LHC signals of triplet scalars as dark matter portal: cut-based approach and improvement with gradient boosting and neural networks

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Motivation

• Consider some unknown particles constitute the dark matter (DM) content of our universe.
• How do they interact with the known particles in the SM?
• Is there any terrestrial signature of such interactions?
• The recently discovered 125-GeV scalar can be a portal to the dark sector.
• Problem: current XENON1T experiment data, strongly disfavor that possibility unless the Higgs-DM coupling is extremely small (≤10^{-3} for an SU(2) singlet scalar DM) which is incompatible with relic density bounds.
• Solutions: less constrained in an extended electroweak symmetry breaking (EWSB) sector.
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Overview of the Model

• We consider an extension of a Type-II Seesaw scenario containing a $Y=2$ scalar triplet $\Delta$ along with a singlet scalar dark matter candidate $\chi$.

• $\chi$ interacts with $\Delta$ and the SM-like higgs doublet $\Phi$ via terms in the scalar potential,

$$V(\Phi, \Delta, \chi) = a(\Phi^\dagger \Phi) + b^2 \text{Tr}(\Delta^\dagger \Delta) + \frac{1}{2}(M_\chi^2 + (\lambda_D v_D^2 + 2 \lambda_T \omega^2))\chi^2 + c(\Phi^\dagger \Phi)^2 + d^4 \text{Tr}(\Delta^\dagger \Delta) + e^{-h^2 \Phi^\dagger \Phi \text{Tr}(\Delta^\dagger \Delta)} + f^4 \text{Tr}(\Delta^\dagger \Delta^\dagger) \text{Tr}(\Delta \Delta) + \text{h} \Phi^\dagger \Delta^\dagger \Delta \Phi + (t \Phi^\dagger \Delta \tilde{\Phi} + \text{h.c.}) - \lambda_S \chi^4 - \lambda_D \chi^2 \Phi^\dagger \Phi - \lambda_T \chi^2 \text{Tr}(\Delta^\dagger \Delta).$$

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• $\chi$ does not have any VEV. An additional $Z_2$ symmetry prevents $\chi$ from mixing with $\Phi$ and $\Delta$ and only the CP-even scalars can act as portal for dark matter where CP is conserved.
\[ \mathcal{L}_{gauge} = (D_\mu \Phi)^\dagger(D^\mu \Phi) + \frac{1}{2} Tr((D_\mu \Delta)^\dagger(D^\mu \Delta)) \]  

(3)

The gauge interactions will turn out be useful to utilize the Drell-Yan production of triplet dominated states, driven by gauge couplings, where \( \lambda_D \ll \lambda_T \).

\[ L_{Yukawa} = L_{SM,Y} + \sqrt{2} f_{ab} L_a T C_i \sigma^2 \Delta L_b + h.c. \]  

(4)

The neutrino masses are mostly dependent on the triplet VEV \( \omega \) and can be expressed as

\[ M_\nu = 2 f_\omega \]  

(5)

One can get the masses of the neutrinos after the diagonalization of \( M_\nu \) with the help of the PMNS matrix.
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Constraints on relevant parameters of $\mathcal{L}_{\text{Type-II Seesaw}} + \mathcal{L}_\text{DM}$

- Vacuum stability: all quartic terms in scalar potential must be such that the scalar potential remains bounded from below in any direction implies.
  
  $$4c \geq 0, \quad d_4 - f \geq 0, \quad e - h \geq \sqrt{4c(d_4 - 2f)} \geq 0, \quad e - 3h \geq \sqrt{4c(d_4 - 2f)} \geq 0 \quad \text{and} \quad 2f \geq \sqrt{4c + |2h|\sqrt{4c(d_4 - 2f)}} \geq 0.$$  

- For perturbativity at the electroweak scale,
  
  $$|C_{ij}| < 4\pi.$$  

- Tree-level unitarity in the scattering of Higgs bosons and the longitudinal components of the EW gauge bosons demands that the eigenvalues of the scattering matrices have to be less than $8\pi$. 

