Overview of resonant HH/HS/SS production

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Based a lot on e-Print: 2112.12515, in collaboration with H. Abouabid, A. Arhrib, A. Azevedo, J. Falaki, P. Ferreira, M. Mühlleitner

Higgs Pairs Workshop 2022

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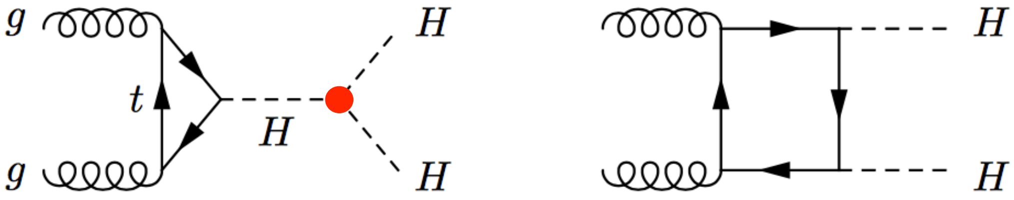
Higgs Pair Production - probing the shape of the potential

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



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

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

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

at 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

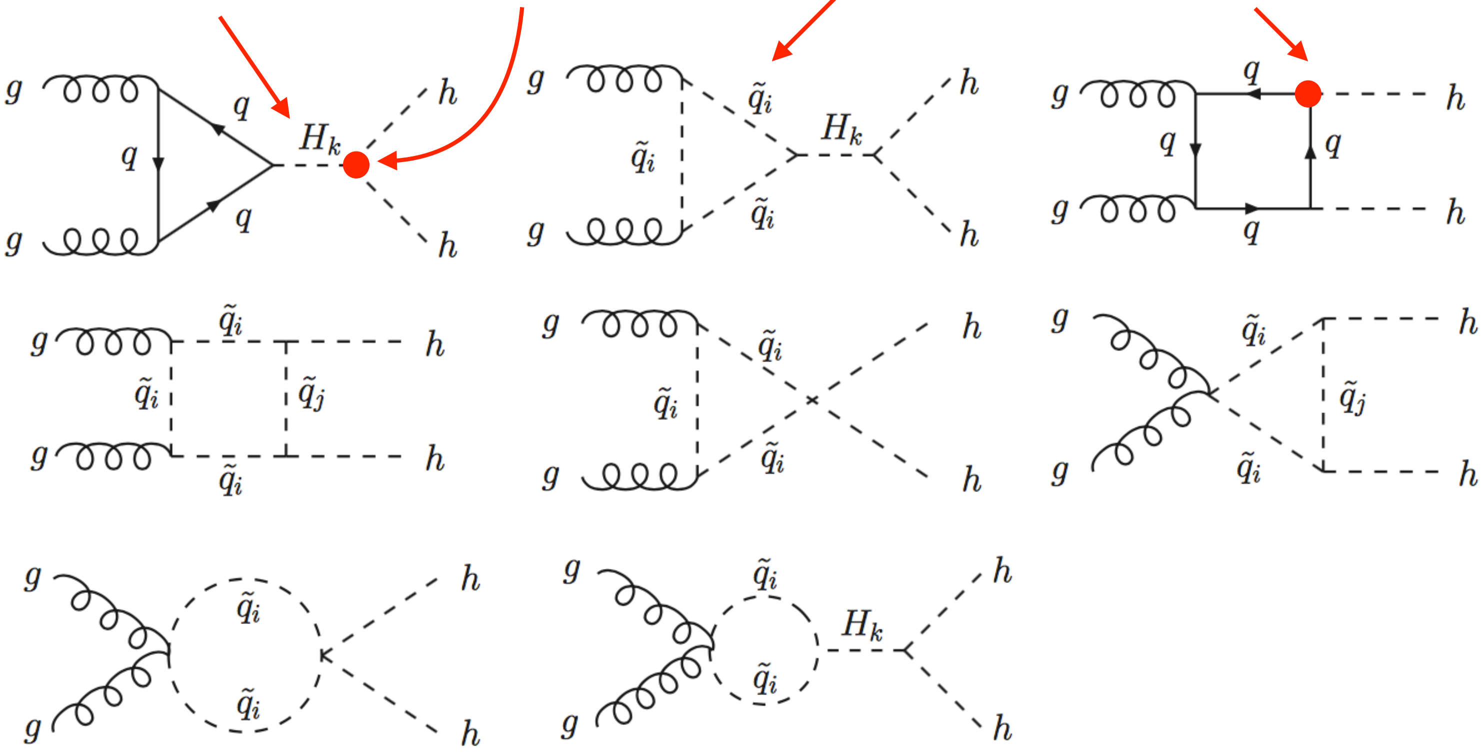
- Challenge: small cross sections and large QCD backgrounds

New Physics Effects in Higgs Pair Production

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

- Example NMSSM:

[taken from Dao, Mühlleitner eal'13]



resonant enhancement for $m_{H_k} = 2*m_h$

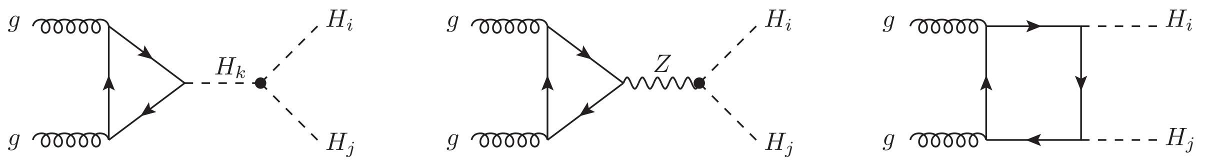
differing from SM value

stop, sbottom

differing from SM value

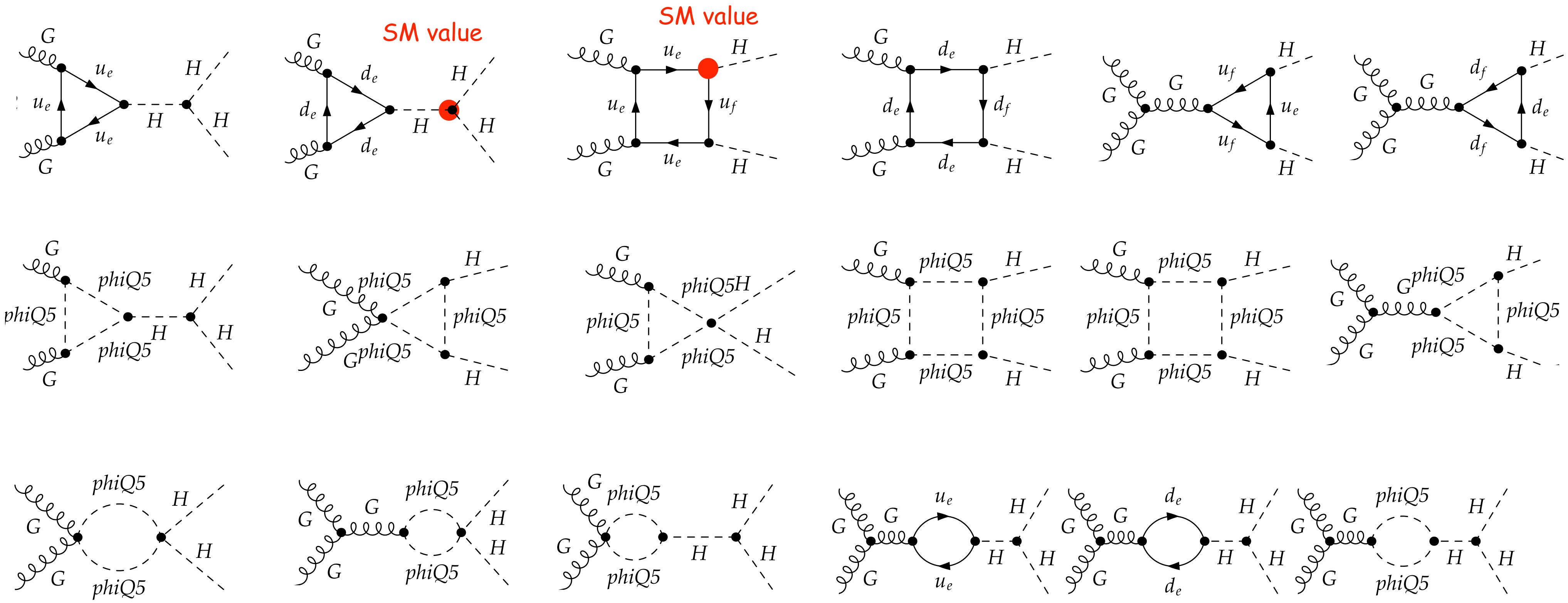
New Physics Effects in Higgs Pair Production

- Example: extended sector only



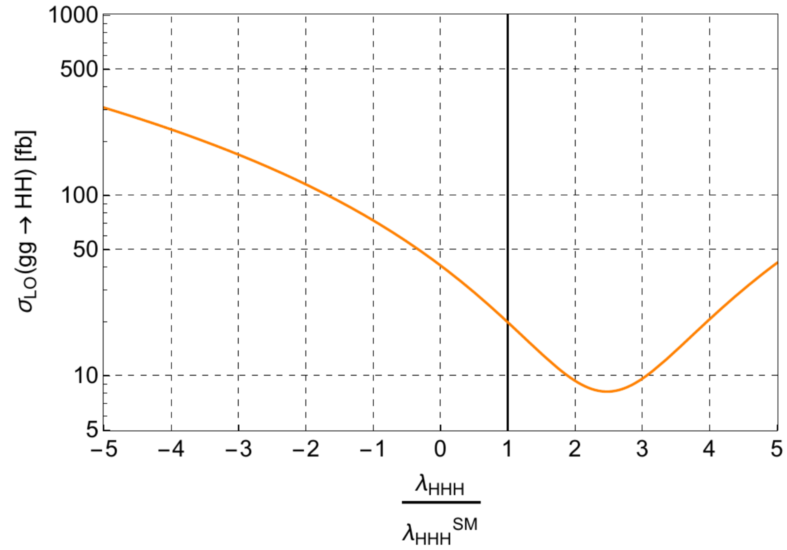
- Example: extension with a strange dark sector

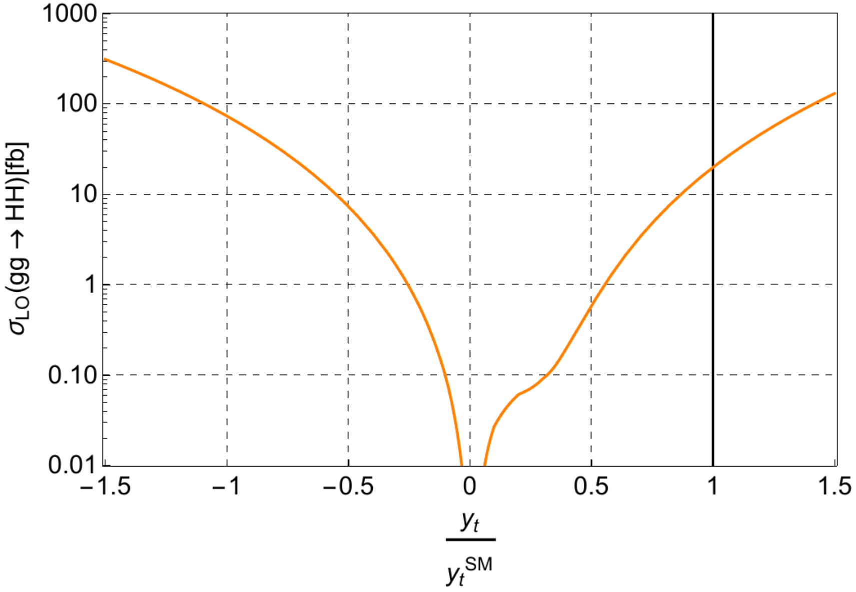
[thanks to D. Neacsu]

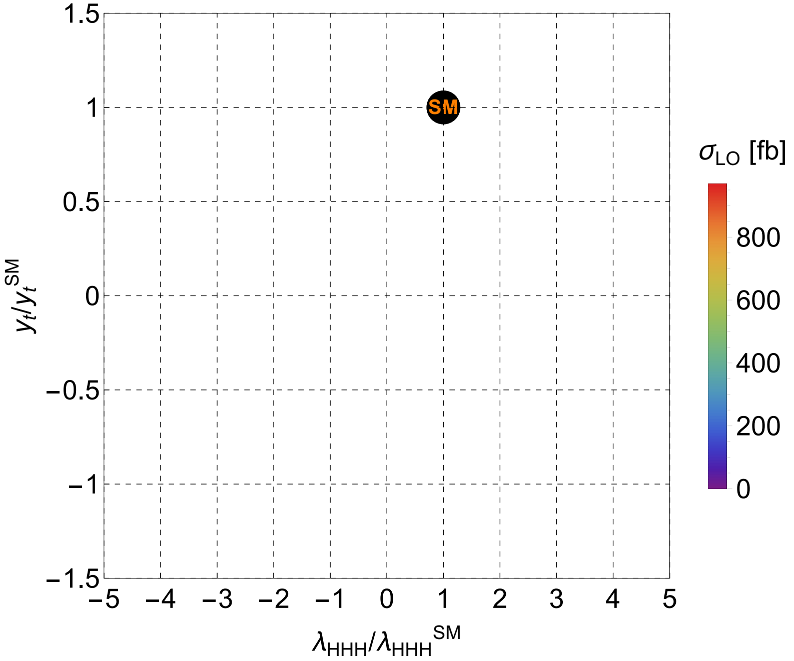

SM value

SM value

Varying the SM couplings



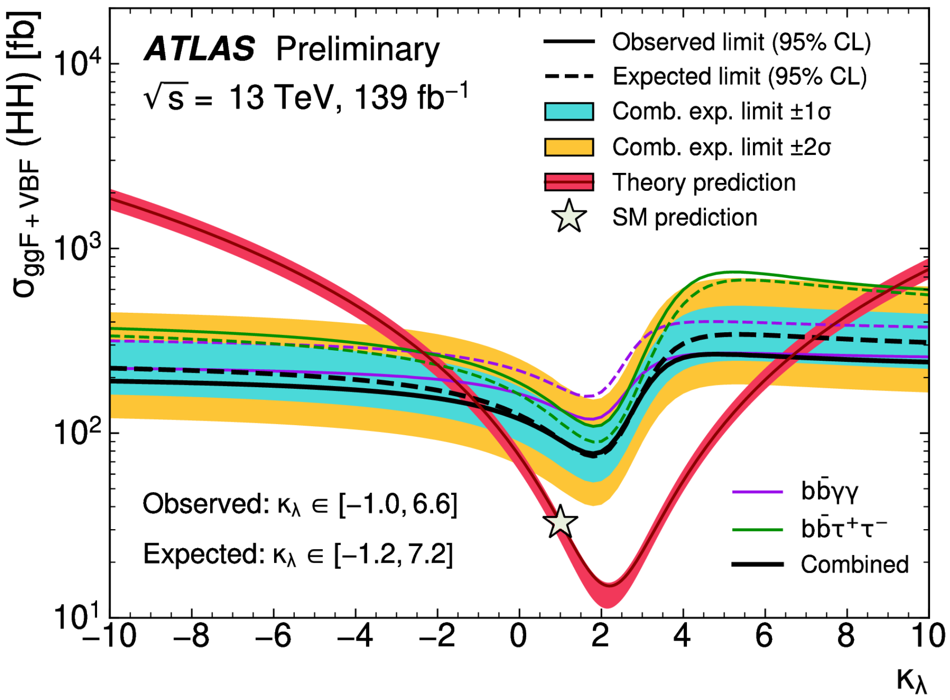




- LO Higgs pair production cross section when we vary the SM Higgs top-Yukawa coupling (upper left), the trilinear Higgs self-coupling (upper right) and both couplings (lower) while keeping all other couplings fixed to the SM values.

