Version 0.1 DRAFT

ATLAS+CMS DARK MATTER FORUM RECOMMENDA-TIONS

Author/contributor list to be added as document is finalized.

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1
Introduction

This is a citation test [HK11].

q

$\chi\,(m_{\mathrm{DM}})$

g_q g_{DM}

$Z'\,(M_{\mathrm{med}})$

$\bar{q}$

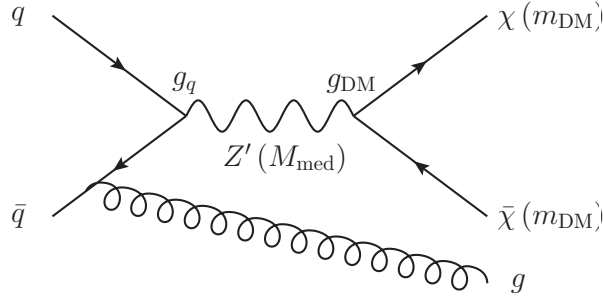$\bar{\chi}\,(m_{\mathrm{DM}})$

g

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 $(M_{\mathrm{med}},\,m_{\mathrm{DM}},\,g_{\mathrm{DM}},\,g_q)$, 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 exchange 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,

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

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

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

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

• Couplings

• Parameter choices (for scan) Vary mediator mass and DM mass

• Generator implementation There are several matrix element implementations of the s-channel vector mediated DM production. This is available in POWHEG, MADGRAPH and also MCFM. The implementation in POWHEG generates DM pair production with 1

parton at Next-to-Leading-Order, whilst Madgraph and MCFM are
at leading order. As shown in POWHEG paperHaisch:2013ata, in-
cluding NLO corrections result in an enhancement in the cross sec-
tion as compared to leading-order (LO) and though this is not sig-
nificant, it does lead to a substantial reduction in the dependence
on the choice of the renormalisation and factorisation scale and
hence the theoretical uncertainty on the signal prediction. Since
NLO calculations are available for the process in POWHEG, we
recommend to proceed with POWHEG as the generator of choice.
In addition to this, studies conducted within the DM forum
have shown that POWHEG is more efficient for the generation
of events all the way out to the tails of the kinematic distributions
(https://indico.cern.ch/event/374678/session/0/material/3/1.pdf).
The input configuration in POWHEG allows you to set parameters
to not generate events below a given kT cut ('bornktmin') and
an additional parameter that ensures sufficient statistics at high
transverse momentum ('bornsuppfact). With these flags set to ap-
propriate variables, it is then possible to use a single POWHEG
sample to generate the Monte Carlo for all signal regions, whereas
with Madgraph more individual samples to be stitched together to
achieve the required statistics out to the tails of the kinematic dis-
tributions. The POWHEG and Madgraph implementations were
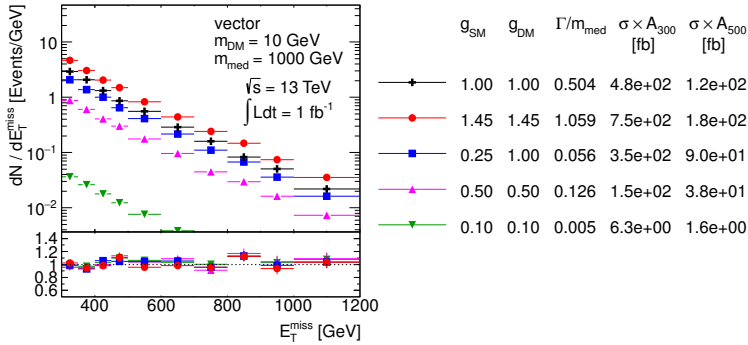compared and the yields obtained from both were found to be
compatible.

Figure 2.2: Scan over couplings

Scalar and pseudoscalar mediator, s-channel exchange

Cross section scaling

Colored scalar mediator, t-channel exchange   An alternative set of
simplified models exist where the mediator is exchanged in the *t-*
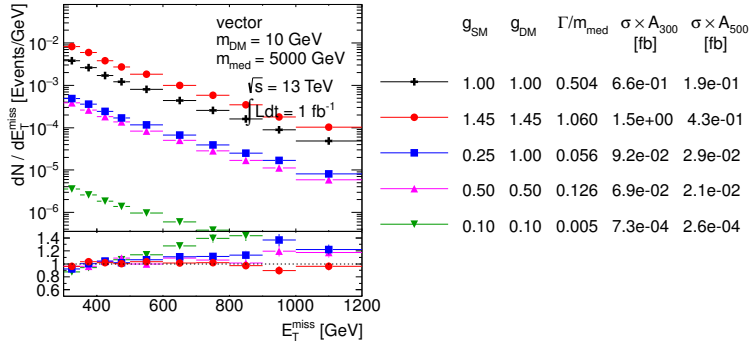channel, thereby coupling the quark and dark matter particle directly.

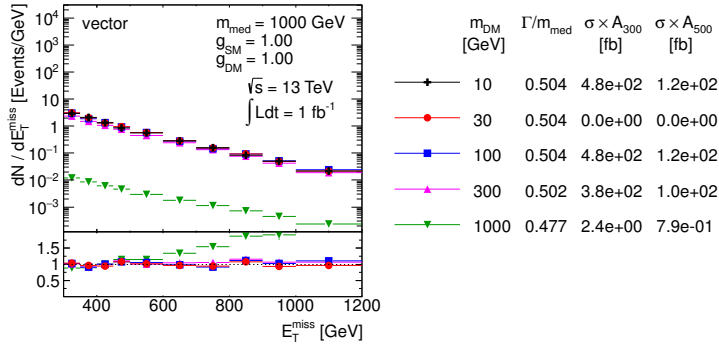| g_{SM}	g_{DM}	Γ/m_{med}	$\sigma \times A_{300}$ [fb]	$\sigma \times A_{500}$ [fb]
1.00	1.00	0.504	6.6e-01	1.9e-01
1.45	1.45	1.060	1.5e+00	4.3e-01
0.25	1.00	0.056	9.2e-02	2.9e-02
0.50	0.50	0.126	6.9e-02	2.1e-02
0.10	0.10	0.005	7.3e-04	2.6e-04

Figure 2.3: Scan over couplings

m_{DM} [GeV]	Γ/m_{med}	$\sigma \times A_{300}$ [fb]	$\sigma \times A_{500}$ [fb]
10	0.504	4.8e+02	1.2e+02
30	0.504	0.0e+00	0.0e+00
100	0.504	4.8e+02	1.2e+02
300	0.502	3.8e+02	1.0e+02
1000	0.477	2.4e+00	7.9e-01

Figure 2.4: Scan over Dark Matter mass

m_{DM} [GeV]	Γ/m_{med}	$\sigma \times A_{300}$ [fb]	$\sigma \times A_{500}$ [fb]
10	0.424	1.9e+04	1.8e+03
30	0.423	1.9e+04	1.7e+03
100	0.398	2.9e+03	4.1e+02
300	0.398	0.0e+00	0.0e+00
1000	0.398	1.6e+00	5.4e-01
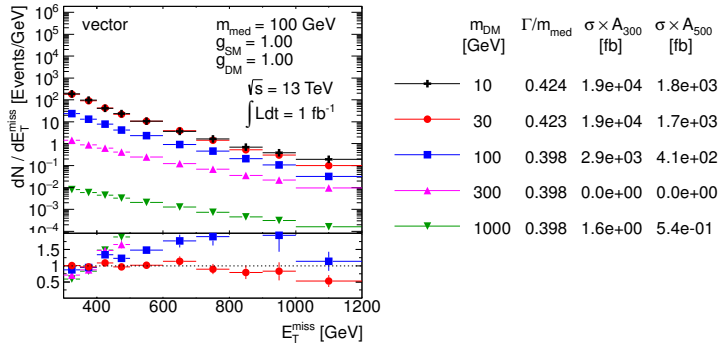
Figure 2.5: Scan over Dark Matter mass

