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Extended scalar sectors at the LHC - my theory overview

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Scalar Extensions of the SM - why do they make us happy?

- They provide Dark Matter candidates compatible with all available experimental constraints;
- They provide new sources of CP-violation;
- They can change the di-Higgs cross section;
- They provide a means of having a strong first order phase transition;
- They provide a 125 GeV scalar in agreement with all data;
- You get a bunch of extra scalars, keeping everybody busy and happy.

All potentials in one slide

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{m_S^2}{2}\Phi_S^2$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

Allows for a decoupling limit

Particle (type) spectrum depends on the symmetries imposed on the model, and whether they are spontaneously broken or not.

with fields

$v_2 = 0$, dark matter, IDM

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} \qquad \Phi_S = v_S + \rho_S$$

The one with the larger spectrum is the N2HDM with two charged and four neutral particles.

$v_S = 0$, singlet dark matter

magenta $\Longrightarrow$ SM

magenta + blue $\Longrightarrow$ RxSM (also CxSM) Complex version - CP-violation

magenta + black $\Longrightarrow$ 2HDM (also C2HDM)

magenta + black + blue + red $\Longrightarrow$ N2HDM

softly broken Z_2 $2HDM: \ \Phi_1 \to \Phi_1; \ \Phi_2 \to -\Phi_2$

softly broken Z_2 $N2HDM: \ \Phi_1 \to \Phi_1; \ \Phi_2 \to -\Phi_2; \ \Phi_S \to \Phi_S$

exact Z_2' $N2HDM: \ \Phi_1 \to \Phi_1; \ \Phi_2 \to \Phi_2; \ \Phi_S \to -\Phi_S$

- **m^2_{12} and λ_5 real** 2HDM
- **m^2_{12} and λ_5 complex** C2HDM

h_{125} couplings (gauge)

Lightest Higgs coupling modifiers (to gauge bosons)

$$g^{hVV}_{2HDM} = \sin(\beta-\alpha) g^{hVV}_{SM}$$

Although the models look very different, the couplings to gauge bosons have the same structure and are multiplied by a numerical factor (except for CP-violating Yukawa couplings).

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

CP-VIOLATING 2HDM

"PSEUDOSCALAR" COMPONENT (DOUBLET)

$$|s_2| = 0 \;\Rightarrow\; h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \;\Rightarrow\; h_1 \text{ is a pure pseudoscalar}$$

$$g^{hVV}_{N2HDM} = \cos\alpha_2 \, g^{hVV}_{2HDM}$$

SINGLET COMPONENT

$(a+ib)$

SM + REAL SINGLET

$$g^{hVV}_{RxSM} = \cos\alpha_1 \, g^{hVV}_{SM}$$

SM + COMPLEX SINGLET

$$g^{hVV}_{CxSM} = \cos\alpha_1 \cos\alpha_2 \, g^{hVV}_{SM}$$

REAL COMPONENT

IMAGINARY COMPONENT

h_{125} couplings (Yukawa)

Type I $\kappa_U^I = \kappa_D^I = \kappa_L^I = \frac{\cos\alpha}{\sin\beta}$

Type II $\kappa_U^{II} = \frac{\cos\alpha}{\sin\beta}$ $\kappa_D^{II} = \kappa_L^{II} = -\frac{\sin\alpha}{\cos\beta}$

Type F(Y) $\kappa_U^F = \kappa_L^F = \frac{\cos\alpha}{\sin\beta}$ $\kappa_D^F = -\frac{\sin\alpha}{\cos\beta}$

Type LS(X) $\kappa_U^{LS} = \kappa_D^{LS} = \frac{\cos\alpha}{\sin\beta}$ $\kappa_L^{LS} = -\frac{\sin\alpha}{\cos\beta}$

These are coupling modifiers relative to the SM coupling. May increase Yukawa relative to the SM.

III = I' = Y = Flipped = 4…

IV = II' = X = Lepton Specific= 3…

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

$$Y_{N2HDM} = \cos\alpha_2 Y_{2HDM}$$

CP-violation

CP violation from P violation

Fermion currents with scalars can be CP (P) violating. Is there room for a CP-violating piece of the SM Higgs?

$\bar{\psi}\psi$ C even P even -> CP even

$\bar{\psi}\gamma_5\psi$ C even P odd -> CP odd

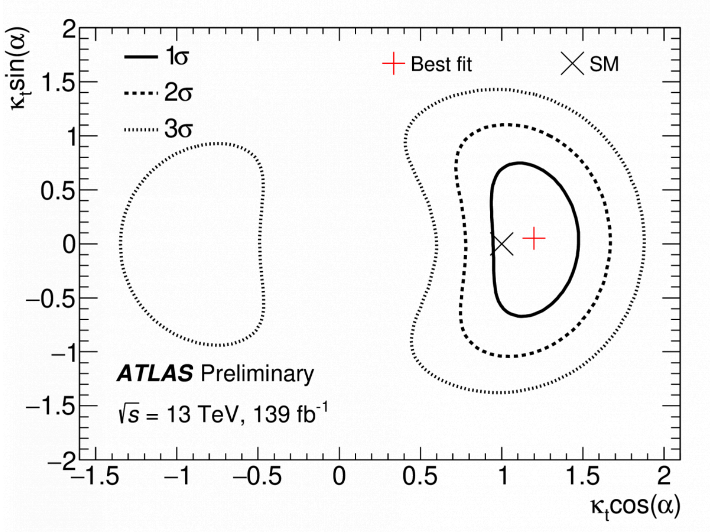
C conserving, CP violating interaction

$$\boxed{\bar{\psi}(a + ib\gamma_5)\psi\,\phi}$$

$$\boxed{pp \to (h \to \gamma\gamma)\bar{t}t}$$

To probe this type of CP-violation we need one Higgs only.

Consistent with the SM. Pure CP-odd coupling excluded at 3.9σ, and |α| > 43° excluded at 95% CL.



$$\mathcal{L}^{CPV}_{\bar{t}th} = -\frac{y_f}{\sqrt{2}}\,\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)\,t\,h$$

$$\kappa_t = \kappa\,\cos\alpha$$

$$\tilde{\kappa}_t = \kappa\,\sin\alpha$$

Rates alone already constrained a lot the CP-odd component.

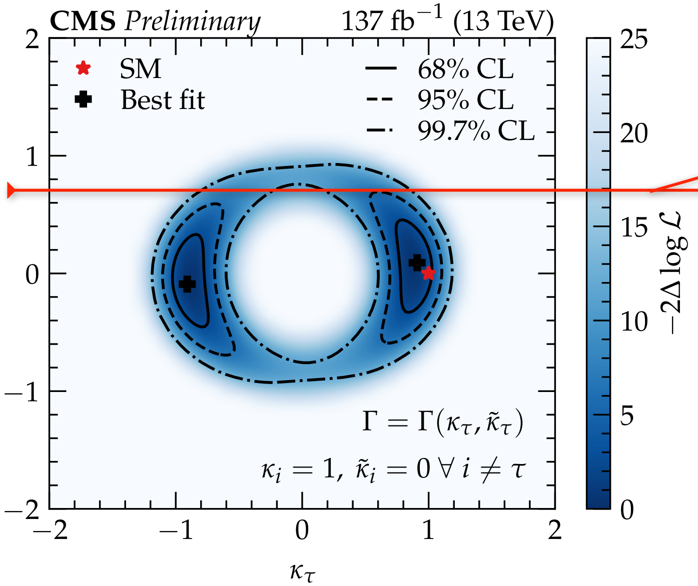
Measurement of CPV angle in ττh

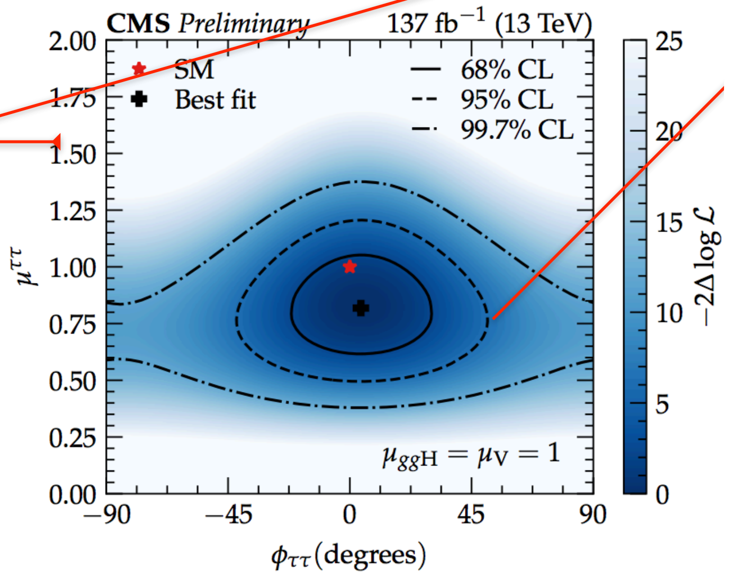
$$\boxed{pp \rightarrow h \rightarrow \tau^+\tau^-}$$

$$\mathscr{L}^{CPV}_{\bar{\tau}\tau h} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(\kappa_\tau + i\tilde{\kappa}_\tau\gamma_5)\,\tau\, h$$

Mixing angle between CP-even and CP-odd τ Yukawa couplings measured 4 ± 17°, compared to an expected uncertainty of ±23° at the 68% confidence level, while at the 95% confidence level the observed (expected) uncertainties were ±36° (±55)°. Compatible with SM predictions.

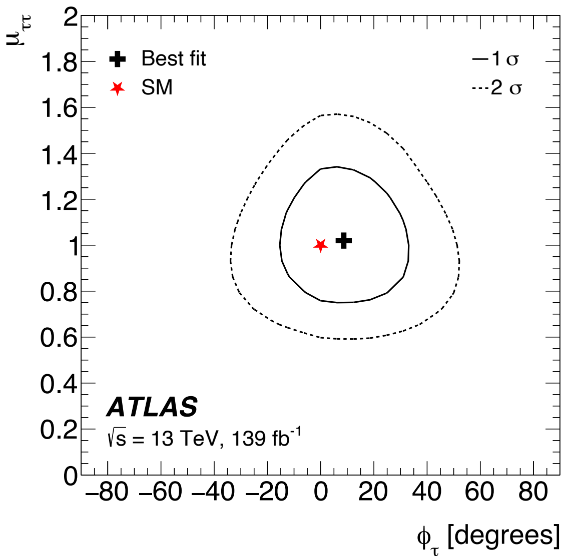
Scenario excluded at 95% CL





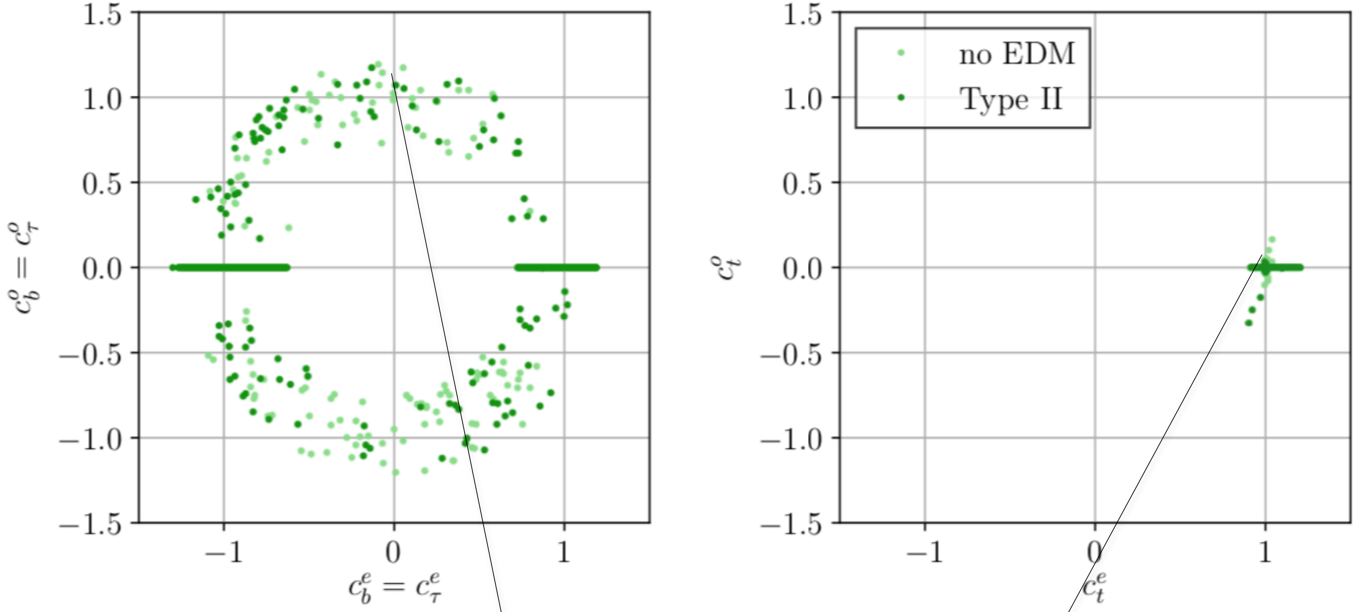
CMS COLLABORATION, CMS-PAS-HIG-20-006

$$\phi_{\tau\tau} = \alpha$$



ATLAS COLLABORATION, ARXIV:2212.05833V1.

