Search for associated production of dark matter with a Higgs boson

[Higgs decays to a pair of bottom quarks]

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Overview

- Search for Dark matter associated with mono Higgs is one of the dark matter Channel at LHC
- Mono Higgs + Dark Matter complements to mono-X like searches
- Looking this search in context of two benchmark models:
  - 2HDM+a Model
  - Z’-Baryonic Model
- Previous study: EXO-16-050 {for boosted category: using CA15 jet}
- For today: Looking for events with large MET and low boosted Higgs {resolved category} in 2016 data
- Plan: Combined resolved + boosted category {2016+2017+2018 data}
Models Overview

Focusing on two Simplified models for this analysis

**2HDM+a Model:**
- type-II 2HDM extended by additional light pseudo scalar (a)
- Model has 14 parameters
  \[
  \{ v, M_h, M_A, M_{H^0}, M_{H^\pm}, M_a, m_\chi \}
  \]
  \[
  \cos(\beta - \alpha), \tan \beta, \sin \theta, \\
  y_\chi, \lambda_3, \lambda_{P1}, \lambda_{P2}
  \]

**Free Parameters:**
- \( M_a, M_A(=M_H=M_{H\pm}) \), \( m_\chi \), \( \sin \theta \), \( \tan \beta \)
- \( m_\chi = 10 \) is fixed for this analysis

More details for parameter choices: [Whitepaper](#)

**Z’ -Baryonic Model:**
- The model is extension of SM by addition of \( U(1)' \) gauge

**Parameters:**
- \( M_{Z'}, m_\chi, g_q, g_x \)
- \( [g_q, g_x] \) are fixed at \([0.25, 1]\)
- \( g_{h'z'}/M_{Z'} \) is unity

Parameter choices are follow recommendation from: [arXiv:1507.00966](#)

![2HDM+a](image1.png)

![Z’ -Baryonic](image2.png)
Background Overview

Three major backgrounds for this analysis

- **Z+jets**: Irreducible background
- **W+jets**: Pose background when lepton is lost
- **Top(TT+SingleTop)**: Pose background when lepton from semi-leptonic TT is lost

Three minor backgrounds

- **DIBOSON**
- **SM H**
- **QCD**

SM process with b quarks and $p_T^{\text{miss}}$ can mimic our signal
Triggers and Dataset

- **Using certified events corresponding to 35.5 fb\(^{-1}\) from Run2016 [B,C,D,E,F,G,H]**

- **MET —> Signal region and Muon control region**

- **SingleElectron —> Electron control regions**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET</td>
<td>PFMET170_*</td>
</tr>
<tr>
<td></td>
<td>HLT_PFMETNoMu90_PFMHTNoMu90_IDTight_v</td>
</tr>
<tr>
<td></td>
<td>HLT_PFMETNoMu100_PFMHTNoMu100_IDTight_v</td>
</tr>
<tr>
<td></td>
<td>HLT_PFMETNoMu110_PFMHTNoMu110_IDTight_v</td>
</tr>
<tr>
<td></td>
<td>HLT_PFMETNoMu120_PFMHTNoMu120_IDTight_v</td>
</tr>
<tr>
<td></td>
<td>HLT_IsoMu24_v, HLT_IsoTkMu24_v</td>
</tr>
<tr>
<td>Single Electron</td>
<td>HLT_Ele27_WPLoose_Gsf</td>
</tr>
<tr>
<td></td>
<td>HLT_Ele27_WPTight_Gsf</td>
</tr>
</tbody>
</table>
Event selection

Baseline Selection

- No CA15 fatjet with $p_T > 200$, SDMass [100,150], $|\eta| < 2.4$
- $\text{PFMET} > 200 \text{ GeV (SR)}$ or hadronic recoil $> 200 \text{ GeV (CR)}$
- $n\text{AK4 jets} = 2$ or $3$
  - $p_T > 50 \text{ GeV , } |\eta| < 2.4$ {for leading and subleading jets}
  - $p_T > 30 \text{ GeV, } |\eta| < 2.4$ {for additional jet}
- Dijets pair {b tagged using deepCSV MWP} as Higgs candidate with $100 < M_{bb} < 150 \text{ GeV}$.
- $\Delta \Phi \text{ (jet, MET )} > 0.5$
- Lepton veto (SR)
Signal Region

- Background shape checked in SR (Signal region blinded)
- MET is shown for SR:
  - $100 < M_{bb} < 150$ GeV
- Will apply $b$ jet regression:
  - To get Higgs mass at correct position
  - To improve signal efficiency

