Di-Higgs-Production Baryogensesis in the C2HDM

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The C2HDM

- The CP-Violating 2HDM: [Ginzburg,Krawczyk,Osland,'02]

  Motivation
  - can provide a strong first order electroweak phase transition (like 2HDM)
  - has additional sources of CP violation (required by electroweak baryogenesis)
  - has rich phenomenology, in particular interesting di-Higgs signatures

- The Model: 2 complex Higgs doublets $\mathbf{\Phi}_1$, $\mathbf{\Phi}_2$,

  CP-violating scalar potential w/ softly broken $\mathbb{Z}_2$ symmetry $\mathbf{\Phi}_1 \to \mathbf{\Phi}_1$, $\mathbf{\Phi}_2 \to -\mathbf{\Phi}_2$

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

complex

- After EWSB: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}$ and $\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$

CP violation for $\phi(\lambda_5) \neq 2\,\phi(m_{12}^2)$

- The Higgs spectrum:

  3 CP-violating neutral Higgs bosons H_1, H_2, H_3, ordered by ascending mass, charged $H^\pm$

  one of the neutral ones corresponds to the SM-like Higgs boson h with mass of 125.09 GeV

- h couplings to gauge bosons:

$$g^{hVV}_{C2HDM} = \cos\alpha_2 \, g^{hVV}_{2HDM}$$

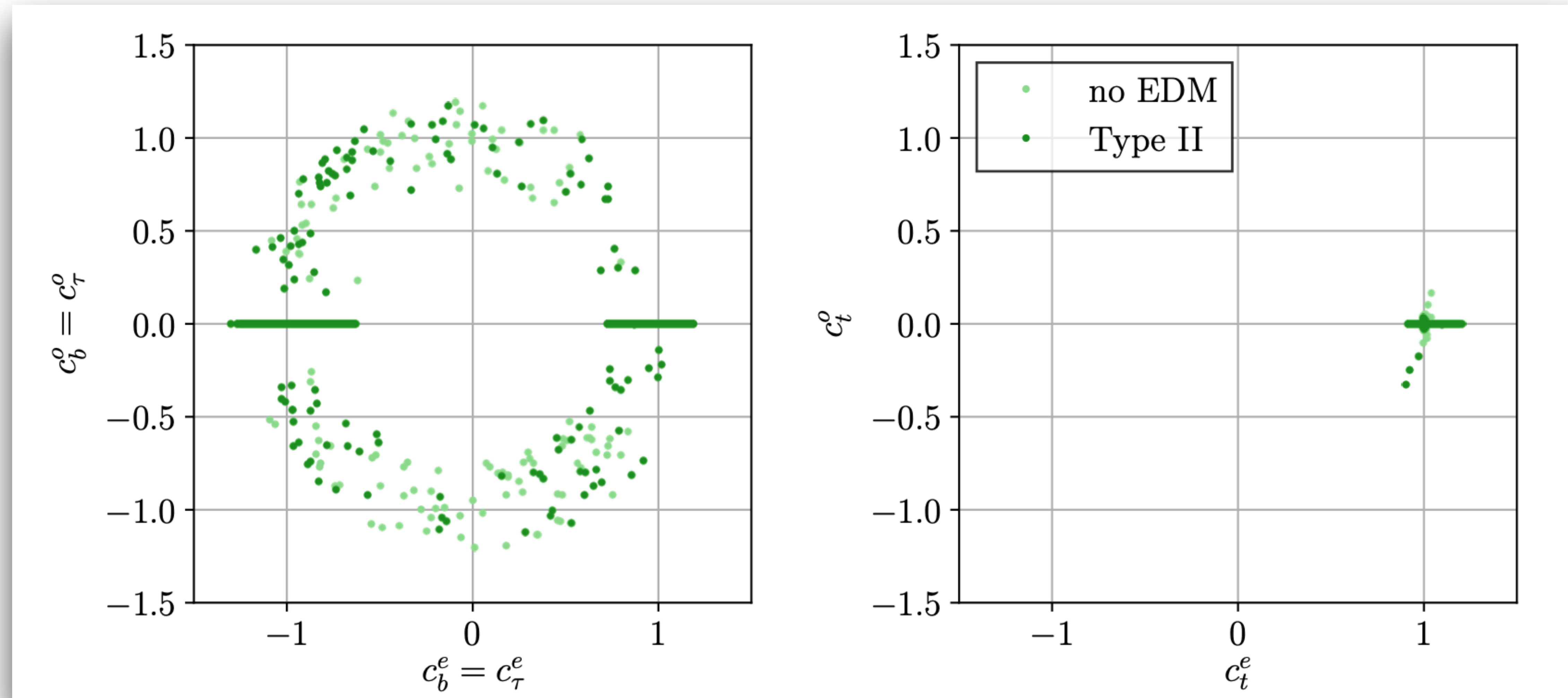
pseudoscalar component

- h Yukawa couplings:

$$Y_{C2HDM} = \cos\alpha_2 Y_{2HDM} \pm i\gamma_5 \sin\alpha_2 \tan\beta (1/\tan\beta)$$

✦ EDM measurements: place stringent constraints on size of CP-violating phase
After taking into account all relevant theoretical and experimental constraints still possible

$H_2=h_{125}$ [Fontes,MM,Romao,Santos,Silva,Wittbrodt,'17]



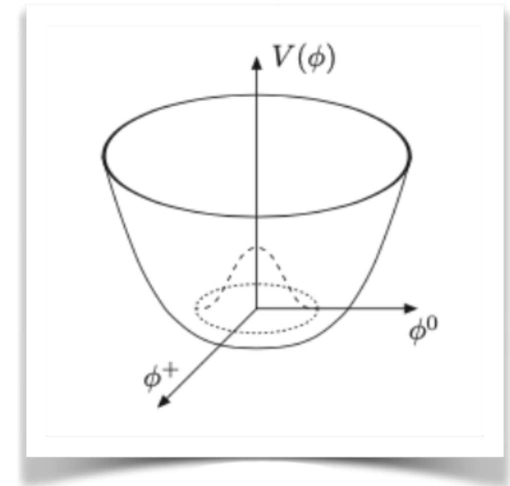
h_{125} couples like pseudoscalar to down-type fermions, like scalar to up-type fermions


Di-Higgs Production

Higgs Pair Production

- Ultimate test of the Higgs mechanism:

Measurement of the scalar boson self-couplings and Reconstruction of the EWSB potential	Experimental verification Of the scalar sector of the EWSB mechanism