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• **phenomenological constraints:**

the $\rho$ parameter, defined as $\rho \equiv m_W^2/(m_Z^2 \cos^2 \theta_W) \equiv 1 - \frac{2\omega^2}{v_D^2 + 4v_T^2}$, 
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• **The experimental bound** on $m_{H^{\pm\pm}}^2$ can be easily determined from 95% CL of $\sigma(pp \to H^{++}H^{--}) \times Br(H^{\pm\pm} \to \ell^\pm \ell^\pm)$, in cases where the same-sign dilepton decay is the dominant channel for the doubly charged scalar.
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• **Constrain from LHC:** Invisible branching ratio of the already observed scalar is not more than 19%.
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  • The thermal relic density of $\chi$ should not exceed the latest Planck data at the 2$\sigma$ level.
  • The $\chi$-nucleon cross section should be below the current upper bound from XENON1T.
Parameter spaces

- We perform a scan of the parameter space

\[ m_\chi \in [60, 500] \text{ GeV}, \quad m_{H^\pm} \in [100, 1000] \text{ GeV}, \quad m_{H^{\pm\pm}} \in [100, 1000] \text{ GeV}, \]
\[ |v_T| \equiv \omega \in [10^{-6}, 4.8] \text{ GeV}, \quad |\sin \alpha| \in [0.999, 1], \]
\[ \lambda_D \in [-12, 12], \quad \lambda_T \in [-12, 12] \]
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- Perturbativity conditions for parameter \( d \) and \( f \) are quite sensitive to the mass eigenvalues of the triplet-dominated states, including their splitting which prefer benchmarks are tilted towards regions corresponding to

\[
m_A \approx \sqrt{\left( \frac{2m_{H^\pm}^2}{v_D^2 + 2\omega^2} - \frac{m_{H^{\pm\pm}}^2}{v_D^2} \right) (v_D^2 + 4\omega^2)} \quad (7)
\]

with \( m_H \approx m_A \) and \( \Delta m = m_{H^\pm} - m_{H^{\pm\pm}} \).
• the allowed region in the $m_{\chi} - \sigma(\chi - N)$ space obtained from the current XENON1T data as well as relic density bound,
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![Graph showing allowed region in $m_\chi - \sigma(\chi-N)$ space](image)

• We use the global fit of neutrino data performed by the NuFITGroup where all neutrino masses are nearly degenerate with the lightest neutrino mass $m_1 \approx 0.1$ eV.
Signals and benchmarks selection

- Having identified the parameter space we proceed to look for experimental probes for the scenario where $H$ can serves as DM portal.

  - For same-sign dilepton final state, we consider DY production of $H^{\pm\pm}H^{\mp}$, followed by the $H^{\pm}$ decaying into $HW^{\pm}$ channel where $H$ can decay invisibly. The $H^{\pm\pm}$ can decay into a same-sign dilepton pair ($\ell^+\ell^+$).

  - To avoid the important decay mode $H^{\pm\pm} \rightarrow H^{\pm}W^{\pm}$, we restrict $|\Delta m| = |m_{H^{\pm}} - m_{H^{\pm\pm}}|$ is within 80 GeV.

  - When the mass gap between $H^{\pm}$ and $H$ exceeds $m_W$, $H^{\pm}$ goes to $HW^{\pm}$ with 50% branching as long as $\omega$ is very small.
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• Distribution of $H^{±±}$ and $H$ decay branchings.

![Graph showing distribution of decay branchings](image_url)

- Some intermediate $\omega \in [10^{-5}, 10^{-4}]$ will help to get moderately good branchings in both these channels at the same time.
• The lower limit on $m_{H^{\pm\pm}}$, from searches in the $\ell^\pm \ell^\pm$ final state depend on the $\text{Br}(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$ as,

![Graph showing the relationship between $m_{H^{++}}$ in GeV and $\text{Br}(H^{++} \rightarrow l^+ l^+)$]
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\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\end{figure}

• The lower limit on $m_{H^{\pm\pm}}$ ranges from $m_{H^{\pm\pm}} > 550$ GeV for $\text{Br}(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \simeq 17\%$ to $m_{H^{\pm\pm}} > 770$ GeV for $\text{Br}(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \simeq 100\%$. 

• $H$ can go to a pair of neutrinos or antineutrinos when the lepton flavor violating yukawa coupling is large enough which will also contribute to invisible decay $H$.

| Parameter | BP 1     | BP 2     | BP 3     |
|-----------|----------|----------|----------|
| $m_H$ in GeV | 423.1   | 615.1   | 615.1   |
| $m_A$ in GeV | 423.1   | 615.1   | 615.1   |
| $m_{H^\pm}$ in GeV | 509.3   | 697.0   | 697.0   |
| $m_{H^{\pm\pm}}$ in GeV | 582.8   | 770.0   | 770.0   |
| $m_\chi$ in GeV | 59.3    | 56.4    | 56.4    |
| $\lambda_S$ | 0.49    | 0.0297  | 0.0297  |
| $\lambda_D$ | 0.00069 | 0.002125 | 0.002125 |
| $\lambda_T$ | 11.258  | 10.51   | 10.51   |
| $\omega$ in GeV | $1.348 \times 10^{-4}$ | $4.074 \times 10^{-5}$ | $7.274 \times 10^{-5}$ |
| $\sigma(pp \rightarrow H^{\pm\pm} H^\mp)$ in fb | 1.19 | 0.43 | 0.43 |
| $Br(H \rightarrow invisible)$ | 0.92 | 0.935 | 0.79 |
| $Br(H^{\pm\pm} \rightarrow \ell^\pm \ell^\mp)$ | 0.228 | 0.95 | 0.65 |
| $Br_{total}$ | 0.1049 | 0.44365 | 0.25675 |
Cut based Analysis

Signal: A pair of same-sign leptons (e/µ) + 2 jets + \( \slash\!\! E_T \).