CP violation from P violation (only strange!)



$$Y_{C2HDM} = a_F + i\gamma_5 b_F$$

$$b_U \approx 0;\ a_D \approx 0$$

A Type II model where H_2 is the SM-like Higgs.

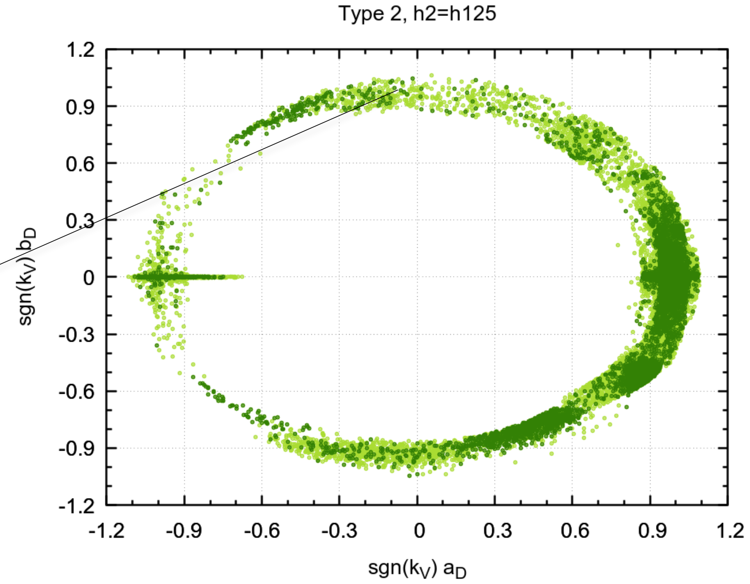
With the latest EDM result [ACME 18]

Find two particles of the same mass one produced in Association with tops as CP-even

$$h_2 = H; pp \to Ht\bar{t}$$

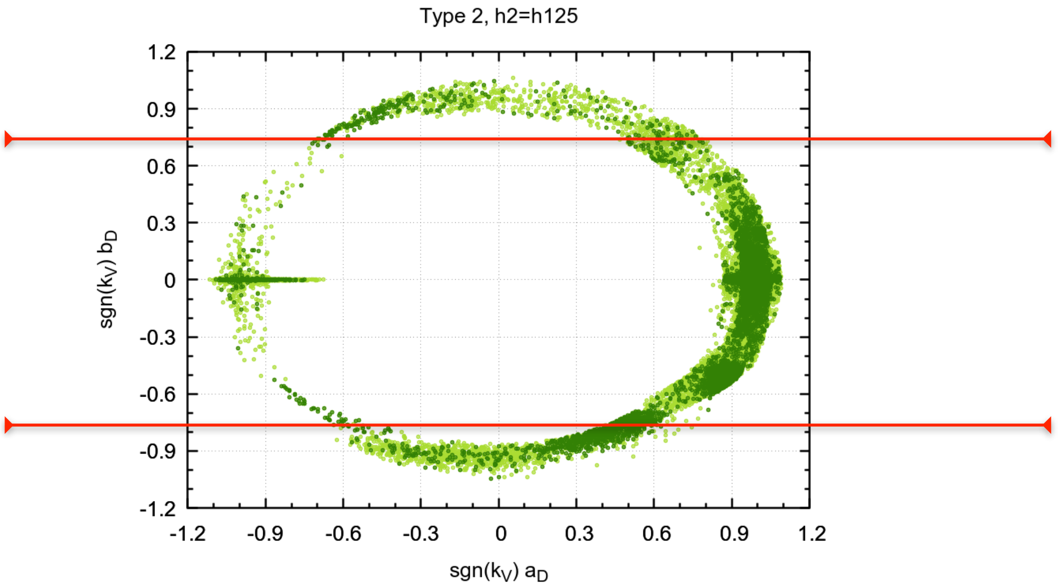
and the other decaying to taus as CP-odd

$$h_2 = A \to \tau^+\tau^-$$



[Fontes eal'15]

CP violation from P violation (only strange!)



LHC (direct) experiments give us information <u>beyond</u> <u>EDMs</u>.

Any scenario in any extension of the SM involving couplings to top-quarks and to tau-leptons, where the 125 GeV has an anomalous coupling (close to pure pseudoscalar) is now excluded. Can we still have

$$h_2 = H; pp \rightarrow Ht\bar{t}$$

and the other decaying to b-quarks as CP-odd?

$$h_2 = A \rightarrow \bar{b}b$$

In many extensions of the SM, probing one Yukawa coupling is not enough!

One attempt I know of

[Alonso eal'21]

$$h \to b\bar{b} \to \Lambda_b\bar{\Lambda}_b$$
$$h \to c\bar{c} \to \Lambda_c\bar{\Lambda}_c$$

"The Higgs boson yields therefore need to be very high to approach sensitivity, O(10^9) events, beyond the reach of all proposed colliders except a high-luminosity 100 TeV muon collider. With such a collider it may be possible to test maximal CP violation at the 2σ level."

CP violation from C violation

Combinations of three decays can also signal CP-violation

$$\boxed{h_1 \to ZZ(+)\, h_2 \to ZZ(+)\, h_2 \to h_1 Z}$$

Here we just need an extra scalar.

Forbidden in the exact alignment limit

$$\boxed{h_1 \to ZZ \;\Leftarrow\; CP(h_1) = 1}$$

$$\boxed{h_3 \to h_2 h_1 \;\Rightarrow\; CP(h_3) = CP(h_2)}$$

Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad CP(h_3) = -\,CP(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad CP(h_{2(3)}) = -\,1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad CP(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

[Fontes eal'15]

C2HDM T1 $H_{SM}=H_1$

Particle	H_1	H_2	H_3	H^+
Mass [GeV]	125.09	265	267	236
Width [GeV]	$4.106\ 10^{-3}$	$3.265\ 10^{-3}$	$4.880\ 10^{-3}$	0.37
σ_{prod} [pb]	49.75	0.76	0.84	

Resonant production : $\sigma_{prod}(H_2) \times BR(H_2\text{->}H_1H_1)$ = 760 fb x 0.252 = 192 fb
+ $\sigma_{prod}(H_3) \times BR(H_3\text{->}H_1H_1)$ = 840 fb x 0.280 = 235 fb

Interesting feature: Test of CP in decays: [Abouabid eal'22]

- $\sigma_{prod}(H_3) \times BR(H_3\text{->}WW)$ = 316 fb and $\sigma_{prod}(H_3) \times BR(H_3\text{->}H_1H_1)$ = 235 fb CP+ AND
- $\sigma_{prod}(H_3) \times BR(H_3\text{->}ZH_1)$ = 76 fb CP-

- $\sigma_{prod}(H_2) \times BR(H_2\text{->}WW)$ = 255 fb and $\sigma_{prod}(H_3) \times BR(H_2\text{->}H_1H_1)$ = 192 fb CP+ AND
- $\sigma_{prod}(H_2) \times BR(H_2\text{->}ZH_1)$ = 122 fb CP-

CP violation from loops (ZZZ)

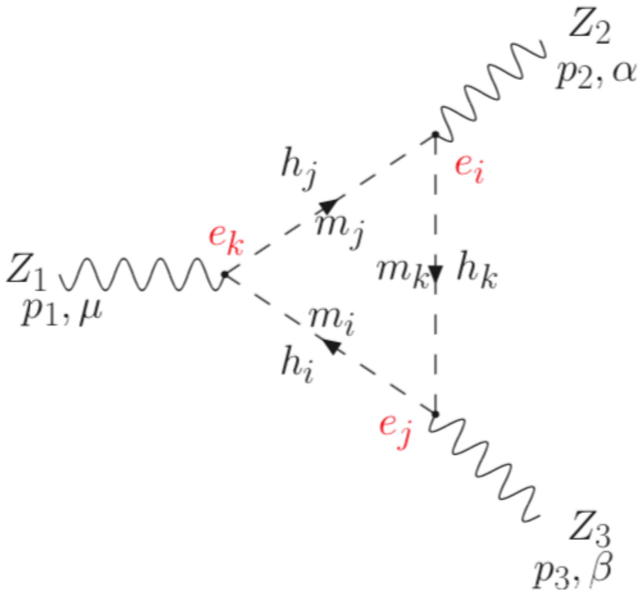
Another possibility of detecting P-even CP-violating signals is via loops. Remember CP-violation could be seen via the combination:

$$h_2 \to h_1 Z \quad CP(h_2) = -\,CP(h_1)$$

$$h_3 \to h_1 Z \quad CP(h_3) = -\,CP(h_1)$$

$$h_3 \to h_2 Z \quad CP(h_3) = -\,CP(h_2)$$

So we can take these three processes and build a nice Feynman diagram.



And see if it is possible to extract information from the measurement of the triple ZZZ anomalous coupling.

[Fontes eal'15, Fontes eal'19]

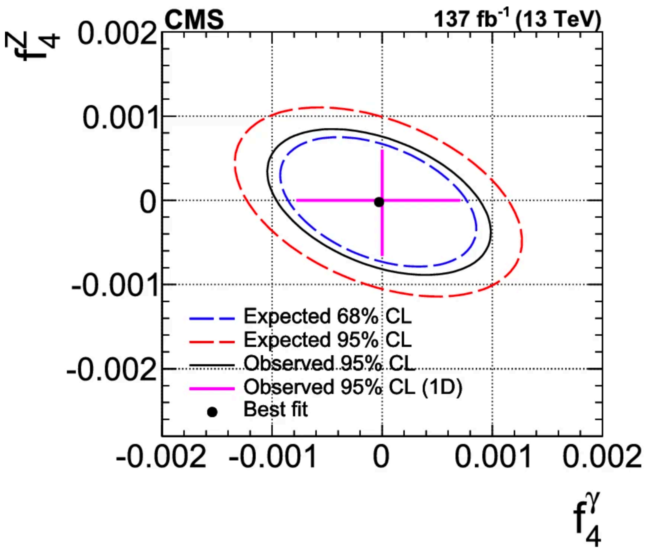
CP violation from loops (ZZZ)

The most general form of the vertex includes a P-even CP-violating term of the form

$$i\Gamma_{\mu\alpha\beta} = -e\frac{p_1^2 - m_Z^2}{m_Z^2} f_4^Z (g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}) + \dots$$

CMS collaboration, EPJC78 (2018) 165. $-1.2 \times 10^{-3} < f_4^Z < 1.0 \times 10^{-3}$

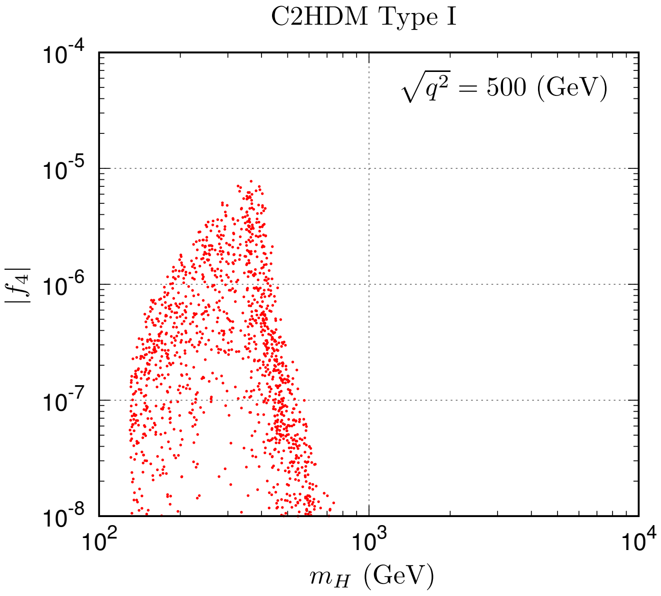
ATLAS collaboration, PRD97 (2018) 032005. $-1.5 \times 10^{-3} < f_4^Z < 1.5 \times 10^{-3}$



CMS collaboration, EPJC81 (2021) 81.

