ATLAS+CMS DARK MATTER FORUM RECOMMENDATIONS

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

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Introduction

This document presents recommendations for the MC production and parameter scans for the various simplified models.

What is the motivation for this report?

First, the physics is compelling. Measurements at the energy frontier can make quantitative statements about dark matter.

Second, in Run-1 at the LHC, there was confusion in the community over the interpretation of the data.

Third, there are reasons to strive for uniformity in interpretation in the different experiments. This will ultimately aid in the combination of data, but also facilitates cross checks of results.

What is the format of this report?

First, it describes the signatures and models of interest for dark matter searches.

Secondly, it provides information on the tools to be used to simulate signals.

Finally, it makes a recommendation on a scan of parameters within those models based on supporting material.

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Overall choices for simplified models

General topics:

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

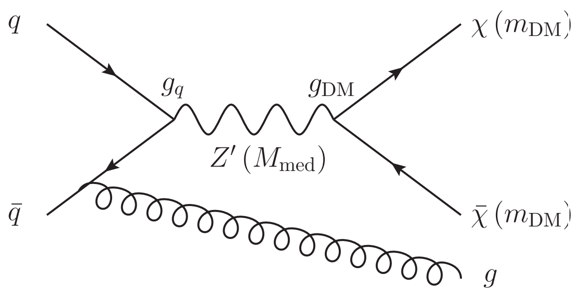


Figure 3.1: Representative Feynman diagram showing the pair production of dark matter particles in association with a parton from the initial state via a vector or axial-vector mediator. The cross section and kinematics depend upon the mediator and dark matter masses, and the mediator couplings to dark matter and quarks respectively: $(M_{\rm med}, m_{\rm DM}, g_{\rm DM}, g_{\rm q})$.

3

Recommended models for all MET+X analyses

3.1 Vector and axial vector mediator, s-channel exchange

A simple extension of the Standard Model (SM) is an additional $U(1)$ gauge symmetry, where a dark matter (DM) candidate particle has charges only under this new group. Assuming that some SM particles are also charged under this group, then a new vector boson can mediate interactions between the SM and DM.

We consider the case of a DM particle that is a Dirac fermion and where the production proceeds via the exchange of a spin-1 mediator in the s-channel. We consider vector and axial-vector couplings between the spin-1 mediator and SM and DM fields, with the corresponding interaction Lagrangians:

$$\mathcal{L}_{\rm vector} = g_{\rm q} \sum_{q=udscbt} Z'_\mu \bar{q} \gamma^\mu q + g_{\rm DM} Z'_\mu \bar{\chi} \gamma^\mu \chi \tag{3.1}$$

$$\mathcal{L}_{\rm axial-vector} = g_{\rm q} \sum_{q=udscbt} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_{\rm DM} Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi. \tag{3.2}$$

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.

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:

$$\Gamma^{V/A}_{\text{min}} = \Gamma^{V/A}_{\bar{\chi}\chi} + \sum_q \Gamma^{V/A}_{\bar{q}q}. \tag{3.3}$$

The leading order expressions for the partial widths are:

$$\Gamma^{\text{V}}_{\bar{\chi}\chi} = \frac{g^2_{\text{DM}} M_{\text{med}}}{12\pi}\left(1 + \frac{2m^2_{\text{DM}}}{M^2_{\text{med}}}\right)\beta_{DM}\theta(M_{\text{med}} - 2m_{\text{DM}}) \tag{3.4}$$

$$\Gamma^{\text{V}}_{\bar{q}q} = \frac{3g^2_{\text{q}} M_{\text{med}}}{12\pi}\left(1 + \frac{2m^2_q}{M^2_{\text{med}}}\right)\beta_q\theta(M_{\text{med}} - 2m_q) \tag{3.5}$$

$$\Gamma^{\text{A}}_{\bar{\chi}\chi} = \frac{g^2_{\text{DM}} M_{\text{med}}}{12\pi}\beta^{3/2}_{DM}\theta(M_{\text{med}} - 2m_{\text{DM}}) \tag{3.6}$$

$$\Gamma^{\text{A}}_{\bar{q}q} = \frac{3g^2_{\text{q}} M_{\text{med}}}{12\pi}\beta^{3/2}_q\theta(M_{\text{med}} - 2m_q)\ , \tag{3.7}$$

$\theta(x)$ denotes the Heaviside step function, and $\beta_f = \sqrt{1 - \frac{4m^2_f}{M^2_{\text{med}}}}$ is the velocity of the fermion f in the mediator rest frame. Note the color factor 3 in the quark terms. Figure 3.2 shows the minimal width as a function of mediator mass for both vector and axial-vector mediators assuming g_{q} =g_{DM} =1. With this choice of the couplings, the dominant contribution to the minimal width comes from the quarks due to the color factor enhancement and the large number of them.

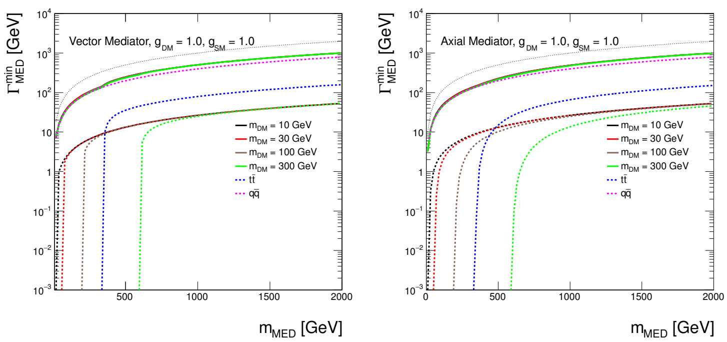


Figure 3.2: Minimal width as a function of mediator mass for vector and axial-vector mediator assuming couplings of 1. The total width is shown as solid lines for Dark Matter masses of 10 GeV, 30 GeV, 100 GeV and 300 GeV in black, red, brown and green, respectively. The individual contributions from Dark Matter are indicated by dotted lines with the same colors. The contribution from all quarks but top is shown as magenta dotted line and the contribution from top quarks only is illustrated by the dotted blue line. The dotted black line shows the extreme case $\Gamma_{\text{min}} = M_{\text{med}}$.

The simplified models described here have four free parameters: mediator mass M_{med}, Dark Matter mass m_{DM}, coupling of the mediator to quarks g_{q} and coupling of the mediator to Dark Matter g_{DM}. In order to determine an optimal choice of the parameter grid for presentation of the early Run-2 results, dependencies of the kinematic quantities and cross sections on the individual parameters need to be studied. The following paragraphs list the main observations from the scans over the parameters that support the final proposal for the parameter grid.

Scan over the couplings Figure 3.3 reveals there are no differences in the shape of the $\not{E}_T$ distribution among the samples where the pair of 10 GeV Dark Matter particles are produced on-shell from the mediator of 1 TeV, generated with different choice of the coupling strength. The considered coupling values range from 0.1 to 1.45, where the latter value approximates the maximum allowed coupling value, holding $g_q = g_{DM}$, such that $\Gamma_{min} < M_{med}$. Based on similar plots for different choices of mediator and Dark Matter masses, it is concluded that the shapes of kinematic distributions are not altered either for the on-shell Dark Matter production where $M_{med} > 2m_{DM}$, or for the off-shell Dark Matter production where $M_{med} < 2m_{DM}$. Only the cross sections change. Differences in kinematic distributions are expected only close to the transition region where both on-shell and off-shell regimes mix.

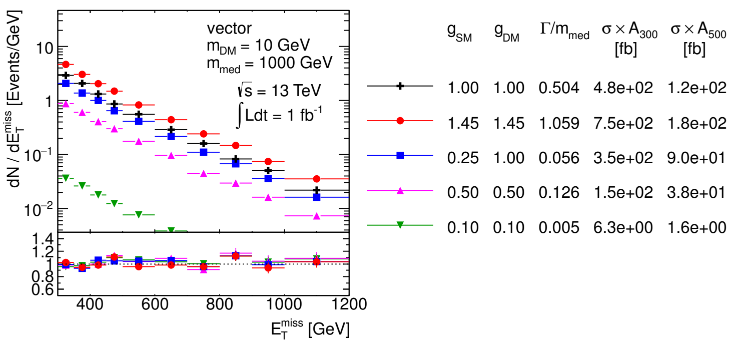


Figure 3.3: Scan over couplings. The $\not{E}_T$ distribution is compared for the vector mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not{E}_T > 300\,\text{GeV}$ and $\not{E}_T > 500\,\text{GeV}$ cut, respectively.

The only situation requiring a more careful treatment is the case of extremely heavy and narrow mediators, which can arise for small coupling strengths. Upon close examination, it was determined that this case is not peculiar. However, the complete story is a cautionary tale about understanding the details of tools applied. Figure 3.4 suggests a change in the shape of the $\not{E}_T$ distribution for 5 TeV mediator once Γ_{min}/M_{med} gets down to the order of percent or below. This, however, does not come from physics, but is an artifact of the generator implementation, where a cutoff for the regions far away from the mediator mass is often used. This is illustrated in Fig. 3.5 showing the invariant mass of the Dark Matter pair in the samples generated for 7 TeV mediator with different coupling strength. In all cases, it is expected to observe a peak around the mediator mass with a tail extending to $m_{\bar{\chi}\chi} \to 0$, significantly enhanced by parton distribution functions at low Bjorken x. For coupling strength 1 and 3, the massive enhancement at $m_{\bar{\chi}\chi} \to 0$ implies the resonant production at $m_{\bar{\chi}\chi} = 7\,\text{TeV}$ is statistically suppressed such that barely any events are generated there. However, for narrower mediators with couplings below 1, the peak around 7 TeV is clearly visible in the generated sample and the dominant tail at $m_{\bar{\chi}\chi} \to 0$ is artificially cut off, leading to unphysical cross section predictions and kinematic shapes. This explains why the sample with the narrowest mediator in Fig. 3.4 is heavily suppressed in terms of production cross section and also gives different $\not{E}_T$ shape. In general, for such extreme parameter choices the EFT model should give the correct answer. **[TODO: add results of ongoing study.]**

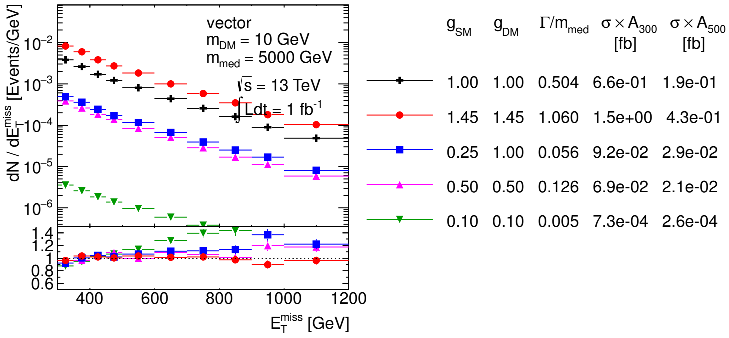


Figure 3.4: Scan over couplings. The $\not{E}_T$ distribution is compared for the vector mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not{E}_T > 300\,\text{GeV}$ and $\not{E}_T > 500\,\text{GeV}$ cut, respectively.

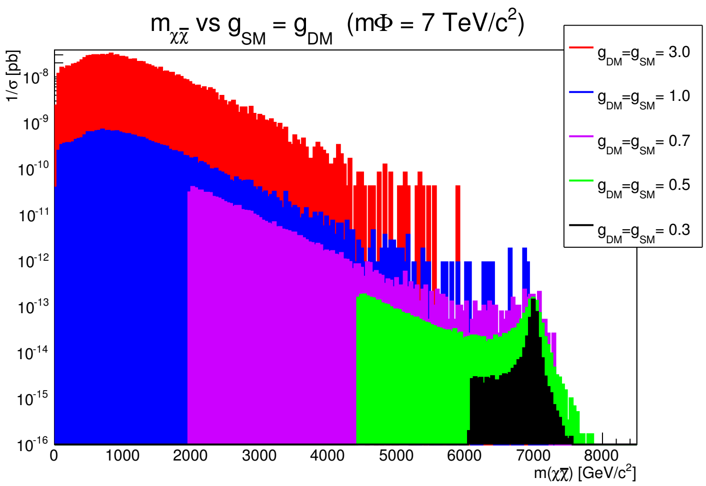


Figure 3.5: Invariant mass of the Dark Matter pair in the samples with $M_{\text{med}} = 7\,\text{TeV}$ and different coupling strengths.

Scan over the Dark Matter mass For the fixed mediator mass and couplings, both the cross section and the kinematic distributions remain similar for different Dark Matter masses as long as $M_{\text{med}} > 2m_{\text{DM}}$. This simply reflects the fact that most mediators are produced on-shell, and the details of the invisible decay are unimportant. This is illustrated in Fig. 3.6 for an example of M_{med} =1 TeV $10\,\text{GeV} < m_{\text{DM}} < 300\,\text{GeV}$. It is observed that the cross section decreases as the m_{DM} approaches $M_{\text{med}}/2$. Once the Dark Matter pair is produced off-shell, the cross section of such simplified model is suppressed and the $\not{E}_T$ spectrum hardens, as demonstrated with the choice of m_{DM} =1 TeV in the same plot. Figure 3.7 reveals the $\not{E}_T$ spectrum hardens further with increasing m_{DM}, accompanied by the gradual decrease of the cross section. From these observations one can conclude:

- A coarse binning along m_{DM} is sufficient at $M_{\text{med}} \gg 2m_{\text{DM}}$.
- Finer binning is needed in order to capture the changes in the cross section and kinematic quantities close to the production threshold on both sides around $M_{\text{med}} = 2m_{\text{DM}}$.
- Due to the significant cross section suppression of the off-shell Dark Matter pair production, it is not necessary to populate the parameter space $M_{\text{med}} \ll 2m_{\text{DM}}$ since the LHC is not going to be able to probe the models there.

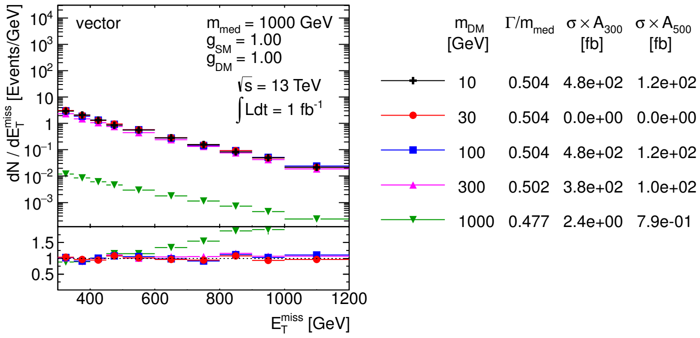


Figure 3.6: Scan over Dark Matter mass. The $\not{E}_T$ distribution is compared for the vector mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not{E}_T > 300\,\text{GeV}$ and $\not{E}_T > 500\,\text{GeV}$ cut, respectively.

