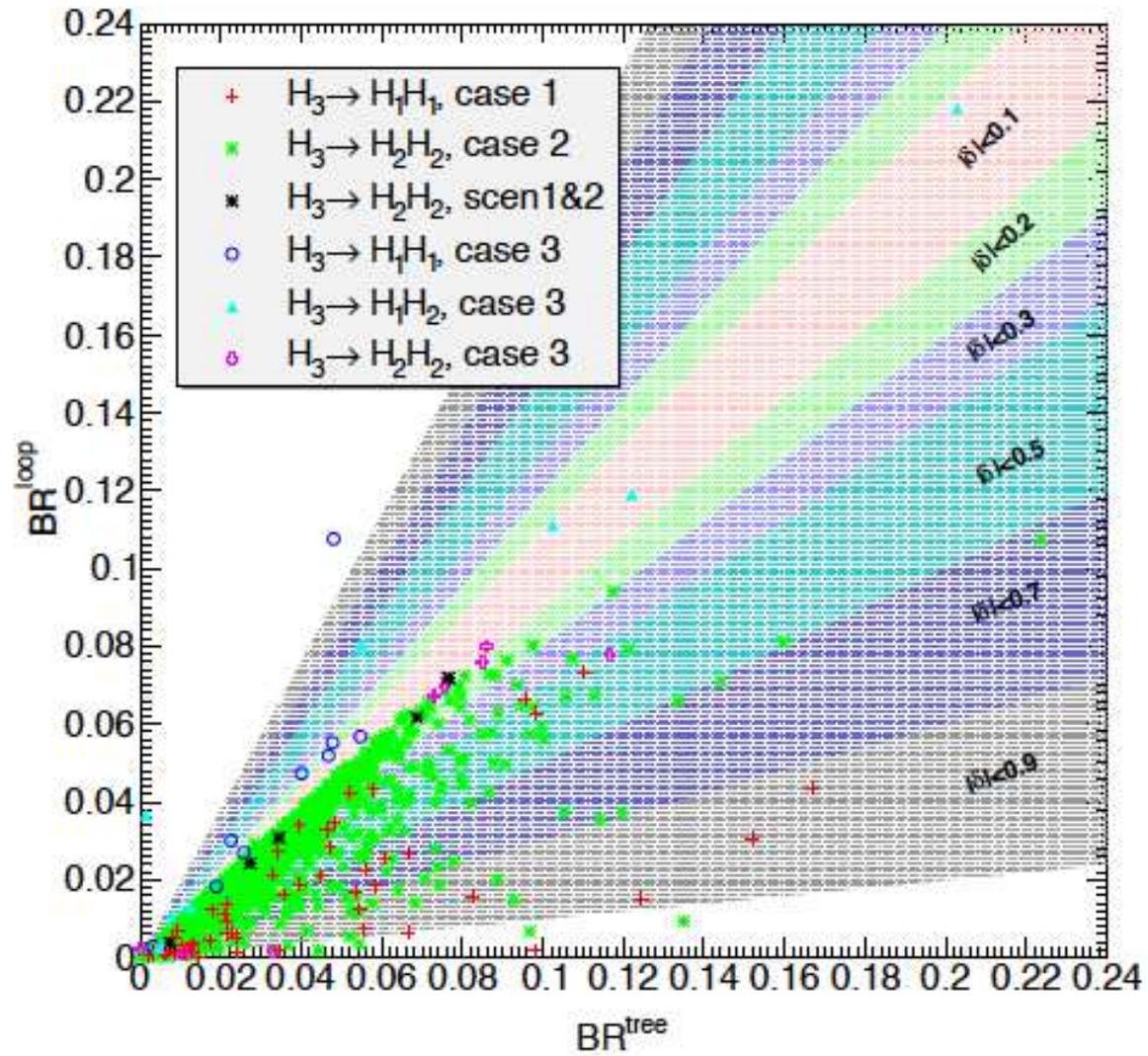
## Loop Corrected Trilinear $\mathcal{N}$ MSSM Higgs Self-Coupling

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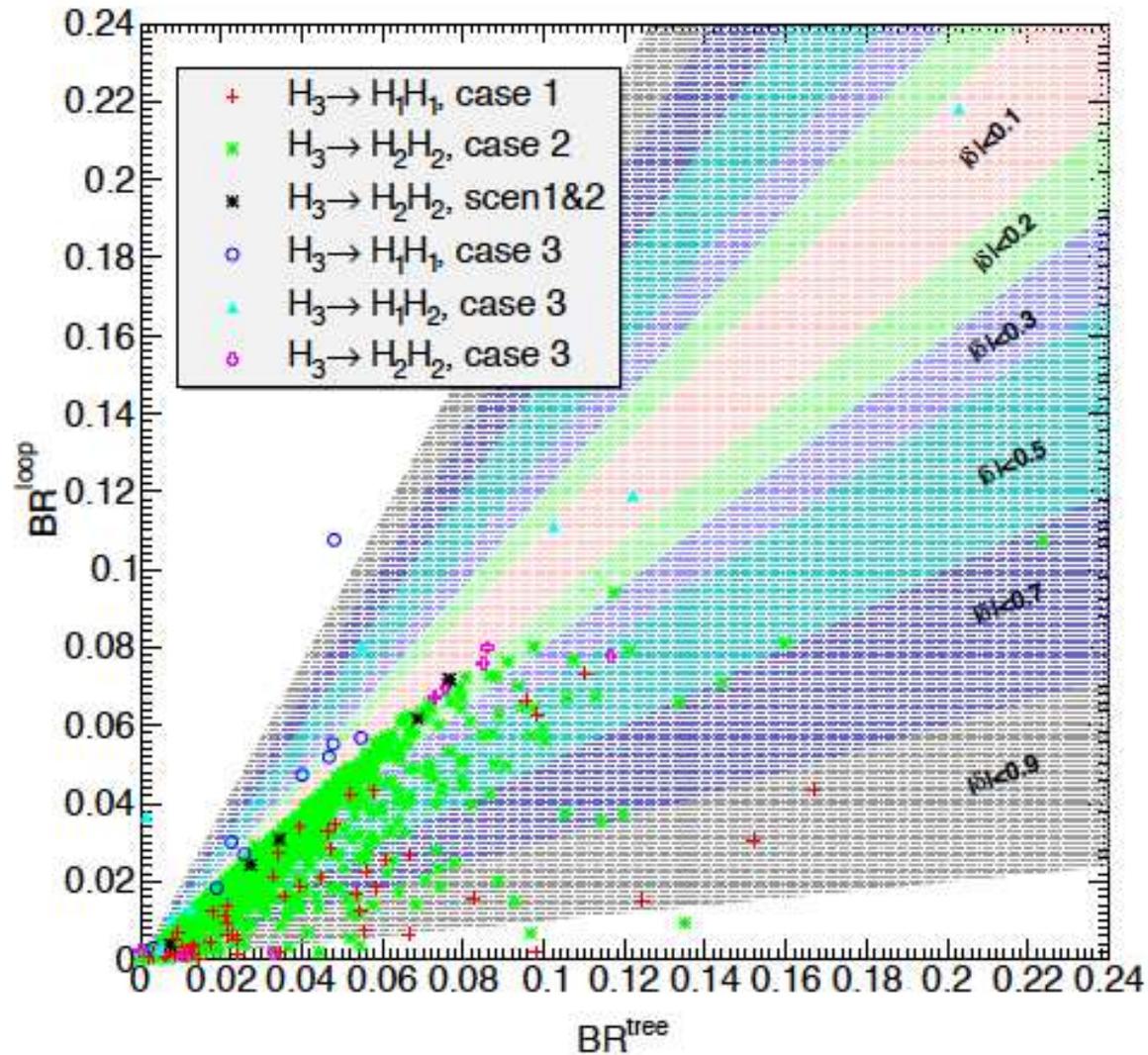
- **Higgs mass and self-couplings:** determined from Higgs potential  $\rightsquigarrow$  consistent description of Higgs sector at higher order requires loop corrections to masses **and** self-couplings

$\Rightarrow$  determination of higher order corrections to trilinear Higgs self-couplings

- \* one-loop corrections in real NMSSM [Dao,MMM,Streicher,Walz '13]
- \* two-loop corrections in complex NMSSM [MMM,Nhung Dao,Ziesche '15]



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



- \* Effect of higher order corrections on branching ratios can be up to 90% and higher
- \* Black points: excluded if only tree-level BR considered

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# Benchmarks for *Higgs Pair Production*

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## Higgs Pair Production in *BSM* Sample Models

