Dark Sector Searches at CMS

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ON BEHALF OF THE CMS COLLABORATION

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SM interactions are understood pretty well
New physics signature

- Astrophysical observations indicate the existence of dark matter
- No observation in laboratory
- Several models with various type of interactions

- Dark sector interactions can give non-prompt signatures we should be looking for

- Challenging!
  - Analyses often require complex trigger strategies
  - Final states may require dedicated reconstruction techniques
  - Unconventional ways
Dark sector signatures & challenges

Displaced muon pairs

Small couplings

Displaced jets

Solenoidal Magnet

Emerging Jets

Limited phase space

Decays via heavy particle

Higgs mediated DM

3.8T
Dark Photons in ZH decays

- Search for a scalar boson produced in association with a Z boson and decaying to an invisible particle together with an isolated photon.

- Dark photon couples to the Higgs boson through a charged dark sector.

### Variable of interest: $m_T$ (MET, photon):

$$m_T \equiv \sqrt{2p_T^{miss}E_T^{\gamma}[1 - \cos(\Delta\phi_{p_T^{miss},E_T^{\gamma}})]}$$

- Jacobian peak structure with end-point at $m_T \sim m_H$, flat or lower values for background.
Dark Photons in ZH decays

CMS PAS EXO-19-007

**Control Regions**

- M$_T$ distributions
- Signal topology

**CMS Preliminary**

- e$\mu$
- WZ
- ZZ

137.4 fb$^{-1}$ (13 TeV)
Dark Photons in ZH decays

<table>
<thead>
<tr>
<th>Process</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>14</td>
</tr>
<tr>
<td>Nonresonant bkg.</td>
<td>2.4 ± 1.1</td>
</tr>
<tr>
<td>WZ</td>
<td>8.1 ± 2.0</td>
</tr>
<tr>
<td>ZZ</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>Zγ</td>
<td>0.7 ± 0.7</td>
</tr>
<tr>
<td>Other bkg.</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>13.3 ± 3.8</td>
</tr>
<tr>
<td>ZH$_{125}$ (BR=10%)</td>
<td>17.9 ± 1.2 (1.42 ± 0.09 %)</td>
</tr>
<tr>
<td>ZH$_{200}$ (BR=10%)</td>
<td>12.3 ± 0.8 (4.32 ± 0.28 %)</td>
</tr>
<tr>
<td>ZH$_{300}$ (BR=10%)</td>
<td>3.9 ± 0.2 (6.80 ± 0.34 %)</td>
</tr>
</tbody>
</table>

Observed yields, bkg estimates and signal predictions in the signal region.

Signal predictions for BR(H→invisible+γ) = 10% assuming SM ZH cross section for given H mass

The observed and expected 95% CL upper limits at m$_{H} = 125$ GeV assuming SM production rate on BR(H→invisible+γ) are 4.6% and 3.6%, respectively.
Emerging Jets

- Class of models includes new, electrically-neutral fermions called “dark quarks”
- Not charged under the forces of the SM but are charged under a new force in the dark sector (“dark QCD”) that has confining properties similar to SM QCD
- Such models naturally explain the observed mass densities of baryonic matter and dark matter
- This search consider particularly, the dark QCD model of Bai, Schwaller, Stolarski, and Weiler (BSSW) that predicts “emerging jets”

**Emerging Jets (EJs):** Long-lived dark hadrons giving rise to displaced vertices when decaying to SM hadrons
Emerging Jets

- Use of displacement and associated tracks and vertices to tag EJs
- 4 Jets: either 2-EJs or 1-EJ and large MET
- Multijets with b-jets main background: use data-driven estimates, studied as a function of track multiplicity

The $H_T$ and number of associated tracks of the observed data events and expected background in one of the CRs
Emerging Jets

- Dark pion decay lengths between 5 and 225 mm for dark mediators with masses between 400 and 1250 GeV are excluded.
- First dedicated search for the pair production of a new particle that decays to a jet and an emerging jet.

### Requirements on the variables used in identifying emerging jets

<table>
<thead>
<tr>
<th>Criteria group</th>
<th>$P_{\text{dz}}$ ($&lt;\text{cm}$)</th>
<th>$D_N$ ($&lt;\text{cm}$)</th>
<th>$\langle IP_{2D}\rangle$ ($\text{cm}$)</th>
<th>$\alpha_{3D}$ ($&lt;\text{cm}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMJ-1</td>
<td>2.5</td>
<td>4</td>
<td>0.05</td>
<td>0.25</td>
</tr>
<tr>
<td>EMJ-2</td>
<td>4.0</td>
<td>4</td>
<td>0.10</td>
<td>0.25</td>
</tr>
<tr>
<td>EMJ-3</td>
<td>4.0</td>
<td>20</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>EMJ-4</td>
<td>2.5</td>
<td>4</td>
<td>0.10</td>
<td>0.25</td>
</tr>
<tr>
<td>EMJ-5</td>
<td>2.5</td>
<td>20</td>
<td>0.05</td>
<td>0.25</td>
</tr>
<tr>
<td>EMJ-6</td>
<td>2.5</td>
<td>10</td>
<td>0.05</td>
<td>0.25</td>
</tr>
<tr>
<td>EMJ-7</td>
<td>2.5</td>
<td>4</td>
<td>0.05</td>
<td>0.40</td>
</tr>
<tr>
<td>EMJ-8</td>
<td>4.0</td>
<td>20</td>
<td>0.10</td>
<td>0.50</td>
</tr>
</tbody>
</table>

