Search for Dark Matter at CMS

Anwar Bhatti

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What we Understand Today?

Chemical Elements: (other than H & He) 0.03%

Neutrinos: 0.47%

Stars: 0.5%

Free H & He: 4%

Dark Matter: 25%

Dark Energy: 70%

95% Mystery
Why we need Dark Matter?

Anisotropy in CMB $\rightarrow$ cold massive particles
Weakly Interacting Massive Particles (WIMPs)

- Postulate a new species of elementary particles
- Weakly Interacting Massive Particles
- They are produced in the Big Bang and interact via:
  \[ \chi + \chi \leftrightarrow \text{SM} + \text{SM} \]
- As the universe expands and temperature falls, they become diluted, and eventually can not find each other, so they freeze out
- Their relic density is related to their interaction strength, inversely proportional to the thermal averaged annihilation cross section (\( <\sigma v> \)).

Weakly interacting particles with weak scale masses naturally give the right relic abundance- “WIMP miracle”
Dark Matter Particle Searches

Needs independent verification from non-astrophysical experiment

1. Direct Detection Experiments
   - Dark Matter-nucleus scattering
   - Low mass DM particles not probed yet.
   - Less sensitive to spin-dependent coupling
   - XENON-100, CDMS, CoGeNT

2. Indirect Detection Experiments
   - Observe annihilation products
   - Low mass DM particles not accessible
   - Depends on DM density and annihilation model
   - Super-Kamiokande, IceCube

3. Collider Experiments
   - Laboratory production of DM particles
   - Sensitive to huge mass range
   - Both spin-dependent and spin-independent couplings
   - Tevatron, LHC

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Phenomenology for direct pair production

- **Effective Field theory:**
  - Mediator is heavy and can be integrated out
  - Contact interaction

\[ \mathcal{L} = \mathcal{L}_{SM} + i \bar{X} \gamma^\mu \partial_\mu X - M_X \bar{X} X + \sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} [\bar{X} \Gamma_i^X X] [\bar{q} \Gamma_j^q q], \]

SM Lagrangian

kinetic terms for DM

set of 4-Fermion interactions between DM and SM quarks

Operators $\Gamma$ describe scalar, pseudoscalar, vector, axial vector, tensor interactions

**We consider**

- DM particles with mass 1 GeV to 1 TeV
- Vector and axial vector interactions
Monojets Search

Baseline cut:
MET > 200 GeV, at most two jets with jet $p_T > 30$ GeV
Leading jet $p_T > 110$ GeV, $|\eta| < 2.4$
$\Delta \phi (\text{jet}_1, \text{jet}_2) < 2.5$ (QCD rejection)
Reject events with electron, muons, isolated tracks $P_T > 10$ GeV
MonoJet Search

Cut and count: Apply event selection and count the number of events in signal region

- Look for excess of events above those expected from SM backgrounds
- Understanding backgrounds is crucial.
- Determine from data control regions

Signal

Backgrounds

Z(νν) + Jets, just like signal

W+jets, e/u is not detected, τ decays hadronically

QCD, jet is mismeasured, producing Met
Background Estimation

Estimation of $Z\rightarrow\nu\nu$

- Control sample $Z\rightarrow\mu\mu$
- Select 2 opposite sign muons same as signal
- Well isolated muons $p_T > 20$ GeV, $|\eta| < 2.1$
- Invariant mass between 60-120 GeV
- Uncertainty $\sim 11\%$ mainly from stats 10%

Estimation of $W$-jet where lepton is lost

- Control sample $W\rightarrow\mu\nu$
- Select single muon same as signal
- Well isolated muon $p_T > 20$ GeV, $|\eta| < 2.1$
- Transverse mass between 50-100 GeV
- Uncertainty $\sim 11\%$ mainly from acceptance (8%) and selection efficiency (7%)
Results

- Backgrounds after full event selection:
  - $Z(\nu\nu)$ ($\approx 70\%$), $W +$ jets ($\approx 30\%$), data-driven
  - QCD, top, $Z +$ jets negligible ($\approx 1\%$), estimated from MC.

<table>
<thead>
<tr>
<th>$E_T^{miss}$ (GeV/c)</th>
<th>≥ 250</th>
<th>≥ 300</th>
<th>≥ 350</th>
<th>≥ 400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Events</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z(\nu\bar{\nu})+jets$</td>
<td>5106 ± 271</td>
<td>1908 ± 143</td>
<td>900 ± 94</td>
<td>433 ± 62</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>2632 ± 237</td>
<td>816 ± 83</td>
<td>312 ± 35</td>
<td>135 ± 17</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>69.8 ± 69.8</td>
<td>22.6 ± 22.6</td>
<td>8.5 ± 8.5</td>
<td>3.0 ± 3.0</td>
</tr>
<tr>
<td>$Z(\ell\ell)+jets$</td>
<td>22.3 ± 22.3</td>
<td>6.1 ± 6.1</td>
<td>2.0 ± 2.0</td>
<td>0.6 ± 0.6</td>
</tr>
<tr>
<td>Single $t$</td>
<td>10.2 ± 10.2</td>
<td>2.7 ± 2.7</td>
<td>1.1 ± 1.1</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td>QCD Multijets</td>
<td>2.2 ± 2.2</td>
<td>1.3 ± 1.3</td>
<td>1.3 ± 1.3</td>
<td>1.3 ± 1.3</td>
</tr>
<tr>
<td>Total SM</td>
<td>7842 ± 367</td>
<td>2757 ± 167</td>
<td>1225 ± 101</td>
<td>573±65</td>
</tr>
<tr>
<td>Data</td>
<td>7584</td>
<td>2774</td>
<td>1142</td>
<td>522</td>
</tr>
<tr>
<td>Expected upper limit non-SM</td>
<td>779</td>
<td>325</td>
<td>200</td>
<td>118</td>
</tr>
<tr>
<td>Observed upper limit non-SM</td>
<td>600</td>
<td>368</td>
<td>158</td>
<td>95</td>
</tr>
</tbody>
</table>
Monophoton basic selection