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- What is the present general picture in BSM models?
- Sample benchmark models: CP-violating 2HDM (C2HDM) and NMSSM
  - common feature: extended Higgs sector with  $\geq 3$  neutral Higgs bosons  
 $\rightsquigarrow$  possibility of  $gg \rightarrow H_j H_k$  with  $H_j \neq H_k$
  - different: NMSSM Higgs self-couplings in terms of gauge couplings  
C2HDM Higgs self-couplings free (modulo exp. & theor. constraints)

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## Scans and Notation

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- **Scan in C2HDM & NMSSM spaces:**

keep only points compatible with theoretical and experimental constraints

- **Notation C2HDM & NMSSM:**

$h$  - SM-like Higgs boson

$H_{\downarrow}$  - lighter non-SM-like Higgs boson

$H_{\uparrow}$  - heavier non-SM-like Higgs boson

- **Additionally in NMSSM:**

$A_{\downarrow}$  - lighter non-SM-like pseudoscalar Higgs boson

$A_{\uparrow}$  - heavier non-SM-like pseudoscalar Higgs boson

$h, H_{\downarrow}, H_{\uparrow}$  CP-mixing states in C2HDM, pure scalars in CP-conserving NMSSM

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## Interplay Single Higgs and Di-Higgs Production

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- **Heavy Higgs Bosons:**

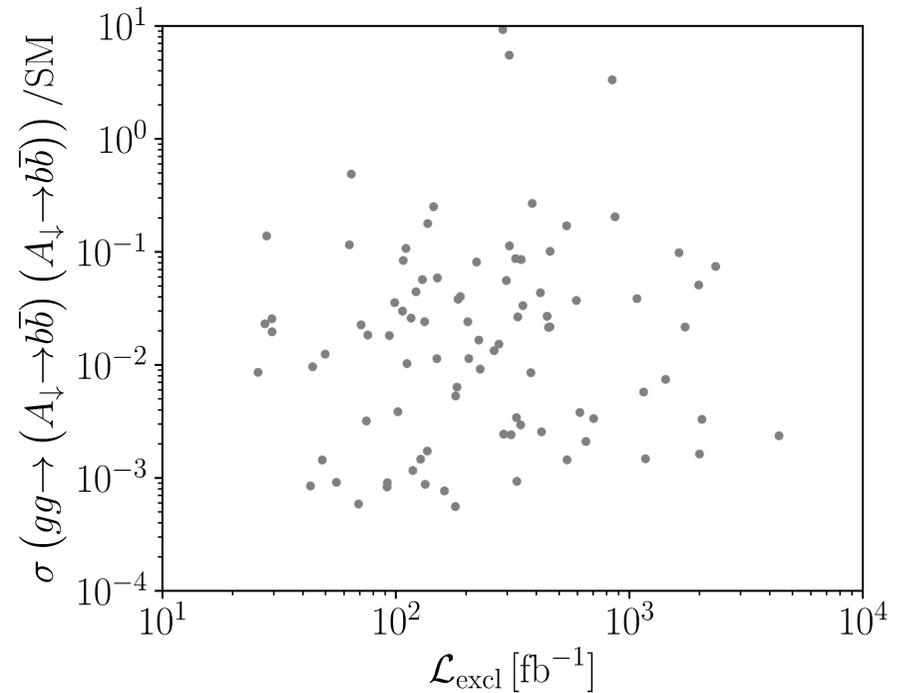
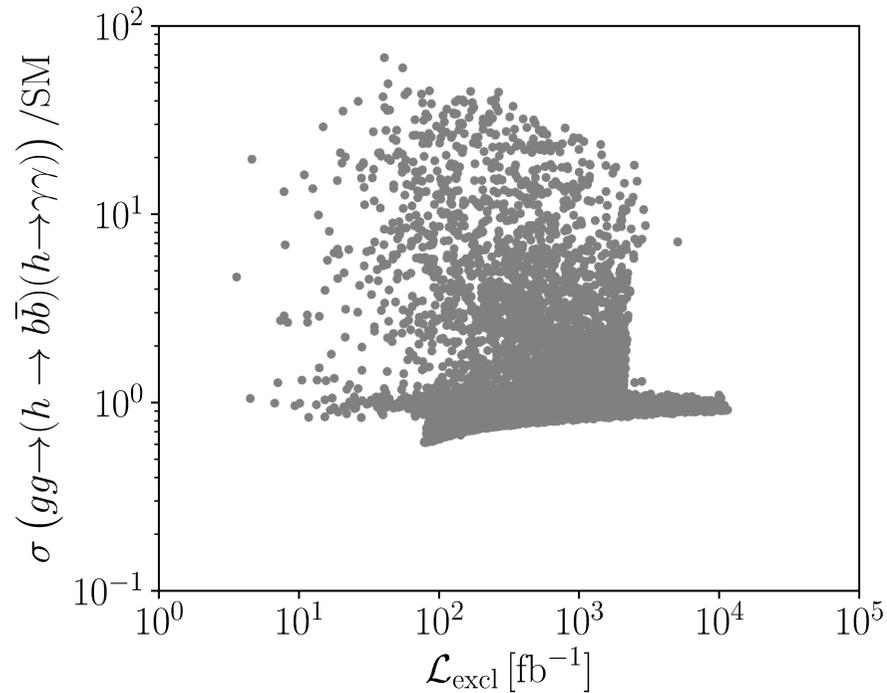
- \* decay into  $t\bar{t}$  if kinematically possible
- \* exotic 4-top final state from production of heavy Higgs boson pair
- \* large rates constrained by single Higgs production in  $t\bar{t}$  final state
- \* ← no experimental data available
- \* encourage experiments to look into these single Higgs signatures

- **Light Higgs Bosons:**

- \* light Higgs states below 125 GeV possible
- \* huge di-Higgs cross sections
- \* dominant decays into  $b\bar{b}$ ,  $\tau\bar{\tau}$ ,  $\gamma\gamma$
- \* large rates constrained by single production of light Higgs bosons
- \* encourage experiments to look for light Higgs bosons

## Scatter Plots C2HDM (left) $\mathcal{N}$ MSSM (right)

[Basler, Dawson, Englert, MM '18]



- Left: C2HDM T1  $hh \rightarrow 2b\bar{b}\gamma$ ; large  $t\bar{t}$  rates responsible for exclusion beyond HiggsBounds

## Maximum Cross Section Values

- Maximum cross section values C2HDM:

$H_i H_j / \text{model}$	T1	T2
$hh$	794	63.2
$hH_{\downarrow}$	49.17	11.38
$hH_{\uparrow}$	17.65	13.50
$H_{\downarrow} H_{\downarrow}$	3196	0.31
$H_{\downarrow} H_{\uparrow}$	12.58	0.31
$H_{\uparrow} H_{\uparrow}$	7.10	0.23

T1 - Type 1, T2 - Type 2

- Maximum cross section values NMSSM:

$H_i H_j$	NMSSM
$hh$	34
$hH_{\downarrow}$	125
$hA_{\downarrow}$	70
$hH_{\uparrow}$	1.14
$H_{\downarrow} H_{\downarrow}$	20862
$H_{\downarrow} H_{\uparrow}$	0.2
$H_{\uparrow} H_{\uparrow}$	0.004
$A_{\downarrow} A_{\downarrow}$	70

cxns (in fb) at LO; NLO adds factor  $\sim 2$ ; exclusion luminosity  $\geq 64 \text{ fb}^{-1}$

## C2HDM and NMSSM Benchmark Points - Max $\sigma(hh \rightarrow (b\bar{b})(b\bar{b}))$

	C2HDM T1		NMSSM	
$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.09	$3.64 \cdot 10^{-3}$	125.03	$3.60 \cdot 10^{-3}$
$m_{H_2}/\Gamma_{\text{tot}}$ [GeV]	310.99	0.35	170.66 ( <i>S</i> )	0.27
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	314.63	1.44	454.90	2.80
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	372.62	0.99	440.31	3.77
$m_{A_1(S)}/\Gamma_{\text{tot}}$ [GeV]			69.03	$7.26 \cdot 10^{-5}$
$m_{A_2}/\Gamma_{\text{tot}}$ [GeV]			446.26	3.77
$\sigma_{hh}^{\text{LO}}$ [fb]	781		34.18	
$\sigma_{hh \rightarrow 4b}^{\text{LO}}/\text{wrt. SM}$ [fb]	261	42	12.42	1.99
$\mathcal{L}_{\text{excl}}$ [fb $^{-1}$ ]	266		287	