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

Experimental Results - Limits on Trilinear Higgs Self-Coupling

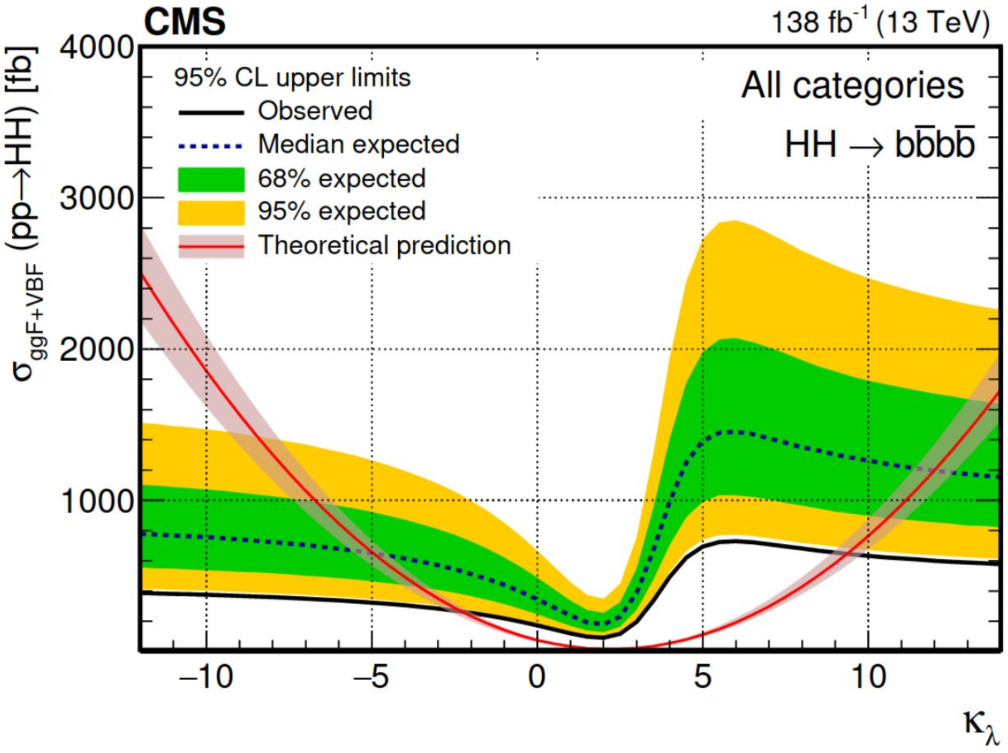


[Rui Zhang, ATLAS, this workshop]

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

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

[Fabio Monti, CMS, this workshop]



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

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

Today we have

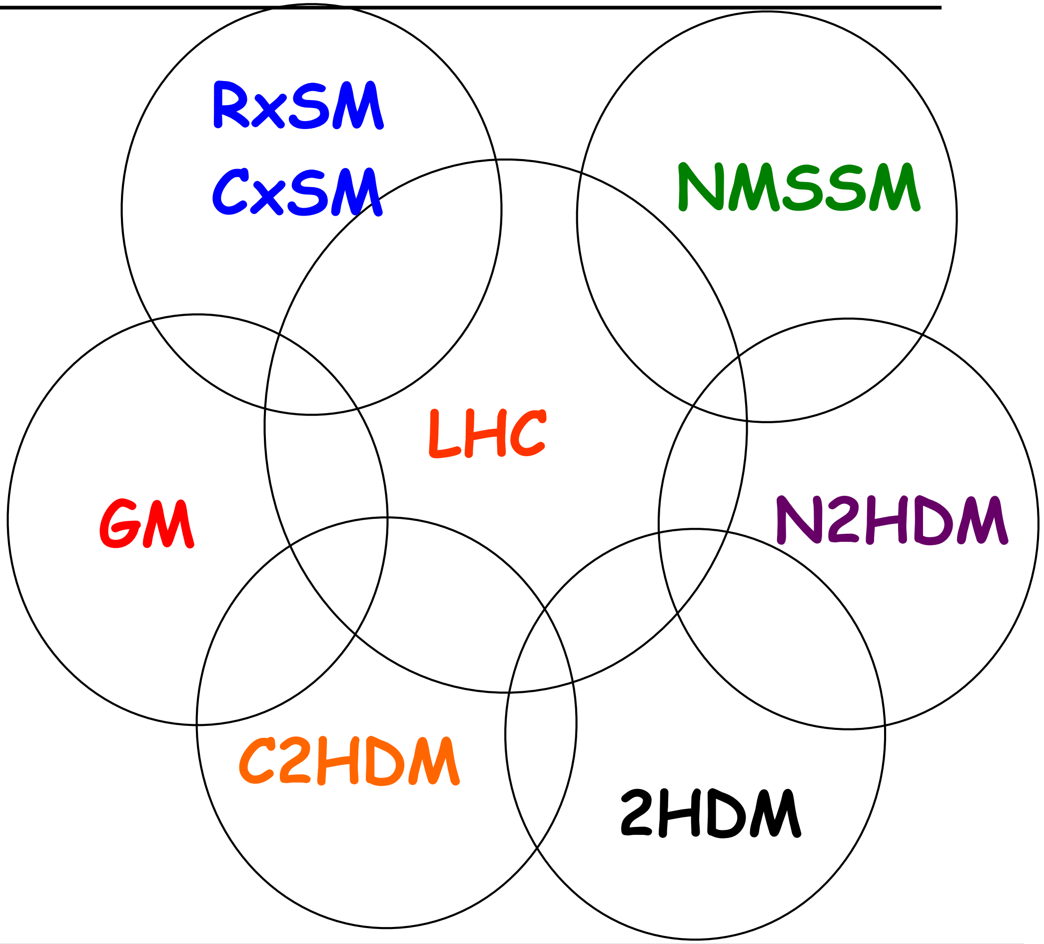
An overview of Higgs Pair production possibilities including theoretical and experimental constraints in BSM Higgs sectors.

benchmark points / lines / planes for experiment

Extensions of the SM

	CxSM (RxSM)	2HDM	C2HDM	N2HDM
Model	SM+Singlet	SM+Doublet	SM+Doublet	2HDM+Singlet
Scalars	$h_{1,2,(3)}$ (CP even)	H, h, A, $H^\pm$	$H_{1,2,3}$ (no CP), $H^\pm$	$h_{1,2,3}$ (CP-even), A, $H^\pm$
Motivation	DM, Baryogenesis	+ $H^\pm$	+ CP violation	+ ...

- There is a 125 GeV Higgs (other scalars can be lighter and/or heavier).
- From the 2HDM on, tan β=v_2/v_1. Also charged Higgs are present.
- Models (except singlet extensions) can be CP-violating.
- They all have ρ=1 at tree-level.
- You get a few more scalars (CP-odd or CP-even or with no definite CP)
- In case all neutral scalars mix there will be three mixing angles
- They can have dark matter candidates (or not)



The potentials

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

Particle (type) spectrum depends on the symmetries imposed on the model, and whether they are spontaneously broken or not. There are two charged particles and 4 neutral.

with fields

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

The model can be CP violating or not.

magenta $\Longrightarrow$ SM

magenta + blue $\Longrightarrow$ RxSM (also CxSM)

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

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

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

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

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

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

	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)

Models

Model	Higgs Fields	Spectrum
R2HDM	2 SU(2) doublets, CP-conserving	h, H, A, H^+
C2HDM	2 SU(2) doublets, CP-violating	H_1, H_2, H_3, H^+
N2HDM	2 SU(2) doublets, 1 real singlet, CP-conserving	H_1, H_2, H_3, A, H^+
NMSSM	2 SU(2) doublets, 1 complex singlet super-field, CP-conserving	H_1, H_2, H_3, A_1, A_2, H^+

h_{125} couplings (gauge)

Lightest Higgs coupling modifiers (to gauge bosons)

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

CP-VIOLATING 2HDM

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

"PSEUDOSCALAR" COMPONENT (DOUBLET)

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

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

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

SINGLET COMPONENT

$$(a + ib)$$

SM + REAL SINGLET

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

SM + COMPLEX SINGLET

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

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…

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

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

Overview of resonant production

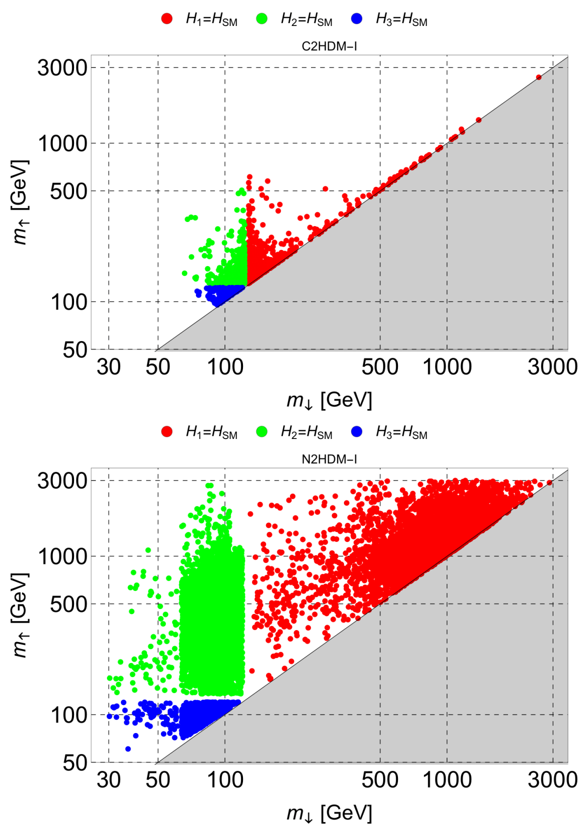
Remarks

- 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

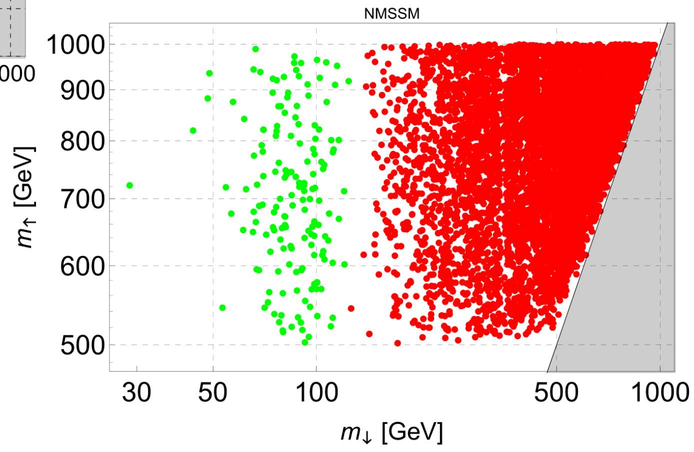
- Plots presented in the following at LO (time saving in large scans) multiplied by 2 (to approximate NLO value); NLO QCD HTL: K-factor ~1.4-.1.9 [Gröber,MM,Spira,´17];
  benchmark points will include NLO corrections calculated with HPAIR

Allowed SM-like Higgs in each model



From very constrained (C2HDM).

To very unconstrained (N2HDM).



What is resonant?

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

- If $m_{H_k} < m_{H_i} + m_{H_j}$ - clear case of "non-resonant" production.
- If $m_{H_k} > m_{H_i} + m_{H_j}$, resonance contribution may be suppressed (small couplings, large masses, large widths or destructive interference).

From an experimental point of view, the cross section would not be distinguishable from "non-resonant" production then. So our recipe is:

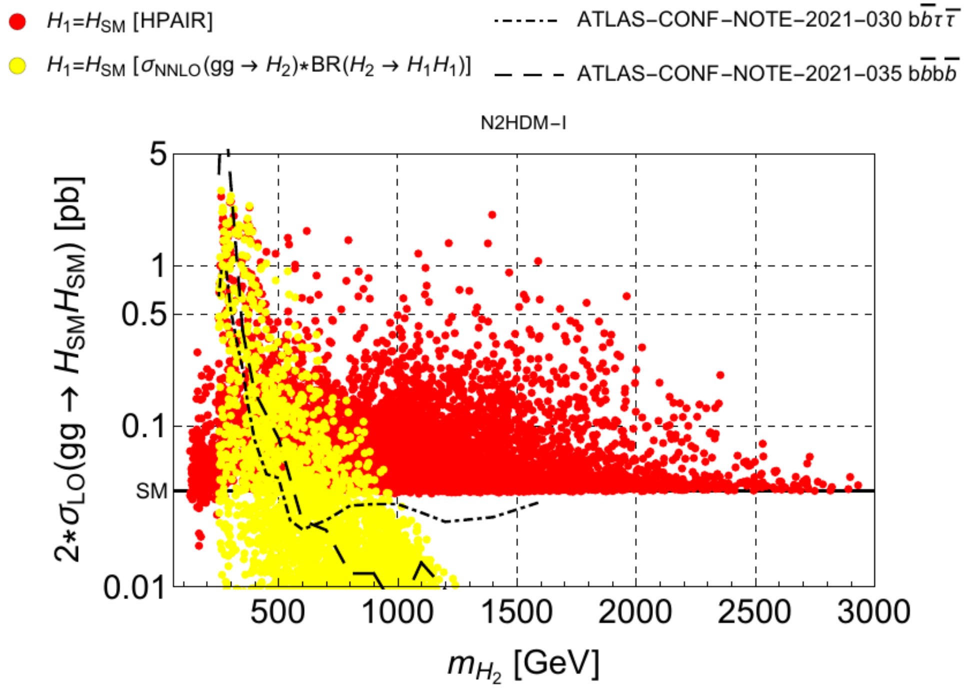
- HiggsBounds turned off for di-Higgs.
- Use Sushi to calculate $\sigma(H_k)$, for all possible intermediate resonances H_k (NNLO QCD).
- Calculate $\sigma(H_k) \times BR(H_k \to H_{SM} H_{SM})$ and compare with experiment.
- Exception - exp. limits assume narrow resonances, keep points if $(\Gamma_{tot}(H_k)/m_{H_k})_{limit}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

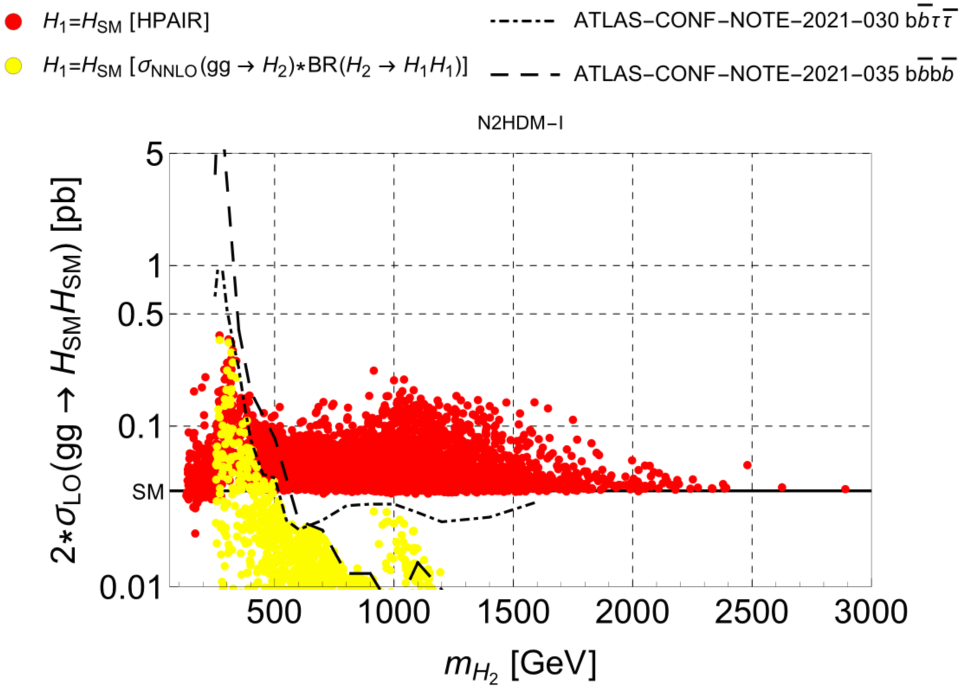
Final states: most recent 4b, (2b)(2τ), (2b)(2γ), (2b)(2W), (2b)(ZZ), (2W)(2γ) and 4W

Suppress interfering Higgs signals by forcing any other neutral scalar mass to deviate by more than ±2.5 GeV from $m_{H_{SM}}$.

