

## TRSM benchmark planes - EPS-HEP2023 update

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I briefly review the Benchmark Planes in the Two-Real-Singlet Model (TRSM), a model that enhances the Standard Model (SM) scalar sector by two real singlets that obey a  $\mathbb{Z}_2 \times \mathbb{Z}'_2$  symmetry. All fields acquire a vacuum expectation value, that softly breaks the above symmetry and leads to mixing of all CP even neutral states. Furthermore, all interactions with SM-like particles are inherited from the SM-like doublet via mixing. I remind the readers of the previously proposed benchmark planes, and briefly discuss possible production at future Higgs factories, as well as regions in a more generic scan of the model. Results are based on previous work presented in [1–3].

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## 1. Introduction and benchmark planes

The model presented here has already been widely discussed in the literature [1, 2, 4], to which we refer the reader for more details. We here just briefly repeat the main characteristics for reference. The Two-Real-Singlet Model (TRSM) is a new physics model that enhances the Standard Model (SM) electroweak sector by two additional fields that are singlets under the SM gauge group. The fields obey an additional  $\mathbb{Z}_2 \otimes \mathbb{Z}'_2$  symmetry. All scalar fields acquire a vacuum expectation value, and all CP even neutral states are related to the gauge eigenstates via mixing. In order to comply with current observations by the LHC experiments, one of the resulting three CP even neutral scalars has to show properties in agreement with the measurements of the Higgs boson by the LHC experiments [5, 6].

The original benchmark planes (BPs) have been proposed in [1]. They can be classified as either asymmetric (AS) production and decay, in the form of  $pp \rightarrow h_3 \rightarrow h_1 h_2$ , or symmetric (S) decays in the form of  $pp \rightarrow h_i \rightarrow h_j h_j$ , where in our study none of the scalars corresponds to the 125 GeV resonance. We follow the convention that  $M_1 \leq M_2 \leq M_3$  for the masses of the scalars  $h_{1,2,3}$  in the mass eigenstates.

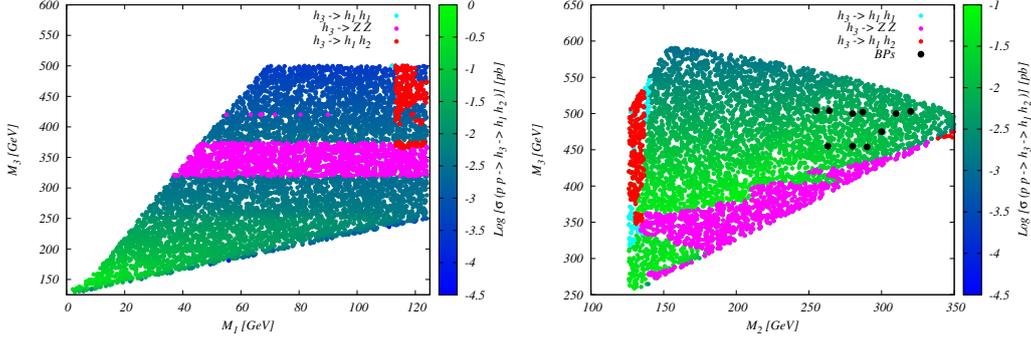
The BPs have been widely discussed in e.g. [1–3]. Although by now several searches exist that in principle are sensitive to some of the benchmark planes (see section 2), the model still renders quite a few final state signatures that so far have not yet been investigated by the LHC experiments. We here display four of the BPs, where we also list maximal cross sections that can be obtained at a 13 TeV  $pp$  collider:

- **AS BP2:**  $h_3 \rightarrow h_1 h_2$  ( $h_2 = h_{125}$ ): SM-like decays for both scalars:  $\sim 0.6$  pb
- **AS BP3:**  $h_3 \rightarrow h_1 h_2$  ( $h_1 = h_{125}$ ): (a) SM-like decays for both scalars  $\sim 0.3$  pb; (b)  $h_1^3$  final states:  $\sim 0.14$  pb
- **S BP4:**  $h_2 \rightarrow h_1 h_1$  ( $h_3 = h_{125}$ ): up to 60 pb
- **S BP6:**  $h_3 \rightarrow h_2 h_2$  ( $h_1 = h_{125}$ ): SM-like decays: up to 0.5 pb;  $h_1^4$  final states: around 14 fb