### Expected and observed event yields for each selection set

<table>
<thead>
<tr>
<th>Set number</th>
<th>Expected</th>
<th>Observed</th>
<th>Signal</th>
<th>Model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>168 ± 15 ± 5</td>
<td>131</td>
<td>36.7 ± 4.0</td>
<td>$m_{\text{XDK}}$ [GeV]</td>
</tr>
<tr>
<td>2</td>
<td>31.8 ± 5.0 ± 1.4</td>
<td>47</td>
<td>(14.6 ± 2.6) $\times 10^2$</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>19.4 ± 7.0 ± 5.5</td>
<td>20</td>
<td>15.6 ± 1.6</td>
<td>1250</td>
</tr>
<tr>
<td>4</td>
<td>22.5 ± 2.5 ± 1.5</td>
<td>16</td>
<td>15.1 ± 2.0</td>
<td>1000</td>
</tr>
<tr>
<td>5</td>
<td>13.9 ± 1.9 ± 0.6</td>
<td>14</td>
<td>35.3 ± 4.0</td>
<td>1000</td>
</tr>
<tr>
<td>6</td>
<td>9.4 ± 2.0 ± 0.3</td>
<td>11</td>
<td>20.7 ± 2.5</td>
<td>1000</td>
</tr>
<tr>
<td>7</td>
<td>4.40 ± 0.84 ± 0.02</td>
<td>2</td>
<td>5.61 ± 0.64</td>
<td>1250</td>
</tr>
</tbody>
</table>
Dark Photons to 4 Muons

• Search for the pair production of a light boson that decays into a pair of muons

• Interpretations: Supersymmetry (SUSY) models with hidden sectors (dark SUSY)
  • Breaking of a new $U(1)_D$ symmetry gives rise to a massive dark photon $\gamma_D$

  
  ![Diagram of dark photon decay](image)

  Dark neutralino: undetected (MET)

  Non-dark neutralino

  Couple of oppositely charged muon pairs

  $m_h = 125\text{GeV}; m_{n1} = 10\text{ GeV}$

• The lifetime, and thus the displacement, of the dark photon is dependent upon kinematic mixing parameter $\epsilon$ and the mass of the dark photon
Dark Photons to 4 Muons

- Similar invariant mass for muon pairs
- Negligible backgrounds: bb, J/ψ pair production, Z+ J/ψ, electroweak 4μ via off-shell Zs

Triangles: Data events in SR
Bullets: Data events outside SR

No observed excesses: constrain γ_D masses 0.25 – 8.5 GeV
Higgs invisible

• Search for invisible decays of a Higgs boson in association with jets
• Search exploits large $m_{ jj}$ and $|\Delta \eta_{ jj}|$ that characterize VBF higgs production
• Major background (95%): $Z(\nu \nu)+$jets and $W(\ell \nu)+$jets

Upper limit on $B(H \rightarrow \text{inv})$ of 0.19 (0.15) at 95% CL, assuming SM production rates for the Higgs boson and a Higgs boson mass of 125.09 GeV
Higgs invisible

Interpretations: Higgs portal models of Dark Model interactions

Observed 95% CL upper limits on \((\sigma / \sigma_{SM})\) \(B(H \rightarrow \text{inv})\), whose production \(x_s\) varies as a function of coupling multipliers

The observed 90% CL upper limit of \(B(H \rightarrow \text{inv}) < 0.16\) is interpreted in terms of Higgs-portal models of dark matter (DM) interactions

Limits provides the strongest constraints on fermion (scalar) DM particles with masses smaller than about 18 (7) GeV
Invisible Higgs boson decays using ttH production

First upper bounds on the branching fraction of invisible Higgs boson decays (H → inv) using ttH production

The observed (expected) upper limits on B(H → inv) at the 95% CL are 0.85 (0.73), 0.71 (0.87), and 0.89 (1.06) at the 95% CL for the all-hadronic, semi-leptonic, and di-leptonic final states, respectively.

Combined observed (expected) upper limit for BR(H → inv) < 0.46 (0.48) at the 95% CL for a Higgs boson mass of 125 GeV
Summary

- No excess yet
  - New ideas, brain-storming to continue

- Lots of exciting searches from CMS on-going

- Highlighted several recent results on Dark sector searches today

- Displaced vertices searches continue to attract new efforts and ideas

- A lot of room for new searches in this comparatively unexplored frontier

Stay tuned for more results!
EXTRA MATERIAL
Higgs invisible


[Graphs showing CMS results for Higgs boson signals]