Search for Dark Matter in X+MET signatures at the LHC

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Thursday 16th June 2016
Collider Searches for Dark Matter

Though the presence of Dark Matter is well established, its particle content is an open question.

- **Dark Matter** - needed to explain:
  - WIMP dark matter is one attractive option.
    - Produced in early universe, now in thermal relic density.
    - Interaction with quarks via heavy mediator pair-production.
    - Search for signatures of Dark Matter at the LHC through tagging ISR, or searching for mediator production.
Any WIMP DM produced at collider experiments will interact weakly and pass invisibly through the detector.

Inferred through ‘Missing $E_T$’ ($E_T^{\text{miss}}$) when event does not balance in plane transverse to beam.

Consequently, collider searches focus on events with production of a SM particle(s) (X) with large $E_T^{\text{miss}}$: X+MET

Initial state radiation (photons, jet, vector bosons) can also be used to tag DM pair production.

Lepton vetoes can be used to reduce backgrounds containing genuine sources of $E_T^{\text{miss}}$. 
LHC Searches for WIMP Dark Matter

Assume dark matter has very small couplings to the SM.

Use information from astrophysics, detection experiments to focus search.

Need a model for comparisons with astrophysics.

The LHC can investigate and characterise the interaction between DM and SM.

For Run-2, focus on simplified models, with mediator.

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EFTs and simplified models

[arXiv:1507.00966] [arXiv:1506.03116] [arxiv:1603.04156]
Simplified models provide a solution to the question of Effective Field Theory (EFT) validity.

**Parameters**: mediator mass, couplings to SM and DM, width, DM mass.

Mediator also a discovery target - strength of LHC searches.

Explore the complementarity of different channels.

Can also be investigated by EFT, with interactions between the WIMPs and SM particles.

Caveat: momentum transfer must be below the EFT interaction scale for validity.

(from 1503.05916)
LHC searches for Dark Matter in X+MET channels

- (Mono-)jet plus $E_T^{\text{miss}}$
- $\gamma/W/Z$ & $E_T^{\text{miss}}$
- Dijet searches
- Heavy quarks & $E_T^{\text{miss}}$
- Higgs plus $E_T^{\text{miss}}$

Conclusions & Outlook

More details tomorrow:
Ruth Pottgen & Bo Jayatilaka
The highest $E_{\text{miss}}^T$ monojet event in the 2015 ATLAS data

jet $p_T = 973$ GeV
$E_{\text{miss}}^T = 954$ GeV
Jet Dark Matter Searches

Mono-jet (inc. $V \rightarrow qq$) (1)

Look for an excess of events with:
- $E_T^{\text{miss}} > 200$ GeV, $R = 0.8$ jet with $p_T > 250$ GeV
- Separate mono-$V$ from monojet with $E_T^{\text{miss}} > 250$ and boson-tagging: $(65 < m_j < 105, \text{N-subjettiness: } \tau_2/\tau_1 < 0.6)$.
- The post-fit signal regions for monojet (L) and mono-$V$ (R):

![Graph showing data and background predictions](image)

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7 / 46
- Z/W+jets backgrounds estimated with ten CRs: 1-2-e/µ,γ+jets
- Orthogonal by SR lepton/photon vetoes.
- Model SM $E_T^{miss}$ shape in SR.
- $g_q = 1$, $g_{SM} = 1$:
  Vector/axial-vector mediators < 1.3 TeV excluded.

**Graph:**

- CMS Preliminary
- 2.3 fb$^{-1}$ (13 TeV)
- Axial-vector, Dirac, $g_q = 1$, $g_{SM} = 1$
- Median Expected (8 TeV) 90% CL
- Median Expected (13 TeV) 90% CL
- Observed (8 TeV) 90% CL
- Observed (13 TeV) 90% CL
- PICO-60
- PICO-2L
- IceCube $\gamma\gamma$
- Super-K $\tau\tau$
Look for events with a jet, $p_T > 250$ GeV, $E_T^{miss} > 250$ GeV, separated from any jet with $p_T > 30$ GeV.

Lepton veto.

$W/Z+jets$ estimated with simultaneous fit in $(1e,1-/2-\mu)$ control regions.

Non-collision and multijet rates from data.

$m_\chi$ excluded up to 250 GeV for $g_q = 0.25$. 

**Jet Dark Matter Searches**

Mono-jet (3)  

[arXiv:1604.07773]
Tag ISR boson.
- Look for a boosted boson recoiling against DM particles.
- Search for an R=1.0 jet and $E_T^{miss} (>250$ GeV), tagging bosons using jet mass and $D_2$ (dominant uncertainty $\sim 10\%$).
- Main backgrounds: W+jets, Z+jets and $t\bar{t}$.
- Vector-mediated simplified model - already probing low $m_\chi$ with 2015 data!
Look for high $p_T (> 150$ GeV) photon, opposite $E_T^{miss}$.

Use 1-/2-$\mu$, 2-el, and lower $E_T^{miss}$-jet CRs to estimate backgrounds ($Z(\nu\nu)+\gamma$, $W/Z+\gamma$, $\gamma+\text{jets}$). Lepton veto.

Dominant uncertainties: statistics (9%), $e\rightarrow \gamma$ fake factor (6%)
Interpretation via Axial-vector model.

- For large $g_{DM}$, rule out a large range of mediator masses with $m_{\chi} < 150$ GeV.
- Limits on the EFT: $\gamma \gamma \chi \chi$
- Stringent DM cross-section limits at low masses.
Isolated $\gamma$, $p_T > 175$ GeV, $|\eta| < 1.44$

$E_T^{miss} > 170$ GeV.

$Z/\gamma + \gamma$ from MC and CR, data-driven estimate of e/jets mis-identified as $\gamma$.

Limits set on vector/axial-vector mediator scenarios.
High-mass searches provide constraints for massive mediators.

Weaker constraints at lower masses, due to the large prescales on triggers.

Need alternative approaches to access mediators below $\sim 1$ TeV.

Complementary strategies...
Jet Dark Matter Searches

Trigger Level Analysis

- Write out trigger jets for all events with $H_T > 250$ GeV, (jet $p_T > 40$ GeV).
- Considerable improvement on sensitivity at lower masses.

