Searches for Dark Matter with the ATLAS experiment

Cosmology on Safari, Bonamanzi, January 2015

Olof Lundberg
Stockholm University
On behalf of the ATLAS collaboration
Thanks for the chance to come to Bonamanzi!
Introduction: WIMP hunting

Dark Matter particles:
Non-baryonic, neutral, cold (massive) Hopefully weakly interacting: WIMP

Three complementary strategies:
• Direct detection (shake)
• Indirect detection (break)
• Collider production (make)

Scope of talk:
• Introduce the machinery
• Present some ATLAS strategies (mono-X, Invisible Higgs..)
• Present results and prospects

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WIMPS/Leopards: Probably around, very hard to find..
The Large Hadron Collider

Proton collisions at unprecedented energies and high luminosity

Design capacity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ @ 14 TeV

2011: $4.7 \text{ fb}^{-1}$ @ 7 TeV  \hspace{1cm} (1 fb$^{-1}$ = $10^{39} \text{ cm}^{-2}$)
2012: $20.3 \text{ fb}^{-1}$ @ 8 TeV

More integrated luminosity $\rightarrow$ Increased sensitivity to new physics

Restarting in April: 13 TeV center of mass collisions
Aiming for $300 \text{ fb}^{-1}$ of 14 TeV collisions by the end of 2021
The ATLAS detector

Trackers, calorimeters, several muon detectors in order to detect $e, \mu, \tau, \gamma$, and hadronic jets originating in partons. Designed to examine 40 million events every second. A sophisticated 3-level trigger system in place, 100k events per second pass the first trigger level $\rightarrow O(100)$ events per second saved for analysis.
Detecting neutrinos and WIMPs

Hermetic detector: Conservation of momentum means no net momentum in \textit{transverse} plane. Missing energy in the transverse plane implies non-detectable particles.

\[ E_{\text{miss}}^{T} = - \sum p_{T}^{jet} - \sum p_{T}^{e} - \sum p_{T}^{\mu} - \sum p_{T}^{\gamma} - \sum p_{T}^{soft} \]

Sensitive to transverse momentum carried by non-interacting particles – neutrinos or WIMPs.
Mono-X

Pair produced WIMPs with an Initial State Radiation handle, or WIMPS produced in association with one or more SM particles

Large missing momentum recoiling against particle(s) from radiation

Final limits comparable to direct and indirect detection experiments

So far performed with radiation of

- Gluon/quark (mono-jet)
- Photon
- W and Z boson
**Mono-X**

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Mono-X

Effective Field Theory approach:

Mediator assumed very heavy → contact interaction

Assume an effective DM-SM operator and type of WIMP (scalar/fermion) – two free parameters: wimp mass and mass scale of interaction $M_* = m_{\text{med}} \sqrt{g_{\text{SM}} g_{\text{DM}}}$

Strength: Agnostic search, comparable to indirect/direct detection

Weakness: Incomplete description for $Q$ (mom. transfer) $> \Lambda$ (cutoff scale)

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Type of interaction</th>
</tr>
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<tbody>
<tr>
<td>D1</td>
<td>$\frac{m_q}{M_*^2} \bar{\chi} \chi q \bar{q}$</td>
<td>Scalar, WIMP-quark</td>
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<tr>
<td>D5</td>
<td>$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$</td>
<td>Vector</td>
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<td>D8</td>
<td>$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$</td>
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<td>D9</td>
<td>$\frac{1}{M_*^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$</td>
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<td>D11</td>
<td>$\frac{\alpha_s}{(4M_*^2)^3} \bar{\chi} \chi G_{\mu\nu} \tilde{G}_{\mu\nu}$</td>
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Mono-X

**Simplified Model approach:**

Include mediator explicitly

More model parameters →
model on the right $m_\chi$, $m_V$, $\Gamma_V$
and $v g_{SM} g_{DM}$

Strength: Complete description for physics at LHC

Weakness: Some loss of generality to EFT

More Mono-X final states can be interpreted in simplified model framework but suppressed when based on ISR: mono-top, mono-Higgs...
**Monojet**