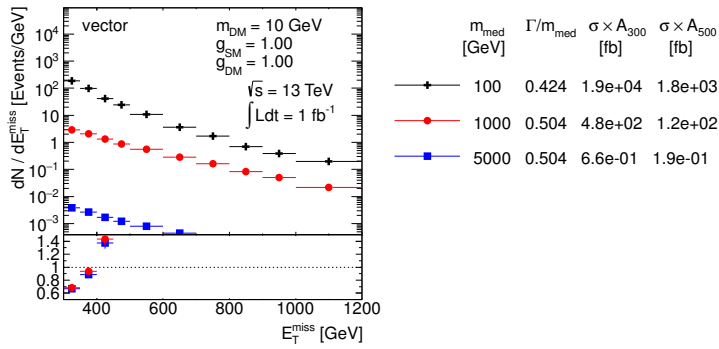| m_{med} [GeV]	Γ/m_{med}	$\sigma \times A_{300}$ [fb]	$\sigma \times A_{500}$ [fb]
100	0.424	1.9e+04	1.8e+03
1000	0.504	4.8e+02	1.2e+02
5000	0.504	6.6e-01	1.9e-01

Figure 2.6: Scan over mediator mass
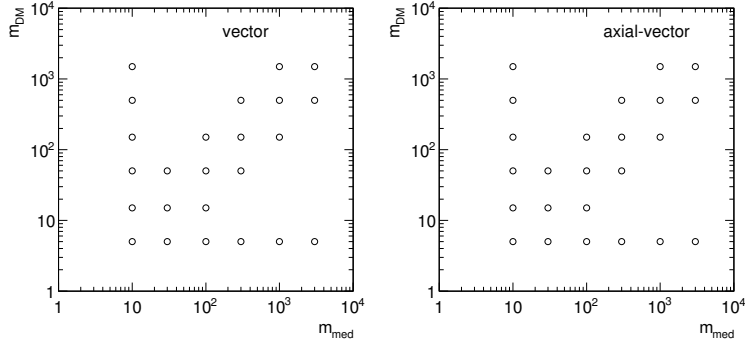
Figure 2.7: Parameter grid
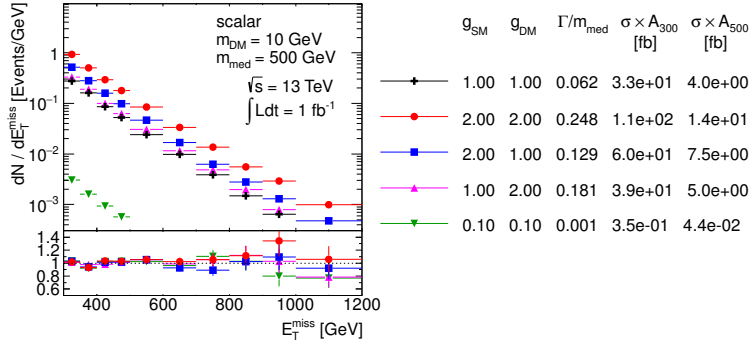
Figure 2.8: Scan over couplings

g_{SM}	g_{DM}	Γ/m_{med}	$\sigma \times A_{300}$ [fb]	$\sigma \times A_{500}$ [fb]
1.00	1.00	0.062	3.3e+01	4.0e+00
2.00	2.00	0.248	1.1e+02	1.4e+01
2.00	1.00	0.129	6.0e+01	7.5e+00
1.00	2.00	0.181	3.9e+01	5.0e+00
0.10	0.10	0.001	3.5e-01	4.4e-02
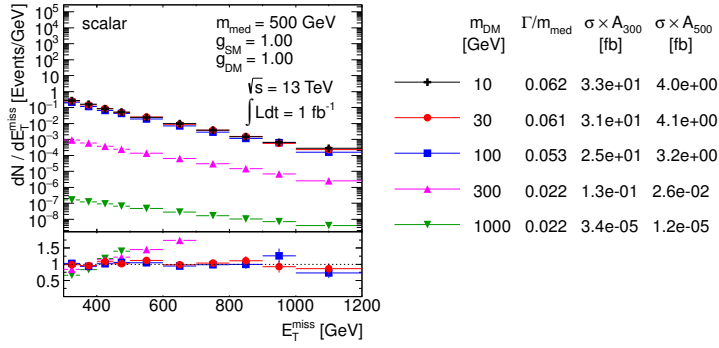
Figure 2.9: Scan over Dark Matter mass

m_{DM} [GeV]	Γ/m_{med}	$\sigma \times A_{300}$ [fb]	$\sigma \times A_{500}$ [fb]
10	0.062	3.3e+01	4.0e+00
30	0.061	3.1e+01	4.1e+00
100	0.053	2.5e+01	3.2e+00
300	0.022	1.3e-01	2.6e-02
1000	0.022	3.4e-05	1.2e-05
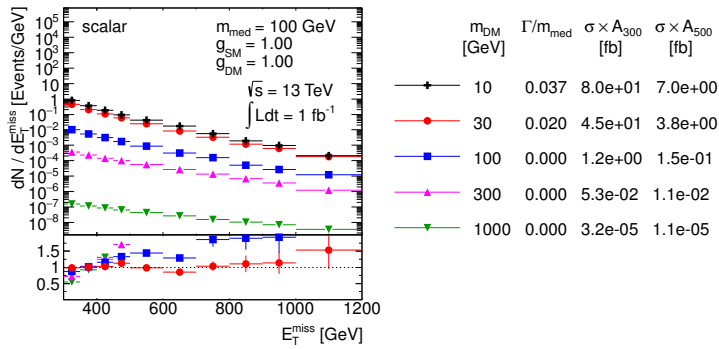
Figure 2.10: Scan over Dark Matter mass

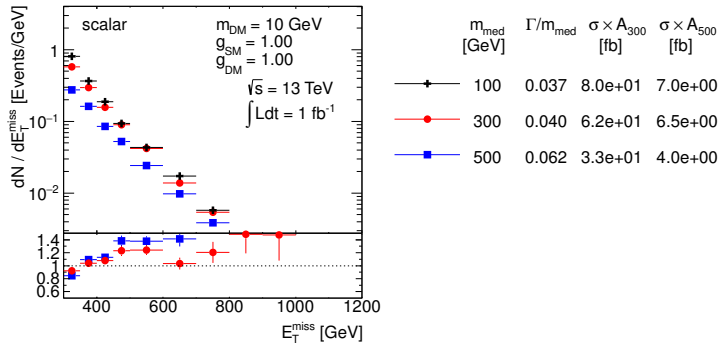| m_{DM} [GeV]	Γ/m_{med}	$\sigma \times A_{300}$ [fb]	$\sigma \times A_{500}$ [fb]
10	0.037	8.0e+01	7.0e+00
30	0.020	4.5e+01	3.8e+00
100	0.000	1.2e+00	1.5e-01
300	0.000	5.3e-02	1.1e-02
1000	0.000	3.2e-05	1.1e-05