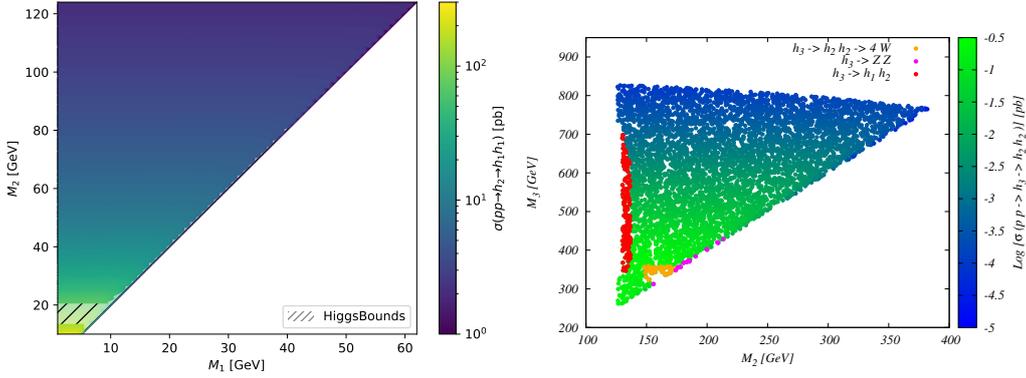
The corresponding BPs are shown in figures 1 and 2, respectively. The label  $h_3 \rightarrow h_1 h_2$  refers to regions in the parameter space excluded by [7], while  $h_3 \rightarrow h_1 h_1$  correspond to results from [8–10] and  $h_3 \rightarrow ZZ$  from [11], respectively. For BP6, the ATLAS search  $h_3 \rightarrow h_2 h_2 \rightarrow W^+ W^- W^+ W^-$  [12] is also sensitive. A more detailed discussion on updates is presented in [3]. The exclusion bounds have been obtained via the publicly available tool HiggsTools [13].

## 2. LHC interpretations

Two experimental searches have by now made use of the predictions obtained within the TRSM to interpret regions in parameter space that are excluded: a CMS search for asymmetric production and subsequent decay into  $b\bar{b}b\bar{b}$  final states [14], as well as  $b\bar{b}\gamma\gamma$  in [15]. Maximal rates for these within the TRSM are documented in [16, 17]. Figures 3 (taken from [14]) and 4 (taken from [15]) show the expected and observed limits in these searches for the TRSM and NMSSM [18].



**Figure 1:** Parameter regions in BP2 (left) and BP3 (right) with updated constraints; see text for details.



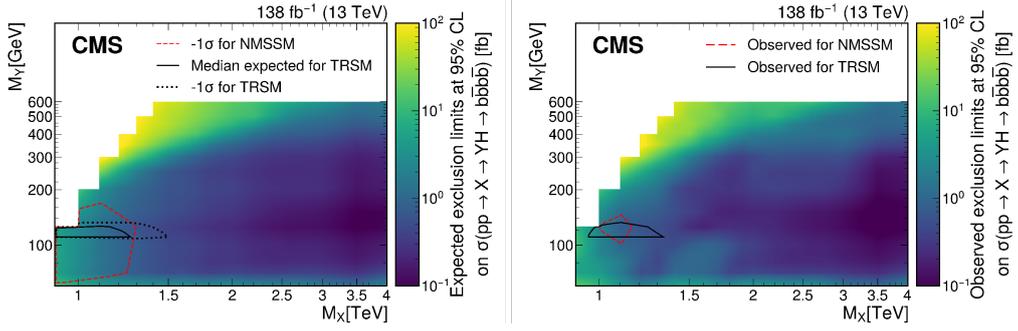
**Figure 2:** Parameter regions in BP4 (left) and BP6 (right) with updated constraints; see text for details.