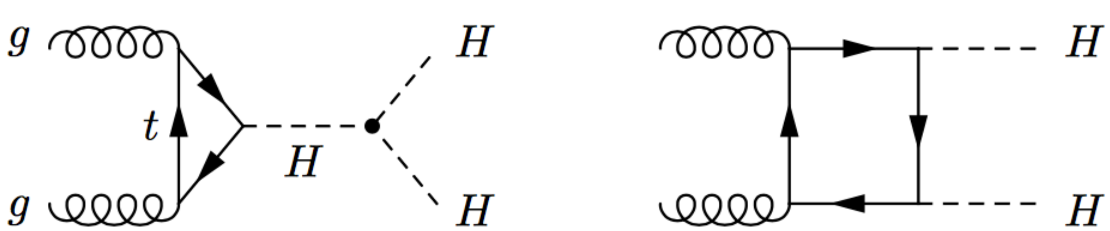


- Test of Higgs self-couplings at colliders :

λ_{HHH} via Higgs pair production

λ_{HHHH} via triple Higgs production

- SM Higgs pair production at the LHC - dominant process: gluon fusion



SM: destructive interference
triangle and box diagrams

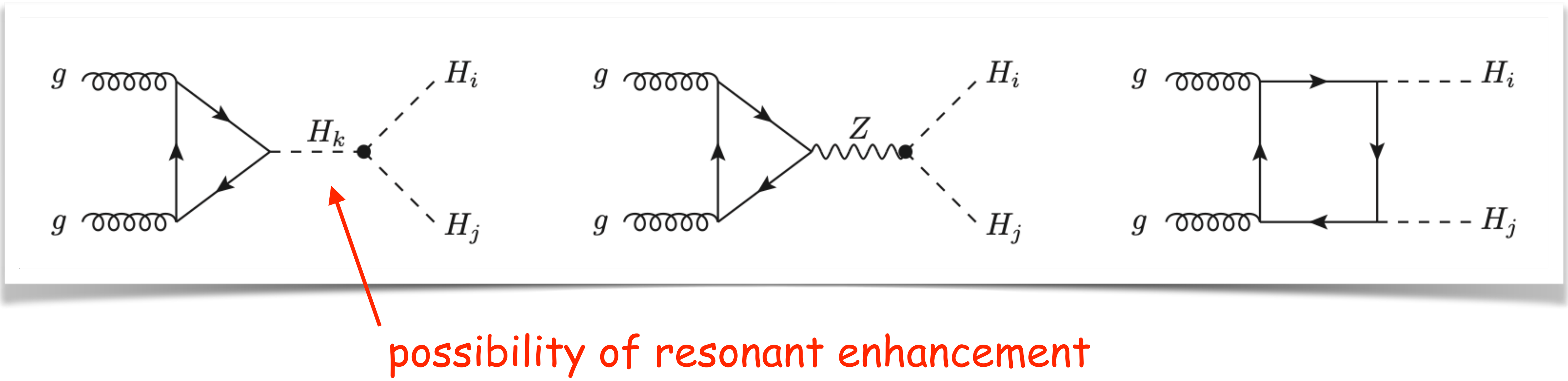
$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%} \text{ fb}$$

Challenge: small cxn and large QCD bkg

at FT_{approx}: full NNLO QCD in the heavy-top-limit with full LO and NLO mass effects and full mass dependence in the one-loop double real corrections at NNLO

Higgs Pair Production in the C2HDM

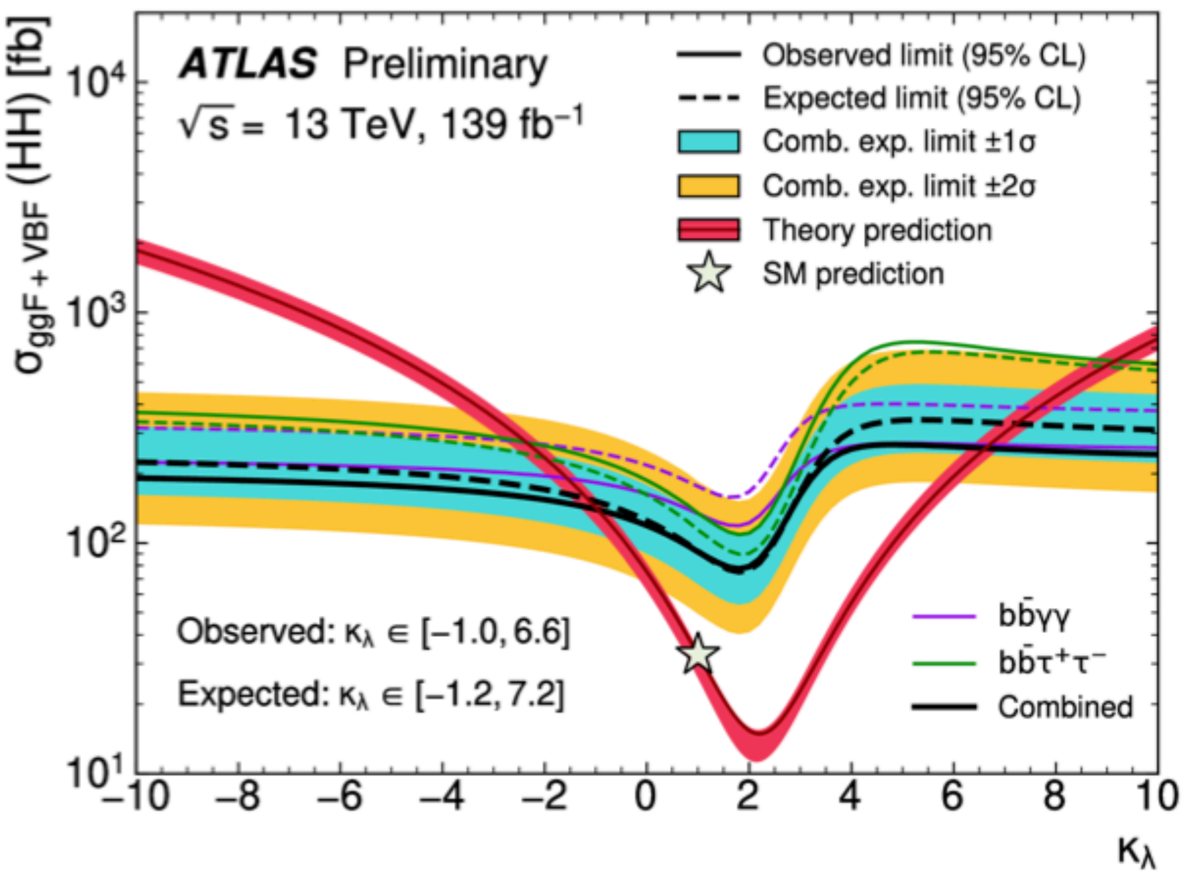
✦ Higgs pair production in the C2HDM: [Gröber,MM,Spira,'17]



