Recent results from a search for Dark Matter production in the CMS experiment

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On behalf of the CMS Collaboration
There is strong astrophysical evidence for the existence of dark matter

- Evidence from bullet cluster, gravitational lensing, rotation curves

Direct detection experiments

- Aim to observe recoil of dark matter off nucleus
- Excesses observed by several experiments, not confirmed by others

Need for independent verification from non-astrophysical experiments

- Low mass region not accessible to direct detection experiments
- Limited by threshold effects, energy scale, backgrounds; less sensitive to spin-dependent couplings

Colliders provide alternative, complementary way to search for dark matter
In framework of effective theory, assume DM(χ) is a Dirac fermion and interaction is characterized by *contact interaction*

- Set mass of mediator (M) to very high value

✓ heavy mediator can be integrated out

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

- Consider two possibilities:
  a) Vector mediator:
     - Spin dependent
  b) Axial-Vector mediator:
     - Spin independent

**Effective operators**

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

\[ \mathcal{O}_{AV} = \frac{(\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{q} \gamma^\mu \gamma_5 q)}{\Lambda^2} \]
Dark Matter production results in missing transverse energy (MET).

Photons (or jets from a gluon) can be radiated from quarks:
- monophoton (or monojet) plus MET.
### CMS Detector

#### Pixels Tracker
- ECAL
- HCAL
- Solenoid
- Steel Yoke
- Muons

#### SILICON TRACKER
- Pixels (100 x 150 μm²)
  - ~1m² ~66M channels
- Microstrips (80-150μm)
  - ~200m² ~2 BM channels

#### CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76k scintillating PbWO₄ crystals

#### PRESHOWER
- Silicon strips
  - ~16m² ~137k channels

#### STEEL RETURN YOKE
- ~13000 tonnes

#### SUPERCONDUCTING SOLENOID
- Nobium-titanium coil
  - carrying ~16000 A

#### HADRON CALORIMETER (HCAL)
- Brass + plastic scintillator
  - ~7k channels

#### FORWARD CALORIMETER
- Steel + quartz fibres
  - ~2k channels

### Specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total weight</td>
<td>14000 tonnes</td>
</tr>
<tr>
<td>Overall diameter</td>
<td>15.0 m</td>
</tr>
<tr>
<td>Overall length</td>
<td>28.7 m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>3.8 T</td>
</tr>
</tbody>
</table>

### Muon Chambers
- Barrel: 250 drift tube & 480 resistive plate chambers
- Endcaps: 473 cathode strip & 432 resistive plate chambers
Monophoton- Search Details

- **Require a photon in an event:**
  - High energy photon: $p_T(\gamma) > 145$ GeV/c
  - In the central part of the detector: $|\eta| < 1.442$
  - 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 ($\Delta R < 0.4, E_{\text{HCAL}}/E_{\text{ECAL}} < 0.05$)
  - Shower shape consistent with photon: $\sigma_{\text{inh}} < 0.013$
  - All reconstructed vertices are used for isolation calculations.

- **MET > 130 GeV, using a particle flow method**

- **Remove events with excessive activity**
  - No central jet: veto events with $p_T(\text{jet}) > 40$ GeV/c and $|\eta_{\text{jet}}| < 3.0$
  - No tracks with $p_T > 20$ GeV/c
Monophoton- Event Display
Monophoton - Backgrounds

- **Backgrounds estimated from MC and data-driven (DD) techniques**
  - Backgrounds from pp collisions
    - $pp \rightarrow Z \gamma \rightarrow \nu\nu\gamma$: irreducible background (MC)
    - $pp \rightarrow W \rightarrow e\nu$: electron mis-identified as photon (DD)
    - $pp \rightarrow \text{jets} \rightarrow \text{“}\gamma\text{”} + \text{MET}$: one jet mimics photon, MET from jet mis-measurement (DD)
    - $pp \rightarrow \gamma + \text{jet}$: MET from jet mis-measurement (MC)
    - $pp \rightarrow W\gamma \rightarrow l\nu\gamma$: charged lepton escapes detection (MC)
    - $pp \rightarrow \gamma\gamma$: one photon mis-measured to give MET (MC)

- Backgrounds unrelated to pp collisions
  - Showers induced by cosmics: identified and removed (DD)
  - Neutron-induced signals: identified and removed (DD)
  - Beam halo: mostly removed; a residual contribution estimated (DD)

