Higgs Pair Production in the SM and Beyond

Milada Margarete Mühlleitner (KIT)

HPNP 2019

'Higgs as a Probe of New Physics'

Oksaka University, 18-22 Feb 2019

$\mathcal{O}$utline

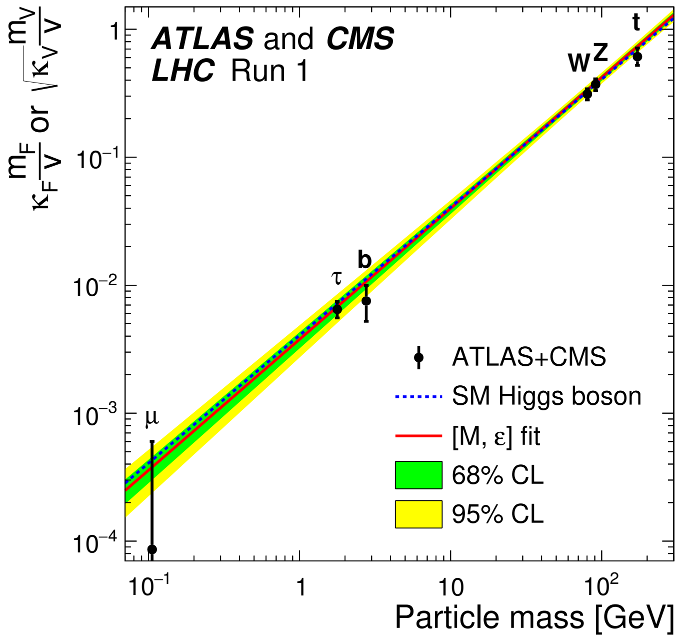
- ◇ Motivation for Higgs pair production
- ◇ Higher-order corrections to Higgs pair production
  - ∗ Mass effects at NLO
- ◇ Di-Higgs production beyond the Standard Model
  - ∗ New physics effects
- ◇ Di-Higgs production in sample benchmark models
  - ∗ C2HDM and NMSSM
- ◇ Higgs self-couplings and baryogenesis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

Disclaimer: Main focus on own work

Motivation

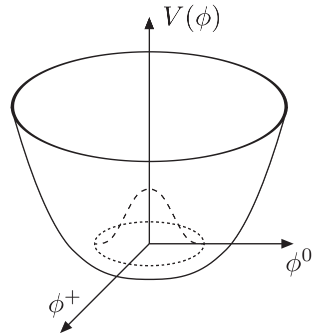
- **Higgs Discovery $\rightsquigarrow$ New Era of Particle Physics**
  - Structurally completes SM, self-consistent framework to describe physics up to the Planck scale
- **SM Higgs couplings:**
  - $g_{Hf\bar{f}} \sim \frac{m_f}{v}$ and $\sqrt{g_{HVV}} \sim \frac{m_V}{v}$
- **Higgs self-coupling strength:**
  - still unknown

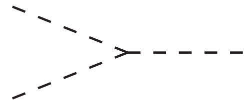
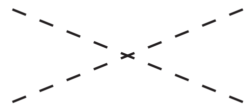
[ATLAS/CMS, JHEP08(2016)045]



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:

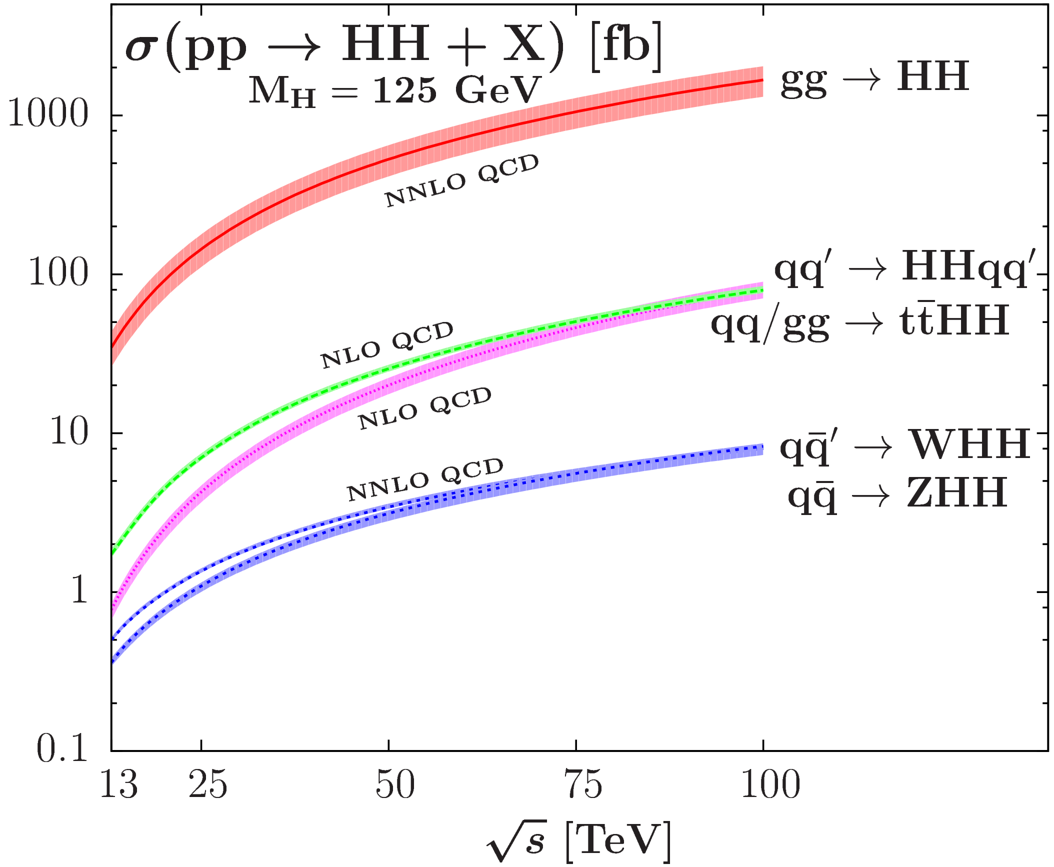
$\boldsymbol{\lambda_{HHH}}$ via pair production

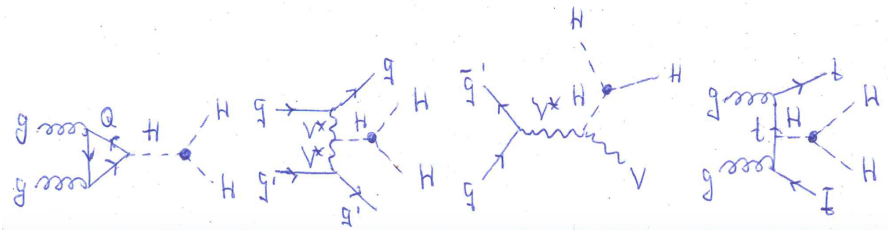
$\boldsymbol{\lambda_{HHHH}}$ via triple production

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

$\mathcal{D}$ouble $\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{P}$rocesses

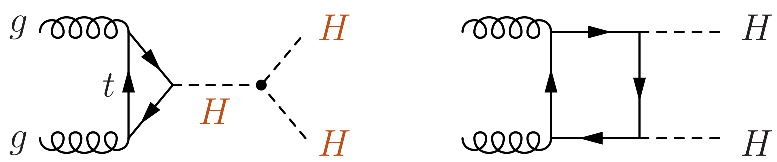
Baglio,Djouadi,Quevillon





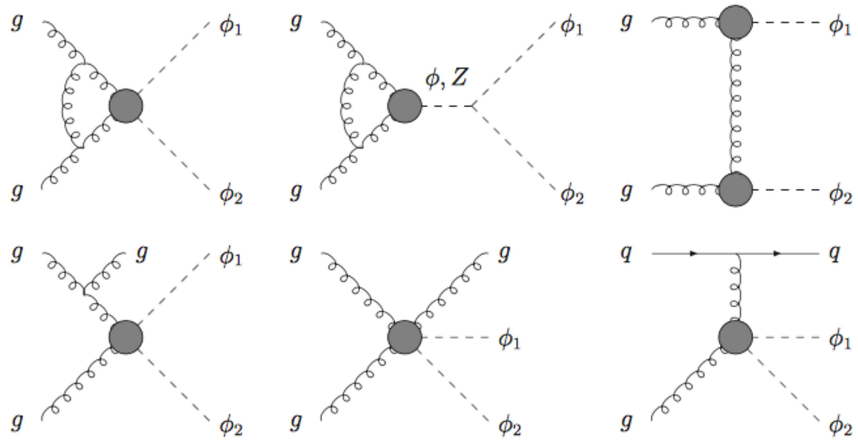
Higher-Order Corrections

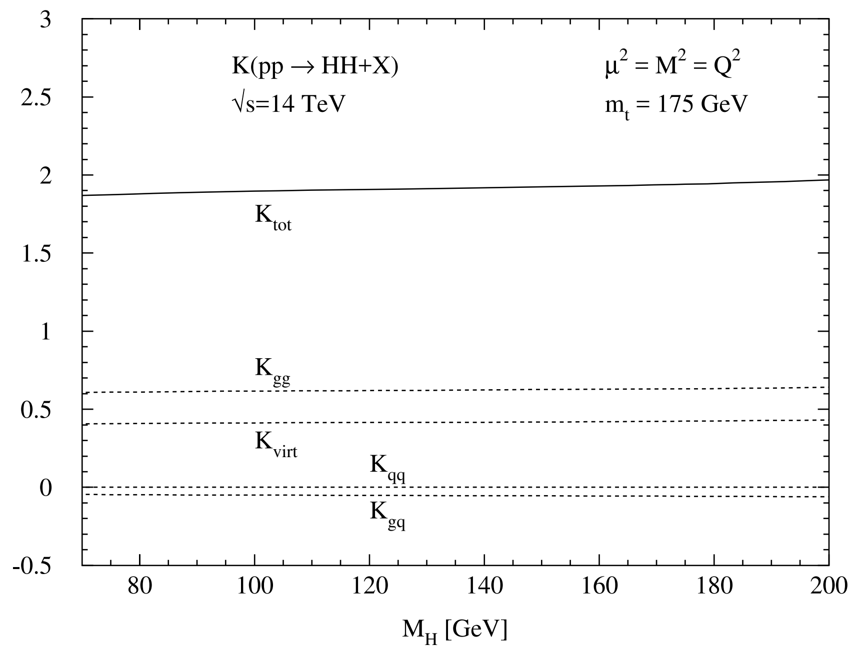
- **Gluon fusion:** loop induced, third generation dominant $\rightsquigarrow t, b$



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

[Dawson,Dittmaier,Spira]





Status Higher Order Corrections

• 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

$\mathcal{F}$ull $\mathcal{N}$LO $\mathcal{C}$alculation

- **Full NLO calculation:** top only

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

  numerical integration, sector decomposition, tensor reduction, contour deformation

  14TeV: $(m_t = 173\text{GeV})$ $\sigma_{\text{NLO}} = 32.91(10)^{+13.8\%}_{-12.8\%}$ fb

  $\sigma^{\text{HTL}}_{\text{NLO}} = 38.75^{+18\%}_{-15\%}$ fb ($\leftarrow$ HPAIR)

