Searches for Dark Matter with the ATLAS Detector

Sarah Barnes
On behalf of the ATLAS collaboration.

Pheno2018
Pittsburgh, USA

May 2018
DM particles do not interact with the strong or electroweak forces and so cannot be observed in the ATLAS detector ....

....SM particles are therefore used to tag an event which may be interesting.

Two typical signatures at the LHC – Large possible zoo of final states!
As of yet no significant excess has been observed

Mono-X

- Search for DM pair production.
- Missing transverse momentum (MET) recoiling against visible “X”, where X = jet, γ, W, Z, Z', ISR, Higgs....

Di-X resonance

- Search for mediator which decays to SM but also couples to DM.
- No MET in the final state, look just for mediator.
- Search for a resonance in uniformly falling dijet, dilepton, tbar mass spectrum.
Study of Dark Matter at LHC

Effective field theories (EFT)

* LHC Run-1 focus.
  * Contact interactions between standard model (SM) and DM.
  * Invalid at large momentum transfer.
  * Parameterised by energy scale and $m_{DM}$

Simplified Models (with mediator)

* LHC Run-2 focus.
  * Introduce mediator that coupled to SM and DM. (resolves contact interaction to s-/t-channel interactions)
  * Natural (more complete) solution to EFT invalidity.
  * Contain long lived DM candidates.
  * More parameters: masses and couplings.

Complete Models

* eg. MSSM, Little Higgs, UED
  * Derived to explain hierarchy problem
  * Naturally provide DM candidate
DM Mediators

Wide variety of different mediators considered

- **Mono-jet**
  - arXiv:1711.03301v2

- **Mono-photon**
  - arXiv:1704.03848v2

- **Mono-HF**
  - arXiv:1710.11412

Wide array of different final states!

- **Mono-V**
  - ATLAS-CONF-2018-005

- **Mono-H → inv**
  - ATLAS-CONF-2018-005

- **Mono-H → γγ**
  - arXiv:1706.03948v3

- **Mono-H → bb**
  - arXiv:1707.01302v3

- **Mono-Z(II)**
  - PLB 776 (2017) 318

- **Mono-ZH**
  - PLB 776 (2017) 318

Leptophobic axial-vector Z’ simplified model considered for dijet resonance searches.

- Simplified models with spin 1 mediators (vector / axial-vector)
- Simplified models with spin 0 mediators (scalar / pseudoscalar and color charged / non colour charged)
- Simplified models involving Higgs and/or additional Higgs bosons.
Mono-X Searches

Many results, this talk will focus on just a few of the most recent searches
Mono-X Overview

Many similarities between the different mono-X searches.

**Selection and Backgrounds**

* Select events with large MET + SM particles for triggering.

* Generally dominant backgrounds from W+jets, Z+jets and ttbar. Also, contributions from irreducible di-boson backgrounds and multijet backgrounds.

**Limits** (often model dependent, couplings and masses fixed)

* If no significant excess is observed limits are generally set.
  - Exclude regions in DM mass and/or mediator mass.
  - Production cross-section.
  - Limits on spin X-Nucleon cross-section

**Analysis Strategy**

* Generally perform a simultaneous profile-likelihood fit of signal regions (SR) + control regions (CR).

* Control regions are included to further constrain background normalisation.

* Validation regions are also often used to control and test background estimation.
* Final state of at least one energetic jet ($p_T > 250$ GeV) + MET.

* Many different possible models considered with spin 1 and 0 mediators.

* Two sets of signal regions included, inclusive (model-independent search) and exclusive (model-dependent) in MET.

Analysis not yet sensitive to pseudoscalar models. Cross-sections 2-3x larger than signal excluded for low mass WIMPS and mediator masses below 300 GeV.

Analysis benefits greatly from theory corrections to underlying cross-section!

V+jet modeled at NNLO QCD & NLO EW

Channel now systematically limited by lepton efficiency scale factor corrections – major hurdle for full run-2.

Brand new result

* Select MET + 2 small-R jets (resolved) or 1 large-R jet (merged).
* Analysis split into 3 lepton multiplicities and 3 b-tag multiplicities – significantly increases sensitivity ~30%.
* Use 0-lepton signal region (SR) and 1/2-lepton control regions (CR).

No significant excess
Systematically limited result.

branching ratio $\mathcal{B}_{H \rightarrow \text{inv.}}$
observed (expected) upper limit of 0.83 (0.58$^{+0.23}_{-0.16}$)}
**Mono-Z’ Hadronic Search**

*Also select MET + 2 small-R jets (resolved) or 1 large-R jet (merged).*

* General resonance search for Z’ mass, mass between 80 – 500 GeV.

* 2 models considered, each with light and heavy dark sector.

* Similar selection/prescription as mono-V analysis.

* Mass window optimised for each Z’ mass point.

---

**ATLAS-CONF-2018-005**

---

**Systematically limited result.**

---

**No significant excess**

Max local significance : 3σ,
Max global significance 2.2σ
**HF + MET Search**

* Select MET in association with top and bottom quarks.
* 5 signal regions considered, Independent fit performed for each SR.

