The existence of a Dark Matter (DM) particle is a well-established hypothesis that explains a range of astrophysical and cosmological measurements. The presence of a non-baryonic component in the universe is inferred from the observation of its gravitational interactions.

How can we study the Dark Matter?

- **direct detection** based on scattering interaction detections (DAMA, LUX etc.)
- **indirect detection** experiments that look for final states given by the DM annihilation (AMS, Ice-Cube etc.)
- Pair **production at LHC** with large missing energy in the detector

The detection of DM candidates in a collider can give complementary results with respect to the other DM detections.
DM search at LHC, in theory

Effective Field Theory
simpler but not valid at high $Q^2$
Several EFT operators were considered (arxiv:1502.01518).

Simplified Models
A minimal width mediator (vector, axial-vector, scalar, pseudo-scalar...) couples to SM and DM particles ($\sigma \sim g_q^2 g_{DM}^2$).
4 parameters:
DM & mediator masses, DM & SM couplings


s-channel is considered for the firsts results.
WIMP treated as Dirac fermion for simplicity.
DM search at LHC, in practice

**Mono-X signatures**

Search for high MET excesses.

General Analysis Strategy:
- Require MET ($\rightarrow$ recoil system $p_T$)
- Select for X (jet, photon...)
- Veto other objects
- Additional cuts to suppress backgrounds
- Data-driven techniques to estimate background $\rightarrow$ control region with inverted vetoes

**Resonance search**

Mediator can decay back to quarks $\rightarrow$ dijet events ($\sigma \sim g_q^4$).
- Probed **high mass** mediator (because the single jet trigger plateau).
- Data-scouting could probe **low mass** region (not in this talk).
2D Mass plot

\[ \Omega > \Omega_{\text{WMAP}} \]

\[ m_{\text{Med}} = 2m_{\text{DM}} \]

Perturbativity unitarity

EFT
2D Mass plot

\[ \Omega > \Omega_{\text{WMAP}} \]

\[ m_{\text{Med}} = 2m_{\text{DM}} \]

Diagram showing the relationship between mediator mass and dark matter mass with regions marked for perturbativity and unitarity constraints. Diagram includes representations of Mono-X and Dijet processes with associated coupling and mediator mass axes. EFT is indicated in the diagram.
Most sensitive mono-X channel for ISR processes (paying only $\alpha_s$)

Residual dominant backgrounds given by the $Z(\nu\nu)+\text{jets}$ and $W(\tau\nu+\text{had}+\nu)+\text{jets}$ processes

3 control regions are defined (1$\mu$, 2$\mu$, 1$e$) to evaluate the V+jets backgrounds.

**MET** > 70 GeV trigger

- Jet $p_T$ > 250 GeV, $|\eta| < 2.4$, tight quality
- $e$ & $\mu$ veto
- Up to 3 other jets ($p_T$ > 30 GeV)

**SR**

**MET** > 250 GeV

**Z(\nu\nu)*, W(\mu\nu)** → CR1$\mu$

**W(\tau\nu), W(\nu\nu), Z\tau\tau** → CR1$e$

**Z(\mu\mu)** → CR2$\mu$

**Z(\nu\nu), diboson, top** → MC

**Multijet and NCB** → data

*low statistics in CR2$\mu$

**MET ~ boson** $p_T$

**muons treated as invisibles in the MET calculation**

Systematic for the $W/Z$ ratio vs $p_T$ and the EW/QCD corrections differences
Mono-jet (fit strategy)

MET binned simultaneous fit is performed:

\[ k_1 \mu^{(i)} \times Z(\nu\nu) + \text{jets} + k_1 e^{(i)} \times W(\tau\nu) + \text{jets} + k_2 \mu^{(i)} \times Z(\mu\mu) + \text{jets} + \ldots \]

where \( i = 1, \ldots, N_{\text{bin}} \)

\( \text{MET} \in [250, 300, 350, 400, 500, 600, 700, \infty] \text{GeV} \)

\[ \text{MET} = 954 \text{ GeV} \]
\[ \text{jet } p_T = 973 \text{ GeV} \]

Dominant uncertainties (total 4-12\%):

- statistical (3-10\%),
- top (~3\%),
- boson+jet modeling (2-5\%)

low MET bins ➞ systematics unc. dominates
high MET bins ➞ statistical unc. dominates.