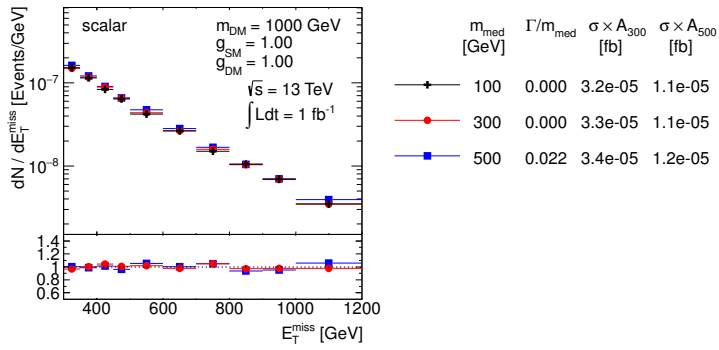Figure 2.11: Scan over mediator mass
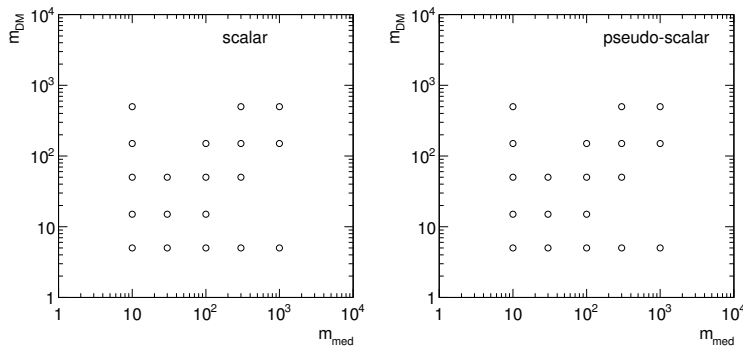

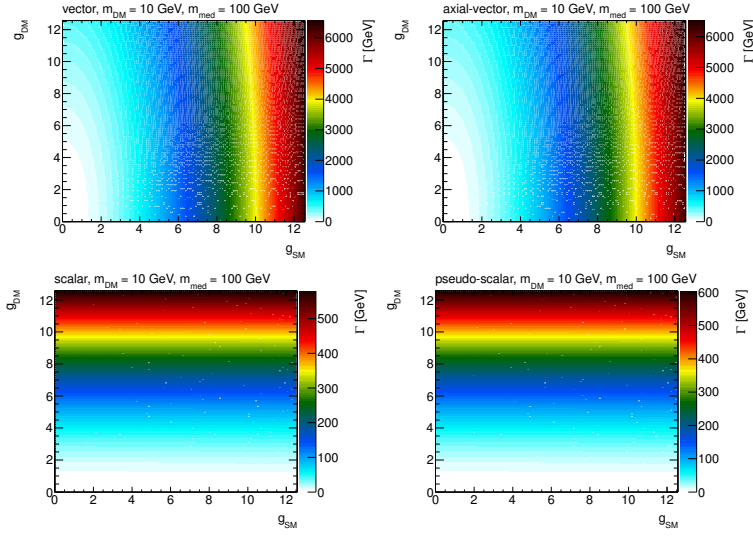Figure 2.12: Scan over mediator mass

Figure 2.13: Parameter grid
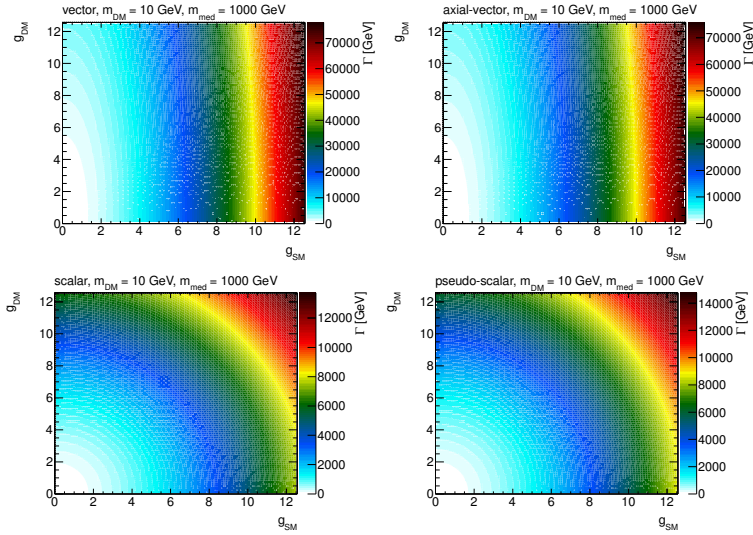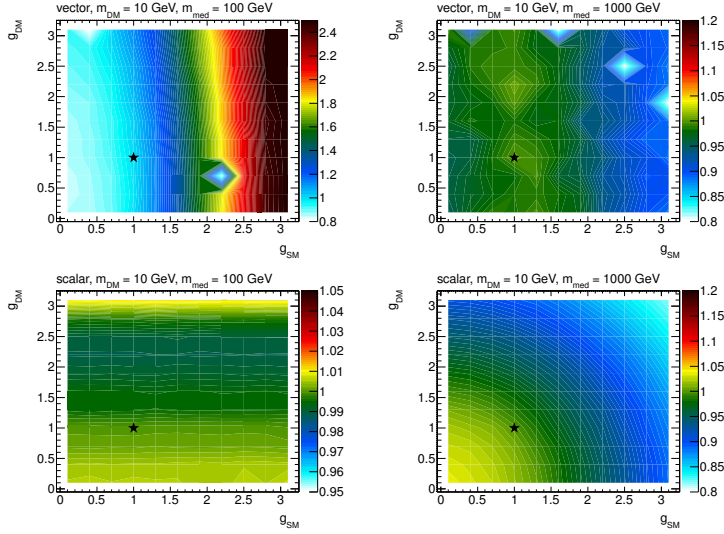
Figure 2.14: Mediator width

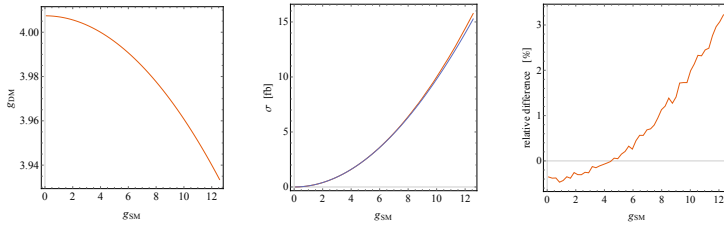
Figure 2.15: Mediator width

Figure 2.16: Scaling on-shell

Figure 2.17: Scaling along the lines of constnat width

Under the assumption that χ is a Standard Model (SM) singlet, the mediating particle, labeled ϕ, is necessarily charged and coloured. This model is parallel to, and partially motivated by, the squark of the MSSM, but in this case the χ is chosen to be Dirac. Following the example of Ref. [PVZ14], the interaction Lagrangian is written as

$$\mathcal{L}_{\text{int}} = g \sum_{i=1,2,3} (\phi_L^i \bar{Q}_L^i + \phi_{uR}^i \bar{u}_R^i + \phi_{dR}^i \bar{d}_R^i)\chi \qquad (2.8)$$

(Note: [PVZ14] uses only i = 1,2, but I think it's fine to extend this to 3 here.) where Q_L^i, u_R^i and d_R^i are the SM quarks and ϕ_L^i, ϕ_{uR}^i and ϕ_{dR}^i are the corresponding mediators, which (unlike the s-channel mediators) must be heavier than χ. These mediators have SM gauge representations under $(SU(3), SU(2))_Y$ of $(3,2)_{-1/6}$, $(3,1)_{2/3}$ and $(3,1)_{-1/3}$ respectively. Variations of the model previously studied include coupling to the left-handed quarks only [CEHL14, BDSJ$^+$14], to the ϕ_{uR}^i [DNRT13] or ϕ_{dR}^i [PVZ14, A$^+$14b], or some combination [BB13, AWZ14].

