TRSM Light Scalars in the Spotlight of the LHC

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Based on work with:

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MOTIVATION

The Standard Model (SM) Higgs sector may be extended by adding additional gauge-singlet real scalar fields.

- TRSM is one of the simplest multi-scalar extensions, featuring two real singlets in addition to the SM Higgs doublet.
  [Robens ea, Eur.Phys.J.C 80 (2020) 2, 151; Robens, Symmetry 15 (2023) 27]

- It provides a rich phenomenology for:
  - **Electroweak symmetry breaking** (EWSB) dynamics.
  - **Dark matter candidates** (if one singlet is stabilized by a discrete symmetry).
  - **Electroweak baryogenesis** (via a strong first-order phase transition).
  - **Exotic Higgs decays** and **resonant signatures** testable at colliders.

MOTIVATION

- Both ATLAS and CMS have explored several decay channels for di-Higgs production:

BRs	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

  - $bbbb$: BR (33.6%), Huge QCD background
  - $bbWW$: balance BR (24.9%) and background
  - $bb\tau\tau$: Clean signature with moderate BR (7.4%)
  - $bb\gamma\gamma$: Very clean signature with low BR (0.26%)
  - $4W$: Multi-leptons,but complex reconstruction
  - $bbZZ$: Multiple final states depending on Z decays

Channel	Collaboration	Masse Range	HiggsTools
$S \to HH \to 2b2\gamma$	CMS	250GeV $< m_S <$ 900	✓
$S \to HH \to 2b2\tau$	CMS	250GeV $< m_S <$ 900GeV	✓
$H \to aa \to 2b2\mu$	CMS	15GeV $< m_a <$ 60GeV	✓
$H \to aa \to 2b2\mu$	ATLAS	15GeV $< m_a <$ 60GeV	✓
$H \to aa \to 2\mu2\tau$	CMS	15GeV $< m_a <$ 61.5GeV	✓
$H \to aa \to 2b2\tau$	CMS	15GeV $< m_a <$ 60GeV	✓
$H \to aa \to 4\gamma$	CMS	15GeV $< m_a <$ 60GeV	✓
$H \to aa \to 2\mu2\tau$	CMS	3.6GeV $< m_a <$ 21GeV	✓
$H \to aa \to 2b2\mu$	ATLAS	15GeV $< m_a <$ 60GeV	✓
$S \to HH \to bbVV$	CMS	260GeV $< m_S <$ 900GeV	✓
$H \to aa \to 4b$	ATLAS	20GeV $< m_a <$ 60GeV	✓
$S \to HH \to 2b2\gamma$	ATLAS	260GeV $< m_S <$ 1000	✓
$S \to HH \to 2b2\gamma$	ATLAS	250GeV $< m_S <$ 1000	✓

Table: Recent Limits on di-Higgs decays established by ATLAS and CMS AT LHC.

Two Real Singlet Model (TRSM)

- Extending the Standard Model by Real Singlet Scalar Fields

  [Robens ea, Eur.Phys.J.C 80 (2020) 2, 151; Robens, Symmetry 15 (2023) 27]

- The scalar potential of n real scalar singlet fields ϕ_i

$$V(\Phi, \phi_i) = V_{\text{singlets}}(\Phi, \phi_i) + V_{SM}(\Phi) \tag{1}$$

  with the most general renormalizable expression for $V_{\text{singlets}}(\Phi, \phi_i)$ given by:

$$V_{\text{singlets}}\ (\Phi, \phi_i) = a_i\phi_i + m_{ij}\phi_i\phi_j + T_{ijk}\phi_i\phi_j\phi_k + \lambda_{ijkl}\phi_i\phi_j\phi_k\phi_l \tag{2}$$

$$+ T_{iHH}\phi_i\left(\Phi^\dagger\Phi\right) + \lambda_{ijHH}\phi_i\phi_j\left(\Phi^\dagger\Phi\right) \tag{3}$$

  with real coefficient tensors.

- In this work we focus on the TRSM, which introduces two extra real scalar fields S and X.