Record trigger jets in events with an L1 trigger jet $E_T > 75$ GeV:
- $p_T > 185$ GeV, $|y^*| < 0.6$
- Use reduced $y^*$ cut ($< 0.3$) to access lowest masses.

![Graph 1](image1)

- CMS
- Data
- Background fit
- $Z_b$ (M = 700 GeV, $g_b = 0.37$)
- $Z_b$ (M = 1200 GeV, $g_b = 0.84$)

![Graph 2](image2)

- ATLAS Preliminary
- $\sqrt{s}=13$ TeV, 3.4 fb$^{-1}$
- Data
- Background fit
- BumpHunter interval
- $p$-value = 0.44
- Fit Range: 443 - 1236 GeV
- $|y^*| < 0.6$
Jet Dark Matter Searches

Other approaches for lower masses

Search for resonances decaying to a jet pair in association with a photon from ISR.

- Use a lower $p_T$ ISR photon to access lower resonance masses.
- Trigger on the event with the photon, and construct dijet $m_{jj}$, down to 200 GeV.
  - $\gamma$, $p_T > 130$ GeV, and 2+ jets ($p_T > 25$ GeV).
  - Photon separated from closest jet by $\Delta R > 0.85$.
  - $y_{jj} = |y_j1 - y_j2|/2 < 0.8$
- Background fit with functional form, as for dijet analysis.
- Exclude masses down to 250 GeV ($g_{SM} > 0.26$).
Low mass summary (with 13 TeV high-mass)

ATLAS Preliminary

\[ \sqrt{s} = 13 \text{ TeV}; 3.2-3.4 \text{ fb}^{-1} \]

- Obs. limit, Low-mass dijet (TLA)
- Exp. limit, Low-mass dijet (TLA)
- Obs. limit, High-mass dijet
- Exp. limit, High-mass dijet
- Obs. limit, Dijet + \gamma
- Exp. limit, Dijet + \gamma

ATLAS-CONF-2016-029

Mono-jet and Dijet Complementarity

Relative exclusion power depends on the relative model couplings, $g_q$ and $g_{DM} = g_\chi$. 

\[ g_q = 0.25, \quad g_{DM} = 1 \]
Heavy flavour DM searches

mono-b searches

- Search for DM in association with one or more b/t-quarks.
- Important for (pseudo-)scalar mediators.

- $E_T^{miss} > 200$ GeV, lepton veto, require 1(2) b-tagged jets with $p_T > 50$ GeV.
Hadronic top decay in association with $E_T^{miss}$.

Select b-tagged large-R jet with $110 < m < 210$ GeV, $\tau_3/\tau_2$, with $E_T^{miss} > 250$ GeV.

Veto extra b-tags or charged leptons.

$E_T^{miss}$ search, using 1/2-e/µ, γ+jet regions.

For $a_{FC} = b_{FC} = 0.1$, mass exclusion $M_V = 300 – 1100$ GeV.
DM Mediator Mass Summary

**CMS Preliminary**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Exclusion Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM + jets/V(φf)</td>
<td>Vector; (g_{DM} = g_q = 1)</td>
</tr>
<tr>
<td>DM + jets/V(φf)</td>
<td>Axial vector; (g_{DM} = g_q = 1)</td>
</tr>
<tr>
<td>DM + γ</td>
<td>Vector; (g_{DM} = g_q = 1), (g_q = 0.25)</td>
</tr>
<tr>
<td>DM + γ</td>
<td>Axial vector; (g_{DM} = g_q = 1), (g_q = 0.25)</td>
</tr>
<tr>
<td>DM + t</td>
<td>FC Vector; (a_{FC} = b_{FC} = 0.1)</td>
</tr>
<tr>
<td>DM + jets/V(φf)</td>
<td>Scalar; (g_{DM} = g_q = 1)</td>
</tr>
<tr>
<td>DM + jets/V(φf)</td>
<td>Pseudoscalar; (g_{DM} = g_q = 1)</td>
</tr>
<tr>
<td>DM + b\bar{b}/t\bar{t}</td>
<td>(\sigma/\sigma_0 = 5)</td>
</tr>
<tr>
<td>DM + b\bar{b}/t\bar{t}</td>
<td>Pseudoscalar; (g_{DM} = g_q = 1)</td>
</tr>
</tbody>
</table>

**Dark Matter Summary* - June 2016**

*Observed limits
Theory uncertainties not included
spin 0 mediator
spin 1 mediator

Mediator exclusion
DM exclusion

**EXO-16-013**
13TeV, 2.3fb
90%CL

**EXO-16-013**
13TeV, 2.3fb
90%CL

**EXO-16-014**
13TeV, 2.3fb
95%CL

**EXO-16-014**
13TeV, 2.3fb
95%CL

**EXO-16-017**
13TeV, 2.3fb
95%CL

**EXO-12-055**
8TeV, 19.7fb
90%CL

**EXO-12-055**
8TeV, 19.7fb
90%CL

**B2G-15-007**
13TeV, 2.17fb
95%CL

**B2G-15-007**
13TeV, 2.17fb
95%CL

Maximal excluded mass [GeV]

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21 / 46
Higgs could couple to dark sector too.

Boosted and 3 resolved channels ($E_T^{miss}$), 2 b-tags.

Main backgrounds: W/Z+jets, $t\bar{t}$ - estimated from 1-/2-lepton control regions.

Z’ vector model. $g_{DM} = 1, g_{q} = 1/3$.

$\rightarrow m_{Z'} < 900 \text{ GeV}$ is excluded.

$\rightarrow$ Constraints on 2HDM, $m_{A} < 500 \text{ GeV}$
Searches in Higgs channels

mono-Higgs searches to diphotons

- Look for H boson recoiling against DM.
- 4 signal regions.

- Signal and background are estimated with functional fit to $m_{\gamma\gamma}$ distribution.
  - Statistical error dominates.
  - Vector simplified model
  - Heavy scalar interpretation.
Searches in Higgs channels
Invisible decays of a Higgs boson

- Look for VBF Higgs decay to invisibles.
- Signal and background yields from fits to control regions
  - $Z(\mu\mu)$, $W(e\nu,\mu\nu,\tau\nu)$, multijet.
- Limit on invisible BF is 69\% from 2015 data, improving to 32\% with Run-1 combination.

