Dark Matter Searches in ATLAS

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on behalf of the ATLAS Collaboration

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PRISMA Cluster of Excellence

Rencontres de Moriond
Very High Energy Phenomena in the Universe
La Thuile, March 2017
Outline

• Dark Matter production @ pp colliders

• LHC and ATLAS

• Searches for Dark Matter particles
  • Monojet, Mono-Photon
  • Mono-W/Z
  • Mono-h
  • DM and Heavy Flavour
  • Dijet resonances

• Summary & Conclusions

“All right... which of you punks is responsible for dark matter?”
DM production @ pp colliders
DM production @ Colliders

- **Evidence** for DM first observed in galactic rotation curves
  - Today only one of many hints

- **Assumption** for the search at colliders:
  - DM particles interact with SM particles not just via Gravity
  - For simplicity DM assumed to be
    - a single Dirac fermion WIMP, stable on collider timescales and non-interacting with the detector
Production mechanisms

- **Simplified models**
  - Combined effort from ATLAS+CMS+Theory "Dark Matter Forum"
  - s-channel exchange of a mediator (new gauge boson) that couples to both SM and DM particles and ISR radiation (gluon or photon)
  - t-channel exchange of a charged color triplet
  - Free parameters: two masses (DM and mediator) and two couplings (SM and DM) [and width of mediator]
- **Direct DM-boson couplings** (very heavy mediator, EFT)
Dark Matter Searches in ATLAS

• pp Collider
• Run-2: \( \sqrt{s} = 13 \text{ TeV} \)
• Peak \( L > 1.4 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)
• 25ns bunch spacing
• High data taking efficiency (>90%)
• Nearly 4\pi coverage, excellent particle reconstruction and identification
Missing Transverse Energy

- Reconstruction of particles that do not interact with the detector is crucial for searches for DM particles.
  - Infer from transverse momentum imbalance of all reconstructed objects → Missing transverse Energy (MET)

- Effects due to additional collisions can be mitigated using information from the tracking detector → Track-based Soft Term (TST)

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**Graph:**

- **ATLAS** Preliminary
  - Data 2016, \( \sqrt{s} = 13 \text{ TeV} \)
  - \( Z \to \text{ee} \), 8.5 fb\(^{-1} \)
  - 0 jets, \( p_T > 20 \text{ GeV} \)
Jet reconstruction

- Quarks and gluons produced in the hard interaction undergo fragmentation and hadronization before entering the ATLAS detector.
- Reconstructed as so called “Jets” via a clustering algorithm (anti-k_t) using calorimeter clusters as input.
- Combines recursively pairs of objects based on their distance, that is related to
  \[ \Delta R_{ij} = \sqrt{\Delta \eta_{ij}^2 + \Delta \phi_{ij}^2} \]
- Radius parameter R defines final size of jets (standard: 0.4, large: 1.0)
- Can look for substructure in large jets (close-by jets reconstructed as one jet)
DM Searches
Monojet event

1 jet with $p_T$ of 973 GeV balanced by MET of 954 GeV

Figure 2.1: Representative Feynman diagram showing the pair production of Dark Matter particles in association with a parton from the initial state via a vector or axial-vector mediator. The cross section and kinematics depend upon the mediator and Dark Matter masses, and the mediator couplings to Dark Matter and quarks respectively: $(M_{\text{med}}, m_c, g_c, g_q)$.

$L_{\text{vector}} = g_q \bar{q} = u, d, s, c, b, t$

$L_{\text{axial vector}} = g_q \bar{q} = u, d, s, c, b, t$

$Z_0^\mu \bar{q} g^{\mu} q + g_c Z_0^\mu \bar{c} g^{\mu} c$ (2.1)

$\chi(\bar{q}gq)$

$q$ denotes the Heaviside step function, and $b_f = r_1 4 m_f^2 M_{\text{med}}^2$ is the velocity of the fermion $f$ with mass $m_f$ in the mediator rest frame. Note the color factor 3 in the quark terms. Figure 2.2 shows the minimal width as a function of mediator mass for both vector and axial-vector mediators assuming the coupling choice $g_q = g_c = 1$. With this choice of the couplings, the dominant contribution to the minimal width comes from the quarks, due to the combined quark number and color factor enhancement. We specifically assume that the vector mediator does not couple to leptons. If such a coupling were present, it would have a minor effect in increasing the mediator width, but it would also bring in constraints from measurements of the Drell-Yan process that would unnecessarily restrict the model space.
• SM processes can also lead to monojet-like signatures