  $\Rightarrow$ -15% mass effects on top of LO $\rightarrow$ T

- **New expansion/extrapolation methods:**

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

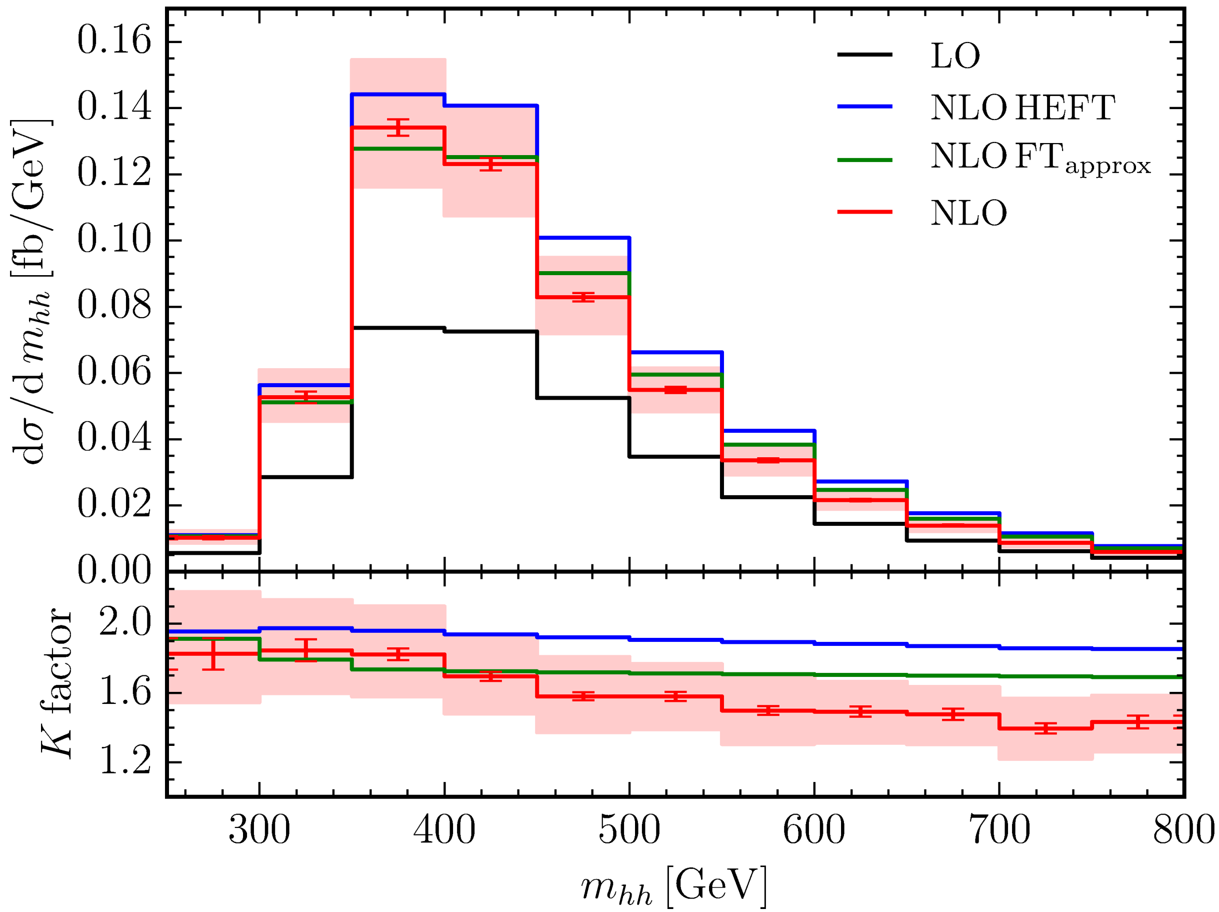
  14TeV: $(m_t = 172.5\text{GeV})$ $\sigma_{\text{NLO}} = 32.78(7)^{+13.5\%}_{-12.5\%}$ fb

  $\sigma^{\text{HTL}}_{\text{NLO}} = 38.66^{+18\%}_{-15\%}$ fb ($\leftarrow$ HPAIR)

  $\Rightarrow$ -15% mass effects on top of LO $\rightarrow$ T

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

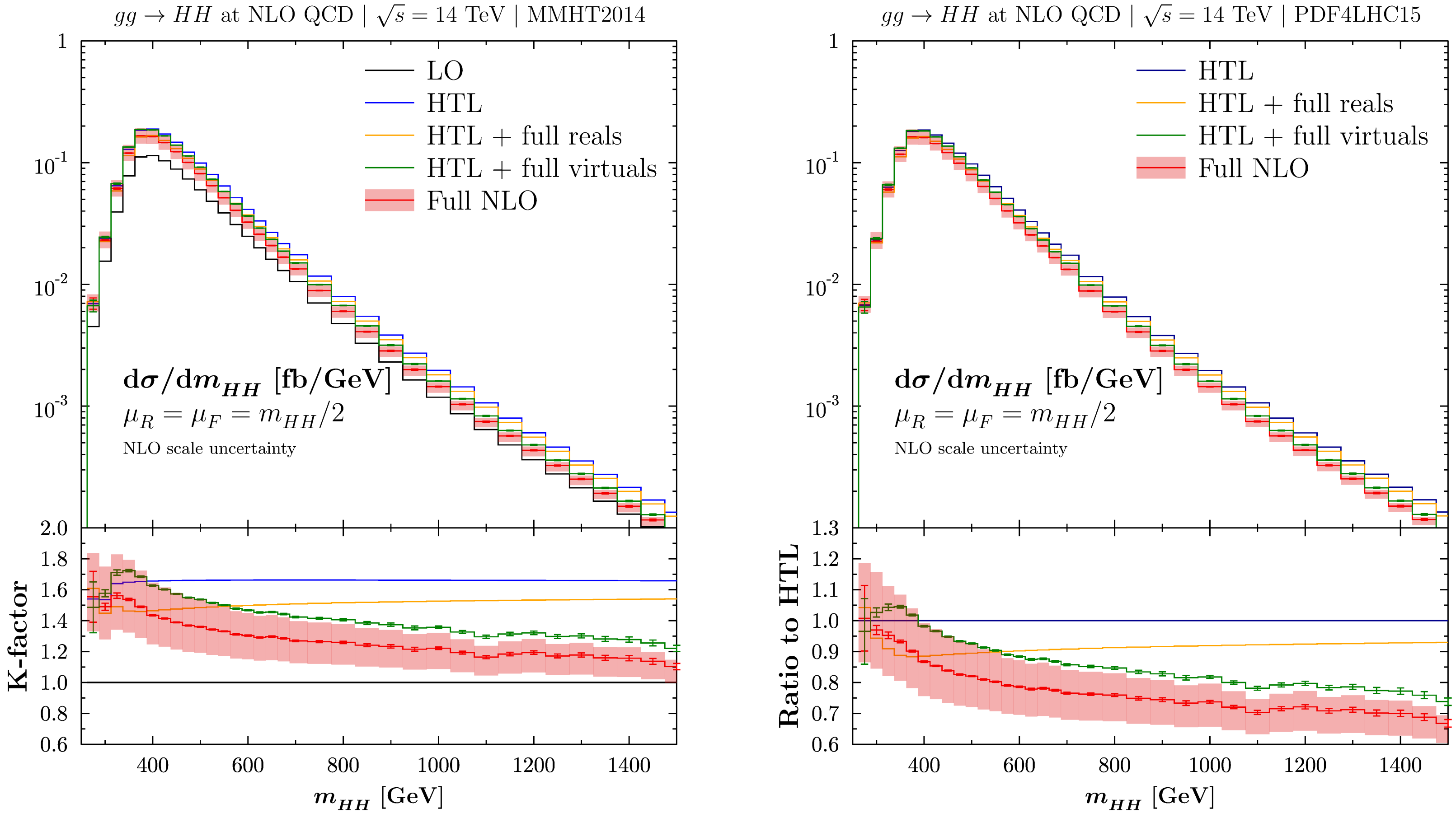


Red: full result w/ mass dependence; blue/green approximations; scale variation: $\mu = (0.5...2)m_{hh}/2$

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

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

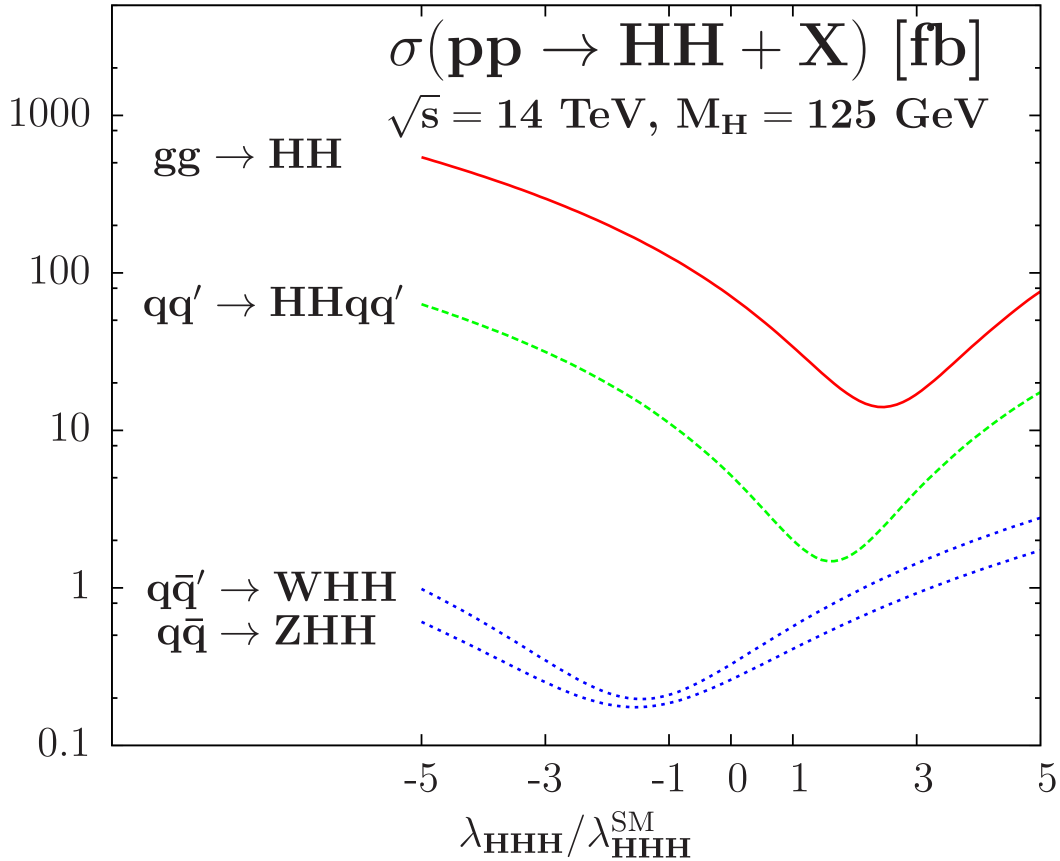
Baglio,Campanario.Glauss,MM,Streicher,Spira '18



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

$\mathcal{D}$ependence on $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling

Baglio,Djouadi,Gröber,MM,Quevillon,Spira

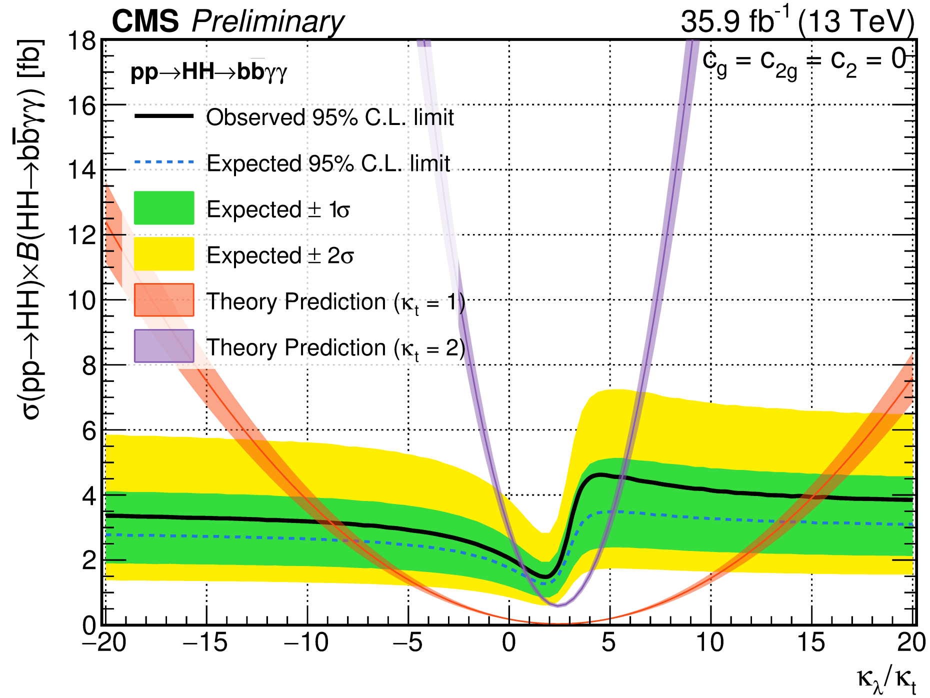


- threshold region sensitive to λ; large M_{HH} sensitive to New Physics
- $gg \to HH$: $\frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$; decreasing with M_{HH}^2

