Overview of Dark Matter searches with Mono-X signatures at ATLAS

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Tuesday 9th December 2014
Any DM produced at collider experiments, will interact weakly, and pass invisibly from 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) with large $E_T^{\text{miss}}$(Mono-X).

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 $E_T^{\text{miss}}$. 
Example: Monojet Event
Outline

- ATLAS Status and Data-taking
- ATLAS searches for Dark Matter
  - Photon plus $E_T^{miss}$
  - Heavy quarks & $E_T^{miss}$
  - One lepton & $E_T^{miss}$
  - Monojet plus $E_T^{miss}$
- Outlook toward LHC Run-2
- Summary
The ATLAS Detector

The ATLAS Experiment took data very efficiently throughout 2012 - recording over over 20 fb$^{-1}$ of good data for analysis.

James Frost (University of Oxford)
Exotics Results
Searching for new phenomena at the energy frontier

- Cannot possibly summarise the full Exotic physics output of the Collaboration, there are 23 papers on the 2012 data, and many more conference notes.

In this talk I will focus on searches for Dark Matter: $\Rightarrow$ Mono-X & $E_T^{miss}$ searches

### ATLAS Exotics Searches* - 95% CL Exclusion

*Only a selection of the available mass limits on new states or phenomena is shown.

For full details, and other interesting analyses...

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

James Frost (University of Oxford)
Collider Searches for Dark Matter

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

- WIMP dark matter is one attractive option.
  - Interaction with quarks via heavy mediator would lead to pair-production.

- Can be investigated by effective field theories, with interactions between the WIMPs and SM particles.
- Contact interaction for production mechanism.
Effective field theories provide a simple, convenient framework for translation of collider limits into DM cross-section.

Caveat: momentum transfer must be below the EFT interaction scale for validity.
- Use simplified models with an explicit mediator.
- Remove events failing to pass this constraint (‘truncation’)

Common EFTs for Dirac fermion WIMPs:
- D1 (scalar)
- D5 (vector)
- D8 (axial-vector)
- D9 (tensor)

Parameterised by DM mass ($M_\chi$) and suppression scale for the mediator, $M_*$, ($M_* = m_\nu / \sqrt{g_f g_\chi}$).
Look for an excess of events with:

- Large $E_T^{\text{miss}} (> 150 \text{ GeV})$, separated from any jet or photon.
- A high transverse momentum ($p_T > 125 \text{ GeV}$) photon, $|\eta| < 1.37$.
- No more than one jet, and no leptons.

- Event samples in control regions are fit to deliver the normalisations of the main $W\gamma$ and $Z\gamma$ background processes.
- The single muon $W\gamma$ (L) and two electron $Z\gamma$ (R) backgrounds:

![Graphs showing event distributions for different processes and backgrounds.](image)
No sign of any excess.

Set limits on $M_*$, for given $M_\chi$.

Upper limit of fiducial cross-section is 6.1 fb at 95% C.L.

Limits of $M_*$ range from 750-1000 GeV.
Lower $M_\chi$ limits provide upper limits on the WIMP-nucleon interaction cross-section:

- This ATLAS result extends limits at low masses $M_\chi < 10$ GeV.
ATLAS Dark Matter Searches

Heavy Quarks plus $E_T^{\text{miss}}(1)$ [arXiv:1410.4031]

- Target DM production in association with 1-2 heavy quarks.
- Present also in b-FDM models.
- Probes scalar and tensor interactions between quarks and DM.
- Design signal regions for b-jet and top quark production.

The signal region for b-quark jets selects events with:
- $E_T^{\text{miss}} > 300$ GeV, separated from jets, b-jet $p_T > 100$ GeV.
- Low jet multiplicity ($n_{jets} < 5$), no leptons.

Irreducible $Z \rightarrow \nu\bar{\nu}$ dominates.
The signal region for $t\bar{t}$ selects events with:

- A single isolated lepton, four jets with $p_T > 60$ GeV
- b-jet with $p_T > 60$ GeV.
- $E_T^{miss} > 270$ GeV, separated from the two leading jets; $m_T > 130$ GeV
- Dileptonic top suppressed by additional kinematic constraints.
The data are consistent with SM expectations with no sign of an excess.

- Limits are again set on $M_*$ and converted into $\sigma_{\chi-N}$.
- The limits are particularly stronger in the low mass region, and represent a substantial improvement on previous ATLAS results.

ATLAS Dark Matter Searches
Heavy Quarks plus $E_T^{\text{miss}}(3)$ [arXiv:1410.4031]
Select events with exactly one high $p_T$, isolated lepton and large $E_T^{miss}$.