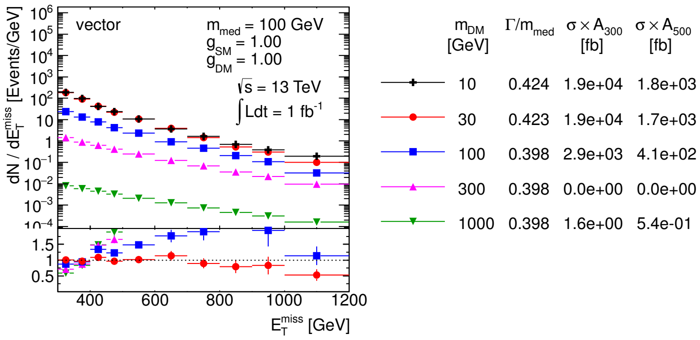


Figure 3.7: Scan over Dark Matter mass. The $\not{E}_T$ distribution is compared for the vector mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not{E}_T > 300\,\text{GeV}$ and $\not{E}_T > 500\,\text{GeV}$ cut, respectively.

Scan over the mediator mass Changing the mediator mass for fixed Dark Matter mass and couplings leads to significant differences in cross section and shapes of the kinematic variables for $M_{\text{med}} > 2m_{\text{DM}}$ as shown in Fig. 3.8. As expected, higher mediator masses lead to harder $\not{E}_T$ spectra. On the other hand, the $\not{E}_T$ shapes are similar in the off-shell Dark Matter production regime. This is illustrated in Fig. 3.9. Therefore, a coarse binning in m_{DM} is sufficient at $M_{\text{med}} \ll 2m_{\text{DM}}$.

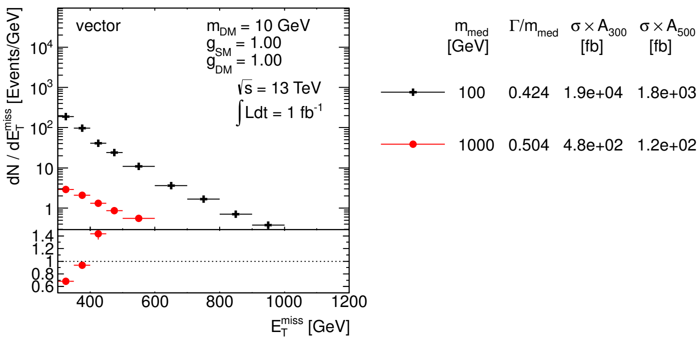


Figure 3.8: Scan over mediator mass. The $\not{E}_T$ distribution is compared for the vector mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not{E}_T > 300\,\text{GeV}$ and $\not{E}_T > 500\,\text{GeV}$ cut, respectively.

Proposed parameter grid It is difficult to visualize a four dimensional scan. However, it is convenient to study the parameter dependence, and present results, in two projections: (a) the M_{med}–m_{DM} plane for a particular choice of the couplings, and

(b) the g_{q}–g_{DM} plane for a particular choice of the masses.

We choose to display the results in the M_{med}–m_{DM} plane for the choice of the couplings $g_{\text{q}} = g_{\text{DM}} = 1$. In order to motivate

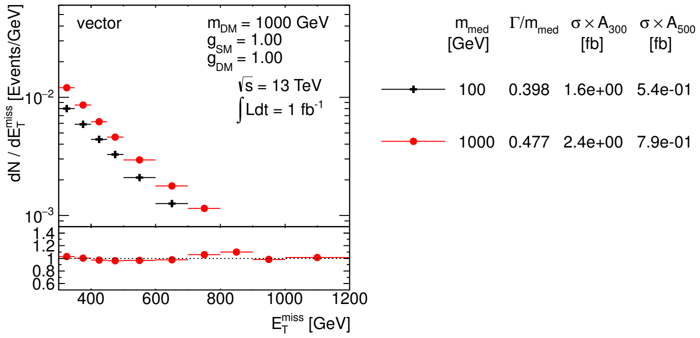


Figure 3.9: Scan over mediator mass. The $\not\!\!E_T$ distribution is compared for the vector mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not\!\!E_T > 300$ GeV and $\not\!\!E_T > 500$ GeV cut, respectively.

the highest mediator mass grid point, the expected sensitivity of Run-2 LHC data needs to be taken into account. The expected upper limit at 95% confidence level on the product of cross section, acceptance and efficiency, $\sigma \times A \times \epsilon$, in the final Run-1 ATLAS mono-jet analysis [A$^+$15] is 51 fb and 7.2 fb for $\not\!\!E_T > 300$ GeV and $\not\!\!E_T > 500$ GeV, respectively. The ATLAS 14 TeV prospects [ATL14] predict twice better sensitivity with the first 5 fb^{-1} of data already. Given the cross section for V+jets processes increases by roughly a factor 2 when going from $\sqrt{s} = 8$ TeV to 13 TeV, similar fiducial cross section limits can be expected with the first Run-2 data as from the final Run-1 analysis. The generator level cross section times the acceptance at $\not\!\!E_T > 500$ GeV for the model with couplings $g_q = g_{DM} = 1$, light Dark Matter of 10 GeV and 1 TeV vector mediator is at the order of 100 fb, i.e. the early Run-2 mono-jet analysis is going to be sensitive to heavier mediators than this. The value of $\sigma \times A$ at $\not\!\!E_T > 500$ GeV for 5 TeV vector mediator is at the order of 0.1 fb, therefore this model probably lies beyond the reach of the LHC.

Based on these arguments, the following M_{med} grid points are chosen, roughly equidistant in the logarithmic scale: 10 GeV, 20 GeV, 50 GeV, 100 GeV, 200 GeV, 300 GeV, 500 GeV, 1000 GeV and 2000 GeV. Given the fact that significant changes in cross section happen around the $M_{med} = 2m_{DM}$ threshold, the m_{DM} grid points are taken at approximately $M_{med}/2$, namely: 10 GeV, 50 GeV, 150 GeV, 500 GeV and 1000 GeV. Points on the on-shell diagonal are always chosen to be 5 GeV away from the threshold, to avoid numerical instabilities in the event generation. The detailed studies of the impact of the parameter changes on the cross section and kinematic distributions presented earlier in this section support removing some of the grid points and rely on interpolation. The optimised grids proposed for the vector and axial-vector mediators are given in Table. 3.1, containing 29 mass points each. One point at very high mediator mass (5 TeV) is added for each of the DM masses scanned, to aid the reinterpretation of results in terms of contact interaction operators (EFTs).

The presentation of the results in the g_q–g_{DM} plane for fixed masses benefits from cross section scaling and is discussed in Section 3.3.

m_{DM}/GeV	m_{med}/GeV									
1	10	20	50	100	200	300	500	1000	2000	5000
10	10	15	50	100	″	″	″	″	″	″
50	10		50	95	200	300	″	″	″	″
150	10				200	295	500	″	″	″
500	10						500	995	2000	″
1000	10							1000	1995	5000

Table 3.1: Simplified model benchmarks for $s-$channel simplified models (spin-1 mediators decaying to Dirac DM fermions in the V and A case, taking the minimum width for g_{q} = g_{DM} = 1)

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 (NLO), whilst MADGRAPH and MCFM are at leading order (LO). As shown in POWHEG Ref. [HKR13], including NLO corrections result in an enhancement in the cross section as compared to LO and though this is not significant, it does lead to a substantial reduction in the dependence on the choice of the renormalization and factorization 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.

3.2 *Scalar and pseudoscalar mediator, s-channel exchange*

One of the most simple UV complete extensions of the effective field theory approach is the addition of a scalar/pseudoscalar mediator between DM and SM. A gauge singlet mediator can have tree-level interactions with a singlet DM particle that is either a Dirac or Majorana fermion, or DM that is a scalar itself. The spin-0 mediator can either be a real or complex scalar; a complex scalar contains both scalar and pseudoscalar particles, whereas the real field only contains the scalar particle. In this document we consider only two of the possible choices for this simplified model: one where the interaction with the SM is mediated by a real scalar, and the second where we consider only a light pseudoscalar, assuming that the associated scalar is decoupled from the low-energy spectrum. The kinematics of the two cases is sufficiently different to suggest that further investigation of the complex scalar case is needed but left for future studies.

Couplings to the SM fermions can be arranged by mixing with the SM Higgs. Such models have interesting connections with Higgs physics, and can be viewed as generalizations of the Higgs portal to DM. The most general scalar mediator models will have renormalizable interactions between the SM Higgs and the new scalar ϕ or pseudoscalar 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 specialized searches which cannot be generalized to a broad class of models (unlike, for instance, the $\not{E}_T +$ jets searches).

As a result, for this class of minimal simplified models with spin-0 mediators, we will focus primarily on couplings to fermions and loop-induced couplings to gluons.

Minimal Flavor Violation (MFV) implies that scalar couplings to fermions will be proportional to the fermion mass. However, they can differ for up- and down-type quarks and for charged leptons.

Following the assumption that DM is a fermion χ, which couples to the SM only through a scalar ϕ or pseudoscalar a, the most general tree-level interaction Lagrangians compatible with the MFV assumption are [CRTW14, ADR$^+$14, BFG15]:

$$\mathcal{L}_\phi = g_\chi \phi \bar{\chi}\chi + \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right) , \quad (3.8)$$

$$\mathcal{L}_a = i g_\chi a \bar{\chi}\gamma_5 \chi + \frac{ia}{\sqrt{2}} \sum_i \Big(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \Big) . \quad (3.9)$$

Here the sums run over the all SM generations; the Yukawa couplings y_i^f are normalized to $y_i^f = \sqrt{2} m_i^f / v$ where $v \simeq 246\,\mathrm{GeV}$ represents the Higgs vacuum expectation value (VEV). While the couplings g_u, g_d, g_ℓ to SM fermions are factors multiplying the SM Yukawa structure, we parametrise the DM-mediator coupling as g_χ, without any additional Yukawa structure between the mediator and the dark sector.

As already stated we only choose a minimal set of interactions that do not include interactions with the SM Higgs field. For simplicity, we also assume universal SM-mediator couplings $g_v = g_u = g_d = g_\ell$

Given these simplifications, the minimal set of parameters under consideration is

$$\left\{ m_\chi,\ m_{\phi/a},\ g_\chi,\ g_v \right\} . \quad (3.10)$$

We choose to consider the minimal mediator width given by

$$\Gamma_{\min}^{S/P} = \Gamma_{\bar{\chi}\chi}^{S/P} + \sum_q \Gamma_{\bar{q}q}^{S/P} + \Gamma_{gg}^{S/P}, \quad (3.11)$$

with the following LO expressions for the partial widths:

$$\Gamma^{\mathrm{S}}_{\bar{\chi}\chi} = \frac{g_{\mathrm{DM}}^2 M_{\mathrm{med}}}{8\pi} \beta_{DM}^{3/2} \theta(M_{\mathrm{med}} - 2m_{\mathrm{DM}}) \quad (3.12)$$

$$\Gamma^{\mathrm{S}}_{\bar{q}q} = \frac{3 g_{\mathrm{q}}^2 M_{\mathrm{med}}}{8\pi} \frac{m_q^2}{v^2} \beta_q^{3/2} \theta(M_{\mathrm{med}} - 2m_q) \quad (3.13)$$

$$\Gamma^{\mathrm{S}}_{gg} = \frac{g_{\mathrm{q}}^2 \alpha_s^2}{2\pi^3 v^2 M_{\mathrm{med}}} \left| \sum_q m_q^2 F_{\mathrm{S}} \left(\frac{4m_q^2}{M_{\mathrm{med}}^2} \right) \right|^2 \quad (3.14)$$

$$\Gamma^{\mathrm{P}}_{\bar{\chi}\chi} = \frac{g_{\mathrm{DM}}^2 M_{\mathrm{med}}}{8\pi} \beta_{DM} \theta(M_{\mathrm{med}} - 2m_{\mathrm{DM}}) \quad (3.15)$$

$$\Gamma^{\mathrm{P}}_{\bar{q}q} = \frac{3 g_{\mathrm{q}}^2 M_{\mathrm{med}}}{8\pi} \frac{m_q^2}{v^2} \beta_q \theta(M_{\mathrm{med}} - 2m_q) \quad (3.16)$$

$$\Gamma^{\mathrm{P}}_{gg} = \frac{g_{\mathrm{q}}^2 \alpha_s^2}{2\pi^3 v^2 M_{\mathrm{med}}} \left| \sum_q m_q^2 F_{\mathrm{P}} \left(\frac{4m_q^2}{M_{\mathrm{med}}^2} \right) \right|^2 , \quad (3.17)$$

with the form factors defined as

$$F_S(x) = 1 + (1 - x)\arctan^2\left(\frac{1}{\sqrt{x-1}}\right) \tag{3.18}$$

$$F_P(x) = \arctan^2\left(\frac{1}{\sqrt{x-1}}\right) . \tag{3.19}$$

The minimal width for scalar and pseudo-scalar mediators with $g_q = g_{DM} = 1$ are shown in Fig. 3.10, illustrating the effect of choosing the SM Higgs-like Yukawa couplings for the SM fermions. For the mediator mass above twice the top quark mass m_t, the minimal width receives the dominant contribution from the top quark. For lighter mediator masses, Dark Matter dominates as the couplings to lighter quarks are Yukawa suppressed. Note that the partial width coming from gluons through loops can be safely neglected [HR15].

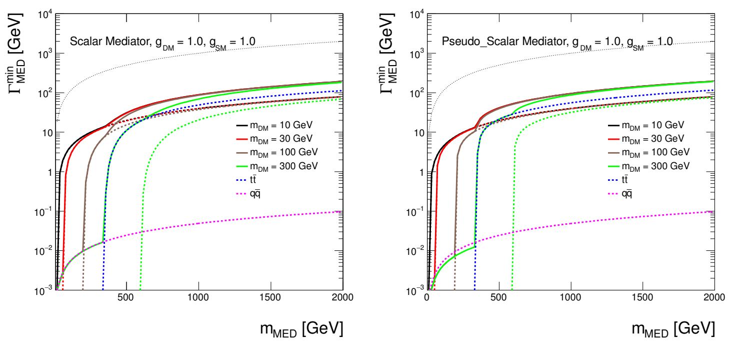


Figure 3.10: Minimal width as a function of mediator mass for scalar and pseudo-scalar mediator assuming couplings of 1. The total width is shown as solid lines for Dark Matter masses of 10 GeV, 30 GeV, 100 GeV and 300 GeV in black, red, brown and green, respectively. The individual contributions from Dark Matter are indicated by dotted lines with the same colors. The contribution from all quarks but top is shown as magenta dotted line and the contribution from top quarks only is illustrated by the dotted blue line. The dotted black line shows the extreme case $\Gamma_{min} = M_{med}$.