**SRb1**  
Colour charged  
\(b\bar{b}\)  

**SRb2**  
Colour neutral, \(m_{\text{med}} < 100\text{GeV}\)  

**SRt1**  
Hadronic decay, \(m_{\text{med}} < 100 - 350\text{GeV}\)

**SRt2**  
Hadronic decay, \(m_{\text{med}} = 100 - 350\text{GeV}\)

**SRt3**  
Dileptonic decay, \(m_{\text{med}} < 100\text{GeV}\)

First ATLAS limits on \(bb+\phi/a\) models  
Most stringent limits on \(tt+\phi/a\) models.

No significant excess observed

Limits \(\sim300\times\) nominal cross-section for low mass mediator in \(b\)-quark final states

31 Oct 2017  
arXiv:1710.11412

sarahr.barnes@cern.ch  
Pheno2018  
May 2018
* Require MET + 2 same flavor opposite sign leptons.

* Higgs decays to invisible with low BR (~0.1%). Any deviation would indicate new physics.

* Mass cut defined within 15 GeV of Z peak.

* Main background from ZZ production.

Study both vector and axial-vector mediator models.

Axial-vector and Vector model: $g_q = 0.25$, $g_i = 0$, $g_{\chi} = 1$.
Resonance Searches
Will focus on dijet searches
* Dijet events primarily from $2 \rightarrow 2$ parton scattering via strong interaction, QCD predicts a smoothly decreasing $m_{jj}$ distribution. New resonant state may appear as an excess in this distribution.

* Search for two-jet final state, $p_T > 440$ (60) GeV for lead (sublead) jet.
* Single jet triggers used $p_T > 380$ GeV
* Signal regions studied: $|y^*| < 0.6$ for DM model
* Many BSM models considered.

$y^* = (y_1 - y_2)/2$, where $y$ is rapidity of each jet

No significant excess observed.

Background estimated using sliding window fit – new approach

Max global significance = $0.63\sigma$
* Raised trigger thresholds at high lumi lead to difficulty in the low mediator mass/low coupling strength regime.

* Reduced set of info from trigger is recorded/analysed – increases rate by factor 2.

* Calibration is difficult due to lack of tracking for trigger-level jets – dedicated calibration obtained similar precision to offline.

* Due to high statistical precision also sensitive to detector/calibration-induced fluctuations.

No significant excess – max global significance at 0.16σ
Dijet + ISR Resonance Searches

No significant excess
max global significance at 0.85σ/0.9σ for resolved γ/jet channel
max global significance at 0.8σ/1.1σ for boosted γ/jet channel

* Two additional dijet searches performed in addition with high $p_T$ ISR photon or jet.
* Both boosted (one large-R jet with substructure) and resolved analyses performed (two small-R jets).
* ISR jets helps to reduce the background rates associated with standard dijet searched allowing lower mediator masses to be studied.

No significant excess
Max local (global) significance : 2.4σ (1.2σ).

Lowest mediator mass significantly lower than standard dijet searches

Large amount of work from CP groups to understand large-R jet and their substructure.

Challenge for full run-2 is to further improve the jet CP:
* Use track calo-clusters as an input to jet reconstruction
  ATL-PHYS-PUB-2017-015
* Improvements to jet reconstruction and grooming algorithms
  ATL-PHYS-PUB-2017-020

Aug 8, 2016
26 Jan 2018
ATLAS-CONF-2016-070 (resolved)
arXiv:1801.08769v1 (boosted)
Dijet searches can exclude mediator masses between 50 GeV and 2.7 TeV for almost whole DM mass range.

Updated results TLA available – will push further down in mediator mass

Mono-V results

Axial-vector mediator, Dirac DM
\[ g_q = 0.25, \ g = 0, \ g_{DM} = 1 \]

All limits at 95% CL
Comparison to Direct Detection

ATLAS results can be translated into the direct detection plane (prescription detailed here: arXiv:1603.04156v1)

Under these assumptions ATLAS searches most sensitive at low DM mass – provides nice complementarity!

Spin Independent cross-section in scenarios of Z' like mediator – other versions of this plot exist for various scenarios.

sarah.barnes@cern.ch

Pheno2018

May 2018
Many searches for Dark Matter have already been performed and are in the process of being performed at the ATLAS experiment.

* Limits have been set on several simplified Dark Matter models, mainly including simplified models with spin-0 and spin-1 mediators and Higgs bosons.

* So far, no evidence for physics beyond the SM has been found.

* LHC searches are complimentary to direct searches.