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

➢ Counting Experiment
Background processes describe the data well and no excess is observed.
Signal Generation
- Dark Matter model follows effective theory outlined in earlier slide
- Madgraph4 + Pythia6 generation with 10 TeV mediator mass and assume cross section scales as $\Lambda^{-4}$.
- Similar sensitivity to spin-dependent and spin-independent

Acceptance times efficiency for Dark Matter signal
- $A \times \varepsilon \approx 0.3$, for both vector operator and axial-vector operator
- Kinematics mainly from ISR photon; $A \times \varepsilon$ is fairly constant in the range $m_\chi = 1\text{-}1000$ GeV

Systematic uncertainties
- Stats. Uncertainty 1.7%
- Photon PT uncertainty 2.3%
- Jet Energy Scale 1.2%
- MET modeling 0.5%
- Pile-up modeling 2.4%
- Jet veto modeling 10%
Limit-setting
- For an integrated luminosity of $5.0 \text{ fb}^{-1}$: $75.1 \pm 9.5$ expected and $73$ observed
- $90\%$ CL limits shown below, “expected” limits in parenthesis ($95\%$ also available)

Extraction of $\chi$-nucleon cross section
- Upper limits on cross sections give lower limits on the scale $\Lambda$, assuming a $\Lambda^{-4}$ behavior
- The lower limits on $\Lambda$ are then used to calculate the $\chi$-nucleon cross section limits versus DM mass

$$\sigma_{SI} = 9 \frac{\mu^2}{\pi \Lambda^4} \quad \sigma_{SD} = 0.33 \frac{\mu^2}{\pi \Lambda^4} \quad \text{where} \quad \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

[OBSERVED(EXPECTED) 90% CL upper limits on the DM production cross section $\sigma$, and 90% CL lower limits on the cutoff scale $\Lambda$ for vector and axial-vector operators as a function of the dark matter mass $M_\chi$]
Monophoton - spin-independent limits

$\chi$-Nucleon Cross Section $[\text{cm}^2]$

Spin Independent
- CMS (90%CL)
- CDMS II 2011
- CDF
- CDMS II 2010
- XENON100
- CoGeNT 2011

CMS, $\sqrt{s} = 7$ TeV

5.0 fb$^{-1}$

$M_\chi$ [GeV]

[CDMS II: Science 327 (2010) 1619]
Monophoton - spin-dependent limits

CMS, $\sqrt{s} = 7$ TeV
$5.0$ fb$^{-1}$

$\chi$-Nucleon Cross Section [cm$^2$]

$M_\chi$ [GeV]

Spin Dependent
- CMS (90% CL)
- CDF
- IceCube ($\chi\chi \rightarrow W^+W^-$)
- Super-K I+II+III ($\chi\chi \rightarrow W^+W^-$)

[CDMS II: Science 327 (2010) 1619]
Monojet - search details

- Select sample of Monojet+MET events (keeping muons)
  - Basic cuts on jet constituents - charged and neutral HAD and EM fractions
  - Removes cosmics, instrumental backgrounds, mis-measured jets

- Basic topological selection
  - MET > 200 GeV, number of Jets = 1 or 2
  - Particle flow jets; anti-k_T with R = 0.5
  - Leading Jet: p_T > 110 GeV, |η|<2.4
  - Second Jet: p_T > 30 GeV
  - Δφ(jet1,jet2) < 2.5

• Monojet Signal Sample (Lepton Rejection)
  - Reject events with e, μ isolated in a cone of ΔR = 0.3
  - Reject events with tracks isolated in a cone of ΔR = 0.3
  - MET > 350 GeV for DM search

• Data-driven Background Estimation (Lepton Identification)
  - Isolated muon > 20 GeV/c
  - Obtain Z+jet sample from M(μμ), W+jet sample from pT(μ)+MET
Monojet – event display
Monojet - basic selection

- Basic topological selection
  - MET > 200 GeV, number of Jets = 1 or 2
  - Leading Jet: $p_T > 110$ GeV, $|\eta| < 2.4$
  - Second Jet: $p_T > 30$ GeV
  - $\Delta \phi(\text{jet1, jet2}) < 2.5$

QCD rejection accomplished by topological cuts
Final monojet signal sample obtained by
- Rejecting events with isolated $e$, $\mu$
- Rejecting events with isolated tracks

Good agreement for full MET range
- Sensitivity to new physics (DM, ADD) in the tails

Optimize search for best expected sensitivity to new physics:
- MET $> 350$ GeV for DM search