Similarly as in the case of the vector and axial-vector couplings of spin-1 mediators, scans in the parameter space are performed also for the scalar and pseudo-scalar couplings of the spin-0 mediators in order to decide on the optimised parameter grid for the presentation of Run-2 results. Figures 3.11- 3.15 show the scans over the couplings, Dark Matter mass and mediator mass and the same conclusions apply as in Section 3.1.

Since the top quark gives the dominant contribution to the mediator width due to SM Higgs-like Yukawa couplings, the effect of the kinematic threshold at $M_{med} = 2m_t$ was studied in detail. A scan over the mediator mass is shown in Fig. 3.15 where M_{med} = 300 GeV and 500 GeV are chosen to be below and above $2m_t$. The off-shell Dark Matter production regime is assumed by taking $m_{DM} = 1$ TeV in order to allow studying solely the effects of the couplings to quarks. No differences in the kinematic distributions are observed and also the cross sections remain similar in this case. Therefore, it is concluded that no significant changes appear for mediator masses around the $2m_t$ threshold.

The optimized parameter grid in the M_{med}–m_{DM} plane for scalar and pseudo-scalar mediators is motivated by similar arguments as in the previous section. Therefore, a similar pattern is followed here, taking again $g_q = g_{DM} = 1$. Only the sensitivity to the highest mediator masses has to be revisited. The generator level

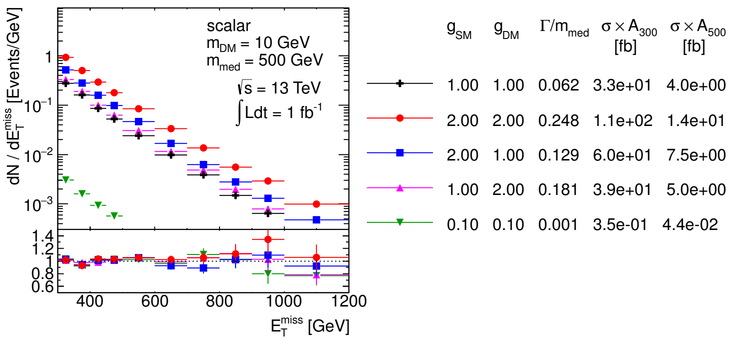


Figure 3.11: Scan over couplings. The $\not{E}_T$ distribution is compared for the scalar mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not{E}_T > 300\,\text{GeV}$ and $\not{E}_T > 500\,\text{GeV}$ cut, respectively.

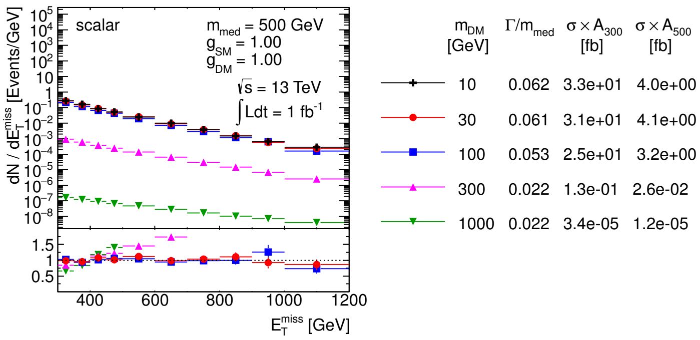


Figure 3.12: Scan over Dark Matter mass. The $\not{E}_T$ distribution is compared for the scalar mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not{E}_T > 300\,\text{GeV}$ and $\not{E}_T > 500\,\text{GeV}$ cut, respectively.

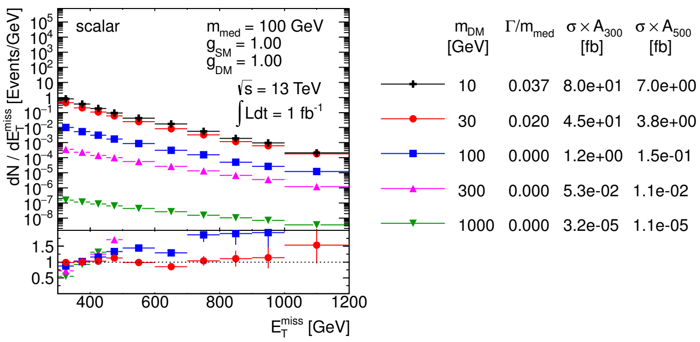


Figure 3.13: Scan over Dark Matter mass. The $\not{E}_T$ distribution is compared for the scalar mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not{E}_T > 300\,\text{GeV}$ and $\not{E}_T > 500\,\text{GeV}$ cut, respectively.

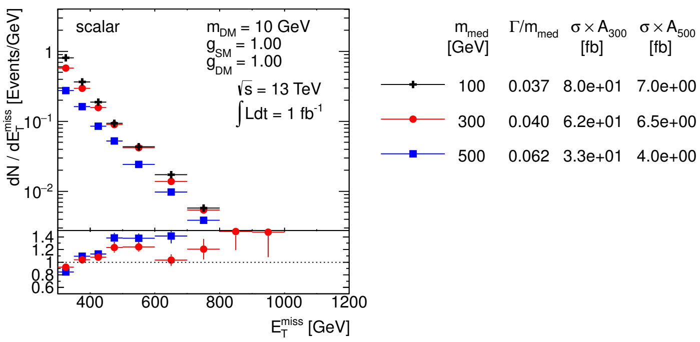


Figure 3.14: Scan over mediator mass. The $\not{E}_T$ distribution is compared for the scalar mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not{E}_T > 300\,\text{GeV}$ and $\not{E}_T > 500\,\text{GeV}$ cut, respectively.

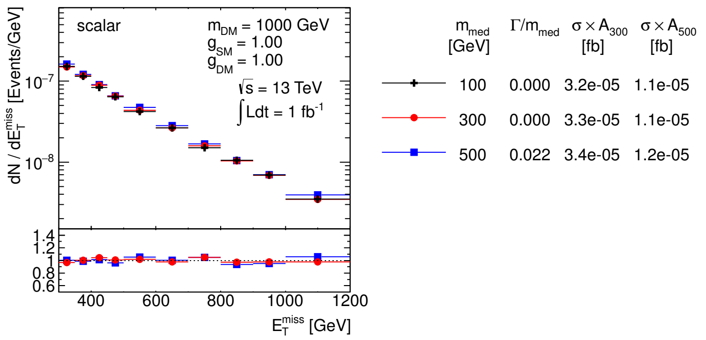


Figure 3.15: Scan over mediator mass. The $\not\!\!E_T$ distribution is compared for the scalar mediator models using the parameters as indicated. Ratios of the normalized distributions with respect to the first one are shown. A_{300} and A_{500} in the table denote the acceptance of the $\not\!\!E_T > 300\,\mathrm{GeV}$ and $\not\!\!E_T > 500\,\mathrm{GeV}$ cut, respectively.

cross section times the acceptance at $\not\!\!E_T > 500\,\mathrm{GeV}$ for the model with couplings $g_\mathrm{q} = g_\mathrm{DM} = 1$, light Dark Matter of 10 GeV and 500 GeV scalar mediator is at the order of 10 fb, i.e. just at the edge of the early Run-2 sensitivity. Increasing the mediator mass to 1 TeV pushes the product $\sigma \times A$ down to approximately 0.1 fb, beyond the LHC sensitivity. Therefore, we choose to remove the 2 TeV mediator mass from the grid and present the final grid with 26 mass points only in Fig. 3.2. One point at very high mediator mass (5 TeV) is added for each of the DM masses scanned, to aid the reinterpretation of results in terms of contact interaction operators (EFTs).

m_DM (GeV)	m_med (GeV)								
1	10	20	50	100	200	300	500	1000	5000
10	10	15	50	100					5000
50	10		50	95	200	300			5000
150	10				200	295	500		5000
500	10						500	995	5000
1000	10							1000	5000

Table 3.2: Simplified model benchmarks for $s-$channel simplified models (spin-0 mediators decaying to Dirac DM fermions in the scalar and pseudoscalar case, taking the minimum width for $g_\mathrm{q} = g_\mathrm{DM} = 1$)

The proposal for the scan in the g_q–g_DM plane is described in the following section.

Implementation The matrix element implementation of the s-channel spin-0 mediated DM production is available in POWHEG with the full top-loop calculation at LO [HR15].

3.3 *Cross section scaling*

The aim of the parameter grid optimization is to find out whether certain parts of the parameter space can be omitted and one can rely on the neighboring grid points in order to populate the missing parts. There are two ways of doing this:

- Interpolation is used in-between the grid points that are close enough such that finer granularity is not needed for the presentation purposes, or between the points where smooth or no changes of the results are expected. The latter argument is exactly the one that motivates the reduction of the grid points in the M_med–m_DM plane.

- Recalculation of the results can be used when the dependencies with respect to the neighboring grid points are known.

The results of the scan over the couplings presented in the previous sections indicate there are no changes in kinematic distributions for different choices of the coupling strengths. This means that the acceptance remains the same in the whole g_{q}–g_{DM} plane and it is sufficient to perform the detector simulation only for one single choice of $g_{\mathrm{q}}, g_{\mathrm{DM}}$. The resulting truth-level selection acceptance and the detector reconstruction efficiency can then be applied to all remaining grid points in the g_{q}–g_{DM} plane where only the generator-level cross section needs to be known. This significantly reduces the computing time as the detector response is by far the most expensive part of the Monte Carlo sample production. However, the number of generated samples can be reduced even further if a parameterization of the cross section dependence from one grid point to another exists.

Let us now elaborate on a cross section scaling procedure. The propagator on the s-channel exchange is written in a Breit-Wigner form as $\frac{1}{q^2-M_{\mathrm{med}}^2+iM_{\mathrm{med}}\Gamma}$, where q is the momentum transfer calculated from the two partons entering the hard process after the initial state radiation, which is equivalent to the invariant mass of the Dark Matter pair. The size of the momenum transfer with respect to the mediator mass allows to classify the production in the following way:

- off-shell production when $q^2 \gg M_{\mathrm{med}}$ leading to suppressed cross sections,
- on-shell production when $q^2 \sim M_{\mathrm{med}}$ leading to enhanced cross sections,
- effective field theory (EFT) limit when $q^2 \ll M_{\mathrm{med}}$.

All three categories can be distinguished in Fig. 3.16 showing the upper limit on the interaction scale $M^* \equiv M_{\mathrm{med}}/\sqrt{g_{\mathrm{q}}g_{\mathrm{DM}}}$ for vector mediator. In the case of the off-shell production and the EFT limit, the first term in the propagator dominates which reduces the dependence on the mediator width. Therefore, in these cases one can approximate the cross section as

$$\sigma \propto g_{\mathrm{q}}^2 g_{\mathrm{DM}}^2. \tag{3.20}$$

The on-shell production regime is the most interesting one as it gives the best chances for a discovery at the LHC given the cross section enhancement. The propagator term with the width cannot be neglected in this case and, in the narrow width approximation which requires $\Gamma \ll M_{\mathrm{med}}$, one can integrate

$$\int \frac{ds}{(s-M_{\mathrm{med}}^2)^2 + M_{\mathrm{med}}^2\Gamma^2} = \frac{\pi}{M_{\mathrm{med}}\Gamma} \tag{3.21}$$

which further implies the cross section scaling

$$\sigma \propto \frac{g_{\mathrm{q}}^2 g_{\mathrm{DM}}^2}{\Gamma}. \tag{3.22}$$

The narrow with approximation is important here as it ensures an integration over parton distribution functions (PDFs) can be neglected. In other words, it is assumed the integrant in Eq. 3.21 is non-zero only for a small region of s, such that the PDFs can be taken to be constant in this range. Since $\Gamma \sim g_\mathrm{q}^2 + g_\mathrm{DM}^2$, one can simplify this rule in the extreme cases as follows

$$\sigma \;\propto\; \frac{g_\mathrm{q}^2 g_\mathrm{DM}^2}{g_\mathrm{q}^2 + g_\mathrm{DM}^2} \xrightarrow{g_\mathrm{q} \ll g_\mathrm{DM}} g_\mathrm{q}^2 \tag{3.23}$$

$$\sigma \;\propto\; \frac{g_\mathrm{q}^2 g_\mathrm{DM}^2}{g_\mathrm{q}^2 + g_\mathrm{DM}^2} \xrightarrow{g_\mathrm{q} \gg g_\mathrm{DM}} g_\mathrm{DM}^2 \,. \tag{3.24}$$

However, it is important to keep in mind that there is no simple scaling rule for how the cross section changes with the Dark Matter mass and the mediator mass, or for mediators with a large width, because PDFs matter in such cases as well. Therefore, the scaling procedure outlined above is expected to work only for fixed masses and fixed mediator width, assuming the narrow width approximation applies.

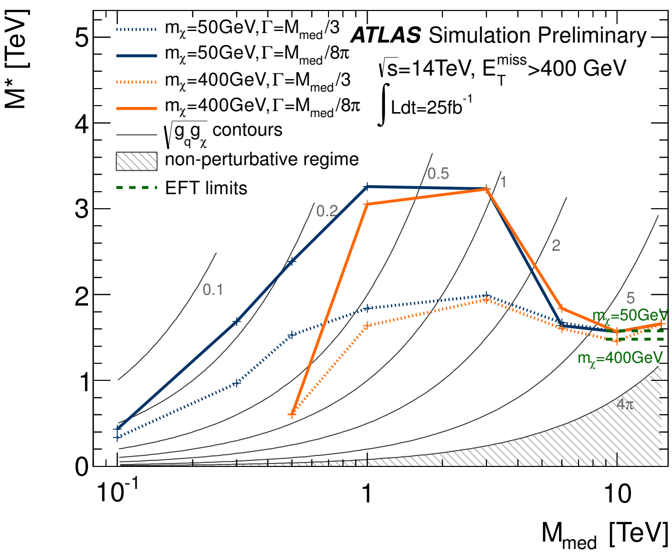


Figure 3.16: Comparison of the 95% CL lower limits on the scale of the interaction of a Z'-like simplified model at 14 TeV, in terms of the mediator mass. Corresponding limits from EFT models are shown on the same plot as green dashed lines to show equivalence between the two models for high mediator masses. Taken from Ref. [ATL14].

Figures 3.17 and 3.18 show the minimal width in the g_q–g_DM plane for all vector, axial-vector, scalar and pseudo-scalar mediators for $M_\mathrm{med} = 100\,\mathrm{GeV}$ and $1000\,\mathrm{GeV}$, respectively, taking $m_\mathrm{DM} = 10\,\mathrm{GeV}$. The individual colors indicate the lines of constant width along which the cross section scaling works. For vector and axial-vector mediators, the minimal width is predominantly defined by g_q due to the number of quark flavors and the color factor. On the contrary, both the Standard Model and Dark Matter partial width have comparable contributions in case of scalar and pseudo-scalar mediators if the top quark channel is open ($M_\mathrm{med} > 2m_t$). However, mostly g_DM defines the minimal width for $M_\mathrm{med} < 2m_t$ due to the Yukawa-suppressed light quark couplings.