* Unlikely that with more data will turn most sensitive channel (mono-jet) into a discovery machine. We need to get more creative!
  * Better CP.
  * New signatures.
  * Better modeling of backgrounds (Theory).
Backup
Lots of experimental evidence for the existence of Dark Matter (DM):

* Galactic rotation curves
* Bullet cluster / Gravitational lensing
* Cosmic microwave background

Requirements:

* Interacts gravitationally
* Cosmologically stable
* Electrically neutral
* Massive and weakly interacting

Many candidates:

- WIMPs – Weakly interacting massive particles
- SUSY – eg. LSP
Mono-H → bb Search

* Require MET + Higgs boson decaying to bb
* Analysis interpreted in terms of 2HDM model with additional U(1)$_{Z'}$ gauge symmetry (Z'-2HDM).
* Both a resolved and merged regime are considered for the b-tagged jets.
* Four signal regions considered in bins of MET.
* Require MET + Higgs boson decaying to $\gamma\gamma$
* Analysis interpreted in terms of 2HDM model with additional $U(1)_Z$ gauge symmetry ($Z'\text{-}2\text{HDM}$).
* Also consider $Z'_B$ model and heavy scalar model.

**Z'_B model**

**Z'\text{-}2\text{HDM model}**

Gain sensitivity at low DM mass.
* Require MET + high energy photon.
* Consider both simplified and EFT model.
* Single photon trigger used.
* Dominant backgrounds from Wγ/Zγ and γ+jets.
* 5 signal regions used, in bins of MET.

Study both vector and axial-vector mediator models. \( g_q = 0.25, g_l = 0, g_\chi = 1 \)

ATLAS

Exclusion at 90% CL
Vector mediator
Dirac DM
\( g_q = 0.25, g_\chi = 1, g_l = 0 \)

Gain sensitivity at low DM mass.
* Search for Higgs(125) decaying to dark photons using two different models.
* Dark photons decay to SM particles, which would be observed as light “lepton” jets originating from a displaced vertex.
* Light jets contain just electrons, muons and pions.
* Select MET + light lepton jets.

No significant excess
**Where do we go next?**

* Still a lot of sensitivity to be gained by performing analyses with the full run-2 data.
  - increased statistics and lower systematics from performance groups / lumi.
* WIMP case is still strong though maybe less simple than expected.
* Need to develop new models, though some conflict as to where to go.
* Experimental uncertainties now limiting results, need to improve techniques and increase data.
* Also need to reduce theoretical uncertainties.
Dijet Summary

ATLAS Preliminary April 2018

$\sqrt{s} = 13$ TeV, 3.6-37.0 fb$^{-1}$

95% CL upper limits
- Observed
- Expected

- Large-$R$ jet + ISR, 36.1 fb$^{-1}$
  arXiv: 1801.08769
- Dijet + ISR ($\gamma$), 15.5 fb$^{-1}$
  ATLAS-CONF-2016-070
- Dijet + ISR (jet), 15.5 fb$^{-1}$
  ATLAS-CONF-2016-070
- Dijet TLA, 3.6-29.7 fb$^{-1}$
  arXiv: 1804.03496
- Dijet, 37.0 fb$^{-1}$

Axial vector mediator
Dirac Dark Matter
$m_{DM} = 10$ TeV

$|y_{12}| < 0.3$
$|y_{12}| < 0.6$

$m_Z$ [GeV]
Table 3: Data and SM background predictions in the signal region for several inclusive $E_T^{\text{miss}}$ selections, as determined using separate one-bin likelihood fits in the control regions. 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. The dash “$-$” denotes negligible background contributions.

<table>
<thead>
<tr>
<th>Inclusive Signal Region</th>
<th>IM1</th>
<th>IM3</th>
<th>IM5</th>
<th>IM7</th>
<th>IM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events (36.1 fb$^{-1}$)</td>
<td>255486</td>
<td>76808</td>
<td>13680</td>
<td>2122</td>
<td>245</td>
</tr>
<tr>
<td>SM prediction</td>
<td>245900 ± 5800</td>
<td>73000 ± 1900</td>
<td>12720 ± 340</td>
<td>2017 ± 90</td>
<td>238 ± 23</td>
</tr>
<tr>
<td>$W(\rightarrow e\nu)$</td>
<td>20600 ± 620</td>
<td>4930 ± 220</td>
<td>682 ± 33</td>
<td>63 ± 8</td>
<td>7 ± 2</td>
</tr>
<tr>
<td>$W(\rightarrow \mu\nu)$</td>
<td>20860 ± 840</td>
<td>5380 ± 280</td>
<td>750 ± 44</td>
<td>115 ± 13</td>
<td>17 ± 2</td>
</tr>
<tr>
<td>$W(\rightarrow \tau\nu)$</td>
<td>50300 ± 1500</td>
<td>12280 ± 520</td>
<td>1880 ± 63</td>
<td>261 ± 13</td>
<td>24 ± 3</td>
</tr>
<tr>
<td>$Z/\gamma^*(\rightarrow e^+e^-)$</td>
<td>0.11 ± 0.03</td>
<td>0.03 ± 0.01</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$Z/\gamma^*(\rightarrow \mu^+\mu^-)$</td>
<td>364 ± 32</td>
<td>107 ± 9</td>
<td>10 ± 1</td>
<td>1.8 ± 0.5</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td>$Z/\gamma^*(\rightarrow \tau^+\tau^-)$</td>
<td>812 ± 32</td>
<td>178 ± 8</td>
<td>24 ± 1</td>
<td>3.5 ± 0.5</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>$Z(\rightarrow \nu\bar{\nu})$</td>
<td>137800 ± 3900</td>
<td>45700 ± 1300</td>
<td>8580 ± 260</td>
<td>1458 ± 76</td>
<td>176 ± 18</td>
</tr>
<tr>
<td>$t\bar{t}$, single top</td>
<td>8600 ± 1100</td>
<td>2110 ± 280</td>
<td>269 ± 42</td>
<td>26 ± 10</td>
<td>0 ± 1</td>
</tr>
<tr>
<td>Diboson</td>
<td>5230 ± 400</td>
<td>2220 ± 170</td>
<td>507 ± 64</td>
<td>88 ± 19</td>
<td>13 ± 4</td>
</tr>
<tr>
<td>Multijet background</td>
<td>700 ± 700</td>
<td>51 ± 50</td>
<td>8 ± 8</td>
<td>1 ± 1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Non-collision background</td>
<td>360 ± 360</td>
<td>51 ± 51</td>
<td>4 ± 4</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Table 6: Observed and expected 95% CL upper limits on the number of signal events, $S_{\text{obs}}^{95}$ and $S_{\text{exp}}^{95}$, and on the visible cross section, defined as the product of cross section, acceptance and efficiency, $\langle \sigma \rangle_{\text{obs}}^{95}$, for the IM1–IM10 selections.