• **Main backgrounds**
  - $Z \rightarrow \nu \bar{\nu} + \text{jets}$ and $W \rightarrow \tau \nu + \text{jets}$
  - Constrained using control regions selecting $W \rightarrow \mu \nu$ events, e.g.

\[
N_{Z(\rightarrow \nu \bar{\nu})}^{\text{signal}} = (N_{W(\rightarrow \mu \nu),\text{control}} - N_{W(\rightarrow \mu \nu),\text{control}}^{\text{non-W}}) \times \frac{N_{MC(Z(\rightarrow \nu \bar{\nu}))}^{\text{signal}}}{N_{MC}^{W(\rightarrow \mu \nu),\text{control}}}
\]

where the $\mu$ is considered invisible and added to the MET

=> reduced systematic uncertainties

• EW corrections/uncertainties for $W/Z+\text{jets}$ important

• Diboson and top quark background estimated from MC simulation only
Monojets - Signal region

- Signal regions are defined in inclusive (IM) and exclusive (EM) regions of MET

<table>
<thead>
<tr>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary vertex</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 250 \text{ GeV}$</td>
</tr>
<tr>
<td>Leading jet with $p_T &gt; 250 \text{ GeV}$ and $</td>
</tr>
<tr>
<td>At most four jets with $p_T &gt; 30 \text{ GeV}$ and $</td>
</tr>
<tr>
<td>$\Delta\phi(\text{jet}, \vec{p}_T^{\text{miss}}) &gt; 0.4$</td>
</tr>
<tr>
<td>Jet quality requirements</td>
</tr>
<tr>
<td>No identified muons with $p_T &gt; 10 \text{ GeV}$ or electrons with $p_T &gt; 20 \text{ GeV}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inclusive signal region</th>
<th>IM1</th>
<th>IM2</th>
<th>IM3</th>
<th>IM4</th>
<th>IM5</th>
<th>IM6</th>
<th>IM7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$ (GeV)</td>
<td>&gt; 250</td>
<td>&gt; 300</td>
<td>&gt; 350</td>
<td>&gt; 400</td>
<td>&gt; 500</td>
<td>&gt; 600</td>
<td>&gt; 700</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exclusive signal region</th>
<th>EM1</th>
<th>EM2</th>
<th>EM3</th>
<th>EM4</th>
<th>EM5</th>
<th>EM6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$ (GeV)</td>
<td>[250–300]</td>
<td>[300–350]</td>
<td>[350–400]</td>
<td>[400–500]</td>
<td>[500–600]</td>
<td>[600–700]</td>
</tr>
</tbody>
</table>

- Combined fit of control and signal regions to extract result
- MET dependent normalisation factors extracted within fit
- No significant excess above SM backgrounds observed

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14 Dark Matter Searches in ATLAS
• Limits given in plane of DM and mediator mass (left, CL=95%)
• Can be compared to limits from direct detection experiments (right, CL=90%)
• Model dependent (Axial Vector, \( g_q = 0.25, g_\chi = 1.0 \))!
Monophoton event

1 photon with $p_T$ of 265 GeV balanced by MET of 268 GeV
Monophoton analysis

- Events with isolated photon ($p_T > 150$ GeV) and MET ($> 150$ GeV) selected
  - Lepton veto
  - at most one jet
- Data driven background estimates in control regions
  - MET dependent normalisation factors (new w.r.t. to 3.2fb$^{-1}$ analysis)
  - dedicated methods for fake photons from electrons and jets
- No excess above SM expectation observed
- Translate into limits on Vector and Axial-vector mediator models
- Systematic uncertainties important
  - Esp. jet fake rate and jet energy scale
Monophoton results

- Results can also be translated into $\chi$-proton spin-dependent scattering cross-sections for comparison with direct searches
- LHC complements direct searches towards lower DM masses

Truncation effect visible for smaller couplings
EFT invalid for $M_{\text{cut}} = g^* M_*$