Backgrounds:
1. \( t\bar{t} \) semileptonic decay which leads to non-prompt leptons in the final state.
2. \( W + \) jets which contributes by producing non-prompt leptons.
3. \( t\bar{t}W^{\pm} \) with semileptonic decay of \( t\bar{t} \).
4. \( W^{\pm}Z \) with leptonic decay of \( W^{\pm} \) and \( Z \).
5. Charge misidentification of leptons.
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   2) \(W\) + jets which contributes by producing non-prompt leptons.
   3) \(t\bar{t}W^\pm\) with semileptonic decay of \(t\bar{t}\).
   4) \(W^\pm Z\) with leptonic decay of \(W^\pm\) and \(Z\).
   5) Charge misidentification of leptons.
Figure: Distribution of some observable signal and background processes.
Figure: Distribution of cluster transverse mass(left) and transverse mass(right) for the three signal BPs and backgrounds.

with,

$$M_{\text{cluster}} = \sqrt{m^2_{2j} + \left( \sum \vec{p}_T^j \right)^2} + \sqrt{m^2_{\ell\ell} + \left( \sum \vec{p}_T^\ell \right)^2} + E_T$$  \hspace{1cm} (8)

$$M_T = \sqrt{(\sqrt{m^2_{\ell\ell} + \left( \sum \vec{p}_T^\ell \right)^2} + E_T)^2 - \left( \sum \vec{p}_T^\ell + E_T \right)^2}. \hspace{1cm} (9)$$
Cut based Analysis

**Results:**

1) **Cut 1:** The invariant mass of the same-sign dileptons $m_{ll} > 400$ GeV with $E_T > 350$ GeV.

2) **Cut 2:** Cluster transverse mass $M_{cluster} > 700$ GeV, Transverse mass $M_T > 550$ GeV with $H_T > 700$ GeV.

3) **Cut 3:** $p_T$ of the leading lepton $> 250$ GeV and $p_T$ of the sub-leading lepton $> 200$ GeV.
Motivation Overview of the Model Constraints on relevant parameters of $\mathcal{L}_{\text{TYPE-II Seesaw}} + \mathcal{L}_{\text{DM}}$ Parameter spaces Signals and benchmarks

Cut based Analysis

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• we calculated the projected significance ($S$) in the same sign dilepton channel for each benchmark point, for **14 TeV LHC with 3000 fb$^{-1}$**. The significance $S$ is defined as follows:

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| BP   | $S$   |
|------|-------|
| BP 1 | 3.4 $\sigma$ |
| BP 2 | 8.3 $\sigma$ |
| BP 3 | 5.0 $\sigma$ |
Multivariate analysis and Neural Network techniques

- we further explore the possibility of improvement in the analysis with some recently developed techniques like Gradient Boosted Decision Trees and Artificial Neural Network (ANN).
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Multivariate analysis and Neural Network techniques

- we further explore the possibility of improvement in the analysis with some recently developed techniques like Gradient Boosted Decision Trees and Artificial Neural Network (ANN).
- We have used 12 input variables for training and validation of our data sample.
- 80% of the total dataset are used for training purpose and 20% for validation.
**ROC curves**

**Figure**: ROC curves of BP 1 (top left), BP 2 (top right) and BP 3 (bottom centre) with ANN and XGBoost.
Multivariate analysis and Neural Network techniques

## Significance

| BP   | $S$ (Cut - based) | $S$ (ANN) | $S$ (XGBoost) |
|------|-------------------|-----------|---------------|
| BP 1 | 3.4$\sigma$       | 5.9 $\sigma$ | 7.8 $\sigma$ |
| BP 2 | 8.3$\sigma$       | 9.3 $\sigma$ | 11.6 $\sigma$ |
| BP 3 | 5.0$\sigma$       | 6.4 $\sigma$ | 7.9 $\sigma$ |

**Table:** Signal significance for the benchmark points at 14 TeV with $\mathcal{L} = 3000$ $fb^{-1}$ with ANN and XGBoost.
Conclusion