**Event Selection:**
1 Jet w. $p_T > 120$ GeV  
$E_T^{miss} > 120$ GeV  
$E_T^{miss}$ back-to-back w. jet(s)  
Maximum 2 jets  
No leptons  
*Several signal regions with increasing $E_T^{miss}$ and jet $p_T$*

**Backgrounds:**
$Z \rightarrow \nu\nu$ (+ jets)  
$W \rightarrow l\nu$ (+ jets) (lepton lost)

Estimated using 2 dedicated  
*Control Regions* (more in backup)

Less important: Top, multi-jet,  
$Z \rightarrow l\nu$ & Diboson production

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**ATLAS Preliminary**

\[
\int L dt = 10.5 \text{fb}^{-1} \\
\sqrt{s} = 8 \text{ TeV}
\]

<table>
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<tr>
<th>Data / BG</th>
<th>Total BG</th>
<th>$Z (\rightarrow \nu\nu) +$ jets</th>
<th>$W (\rightarrow l\nu) +$ jets</th>
<th>Multi-jet</th>
<th>Non-collision BG</th>
<th>$Z (\rightarrow l\nu) +$ jets</th>
<th>Dibosons</th>
<th>$t\bar{t}$ + single top</th>
<th>ADD $n=2, M_e=3$ TeV (x5)</th>
<th>$D5 M=800$ GeV, $M=670$ GeV (x5)</th>
<th>$\tilde{G} + \tilde{g}, M_{\tilde{g}}=1$ TeV, $M_{\tilde{g}}=10^7$ eV (x5)</th>
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**NOTE:** BASED ON 10.5 fb$^{-1}$!
Monojet

Event Selection:
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$E_T^{miss} > 120$ GeV
$E_T^{miss}$ back-to-back w. jet(s)
Maximum 2 jets
No leptons
Several signal regions with increasing $E_T^{miss}$ and jet $p_T$

Backgrounds:
$Z \rightarrow \nu \nu$ (+ jets)
$W \rightarrow l \nu$ (+ jets) (lepton lost)

Estimated using 2 dedicated Control Regions (more in backup)

Less important: Top, multi-jet, $Z \rightarrow l l$ & Diboson production

NOTE: BASED ON 10.5 fb$^{-1}$!
Monophoton

Event Selection:
Highly energetic photon, large MET, no leptons, not more than 1 jet

Backgrounds:
Z→νν + γ
Wγ and Zγ production (with leptons lost), W/Z production where lepton or jet taken to be γ

Estimated using dedicated Control Regions (more in backup)

Less important: Top pair, multi-jet, γ+jet & Diboson production

Mono-jet/photon Limits

No excess above SM expectations observed – used to set limits

For EFT in monophoton, lack of validity handled by truncation of valid signal points.

Signal points removed if Q > m_{med} = M_*/\sqrt{g_{SM} g_{DM}}

Two choices of M_* tested, g_{SM} g_{DM} = 1 and g_{SM} g_{DM} = 4\pi

Monojet sets only ATLAS limits on operator D11 (gluon-DM interaction)

New monojet results using full 8 TeV dataset in the pipelines
Mono-jet/photon limits

Monophoton simplified model w. Z’-like heavy gauge boson mediating DM-SM

Tested for $\Gamma = M_{\text{med}}/3$ and $\Gamma = M_{\text{med}}/4\pi$

Mono-jet/photon limits

Second EFT model possible for monophoton, inspired by the Fermi-LAT 130 GeV line.

Using dim. 6 and dim. 7 operators introduced in A Nelson et al. in Physical Review D 89, 056011 (2014)

Parameters $k_1$ and $k_2$ control couplings of DM to U(1) and SU(2) gauge sectors respectively.

Mono-W/Z

**Event Selection (hadronic):**
1 big jet, containing 2 sub-jets, compatible with W/Z mass
Big jet $p_T > 250$ GeV
$E_T^{miss} > 350$ or $500$ GeV
No leptons or extra jets

**Backgrounds:**
- $Z \rightarrow \nu \nu$ (+ jets)
- $W \rightarrow l \nu$ (+ jets) (lepton lost)

Estimated using dedicated
*Control Regions* (more in backup)

Less important: Top, $Z \rightarrow ll$ & Diboson production

Mono-W/Z

Event Selection (leptonic Z):
2 leptons (ee or \( \mu \mu \)) with invariant mass consistent with Z decay

No jets, no third lepton. Large \( E_T \)(miss).