✦ General analysis: [Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

Scan in parameter space of the model
Inclusion of theor. & exp. constraints, also most recent di-Higgs constraints
At NLO: QCD corrections in the heavy top mass limit

Experimental Results - Limits on Trilinear Higgs Self-Coupling



[Rui Zhang, ATLAS, HH Workshop´22]

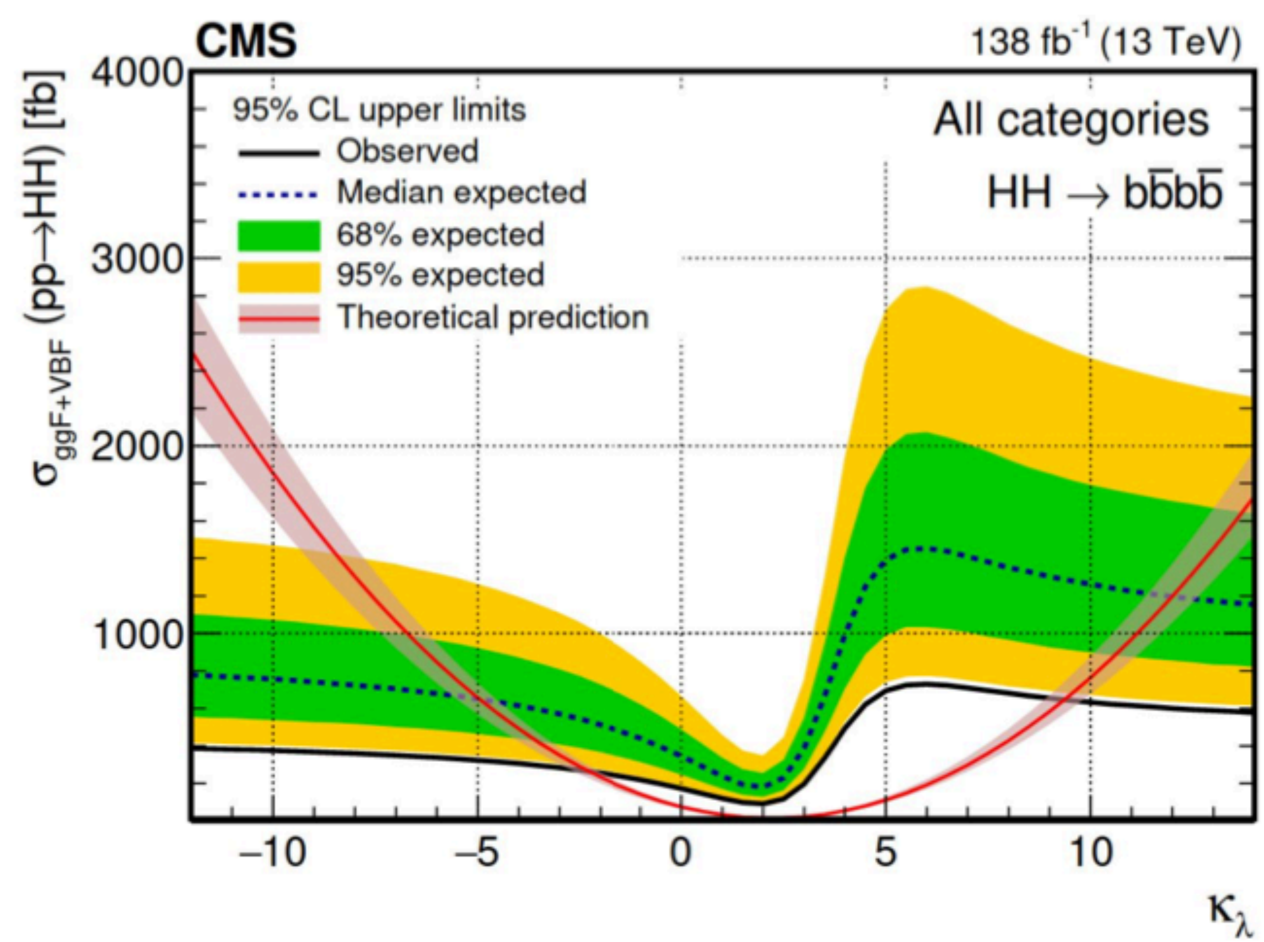
Observed: $\kappa_\lambda \in [-1.0, 6.6]$

Expected: $\kappa_\lambda \in [-1.2, 7.2]$

[Fabio Monti, CMS, HH Workshop´22]

Obs. $k_\lambda \in$ **[-2.3, 9.4]**

Exp. $k_\lambda \in$ [-5.0, 12.0]



How Define Resonant di-Higgs Production?

Additional Higgs bosons H_k: possible resonant enhancement of the di-Higgs cross section

* If $m_{Hk} < m_{Hi} + m_{Hj}$ then clear case of „non-resonant" production
* If $m_{Hk} > m_{Hi} + m_{Hj}$: resonance contribution may be suppressed due to small couplings, large masses, large widths or destructive interference effects

From an experimental point of view the cross section would not be distinguishable from „non-resonant" production then. => Our recipe:

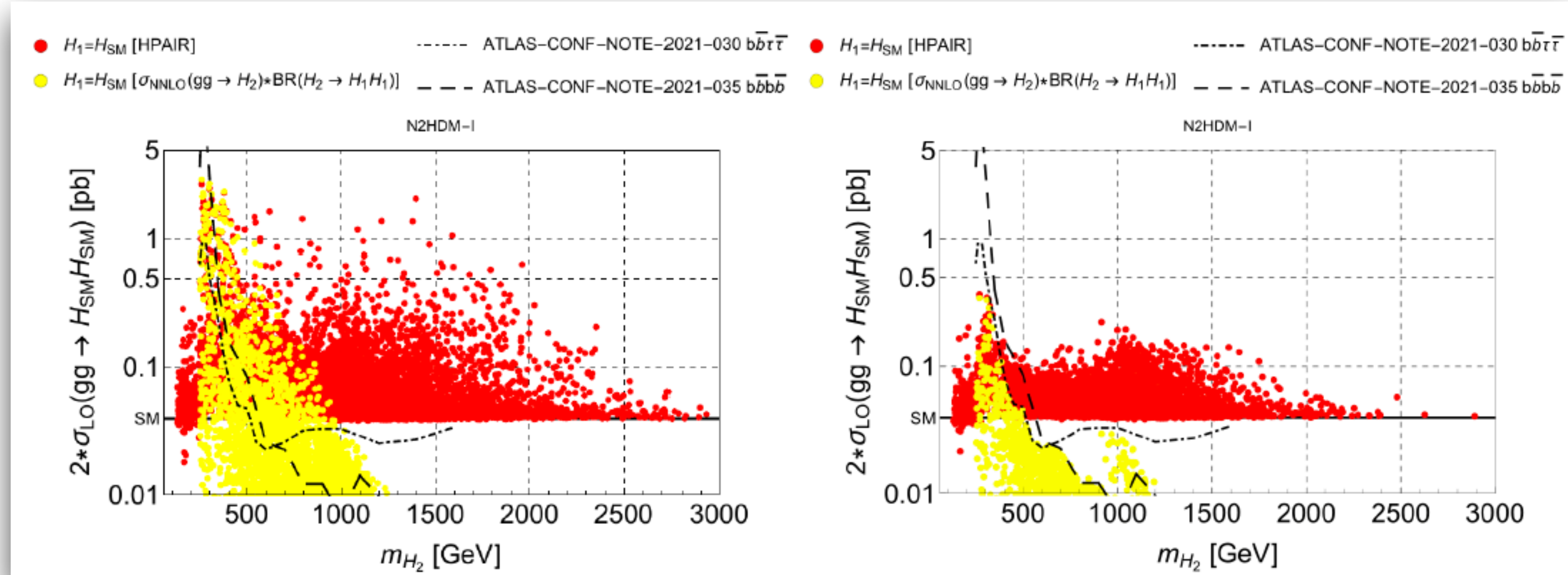
* HiggsBounds turned off for di-Higgs
* Use SusHi to calculate $\sigma(H_k)$ for all possible intermediate resonances H_k at NNLO QCD
* Calculate $\sigma(H_k) \times BR(H_k \to H_{SM} H_{SM})$ and compare it with experiment
* Exception: exp. limits assume narrow resonance -> we keep points if $(\Gamma_{tot}(H_k)/m_{Hk})_{limit} > 5\%$

Provided final states on request: 4b, (2b)(2tau), (2b)(2gamma), (2b)(2W), (2b)(2Z), (2W)(2gamma), 4W

Suppress interfering Higgs signals by excluding scenarios with neighboring Higgs masses below 5 GeV.

Application of limits: example N2HDM

[Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

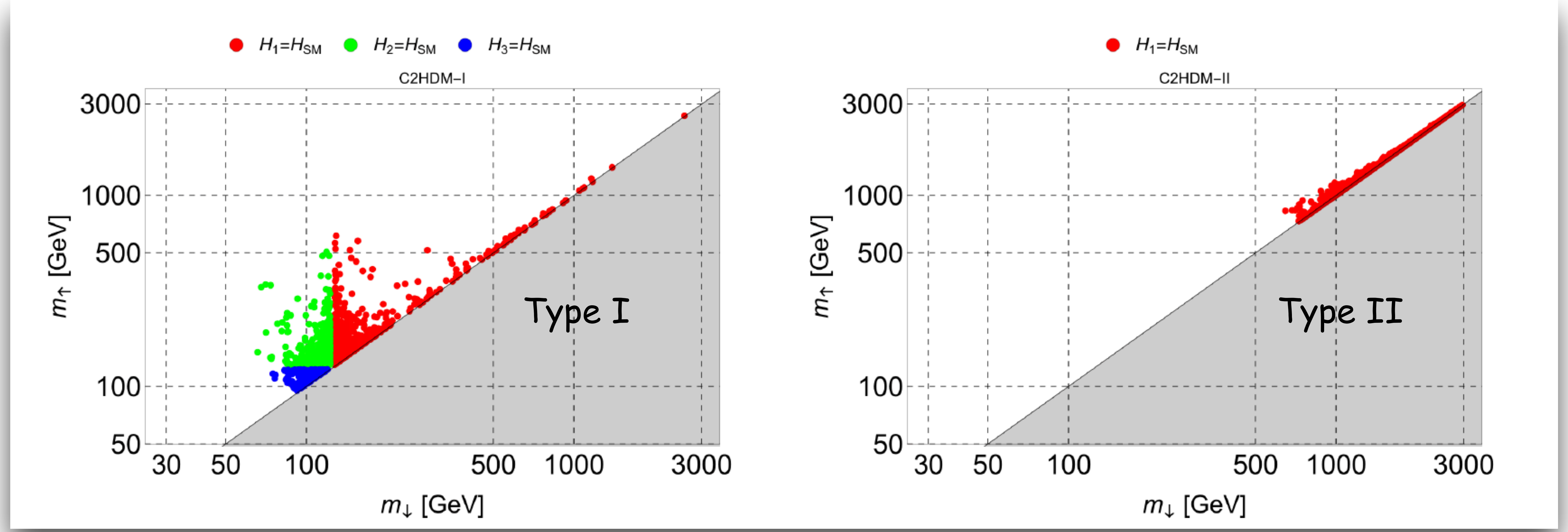


$b\bar{b}\gamma\gamma$ dominates sensitivity at low m_X	$b\bar{b}b\bar{b}$ dominates sensitivity at high m_X
$b\bar{b}\tau\tau$ dominates sensitivity at medium m_X	

Experimental constraints from resonant searches applied on yellow points:
Resonant heavy Higgs production w/ subsequent decay into two SM-like Higgs bosons

Allowed Mass Spectrum of the C2HDM

[Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]



- rather compressed spectrum

[Misiak,Rehman,Steinhauser,'20]

