Dark Matter Searches at the LHC

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On behalf of the ATLAS and CMS collaborations
Dark Matter Observation

**Cosmological observation**

Dark matter properties:
- Stable,
- Gravitationally interacting,
- Cold (non-relativistic),
- Dark (Does not interact with light)
Dark Matter Interaction

For WIMPs

thermal freeze-out (early Univ.)
indirect detection (now)

$E_R = \frac{q^2}{2\mu}$

$\mu = m_\chi m_N$

$\theta$ = scattering angle in the center of mass system

production at colliders

$DM \rightarrow SM$

$SM \rightarrow DM$
Dark Matter Production at Colliders

- Probe SM – dark matter particle interactions up to the TeV scale
- Measure the properties of the dark matter particles (once detected)
- Develop methods to enhance the complementarity with direct and indirect dark matter searches
Dark Matter Models

**Contact interaction**
valid for $Q^2$ much smaller than effective scale

**Renormalisable theories**
information on dark matter particle and mediator
LHC Run-2 DM searches harmonised

**More Complex Models**
complex phenomenology (e.g. SUSY)

**EFT**

**Simplified Models**

**Complete Theories**

**MSSM**

**LED**

**Completeness**

**Complexity**
Direct production

Generally referred to as “Mono-X” searches

Search for deviation from the Standard Model expectation

Missing transverse energy plus visible objects

DM production through the Higgs portal!

All Higgs production modes can be studied!

Most sensitive channel is the VBF production

CMS & ATLAS Collaborations search for DM in many ways:

Dark matter (DM) searches at the LHC

Search for deviation from the Standard Model expectation
Direct production

Generally referred to as “Mono-X” searches

Missing transverse energy plus visible objects

Search for deviation from the Standard Model expectation

ATLAS mono-jet candidate
Mono-X / Missing Energy

Mono-Jet & Xsec Ratio

Mono-Photon

Mono-W/Z hadronic

Mono-Z(II)

Heavy Quarks (t,b)

Mono-H

Properties of the new Mediator

<table>
<thead>
<tr>
<th>Model Type</th>
<th>spin</th>
<th>parity</th>
<th>color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simpli</td>
<td>1</td>
<td>+1, -1</td>
<td>neutral</td>
</tr>
<tr>
<td>Simpli</td>
<td>0</td>
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<tr>
<td>Simpli</td>
<td>0</td>
<td>+1</td>
<td>charged</td>
</tr>
<tr>
<td>Simpli</td>
<td></td>
<td></td>
<td>Models with a Higgs boson</td>
</tr>
<tr>
<td>EFT</td>
<td></td>
<td></td>
<td>Higher-dimensional operators</td>
</tr>
</tbody>
</table>
Mono-jet/V(had) Search

Most powerful search at hadron colliders

- Main backgrounds: $Z(\nu \nu) + \text{jets}$ - 0(55-70%), $W(l\nu)+\text{jets}$ 0(35-20%)
- Precision on the background estimate: 2-7%
Systematically limited

35.9 fb⁻¹ (13 TeV)

Statistically limited

CMS: PRD 97 (2018) 092005
ATLAS: JHEP 01 (2018) 126

Mono-jet/V(had) Search

CMS

monojet

Vector med, Dirac DM, $g_q = 0.25$, $g_{DM} = 1$

- Median expected 95% CL
- ± 1 $\sigma_{\text{experiment}}$
- Observed 95% CL
- Observed ± theory unc.

$\Omega_c h^2 \approx 0.12$
Mono-jet Searches

Scalar coloured 't-channel'

Spin-1 axial-vector s-channel

**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

95% CL limits

Coloured scalar mediator

g = 1

$g = 1$

Coloured scalar mediator

Relic density (MadDM)

**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Axial-Vector Mediator

Dirac Fermion DM

g$ = 0.25$, $g = 1.0$

95% CL limits

$g = 0.25$, $g = 1.0$

Relic density (MadDM)
Mono-V(hadronic) Search

Large-R jets for boosted $W/Z$ hadronic decays

- Sub-structure information for discrimination
- $Z(\nu\nu)/W(\ell\nu)$+jets dominant background $\rightarrow$ normalised in CRs
- main uncertainty: large-R jet modelling

$E_T^{\text{miss}} > 200$ GeV

$\mu/e$ veto

$W/Z$

$\ell\nu$ veto

$E_T^{\text{miss}} > 200$ GeV

ATLAS

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

SR: merged topology

0 leptons, 2 b-tags

$10^2$ limits on visible cross-section

$\sigma_{\text{vis}, W+DM}^{\text{upper limit}}$ at 95% CL

After all selections, inclusive in $b$-tag multiplicity

inclusive in $m_{jj}$

ATLAS

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Observed 95% CL

Expected 95% CL ($\pm \sigma$)