- ◇  $\sigma^{\text{NLO}} \approx 2\sigma^{\text{LO}}$ ; T1 = type 1
- ◇ C2HDM enhancement due to resonant  $H_2, H_3$  production w/ subsequent decay into  $hh$
- ◇ NMSSM:  $S$  means singlet-like;  $H_2$  and  $A_1$  are singlet-like

## C2HDM and $\mathcal{N}$ MSSM Benchmark Points - $\text{Max } \sigma(SS/hS \rightarrow (b\bar{b})(b\bar{b}))$

C2HDM T1			NMSSM - 1		
$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.09	$3.74 \cdot 10^{-3}$	$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.03	$3.60 \cdot 10^{-3}$
$m_{H_2(S)}/\Gamma_{\text{tot}}$ [GeV]	131.48	$7.95 \cdot 10^{-4}$	$m_{H_2(S)}/\Gamma_{\text{tot}}$ [GeV]	170.66	0.27
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	313.33	6.45	$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	454.90	2.80
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	311.54	5.79	$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	440.31	3.77
			$m_{A_1(S)}/\Gamma_{\text{tot}}$ [GeV]	69.03	$7.26 \cdot 10^{-5}$
			$m_{A_2}/\Gamma_{\text{tot}}$ [GeV]	446.26	4.34
$\sigma_{SS}^{\text{LO}}$ [pb]	3.20		$\sigma_{A_S A_S}^{\text{LO}}$ [fb]	69.78	
$\sigma_{SS \rightarrow 4b}^{\text{LO}}$ [pb]	1.26		$\sigma_{A_S A_S \rightarrow 4b}^{\text{LO}}$ [fb]	57.58	
$\sigma_{Sh}^{\text{LO}}$ [fb]	49.17		$\sigma_{A_S h}^{\text{LO}}$ [fb]	69.97	
$\sigma_{Sh \rightarrow 4b}^{\text{LO}}$ [fb]	17.79		$\sigma_{A_S h \rightarrow 4b}^{\text{LO}}$ [fb]	38.32	
$\mathcal{L}_{\text{excl}}$ [fb $^{-1}$ ]	287			287	

- ◇ C2HDM:  $S$  here means large pseudoscalar admixture
- ◇ C2HDM:  $H_2 H_2 = SS$  enhancement due to resonant  $H_3$  production w/ decay into  $SS$
- ◇ C2HDM:  $h A_S / A_S A_S$  enhancement due to resonant  $A_2 / H_2$  prod w/ decay into  $h A_S / A_S A_S$

## C2HDM and $\mathcal{N}$ MSSM Benchmark Points - $\text{Max } \sigma(SS/hS \rightarrow (b\bar{b})(b\bar{b}))$

C2HDM T1			NMSSM - 2		
$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.09	$3.74 \cdot 10^{-3}$	$m_{H_1(S)}/\Gamma_{\text{tot}}$ [GeV]	100.11	$1.00 \cdot 10^{-3}$
$m_{H_2(S)}/\Gamma_{\text{tot}}$ [GeV]	131.48	$7.95 \cdot 10^{-4}$	$m_{H_2}/\Gamma_{\text{tot}}$ [GeV]	125.23	$3.57 \cdot 10^{-3}$
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	313.33	6.45	$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	660.38	7.80
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	311.54	5.79	$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	651.11	7.54
			$m_{A_1(S)}/\Gamma_{\text{tot}}$ [GeV]	217.21	$6.92 \cdot 10^{-4}$
			$m_{A_2}/\Gamma_{\text{tot}}$ [GeV]	657.01	8.73
$\sigma_{SS}^{\text{LO}}$ [pb]	3.20				
$\sigma_{SS \rightarrow 4b}^{\text{LO}}$ [pb]	1.26				
$\sigma_{Sh}^{\text{LO}}$ [fb]	49.17		$\sigma_{H_S h}^{\text{LO}}$ [fb]	15.68	
$\sigma_{Sh \rightarrow 4b}^{\text{LO}}$ [fb]	17.79		$\sigma_{H_S h \rightarrow 4b}^{\text{LO}}$ [fb]	8.43	
$\mathcal{L}_{\text{excl}}$ [fb $^{-1}$ ]	287			183	

◇ C2HDM:  $S$  here means large pseudoscalar admixture

◇ C2HDM:  $H_2 H_2 = SS$  enhancement due to resonant  $H_3$  production w/ decay into  $SS$

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## Conclusions

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### ◇ Di-Higgs Production

- \* requires sophisticated experimental techniques & high precision theory predictions

### ◇ Beyond the Standard Model

- \* Higgs pair production can be enhanced
- \* New: 2 different Higgs bosons in the final state; cascade Higgs-to-Higgs decays in non-minimal Higgs sector extensions

### ◇ Higgs Pair Production in Benchmark Models

- \* C2HDM and NMSSM show these features

*Thank You For Your Attention!*



# KIT-NEP '19

Theory Challenges in  
Higher-Order New Physics Calculations

7-9 October 2019  
Karlsruhe Institute of Technology

Organizing Committee

Margarete Mühlleitner  
Seraina Glaus  
Marcel Krause  
Stefan Liebler  
Shruti Patel

 <https://indico.scc.kit.edu/event/573/>

 [kit-nep@lists.kit.edu](mailto:kit-nep@lists.kit.edu)

  
Karlsruhe Institute of Technology

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## Combination *D*irect and *I*ndirect $\mathcal{E}$ ffects

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- **A (more) global view on the Higgs self-coupling:**

- \*  $\lambda_{3H}$  constrained at  $e^+e^-$  via quantum corrections in single  $H$  production [McCullough]
- \* indirect measurement of  $\lambda_{3H}$  through EW corrections in single  $H$  processes at LHC [Gorbahn,Haisch; Degrassi eal; Bizon eal]
- \* EW precision measurements to constrain  $\lambda_{3H}$  [Degrassi eal; Kribs eal]
- \* joined analysis of  $\lambda_{3H}$  indirect effects on single  $H$  production and direct effects on di-Higgs production; differential distributions crucial [Di Vita eal (also ee); Maltoni eal]

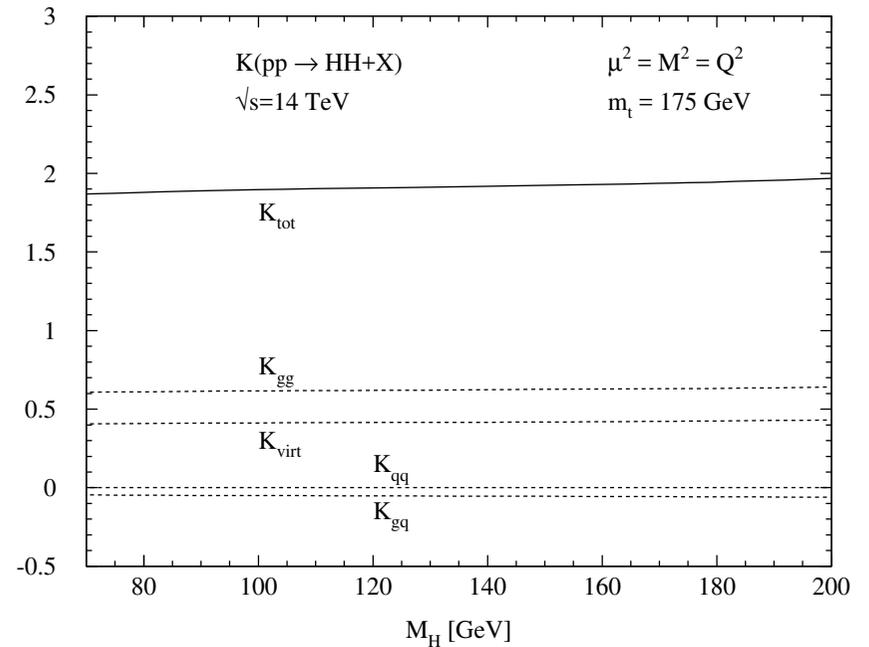
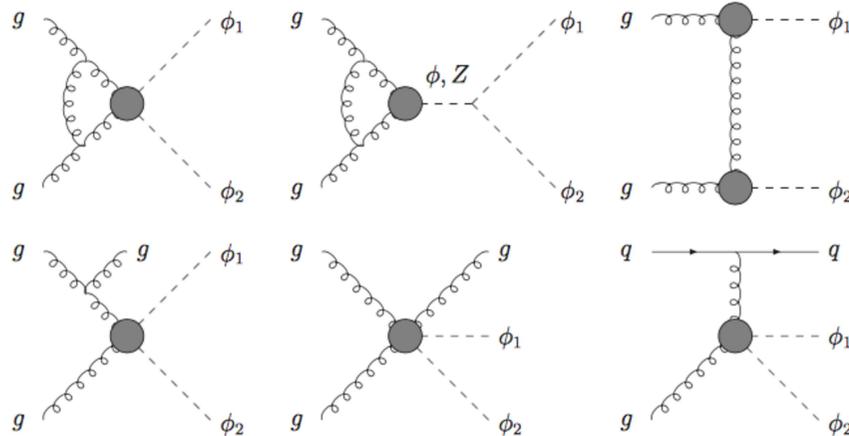
# Main Production Channel at the $\mathcal{LHC}$