The performance of the cross section scaling is demonstrated in Fig. 3.19 where two mass points $M_\mathrm{med} = 100\,\mathrm{GeV}$ and 1 TeV with

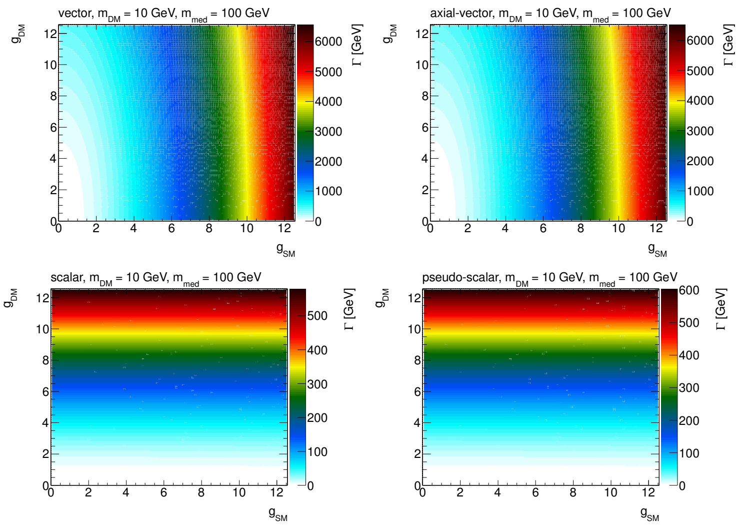


Figure 3.17: Minimal width for vector, axial-vector, scalar and pseudo-scalar mediators as a function of the individual couplings g_{q} and g_{DM}, assuming $M_{\mathrm{med}} = 100\,\mathrm{GeV}$ and $m_{\mathrm{DM}} = 10\,\mathrm{GeV}$.

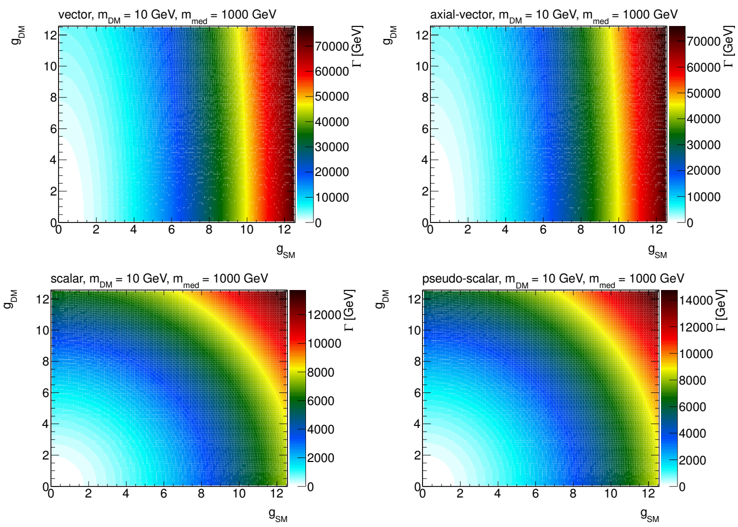


Figure 3.18: Minimal width for vector, axial-vector, scalar and pseudo-scalar mediators as a function of the individual couplings g_{q} and g_{DM}, assuming $M_{\mathrm{med}} = 1\,\mathrm{TeV}$ and $m_{\mathrm{DM}} = 10\,\mathrm{GeV}$.

$m_{\rm DM} = 10\,\rm GeV$ are chosen and rescaled from the starting point $g_q = g_{\rm DM} = 1$ according to Eq. 3.22 to populate the whole g_q–$g_{\rm DM}$ plane. This means the width is not kept constant in this test and this is done in purpose in order to point out deviations from the scaling when the width is altered. For each mass point, the rescaled cross section is compared to the generator cross section and the ratio of the two is plotted. For the given choice of the mass points, the scaling seems to work approximately with the precision of $\sim 20\%$ in the region where $\Gamma_{\rm min} < M_{\rm med}$. Constant colors indicate the lines along which the cross section scaling works precisely and there is a remarkable resemblance of the patterns shown in the plots of the mediator width. To prove the scaling along the lines of constant width works, one such line is chosen in Fig. 3.20 for a scalar mediator, defined by $M_{\rm med} = 300\,\rm GeV$, $m_{\rm DM} = 100\,\rm GeV$, $g_q = g_{\rm DM} = 1$, and the rescaled and generated cross sections are found to agree within 3%.

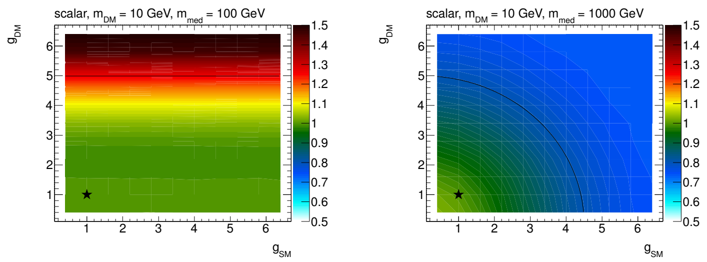


Figure 3.19: Ratio of the rescaled and generated cross sections in the g_q–$g_{\rm DM}$ plane. The point at $g_q = g_{\rm DM} = 1$, taken as a reference for the rescaling, is denoted by a star symbol. Scalar model with $M_{\rm med} = 100\,\rm GeV$ (left) and 1 TeV (right) is plotted for $m_{\rm DM} = 10\,\rm GeV$. The limiting case $\Gamma_{\rm min} = M_{\rm med}$ is shown as a black line.

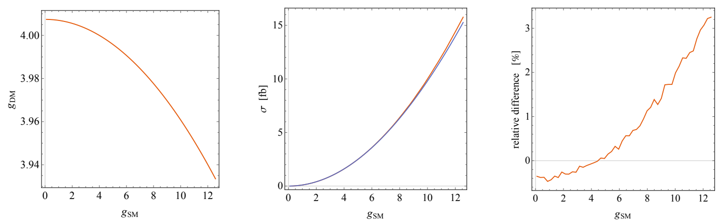


Figure 3.20: Scaling along the lines of constant width. The line of constant width for $M_{\rm med} = 300\,\rm GeV$ and $m_{\rm DM} = 100\,\rm GeV$, intercepting $g_q = g_{\rm DM} = 4$ is shown on left. The generated and rescaled cross sections are compared in the middle, the corresponding ratio is shown on right.

Proposed parameter grid We propose to present the results in the g_q–$g_{\rm DM}$ plane using the following prescription:

- Since the shapes of kinematic quantities do not change for different couplings, use the acceptance and efficiency for the available $m_{\rm DM} = 50\,\rm GeV$, $M_{\rm med} = 300\,\rm GeV$, $g_q = g_{\rm DM} = 1$ grid point from the $M_{\rm med}$–$m_{\rm DM}$ plane for the scalar and pseudo-scalar mediator. In case of the vector and axial-vector mediator, use the grid point $m_{\rm DM} = 50\,\rm GeV$, $M_{\rm med} = 1\,\rm TeV$, $g_q = g_{\rm DM} = 1$.
- Generate additional samples in order to get generator cross sections only. For scalar and pseudo-scalar mediator, choose $m_{\rm DM} = 50\,\rm GeV$, $M_{\rm med} = 300\,\rm GeV$ with the following values for $g_q = g_{\rm DM}$: 0.1, 2, 3, 4, 5, 6. For vector and axial vector mediator, choose $m_{\rm DM} = 50\,\rm GeV$, $M_{\rm med} = 1\,\rm TeV$ with the following values for $g_q = g_{\rm DM}$: 0.1, 0.25, 0.5, 0.75, 1.25, 1.5. The upper values are defined by the minimal width reaching the mediator mass.

- Rescale the generator cross sections along the lines of constant width in order to populate the whole g_q–g_{DM} plane.

Rescaling to different mediator width In general there may be an interest to consider larger mediator masses than Γ_{min} in order to accommodate further couplings of the mediator. The cross section scaling method described above can be used to reinterpret the results presented for the minimal width, since multiplying the width by factor n is equivalent to changing the coupling strength by factor $\sqrt{n}$, i.e.

$$\sigma(g_q, g_{\text{DM}}, n\Gamma_{\text{min}}(g_q, g_{\text{DM}})) \propto \frac{g_q^2 g_{\text{DM}}^2}{\Gamma_{\text{min}}(\sqrt{n}g_q, \sqrt{n}g_{\text{DM}})} \,. \tag{3.25}$$

The cross section for the sample with couplings g_q and g_{DM} and modified mediator width $\Gamma = n\Gamma_{\text{min}}$ can therefore be rescaled from a sample generated with the minimal width corresponding to the couplings scaled by $\sqrt{n}$ as described in the following formula.

$$\sigma(g_q, g_{\text{DM}}, n\Gamma_{\text{min}}(g_q, g_{\text{DM}})) = \frac{1}{n^2}\sigma(\sqrt{n}g_q, \sqrt{n}g_{\text{DM}}, \Gamma_{\text{min}}(\sqrt{n}g_q, \sqrt{n}g_{\text{DM}})) \tag{3.26}$$

Here, it is again assumed the narrow width approximation applies. The advantage of doing this is in the fact that no event selection and detector response needs to be simulated since the changes in couplings do not have an effect on the shapes of kinematic distributions.

3.3.1 POWHEG settings

This section describes specific settings for the Dark Matter models needed to run the POWHEG generation.

- The POWHEG implementation allows to generate a single sample that provides sufficient statistics in all mono-jet analysis signal regions. POWHEG generates weighted events and the `bornsuppfact` parameter is used to set the event suppression factor according to

$$F(k_{\text{T}}) = \frac{k_{\text{T}}^2}{k_{\text{T}}^2 + \texttt{bornsuppfact}^2} \,. \tag{3.27}$$

  In this way, the events at low $\not{E}_T$ are suppressed and receive higher event weights which ensures higher statistics at high $\not{E}_T$. We recommend to set `bornsuppfact` to 1000.

- The `bornktmin` parameter allows to suppress the low $\not{E}_T$ region even further by starting the generation at a certain value of k_{T}. It is recommended to set this parameter to half the lower analysis $\not{E}_T$ cut, therefore the proposed value for `bornktmin` is 150.

- Set `runningwidth` to 0.

- Set `mass_low` and `mass_high` to -1.

- The minimal values for `ncall1`, `itmx1`, `ncall2`, `itmx2` are 250000, 5, 1000000, 5 for the DMV model, respectively. In order to increase speed, set `foldsci` and `foldy` to 2 and keep `foldphi` at 1.
- The minimal values for `ncall1`, `itmx1`, `ncall2`, `itmx2` are 100000, 5, 100000, 5 for the DMS_tloop model, respectively.
- Allow negative weights for the DMV model by setting `withnegweights` to 1.
- Since the DMS_tloop model is a leading order process, set `LOevents` and `bornonly` are set to 1 internally.

[Comment on proper PDF sets to use, concerns about sea quark PDF in b-initiated diagrams (perhaps the latter belongs in the b-flavored DM section]

3.4 *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. 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. An important difference with respect to the MSSM is that **[illustrate that diagram is no longer forced to be small. Should forum provide formulae to relate our parameters to MSSM searches?]**. Following the example of Ref. [PVZ14], the interaction Lagrangian is written as

$$\mathcal{L}_{\text{int}} = g \sum_{i=1,2,3} (\phi^i_L \bar{Q}^i_L + \phi^i_{uR} \bar{u}^i_R + \phi^i_{dR} \bar{d}^i_R)\chi \qquad (3.28)$$

(Note: [PVZ14] uses only i = 1,2, but I think it's fine to extend this to 3 here.) where Q^i_L, u^i_R and d^i_R are the SM quarks and ϕ^i_L, ϕ^i_{uR} and ϕ^i_{dR} 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$^+$14], to the ϕ^i_{uR} [DNRT13] or ϕ^i_{dR} [PVZ14, A$^+$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

$$\{m_\chi, M_\phi, g\}. \qquad (3.29)$$

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

$$\{m_\chi,\ M_{\phi_{1,2}},\ M_{\phi_3},\ g_{1,2},\ g_3\}. \tag{3.30}$$

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

$$\begin{aligned}\Gamma(\phi_i \to \bar{u}_i\chi) = \frac{g_i^2}{16\pi M_{\phi_i}^3}&(M_{\phi_i}^2 - m_{u_i}^2 - m_\chi^2)\\ &\times \sqrt{M_{\phi_i}^4 + m_{u_i}^4 + m_\chi^4 - 2M_{\phi_i}^2 m_{u_i}^2 - 2M_{\phi_i}^2 m_\chi^2 - 2m_{u_i}^2 m_\chi^2}\,,\end{aligned} \tag{3.31}$$

this reduces to

$$\frac{g_i^2 M_{\phi_i}}{16\pi}\left(1 - \frac{m_\chi^2}{M_{\phi_i}^2}\right)^2 \tag{3.32}$$

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.

4
Specific models for signatures with heavy flavor quarks

4.1 $b\bar{b}$+MET models

4.2 Models with a single $b-$quark + MET

4.3 $t\bar{t}$+MET models

As described in Section 3.2, a model with a scalar/pseudoscalar particle mediating the DM-SM interactions is one of the simplest UV completions of our EFT models.

The expected signal of DM pair production depends on the production rate defined by the dark matter mass m_χ, mediator $m_{\phi/a}$, on the couplings g_i and on the branching ratio defined by the total decay width of the mediator ϕ/a. We calculate the minimum possible width (assuming only decays into the dark matter and the Standard Model fermions) that is consistent with a given value of $g_\chi g_q$, and assuming all couplings to SM particles equal $g_{\mathrm{q}} = g_u = g_d = g_\ell$. These are given by Eq. (4.1) [BFG15].

$$\begin{aligned}\Gamma_{\phi,a} =& \sum_f N_c \frac{y_f^2 g_q^2 m_{\phi,a}}{16\pi}\left(1-\frac{4m_f^2}{m_{\phi,a}^2}\right)^{3/2} + \frac{g_\chi^2 m_{\phi,a}}{8\pi}\left(1-\frac{4m_\chi^2}{m_{\phi,a}^2}\right)^{3/2} \\ &+ \frac{\alpha_s^2 y_t^2 g_q^2 m_{\phi,a}^3}{32\pi^3 v^2}\left|f_{\phi,a}\left(\frac{4m_t^2}{m_{\phi,a}^2}\right)\right|^2\end{aligned} \tag{4.1}$$

where

$$f_\phi(\tau) = \tau\left[1+(1-\tau)\arctan^2\left(\frac{1}{\sqrt{\tau-1}}\right)\right], \qquad f_a(\tau) = \tau\arctan^2\left(\frac{1}{\sqrt{\tau-1}}\right). \tag{4.2}$$

The first term in each width corresponds to the decay into SM fermions, and 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 DM, assuming that is kinematically allowed. The factor of two between the decay into SM fermions and into DM is a result of our choice of normalization of the Yukawa couplings due to spin dependencies. The last two terms correspond to decay into gluons. Since we have assumed that $g_{\mathrm{q}} = g_u = g_d = g_\ell$, we have included in the partial decay widths $\Gamma(\phi/a \to gg)$ only the contributions stemming from top loops, which provide the by far largest corrections given that $y_t \gg y_b$ etc. At the loop level the mediators can decay not only to gluons but also to pairs of photons and other final states if kinematical accessible. However the decay rates $\Gamma(\phi/a \to gg)$ are always larger than the other loop-induced partial widths, and in consequence the total decay widths $\Gamma_{\phi/a}$ are well approximated by the corresponding sum of the individual partial decay widths involving DM, fermion or gluon pairs. It should be noted that if $m_{\phi/a} > 2m_t$ the total widths of ϕ/a will typically be dominated by the partial widths to top quarks.