### Signal yield per bin

<table>
<thead>
<tr>
<th>$p_T^{miss}$ - bin</th>
<th>200-270GeV</th>
<th>270-345GeV</th>
<th>345-480GeV</th>
<th>$&gt;480$GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$+jets</td>
<td>138.54</td>
<td>36.08</td>
<td>15.75</td>
<td>4.98</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>507.06</td>
<td>53.21</td>
<td>9.88</td>
<td>0.04</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>55.15</td>
<td>5.23</td>
<td>1.69</td>
<td>0.60</td>
</tr>
<tr>
<td>Single top</td>
<td>46.99</td>
<td>7.95</td>
<td>1.76</td>
<td>0.24</td>
</tr>
<tr>
<td>Diboson</td>
<td>11.59</td>
<td>4.47</td>
<td>3.31</td>
<td>0.00</td>
</tr>
<tr>
<td>SM h</td>
<td>3.11</td>
<td>0.81</td>
<td>0.32</td>
<td>0.08</td>
</tr>
<tr>
<td>$\sum$(SM)</td>
<td>765.64</td>
<td>107.54</td>
<td>32.50</td>
<td>5.4</td>
</tr>
<tr>
<td>Data</td>
<td>_</td>
<td>_</td>
<td>_</td>
<td>_</td>
</tr>
<tr>
<td>2HDM+a, $m_A = 1$TeV, $m_a = 150$GeV</td>
<td>8.89</td>
<td>7.14</td>
<td>11.53</td>
<td>3.79</td>
</tr>
<tr>
<td>Bar. $Z'$, $m_{Z'} = .2$TeV, $m_{\chi} = 50$GeV</td>
<td>175.25</td>
<td>67.42</td>
<td>34.25</td>
<td>14.28</td>
</tr>
</tbody>
</table>

Deepak Kumar
## Resolved vs Boosted

### Resolved Analysis Yield

<table>
<thead>
<tr>
<th>$p_T^{miss} - bin$</th>
<th>200-270GeV</th>
<th>270-345GeV</th>
<th>345-480GeV</th>
<th>&gt;480GeV</th>
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<td>5.4</td>
</tr>
<tr>
<td>Data</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

2HDM+a, $m_A = 1$TeV, $m_a = 150$GeV:
- 8.89
- 7.14
- 11.53
- 3.79

Bar. $Z'$, $m_{Z'} = 0.2$TeV, $m_{\chi} = 50$GeV:
- 175.25
- 67.42
- 34.25
- 14.28

### Boosted Analysis Yield

<table>
<thead>
<tr>
<th>$p_T^{miss}$-bin</th>
<th>200-270 GeV</th>
<th>270-350 GeV</th>
<th>350-475 GeV</th>
<th>&gt;475 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z+jets</td>
<td>248.9 ± 22.2</td>
<td>97.2 ± 8.5</td>
<td>32.6 ± 3.6</td>
<td>11.1 ± 1.9</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>199.2 ± 13.5</td>
<td>52.1 ± 5.2</td>
<td>11.1 ± 2.0</td>
<td>0.7 ± 0.4</td>
</tr>
<tr>
<td>W+jets</td>
<td>121.6 ± 21.6</td>
<td>45.0 ± 8.7</td>
<td>8.4 ± 1.9</td>
<td>2.9 ± 0.9</td>
</tr>
<tr>
<td>Single top</td>
<td>21.0 ± 4.2</td>
<td>6.1 ± 1.2</td>
<td>0.9 ± 0.2</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Diboson</td>
<td>16.0 ± 3.1</td>
<td>7.6 ± 1.5</td>
<td>2.4 ± 0.5</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>SM h</td>
<td>12.6 ± 1.4</td>
<td>6.6 ± 0.7</td>
<td>3.3 ± 0.3</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>$\sum (SM)$</td>
<td>619.3 ± 20.1</td>
<td>214.6 ± 8.1</td>
<td>58.7 ± 3.7</td>
<td>17.2 ± 2.0</td>
</tr>
<tr>
<td>Data</td>
<td>619</td>
<td>214</td>
<td>59</td>
<td>21</td>
</tr>
</tbody>
</table>

2HDM+a, $m_A = 1$TeV, $m_a = 150$GeV:
- 5.7 ± 0.6
- 9.8 ± 1.1
- 18.5 ± 2.1
- 5.2 ± 0.6

Bar. $Z'$, $m_{Z'} = 0.2$TeV, $m_{\chi} = 50$GeV:
- 184.2 ± 20.0
- 118.1 ± 12.8
- 69.5 ± 7.7
- 28.9 ± 3.3

