Resonant Benchmarks hh, hS, SS for the LHC

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

- **Next-to-Minimal Supersymmetric Extension of the SM: NMSSM**

  Fayet; Kaul eal; Barbieri eal; Dine eal; Nilles eal; Frere eal; Derendinger eal; Ellis eal;
  Drees; Ellwanger eal; Savoy; Elliott eal; Gunion eal; Franke eal; Maniatis; Djouadi eal; Mahmoudi eal; ...

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

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

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

- **Significant changes of Higgs boson phenomenology**

The C2HDM

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

- **CP Violation:** m_{12}^2, λ_5 can be complex (all others real); indep. phase $\rightsquigarrow$ CP violation
- **Particle content:**

  3 neutral CP-mixing Higgs bosons H_1, H_2, H_3

  1 charged Higgs pair $H^\pm$

- **Flavour-Changing Neutral Currents (FCNC) at tree-level:** forbidden by $\mathbb{Z}_2$ symmetry

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

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

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

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

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

- **Experimental constraints::**
  - S, T, U parameters for EW precision observables [Baak eal '14]
  - $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{ hadrons})$ and $B \to X_s\gamma$ [Haber,Logan '99;Deschamps eal '09; Mahmoudi,Stal '09; Steinhauser eal '17]
  - Higgs exclusion bounds by `HiggsBounds` [Bechtle eal '08,'11,'13]
  - Higgs rates checked via `SUSHI` and `C2HDM_HDECAY`, `HiggsSignals` [Harlander eal; Fontes eal; Bechtle eal]
  - Electric dipole moment of the electron [The ACME Collaboration '18]

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

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

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

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

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

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

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

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

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

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

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

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

(1) $\mathcal{C}$2HDM $\mathcal{B}$enchmark $\mathcal{P}$oint - $\mathcal{M}$ax $\sigma(hh \to (b\bar{b})(b\bar{b}))$

$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.09	$3.64 \cdot 10^{-3}$
$m_{H_2}/\Gamma_{\text{tot}}$ [GeV]	310.99	0.35
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	314.63	1.44
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	372.62	0.99
σ^{LO}_{hh} [fb]	781	
$\sigma^{\text{LO}}_{hh\to 4b}$/wrt. SM [fb]	261	42
$\mathcal{L}_{\text{excl}}$ [fb^{-1}]	266	
Re(m^2_{12}) [GeV^2]	14860	
α_1	1.160	
α_2	$-6.066 \cdot 10^{-3}$	
α_3	1.2338	
$\tan\beta$	5.088	
R^2_{13}	$3.680 \cdot 10^{-5}$	
R^2_{23}	0.890	
R^2_{33}	0.110	

- R^2_{i3} quantifies singlet admixture
- $\sigma^{\text{NLO}} \sim 2\sigma^{\text{LO}}$
- enhancement due to resonant H_2, H_3 production w/ subsequent decay into hh: BR$(H_2 \to hh = 0.428)$, BR$(H_3 \to hh = 0.707)$

(2) $\mathcal{C}$2HDM $\mathcal{B}$enchmark $\mathcal{P}$oint - $\mathcal{M}$ax $\sigma(SS/hS \to (b\bar{b})(b\bar{b}))$

$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.09	$3.74 \cdot 10^{-3}$
$m_{H_{2(S)}}/\Gamma_{\text{tot}}$ [GeV]	131.48	$7.95 \cdot 10^{-4}$
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	313.33	6.45
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	311.54	5.79
σ^{LO}_{SS} [pb]	3.20	
$\sigma^{\text{LO}}_{SS\to 4b}$ [pb]	1.26	
σ^{LO}_{Sh} [fb]	49.17	
$\sigma^{\text{LO}}_{Sh\to 4b}$ [fb]	17.79	
$\mathcal{L}_{\text{excl}}$ [fb^{-1}]	287	
Re(m_{12}^2) [GeV^2]	13786	
α_1	1.041	
α_2	0.0262	
α_3	-1.570	
$\tan\beta$	2.220	