4.3.1 *Parameter scan*

As discussed in Sec. 3.2, the MFV assumption for spin-0 mediators leads to quark mass dependent Yukawa couplings, and therefore dominant couplings to top quarks. This motivates dedicated DM+$t\bar{t}$ searches. The benchmark chosen for these searches follows the assumptions mentioned in the previous Section: we consider a Dirac fermion DM particle, universal couplings to quarks, and minimum mediator width.

The benchmark points scanning the model parameters have been selected to ensure that the kinematic features of the parameter space are sufficiently represented. Detailed studies were performed to identify points in the $m_{\rm DM}$, $m_{\phi,a}$, $g_{\rm DM}$, $g_{\rm q}$ (and $\Gamma_{\phi,a}$) parameter space that differ significantly from each other in terms of expected detector acceptance. Because missing transverse momentum is the key observable for searches, the mediator p_T spectra is taken to represent the main kinematics of a model. Another consideration in determining the set of benchmarks is to focus on the phase space where we expect the searches to be sensitive during the 2015 LHC run. Based on a projected integrated luminosity of 30 fb^{-1} expected for 2015, we disregard model points with a cross section times branching ratio smaller than 0.1 fb.

4.3.2 *Parameter scan*

The kinematics is most dependent on the masses $m_{\rm DM}$ and $m_{\phi,a}$. Figure 4.1 and 4.2 show typical dependencies for scalar and pseudoscalar couplings respectively. Typically, the mediator p_T spectra broadens with larger $m_{\phi,a}$. The kinematics are also quite different between on-shell and off-shell production. Furthermore, the kinematic differences between scalar and pseudoscalar are large with light mediator masses and are reduced for larger masses. It is therefore important to benchmark points covering on-shell and off-shell production with sufficient granularity.

Typically only weak dependencies on width or equivalently couplings are observed (see Fig 4.4), except for large mediator masses of ~ 1.5 TeV or for very small couplings of $\sim 10^{-2}$. These regimes where width effects are significant have production cross sections

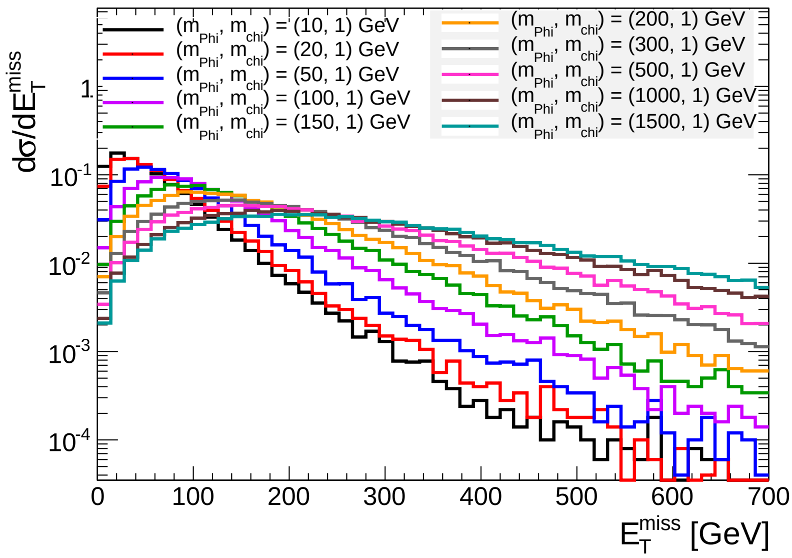


Figure 4.1: Example of the dependence of the kinematics on the scalar mediator mass. The Dark Matter mass is fixed to be 1GeV.

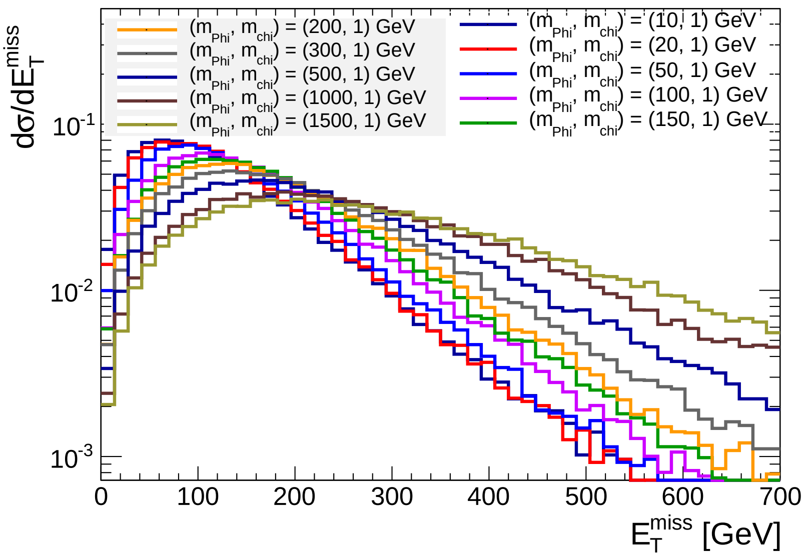


Figure 4.2: Example of the dependence of the kinematics on the pseudoscalar mediator mass. The Dark Matter mass is fixed to be 1GeV.

that are too small to be relevant for 30 fb^{-1} and are not considered here. However, with the full Run-2 dataset, such models may be within reach. The weak dependence on the typical width values can be understood as the parton distribution function are the dominant effect on mediator production. In other words, for couplings $\sim O(1)$ the width is large enough that the p_T of the mediator is determined mainly by the PDF.

Another case where the width can impact the kinematics is when $m_{\phi,a}$ is slightly larger than $2m_\chi$. Here, the width determines the relative contribution between on-shell and off-shell production. An

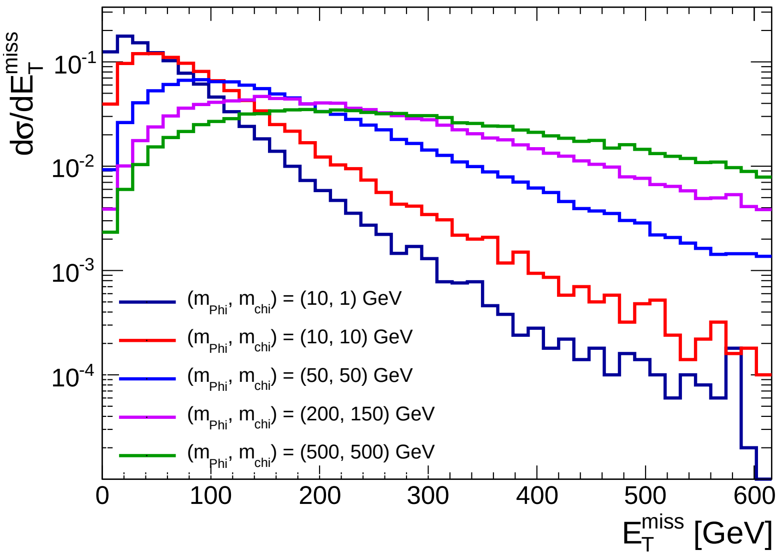


Figure 4.3: Example of the dependence of the kinematic for points of the grid proposed in Tab. 3.2 close to the $m_{\phi,a} \sim 2m_\chi$ limit.[3]

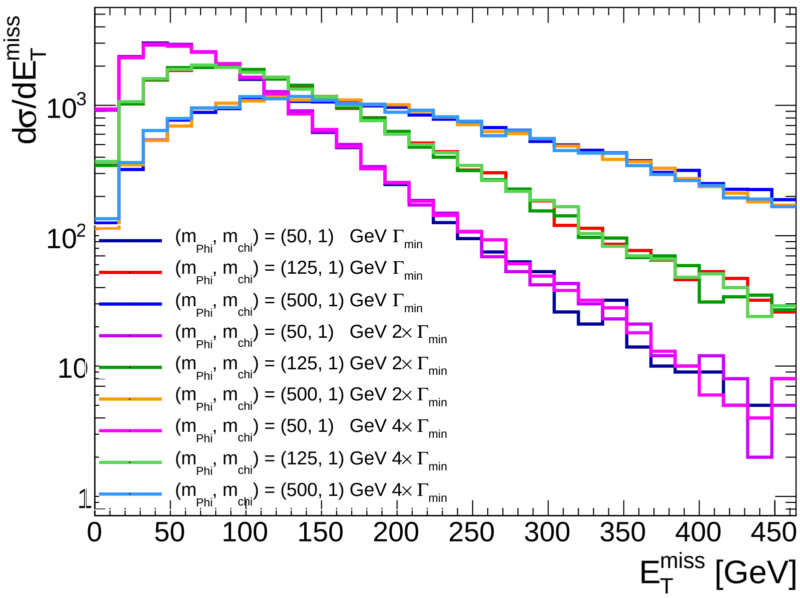


Figure 4.4: Study of the dependence of kinematics on the width of a scalar mediator. The width is increased up to four times the minimal width for each mediator and dark matter mass combination.

example is given in Fig. 4.5. In our recommendations we propose to use for simplicity the minimal width, as this is represents the most conservative choice to interpret the LHC results. **[TODO: mention larger widths too]**

Given that the kinematics are similar for all couplings $\sim O(1)$, we recommend to generate only samples with $g_{\rm DM} = g_{\rm q} = 1$. It follows from this that these benchmark points should be a good approximation for non-unity couplings and for $g_{\rm DM} \neq g_{\rm q}$, provided that the sample is rescaled to the appropriate cross section times

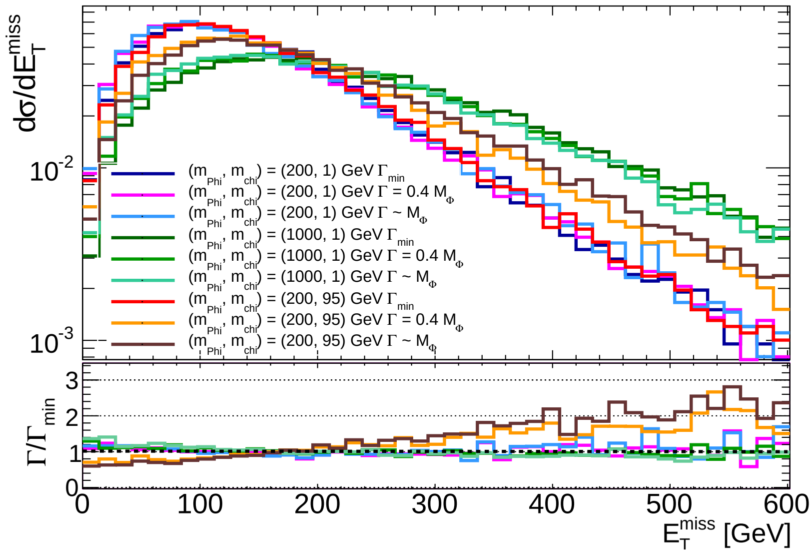


Figure 4.5: Dependence of the kinematics on the width of a scalar mediator. The width is increased up to the mediator mass. Choices of mediator and dark matter masses such that $m_{\phi,a}$ is slightly larger than $2m_\chi$ is the only case that shows a sizeable variation of the kinematics as a function of the width.

branching ratio. While the simple scaling function $\sigma' * BR' = [\sigma * BR] * (g'_{\mathrm{q}}/g_{\mathrm{q}})^2 * (g'_{\mathrm{DM}}/g_{\mathrm{DM}})^2 * (\Gamma/\Gamma')$ is sufficient for a limited range of coupling values (see Fig. 4.6 for example), we also choose to provide instead a table of cross section times branching ratio values over a large range of couplings to support interpretation of search results (see the Appendix C). The table lists couplings from $g = 0.1$ to $g = 3.5$, where the upper limit is chosen to close to the perturbative limit.

The points for the parameter scan chosen for this model are listed in Table 3.2, chosen to be harmonized with those for other analyses employing the same scalar model as benchmark. Based on the sensitivity considerations above, DM masses are only simulated up to 500 GeV, leading to a total of 24 benchmark points.

In addition to the considerations discussed in the preceding subsections, very light DM fermions are included ($m_{\mathrm{DM}} = 10\,\mathrm{GeV}$) as this is a region where colliders have a complementary sensitivity to current direct detection experiments.

4.4 *Models with a single top−quark + MET*

Many different theories predict final states with a single top and associated missing transverse momentum (monotop), some of them including dark matter candidates. A simplified model encompassing the processes leading to this phenomenology is described in Refs. [AFM11, AAB+14, BCDF15], and is adopted as one of the benchmarks for Run 2 LHC searches.

A dark matter candidate χ and a new particle M (vector or scalar) are added to the SM, in a theory that respects the $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry and produces a single top quark in association

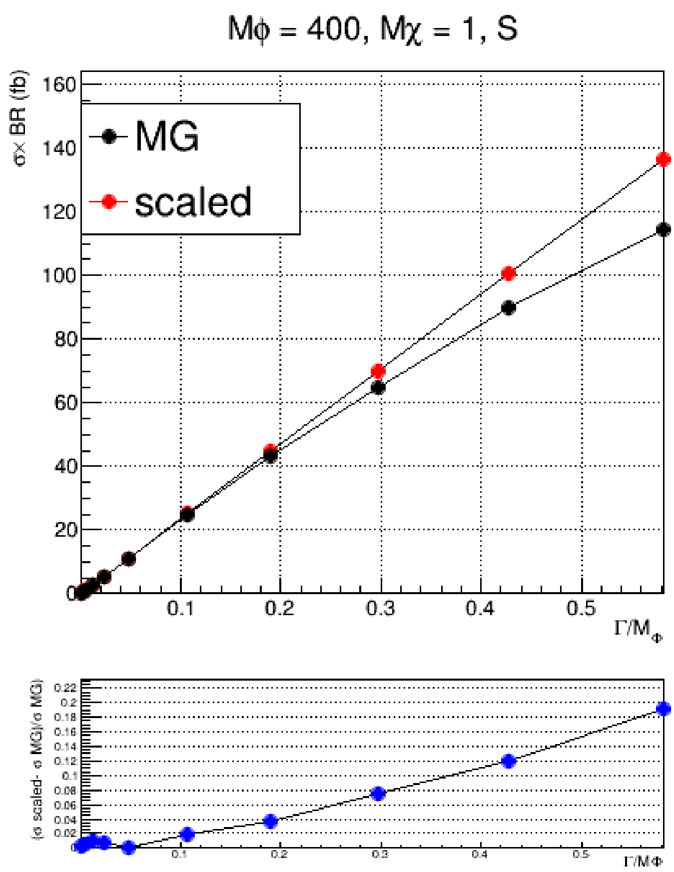


Figure 4.6: An example comparing a simple cross section scaling versus the computation from the generator, for a scalar model with $m_\phi = 400\,\text{GeV}$, $m_{\text{DM}} = 1\,\text{GeV}$ and all couplings set to unity. In this example, the scaling relationship holds for Γ_ϕ / m_ϕ below 0.2, beyond which finite width effects become important and the simple scaling breaks down.

with either the DM particle or a new particle decaying invisibly.