Two Real Singlet Model (TRSM)

- In order to reduce the number of free parameters two discrete Z_2 symmetries are introduced:

$$\mathcal{Z}_2^S : S \longrightarrow -S,\ X \longrightarrow X,\ SM \longrightarrow SM, \tag{4}$$
$$\mathcal{Z}_2^X : X \longrightarrow -X,\ S \longrightarrow S,\ SM \longrightarrow SM. \tag{5}$$

- The most general renormalizable scalar potential invariant under the $\mathcal{Z}_2^S \otimes \mathcal{Z}_2^X$ symmetry is given by:

$$V = \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi \left(\Phi^\dagger \Phi\right)^2 + \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2. \tag{6}$$

- All coefficients in eq. (6) are real, thus the scalar potential contains nine free real couplings parameters:

$$\mu_\Phi, \lambda_\Phi, \mu_S, \lambda_S, \mu_X, \lambda_X, \lambda_{\Phi S}, \lambda_{\Phi X}, \lambda_{XS} \tag{7}$$

Two Real Singlet Model (TRSM)

Depending on the vevs acquired by the scalars different *phases* of the model can be realized. The fields can be decompose (in unitary gauge) as:

$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi_h + v}{\sqrt{2}} \end{pmatrix}, \quad S = \frac{\phi_S + v_S}{\sqrt{2}}, \quad X = \frac{\phi_X + v_X}{\sqrt{2}} \tag{8}$$

leading to the tadpole equations

$$-v\mu_\Phi^2 = v^3\lambda_\Phi + \frac{vv_S^2}{2}\lambda_{\Phi S} + \frac{vv_X^2}{2}\lambda_{\Phi X} \tag{9}$$

$$-v_S\mu_S^2 = v_S^3\lambda_S + \frac{v^2 v_S}{2}\lambda_{\Phi S} + \frac{v_S v_X^2}{2}\lambda_{SX} \tag{10}$$

$$-v_X\mu_X^2 = v_X^3\lambda_X + \frac{v^2 v_X}{2}\lambda_{\Phi X} + \frac{v_S^2 v_X}{2}\lambda_{SX}. \tag{11}$$

These have solutions for any values of v, v_S, v_X.

Two Real Singlet Model (TRSM)

- If $v_X = 0$ the field ϕ_X does not mix with $\phi_{h,S}$. $\Longrightarrow$ candidate particle for dark matter (DM). The phenomenology of the two visible scalar states is very similar to the real singlet extension.
- If both singlet vevs vanish, ϕ_h is the SM Higgs boson. $\Longrightarrow$ $\phi_{S,X}$ form separate dark sectors stabilized by their respective $\mathbb{Z}_2$ symmetries. $\Longrightarrow$ Collider phenomenology is (at tree-level) only impacted by possible invisible decays of h_{125} to the DM particles.
- Broken phase (vev$\neq 0$), leads to the most interesting collider phenomenology. The mass eigenstates $h_{1,2,3}$ are related to the fields $\phi_{h,S,X}$ through the 3×3 orthogonal mixing matrix R

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_h \\ \phi_S \\ \phi_X \end{pmatrix} . \tag{12}$$

We assume the mass eigenstates to be ordered by their masses

$$M_1 \leq M_2 \leq M_3 \tag{13}$$

and parametrize the mixing matrix R by three mixing angles, θ_{hS}, θ_{hX}, θ_{SX}. Using the short-hand notation

$$s_1 \equiv \sin\theta_{hS}, \quad s_2 \equiv \sin\theta_{hX}, \quad s_3 \equiv \sin\theta_{SX}, \quad c_1 \equiv \cos\theta_{hS}, \ldots \tag{14}$$

it is given by

$$R = \begin{pmatrix} c_1 c_2 & -s_1 c_2 & -s_2 \\ s_1 c_3 - c_1 s_2 s_3 & c_1 c_3 + s_1 s_2 s_3 & -c_2 s_3 \\ c_1 s_2 c_3 + s_1 s_3 & s_1 s_2 c_3 - c_1 s_3 & c_2 c_3 \end{pmatrix} . \tag{15}$$

Two Real Singlet Model (TRSM)

- Where the angles θ can be chosen to lie in

$$-\frac{\pi}{2} \leq \theta_{hS}, \theta_{hX}, \theta_{SX} < \frac{\pi}{2} \tag{16}$$