- **Gluon fusion:** loop induced, third generation dominant  $\rightsquigarrow t, b$



- **NLO QCD corrections (HTL):**  $\sim 90 - 100\%$  [ $M_H^2 \ll 4m_t^2, \mu = M_{HH}$ ]

[Dawson, Dittmaier, Spira]



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## Status Higher Order Corrections

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- 2-loop QCD corrections      large top mass expansion,  $\pm 10\%$       Grigo, Hoff, Melnikov, Steinhauser
- NLO mass effects @ NLO  
in real corrections       $\sim -10\%$       Frederix, Frixione, Hirschi, Maltoni,  
Mattelaer, Torrielli, Vryonidou, Zaro
- NNLO QCD corrections       $M_H^2 \ll 4m_t^2, \sim 20\%$       de Florian, Mazzitelli;  
Grigo, Melnikov, Steinhauser
- Soft gluon resummation       $M_H^2 \ll 4m_t^2, \sim 10\%$       Shao, Li, Li, Wang;  
de Florian, Mazzitelli
- NLO: small quark mass exp.       $Q^2 \gg m_t^2$       Davies, Mishima,  
Steinhauser, Wellmann
- NNLO Monte Carlo      full top-mass effects @ NLO,  
+10 to +20% in distributions      Grazzini, Heinrich, Jones,  
Kallweit, Kerner, Lindert, Mazzitelli
- At NLO      matching to parton showers      Heinrich, Jones, Kerner,  
Luisoni, Vryonidou

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## Full NLO Calculation

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- **Full NLO calculation: top only**

Borowka, Greiner, Heinrich, Jones,  
Kerner, Schlenk, Schubert, Zirke

numerical integration, sector decomposition, tensor reduction, contour deformation

$$14\text{TeV: } (m_t = 173\text{GeV}) \quad \sigma_{\text{NLO}} = 32.91(10)_{-12.8\%}^{+13.8\%} \text{ fb}$$
$$\sigma_{\text{NLO}}^{\text{HTL}} = 38.75_{-15\%}^{+18\%} \text{ fb} \quad (\leftarrow \text{HPAIR})$$

⇒ -15% mass effects on top of LO

→ T

- **New expansion/extrapolation methods:**

(i)  $1/m_t^2$  expansion + conformal mapping + Padé approximants

Gröber, Maier, Rauh

(ii)  $p_T^2$  expansion

Bonciani, Degrassi, Giardino, Gröber

- **Full NLO calculation: top only** first independent cross-check

Baglio, Campanario, Glaus  
MM, Spira, Streicher

numerical integration, IR subtraction, no tensor reduction, Richardson extrapolation

$$14\text{TeV: } (m_t = 172.5\text{GeV}) \quad \sigma_{\text{NLO}} = 32.78(7)_{-12.5\%}^{+13.5\%} \text{ fb}$$
$$\sigma_{\text{NLO}}^{\text{HTL}} = 38.66_{-15\%}^{+18\%} \text{ fb} \quad (\leftarrow \text{HPAIR})$$

⇒ -15% mass effects on top of LO

→ T

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## The $\mathcal{NMSSM}$ Higgs Sector

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- **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  $\rightsquigarrow$

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

7 Higgs bosons:  $H_1, H_2, H_3, A_1, A_2, H^+, H^-$

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

- **Significant changes of Higgs boson phenomenology**

## The C2HDM

$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[ m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right].$$

- **CP Violation:**  $m_{12}^2$ ,  $\lambda_5$  can be complex (all others real);  $m_{12}^2 \neq \lambda_5 \rightsquigarrow$  CP violation
- **Particle content:**
  - 3 neutral CP-mixing Higgs bosons  $H_1, H_2, H_3$
  - 1 charged Higgs pair  $H^\pm$
- **Flavour-Changing Neutral Currents (FCNC) at tree-level:** forbidden by  $\mathbb{Z}_2$  symmetry

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2.$$

	Type I	Type II	Lepton-Specific	Flipped
Up-type quarks	$\Phi_2$	$\Phi_2$	$\Phi_2$	$\Phi_2$
Down-type quarks	$\Phi_2$	$\Phi_1$	$\Phi_2$	$\Phi_1$
Leptons	$\Phi_2$	$\Phi_1$	$\Phi_1$	$\Phi_2$

## The C2HDM

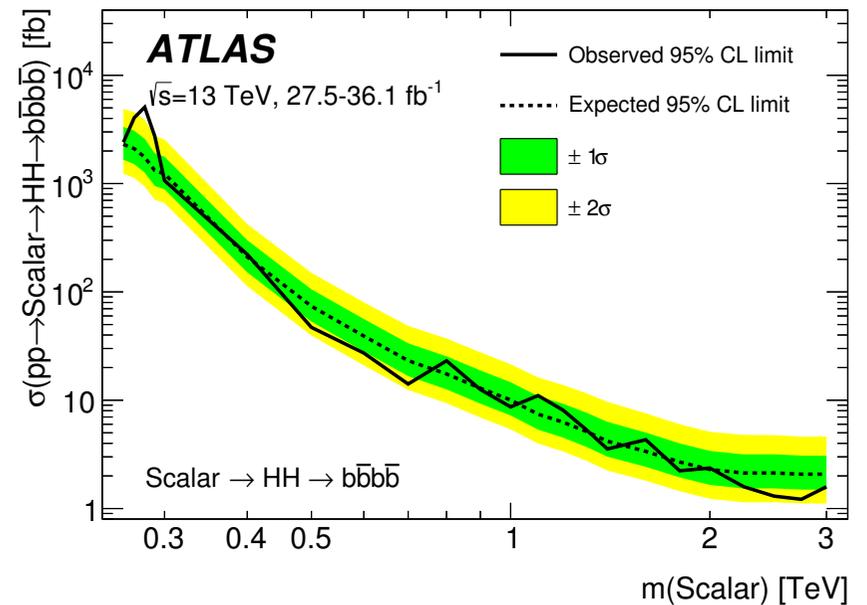
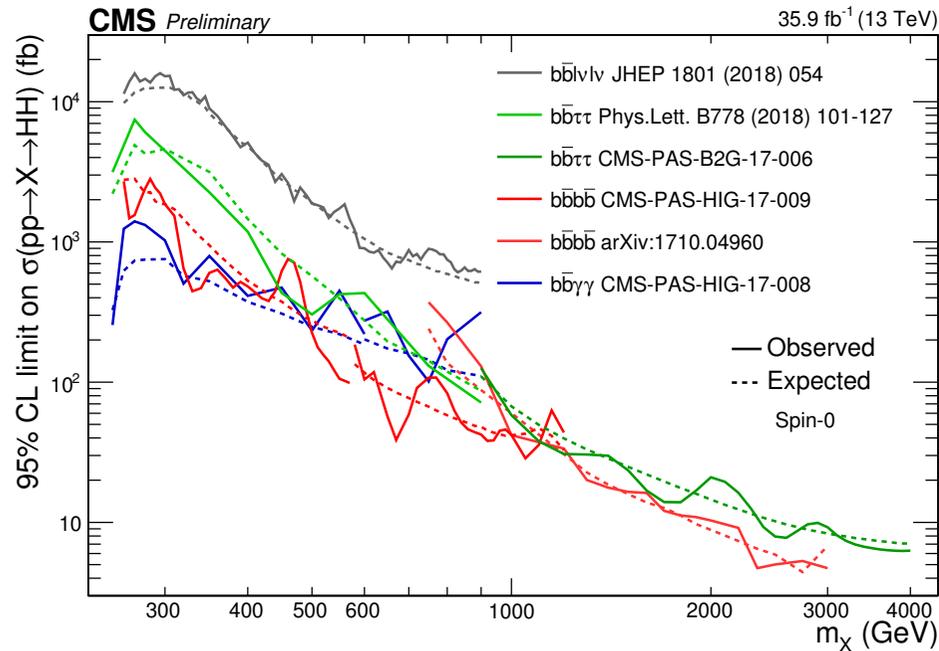
$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[ m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right].$$