Event Selection (leptonic W):
Exactly one high-momentum electron or muon, and \( E_T \)(miss) from neutrino

Large \( m_T \) (invariant mass in transverse plane), incompatible with decay from directly produced W


JHEP 09 (2014) 037
Mono-W/Z

Interference between diagrams with W radiating from d or u:
Destructive if \([C(u)=C(d)]\) or constructive if \([C(u)= -C(d)]\)

Leptonic Mono-Z again allows test of Fermi-inspired 6-dim and 7-dim operator theory. Relative contribution of Z and \(\gamma\) is a parameter
Compared to direct detection

Spin-dependent: colliders set strong limits at very low WIMP mass: *No lower mass limit*. Note again that the collider lines are under assumptions not made for non-colliders.

Mono-photon not included here – sets worse limits for the investigated operators.
Compared to direct detection

For spin-dependent interaction ATLAS is competitive over the full investigated mass range. Again: Note that collider results are under somewhat different sets of assumptions.
Mono-top

Left: $+2/3$-charged boson $S$ decays to top and a neutral fermion, which in turn may decay (possible in SU(5) or hylogenesis models).

Production of right-handed top quark and a spin-1 neutral color-singlet (possible in supersymmetry models). The neutral particle can decay to a pair of dark matter candidates.
Mono-top

Event Selection:
1 lepton (e,μ)
1 jet, tagged as from a b quark
$E_T^{(\text{miss})} > 35 \text{ GeV}$
Topology of event consistent with t decay, in two somewhat differing signal regions

Backgrounds:
t quark pairs, $W \rightarrow l\nu$ (+ jets), multi-jet

Apart from multi-jet, estimated from simulation and tested in special validation regions.

Less important: $Z \rightarrow ll$, Diboson production.

Model excluded if it predicts more events than the observed limit. In plots above $a_{\text{res}}$ and $a_{\text{non-res}}$ are coupling matrices in the SM-nonSM vertices.
Heavy flavor + MET

\[ \mathcal{O}_{\text{scalar}} = \sum_q \frac{m_q}{M_N^*} \bar{q}q\chi\bar{\chi} \] possible to probe using heavy quarks

Simplified Model with “b-flavored” DM (b-FDM). Proposed to explain the gamma ray excess from galactic centre seen by Fermi-LAT and interpreted as DM annihilating to b quark pairs.

Fermi line interpretation in T. Daylan et al. (2014) arXiv:1402.6703

Heavy flavor + MET, top pair signal

Event Selection:
At least 4 jets, at least 1 from b
$E_T^{\text{miss}} > 270$ GeV
1 lepton
Advanced kinematic cuts to reduce SM t pairs

Backgrounds:
SM top quark pairs

Estimated using dedicated Control Regions (more in backup)

Less important: Single top production, $W/Z+$jets

This region used to search for $tt$ pairs, where 1 top quark goes $t \rightarrow Wb \rightarrow lvb$ and one goes $t \rightarrow Wb \rightarrow qqb$

Heavy flavor + MET

Limits on D1 operator strongest ATLAS limit. Notice truncation (lines become dotted)

At the interesting WIMP mass around 35 GeV, mediator masses between ~300-500 GeV excluded
Invisible Higgs

Some theoretical extensions to the SM have Higgs boson decay to invisible particles. Sensitive for $m_\chi < m_H/2$

Searches for Higgs $\rightarrow$ invisible performed in two ways

- Associated ZH decay, Z decaying to 2 leptons, H to WIMP pair
- Reinterpretation of Mono-W/Z hadronic – H $\rightarrow$ WIMPs, W/Z to jets
Associated ZH production, Z→ll, H→χχ

Event Selection:
2 leptons (ee, μμ)
Large $E_T^{\text{miss}}$
Leptons back-to-back with $E_T^{\text{miss}}$ (Z with Higgs)
No jets