In the TRSM, the nine parameters of the scalar potential can be expressed in terms of the three physical Higgs masses, the three mixing angles, and the three vacuum expectation values (vevs). These relations are given by:

$$\lambda_\Phi = \frac{1}{2v^2}\sum_i m_i^2 R_{i1}^2, \qquad \lambda_S = \frac{1}{2v_S^2}\sum_i m_i^2 R_{i2}^2, \qquad \lambda_X = \frac{1}{2v_X^2}\sum_i m_i^2 R_{i3}^2,$$

$$\lambda_{\Phi S} = \frac{1}{vv_S}\sum_i m_i^2 R_{i1} R_{i2}, \quad \lambda_{\Phi X} = \frac{1}{vv_X}\sum_i m_i^2 R_{i1} R_{i3}, \quad \lambda_{SX} = \frac{1}{v_S v_X}\sum_i m_i^2 R_{i2} R_{i3}, \tag{17}$$

Two Real Singlet Model (TRSM)

$$M_1, M_2, M_3, \theta_{hS}, \theta_{SX}, \theta_{hX}, v_S, v_X, v_h$$

where M represents mass, θ is the mixing angle and v is the vacuum expectation value.

- Due to EWSB, $v_h = v_{\rm SM} = 246$ GeV, $M_i = 125$ GeV and are SM-like - and thus we end with seven free independent input parameters.

$$M_2, M_3, \theta_{hS}, \theta_{SX}, \theta_{hX}, v_S, v_X$$

- As we choose $v_S, v_X \neq 0$, thus $\mathcal{Z}_2$ symmetries are spontaneously broken, and the fields $\phi_{h,S,X}$ mix into three physical scalar states (h_i), *broken phase.*

$$pp \to h_i \to h_j h_k$$

  - Asymmetric if $i, j, k \in [1, 2, 3]$ and $i \neq j \neq k$
  - Symmetric: if $j = k$.

- Cascade Decays: if kinematics allows, one can also have a process such as $h_3 \to h_1 h_2$ with $h_2 \to h_1 h_1$.
- In all cases, one can have SM final states.

Benchmark Planes (BPs)

- Six benchmark scenarios are considered (as motivation) [T. Robens ea, Eur.Phys.J.C 80 (2020) 2, 151].

Benchmark Scenario	h_{SM} Candidate	Target Signatures	Possible successive decays
BP1	h_3	$h_3 \to h_2 h_1$	$h_2 \to h_1 h_1$ if $m_{h_2} > 2m_{h_1}$
BP2	h_2	$h_3 \to h_1 h_2$	–
BP3	h_1	$h_3 \to h_1 h_2$	$h_2 \to h_1 h_1$ if $m_{h_2} > 250$GeV
BP4	h_3	$h_2 \to h_1 h_1$	–
BP5	h_2	$h_3 \to h_1 h_1$	–
BP6	h_1	$h_3 \to h_2 h_2$	$h_2 \to h_1 h_1$ if $m_{h_2} > 250$Gev

- Our Strategy : Scan BSM Parameters (BP4), keeping only points passing various available constraints.
  - Unitarity constraint, Perturbativity, Vacuum Stability.
  - Oblique parameters: S, T, U

    ScannerS Code (M. Mühlleitner, M. O. P. Sampaio, R. Santos & J. Wittbrodt)
    [Eur.Phys.J.C 82 (2022) 3, 198]
  - Constraints of flavour physics observables.

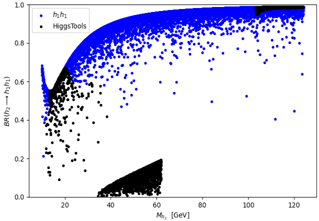
    Are not relevant as the singlets do not change the Yukawa sector.
  - Exclusion limits at 95% Confidence Level (CL) from Higgs searches at colliders (LEP, Tevatron and LHC). Higgs boson signal strength measurements.

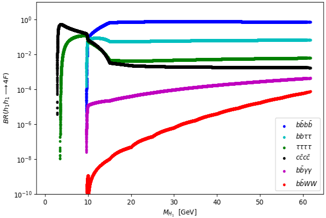
    HiggsBounds (P. Bechtle et al), and HiggsSignal (P. Bechtle et al): HiggsTools (H. Bahl et al)
    [Comput.Phys.Commun. 291 (2023) 108803]

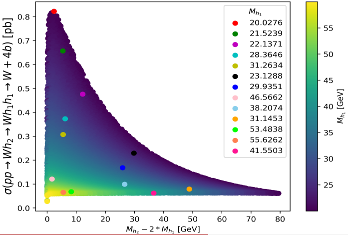
Parameters	M_{H_1}	M_{H_2}	M_{H_3}	θ_{hs}	θ_{hx}	θ_{sx}	v_ϕ	v_s	v_x
Ranges	[1, 62]	[1, 124]	125.09	-1.284	1.309	-1.509	v_{sm}	990	310