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Conclusion

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- We find various considerable parameter spaces allowed by all constrains and investigate whether this can be probed in high luminosity LHC.
- We concentrate on same sign dilepton + 2 jets + missing energy searches.
- Firstly by cut based analysis we identify efficient observables and put optimum cuts to this to calculate projected signal significance that can be achieved at the future high-luminosity LHC.
- Next we further improve the significance through machine learning techniques.
Thank You
Masses in terms of parameters,

\[
m_h^2 \approx 2c v_D^2 + \frac{(e-h-2q)^2}{2c-q} \omega^2, \tag{11}
\]

\[
m_H^2 \approx q v_D^2 - \left[\frac{(e-h-2q)^2}{2c-q} - 2d\right] \omega^2, \tag{12}
\]

\[
m_A^2 = q(v_D^2 + 4\omega^2), \tag{13}
\]

\[
m_{H^{\pm\pm}}^2 = (h+q)v_D^2 + 2f\omega^2, \tag{14}
\]

\[
m_{H^\pm}^2 = (q + \frac{h}{2})(v_D^2 + 2\omega^2) \tag{15}
\]
Mixing angles in terms of parameters,

\[ \tan \alpha = \frac{\sqrt{(q - 2c)^2 v_D^2 + (2dq - 4cd + (h - e + 2q)^2)}w^2}{(h - e + 2q)\omega}, \quad (16) \]

\[ \tan \beta = \frac{2\omega}{v_D}, \quad (17) \]

\[ \tan \beta' = \frac{\sqrt{2}\omega}{v_D} \quad (18) \]

and the neutrino mass matrix,

\[ M_\nu = \begin{pmatrix} 98.6e^{i0.0244} & 14.4e^{-i1.64} & 12.3e^{-i1.65} \\ 14.4e^{-i1.64} & 106e^{-i0.0120} & 4.93e^{-i0.22} \\ 12.3e^{-i1.65} & 4.93e^{-i0.22} & 104e^{-i0.0085} \end{pmatrix} \quad (19) \]
Motivation Overview of the Model Constraints on relevant parameters of $L_{\text{TYPE-II SEESAW}} + L_{\text{DM}}$ Parameter spaces Signals and ...
Motivation
Overview of the Model
Constraints on relevant parameters of $L_{\text{TYPE-II SEESAW}} + L_{DM}$
Parameter spaces
Signals and benchmarks selection
Collider Analysis
Conclusion

Back-up slides: 4

|         | BP 1 | BP 2 | BP 3 | $t\bar{t}$ | $W + \text{jets}$ | $t\bar{t}W$ | WZ |
|---------|------|------|------|------------|--------------------|-------------|----|
| $\sigma(fb)$ | 0.19 | 0.12 | 0.11 | $3.09 \times 10^5$ | $2.8 \times 10^7$ | 9.77 | 355.10 |
| Cut 1   | 99.3%| 99.6%| 99.6%| 0.2%       | 0.15%            | 2.1%        | 1.8%|
| Cut 2   | 99.2%| 99.6%| 99.6%| 0.1%       | 0.08%            | 1.7%        | 1.3%|
| Cut 3   | 96.8%| 99.2%| 99.1%| 0.06%      | 0.03%            | 0.9%        | 0.4%|
| Cut 4   | 96.8%| 99.2%| 99.1%| 0.05%      | 0.026%           | 0.8%        | 0.3%|
| Cut 5   | 73.5%| 87.4%| 87.6%| 0.01%      | 0.003%           | 0.07%       | 0.04%|
| Cut 6   | 40.2%| 62.5%| 62.4%| 0.002%     | 0.0009%          | 0.01%       | 0.005%|

Table: Signal and background efficiencies after applying various cuts at 14 TeV. The cross-sections are calculated at NLO.
### Variable | Definition
--- | ---
$P_{l_1}^T$ | Transverse momentum of the leading lepton
$P_{l_2}^T$ | Transverse momentum of the sub-leading lepton
$E_T^{miss}$ | Missing transverse energy
$N_j$ | No of jets in the event
$m_{ll}$ | Invariant mass of the same-sign dilepton pair
$P_j^T$ | Transverse momentum of the leading jet
$P_{j_1}^T$ | Transverse momentum of the sub-leading jet
$m_{jj}$ | Invariant mass of the jets
$m_{cluster}$ | The cluster transverse mass
$m_{transverse}$ | Transverse mass
$H_T$ | Scalar sum of $p_T$ of all the final state particles
$\Delta R_{ll}$ | $\Delta R$ between two leptons