Recent Results from a Search for Dark Matter Production in the CMS Experiment

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Dark Matter Production at the LHC

Elastic Scattering (t-channel)          Pair Production (s-channel)

Direct Searches                                Collider Searches

Radiation of a photon (or, gluon) in the initial state makes the process visible. QED vertex well understood.

We present results from a search in the Monophoton ($\gamma + E_T^{\text{miss}}$) final state.
Bai, Fox and Harnik [JHEP 1012:048(2010)] have cast this process as a contact interaction with effective operators:

\[ O_V = \frac{\overline{x}\gamma_\mu x (\overline{q}\gamma^\mu q)}{\Lambda^2} \]

Vector Operator

\[ O_A = \frac{\overline{x}\gamma_\mu \gamma^5 x (\overline{q}\gamma^\mu \gamma_5 q)}{\Lambda^2} \]

Axial-Vector Operator

The operators provide cross sections that depend on the scale \( \Lambda \) and \( m_{DM} \), the mass of the DM particle. The vector operator leads to spin-independent (SI) and the axial-vector operator to the spin-dependent (SD) cross section:

\[ \sigma_{SI} = \frac{9}{\pi} \left( \frac{\mu}{\Lambda^2} \right)^2 \]

(SI)

\[ \sigma_{SD} = \frac{0.33}{\pi} \left( \frac{\mu}{\Lambda^2} \right)^2 \]

(SD)

Where \( \mu \) is the reduced mass

\[ \mu = \frac{m_{DM} m_p}{m_{DM} + m_p} \]
1. Require a photon candidate with:

✓ $p_T^\gamma > 145$ GeV
✓ $|\eta^\gamma| < 1.4442$
✓ $\sigma_{\eta\eta} < 0.013$

($\sigma_{\eta\eta}$ is a measure of the transverse profile of the shower. This cut ensures that the candidate is consistent with the shape expected from a photon)

2. Require sufficient $E_T^{\text{miss}}$, calculated using a particle flow method:

✓ $\text{pfMET} > 130$ GeV

3. Remove events with excessive hadronic activity:

✓ No pf-jet with $p_T > 40$ GeV and $|\eta^{\text{jet}}| < 3.0$
✓ No track with $p_T > 20$ GeV with $\Delta R > 0.04$ from $\gamma$ candidate, where $\Delta R^2 = \Delta\phi^2 + \Delta\eta^2$
Selection of Isolated Photons

**Hadron Calorimeter (HCAL)**
- Hollow Cone: $0.15 < \Delta R < 0.4$
- $\Sigma p_T$ in hollow cone < $2.2 + 0.0025 \times p_T^\gamma$
- $E_{HCAL}$ in solid cone)/$E_{ECAL}$ < 0.05

**EM Calorimeter (ECAL)**
- Hollow Cone: $0.06 < \Delta R < 0.4$
- $\Sigma p_T$ in hollow cone < $4.2 + 0.006 \times p_T^\gamma$

**Tracker**
- Hollow Cone: $0.04 < \Delta R < 0.4$
- $\Sigma p_T$ in hollow cone < $2.0 + 0.001 \times p_T^\gamma$
- Electrons vetoed by hits in pixel tracker

\[ \Delta R^2 = \Delta \phi^2 + \Delta \eta^2 \]

All reconstructed vertices are used for isolation calculations.
Highest $p_T^{\gamma}$ Monophoton Event Observed

$p_T^{\gamma} = 384$ GeV

$E_{\text{miss}} = 407$ GeV
Backgrounds are estimated using a combination of data-driven (DD) and monte carlo (MC) techniques.

- \( pp \rightarrow Z \gamma \rightarrow \nu\nu \gamma \)  [irreducible background. Estimated to NLO]  MC
- \( pp \rightarrow W \rightarrow e\nu \)  [electron misidentified as \( \gamma \)]  DD
- \( pp \rightarrow N_{\text{jets}} \rightarrow "\gamma" + E_{T}^{\text{miss}} \)  [One jet mimics \( \gamma \); \( E_{T}^{\text{miss}} \) due to mismeasurement of jets. Appreciable due to very high rate for \( N_{\text{jets}} \).]  DD
- \( pp \rightarrow \gamma + \text{jet} \)  [\( E_{T}^{\text{miss}} \) due to mismeasurement of jet]  MC
- \( pp \rightarrow W\gamma \rightarrow l\nu\gamma \)  [charged lepton escapes detection]  MC
- \( pp \rightarrow \gamma \gamma \)  [one photon mismeasured to create \( E_{T}^{\text{miss}} \)]  MC

