Search for DM particles produced in association with a dark Higgs boson decaying to two W bosons

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Dark Higgs model

- Simplified model for DM production at the LHC, extends spin-1 mediator models of LHC DM WG
  - Majorana DM ($X$) interacts with two different mediators:
    - massive vector boson $Z'$ and a dark Higgs $s$

Interactions:

SM Quarks $\mathcal{L}_X = -g q Z'^\mu \bar{q} \gamma_\mu q$

Dark Sector $\mathcal{L}_X = -\frac{1}{2} g_X Z'^{\mu \nu} \bar{X} \gamma^5 \gamma_\mu \gamma_\nu X - g_X \frac{m_X}{m_{Z'}} s \bar{X} X + 2 g_X Z'^{\mu} Z'^{\nu} (g_X s^2 + m_{Z'} s)$
Model parameters

- Model generation $s \rightarrow WW \rightarrow 2l2\nu / lvqq'$ with Madgraph LO:
  - ZpHiggs_UFO
- Parameters and their recommended value from LHC DM WG: [https://arxiv.org/abs/1507.00966](https://arxiv.org/abs/1507.00966)
  - Small mixing between dark-Higgs ($s$) and SM Higgs: $\theta = 0.01$
  - Dark-sector coupling $g_\chi = 1$
  - Quark-$Z'$ coupling $g_q = 0.25$
- Analysis mass scan (GeV):
  - $m_\chi = [100, 150, 200, 300]$
  - $m_s = [160, 180, 200, 300, 400]$
  - $m_{Z'} = [200 - 2500]$
- $Z'$ and $s$ bosons widths, relative to their masses, are below 1%.
**Analysis selection:** $s \to WW \to 2l2\nu$

### $2l2\nu$ Selections
- nLeptons $\geq 2$
- Different flavour
- Opposite sign
- $p_T^{l1} / p_T^{l2} > 25 / 20$ GeV
- MET $> 20$ GeV
- $\min(\text{proj.MET, proj.MET}^{Tk}) > 20$ GeV
- Veto 3rd loose leptons if $p_T^{l3} > 10$ GeV
- b-veto DeepCSV LooseWP
  - $p_T^{ll} > 30$ GeV
  - $m^{ll} > 12$ GeV
  - $\Delta R(l, l) < 2.5$
  - $m_T(ll + \text{MET}) > 50$ GeV

- 2l + MET final state selection
- Reduce top-quark background
- Reduce non-prompt background
- Target dark Higgs topology

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Analysis selection: $s \rightarrow WW \rightarrow 2lqq'$

**lvjj Selections**

- nLeptons $\geq 1$
- nJet Clean $\geq 2$
  - ($p_T > 30$ GeV)
- $p_T^{l1} >$ trigger threshold
- Veto 2nd loose leptons if $p_T^{l2} > 10$ GeV
- $65 < m_{jj} < 105$ GeV
- b-veto DeepCSV LooseWP (excluding W candidate jets)
- $\Delta \phi(jj, \text{MET}) > 2$
- $\Delta \phi(jj,l) < 1.8$, $\Delta R(jj,l) < 3$
- $m_T(l + \text{MET}) > 80$ GeV
- MET $> 60$ GeV
- $p_T^{ljj} > 60$ GeV

1 + 2 jets final state selection

Reduce W+jets background

Reduce top-quark background

Target dark Higgs topology
## Background estimation overview

<table>
<thead>
<tr>
<th>Process</th>
<th>Analysis</th>
<th>Estimation</th>
<th>CR/Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>2l2v</td>
<td><strong>MC + normalization</strong> freely floating,</td>
<td>Invert b-veto</td>
</tr>
<tr>
<td></td>
<td>lvjj</td>
<td>constrained by CR</td>
<td></td>
</tr>
<tr>
<td>W+jets</td>
<td>lvjj</td>
<td><strong>MC + normalization</strong> freely floating,</td>
<td>**m_{jj} &lt; 65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>constrained by CR</td>
<td></td>
</tr>
<tr>
<td>Non-prompt</td>
<td>2l2v</td>
<td><strong>Fully data-driven estimation</strong></td>
<td>Same lepton charge</td>
</tr>
<tr>
<td></td>
<td>lvjj</td>
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<td></td>
</tr>
<tr>
<td>WW</td>
<td>2l2v</td>
<td><strong>MC + normalization</strong> freely floating,</td>
<td><strong>ΔR(l,l) &gt; 2.5</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>constrained by CR</td>
<td></td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>2l2v</td>
<td><strong>MC + normalization</strong> freely floating,</td>
<td><strong>m_{T}(l+MET) &lt; 50 GeV</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>constrained by CR</td>
<td></td>
</tr>
</tbody>
</table>

