Version 0.1 DRAFT

ATLAS+CMS DARK MATTER FORUM RECOMMENDATIONS

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1
Introduction

This is a citation test Harris and Kousouris [2011].

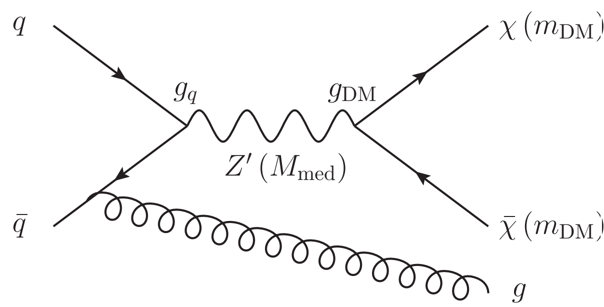

Figure 2.1: The diagram shows the pair production of dark matter particles in association with a parton from the initial state via an s-channel vector or axial-vector mediator. The process if specified by ($M_{\rm med}$, $m_{\rm DM}$, $g_{\rm DM}$, g_q), the mediator and dark matter masses, and the mediator couplings to dark matter and quarks respectively.

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List of simplified models: choices and implementation

General topics:

- choice of Dark Matter type: Dirac (unless specified otherwise) and what we might be missing
- MFV and what we might be missing

2.1 *Generic models for mono-jet signatures*

Vector and axial vector mediator, s-channel exchange

- Matrix Element implementations (with references)
  - Production mechanism
  - Lagrangian We consider the case of a dark matter particle that is a Dirac fermion and where the production proceeds via the exhange of a spin-1 s-channel mediator. We consider the following interactions between the DM and SM fields including a vector mediator with:
    (a) vector couplings to DM and SM.
    (b) axial-vector couplings to DM and SM.

$$\mathcal{L}_{\text{vector}} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q + g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi \tag{2.1}$$

$$\mathcal{L}_{\text{axial}} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi \tag{2.2}$$

where the coupling extends over all the quarks and universal couplings are assumed for all the quarks. It is also possible to consider another model in which mixed vector and axial-vector couplings are considered, for instance the couplings to the quarks are vector whereas those to DM are axial-vector. As a starting point, we consider only the models with the vector couplings only and axial vector couplings only. Studies have been performed to see if the case of a mixed coupling can be simply extracted from the other models by some reweighting procedure to take account of the difference in cross section. This would assume that the difference between the pure and mixed couplings case does not affect the kinematics of the event.

– Definition of minimal width We assume that no additional visible or invisible decays contribute to the width of the mediator, this is referred to as the minimal width and it is defined as follows for the vector and axial-vector models.

$$\Gamma_{\text{min}} = \Gamma_{\bar{\chi}\chi} + \sum_q N_c \Gamma_{\bar{q}q} \tag{2.3}$$

where the individual contributions to this from the partial width are from,

$$\Gamma^{\text{vector}}_{\bar{\chi}\chi} = \frac{g_{\text{DM}}^2 M_{\text{med}}}{12\pi}\left(1 + \frac{2m_{\text{DM}}^2}{M_{\text{med}}^2}\right)\sqrt{1 - \frac{4m_{\text{DM}}^2}{M_{\text{med}}^2}} \tag{2.4}$$

$$\Gamma^{\text{vector}}_{\bar{q}q} = \frac{3g_q^2 M_{\text{med}}}{12\pi}\left(1 + \frac{2m_q^2}{M_{\text{med}}^2}\right)\sqrt{1 - \frac{4m_q^2}{M_{\text{med}}^2}} \tag{2.5}$$

$$\Gamma^{\text{axial}}_{\bar{\chi}\chi} = \frac{g_{\text{DM}}^2 M_{\text{med}}}{12\pi}\left(1 - \frac{4m_{\text{DM}}^2}{M_{\text{med}}^2}\right)^{3/2} \tag{2.6}$$

$$\Gamma^{\text{axial}}_{\bar{q}q} = \frac{3g_q^2 M_{\text{med}}}{12\pi}\left(1 - \frac{4m_q^2}{M_{\text{med}}^2}\right)^{3/2} . \tag{2.7}$$

- Couplings
- Parameter choices (for scan) Vary mediator mass and DM mass
- Generator implementation

Scalar and pseudoscalar mediator, s-channel exchange

Colored scalar mediator, t-channel exchange

2.2 *Specific models for signatures with EW bosons*

In this Section, we consider models with a photon, a W boson, a Z boson or a Higgs boson in the final state, accompanied by Dark Matter particles that either couple directly to the boson or are mediated by a new particle. The experimental signature is identified as *V+MET*.

