Search for Light Scalars in the TRSM at the LHC

Mohamed OUCHEMHOU

Rudjer Boskovic Institute (RBI), Bijenicka cesta 54, 10000 Zagreb, Croatia.

Based on work with:

Aman Desai, Kristin Lohwasser, Tania Robens

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MOTIVATION

- BSM models (SM+doublet, Singlets, Triplets, etc.) motivate additional attributes of the new di-Higgs final states that can be accessed by the LHC experiments in a variety of signatures, including $(H \longrightarrow aa, hh)$.
- Upper bounds on light Higgs decay rates have been established via experiments.

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	✓
$H \to aa \to 2\mu 2\tau$	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	✓
$H \to aa \to 2\mu 2\tau$	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)

- Extensions of the SM by scalar singlets are among the simplest possible model beyond the SM (BSM).
- TRSM : adds two real singlet degrees of freedom to the SM, two real singlet fields S and X.

  [Robens ea, Eur.Phys.J.C 80 (2020) 2, 151; Robens, Symmetry 15 (2023) 27]
- In order to reduce the number of free parameters two discrete Z_2 symmetries are introduced:

$$\mathcal{Z}_2^S : S \longrightarrow -S,\; X \longrightarrow X,\; SM \longrightarrow SM, \tag{1}$$

$$\mathcal{Z}_2^X : X \longrightarrow -X,\; S \longrightarrow S,\; SM \longrightarrow SM. \tag{2}$$

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

$$V = \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2. \tag{3}$$

- All coefficients in eq. (3) are real, thus the scalar potential contains nine free parameters

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

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

Phenomenological Benchmarks and Test Points (BPs)

- Six benchmark scenarios are considered (as motivation) [A. Papaefstathiou ea, JHEP 05 (2021) 193].

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.

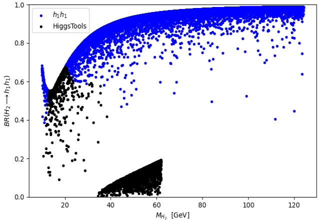
    HiggsBounds (P. Bechtle et al), and HiggsSignal (P. Bechtle et al): HiggsTools (H. Bahl et al)
    [Comput.Phys.Commun. 291 (2023) 108803]

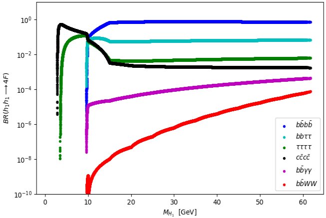
Parameters	M_{H_1}	M_{H_2}	M_{H_3}	θ_{hs}	θ_{hx}	θ_{sx}	v_ϕ	v_s	v_x
Ranges	[1, 62]	[1, 124]	125.09	−1.284	1.309	−1.509	v_{sm}	990	310

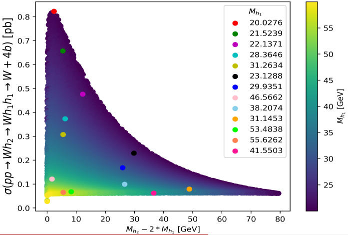
4f ANALYSIS (TRSM)

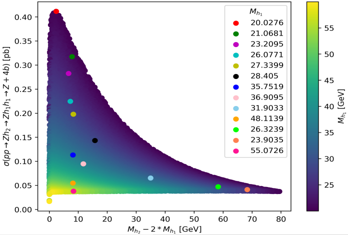
- TRSM can accommodate light scalars.
- $\Gamma(h_1)$ is dominated by $b\bar{b}$ and $\tau\tau$,so, $4b$, $2b2\tau$, and 4τ are promising signatures at TRSM.

- $\sigma^{Vh}(b\bar{b}b\bar{b}+W(Z))$ 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.