Minimal Flavour Violation (MFV) requires that the mediator masses for each flavour be equal; the same logic also applies to the

couplings g. The available parameters are then

$$\{m_\chi, M_\phi, g\}. \tag{2.9}$$

In practice, the third mediator mass and coupling could be separated from the other two, if higher order corrections to the MFV prediction arise due to the large top Yukawa coupling – a common variation is then to define this split between the first two generations and the third, so the parameters are extended to

$$\{m_\chi, M_{\phi_{1,2}}, M_{\phi_3}, g_{1,2}, g_3\}. \tag{2.10}$$

The width of each mediator is expressed, using the example of decay to an up quark, as

$$\Gamma(\phi_i \rightarrow \bar{u}_i \chi) = \frac{g_i^2}{16\pi M_{\phi_i}^3} (M_{\phi_i}^2 - m_{u_i}^2 - m_\chi^2)$$
$$\times \sqrt{M_{\phi_i}^4 + m_{u_i}^4 + m_\chi^4 - 2M_{\phi_i}^2 m_{u_i}^2 - 2M_{\phi_i}^2 m_\chi^2 - 2m_{u_i}^2 m_\chi^2}, \tag{2.11}$$

this reduces to

$$\frac{g_i^2 M_{\phi_i}}{16\pi} \left(1 - \frac{m_\chi^2}{M_{\phi_i}^2}\right)^2 \tag{2.12}$$

in the limit $M_{\phi_i}, m_\chi \gg m_{u_i}$.

An interesting point of difference with the s-channel simplified models is that the mediator can radiate a SM object, such as a jet or gauge boson, thus providing three separate mono-X diagrams which must be considered together in calculations. This model can also give a signal in the di-jet + MET channel when, for example, the χ is exchanged in the t-channel and the resulting ϕ pair each decay to a jet + χ.

2.2   Scalar models

2.3   Spin-0 Mediators

One of the most straightforward Simplified Models to contemplate is connecting dark matter to the visible sector through a spin-0 mediator, either a scalar or a pseudoscalar. Such models have intriguing connections with Higgs physics, and can be viewed as generalizations of the Higgs Portal to dark matter. The most general scalar

mediator models will of course have renormalizable interactions
between the Standard Model Higgs and the new scalar ϕ or pseu-
doscalar A, as well as ϕ/A interactions with electroweak gauge
bosons. Such interactions are model-dependent, often subject to
constraints from electroweak-precision tests, and would suggest spe-
cialized searches which cannot be generalized to a broad class of
models (unlike the $\not{E}_T$ plus jets searches, for example). As a result,
for this class of simplified models with spin-0 mediators, we suggest
focusing exclusively on the couplings to fermions, and induced cou-
plings to gluons, leaving the possibilities opened up by couplings to
the electroweak sector to the discussion of Higgs Portal dark matter.

In our benchmark models, we will consider two possibilities for
the CP assignment of the mediator (scalar and pseudoscalar), and
two spin-assignments for the dark matter itself (scalar and fermionic).
We provide here the Simplified Model for the interactions of the me-
diator, the relevant equations for scattering with nucleons and self-
annihilation, and a discussion of some important issues in simulating
events at the LHC. Throughout, we will assume Minimal Flavor Vi-
olation (MFV) for the couplings of the mediators to Standard Model
fermions.

2.3.1   *Fermionic Dark Matter*

Assuming dark matter is a fermion χ who's interactions with the
Standard Model proceed only through a scalar ϕ or pseudoscalar a,
the most general Lagrangian at tree-level are

$$\mathcal{L}_{\text{fermion},\phi} = \mathcal{L}_{\text{SM}} + i\bar{\chi}\not{\partial}\chi + m_\chi\bar{\chi}\chi + |\partial_\mu\phi|^2 + \frac{1}{2}m_\phi^2\phi^2 + g_\chi\phi\bar{\chi}\chi + \sum_f \frac{g_v y_f}{\sqrt{2}}\phi\bar{f}f \quad (2.13)$$

$$\mathcal{L}_{\text{fermion},a} = \mathcal{L}_{\text{SM}} + i\bar{\chi}\not{\partial}\chi + m_\chi\bar{\chi}\chi + |\partial_\mu a|^2 + \frac{1}{2}m_a^2 a^2 + ig_\chi a\bar{\chi}\gamma^5\chi + \sum_f i\frac{g_v y_f}{\sqrt{2}}a\bar{f}\gamma^5 f \quad (2.14)$$

Here, we have made several simplifying assumptions. First, we as-
sume that the coupling to visible-sector fermions is MFV, and propor-
tional to a single universal coupling g_v. Thus, the coupling of ϕ or a
to any flavor of fermion f is set by $g_v \times y_f$, where y_f is the Standard
Model yukawa $y_f = \sqrt{2}m_f/v$.[1] It is not hard to imagine scenar-
ios that still possess the positive qualities of the MFV assumption
but have non-universal g_v; for example, couplings only to up-type
quarks, or only to leptons. We do not single out any of these op-
tions here in our benchmark models, but remind the reader that it
is desirable to have experimental constraints sensitive to couplings
to different flavors of fermions. Similarly, since there is no "MFV"
motivation for the structure of dark matter-mediator couplings in the
dark sector, and it is of course not known whether the dark matter

[1] This normalization for the yukawas
assumes $v = 246$ GeV and $y_t \sim 1$.

mass m_χ is set by only by the Higgs vev v (indeed this would seem to be somewhat unlikely, given the direct detection constraints on dark matter as containing a pure $SU(2)_L$ doublet) we parametrize the dark matter-mediator coupling by g_χ, rather than by some number times a yukawa coupling proportional to m_χ.

Finally, the most general Lagrangians including new scalars or pseudoscalars should have a potential V containing possible interactions with the Higgs h. As stated in the introduction, we choose to take a more minimal set of possible interactions, and leave discussions of the Higgs interactions to the sections on the Higgs Portal.

Given the Lagrangians in Eqs. (2.13) and 2.14, the low-energy Lagrangian will develop loop-level couplings between the mediator ϕ/a and gluons and photons. This proceeds through loops exactly analogous to the loop-level couplings between the Higgs and gluons and photons. Due to our MFV assumption, as with Higgs physics, the top quark loop will dominate, with the bottom quark playing a minor role. Ignoring all couplings except those to the top, the induced couplings to *on-shell* external gluons and photons are

$$\mathcal{L}_{\text{loop},\phi} = \frac{\alpha_S}{8\pi}\frac{gv y_t}{v}f_\phi\left(\frac{4m_t^2}{m_\phi^2}\right)\phi G^{a,\mu\nu}G_{\mu\nu}^a + \frac{\alpha}{8\pi}\left(N_c Q_t^2\right)\frac{gv y_t}{v}f_\phi\left(\frac{4m_t^2}{m_\phi^2}\right)\phi F^{\mu\nu}F_{\mu\nu} \quad (2.15)$$

