Reinterpreting ATLAS monojet results using simplified models

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Abstract

The 8 TeV LHC run set the most stringent collider limits on particle dark matter yet, surpassing the sensitivities of the most advanced direct and indirect detection experiments in some parts of parameter space. However the interpretation of LHC results has for the purposes of model-independence and ease of comparison to other experiments so far mainly been done in an effective field theory framework which integrates out the mediator under the assumption it is heavier than the scale of the interaction, which is not necessarily a valid assumption at the LHC. This report presents a reinterpretation of 10.5 fb^{-1} of ATLAS 8 TeV data in terms of so-called simplified models which introduce model-independent mediators as degrees of freedom that can be taken into consideration when setting limits, together with a study of the expected limits that can be set with the first 20 fb^{-1} of data from the 14 TeV LHC.

August 22, 2014

1 Introduction

There is a range of astronomical measurements which imply the density of visible matter in the universe is far too low to account for observed large scale gravitational interactions [1][2]. This phenomenon is commonly referred to as dark matter (*DM*), but its microscopic nature, assuming it can be explained by some kind of massive particle, is not known as none of the Standard Model particles are adequate DM particle candidates [3]. One family of DM particle candidates of special interest to the LHC experiments are weakly interacting[1] massive particles (*WIMPs*), which as the name suggests are weakly interacting particles with a mass in the range from a few GeV to a few TeV. Measurements by the WMAP satellite suggest such a particle with electroweak-scale interaction cross sections would be a viable cold DM candidate, a fact referred to as the WIMP miracle [4]. From now on I will refer to WIMPs as DM candidates for simplicity since we only will discuss searches that take place at the LHC.

Events with only a single hard jet (*monojet events*) necessarily have a large amount of missing transverse energy and momentum[2]. These events are a good probe for beyond the Standard Model physics since they are relatively rare within the Standard Model where the only major contributions come from events where a Z decays to a $\nu\bar{\nu}$ pair or the charged lepton from a W decay is not reconstructed. In both of these cases the jet is radiated off the coloured initial state as so-called initial state radiation (*ISR*). The existence of a DM candidate would imply monojet events also could be created through the production of a DM pair $\chi\bar{\chi}$ again with a jet from ISR, which would modify the cross section of monojet events in the regions of phase space where this is kinematically possible. For example events with very large amounts of E_T^{miss} could be produced by a highly boosted DM pair recoiling against a hard ISR jet.

In this report I will present a study of a complementary approach to setting limits on DM candidate masses, reinterpreting previous 8 TeV results published by ATLAS [5, 6] and making predictions about its reach with the 14 TeV LHC.

2 Overview of the analysis

The analysis is identical to that in [5, 6] for the 8 TeV sample to allow for cross-validation of signal acceptances after detector simulation and object reconstruction, and identical to that in [7] for the 14 TeV sample to allow reuse of the background estimates. In short, we look for events with a single hard jet and a large amount of E_T^{miss}. The search is divided into four signal regions (SRs) for the 8 TeV analysis and three signal regions for the 14 TeV analysis presented below in tables 1 and 2. Note that in both cases jets are found with the anti-k_t algorithm [8] with $R = 0.4$ but the 8 TeV analysis uses a jet p_T cut of 30 GeV, whereas the 14 TeV analysis uses a jet p_T cut of 50 GeV.

Region	SR1	SR2	SR3	SR4
p_T^{j1} & $E_T^{\mathrm{miss}} >$	120 GeV	220 GeV	350 GeV	500 GeV

Table 1: Signal region definitions for the 8 TeV analysis.

Region	SR5	SR6	SR7
$p_T^{j1} >$	300 GeV	300 GeV	300 GeV
$E_T^{\mathrm{miss}} >$	400 GeV	600 GeV	800 GeV

Table 2: Signal region definitions for the 14 TeV analysis.

Additionally events are required to fulfill some kinematic and topological cuts to further suppress standard model and instrumental backgrounds: $|\eta^{j1}| < 2$, $|\Delta\phi(\mathbf{p}_T^{\mathrm{miss}}, \mathbf{p}_T^{j2})| > 0.5$, $N_{\mathrm{jets}} \leq 2$, $N_{\mathrm{leptons}} = 0$.

[1]Either through the Standard Model weak interaction or some new interaction.