![Diagram of Higgs boson decays](image_url)

CMS-PAS-HIG-16-009

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Conclusions and Outlook

- The LHC machine and experiments performed very well during the start of LHC Run-2 in 2015.
- Wide range of DM channels being probed with 2015 data.
- Important part of the LHC programme, with new techniques and methodologies.
- Simplified models provide framework for comparison of other channels, direct and indirect detection experiments.
  - Common set of benchmark models.
- 2016 data will bring greater sensitivity - Many more results with 13 TeV data coming soon!
- Great complementarity with non-LHC experiments
BACKUP SLIDES
# Summary of ATLAS Exotics Results

ATLAS Exotics Searches* - 95% CL Exclusion

**Status:** March 2016

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( \tilde{M}_{\text{max}} )</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD Fox + g/g</td>
<td>( \pm 2 \pm 1 )</td>
<td>Yes</td>
<td>3.2</td>
<td>4.7 TeV</td>
<td>Preliminary</td>
</tr>
<tr>
<td>ADD non-resonant ( \ell \ell )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ADD GB 0 &amp; 1</td>
<td>(-1 \pm 1 )</td>
<td>1</td>
<td>5.2 TeV</td>
<td>-</td>
<td>14072410</td>
</tr>
<tr>
<td>ADD GB ( \pm 2 )</td>
<td>(-2 \pm 2 )</td>
<td>1</td>
<td>3.6 TeV</td>
<td>-</td>
<td>15710396</td>
</tr>
<tr>
<td>ADD BH high ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>3.2</td>
<td>8.3 TeV</td>
<td>Preliminary</td>
</tr>
<tr>
<td>ADD BH multi</td>
<td>(-2 \pm 3 )</td>
<td>-</td>
<td>3.6</td>
<td>-</td>
<td>15170150</td>
</tr>
<tr>
<td>RSI ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>15161000</td>
</tr>
<tr>
<td>RSI ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>15040511</td>
</tr>
<tr>
<td>Bulk RS ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>15040511</td>
</tr>
<tr>
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<td>20.3</td>
<td>-</td>
<td>15040511</td>
</tr>
<tr>
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<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>15040511</td>
</tr>
<tr>
<td>Bulk RS ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>15040511</td>
</tr>
</tbody>
</table>

**Gauge bosons**

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( \tilde{M}_{\text{max}} )</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SSM ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SSM ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>-</td>
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<tr>
<td>SSM ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SSM ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SSM ( \pm 2 \pm 1 )</td>
<td>(-2 \pm 1 \pm 2 )</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>-</td>
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</table>

**ATLAS Preliminary**

<table>
<thead>
<tr>
<th>( \sqrt{s} = 8 \text{ TeV} )</th>
<th>( \sqrt{s} = 13 \text{ TeV} )</th>
<th>Mass scale (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 1 )</td>
<td>( 1 )</td>
<td>( 1 )</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

1 Small-radius (large-radius) jets are denoted by the letter (J).
Summary of CMS Exotics Results


James Frost (University of Oxford)
Leptonic top quark decay in association with $E_T^{miss}$.

- Isolated muon, $p_T^W > 50$ GeV, 1 b-tagged jet ($p_T > 70$ GeV), $E_T^{miss} > 100$ GeV.
- Look for broadening of $M_T^W$.
- Model $W+$jets, $t\bar{t}$ fit in control regions.
- For $a = 0.1$, scalar masses below 1610 GeV excluded.
Jet Dark Matter Searches

Mono-jet (inc. $V \rightarrow qq$)

[CMS-PAS-EXO-16-013]

James Frost (University of Oxford)