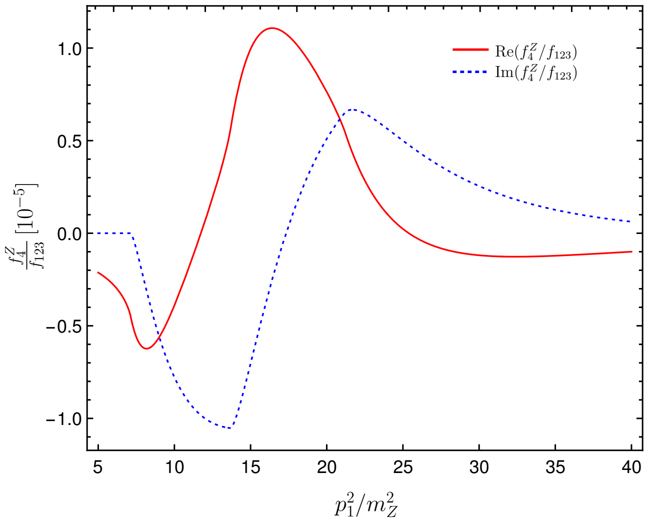
Plot for the C2HDM

[Bélusca-Maïto eal'18]



Plot for CP in the Dark

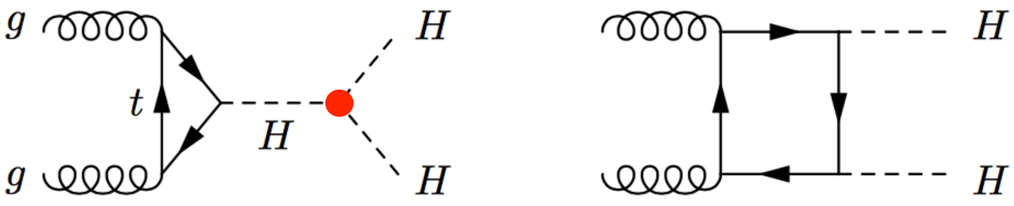
[Azevedo eal'18]



Higgs pair production

Higgs Pair Production - probing the shape of the potential

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



✳ mediated by top and bottom loops
✳ SM: destructive interference triangle and box diagrams

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

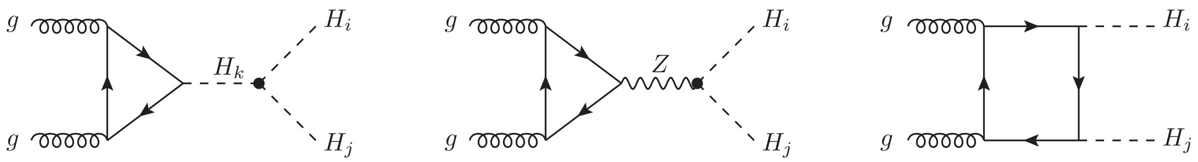
[Grazzini eal'19; Baglio eal,'20]
for extensive list of refs.
see |di Micco eal'19]

at $\text{FT}_{\text{approx}}$: 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

- Challenge: small cross sections and large QCD backgrounds

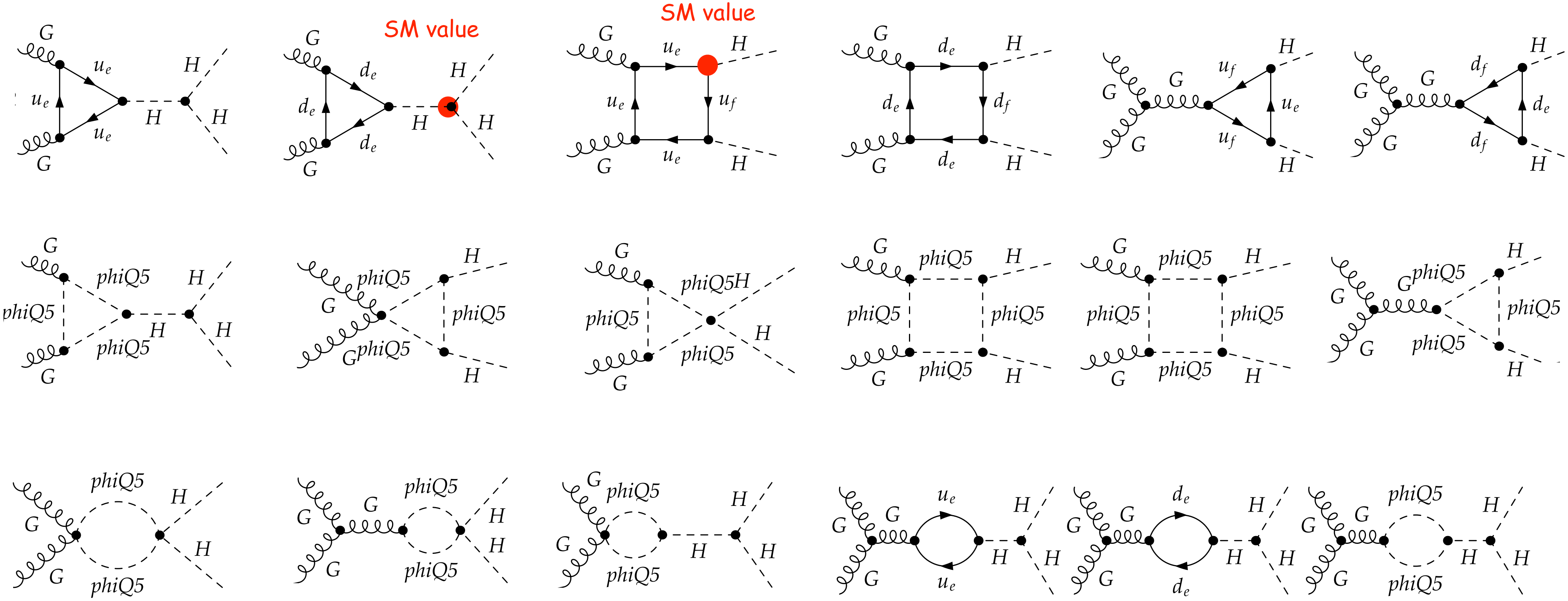
New Physics Effects in Higgs Pair Production

- Example: extended sector only



- Example: extension with a strange dark sector

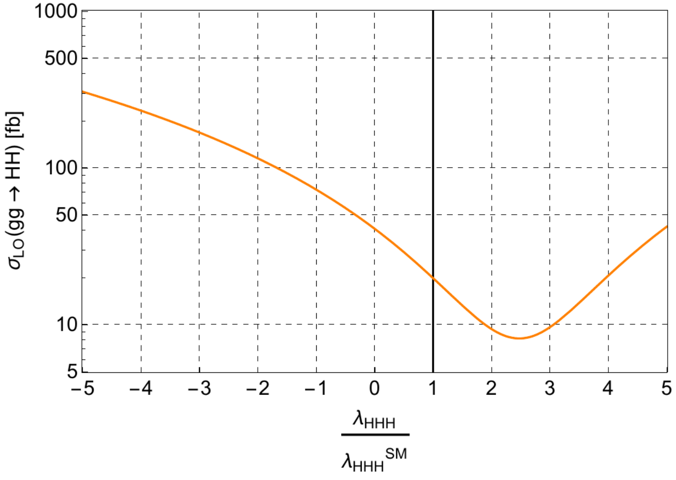
[thanks to D. Neacsu]

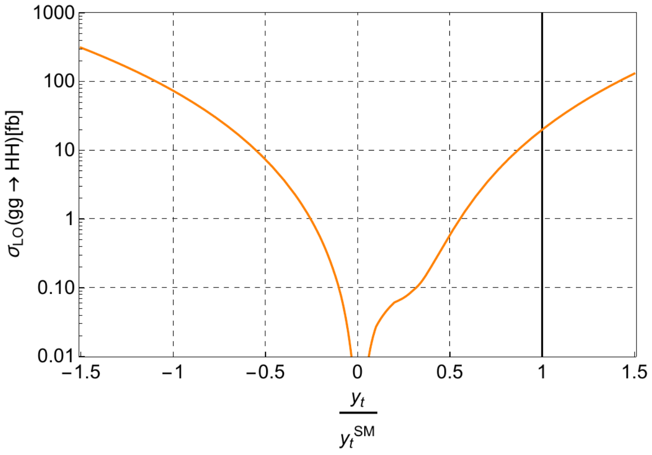

SM value

SM value

Varying the SM couplings

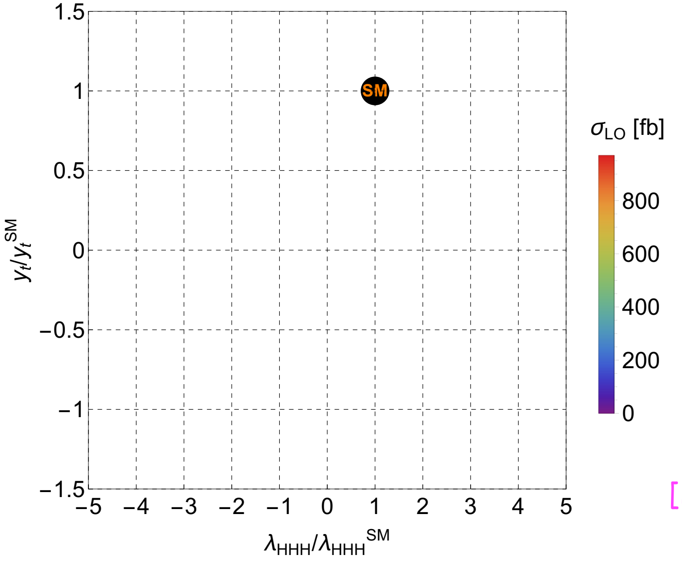
- Cross section: - different trilinear couplings - different Yukawa couplings - new particles in the loop - resonant enhancement

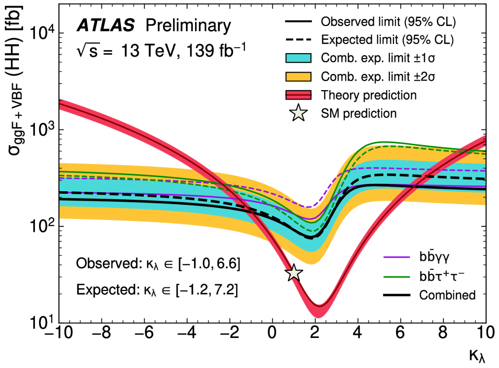




- LO Higgs pair production varying the SM Higgs top-Yukawa coupling/the trilinear Higgs self-coupling/both couplings (lower) while keeping all other couplings fixed to the SM values.

- Destructive interference largest for $\lambda_{HHH}/\lambda^{SM}$ = 2.48. Cross section drops to zero (modulo b-quark contribution) for y_t = 0.