- Type II: only H_1=H_{SM} possible <- B-> s gamma implies $m_{H^\pm}$ > 800 GeV

Allowed Coupling Deviations

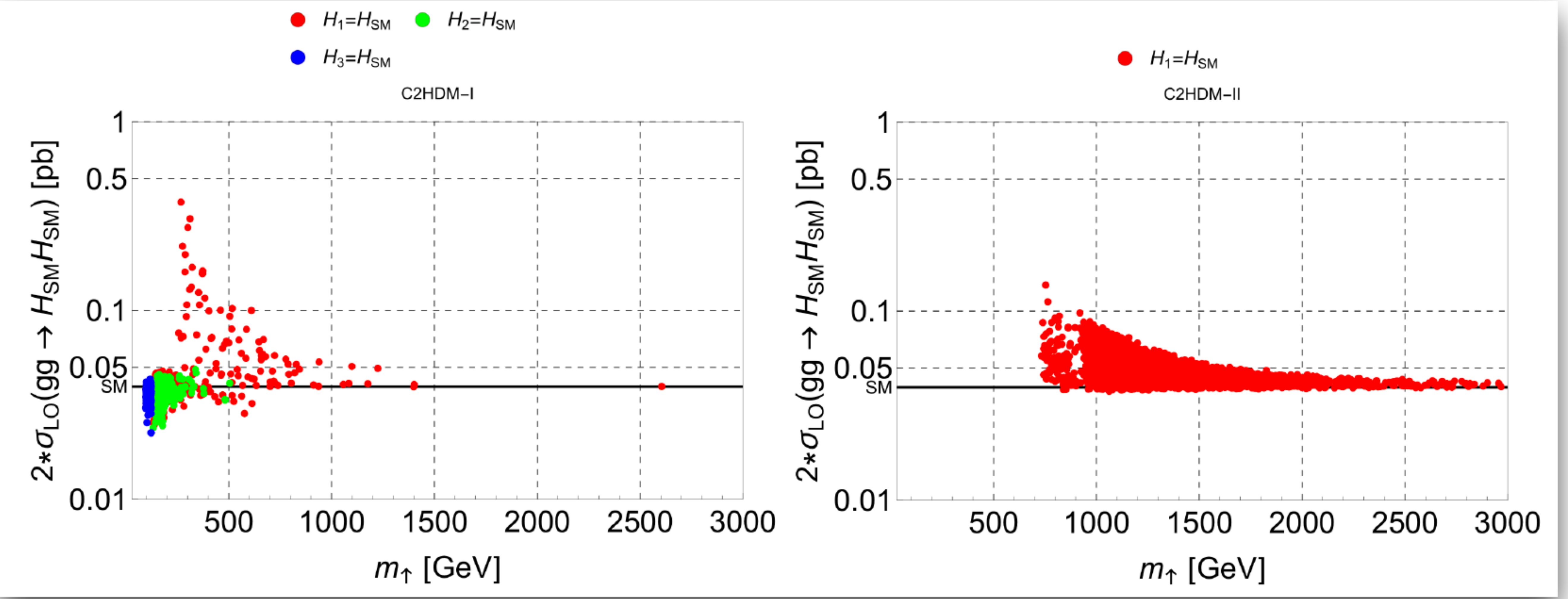
[Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

	R2HDM		C2HDM	
	$y^{\rm R2HDM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm R2HDM}_{3H_{\rm SM}}/\lambda_{3H}$	$y^{\rm C2HDM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm C2HDM}_{3H_{\rm SM}}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	–	–
heavy II	–	–	–	–

	N2HDM		NMSSM	
	$y^{\rm N2HDM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm N2HDM}_{3H_{\rm SM}}/\lambda_{3H}$	$y^{\rm NMSSM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm NMSSM}_{3H_{\rm SM}}/\lambda_{3H}$
light I	0.895...1.079	-1.160...1.004	n.a.	n.a.
medium I	0.874...1.049	-1.247...1.168	n.a.	n.a.
heavy I	0.893...1.030	0.770...1.112	n.a.	n.a.
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	–	–	–	–

Higgs Pair Production Cross Sections

[Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]



Maximum Possible Di-Higgs Cross Section Values

[Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

Non-Resonant

in fb	H_1	H_2	H_3
R2HDM-I	59	49	
R2HDM-II	–	–	
C2HDM-I	46	44	42
C2HDM-II	–	–	–
N2HDM-I	50	52	44
N2HDM-II	–	–	–
NMSSM	–	–	–

Resonant

in fb	H_1	H_2
R2HDM-I	444	n.a.
R2HDM-II	81	n.a.
C2HDM-I	387	47
C2HDM-II	130	–
N2HDM-I	376	344
N2HDM-II	188	63
NMSSM	183	65

SM Cross Section (NLO QCD, heavy top limit): 38 fb

max. enhancement: non-resonant: 1.2, resonant: 10.2

Interesting Benchmark Point w.r.t test of CP violation

C2HDM Type I [Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

input parameters

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	$\mathrm{Re}(m_{12}^2)$ [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

results

$\sigma^{\rm NLO}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\rm NNLO}_{H_1}$ [pb]	$\sigma^{\rm NNLO}_{H_2}$ [pb]	$\sigma^{\rm NNLO}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\sigma(H_2)\times \mathrm{BR}(H_2\to H_1H_1) = 191 \text{ fb}, \quad \sigma(H_2)\times \mathrm{BR}(H_2\to WW) = 254 \text{ fb},$$
$$\sigma(H_2)\times \mathrm{BR}(H_2\to ZZ) = 109 \text{ fb}, \quad \sigma(H_2)\times \mathrm{BR}(H_2\to ZH_1) = 122 \text{ fb},$$
$$\sigma(H_3)\times \mathrm{BR}(H_3\to H_1H_1) = 235 \text{ fb}, \quad \sigma(H_3)\times \mathrm{BR}(H_3\to WW) = 315 \text{ fb},$$
$$\sigma(H_3)\times \mathrm{BR}(H_3\to ZZ) = 136 \text{ fb}, \quad \sigma(H_3)\times \mathrm{BR}(H_3\to ZH_1) = 76 \text{ fb}.$$

Simultaneous measurements of 'CP-even decays' (H_1H_1,VV) and 'CP-odd decays' (VH_1)
=> CP violation

Interesting Benchmark Point w.r.t test of CP violation

C2HDM Type I

[Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

input parameters

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	$\mathrm{Re}(m_{12}^2)$ [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