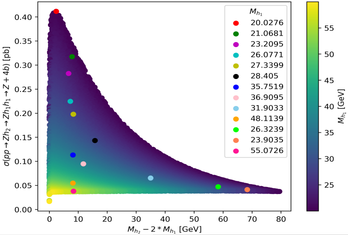
4f ANALYSIS (TRSM)

- TRSM can accommodate light scalars.
- $\Gamma(h_1)$ is dominated by $b\bar{b}$ and $\tau\tau$,so, $4b$, $2b2\tau$, and 4τ are promising signatures at TRSM.
- $\sigma^{Vh}(b\bar{b}b\bar{b} + W(Z))$ reaches 0.82(0.41) pb when BR($h \to bb$) reach its maximum.
- ATLAS(CMS) upper limit: 10.9%(8.9%) on the BR(h→BSM) at 95% CL.



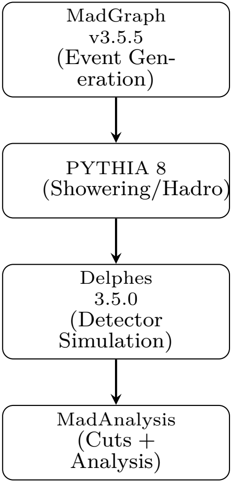




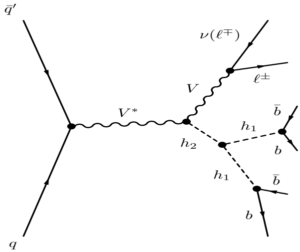


$bbbb + W(Z)$ ANALYSIS

MC toolbox

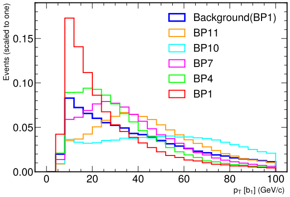


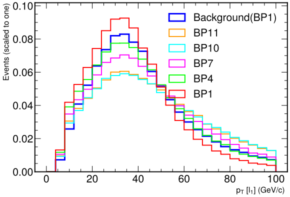
Targeted Signal



- ✓ Full SM background processes are considered : $pp \longrightarrow b\bar{b}b\bar{b}\ell\nu_l$, $b\bar{b}b\bar{b}\ell\ell$
- ✓ CMS standard parameter card within assumed low-pt.
  - ⋆ b-jets: pT > 5 GeV, within $|\eta| < 2.5$
  - ⋆ Leading lepton: pT > 5 GeV, within $|\eta| < 2.5$
  - ⋆ Leading jets: pT > 5 GeV, within $|\eta| < 2.5$
  - ⋆ $\Delta R_{ij} > 0.4$, to ensure resolved b-jets, jet and leptons, where $x, y = \ell, j, b$.

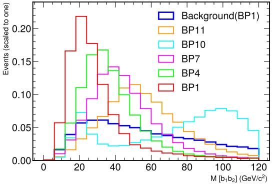
$bbbb\ell^+\nu_l$ Preliminary Analysis

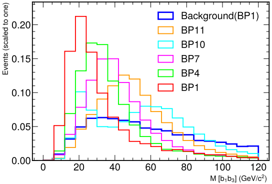


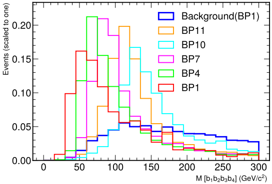


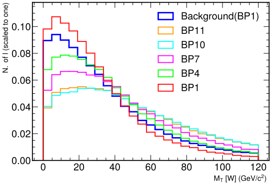
- Soft b-(anti quarks) with low pT
- Soft leptons with low pT
- we use the CMS defaults card for our full detector simulation, assumed low-pt. $\Longrightarrow$ Nevertheless, for a real experimental environment (CMS/ATLAS Run 3), the targeted final states $(bbbb\ell\nu_\ell)$ would be selected using any suitable cross-trigger:
- **single-lepton triggers**:
  - ✓ Threshold pT(μ/e): 24/27 GeV
  - ✓ Isolation(μ/e):0.15/0.10
  - ✓ Efficiency(μ/e): $90 - 95\%$
  - ✓ Fake rate(μ/e): $10^{-4}(10^{-5})$
- **lepton + jets cross-triggers** :
  - ✓ PT(ℓ) > 17 GeV + 1 jet PT > 30 GeV
  - ✓ Isolation:Tight lepton isolation still applied
  - ✓ Efficiency for real leptons 90%
  - ✓ Jet requirements: ≥ 3,