What is resonant? The N2HDM-I

Impact from resonant searches (N2HDM-I with H_1 SM-like Higgs). Yellow points passed described constraints. $\sigma(H_k) \times BR(H_k \to H_{SM}H_{SM})$ with SusHi and dedicated codes for branching ratios. Dashed line (4b) and the dot-dashed line (2b2τ) are the experimental limits obtained from resonant di-Higgs production. Limits applied both on H_2 and H_3 production.





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

$b\bar{b}b\bar{b}$ dominates sensitivity at high m_X

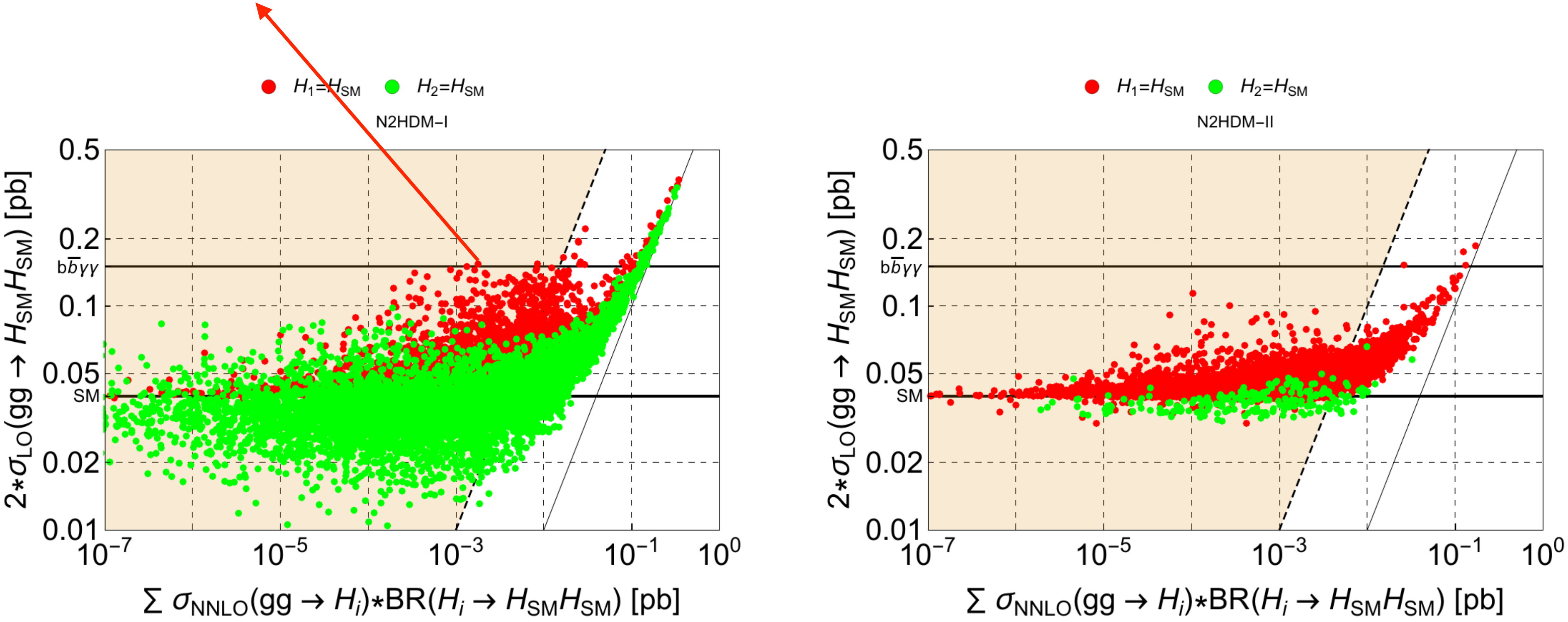
$b\bar{b}\tau\tau$ dominates sensitivity at medium m_X

Situation after applying the experimental constraints. Some of the yellow points above the experimental limits do not fulfil $(\Gamma_{tot}(H_k)/m_{H_k})_{limit} < 5\%$.

What is resonant? - the N2HDM

Low impact from non-resonant searches. Most stringent search (2b)(2γ) already constraints the (non-resonant Higgs search constraints start to play a role but only for this model).

(2b)(2γ) start cutting on the N2HDM-I (with $H_1 \equiv H_{SM}$) parameter space.

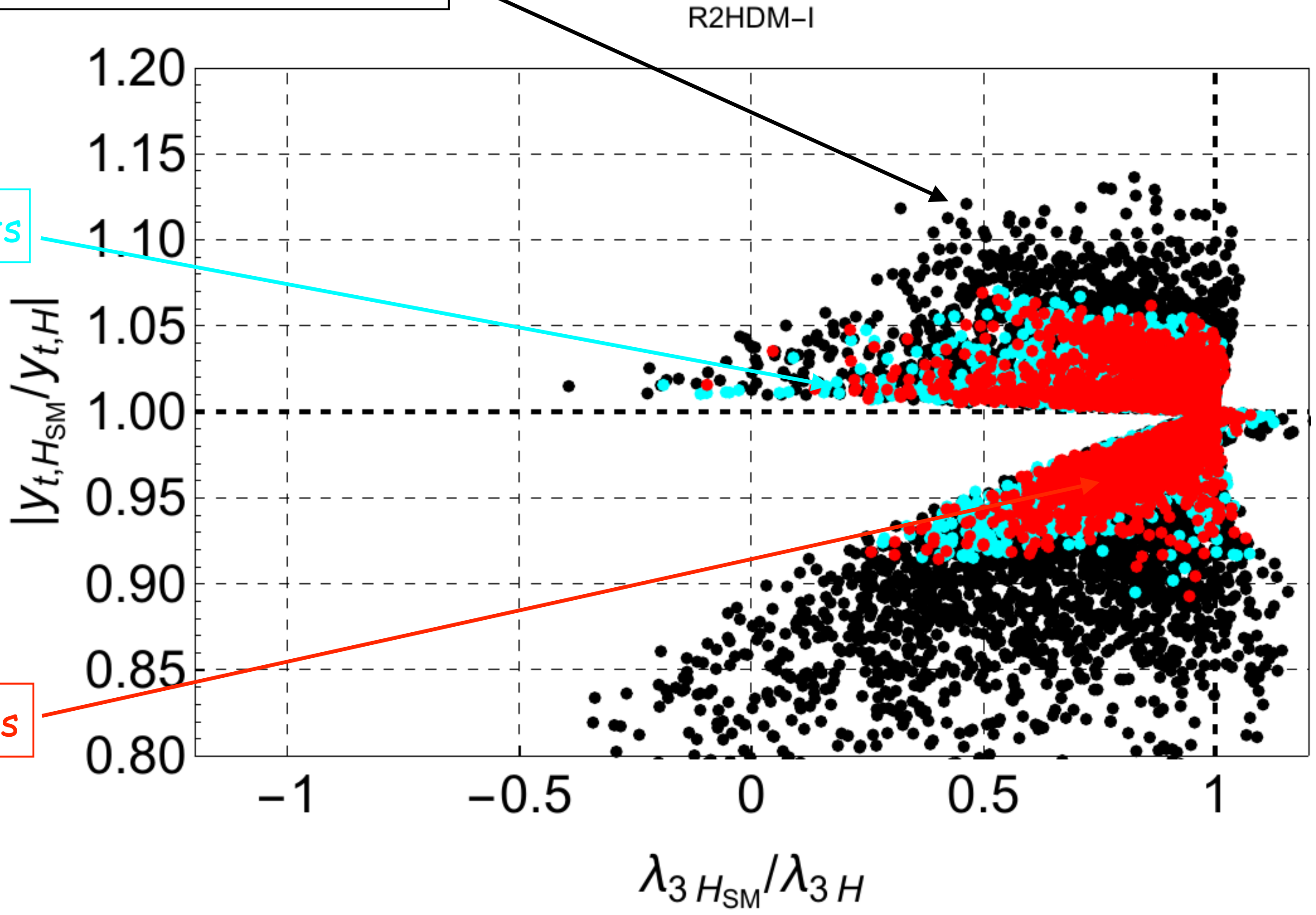


Cross section resonantly dominated if

$\sigma(gg \to H_{SM}H_{SM}) < 0.1\, \sigma(H_k) \times BR(H_k \to H_{SM}H_{SM})$.

Region shown by the diagonal dashed line in each plot. Shaded region where we apply the non-resonant search limits.

R2HDM T1: Impact H and HH Constraints



All but single Higgs constraints

All but double Higgs constraints

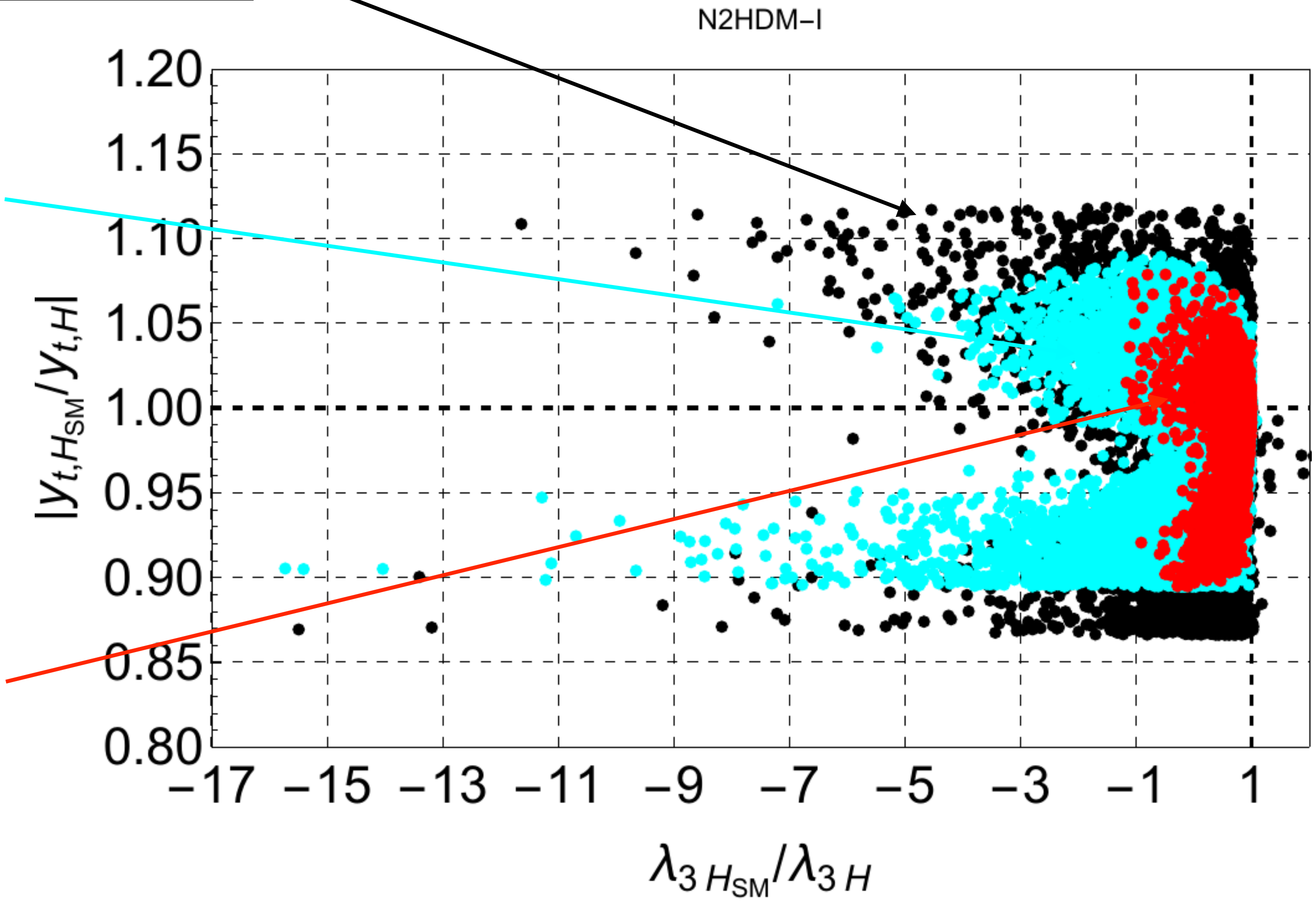
All, incl. double Higgs constraints

N2HDM T1: Impact H and HH Constraints

All but single Higgs constraints

All but double Higgs constraints

All, incl. double Higgs constraints



Ranges for the trilinear couplings

	R2HDM		C2HDM	
	$y_{t,H_{\rm SM}}^{\rm R2HDM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm R2HDM}/\lambda_{3H}$	$y_{t,H_{\rm SM}}^{\rm C2HDM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm C2HDM}/\lambda_{3H}$
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	
	$y_{t,H_{\rm SM}}^{\rm N2HDM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm N2HDM}/\lambda_{3H}$	$y_{t,H_{\rm SM}}^{\rm NMSSM}/y_{t,H}$	$\lambda_{3H_{\rm SM}}^{\rm NMSSM}/\lambda_{3H}$
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	–	–	–	–

Still compatible with zero

Highlights from resonant production

Maximum Cross Section Values - Resonant

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

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

NLO SM value: 38 fb

N2HDM T1 $H_{SM}=H_2$

Particle	H_1	H_2	H_3	A	H^+
Mass [GeV]	75	125.09	311	646	659
Width [GeV]	$4.67\ 10^{-4}$	$3.61\ 10^{-3}$	0.137	57.43	62.72
σ_{prod} [pb]	29.98	42.39	3.08	0.95	

Resonance production : $\sigma_{prod}(H_3) \times BR(H_3\text{->}H_2H_2) = 3.08$ pb x 0.123 = 379 fb

Interesting feature: large ZH_1H_2, ZH_2H_2 production:

- $\sigma_{prod}(A) \times BR(A\text{->}ZH_3) \times BR(H_3\text{->}H_1H_2) = 366$ fb tests $\lambda(H_1H_2H_3)$
- $\sigma_{prod}(A) \times BR(A\text{->}ZH_3) \times BR(H_3\text{->}H_2H_2) = 54$ fb tests $\lambda(H_3H_2H_2)$

requires mass gaps A-ZH_3 and H_3-H_1H_1 / H_3-H_1H_2

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	

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

Interesting feature: Test of CP in decays:

- $\sigma_{prod}(H_3) \times BR(H_3\text{->}WW) = 316$ 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 C violation

$$h_1 \to ZZ(+)h_2 \to ZZ(+)h_2 \to h_1 Z$$

Combinations of three decays

Many other combinations

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

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

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...

