Non-Hadronic Searches for Dark Matter at CMS

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SUSY 2016 July 4-8
Melbourne, Australia
Outline

- Signatures of Dark Matter at the CMS
- Detection in CMS
- Different Channels
  - Monophoton: 2015 (2.3 fb$^{-1}$)
  - Mono-boson (W): 2012 (19.7 fb$^{-1}$)
  - Mono-boson (Z): 2012 (19.7 fb$^{-1}$)
  - ZH: 2015 (2.3 fb$^{-1}$)
Detection Techniques

- Three major categories of investigations.
- Important to maintain the theoretical connection between these approaches.
Detection Techniques

Scattering of DM particles on nuclei of detector material; detect recoil. For a given cross section, sensitivity scales with detector size.
Detection Techniques

Assume annihilation of DM particles, eg. In the sun. Detect annihilation products.

Indirect Detection

Scattering of DM particles on nuclei of detector material; detect recoil. For a given cross section sensitivity scales with detector size.
Detection Techniques

Assume annihilation of DM particles, eg. In the sun. Detect annihilation products.

Indirect Detection

Direct Detection

DM

SM

DM

SM

Indirect Detection

Collider

DM may be pair produced in pp collisions at the LHC, with masses <1/2 parton-parton c.o.m. Yields experimental signature of MET

Scattering of DM particles on nuclei of detector material; detect recoil. For a given cross section sensitivity scales with detector size.
Dark Matter at the LHC (Run-1)

New physics expressed with a contact interaction between DM and SM particles.

Use effective field theory (EFT) to describe interactions in a model independent way.

Signature oriented search
EFT and Simplified Models

- EFT depend only on **two parameters**:
  - DM mass $m_\chi$ and interaction scale $\Lambda \approx M / \sqrt{g_\chi g_q}$

- EFT are reliable only if $M^2 \gg <Q^2>$ — not always true at LHC energies!

- **Truncation**: remove signal events where $Q^2 > M^2 \sim g_\chi g_q \Lambda^2$

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
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<tbody>
<tr>
<td>D1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_q}{M^2} \bar{\chi} q \bar{q}$</td>
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<tr>
<td>D5</td>
<td>$qq$</td>
<td>vector</td>
<td>$\frac{1}{M^2} \bar{\chi} \gamma^{\mu} \chi q \bar{q} \gamma_{\mu}$</td>
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<tr>
<td>D8</td>
<td>$qq$</td>
<td>axial-vector</td>
<td>$\frac{1}{M^2} \bar{\chi} \gamma^{\mu} \gamma^5 \chi q \bar{q} \gamma^{\mu} \gamma^5 q$</td>
</tr>
<tr>
<td>D9</td>
<td>$qq$</td>
<td>tensor</td>
<td>$\frac{1}{M^2} \bar{\chi} \sigma^{\mu\nu} \chi q \bar{q} \sigma_{\mu\nu} q$</td>
</tr>
</tbody>
</table>

$\chi$ is a Dirac fermion
How to make DM visible at the LHC?

Mono-X Signatures – simple and striking

- **2012**
  - MonoZ+MET
    - CMS-PAS-EXO-12-060
    - Full 2012 dataset 20/ fb

- **2015**
  - Monophoton+ MET
    - CMS-PAS-EXO-15-014
    - Full 2015 dataset 2.3/ fb

- **2012**
  - MonoW+ MET
    - CMS-PAS-EXO-13-004
    - Full 2012 dataset 20/ fb

- **Monotop+MET**
- See talk of Douglas Ryan Berry
- **Bbbar/TTBar**
Search for Pair Produced Dark Matter in **Mono-photon** Channel

- Characterized by a high-energy photon and large $E_T^{\text{miss}}$
  - Photon from initial-state EM radiation
    - 8 TeV: EFT with contact interaction, $qq\chi\chi$
    - 13 TeV: Simplified model with intermediate boson in s-channel, $qq \rightarrow V \rightarrow \chi\chi$

- Electroweak model with direct photon-DM interaction
  - 13 TeV only: EFT with dimension-7 operator, $\gamma\gamma\chi\chi$