Observed 95% CL
Expected ± 1σ
Expected ± 2σ
truncated limits
Mono-W/Z Analysis

• Can also produce a W or Z together with DM particles. Two models considered:
  • Simplified Model with mediator in s-channel
  • Seven-dimensional VVχχ EFT

• Analysis strategy:
  • Select events with MET>300 GeV and boosted hadronically decaying W/Z (p_T>200 GeV)
    • Reconstructed as single large-R (1.0) jet
    • Make use of jet substructure inside large-R jets (also major source of systematic uncertainties -> 5-13% on yield)
  • Dominant background Z→νν constrained via Z→μμ
Mono-W/Z event candidate
**Mono-W/Z Results**

- No excess over SM prediction observed
- Results interpreted in
  - EFT model
    (mass scale of the model vs DM mass)
  - Simplified model
    (observed limit on the signal strength in plane of mediator and DM mass)
**Mono-Higgs → bb**

- Search for h+MET with h→bb
- **Two event categories** depending on boost of Higgs (split at MET=500 GeV)
- Two small jets (R=0.4, resolved) or one large-R jet (R=1.0, merged, substructure analysis)

<table>
<thead>
<tr>
<th>$E_{T}^{\text{miss}}$ [GeV]</th>
<th>Resolved</th>
<th>Merged</th>
</tr>
</thead>
<tbody>
<tr>
<td>150–200</td>
<td>200–350</td>
<td>350–500</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>259 ± 27</td>
<td>171 ± 13</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>95 ± 28</td>
<td>70 ± 22</td>
</tr>
<tr>
<td>$t\bar{t}$ &amp; Single top</td>
<td>1444 ± 44</td>
<td>656 ± 25</td>
</tr>
<tr>
<td>Multijet</td>
<td>21 ± 10</td>
<td>11.0 ± 5.0</td>
</tr>
<tr>
<td>Diboson</td>
<td>17.8 ± 1.6</td>
<td>18.7 ± 1.0</td>
</tr>
<tr>
<td>SM $Vh$</td>
<td>2.8 ± 1.3</td>
<td>2.8 ± 1.4</td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>1840 ± 33</td>
<td>930 ± 20</td>
</tr>
<tr>
<td>Data</td>
<td>1830</td>
<td>942</td>
</tr>
<tr>
<td>Exp. Signal</td>
<td>8.0 ± 0.8</td>
<td>24.5 ± 1.8</td>
</tr>
</tbody>
</table>

Graph showing the distribution of events with 2 b-tags, resolved and merged categories for $E_{T}^{\text{miss}}$.
• Results extracted from fit to dijet (resolved) or single jet (merged) mass
• Analysis limited by Data statistics
• No excess from SM background observed
• Result interpreted as limit in DM-mediator mass plane

mono-H → γγ analysis (not covered here): ATLAS-CONF-2016-087
• Associated production of DM with bottom quarks
• Exactly 2 b-tagged jets are required
• MET > 150 GeV
• No additional jet with more than 60 GeV
• Background reduction by requiring large angular separation and momentum imbalance between b-jets

\[ \text{Imb}(b_1, b_2) = \frac{p_T(b_1) - p_T(b_2)}{p_T(b_1) + p_T(b_2)} \]
DM + Heavy Flavour

- No excess over SM background has been observed
- Translates into upper limit on production cross-section for a scalar and a pseudo scalar mediator decaying into DM particles

### Table 3: Observed and Expected 95% CL Upper Limits on the Visible Cross-section

<table>
<thead>
<tr>
<th>Signal Channel</th>
<th>Observed 95% CL</th>
<th>Expected 95% CL</th>
</tr>
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<tbody>
<tr>
<td>SR 1</td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
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<tr>
<td>SR 3</td>
<td></td>
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<tr>
<td>SR 4</td>
<td></td>
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</tbody>
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Legend:
- Exp. ±1σ: Expected upper limit at 95% CL
- Exp. ±2σ: Expected upper limit at 95% CL
- Observed 95% CL: Observed upper limit at 95% CL

### Figures

- Scalar: bb+a, a → χ
- Pseudoscalar: bb+a, a → χ

### ATLAS Preliminary

\( \sigma/\sigma (g=1.0) \)

1. Translates into upper limit on production cross-section for a scalar and a pseudo scalar mediator decaying into DM particles.
2. No excess over SM background has been observed.