The procedure consists of estimating expected number of events from SM processes (and other backgrounds) and look for excess of events.

\[ \rightarrow \text{Counting Experiment} \]
Backgrounds Unrelated to pp Collisions

1. Beam Halo Muon Induced Showers
   Mostly removed. Residual estimated.

2. Cosmic Muon Induced Showers
   Identified and removed

3. Neutron Induced Spurious Signals ("Spikes")
   Identified and removed
Background processes describe the data well and no excess is observed.
Limit Setting Procedure - I

- Find cross sections using a monte carlo simulation [Fox, Harnik and Kopp].
- Fix $\Lambda = 10$ TeV and assume cross section scales as $\Lambda^{-4}$.
- Events are generated using MADGRAPH-4 and PYTHIA-6.

<table>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>Vector Operator $\sigma$ (fb)</th>
<th>Axial-Vector Operator $\sigma$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.530 E-04</td>
<td>1.524 E-04</td>
</tr>
<tr>
<td>10</td>
<td>1.525 E-04</td>
<td>1.520 E-04</td>
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<tr>
<td>100</td>
<td>1.489 E-04</td>
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<tr>
<td>500</td>
<td>5.222 E-05</td>
<td>2.254 E-05</td>
</tr>
<tr>
<td>1000</td>
<td>5.127 E-06</td>
<td>1.220 E-06</td>
</tr>
</tbody>
</table>

Cross sections for:

- $p_{T\gamma} > 125$ GeV
- $|\eta\gamma| < 1.5$

Due to the lack of any $A^2$ coherence factor, the sensitivity to spin-dependent and spin-independent interactions is quite similar.
Limit Setting Procedure - II

- Obtain Acceptance*Efficiency using the monte carlo samples and processing them through the Monophoton selection.

- In the leading order, kinematics of the events are determined solely by the ISR photon => $A^\text{eff}$ is fairly constant for $m_{DM}$ in the range 1-1000 GeV.

<table>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>Vector Operator $A \times \epsilon_{MC}$</th>
<th>Axial-Vector Operator $A \times \epsilon_{MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>1000</td>
<td>0.310</td>
<td>0.314</td>
</tr>
</tbody>
</table>

Systematic uncertainties:
- Stats. uncertainty : 1.7 %
- Photon $P_T$ uncertainty : 2.3 %
- Jet Energy Scale : 1.2 %
- MET modeling : 0.5 %
- Pile Up modeling : 2.4 %
Limit Setting Procedure - III

- For an integrated luminosity 4.67 fb⁻¹, 71.9 ± 9.1 expected and 73 observed.
- Both 90% CL (Direct search norm) and 95% CL (Collider norm) limits are shown.

### For Vector Operator

Expected limits shown parenthetically.

Upper limits on **Monophoton** cross section have been translated into lower limits on \( \Lambda \), assuming a \( \Lambda^{-4} \) behavior.

### For Axial Vector Operator

The lower limits on \( \Lambda \) are then used to plot **DM-nucleon** cross section limits versus \( m_{DM} \).
Spin Independent Limits: Spin-independent

There is no mass threshold. The analysis has been restricted to be > 1 GeV.

\[ \sigma_{SI} = \frac{9}{\pi} \left( \frac{\mu}{\Lambda^2} \right)^2 \]


Spin Dependent

\[ \sigma_{SD} = \frac{0.33}{\pi} \left( \frac{\mu}{\Lambda^2} \right)^2 \]


Conclusions

- A search for dark matter production was performed in the Monophoton final state using 4.67 fb\(^{-1}\) of integrated luminosity accumulated by the CMS experiment in 2011.

- We observe no excess over Standard Model expectation in this final state. The Monophoton (\(\gamma + \text{DM}\)) cross section upper limit is estimated to be 16.1-16.8 fb and 16.1-17.6 fb for SI and SD respectively at 90%CL for the entire mass range of 1 GeV to 1 TeV.

- In the SI case, DM masses below about 3.5 GeV, inaccessible to earlier measurements, are excluded for DM-nucleon cross sections above ~5 fb at 90%CL.

- In the SD case, DM masses in the range 1-1000 GeV are excluded for DM-nucleon cross sections well below the earlier limits.

- LHC will begin operations at 8 TeV and an integrated luminosity of 15 fb\(^{-1}\) is expected in 2012. The Monophoton threshold in the CMS trigger is not expected to change by much. Enhanced discovery potential, especially in the low mass regime, is anticipated.
Thank You