Within this model, two distinct processes can lead to monotop production:

- resonant production, as shown in the diagram of Fig. 4.7 (a), where a scalar (S in the figure, φ in the following) or vector (X) field are exchanged in the s-channel, and decay into the a spin 1/2 invisible DM candidate (called f_{met} in the figure) and a top quark;
- non-resonant production, as shown in the diagrams of Fig. 4.7 (b) and (c), where a flavor-changing interaction produces a top quark in association with a new colored scalar (Φ) or vector (V). The new colored particles, called v_{met} in the figure, decay invisibly, e.g. to a pair of DM particles. v_{met} can also decay into a top quark and an up quark, leading to a same-sign top quark final state; a detailed study of the complementarity of this signature is beyond the scope of this Forum report.

In the following, resonant and non-resonant production are treated independently as separate benchmarks. Only the case of

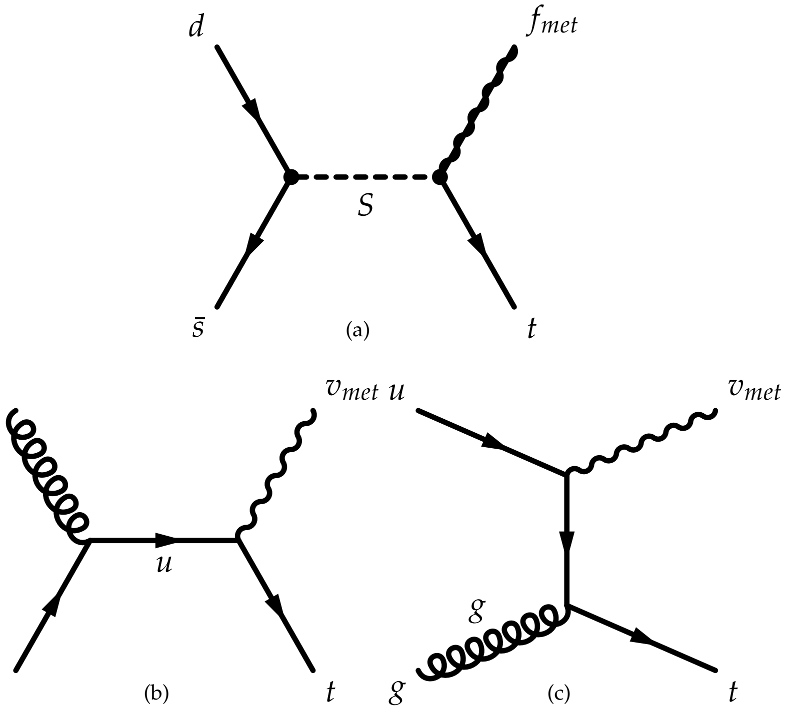


Figure 4.7: Feynman diagram of leading order processes leading to monotop events: production of a coloured scalar resonance S decaying into a top quark and a spin-1/2 fermion f_{met} (a), $s-$ (b) and t-channel (b) non resonant production of a top quark in association with a spin-1 boson v_{met}.

a scalar resonance is considered for the resonant model, while the case of vector resonances is left for future studies.

Resonant production

In this case, a colored 2/3-charged scalar ($\varphi^{\pm}$) is produced resonantly and decays into a top quark and a spin-1/2 invisible particle, χ. The dynamics of the new sector is described by the following Lagrangian:

$$\begin{aligned}\mathcal{L} = \Big[& \varphi \bar{d}^c \left[a^q_{SR} + b^q_{SR}\gamma_5 \right] d + \varphi \bar{u} \left[a^{1/2}_{SR} + b^{1/2}_{SR}\gamma_5 \right] \chi \\ & + X_\mu \bar{d}^c \gamma^\mu \left[a^q_{VR} + b^q_{VR}\gamma_5 \right] d + X_\mu \bar{u} \gamma^\mu \left[a^{1/2}_{VR} + b^{1/2}_{VR}\gamma_5 \right] \chi + \text{h.c.} \Big]\end{aligned} \tag{4.3}$$

where u (d) stands for any up-quark ($down$-quark), the index S (V) stands for scalar (vector) field, and the index q runs over the three quark generations.

In the notation of [AAB+14], the couplings of the new colored fields to down-type quarks are embedded into the 3×3 matrices $a^q_{\{S,V\}R}$ (scalar/vector couplings) and $b^q_{\{S,V\}R}$ (pseudoscalar/axial vector couplings) while those to the DM candidate χ and one single up-type quarks are given by the three-component vectors $a^{1/2}_{\{S,V\}R}$ and $b^{1/2}_{\{S,V\}R}$ in flavor space.

In the following, we only consider the model with a new colored scalar, as the requirement of invariance under $SU(2)_L X U(1)_Y$ would require the introduction of further particles in the case of a new colored vector [BCDF15].

Non-Resonant production

For the non-resonant production, the top quark is produced in association with the new particle: either a new scalar (ϕ) or a new vector (V). For simplicity, we only consider the case of a vector new particle, as the scalar case would involve a mixing with the SM Higgs boson and therefore a larger parameter space. The Lagrangian describing the dynamics of the non-resonant case is:

$$\mathcal{L} = \left[\phi \bar{u}\left[a^0_{FC}+b^0_{FC}\gamma_5\right]u+V_\mu\bar{u}\gamma^\mu\left[a^1_{FC}+b^1_{FC}\gamma_5\right]u+\text{h.c.}\right] \tag{4.4}$$

The strength of the interactions among these two states and a pair of up-type quarks is modeled via two 3×3 matrices in flavor space $a^{\{0,1\}}_{FC}$ for the scalar/vector couplings and $b^{\{0,1\}}_{FC}$ for the pseudoscalar/axial vector couplings.

Model parameters and assumptions

The models considered as benchmarks for the first LHC searches contain further assumptions in terms of the flavour and chiral structure of the model with respect to the full Lagrangians of equations (4.3) and (4.4). These assumptions are qualitatively discussed below.

Assumptions in the flavour and chiral structure of the models We only consider right-handed quark components, in order to simplify the model phenomenology. The representation of the left-handed components under the $\mathrm{SU}(2)_L$ symmetry would lead to a coupling to *down*-type quarks, since the effective theory is invariant under $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ gauge symmetry. Having a coupling between the new particle and *down*-type quarks would complicate the collider phenomenology, adding the $V \to b\bar{d} + \bar{b}d$ decay mode in addition to the invisible decay mode. This in turn sets the scalar (vector) and pseudoscalar (axial vector) matrices to have elements of equal values.

Furthermore, in order to be visible at the LHC in the monotop final state, these models must include a strong coupling between the new particle ϕ and $t\chi$. The same kind of assumption exists for the non-resonant production. This means that only the couplings between the new scalar resonance and light quarks (a_{VR}, a_{SR}), and the couplings between the new vector, the top quark and light quarks (a_{FC}), are set to non-zero values

$$(a^q_{VR})_{11} = (a^{1/2}_{VR})_3 = a \tag{4.5}$$

Implementation

This Section describes the notations used in the MadGraph model convention, in term of the ones introduced in the previous Section.

The Madgraph model [Fuk] used for these benchmarks corresponds to the Lagrangian from [AFM11]. Each coupling constant of this model can be set via the parameter card and the blocks which are relevant for the two models used for the experimental searches are described below. The relevant parameters in the MadGraph parameter cards, also expressed in the notation introduced in the previous Section, are as follows for the two models considered.

1. Resonant scalar model described by the Lagrangian (4.3)
   - `AQS` and `BQS`: 3×3 matrices (flavour space) fixing the coupling of the scalar ϕ (S stands for scalar) and *down*-type quarks (Q stands for quarks), previously called a/b_{SR}.
   - `A12S` and `B12S`: 3×1 matrices (flavour space) fixing the coupling of the DM candidate χ (where 12 stands for spin-1/2 fermion) and *up*-type quarks, previously called $a_{VR}^{1/2}$.
   - particle names: the scalar $\phi^{\pm}$ is labeled S and the fermion χ is f_{met}
2. Non-resonant vectorial model described by the Lagrangian (4.4)
   - `A1FC` and `B1FC`: 3×3 matrices (flavour space) fixing the coupling of the vector V (1 stands for vector) and *up*-type quarks, previously called a_{FC}^{0}.
   - particle name: the vector V is labelled v_{met}, while the dark matter candidate χ is not implemented (as this model assumes $\mathrm{BR}(V \to \chi\chi) = 100\%$)

The width of the scalar resonance and of the new vector are set to only the allowed decays in the models, namely a DM candidate and a top quark for the resonant model.

Parameter scan

The relevant parameters for the resonant model are:

- The mass of the new scalar ϕ;
- The mass of the DM candidate χ;
- The coupling of the new scalar to the DM candidate and top quark a, related to the width of the scalar in the minimal width assumption;

The relevant parameters for the non-resonant model are:

- The mass of the new vector V;
- The mass of the DM candidate χ;
- The coupling of the new vector to the up and top quark a, related to the width of the scalar in the minimal width assumption;
- The coupling of the new vector to the DM candidate χ, related to the branching fraction of the vector into invisible and visible particle, and as a consequence to the width of the vector.

It has been checked for the non-resonant model that the relevant kinematics does not change when changing the width of the resonance. Figures 4.8, 4.9 and 4.10 show the V mass distribution, the transverse momentum for V and for the top quark from the $V \to t\bar{u}$ decay, for different V masses and widths. These figures are relevant independently of the V decay mode (be it visible or invisible).

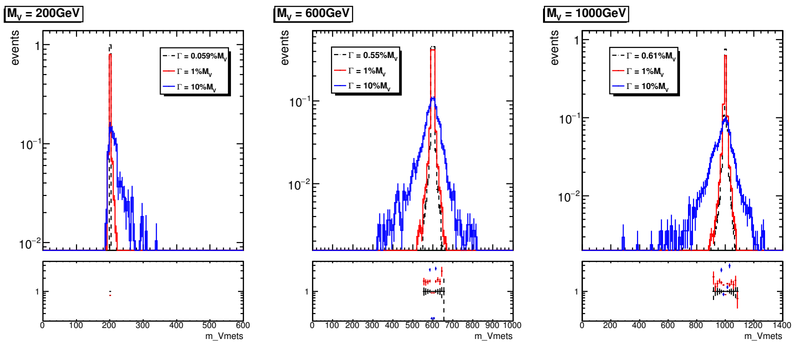


Figure 4.8: Distribution of V invariant mass for the $gu \to tV(\to t\bar{u})$ (on-shell V) for m_V = 200, 600, 1000 GeV (from left to right) and for three different visible decay width (computed from Madgraph directly according to the allowed decays and their couplings, 1% and 10%).

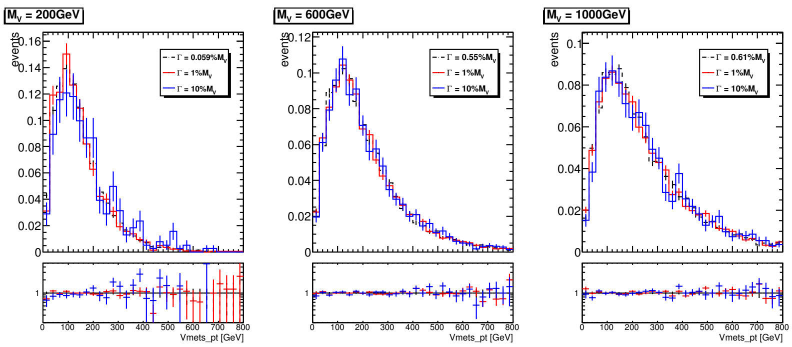


Figure 4.9: Distribution of the V p_T for the $gu \to tV(\to t\bar{u})$ (on-shell V) for m_V = 200, 600, 1000 GeV (from left to right) and for three different visible decay width (computed from Madgraph directly, 1% and 10%).

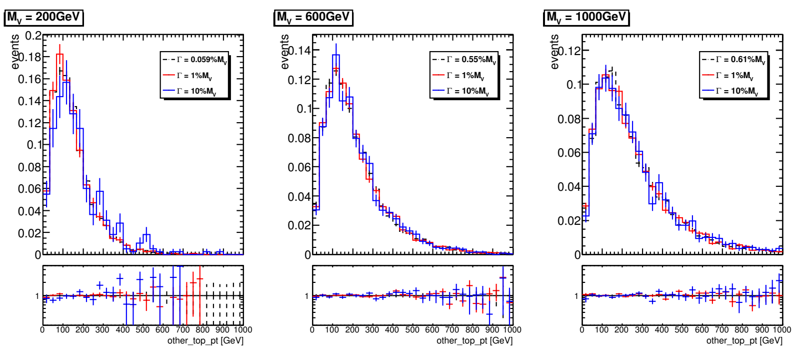


Figure 4.10: Distribution of the top quark p_T produced in association with V in $gu \to tV$ for m_V = 200, 600, 1000 GeV (from left to right) and for three different visible decay width (computed from Madgraph directly, 1% and 10%).

The limited timescale allowed to reach a consensus for the recommendations contained in this document has not allowed further studies on the parameter scan of these models. The two Collaborations have however agreed to continue studying these models and agree on a common parameter scan, following the same path as for other models described in this document.

5
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 some are demanded by gauge coupling relations in models where the gluon provides the experimentally detectable signature, and also as stand-alone models with final states that cannot be generated by the models in Section 3.