### 3. Processes at Higgs factories

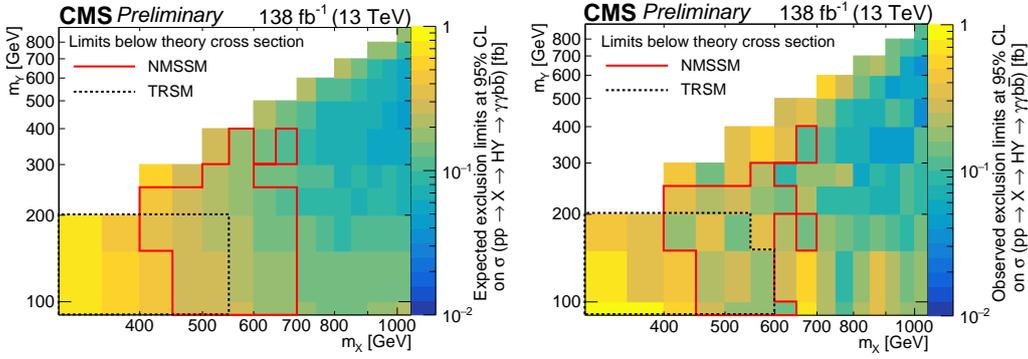
In the European Strategy report [19, 20], Higgs factories were identified as one of the high priority projects after the HL-LHC. At such machines, new physics scalar states could also be produced in the mass range up to  $\sim 160$  GeV depending on the collider process.

In general, additional light scalar states can be singly produced e.g. via so-called scalar-strahlung  $e^+e^- \rightarrow Zh$ , or in the VBF-type topologies with  $e^+e^- \rightarrow \nu_e \bar{\nu}_e h$ . As we cannot impose a direct cut on the rapidity of the neutrinos, also scalar strahlung can contribute to the latter final state if  $Z \rightarrow \nu_e \bar{\nu}_e$ . Leading-order predictions for  $Zh$  production at  $e^+e^-$  colliders for low mass scalars which are Standard Model (SM)-like, using Madgraph5 [21], are shown in figure 5 for a center-of-mass energy of 250 GeV. While for lower masses VBF production still plays a role, for higher scalar masses the dominant contribution stems from  $Zh$  production.

It is then interesting to see which parameter range is still available for such light scalar states in the TRSM, where now  $\sin \alpha$  corresponds to the rescaling angle with respect to the coupling of a SM-like Higgs at a certain mass  $M_i$ . The allowed parameter space is shown in figure 6. Results after convolution with production cross sections and decay rates are shown in figure 7. We see that total production rates can be in the 20 – 30 fb range, while dominant decay rates are into  $b\bar{b}$  and  $h_1 h_1$  final states; the latter would lead to  $Zh_1 h_1$  with typical decays to  $Zb\bar{b}b\bar{b}$  final states, a



**Figure 3:** Expected (left) and observed (right) 95% confidence limits for the  $pp \rightarrow h_3 \rightarrow h_2 h_1$  search, with subsequent decays into  $b\bar{b}b\bar{b}$ . For both models, maximal mass regions up to  $M_3 \sim 1.4$  TeV,  $M_2 \sim 140$  GeV can be excluded.



**Figure 4:** Expected (left) and observed (right) 95% confidence limits for the  $pp \rightarrow h_3 \rightarrow h_2 h_1$  search, with subsequent decays into  $b\bar{b}\gamma\gamma$ . Depending on the model, maximal mass regions up to  $m_3 \sim 800$  GeV,  $m_2 \sim 400$  GeV can be excluded.

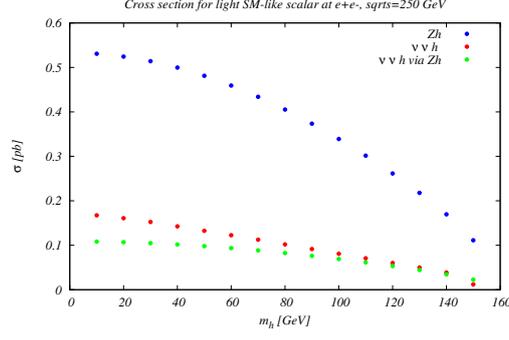
signature that so far has not been explored yet. We also observe  $c\bar{c}$  and  $\tau^+\tau^-$  final states in some regions of the parameter space. Ref. [24] shows some preliminary studies of discovery prospects.