Data

W+jets

Z+jets

tt + single top

Diboson

Multijet

Background Uncertainty

Pre-fit Background

- Dark Higgs Model
  
  $m = 90$ GeV, $m_{\chi} = 5$ GeV

- Dark Fermion Model
  
  $m = 180$ GeV, $m_{\chi} = 45$ GeV

$400\rightarrow1400$

Events / GeV

Data/SM

Sensitivity

$E_T^{\text{miss}}$ [GeV]
Dark matter with b and t

- Favoured if couplings are Yukawa-like
- Scalar or pseudo-scalar mediators

Mono-b plus MET

![Feynman diagram](image)

Dark matter with b and t


Matter particles in association with a quark. Such models have been studied in Refs. [1–3] mediating particle, labeled a medi- 

directionally, leading to a di g

Table 3 represents the final combined limits (SL + AH) for the t/ solid horizontal line corresponds to dashed line with the 68 and 95% CL uncertainty bands in green and yellow, respectively. The 

the t

final results up to 14%.

The observed limit on the sum of both signals is represented by the black solid line, while its 

the t+DM mode. Additionally, the 

t+DM limit alone is given by the red dash-dotted line. The observed limit on the sum of 

Results

16

The theoretical cross sections 

the approximation and the CL 

The expected limit for the t/ doscalar (right) models. The expected limit for the t+DM signal alone is depicted by the blue dash-dotted line, while 

95% CL observed

Met+ top

Reject top pairs background with top reconstruction or mT2-based variables

CMS

Scalar

Pseudo-scalar

35.9 fb⁻¹ (13 TeV)

35.9 fb⁻¹ (13 TeV)
Mono-h(bb) Search

Probe coupling of Higgs boson to mediator

- \( m(jj) \) resonance or \( m(J)[\sim m(h) \),
- top and Z+jets dominant backgrounds,
- normalised in lepton control regions

150 GeV < \( E_{T}^{\text{miss}} \) < 500 GeV

\[ 150 \text{ GeV} < E_{T}^{\text{miss}} < 500 \text{ GeV} \]

**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, 79.8 \text{ fb}^{-1} \]

SR (Merged): 0 lepton, \( E_{T}^{\text{miss}} > 500 \text{ GeV} \)

2 b-tags

- Data
- SM vh
- Diboson
- / + single top
- Z+jets
- W+jets
- Background Uncertainty
- Pre-fit Background
- mono-h Z'-2HDM

\[ m_{Z'} = 1400 \text{ GeV}, m_{A} = 600 \text{ GeV}, \]
\[ \sigma_{\text{signal}} = 3.75 \text{ fb} \]

**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, 79.8 \text{ fb}^{-1} \]

- Observed 95\% CL
- Expected 95\% CL (+1\%)
- PRL 119, 181804

\( h(bb) + E_{T}^{\text{miss}}; Z'+2\text{HDM simplified model} \)

\( \tan \beta = 1, g_{Z} = 0.8, m_{A} = 100 \text{ GeV}, m_{H} = m_{H'} = 300 \text{ GeV} \)
Mono-h(\gamma\gamma) Search

h\rightarrow\gamma\gamma$ low rate but clean signal

- background from $\gamma\gamma$ or $V\gamma$
- large MET from pile-up jets
- look for resonances in $m(\gamma\gamma)$

$E_T^{\text{miss}} > 90\text{ GeV}$

**ATLAS**

$Z'$-2HDM

- $pp \rightarrow h(\gamma\gamma) + \chi \chi$, $Z'$-2HDM model
  - $\tan \beta = 1.0$, $g_\chi = 0.3$
  - $m_h = 100\text{ GeV}$, $m_\chi = 1\text{ TeV}$, $m_{Z'} = 300\text{ GeV}$

- Heavy scalar, Scalar DM $m_\chi = 60\text{ GeV}$, $m_h = 275\text{ GeV}$

**ATLAS**

$pp \rightarrow h(\gamma\gamma) + \chi \chi$, $Z'$-2HDM model

- $\sin \theta = 0.3$, $g_\chi = 1/3$, $g_\chi = 1$, $m_\chi = 1\text{ GeV}$

**CMS**: arXiv:1908.01713
New signature
arXiv:1908.02699

**Mono-Z(\(ll\))\(\gamma\) Search**

- Low-background signature
- Main backgrounds: ZW+ZZ estimated through CRs

Massless dark photon

\[ P_T^{\text{miss}} > 110 \text{ GeV} \]
\[ E_T^{\gamma} > 25 \text{ GeV} \]

137.4 fb\(^{-1}\) (13 TeV)

Signal extracted by fitting \(m_T\) in bins of |\(\eta(\gamma)\)|

**CMS Preliminary**

\[ |\eta(\gamma)| < 1 \]