[2]Our notation is $E_T^{\mathrm{miss}} = |\mathbf{p}_T^{\mathrm{miss}}|$.

Further details are not relevant for the purposes of this reinterpretation but can be found in [5, 7]. An example of the distributions of p_T^{j1} and E_T^{miss} in SR1 can be found in figure 1.

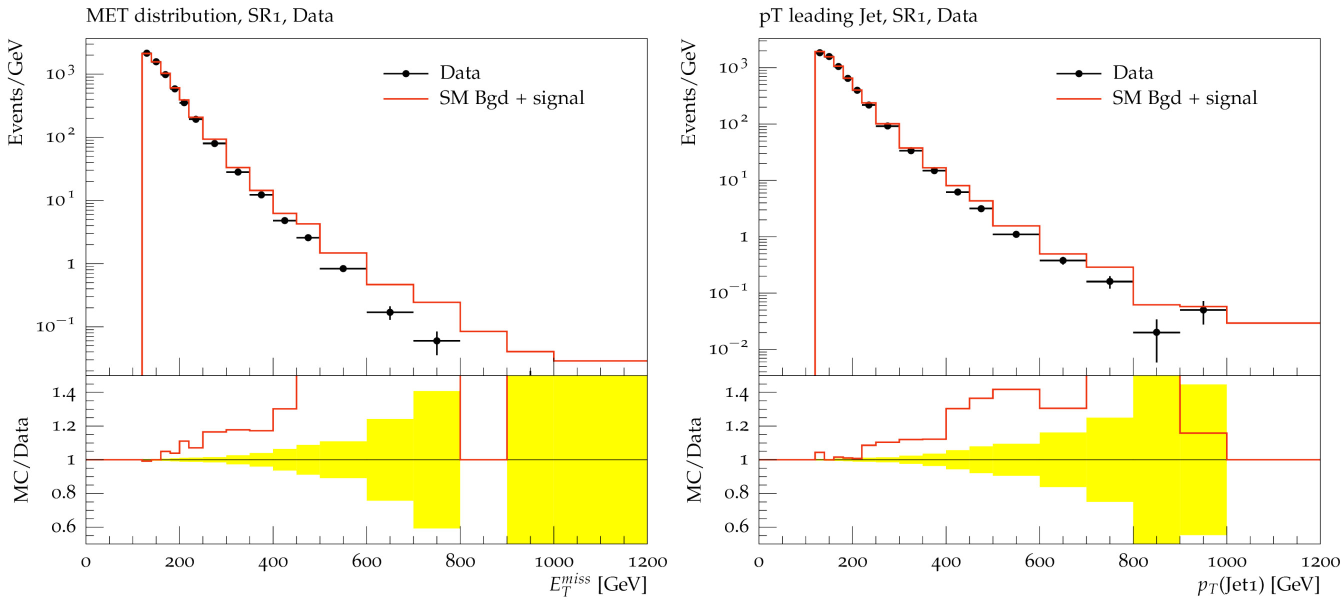
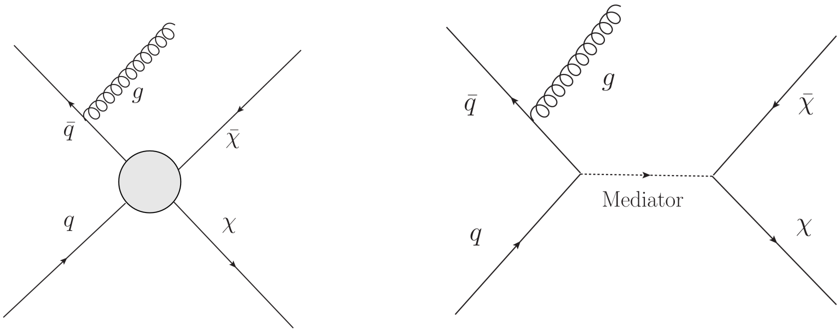


Figure 1: E_T^{miss} (left) and p_T^{j1} (right) distributions in SR1 for a D5 simplified model sample with $M_\chi = 100$ GeV, $M_\xi = 1000$ GeV, and $\Gamma_\xi = M_\xi/3$, comparing a SM background + signal sample to 10.5fb^{-1} ATLAS 8 TeV data where both are scaled to luminosity $\times$ cross section.