Main backgrounds:
ZZ & WZ production

Estimated in simulation, tested in dedicated Validation Regions (more in backup)

Associated ZH production

BR(H→inv) < 75% at 95% CL, for the ~125 GeV Higgs. Converting production cross section to limits on Higgs Portal DM models provide strong, but of course very model-dependent limits.
Prospects for Run 2

Going to 13-14 TeV energies increases the sensitivity to new physics

Also means challenges associated with the higher luminosity: Going from ~20 to ~60 interactions per crossing

Simulated monojet sensitivity: Large increase directly with higher energy, slower increase when going to 3000 fb\(^{-1}\)

Ambition to go towards a more systematic search with simplified models
Summary

Findings are so far consistent with SM expectations, limits are set on new physics using EFT approach as well as in several simplified models.

Searches of “Mono-X” type set upper limits on the effective scale of the DM-SM interaction for given WIMP masses. For given operators these limits can range up to above 1 TeV for low mass WIMPs.

Compared to direct detection experiments ATLAS tends to set strong limits for low mass WIMPs in the spin-independent case, and over the whole covered mass range for the spin-dependent case.

Searches for Higgs decays to invisible states and final states with quarks and $E_T^{\text{miss}}$ have been presented. Heavy quarks in the final state allows stricter limits on the scalar effective operator interaction, and the invisible Higgs searches so far set an upper limit on Higgs decay to invisible particles at 75%.

ATLAS sensitivity at 14 TeV increases significantly with the higher energy, but not necessarily with more data: This will be an interesting year!
BACKUP SLIDES
## SUSY searches

### ATLAS SUSY Searches - 95% CL Lower Limits

**Status:** ICHEP 2014  
**√s = 7, 8 TeV**

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### EW Direct

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### EW Long-lived particles

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### RPV

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<th>Jets</th>
<th>E_{T}\text{miss}^{miss} (GeV)</th>
<th>∫L dτ (fb^{-1})</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar gluon pair, sgluon &lt;→ q̅q̅</td>
<td>0</td>
<td>4</td>
<td>Yes</td>
<td>20.3</td>
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**√s = 7 TeV full data**  
**√s = 8 TeV full data**  
**√s = 8 TeV partial data**

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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*
Monojet background

Z→νν background, as well as W→lν background from three control regions with leptons
Monophoton background

Z and W + γ backgrounds estimated using 3 control regions with leptons, where normalization factors are extracted and applied in SR.
Mono-WZ hadronic

W hadronic decay with large jets validated in tt CR, where we demand one muon, two jets separated from big jet and at least one b-tag

W/Z + jets background estimated using control region with muon veto inverted, and extrapolation depending on $m_{\text{jet}}$ extracted
Mono-WZ leptonic backgrounds

For leptonic W, multi-jet is estimated using enriched CR and *matrix method* or inverted isolation technique.

For leptonic Z:
- WW, t, Wt and ττ using eμ CR
- Z + jets uses ABCD with $E_T^{\text{miss}}$ and $\eta$ as the uncorrelated variables, and extrapolation of $\Delta\phi(E_T^{\text{miss}}, p_T^{\perp})$ from low $E_T^{\text{miss}}$ region to SR
- W + jets extrapolated from reversed isolation at low $E_T^{\text{miss}}$ to SR.
- All validated in non-SR regions
Monotop Backgrounds

CR1 enriched in W+jets and multi-jet by putting it in W window

CR3 enriched in tt by requiring second b-jet and high $m_T$.

These CR:s are to validate the background estimates from MC.
Heavy quark analysis background

Top pair background taken from control region where $m_T$ lower and the requirements to reject these in SR are loosened

Wlv background from control region with inverted b-tagging requirement (0 b-jets)
ZH Backgrounds

WZ background validated in 3-lepton CR

Backgrounds with two leptons from non-W/Z decays estimated in an eμ CR

Zee and Zμμ backgrounds in sideband regions, all cuts apply except failing one or two topological cuts
Prospects for Run 2

Include more systematized simplified model searches

Several dedicated studies pointing out strategies using s-channel and t-channel vector or scalar mediators


Many of these models open windows for new non-mono signatures (di- or multi-jets)