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Leptons	$\Phi_2$	$\Phi_1$	$\Phi_1$	$\Phi_2$

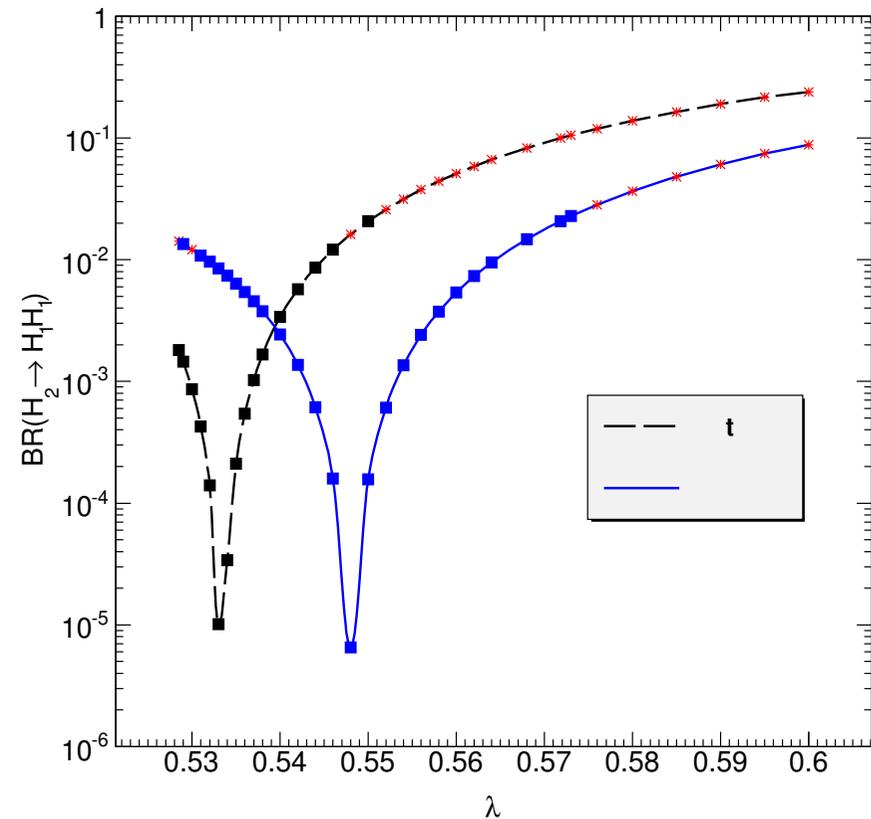
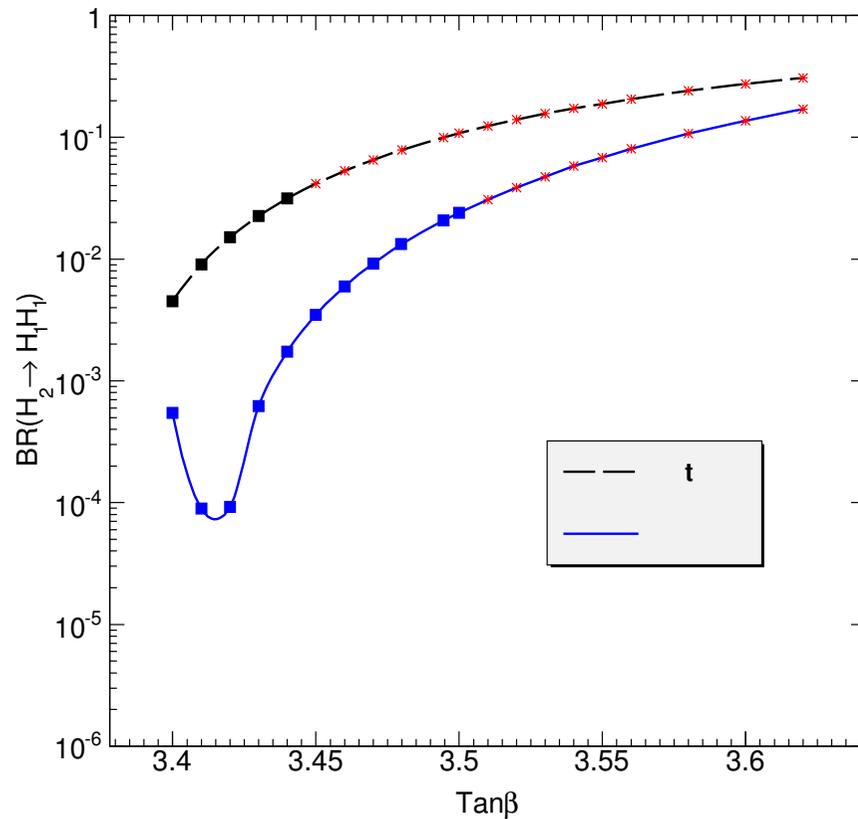
# Experimental Results - Implications for BSM SM-like Higgs Pair Production



- limits  $\mathcal{O}(\text{pb})$  for  $m_X \leq 300$  GeV
- limits  $\mathcal{O}(\text{fb})$  for  $m_X \geq 1$  TeV  $\rightsquigarrow$  severely limits enhancement in  $hh$  production

# Impact of Loop-Corrected Self-Coupling on (Non-)Exclusion

[Dao,MMM,Streicher,Walz]



$H_2 \equiv 125$  GeV Higgs; dashed - tree-level; full - loop-corrected; red - excluded

# (1) C2HDM Benchmark Point - Max $\sigma(hh \rightarrow (b\bar{b})(b\bar{b}))$

$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.09	$3.64 \cdot 10^{-3}$
$m_{H_2}/\Gamma_{\text{tot}}$ [GeV]	310.99	0.35
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	314.63	1.44
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	372.62	0.99
$\sigma_{hh}^{\text{LO}}$ [fb]	781	
$\sigma_{hh \rightarrow 4b}^{\text{LO}}/\text{wrt. SM}$ [fb]	261	42
$\mathcal{L}_{\text{excl}}$ [fb $^{-1}$ ]	266	
$\text{Re}(m_{12}^2)$ [GeV $^2$ ]	14860	
$\alpha_1$	1.160	
$\alpha_2$	$-6.066 \cdot 10^{-3}$	
$\alpha_3$	1.2338	
$\tan \beta$	5.088	
$R_{13}^2$	$3.680 \cdot 10^{-5}$	
$R_{23}^2$	0.890	
$R_{33}^2$	0.110	

◇  $R_{i3}^2$  quantifies  
singlet admixture

◇  $\sigma^{\text{NLO}} \sim 2\sigma^{\text{LO}}$

◇ enhancement due to  
resonant  $H_2, H_3$  production  
w/ subsequent decay into  $hh$ :  
 $\text{BR}(H_2 \rightarrow hh) = 0.428$ ,  
 $\text{BR}(H_3 \rightarrow hh) = 0.707$

## (2) C2HDM Benchmark Point - Max $\sigma(SS/hS \rightarrow (b\bar{b})(b\bar{b}))$

$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.09	$3.74 \cdot 10^{-3}$
$m_{H_2(S)}/\Gamma_{\text{tot}}$ [GeV]	131.48	$7.95 \cdot 10^{-4}$
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	313.33	6.45
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	311.54	5.79
$\sigma_{SS}^{\text{LO}}$ [pb]	3.20	
$\sigma_{SS \rightarrow 4b}^{\text{LO}}$ [pb]	1.26	
$\sigma_{Sh}^{\text{LO}}$ [fb]	49.17	
$\sigma_{Sh \rightarrow 4b}^{\text{LO}}$ [fb]	17.79	
$\mathcal{L}_{\text{excl}}$ [fb $^{-1}$ ]	287	
$\text{Re}(m_{12}^2)$ [GeV $^2$ ]	13786	
$\alpha_1$	1.041	
$\alpha_2$	0.0262	
$\alpha_3$	-1.570	
$\tan \beta$	2.220	

◇  $S$  here means large pseudoscalar admixture

◇  $\sigma^{\text{NLO}} \sim 2\sigma^{\text{LO}}$

◇  $H_2H_2 = SS$  enhancement due to resonant  $H_3$  production w/ subsequent decay into  $SS$ :  
BR( $H_3 \rightarrow SS$ ) = 0.456