3 Dark matter models used for limit setting

There are many proposed models which can accommodate a WIMP: supersymmetric theories with R-parity conservation where the lightest supersymmetric particle is neutral are perhaps the most famous. Setting limits on a specific model is of limited use since it isn't clear how such limits can be translated to other models. The most commonly used approach to set limits on DM masses with the LHC experiments has therefore so far been to make the assumption that the required mediator (the intermediate particle which couples to both the SM and the DM) is heavy enough for an effective field theory (*EFT*) to be used, estimating the pair production to be a contact interaction between the SM and the DM (see [5, 9, 10]). This allows for model-independent limits to be set on the production cross section, and easy comparison to direct and indirect detection experiments. However it has recently been shown that the assumption that the mediator is heavy enough for the EFT to be valid for all of the parameter space probed at the LHC is not valid [11]. This means limits set on the EFT model might be considerably weaker than one would naively expect. In this report I will use the results from previous monojet analyses that considered EFT models in their WIMP interpretation to set limits on a so-called simplified model where we introduce an explicit mediator to make the theory UV complete, without making any further assumptions about the wider model context [12]. The difference (in terms of Feynman diagrams) between the EFT approach and the simplified model approach can be seen in figures 2a and 2b, and is considered in terms of operators in section 4. These models have recently been used by both the ATLAS and CMS experiments for setting limits on the coupling $\sqrt{g_q g_\chi}$ but with a few exceptions [13] there has been little effort to study the whole two-dimensional parameter space of M_χ and M_ξ (where these denote the masses of the dark matter candidate and the mediator), which will be the aim of this report, together with a study of the potential of this approach at the 14 TeV LHC.



(a) Diagram for EFT model.

(b) Diagram for simplified model with mediator.

Figure 2: The two families of s-channel models used for limit-setting on DM candidates using monojet searches at ATLAS and CMS.

4 Setting limits on simplified models

In this report I will only set limits on the so-called D5 operator in the s-channel, which in the EFT approach is given by:

$$\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q \tag{1}$$

The D5 operator assumes the dark matter candidate χ is a Dirac fermion and the mediator ξ is a vector, with vector couplings on both ends. The simplified model operator is therefore:

$$g_q\bar{q}\gamma^\mu q\xi_\mu + g_\chi\bar{\chi}\gamma_\mu\chi\xi^\mu \tag{2}$$

To set limits on this operator I generate Monte Carlo samples in a grid of M_χ and M_ξ values for two different values of the mediator width $\Gamma_\xi = M_\xi/3, M_\xi/8\pi$ by writing down the simplified model Lagrangian in Feynrules [14] and then using the output model to generate parton level events in Madgraph5 2.1.2 [15]. These events are then passed through Pythia 8.185 [16] for parton showering and hadronisation. Using the HepMC event format [17] these physical events are then passed on to beta version 0.9 of the ATOM framework for detector simulation and object reconstruction based on the ATLAS detector, and analysis using the Rivet framework [18]. The procedure has been validated by going through the entire chain with an EFT operator instead and comparing signal acceptances to those presented in [5], and it was found that the results were within quoted errors in all signal regions for the D5 EFT operator (1) with $M_\chi = 10$ GeV. The model-independent statistical limits based on the $\mathrm{CL_s}$ [19] procedure have also been validated against the limits quoted in [6, 5], with the procedures differing in that we use no systematic uncertainty profiling, and were found to be in good agreement in most cases as presented in table 3.

Region	SR1	SR2	SR3	SR4
$(\mathrm{C.L.}_{\mathrm{own}}$ - $\mathrm{C.L.}_{\mathrm{paper}})/\mathrm{C.L.}_{\mathrm{paper}}$ [6]	0.098	0.274	-0.084	-0.513
$(\mathrm{C.L.}_{\mathrm{own}}$ - $\mathrm{C.L.}_{\mathrm{paper}})/\mathrm{C.L.}_{\mathrm{paper}}$ [5]	0.020	-0.104	0.118	-0.061

Table 3: Differences in limits set to those quoted in [5, 6].