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Thursday 16th June 2016 30 / 46
<table>
<thead>
<tr>
<th>$E_T^{miss}$ Range (GeV)</th>
<th>$Z(\nu\nu)+jets$</th>
<th>$W(\ell\nu)+jets$</th>
<th>$Z(\ell\ell)+jets$</th>
<th>$\gamma+jets$</th>
<th>Top</th>
<th>Diboson</th>
<th>QCD</th>
<th>Total (Pre-fit)</th>
<th>Total (Post-fit)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 – 230</td>
<td>14919 ± 221</td>
<td>11976 ± 196</td>
<td>207 ± 13</td>
<td>230 ± 14</td>
<td>564 ± 55</td>
<td>251 ± 41</td>
<td>508 ± 171</td>
<td>27761 ± 1464</td>
<td>28654 ± 171</td>
<td>28601</td>
</tr>
<tr>
<td>230 – 260</td>
<td>7974 ± 116</td>
<td>5776 ± 101</td>
<td>92.9 ± 5.7</td>
<td>101 ± 6</td>
<td>267 ± 26</td>
<td>157 ± 26</td>
<td>308 ± 104</td>
<td>14114 ± 757</td>
<td>14675 ± 97</td>
<td>14756</td>
</tr>
<tr>
<td>260 – 290</td>
<td>4467 ± 70</td>
<td>2867 ± 50</td>
<td>37.9 ± 2.3</td>
<td>63.7 ± 3.9</td>
<td>116 ± 11</td>
<td>77.3 ± 12.7</td>
<td>38.3 ± 21.0</td>
<td>7193 ± 351</td>
<td>7666 ± 68</td>
<td>7770</td>
</tr>
<tr>
<td>290 – 320</td>
<td>2518 ± 46</td>
<td>1520 ± 34</td>
<td>18.4 ± 1.1</td>
<td>29.6 ± 1.8</td>
<td>56.7 ± 5.6</td>
<td>42.9 ± 7.1</td>
<td>29.8 ± 10.5</td>
<td>4083 ± 204</td>
<td>4215 ± 48</td>
<td>4195</td>
</tr>
<tr>
<td>320 – 350</td>
<td>1496 ± 35</td>
<td>818 ± 20</td>
<td>10.0 ± 0.6</td>
<td>19.7 ± 1.2</td>
<td>33.6 ± 3.3</td>
<td>25.4 ± 4.2</td>
<td>9.0 ± 5.4</td>
<td>2385 ± 118</td>
<td>2407 ± 37</td>
<td>2364</td>
</tr>
<tr>
<td>350 – 390</td>
<td>1204 ± 31</td>
<td>555 ± 13</td>
<td>3.9 ± 0.2</td>
<td>12.7 ± 0.8</td>
<td>24.5 ± 2.4</td>
<td>22.1 ± 3.6</td>
<td>6.0 ± 1.3</td>
<td>1817 ± 87</td>
<td>1826 ± 32</td>
<td>1875</td>
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<tr>
<td>390 – 430</td>
<td>684 ± 20</td>
<td>275 ± 9</td>
<td>2.1 ± 0.1</td>
<td>8.3 ± 0.5</td>
<td>9.8 ± 1.0</td>
<td>13.9 ± 2.3</td>
<td>3.0 ± 1.6</td>
<td>978 ± 45</td>
<td>998 ± 23</td>
<td>1006</td>
</tr>
<tr>
<td>430 – 470</td>
<td>382 ± 14</td>
<td>155 ± 6</td>
<td>0.96 ± 0.06</td>
<td>4.9 ± 0.3</td>
<td>9.4 ± 0.9</td>
<td>6.6 ± 1.1</td>
<td>1.0 ± 0.8</td>
<td>589 ± 30</td>
<td>574 ± 17</td>
<td>543</td>
</tr>
<tr>
<td>470 – 510</td>
<td>248 ± 11</td>
<td>87.3 ± 3.8</td>
<td>0.47 ± 0.03</td>
<td>3.7 ± 0.2</td>
<td>2.2 ± 0.02</td>
<td>5.1 ± 0.8</td>
<td>0.65 ± 0.44</td>
<td>337 ± 15</td>
<td>344 ± 12</td>
<td>349</td>
</tr>
<tr>
<td>510 – 550</td>
<td>160 ± 8</td>
<td>52.2 ± 2.7</td>
<td>0.23 ± 0.01</td>
<td>2.0 ± 0.1</td>
<td>2.7 ± 0.3</td>
<td>2.2 ± 0.4</td>
<td>0.28 ± 0.19</td>
<td>211 ± 9</td>
<td>219 ± 9</td>
<td>216</td>
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<tr>
<td>550 – 590</td>
<td>99.5 ± 6.0</td>
<td>29.2 ± 1.9</td>
<td>0.12 ± 0.01</td>
<td>1.8 ± 0.1</td>
<td>0.94 ± 0.09</td>
<td>2.0 ± 0.3</td>
<td>0.19 ± 0.14</td>
<td>134 ± 6</td>
<td>134 ± 7</td>
<td>142</td>
</tr>
<tr>
<td>590 – 640</td>
<td>77.3 ± 4.9</td>
<td>18.9 ± 1.4</td>
<td>0.09 ± 0.01</td>
<td>0.46 ± 0.03</td>
<td>&lt; 0.13</td>
<td>1.7 ± 0.3</td>
<td>0.11 ± 0.08</td>
<td>100 ± 4</td>
<td>100 ± 4</td>
<td>111</td>
</tr>
<tr>
<td>640 – 690</td>
<td>44.8 ± 3.5</td>
<td>11.2 ± 0.9</td>
<td>0.017 ± 0.001</td>
<td>0.19 ± 0.01</td>
<td>&lt; 0.13</td>
<td>1.5 ± 0.2</td>
<td>0.06 ± 0.05</td>
<td>39.6 ± 2.6</td>
<td>58.0 ± 4.1</td>
<td>61</td>
</tr>
<tr>
<td>690 – 740</td>
<td>27.8 ± 2.5</td>
<td>6.1 ± 0.6</td>
<td>0.013 ± 0.0008</td>
<td>0.57 ± 0.04</td>
<td>&lt; 0.13</td>
<td>0.69 ± 0.11</td>
<td>0.02 ± 0.02</td>
<td>36.6 ± 1.5</td>
<td>35.2 ± 2.9</td>
<td>32</td>
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<tr>
<td>740 – 790</td>
<td>21.8 ± 2.3</td>
<td>5.3 ± 0.6</td>
<td>&lt; 0.005</td>
<td>0.28 ± 0.02</td>
<td>0.23 ± 0.02</td>
<td>0.11 ± 0.02</td>
<td>0.02 ± 0.02</td>
<td>23.8 ± 1.0</td>
<td>27.7 ± 2.7</td>
<td>28</td>
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<tr>
<td>790 – 840</td>
<td>13.5 ± 1.9</td>
<td>2.8 ± 0.4</td>
<td>&lt; 0.005</td>
<td>0.18 ± 0.01</td>
<td>0.27 ± 0.03</td>
<td>0.010 ± 0.001</td>
<td>0.08 ± 0.007</td>
<td>15.3 ± 0.7</td>
<td>16.8 ± 2.2</td>
<td>14</td>
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<tr>
<td>840 – 900</td>
<td>9.5 ± 1.4</td>
<td>2.0 ± 0.3</td>
<td>&lt; 0.005</td>
<td>0.28 ± 0.02</td>
<td>&lt; 0.13</td>
<td>0.25 ± 0.04</td>
<td>&lt; 0.008</td>
<td>12.2 ± 0.6</td>
<td>12.0 ± 1.6</td>
<td>13</td>
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<tr>
<td>900 – 960</td>
<td>5.4 ± 1.0</td>
<td>1.1 ± 0.2</td>
<td>&lt; 0.005</td>
<td>&lt; 0.08</td>
<td>&lt; 0.13</td>
<td>0.37 ± 0.06</td>
<td>&lt; 0.008</td>
<td>7.6 ± 0.3</td>
<td>6.9 ± 1.2</td>
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<td>960 – 1020</td>
<td>3.3 ± 0.8</td>
<td>0.77 ± 0.21</td>
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<td>0.12 ± 0.01</td>
<td>&lt; 0.13</td>
<td>0.23 ± 0.04</td>
<td>&lt; 0.008</td>
<td>5.2 ± 0.3</td>
<td>4.5 ± 1.0</td>
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</tr>
<tr>
<td>1020 – 1160</td>
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<td>0.52 ± 0.16</td>
<td>&lt; 0.005</td>
<td>&lt; 0.08</td>
<td>&lt; 0.13</td>
<td>0.16 ± 0.03</td>
<td>&lt; 0.008</td>
<td>3.6 ± 0.2</td>
<td>3.2 ± 0.9</td>
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</tr>
<tr>
<td>1160 – 1250</td>
<td>1.7 ± 0.6</td>
<td>0.3 ± 0.11</td>
<td>&lt; 0.005</td>
<td>&lt; 0.08</td>
<td>&lt; 0.13</td>
<td>0.16 ± 0.03</td>
<td>&lt; 0.008</td>
<td>2.3 ± 0.1</td>
<td>2.2 ± 0.7</td>
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</tr>
<tr>
<td>&gt; 1250</td>
<td>1.4 ± 0.5</td>
<td>0.19 ± 0.08</td>
<td>&lt; 0.005</td>
<td>&lt; 0.08</td>
<td>&lt; 0.13</td>
<td>0.06 ± 0.01</td>
<td>&lt; 0.008</td>
<td>1.6 ± 0.1</td>
<td>1.6 ± 0.6</td>
<td>3</td>
</tr>
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</table>
Jet Dark Matter Searches