Sensitive to $W'$ production, but also to DM pair production, with a radiated W boson.

The SM process $W \rightarrow l\nu$ dominates the background, which is well modelled, with no sign of an excess.
Observed limits on $M_*$ as a function of the DM particle mass ($m_\chi$) at 90% CL for the combination of the electron and muon channel, for various operators.

Other ATLAS searches for hadronically-decaying W/Z (1309.4017) and leptonic decays of Z (1404.0051) are shown.
Channels with a single jet and large $E_T^{\text{miss}}$ (mono-jet events) are also sensitive to DM production.

Right plot is the result of ATLAS mono-jet analysis, which used $10.5 \text{ fb}^{-1}$ and required:

- $E_T^{\text{miss}} > 120 \text{ GeV}$,
- jet with $p_T > 120 \text{ GeV}$,
- lepton vetoes

Excluded $M_* < \sim 700 \text{ GeV}$ for $M_\chi < \sim 1 \text{ TeV}$ at 90% C.L.
The increase in energy in Run-2 makes LHC searches considerably more sensitive to Dark Matter.

Even a single year’s Run-2 data allows a large improvement on Run-1 limits.

Further improvements are feasible with more luminosity, better control of systematics and raised $E_T^{miss}$ cuts.

How much luminosity would be needed to make a discovery?

One year of LHC Run-2 data - DM signal up to $M_\star = 1500$ GeV.

Final reach from $\sim 2500$ GeV.
Conclusions

- The LHC and ATLAS performed very well during LHC Run-1.
- The 2012 dataset is a very sensitive and extensive dataset, with the ability to search for new phenomena and dark matter in a wide variety of channels.
- Standard signatures are $E_{\text{miss}}^T$ in association with ISR or other SM particles.
- No signs of (collider) dark matter or any new physics yet.
- Collider experiments provide a nice complementarity to direct DM searches, and are particularly sensitive at low DM masses. (Comparison possible only within the limits of the EFT approach.)
- The LHC will soon begin operating at a new record energy, which will bring with it much greater sensitivity to Dark Matter and other potential new physics, even within the first year of 13 TeV running in 2015.
BACKUP SLIDES
Summary of ATLAS Exotics Results

**ATLAS Exotics Searches** - 95% CL Exclusion

**Status:** ICHEP 2014

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<th>Model</th>
<th>Jets</th>
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**$\mathcal{L} dt = (10 - 20.3) \text{ fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV**

**James Frost (University of Oxford)**

**CosPA 2014**

**Tuesday 9th December 2014 20 / 23**

*Only a selection of the available mass limits on new states or phenomena is shown.
Upper limits at 95% CL on the WIMP simplified model coupling parameter, $\sqrt{g_f \times g_\chi}$, with vector coupling and mediator width $\Gamma = m_V$

- Observed lower limits at 95% CL on the EFT suppression scale $M_*$ as a function of the mediator mass $m_V$, for a $Z'$-like mediator with vector interactions. For a dark matter mass $m_\chi$ of 50 or 400 GeV, results are shown for different values of the mediator total decay width $\Gamma$ and compared to the EFT observed limit results for a D5 (vector) interaction. $M_*$ vs $m_V$ contours for an overall coupling $\sqrt{g_f \times g_\chi} = 0.1, 0.2, 0.5, 1, 2, 5, 4\pi$ are also shown. The corresponding limits from the D5 operator are shown as a dashed line.
Example of DM production in the b-FDM model.

Exclusion contour at 95% CL for the b-FDM model from combined results of SR1 and SR2. The expected limit is given by the dashed line, and the yellow band indicates the $\pm 1\sigma$ uncertainty. The observed limit is given by the solid red line. The region beneath the curve indicating the observed limit is excluded.
ATLAS Dark Matter Searches

Heavy Quarks plus $E_T^{miss}$ [arXiv:1410.4031]

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### Selections for signal regions 1–4.

Variables $p_T^{ij}$ ($p_T^{bj}$) represent the transverse momentum of the $i$-th jet (b-tagged jet). The asymmetric transverse mass $amT_2$, topness, $m_{jj}$ and Razor R are used to reject the abundant top quark background.

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Comparison between data and expected SM background. R variable for SR3 excluding the selection on R and for an example signal with the operator D1. Other backgrounds are composed of diboson and multijet production. The expected signal for $\chi$ anti-$\chi + \bar{t}t$ (SR3, 4) production for $m_\chi = 10$ GeV is given by the red line. The final selection requirements are indicated by an arrow. The error bars represent the statistical uncertainty. The dashed area shows the systematic uncertainty on the background estimation. Events with values exceeding the range presented are included in the highest bin.