Once the number of expected events in each signal region for a particular simplified model has been found, I compare this number to the observed number of events (for 8 TeV where data is available [6]) and the expected number of SM background events (for both 8 TeV and 14 TeV) to derive 95% $\mathrm{CL_s}$ upper exclusion limits on $\sqrt{g_q g_\chi}$ for 8 TeV and expected 95% $\mathrm{CL_s}$ upper exclusion limits for 14 TeV, by assuming we can reweight the number of events for a certain value of the coupling straightforwardly, so that $\sigma_{\mathrm{vis}} \propto (\sqrt{g_q g_\chi})^4$ where σ_{vis} is the visible cross section. This assumption is not entirely justified since we find that changing the value of the width of the mediator changes the visible cross section, and the width depends on the coupling (assuming no additional invisible decays):

$$\Gamma_{\xi} = \Gamma(\xi \rightarrow \chi\bar{\chi})\Theta(M_{\xi} - 2M_{\chi}) + \sum_{q} \Gamma(\xi \rightarrow q\bar{q})\Theta(M_{\xi} - 2M_{q})$$
$$\Gamma(\xi \rightarrow \chi\bar{\chi}) \propto g_{\chi}^{2}, \quad \Gamma(\xi \rightarrow q\bar{q}) \propto g_{q}^{2} \tag{3}$$

Equation (3) shows the dependence of Γ_{ξ} on the couplings g_q and g_{χ}, taken from [20]. However a more thorough study including this effect is outside the scope of this report.

5 Results for 8 TeV

The results using 10.5 fb^{-1} of 8 TeV data collected by the ATLAS detector, first presented in [5], are given in figure 3.

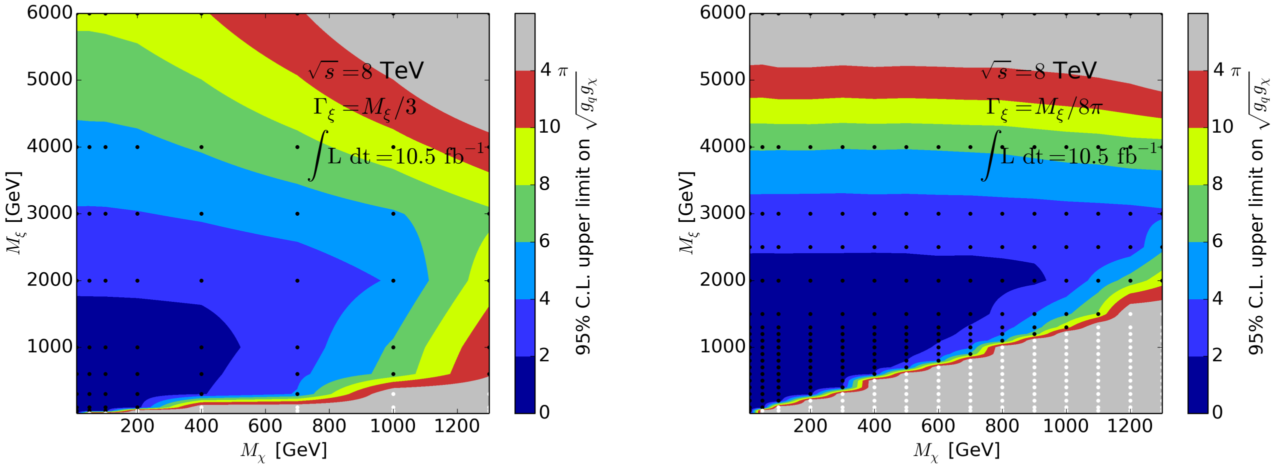


Figure 3: 95% C.L. upper limits set on the coupling $\sqrt{g_q g_{\chi}}$ using 10.5 fb^{-1} of 8 TeV data as a function of M_{χ} and M_{ξ} for $\Gamma_{\xi} = M_{\xi}/3$ (left) and $\Gamma_{\xi} = M_{\xi}/8\pi$ (right). Note the black dots indicate an a knot for the interpolation which had events passing in the analysis, whereas the white dots are attempted knots which had no events pass in the analysis. Values above 4π are outside of the range of validity of the model. The interpolation is linear, and points which had no events pass are set just outside the range of validity so results in regions between a black and a white dot are speculative.