### Table 4: Results

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<td>SR 4</td>
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<td></td>
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<tr>
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<td></td>
</tr>
<tr>
<td>SR 4</td>
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</tr>
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Legend:
- Exp. ±1σ: Expected upper limit at 95% CL
- Exp. ±2σ: Expected upper limit at 95% CL
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### ATLAS Preliminary

\( \sigma/\sigma (g=1.0) \)

1. Translates into upper limit on production cross-section for a scalar and a pseudo scalar mediator decaying into DM particles.
2. No excess over SM background has been observed.
**Dijet resonances**

- DM mediator couples to SM particle and hence can also decay into SM particles
- Search for new resonance in dijet invariant mass spectrum
- N.B.: finding a new resonance does not mean we discovered DM!

**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, 37.0 \text{ fb}^{-1} \]

- Data
- Background fit
- BumpHunter interval
- \( q^* \), \( m_{q^*} = 4.0 \text{ TeV} \)
- \( q^* \), \( m_{q^*} = 5.0 \text{ TeV} \)

\[ |y^*| < 0.6 \]

Fit Range: 1.1 - 8.2 TeV

\( p_T \), \( J_{ES} \) Uncertainty

\[ m_{q^*} [\text{TeV}] \]

No excess

\[ \sigma_{q^*} \]

\[ \text{ATLAS Preliminary} \]

\[ \sqrt{s} = 13 \text{ TeV}, 37.0 \text{ fb}^{-1} \]

- Observed limit
- Expected limit

\[ 1.5, 2, 2.5, 3, 3.5 \text{ TeV} \]
**Dijet resonances**

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- Search for new resonance in dijet invariant mass spectrum
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**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, 37.0 \text{ fb}^{-1} \]

- Data
- Background fit
- Bump Hunter interval
- \( q^* \), \( m_q = 4.0 \text{ TeV} \)
- \( q^* \), \( m_q = 5.0 \text{ TeV} \)

No excess

Limits for different gaussian widths of mediator (particle level)

---

\[ \sigma \times A \times BR [\text{pb}] \]

\( \sigma \times A \times BR [\text{pb}] \)

Exp. 95% CL upper limit for \( \sigma_d/m_\alpha = 0 \)

Expected \( \pm 1 \sigma \) and \( \pm 2 \sigma \)

Obs. 95% CL upper limit for:

- \( \sigma_d/m_\alpha = 0.15 \)
- \( \sigma_d/m_\alpha = 0.10 \)
- \( \sigma_d/m_\alpha = 0.07 \)
- \( \sigma_d/m_\alpha = 0.03 \)
- \( \sigma_d/m_\alpha = 0 \)
Low mass dijet resonances

- SM cross-section for dijet production huge at the LHC
- Default analysis has to start above 1 TeV due to trigger and DAQ constraints
- 2 ways to circumvent this problem:
  - Dedicated data stream with minimal event information (jets) allows to go down to 450 GeV
  - Select events with additional initial state radiation of a photon/jet (trigger)

Not yet updated with latest results!
SM cross-section for dijet production huge at the LHC

- Default analysis has to start above 1 TeV due to trigger and DAQ constraints

2 ways to circumvent this problem:

- Dedicated data stream with minimal event information (jets) allows to go down to 450 GeV
- Select events with additional initial state radiation of a photon/jet (trigger)

New dijet result shifts exclusion to slightly higher values
• No evidence for DM found in any channel

• Large phase space closed by resonance searches

• $g_q = 0.25$ too “optimistic”?

Not yet updated with latest results!
Everything together

DM Simplified Model Exclusions  ATLAS Preliminary  August 2016

Mediator Mass [TeV]

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6

DM Mass [TeV]

0.2 0.4 0.6 0.8 1 1.2 1.4 1.6

Not yet updated with latest results!

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29  Dark Matter Searches in ATLAS
• Collider searches can provide valuable input to the search for Dark Matter
  • Especially at low masses

• Results are mostly interpreted in simplified models (required at LHC) that contain a dedicated mediator particle
  • Can also look for any sign of such a mediator particle (resonances)

• Unfortunately so far no evidence for physics beyond the Standard Model has been found

• Not all analyses make use of all of the available data yet and the LHC will provide plenty of new data in the coming years
  • Stay tuned!
### Table 7: Data and SM background predictions in the signal region for several inclusive and exclusive \(E_T^{miss}\) selections. For the SM prediction both the statistical and systematic uncertainties are included. In each signal region, the individual uncertainties for the different background processes can be correlated, and do not necessarily add in quadrature to the total background uncertainty.