**137.4 fb^{-1} (13 TeV)**

**CMS Preliminary**

\(ZH \rightarrow 2l + \text{p}_T^{\text{miss}} + \gamma\)

\[ \sigma_{ZH} \times B(H \rightarrow \text{inv.} + \gamma) (\text{pb}) \]

\[ 10^{-2} \rightarrow 10^{-1} \]

\[ 10^{-2} \rightarrow 10^{-1} \]

**\(m_H\) [GeV]**

\(140 \rightarrow 300\)
Mono-Leptoquark Search

- Leptoquark (c/s+μ)
- $p_{T\text{miss}} > 100$ GeV, $p_T(\mu/j) > 50/100$ GeV
- e/τ/b/Z vetoes
- look for a peak in $m(\mu/j)$ distribution

**Graphs:**

- Observed vs. Expected events
- Distribution of $m_{\mu j}$ vs. Observed $m_{DM}$
- CMS upper limit at 95% CL on $\sigma_{B}[fb]$
Higgs Portal

Most sensitive channel is VBF production

VBF $qqH$

Z(W) $H$

ggH

processes searched for

ATLAS

$$\text{BR}(H\rightarrow \text{inv}) < 0.26 \ (0.17 \ \text{exp}) @ 95\% \ CL$$

CMS

$$\text{BR}(H\rightarrow \text{inv}) < 0.19 \ (0.15 \ \text{exp}) @ 95\% \ CL$$

$95\% \ CL$ upper limit on $\alpha \times \text{BR}(H \rightarrow \text{inv}) / \sigma_{\text{SM}}$

Observed

- Median expected

68% expected

95% expected

all data combined $m_{DM} < m_H / 2$

PLB 793 (2019) 499

PRL 122 (2019) 231801

PLB 793 (2019) 520
Searches for the Mediators

No dark matter in the final state: model dependent indirectly constrain

Constraints on couplings (See exclusion plots)

Traditional bump-hunting: look for di-jet resonances
Constraints on Couplings

**ATLAS** Preliminary

$\sqrt{s} = 13$ TeV, 3.6-80.5 fb$^{-1}$

July 2019

95% CL upper limits

- **Observed**
- **Expected**

- **Boosted dijet + ISR**
  - 36.1 fb$^{-1}$

- **Boosted di-$b$ + ISR**
  - 80.5 fb$^{-1}$
  - ATLAS-CONF-2018-052

- **Dijet + ISR**
  - 75.8 & 76.6 fb$^{-1}$

- **Dijet + b**
  - 75.8 & 76.6 fb$^{-1}$

- **$b\bar{b}$ resonance**
  - 24.3 & 36.1 fb$^{-1}$

- **Dijet TLA**
  - 3.6 & 20.7 fb$^{-1}$

- **$t\bar{t}$ resonance**
  - 36.1 fb$^{-1}$

- **Dijet**
  - 37.0 fb$^{-1}$

- **Dijet angular**
  - 37.0 fb$^{-1}$
Constraints on Couplings

CMS Preliminary

EPS 2019

95% CL exclusions

- Observed
- Expected

\[ \Gamma_{Z'} / M_{Z'} < \text{-5\%} \]

- tt resonance, [arXiv:1810.05905]
  - 35.9 fb\(^{-1}\), 13 TeV

- Boosted Dijet+γ [arXiv:1905.10333]
  - 35.9 fb\(^{-1}\), 13 TeV

- Boosted Dijet [EXO-18-012]
  - 77.0 fb\(^{-1}\), 13 TeV

- Dijet b-tagged [arXiv:1802.06149]
  - 19.7 fb\(^{-1}\), 8 TeV

- Dijet scouting [arXiv:1604.08907]
  - 19.7 fb\(^{-1}\), 8 TeV

- Dijet scouting [arXiv:1806.00843]
  - 35.9 fb\(^{-1}\), 13 TeV

- Dijet [EXO-19-012]
  - 137 fb\(^{-1}\), 13 TeV

- Brod Dijet [arXiv:1806.00843]
  - 35.9 fb\(^{-1}\), 13 TeV

\[ \Gamma_{Z'} / M_{Z'} < \text{-30\%} \]

- Dijet γ [arXiv:1803.08030]
  - 35.9 fb\(^{-1}\), 13 TeV

\[ \Gamma_{Z'} / M_{Z'} < \text{-100\%} \]
Interpretation

Exclusions directly depend on couplings and Dark Matter
Interpretation

Exclusions directly depend on couplings and Dark Matter
Comparison with Direct Detection

Model dependent comparison

Complementarity between LHC and direct detection experiments
Conclusion/Outlook

Much more to come from Run2 data... ... and then....

JHEP 1501 (2015) 037

arXiv:1712.04793

Discovery