Challenge Di-Higgs Production

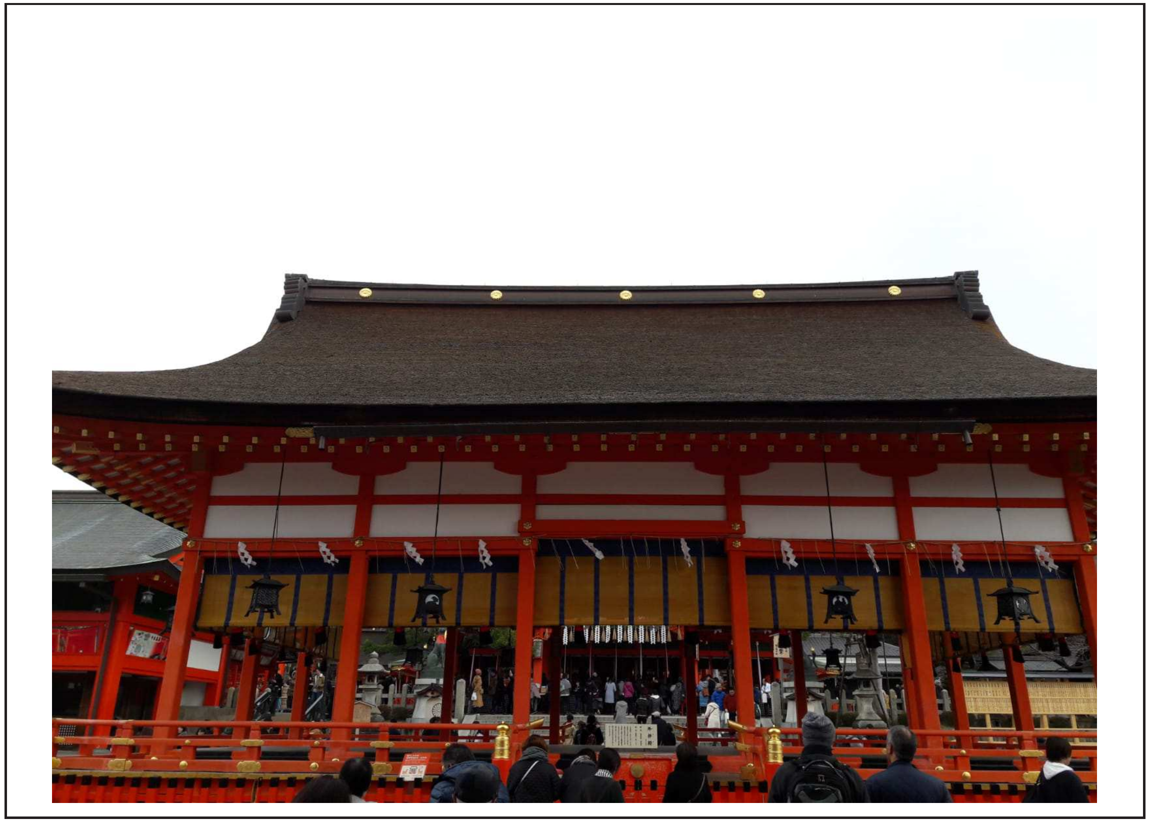
- **Small signal + large QCD background ⇝ Experimental challenge!**
  $\mathcal{O}(\pm(15-20)\lambda^{\text{SM}}_{HHH})$ [ATLAS,CMS]

[CMS-PAS-HIG-17-008]



- **Prospects in $b\bar{b}\gamma\gamma$ final state:** $-0.8 < \lambda_{hhh}/\lambda^{\text{SM}}_{hhh} < 7.7$ [ATL-PHYS-PUB-2017-001]

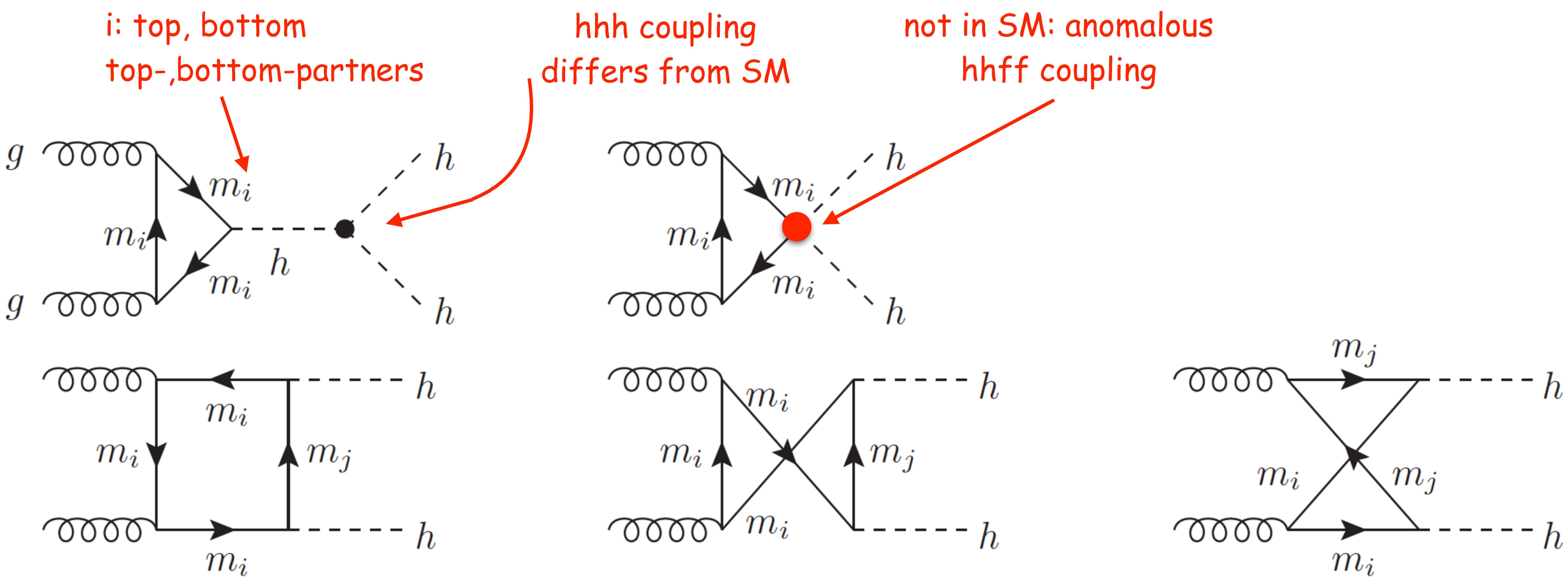
$\mathcal{B}$SM $\mathcal{H}$iggs $\mathcal{P}$air $\mathcal{P}$roduction



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

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

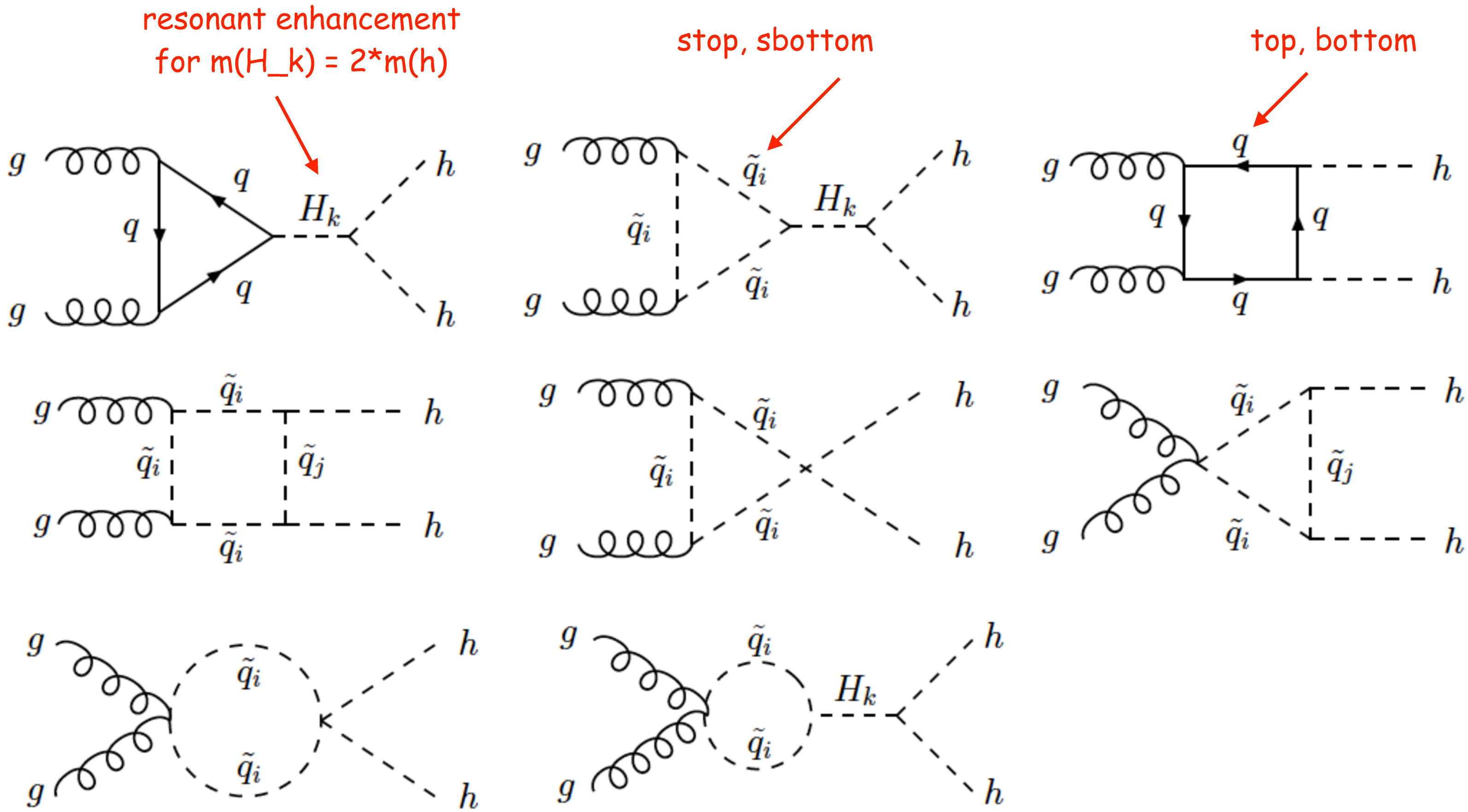
  $*$ different λ_{3H}; $*$ novel couplings; $*$ novel particles in the loop; $*$ resonant enhancement



Di-Higgs Production Beyond the SM

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

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



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

- **How large can λ_{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, Riembau, 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]

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

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

$\mathcal{H}$igher-$\mathcal{O}$rder $\mathcal{C}$orrections - $\mathcal{B}$eyond the $\mathcal{S}$M

- **Higher-order corrections to σ_{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; Moyoti eal; ...]
  - 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; Dobado eal; Arhrib eal; Aoki eal; Kanemura eal; Senaha; Spira,Brucherseifer; Nhung,MM,Streicher,Walz; MM,Nhung,Ziesche; Krause,Santos,MM,Ziesche; Braathen eal; ...]

  implementation in tools: `H-COUP` (renorm. Higgs couplings) [Kanemura,Kikuchi,Sakurai,Yagyu]
  `2HDECAY` (HO decays) [Krause,MM,Spira]

$\mathcal{N}$ew $\mathcal{T}$ool 2$\mathcal{H}$DECAY

- **2HDECAY:** [Krause,MM,Spira '18]