Good agreement is observed between data (21447) and MC expectations (21730 ± 940).

Interpret results as limits
Mono-jet (results)

Results interpretation:

*axial vector mediator, $g_q=0.25$, $g_{DM}=1$*

(as recommended by the LHC Dark Matter Working group arXiv:1603.04156)

Contour Limit in the 2D plane

DM vs Mediator mass

Limit on DM-proton scattering cross-section.

LHC limit gives complementary results wrt direct detection experiments
Mono-jet (results)

**On-shell**
- high xsecs
- LHC exclusion

**Off-shell**
- low xsec
- relic DM underproduced

Heavy mediator
- production suppressed ($\sigma_{SD} \sim M_{\text{med}}^{-4}$)
- relic DM overproduced
A simultaneous fit between the inclusive MET regions is performed.

**Dominant uncertainties** (total 11%):
- statistical unc. in the CRs (9%)
- $e \rightarrow \gamma$ fake factor (6%)

**4 control regions** to constrain $Z/W+\gamma$ and $\gamma+\text{jet}$

Fake $\gamma$s evaluated from electron and jets.

A simultaneous fit between the inclusive MET regions is performed.

**It excludes a subset of the monojet space.**

Lower statistics than mono-jet channel ($\alpha_{EM}<<\alpha_s$).

Sensitive to contact interaction of type $\gamma\gamma$.
Mediator can decay back to quarks → dijet signatures.

Limited by the single jet trigger threshold ($m_{jj} \sim 1\text{TeV}$).

A data-driven fit is performed to evaluate the background.

No relevant excesses are observed in the dijet mass distributions.

Jet $p_T > 360\text{GeV}$ trigger

$m_{jj} > 1.1 \text{ TeV}$

$|y^*| = |y_1 - y_2|/2 < 0.6$

Jet $p_T > 440,50 \text{ GeV}$

$1.53 - 1.61 \text{ TeV}$

$p$-value 0.67)
Summary (few) DM LHC results

Axial-vector mediator, Dirac DM
\( g_q = 0.25, \ g_{DM} = 1 \)

DM Simplified Model Exclusions

ATLAS Preliminary

April 2016

\( E_T^{miss} + \gamma \text{ 13 TeV} \)

arXiv:1604.01306

\( E_T^{miss} + \text{jet 13 TeV} \)

arXiv:1604.07773

Dijet 8 TeV

Dijet 13 TeV


2 \times \text{DM Mass} = \text{Mediator Mass}

\( \Omega_c h^2 < 0.12 \)

Thermal relic \( \Omega_c h^2 = 0.12 \)

Dijet 13 TeV


Permutative unitarity

2014-2015

Emiss + jet 2.2 TeV
Other channels, other models

**Mono-W/Z hadronic**

*MET>80GeV trigger*
- \(\text{anti-}k_T\ R=1.0\) jet with trimming, \(p_T>200\text{GeV}\), \(|\eta|<2\), tagging hadronic \(W/Z\) decay using jet mass & substructure (bifurcation variable D2)
- \(e\ & \mu \text{ veto}\)
- Track \(MET>30\text{ GeV}\)
- \(MET>250\text{ GeV}\)

Sensitive to contact interaction of type \(ZZ\chi\chi\)

*MET>30 GeV trigger*
- \(\text{e} \& \mu \text{ veto}\)
- \(<90^\circ\>
- \(\text{Track MET} > 30\text{ GeV}\)

**Mono-Higgs(bb)**

*MET>70GeV trigger*
- \(\text{anti-}k_T\ R=1.0\) jet with trimming, \(p_T>200\text{GeV}\), \(|\eta|<2\), associated with two track jets
- \(e\ & \mu \text{ veto}\)
- \(MET>500\text{ GeV}\)
- \(MET\epsilon[150,500]\text{ GeV}\)