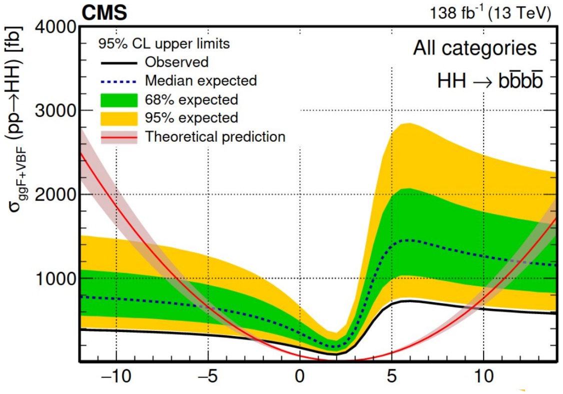


Obs. $k_\lambda \in$ [-2.3, 9.4]

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

[F. Monti, CMS, Higgs Pair Workshop, Dubrovnik 22]

[R. Zhang, ATLAS, Higgs Pair Workshop, Dubrovnik 22]



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

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

Models and final states

	Model	Higgs Spectrum	In principle possible Higgs pair final states from resonant production
Singlet	RxSM SM+real singlet	‘dark phase’: H_{SM}, DM ‘broken phase’: H_{SM}, S	DMDM $H_{SM}H_{SM}$ SS
	TRSM SM+2real singlets	‘broken phase’: H_{SM},H_1,H_2	$H_{SM}H_{SM}$ H_1H_1 H_2H_2 H_1H_2 $H_{SM}H_1$
	CxSM SM+complex singlet	‘dark phase’: H_{SM},S,DM ‘broken phase’: H_{SM},H_1,H_2	$H_{SM}H_{SM}$ SS DMDM $H_{SM}H_{SM}$ H_1H_1 H_2H_2 H_1H_2 $H_{SM}H_1$
Doublet	2HDM 2 Higgs doublets	CP-conserving: H_{SM},H,A	$H_{SM}H_{SM}$ HH
	MSSM 2 Higgs doublets, SUSY!	CP-conserving: H_{SM},H,A	$H_{SM}H_{SM}$ no HH (due to constraints)
	C2HDM 2 doublets, 3 Higgses mix	CP-violating: H_{SM},H_1,H_2	$H_{SM}H_{SM}$ H_1H_1 H_2H_2 H_1H_2 $H_{SM}H_1$
Doublet+Singlet	N2HDM 2 doublets, 1 real singlet	H_{SM},H_1,H_2,A	$H_{SM}H_{SM}$ H_1H_1 H_2H_2 H_1H_2 $H_{SM}H_1$
	2HDM+S 2 doublets + 1 complex singlet	H_{SM},H_1,H_2,A_1,A_2	$H_{SM}H_{SM}$ H_1H_1 H_2H_2 $H_{SM}H_1$ $H_{SM}A_1$ H_1H_2 A_1H_1 A_1H_2
	NMSSM SUSY! 2 doublets + 1 complex singlet	H_{SM},H_1,H_2,A_1,A_2	$H_{SM}H_{SM}$ H_1H_1 $H_{SM}H_1$ $H_{SM}A_1$ A_1H_1 (no H_2H_2,A_1H_2,H_1H_2 ← constraints)

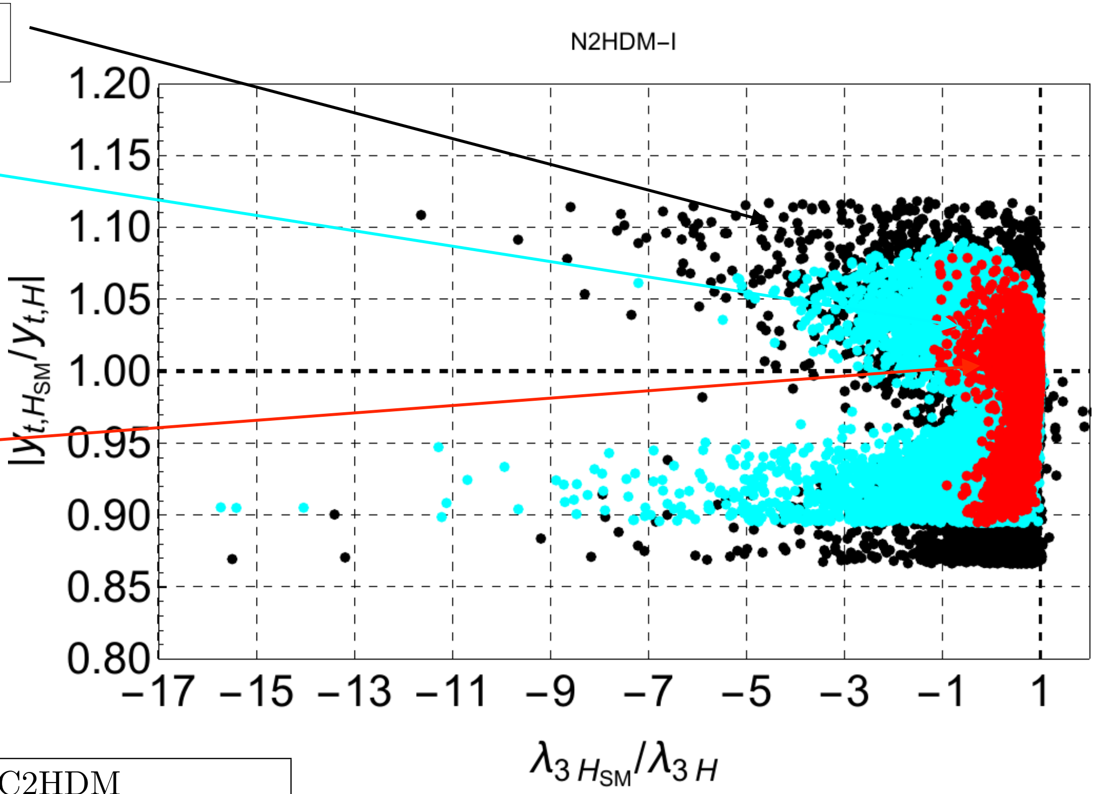
[Abouabid eal’22]

N2HDM T1: Impact H and HH Constraints

All but single Higgs constraints

All but double Higgs constraints

All, incl. double Higgs constraints



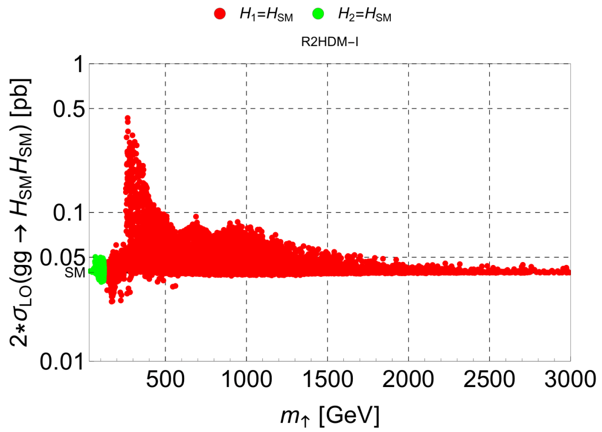
	R2HDM		C2HDM	
	$y^{\text{R2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{R2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$	$y^{\text{C2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{C2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	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	–	–	–	–

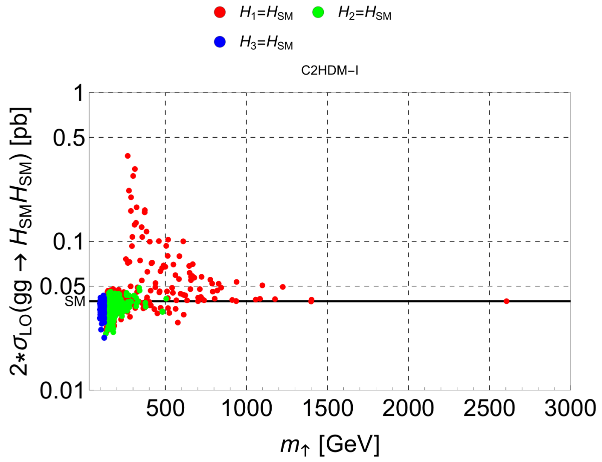
Still compatible with zero

Maximum Cross Section Values for $H_{SM}H_{SM}$ final states - Resonant

NLO SM value: 38 fb

SM-like Model	H1	H2
R2HDM T1	444 fb	
R2HDM T2	81 fb	
C2HDM T1	387 fb	47 fb
C2HDM T2	130 fb	no point
N2HDM T1	376 fb	344 fb
N2HDM T2	188 fb	63 fb
NMSSM	183 fb	65 fb





Maximum values of cross sections in the different models with with one of the scalars being the SM-like Higgs.

2 (approx K-factor)* SIGMA (HH)_SM@LO (from HPAIR) = 39 fb

Multi Higgs Final States

No SM-like Higgs in the final state.

Model	SM-like Higgs	Signature	m_Φ [GeV]	Rate [fb]	K-factor
N2HDM-I	H_3	$H_1H_1 \to (b\bar{b})(b\bar{b})$	41	14538	2.18
	H_3	$H_1H_1 \to (4b); (4\gamma)$	41	4545 ; 700	2.24
	H_1	$AA \to (b\bar{b})(b\bar{b})$	75	6117	2.11
	H_1	$H_2H_2 \to (b\bar{b})(b\bar{b})$	146	73	2.01
	H_2	$AA \to (b\bar{b})(b\bar{b})$	80	2875	2.13
	H_2	$AH_1 \to (b\bar{b})(b\bar{b})$	m_A : 87 m_{H_1} : 91	921	2.09
	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	47	8968	2.17
N2HDM-II	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	44	1146	2.18
C2HDM-I	H_1	$H_2H_2 \to (b\bar{b})(b\bar{b})$	128	475	2.07
	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	66	814	2.16
	H_3	$H_1H_1 \to (b\bar{b})(b\bar{b})$	84	31	2.09
NMSSM	H_1	$A_1A_1 \to (b\bar{b})(b\bar{b})$	166	359	1.95
	H_1	$A_1A_1 \to (\gamma\gamma)(\gamma\gamma)$	179	34	1.96
	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	48	3359	2.18
	H_2	$A_1A_1 \to (b\bar{b})(b\bar{b})$	54	1100	2.18
	H_1	$A_1A_1 \to (t\bar{t})(t\bar{t})$	350	20	1.82

One SM-like Higgs in the final state.

Model	Mixed Higgs State	m_Φ [GeV]	Rate [fb]	K-factor
R2HDM-I	$AH_1(\equiv H_{\rm SM})$	82	46	2.02
	$H_1H_2(\equiv H_{\rm SM})$	68	35	1.97
C2HDM-I	$H_2H_1(\equiv H_{\rm SM})$	128	19	2.02
	$H_1H_2(\equiv H_{\rm SM})$	122	14	2.01
	$H_1H_3(\equiv H_{\rm SM})$	99	11	1.96
N2HDM-I	$H_2H_1(\equiv H_{\rm SM})$	146	105	2.01
	$AH_1(\equiv H_{\rm SM})$	75	830	2.06
	$H_1H_2(\equiv H_{\rm SM})$	54	2110	2.09
	$AH_2(\equiv H_{\rm SM})$	101	277	2.04
	$H_1H_3(\equiv H_{\rm SM})$	73	44	1.97
	$H_2H_3(\equiv H_{\rm SM})$	83	30	1.97
	$AH_3(\equiv H_{\rm SM})$	69	19	2.01
N2HDM-II	$H_1H_2(\equiv H_{\rm SM})$	103	18	1.86
NMSSM	$A_1H_1(\equiv H_{\rm SM})$	113	201	1.92
	$H_2H_1(\equiv H_{\rm SM})$	167	43	1.91
	$A_1H_2(\equiv H_{\rm SM})$	87	40	1.94
	$H_1H_2(\equiv H_{\rm SM})$	80	59	1.90

Maximum rates in the 4b final state.
All cross section values at NLO.

More benchmarks and details of each BP can be provided upon request.

The last slide - Single Higgs vs. Di-Higgs

N2HDM-I and NMSSM - final state with 3 SM-like Higgs bosons (H_1). NLO rates above 10 fb.

Di-Higgs states larger/comparable with direct production.

Reason: non-SM-like Higgs is singlet-like (suppressed couplings to SM-like particles) and/or is more down- than up-type like (suppressed direct production).

