Search for Dark Matter at the CMS Experiment

Norraphat SRIMANOBHAS (Chulalongkorn U., Thailand)
on behalf of the CMS Collaboration

DARK2012: Dark Forces at Accelerators
The Istituto Nazionale di Fisica Nucleare (INFN)
laboratory of Frascati, Frascati, Lazio, ITALY
Search for Dark Matter

Strong evidences for the existence of dark matter, i.e.:

- Galactic rotation curves
- Strong Gravitational Lensing
- Bullet cluster
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

Needs independent verifications from various astrophysical and non-astrophysical experiments.
Search for Dark Matter at the Collider

**Signal Characteristics**
- Missing transverse energy (MET) results from the Dark Matter production.
  - Vector sum of all reconstructed particles (Particle Flow method)
- Photons or jets can be radiated from quarks.
- Trigger on a single photon or a single jet with the large missing transverse energy.
Search for Dark Matter at the Collider

Assumptions:
- DM particle is only new state accessible to the collider.
- Mediator is heavy, and can be integrated out.

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

- Contact interaction.

For vector mediator (Spin-Independent):

\[ \mathcal{O}_V = \frac{(\bar{\chi} \gamma_\mu \chi)(\bar{q} \gamma^\mu q)}{\Lambda^2} \]

For axial- vector mediator (Spin-Dependent):

\[ \mathcal{O}_{AV} = \frac{(\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{q} \gamma^\mu \gamma_5 q)}{\Lambda^2} \]

Signal Generator:
Madgraph4 + Pythia6.

Cross section depends on the mass of DM, and the scale \( \Lambda \),

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

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

where \( \mu = \frac{m_\chi m_p}{m_\chi + m_p} \)

[Bai, Fox and Harnik, JHEP 1012:048 (2010)]

The 66 million silicon pixels and 9.3 million silicon strips, forming the tracker, are used to determine the trajectories of charged particles. The multilayer silicon detectors provide accurate tracking of charged particles with excellent efficiency, especially important for the high-pileup conditions at the LHC. The magnetic field curves the trajectories of charged particles, allowing the measurement of their momenta. The track-finding efficiency is more than 99% and the uncertainty in the measurement of transverse momentum, $p_T$, (projection of the momentum vector onto the plane perpendicular to the beam axis) is between 1.5% and 3% for charged tracks of $p_T \sim 100$ GeV. By extrapolating tracks back towards their origins the precise proton-proton interaction points, or collision vertices, can be determined. Decay vertices of long-lived particles containing heavy-quark flavors, such as $B$-mesons, can similarly be identified and reconstructed. Such "b-tagging" is particularly useful in searches for previously unobserved particles, such as the Higgs boson.

The electromagnetic calorimeter (ECAL) absorbs photons and electrons. These produce showers of particles in the dense crystal material, which yield scintillation light detected by photo-detectors glued to the rear faces of the 75,848 crystals. The amount of light detected is proportional to the energy of the incoming electron or photon, allowing their energies to be determined with a precision of about 1% in the region of interest for the analyses reported here. Since electrons are charged particles they can be discriminated from photons by matching the ECAL signal with a track reconstructed in the tracker.

Hadrons can also initiate showers in the ECAL, but they generally penetrate further into the detector, reaching the hadron calorimeter (HCAL) surrounding the ECAL. The measurements of particle energies in the HCAL are not as precise as those of the ECAL but are well adapted to the needs of the CMS physics program.

The solenoid is surrounded by a large detector system that identifies and measures momenta of muons. It comprises three different types of gas-ionization detectors that enable muon momenta to be measured.
Triggers used for Dark Matter search at CMS

### Monojet + MET
- Unprescaled jet+MET triggers.
- Fully efficient with $|\eta_{\text{jet}}| < 2.4$ and $P_T^{\text{jet}} > 110$ GeV/c.
- Fully efficient with MET > 200 GeV.

### Monophoton + MET
- Unprescaled single-photon triggers.
- Fully efficient with $|\eta_{\text{photon}}| < 1.442$ and $P_T^{\text{photon}} > 145$ GeV/c.
Monojet study at CMS

**Extra Dimensions** : The Hierarchy Problem and New Dimensions at a Millimeter, hep-ph/9803315

**Unparticles** : Unparticle Physics, hep-ph/0703260

**Dark Matter**
- Missing Energy Signatures of Dark Matter at the LHC, 1109.4398
- Taking a Razor to Dark Matter Parameter Space at the LHC, 1203.1662
- Inelastic Dark Matter at the LHC, 1109.4144
- Constraints on Light Majorana Dark Matter from Colliders, 1005.1286
- Constraints on Dark Matter from Colliders, 1008.1783
- LHC Bounds on Interactions of Dark Matter, 1108.1196
- LHC Bounds on UV-Complete Models of Dark Matter, 1111.2359
- Light dark matter and Z' dark force at colliders, 1202.2894
- LHC and Tevatron bounds on the dark matter direct detection cross-section for vector mediators, 1204.3839

**Light stop and compressed mass spectra**
- Light Stop Searches at the LHC with Monojet Events, 1201.5714
- Light Stop Searches at the LHC in Events with two b-Jets and Missing Energy, 1011.5508
- Light Stop Searches at the LHC in Events with One Hard Photon or Jet and Missing Energy, 0808.2298
- Searching for Direct Stop Production in Hadronic Top Data at the LHC, 1205.5816
- How low can SUSY go? Matching, monojets and compressed spectra, 1207.1613

**Higgs**
- Direct detection of Higgs-portal dark matter at the LHC, 1205.3169
- Reconstructing Higgs boson properties from the LHC and Tevatron data, 1203.4254

**Other**
- Searches for New Physics: Les Houches Recommendations for the Presentation of LHC Results, S. Kraml et al, 1203.2489
- Supersymmetry production cross sections in pp collisions at sqrt(s) = 7 TeV, 1206.2892
- Monotops at the LHC, 1106.619
- Supersymmetric Monojets at the Large Hadron Collider, 1010.4261

Sarah Alam Malik
Search for Dark Matter in Monojet events

- Event Cleaning using cuts based on jet constituents.
- Large missing transverse energy, MET > 350 GeV.
- One energetic jet, $p_T > 110$ GeV/c, $|\eta| < 2.4$.
- Allow one additional jet (if it has $p_T > 30$ GeV/c).