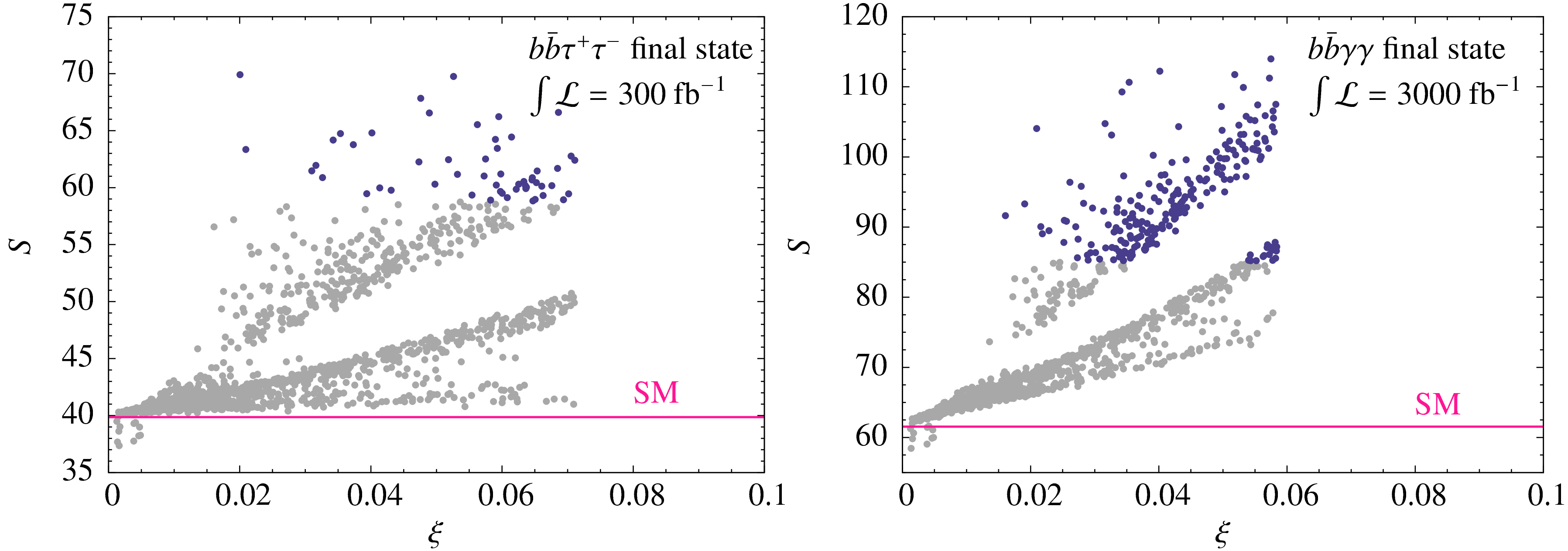
  A tool for the electroweak one-loop corrections to Higgs decays in the 2HDM including the state-of-the-art QCD corrections

- **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: $S_{\text{SM}} + 3\sqrt{S_{\text{SM}}} \leq S$ or $S_{\text{SM}} - 3\sqrt{S_{\text{SM}}} \geq S$

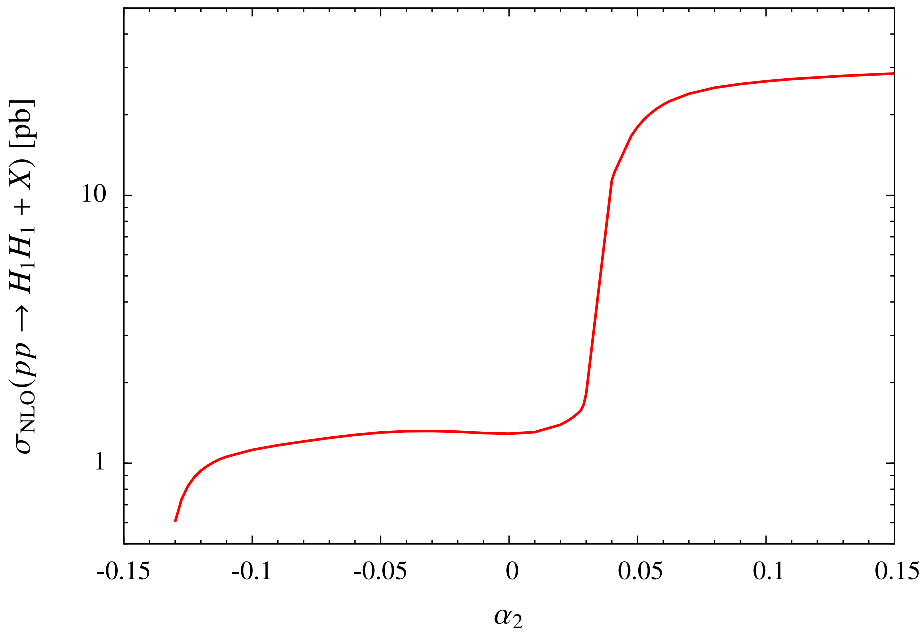
Assumption: Deviations of Higgs couplings to SM particles $<$ projected experimental sensitivity

$\mathcal{C}$2HDM $\mathcal{H}$iggs $\mathcal{P}$air $\mathcal{P}$roduction

- **3 CP-mixed neutral scalars in C2HDM:**
  Resonant heavy Higgs producion possible $\rightsquigarrow$ strong increase of cxn

α_2 CP mixing angle; cxn 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]

Benchmarks for Higgs Pair Production

$\mathcal{H}$iggs $\mathcal{P}$air $\mathcal{P}$roduction in $\mathcal{BSM}$ $\mathcal{S}$ample $\mathcal{M}$odels

- **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 $gg \to H_j H_k$ 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)

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

- **Next-to-Minimal Supersymmetric Extension of the SM: NMSSM**
  Fayet; Kaul eal; Barbieri eal; Dine eal; Nilles eal; Frere eal; Derendinger eal; Ellis eal;
  Drees; Ellwanger eal; Savoy; Elliott eal; Gunion eal; Franke eal; Maniatis; Djouadi eal; Mahmoudi eal; ...

- **SUSY Higgs Sector:** at least 2 complex Higgs doublets, NMSSM: plus complex singlet field $\rightsquigarrow$

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

7 Higgs bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0$ $(i = 1, ..., 5)$

- **Significant changes of Higgs boson phenomenology**

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, λ_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

$$\Phi_1 \to \Phi_1 \ , \qquad \Phi_2 \to -\Phi_2 \ .$$

	Type I	Type II	Lepton-Specific	Flipped
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Leptons	Φ_2	Φ_1	Φ_1	Φ_2

$\mathcal{T}$he $\mathcal{C}$2HDM

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

- **CP Violation:** m_{12}^2, λ_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

$$\Phi_1 \to \Phi_1 \; , \qquad \Phi_2 \to -\Phi_2 \; .$$

	Type I	Type II	Lepton-Specific	Flipped
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Leptons	Φ_2	Φ_1	Φ_1	Φ_2

$\mathcal{S}$cans and $\mathcal{N}$otation

- **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

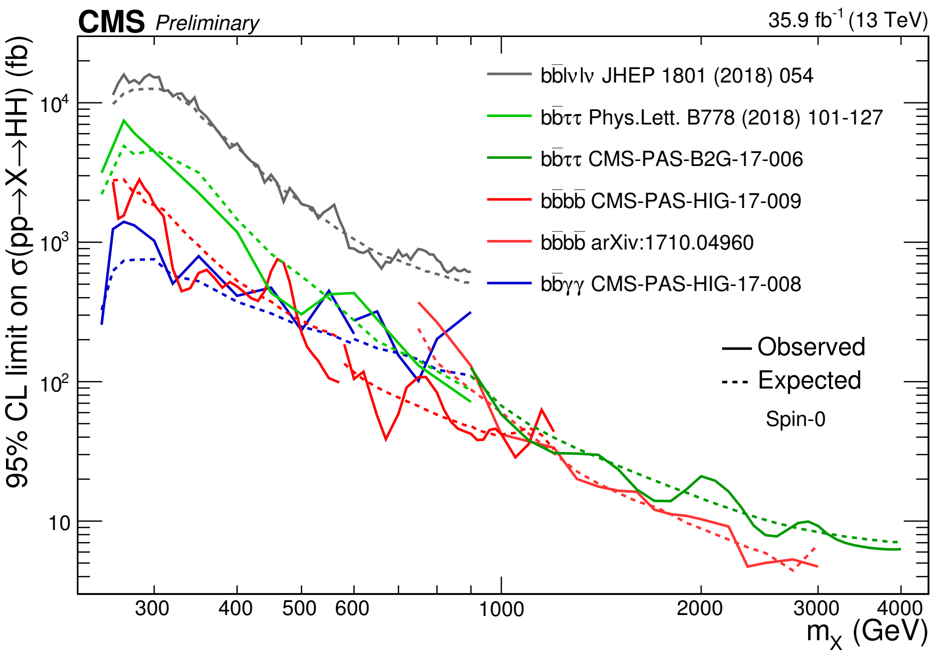
- **Additionally in NMSSM:**

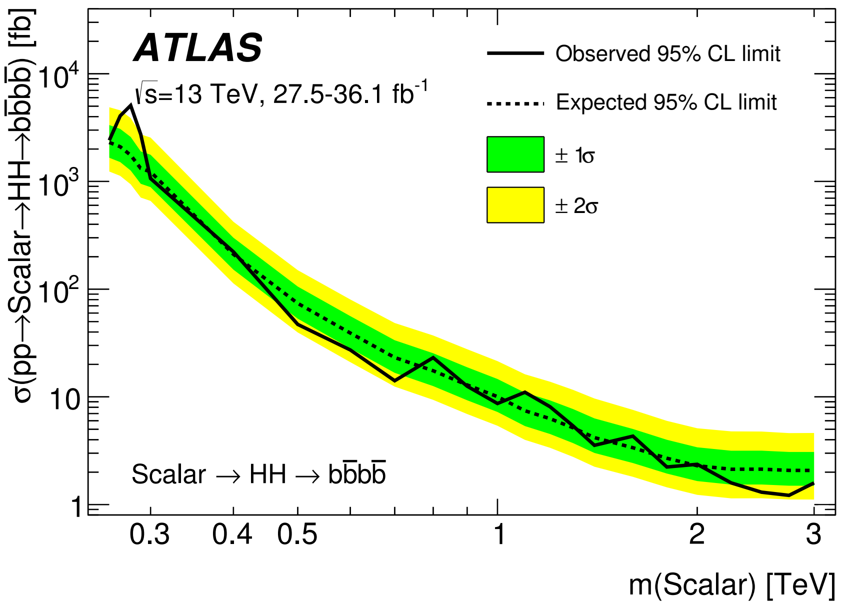
  $A_\downarrow$ - lighter non-SM-like pseudoscalar Higgs boson

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

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

Experimental Results - Implications for BSM SM-likeHiggs Pair Production





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

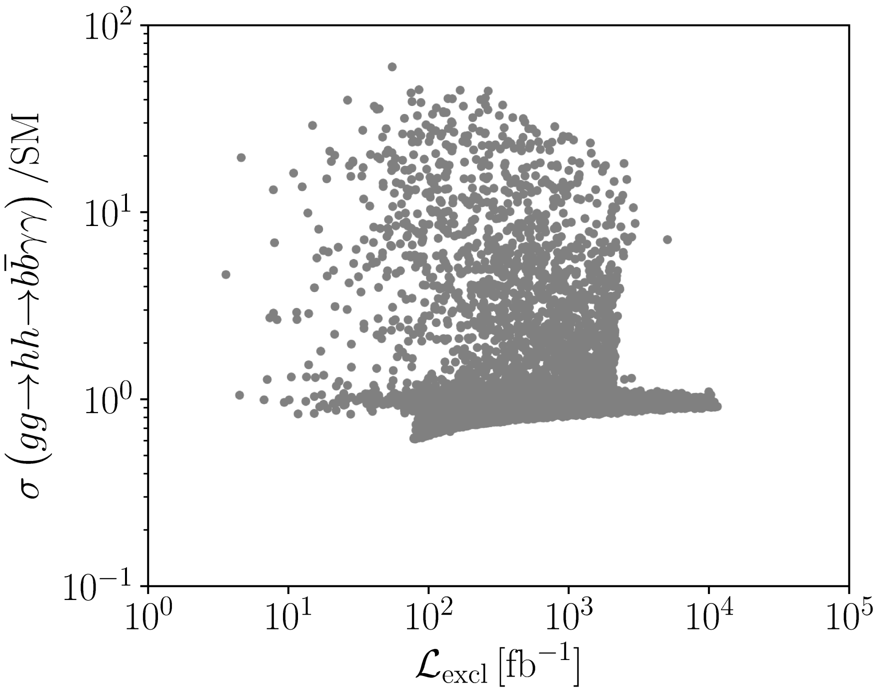
$\mathcal{I}$nterplay $\mathcal{S}$ingle $\mathcal{H}$iggs and $\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction

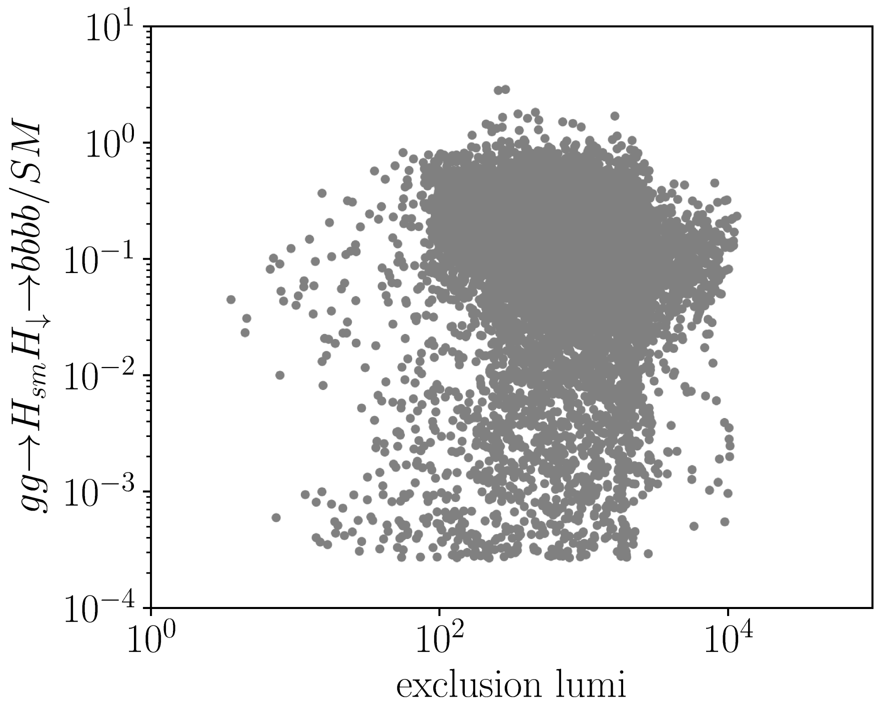
- **Heavy Higgs Bosons:**
  - ∗ decay into $t\bar{t}$ if kinematically possible
  - ∗ exotic 4-top final state from producton of heavy Higgs boson pair
  - ∗ large rates constrained by single Higgs production in $t\bar{t}$ final state
  - ∗ $\leftarrow$ no experimental data available
  - ∗ encourage 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

$\mathcal{S}$catter $\mathcal{P}$lots $\mathcal{C}$2HDM

[Basler,Dawson,Englert,MM '18]

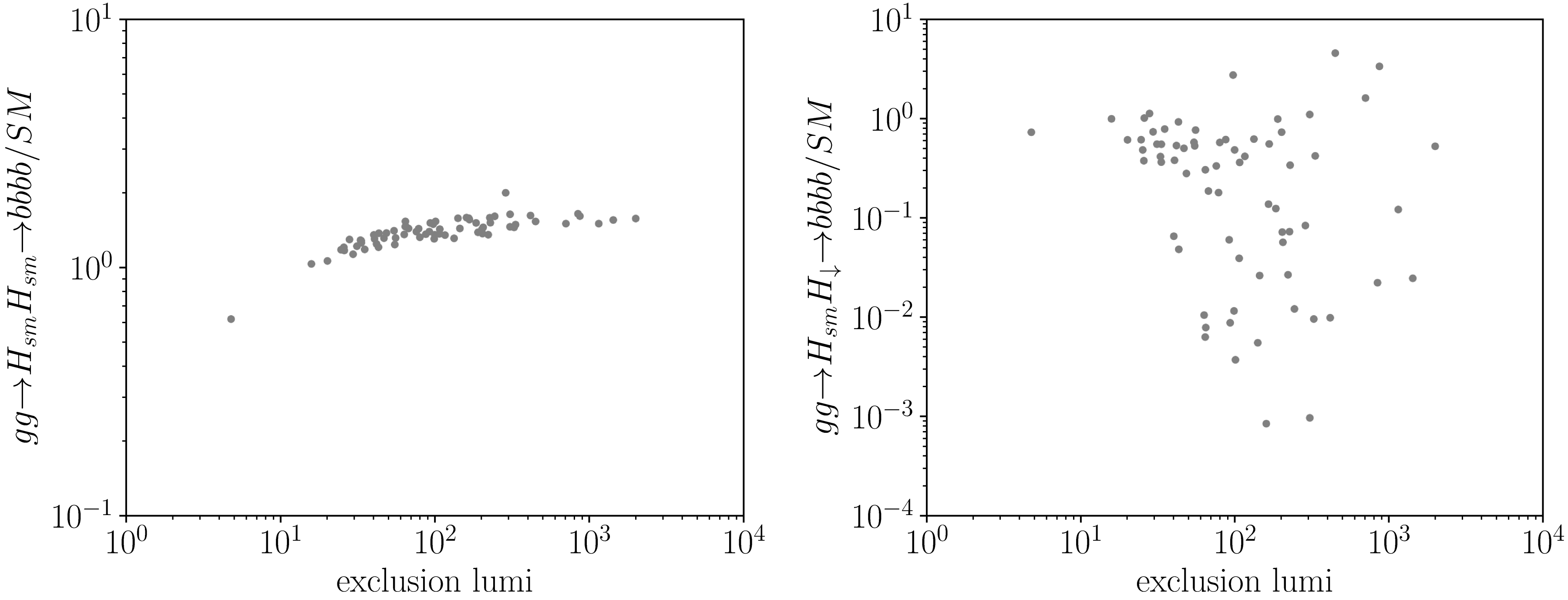




- Left: C2HDM T1 $hh \to 2b2\gamma$; large $t\bar{t}$ rates responsible for exclusion beyond `HiggsBounds`
- Right: C2HDM T1 $hH_{\downarrow} \to 4b$ enhanced by about a factor of 3

$\mathcal{S}$catter $\mathcal{P}$lots $\mathcal{N}$MSSM

[Basler,Dawson,Englert,MM '18]



- Left: NMSSM $hh \to 4b$: barely enhanced compared to SM `HiggsBounds`
- Right: NMSSM $hH_{\downarrow} \to 4b$: enhanced by about a factor of 5

Maximum Cross Section Values

- **Maximum cross section values C2HDM:**

H_iH_j/model	T1	T2
hh	794	34.2
$hH_\downarrow$	49.17	11.38
$hH_\uparrow$	17.65	10.84
$H_\downarrow H_\downarrow$	3196	0.18
$H_\downarrow H_\uparrow$	12.58	0.11
$H_\uparrow H_\uparrow$	7.10	0.18

T1 - Type 1, T2 - Type 2

- **Maximum cross section values NMSSM:**

H_iH_j	NMSSM
hh	34
$hH_\downarrow$	125
$hA_\downarrow$	70
$hH_\uparrow$	1.1
$H_\downarrow H_\downarrow$	3.7
$H_\downarrow H_\uparrow$	0.2
$H_\uparrow H_\uparrow$	0.004
$A_\downarrow A_\downarrow$	70

$\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{C}$ouplings and $\mathcal{E}$lectroweak $\mathcal{B}$aryogenesis

$\mathcal{L}$ink $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$ouplings - $\mathcal{E}$lectroweak $\mathcal{B}$aryogenesis

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:** [Sakharov '67]
  - $*$ (i) B number violaton (sphaleron processes)
  - $*$ (ii) C and CP violation
  - $*$ (iii) Departure from thermal equilibrium

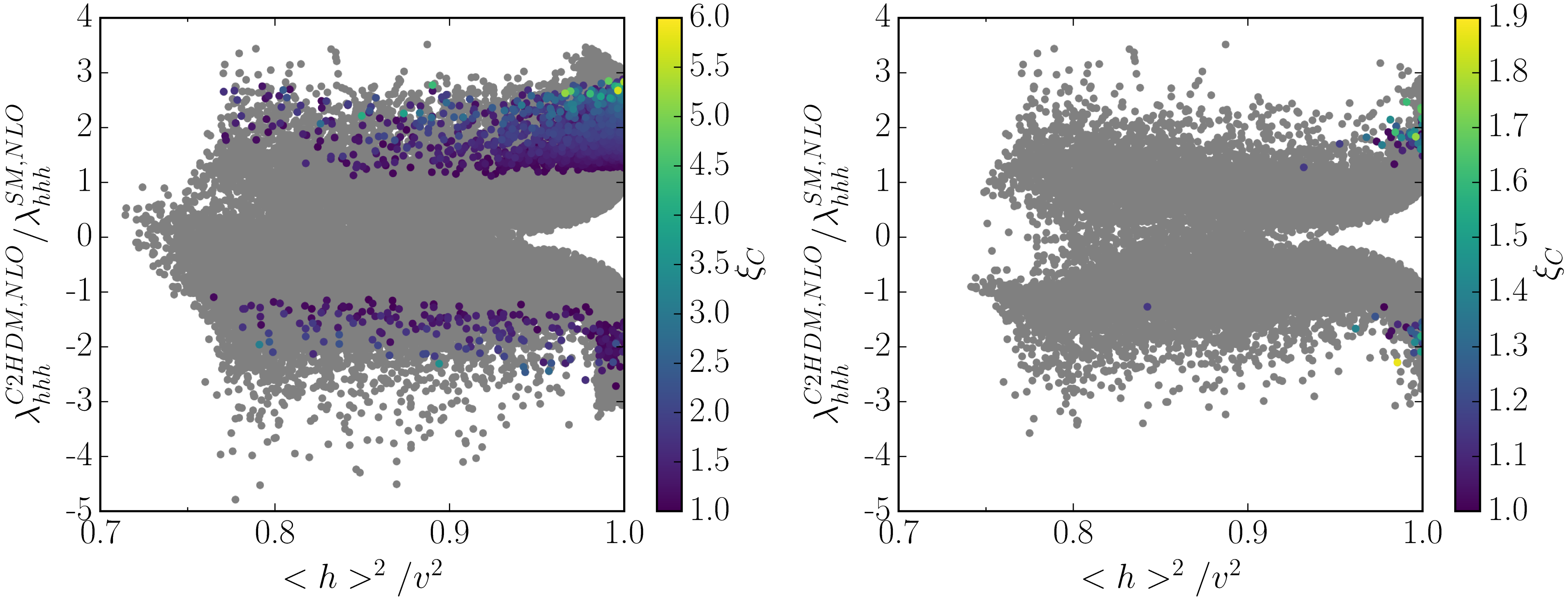
- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition

$\mathcal{E}$ffects on the $\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling - $\mathcal{C}$2HDM

Type I, $H_1 = h$ - right plot: only CP-violating points [Basler,MM,Wittbrodt '17]



∗ Grey: exp+theor constraints, colour $\xi_c \geq 1$

∗ $1.1 \lesssim \left|\frac{\lambda_{hhh}^{\text{C2HDM,NLO}}}{\lambda_{hhh}^{\text{SM,NLO}}}\right| \lesssim 2.9$

∗ CP-odd part of $h \lesssim 24\% \xrightarrow{\text{EWPT}} \sim 2.5\%$

∗ See also recent work by [Plehn eal '17; Spannowsky eal '17]

$\mathcal{N}$ew $\mathcal{T}$ool $\mathcal{B}$SMPT

- **BSMPT - Beyond the Standard Model Phase Transitions:** [Basler,MM '18]
  A C++ tool for the electroweak phase transition in extended Higgs sectors
  Computation of loop-corrected effective potential at $T \neq 0$ including the thermal masses
  Renormalization based on physical conditions (see backup slides)

- **Webpage:** https://github.com/phbasler/BSMPT

- **Features:**

  * Computation of $\xi_c = v_c/T_c$
  * Calculation of evolution of the VEV(s) with T
  * Calculation of the global minimum of the 1-loop-corrected potential at $T = 0$
  * Computation of the loop-corrected trilinear Higgs self-couplings in the "on-shell" scheme

- **Models:** generic code allows for easy implementation of new models
  implemented models: 2HDM, C2HDM, N2HDM

$\mathcal{B}$enchmark $\mathcal{P}$oint

m_{H_1} [GeV]	125.09
m_{H_2} [GeV]	291.49
$m_{H^\pm}$ [GeV]	543.30
Re(m_{12}^2) [GeV^2]	15590
α_1	1.366
α_2	-0.028
α_3	0.086
$\tan\beta$	5.08
m_{H_3} [GeV]	548.97
ξ_c	1.52
R_{13}^2	$7.641 \cdot 10^{-4}$
R_{23}^2	$7.436 \cdot 10^{-3}$
R_{33}^2	0.992
σ_{hh}^{NLO} [fb]	217.95

BR(H_2)	BR$(H_2 \to H_1H_1)$ = 0.400
	BR$(H_2 \to ZH_1)$ = 0.294
	BR$(H_2 \to WW)$ = 0.156
BR(H_3)	BR$(H_3 \to ZH_2)$=0.940
	BR$(H_3 \to t\bar{t})$=0.056
	BR$(H_3 \to WW)$=0.002
BR$(H^\pm)$	BR$(H^\pm \to WH_2)$=0.943
	BR$(H^+ \to t\bar{b})$=0.054
	BR$(H^\pm \to WH_1)$=0.002

Combination of rates to identify CP violation:

* type I, H_1 SM-like, mostly CP-even
* $H_2 \to ZH_1 \wedge H_2 \to WW$
  forbidden w/o CP violation

see also [Branco eal '99;Fontes eal '15,King eal '15]

Conclusions

◇ 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

◇ Link to baryogenesis:

∗ Requires enhanced Higgs self-couplings in C2HDM

Thank You For Your Attention!