<table>
<thead>
<tr>
<th>Selection</th>
<th>$\langle \sigma \rangle_{\text{obs}}^{95}$ [fb]</th>
<th>$S_{\text{obs}}^{95}$</th>
<th>$S_{\text{exp}}^{95}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM1</td>
<td>531</td>
<td>19135</td>
<td>11700$^{+4400}_{-3300}$</td>
</tr>
<tr>
<td>IM2</td>
<td>330</td>
<td>11903</td>
<td>7000$^{+2600}_{-2600}$</td>
</tr>
<tr>
<td>IM3</td>
<td>188</td>
<td>6771</td>
<td>4000$^{+1400}_{-1100}$</td>
</tr>
<tr>
<td>IM4</td>
<td>93</td>
<td>3344</td>
<td>2100$^{+770}_{-590}$</td>
</tr>
<tr>
<td>IM5</td>
<td>43</td>
<td>1546</td>
<td>770$^{+280}_{-220}$</td>
</tr>
<tr>
<td>IM6</td>
<td>19</td>
<td>696</td>
<td>360$^{+130}_{-100}$</td>
</tr>
<tr>
<td>IM7</td>
<td>7.7</td>
<td>276</td>
<td>204$^{+74}_{-57}$</td>
</tr>
<tr>
<td>IM8</td>
<td>4.9</td>
<td>178</td>
<td>126$^{+47}_{-35}$</td>
</tr>
<tr>
<td>IM9</td>
<td>2.2</td>
<td>79</td>
<td>76$^{+29}_{-21}$</td>
</tr>
<tr>
<td>IM10</td>
<td>1.6</td>
<td>59</td>
<td>56$^{+21}_{-16}$</td>
</tr>
</tbody>
</table>
A comparison of the inferred limits (black line) to the constraints from direct detection experiments (purple line) on the spin-dependent WIMP–proton scattering cross section in the context of the simplified model with axial-vector couplings. Unlike in the $m_{ZA} - m_\chi$ parameter plane, the limits are shown at 90% CL. The results from this analysis, excluding the region to the left of the contour, are compared with limits from the PICO [95] experiment. The comparison is model-dependent and solely valid in the context of this model, assuming minimal mediator width and the coupling values $g_q = 1/4$ and $g_\chi = 1$. 

\[\sigma_{SD}(\chi\text{-proton}) [\text{cm}^2]\]

\[m_\chi [\text{GeV}]\]
Figure 7: Observed and expected 95\% CL limits on the signal strength $\mu \equiv \sigma^{95\%\, \text{CL}} / \sigma$ as a function of (a) the mediator mass for a very light WIMP and (b) the WIMP mass for $m_{Z_p} = 10$ GeV, in a model with spin-0 pseudoscalar mediator and $g_q = g_\gamma = 1.0$. The bands indicate the $\pm 1\sigma$ theory uncertainties in the observed limit and the $\pm 1\sigma$ and $\pm 2\sigma$ ranges of the expected limit in the absence of a signal.
**Final states for HF+MET**

**DM + t\bar{t}: Hadronic channel 2 SRs**
- Large $E_T^{\text{miss}}$
- 4 Jets with 2 $b$-tagged jets

Arxiv:1710.11412

**DM + b\bar{b}: Hadronic channel 2 SRs**
- Very large $E_T^{\text{miss}}$ (600, 180 GeV)
- 2 Jets with 1 $b$-tagged jets

Arxiv:1710.11412

**DM + t\bar{t}: Single leptons channel 3 SRs**
- Large $E_T^{\text{miss}} > 230$ GeV
- At least 2 Jets with 1 $b$-tagged jet