C2HDM – Fontes, Romão, RS, Silva, PRD92 (2015) 5, 055014

CNMSSM – King, Mühlleitner, Nevzorov, Walz; NPB901 (2015) 526-555

The C and the P in CP violation

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

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

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

C conserving, CP violating interaction

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

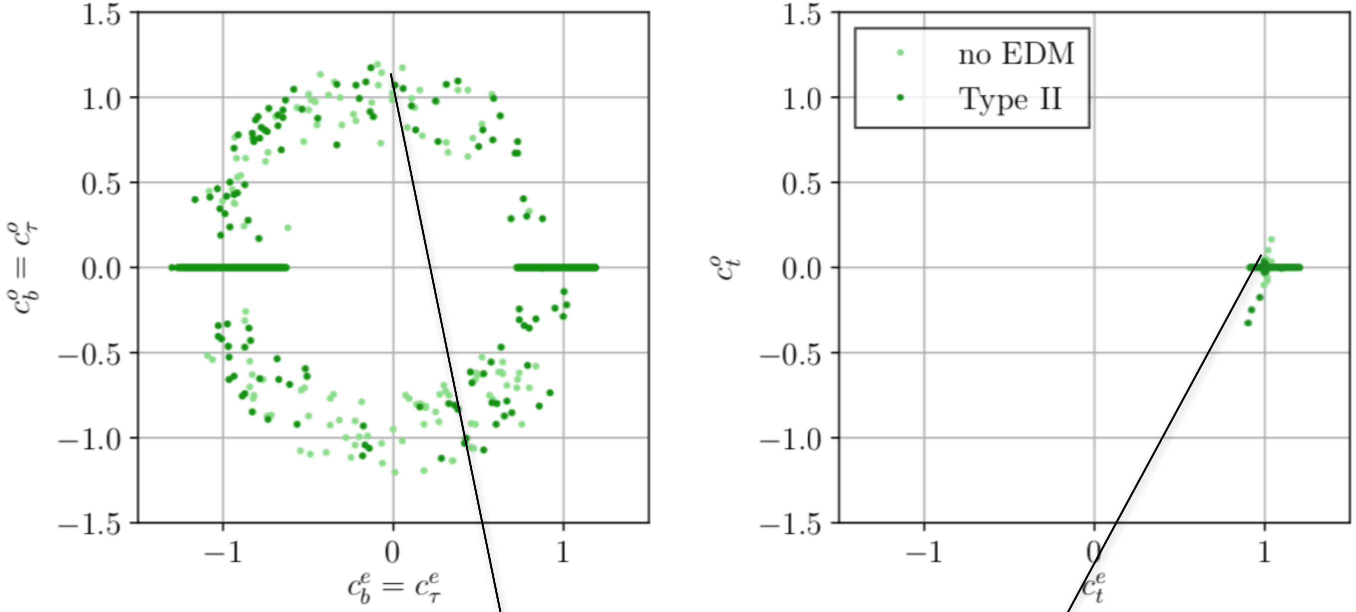
$$\boxed{\begin{array}{l} P(h) = 1;\; P(A) = 1;\; C(h) = 1\; C(A) = -1; \\ C(Z_\mu \partial^\mu A h) = 1; P(Z_\mu \partial^\mu A h) = 1 \end{array}}$$

Example: the 2HDM

$$\boxed{\begin{array}{l} P(h_1) = 1;\; P(h_2) = 1;\; C(h_1) = 1\; C(h_2) = 1 \\ C(Z_\mu \partial^\mu h_1 h_2) = -1; P(Z_\mu \partial^\mu h_1 h_2) = 1 \end{array}}$$

Any two scalars with
the same C and P
numbers

A short detour from the main theme



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

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

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

Find two particles of the same mass one decaying to tops as CP-even

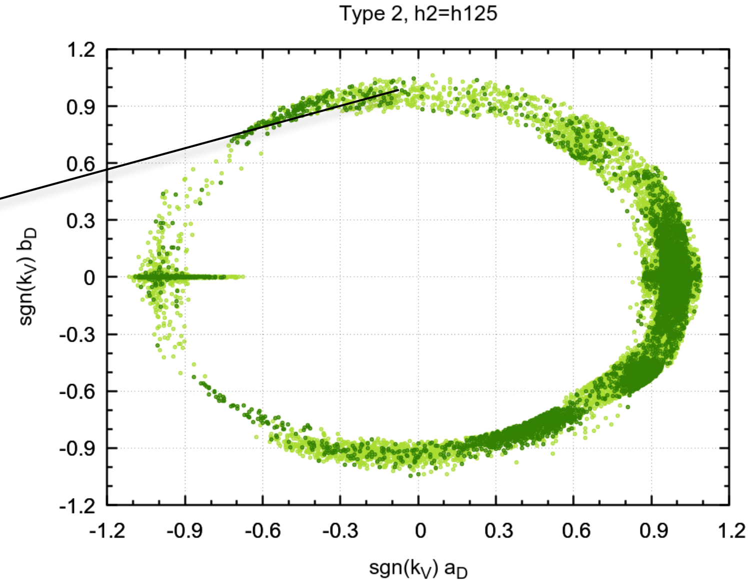
$$h_2 = H; pp \to Ht\bar{t}$$

and the other decaying to taus as CP-odd

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

Probing one Yukawa coupling is not enough!

With the new EDM result



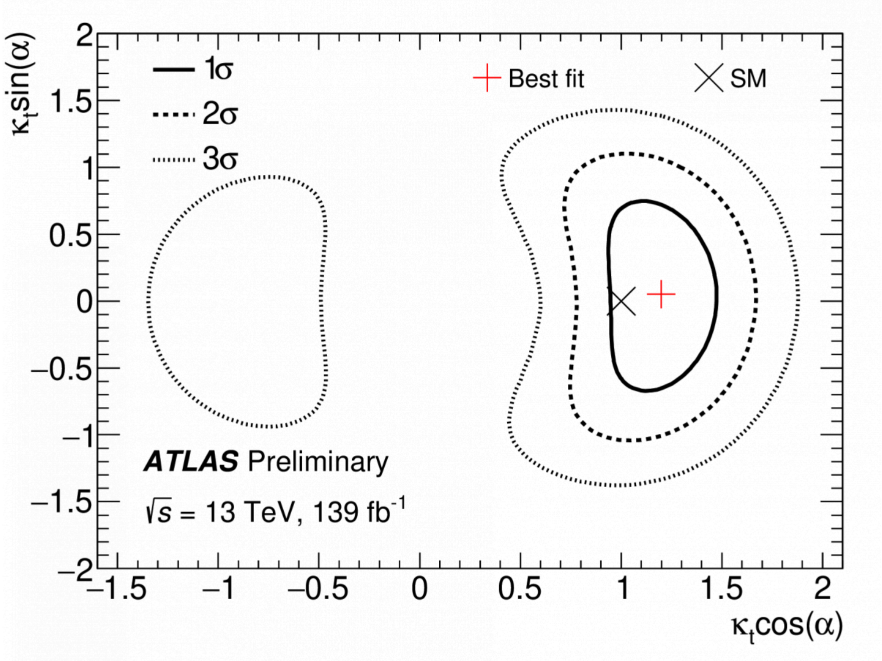
Fontes, Mühlleitner, Romão, RS, Silva, Wittbrodt, JHEP 1802 (2018) 073.

Measurement of CPV angle in tth

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

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

All measurements are consistent with the SM expectations, and the possibility of a pure CP-odd coupling between the Higgs boson and top quark is severely constrained. A pure CP-odd coupling is excluded at 3.9σ, and |α| > 43° is excluded at 95% CL.



ATLAS collaboration, PRL 125 (2020) 6, 061802

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

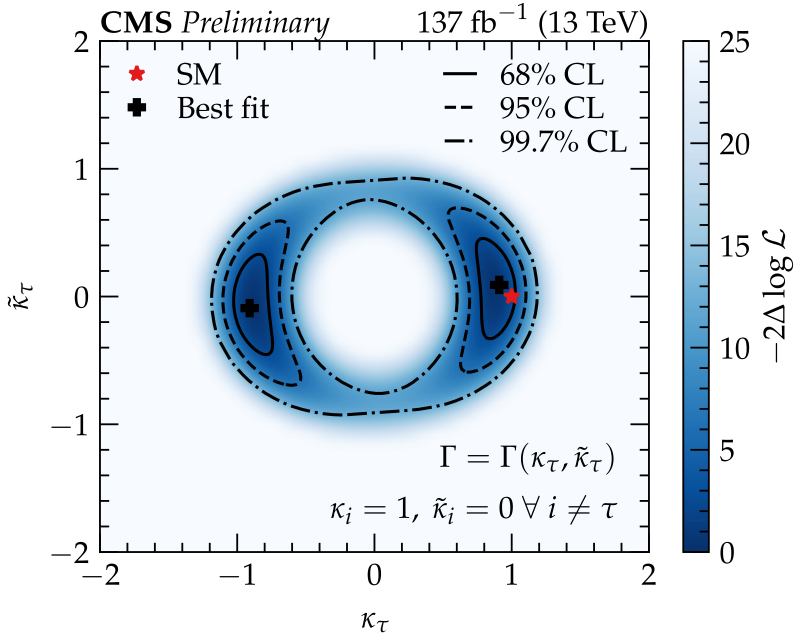
$$\tilde{\kappa}_t = \kappa\,\sin\alpha$$

Measurement of CPV angle in ττh

$$pp \to h \to \tau^+\tau^-$$

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

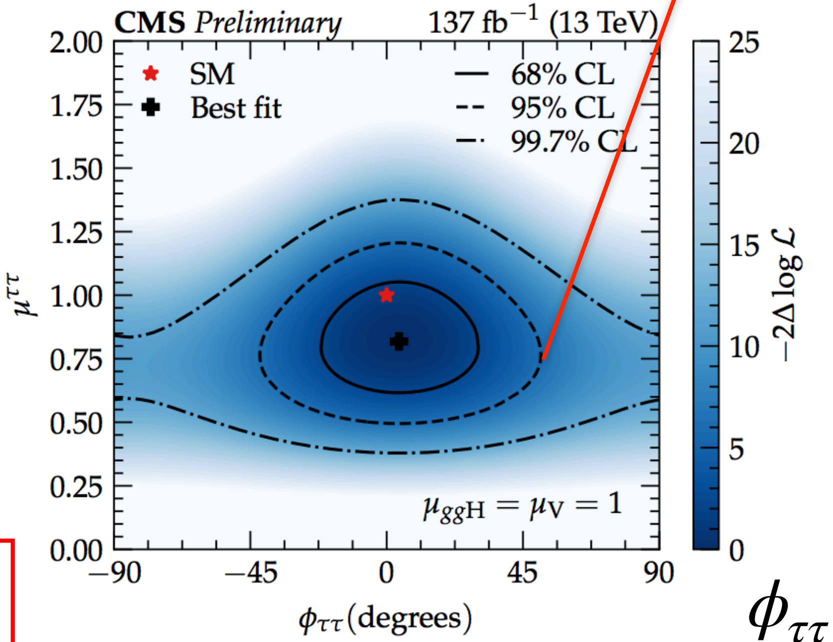
Mixing angle between CP-even and CP-odd τ Yukawa couplings measured 4 ± 17°, compared to an expected uncertainty of ±23° at the 68% confidence level, while at the 95% confidence level the observed (expected) uncertainties were ±36° (±55)°. Compatible with SM predictions.



CMS collaboration, CMS-PAS-HIG-20-006

$$h_2 = H; pp \to Ht\bar{t}$$
$$h_2 = A \to \tau^+\tau^-$$

Scenario excluded at 95% CL

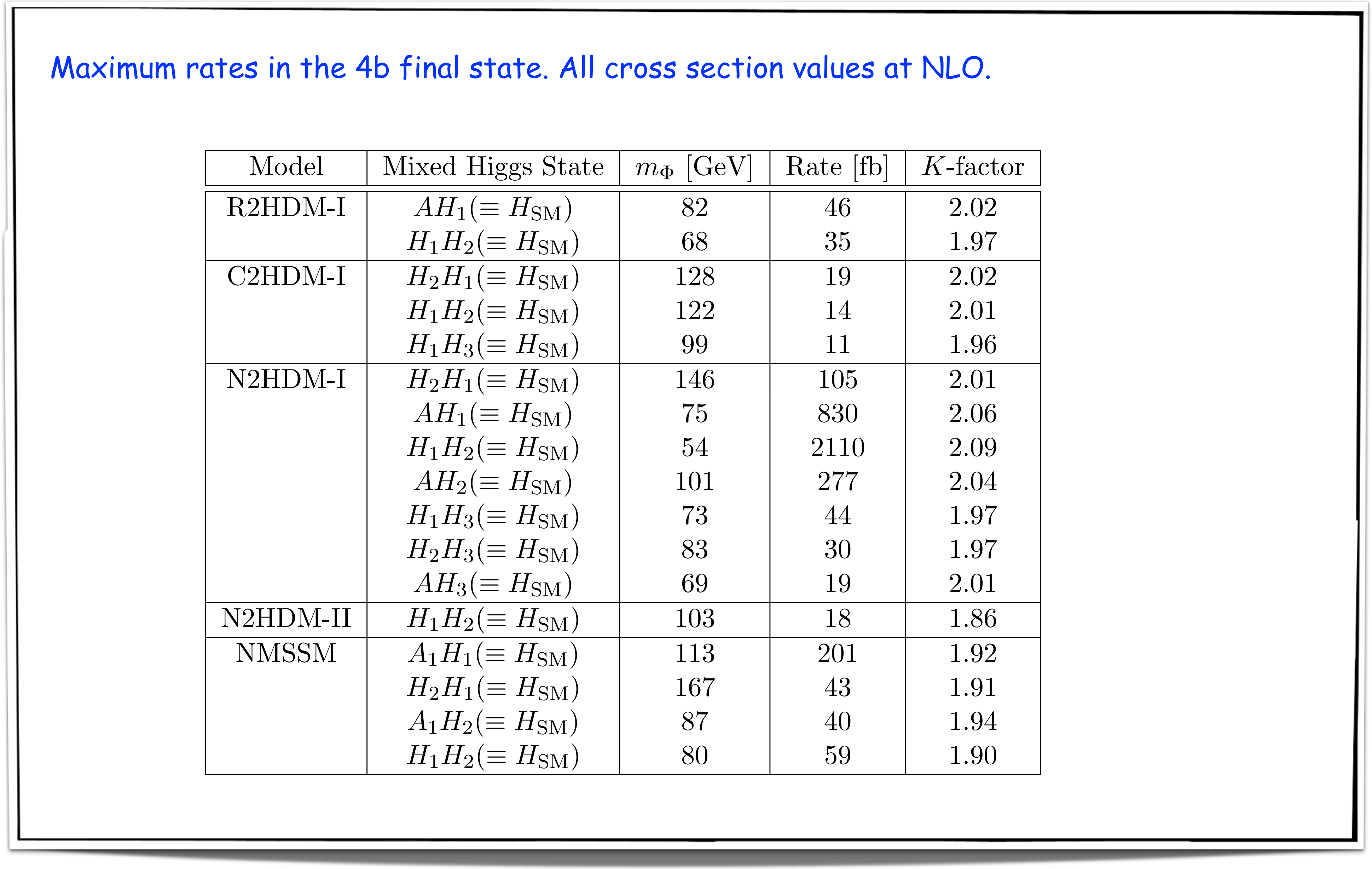


$$\phi_{\tau\tau} = \alpha$$

Direct Searches at LHC 1 EDMs 0

Other Higgs Pairs final states

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

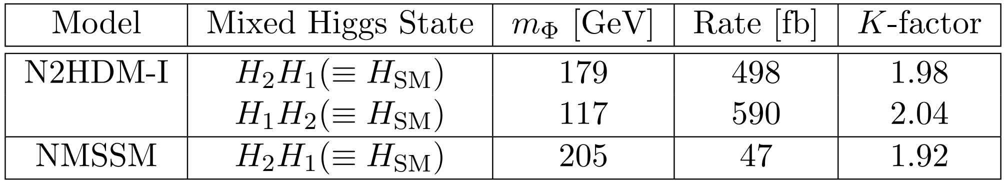


Maximum rates in the 4b final state. All cross section values at NLO.