results

$\sigma_{H_1H_1}^{\mathrm{NLO}}$ [fb]	K-factor	$\Gamma_{H_1}^{\mathrm{tot}}$ [GeV]	$\Gamma_{H_2}^{\mathrm{tot}}$ [GeV]	$\Gamma_{H_3}^{\mathrm{tot}}$ [GeV]	$\Gamma_{H^\pm}^{\mathrm{tot}}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma_{H_1}^{\mathrm{NNLO}}$ [pb]	$\sigma_{H_2}^{\mathrm{NNLO}}$ [pb]	$\sigma_{H_3}^{\mathrm{NNLO}}$ [pb]	
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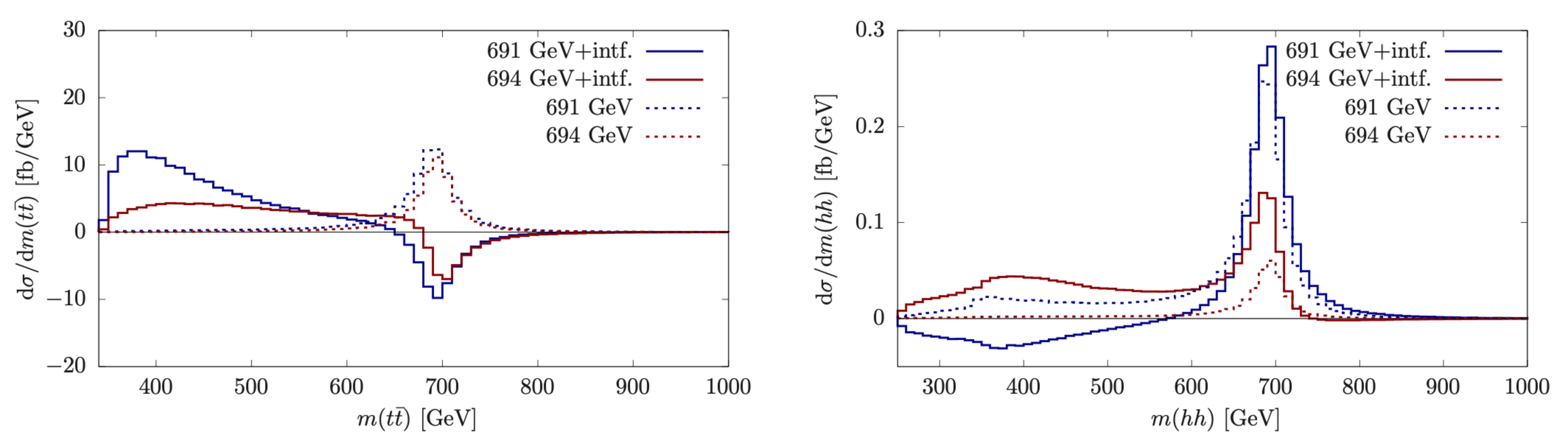
Simultaneous measurements of 'CP-even decays' (H_1H_1,VV) and 'CP-odd decays' (VH_1)
=> CP violation

Di-Higgs Peaks and Top Valleys

degenerate mass spectrum! $|m_{H_2} - m_{H_3}| < 0.1\, m_{H_3}$ [Basler,Dawson,Englert,MM,'21]



heavy Higgs production
w/ subsequent decay into tt
destructive interference effects
between signal and SM background

heavy Higgs production
w/ subsequent decay into SM-like hh
constructive signal-signal
interference effects


Implications of
Baryogenesis

Electroweak Baryogenesis

- **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

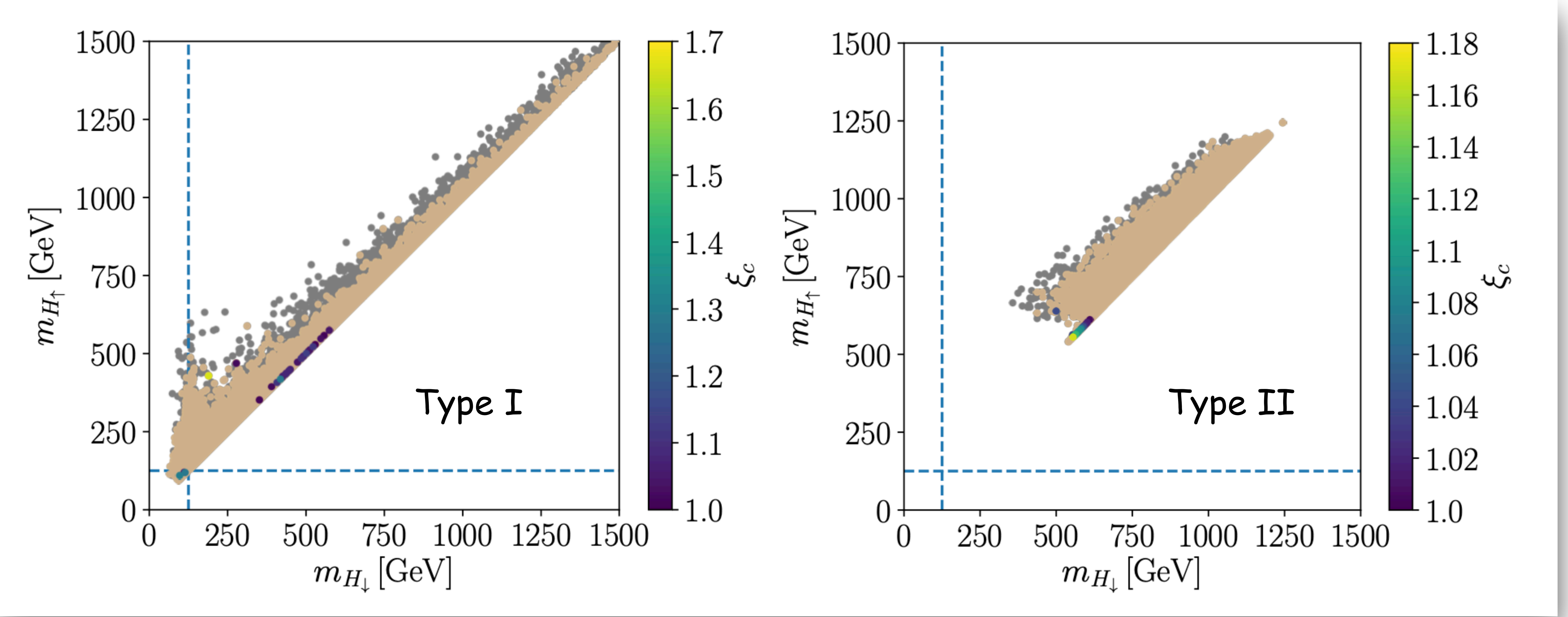
- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

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

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

SFOEWPT and Mass Spectrum

[Basler,MM,Müller,'19]



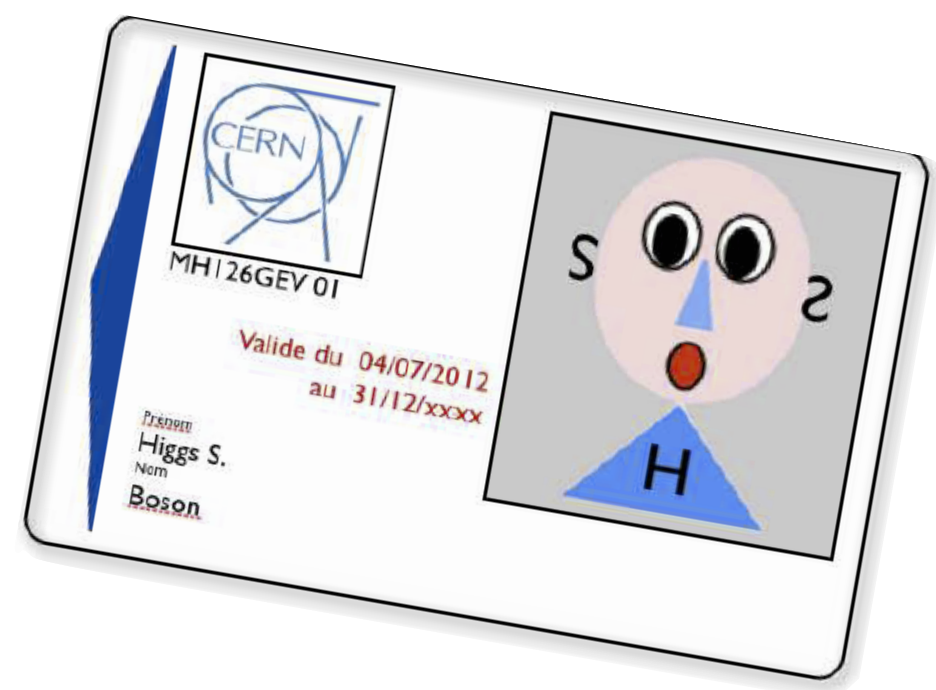
SFOEWPT tightens mass gap: $\Delta_{m_{H_i},m_{H_j}} = \min_{m_{H_i} \neq m_{H_j}} |m_{H_i} - m_{H_j}|$ with $H_{i,j} \in \{h, H_\downarrow, H_\uparrow, H^\pm\}$