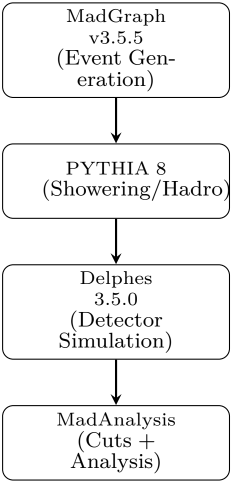




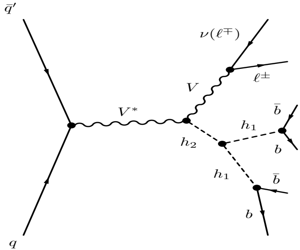


$bbbb + W(Z)$ ANALYSIS

MC toolbox

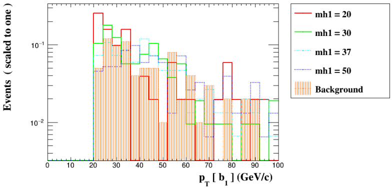


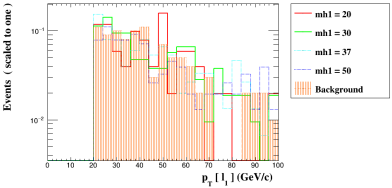
Targeted Signal



- ✓ Full SM background processes are considered : $pp \longrightarrow b\bar{b}b\bar{b}\ell\nu_l$, $b\bar{b}b\bar{b}\ell\ell$
- ✓ Basic Selection Cuts Applied to Generated Events.
  - ⋆ b-jets: pT > 20 GeV, within $|\eta| < 2.5$
  - ⋆ Leading lepton: pT > 20 GeV, within $|\eta| < 2.5$
  - ⋆ Leading jets: pT > 15 GeV, within $|\eta| < 2.5$
  - ⋆ $\Delta R_{ij} > 4$, to ensure resolved b-jets, jet and leptons, where $x, y = \ell, j, b$.

W^+h_2 : $bbbb\ell^+\nu_l$ ANALYSIS



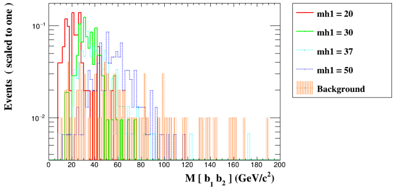


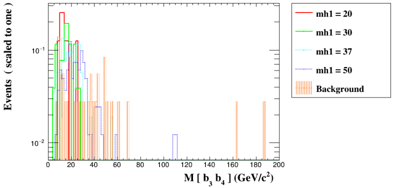
- Soft b-(anti quarks) with low pT
- Soft leptons with low pT
- In this study, we focus on the parton- and hadron-level simulation without full detector effects. $\Longrightarrow$ Nevertheless, in a real experimental environment (CMS/ATLAS Run 3), the targeted final states ($bbbb\ell\nu_\ell$) would be selected using:

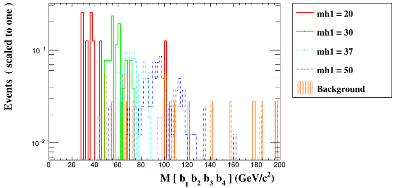
- **single-lepton triggers**:
  - ✓ Threshold pT(μ/e): 24/27 GeV
  - ✓ Isolation(μ/e):0.15/0.10
  - ✓ Efficiency(μ/e): 9095%
  - ✓ Fake rate(μ/e): Very low

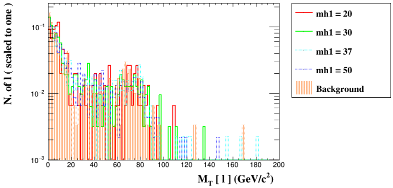
- **lepton + jets cross-triggers** :
  - ✓ PT(ℓ) > 17 GeV + 1 jet PT > 30 GeV
  - ✓ Isolation:Tight lepton isolation still applied
  - ✓ Efficiency for real leptons 90%
  - ✓ Jet requirements: $\geq$ 1 or 2

W^+h_2 : $bbbb\ell^+\nu_l$ ANALYSIS





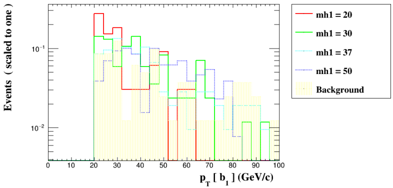


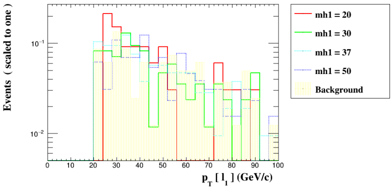


✓ Event selection requirements :