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

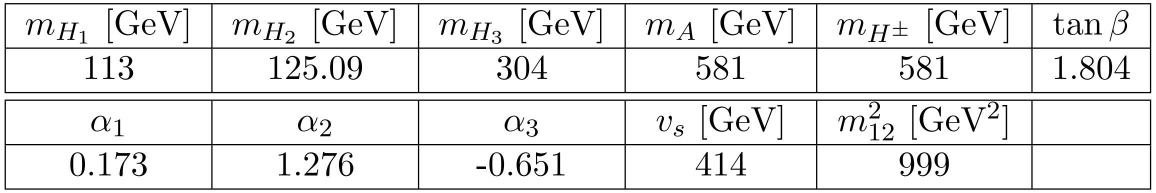
A(H$_i$)H$_{SM}$ Production (2b2W)

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



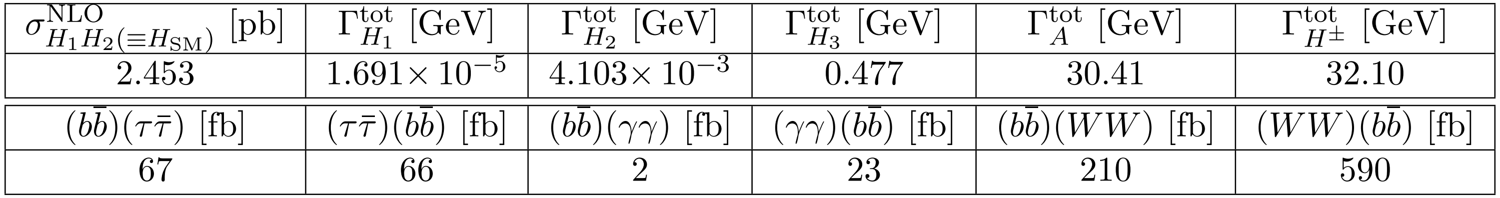
Model	Mixed Higgs State	m_Φ [GeV]	Rate [fb]	K-factor
N2HDM-I	$H_2H_1(\equiv H_{\rm SM})$	179	498	1.98
	$H_1H_2(\equiv H_{\rm SM})$	117	590	2.04
NMSSM	$H_2H_1(\equiv H_{\rm SM})$	205	47	1.92

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

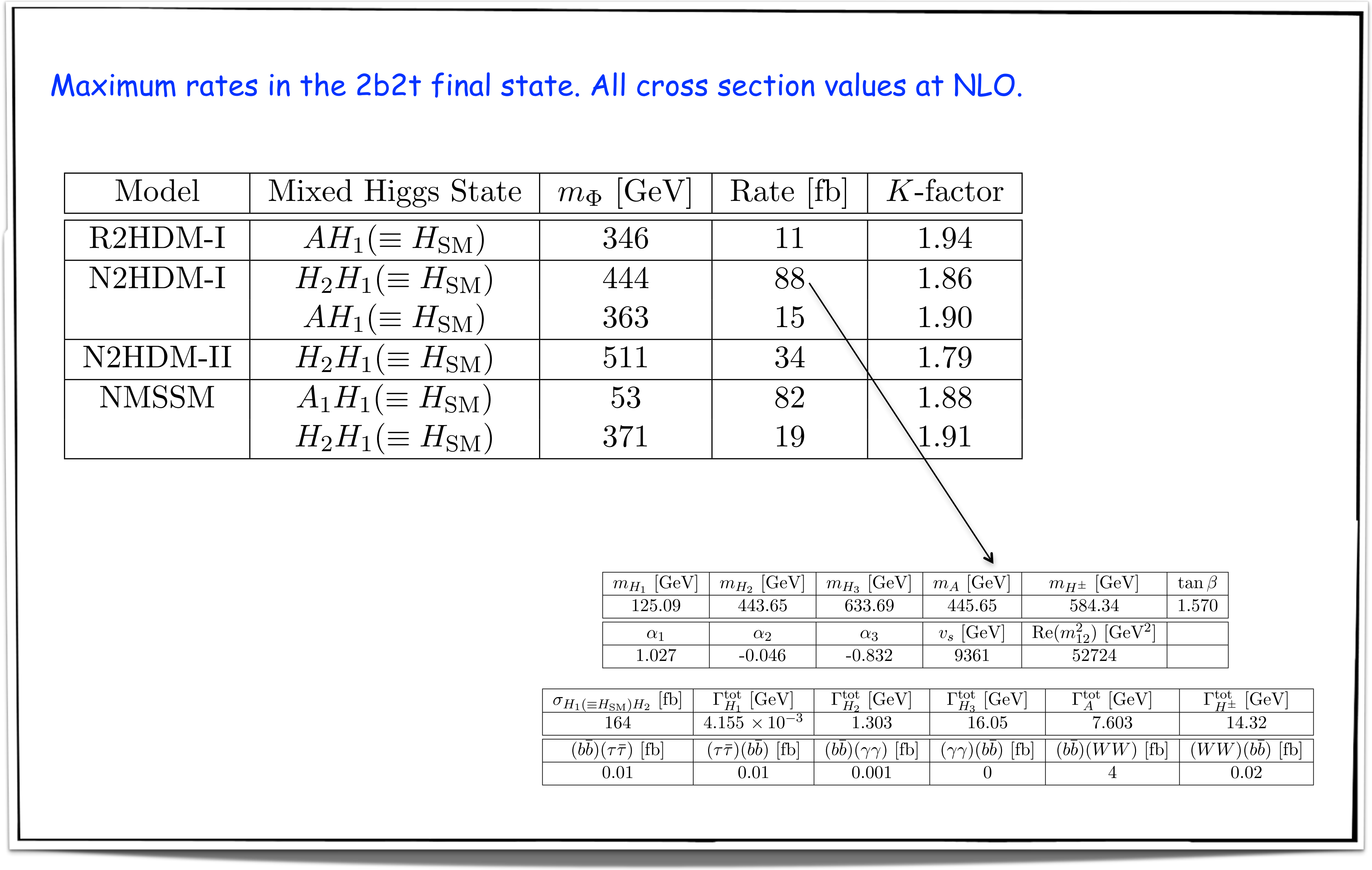
α_1	α_2	α_3	v_s [GeV]	m_{12}^2 [GeV^2]	
0.173	1.276	-0.651	414	999	



$\sigma^{\rm NLO}_{H_1H_2(\equiv H_{\rm SM})}$ [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

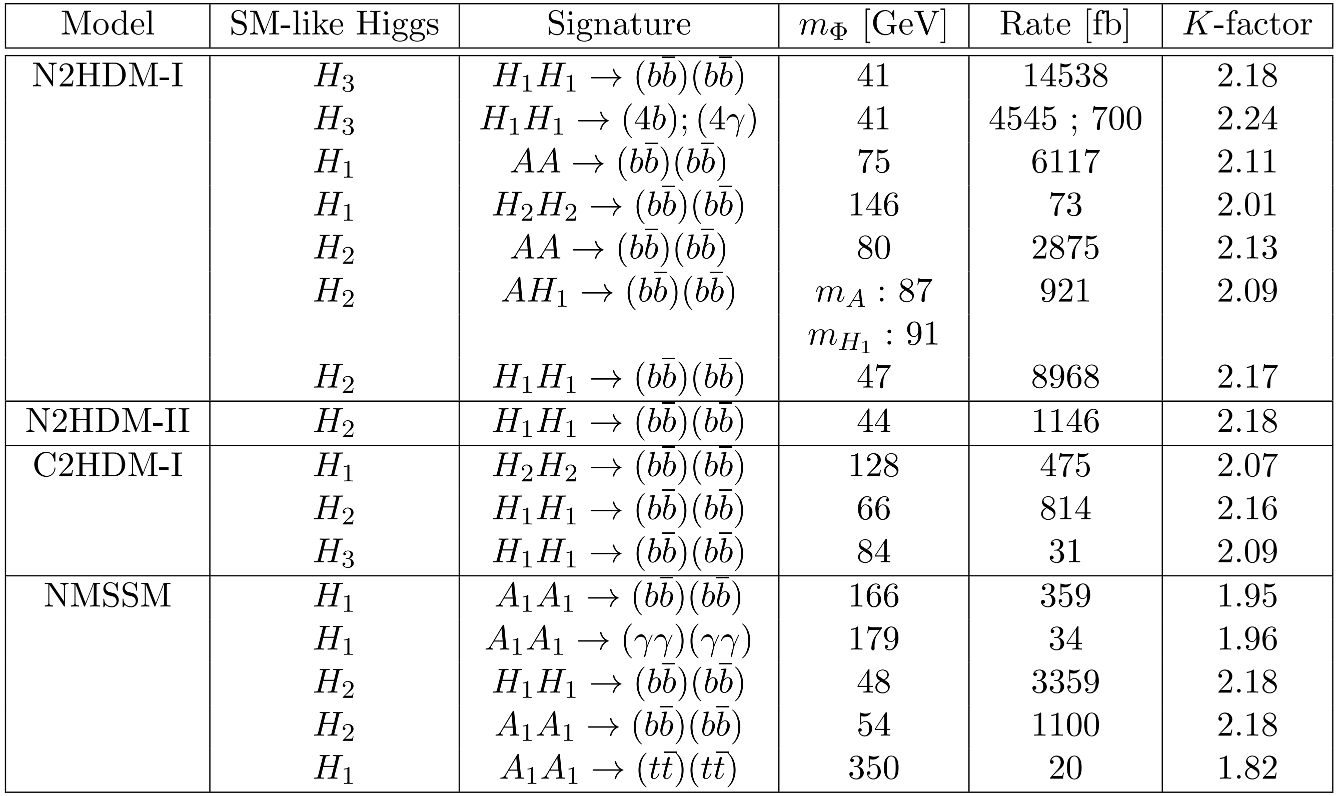
Model	Mixed Higgs State	m_{Φ_1} [GeV]	m_{Φ_2} [GeV]	Rate [fb]	K-factor
N2HDM-I	$H_2H_3(\equiv H_{\rm SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	98	41	15	1.95
	$H_2H_1(\equiv H_{\rm SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	282	-	40	1.96
	$H_2H_1(\equiv H_{\rm SM})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



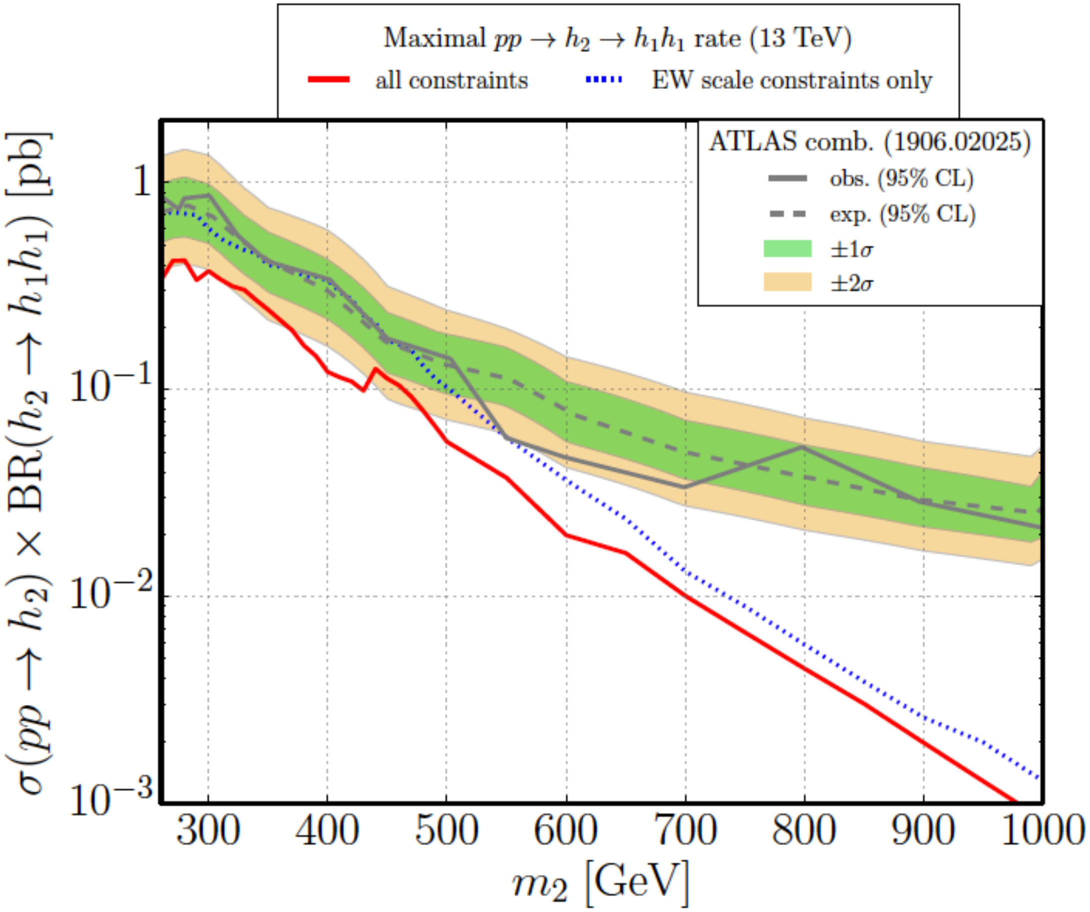
Model	SM-like Higgs	Signature	m_Φ [GeV]	Rate [fb]	K-factor
N2HDM-I	H_3	$H_1H_1 \to (b\bar{b})(b\bar{b})$	41	14538	2.18
	H_3	$H_1H_1 \to (4b);(4\gamma)$	41	4545 ; 700	2.24
	H_1	$AA \to (b\bar{b})(b\bar{b})$	75	6117	2.11
	H_1	$H_2H_2 \to (b\bar{b})(b\bar{b})$	146	73	2.01
	H_2	$AA \to (b\bar{b})(b\bar{b})$	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.

Views from previous works

Real Singlet Extension versus experimental di-Higgs searches

Dawson, Lewis, Robens, Stefaniak, Sullivan, Review in Physics (2020) 100045



[update from Review in Physics (2020) 100045]

hh searches: relevant constraint for $m_{h2} \lesssim 450$ GeV

2 Real Scalar Extension

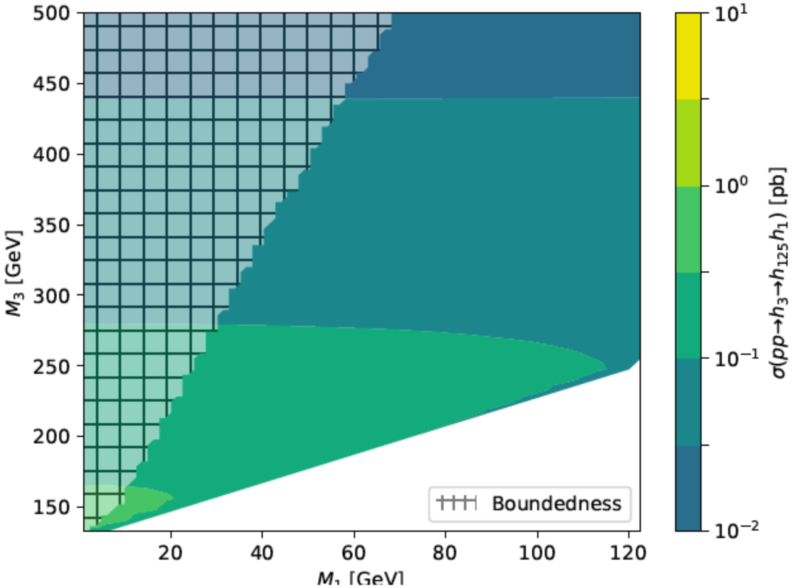
Robens, Stefaniak, Wittbrodt, Eur. Phys. J. C80 (2020) no.2, 151
also Barducci, Mimasu, No, Vernieri, Zurita, JHEP 2002 (2020) 00

BP2: $h_3 \rightarrow h_{125} h_2$

up to 0.6 pb at 13 TeV LHC

dominant decays:

$b\bar{b}b\bar{b}$ **(up to** 60%**)**, $b\bar{b}WW$ **(up to** 25%**)**



$$V = \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2 \,.$$

BP5: $h_3 \rightarrow h_1 h_1$

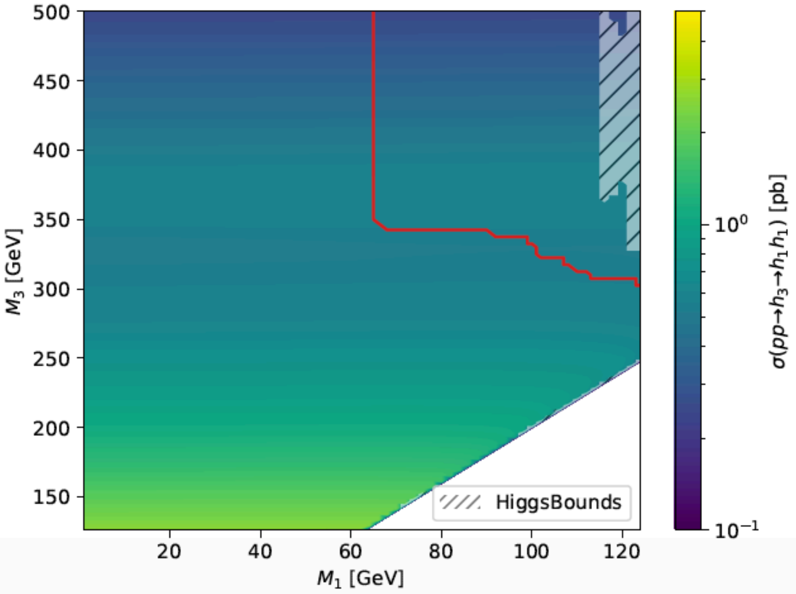
up to 2.5 pb at 13 TeV LHC

dominant decays:

$b\bar{b}b\bar{b}$ **(up to** 80%**)**, $b\bar{b}\tau\tau$ **(up to** 15%**)**

within **red contour:** $b\bar{b}b\bar{b}$ **sensitivity *,**

$\int \mathcal{L} = 35.9\,\mathrm{fb}^{-1}$



TRSM Benchmark Planes - Snowmass White Paper

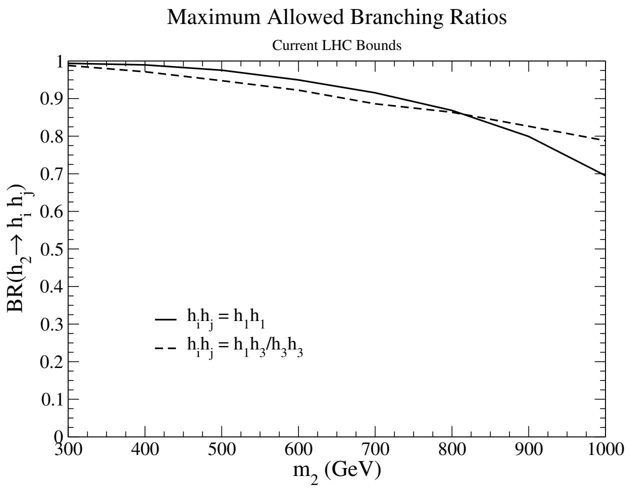
Tania Robens[1,*]

Complex Scalar Extension

Adhikari, Lane, Lewis, Sullivan, 2022 Snowmass

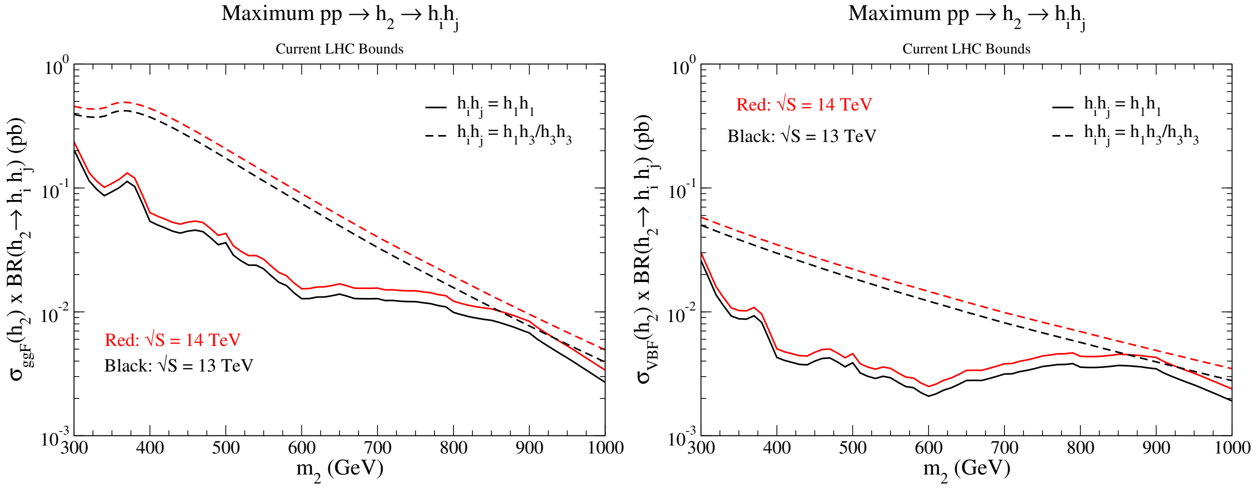
$$
\begin{aligned}
V(\Phi,S_c) \;=\; & \frac{\mu^2}{2}\Phi^\dagger\Phi+\frac{\lambda}{4}(\Phi^\dagger\Phi)^4+\frac{b_2}{2}|S_c|^2+\frac{d_2}{4}|S_c|^4+\frac{\delta_2}{2}\Phi^\dagger\Phi|S_c|^2\\
&+\Bigg(a_1\,S_c+\frac{b_1}{4}\,S_c^2+\frac{e_1}{6}\,S_c^3+\frac{e_2}{6}S_c|S_c|^2+\frac{\delta_1}{4}\Phi^\dagger\Phi\,S_c+\frac{\delta_3}{4}\Phi^\dagger\Phi\,S_c^2\\
&+\frac{d_1}{8}S_c^4+\frac{d_3}{8}S_c^2|S_c|^2+\text{h.c.}\Bigg)
\end{aligned}
$$

Paper to appear soon - maximum BRs for resonant double SM Higgs production, resonant production of a SM-like Higgs + new scalar, and double resonant new scalar production. Bus between 0.7 and 1. Direct production, the main production of a new scalar resonance may be from the s-channel production and decay of another scalar resonance.



(a)

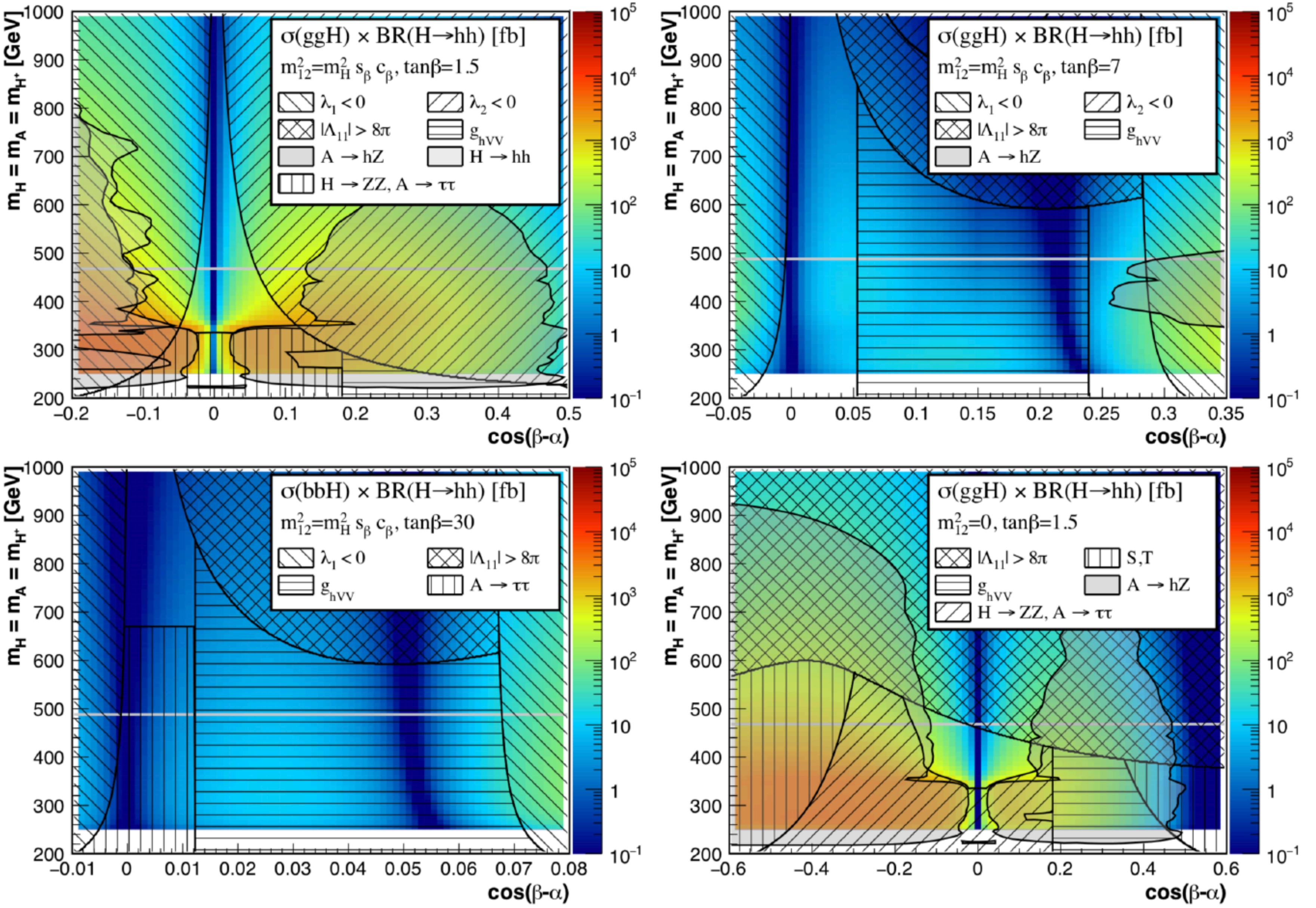
- ✦ Ian talk today 14.45



Type II 2HDM: H->hh

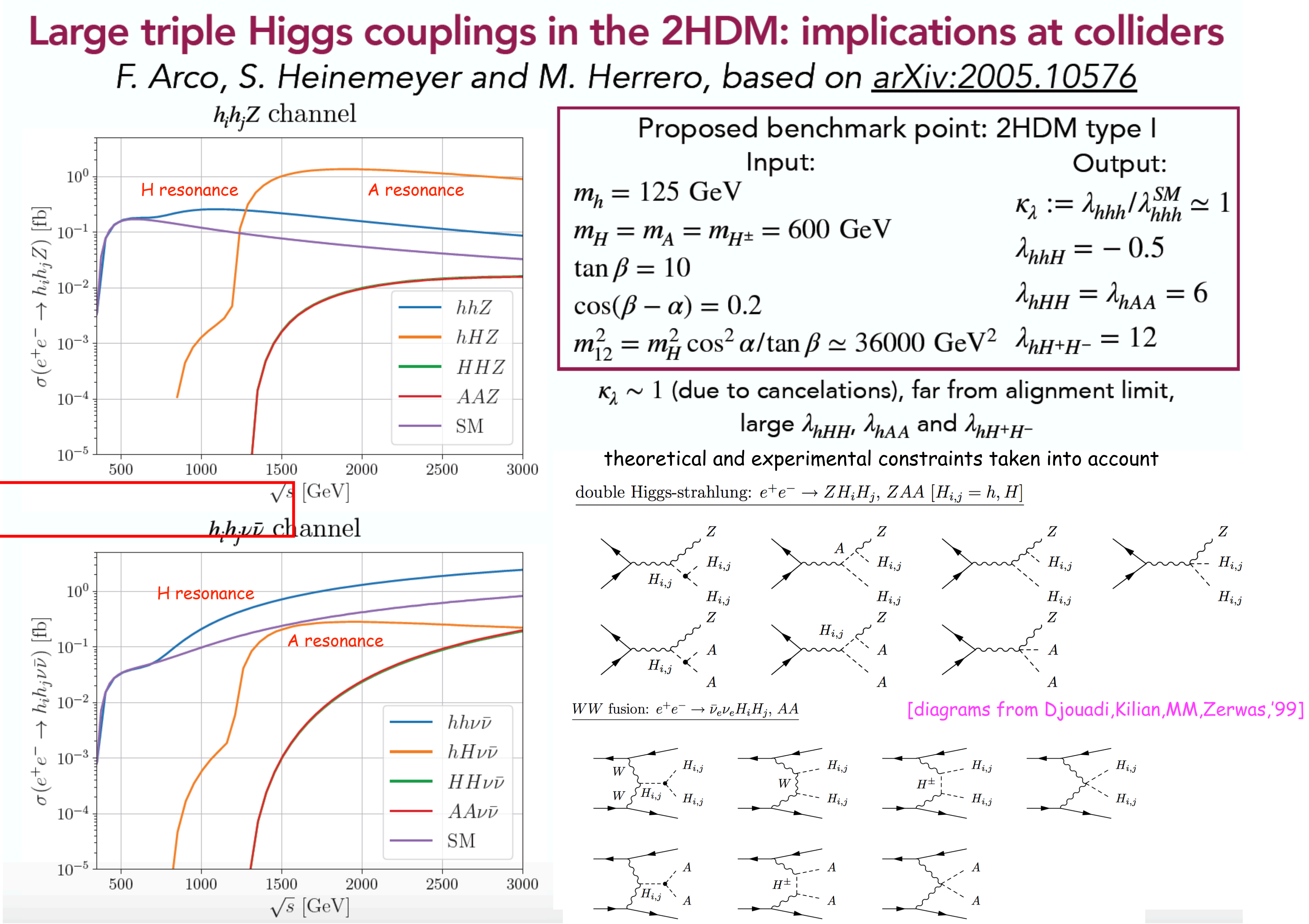
Kling, No, Su, JHEP09 (2016) 093

13 TeV LHC



2HDM Higgs Pairs at ee Collider

✦ Francisco talk tomorrow 17.15



Large triple Higgs couplings in the 2HDM: implications at colliders

F. Arco, S. Heinemeyer and M. Herrero, based on arXiv:2005.10576

$h_i h_j Z$ channel

$h_i h_j \nu\bar{\nu}$ channel

Proposed benchmark point: 2HDM type I

Input:

$m_h = 125$ GeV

$m_H = m_A = m_{H^\pm} = 600$ GeV

$\tan\beta = 10$

$\cos(\beta - \alpha) = 0.2$

$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta \simeq 36000\ \mathrm{GeV}^2$

Output:

$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{SM} \simeq 1$

$\lambda_{hhH} = -0.5$

$\lambda_{hHH} = \lambda_{hAA} = 6$

$\lambda_{hH^+H^-} = 12$

$\kappa_\lambda \sim 1$ (due to cancelations), far from alignment limit,
large λ_{hHH}, λ_{hAA} and $\lambda_{hH^+H^-}$

theoretical and experimental constraints taken into account

double Higgs-strahlung: $e^+e^- \to ZH_iH_j,\ ZAA\ [H_{i,j} = h, H]$

WW fusion: $e^+e^- \to \bar{\nu}_e \nu_e H_i H_j,\ AA$

[diagrams from Djouadi,Kilian,MM,Zerwas,'99]

CP-Violating 2HDM (C2HDM)

