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

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On behalf of CMS Collaboration

Roadmap of Dark Matter models for Run 3
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An approach to probe DM at the LHC is based on a two-mediator DM (2MDM) scenario:

- Two new bosons: $Z'$ (spin 1) and dark-Higgs ($s$) (spin 0)
- Dark-Higgs mixes minimally with the SM Higgs: constraint from measurements of the Higgs signal strengths.
- Dark Higgs is the lightest state in the dark sector: $m_s \lesssim 2m_\chi$
Dark Higgs Model

• The interactions between the dark-Higgs s and SM arise from mixing between the two Higgs bosons.
• Six independent parameters:

<table>
<thead>
<tr>
<th>Particle masses</th>
<th>Coupling constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM mass</td>
<td>$m_\chi$</td>
</tr>
<tr>
<td>$Z'$ mass</td>
<td>$m_{Z'}$</td>
</tr>
<tr>
<td>Dark-Higgs mass</td>
<td>$m_s$</td>
</tr>
<tr>
<td>Dark-sector coupling</td>
<td>$g_\chi$</td>
</tr>
<tr>
<td>Quark-$Z'$ coupling</td>
<td>$g_q$</td>
</tr>
<tr>
<td>Higgs mixing angle</td>
<td>$\theta$</td>
</tr>
</tbody>
</table>

• Parameters and their recommended values from LHC DM WG: 
  1507.00966
  • Small mixing between dark-Higgs (s) and SM Higgs: $\theta = 0.01$
  • Dark-sector coupling $g_\chi = 1$
  • Quark-$Z'$ coupling $g_q = 0.25$
Dark Higgs: $MET + s(WW)$

- Search directly for the dark Higgs production.
- Dominant Dark Higgs decay modes:
  - $b\bar{b}$ for $m_s < 160$ GeV
  - $WW$ for $m_s > 160$ GeV
- First attempt at CMS using $WW$ final state targeting:
  - $MET + s(WW), WW \rightarrow 2l 2\nu$
  - $MET + s(WW), WW \rightarrow l\nu q\bar{q}$
Analysis selection: \( s \rightarrow WW \rightarrow 2l2\nu \)

### 2\(l\)2\(\nu\) Selections

- \( n\text{Leptons} \geq 2 \)
- Different flavour
- Opposite sign
- \( p_T^{l_1} / p_T^{l_2} > 25 / 20 \text{ GeV} \)
- \( \text{MET} > 20 \text{ GeV} \)
- \( \min(\text{proj.MET, proj.MET}^{Tk}) > 20 \text{ GeV} \)
- Veto 3rd loose leptons if \( p_T^{l_3} > 10 \text{ GeV} \)
- b-veto DeepCSV LooseWP
- \( p_T^{ll} > 30 \text{ GeV} \)
- \( m^{ll} > 12 \text{ GeV} \)
- \( \Delta R(l, l) < 2.5 \)
- \( m_T(ll + \text{MET}) > 50 \text{ GeV} \)

- 2lep + MET final state selection
- Reduce top-quark background
- Reduce non-prompt background
- Target dark-Higgs topology
### Analysis selection: $s \rightarrow WW \rightarrow 2lqq'$

<table>
<thead>
<tr>
<th>$l\nu jj$ Selections</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$Leptons $\geq 1$</td>
</tr>
<tr>
<td>$n$Jet Clean $\geq 2$</td>
</tr>
<tr>
<td>$(p_T &gt; 30 \text{ GeV})$</td>
</tr>
<tr>
<td>$p_T^{l_1} &gt;$ trigger threshold</td>
</tr>
<tr>
<td>Veto 2nd loose leptons if $p_T^{l_2} &gt; 10 \text{ GeV}$</td>
</tr>
<tr>
<td>$65 &lt; m_{jj} &lt; 105 \text{ GeV}$</td>
</tr>
<tr>
<td>$b$-veto DeepCSV LooseWP (excluding $W$ candidate jets)</td>
</tr>
<tr>
<td>$\Delta \phi(ljj, \text{MET}) &gt; 2$</td>
</tr>
<tr>
<td>$\Delta \phi(jj, l) &lt; 1.8$, $\Delta R(jj, l) &lt; 3$</td>
</tr>
<tr>
<td>$m_T(l + \text{MET}) &gt; 80 \text{ GeV}$</td>
</tr>
<tr>
<td>(\text{MET} &gt; 60 \text{ GeV})</td>
</tr>
<tr>
<td>$p_T^{ljj} &gt; 60 \text{ GeV}$</td>
</tr>
</tbody>
</table>

- 1lep + 2 jets final state selection.
- Reduce $W$+jets background
- Reduce top-quark background
- Target dark-Higgs topology