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	281.54	441.25	386.98	421.81	1.990

α_1	α_2	α_3	v_s [GeV]	$\text{Re}(m_{12}^2)$ [GeV^2]	
1.153	0.159	0.989	9639	29769	

$$\boxed{\sigma^{\text{NLO}}_{H_1H_2} \times \text{BR}(H_2 \to H_1H_1) \times \text{BR}(H_1 \to b\bar{b})^3 = 509 \cdot 0.37 \cdot 0.60^3 \text{ fb} = 40 \text{ fb}}$$

$$\sigma^{\text{NNLO}}(H_2) \times \text{BR}(H_2 \to H_1H_1) \times \text{BR}(H_1 \to b\bar{b})^2 = 161 \cdot 0.37 \cdot 0.60^2 \text{ fb} = 21 \text{ fb}$$

$$\sigma^{\text{NNLO}}(H_2) \times \text{BR}(H_2 \to WW) = 161 \cdot 0.44 \text{ fb} = 71 \text{ fb}$$

Non-SM- like H_2 has better chances of being discovered in di-Higgs than in single Higgs channels (W bosons still have to decay).

Summary

- Direct searches for a CP-odd component in the Higgs Yukawa couplings gives information that cannot be obtained from the EDMs.
- Anomalous couplings experimental information is moving closer to the largest theoretical estimates in simple models with CP-violation in the scalar sector.
- Large scan in various BSM models taking into account theoretical and experimental constraints.
- Non-resonant SM Higgs pair cxns in BSM models can be significantly larger than in the SM.
- Numerous BSM Higgs sector extensions with large variety of (resonant) Higgs pair final states.
- Single Higgs production impacts Yukawa coupling and thereby trilinear Higgs coupling.
- Large enhancement through resonant production -> also ZHiHj and triple or quartic Higgs production possible; test of CP violation through Higgs decays possible.
- Will continue to provide benchmark points - INPUT WELCOME!

The End

CP violation from loops (hWW)

In this case we start with the most general WWh vertex

$$\mathcal{M}(hW^+W^-) \sim a_1^{W^+W^-} m_W^2 \epsilon^*_{W^+}\epsilon^*_{W^-} + a_3^{W^+W^-} f^{*+}_{\mu\nu}\tilde{f}^{*-\mu\nu}$$

Term coming from a CPV operator.
Contribution from the SM at 2-loop

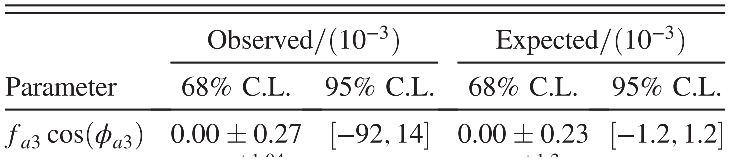
Term in the SM at tree-level
but also in models with CP-violation

$$\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}} \in [-0.81, 0.31]$$

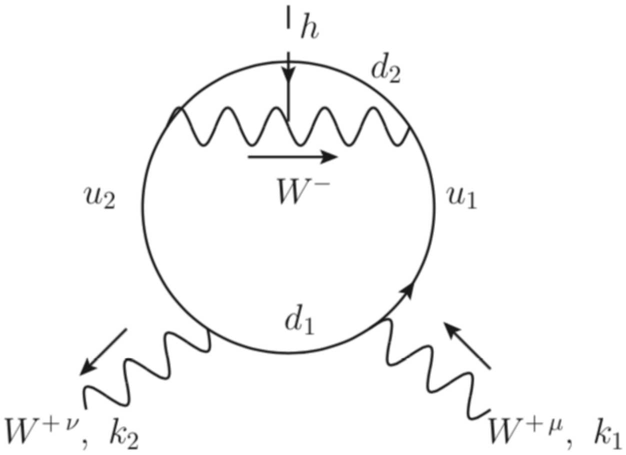
Experimental bound from ATLAS and CMS

ATLAS collaboration, EPJC 76 (2016) 658.

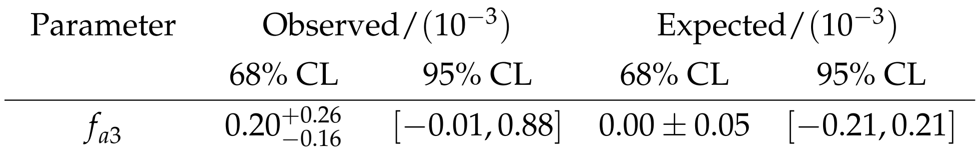
CMS collaboration, PRD100 (2019) 112002.



	Observed/(10^{-3})		Expected/(10^{-3})	
Parameter	68% C.L.	95% C.L.	68% C.L.	95% C.L.
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$



The SM contribution should be proportional to the Jarlskog invariant $J = \mathrm{Im}(V_{ud}V_{cd}^{*} V_{cs}V_{cd}^{*}) = 3.00\times10^{-5}$. The CPV hW^+W^- vertex can only be generated at two-loop.



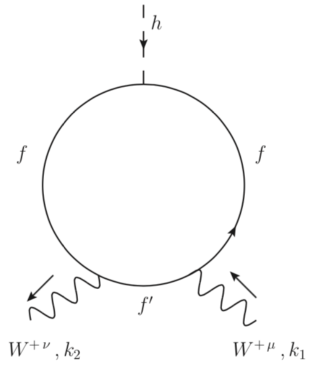
Parameter	Observed/(10^{-3})		Expected/(10^{-3})	
	68% CL	95% CL	68% CL	95% CL
f_{a3}	$0.20^{+0.26}_{-0.16}$	$[-0.01, 0.88]$	0.00 ± 0.05	$[-0.21, 0.21]$

CMS collaboration, ArXiv:2205.05120v1.

The bound has improved at least two orders of magnitude

CP violation from loops (hWW)

THE C2HDM



Starting with f=t and f'=b

Is it worth it?

$$i\mathcal{M}_{tb}^{\rm C2HDM} \sim \frac{ig^2 N_c c_t^o}{16\pi^2 v}\frac{m_t^2}{m_W^2}|V_{tb}|^2 \epsilon_{\mu\nu\rho\sigma} k_1^\rho k_2^\sigma \mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right)$$

$$\mathcal{I}_1(x,y) \equiv \int_0^1 d\alpha \frac{\alpha^2}{\alpha x + (1-\alpha)y - \alpha(1-\alpha)}$$

And because f=b and f'=t can also contribute, the final result is

$$c_{\rm CPV}^{\rm C2HDM} = \frac{N_c g^2}{32\pi^2}|V_{tb}|^2 \left[\frac{c_t^o m_t^2}{m_W^2}\mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right) + \frac{c_b^o m_b^2}{m_W^2}\mathcal{I}_1\left(\frac{m_b^2}{m_W^2}, \frac{m_t^2}{m_W^2}\right)\right]$$

$$c_{\rm CPV} = 2\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}}$$

$$\boxed{c_{\rm CPV}^{\rm C2HDM} \simeq 6.6 \times 10^{-4} \sim \mathcal{O}(10^{-3})}$$

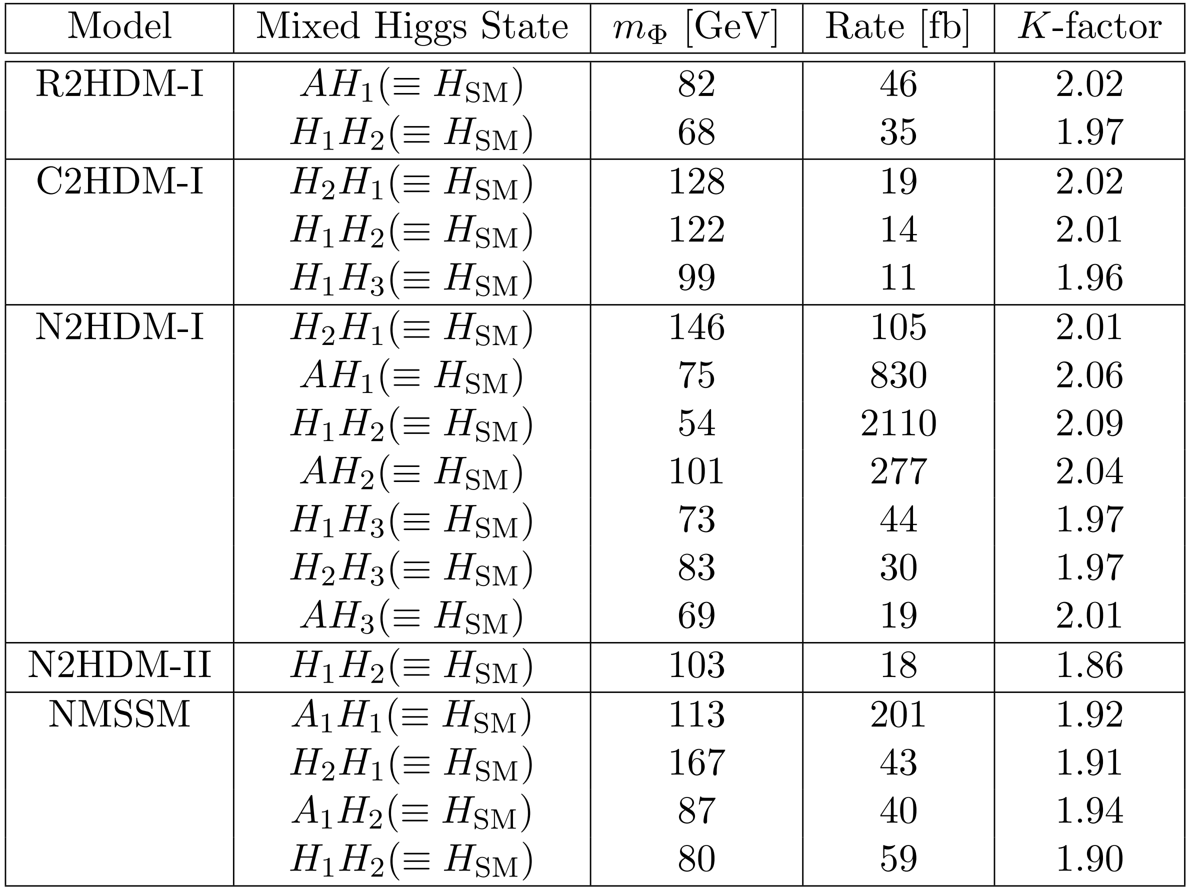
USING ALL EXPERIMENTAL (AND THEORETICAL) BOUNDS

[Huang eal'20]

Other Higgs Pairs final states

$A(H_i)H_{SM}$ Production (4b)

Maximum rates in the 4b final state. All cross section values at NLO.



Model	Mixed Higgs State	m_Φ [GeV]	Rate [fb]	K-factor
R2HDM-I	$AH_1(\equiv H_{\rm SM})$	82	46	2.02
	$H_1H_2(\equiv H_{\rm SM})$	68	35	1.97
C2HDM-I	$H_2H_1(\equiv H_{\rm SM})$	128	19	2.02
	$H_1H_2(\equiv H_{\rm SM})$	122	14	2.01
	$H_1H_3(\equiv H_{\rm SM})$	99	11	1.96
N2HDM-I	$H_2H_1(\equiv H_{\rm SM})$	146	105	2.01
	$AH_1(\equiv H_{\rm SM})$	75	830	2.06
	$H_1H_2(\equiv H_{\rm SM})$	54	2110	2.09
	$AH_2(\equiv H_{\rm SM})$	101	277	2.04
	$H_1H_3(\equiv H_{\rm SM})$	73	44	1.97
	$H_2H_3(\equiv H_{\rm SM})$	83	30	1.97
	$AH_3(\equiv H_{\rm SM})$	69	19	2.01
N2HDM-II	$H_1H_2(\equiv H_{\rm SM})$	103	18	1.86
NMSSM	$A_1H_1(\equiv H_{\rm SM})$	113	201	1.92
	$H_2H_1(\equiv H_{\rm SM})$	167	43	1.91
	$A_1H_2(\equiv H_{\rm SM})$	87	40	1.94
	$H_1H_2(\equiv H_{\rm SM})$	80	59	1.90

A(H_i)H_{SM} Production (2b2W)

Maximum rates in the 2b2W final state. All cross section values at NLO

Model	Mixed Higgs State	m_Φ [GeV]	Rate [fb]	K-factor
N2HDM-I	$H_2H_1(\equiv H_{\rm SM})$	179	498	1.98
	$H_1H_2(\equiv H_{\rm SM})$	117	590	2.04
NMSSM	$H_2H_1(\equiv H_{\rm SM})$	205	47	1.92