---

EXO-16-050
Control Regions

To properly model major background for this analysis

- 6 control regions are defined based on number of leptons, flavour and additional jets.
- Z(νν)+jets background in SR is modelled using Z(νν)+jets enriched region.
- W(lν)+jets background (lepton lost) in SR is modelled using high statistics W(lν)+2jets enriched region.
- TT(semi leptonic) background modelled using W(lν)+jets(>2jets)
- Hadronic recoil used as proxy for MET in CRs

\[ U = - (MET + \sum p_T^{lepton}) \]
## Event Selection

<table>
<thead>
<tr>
<th>Category</th>
<th>W→ev</th>
<th>W→μν</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Electron</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>#Muon</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Lepton 1</td>
<td>Tight ID</td>
<td>Tight ID</td>
</tr>
<tr>
<td>Lepton 2</td>
<td>veto</td>
<td>veto</td>
</tr>
<tr>
<td>Recoil</td>
<td>W Recoil &gt; 200 GeV</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>50 GeV &lt; W Trans Mass &lt; 160 GeV</td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>bJets</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>M(bb)</td>
<td>100 GeV &lt; Mbb &lt; 150 GeV</td>
<td></td>
</tr>
<tr>
<td>CA15Jet</td>
<td>veto</td>
<td></td>
</tr>
</tbody>
</table>

## CR Plots

- **W→ev CR**
  - W CR (e)
  - Data/Pred.
  - Events vs. Hadronic Recoil (GeV)
  - Data/(Stat + Syst.)

- **W→μν CR**
  - W CR (μ)
  - Data/Pred.
  - Events vs. Hadronic Recoil (GeV)
  - Data/(Stat + Syst.)

*Work in progress*
**ZCR**

### Event Selection

<table>
<thead>
<tr>
<th></th>
<th>Z→ee</th>
<th>Z→μμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Electron</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>#Muon</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Lepton 1 p&lt;sub&gt;T&lt;/sub&gt; &gt; 30 GeV</td>
<td>p&lt;sub&gt;T&lt;/sub&gt; &gt; 30</td>
<td></td>
</tr>
<tr>
<td>Tight ID</td>
<td>Tight ID</td>
<td></td>
</tr>
<tr>
<td>Iso &lt; 0.15</td>
<td>Tight ID</td>
<td></td>
</tr>
<tr>
<td>p&lt;sub&gt;T&lt;/sub&gt; &gt; 10 GeV</td>
<td>p&lt;sub&gt;T&lt;/sub&gt; &gt; 10 GeV</td>
<td></td>
</tr>
<tr>
<td>Lepton 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tight ID</td>
<td>Tight ID</td>
<td></td>
</tr>
<tr>
<td>Iso &lt; 0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recoil</td>
<td>Z Recoil &gt; 200 GeV</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>70 GeV &lt; Reco Z Mass &lt; 110 GeV</td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td>2 or 3</td>
<td></td>
</tr>
<tr>
<td>bJets</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>M(bb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA15Jet</td>
<td>veto</td>
<td></td>
</tr>
</tbody>
</table>

### CR Plots

- **Dielectron CR**
  - **Mass**
    - 70 GeV < Reco Z Mass < 110 GeV
  - **Jets**
    - 2 or 3
  - **bJets**
    - 2
  - **M(bb)**
    - Withdrawn
  - **CA15Jet**
    - Veto

- **Dimuon CR**
  - **Mass**
    - 70 GeV < Reco Z Mass < 110 GeV
  - **Jets**
    - 2 or 3
  - **bJets**
    - 2
  - **M(bb)**
    - Withdrawn
  - **CA15Jet**
    - Veto
# Event Selection

<table>
<thead>
<tr>
<th></th>
<th>Top(ev)</th>
<th>Top(μν)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Electron</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>#Muon</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Lepton 1</td>
<td>p_T &gt; 30</td>
<td>p_T &gt; 30</td>
</tr>
<tr>
<td></td>
<td>Tight ID</td>
<td>Tight ID</td>
</tr>
<tr>
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<td>veto</td>
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<td>Recoil</td>
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<td>Mass</td>
<td>50 GeV &lt; W Trans Mass &lt; 160 GeV</td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td>&gt;2</td>
<td></td>
</tr>
<tr>
<td>bJets</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>M(bb)</td>
<td>100 GeV &lt; Mbb &lt; 150 GeV</td>
<td></td>
</tr>
<tr>
<td>CA15Jet</td>
<td>veto</td>
<td></td>
</tr>
</tbody>
</table>

# CR Plots

- **Top(eν)**
  - **Top(μν)**
  - **#Electron**
  - **#Muon**
  - **Lepton 1**
  - **Lepton 2**
  - **Recoil**
  - **Mass**
  - **Jets**
  - **bJets**
  - **M(bb)**
  - **CA15Jet**

- **Event Selection**
  - **Lepton 1**
  - **Lepton 2**

- **CR Plots**
  - **Top(eν)**
  - **Top(μν)**
  - **#Electron**
  - **#Muon**
  - **Lepton 1**
  - **Lepton 2**
  - **Recoil**
  - **Mass**
  - **Jets**
  - **bJets**
  - **M(bb)**
  - **CA15Jet**

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DAE-BRNS High Energy Physics Symposium
## Systematics Uncertainty