$$\text{Type I}: \max_{\text{sample}} \Delta_{m_{H_i},m_{H_j}} \approx 61 \text{ GeV} \xrightarrow{\text{EWPT}} \approx 21 \text{ GeV}$$

$$\text{Type II}: \max_{\text{sample}} \Delta_{m_{H_i},m_{H_j}} \approx 62 \text{ GeV} \xrightarrow{\text{EWPT}} \approx 33 \text{ GeV}$$

Conclusions

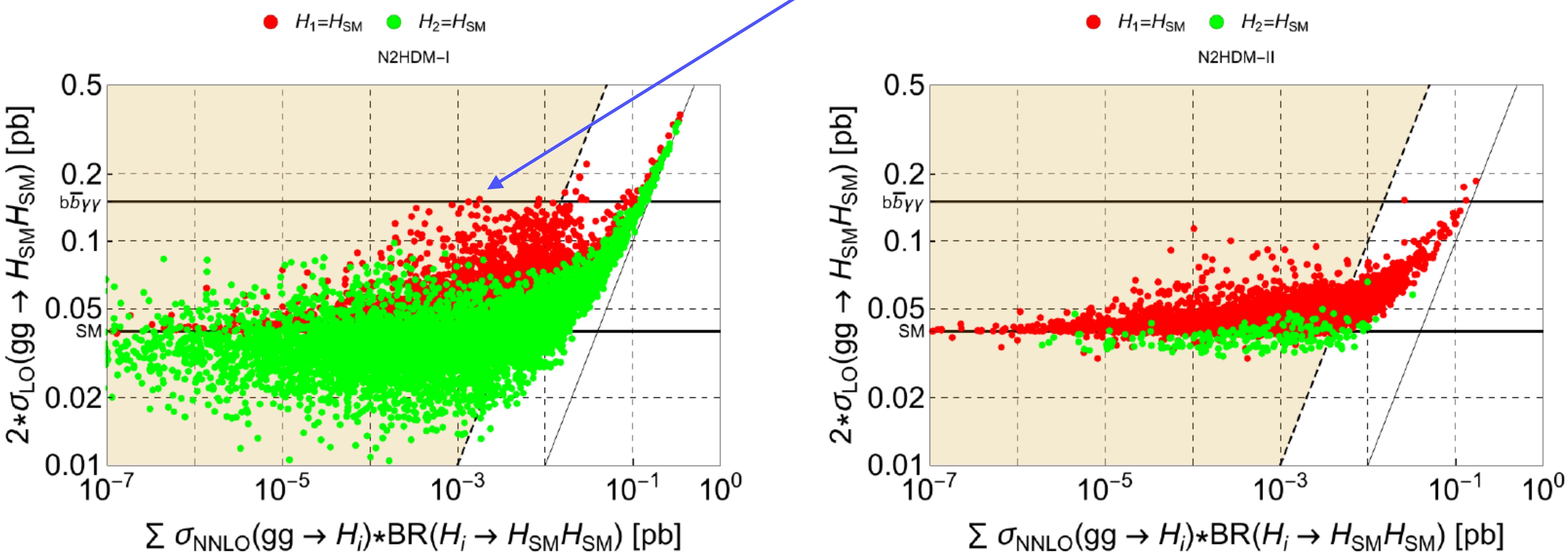
- C2HDM well motivated (baryogenesis (SFOEWPT/CPviol), rich phenomenology)
- Exp. & theoretical constraints => compressed mass spectrum
- Di-Higgs cross sections: 1.2 (continuum) and 10.2 (resonant) times the SM value
- CP violation can be tested in combination of Higgs decays into di-Higgs, VH, VV
- Requirement of an SFOEWPT tightens mass gaps in spectrum further



Thank you for your attention!