**New 2015 results**


CMS-PAS-EXO-16-014
Mono-photon : Event Selection

*Search for single photon recoiling against MET*

- One energetic photon $p_T > 175$ GeV, $|\eta| < 1.44$
- Missing Transverse Energy : $\text{MET} > 170$ GeV
- Azimuthal separation between photon and MET $\Delta\Phi (\text{photon, MET}) > 2$

**Reject backgrounds**

- Backgrounds with leptons ($W \rightarrow \ell\nu, Z \rightarrow \ell\ell$)
  - **Lepton veto**: reject $e$ or $\mu$ with $p_T > 10$ GeV

- **Noncollision backgrounds** (electronic noise, beam-halo & cosmic-ray muons):
  - **Timing**: EM showers within $\pm 3$ ns of the time expected for collision product

- Backgrounds with jets ($\gamma + \text{jets}$)
  - Azimuthal separation between closest jet and MET $\Delta\Phi (\text{jet, MET}) > 0.5$
Mono-Photon: Main Backgrounds

\[ Z\gamma \to \nu\nu\gamma, \ W\gamma \to (\ell)v\gamma \ (\ell \text{ not reconstructed}) \sim 80\% \text{ of total background} \]

- estimated from simulations with NNLO QCD & NLO EW corrections
- validated using data control samples: \( Z\gamma \to \ell^+\ell^-\gamma, \ W\gamma \to \ell v\gamma \)

\[ W \to e\nu \text{ with } e \text{ misidentified as a photon} \]

- measured in \( W \to e\nu \) data, with data-driven \( e \to \gamma \) mis-ID rate

**QCD multijet** events with a jet misidentified as a photon

- measured in jet-enriched data, with data-driven jet \( \to \gamma \) mis-ID rate

**Fake photons**

**Noncollision**

Noncollision background (mostly beam halo)

Measured in data from a template fit to calorimeter timing profiles
Mono-photon Results: Photon $E_T$ Spectra

$\sqrt{s} = 8$ TeV, $L = 19.6$ fb$^{-1}$

- $\gamma + \text{jet, } W(\mu\nu), \gamma\gamma, Z(l\nu)$
- Beam halo
- Jet $\rightarrow \gamma$ MisID
- Electron $\rightarrow \gamma$ MisID
- $W\gamma \rightarrow l\nu\gamma$
- $Z\gamma \rightarrow \nu\nu\gamma$

Data, Bkg. uncertainty, SM + ADD ($M_D = 2$ TeV, $n=3$)

$\sqrt{s} = 13$ TeV, $L = 2.3$ fb$^{-1}$

- $\gamma + \text{jet, } W(\mu\nu), Z(l\nu)$
- Beam-halo
- Spikes
- Jet $\rightarrow \gamma$ MisID
- Electron $\rightarrow \gamma$ MisID
- ADD, MD = 2 TeV, n = 5
- Bkg. uncertainty

Data

Bhawna Gomber, Dark Matter Searches at CMS 7/5/16
Mono-photon

Results: Limits on Visible Cross Section

- Using the CLs construct and a profile-likelihood test statistic, 95% CL limits are set on the cross section \( \times \) acceptance at 8 TeV, in a region defined by \( E_T^{\text{miss}} > 140 \) GeV and different photon \( E_T^\gamma \) minimum cuts.

- For comparison, the limit on the 13 TeV cross section is shown for \( E_T^{\text{miss}} > 170 \) GeV, \( E_T^\gamma > 175 \) GeV:
  \[
  \sigma_{13 \text{ TeV}} \times A < 10.7 \text{ fb}
  \]
Mono-photon

Interpretation: Vector and Axial-Vector Mediators

- Comparing the cross section limits with models of DM production via vector and axial-vector mediators, constraints on such models are set in the DM mass-mediator mass plane, \( m_{\text{DM}} - M_{\text{med}} \).