A BP for N2HDM-I in various final states

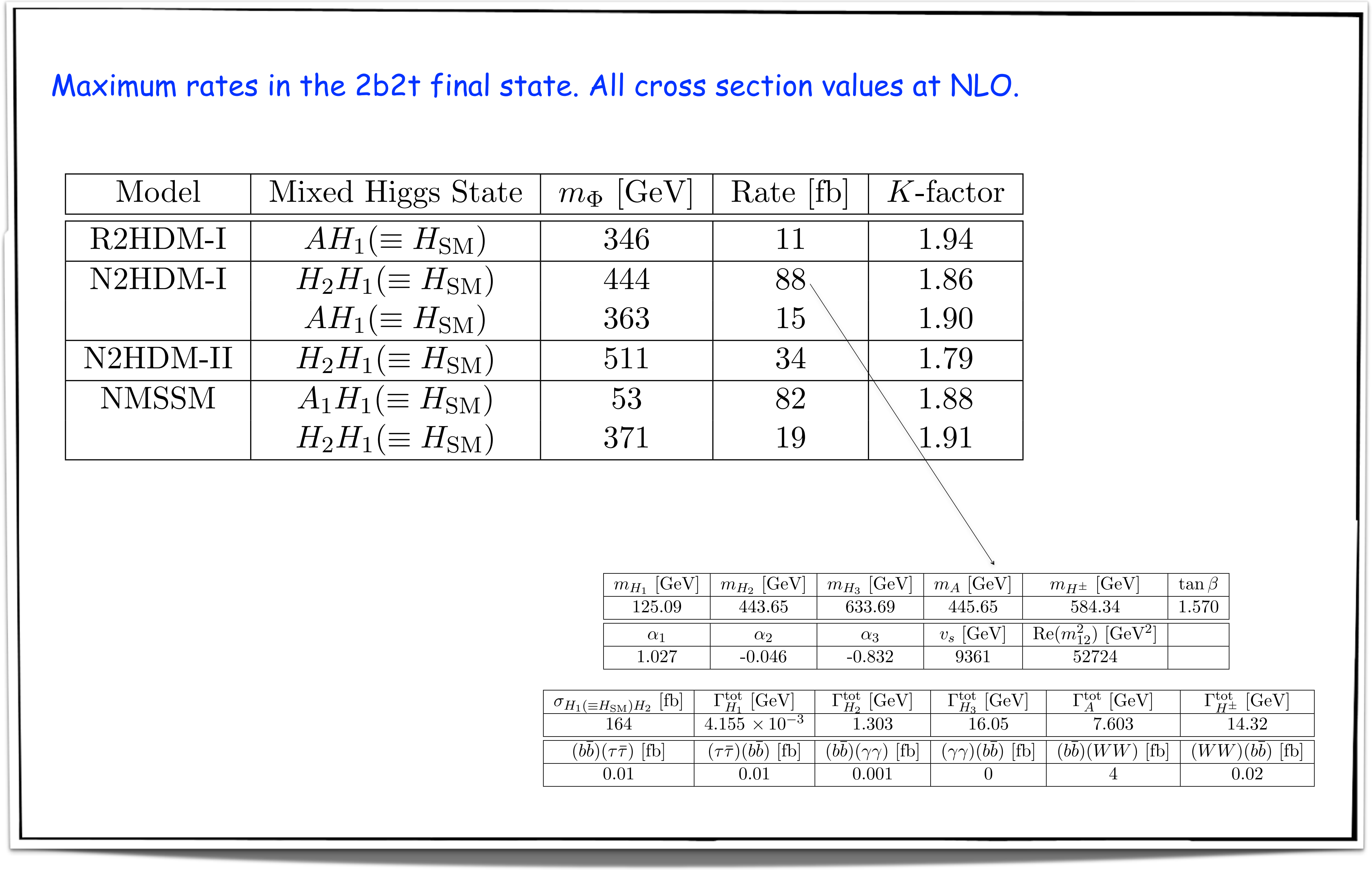
m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
113	125.09	304	581	581	1.804

α_1	α_2	α_3	v_s [GeV]	m_{12}^2 [GeV^2]	
0.173	1.276	-0.651	414	999	

$\sigma^{\rm NLO}_{H_1H_2(\equiv H_{\rm SM})}$ [pb]	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{A}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
2.453	1.691×10^{-5}	4.103×10^{-3}	0.477	30.41	32.10

$(b\bar{b})(\tau\bar{\tau})$ [fb]	$(\tau\bar{\tau})(b\bar{b})$ [fb]	$(b\bar{b})(\gamma\gamma)$ [fb]	$(\gamma\gamma)(b\bar{b})$ [fb]	$(b\bar{b})(WW)$ [fb]	$(WW)(b\bar{b})$ [fb]
67	66	2	23	210	590

$A(H_i)H_{SM}$ Production (2b2t)



Maximum rates in the 2b2t final state. All cross section values at NLO.

Model	Mixed Higgs State	m_Φ [GeV]	Rate [fb]	K-factor
R2HDM-I	$AH_1(\equiv H_{\rm SM})$	346	11	1.94
N2HDM-I	$H_2H_1(\equiv H_{\rm SM})$	444	88	1.86
	$AH_1(\equiv H_{\rm SM})$	363	15	1.90
N2HDM-II	$H_2H_1(\equiv H_{\rm SM})$	511	34	1.79
NMSSM	$A_1H_1(\equiv H_{\rm SM})$	53	82	1.88
	$H_2H_1(\equiv H_{\rm SM})$	371	19	1.91

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	443.65	633.69	445.65	584.34	1.570

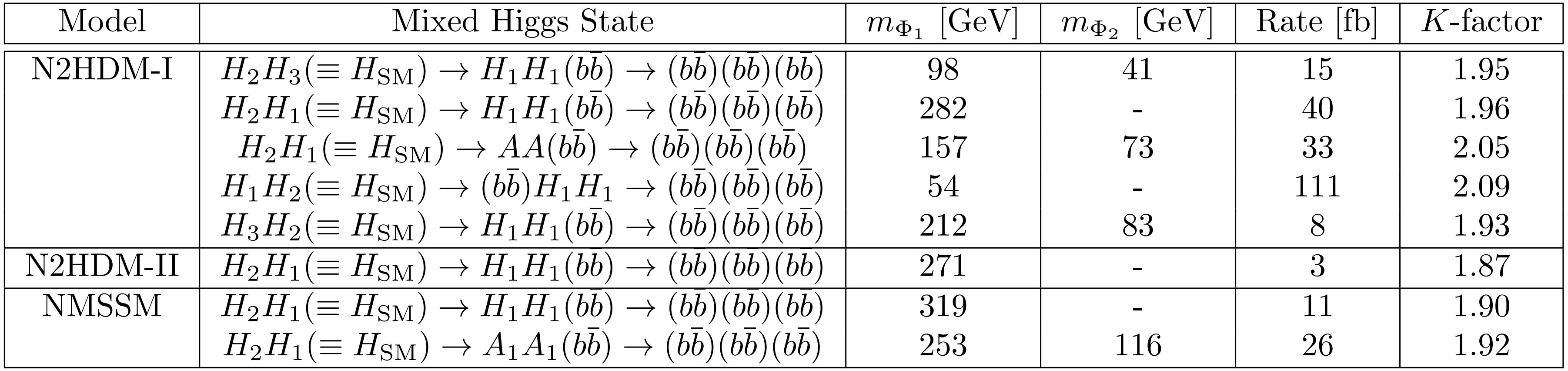
α_1	α_2	α_3	v_s [GeV]	${\rm Re}(m_{12}^2)$ [GeV^2]	
1.027	-0.046	-0.832	9361	52724	

$\sigma_{H_1(\equiv H_{\rm SM})H_2}$ [fb]	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{A}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
164	4.155×10^{-3}	1.303	16.05	7.603	14.32

$(b\bar{b})(\tau\bar{\tau})$ [fb]	$(\tau\bar{\tau})(b\bar{b})$ [fb]	$(b\bar{b})(\gamma\gamma)$ [fb]	$(\gamma\gamma)(b\bar{b})$ [fb]	$(b\bar{b})(WW)$ [fb]	$(WW)(b\bar{b})$ [fb]
0.01	0.01	0.001	0	4	0.02

Multi Higgs Final States (one SM Higgs)

Cascade decays with a SM-like Higgs in the final states



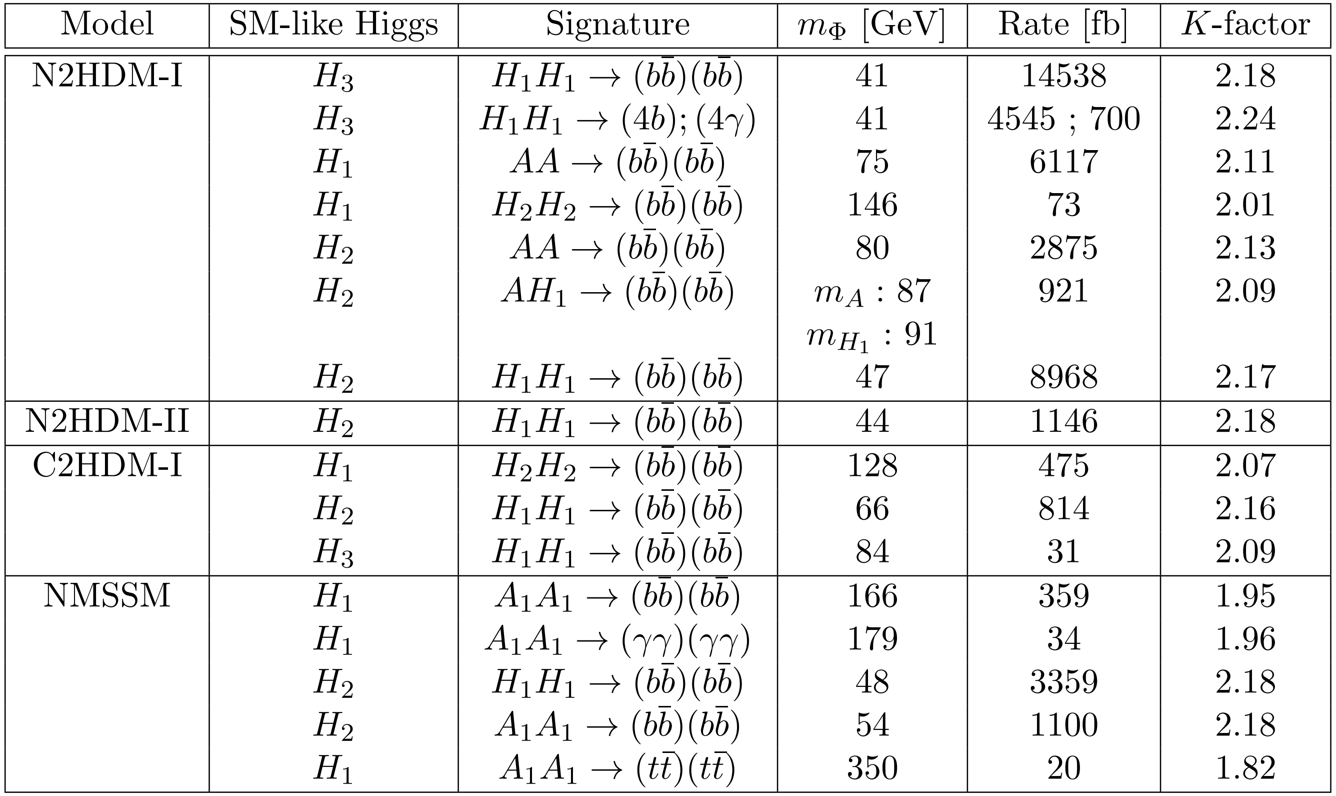
Model	Mixed Higgs State	m_{Φ_1} [GeV]	m_{Φ_2} [GeV]	Rate [fb]	K-factor
N2HDM-I	$H_2H_3(\equiv H_{\mathrm{SM}}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	98	41	15	1.95
	$H_2H_1(\equiv H_{\mathrm{SM}}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	282	-	40	1.96
	$H_2H_1(\equiv H_{\mathrm{SM}}) \to AA(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	157	73	33	2.05
	$H_1H_2(\equiv H_{\mathrm{SM}}) \to (b\bar{b})H_1H_1 \to (b\bar{b})(b\bar{b})(b\bar{b})$	54	-	111	2.09
	$H_3H_2(\equiv H_{\mathrm{SM}}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	212	83	8	1.93
N2HDM-II	$H_2H_1(\equiv H_{\mathrm{SM}}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	271	-	3	1.87
NMSSM	$H_2H_1(\equiv H_{\mathrm{SM}}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	319	-	11	1.90
	$H_2H_1(\equiv H_{\mathrm{SM}}) \to A_1A_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	253	116	26	1.92