$$\mathcal{L}_{\text{loop},a} = \frac{\alpha_S}{4\pi}\frac{gv y_t}{v}f_a\left(\frac{4m_t^2}{m_\phi^2}\right)a G^{a,\mu\nu}\tilde{G}_{\mu\nu}^a + \frac{\alpha}{4\pi}\left(N_c Q_t^2\right)\frac{gv y_t}{v}f_a\left(\frac{4m_t^2}{m_\phi^2}\right)a F^{\mu\nu}\tilde{F}_{\mu\nu} \quad (2.16)$$

where α_S and α are the QCD and QED fine-structure constants, $N_c = 3$ is the number of quark colors, $Q_t = 2/3$ is the top-quark charge, and the loop integrals are

$$f_\phi(\tau) = \begin{cases} \tau\left(1 + (1-\tau)\left[\arcsin\frac{1}{\sqrt{\tau}}\right]^2\right), & \tau < 1, \\ \tau\left(1 + (1-\tau)\left(-\frac{1}{4}\right)\left[\ln\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2\right), & \tau > 1, \end{cases} \quad (2.17)$$

$$f_a(\tau) = \begin{cases} \tau\left[\arcsin\frac{1}{\sqrt{\tau}}\right]^2, & \tau < 1, \\ \tau\left(-\frac{1}{4}\right)\left[\ln\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2, & \tau > 1. \end{cases} \quad (2.18)$$

It is important to remember the values of the loop-induced couplings shown here are correct only in the limit of on-shell external gauge bosons, and where the internal momenta in the loops are small compared to the top mass. They should not be used in Monte Carlo even-generation with gluon jets that have large p_T when compared to m_t, or when the mediators themselves have high p_T. The tree-level couplings of scalar and pseudoscalar mediators to quarks can be used in event-generation through programs like `MadGraph5` as with any other new physics model, and model files are available for these purposes. Correct event generation of scalars/pseudoscalar mediators being produced primarily through the gluon couplings must use more specialized event

generation routines, capable of resolving the loop. Such codes include `MCFM` and `Sherpa`, but are not as yet ready for out-of-the-box use in the same manner as `MadGraph`.

These Simplified Models have four free parameters: the universal coupling g_v, the dark coupling g_χ, the dark matter mass m_χ, and the mediator mass m_ϕ or m_a. From this, all phenomenology can be calculated. However, one of the critical derived quantities, the mediator width, deserves special discussion. Under the minimal model, the widths for the mediators are given by:

$$
\begin{aligned}
\Gamma_\phi \;=\; & \sum_f N_C \frac{y_f^2 g_v^2 m_\phi}{16\pi} \left(1 - \frac{4m_f^2}{m_\phi^2}\right)^{3/2} + \frac{g_\chi^2 m_\phi}{8\pi} \left(1 - \frac{4m_\chi^2}{m_\phi^2}\right)^{3/2} \quad (2.19)\\
& + \frac{\alpha_S^2 y_t^2 g_v^2 m_\phi^3}{32\pi^3 v^2} \left| f_\phi\left(\frac{4m_t^2}{m_\phi^2}\right)\right|^2 + \frac{\alpha^2 y_t^2 g_v^2 m_\phi^3}{16 \times 9\pi^3 v^2} \left| f_\phi\left(\frac{4m_t^2}{m_\phi^2}\right)\right|^2 \\[2mm]
\Gamma_a \;=\; & \sum_f N_C \frac{y_f^2 g_v^2 m_a}{16\pi} \left(1 - \frac{4m_f^2}{m_a^2}\right)^{1/2} + \frac{g_\chi^2 m_a}{8\pi} \left(1 - \frac{4m_\chi^2}{m_a^2}\right)^{1/2} \quad (2.20)\\
& + \frac{\alpha_S^2 y_t^2 g_v^2 m_a^3}{8\pi^3 v^2} \left| f_a\left(\frac{4m_t^2}{m_\phi^2}\right)\right|^2 + \frac{\alpha^2 y_t^2 g_v^2 m_a^3}{4 \times 9\pi^3 v^2} \left| f_a\left(\frac{4m_t^2}{m_a^2}\right)\right|^2
\end{aligned}
$$

Here, the first term in each width corresponds to the decay into Standard Model fermions (the sum runs over all kinematically available fermions, $N_C = 3$ for quarks and $N_C = 1$ for leptons). The second term is the decay into dark matter (assuming that this decay is kinematically allowed), and the last two terms correspond to decay into gluons and photon pairs. The factor of 2 between the decay into Standard Model fermions and into dark matter is a result of our choice of normalization of the yukawa couplings.

In colliders, if the mediator is produced on-shell, as is the primary mode of dark matter production when $m_\chi < m_{\phi/a}/2$ and $m_{\phi/a} \ll \sqrt{\hat{s}}$ (where $\sqrt{\hat{s}}$ is some characteristic c.o.m. at the collider in question), the cross section of dark matter production will be proportional to the branching ratio into dark matter. The total production of the mediator will go as g_v^2, and the decay into invisible dark matter will be $\propto g_\chi^2/\Gamma_{\phi/a}$, with the appropriate kinematic factors. This confounds the easy factorization of limits on the four-dimensional parameter space, since while the total cross section will have an overall dependence on the product $g_\chi^2 \times g_v^2$, it will also depend on $\Gamma_{\phi/a}$, which even in the minimal model depends on the sum of g_χ^2 and g_v^2 (with kinematic factors inserted).

In addition, as this is a Simplified Model, it is possible that the mediator can decay into additional states present in a full theory that we have neglected. For example, the mediator could decay into additional new charged particles which themselves eventually decay into dark matter, but with additional visible particles that would

move the event out of the selection criteria of monojets or similar missing energy searches. Thus, the widths calculated in Eqs. (2.19) and (2.20) are lower bounds on the total width.

As a result of these issues, the width of the mediator is often treated as an independent variable in Simplified Models with s-channel production of dark matter. Fortunately, for on-shell production, the effect of changing the width is only a rescaling of the total event rate assuming that $\Gamma_{\phi/a} < m_{\phi/a}$ [BFG15], which is a necessary condition for a valid weakly coupled theory. As a result, changing the width just rescales the total event rate at colliders. In the case when the dark matter is produced through an off-shell mediator, the width is not relevant. We therefore recommend that experimental and theoretical bounds on s-channel models make the assumption that the width is minimal, set by Eqs. (2.19) or (2.20), and treat it as a dependent quantity, rather than an additional free parameter.

Furthermore, as we are dealing with a 4D parameter space, it is necessary to consider how to reduce the parameter space to display results which can be compared between experiments and with theory. Clearly, the dependence of the constraints from experiments on the masses m_χ and $m_{\phi/a}$ cannot be suppressed, as the bounds will have non-trivial kinematic dependences on the masses. This leaves the couplings g_χ and g_v. The most straightforward assumption to make is to set $g_\chi = g_v$. This has the somewhat unfortunate result of making certain types of experimental results appear more effective than others. For example, with $g_\chi = g_v$, we expect the mediator branching ratio to dark matter to completely dominate over the visible channels, unless the top channel is kinematically allowed. This would make resonance searches in visible channels for the mediator appear to be uncompetitive. However, some choice must be made, and setting the two couplings equal to each other is perhaps the simplest.

We now turn to the constraints on these models from non-collider experiments: thermal relic abundances, indirect detection, and direct detection. The first two results can be considered together, as they depend on the same set of annihilation cross sections.