Arxiv:1711.11520

**DM + t\bar{t}: Di-lepton channel 1 SR**
- Large $E_T^{\text{miss}}$
- 1 $b$-tagged Jets

Arxiv:1710.11412
The SRt1 was originally optimised for low-mass scalar mediators, while SRt2 was optimised for high-mass scalar mediators and pseudoscalar mediators. However, SRt1 is strongly affected by systematic uncertainties in the $t\bar{t}$ modelling and therefore SRt2 sets more stringent limits for the whole parameter space.
### Systematics for HF+MET

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>SRb1 [%]</th>
<th>SRb2 [%]</th>
<th>SRt1 [%]</th>
<th>SRt2 [%]</th>
<th>SRt3 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td>18</td>
<td>15–18</td>
<td>29</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td><strong>Z theoretical uncertainties</strong></td>
<td>5.7</td>
<td>7.9–12</td>
<td>5.0</td>
<td>2.1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>$t\bar{t}+Z$ theoretical uncertainties</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>3.3</td>
<td>5.3</td>
<td>8.4</td>
</tr>
<tr>
<td>$t\bar{t}$ theoretical uncertainties</td>
<td>&lt;1</td>
<td>2.7–9.8</td>
<td>17</td>
<td>5.7</td>
<td>11</td>
</tr>
<tr>
<td><strong>MC statistical uncertainties</strong></td>
<td>6.4</td>
<td>4.8–6.4</td>
<td>15</td>
<td>5.9</td>
<td>18</td>
</tr>
<tr>
<td><strong>Z fitted normalisation</strong></td>
<td>13</td>
<td>12–19</td>
<td>2.3</td>
<td>3.4</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}+Z$ fitted normalisation</td>
<td>-</td>
<td>-</td>
<td>2.2</td>
<td>3.5</td>
<td>7.1</td>
</tr>
<tr>
<td>$t\bar{t}$ fitted normalisation</td>
<td>-</td>
<td>1.9–4.2</td>
<td>3.9</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Fake or non-prompt leptons</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.9</td>
</tr>
<tr>
<td><strong>Pile-up</strong></td>
<td>3.8</td>
<td>&lt;1–1.4</td>
<td>6.8</td>
<td>5.5</td>
<td>&lt;1</td>
</tr>
<tr>
<td><strong>Jet energy resolution</strong></td>
<td>1.5</td>
<td>1.3–6.9</td>
<td>7.0</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td><strong>Jet energy scale</strong></td>
<td>7.7</td>
<td>5.0–10</td>
<td>5.0</td>
<td>2.8</td>
<td>8.2</td>
</tr>
<tr>
<td><strong>$E_T^{miss}$ soft term</strong></td>
<td>&lt;1</td>
<td>4.3–6.3</td>
<td>2.0</td>
<td>&lt;1</td>
<td>12</td>
</tr>
<tr>
<td><strong>b-tagging</strong></td>
<td>&lt;1</td>
<td>2.4–6.9</td>
<td>8.6</td>
<td>3.1</td>
<td>&lt;1</td>
</tr>
<tr>
<td></td>
<td>SRb1</td>
<td>SRb2-bin1</td>
<td>SRb2-bin2</td>
<td>SRb2-bin3</td>
<td>SRb2-bin4</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>Observed</td>
<td>19</td>
<td>88</td>
<td>88</td>
<td>90</td>
<td>82</td>
</tr>
<tr>
<td>Total background (fit)</td>
<td>16.9 ± 3.3</td>
<td>77 ± 13</td>
<td>72 ± 11</td>
<td>76 ± 13</td>
<td>66.4 ± 9.1</td>
</tr>
<tr>
<td>Z/γ*+ jets</td>
<td>14.2 ± 3.1</td>
<td>39.7 ± 6.3</td>
<td>44.4 ± 6.6</td>
<td>53.3 ± 9.9</td>
<td>55.6 ± 8.6</td>
</tr>
<tr>
<td>t(t)</td>
<td>0.58^{+0.60}_{-0.58}</td>
<td>17.8 ± 6.5</td>
<td>13.8 ± 5.5</td>
<td>14.0 ± 4.7</td>
<td>7.0 ± 2.9</td>
</tr>
<tr>
<td>Single top quark</td>
<td>0.25^{+0.42}_{-0.25}</td>
<td>14.7 ± 5.8</td>
<td>10.2 ± 3.7</td>
<td>5.5 ± 3.1</td>
<td>2.6 ± 1.7</td>
</tr>
<tr>
<td>Others</td>
<td>2.0 ± 1.1</td>
<td>5.2 ± 3.4</td>
<td>3.4^{+1.7}_{-1.6}</td>
<td>2.7 ± 1.1</td>
<td>1.3 ± 1.0</td>
</tr>
<tr>
<td>Z/γ*+ jets (pre-fit)</td>
<td>12.1</td>
<td>30.6</td>
<td>34.2</td>
<td>41.1</td>
<td>42.8</td>
</tr>
<tr>
<td>t(t) (pre-fit)</td>
<td>-</td>
<td>27.1</td>
<td>21.1</td>
<td>21.4</td>
<td>10.6</td>
</tr>
</tbody>
</table>