Search high MET events for DM
**Monojet - analysis cut flow**

- Primary backgrounds normalized to data-driven estimation
- Remaining backgrounds after full event selection are: $Z(vv)$ ($\approx 70\%$), $W+$jets ($\approx 30\%$),
- Other backgrounds from QCD, top, $Z+$jets negligible ($\approx 1\%$) - estimated from MC

<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><strong>Process</strong></td>
<td>Events</td>
<td>Events</td>
<td>Events</td>
<td>Events</td>
</tr>
<tr>
<td>$Z(v\bar{v})+$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>
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<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><strong>Total SM</strong></td>
<td>7842 ± 367</td>
<td>2757 ± 167</td>
<td>1225 ± 101</td>
<td>573 ± 65</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>7584</td>
<td>2774</td>
<td>1142</td>
<td>522</td>
</tr>
</tbody>
</table>
Data-driven estimation of $Z$+jets $\rightarrow$ $\mu\mu$+jets
- $Z$+jets $\rightarrow$ $\mu\mu$+jets control sample derived directly from monojet data sample
- Require two muons passing selection
- Invariant mass 60-120 GeV, opposite sign
- Uncertainty in method is 10.4% mainly from stats (9.5%)

Similar for $W$+jets $\rightarrow$ $vl$+jets, where lepton is “lost”
- Lepton lost if outside detector acceptance or not reconstructed/isolated
- Require single lepton and $M_T$ between 50-100 GeV
- Primary uncertainties from uncertainties on acceptance (7.7 %) and selection efficiency (6.8 %)
- Total uncertainty in method is 11.3%

Data-driven measure of main backgrounds
Monojet - Dark Matter Signal

- Monojet Signal Generation
  - Madgraph5 + Pythia6 generation with 40 TeV mediator mass
- Systematic uncertainties ≤15%, main contributions from
  - Jet Energy Scale
  - PDF (PDF4LHC)
  - Jet Energy Resolution
  - Luminosity
- Final numbers for MET > 350 GeV: 1225 ± 101 background, 1142 data

<table>
<thead>
<tr>
<th>$M_X$ (GeV/c²)</th>
<th>Spin-dependent $\Lambda$ (GeV)</th>
<th>$\sigma_{XN}$ (cm²)</th>
<th>Spin-independent $\Lambda$ (GeV)</th>
<th>$\sigma_{XN}$ (cm²)</th>
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<tr>
<td>0.1</td>
<td>754</td>
<td>$1.03 \times 10^{-42}$</td>
<td>749</td>
<td>$2.90 \times 10^{-41}$</td>
</tr>
<tr>
<td>1</td>
<td>755</td>
<td>$2.94 \times 10^{-41}$</td>
<td>751</td>
<td>$8.21 \times 10^{-40}$</td>
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<tr>
<td>10</td>
<td>765</td>
<td>$8.79 \times 10^{-41}$</td>
<td>760</td>
<td>$2.47 \times 10^{-39}$</td>
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<tr>
<td>100</td>
<td>736</td>
<td>$1.21 \times 10^{-40}$</td>
<td>764</td>
<td>$2.83 \times 10^{-39}$</td>
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<tr>
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<td>677</td>
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<td>$4.30 \times 10^{-39}$</td>
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<td>400</td>
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<td>$4.74 \times 10^{-40}$</td>
<td>631</td>
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<tr>
<td>700</td>
<td>341</td>
<td>$2.65 \times 10^{-39}$</td>
<td>455</td>
<td>$2.28 \times 10^{-38}$</td>
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<tr>
<td>1000</td>
<td>206</td>
<td>$1.98 \times 10^{-38}$</td>
<td>302</td>
<td>$1.18 \times 10^{-37}$</td>
</tr>
</tbody>
</table>
Dark Matter spin-independent limits

Best limits for low mass DM, below 3.5 GeV, a region as yet unexplored by direct detection experiments
Limits represent the most stringent constraints by several orders of magnitude over entire 0.1-200 GeV mass range
Summary

- Presented searches for new physics in monojet and monophoton channels using 5.0 fb⁻¹ of data.

- Predictions for SM background consistent with observed data, *no excess* found. Limits are set on Dark Matter production, resulting in a significant extension of previously excluded parameter space:

  - For spin-independent models, best limits for low mass DM, below 3.5 GeV, a region as yet unexplored by the direct-detection experiments.

  - For spin-dependent models, limits represent the most stringent constraints by several orders of magnitude over entire 0.1-200 GeV mass range studied.

References: EXO-11-059 (monojet) and EXO-11-096 (monophoton) at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
Thank you!