Impact of Di-Higgs Searches on N2HDM parameter space

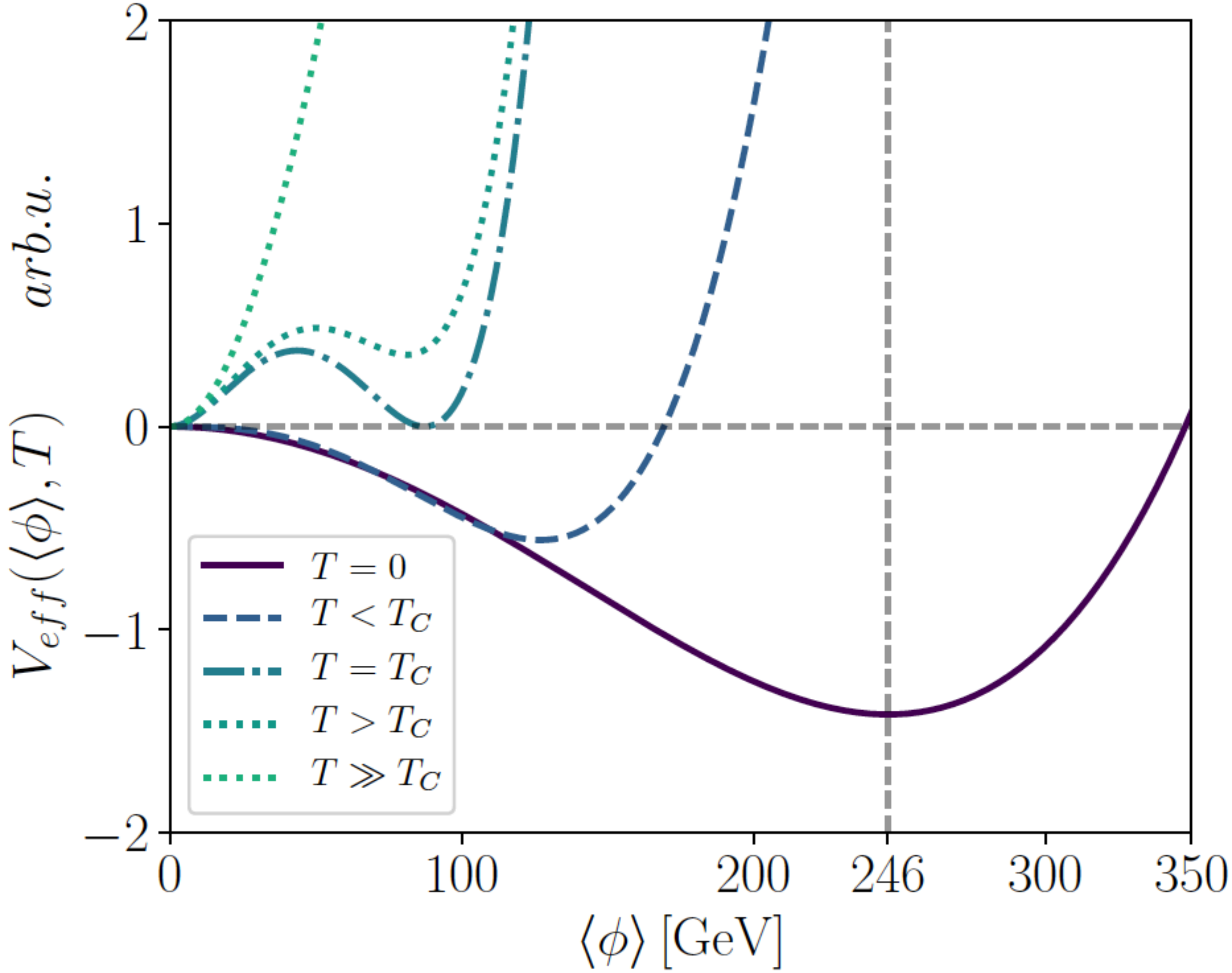
Non-resonant experimental searches start cutting in N2HDM parameter space



Cross section resonantly dominated if $\sigma(H_k) \times BR(H_k \to H_{SM} H_{SM}) > 0.1\, \sigma(H_k H_k)$

Non-resonant experimental search limits applied

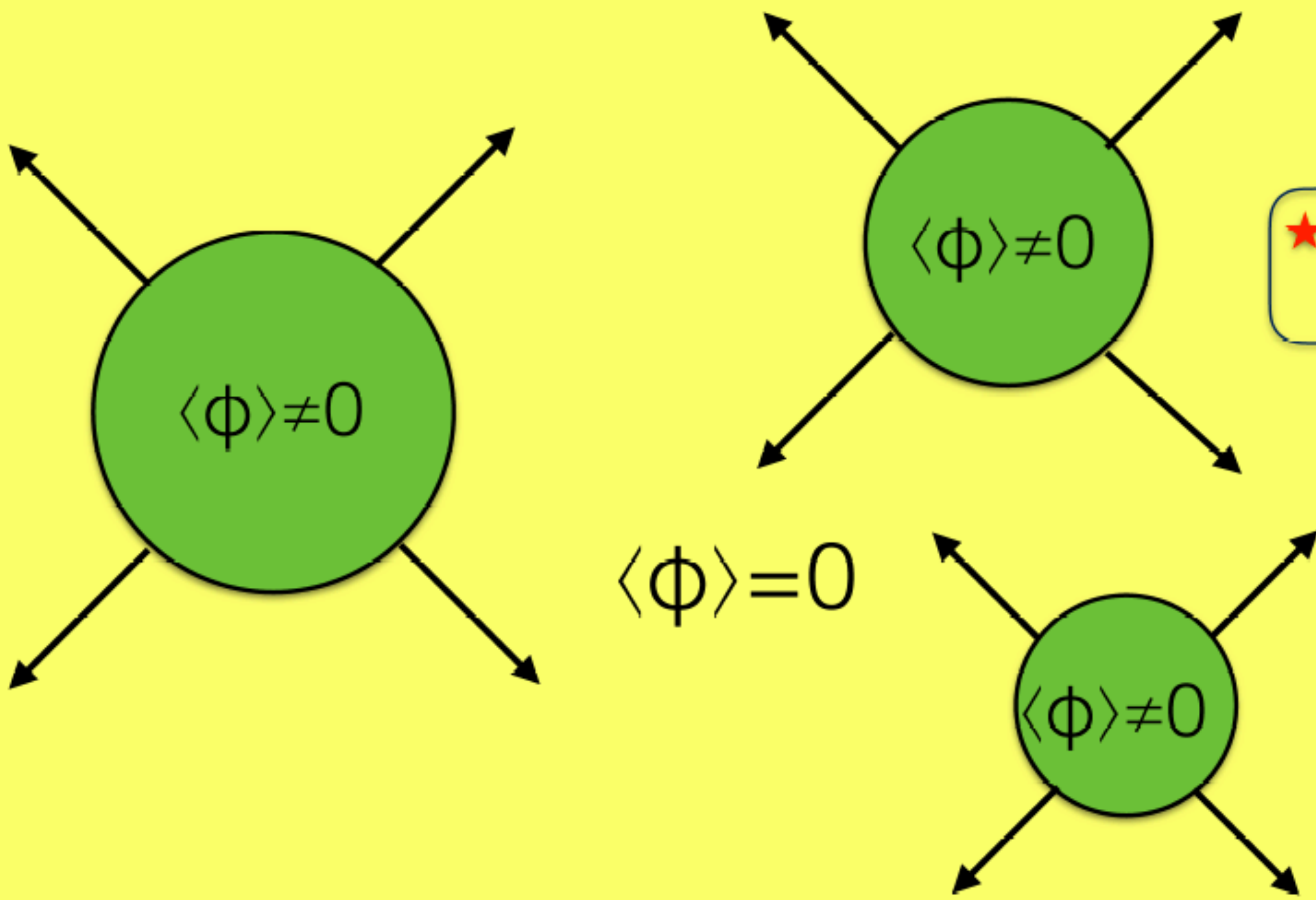
Strong First Order Electroweak Phase Transition



Baryogenesis in a Nutshell

Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum

They expand & particles in plasma interact with the phase interface in a CP-violating way



★ $\langle\phi_c(T_c)\rangle/T_c \geq 1$

ϕ_c, T_c

VEV and T at EW phase transition

CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall

Produced baryons muss not be washed out by sphaleron processes in symmetric phase in front of bubble wall★