Photon selection

- High energy photon: $p_T > 145$ GeV
- Central region of detector, $|\eta| < 1.4442$
- Shower shape in calorimeter consistent with photon

MET requirement

- $MET > 130$ GeV, vector sum of all reconstructed particles

Remove excessive hadronic activity

- No jet with $p_T > 40$ GeV and $|\eta| < 3.0$
Monophoton Backgrounds

Backgrounds estimated from MC and data-driven techniques

Backgrounds from pp collisions:
- $pp \rightarrow Z\gamma \rightarrow \nu\nu\gamma$: Irreducible background (from MC)
- $pp \rightarrow W \rightarrow e\nu$: Electron misidentified as photon (from data)
- $pp \rightarrow \text{jets} \rightarrow \gamma + \text{MET}$: One jet mimics photon, MET from jet mismeasurement (from data)
- $pp \rightarrow \gamma + \text{jet}$: MET from jet mismeasurement (from MC)
- $pp \rightarrow W\gamma \rightarrow l\nu\gamma$: Charged lepton escapes detection (from MC)
- $pp \rightarrow \gamma\gamma$: One photon mismeasured to give MET (from MC)

Other backgrounds:
- Showers induced by cosmic rays:
  - Identified and removed
- Neutron-induced signals:
  - Identified and removed
- Beam halo: Mostly removed;
  - residual contribution estimated from data

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Mimics Photon</td>
<td>11.2 ± 2.8</td>
</tr>
<tr>
<td>Beam Halo</td>
<td>11.1 ± 5.6</td>
</tr>
<tr>
<td>Electron Mimics Photon</td>
<td>3.5 ± 1.5</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>3.0 ± 1.0</td>
</tr>
<tr>
<td>$\gamma + \text{jet}$</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>$Z(\nu\bar{\nu})\gamma$</td>
<td>45.3 ± 6.9</td>
</tr>
<tr>
<td>Total Background</td>
<td>75.1 ± 9.5</td>
</tr>
<tr>
<td>Total Observed Candidates</td>
<td>73</td>
</tr>
</tbody>
</table>
Monophoton Search Results

- Distributions for photon $p_T$ and MET
  Background processes describe data well
- No excess of events over expected SM backgrounds
  Total background: $71.9 \pm 9.1$
  Total observed candidates: 73
Pair Production of DM particles

Convert the results to DM-nucleon cross section to compared with direct detection experiments

\[ \mathcal{O}_V = \frac{\bar{\chi}\gamma_\mu\chi}{\Lambda^2}, \text{Spin Independent} \]

\[ \mathcal{O}_{AV} = \frac{\bar{\chi}\gamma_\mu\gamma_5\chi}{\Lambda^2}, \text{Spin Dependent} \]

\[ \Lambda = M/\sqrt{g_\chi g_q} \]

\[ \Lambda^4 = \Lambda_{d}^4 + \Lambda_{u}^4 \]

\[ \mu = \frac{m_\chi m_p}{m_\chi + m_p} \]

\[ \sigma_{SI} = 9 \frac{\mu^2}{\pi \Lambda^4} \]

\[ \sigma_{SD} = 0.33 \frac{\mu^2}{\pi \Lambda^4} \]

M: Mediator Mass

\[ g_\chi \text{ and } g_q \]: coupling to dark matter and SM quark

arXiV: 1109.4398 Fox, Harnik et. al.
Spin-independent DM-nucleon cross section

\[ \sigma_{\text{Nucleon}} = \chi M^{-1} \times 10^{12} \text{cm}^2 \]

- CMS MonoJet
- CMS MonoPhoton
- CDF 2012
- XENON-100
- CoGeNT 2011
- CDMSII 2011
- CDMSII 2010

CMS
\[ \sqrt{s} = 7 \text{ TeV} \]
\[ \int L \, dt = 5.0 \text{ fb}^{-1} \]

Best Limit for dark matter mass < 3.5 GeV
Unexplored by direct detection experiments for spin independent case

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Spin-dependent DM-nucleon cross section

Most stringent limits – improved by several orders of magnitude over 0.1 - 200 GeV mass range for spin-dependent case
Examples of signal events

A monojet event,
\[ p_T^{\text{jet}} = 547 \text{ GeV}, \text{MET} = 598 \text{ GeV} \]

A monophoton event,
\[ \text{Photon } p_T = 384 \text{ GeV}, \text{MET} = 407 \text{ GeV} \]
Summary

- Results of searches for dark matter at CMS using monojet/monophoton + missing transverse energy are presented.
  - Set limits on DM-nucleon scattering cross-section
  - Competitive constraints on spin-dependent cross section over large DM mass range
  - Extend spin-independent bounds into low DM mass
    - DM mass < 3.5 GeV, previously unexplored region

- Collider searches are complementary to direct detection.
Backup
Monophoton – Event Display
A Monojet Event

$MET = 359 \text{ GeV}$

$p_T(jet1) = 331 \text{ GeV}$
Limits on DM-nucleon cross section

Best Limit for dark matter mass < 3.5 GeV unexplored by direct detection experiments for spin independent case

Most stringent limits - constraints by several orders of magnitude over entire 1-200 GeV mass range for spin-dependent case