The largest cross section we have obtained with 4 SM-like Higgs bosons is for the N2HDM-I

$$\sigma(pp \to H_2H_2 \to H_1H_1H_1H_1 \to 4(b\bar{b}) = 1.4\,\mathrm{fb}$$

Multi Higgs Final States (no SM Higgs)

No SM-like Higgs in the final states



Model	SM-like Higgs	Signature	m_Φ [GeV]	Rate [fb]	K-factor
N2HDM-I	H_3	$H_1H_1 \to (b\bar{b})(b\bar{b})$	41	14538	2.18
	H_3	$H_1H_1 \to (4b); (4\gamma)$	41	4545 ; 700	2.24
	H_1	$AA \to (b\bar{b})(b\bar{b})$	75	6117	2.11
	H_1	$H_2H_2 \to (b\bar{b})(b\bar{b})$	146	73	2.01
	H_2	$AA \to (b\bar{b})(b\bar{b})$	80	2875	2.13
	H_2	$AH_1 \to (b\bar{b})(b\bar{b})$	m_A : 87 m_{H_1} : 91	921	2.09
	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	47	8968	2.17
N2HDM-II	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	44	1146	2.18
C2HDM-I	H_1	$H_2H_2 \to (b\bar{b})(b\bar{b})$	128	475	2.07
	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	66	814	2.16
	H_3	$H_1H_1 \to (b\bar{b})(b\bar{b})$	84	31	2.09
NMSSM	H_1	$A_1A_1 \to (b\bar{b})(b\bar{b})$	166	359	1.95
	H_1	$A_1A_1 \to (\gamma\gamma)(\gamma\gamma)$	179	34	1.96
	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	48	3359	2.18
	H_2	$A_1A_1 \to (b\bar{b})(b\bar{b})$	54	1100	2.18
	H_1	$A_1A_1 \to (t\bar{t})(t\bar{t})$	350	20	1.82

Other benchmark points in the paper. More benchmarks and details of each BP can be provided upon request.

Codes used

Remarks

- Scan in parameter spaces of all models to check for compatibility with theoretical and experimental constraints (using ScannerS [Coimbra,Sampaio,Santos,´13],[MM,Sampaio,Santos,Wittbrodt,´20]);
  ATLAS-CONF-NOTE-2021-030
  Higgs pair exclusion limits included beyond those in HiggsBounds: bbbb [ATLAS,1804.06174], bb$\gamma\gamma$
  ATLAS-CONF-NOTE-2021-035
  [ATLAS,1807.04873], bb$\tau\tau$ [ATLAS,1808.00336], bb$\tau\tau$ [ATLAS,2007.14811], bbWW [ATLAS,1811.04671], bbZZ [CMS,2006.06391], WW$\gamma\gamma$ [ATLAS,1807.08567], WWWW [ATLAS,1811.11028]

- Computation of Higgs pair production including non-resonant and resonant production with HPAIR [Spira] for C2HDM [Gröber,MM,Spira,´17], NMSSM [Dao,MM,Streicher,Walz,´13], 2HDM [MM], N2HDM [MM]: computes NLO Born-improved HTL cxn

- Plots presented in the following at LO (time saving in large scans) multiplied by 2 (to approximate NLO value); NLO QCD HTL: K-factor ~1.4-.1.9 [Gröber,MM,Spira,´17];
  benchmark points will include NLO corrections calculated with HPAIR

HDECAY and its variations

- Based on implementation of new models in HDECAY (includes SM, MSSM and 2HDM)
- Stand-alone codes with inclusion of relevant QCD corrections and off-shell decays. EW corrections turned off.

Djouadi, Kalinowski, Spira, CPC 108 (1998) 56.
Djouadi, Kalinowski, Mühlleitner, Spira, CPC 238 (2019) 214.

sHDECAY (http://www.itp.kit.edu/~maggie/sHDECAY/)

- Real singlet + SM in symmetric (dark) phase, RxSM-dark: 1 Higgs + 1 Dark
- Real singlet + SM in broken phase, RxSM-broken: 1 mixing Higgs
- Complex singlet + SM in symmetric phase, CxSM-dark: 2 mixing Higgs + 1 Dark
- Complex singlet + SM in broken phase, CxSM-broken: 3 mixing Higgs

Costa, Mühlleitner, Sampaio, RS, JHEP 06 (2016) 034.

HDECAY and its variations

N2HDECAY (CP-conserving) (http://www.itp.kit.edu/~maggie/N2HDECAY/) and (https://gitlab.com/jonaswittbrodt/N2HDECAY)

- 2HDM + real singlet in broken phase (dark) phase, 3 CP-even, 1 CP-odd, 1 Charged scalar
- 2HDM + real singlet in unbroken phase (singlet DM), 2 CP-even, 1 CP-odd, 1 Charged, 1DM
- 2HDM + real singlet in unbroken phase (IDM+singlet), 2 CP-even + IDM

MÜHLLEITNER, SAMPAIO, RS, WITTBRODTM JHEP 1703 (2017) 094.

ENGELN, MÜHLLEITNER, WITTBRODT CPC 234 (2019), 256.

C2HDECAY (http://www.itp.kit.edu/~maggie/C2HDM/)

- CP-violating 2HDM: 3 CP-mixed scalars, 1 charged Higgs pair

MÜHLLEITNER, ROMÃO, RS, SILVA, WITTBRODT, JHEP 180206 (2018) 073.

More decays

2HDECAY (CP-conserving) EW corrections to 2HDM scalar decays in different gauge independent renormalisation schemes (https://github.com/marcel-krause/2HDECAY)

Krause, Mühlleitner, Spira, CPC 246 (2020) 106852.

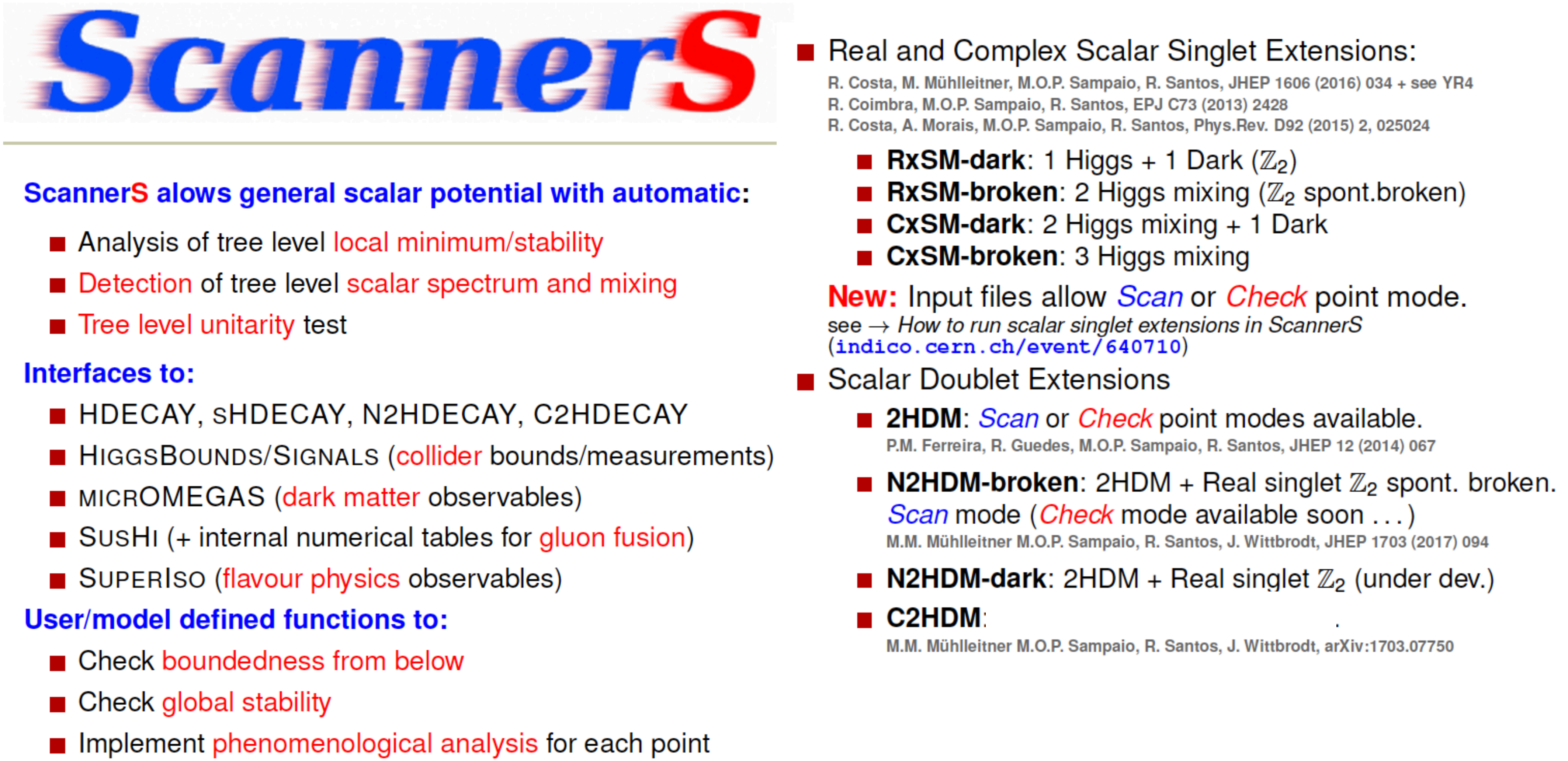
Altenkamp, Dittmaier, Rzehak, JHEP 09 (2017) 134.

Denner, Dittmaier, Lang, JHEP 11 (2018) 104.

ewN2HDECAY (CP-conserving) EW corrections in the broken N2HDM in different gauge independent renormalisation schemes (https://github.com/marcel-krause/ewN2HDECAY)

Krause, Mühlleitner, 1904.02103.

anyHDECAY (Wittbrodt) Modern C++17 library that wraps the non-supersymmetric HDECAY variants (https://gitlab.com/jonaswittbrodt/anyhdecay)



ScannerS

ScannerS allows general scalar potential with automatic:

- Analysis of tree level local minimum/stability
- Detection of tree level scalar spectrum and mixing
- Tree level unitarity test

Interfaces to:

- HDECAY, sHDECAY, N2HDECAY, C2HDECAY
- HIGGSBOUNDS/SIGNALS (collider bounds/measurements)
- MICROMEGAS (dark matter observables)
- SUSHI (+ internal numerical tables for gluon fusion)
- SUPERISO (flavour physics observables)

User/model defined functions to:

- Check boundedness from below
- Check global stability
- Implement phenomenological analysis for each point

- Real and Complex Scalar Singlet Extensions:
  R. Costa, M. Mühlleitner, M.O.P. Sampaio, R. Santos, JHEP 1606 (2016) 034 + see YR4
  R. Coimbra, M.O.P. Sampaio, R. Santos, EPJ C73 (2013) 2428
  R. Costa, A. Morais, M.O.P. Sampaio, R. Santos, Phys.Rev. D92 (2015) 2, 025024
  - **RxSM-dark**: 1 Higgs + 1 Dark ($\mathbb{Z}_2$)
  - **RxSM-broken**: 2 Higgs mixing ($\mathbb{Z}_2$ spont.broken)
  - **CxSM-dark**: 2 Higgs mixing + 1 Dark
  - **CxSM-broken**: 3 Higgs mixing

  New: Input files allow *Scan* or *Check* point mode.
  see → *How to run scalar singlet extensions in ScannerS*
  (`indico.cern.ch/event/640710`)
- Scalar Doublet Extensions
  - **2HDM**: *Scan* or *Check* point modes available.
    P.M. Ferreira, R. Guedes, M.O.P. Sampaio, R. Santos, JHEP 12 (2014) 067
  - **N2HDM-broken**: 2HDM + Real singlet $\mathbb{Z}_2$ spont. broken.
    Scan mode (*Check* mode available soon . . .)
    M.M. Mühlleitner M.O.P. Sampaio, R. Santos, J. Wittbrodt, JHEP 1703 (2017) 094
  - **N2HDM-dark**: 2HDM + Real singlet $\mathbb{Z}_2$ (under dev.)
  - **C2HDM**: .
    M.M. Mühlleitner M.O.P. Sampaio, R. Santos, J. Wittbrodt, arXiv:1703.07750

COIMBRA, SAMPAIO, RS, EPJ C73 (2013) 2428.