Calculation

$$\sigma_{\rm NLO} = \sigma_{\rm LO} + \Delta\sigma_{\rm virt} + \Delta\sigma_{gg} + \Delta\sigma_{qg} + \Delta\sigma_{q\bar{q}},$$

with

$$\sigma_{\rm LO} = \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\rm LO}\left(Q^2 = \tau s\right),$$

$$\Delta\sigma_{\rm virt} = \frac{\alpha_s\left(\mu_R^2\right)}{\pi} \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\rm LO}\left(Q^2 = \tau s\right) C_{\rm virt}\left(Q^2\right),$$

$$\Delta\sigma_{ij} = \frac{\alpha_s\left(\mu_R^2\right)}{\pi} \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{ij}}{d\tau} \int_{\frac{\tau_0}{\tau}}^{1} \frac{dz}{z} \hat{\sigma}_{\rm LO}\left(Q^2 = z\tau s\right) C_{ij}(z)$$

where

$$C_{gg} = -zP_{gg}(z)\log\frac{\mu_F^2}{\tau s} + d_{gg}(z) + 6[1 + z^4 + (1-z)^4]\left(\frac{\log(1-z)}{1-z}\right)_+,$$

$$C_{gq} = -\frac{z}{2}P_{gq}(z)\log\frac{\mu_F^2}{\tau s(1-z)^2} + d_{gq}(z),$$

$$C_{q\bar{q}} = d_{q\bar{q}}(z)$$

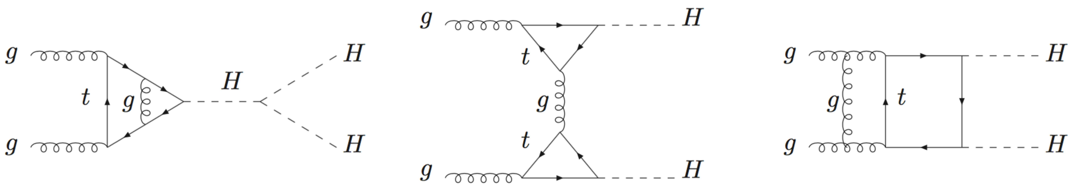
$\mathcal{C}$alculation $\mathcal{C}$ontinued

In the heavy top limit (HTL)

$$
\begin{aligned}
C_{\text{virt}} &\to \pi^2 + \frac{11}{2} + C_{\triangle\triangle} \\
d_{gg} &\to -\frac{11}{2}(1-z)^3 \\
d_{gq} &\to= \frac{2}{3}z^2 - (1-z)^2, \\
d_{q\bar{q}} &\to \frac{32}{27}(1-z)^3
\end{aligned}
$$

- **Virtual corrections**

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



  $*$ full diagram w/o tensor reduction $\to$ 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
  $[m_t^2 \to m_t^2(1-ih)]$

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

$\mathcal{V}$irtual $\mathcal{C}$orrections $\mathcal{C}$ontinued

- **Renormalization:** α_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 $(h \to 0)$

Real Corrections

- **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`]

$\mathcal{C}$2HDM $\mathcal{P}$arameter $\mathcal{S}$can

- **Scan over parameter space:**
  with `ScannerS`, checks for: [Coimbra,Sampaio,Santos '13; Ferreira,Guedes,Sampaio,Santos '14]

- **Theoretical constraints:**
  boundedness from below, tree-level perturbative unitarity, EW vacuum is global minimum of tree-level potential and also NLO [`BSMPT`, Basler,MMM '18]

- **Experimental constraints::**

  * S, T, U parameters for EW precision observables [Baak eal '14]
  * $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{ hadrons})$ and $B \to X_s\gamma$ [Haber,Logan '99;Deschamps eal '09; Mahmoudi,Stal '09; Steinhauser eal '17]
  * Higgs exclusion bounds by `HiggsBounds` [Bechtle eal '08,'11,'13]
  * Higgs rates checked via `SUSHI` and `C2HDM_HDECAY` [Harlander eal; Fontes eal]
  * Electric dipole moment of the electron [The ACME Collaboration]

$\mathcal{C}$2HDM $\mathcal{S}$can $\mathcal{R}$anges

	t_β	$\alpha_{1,2,3}$	Re(m_{12}^2) [TeV^2]	$m_{H^\pm}$ [TeV]	$m_{H_i \neq h}$ [TeV]
min	0.8	$-\frac{\pi}{2}$	0	0.15/0.59	0.01
max	20	$\frac{\pi}{2}$	0.5	1.5	1.5

$$10 \text{ GeV } \leq m_{H_j} < 1.5 \text{ TeV}$$

$$\begin{aligned} \alpha(M_Z) &= 1/127.92, & \alpha_s^{\overline{\text{MS}}}(M_Z) &= 0.118, \\ M_Z &= 91.187 \text{ GeV}, & M_W &= 80.358 \text{ GeV}, \\ m_t &= 172.5 \text{ GeV}, & m_b^{\overline{\text{MS}}}(m_b^{\overline{\text{MS}}}) &= 4.18 \text{ GeV}, \\ m_\tau &= 1.777 \text{ GeV}. \end{aligned}$$

$\mathcal{N}$MSSM $\mathcal{S}$can

- **Conditions on the parameter scan:**
  - ∗ At least one CP-even Higgs boson $H_i \equiv h$ with: 124 GeV $\lesssim M_h \lesssim 126$ GeV
  - ∗ Compatibility with μ_{XX}^{exp} $(X = b, \tau, \gamma, W, Z)$ [SusHi, NMSSMTools, NMSSMCALC]
  - ∗ Compatibility with Higgs exclusion bounds [HiggsBounds]
  - ∗ Compatibility with SUSY searches
  - ∗ Compatibility w/ DM constraints [PLANCK, LUX, XENON1T, micrOmegas]

Constraints from low-energy observables, from LEP, Tevatron and LHC searches [NMSSMTools]

$\mathcal{N}$MSSM $\mathcal{S}$can $\mathcal{R}$anges

	t_β	λ	κ	M_1	M_2	M_3	A_t	A_b	A_τ	$m_{\tilde{Q}_3}$	$m_{\tilde{L}_3}$	A_λ	A_κ	μ_{eff}
				in TeV										
min	1	0	-0.7	0.1	0.2	1.3	-6	-6	-3	0.6	0.6	-2	-2	-5
max	50	0.7	0.7	1	2	7	6	6	3	4	4	2	2	5

$$m_{\tilde{t}_R} = m_{\tilde{Q}_3}\ , \quad m_{\tilde{\tau}_R} = m_{\tilde{L}_3} \quad \text{and} \quad m_{\tilde{b}_R} = 3\ \text{TeV}$$

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

$$\lambda^2 + \kappa^2 < 0.7^2$$

$\mathcal{C}$2HDM T1 $\mathcal{B}$enchmark $\mathcal{P}$oints

	T1BP5	T1BP6
m_{H_1} [GeV]	125.09	62.67
m_{H_2} [GeV]	265.60	125.09
$m_{H^\pm}$ [GeV]	307.47	164.35
Re(m_{12}^2) [GeV^2]	11435	130
α_1	1.246	-0.145
α_2	$7.125 \cdot 10^{-3}$	-0.0536
α_3	-1.478	-0.0650
$\tan\beta$	5.54	8.26
m_{H_3} [GeV]	279.70	138.01
R_{13}^2	$5.077 \cdot 10^{-5}$	$2.870 \cdot 10^{-3}$
R_{23}^2	0.991	$4.212 \cdot 10^{-3}$
R_{33}^2	$8.611 \cdot 10^{-3}$	0.993
$\mathcal{L}_{\text{excl}}$ [fb^{-1}]	1082	2579
σ_{hh}^{NLO} [fb]	897.74	37.26
K-factor	2.06	1.95

R_{i3}^2 quantifies singlet admixture

$\mathcal{C}$2HDM T1 $\mathcal{B}$enchmark $\mathcal{P}$oints - $\mathcal{C}$ontinued

- **C2HDM rates normalized to SM rate for di-Higgs final state $[H_iH_j]$:**

  $(xx)(yy)$: $[pp \to H_iH_j \to (xx)(yy)]/[pp \to H^{\rm SM}H^{\rm SM} \to (xx)(yy)]$

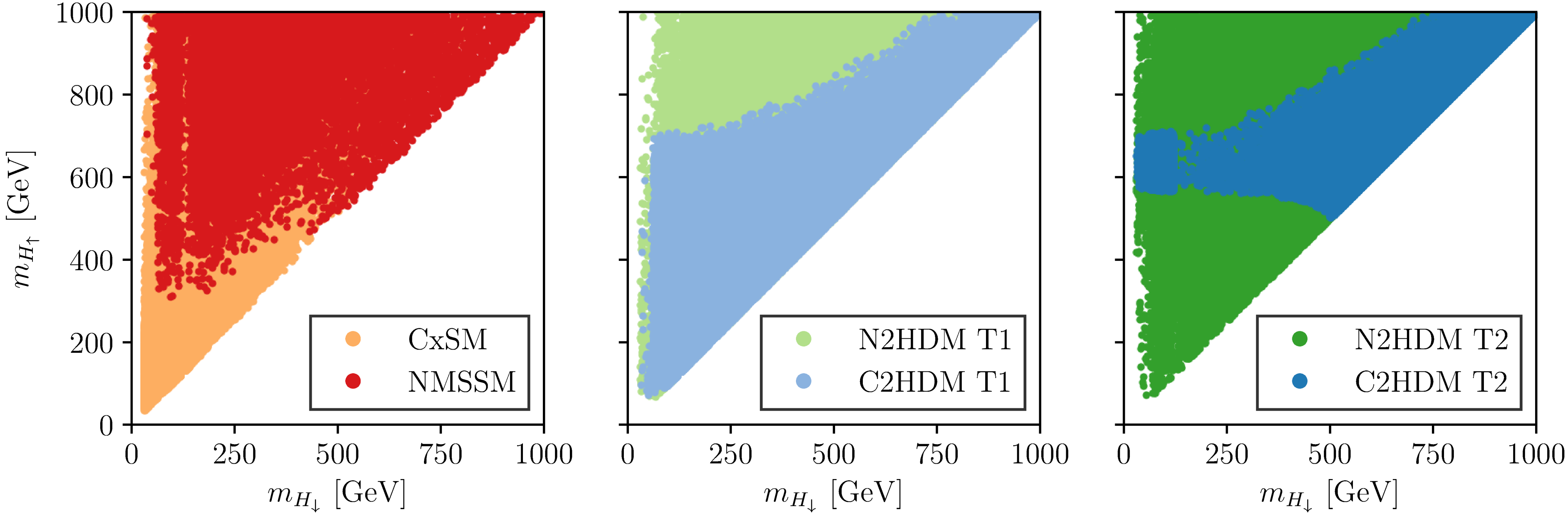
	T1BP5	T1BP6
$(b\bar{b})(b\bar{b})_{H_iH_j}$ [fb]	$[hh]$: 23.80	$[H_\downarrow H_\downarrow]$: 145
$(b\bar{b})(\tau\bar{\tau})_{H_iH_j}$ [fb]	$[hh]$: 23.51	$[H_\downarrow H_\downarrow]$: 124
$(b\bar{b})(\gamma\gamma)_{H_iH_j}$ [fb]	$[hh]$: 24.32	$[H_\downarrow H_\downarrow]$: 0.29

- T1BP5: enhanced hh production due to resonant $H_\downarrow$, $H_\uparrow$ production

- T1BP6: enhanced $H_\downarrow H_\downarrow$ production due light $H_\downarrow$ and due to resonant $H_\uparrow$ production