<table>
<thead>
<tr>
<th>Signal Region</th>
<th>IM1</th>
<th>EM3</th>
<th>EM5</th>
<th>IM7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events (3.2 fb(^{-1}))</td>
<td>21447</td>
<td>2939</td>
<td>747</td>
<td>185</td>
</tr>
<tr>
<td>SM prediction</td>
<td>21730 ± 940</td>
<td>3210 ± 170</td>
<td>686 ± 50</td>
<td>167 ± 20</td>
</tr>
<tr>
<td>(W(\rightarrow e\nu))</td>
<td>1710 ± 170</td>
<td>228 ± 26</td>
<td>37 ± 7</td>
<td>7 ± 2</td>
</tr>
<tr>
<td>(W(\rightarrow \mu\nu))</td>
<td>1950 ± 170</td>
<td>263 ± 28</td>
<td>44 ± 8</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>(W(\rightarrow \tau\nu))</td>
<td>3980 ± 310</td>
<td>551 ± 47</td>
<td>101 ± 15</td>
<td>19 ± 4</td>
</tr>
<tr>
<td>(Z/\gamma^*(\rightarrow e^+e^-))</td>
<td>0.01 ± 0.01</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(Z/\gamma^*(\rightarrow \mu^+\mu^-))</td>
<td>76 ± 30</td>
<td>9 ± 5</td>
<td>5 ± 2</td>
<td>2 ± 1</td>
</tr>
<tr>
<td>(Z/\gamma^*(\rightarrow \tau^+\tau^-))</td>
<td>48 ± 7</td>
<td>5 ± 1</td>
<td>0.9 ± 0.2</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>(Z(\rightarrow \nu\bar{\nu}))</td>
<td>12520 ± 700</td>
<td>1940 ± 130</td>
<td>443 ± 42</td>
<td>109 ± 18</td>
</tr>
<tr>
<td>(t\bar{t}, \text{ single top})</td>
<td>780 ± 240</td>
<td>108 ± 32</td>
<td>19 ± 7</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>Dibosons</td>
<td>506 ± 48</td>
<td>82 ± 8</td>
<td>36 ± 5</td>
<td>15 ± 2</td>
</tr>
<tr>
<td>Multijets</td>
<td>51 ± 50</td>
<td>6 ± 6</td>
<td>1 ± 1</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td>Non-collision background</td>
<td>110 ± 110</td>
<td>19 ± 19</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
### Table 6