3 MET sub-regions: [150, 200, 350, 500] GeV

*MET>250 GeV trigger*
- \(\text{Track MET} > 30\text{ GeV}\)
Other mono-X signatures

mono-Higgs(4l)
ATLAS-CONF-2015-059

mono-Higgs(γγ)
ATLAS-CONF-2016-011

mono-HF (8TeV)
arXiv:1410.4031

Giuliano Gustavino
Conclusions

DM searches at 13TeV have just started!
The harmonization between most of the analyses using a common set of simplified models allows to compare easily:
- mono-X and dijet searches;
- collider, direct and indirect detection experiment’s results;
- particle physics and cosmological limits.

The data collection expected in the next year can:
- cover higher MET/jet $p_T$ regimes
- open other scenarios (like pseudo-scalar mediators for monojet);
- reduce the statistical uncertainties;
- improve the sensitivity.

New ideas and new strategies to increase the discovery potential!

A wide spectrum of parameters range is still unexplored (don’t forget the coupling axis ;))!
Waiting also for new 13TeV results from
- mono-HF that looks for a set of models don’t covered by the other mono-X analysis (scalar mediators and t-channels);
- Dijet data scouting could cover also the low mediator mass region quite independently from the DM mass!

Giuliano Gustavino
8TeV Monojet results

Limit on Spin independent and Spin dependent WIMP-nucleon interaction xsec

\[ M^* = \frac{M_{\text{med}}}{(g_{\text{SM}}g_{\text{DM}})^{1/2}} \]

Limits on DM particles which couple to SM quarks via a \( Z' \) boson

EFT results optimistics
EFT results pessimistics

limit of high \( M_{\text{med}} \) is the EFT (\( M_{\text{med}} \gg \sqrt{s} \))
Simiplified Models (axial vector mediator)

\[ \mathcal{L}_{axial-vector} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi \]

\[ \Gamma^A_{\text{min}} = \frac{g_\chi^2 M_{\text{med}}}{12\pi} \beta^3_{DM} \theta(M_{\text{med}} - 2m_\chi) + \sum_q \frac{3g_q^2 M_{\text{med}}}{12\pi} \beta^3_q \theta(M_{\text{med}} - 2m_q) \]

\[ \beta_f = \sqrt{1 - \frac{4m^2_f}{M^2_{\text{med}}}} \]

propagator \sim \frac{1}{Q^2_{tr} - M^2_{\text{med}} + iM_{\text{med}} \Gamma}

\text{Width}

\text{off-shell} \quad Q_{tr} \gg M_{\text{med}} \quad \sigma \propto g_q^2 g_\chi^2

\text{EFT} \quad Q_{tr} \ll M_{\text{med}}

\text{on-shell} \quad Q_{tr} \sim M_{\text{med}} \quad \sigma \propto \frac{g_q^2 g_\chi^2}{\Gamma}
**Monojet Control Regions**

### ATLAS

- Data 2015
- Standard Model
- $Z(\to\nu\bar{\nu}) +$ jets
- $W(\to\nu\nu) +$ jets
- $W(\to\mu\nu) +$ jets
- $W(\to\tau\nu) +$ jets
- $Z(\to\ell\ell) +$ jets
- Dibosons
- $t\bar{t} +$ single top

### N_{signal}^{Z(\to\nu\bar{\nu})} = \left( N_{data}^{W(\to\mu\nu),\text{control}} - N_{non-W}^{W(\to\mu\nu),\text{control}} \right) \times \frac{N_{MC}^{Z(\to\nu\bar{\nu})}}{N_{MC}^{W(\to\mu\nu),\text{control}}}$
## Monojet results