* Keeping other pre-selection requirements

Other small processes estimated directly from simulation: \( HWW, V\gamma, V\gamma^*, VZ, VVV \)
Analysis strategy

### Dilepton channel $s \rightarrow WW \rightarrow 2l2\nu$

- 3D fit in $\Delta R_{ll} - m_{ll} - m_T(l_2, \text{MET})$
  - 3 SR in $\Delta R_{ll}$ (strong dependence with dark Higgs mass)

<table>
<thead>
<tr>
<th>$\Delta R_{ll}$</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 1$</td>
<td></td>
</tr>
<tr>
<td>$1 &lt; \Delta R_{ll} &lt; 1.5$</td>
<td></td>
</tr>
<tr>
<td>$1.5 &lt; \Delta R_{ll} &lt; 2.5$</td>
<td></td>
</tr>
</tbody>
</table>

- For $m_{ll}$ and $m_T(l_2, \text{MET})$ the binning is optimized for $\frac{S}{\sqrt{S+B}}$ shape.

- Allow the different signal mass points to populate the 3D parameter space while using the same background modelling procedure.

$$m_T^{\min, p_T^{\text{miss}}} = \sqrt{2p_T^{\min} p_T^{\text{miss}} \left[1 - \cos \Delta \phi(p_T^{\min}, p_T^{\text{miss}})\right]}.$$}

### Semileptonic channel $s \rightarrow WW \rightarrow 2lqq'$

- Using BDT Discriminator

- 13 optimized kinematic inputs:
  - mostly sensitive to MET vs visible particles boost.

- 1 training for entire mass range with $m_Z \geq 800 \text{ GeV}$ samples (boosted samples with small x-sec sensitivity)

- Binning is optimized for $\frac{S}{\sqrt{S+B}}$ shape.
Results: $s \rightarrow WW \rightarrow 2l2\nu$

- Profile likelihood fit for 3 SR, 1 top quark background CR, 1 DY background CR, and 1 WW background CR
  - Signal regions entering in the fit: 2D histograms of $m_{ll} - m_T(l_2, \text{MET})$ for each SR.
  - Control regions information entering in the fit: 1-bin distributions. Top, WW, and DY normalization freely float within the global fit.

No significant excess over the SM prediction
Results: $s \rightarrow WW \rightarrow 2lqq'$

- Profile likelihood fit for 1 SR, 1 Top quark background CR and 1 W+jets background CR:
  - Signal region information entering in the fit: 1D histograms of BDT output score.
  - Control regions information entering in the fit: 1-bin distributions. Top and W+Jets normalization freely float within the global fit

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Finer binning in 2017-2018 to squeeze the sensitivity
Results

\( m_\chi = 100 \text{ GeV} \)

- Observed > Expected (but still below 2 sigma) due to slight data deficit in some of the sensitive bins.

- Most stringent limits for \( m_\chi = 150 \text{ GeV} \):
  - \( m_Z \sim 2 \text{ TeV} \) for \( m_s = 160 - 200 \text{ GeV} \)
  - \( m_s \sim 300 \text{ GeV} \) for \( m_Z \sim = 250 - 1600 \text{ GeV} \)

- \( s \to \chi\chi \) bound reached for \( m_s \geq 2m_\chi \)

- Gray lines indicate where the model parameters produce exactly the current observed relic density.

\( m_\chi = 200 \text{ GeV} \)

\( m_\chi = 300 \text{ GeV} \)
Results

- The couplings combination adopted so far are excluded by di-jet resonances for a wide range of $Z'$ masses, but similar sensitivity as the mono-jet results.

- Would be good to produce limits on $m_\chi - m_{Z'}$, mass plane and explore the lower coupling parameter region where we ‘could’ be complementary to di-jet results.
Results

- Comparison with ATLAS results.
- CMS $s \rightarrow b\bar{b}$ on going for $m_s < 160\text{ GeV}$
Backup
Relic density

• Relic density calculations are performed with the current dark Higgs model assumptions using MadDM

• Gray lines in the limit figures indicate where the model parameters produce exactly the current measurement of the observed relic density.