#### 4. Conclusions

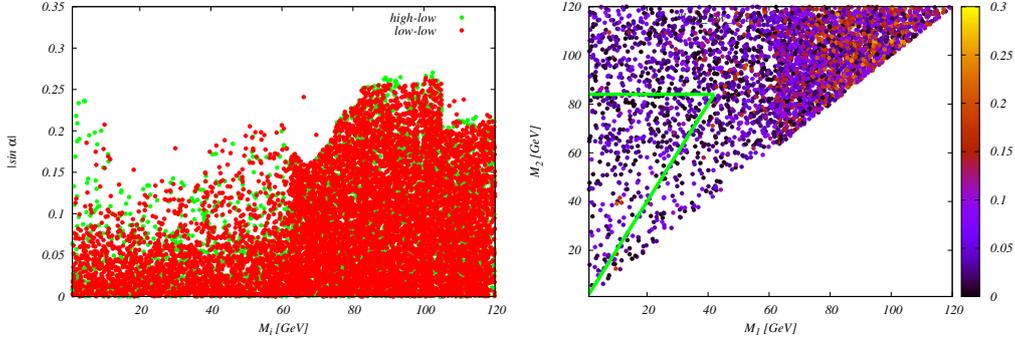
The TRSM is a new physics model that, with a small number of additional new physics parameters, allows for novel final states, in particular asymmetric scalar production and decays. I briefly summarized the current status of benchmark planes originally proposed in [1] as well as possible rates for this model at future facilities, such as Higgs factories. UFO file for the model and maximal cross section values are available upon request.

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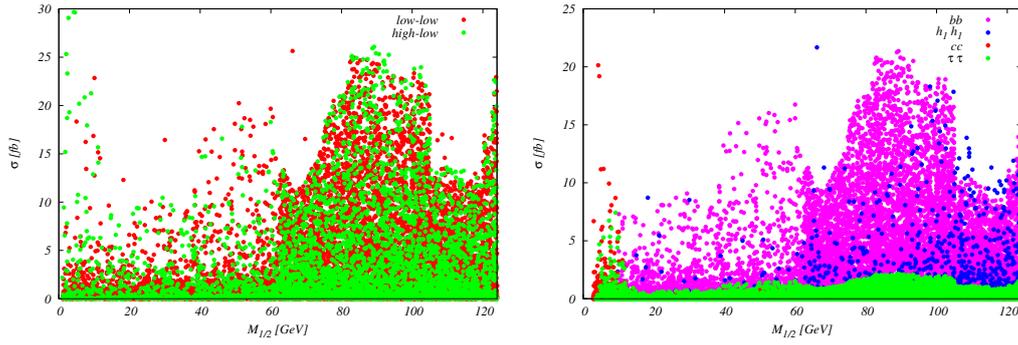
**Figure 5:** Leading-order production cross sections for  $Z h$  and  $h \nu_\ell \bar{\nu}_\ell$  production at an  $e^+ e^-$  collider with a com energy of 250 GeV using Madgraph5 for an SM-like scalar  $h$ . Shown is also the contribution of  $Z h$  to  $\nu_\ell \bar{\nu}_\ell h$  using a factorized approach for the  $Z$  decay. Update of plot in [22], first presented in [23].



**Figure 6:** Available parameter space in the TRSM, with one (high-low) or two (low-low) masses lighter than 125 GeV. *Left:* light scalar mass and mixing angle, with  $\sin \alpha = 0$  corresponding to complete decoupling. *Right:* available parameter space in the  $(m_{h_1}, m_{h_2})$  plane, with color coding denoting the rescaling parameter  $\sin \alpha$  for the lighter scalar  $h_1$ . Within the green triangle,  $h_{125} \rightarrow h_2 h_1 \rightarrow h_1 h_1 h_1$  decays are kinematically allowed. Taken from [22].

## References

- [1] Tania Robens, Tim Stefaniak, and Jonas Wittbrodt. Two-real-scalar-singlet extension of the SM: LHC phenomenology and benchmark scenarios. *Eur. Phys. J. C*, 80(2):151, 2020, 1908.08554.
- [2] Tania Robens. Two-Real-Singlet-Model Benchmark Planes. *Symmetry*, 15(1):27, 2023, 2209.10996.
- [3] Tania Robens. Two-Real-Singlet Model Benchmark Planes – A Moriond Update. In *57th Rencontres de Moriond on QCD and High Energy Interactions*, 5 2023, 2305.08595.
- [4] Andreas Papaefstathiou, Tania Robens, and Gilberto Tetlalmatzi-Xolocotzi. Triple Higgs Boson Production at the Large Hadron Collider with Two Real Singlet Scalars. *JHEP*, 05:193, 2021, 2101.00037.