**Signal benchmarks**

- $m(\phi, \chi) = (20, 1)$ GeV, $g = 1$: $0.238 \pm 0.085$, $0.262 \pm 0.079$, $0.320 \pm 0.082$, $0.277 \pm 0.080$
- $m(a, \chi) = (20, 1)$ GeV, $g = 1$: $0.256 \pm 0.065$, $0.199 \pm 0.060$, $0.308 \pm 0.085$, $0.267 \pm 0.067$
- $m(\phi_b, \chi) = (1000, 35)$ GeV: $18.6 \pm 3.8$
### Yields + statistical uncerts for HF+MET

<table>
<thead>
<tr>
<th></th>
<th>SRt1</th>
<th>SRt2</th>
<th>SRt3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed</strong></td>
<td>23</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td><strong>Total background (fit)</strong></td>
<td>$20.5 \pm 5.8$</td>
<td>$20.4 \pm 2.9$</td>
<td>$15.2 \pm 4.3$</td>
</tr>
<tr>
<td>$\bar{t}\bar{t}$</td>
<td>7.0 ± 3.9</td>
<td>3.1 ± 1.3</td>
<td>4.5 ± 2.5</td>
</tr>
<tr>
<td>$t\bar{t}+Z$</td>
<td>4.3 ± 1.1</td>
<td>6.9 ± 1.4</td>
<td>4.4 ± 1.9</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>3.3 ± 2.6</td>
<td>1.28 ± 0.50</td>
<td>incl. in Fakes/NP</td>
</tr>
<tr>
<td>$Wt$</td>
<td>incl. in Others</td>
<td>incl. in Others</td>
<td>$0.33^{+0.53}_{-0.33}$</td>
</tr>
<tr>
<td>$Z/\gamma^*+$jets</td>
<td>3.7 ± 1.4</td>
<td>6.2 ± 1.1</td>
<td>incl. in Others</td>
</tr>
<tr>
<td>$VV$</td>
<td>incl. in Others</td>
<td>incl. in Others</td>
<td>0.61 ± 0.25</td>
</tr>
<tr>
<td>Fakes/NP</td>
<td>-</td>
<td>-</td>
<td>2.7 ± 1.3</td>
</tr>
<tr>
<td>Others</td>
<td>2.2 ± 1.2</td>
<td>3.00 ± 1.6</td>
<td>2.69 ± 0.93</td>
</tr>
<tr>
<td>$\bar{t}\bar{t}$ (pre-fit)</td>
<td>6.1</td>
<td>2.8</td>
<td>4.0</td>
</tr>
<tr>
<td>$t\bar{t}+Z$ (pre-fit)</td>
<td>3.53</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>$Z/\gamma^*$+ jets (pre-fit)</td>
<td>3.2</td>
<td>5.72</td>
<td>-</td>
</tr>
</tbody>
</table>

**Signal benchmarks**

- $m(\phi, \chi) = (20, 1)$ GeV, $g = 1$
  - $9.3 \pm 1.6$  
  - $12.8 \pm 1.9$  
  - $21.0 \pm 2.3$  
- $m(a, \chi) = (20, 1)$ GeV, $g = 1$
  - $7.6 \pm 1.5$  
  - $12.1 \pm 1.8$  
  - $14.1 \pm 1.6$  
- $m(\phi, \chi) = (100, 1)$ GeV, $g = 1$
  - $6.5 \pm 1.3$  
  - $10.1 \pm 1.5$  
  - $11.5 \pm 1.5$  
- $m(a, \chi) = (100, 1)$ GeV, $g = 1$
  - $6.2 \pm 1.2$  
  - $11.5 \pm 2.0$  
  - $11.9 \pm 1.5$  

sarah.barnes@cern.ch  
Pheno2018  
May 2018
HF+MET color charged mediator

\( M_\chi = 35 \text{ GeV} \)

\( \lambda b \) set to the measured relic density

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

SRb1 Limits at 95\% CL

- Observed
- Expected \((\pm 1 \sigma_{\text{exp}})\)

\( E_{T}^{\text{miss}} + 1b, 20 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \)

\( E_{T}^{\text{miss}} + 2b, 36.1 \text{ fb}^{-1}, \sqrt{s} = 13 \text{ TeV} \)
For each dark-matter and mediator mass pair, the exclusion limit on the production cross-section of colour-neutral scalar mediator particles can be converted into a limit on the spin-independent DM–nucleon scattering cross-section.
Table 1: Event selection criteria in the $\ell\ell + E_T^{\text{miss}}$ search.