Mono-jet (inc. \(V \rightarrow qq\)) (2) [CMS-PAS-EXO-16-013]

James Frost (University of Oxford)
Jet Dark Matter Searches

Mono-jet (3) [arXiv:1604.07773]

James Frost (University of Oxford)

LHCP 2016
Thursday 16th June 2016 33 / 46

Selection criteria

- Primary vertex
  $E_T^{miss} > 250$ GeV
- Leading jet with $p_T > 250$ GeV and $|y| < 2.4$
- At most four jets with $p_T > 30$ GeV and $|y| < 2.8$
- $\Delta$($\text{jet}, \mu_0^{\text{miss}}$) $> 0.4$
- Jet quality requirements
  - No identified muons with $p_T > 10$ GeV or electrons with $p_T > 20$ GeV

Inclusive signal region

<table>
<thead>
<tr>
<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>$E_T^{miss}$ (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>
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</table>

Exclusive signal region

<table>
<thead>
<tr>
<th>EM1</th>
<th>EM2</th>
<th>EM3</th>
<th>EM4</th>
<th>EM5</th>
<th>EM6</th>
<th>EM7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{miss}$ (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>
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</table>

<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>$W(\rightarrow e\nu)$</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>1920 ± 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>76 ± 30</td>
<td>9 ± 5</td>
<td>5 ± 2</td>
<td>2 ± 1</td>
</tr>
<tr>
<td>$Z/\gamma^* (\rightarrow \mu^+\mu^-)$</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>$t\bar{t}$, 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>
<thead>
<tr>
<th>Signal Region</th>
<th>IM1</th>
<th>IM2</th>
<th>IM3</th>
<th>IM4</th>
<th>IM5</th>
<th>IM6</th>
<th>IM7</th>
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</thead>
<tbody>
<tr>
<td>Observed events (3.2 fb$^{-1}$)</td>
<td>21447</td>
<td>11975</td>
<td>6433</td>
<td>3494</td>
<td>1170</td>
<td>423</td>
<td>185</td>
</tr>
<tr>
<td>SM prediction</td>
<td>21730 ± 940</td>
<td>12340 ± 570</td>
<td>6570 ± 340</td>
<td>3390 ± 200</td>
<td>1125 ± 77</td>
<td>441 ± 39</td>
<td>167 ± 20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>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>Observed events</td>
<td>9472</td>
<td>5543</td>
<td>2890</td>
<td>2324</td>
<td>747</td>
<td>238</td>
</tr>
<tr>
<td>SM prediction</td>
<td>9400 ± 410</td>
<td>5770 ± 260</td>
<td>3210 ± 170</td>
<td>2260 ± 140</td>
<td>686 ± 50</td>
<td>271 ± 28</td>
</tr>
</tbody>
</table>

ATLAS

$\sqrt{s} = 13$ TeV, 3.2 $fb^{-1}$

Multijets Control Region

$p_T^{miss}$ > 250 GeV, $E_T^{miss}$ > 250 GeV

Events

ATLAS

Data 2015

- Standard Model
- $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$
- $W(\rightarrow \nu\bar{\nu}) + \text{jets}$
- $W(\rightarrow \mu\nu) + \text{jets}$
- $Z(\rightarrow \mu\nu) + \text{jets}$
- $t\bar{t}$ + single top
- Dibosons
- Multijets + HCB

SM

- $W(\rightarrow e\nu)$ CR
- $W(\rightarrow \mu\nu)$ CR
- $Z(\rightarrow \mu\nu)$ CR
- SR

James Frost (University of Oxford) LHCP 2016 Thursday 16th June 2016 33 / 46
Boson + $E_T^{miss}$ DM Searches

Mono-W/Z Search

[ATLAS-CONF-2015-080]

<table>
<thead>
<tr>
<th>Process</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$+jets</td>
<td>519 ± 31</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>326 ± 22</td>
</tr>
<tr>
<td>$tt\bar{t}$ and single-top</td>
<td>217 ± 18</td>
</tr>
<tr>
<td>Diboson</td>
<td>88 ± 12</td>
</tr>
<tr>
<td>Total Background</td>
<td>1150 ± 30</td>
</tr>
<tr>
<td>Data</td>
<td>1143</td>
</tr>
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</table>
Boson + $E_T^{miss}$ DM searches

Mono-photon search (I)  
[arxiv:1604.01306]