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059
Search for Dark Matter in Monojet events

- Reject event if it has more than 2 jets ($p_T > 30$ GeV/c).
- Reject event if $\Delta \phi (\text{jet}1, \text{jet}2) > 2.5$, QCD rejection.
- Reject event if it has an isolated electrons, an isolated muons, or isolated tracks with $p_T > 10$ GeV/c.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059
Background of DM Monojet events

**Z(νν)+jets, just like signal.**
(Data-Driven)

**W+jets, e or μ is not identified** (Data-Driven),
or \(τ\) decays hadronically (MC).

**QCD, jet is mismeasured, producing MET** (MC).
Background of DM Monojet events

Data-driven estimation: $Z \rightarrow \nu \nu$

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

$$N(Z \rightarrow \nu \nu) = \frac{N^{obs} - N^{bgd}}{A \times \epsilon} \cdot R\left(\frac{Z \rightarrow \nu \nu}{Z \rightarrow ll}\right)$$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059
Background of DM Monojet events

Data-driven estimation: W+jets where lepton is lost

- Control sample W→μν.
- Select single muon same as signal.
- Well isolated muon pT >20 GeV/c, |η| < 2.1.
- Transverse mass between 50-100 GeV/c².
- Uncertainty ~11% mainly from acceptance (8%), and selection efficiency (7%)

![Graph showing the invariant mass and transverse momentum distribution of the dimuon pair](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059)

\[
N_{A} = N_{\text{tot}} \cdot (1 - A) \\
N_{\epsilon} = N_{\text{tot}} \cdot A \cdot (1 - \epsilon)
\]

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059
Search for Dark Matter in Monojet events

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV/c)</th>
<th>$\geq 250$</th>
<th>$\geq 300$</th>
<th>$\geq 350$</th>
<th>$\geq 400$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Events</td>
<td>Events</td>
<td>Events</td>
<td>Events</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>

The Standard Model background prediction compared with data passing selection cuts for various MET thresholds in number of events corresponding to integrated luminosity of 5 $fb^{-1}$.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059
Search for Dark Matter in Monojet events

\[
\text{MET} = 598.3 \text{ GeV} \\
\text{P}_{\text{jet}} = 574.2 \text{ GeV/c}
\]

[Link to CERN TWiki page](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059)
Search for Dark Matter in Monophoton events

Selection:
- High energy photon, \( p_T > 145 \text{ GeV}/c \).
- Central region of detector, \(|\eta| < 1.442\).
- Shower shape in calorimeter consistent with photon.
- Large missing transverse energy, \( \text{MET} > 130 \text{ GeV} \).

Remove events with excessive nearby activity:
- Veto events with nearby tracks or pixel stubs
- Veto events with significant electromagnetic calorimeter activity (\( \Delta R < 0.4 \))
- Veto events with significant hadronic activity (\( \Delta R < 0.4, \text{EHCAL}/\text{EECAL} < 0.05 \))
- No central jet: veto events with \( p_T(\text{jet}) > 40 \text{ GeV}/c \) and \(|\eta_{\text{jet}}| < 3.0 \)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11096
Background of DM Monophoton events

Backgrounds from pp collisions

- $pp \rightarrow Z \gamma \rightarrow \nu\nu \gamma$
- $pp \rightarrow W \rightarrow e\nu$
- $pp \rightarrow \text{jets} \rightarrow \text{“}\gamma\text{”} + \text{MET}$

- $pp \rightarrow \gamma + \text{jet}$
- $pp \rightarrow W\gamma \rightarrow l\nu\gamma$
- $pp \rightarrow \gamma \gamma$

Irreducible background (MC)
Electron mis-identified as photon (Data-Driven)
One jet mimics photon, MET from jet mismeasurement (Data-Driven)
MET from jet mis-measurement (MC)
Charged lepton escapes detection (MC)
One photon mis-measured to give MET (MC)

Backgrounds unrelated to pp collisions

- Showers induced by cosmics
  Identified and removed (Data-Driven)
- Neutron-induced signals
  Identified and removed (Data-Driven)
- Beam halo
  Mostly removed, A residual contribution estimated (Data-Driven)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11096
Search for Dark Matter in Monophoton events

\[ \text{MET} = 407 \text{ GeV} \]
\[ P_T^{\text{photon}} = 384 \text{ GeV/c} \]

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11096
The 90% CL upper limits on the dark matter-nucleon scattering cross section versus dark matter mass for the spin-independent models.

Unexplored region of DM mass < 3.5 GeV.
The 90% CL upper limits on the dark matter-nucleon scattering cross section versus dark matter mass for the spin-dependent models.

Stringent constrains over 1-200 GeV mass range.
- Presented the results from searches for dark matter from monojet+MET and monophoton+MET channels at CMS using 5.0 fb$^{-1}$ of 2011 LHC Data (7TeV).

- Predictions for Standard Model background consistent with observed data.

- Limits were set on DM-Nucleon scattering cross-section, to compare with direct and indirect detection measurements.

- Looking forward for 2012 Data.

References
Monophoton+MET
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11096

Monojet+MET
JHEP 1209 (2012) 094  
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059