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>SRI1</th>
<th>SRI2</th>
<th>SRI3</th>
<th>SRE1</th>
<th>SRE2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background</td>
<td>2600</td>
<td>765</td>
<td>273</td>
<td>1900</td>
<td>501</td>
</tr>
<tr>
<td>Total (statistical+systematic) uncertainty</td>
<td>6.1%</td>
<td>7.7%</td>
<td>13.5%</td>
<td>7.7%</td>
<td>8.8%</td>
</tr>
<tr>
<td>Statistical uncertainty only</td>
<td>4.3%</td>
<td>6.2%</td>
<td>10.4%</td>
<td>5.5%</td>
<td>7.8%</td>
</tr>
<tr>
<td>Jet fake rate (Section 6.4)</td>
<td>1.3%</td>
<td>3.0%</td>
<td>5.3%</td>
<td>1.7%</td>
<td>3.3%</td>
</tr>
<tr>
<td>Electron fake rate (Section 6.3)</td>
<td>1.5%</td>
<td>1.5%</td>
<td>1.2%</td>
<td>1.5%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Jet energy scale [54]</td>
<td>4.1%</td>
<td>1.9%</td>
<td>1.4%</td>
<td>5.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Jet energy resolution [66]</td>
<td>0.7%</td>
<td>0.2%</td>
<td>0.5%</td>
<td>0.8%</td>
<td>0.3%</td>
</tr>
<tr>
<td>$E_T^{miss}$ soft term scale and resolution [58]</td>
<td>0.9%</td>
<td>0.4%</td>
<td>0.7%</td>
<td>1.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Muon reconstruction/isolation efficiency [50]</td>
<td>1.4%</td>
<td>1.3%</td>
<td>1.6%</td>
<td>1.3%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Electron reco/identification/isolation efficiency [67]</td>
<td>1.0%</td>
<td>1.3%</td>
<td>1.3%</td>
<td>0.8%</td>
<td>1.2%</td>
</tr>
<tr>
<td>Electron and photon energy scale [48]</td>
<td>0.2%</td>
<td>0.5%</td>
<td>0.4%</td>
<td>&lt; 0.1%</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Electron and photon energy resolution [48]</td>
<td>&lt; 0.1%</td>
<td>0.3%</td>
<td>0.2%</td>
<td>0.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Photon efficiency [49]</td>
<td>0.1%</td>
<td>1.0%</td>
<td>&lt; 0.1%</td>
<td>0.2%</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>$\gamma$+jets modelling</td>
<td>1.5%</td>
<td>0.3%</td>
<td>0.3%</td>
<td>2.3%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$\langle \mu \rangle$ distribution in MC simulation (Section 3)</td>
<td>1.3%</td>
<td>0.3%</td>
<td>0.9%</td>
<td>1.7%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>
The 90% CL exclusion limit on the $\chi$–proton scattering cross section (left) and $\chi$–nucleon scattering (right) in a simplified model of dark-matter production involving an axial-vector operator (left) and vector-operator (right), Dirac DM and couplings $g_q = 0.25$, $g_\chi = 1$ and $g_l = 0$ as a function of the dark-matter mass $m_\chi$. 
Table 1:
The percentage impact of the various sources of uncertainty on the expected production cross-section for the signal in the vector-mediator model with $m_{Z^0} = 2000$ GeV and $m_A = 1$ GeV, normalised to a cross section of 0.1 pb.

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Impact [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>23.0</td>
</tr>
<tr>
<td>Statistical</td>
<td>20.5</td>
</tr>
<tr>
<td>Systematic</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Experimental Uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Impact [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$-tagging</td>
<td>6.6</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4.4</td>
</tr>
<tr>
<td>Jets+$E_T^{miss}$</td>
<td>2.8</td>
</tr>
<tr>
<td>Leptons</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Theoretical and Modelling Uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Impact [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>5.1</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>3.4</td>
</tr>
<tr>
<td>Signal</td>
<td>2.6</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>1.5</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.6</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.5</td>
</tr>
<tr>
<td>$Vh (h \rightarrow b\overline{b})$</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Mono-Higgs \( \rightarrow \gamma\gamma \)

- Two simplified models
- Split events in 4 categories and look around invariant diphoton mass
- No excess found

<table>
<thead>
<tr>
<th>Category</th>
<th>( S_{E^{\text{miss}}} ) [( \sqrt{\text{GeV}} )]</th>
<th>( p_T^{\gamma\gamma} ) [( \text{GeV} )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High ( S_{E^{\text{miss}}} ), high ( p_T^{\gamma\gamma} )</td>
<td>&gt; 7</td>
<td>&gt; 90</td>
</tr>
<tr>
<td>High ( S_{E^{\text{miss}}} ), low ( p_T^{\gamma\gamma} )</td>
<td>&gt; 7</td>
<td>( \leq 90 )</td>
</tr>
<tr>
<td>Intermediate ( S_{E^{\text{miss}}} )</td>
<td>&gt; 4 and ( \leq 7 )</td>
<td>&gt; 25</td>
</tr>
<tr>
<td>Rest</td>
<td>-</td>
<td>&gt; 15</td>
</tr>
</tbody>
</table>

- The non-resonant background contribution is evaluated from data by fitting an analytic function to the lower and upper tails.
- The spurious signal test is performed in the intermediate and the rest categories, which have suitable numbers of events to enable such a test. An exponential of a second order polynomial is found to fulfill the requirements.

- Figure 3: A histogram showing the diphoton mass distribution with data and MC samples from the relevant signal and SM Higgs boson.

- Table 2: Optimized criteria used in the categorization. A '-' denotes no requirement on that observable in that category.

- C. Schmitt - 18/03/17