Thermal Cross Sections   The thermally-average annihilation of dark matter through the spin-0 mediators can be calculated from the Simplified Model Eqs. (2.13) and (2.14). The resulting cross sections for annihilation into Standard Model fermions, as a function of the dark

259 matter temperature T are

$$\langle \sigma v \rangle (\chi \bar{\chi} \to \phi^* \to f\bar{f}) \;\; = \;\; N_c \frac{3g_\chi^2 g_v^2 y_f^2 (m_\chi^2 - m_f^2)^{3/2}}{8\pi m_\chi^2 \left[(m_\phi^2 - 4m_\chi^2)^2 + m_\phi^2 \Gamma_\phi^2 \right]} T,$$

$$\langle \sigma v \rangle (\chi \bar{\chi} \to a^* \to f\bar{f}) \;\; = \;\; N_c \frac{g_\chi^2 g_v^2 y_f^2}{4\pi \left[(m_a^2 - 4m_\chi^2)^2 + m_a^2 \Gamma_a^2 \right]} \left[m_\chi^2 \sqrt{1 - \frac{m_f^2}{m_\chi^2}} + \frac{3m_f^2}{4m_\chi \sqrt{1 - \frac{m_f^2}{m_\chi^2}}} T \right].$$

260 Notably, the scalar mediators do not have a temperature-independent
261 contribution their annihilation cross section, while pseudoscalars do.
262 As $T \propto v^2$, where v is the dark matter velocity, there is no velocity-
263 independent annihilation through scalars. As, in the Universe today,
264 $v \lesssim 10^{-3}$, this means there are no non-trivial constraints on dark
265 matter annihilation from indirect detection in the scalar mediator
266 model.
267   The pseudoscalar model, on the other hand, does have relevant
268 constraints from indirect detection. These can be obtained from
269 Eq. 2.21 by setting $T \to 0$, and considering annihilation into the
270 relevant Standard Model channel(s). Most constraints from indirect
271 detection are written in terms of a single annihilation channel, and
272 so the constraints for the full Simplified Model (with multiple anni-
273 hilation channels open) require some modification of the available
274 results. Good estimates can be obtained by considering the most
275 massive fermion into which the dark matter can annihilate (typi-
276 cally the b or t quark), as this will tend to dominate the annihilation
277 cross section. Note that, outside of resonance, the width is relatively
278 unimportant to the indirect detection constraints.

The thermal relic calculation requires the same input cross sections
as the indirect detection. Here, the cross sections are summed over all
kinematically available final states, and can be written parametrically
as

$$\langle \sigma v \rangle = a + bT.$$

The thermal relic abundance of dark matter is then

$$\Omega_\chi h^2 = \frac{1.04 \times 10^9 \text{ GeV}}{m_{\text{Planck}}} \frac{x_f}{\sqrt{g_\star}} \frac{1}{a + b m_\chi x_f^{-1}}, \qquad (2.21)$$

where $x_f \sim 25$ is m_χ over the freeze-out temperature, and g_{star} is the
number of degrees of freedom active at the time of freeze-out. For
reasonable early Universe parameters, the correct relic abundance
occurs when

$$3 \times 10^{-26} \text{ cm}^3/\text{s} = 2.57 \times 10^{-9} \text{ GeV}^{-2} = a + \frac{b m_\chi}{x_f}. \qquad (2.22)$$

279   Keep in mind that these equations require some modification when
280   the dark matter-mediator system is on resonance. Further, recall
281   that we do not know dark matter is a thermal relic, or that the only
282   annihilation process in play in the early Universe is through the
283   mediator. Therefore, while it is appropriate to compare the sensitivity
284   of experimental results to the thermal cross section, this is not the
285   only range of parameters of theoretical interest.

286   *Direct Detection*   As noted previously, the scalar mediator model has
287   no indirect detection constraints, while the pseudoscalar does. The
288   situation is reversed in direct detection: the pseudoscalar mediator
289   has no velocity- or momentum-unsuppressed interactions with nucle-
290   ons, while the scalar mediator induces a spin-independent scattering
291   cross section. These constraints are very powerful compared to the
292   present collider bounds, especially when $m_\chi > 10$ GeV. As with
293   indirect detection, for weakly coupled theories, the direct detection
294   bounds are relatively independent of the width.
295   For the scalar mediator model, the interaction with direct detection
296   nuclear targets is (to good approximation) isospin-conserving. There-
297   fore, the bound on scattering with nucleons can be applied to either
298   the dark matter-proton or dark matter-neutron cross section, given by

$$\sigma_{\chi-p,n} = \frac{\mu^2}{\pi} f_{p,n}^2 \tag{2.23}$$

$$f_{p,n} = \sum_{q=u,d,s} f_q^{p,n} \frac{m_{p,n}}{m_q} \left(\frac{g_\chi g_v y_q}{\sqrt{2} m_\phi^2} \right) + \frac{2}{27} f_{TG}^{p,n} \sum_{q=c,b,t} \frac{m_{p,n}}{m_q} \left(\frac{g_\chi g_v y_q}{\sqrt{2} m_\phi^2} \right) \tag{2.24}$$

299   where μ is the dark matter-nucleon reduced mass $\mu = (m_\chi m_{p,n})/(m_\chi +$
300    $m_{p,n})$, and the nuclear matrix elements $f_q^{p,n}$ and $f_{TG}^{p,n}$ must be ex-
301   tracted from lattice QCD. For our purposes, the neutron and pro-
302   ton matrix elements are essentially identical. Using the values from
303   Ref. [FHZ10] gives (for both protons and neutrons)

$$f_u = 0.02 \tag{2.25}$$

$$f_d = 0.026 \tag{2.26}$$

$$f_s = 0.118 \tag{2.27}$$

$$f_{TG} = 0.84 \tag{2.28}$$

304   .

305   ## 2.4   *Specific models for signatures with EW bosons*

306   In this Section, we consider models with a photon, a W boson, a
307   Z boson or a Higgs boson in the final state, accompanied by Dark

308 Matter particles that either couple directly to the boson or are medi-
309 ated by a new particle. The experimental signature is identified as
310 *V+MET*.
311   These models are interesting both as extensions of models where
312 the gluon provides the experimentally detectable signature, and as
313 stand-alone models with final states that cannot be generated by the
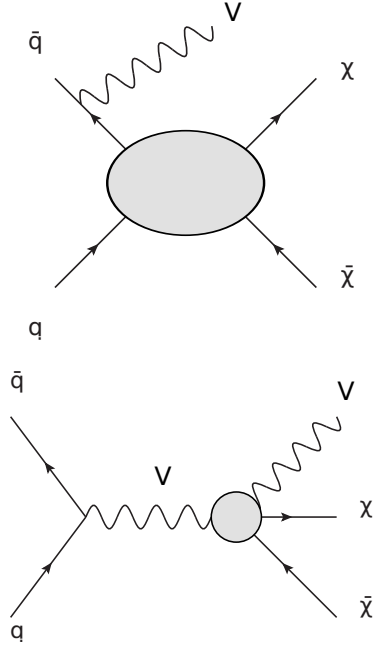314 models in Section 2.1.

Figure 2.18: Sketch of benchmark models including a contact interaction for V+MET searches, adapted from [NCC$^+$14].

315   The models considered can be divided in categories:

316 *Models including a contact operator, where the boson is radiated from the initial state*
317   As depicted in the top diagram of Figure 2.18, these models follow
318   the nomenclature and theory for the EFT benchmarks commonly
319   used by MET+X searches [GIR$^+$10]. These models have been used
320   in past experimental searches [Kha14, Aad14b, K$^+$14, Aad14b,
321   A$^+$14a, Aad14a], and they will not be described here.

322 *Models including a contact operator, where the boson is directly coupled to DM*
323   Shown in the bottom of Figure 2.18, these models allow for a con-
324   tact interaction vertex that directly couples the boson to Dark
325   Matter.

