



# Search for Dark Matter in association with a hadronically decaying Z' vector boson at 13 TeV with the ATLAS detector.

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### CLHCP Conference Nanjing, China

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\* Existence of Dark Matter (DM) is well established from many astrophysical measurements.

\* Galactic rotation curves, Bullet cluster, CMB measurements etc...

\* There are however no known interactions of DM beyond gravity.

\* It could be possible that there is a weak coupling between DM and SM (or BSM) particles - Weakly Interacting Massive Particle (WIMP) Interaction.

\* ATLAS searches make the assumption that **DM** is a WIMP.



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 $\rightarrow$  leads to an imbalance in the event in the transverse plane, known as missing transverse energy (MET).

\* Collider searches therefore focus on the production of SM particles (X) in association with large MET. This is denoted "X+MET".

\* Lepton vetoes are used to reduce backgrounds with other sources of MET.

\* Limits on DM and production have previously been set in many X+MET final states at ATLAS, mono-H, mono-gamma, mono-jet and mono-V.



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# **Summary of recent X+MET searches at ATLAS**





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1000

2000

m<sub>z</sub> [GeV]

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m<sub>z.</sub> [GeV]

4.

2000

1000

arXiv:1711.03301v1

# Summary of recent X+MET searches at ATLAS

#### $Z_A$ $\bar{x}$ (a) $g_{q\chi}$ $g_{q\chi}$ $g_{q\chi}$ [GeV] کی 1000 ق Expected limit $\pm 2 \sigma$ ATLAS ΔΤΙ Δς 1000 xpected limit ( $\pm 1\sigma_{exp}$ ) √s = 13 TeV. 36.1 fb √s = 13 TeV. 36.1 fb<sup>-</sup> Expected limit ( $\pm 1\sigma_{ex}$ ved limit (± $1\sigma_{\text{theorem}}^{\text{PDF, scale}}$ Ĕ Vector Mediato Axial-Vector Mediate Dirac Fermion DM Observed limit ( $\pm 1\sigma_{\text{there}}^{\text{PDF, s}}$ Dirac Fermion DM erturbativity Limi g\_ = 0.25, g\_ = 1.0 g<sub>a</sub> = 0.25, g<sub>y</sub> = 1.0 Relic Density (MadDM) 95% CL limits 95% CL limits ATLAS √s = 13 TeV. 3.2 fb 500 500

### Mono-jet (2017)

\* Many different signal models considered.

\* limits shown for WIMP pair production with s-channel axial vector and vector mediator.

### **Selection:**

- \* MET > 250 GeV
- \* high pT jet (>250 GeV)

**Fit MET distribution** 

\* Two sets of signal regions, with inclusive and exclusive MET selection for model independent and model dependent limits.

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# Summary of recent X+MET searches at ATLAS

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### Mono-H (2017)

\* limits presented for Z'-2HDM and vector mediator models

### **Selection :**

- \* MET> 150 GeV
- \* >1 Large-R jet or >2 small-R jets.
- \* b-tag splitting applied.
- \* 3 MET Categories (resolved) \* MET > 500 GeV (boosted)

Fit dijet or large-R jet mass distribution



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arXiv:1609.04572v2

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# Summary of recent X+MET searches at ATLAS



### Mono-V (2015)

#### **General selection :**

\* Large MET > 200 or 250 GeV for signal or control regions.

\* >=1 Large-R jet, with substructure.

#### Signal region

- \* Lepton veto
- \* Mass window applied.
- \* Anti-QCD requirements.

#### W+jets and ttbar control region

\* exactly 1 muon

 $^{\ast}$  0 (1) b-tagged jet associated with large-R jet for W+jets (ttbar)

#### **Z+jets control region**

- \* 2 muons
- \* 66 < m( $\mu\mu$ ) < 116 GeV

#### Strategy

\* Apply a cut on the jet mass and fit using the MET distribution.



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#### Simplified model with s-channel mediator.



# \* Mono-Z' is a currently unexplored final state for Dark Matter searches.

\* Two simplified signal models considered, Dark Higgstrahlung and Light Z' vector.

\* Aim to set limits on parameters  $g_a$  and  $g_x$  or  $g_{hD}$ 







\* Boosting from MET allows for a gain in sensitivity at low Z' mass compared with dijet searches.

\* At low mass dijet searches are also difficult due to large QCD background.