<table>
<thead>
<tr>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Two leptons</strong></td>
</tr>
<tr>
<td>Two opposite-sign leptons, leading (subleading) $p_T &gt; 30$ (20) GeV</td>
</tr>
<tr>
<td><strong>Third lepton veto</strong></td>
</tr>
<tr>
<td>Veto events if any additional lepton with $p_T &gt; 7$ GeV</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
</tr>
<tr>
<td>$76 &lt; m_{\ell\ell} &lt; 106$ GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ and $E_T^{\text{miss}}/H_T$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 90$ GeV and $E_T^{\text{miss}}/H_T &gt; 0.6$</td>
</tr>
<tr>
<td>$\Delta\phi(p_T^{\ell\ell}, E_T^{\text{miss}})$</td>
</tr>
<tr>
<td>$\Delta\phi(p_T^{\ell\ell}, E_T^{\text{miss}}) &gt; 2.7$ radians</td>
</tr>
<tr>
<td>$\Delta R_{\ell\ell}$</td>
</tr>
<tr>
<td>$\Delta R_{\ell\ell} &lt; 1.8$</td>
</tr>
<tr>
<td>Fractional $p_T$ difference</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$b$-jets veto</td>
</tr>
<tr>
<td>$N(b$-jets$) = 0$ with $b$-jet $p_T &gt; 20$ GeV and $</td>
</tr>
</tbody>
</table>
### MonoZH yields

<table>
<thead>
<tr>
<th>Final State</th>
<th>ee</th>
<th>μμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Data</td>
<td>437</td>
<td>497</td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ZH \rightarrow \ell\ell + \text{inv} \ (B_{H\rightarrow\text{inv}} = 30%)$</td>
<td>$32 \pm 1 \pm 3$</td>
<td>$34 \pm 1 \pm 3$</td>
</tr>
<tr>
<td>DM ($m_{\text{med}} = 500 \text{ GeV}, m_\chi = 100 \text{ GeV}) \times 0.27$</td>
<td>$10.8 \pm 0.3 \pm 0.8$</td>
<td>$11.1 \pm 0.3 \pm 0.8$</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$qqZZ$</td>
<td>$212 \pm 3 \pm 15$</td>
<td>$221 \pm 3 \pm 17$</td>
</tr>
<tr>
<td>$ggZZ$</td>
<td>$18.9 \pm 0.3 \pm 11.2$</td>
<td>$19.3 \pm 0.3 \pm 11.4$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$106 \pm 2 \pm 6$</td>
<td>$113 \pm 3 \pm 5$</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>$30 \pm 1 \pm 28$</td>
<td>$37 \pm 1 \pm 19$</td>
</tr>
<tr>
<td>Non-resonant-$\ell\ell$</td>
<td>$30 \pm 4 \pm 2$</td>
<td>$33 \pm 4 \pm 2$</td>
</tr>
<tr>
<td>Others</td>
<td>$1.4 \pm 0.1 \pm 0.2$</td>
<td>$2.5 \pm 2.0 \pm 0.8$</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td>$399 \pm 6 \pm 34$</td>
<td>$426 \pm 6 \pm 28$</td>
</tr>
</tbody>
</table>
Table 2: The 95% CL lower limits on the masses of ADD quantum black holes (BLACKMAX event generator), $W'$ and $W^*$ bosons, excited quarks, and $Z'$ bosons for selected coupling values from the resonance search, as well as on the scale of contact interactions for constructive ($\eta_{LL} = -1$) and destructive ($\eta_{LL} = +1$) interference from the angular analysis. Where an additional range is listed, masses within the range are also excluded. Full limits on the $Z'$ model are provided in Figure 4.

<table>
<thead>
<tr>
<th>Model</th>
<th>95% CL exclusion limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>Quantum black hole</td>
<td>8.9 TeV</td>
</tr>
<tr>
<td>$W'$</td>
<td>3.6 TeV</td>
</tr>
<tr>
<td>$W^*$</td>
<td>3.4 TeV</td>
</tr>
<tr>
<td></td>
<td>3.77 TeV – 3.85 TeV</td>
</tr>
<tr>
<td>Excited quark</td>
<td>6.0 TeV</td>
</tr>
<tr>
<td>$Z'(g_q = 0.1)$</td>
<td>2.1 TeV</td>
</tr>
<tr>
<td>$Z'(g_q = 0.2)$</td>
<td>2.9 TeV</td>
</tr>
<tr>
<td>Contact interaction ($\eta_{LL} = -1$)</td>
<td>21.8 TeV</td>
</tr>
<tr>
<td>Contact interaction ($\eta_{LL} = +1$)</td>
<td>13.1 TeV</td>
</tr>
</tbody>
</table>
Prior searches use form:

\[ f(z) = p_1 (1 - z)^{p_2} \frac{z^{p_3} \log z}{1 - z^{p_4}} \]

Where \( z = \frac{m_{jj}}{\sqrt{s}} \) and \( p_i \) are parameters which describe dijet mass distributions at lower collision energies.

At higher \( E \) a single global fit can no longer be relied upon due to the tail of the distribution.
Old method still viable for this analysis but good test for a new method while comparison can be made.
Instead use sliding window fit.

Use 3 param fit function to fit different sections of the distribution.
Results are comparable to past results and performs well with injected signals of any width.