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

329 *V-specific simplified models* These models postulate direct couplings
330   of new mediators to bosons, e.g. they couple the Higgs boson to a

new scalar [CDM+14].

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 [ZBW13], 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 [CDM+14]. However, the presence of photons leptons from W and Z decays and W or Z bosons decaying hadronically allows to reject the background more effectively, making Z/gamma/W+MET searches still worth comparing with searches in the jet+MET final state.

Vector mediator exchanged in the s-channel   The case for searches with W bosons in the final state has so far been strenghtened by the presence of particular choices of couplings between the WIMP and the up and down quarks which enhance W radiation [BT13], in the case of the exchange of a vector mediator in the s-channel. Run-1 searches have considered 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 leads to a large increase in the cross-section of the process, and modifies the spectrum of missing transverse energy or transverse mass used for the searches. The sensitivity of the W+MET search for this benchmark in this case surpasses that of the jet+MET search. However, as shown in Ref. [BCD+15], the cross-section increase is due to the production of longitudinally polarized W bosons, as a consequence of a violation of electroweak gauge symmetries. Unless further particles are introduced (in a fashion similar to the Higgs boson in the Standard Model), choosing a value of $\xi = -1$

for this simplified model will lead to a manifest violation of unitarity at LHC energies. The simplified model with a vector mediator exchanged in the s-channel model can still be considered as a benchmark for searches with a W boson if $\xi = 1$. We leave the study of further models with cross-section enhancements due to different couplings to up and down quarks for studies beyond the early LHC searches covered in this document. **[TODO: Substitute the following sentence with Yang Bai's paragraph]**. An example of such model is the case of both DM and SM Higgs charged under a new U(1)', with a a small mass mixing between SM Z-boson and the new Zprime. This leads to different effective DM couplings to u_L and d_L, proportional to their coupling to the Z boson.

The scan in the parameters that characterize of this model follow what already detailed in Section 2.1.

As in the case of the jet+MET models, the width does not have a significant impact on the kinematic distributions relevant for those searches. An example of the particle-level analysis acceptance using simplified cuts **[TODO: add cuts]** for the photon+MET analysis is shown in Figure 2.19.

Figure 2.19: Analysis acceptance for the photon+MET analysis when varying the mediator width, in the case of a vector mediator exchanged in the $s-$channel

Examples of relevant kinematic distributions for selected benchmark points are shown in Fig. 2.24; leading-order cross-sections for the chosen benchmark points are shown in Table **?? [TODO: Insert table of cross-sections]**.

Colored scalar mediator exchanged in the s-channel   t-channel colored scalar, to be completed...

Model implementation   These models are generated at leading order with MadGraph 2.2.2, and parameter cards can be found on SVN **[TODO: Add SVN location]**. The parton shower is done using Pythia 8, with a matching scale of... **[TODO: To be completed.]**

EFT MODELS WITH DIRECT DM-BOSON COUPLINGS

(a) Missing transverse momentum distribution for the photon+MET final state.

(b) Missing transverse momentum distribution for the leptonic Z+MET final state.

(c) Transverse mass (m_T) for the leptonic W+MET final state.

(d) Fat **[Insert algorithm]** jet mass (m_T) for the the hadronic W+MET final state.

Figure 2.20: Kinematic distributions relevant for searches with W, Z and photons in the final state, for the simplified model with a vector mediator exchanged in the $s-$channel.

A complete list of effective operators with direct DM/boson couplings for Dirac DM, up to dimension 7, can be found in [CHLR13].

Following the notation of [CNS$^+$13], the dimension 5 benchmark models from this category have a Lagrangian that includes terms such as:

$$\frac{m_W^2}{\Lambda_5^3}\ \bar{\chi}\chi\ W^{+\mu}W_\mu^- + \frac{m_Z^2}{2\Lambda_5^3}\ \bar{\chi}\chi\ Z^\mu Z_\mu\ . \qquad (2.29)$$

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. **[TODO: Ask Linda to explain this better than I**

did.]. In these models, a clear relation exists between final states with photons, EW bosons and Higgs boson. **[TODO: see if mono-Higgs studies exist for these operators, include them 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:

$$\frac{1}{\Lambda_{7,S}^3} \, \bar{\chi}\chi \, \sum_i k_i F_i^{\mu\nu} F_{\mu\nu}^i + \frac{1}{\Lambda_{7,S}^3} \, \bar{\chi}\chi \, \sum_i k_i F_i^{\mu\nu} \tilde{F}_{\mu\nu}^i \tag{2.30}$$

The Lagrangian with pseudoscalar coupling includes the following terms:

$$\frac{1}{\Lambda_{7,PS}^3} \, \bar{\chi}\gamma^5\chi \, \sum_i k_i F_i^{\mu\nu} F_{\mu\nu}^i + \frac{1}{\Lambda_{7,PS}^3} \, \bar{\chi}\gamma^5\chi \, \sum_i k_i F_i^{\mu\nu} \tilde{F}_{\mu\nu}^i \tag{2.31}$$

The cut-off scales Λ for the separate terms can be related to operators with different Lorentz structure from Ref. [CHLR13]. Given that they do not lead to substantial differences for collider searches as shown in Figure 2 of Ref. [CNS+13], they have been denoted as $\Lambda_{7,S}$ for the scalar case and $\Lambda_{7,PS}$ for the pseudoscalar case.

The k_i coefficients for the dimension 7 models are related to the couplings of DM to pairs of gauge bosons by gauge invariance:

$$g_{WW} = \frac{2k_2}{s_w^2 \Lambda_7^3} \tag{2.32}$$

$$g_{ZZ} = \frac{1}{4s_w^2 \Lambda_7^3} \left(\frac{k_1 s_w^2}{c_w^2} + \frac{k_2 c_w^2}{s_w^2} \right) \tag{2.33}$$

$$g_{\gamma\gamma} = \frac{1}{4c_w^2} \frac{k_1 + k_2}{\Lambda_7^3} \tag{2.34}$$

$$g_{Z\gamma} = \frac{1}{2s_w c_w \Lambda_7^3} \left(\frac{k_2}{s_w^2} - \frac{k_1}{c_w^2} \right) \tag{2.35}$$

where s_w and c_w are respectively the sine and cosine of the weak mixing angle.

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.

436 The coefficients k_1 and k_2 are related to the coefficients c_1 and
437 c_2 in the equivalent models of Ref. [CHH15] as $k_2 = s_w^2 * c_2$ and
438 $k_1 = c_w^2 * c_1$.

439 **[TODO: Linda will possibly complete/correct this paragraph]**
440 UV completions of such operators where the dominant signature
441 is a single photon or EW boson are possible, for example through
442 the exchange of a W′ or a Z′. They are left as benchmarks for future
443 searches as their implementation may require loop diagrams and
444 need further studies beyond the timescale of this Forum.

445 As shown in Fig. 2.21 kinematics of this model can be approxi-
446 mated by that of a simplified model including a high-mass scalar
447 mediator exchanged in the s-channel. For this reason, the list of
448 benchmark models with direct boson-DM couplings only includes
449 dimension 7 operators. **[TODO: then we need to recommend the**
450 **scalar mediator, but then the sensitivity is very poor wrt monojets**
451 **- however, I still prefer to generate a few (high-mass) simplified**
452 **model points wrt an EFT if given the choice.]**

Figure 2.21: Comparison of the missing transverse momentum for the simplified model where a scalar mediator is exchanged in the s-channel and the model including a dimension-5 scalar contact operator, in the leptonic Z+MET final state

453 The kinematic distributions for dimension-7 scalar and pseu-
454 doscalar operators only shows small differences, as shown in Fig. 2.22.