James Frost (University of Oxford)
LHCP 2016  
Thursday 16th June 2016 35 / 46

<table>
<thead>
<tr>
<th></th>
<th>SR</th>
<th>1muCR</th>
<th>2muCR</th>
<th>2eleCR</th>
<th>PhJetCR</th>
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<tbody>
<tr>
<td>Observed events</td>
<td>264</td>
<td>145</td>
<td>29</td>
<td>20</td>
<td>214</td>
</tr>
<tr>
<td>Fitted Background</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z(→ νν)γ$</td>
<td>171±29</td>
<td>0.15±0.03</td>
<td>0.00±0.00</td>
<td>0.00±0.00</td>
<td>8.6±1.4</td>
</tr>
<tr>
<td>$W(→ ℓν)γ$</td>
<td>58±9</td>
<td>119±17</td>
<td>0.14±0.04</td>
<td>0.11±0.03</td>
<td>22±4</td>
</tr>
<tr>
<td>$Z(→ ℓℓ)γ$</td>
<td>3.3±0.6</td>
<td>7.9±1.3</td>
<td>26±4</td>
<td>20±3</td>
<td>1.2±0.2</td>
</tr>
<tr>
<td>$γ + jets$</td>
<td>15±4</td>
<td>0.7±0.5</td>
<td>0.00±0.00</td>
<td>0.03±0.03</td>
<td>166±17</td>
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<tr>
<td>Fake photons from electrons</td>
<td>22±18</td>
<td>1.7±1.5</td>
<td>0.05±0.05</td>
<td>0.00±0.00</td>
<td>5.8±5.1</td>
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<tr>
<td>Fake photons from jets</td>
<td>26±12</td>
<td>16±11</td>
<td>1.1±0.8</td>
<td>2.5±1.3</td>
<td>9.9±3.1</td>
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<td>Pre-fit background</td>
<td>249±29</td>
<td>105±14</td>
<td>23±2</td>
<td>19±2</td>
<td>209±50</td>
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<table>
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<th>Value</th>
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<td>Total background</td>
<td>295</td>
</tr>
<tr>
<td>Total background uncertainty</td>
<td>11%</td>
</tr>
<tr>
<td>Electron fake rate</td>
<td>5.8%</td>
</tr>
<tr>
<td>PDF uncertainties</td>
<td>2.8%</td>
</tr>
<tr>
<td>Jet fake rate</td>
<td>2.4%</td>
</tr>
<tr>
<td>Muons reconstruction/isolation efficiency</td>
<td>1.5%</td>
</tr>
<tr>
<td>Electrons reconstruction/identification/isolation efficiency</td>
<td>1.3%</td>
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<tr>
<td>Jet energy resolution [62]</td>
<td>1.2%</td>
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<tr>
<td>Photon energy scale</td>
<td>0.6%</td>
</tr>
<tr>
<td>$E_T^{miss}$ soft term scale and resolution</td>
<td>0.4%</td>
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<tr>
<td>Photon energy resolution</td>
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<td>Jet energy scale [50]</td>
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### Dark Matter Searches

#### mono-photon search

#### CMS-PAS-EXO-16-014

<table>
<thead>
<tr>
<th>Process</th>
<th>Estimate</th>
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<tbody>
<tr>
<td>$Z(\rightarrow \nu\bar{\nu}) + \gamma$</td>
<td>41.7 ± 5.9</td>
</tr>
<tr>
<td>$W(\rightarrow \ell \nu) + \gamma$</td>
<td>10.6 ± 1.5</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>7.3 ± 0.7</td>
</tr>
<tr>
<td>jet → $\gamma$ fakes</td>
<td>1.7 ± 0.6</td>
</tr>
<tr>
<td>Beam halo</td>
<td>5.9 ± 4.7</td>
</tr>
<tr>
<td>Spikes</td>
<td>5.6 ± 2.2</td>
</tr>
<tr>
<td>$t\bar{t}\gamma$</td>
<td>1.5 ± 0.1</td>
</tr>
<tr>
<td>$W\mu\nu$</td>
<td>0.9 ± 0.7</td>
</tr>
<tr>
<td>$Z(\ell\ell)\gamma$</td>
<td>0.5 ± 0.04</td>
</tr>
<tr>
<td>$\gamma + jet$</td>
<td>0.01 ± 0.01</td>
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<tr>
<td>Total background</td>
<td>76.0 ± 8.1</td>
</tr>
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<td>Data</td>
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</table>

**Sources**

<table>
<thead>
<tr>
<th>Sources</th>
<th>$Z(\nu\bar{\nu}) + \gamma$</th>
<th>$W\gamma$</th>
<th>Jets faking $\gamma$</th>
<th>Electron faking $\gamma$</th>
<th>jet+$\gamma$</th>
<th>Beam Halo</th>
<th>Spikes</th>
<th>Other bkggs</th>
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<tr>
<td>Luminosity</td>
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<td>2.7%</td>
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<td>-</td>
<td>2.7%</td>
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<td>2.7%</td>
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<tr>
<td>PDF and Scale</td>
<td>5.4%</td>
<td>8.9%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>EWK corrections</td>
<td>11%</td>
<td>7%</td>
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<td>35%</td>
<td>-</td>
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<tr>
<td>Electron faking $\gamma$</td>
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<td>8%</td>
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<td>-</td>
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<tr>
<td>Jet+$\gamma$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100%</td>
<td>-</td>
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<tr>
<td>Jet, $E_T$, $\gamma$ energy scale</td>
<td>3.2%</td>
<td>4.2%</td>
<td>-</td>
<td>-</td>
<td>3%</td>
<td>-</td>
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<td>3%</td>
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<tr>
<td>Scale Factors</td>
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<td>BeamHalo</td>
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<td>Spikes</td>
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</table>
Jet Dark Matter Searches
Trigger Level Analysis

CMS Simulation

M = 900 GeV

- quark-antiquark
- quark-gluon
- gluon-gluon

Wide jets

<table>
<thead>
<tr>
<th>Normalized yield / GeV</th>
</tr>
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<tbody>
<tr>
<td>0.005</td>
</tr>
<tr>
<td>0.0045</td>
</tr>
<tr>
<td>0.004</td>
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<tr>
<td>0.0035</td>
</tr>
<tr>
<td>0.003</td>
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<tr>
<td>0.0025</td>
</tr>
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<td>0.002</td>
</tr>
<tr>
<td>0.0015</td>
</tr>
<tr>
<td>0.001</td>
</tr>
<tr>
<td>0.0005</td>
</tr>
<tr>
<td>0.00025</td>
</tr>
</tbody>
</table>

Dijet mass [GeV]