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

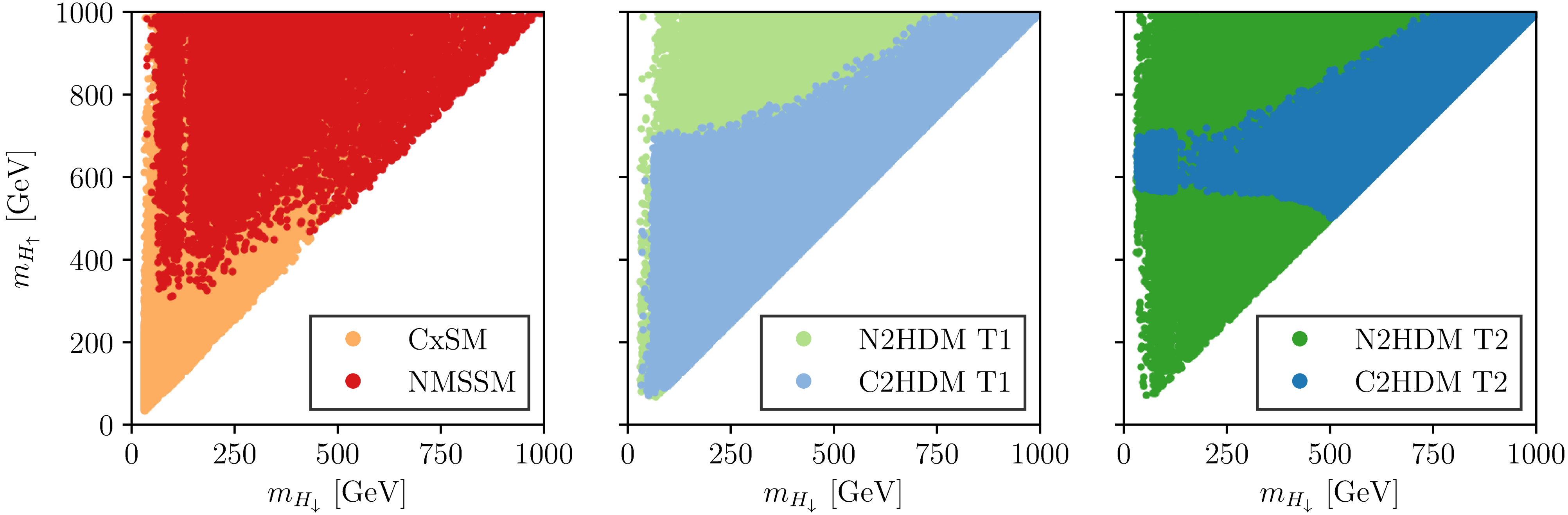
[MM,Sampaio,Santos,Wittbrodt '17]



- 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]

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

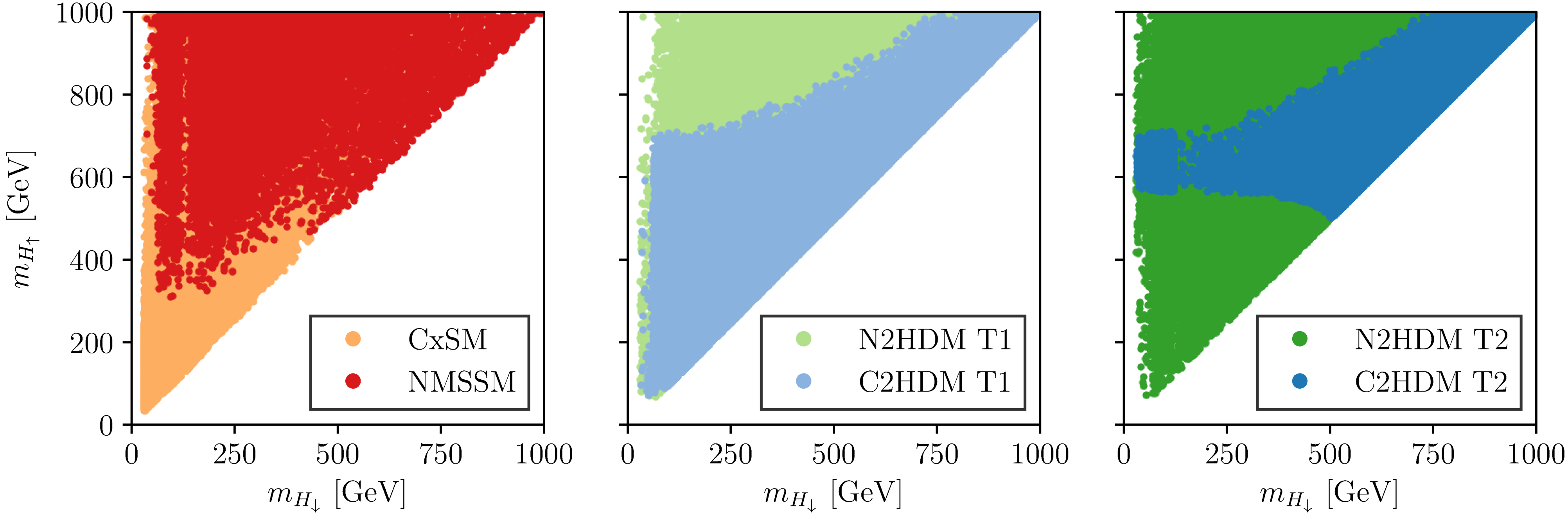
[MM,Sampaio,Santos,Wittbrodt '17]



- 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

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

[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

$\mathcal{F}$eatures of the $\mathcal{M}$odels

- **Common features**
  - ∗ 3 neutral CP-even or 3 neutral CP-mixed Higgs bosons
  - ∗ Mass eigenstates w/ non-vanishing singlet or CP-admixture
    Note: CP-mixing measurement difficult $\rightsquigarrow$
    in first phase after discovery of additional Higgs bosons
    singlet and pseudoscalar admixture not distinguishable

- **Different features:**
  - ∗ Based on different underlying symmetries! $\rightsquigarrow$ implications for phenomenology

- **Notation:**

  SM-like Higgs: h_{125}

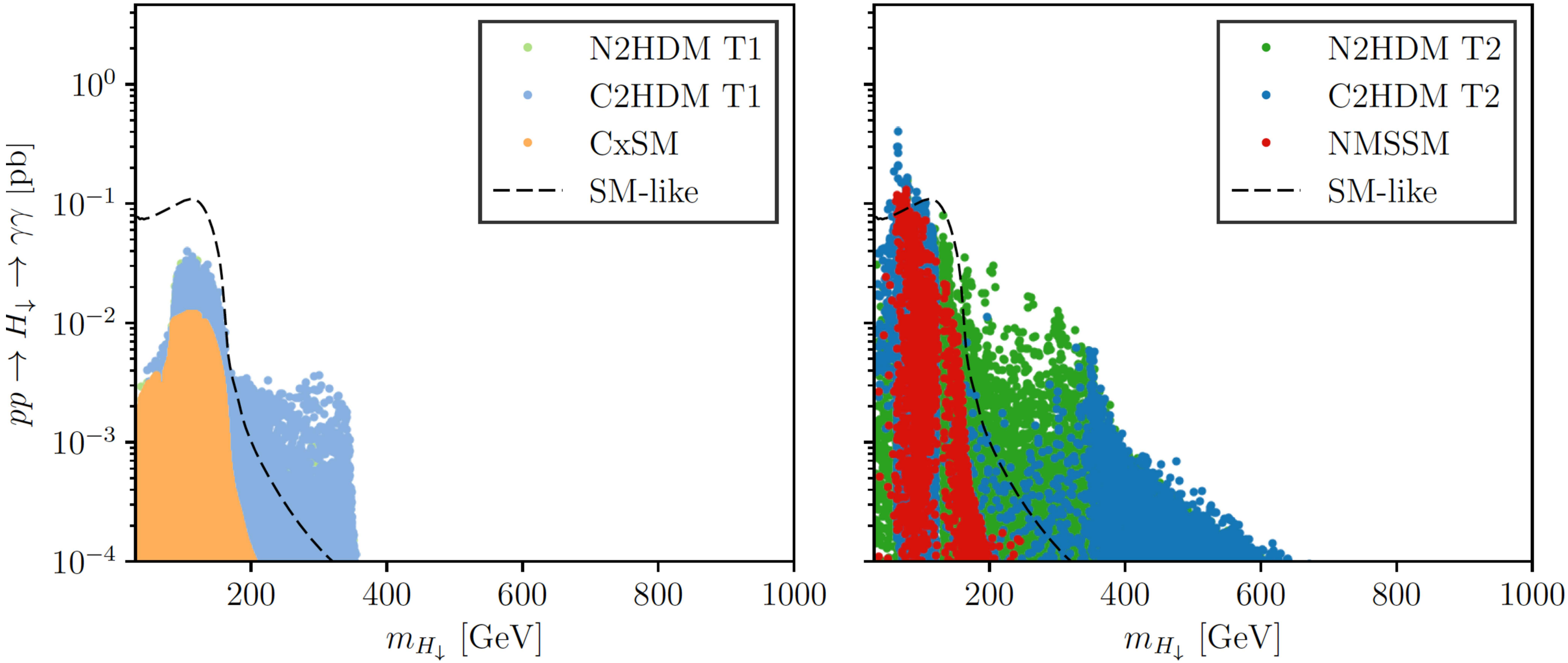
  Non-SM-like CP-even/CP-mixed Higgs bosons: $H_\downarrow$, $H_\uparrow$ $(m_{H_\downarrow} < m_{H_\uparrow})$

  Pseudoscalar of the N2HDM: A

  Pseudoscalar of the NMSSM: A_1, A_2

𝒟ecay ℛates in 𝒫hoton ℱinal 𝒮tates

[MM,Sampaio,Santos,Wittbrodt '17]



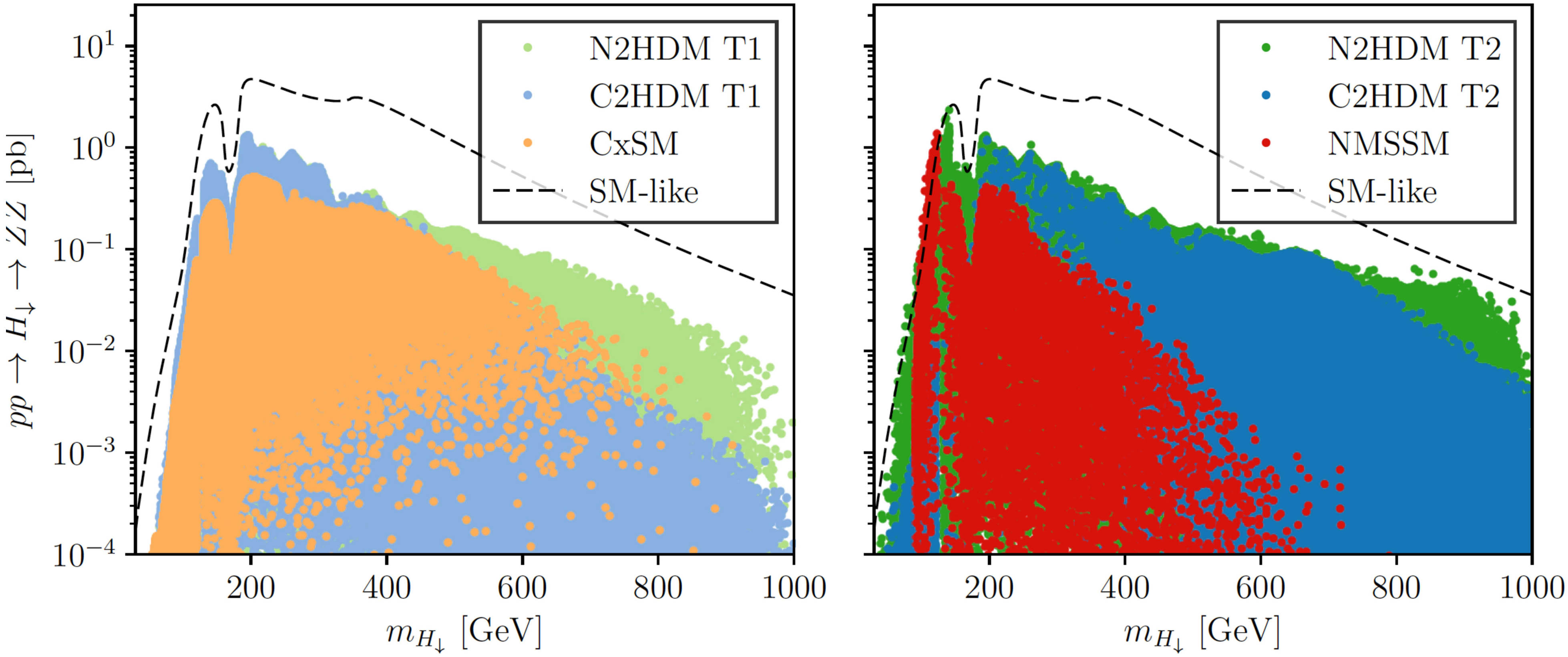
Comments: - Enhanced rates below 125 GeV in NMSSM, type II N2HDM and C2HDM