- 13 TeV data, 2.3 fb\(^{-1}\): counting experiment approach, simplified.
Translate production cross-section limit into DM-nucleon limit

- Purpose: to compare to direct detection limits
For each model, limits on the **DM-pair production** at the LHC ($qq \rightarrow \chi\chi$) Translated into limits on the **DM-nucleon elastic scattering** ($\chi N \rightarrow \chi N$) and compared with results from **direct-detection experiments**
Mono-photon: Electroweak Dim-7 Operator

- **EFT with contact interaction** of type $\gamma \chi \chi$ opens channel $qq \rightarrow \gamma^* \rightarrow \gamma \chi \chi$
- Two main parameters: DM mass $m_{DM}$ and suppression scale $\Lambda$
- Upper limits on the production cross section are translated into lower limits on $\Lambda$

For low DM mass, values of $\Lambda$ up to $\sim 540$ GeV are excluded at 95% CL.
Search for Pair Produced Dark Matter in **Mono-$W(\ell\nu)$ Channel**

**Signature:** $W$+MET

- high $p_T$ electron +MET
- high $p_T$ muon + MET

**CMS-PAS-EXO-13-004**

20/fb of 2012 pp data at 8 TeV

**Phys. Rev. D 91, 092005**

2012 results
**Mono-W(ℓν) : Interference**

- Lower rate than mono-jet and mono-photon, but cleaner signature
  - Lower background, lower trigger thresholds

- Mono-jet/photon channel insensitive to quark type

- For W possibly different coupling to u- and d-type quarks

  If \( C(u) = C(d) \) destructive interference

  If \( C(u) = -C(d) \) constructive interference **mono-boson more sensitive than mono-jet**

\[
\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \quad \bar{\chi} \quad \xi \cdot \bar{d} \quad \bar{\chi}
\]

Neutrino+DM contribute to MET
Mono-W(ℓν) Selection

Event Selection

■ Single electron (muon) trigger with \( p_T > 85 \) \((40) \) GeV

■ Kinematics selection:
  ■ \( 0.4 < \frac{p_T}{MET} < 2 \)
  ■ \( \Delta \Phi > 2.5 \)

Transverse Mass distribution

\[ M_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{miss} \cdot (1 - \cos \Delta \phi_{\ell,\nu})} \]

Background

■ Derived from simulation
■ Challenge High MT tail
■ Main bkg: \( W \rightarrow l\nu \) with \( M_T \) binned K-factor
■ NLO xsec

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Mono-\(W(\ell\nu)\): Results and Interpretation

- Analysis performed on 19.7 \(fb^{-1}\) of data at 8 TeV
- Interpretation in terms of DM EFT with contact interaction \(qq\chi\chi\)
  - Limits on the \(pp \rightarrow W(\ell\nu)\chi\chi\) production from binned-likelihood fit to \(M_T\) spectrum
  - Converted to limits on the effective scale \(\Lambda\)

**Lower limit on \(\Lambda\)**

Spin-independent vector operator D5

(similar limits for axial-vector operator D8)

\(\Lambda > 0.3 - 1\) TeV, depending on the model parameter

For constructive interference \((\xi = -1)\) exclusion limits comparable with those from monojet
Search for Pair Produced Dark Matter in \textbf{Mono-Z(\ell\ell)} Channel

- Characterized by a \textit{pair of leptons} from a $Z$ boson + large $E_T^{\text{miss}}$
- Very clear signature, relatively low background, simple leptonic triggers

\textbf{Dielectron + $E_T^{\text{miss}}$ event at 8 TeV}

\textbf{Phys. Rev. D 93, 052011}
Mono-$Z(\ell\ell)$: Analysis Strategy

- **Signal selection**
  - Lepton pair $e^+e^-$ or $\mu^+\mu^-$ with mass in $M_Z \pm 10$ GeV and $p_T^{\ell\ell} > 45$ GeV
  - Large $E_T^{\text{miss}}$ + requirements on $\Delta\phi(\ell\ell, p_T^{\text{miss}})$ angle and $E_T^{\text{miss}}/p_T^{\ell\ell}$ balance
  - No additional leptons, no $b$-tagged jets