- 0 200 400 600 800 1000 1200 1400

σ B A [pb]

- 10^5
- 10^4
- 10^3
- 10^2
- 10^1
- 10

Resonance mass [GeV]

- 400 600 800 1000 1200 1400 1600

95% CL upper limits

- Excited quark
- Axigluon
- Gluon-gluon
- Scalar diquark
- W'
- Quark-gluon
- Quark-quark
- RS graviton
Low mass summary

[ATLAS-CONF-2016-029 & ATLAS-CONF-2016-030]

James Frost (University of Oxford)

LHCP 2016
Thursday 16th June 2016 39 / 46
### Searches in Higgs channels

**mono-Higgs searches - bb channel**

#### ATLAS-CONF-2016-019

James Frost (University of Oxford)

LHCP 2016

Thursday 16th June 2016 41 / 46

### Table: Searches in Higgs Channels

<table>
<thead>
<tr>
<th>Region</th>
<th>Signal Region</th>
<th>Z+jets Control Region</th>
<th>W+jets and tt Control Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>$E_T^{\text{miss}}$</td>
<td>$E_T^{\text{miss}}$</td>
<td>Single Lepton</td>
</tr>
<tr>
<td>N(lepton)</td>
<td>0 $\mu$ and e</td>
<td>Exactly 1 $\mu$</td>
<td>Exactly 2 $\mu$ or e</td>
</tr>
</tbody>
</table>

- **Merged**
  - $E_T^{\text{miss}} \geq 500$ GeV
  - $p_T(\mu, E_T^{\text{miss}}) \geq 500$ GeV
  - $p_T(\ell, E_T^{\text{miss}}) \geq 500$ GeV
  - $N(\text{large-}R \text{ jets}) \geq 1$
  - Division by track jet $b$-tags
  - Final discriminant = Large-$R$ jet mass

- **Resolved**
  - $E_T^{\text{miss}} = [150,500]$ GeV
  - $p_T(\mu, E_T^{\text{miss}}) = [150,500]$ GeV
  - $p_T(\ell, E_T^{\text{miss}}) = [150,500]$ GeV
  - $p_T(\ell, E_T^{\text{miss}}) = [150,500]$ GeV
  - $p_T(j^1_{h_T}, j^2_{h_T}) \geq 45$ GeV or $p_T(j^1_{h_T}, j^2_{h_T}) \geq 45$ GeV
  - $\Delta \phi(j^1_{h_T}, j^2_{h_T}) < 140^\circ$
  - $H_T(\text{2jets}) \geq 120$ GeV or $H_T(\text{3jets}) \geq 150$ GeV
  - $\Delta \phi(E_T^{\text{miss}}, h_T) > 120^\circ$
  - $\frac{E_T^{\text{miss}}}{\Sigma p_T(\text{jets, leptons})} \geq 3.5$
  - Division by small-$R$ calorimeter jet $b$-tags
  - Final discriminant = Dijet mass
Searches in Higgs channels
mono-Higgs searches - bb channel

$E_T^{miss}$ (GeV) | Resolved | Merged
--- | --- | ---
150–200 | 200–350 | 350–500 | >500
$Z + jets$ | 259 ± 27 | 171 ± 13 | 14.6 ± 1.2 | 3.80 ± 0.44
$W + jets$ | 95 ± 28 | 70 ± 22 | 7.5 ± 2.4 | 2.48 ± 0.71
$t\bar{t} & Single top$ | 1444 ± 44 | 656 ± 25 | 30.8 ± 1.4 | 4.83 ± 0.88
Multijet | 21 ± 10 | 11 ± 5 | 0.58 ± 0.27 | —
Diboson | 17.8 ± 1.6 | 18.7 ± 1.0 | 2.53 ± 0.22 | 1.20 ± 0.12
$SMVh$ | 2.8 ± 1.3 | 2.8 ± 1.4 | 0.46 ± 0.23 | 0.15 ± 0.08
Tot. Bkg. | 1840 ± 33 | 930 ± 20 | 56.5 ± 2.1 | 12.5 ± 1.3
Data | 1830 | 942 | 56 | 20
Exp. Signal | 80 ± 8 | 245 ± 18 | 161 ± 12 | 149 ± 34
Searches in Higgs channels
mono-Higgs searches to diphotons

\[ \sqrt{s} = 13 \text{ TeV}, \ 3.2 \text{ fb}^{-1} \]

**Rest**

### ATLAS Preliminary

- **Data**
- **Signal + total bkg**
- **Non-resonant bkg + h**
- **Non-resonant bkg**

### Summary Table

<table>
<thead>
<tr>
<th>Category</th>
<th>( E_{\text{miss}} ) [GeV]</th>
<th>( p_T^{\text{hard}} ) [GeV]</th>
<th>( p_T^{\gamma\gamma} ) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High ( E_{\text{miss}} ), high ( p_T^{\gamma\gamma} )</td>
<td>( &gt; 100 )</td>
<td>(-)</td>
<td>( &gt; 100 )</td>
</tr>
<tr>
<td>High ( E_{\text{miss}} ), low ( p_T^{\gamma\gamma} )</td>
<td>( &gt; 100 )</td>
<td>(-)</td>
<td>( \leq 100 )</td>
</tr>
<tr>
<td>Intermediate ( E_{\text{miss}} )</td>
<td>( &gt; 50 ) and ( \leq 100 )</td>
<td>( &gt; 40 )</td>
<td>(-)</td>
</tr>
<tr>
<td>Rest</td>
<td>(-)</td>
<td>(-)</td>
<td>( &gt; 15 )</td>
</tr>
</tbody>
</table>

---

**Process**

- **ggF, h \rightarrow \gamma\gamma**
- **VBF, h \rightarrow \gamma\gamma**
- **Wh, h \rightarrow \gamma\gamma**
- **Zh, h \rightarrow \gamma\gamma**
- **ttW, h \rightarrow \gamma\gamma**
- **bbh, h \rightarrow \gamma\gamma**

**Generators used**

- Powheg [15] + Pythia 8.186
- Powheg + Pythia 8.186
- Pythia 8.186
- Pythia 8.186
- Pythia 8.186

