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].

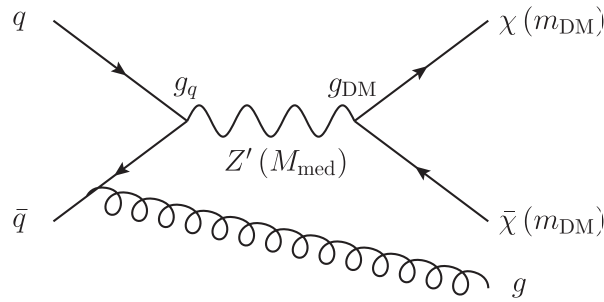

Figure 2.1: The diagram shows the pair production of dark matter particles in association with a parton from the initial state via an s-channel vector or axial-vector mediator. The process if specified by ($M_{\rm med}$, $m_{\rm DM}$, $g_{\rm DM}$, g_q), the mediator and dark matter masses, and the mediator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

2

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,

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

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

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

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

- 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.

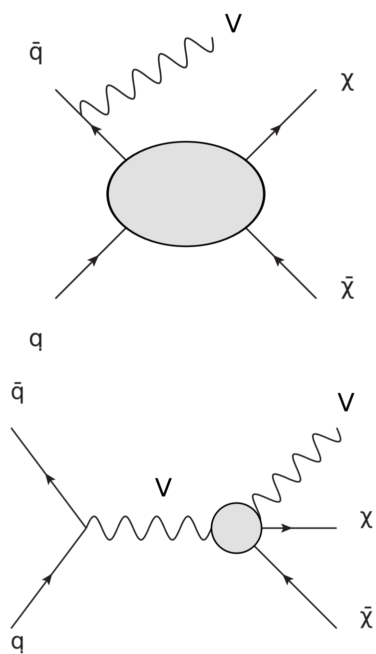

Figure 2.2: Sketch of EFT models for V+MET searches, adapted from [Nelson et al., 2014].

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.

Simplified models with ISR boson radiation Searches in the jet+MET final state are generally more sensitive with respect to final states including bosons, due to the much larger rates of signal events featuring quark or gluon radiation 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 these 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 searches still worth comparing with searches in the jet+MET final state.

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], in the case of the exchange of a vector mediator in the s-channel. We consider three sample cases for the product of up and down quark couplings to the mediator ξ:

- No couplings between mediator and either up or down quarks ($\xi = 0$);
- Same coupling between mediator and each of the quark types ($\xi = 1$);
- Coupling of opposite sign between mediator 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 in the case of constructive interference surpasses that of the jet+MET search.

The above considerations lead to the choice of a vector mediator exchanged in the s-channel as the main benchmark model, in the case of a W/Z boson or a photon are radiated in the initial state.

[CD: Plots I would like for this following section: 1. mT for Wlep, 2. MET for gamma, 3. MET for Z, 4. (wishful thinking) fat jet mass for Whad]

The parameters for the definition and characterization of this model are:

- the mass of the DM particle (m_{DM});
- the mediator mass (m_{Med});
- the mediator width (Γ_{Med});
- the couplings between the DM and the mediator (g_{DM}), and between the mediator and the initial state quarks (g_{SM}); together with the product of the couplings between the mediator and up/down quarks (ξ);
- the chirality of the couplings between DM and mediator, and between mediator and initial state quarks (vector-vector, axial-vector, axial-axial, vector-axial).

The DM and mediator mass ($\mathbf{m_{DM}}, \mathbf{m_{Med}}$) are scanned independently. Different kinematic distributions are obtained with a scan of **N** points in the DM/mediator mass plane, as shown in Figure **??**. The spacing of the points is chosen because **[CD: we need to justify this.]**

The couplings between the DM and the mediator $\mathbf{g_{DM}}$, and the couplings between mediator and initial state quarks $\mathbf{g_{SM}}$ are scanned indipendently following the recommendation for the jet+MET models **[CD: link to monojet parameter scan]**. **[CD: do we have a plot of the dependence of the kinematics on the couplings?]**. The products of the couplings of the mediator to up and down quarks ξ needs to be considered for the three cases separately in the case of the W+MET signature. Figure **??** shows that the constructive and destructive interference options have a similar kinematics. It is therefore recommended to generate two out of the three coupling ratio options (ξ=1 and ξ=0) and rescale the third. **[CD: Kerstin's plot of mT for different values of ξ - how to make it more clear that we can rescale? Or: can we show analytically that having two out of three is sufficient?]**.