These models are interesting both as extensions of models where the gluon provides the experimentally detectable signature, and as stand-alone models with final states that cannot be generated by the models in Section 2.1.

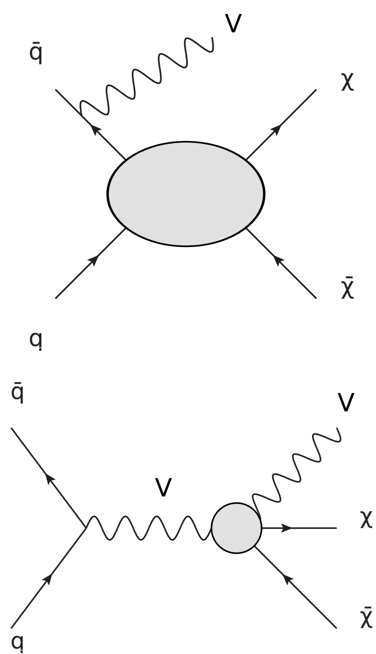

Figure 2.2: Sketch of EFT models for V+MET searches, adapted from [Nelson et al., 2014].

The models considered can be divided in four categories:

EFT models where the boson is radiated from the initial state As depicted in the top diagram of Figure 2.2, these models follow the nomenclature and theory for the EFT benchmarks commonly used by MET+X searches [Goodman et al., 2010].

EFT models where the boson is directly coupled to DM Shown in the bottom of Figure 2.2, these models allow for an EFT vertex that directly couples the boson to Dark Matter.

Simplified models where the boson is radiated from the initial state These models follow those already described in Section 2.1, replacing the initial state gluon with a boson.

V-specific simplified models These models postulate direct couplings of new mediators to bosons, e.g. they couple the Higgs boson to a new scalar [Carpenter et al., 2014].

The following Sections describe the models within these categories, the parameters for each of the benchmark models chosen, the studies towards the choices of the parameters to be scanned, and finally point to the location of their Matrix Element implementation.

EFT models with ISR boson radiation Searches in the mono-jet final state are generally more sensitive with respect to final states including bosons, due to the much larger rates of jet+MET signal events with respect to radiation of bosons [Zhou et al., 2013], in combination with the low branching ratios if leptons from boson decays are required in the final state. The rates for the Higgs boson radiation is too low for EFT models to be considered a viable benchmark [Carpenter et al., 2014].

However, the presence of photons [Kha, 2014, Aad, 2014a], leptons from W and Z decays [Khachatryan et al., 2014, Aad, 2014a, Aad et al., 2014] and W or Z bosons decaying hadronically [Aad, 2014b] allows to reject the background more effectively, making Z/gamma/W+MET search results for simple EFT benchmarks still worth comparing with jet+MET. The three commonly chosen EFT benchmarks for Dirac dark matter that are kinematically distinct for what concerns the observables used in MET+X searches [1] and span a wide range of MET spectrum in the boson+MET searches are, in the notation of [Goodman et al., 2010], the D1 (scalar SM/WIMP interaction), D5 (vector-vector interaction) and D9 (tensor interaction) operator.

[1] [CD: we would need a plot here, or a reference to monojet section where this is shown]

The case for searches with W bosons in the final state is strenghtened by the presence of particular choices of couplings between the WIMP and the up and down quarks which enhance W radiation [Bai and Tait, 2013]. We consider three sample cases for the product of Dirac WIMP/down quark and WIMP/up quark couplings ξ, in the case of a vector or axial-vector interaction [2]:

[2] [CD: refer to VV/AV/VA/AA monojet studies.]

- No couplings between WIMP and either up or down quarks ($\xi = 0$);
- Same coupling between WIMP and each of the quark types ($\xi = 1$);
- Coupling of opposite sign between WIMP and each of the quark types ($\xi = -1$);

The $\xi = -1$ case produces constructive interference between the two diagrams in which a W is produced from an initial state of an up and a down quark. This in turn increases the cross-section of the process and the hardness of the spectrum of missing transverse energy or transverse mass used for the searches. The sensitivity of the W+MET search for this benchmark surpasses that of the jet+MET search, as gluon radiation does not distinguish between different couplings scenarios.