Considering following uncertainty to extract the limit.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi</td>
<td>2.5%</td>
</tr>
<tr>
<td>pile up</td>
<td>~0.1-1%</td>
</tr>
<tr>
<td>btag</td>
<td>Shape(POG)</td>
</tr>
<tr>
<td>Top pT</td>
<td>Shape(50%)</td>
</tr>
<tr>
<td>MET trigger</td>
<td>Shape(monoJ)</td>
</tr>
<tr>
<td>Electron SF</td>
<td>Shape(POG)</td>
</tr>
<tr>
<td>Muon SF</td>
<td>Shape(POG)</td>
</tr>
</tbody>
</table>

- Shape variation obtained by applying 50% as up and down systematic.
- Full difference between the W -> μν and the Z->μ⁺μ⁻ trigger turn on is used as systematic uncertainty.
Results: 2HDM+a model

- Reach of resolved category is very similar to boosted category
- For $m_a=250$ GeV, $m_A=600$ GeV, $\tan\beta=1$, $\sin\theta=0.35$
- $m_A$ scan is in progress

For $m_a=250$ GeV, $m_A=600$ GeV, $\tan\beta=1$, $\sin\theta=0.35$

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Resolved Category

Boosted Category: EXO-16-050

$2HDM+a, \ h \rightarrow b\bar{b}$

$95\%$ C.L. asymptotic limit on $\mu = \sigma / \sigma_{\text{theory}}$

$M_a [\text{GeV}]$

$\sigma / \sigma_{\text{theory}}$
Results: 2HDM+a Model

Resolved Analysis may bring improvement at low $\sin\theta$

Resolved Category

Boosted Category: EXO-16-050
Resoluted Analysis may bring significant improvement to the Analysis.
Summary

- Two models are used in this analysis.
- A search for dark matter in resolved monoH ➔ bb final state is performed.
- This analysis is completely orthogonal to boosted category, by putting CA15 jet veto.
- Preliminary results shows good potential for the resolved Analysis.
Back-up
Signal samples

Z′-Baryonic

- MonoHbb_ZpBaryonic_MZp-*_MChi-*_13TeV-madgraph_MC25ns_LegacyMC

  - MZp=[10,50,100,200,300,500,1000,2000]

2HDMa

- 2HDMa_gg_sinp_0p*_tanb_*_mXd_10_MH3_*_MH2_*_MHC_*

  - MH4=[100,150,200,250,300,350,400,500],
  - MH2=MH3=MHC=[600,700,800,900,1000,1100,1200,1300,1400,1500]

sinp=[0.1,0.2,0.3,0.35,0.4,0.6,0.7,0.8,0.9]

- tanb=[1-50]

---

- genMET distribution changes when we change mediator masses in the both models

- genMET definition:
  \[ \text{genMET} = \sum p_T(\chi, \bar{\chi}) \]
Motivation

☑ All signal events not covered in boosted category (CA15)
☑ Aim to catch the signal falling in resolved category

Fig: deltaR between two b jets

2HDM+a Model

- $M_a=100$ GeV
- $M_a=150$ GeV
- $M_a=200$ GeV
- $M_a=250$ GeV
- $M_a=300$ GeV
- $M_a=350$ GeV
- $M_a=400$ GeV
- $M_a=500$ GeV

Resolved

Boosted
Background Samples

All samples are from the RunSummer16MiniAODv2 campaign

- **Z(→vv) + Jets**
  - ZJetsToNuNu HT-binned samples
  - HT-100ToInf

- **W(→lv)+Jets**
  - WJetsToLNu HT-binned samples
  - HT-100ToInf

- **TT**
  - TT powheg samples

- **Single TOP**
  - ST_s,channel_4f_leptonDecays
  - ST_t,channel_anEtop_4f_inclusiveDecays
  - ST_t,channel_top_4f_inclusiveDecays
  - ST_tW_anEtop_5f_inclusiveDecays
  - ST_tW_top_5f_inclusiveDecays

- **Z(→ll) + Jets**
  - DYJetsToLL_M-50 HT binned samples
  - HT-70ToInf

- **Diboson**
  - ZZ, WZ, WW

- **QCD Multijets**
  - QCD HT-binned samples
  - HT-500ToInf

- **SM H**
  - ZH HToBB ZToNuNu, ZH HToBB ZToLL
  - ggZH HToBB ZToNuNu, ggZH HToBB ZToLL
  - WminusH HToBB WToLNu, WplusH HToBB WToLNu
Figure 6: Comparison on both data and MC between the METNoMu+MHTNoMu trigger efficiency turn on as measured in $W \rightarrow \mu \nu$ and $Z \rightarrow \mu^+\mu^-$ events (left). (Right) Comparison between the data to MC scale factors which show a significant disagreement in the low recoil region; taken from [8].