The **mediator width** is chosen to be the minimal possible width for decays in quarks and Dark Matter assuming the couplings chosen for the scan point, as in Equation **??**. The width of this mediator as a function of the mediator mass **[CD: or some other plot, just to show it does not explode and that we are treating ξ correctly]** is shown in Figure ??. **[CD: is there any plot of the dependence of the MET from the mediator width? This should be the same as the monojet, small difference in what happens to the ISR and MET, so we can just leave the rescaling to larger widths to theorists and trust their width is not too large so that they incur in PDF effects etc. Does this also hold for M_{Wjet}?]**

Similarly to the considerations made for the same model in the jet+MET case, the **chiral structure of the couplings** does not change the kinematics of the main variables used for the search **[CD: this will need a plot to be confirmed]**, so we recommend to restrict to one of the cases, e.g. the axial-vector coupling case for SM and DM particles to the mediator respectively. **[CD: using axial-vector and justifying it with suppression at DD may not be correct, see D'Eramo et al on RGE, will add paper link]**

These models are generated at leading order with MadGraph 2.2.2, and parameter cards can be found on SVN **[CD: how to put this in write-up?]**. The parton shower is done using Pythia 8, with a matching scale of... **[CD: need to figure this out.]**

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

Following the notation of [Carpenter et al., 2013], the dimension 5 benchmark models from this category have a Lagrangian that includes terms such as:

$$\frac{m_W^2}{\Lambda_5^3}\ \bar{\chi}\chi\ W^{+\mu}W^-_\mu + \frac{m_Z^2}{2\Lambda_5^3}\ \bar{\chi}\chi\ Z^\mu Z_\mu\ . \tag{2.8}$$

where m_Z and m_W are the masses of the Z and W boson, W^μ and Z^μ are the fields of the gauge bosons, χ denote the Dark Matter fields and Λ_5 is the effective field theory scale. This operator induces signatures with MET in conjunction with Z and W bosons at tree level, while at loop level it induces couplings to photon pairs and $Z\gamma$ through W loops. **[CD: I believe the paper but I couldn't write this down. How much detail do we want here?]**.

The dimension 7 benchmark models include couplings to the kinetic terms of the EW bosons ($F_i^{\mu\nu}$, with $F_i = 1, 2, 3$ being the field strengths of the SM $U(1)$ and $SU(2)$ gauge groups and $\tilde{F}_i^{\mu\nu}$ their dual tensors). The Lagrangian for the scalar coupling of DM and bosons include terms such as the following:

$$\frac{1}{\Lambda_{7,S}^3}\ \bar{\chi}\chi\ \sum_i k_i F_i^{\mu\nu}F^i_{\mu\nu} + \frac{1}{\Lambda_{7,S}^3}\ \bar{\chi}\chi\ \sum_i k_i F_i^{\mu\nu}\tilde{F}^i_{\mu\nu} \tag{2.9}$$

The Lagrangian with pseudoscalar coupling includes the following term:

$$\frac{1}{\Lambda^3_{7,PS}}\,\bar{\chi}\gamma^5\chi\,\sum_i k_i F_i^{\mu\nu}F^i_{\mu\nu} + \frac{1}{\Lambda^3_{7,PS}}\,\bar{\chi}\gamma^5\chi\,\sum_i k_i F_i^{\mu\nu}\tilde{F}^i_{\mu\nu} \tag{2.10}$$

The cut-off scales Λ for the separate terms can be related to operators with different Lorentz structure from Ref. [Cotta et al., 2013]. Given that they do not lead to substantial differences for collider searches as shown in Figure 2 of Ref. [Carpenter et al., 2013], they have been denoted as $\Lambda_{7,S}$ for the scalar case and $\Lambda_{7,PS}$ for the pseudoscalar case. When no distinction is made, they will be simply called Λ_7.

The k_i coefficients are related to the couplings of DM to pairs of gauge bosons by gauge invariance:

$$g_{WW} = \frac{2k_2}{s_w^2\Lambda_7^3} \tag{2.11}$$

$$g_{ZZ} = \frac{1}{4s_w^2\Lambda_7^3}\left(\frac{k_1 s_w^2}{c_w^2} + \frac{k_2 c_w^2}{s_w^2}\right) \tag{2.12}$$

$$g_{\gamma\gamma} = \frac{1}{4c_w^2}\frac{k_1 + k_2}{\Lambda_7^3} \tag{2.13}$$

$$g_{Z\gamma} = \frac{1}{2s_w c_w \Lambda_7^3}\left(\frac{k_2}{s_w^2} - \frac{k_1}{c_w^2}\right) \tag{2.14}$$

where s_w and c_w are respectively the sine and cosine of the weak mixing angle. **[CD: add here correspondence with Uli's coefficients - it may be useful.]**

The coefficients k_i determine the relative importance of each of the boson channels, and their correlations. For example, for what concerns searches with W, Z and photons:

- k_2 alone controls the rate of the coupling to W boson pairs;
- If $k_1 = k_2$ contributions from both Z and γ exchange appear;
- If $k_1 = c_w^2/s_w^2 k_2$ the γ exchange is negligible.

[CD: discussion on the grid scan, need better internet for that]

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

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