The above considerations lead to the following prioritized list of benchmark models for EFT models with ISR boson radiation:

Vector interaction with vector-vector couplings (D5) . For both jet+MET and boson+MET searches, the kinematic of this operator corresponds to that of couplings that are vector-axial (D7), axial-axial (D8) and axial-vector (D6). In the case of W boson radiation, the three coupling scenarios $\xi = 1, 0, -1$ should be investigated. This operator populates the high MET

Tensor interaction (D9) . As shown in Figure **[CD: add picture from Andy]**, this operator populates a higher MET range with respect to the other operators chosen.

Scalar interaction (D1) . This operator has the lowest cross-section and sensitivity at colliders in this final state, as DM production from light quarks via a scalar interaction is suppressed with respect to heavy quarks. However, it has the hardest MET spectrum of the EFT operators chosen, and results obtained using this operator as benchmark may be used for recasting signals with a similarly hard MET distribution. [3]

[3] Q for Andy/M-E: ZZchichi max gamma: is it the same kinematics regardless of DM? See fig. 2 of ATLAS monoZ.

EFT models with direct DM-boson couplings A complete list of effective operators with direct DM/boson couplings, up to dimension 7, can be found in [Cotta et al., 2013].

Simplified models with ISR boson radiation The choice of simplified models with ISR boson radiation follows both that of the corresponding EFT operators and of the jet+MET models. The primary benchmark model is a vector mediator exchanged in the s-channel [4]. Similarly to the EFT case, we recommend to test the three different coupling scenarios for the W+MET signature. [5].

[4] [CD: link to the monojet section for diagram]

[5] CD: how do we justify having 3 EFT scenarios and only one simplified model? We have the t-channel colored scalar mediator available from earlier ATLAS mono-Z

Specific simplified models

2.3 *Specific models for signatures with heavy flavor quarks*

2.4 *SUSY-inspired simplified models*

3
Validity of EFT approach

4
Recommendations for expressing collider constraints

Bibliography

Robert M. Harris and Konstantinos Kousouris. Searches for dijet resonances at hadron colliders. *Int. J. Modern Phys.*, 26(30n31): 5005–5055, 2011. doi: 10.1142/S0217751X11054905.

Andy Nelson, Linda M. Carpenter, Randel Cotta, Adam Johnstone, and Daniel Whiteson. Confronting the Fermi Line with LHC data: an Effective Theory of Dark Matter Interaction with Photons. *Phys.Rev.*, D89(5):056011, 2014. doi: 10.1103/PhysRevD.89.056011.

Jessica Goodman, Masahiro Ibe, Arvind Rajaraman, William Shepherd, Tim M.P. Tait, et al. Constraints on Dark Matter from Colliders. *Phys.Rev.*, D82:116010, 2010. doi: 10.1103/PhysRevD.82.116010.

Linda Carpenter, Anthony DiFranzo, Michael Mulhearn, Chase Shimmin, Sean Tulin, et al. Mono-Higgs-boson: A new collider probe of dark matter. *Phys.Rev.*, D89(7):075017, 2014. doi: 10.1103/PhysRevD.89.075017.

Ning Zhou, David Berge, and Daniel Whiteson. Mono-everything: combined limits on dark matter production at colliders from multiple final states. *Phys.Rev.*, D87(9):095013, 2013. doi: 10.1103/PhysRevD.87.095013.

Search for new phenomena in monophoton final states in proton-proton collisions at $\sqrt{s}$ = 8 TeV. 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.*, D90(1):012004, 2014a. doi: 10.1103/PhysRevD.90.012004.

Vardan Khachatryan et al. Search for physics beyond the standard model in final states with a lepton and missing transverse energy in proton-proton collisions at $\sqrt{s}$ = 8 TeV. 2014.

Georges Aad et al. Search for new particles in events with one lepton and missing transverse momentum in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector. *JHEP*, 1409:037, 2014. doi: 10.1007/JHEP09(2014)037.

Search for dark matter in events with a hadronically decaying W or Z boson and missing transverse momentum in pp collisions at $\sqrt{s} =$ 8 TeV with the ATLAS detector. *Phys.Rev.Lett.*, 112(4):041802, 2014b. doi: 10.1103/PhysRevLett.112.041802.

Yang Bai and Tim M.P. Tait. Searches with Mono-Leptons. *Phys.Lett.*, B723:384–387, 2013. doi: 10.1016/j.physletb.2013.05.057.

R.C. Cotta, J.L. Hewett, M.P. Le, and T.G. Rizzo. Bounds on Dark Matter Interactions with Electroweak Gauge Bosons. *Phys.Rev.*, D88:116009, 2013. doi: 10.1103/PhysRevD.88.116009.