**PDF set (ME, PS)**

- CT10 [16], CTEQ6L1 [17]
- CT10, CTEQ6L1
- NNPDF2.3LO
- NNPDF2.3LO
- NNPDF2.3LO

**Tune**

- AZNLO [18]
- AZNLO
- A14
- A14
- A14

---

**ATLAS-CONF-2016-011**

James Frost (University of Oxford)  
LHCP 2016  
Thursday 16th June 2016  
43 / 46
## Searches in Higgs channels

**mono-Higgs searches to diphotons**

### ATLAS-CONF-2016-011

---

### Heavy scalar, $m_H = 275$ GeV, $m_X = 60$ GeV

<table>
<thead>
<tr>
<th>Category</th>
<th>Intermediate</th>
<th>High $E_T^{miss}$</th>
<th>High $p_T^{\gamma \gamma}$</th>
<th>High $E_T^{miss}$, Low $p_T^{\gamma \gamma}$</th>
<th>Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>111</td>
<td>0</td>
<td>6</td>
<td>2477</td>
<td></td>
</tr>
</tbody>
</table>

#### Yields
- $16.2 \pm 2.3$
- $11.0 \pm 1.6$

#### Selection Eff(%)
- $3.41 \pm 0.45$
- $2.31 \pm 0.31$
- $3.83 \pm 0.58$
- $2.59 \pm 0.39$
- $26.5 \pm 3.6$
- $17.9 \pm 2.4$

### $Z_H$ model, $m_{Z'} = 10$ GeV, $m_X = 1$ GeV

<table>
<thead>
<tr>
<th>Category</th>
<th>Yields</th>
<th>Selection Eff(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1.54 \pm 0.21$</td>
<td>$15.8 \pm 2.1$</td>
</tr>
<tr>
<td></td>
<td>$1.56 \pm 0.20$</td>
<td>$16.0 \pm 2.1$</td>
</tr>
<tr>
<td></td>
<td>$0.21 \pm 0.03$</td>
<td>$2.19 \pm 0.33$</td>
</tr>
<tr>
<td></td>
<td>$1.03 \pm 0.14$</td>
<td>$10.6 \pm 1.4$</td>
</tr>
</tbody>
</table>

### Backgrounds
- SM Higgs boson: $5.2 \pm 1.6$
- Non-resonant: $110.7 \pm 3.7$
- $0.51 \pm 0.09$
- $1.51 \pm 0.43$
- $0.23 \pm 0.19$
- $3.95 \pm 0.70$
- $98 \pm 16$
- $2372 \pm 17$

### Source | Maximum uncertainty (%)
---|---
**Experimental**
- Luminosity
- Trigger efficiency
- Vertex selection
- Photon identification efficiency
- Photon energy scale
- Photon energy resolution
- Photon isolation efficiency
- $E_T^{miss}$ reconstruction
- Pile-up reweighting
- 5
- 0.4
- 3.6 (Intermediate), 20 (High $E_T^{miss}$)
- 2.8
- 1
- 2
- 4
- 1 (Rest), 20 (Intermediate and High $E_T^{miss}$)
- 4.5

### Theoretical
- QCD scale uncertainty of $ggH$ $p_T$ spectrum
- Modelling of $ggH$ $E_T^{miss}$ spectrum
- PDF
- MPI
- BR($h \rightarrow \gamma \gamma$)
- 10 - 20
- 25
- 9
- 1 (Intermediate), 50 (High $E_T^{miss}$)
- 4.9
Searches in Higgs channels

Invisible decays of a Higgs boson

James Frost (University of Oxford)

LHCP 2016

Thursday 16th June 2016 45 / 46

<table>
<thead>
<tr>
<th>Process</th>
<th>Control Regions</th>
<th>Signal Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ev$</td>
<td>$\pi$</td>
</tr>
<tr>
<td>QCD $Z \to \mu\mu$</td>
<td>3.7 $\pm$ 1.1</td>
<td>2.1 $\pm$ 0.7</td>
</tr>
<tr>
<td>EWK $Z \to \mu\mu$</td>
<td>59 $\pm$ 0.9</td>
<td>4.4 $\pm$ 0.8</td>
</tr>
<tr>
<td>QCD $W \to \mu\mu$</td>
<td>42 $\pm$ 5</td>
<td>13 $\pm$ 2</td>
</tr>
<tr>
<td>EWK $W \to \mu\mu$</td>
<td>53 $\pm$ 6</td>
<td>53 $\pm$ 6</td>
</tr>
<tr>
<td>QCD $W \to ev$</td>
<td>0.38 $\pm$ 0.16</td>
<td>0.2 $\pm$ 0.3</td>
</tr>
<tr>
<td>EWK $W \to ev$</td>
<td>27 $\pm$ 3</td>
<td>27 $\pm$ 3</td>
</tr>
<tr>
<td>QCD $W \to \tau\tau$</td>
<td>11 $\pm$ 2</td>
<td>11 $\pm$ 2</td>
</tr>
<tr>
<td>EWK $W \to \tau\tau$</td>
<td>52 $\pm$ 1.2</td>
<td>52 $\pm$ 1.2</td>
</tr>
<tr>
<td>Top-quark</td>
<td>5.2 $\pm$ 1.2</td>
<td>5.2 $\pm$ 1.2</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>0.22 $\pm$ 0.06</td>
<td>0.22 $\pm$ 0.06</td>
</tr>
<tr>
<td>Dibosons</td>
<td>0.02 $\pm$ 0.02</td>
<td>0.02 $\pm$ 0.02</td>
</tr>
<tr>
<td>Total Bkg</td>
<td>26 $\pm$ 3</td>
<td>26 $\pm$ 3</td>
</tr>
<tr>
<td>Data</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Signal ($m_H = 125$ GeV)</td>
<td>53.6 $\pm$ 4.9</td>
<td>53.6 $\pm$ 4.9</td>
</tr>
<tr>
<td>VBF</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ggH</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
More mediators!

- Further benchmarks? Guide:
  - New experimental signature?
  - Does the kinematics change between models (points)?
  - t-channel exchanges (above)
  - Higgs Portal - scalar coupling to DM and h

- Active topic of LHC DM WG!