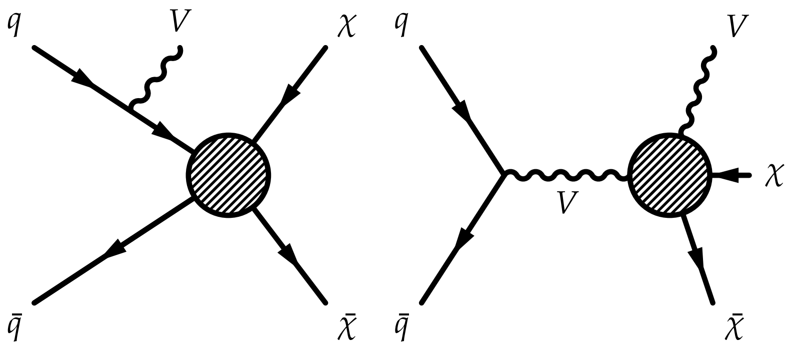


Figure 5.1: Sketch of benchmark models including a contact interaction for V+MET searches, adapted from [NCC+14].

The models considered can be divided in four categories:

Models including a contact operator, where the boson is radiated from the initial state

As depicted in the top diagram of Figure 5.1, these models follow the nomenclature and theory for the EFT benchmarks commonly used by MET+X searches [GIR+10]. These models have been used in past experimental searches [Kha14, Aad14b, K+14, Aad14b, A+14a, Aad14a], and they will not be described here.

Models including a contact operator, where the boson is directly coupled to DM

Shown in the bottom of Figure 5.1, these models allow for a contact interaction vertex that directly couples the boson to Dark Matter.

Simplified models with a boson radiated either from the initial state or from the mediator

These models follow those already described in Section 3, replacing the 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 vector or to a new scalar [CDM+14, BLW14].

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. 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, detailed in Appendix B.

The scan in the parameters that characterize this simplified model for EW boson + MET searches follow what already detailed in Section 3.

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 the generator-level cuts from Ref. [Aad15] for the photon+MET analysis, but raising the photon p_T cut to 150 GeV is shown in Figure 5.2, comparing a width that is set to $\Gamma = M_{med}/3$ to the minimal width (the ratio between the two widths ranges from 1.05 to 1.5 with increasing mediator masses).

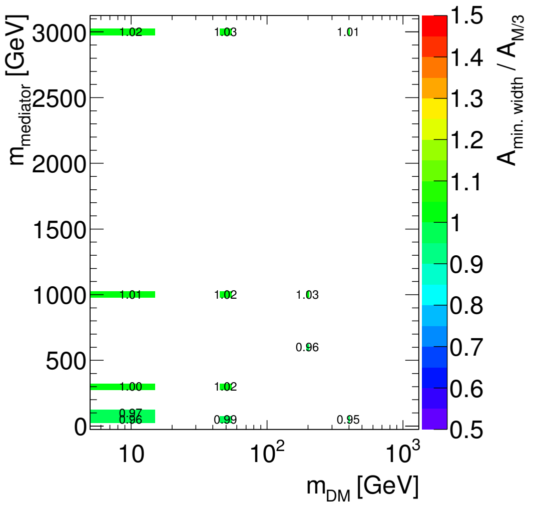
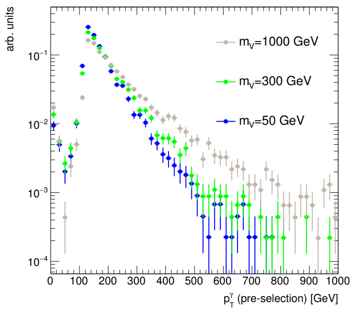


Figure 5.2: Analysis acceptance for the photon+MET analysis when varying the mediator width, in the case of a vector mediator exchanged in the $s-$channel

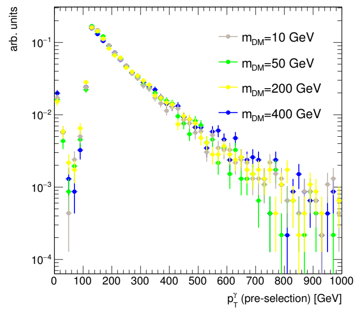
Examples of relevant kinematic distributions for selected benchmark points are shown in Fig. 5.7; leading-order cross-sections for the chosen benchmark points are shown in Table **?? [TODO: Insert table of cross-sections]**.

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.]**



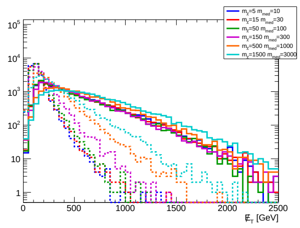
(a) Missing transverse momentum distribution for the photon+MET final state, for different mediator mass choices, for a DM mass of 10 GeV.



(b) Leading photon transverse momentum distribution for the photon+MET final state, for different DM mass choices, with a mediator mass of 1 TeV.

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

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



(e) Missing transverse momentum distribution for the hadronic W+MET final state.

Figure 5.3: 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.

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 [CHLR13].

The lowest dimension benchmark operators we may consider are effective dimension 5. Following the notation of [CNS+13], models from this category have a Lagrangian that includes terms such as:

$$\frac{m_W^2}{\Lambda_5^3}\,\bar{\chi}\chi\,W^{+\mu}W_\mu^- + \frac{m_Z^2}{2\Lambda_5^3}\,\bar{\chi}\chi\,Z^\mu Z_\mu\,. \tag{5.1}$$

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. Note that these operators are of true dimension 7, but reduce to effective dimension 5 once Higgs vevs, contained in the W and Z mass terms, are inserted. As such , one expects these that operators would naturally arise in UV complete models where Dark Matter interacts via a Higgs portal where heavy mediators would couple to the Higgs or other fields in an extended Higgs sector. In such models the full theory may be expected to contain additional operators with Higgs-Dark Matter couplings. Concentrating for the moment on mono-gauge boson signals, the above 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. 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 contain the $SU(2)_L \times U(1)_Y$ gauge-invariant couplings between DM fields and the kinetic terms of the EW bosons. The CP-conserving scalar couplings of this type can be written as

$$\frac{c_1}{\Lambda_S^3}\,\bar{\chi}\chi\, B_{\mu\nu}B^{\mu\nu} + \frac{c_2}{\Lambda_S^3}\,\bar{\chi}\chi\, W^i_{\mu\nu}W^{i,\mu\nu}\,. \tag{5.2}$$

Here $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ and $W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g_2\epsilon^{ijk}W^j_\mu W^k_\mu$ are the $U(1)_Y$ and $SU(2)_L$ field strength tensor, respectively, and g_2 denotes the weak coupling constant. In the case of the pseudoscalar couplings, one has instead

$$\frac{c_1}{\Lambda_P^3}\,\bar{\chi}\gamma_5\chi\, B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{c_2}{\Lambda_P^3}\,\bar{\chi}\gamma_5\chi\, W^i_{\mu\nu}\tilde{W}^{i,\mu\nu}\,, \tag{5.3}$$

where $\tilde{B}_{\mu\nu} = 1/2\,\epsilon_{\mu\nu\lambda\rho}B^{\lambda\rho}$ and $\tilde{W}^i_{\mu\nu} = 1/2\,\epsilon_{\mu\nu\lambda\rho}W^{i,\lambda\rho}$ are the dual field strength tensors. In addition to the CP-conserving interactions (5.2) and (5.3), there are also four CP-violating couplings that are obtained from the above operators by the replacement $\bar{\chi}\chi \leftrightarrow \bar{\chi}\gamma_5\chi$.

The effective interactions introduced in (5.2) and (5.3) appear in models of Rayleigh DM [**?**]. Ultraviolet completions where the operators are generated through loops of states charged under $U(1)_Y$ and/or $SU(2)_L$ have been proposed in [**?**] and their LHC signatures have been studied in [**?**]. If these new charged particles are light, the high-p_T gauge bosons that participate in the MET processes considered here are able to resolve the substructure of the loops. This generically suppresses the cross sections compared to the EFT predictions [**?**], and thus will weaken the bounds on the interaction strengths of DM and the EW gauge bosons to some extent. Furthermore, the light charged mediators may be produced on-shell in pp collisions, rendering direct LHC searches potentially more restrictive than MET searches. Making the above statements precise would require further studies beyond the timescale of this forum.

Since for $\Lambda_S = \Lambda_P$ the effective interactions (5.2) and (5.3) predict essentially the same value of the mono-photon, mono-Z and mono-W cross section [CNS$^+$13, CHH15], we consider below only the former couplings. We emphasise however that measurements of the jet-jet azimuthal angle difference in MET+$2j$ events may be used to disentangle whether DM couples more strongly to the combination $B_{\mu\nu}B^{\mu\nu}$ ($W^i_{\mu\nu}W^{i,\mu\nu}$) or the product $B_{\mu\nu}\tilde{B}^{\mu\nu}$ ($W^i_{\mu\nu}\tilde{W}^{i,\mu\nu}$) of field strength tensors [CHLR13, CHH15].

After EW symmetry breaking the interactions (5.2) induce direct couplings between pairs of DM particles and gauge bosons. The corresponding Feynman rule reads

$$\frac{4i}{\Lambda_S^3}\, g_{V_1V_2}\left(p_1^{\mu_2}p_2^{\mu_1} - g^{\mu_1\mu_2}\, p_1\cdot p_2\right), \tag{5.4}$$

where p_i (μ_i) denotes the momentum (Lorentz index) of the vector field V_i and for simplicity the spinors associated with the DM fields have been dropped. The couplings $g_{V_iV_j}$ take the form

$$\begin{aligned} g_{\gamma\gamma} &= c_w^2 c_1 + s_w^2 c_2\,, \\ g_{\gamma Z} &= -s_w c_w\left(c_1 - c_2\right), \\ g_{ZZ} &= s_w^2 c_1 + c_w^2 c_2\,, \\ g_{WW} &= c_2\,, \end{aligned} \tag{5.5}$$

with s_w (c_w) the sine (cosine) of the weak mixing angle. Note that our coefficients c_1 and c_2 are identical to the coefficients C_B and C_W used in [CHH15], while they are related via $k_1 = \frac{1}{{c_w}^2}c_1$ and $k_2 = \frac{1}{{s_w}^2}c_2$ to the coefficients k_1 and k_2 introduced in [CNS+13].

The coefficients c_1 and c_2 appearing in (5.5) determine the relative importance of each of the MET channels and their correlations. For example, one observes that:

- Only c_2 enters the coupling between DM and W bosons, meaning that only models with $c_2 \neq 0$ predict a mono-W signal;

- If $c_1 = c_2$ the mono-photon (mono-Z) signal does not receive contributions from diagrams involving Z (photon) exchange;

- Since numerically $c_w^2/s_w^2 \simeq 3.3$ the mono-photon channel is particularly sensitive to c_1.

As shown in Fig. 5.4 kinematics of this model can be approximated by that of a simplified model including a high-mass scalar mediator exchanged in the s-channel. For this reason, the list of benchmark models with direct boson-DM couplings only includes dimension 7 operators. **[TODO: then we need to recommend the scalar mediator, but then the sensitivity is very poor wrt monojets - however, I still prefer to generate a few (high-mass) simplified model points wrt an EFT if given the choice.]**

The kinematic distributions for dimension-7 scalar and pseudoscalar operators only shows small differences, as shown in Fig. 5.5.

Similarly, the differences in kinematics for the various signatures are negligible when changing the coefficients k_1 and k_2, as shown in Figure **??**. Only the case $k_1 = k_2 = 1$ is generated as benchmark; other cases are left for reinterpretation as they will only need

Figure 5.4: 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

Figure 5.5: 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

(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.

Figure 5.6: 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.

a rescaling of the cross-sections shown in Table **?? [TODO: add tables with cross sections]** for the various Dark Matter mass points considered.

Examples of relevant kinematic distributions for selected benchmark points are shown in Fig. 5.7.

Completion and validity of EW contact operators **[TODO: mention here discussion with Liantao yesterday]**

As an example of a simplified model corresponding to the

(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 5.7: 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.

dimension-5 EFT operator described above, we consider a Higgs portal with a scalar mediator. Models of this kind are among the most concise versions of simplified models that produce couplings of Dark Matter to pairs of gauge-bosons. Scalar fields may couple directly to pairs of electroweak gauge bosons, but must carry part of the electroweak vev. One may thus consider a simple model where Dark Matter couples to a a scalar singlet mediator, which mixes with the fields in the Higgs sector.

$$L \subset m_s S^2 + \lambda S^2 H^2 + \lambda^{'} S H^2 + y S \chi \overline{\chi} \tag{5.6}$$

Where H is a field in the Higgs sector that contains part of the electroweak vev, S is a heavy scalar singlet and χ is a Dark Matter field. There is then an S channel diagram where DM pairs couple to the singlet field S, which then mixes with a Higgs-sector field, and couples to W and Z bosons. This diagram contains 2 insertions of EW symmetry breaking fields, corresponding in form to the effective dimension-5 operator in the previous section.

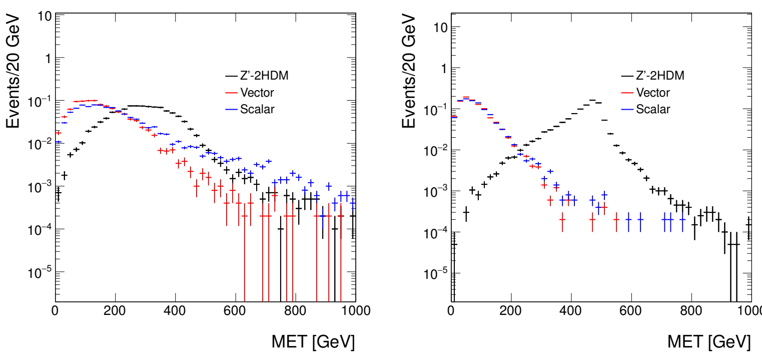
Model implementation The model can be found on the Forum SVN repository [?].

SPECIFIC SIMPLIFIED MODELS INCLUDING EW BOSONS

Three benchmark simplified models [CDM+14, BLW14] are recommended for MET+Higgs searches:

- A model where a vector mediator (Z'_B) is exchanged in the $s-$channel, radiates a Higgs or a Z boson and decays into two DM particles;
- A model where a scalar mediator S couples to the SM only through the SM Higgs and decays to two DM particles;
- A model where a vector Z' is produced resonantly and decays into a Higgs boson plus an intermediate heavy pseudoscalar particle A^0, in turn decaying into two DM particles.

These models have a distinct kinematics, as shown in the comparison of the MET spectra in Fig. 5.8, for high and low mediator masses. Figure **??** shows the MET distribution for models with high mediator masses ($m_S = 1$ TeV, $m_{Z'} = 1$ TeV, $m_{A0} = 1$ TeV) and DM mass of either 50 (Z'_B and A^0 models) or 65 GeV (scalar mediator model). Figure **??** shows the MET distribution for models with low mediator masses ($m_{Z'_B} = 100$ GeV, $m_{Z'} = 1$ TeV, $m_{A0} = 100$ GeV) and DM mass of 1 TeV for all models. **[TODO: Is this sufficient to justify testing them all? Not clear which one should be prioritized.]**



(a) High mediator mass

(b) Low mediator mass

Figure 5.8: Comparison of the missing transverse momentum distributions at generator level in different simplified models leading to a Higgs+MET signature. The model parameter settings are detailed in the text.