- Experiments: test low mass region to probe the models

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

$\mathcal{D}$ecay $\mathcal{R}$ates in $\mathcal{Z}$ $\mathcal{B}$oson $\mathcal{F}$inal $\mathcal{S}$tates

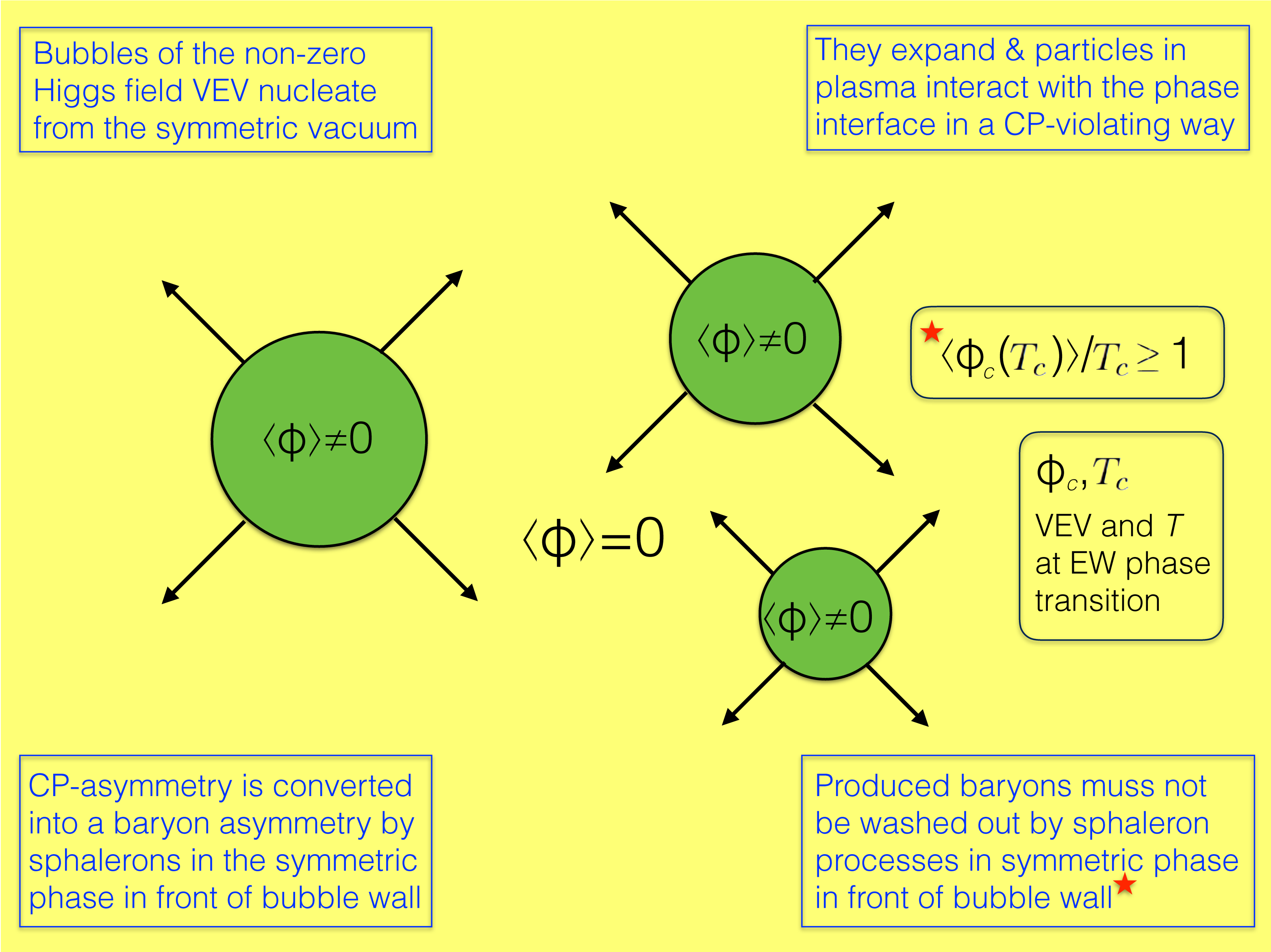
[MM,Sampaio,Santos,Wittbrodt '17]



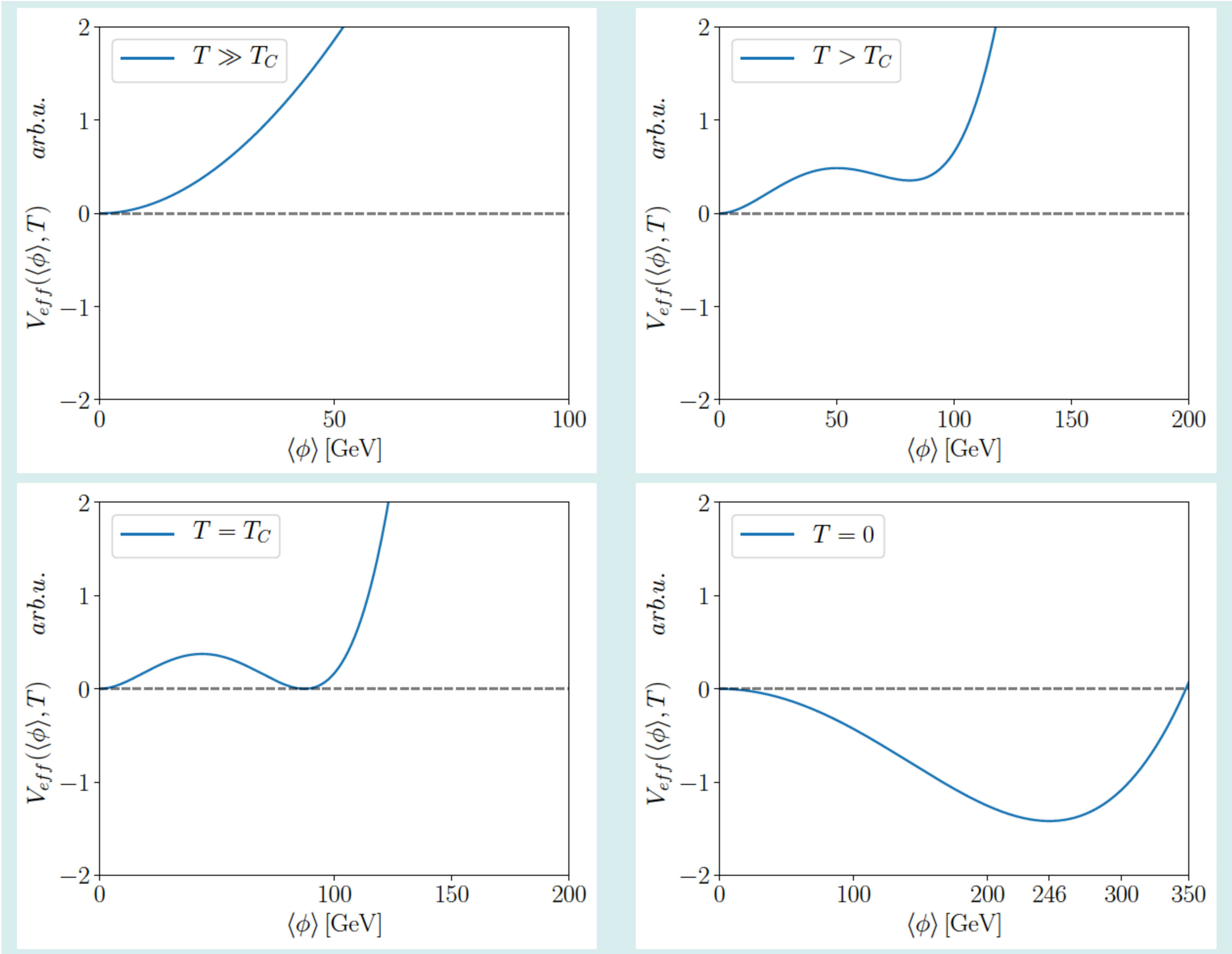
Comments: - Highest rates for large masses in N2HDM

- 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

$\mathcal{B}$aryogenesis in a $\mathcal{N}$utshell



[adapted from Morrissey, Ramsey-Musolf '12]



$T \gg T_C$
$T > T_C$
$T = T_C$
$T = 0$
$V_{eff}(\langle\phi\rangle, T)$ arb.u.
$\langle\phi\rangle$ [GeV]
2
1
0
−1
−2
0
50
100
150
200
246
300
350

$\mathcal{T}$he $\mathcal{L}$oop-$\mathcal{C}$orrected $\mathcal{E}$ffective $\mathcal{P}$otential at $\mathcal{F}$inite $\mathcal{T}$emperature

- **Investigate phase transition:** determine

$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c}$$

for C2HDM taking into account all theoretical and experimental constraints

- **Effective potential at finite temperature:**

$$V_{\text{eff}}^{(1)}(\vec{\omega}, T) = V_{\text{tree}}(\vec{\omega}) + V_{\text{CW}}(\vec{\omega}) + V_{\text{CT}}(\vec{\omega}) + V_T(\vec{\omega}, T)$$

- **$T = 0$ 1-loop contribution:** Coleman-Weinberg contribution [Coleman,Weinberg '73]

$$V_{\text{CW}} = \sum_i \frac{n_i}{64\pi^2} (-1)^{2s_i} m_i^4(\vec{\omega}) \left[\ln\left(\frac{m_i^2(\vec{\omega})}{\mu^2} \right) - c_i \right]$$

n_i number of degrees of freedom
μ renormalization scale, set to VEV $v \approx 246$ GeV
$\overline{\text{MS}}$ renormalization constants $c_i = 5/6$ for bosons, $c_i = 3/2$ otherwise

$\mathcal{T}$he $\mathcal{L}$oop-$\mathcal{C}$orrected $\mathcal{E}$ffective $\mathcal{P}$otential at $\mathcal{F}$inite $\mathcal{T}$emperature

- **The counterterm potential:**
  Choose V_{CT} such that the minimum, the masses and the mixing angles at $T = 0$ remain the same at one-loop level [Basler,Krause,MM,Wittbrodt,Wlotzka '16]

$$\begin{aligned} 0 &= (\partial_{\phi_i} V_{\text{CT}} + \partial_{\phi_i} V_{\text{CW}})|_{\langle\phi\rangle_{T=0}} \\ 0 &= (\partial_{\phi_i}\partial_{\phi_j} V_{\text{CT}} + \partial_{\phi_i}\partial_{\phi_j} V_{\text{CW}})|_{\langle\phi\rangle_{T=0}} \end{aligned}$$

- **$T \neq 0$ contribution:**
  - Thermal loops (fermionic (+) and bosonic (−) integral $J_\pm$) [Carena eal '08]

$$V_T = \sum_i n_i \frac{T^4}{2\pi^2} J_\pm(m_i^2(\vec{\omega})/T^2)$$

  - Thermal mass corrections [Arnold,Espinosa '94]

$$J_-\left(\frac{m_i^2}{T^2}\right) \to J_-\left(\frac{m_i^2}{T^2}\right) - \frac{\pi}{6}(\overline{m}_i^3 - m_i^3)\,, \qquad i = W_L^\pm, Z_L, \gamma_L, \Phi^0, \Phi^\pm$$

  with the thermal masses $\overline{m}_i$

$\mathcal{P}$arameter $\mathcal{S}$can

- **Scan over parameter space:**
  with `ScannerS`, checks for: [Coimbra,Sampaio,Santos '13; Ferreira,Guedes,Sampaio,Santos '14]

- **Theoretical constraints:**
  boundedness from below, tree-level perturbative unitarity, EW vacuum is global minimum of tree-level potential at $T = 0$

- **Experimental constraints::**
  * S, T, U parameters for EW precision observables [Baak eal '14]
  * $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{ hadrons})$ and $B \to X_s\gamma$ [Haber,Logan '99;Deschamps eal '09; Mahmoudi,Stal '09; Steinhauser eal '17]
  * Higgs exclusion bounds by `HiggsBounds` [Bechtle eal '08,'11,'13]
  * Higgs rates checked via `SUSHI` and `C2HDM_HDECAY` [Harlander eal; Fontes eal]
  * Electric dipole moment of the electron [The ACME Collaboration]

- **Calculation of the global electroweak minimum:**
  as function of T to determine $\xi_c \leftarrow$ use of code `BSMPT` [Basler,MM '18]