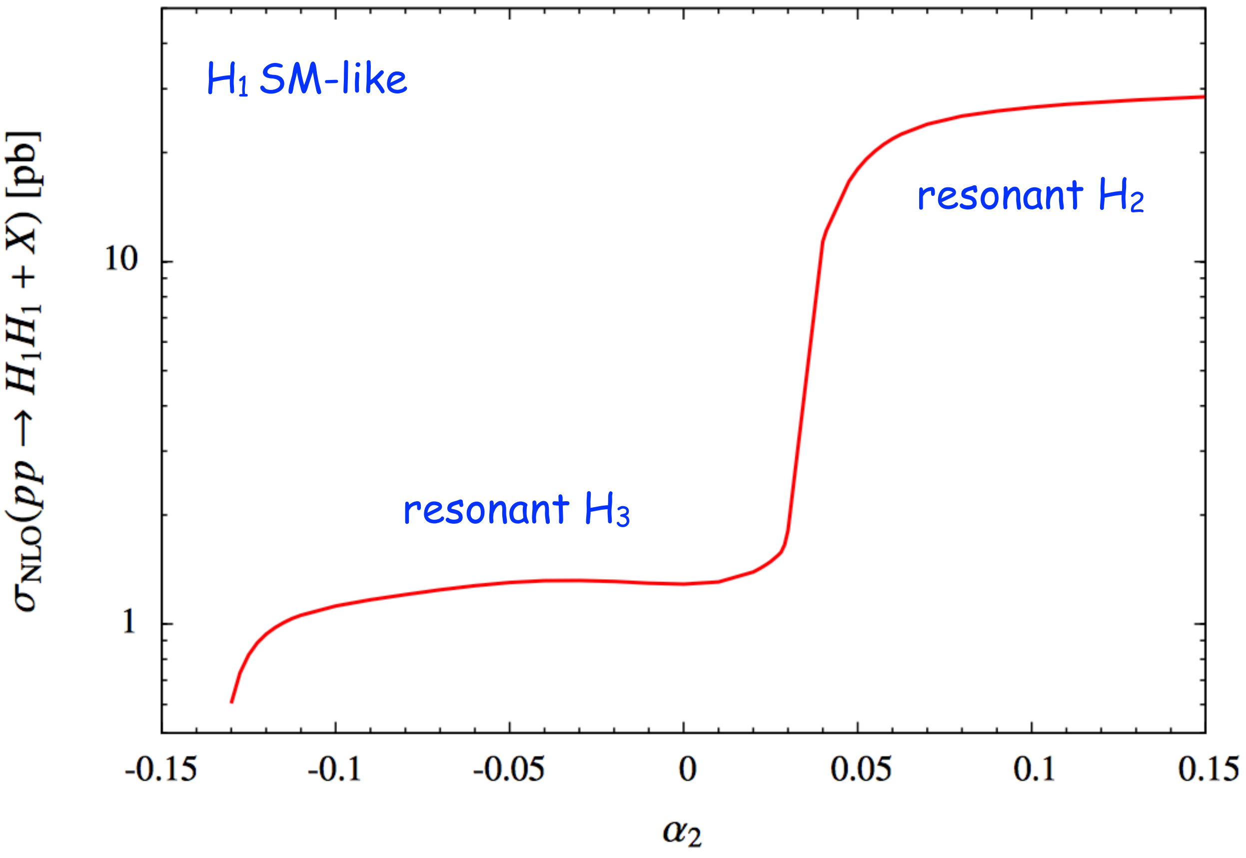
Gröber, Mühlleitner, Spira, Nucl.Phys.B.925 (217) 1

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

complex

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

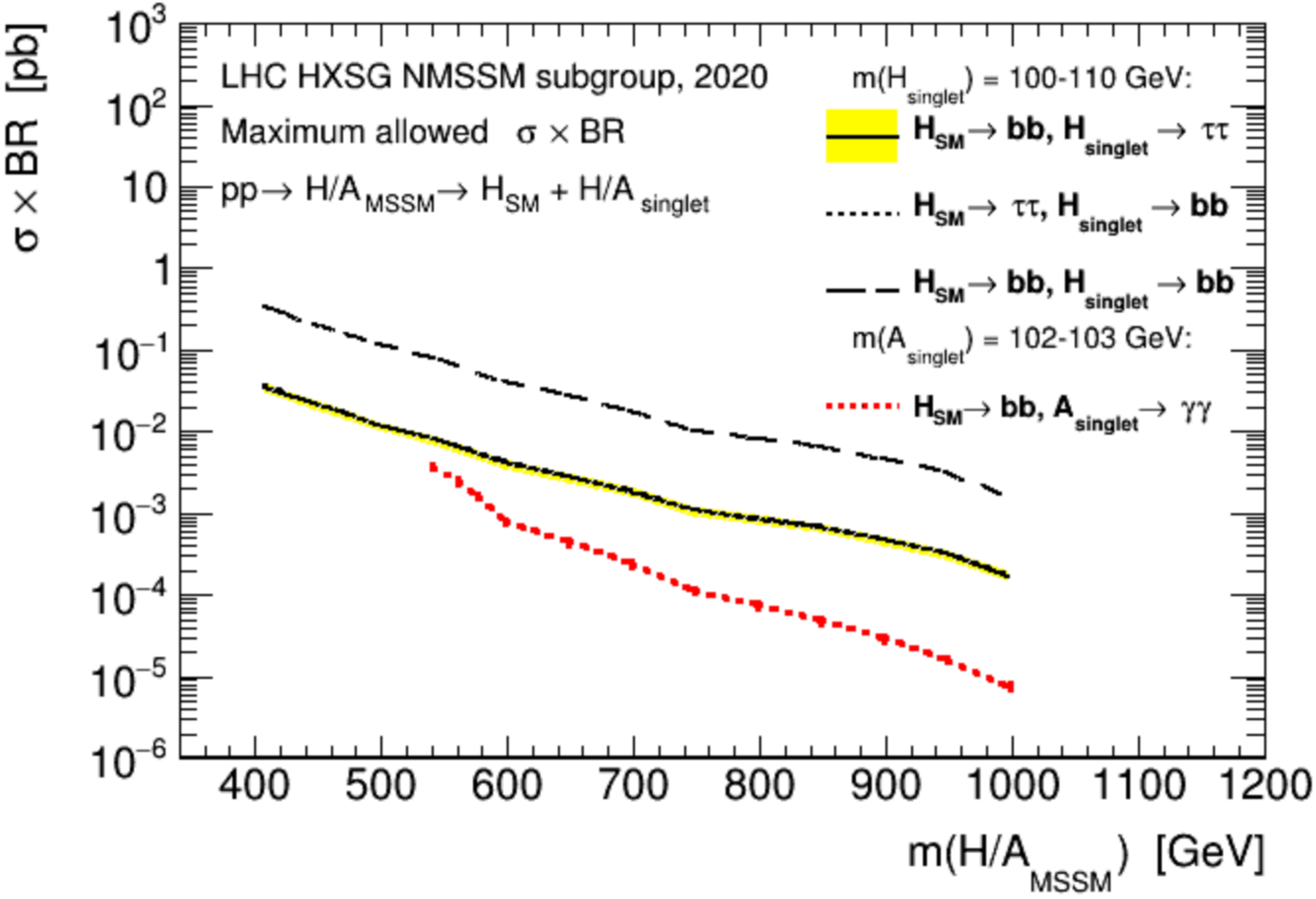
3 neutral CP-mixing Higgs bosons



$$377.6\ \text{GeV} \geq M_{H_2} \geq 277.0\ \text{GeV} \quad \text{and} \quad 1398.2\ \text{GeV} \geq M_{H_3} \geq 377.6\ \text{GeV}$$

NMSSM Benchmarks for Maximum Resonant H_{SM}+Singlet Production

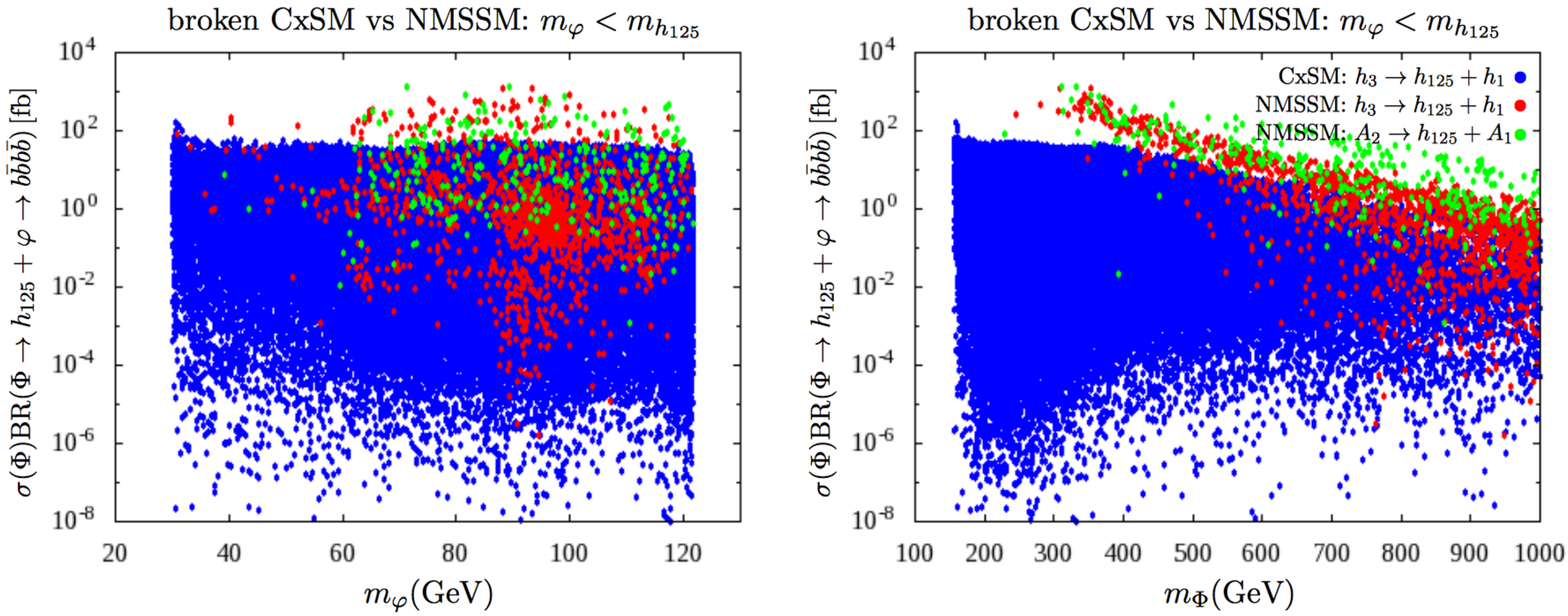
Ellwanger, Basler, Mühlleitner, Rompotis for the LHCHXSWG NMSSM Subgroup



Scan w/ NMSSMCALC and NMSSMTools: exp. constraints Higgs, SUSY, B mesons, Dark Matter

NMSSM and CxSM Comparison in Resonant H_{SM}+Singlet Production

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



Scan in CxSM and NMSSM parameter space w/ experimental and theoretical constraints

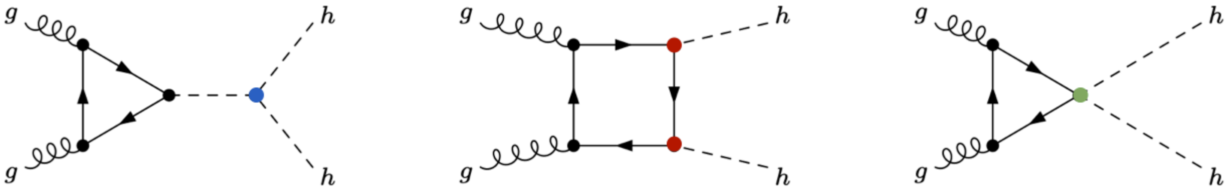
Maximum NMSSM rates can be enhanced by up to two orders of magnitude compared to CxSM
-> model distinction

And now for some completely different

Comparison with EFT

Effective Lagrangian with three terms: c_3, the trilinear coupling modification; c_t, the top-Yukawa coupling modification; c_{tt}, the effective two-Higgs-two-fermion coupling coefficient,

$$\Delta\mathcal{L}_{\text{non-lin}} \supset -m_t t\bar{t}\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{2v^2}\right) - c_3\frac{1}{6}\left(\frac{3M_h^2}{v}\right)h^3$$



The matching relations of our specific models to the EFT Lagrangian is

Higgs-top Yukawa coupling : $g_t^{H_{\text{SM}}}(\alpha_i,\beta) \rightarrow c_t$

trilinear Higgs coupling : $\dfrac{g_3^{H_{\text{SM}}H_{\text{SM}}H_{\text{SM}}}(p_i)}{3M_{H_{\text{SM}}}^2/v} \rightarrow c_3$

two-Higgs-two-top quark coupling : $\sum_{k=1}^{k_{\max}}\left(\dfrac{-v}{m_{H_k}^2}\right) g_3^{H_k H_{\text{SM}}H_{\text{SM}}}(p_i)\, g_t^{H_k}(\alpha_i,\beta) \rightarrow c_{tt}$

Comparison with EFT

Consider the R2HDM-II with the following set of parameters

m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	α	$\tan\beta$	m_{12}^2 [GeV^2]
125.09	1131	1082	1067	-0.924	0.820	552749

$\Rightarrow$ $\texttt{SMEFTBP1:}\ c_3 = 0.782\,,\ c_t = 0.951\,,\ c_{tt} = -0.122\,.$

And the extra choices that impact on c_{tt}

m_{H_2} [GeV]	Γ_{H_2} [GeV]	c_{tt}	$g_3^{H_2 H_1 H_1}$ [GeV]	$\sigma_{\text{R2HDM}}^{\text{w/ res}}$ [fb]	$\sigma_{\text{SMEFT}}^{c_{tt}\neq 0}$ [fb]	ratio
1131	78.80	-0.1222	-504.52	30.5	26.1	86%
1200	89.74	-0.1031	-479.29	27.7	24.8	90%
1500	470.2	-4.853 10^{-2}	-352.42	21.8	21.4	98%

For masses of the order of 1 TeV the ratio is 86% although for 1.5 TeV we get 98%. Note that if we turn-off the H_2 resonance by setting $c_{tt}= 0$, we get

$$\sigma_{\text{R2HDM}}^{\text{w/o res}} = 18.6 \text{ fb} \quad \text{and} \quad \sigma_{\text{SMEFT}}^{c_{tt}=0} = 18.6 \text{ fb}$$

Comparison with EFT

Consider now the N2HDM-I with the following set of parameters

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	269	582	390	380	4.190

α_1	α_2	α_3	v_s [GeV]	$\text{Re}(m_{12}^2)$ [GeV^2]	
1.432	-0.109	0.535	1250	28112	

⇒ $\texttt{SMEFTBP2:}\ c_3 = 0.877\,,\ c_t = 1.012\,,\ c_{tt} = 4.127 \times 10^{-2}$

$$g_t^{H_2} = 0.179 \quad \text{and} \quad g_t^{H_3} = 2.337 \times 10^{-2}$$

Now we vary the H_2 mass but keep H_3 fixed (c_{tt} has now two terms)

m_{H_2}	Γ_{H_2}	$c_{tt}^{H_2}$	c_{tt}	$g_3^{H_2H_1H_1}$	$\sigma^{\text{w/ res}}_{\text{N2HDM}}$ [fb]	$\sigma^{c_{tt}\neq 0}_{\text{SMEFT}}$ [fb]	ratio
269	0.075	4.410×10^{-2}	4.127×10^{-2}	-72.42	183.70	20.56	11%
300	0.083	3.170×10^{-2}	2.877×10^{-2}	-64.80	162.80	21.28	13%
400	0.177	9.544×10^{-3}	6.721×10^{-3}	-34.68	43.33	22.60	52%
420	0.229	6.895×10^{-3}	4.063×10^{-3}	-27.62	31.70	22.76	72%
440	0.284	4.600×10^{-3}	1.767×10^{-3}	-20.22	26.26	22.90	87%
450	0.315	3.564×10^{-3}	7.323×10^{-4}	-16.39	24.84	22.96	92%
500	2.567	-7.132×10^{-4}	-3.545×10^{-3}	4.05	23.56	23.22	99%

$$\sigma^{\text{w/o res}}_{\text{N2HDM}} = 23.05 \text{ fb} \quad \text{and} \quad \sigma^{c_{tt}=0}_{\text{SMEFT}} = 23.01 \text{ fb}$$

In this case we start a ratio of 11%,
but when we set both masses to about 500 GeV we get a ratio of 99%.