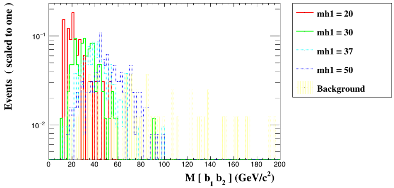
- ⋆ 1-leptons ($e^{\pm}\mu^{\mp}$) and 4 b-jets
- ⋆ m_W-veto : $|m_W - M_T(\ell)| < 10$ GeV
- ⋆ $M_{b1b2} \leq M_{h_1}$ GeV and, $M_{b1..4} \leq M_{H_2}$ GeV
- ⋆ $\not{E}_T, \not{H}_T > 20$ GeV, and $E_T(H_T) > 100(80)$ GeV

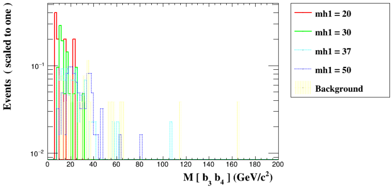
$W^- h_2$: $bbbb\ell^-\bar{\nu}_l$ ANALYSIS

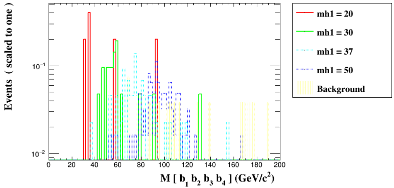


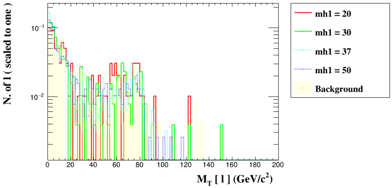


$W^{-}h_2: \; bbbb\ell^{-}\bar{\nu}_l$ ANALYSIS









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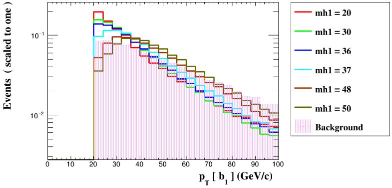
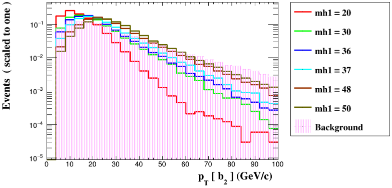
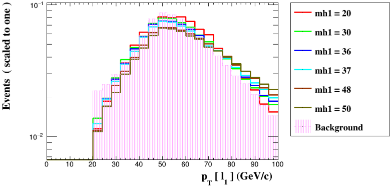
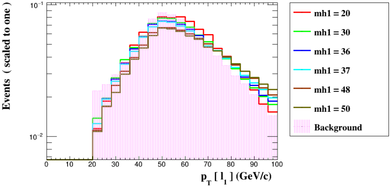
$Zh_2 :\ bbbb\ell^+\ell^-$ ANALYSIS

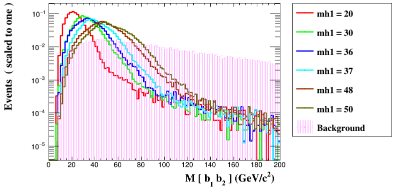


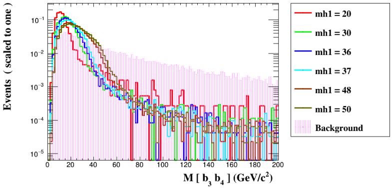


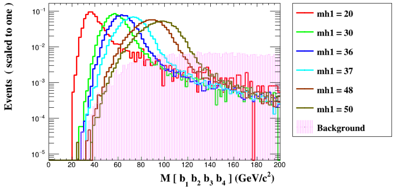


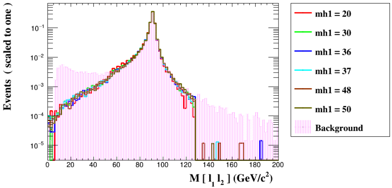


Zh_2 : $bbbb\ell^+\ell^-$ ANALYSIS









✓ Events selection requirements :

- ⋆ 2-leptons ($e^{\pm}\mu^{\mp}$) and 4 b-jets
- ⋆ 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
- ⋆ $\not{E}_T, \not{H}_T > 5(10)$ GeV, and $E_T(H_T) > 100(60)$ 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.

Perspectives

- Dedicated scan/ check for several benchmark points to determine discovery potential at Run 2/3
- Realistic detector simulations using Delphes and appropriate trigger choices may lead to an improvement in the sensitivity of the analysis.
- Investigating other options to extend phase space (low pT b-tagging).
- Explore the TRSM signature sensitivity using HL-LHC and Run 3.

References

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Thank you for your attention.