**Figure 7:** Points in the TRSM taken from figure 6, and convoluted with production cross sections at a 250 GeV Higgs factory (*left*), and additionally with branching ratios of dominant final states (*right*). Update of a figure first presented in [2].

- [5] A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery. *Nature*, 607(7917):52–59, 2022, 2207.00092.
- [6] A portrait of the Higgs boson by the CMS experiment ten years after the discovery. *Nature*, 607(7917):60–68, 2022, 2207.00043.
- [7] Armen Tumasyan et al. Search for a heavy Higgs boson decaying into two lighter Higgs bosons in the  $\tau\tau b\bar{b}$  final state at 13 TeV. *JHEP*, 11:057, 2021, 2106.10361.
- [8] Albert M Sirunyan et al. Combination of searches for Higgs boson pair production in proton-proton collisions at  $\sqrt{s} = 13$  TeV. *Phys. Rev. Lett.*, 122(12):121803, 2019, 1811.09689.
- [9] Morad Aaboud et al. Search for pair production of Higgs bosons in the  $b\bar{b}b\bar{b}$  final state using proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. *JHEP*, 01:030, 2019, 1804.06174.
- [10] Albert M. Sirunyan et al. Search for resonant pair production of Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at 13 TeV. *JHEP*, 08:152, 2018, 1806.03548.
- [11] Georges Aad et al. Search for heavy resonances decaying into a pair of Z bosons in the  $\ell^+\ell^-\ell'^+\ell'^-$  and  $\ell^+\ell^-\nu\bar{\nu}$  final states using 139 fb $^{-1}$  of proton–proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. *Eur. Phys. J. C*, 81(4):332, 2021, 2009.14791.
- [12] Morad Aaboud et al. Search for Higgs boson pair production in the  $WW^{(*)}WW^{(*)}$  decay channel using ATLAS data recorded at  $\sqrt{s} = 13$  TeV. *JHEP*, 05:124, 2019, 1811.11028.
- [13] Henning Bahl, Thomas Biekötter, Sven Heinemeyer, Cheng Li, Steven Paasch, Georg Weiglein, and Jonas Wittbrodt. HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals. *Comput. Phys. Commun.*, 291:108803, 2023, 2210.09332.
- [14] Armen Tumasyan et al. Search for a massive scalar resonance decaying to a light scalar and a Higgs boson in the four b quarks final state with boosted topology. *Phys. Lett. B*, 842:137392, 2023, 2204.12413.

- [15] Search for a new resonance decaying to two scalars in the final state with two bottom quarks and two photons in proton-proton collisions at  $\sqrt{s} = 13$  TeV. Technical report, CERN, Geneva, 2022. CMS-PAS-HIG-21-011.
- [16] Tania Robens.  $b\bar{b}b\bar{b}$  final states in the TRSM for asymmetric production and decay. <https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3EX/rep.pdf>.
- [17] Tania Robens. trsm\_bbgaga.txt. <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX>.
- [18] Ulrich Ellwanger and Cyril Hugonie. Benchmark planes for Higgs-to-Higgs decays in the NMSSM. *Eur. Phys. J. C*, 82(5):406, 2022, 2203.05049.
- [19] Richard Keith Ellis et al. Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020. 10 2019, 1910.11775.
- [20] 2020 Update of the European Strategy for Particle Physics (Brochure). Technical report, Geneva, 2020. CERN-ESU-015.
- [21] Johan Alwall, Michel Herquet, Fabio Maltoni, Olivier Mattelaer, and Tim Stelzer. MadGraph 5 : Going Beyond. *JHEP*, 06:128, 2011, 1106.0522.
- [22] Tania Robens. A Short Overview on Low Mass Scalars at Future Lepton Colliders. *Universe*, 8:286, 2022, 2205.09687.
- [23] Tania Natalie Robens. An overview on low mass scalars at future lepton colliders. *PoS*, ICHEP2022:1041, 11 2022, 2211.10231.
- [24] Aleksander Filip Zarnecki. Prospects for exotic light scalar measurements at the e+e- Higgs factory. *PoS*, EPS-HEP2023:459, 2024.