- **Main backgrounds**
  - $ZZ \rightarrow 2\ell 2\nu$, $WZ \rightarrow 2\ell (\ell)\nu$
    - estimated from simulation (with NLO cross section)
  - $WW$, $tt$, $tW$, $\tau\tau$
    - flavor symmetric, estimated from $e\mu$ data
  - $Z + \text{jets} \rightarrow 2\ell + \text{jets}$
    - estimated from simulation, with data-driven normalization from DY-enriched control sample
Mono-Z(ℓℓ) : Results and Interpretation

- Analysis performed on 19.7 fb\(^{-1}\) of data at 8 TeV in the context of an EFT
  - Limits computed from a profile-likelihood fit to the transverse mass spectrum
  - Limits on the DM-nucleon cross section for different models
  - Truncated limits are also provided
The same data can be used to search for Higgs bosons with invisible decays

- **Higgs-portal models:** Higgs as only mediator between SM and DM

**Signal:** SM-like Higgs (125 GeV), $B(H \rightarrow \text{invisible}) = 100\%$

**8 TeV Transverse mass**

```
Events
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<th>Events</th>
<th>Observed</th>
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<tr>
<td>200</td>
<td>ZZ</td>
</tr>
<tr>
<td>300</td>
<td>WZ</td>
</tr>
<tr>
<td>400</td>
<td>DY(II)+jets</td>
</tr>
<tr>
<td>500</td>
<td>tt,tW,WW,W+jets</td>
</tr>
<tr>
<td>600</td>
<td>ZH(m_H=125GeV), B(H → inv)=100%</td>
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</tbody>
</table>

$\sqrt{s} = 8 \text{ TeV}, L = 19.7 \text{ fb}^{-1}$
```

**13 TeV Transverse mass**

```
Events
<table>
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<th>Events</th>
<th>data</th>
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<td>20</td>
<td>ZH(125)</td>
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<td>WW+top-quark</td>
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<tr>
<td>10</td>
<td>WZ</td>
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<tr>
<td>5</td>
<td>Z+jets/γ</td>
</tr>
<tr>
<td>10</td>
<td>VVV</td>
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</table>

$\sqrt{s} = 13 \text{ TeV}, L = 2.3 \text{ fb}^{-1}$
```

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Mono-$Z(\ell\ell)$: Results and Interpretation

- The same data can be used to search for Higgs bosons with invisible decays

  ➔ Higgs-portal models: Higgs as only mediator between SM and DM

- Signal: SM-like Higgs (125 GeV), $B(H \to \text{invisible}) = 100\%$

  $7+8 \text{ TeV}$

  ![Graph showing $\sigma \times B(H \to \text{invisible})$ vs. $m_H$ for CMS data at 7+8 TeV and 13 TeV with 95% CL limits, observed limits, and expected limits with different luminosities and signal states.]

  $13 \text{ TeV}$

  ![Graph showing $\sigma_{q\bar{q} \to ZH}$ and $\times B(H \to \text{invisible})$ vs. Higgs boson mass at 13 TeV with observed, median expected, and various expected limits.]

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Bhawna Gomber, Dark Matter Searches at CMS
Summary

- **LHC dark matter searches are exciting.**
  - Major opportunity for new physics!
  - No DM yet 😞

- Several LHC BSM searches **reinterpreted** in terms of dark matter models.

- Work **closely with theorists** to develop theoretical assumptions and models.

- **Complementary** to direct detection experiments.

- **LHC Run 2 data taking is going pretty well**
  - New exciting results will come soon. Stay Tuned 😊
Monolepton $\xi = -1$ (max. Sensitivity)

2012 results in comparison to monojet and some direct detection experiments, 90% C.L.
Non-Collision Backgrounds

- Non-collision backgrounds are estimated using the ECAL timing information.

- First we look at full timing distribution of photons:
  - Default supercluster reconstruction algorithm discards hits with $|t| > 3$ ns cut.
  - Full re-reconstruction of 2015 performed removing this constraint.