◇  $R_{13}^2 = 6.838 \cdot 10^{-4}$ ,  
 $R_{23}^2 = 0.999$   
 $R_{33}^2 = 1.412 \cdot 10^{-7}$

### (3) $\mathcal{N}$ MSSM Benchmark Points - Max $\sigma(hh \rightarrow (b\bar{b})(b\bar{b}))$

$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.03	$3.60 \cdot 10^{-3}$	
$m_{H_2(S)}/\Gamma_{\text{tot}}$ [GeV]	170.66	0.27	$\diamond H_2$ singlet-like scalar
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	454.90	2.80	$A_1$ singlet-like pseudoscalar
$m_{A_1(S)}/\Gamma_{\text{tot}}$ [GeV]	69.03	$7.26 \cdot 10^{-5}$	$\diamond \sigma^{\text{NLO}} \sim 2\sigma^{\text{LO}}$
$m_{A_2}/\Gamma_{\text{tot}}$ [GeV]	446.26	4.34	
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	440.31	3.77	
$\sigma_{hh}^{\text{LO}}$ [fb]	34.18		
$\sigma_{hh \rightarrow 4b}^{\text{LO}}/\text{wrt. SM}$ [fb]	12.42	1.99	
$\mathcal{L}_{\text{excl}}$ [ $\text{fb}^{-1}$ ]	287		
$\tan \beta$	2.919		
$\lambda$	0.613		
$\kappa$	0.331		
$A_\lambda$ [GeV]	-348		
$A_\kappa$ [GeV]	-51		
$\mu_{\text{eff}}$ [GeV]	-159		

### (3) $\mathcal{N}$ MSSM Benchmark Points - Also Max $\sigma(hA_S, A_S A_S \rightarrow (b\bar{b})(b\bar{b}))$

$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.03	$3.60 \cdot 10^{-3}$
$m_{H_2(S)}/\Gamma_{\text{tot}}$ [GeV]	170.66	0.27
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	454.90	2.80
$m_{A_1(S)}/\Gamma_{\text{tot}}$ [GeV]	69.03	7.26
$m_{A_2}/\Gamma_{\text{tot}}$ [GeV]	446.26	4.34
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	440.31	3.77
$\sigma_{hA_S}^{\text{LO}}$ [fb]	69.97	
$\sigma_{hA_S \rightarrow 4b}^{\text{LO}}$ [fb]	38.32	
$\sigma_{A_S A_S}^{\text{LO}}$ [fb]	69.78	
$\sigma_{A_S A_S \rightarrow 4b}^{\text{LO}}$ [fb]	57.58	
$\mathcal{L}_{\text{excl}}$ [fb $^{-1}$ ]	287	

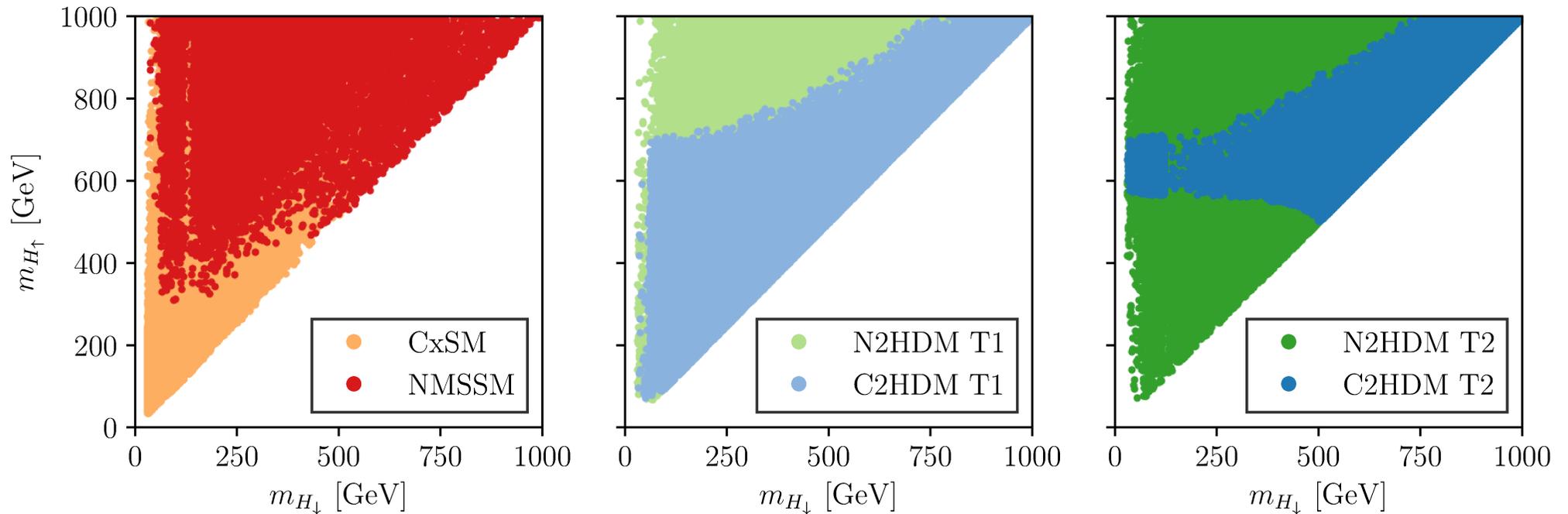
- ◇  $H_2$  singlet-like scalar  
 $A_1$  singlet-like pseudoscalar
- ◇  $\sigma^{\text{NLO}} \sim 2\sigma^{\text{LO}}$
- ◇  $hA_S$  enhancement due to resonant  $A_2$  production w/ subsequent decay into  $hA_{1(S)}$
- ◇  $A_S A_S$  enhancement due to resonant  $H_2$  production w/ subsequent decay into  $A_S A_S$ : BR( $H_2 \rightarrow A_S A_S$ )=0.97

## (4) $\mathcal{N}MSSM$ Benchmark Points - Max $\sigma(hH_S \rightarrow (b\bar{b})(b\bar{b}))$

$m_{H_1(S)}/\Gamma_{\text{tot}}$ [GeV]	100.11	$1.00 \cdot 10^{-3}$	$\diamond H_1$ singlet-like scalar $A_1$ singlet-like pseudoscalar  $\diamond \sigma^{\text{NLO}} \sim 2\sigma^{\text{LO}}$
$m_{H_2}/\Gamma_{\text{tot}}$ [GeV]	125.23	$3.56 \cdot 10^{-3}$	
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	660.38	7.80	
$m_{A_1(S)}/\Gamma_{\text{tot}}$ [GeV]	217.21	$6.92 \cdot 10^{-4}$	
$m_{A_2}/\Gamma_{\text{tot}}$ [GeV]	657.01	8.73	
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	651.11	7.54	
$\sigma_{hH_S}^{\text{LO}}$ [fb]	<b>15.68</b>		
$\sigma_{hH_S \rightarrow 4b}^{\text{LO}}$ [fb]	<b>8.43</b>		
$\mathcal{L}_{\text{excl}}$ [fb $^{-1}$ ]	<b>183</b>		
$\tan \beta$	3.601		
$\lambda$	0.589		
$\kappa$	0.251		
$A_\lambda$ [GeV]	593		
$A_\kappa$ [GeV]	-148		
$\mu_{\text{eff}}$ [GeV]	178		