Alicia Calderon (IFCA) - Run3 DM Roadmap
## 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>2l2ν</td>
<td>MC + normalization freely floating, constrained by CR</td>
<td>Invert b-veto</td>
</tr>
<tr>
<td>W+jets</td>
<td>lvjj</td>
<td>MC + normalization freely floating, constrained by CR</td>
<td>$m_{jj} &lt; 65 \</td>
</tr>
<tr>
<td>Non-prompt</td>
<td>2l2ν</td>
<td>[Fully data-driven estimation]</td>
<td>Same lepton charge</td>
</tr>
<tr>
<td></td>
<td>lvjj</td>
<td></td>
<td>$m_{T}(l + \text{MET}) &lt; 30$</td>
</tr>
<tr>
<td>WW</td>
<td>2l2ν</td>
<td>MC + normalization freely floating, constrained by CR</td>
<td>$\Delta R(l,l) &gt; 2.5$</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>2l2ν</td>
<td>MC + normalization freely floating, constrained by CR</td>
<td>$m_{T}(ll + \text{MET}) &lt; 50 \text{ GeV}$</td>
</tr>
</tbody>
</table>

Other small processes estimated directly from simulation:

$HWW, V\gamma, V\gamma^*, VZ, VVV$

* Keeping other pre-selection requirements
Background estimation overview

\( s \rightarrow WW \rightarrow 2l2\nu \)

**Top CR**

**WW CR**

**Drell-Yan CR**

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Background estimation overview

\[ s \rightarrow WW \rightarrow 2lqq' \]

Top CR

W+Jets CR

138 fb\(^{-1}\) (13 TeV)
Analysis strategy $s \rightarrow WW \rightarrow 2l2\nu$

- **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)

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

- 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.
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
Analysis strategy $s \rightarrow WW \rightarrow 2lqq'$

- Using a **BDT Discriminator**

- 11 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.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{W}$</td>
<td>$p_T$ of the vectorial sum of the W candidate jets</td>
</tr>
<tr>
<td>$p_T^{j}$</td>
<td>$p_T$ of the vectorial sum of the visible particles</td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$</td>
<td>Magnitude of the missing transverse momentum vector</td>
</tr>
<tr>
<td>$\Delta \eta_{\ell,ij}$ and $\Delta \phi_{\ell,ij}$</td>
<td>$\Delta \eta$ and $\Delta \phi$ between the lepton and the dijet system</td>
</tr>
<tr>
<td>$\Delta \eta_{ij}$ and $\Delta \phi_{ij}$</td>
<td>$\Delta \eta$ and $\Delta \phi$ between the W candidate jets</td>
</tr>
<tr>
<td>$</td>
<td>\eta_{\ell}</td>
</tr>
<tr>
<td>$\Delta \phi_{\ell,\vec{p}_T^{\text{miss}}}$</td>
<td>$\Delta \phi$ between the lepton and $\vec{p}_T^{\text{miss}}$</td>
</tr>
<tr>
<td>$\Delta \phi_{jj,\vec{p}_T^{\text{miss}}}$</td>
<td>$\Delta \phi$ between the vectorial sum of the visible particles and $\vec{p}_T^{\text{miss}}$</td>
</tr>
<tr>
<td>$\min(p_T^{\ell}, p_T^{j}) / p_T^{\text{miss}}$</td>
<td>Minimum of the lepton $p_T$ and the next-to-leading W candidate jet $p_T$, divided by $p_T^{\text{miss}}$</td>
</tr>
<tr>
<td>$\max(p_T^{\ell}, p_T^{j}) / p_T^{\text{miss}}$</td>
<td>Maximum of the lepton $p_T$ and the leading W candidate jet $p_T$, divided by $p_T^{\text{miss}}$</td>
</tr>
<tr>
<td>$\max(p_T^{\ell}, p_T^{j}) / m_{jj,\vec{p}_T^{\text{miss}}}$</td>
<td>Maximum of the lepton $p_T$ and the leading W candidate jet $p_T$, divided by the invariant mass of the system of all visible particles and $\vec{p}_T^{\text{miss}}$, which is taken to be massless</td>
</tr>
</tbody>
</table>
**Results:** $s \to WW \to 2l2\nu$

- 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.

Finer binning in 2017-2018 to squeeze the sensitivity
**Dark Higgs:**

**MET + s(WW)**

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

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

- Gray lines indicate where the model parameters produce exactly the current observed relic density, using MadDM (Europhys. J. C 83 (2023) 241).
Dark Higgs: $MET + s(WW)$

- Most stringent limits for $m_\chi = 150 \text{ GeV}$:
  - For $m_s = 160 - 200 \text{ GeV}$
    $< m_{Z^'} \sim 2.2 \text{ TeV}$
  - For $m_{Z^'} = 250 - 1600 \text{ GeV}$
    $160 < m_s < \sim 300 \text{ GeV}$
Final remarks

• The coupling $g_q$ 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 explore the lower coupling parameter region where we ‘could’ be complementary to di-jet results.

Exclusion limits of the dijet and monophoton CMS+ATLAS combined, corresponding to 36 fb−1 of LHC 13 TeV data.

Exclusion limits of the dijet and dileptons CMS+ATLAS combined, corresponding 8TeV and initial 13TeV of LHC data.
Backup
Model parameters

• Search directly for the dark Higgs production.

• Dominant Dark Higgs decay modes:
  • $b\bar{b}$ for $m_s < 160$ GeV
  • $WW$ for $m_s > 160$ GeV

• First attempt at CMS using $WW$ final state targeting: JHEP03(2024)134
  • $MET + s(WW), WW \rightarrow 2l 2\nu$
  • $MET + s(WW), WW \rightarrow l\nu qq'$

• Model generation with Madgraph @LO: ZpHiggs_UFO

• 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%.
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.