### 250 GeV < MET < 300 GeV

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Observed Events (3.2 fb⁻¹)</th>
<th>SM Prediction (post-fit)</th>
<th>Fitted $W(\rightarrow \ell\nu)$</th>
<th>Fitted $W(\rightarrow \ell\nu)$</th>
<th>Fitted $Z(\rightarrow \ell\ell)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>9472</td>
<td>1693</td>
<td>4202</td>
<td>611</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9400 ± 410</td>
<td>1693 ± 41</td>
<td>4202 ± 65</td>
<td>611 ± 25</td>
</tr>
</tbody>
</table>

### MET > 700 GeV

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Observed Events (3.2 fb⁻¹)</th>
<th>SM Prediction (post-fit)</th>
<th>Fitted $W(\rightarrow \ell\nu)$</th>
<th>Fitted $W(\rightarrow \ell\nu)$</th>
<th>Fitted $Z(\rightarrow \ell\ell)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>185</td>
<td>32</td>
<td>95</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>166 ± 20</td>
<td>32 ± 6</td>
<td>95 ± 10</td>
<td>15 ± 4</td>
</tr>
</tbody>
</table>

### MC exp. SM events

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Observed Events</th>
<th>SM Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9620 ± 580</td>
<td>1880 ± 150</td>
</tr>
<tr>
<td></td>
<td>4140 ± 260</td>
<td>610 ± 42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Observed Events</th>
<th>SM Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>186 ± 15</td>
<td>34 ± 3</td>
</tr>
<tr>
<td></td>
<td>106 ± 9</td>
<td>13 ± 1</td>
</tr>
</tbody>
</table>

### Fit input

- $W(\rightarrow \ell\nu)$: 8 ± 1, 23 ± 2
- $W(\rightarrow \ell\nu)$: 12 ± 2, 0.06 ± 0.01, 81 ± 7, 0.01 ± 0
- $W(\rightarrow \ell\nu)$: 21 ± 2, 5 ± 0.4, 5 ± 1, 0.01 ± 0
- $Z(\rightarrow \ell\ell)$: 1.5 ± 0.4, 0.9 ± 0.1, 11 ± 1
- $Z(\rightarrow \ell\ell)$: 0.22 ± 0.03, 0.18 ± 0.01, 0.19 ± 0.02, 0.02 ± 0
- $Z(\rightarrow \ell\ell)$: 125 ± 12, 0.06 ± 0.01, 0.01 ± 0
- $Z(\rightarrow \ell\ell)$: 3 ± 1, 3 ± 1, 9 ± 4, 0.4 ± 0.2
- $Z(\rightarrow \ell\ell)$: 15 ± 2, 3.5 ± 0.3, 9 ± 2, 1 ± 0.3

### Other Categories

- Multijets: 0.4 ± 0.4
- NCB: —
Monojet Limits

Mono-jet limits with fixed mediator & DM mass and variable coupling

Contour Limit in the 3D plot with DM vs Mediator mass vs µ UL @95%
**Mono-photon** (arXiv:1604.01306)

**Photon p_T > 120 GeV trigger**

- Photon p_T > 150 GeV, \(|\eta| < 2.37\), tight quality
- e & μ veto
- MET > 150 GeV

An additional jet is permitted (p_T > 30 GeV)

**4 control regions** are defined:
- 2μ and 2e CRs → Z+γ
- 1μ CR → W+γ
- γ+jet CR (85 < MET < 110 GeV, Δφ(MET,γ) < 3.0) → γ+jet
- fake γs evaluated from
  - electrons using e→γ misID factor in ee vs eγ events,
  - jets with an ABCD method using photon quality & isolation.

A simultaneous fit between the inclusive regions is performed.

**Dominant uncertainties (total 11%)**:
- statistical unc. in the CRs (9%)
- e→γ fake factor (6%)

<table>
<thead>
<tr>
<th></th>
<th>SR</th>
<th>1μuCR</th>
<th>2μuCR</th>
<th>2eCR</th>
<th>PhJetCR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed events</strong></td>
<td>264</td>
<td>145</td>
<td>29</td>
<td>20</td>
<td>214</td>
</tr>
<tr>
<td><strong>Fitted Background</strong></td>
<td>295±34</td>
<td>145±12</td>
<td>27±4</td>
<td>23±3</td>
<td>214±15</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>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td><strong>Pre-fit background</strong></td>
<td>249±29</td>
<td>105±14</td>
<td>23±2</td>
<td>19±2</td>
<td>209±50</td>
</tr>
</tbody>
</table>
Mono-photon (results)

Results interpreted in the same simplified model used in monojet: it excludes a subset of the monojet space.