Figure 2.22: Comparison of the missing transverse momentum for the scalar and pseudoscalar operators with direct interaction between DM and photon, in the photon+MET final state

455 Similarly, the differences in kinematics for the various signatures
456 are negligible when changing the coefficients k_1 and k_2, as shown in
457 Figure **??**. Only the case $k_1 = k_2 = 1$ is generated as benchmark; other

458 cases are left for reinterpretation as they will only need a rescaling of
459 the cross-sections shown in Table **?? [TODO: add tables with cross**
460 **sections]** for the various Dark Matter mass points considered.

(a) Missing transverse momentum distribution for the photon+MET final state.

Figure 2.23: Kinematic distributions relevant for searches with W, Z and photons in the final state, for for the scalar and pseudoscalar operators representing direct interactions between DM and bosons.

(b) Missing transverse momentum distribution for the leptonic Z+MET final state.

(c) Transverse mass (m_T) for the leptonic W+MET final state.

461 Examples of relevant kinematic distributions for selected bench-
462 mark points are shown in Fig. 2.24.

463 *Specific simplified models* Mono-Higgs, to be completed...

464 *2.5 Specific models for signatures with heavy flavor quarks*

465 *2.6 SUSY-inspired simplified models*

(a) Missing transverse momentum distribution for the photon+MET final state.

Figure 2.24: Kinematic distributions relevant for searches with W, Z and photons in the final state, for the simplified model with a vector mediator exchanged in the $s-$channel.

(b) Missing transverse momentum distribution for the leptonic Z+MET final state.

(c) Transverse mass (m_T) for the leptonic W+MET final state.

(d) Fat **[Insert algorithm]** jet mass (m_T) for the the hadronic W+MET final state.

3

Validity of EFT approach

Effective Field Theories (EFTs) are an extremely useful tool for DM searches at the LHC. Given the current lack of indications about the nature of the DM particle and its interactions, a model independent interpretation of the collider bounds appears mandatory, especially in complementarity with the reinterpretation of the exclusion limits within a choice of simplified models, which cannot exhaust the set of possible completions of an effective Lagrangian. However EFTs must be used with caution at LHC energies, where the energy scale of the interaction is at a scale where the EFT approximation can no longer be assumed to be valid. Here we summarise some methods that can be used to ensure the validity of the EFT approximation. These methods are described in detail in Refs. [BDSMR14**?** , BDSJ$^+$14, A$^+$15, RWZ15].

*Outline of the procedure described in Refs. [**?** A$^+$15]*

For a tree-level interaction between DM and the Standard Model (SM) via some mediator with mass M, the EFT approximation corresponds to expanding the propagator in powers of Q_{tr}^2/M^2, truncating at lowest order, and combining the remaining parameters into a single parameter M_* (also called Λ). For an example scenario with a Z'-type mediator (leading to some combination of operators D5 to D8 in the EFT limit) this corresponds to setting

$$\frac{g_{\text{DM}} g_q}{Q_{\text{tr}}^2 - M^2} = -\frac{g_{\text{DM}} g_q}{M^2}\left(1 + \frac{Q_{\text{tr}}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\text{tr}}^4}{M^4}\right)\right) \simeq -\frac{1}{M_*^2}, \qquad (3.1)$$

where Q_{tr} is the momentum carried by the mediator, and g_{DM}, g_q are the DM-mediator and quark-mediator couplings respectively. Similar expressions exist for other operators. Clearly the condition that must be satisfied for this approximation to be valid is that $Q_{\text{tr}}^2 < M^2 = g_{\text{DM}} g_q M_*^2$.

We can use this condition to enforce the validity of the EFT approximation by restricting the signal (after the imposition of the cuts

of the analysis) to events for which $Q_{\mathrm{tr}}^2 < M^2$. This truncated signal can then be used to derive the new, truncated limit on M_* as a function of $(m_{\mathrm{DM}}, g_{\mathrm{DM}}g_q)$.

For the example D5-like operator, $\sigma \propto M_*^{-4}$, and so there is a simple rule for converting a rescaled cross section into a rescaled constraint on M_* if the original limit is based on a simple cut-and-count procedure. Defining $\sigma_{\mathrm{EFT}}^{\mathrm{cut}}$ as the cross section truncated such that all events pass the condition $\sqrt{g_{\mathrm{DM}}g_q}M_*^{\mathrm{rescaled}} > Q_{\mathrm{tr}}$, we have

$$M_*^{\mathrm{rescaled}} = \left(\frac{\sigma_{\mathrm{EFT}}}{\sigma_{\mathrm{EFT}}^{\mathrm{cut}}}\right)^{1/4} M_*^{\mathrm{original}}, \qquad (3.2)$$

which can be solved for M_*^{rescaled} via either iteration or a scan (note that M_*^{rescaled} appears on both the LHS and RHS of the equation). Similar relations exist for a given UV completion of each operator. The details and application of this procedure to ATLAS results can be found in Ref. [A+15] for a range of operators. Since this method uses the physical couplings and energy scale Q_{tr}, it gives the strongest possible constraints in the EFT limit while remaining robust by ensuring the validity of the EFT approximation.

Outline of the procedure described in Ref. [RWZ15]

In [RWZ15] a procedure to extract model independent and consistent bounds within the EFT is described. This procedure can be applied to any effective Lagrangian describing the interactions between the DM and the SM, and provides limits that can be directly reinterpreted in any completion of the EFT.

The range of applicability of the EFT is defined by a mass scale M_{cut}, a parameter which marks the upper limit of the range of energy scales at which the EFT can be used reliably, independently of the particular completion of the model. Regardless of the details of the full theory, the energy scale probing the validity of the EFT is less than or equal to the centre-of-mass energy E_{cm}, the total invariant mass of the hard final states of the reaction. Therefore, the condition ensuring the validity of the EFT is, by definition of M_{cut},

$$E_{\mathrm{cm}} < M_{\mathrm{cut}}. \qquad (3.3)$$

For example, in the specific case of a tree level mediation with a single mediator, M_{cut} can be interpreted as the mass of that mediator.

There are then at least three free parameters describing an EFT: the DM mass m_{DM}, the scale M_* of the interaction, and the cutoff scale M_{cut}.

We can use the same technique as above to restrict the signal to the events for which $E_{\mathrm{cm}} < M_{\mathrm{cut}}$, using only these events to derive the exclusion limits on M_* as a function of $(m_{\mathrm{DM}}, M_{\mathrm{cut}})$. We can also define an *effective coupling strength* $M_{\mathrm{cut}} = g_* M_*$, where g_* is a free parameter that substitutes the parameter M_{cut}, and therefore derive exclusions on M_* as a function of (m_{DM}, g_*). This allows us to see how much of the theoretically allowed parameter space has been actually tested and how much is still unexplored; For example, in the Z'-type model considered above, g_* is equal to $\sqrt{g_{\mathrm{DM}} g_q}$. The resulting plots are shown in [RWZ15] for a particular effective operator.

The advantage of this procedure is that the obtained bounds can be directly and easily recast in any completion of the EFT, by computing the parameters M_*, M_{cut} in the full model as functions of the parameters of the complete theory. On the other hand, the resulting limits will be weaker than those obtained using Q_{tr} and a specific UV completion.

4
Recommendations for expressing collider constraints

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