Perform profile likelihood fit to the data in each window using and use the fit value at the center of the window for the background distribution. Then join together the windows.
Figure 5: The 95% CL upper limits obtained from the dijet invariant mass $m_{jj}$ distribution on cross-section times acceptance times branching ratio to two jets, $\sigma \times A \times BR$, for a hypothetical signal with a cross-section $\sigma_G$ that produces a Gaussian contribution to the particle-level $m_{jj}$ distribution, as a function of the mean of the Gaussian mass distribution $m_G$. Observed limits are obtained for five different widths, from a narrow width to 15% of $m_G$. The expected limit and the corresponding $\pm 1\sigma$ and $\pm 2\sigma$ bands are also indicated for a narrow-width resonance.
Dijet +ISR limits and uncertainties

Table 1: The source and relative size of each of the largest uncertainties in the best-fit signal-strength parameter $\mu$ of hypothesised signal production of $Z'$ with $m_{Z'} = 160$ GeV and $m_{Z'} = 220$ GeV.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta\mu/\mu$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m_{Z'} = 160$ GeV</td>
</tr>
<tr>
<td>Transfer factor</td>
<td>90</td>
</tr>
<tr>
<td>Large-R jet</td>
<td>25</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>93</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>10</td>
</tr>
</tbody>
</table>
Calibration steps for trigger-level analysis

1. EM-scale jets
   - Jet finding applied to topological clusters at the electromagnetic scale

2. Jet-area based pileup correction
   - Applied as a function of event pileup $p_T$ density and jet area only

3. Absolute MC-based calibration
   - Corrects the jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated

4. Global sequential calibration
   - Reduces flavor dependence and energy leakage using calorimeter variables only

5. Eta intercalibration
   - Corrects the scale of forward jets in data to that of central jets, using the $p_T$ balance ratio between data and simulation, applied only to data

6. Trigger-to-offline data-derived correction
   - Corrects trigger-level jets to the scale of offline jets, applied only to data

7. Residual in-situ calibration
   - A smooth residual calibration is derived by fitting in-situ measurements and applied only to data

---

derived for offline jets

---

derived specifically for trigger jets

May 2018
Step 4:

Calorimeter-based variables are used to reduce the dependence on the trigger-level jet flavor and to minimize the impact of energy leakage. Only variables related to the trigger-level jet energy fractions in the electromagnetic and hadronic calorimeters and the minimum number of calorimeter cells containing 90% of the trigger-level jet energy are used here since track-based variables, which are normally used in the offline calibration, are not available. With this correction, the trigger-level jet energy resolution is improved by 8% at jet p_T values of 85 GeV and up to 40% for jet p_T values of 1 TeV relative to the previous calibration step.

Step 6:

Any residual difference between trigger-level jets and offline jets is accounted for in a dedicated correction, based on the p_T response and derived from data in bins of jet η and p_T. The size of this correction is on average 1%, with values reaching up to 4% in the endcap regions of the calorimeter.

Final step is in-situ calibration where data-to-sim ratio of the pT balance between well known offline jets and well calibrated objects against which the jets recoil. polynomial log is simultaneously fit to the three input measurements and combined. (Z-> e/μ, γ and multijet)

After the full calibration procedure, the energy of trigger-level jets is equivalent to that of offline jets to better than 0.05% for invariant masses of 400 GeV and their difference is negligible for invariant masses of 1 TeV.
Similar precision obtained compared with the offline calibration.

**Trigger**

Data 2016, $\sqrt{s} = 13$ TeV

- anti-$k_t$, $R = 0.4$, EM+JES + in situ correction
- $\eta = 0.0$

**Offline**

Data 2016, $\sqrt{s} = 13$ TeV

- anti-$k_t$, $R = 0.4$, EM+JES + in situ correction
- $\eta = 0.0$

Fractional JES uncertainty vs. $p_T^{jet}$ [GeV]
TLA Fits

**ATLAS**

- Data, 29.3 fb$^{-1}$, $|y^*| < 0.6$
- Background fit
- BumpHunter interval
- $Z'$, $\sigma \times 500$
  - $m_{Z'} = 750$ GeV, $g_\ell = 0.1$
  - BH $p$-value = 0.44
  - $\chi^2$ $p$-value = 0.13

- Data, 3.6 fb$^{-1}$, $|y^*| < 0.3$
- Background fit
- BumpHunter interval
- $Z'$, $\sigma \times 500$
  - $m_Z = 550$ GeV, $g_\ell = 0.1$
TLA Model independent limits

\[ \sqrt{s} = 13 \text{ TeV} \]

ATLAS

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

95% CL upper limits

**Observed**
- \( \sigma_G/m_G = \text{Res.} \)
- \( \sigma_G/m_G = 0.05 \)
- \( \sigma_G/m_G = 0.07 \)
- \( \sigma_G/m_G = 0.10 \)

**Expected**
- \( \sigma_G/m_G = \text{Res. (± 1-2σ)} \)
- \( \sigma_G/m_G = 0.05 \)
- \( \sigma_G/m_G = 0.07 \)
- \( \sigma_G/m_G = 0.10 \)

\[ |y^*| < 0.3 \quad |y^*| < 0.6 \]

\[ m_G \text{ [GeV]} \]

May 2018