$bbbb\ell^+\nu_l$: Preliminary Analysis







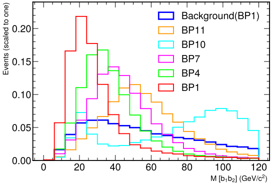


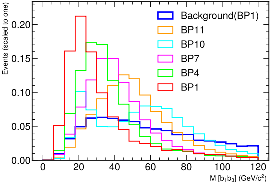
✓ Event selection requirements :

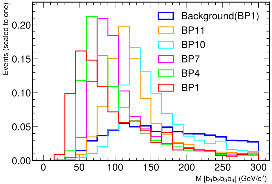
- ⋆ 1-lepton ($e^{\pm}\mu^{\mp}$) and 4 b-jets
- ⋆ $\not{E}_T > 15$ GeV, $PT(b) \geq 8$, $PT(l,j) \geq 10 GeV$
- ⋆ m_W-veto : $|m_W - M_T(\ell)| < 10$ GeV
- ⋆ $M_{b1b2} \leq M_{h_1}$ GeV and, $M_{b1..4} \leq M_{H_2}$ GeV

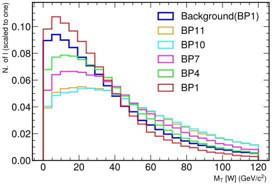
BPs	Sig
BP1	4.2σ
BP4	5.4σ
BP7	4.6σ
BP10	1.2σ
BP11	3.6σ

$bbbb\ell^-\bar{\nu}_l$: Preliminary Analysis









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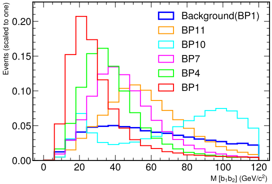
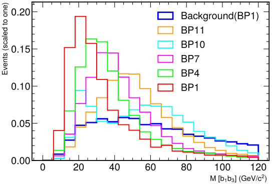
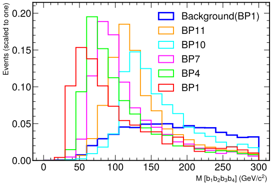
- ⋆ $\not{E}_T > 15$ GeV, $PT(b) \geq 8$, $PT(l, j) \geq 10 GeV$
- ⋆ m_W-veto : $|m_W - M_T(\ell)| < 10$ GeV
- ⋆ $M_{b1b2} \leq M_{h_1}$ GeV and, $M_{b1..4} \leq M_{H_2}$ GeV

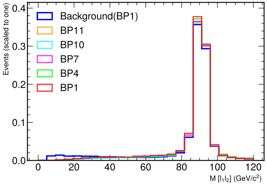
BPs	Sig
BP1	3.7σ
BP4	4.7σ
BP7	4.08σ
BP10	1.02σ
BP11	2.97σ

$bbbb\ell^+\ell^-$: Preliminary Analysis









✓ Event selection requirements :

- ⋆ 2-leptons ($e^{\pm}\mu^{\mp}$) and 4 b-jets
- ⋆ $\not{E}_T > 15$ GeV, $PT(b) \geq 8, PT(l,j) \geq 10GeV$
- ⋆ mZ-veto : $|m_Z - M_{\ell\ell}| < 10$ GeV
- ⋆ $M_{b1b2} \leq M_{h_1}$ GeV and, $M_{b1..4} \leq M_{h_2}$ GeV

Conclusions& Perspective

- In this work, we explored the TRSM framework's potential for optimizing searches for extremely light scalars.
- Focusing on the $hh \to b\bar{b}b\bar{b}$ decays pattern and the associated production of light scalars with a Z or $W^{\pm}$ boson.
- Analyzing the final state particles with basic selections cuts and reconstructing events using CMS standard card.

Perspectives

- Dedicated scan/ check for several benchmark points to determine discovery potential at Run 2/3 and HL-LHC.
- Realistic detector simulations using Delphes and appropriate trigger choices may lead to an improvement in the sensitivity of the analysis.
- Use K-factor (NLO) for Signals and Background.
- Explore the TRSM signature sensitivity using cut-basd analysis or MVA.

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Thank you for your attention.