#### Limits shown taken from phenomenology

8. https://arxiv.org/abs/1504.01386



- \* Final state of the mono-Z' search is very similar to that of the 2015 mono-V search.
- \* Similar selection/strategy can therefore be utilised.
- \* Sensitivity may be gained for the mono-Z' analysis by :
  - 1. Considering resolved events (two small-R jet final state). 2. Adding b-tag splitting due to  $Z' \rightarrow bb$  decays.

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# **Signal Region Comparison**

\* Mono-Z' search will essentially be a generalisation of the mono-V search to many different mass points (general resonance search).

- \* This means that for the mono-Z' search the mass window definitions will need to be re-optimised.
- \* Possible to do this by studying the significance as a function of jet mass.
- \* Expect to derive a mass window which is a function of the Z' mass.

Mass window used for phenomenology studies :

[0.8 x mZ' , mZ' + 30 ] GeV





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\* Expected same backgrounds as with the mono-V analysis:

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* V+jets (~73%)
* ttbar and singletop (~20%)
* Dibosons (~7%)
```

\* Analysis could be improved by adding an estimate of the **QCD multijet** background. (Assumed to be negligible for the 2015 mono-V search).

\* Following from phenomenology paper 2 signal models could be investigated, with two choices of Dark Matter mass (low and high).

\* Fitting strategy used for the mono-V analysis could be similarly applied for the mono-Z' analysis.

\* Profile-likelihood fit to the MET distribution in the signal + control regions is performed.

\* Control regions are used to constrain the V+jets and ttbar backgrounds.

\* Expect similar dominant systematic uncertainties as the mono-V search : Large-R jet momentum, jet energy scale, MC stats, theoretical uncertainties in simulated events.









\* Difference between the shapes in MET for the dark Higgs and light vector model at various Z' mass points.

\* Difference in the spectrum, allowing for differentiation between the models.

\* Light vector model has softer MET spectrum.



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# **Expected Limits (from Phenomenology)**



\* Upper limits on the production cross sections taken from the associated phenomenology paper, calculated using counting experiments (10-100 pb).

\* Expect the limits from the mono-Z' analysis to improve upon these.



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\* An overview of recent X+MET searches at the ATLAS detector was presented.

\* Also, a full introduction to the new mono-Z' analysis has been presented.

\* This analysis represents an exciting new channel through which we can study Dark Matter production at the LHC.

\* Analysis strategy closely related to the 2015 mono-V analysis could be implemented for this analysis, due to similarity in final states.

\* For both the light vector and dark Higgs models expect limits on production cross section to be tighter that 100 – 10 pb, depending on Z' mass considered.

# **Backup Slides**



# **QCD** Multijet Estimate – Template Method.



\* Commonly used method to extract the QCD multijet estimate from data.



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## **Signal Region Selection**

MET > 250 GeV No electrons/muons

At least 1 large-R jet pT(j) > 200 GeV  $|\eta| < 2.0$  m(j) requirement  $D_2$  substructure requirement

MPT\* > 30 GeV

dφ(MET, closest narrow jet) <π/2 dφ(MET,MPT) <π/2 **Control Region Selection** 

MET > 200 GeV

At least 1 large-R jet  $D_2$  substructure requirement

MPT\* > 30 GeV

**Z+jets Control Region Selection** 

 $\begin{array}{l} 2 \text{ muons} \\ 66 \text{ GeV} < m(\mu\mu) < 116 \text{ GeV} \end{array}$ 

W+jets (top) Control Region Selection

Exactly 1 muon 0 (1) b-tagged track jet associated with the large-R jet for W (top).

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Z decay width : light Z' coupling to quarks contributes to the Z hadronic width through  $Z \rightarrow qqZ' \rightarrow 4j$  and through a Zqq vertex correction.

Even if Z' only couples to quarks kinematic mixing of Z' with Z,gamma can be generated at 1 loop.

Dijet constraints : Direct dijet resonance searched constrain Z' coupling to quarks. From UA2 experiment.



2 jets, pT > 20 GeV, |eta| < 2.5Lepton veto Z' from 2 leading pT jets. Mass window [0.8 x mZ' , mZ' + 30] GeV MET > 200 (300) for mZ' < 100 (>100) GeV PT lead lepton (MET threshold – 50) GeV

Soft MET dists and Z' is offshell

20.