- S here means large pseudoscalar admixture
- $\sigma^{\text{NLO}} \sim 2\sigma^{\text{LO}}$
- $H_2H_2 = SS$ enhancement due to resonant H_3 production w/ subsequent decay into SS: BR$(H_3 \to SS = 0.456)$
- $R^2_{13} = 6.838 \cdot 10^{-4}$, $R^2_{23} = 0.999$ $R^2_{33} = 1.412 \cdot 10^{-7}$

(3) $\mathcal{N}$MSSM $\mathcal{B}$enchmark $\mathcal{P}$oints - $\mathcal{M}$ax $\sigma(hh \to (b\bar{b})(b\bar{b}))$

$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.03	$3.60 \cdot 10^{-3}$
$m_{H_{2(S)}}/\Gamma_{\text{tot}}$ [GeV]	170.66	0.27
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	454.90	2.80
$m_{A_{1(S)}}/\Gamma_{\text{tot}}$ [GeV]	69.03	7.26
$m_{A_2}/\Gamma_{\text{tot}}$ [GeV]	446.26	4.34
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	440.31	3.77
σ^{LO}_{hh} [fb]	34.18	
$\sigma^{\text{LO}}_{hh\to 4b}$/wrt. SM [fb]	12.42	1.99
$\mathcal{L}_{\text{excl}}$ [fb^{-1}]	287	
$\tan\beta$	2.919	
λ	0.613	
κ	0.331	
A_λ [GeV]	-348	
A_κ [GeV]	-51	
μ_{eff} [GeV]	-159	

- H_2 singlet-like scalar
  A_1 singlet-like pseudoscalar
- $\sigma^{\text{NLO}} \sim 2\sigma^{\text{LO}}$

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

$m_{H_1}/\Gamma_{\text{tot}}$ [GeV]	125.03	$3.60 \cdot 10^{-3}$
$m_{H_{2(S)}}/\Gamma_{\text{tot}}$ [GeV]	170.66	0.27
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$m_{A_2}/\Gamma_{\text{tot}}$ [GeV]	446.26	4.34
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	440.31	3.77
$\sigma^{\text{LO}}_{hA_S}$ [fb]	69.97	
$\sigma^{\text{LO}}_{hA_S \to 4b}$ [fb]	38.32	
$\sigma^{\text{LO}}_{A_SA_S}$ [fb]	69.78	
$\sigma^{\text{LO}}_{A_SA_S \to 4b}$ [fb]	57.58	
$\mathcal{L}_{\text{excl}}$ [fb^{-1}]	287	

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

(4) $\mathcal{N}$MSSM $\mathcal{B}$enchmark $\mathcal{P}$oints - $\mathcal{M}$ax $\sigma(hH_S \to (b\bar{b})(b\bar{b}))$

$m_{H_1(S)}/\Gamma_{\text{tot}}$ [GeV]	100.11	$1.00 \cdot 10^{-3}$
$m_{H_2}/\Gamma_{\text{tot}}$ [GeV]	125.23	$3.56 \cdot 10^{-3}$
$m_{H_3}/\Gamma_{\text{tot}}$ [GeV]	660.38	7.80
$m_{A_1(S)}/\Gamma_{\text{tot}}$ [GeV]	217.21	$6.92 \cdot 10^{-4}$
$m_{A_2}/\Gamma_{\text{tot}}$ [GeV]	657.01	8.73
$m_{H^\pm}/\Gamma_{\text{tot}}$ [GeV]	651.11	7.54
$\sigma^{\text{LO}}_{hH_S}$ [fb]	15.68	
$\sigma^{\text{LO}}_{hH_S \to 4b}$ [fb]	8.43	
$\mathcal{L}_{\text{excl}}$ [fb^{-1}]	183	
$\tan\beta$	3.601	
λ	0.589	
κ	0.251	
A_λ [GeV]	593	
A_κ [GeV]	-148	
μ_{eff} [GeV]	178	

- H_1 singlet-like scalar
  A_1 singlet-like pseudoscalar
- $\sigma^{\text{NLO}} \sim 2\sigma^{\text{LO}}$

Thank You For Your Attention!