6 Predictions for 14 TeV

The predictions using 20 fb^{-1} of 14 TeV simulation are given in figure 4. Note that the statistical uncertainty on the background predictions has been greatly reduced compared to the 8 TeV results, which accounts for some of the improvement on the limits together with harder E_T^{miss} tails from the signal which increases the distinguishing power of the harder signal regions. Note also that the background prediction does not include $Z \rightarrow ll$ and diboson events which are included in the 8 TeV background estimate, however these make a 1% contribution at 8 TeV and are not expected to play a larger role at 14 TeV so the results should still be reliable. The total uncertainty used for calculating the limit is given by the statistical uncertainty and a 5% systematic uncertainty, treated as separate Gaussian uncertainties.

7 Conclusions

The limits that can be set on the coupling $\sqrt{g_q g_{\chi}}$ for the D5 operator using a simplified model approach should be greatly improved with the first 20 fb^{-1} of 14 TeV LHC data, allowing for the area of the parameter space where its value is limited below 2 to be more than doubled. There are many effects which play into

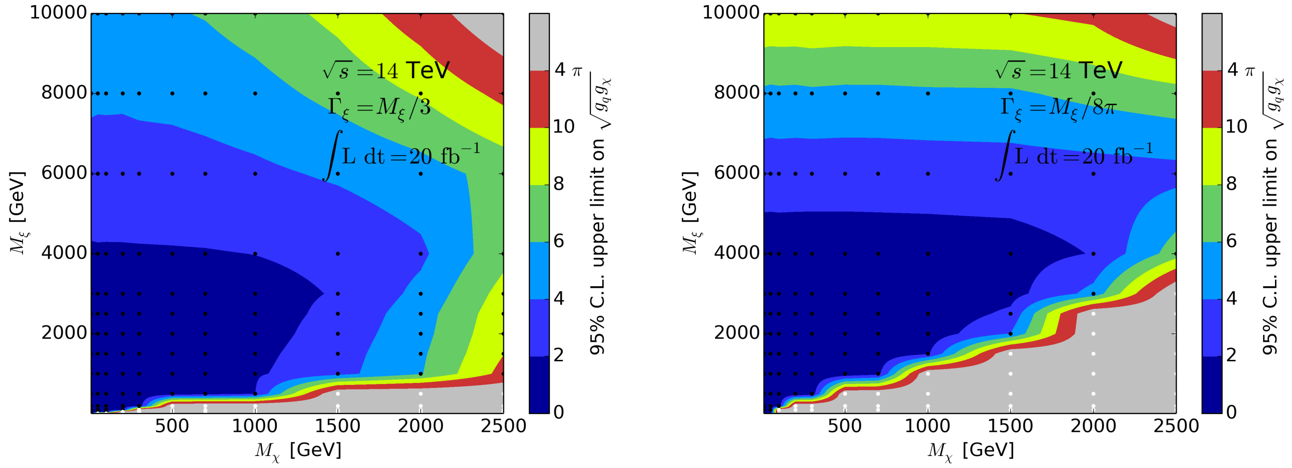


Figure 4: Expected 95% C.L. upper limits set on the coupling $\sqrt{g_q g_\chi}$ using 20 fb^{-1} of 14 TeV simulation as a function of M_χ and M_ξ for $\Gamma_\xi = M_\xi/3$ (left) and $\Gamma_\xi = M_\xi/8\pi$ (right). Note the black dots indicate a knot for the interpolation which had events passing in the analysis, whereas the white dots are attempted knots which had no events pass in the analysis. Values above 4π are outside of the range of validity of the model. The interpolation is linear, and points which had no events pass are set just outside the range of validity so results in regions between a black and a white dot are speculative.

this: the higher center of mass energy allows in particular for harder E_T^{miss} tails which gives the harder signal regions more distinguishing power, and improved statistical uncertainties on the background also contribute.

The results presented in this report could also be derived for any other simplified model operator but due to time constraints I have not done so – a nice continuation for this work would be to derive limits for the case where both couplings are vector-axial as this would give a spin-dependent result to compare to the spin-independent result presented here.

8 Acknowledgments

I would like to thank Andreas and Caterina for giving me this opportunity and for their constant support and help, and Emil and Lingxin for great discussions and their patience with my messy code and ad-hoc scripts. I am also grateful for help with the model files, event generation, and various other topics from Amelia Brennan, help with the limit setting from Ruth Poettgen, help with the event generation and ME $\rightarrow$ PS matching from Johanna Gramling and Stefan Prestel, and help with the 14 TeV background estimates from David Salek.