Limit on the suppression scale $M^*$ for the EFT model with a contact interaction of type $\gamma \gamma \chi \chi$ as a function of the DM mass.

The EFT is not always valid, so a truncation procedure is applied: events having a centre-of-mass energy larger than $M_{cut} = g^* M^*$ are removed and the limit is recomputed.
**Mono-W/Z hadronic**

**ATLAS-CONF-2015-080**

**MET > 80 GeV trigger**

- anti-\(k_T\) \(R=1.0\) jet with trimming, \(p_T>200\ \text{GeV}, \ |\eta|<2\), tagging hadronic W/Z decay using jet mass & substructure (bifurcation variable D2)
- \(\text{e} \& \mu\) veto
- Track \(\text{MET}>30\ \text{GeV}\)
- \(\text{MET}>250\ \text{GeV}\)

3 control regions are defined:

- 2\(\mu\) CR \(\Rightarrow\) Z+jets,
- 1\(\mu\) & no b-jet CR \(\Rightarrow\) W+jets,
- 1\(\mu\) & \(\geq 1\) b-jet CR \(\Rightarrow\) \(\text{t}t\bar{\text{t}}\).

Diboson and single top from MC.

A (track)MET shape fit is performed in the (CRs)SR.

The main systematics are given by the modeling of large-\(R\) parameters (D2 variable and mass) with a 5-10% of the total background.

1143 events are observed in agreement with the expectations 1150\/+/-30.
**Mono-Higgs (bb)**

*ATLAS-CONF-2016-019*

### Resolved
- Jets requirements for the higgs boson reconstruction
- $e$ & $\mu$
- Other cuts to reject mutijet bkg
- $\geq 2$ jets
- Track MET $> 30$ GeV
- 3 MET sub-regions: [150, 200, 350, 500] GeV

### Merged
- **MET** $> 70$ GeV trigger
- Anti-$k_T$ $R=1.0$ jet with trimming, $p_T>200$ GeV, $|\eta|<2$, associated with two track jets
- $e$ & $\mu$
- MET $> 500$ GeV
- Track MET $> 30$ GeV

### 2 Signal Regions:
- Resolved & Merged.

### 3 Categories:
- 0, 1, 2 $b$-tags.

### 2 Control Regions:
- 2l CR $\rightarrow$ Z+jets
- 1$\mu$ CR $\rightarrow$ W+jets & t$t$bar

A simultaneous shape fit to the jet mass distribution is performed.

Main exp. systematic uncertainties arise from:
- $b$-tagging efficiency;
- jet mass/energy calibrations.

No significant excess of events are observed.

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*Giuliano Gustavino*
**Mono-HF**  
(arXiv:1410.4031)

**Selections based on:**

MET, lepton or muon-[b]jet triggers; cuts on # & $p_T$ (b-)jets, MET, $\Delta \Phi$, razor, topness...

**4 signal regions:**

$b+DM$, $bb+DM$, $tt$(had)+DM, $tt$(semi-lep)+DM

**Control regions:**

$Z/\gamma$+jets CR $\Rightarrow Z$(vv)+jet in b and $bb+DM$ SRs

semileptonic CRs $\Rightarrow ttbar$ in $tt+DM$ SR

**Tot. Bkg. Unc:**

9%, 12%, 14%, 14% (stat, flavor tag, top $p_T$…)

**8TeV analysis**

Sensitivity to scalar interactions effective assuming that the lagrangian **minimally violates flavor** (EFT operators $\propto \Sigma m_q$)

Bottom Flavoured Dark Matter model ($b$-FDM) with $m_{DM} \sim 35$ GeV to explain the Galactic Center excess