**Halo Template**: Mip total energy > 4.9 GeV

**Spike Template**: Full candidate selection and reverse the topological shower shape spike cleaning cuts

**Prompt Template**: $W$ Candidates selection with pixel match and good shower shape

**Beam Halo**: 13.41 +/- 6.27 events

**Spike**: 5.63 +/- 2.2 events
Electron Selection

Electrons are reconstructed from energy clusters in the ECAL and tracks from the silicon tracker. Electron ID optimized for high $E_T$ requires:

- $E_T > 85$ GeV
- $|\eta| < 1.442$ (barrel) or $1.56 < |\eta| < 2.5$ (endcap)
- Good quality of track and cluster
- Matching between the two
- Isolation

ECAL made of matrix of fully active crystals. Measured energy resolution $\sim 2\%$

K. Hoepfner, RWTH Aachen | CMS Heavy Resonances |
Muon Selection

High redundancy of mu system, 4 stations along track
Iron between stations may cause **bremsstrahlung**
for O(TeV) muons
\( p_T < 200 \text{ GeV} \) tracker in \( B = 3.8 \text{T} \), \( p_T > 200 \text{ GeV} \) mu+tracker

**Dedicated muon selection:**

- Special algorithm to consider **showering**
- At least 1 **pixel** hit
- Number of **measured tracker layers** > 8
- Transverse impact parameter \( d_0 < = 0.2 \text{cm} \)
  - \( Z' \), 0.02 cm (\( W' \)) reject cosmics, value for \( W' \) tighter than
  - other analyses, \( Z' \) rejects in addition back-to-back muons
- \( \geq 2 \) matched **muon** segments
- Relative track **isolation** <0.10 in \( \Delta R < 0.3 \)
- No cut on **chi2** cut introduces a 4-6% inefficiency for
  - muons >500 GeV

\[ M_{\mu\bar{\mu}} = 1380 \text{ GeV} \]

\[ M_{\mu\bar{\mu}} = 1256 \text{ GeV} \]
Photon Selection

- Background contamination and invariant mass resolution depends on:
  - pseudorapidity
  - cluster shape, i.e. conversion probability (R9)

- Same approach like $H \rightarrow \gamma\gamma$ standard cut-based photon-ID
  - ECAL fiducial region ($|\eta| < 2.4$ excluding EB-EE gap)
  - Isolation and identification requirements:

<table>
<thead>
<tr>
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<th>barrel</th>
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<tbody>
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<td>6</td>
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<td>$R_9$</td>
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<td>0.94</td>
<td>0.24</td>
</tr>
</tbody>
</table>

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Higgs Modes : CMS VBF

Depending on its nature, DM will couple to the Higgs in various ways. Assuming a Higgs -> Invisible branching, one can search in several channels.

Z-> fermions

Di-jets
Higgs Modes : CMS ZH

**Z -> leptons**

**Z -> \(\bar{b}b\)**
CMS VBF + ZH limits

Combination of VBF and ZH, H → invisible

- √s = 8.0 TeV, L = 18.9-19.7 fb⁻¹ (VBF+ZH)
- √s = 7.0 TeV, L = 4.9 fb⁻¹ (ZH)

B(H → inv) < 0.51 @ 90% CL
m_H = 125 GeV

DM-nucleon cross section \(\sigma_{\chi-N}^s\) [pb]

DM Mass \(M_\chi\) [GeV]
Interference Parameterized by $\xi = -1, 0, +1$

Largest cross section for $\xi = -1$
For $M_\chi \lesssim 70$ GeV same cross section for V and AV coupling of fixed $\xi$

Interference type influences $M_T$ shape → impact on sensitivity
Limits on production cross section

\( \zeta = +1 \quad \Lambda < 300 \text{ GeV} \)

\( \zeta = 0 \quad \Lambda < 700 \text{ GeV} \)

\( \zeta = -1 \quad \Lambda < 1000 \text{ GeV} \)
The most tricky case is that of light mediator

First step: put in a mediating particle (e.g. s-channel $Z'$) and look at limits vs $m_z$

EFT gives good/conservative results above a few hundred GeV (high $M$)
- Region I – EFT is good
- Region II – EFT underestimate
- Region III – EFT overestimate

Buchmeller, Dolan, McCabe, arXiv: 1308.6799
Reach at 14 TeV?

Gain sensitivity with increasing sqrt(s).
At 14TeV and 300/fb. Reach in lambda O(x2)
Main challenge MET in high PU.