## Mass Distributions

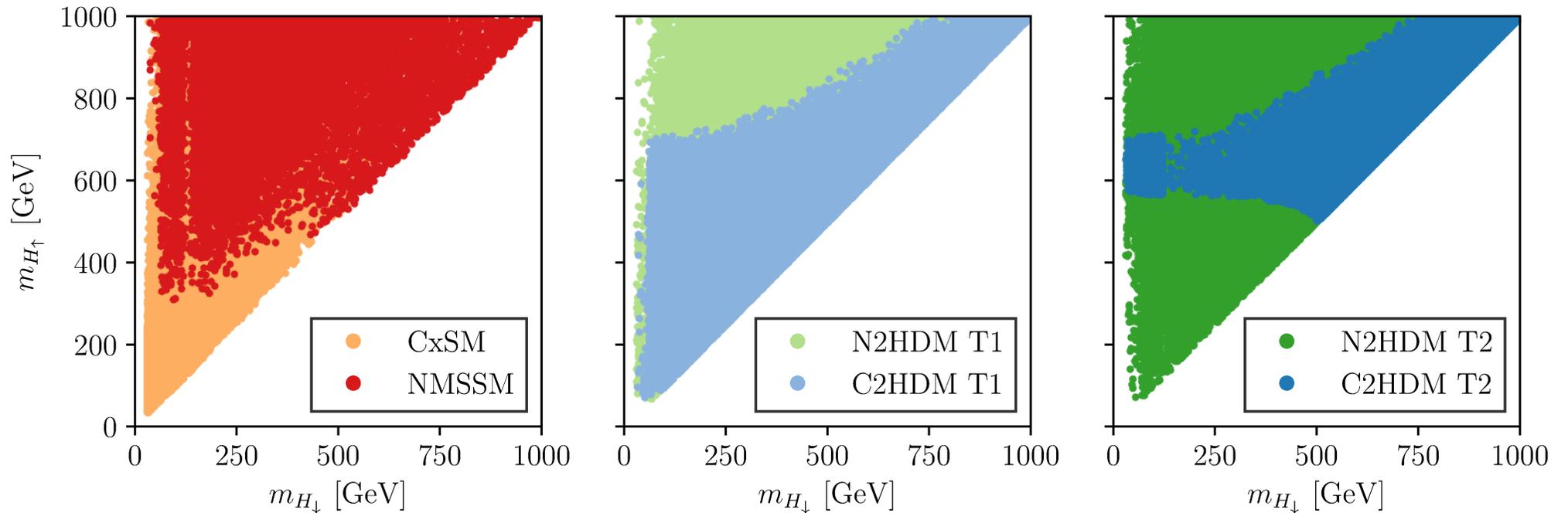
[MM,Sampaio,Santos,Wittbrodt '17]



- Tools for scan: ScannerS, sHDECAY, N2HDECAY
- Degenerate Higgs bosons around 125 GeV not included
- Includes latest bound on  $M_{H^{\pm}}$  (2HDM II)  $> 580$  GeV [Misiak,Steinhauser '17]

## Mass Distributions

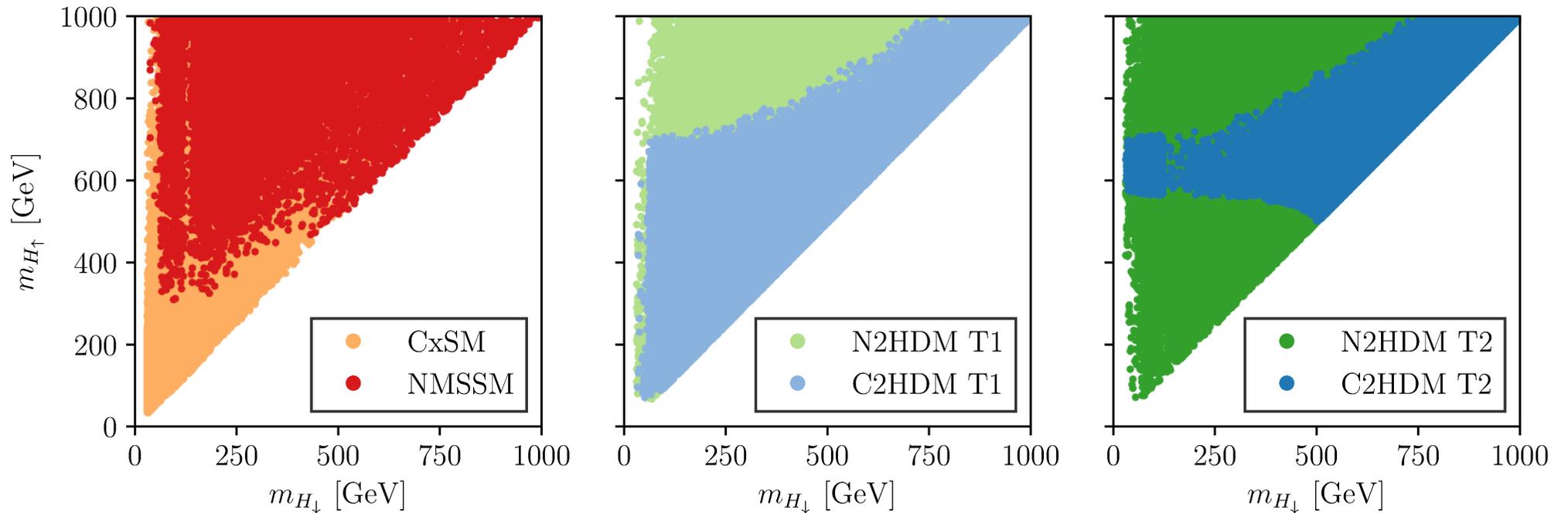
[MM,Sampaio,Santos,Wittbrodt '17]



- All models:  $m_{H_\downarrow} < m_{h_{125}}$  possible (C2HDM: only in the real 2HDM limit)
- Type I N2HDM, CxSM, C2HDM:  $m_{H_\uparrow} < m_{h_{125}}$  possible
- Pseudoscalars (N2HDM, NMSSM) can be lighter than 125 GeV

# Mass Distributions

[MM,Sampaio,Santos,Wittbrodt '17]



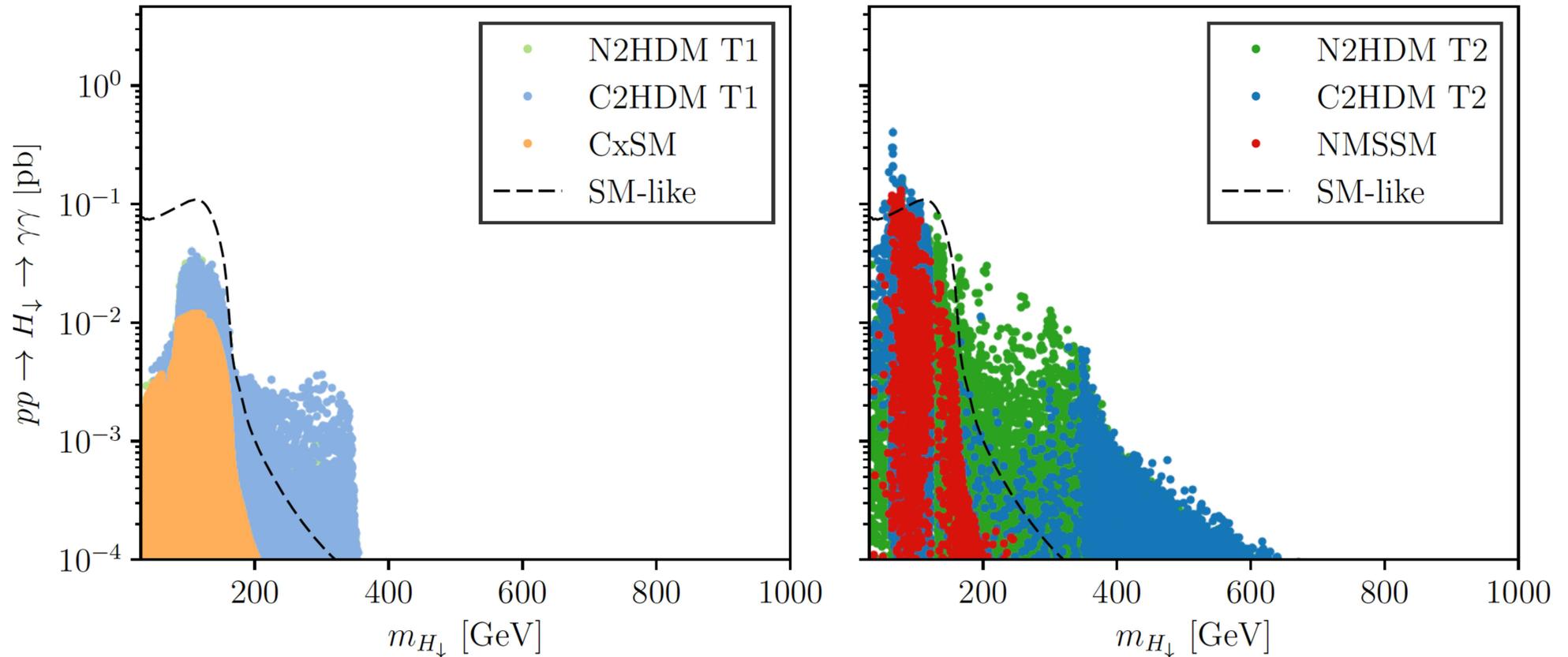
**Goals for experiment:** - Search for Higgs states below 125 GeV:

- into SM final states:  $\gamma\gamma, \tau\tau$

- in Higgs-to-Higgs decays; Higgs  $\rightarrow$  Higgs + gauge boson; SUSY particle final states

## Decay Rates in Photon Final States

[MM,Sampaio,Santos,Wittbrodt '17]