Single Higgs vs. Di-Higgs

The last slide

N2HDM-I and NMSSM - 3 SM-like Higgs bosons (H1). 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]	Re(m_{12}^2) [GeV^2]	
1.153	0.159	0.989	9639	29769	

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

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

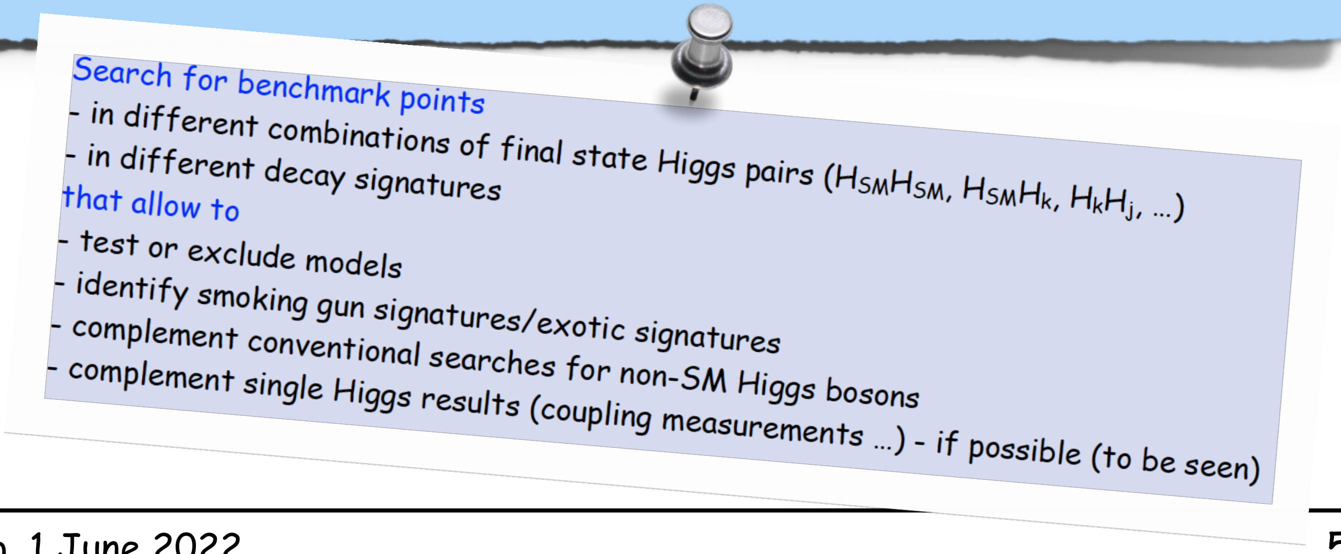
$$\sigma^{\text{NNLO}}(H_2) \times \text{BR}(H_2 \to WW) = 161 \cdot 0.44 \text{ fb} = 71 \text{ fb}$$

H2 BR to bb tiny.

Non-SM- like H2 has better chances of being discovered in di-Higgs than in single Higgs channels (W bosons still have to decay).

Conclusions

- Numerous BSM Higgs sector extensions with large variety of (resonant) Higgs pair final states
- 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 SM
- 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!



Search for benchmark points
- in different combinations of final state Higgs pairs ($H_{SM}H_{SM}$, $H_{SM}H_k$, H_kH_j, ...)
- in different decay signatures

that allow to
- test or exclude models
- identify smoking gun signatures/exotic signatures
- complement conventional searches for non-SM Higgs bosons
- complement single Higgs results (coupling measurements ...) - if possible (to be seen)

Thank you!

Real Singlet Extension

Lewis, Sullivan, PRD96 (2017) 035037; Review in Physics (2020) 100045

- Simplest SM extension: additional real singlet field; no $\mathbb{Z}_2$ symmetry

$$V(\Phi, S) = -\frac{\mu^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + \frac{a_1}{2}\Phi^\dagger\Phi S + \frac{a_2}{2}\Phi^\dagger\Phi S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

- Higgs and singlet mix:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

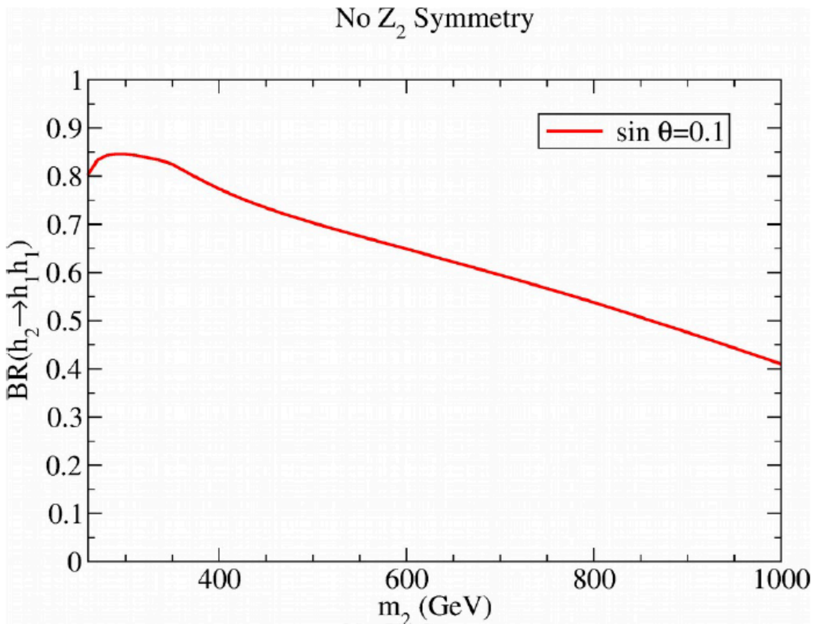
- Simple production rate:

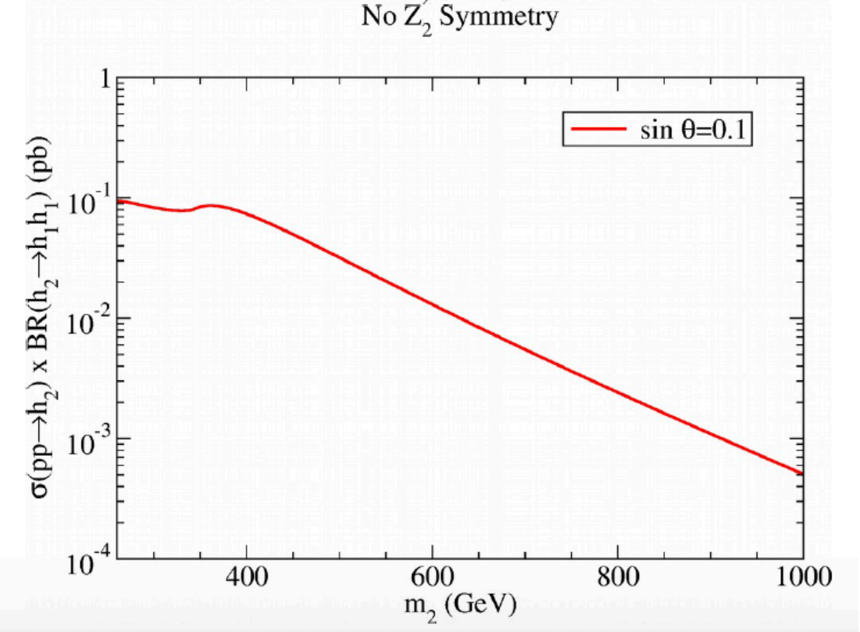
$$\sigma(pp \to h_2) = \sin^2\theta\,\sigma_{SM}(pp \to h_2).$$

- Maximizing resonant di-Higgs production:

$h2 \to h1h1$

perturbative unitarity, correct VEV,
sinθ=0.1 consistent w/ current Higgs constraints


No Z_2 Symmetry

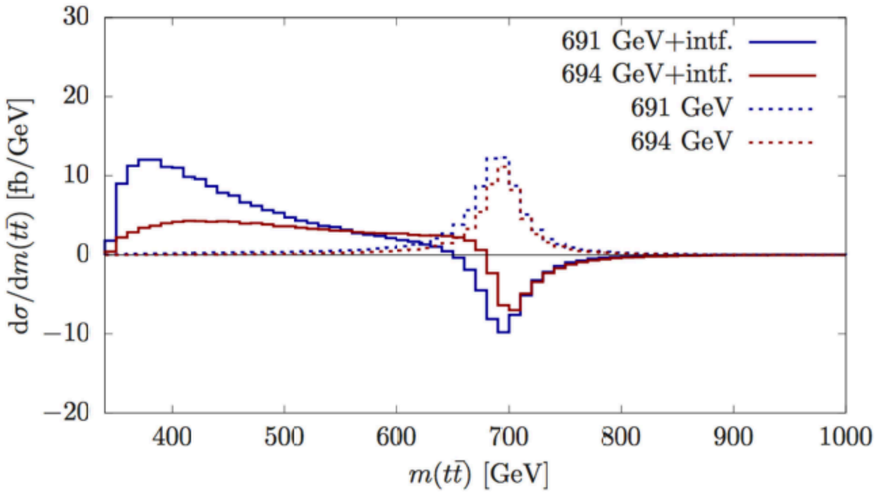

No Z_2 Symmetry

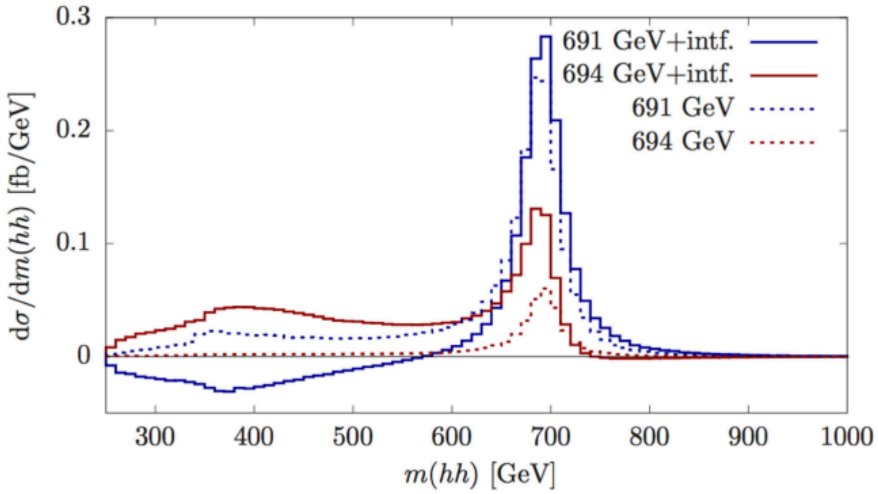
C2HDM: Single versus Double Higgs Production

[Basler,Dawson,Englert,Mühlleitner, Phys.Rev.D101 (2020) 1]

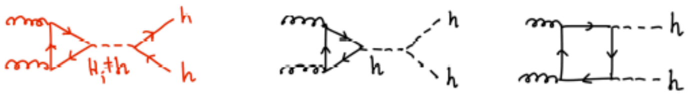
- **Di-Higgs Peaks and Top Valleys** (C2HDM) [Basler,Dawson,Englert,MM, 1909.09987]

  $gg \to H_i \to t\bar{t}$ and $gg \to H_i \to hh$ (h SM-like Higgs boson, $H_i \neq h$)





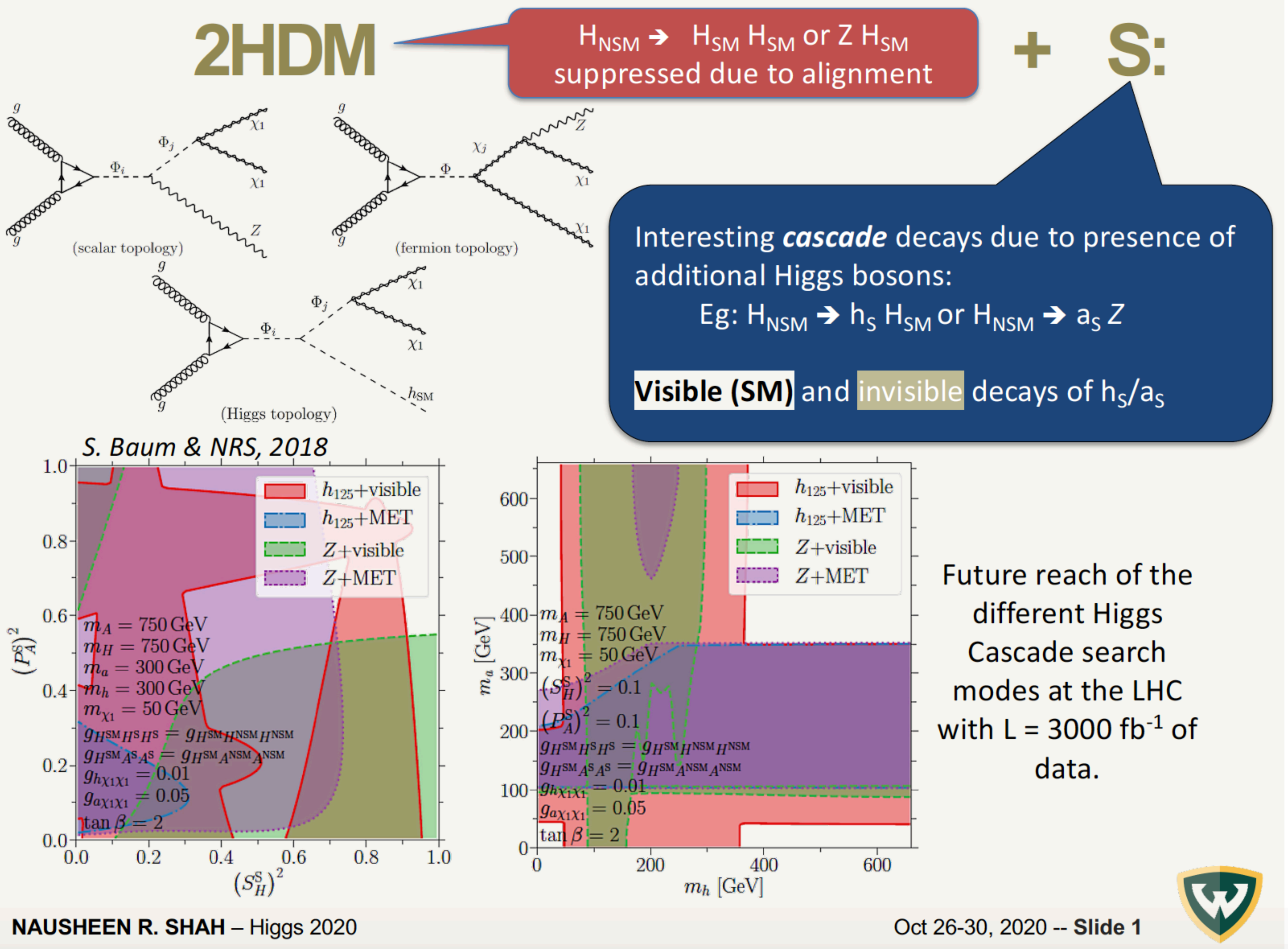
$*$ Destructive signal-background interference may be correlated with constructive signal-signal interference



For interference effects, see also [Dawson,Lewis '15; Djouadi eal '19; Lewis/Carena eal/Bagnaschi eal in 1910.00012]

2HDM+Complex Singlet - h_{125},H,A,h,a

Baum, Shah, JHEP12 (2018) 044



2HDM

H_{NSM} ➔ H_{SM} H_{SM} or Z H_{SM}
suppressed due to alignment

+ **S:**

Interesting ***cascade*** decays due to presence of additional Higgs bosons:

Eg: H_{NSM} ➔ h_S H_{SM} or H_{NSM} ➔ a_S Z

Visible (SM) and invisible decays of h_S/a_S

S. Baum & NRS, 2018

Future reach of the different Higgs Cascade search modes at the LHC with L = 3000 fb^{-1} of data.

NAUSHEEN R. SHAH – Higgs 2020

Oct 26-30, 2020 -- **Slide 1**

in general here
<u>h_{125}+visible</u>
<u>Z+visible:</u>
H->h_{125}h
A-> Zh
<u>mono-Higgs</u>
<u>mono-Z:</u>
A->h_{125}a
H->Za