Recent developments: improvement of performance; simplified installation with automatic dependency management

(https://jonaswittbrodt.gitlab.io/ScannerS/)

MÜHLLEITNER, SAMPAIO, RS, WITTBRODT, 2007.02985.

HPAIR

HPAIR (SPIRA) SM and MSSM, $gg, qq \to hh, HH, AA, hH, hA, HA$ (http://tiger.web.psi.ch/hpair/)

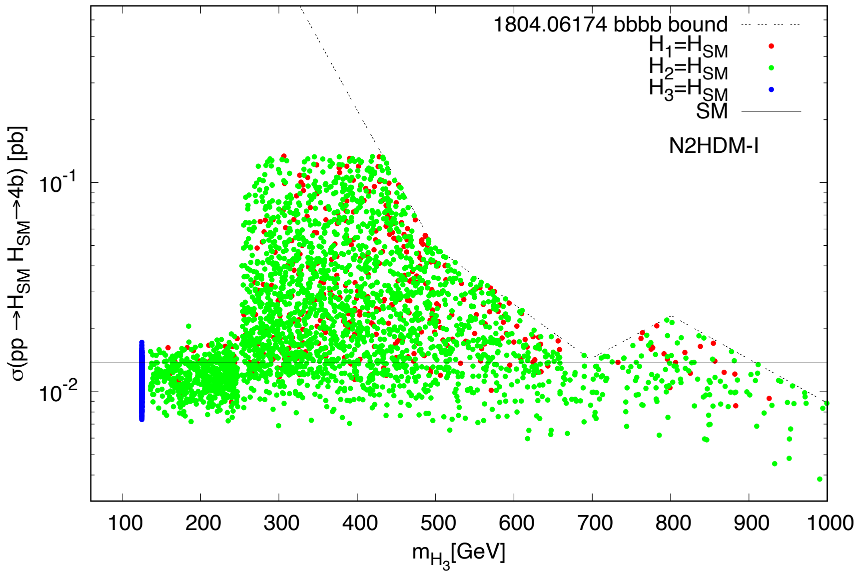
NMSSM version (private)

Baglio, Dao, Gröber, Mühlleitner, Rzehak, EPJ Web Conf. 49 (2013) 12001.

C2HDM version (private)

Gröber, Mühlleitner, Spira, NPB925 (2017) 1.

2HDM and N2HDM versions (private) Mühlleitner



CP violation from C violation

Suppose we have a 2HDM extension of the SM but with no fermions. Also let us assume for the moment that the theory conserves C and P separately. The C and P quantum numbers of the Z boson is

$$C(Z_\mu) = P(Z_\mu) = -1$$

Because we have vertices of the type hhh and HHH,

$$P(h) = P(H) = 1;\; C(h) = C(H) = 1$$

Since the neutral Goldstone couples derivatively to the Z boson (and mixes with the A)

$$P(G_0) = P(A) = 1;\; C(G_0) = C(A) = -1 \qquad C(Z_\mu \partial^\mu A h) = 1; P(Z_\mu \partial^\mu A h) = 1$$

Or without being sloppy

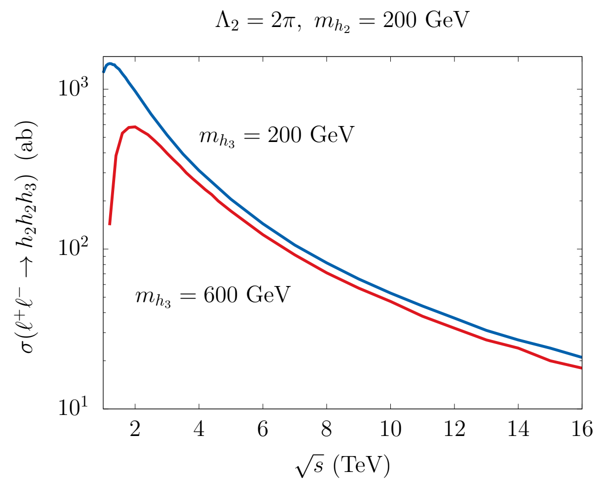
$$C Z_\mu C^{-1} = -Z_\mu; \quad P Z_\mu P^{-1} = Z^\mu$$

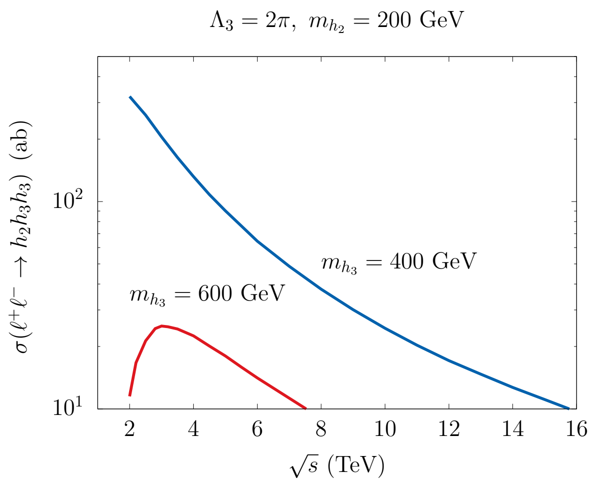
And

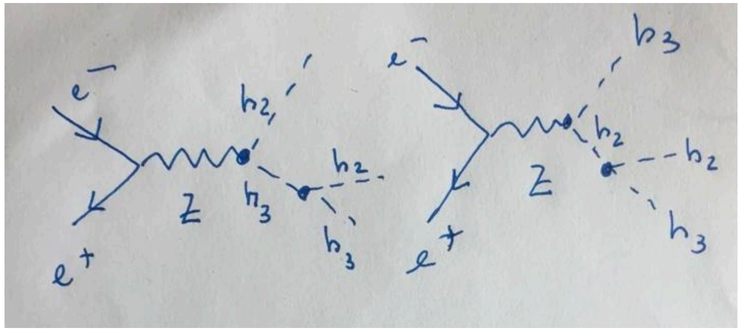
$$P \partial^\mu G_0 Z_\mu P^{-1} = \partial_\mu G_0 Z^\mu$$

C2HDM at future colliders

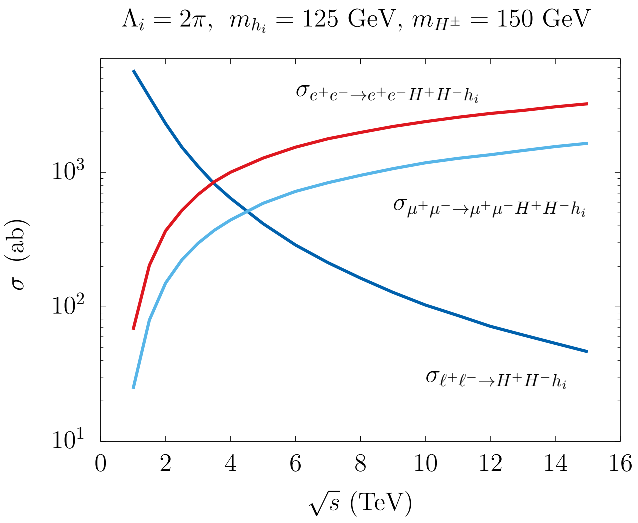
If the new particles are heavier we will need more energy. Still it will be a hard task.

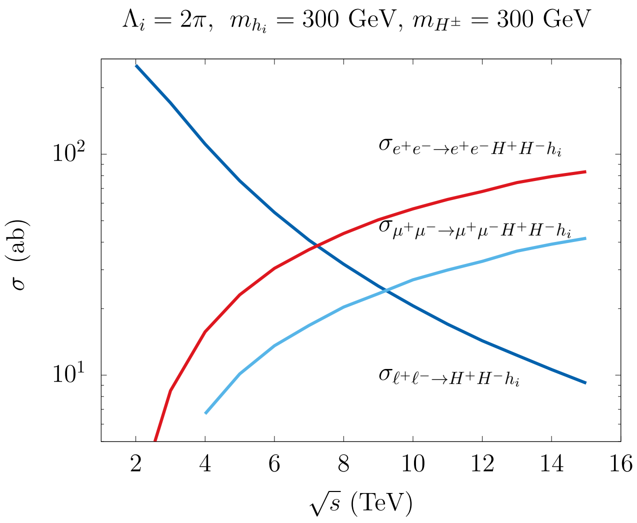

$\Lambda_2 = 2\pi,\ m_{h_2} = 200$ GeV

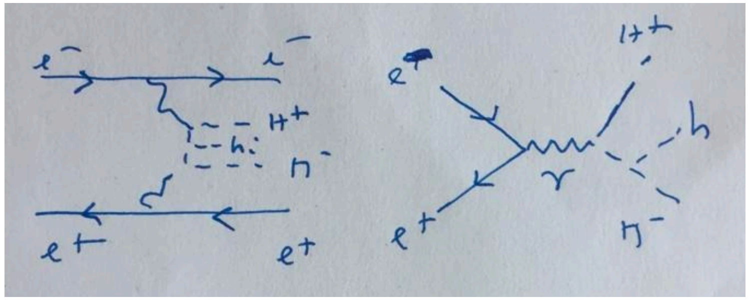

$\Lambda_3 = 2\pi,\ m_{h_2} = 200$ GeV



$h_2h_3h_3$; $h_3h_2h_2$; Zh_2h_3


$\Lambda_i = 2\pi,\ m_{h_i} = 125$ GeV, $m_{H^\pm} = 150$ GeV


$\Lambda_i = 2\pi,\ m_{h_i} = 300$ GeV, $m_{H^\pm} = 300$ GeV



$h_2H^+H^-$; $h_3H^+H^-$; Zh_2h_3

CP violation from P violation (but strange!)

There is a different way to look at the same problem

$\alpha_1 = \pi/2$

$\bar{t}(a_t + i b_t \gamma_5) t\, \phi \qquad b_t \approx 0 \qquad a_t\, \bar{t} t \phi$ **Scalar**

$\bar{\tau}(a_\tau + i b_\tau \gamma_5) \tau\, \phi \qquad a_\tau \approx 0 \qquad b_\tau\, \bar{\tau} \tau\, \phi$ **Pseudoscalar**

If an experiment can tell us that ϕ couples approximately as scalar do top quarks and as a pseudoscalar to tau leptons, it is a sign of CP-violation.

$$g^{hVV}_{C2HDM} = \cos\alpha_2\, \cos(\beta - \alpha_1) g^{hVV}_{SM}$$

$$g^{huu}_{C2HDM} = \left(\cos\alpha_2 \frac{\sin\alpha_1}{\sin\beta} - i \frac{\sin\alpha_2}{\tan\beta} \gamma_5 \right) g^{hff}_{SM}$$

$$g^{hbb}_{C2HDM} = \left(\cos\alpha_2 \frac{\cos\alpha_1}{\cos\beta} - i \sin\alpha_2\, \tan\beta\, \gamma_5 \right) g^{hff}_{SM}$$

Close to 1

$$g^{hVV}_{C2HDM} = \boxed{\cos\alpha_2\, \sin\beta}\, g^{hVV}_{SM}$$

$$g^{huu}_{C2HDM} = \left(\frac{\cos\alpha_2}{\sin\beta} \boxed{- i \frac{\sin\alpha_2}{\tan\beta}} \gamma_5 \right) g^{hff}_{SM}$$

Small

$$g^{hbb}_{C2HDM} = \left(\boxed{-i \sin\alpha_2\, \tan\beta\, \gamma_5} \right) g^{hff}_{SM}$$

Can be large

Experiment tells us

$$\frac{\sin\alpha_2}{\tan\beta} \ll 1 \qquad \textbf{But} \qquad \sin\alpha_2\, \tan\beta = \mathcal{O}(1)$$