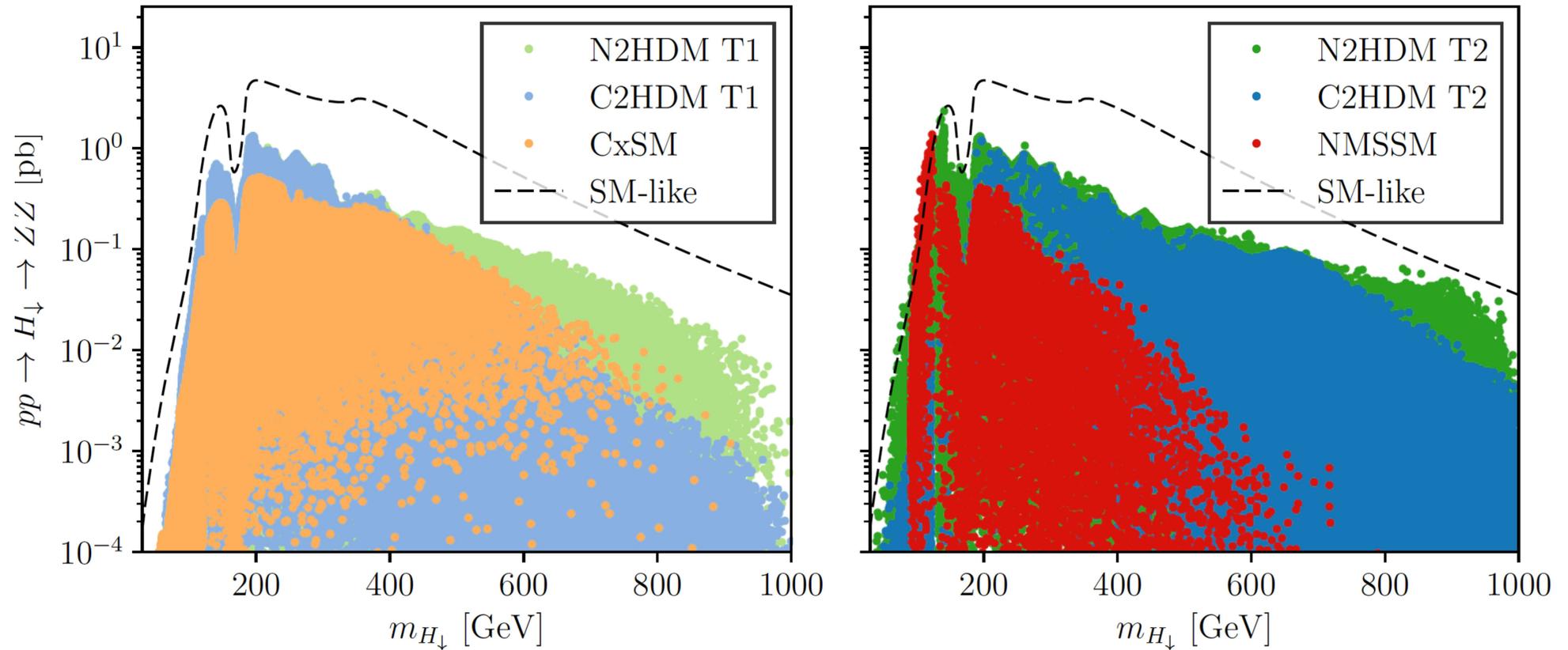
Comments: - Enhanced rates below 125 GeV in NMSSM, type II N2HDM and C2HDM

- **Experiments:** test low mass region to probe the models

- **Distinction based on rates:** rates  $> 5$  fb in 130...350 GeV single out N2HDM II

## Decay Rates in $Z$ Boson Final States

[MM,Sampaio,Santos,Wittbrodt '17]



Comments: - Highest rates for large masses in N2HDM

- **Experimental:** Test high-mass region to probe model

- **Distinction based on rates:** observation of scalar w/  $\mathcal{O}(100)$  fb above 380 GeV excludes NMSSM

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## Calculation

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$$\sigma_{\text{NLO}} = \sigma_{\text{LO}} + \Delta\sigma_{\text{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}},$$

with

$$\begin{aligned} \sigma_{\text{LO}} &= \int_{\tau_0}^1 d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\text{LO}}(Q^2 = \tau s), \\ \Delta\sigma_{\text{virt}} &= \frac{\alpha_s(\mu_R^2)}{\pi} \int_{\tau_0}^1 d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\text{LO}}(Q^2 = \tau s) C_{\text{virt}}(Q^2), \\ \Delta\sigma_{ij} &= \frac{\alpha_s(\mu_R^2)}{\pi} \int_{\tau_0}^1 d\tau \frac{d\mathcal{L}^{ij}}{d\tau} \int_{\frac{\tau_0}{\tau}}^1 \frac{dz}{z} \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s) C_{ij}(z) \end{aligned}$$

where

$$\begin{aligned} C_{gg} &= -zP_{gg}(z) \log \frac{\mu_F^2}{\tau s} + d_{gg}(z) + 6[1 + z^4 + (1 - z)^4] \left( \frac{\log(1 - z)}{1 - z} \right)_+, \\ C_{gq} &= -\frac{z}{2} P_{gq}(z) \log \frac{\mu_F^2}{\tau s(1 - z)^2} + d_{gq}(z), \\ C_{q\bar{q}} &= d_{q\bar{q}}(z) \end{aligned}$$

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## Calculation Continued

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In the heavy top limit (HTL)

$$C_{\text{virt}} \rightarrow \pi^2 + \frac{11}{2} + C_{\Delta\Delta}$$

$$d_{gg} \rightarrow -\frac{11}{2}(1-z)^3$$

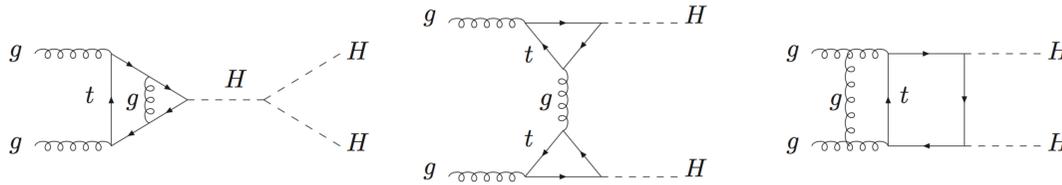
$$d_{gq} \rightarrow \frac{2}{3}z^2 - (1-z)^2,$$

$$d_{q\bar{q}} \rightarrow \frac{32}{27}(1-z)^3$$

# Virtual Corrections

- Virtual corrections

47 generic box diagrams, 8 triangle diagrams ( $\leftarrow$  single Higgs), 1PR ( $\leftarrow H \rightarrow Z\gamma$ )



- \* full diagram w/o tensor reduction  $\rightarrow$  6-dim. Feynman integral

- \* UV singularities: end-point subtractions

$$\int_0^1 dx \frac{f(x)}{(1-x)^{1-\epsilon}} = \int_0^1 dx \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx \frac{f(x) - f(1)}{(1-x)^{1-\epsilon}} = \frac{f(1)}{\epsilon} + \int_0^1 dx \frac{f(x) - f(1)}{1-x} + \mathcal{O}(\epsilon)$$

- \* IR singularities: IR subtraction (based on struc. of integrand and relative to HTL)

- \* thresholds:  $Q^2 \geq 0, 4m_t^2 \rightsquigarrow$  IBP  $\rightsquigarrow$  reduction of power of denominator

$$[m_t^2 \rightarrow m_t^2(1 - ih)]$$

$$\int_0^1 dx \frac{f(x)}{(a + bx)^3} = \frac{f(0)}{2a^2b} - \frac{f(1)}{2b(a+b)^2} + \int_0^1 dx \frac{f'(x)}{2b(a+bx)^2}$$

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## Virtual Corrections Continued

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- **Renormalization:**  $\alpha_s$ :  $\overline{\text{MS}}$ , 5 flavours,  $m_t$ : on-shell
- **Phase space integration:** 7-dim. integrals for  $d\sigma/dQ^2$
- **Infrared mass effects:** after subtraction of HTL [adding back HTL results obtained with HPAIR]
- **Richardson extrapolation:** extraction to narrow-width approximation ( $h \rightarrow 0$ )

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## Real Corrections

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- **Real Corrections:**

- full matrix elements generated with FeynArts and FormCalc
- matrix elements in HTL involving full LO sub-matrix elements subtracted  $\rightsquigarrow$  IR-, COLL-finite  
[adding back HTL results obtained from HPAIR]