Finally I would like to thank the CERN summer student team and the rest of the summer students for a great summer!

Bibliography

[1] D. Clowe, A. Gonzalez, and M. Markevitch [2004], *Weak lensing mass reconstruction of the interacting cluster 1E0657-558: Direct evidence for the existence of dark matter*, Astrophys.J., vol. 604: pp. 596–603, `astro-ph/0312273`

[2] S. M. Faber and R. E. Jackson [1976], *Velocity dispersions and mass-to-light ratios for elliptical galaxies*, Astrophys.J., vol. 204: pp. 668–683

[3] C. Quigg [2008], *Cosmic Neutrinos*, 0802.0013

[4] B. S. Acharya, G. Kane, S. Watson, and P. Kumar [2009], *Nonthermal "WIMP miracle"*, Phys. Rev. D, vol. 80: p. 083529, 0908.2430

[5] G. Aad *et al.* (ATLAS Collaboration) [2013], *Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the ATLAS detector*, JHEP, vol. 1304: p. 075, 1210.4491

[6] [2012], *Search for New Phenomena in Monojet plus Missing Transverse Momentum Final States using 10fb-1 of pp Collisions at sqrts=8 TeV with the ATLAS detector at the LHC*, , no. ATLAS-CONF-2012-147

[7] [2014], *Sensitivity to WIMP Dark Matter in the Final States Containing Jets and Missing Transverse Momentum with the ATLAS Detector at 14 TeV LHC*, , no. ATL-PHYS-PUB-2014-007

[8] M. Cacciari, G. P. Salam, and G. Soyez [2008], *The Anti-k(t) jet clustering algorithm*, JHEP, vol. 0804: p. 063, 0802.1189

[9] G. Aad *et al.* (ATLAS Collaboration) [2011], *Search for new phenomena with the monojet and missing transverse momentum signature using the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions*, Phys.Lett., vol. B705: pp. 294–312, 1106.5327

[10] S. Chatrchyan *et al.* (CMS Collaboration) [2012], *Search for dark matter and large extra dimensions in monojet events in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP, vol. 1209: p. 094, 1206.5663

[11] G. Busoni, A. De Simone, J. Gramling, E. Morgante, and A. Riotto [2014], *On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC, Part II: Complete Analysis for the s-channel*, JCAP, vol. 1406: p. 060, 1402.1275

[12] O. Buchmueller, M. J. Dolan, and C. McCabe [2014], *Beyond Effective Field Theory for Dark Matter Searches at the LHC*, JHEP, vol. 1401: p. 025, 1308.6799

[13] G. Aad *et al.* (ATLAS Collaboration) [2014], *Search for dark matter in events with a Z boson and missing transverse momentum in pp collisions at $\sqrt{s}$=8 TeV with the ATLAS detector*, Phys.Rev., vol. D90: p. 012004, 1404.0051

[14] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks [2014], *FeynRules 2.0 - A complete toolbox for tree-level phenomenology*, Comput.Phys.Commun., vol. 185: pp. 2250–2300, 1310.1921

[15] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer [2011], *MadGraph 5 : Going Beyond*, JHEP, vol. 1106: p. 128, 1106.0522

[16] T. Sjostrand, S. Mrenna, and P. Z. Skands [2008], *A Brief Introduction to PYTHIA 8.1*, Comput.Phys.Commun., vol. 178: pp. 852–867, 0710.3820

[17] M. Dobbs and J. B. Hansen [2001], *The HepMC C++ Monte Carlo event record for High Energy Physics*, Comput.Phys.Commun., vol. 134: pp. 41–46

[18] A. Buckley, J. Butterworth, L. Lonnblad, D. Grellscheid, H. Hoeth, *et al.* [2013], *Rivet user manual*, Comput.Phys.Commun., vol. 184: pp. 2803–2819, 1003.0694

[19] A. L. Read [2002], *Presentation of search results: the CL s technique*, Journal of Physics G: Nuclear and Particle Physics, vol. 28, no. 10: p. 2693, URL http://stacks.iop.org/0954-3899/28/i=10/a=313

[20] O. Buchmueller, M. J. Dolan, S. A. Malik, and C. McCabe [2014], *Characterising dark matter searches at colliders and direct detection experiments: Vector mediators*, 1407.8257