MET+Higgs from a baryonic Z' **[TODO for AB: add baryonic Higgs diagram]**

The first model, shown in Fig. **??** postulates a new gauge boson Z' corresponding to a new $U(1)_B$ baryon number symmetry. The stable baryonic states included in this model are the DM candidate particles. The mass of the Z' boson is acquired through a baryonic Higgs h_B, which mixes with the SM Higgs boson. The interactions between the Z', the quarks and the DM are described by the following Lagrangian:

$$L = g_q \bar{q}\gamma^\mu q Z'_\mu + g_\chi \bar{\chi}\gamma^\mu \chi Z'_\mu. \tag{5.7}$$

The quark couplings g_q are fixed to be equal to one third of the gauge coupling g_B, while the DM coupling to the Z' are proportional to the baryon number and to the gauge coupling ($g_{chi} = B g_B$). No leptonic couples of the Z' are allowed, thus evading dilepton constraints. After incorporating the mixing of the baryonic and SM Higgs bosons, this model is is described by the following Lagrangian term at energies below $m_{Z'}$:

$$L_\mathrm{eff} = -\frac{g_q g_\chi}{m_{Z'}^2}\bar{q}\gamma^\mu q \bar{\chi}\gamma_\mu \chi \left(1 + \frac{g_{hZ'Z'}}{m_{Z'}^2} h\right), \tag{5.8}$$

The first term of this equation gives rise to a term that is equivalent to the radiation of a jet (or another EW gauge boson) in the initial state. The second term describes the interaction between the Z' and the SM Higgs boson, via the coupling $g_{hZ'Z'} = \frac{m'^2_Z sin\theta}{v_B}$, where $sin\theta$ is the mixing angle between the Higgs and the Z' and v_B is the Baryonic Higgs vev.

[TODO: 1- Mention sensitivity difference wrt monojet? 2- Mention why we don't consider the dark Z model?]

Parameter scan

Overall, this model is described by six parameters:

1. the mediator mass m_med, (also referred to as $m_{Z'}$)
2. mass of dark matter, m_{DM}
3. coupling of Z' mediator to dark matter, g_DM
4. coupling of the mediator to quarks, g_q
5. mixing angle between baryonic Higgs and SM-like Higgs boson, $\sin\theta$
6. coupling of the mediator to SM-like Higgs boson, $g_{hZ'Z'}$

The width of the mediator is calculated using all possible decays, namely to quarks, to pairs of DM particles if kinematically allowed,

The dependence of the missing transverse momentum (MET) on the model parameters is studied by varying the parameters one at a time. The variation of parameters other than m_{med} and m_{DM} does not result in significant variations of the MET spectrum, as shown in Figures 5.9. Figure 5.10 shows that for an on-shell mediator, varying m_{DM} with the other parameters fixed does not affect the MET distribution, while the distribution broadens significantly in the case of an off-shell mediator. For this reason, the same grid in m_med, m_DM as for the vector mediator of the jet+MET search (Table **??**) is chosen as a starting point. The coupling between mediator and SM Higgs boson $g_{hZ'Z'}/m_\mathrm{med}$ and the mediator-DM coupling g_DM are fixed to 1, the mediator-quark g_q coupling is fixed to 1/3. Other parameter values can be recasted starting from the results for those model parameters. More detailed studies are required to estimate the reach of the analysis with respect to all points in the grid and therefore decide on a smaller set of grid points to be generated; those are left to the individual analyses. **[TODO: can we get sensitivity to all the points for all signatures?]**

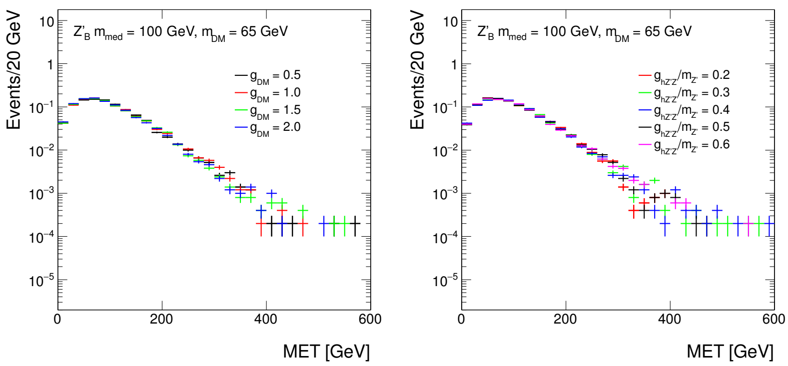


Figure 5.9: Missing transverse momentum distributions at generator level in the vector mediator scenario for different values of: the mediator-dark matter coupling g_{DM} (left), and the coupling between the mediator and the SM-like Higgs boson, scaled by the mediator mass, $g_{hZ'Z'}/m_{Z'}$ (right).

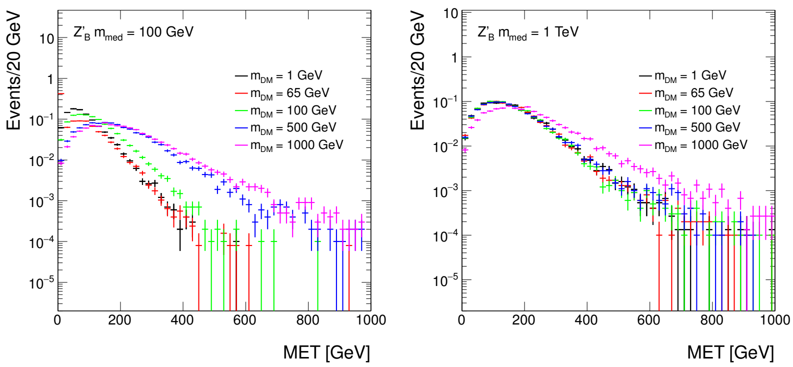


Figure 5.10: Missing transverse momentum distributions at generator level in the vector mediator scenario: for different values of the dark matter mass m_{DM} and a mediator mass of m_{med} = 100 GeV (left) and m_{med} = 1 TeV (right).

Cross-section scaling (to be added)

Model implementation

[SVN repo and MG details to be added here]

MET+Higgs from a scalar mediator A real scalar singlet S coupling to DM can be introduced as a portal between SM and the dark sector through the Higgs field. The new scalar mixes with the SM Higgs boson, and couples to DM through a Yukawa term y_χ. The relevant Lagrangian terms for this model are:

$$L \supset -y_\chi \bar{\chi}\chi(cos\theta S - sin\theta h) - \frac{m_q}{v}\bar{q}q(cos\theta h + sin\theta S) \qquad (5.9)$$

where θ is the mixing angle between the Higgs boson and the new scalar. Mono-Higgs signals arise **[TODO: add the Lagrangian explaining why g_b is there]**

Parameter scan

This model is described by five parameters:

1. the Yukawa coupling of heavy scalar to dark matter (DM), g_{DM} (also referred to as y_χ)

2. the mixing angle between heavy scalar and SM-like Higgs boson, $\sin\theta$

3. the new physics coupling, g_b

4. mass of heavy scalar, m_{med}

5. mass of dark matter, m_{DM}

The mixing angle is constrained from current Higgs data to satisfy $\cos\theta = 1$ within 10% and therefore $\sin\theta \lesssim 0.4$. This provides a starting point for the parameter scan in this model: we recommend to set $\sin\theta = 0.3$. Figure 5.12 shows that there is no dependence of the kinematics from the value of this angle, and different values can be obtained via rescaling the results for this mixing angle according to the cross-section. It can also be observed from Figures 5.13 and 5.11 that the kinematics of this model follows that of the equivalent jet+MET model: only small changes are observed in the on-shell region, while the relevant distributions diverge when the mediator is off-shell. For this reason, the same grid in m_{med}, m_{DM} as for the scalar mediator of the jet+MET search (Table **??**) is chosen as a starting point. The Yukawa coupling to DM y_{DM} is set to 1, the new physics coupling between scalar and SM Higgs b = 3. Results for other values can be obtained via a rescaling of the results for these parameters. More detailed studies are required to estimate the reach of the analysis with respect to all points in the grid and therefore decide on a smaller set of grid points to be generated; those are left to the individual analyses. **[TODO: can we get sensitivity to all the points for all signatures?]**

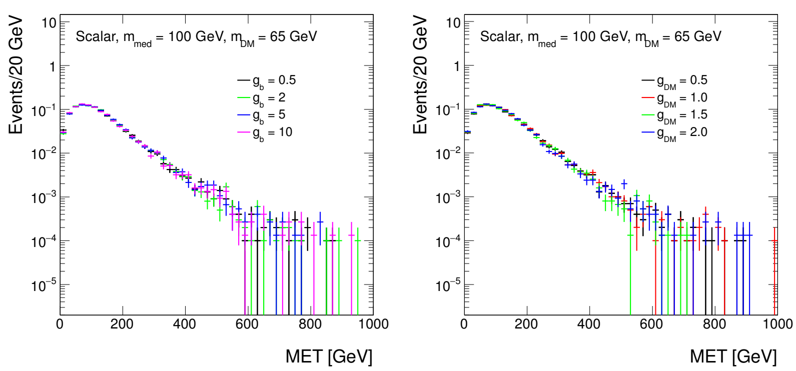


Figure 5.11: Missing transverse momentum distributions at generator level in the scalar mediator scenario, for different values of: the new physics coupling g_b (left), and the mediator-dark matter coupling g_{DM} (right).

Cross-section scaling (to be added)

Model implementation

The Madgraph parameter cards can be found on the Forum repository. In this model, the contribution from the $ggh S$ box is included through an effective Lagrangian evaluated in the large m_t limit. This may overestimate the rates of $h + \not{E}_T$ signal [**?**], but a full evaluation is left to future studies. The parton shower for these models is implemented in Pythia. It is recommended to let Pythia decay the Higgs boson, in order to make the BR consistent with HDECAY.

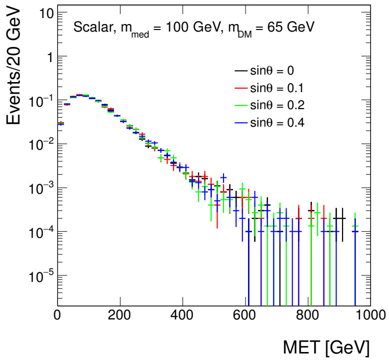


Figure 5.12: Missing transverse momentum distributions at generator level in the scalar mediator scenario: for different values of the mixing angle $\sin\theta$.

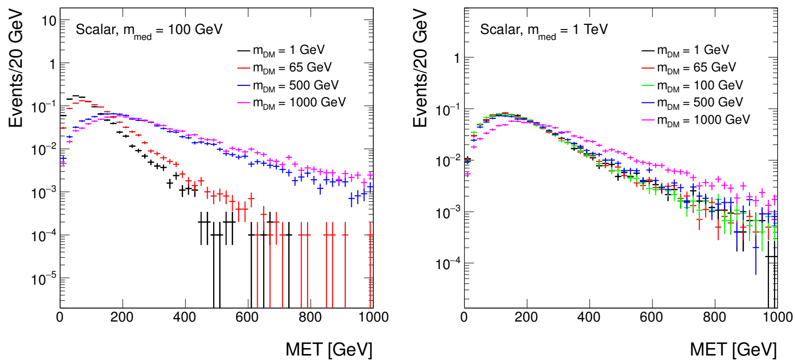


Figure 5.13: Missing transverse momentum distributions at generator level in the scalar mediator scenario: for different values of the dark matter mass m_{DM} and a mediator mass of m_{med} = 100 GeV (left) and m_{med} = 1 TeV (right).

Higgs+MET signal from 2HDM model with a Z' and a new pseudoscalar

In this simplified model [BLW14], a new Z' resonance decays to a Higgs boson h plus a heavy pseudoscalar state A in the 2HDM framework, which in turn decays to a DM pair. The motivation for coupling the dark matter to the pseudoscalar is that dark matter coupling to higgs or Z' is generically constrained by other signal channels and direct detection. An advantage of including this model is that it has different kinematics due to the on-shell Z' production, where for heavy Z' masses the MET and pT spectra are much harder. This model can satisfy electroweak precision tests and constraints from dijet resonance searches, and still give a potentially observable Higgs+MET signal.

This model comprises two doublets, where Φ_u couples to up-type quarks and Φ_d couples to down-type quarks and leptons:

$$-\mathcal{L} \supset y_u Q\tilde{\Phi}_u \bar{u} + y_d Q\Phi_d \bar{d} + y_e L\Phi_d \bar{e} + \text{h.c.} \tag{5.10}$$

After electroweak symmetry breaking, the Higgs doublets attain vevs v_u and v_d, and in unitary gauge the doublets are parametrized as

$$\begin{aligned} \Phi_d &= \frac{1}{\sqrt{2}} \begin{pmatrix} -\sin\beta\ H^+ \\ v_d - \sin\alpha\ h + \cos\alpha\ H - i\sin\beta\ A^0 \end{pmatrix} , \\ \Phi_u &= \frac{1}{\sqrt{2}} \begin{pmatrix} \cos\beta\ H^+ \\ v_u + \cos\alpha\ h + \sin\alpha\ H + i\cos\beta\ A^0 \end{pmatrix} \end{aligned} \tag{5.11}$$

where h, H are neutral CP-even scalars and A^0 is a neutral CP-odd scalar. In this framework, $\tan\beta \equiv v_u/v_d$, and α is the mixing angle that diagonalizes the $h - H$ mass squared matrix. We take $\alpha = \beta - \pi/2$, in the limit where h has SM-like couplings to fermions and gauge bosons as per Ref. [**?**], and $\tan\beta \geq 0.3$ as implied from the perturbativity of the top Yukawa coupling. The Higgs vevs lead to $Z - Z'$ mass mixing, with a mixing parameter given by

$$\begin{aligned}\epsilon &\equiv \frac{1}{M_{Z'}^2 - M_Z^2}\frac{g g_z}{2\cos\theta_w}(z_d v_d^2 + z_u v_u^2) \\ &= \frac{(M_Z^0)^2}{M_{Z'}^2 - M_Z^2}\frac{2 g_z \cos\theta_w}{g} z_u \sin^2\beta. \end{aligned} \tag{5.12}$$

The production cross section for this model scales as $(g_z)^2$, as the decay width for this process to leading order in ϵ (Eq. 5.12) is

$$\Gamma_{Z'\to hA^0} = (g_z \cos\alpha\cos\beta)^2 \frac{|p|}{24\pi}\frac{|p|^2}{M_{Z'}^2}. \tag{5.13}$$

where the center of mass momentum for the decay products $|p| = \frac{1}{2M_{Z'}}\lambda^{1/2}(M_{Z'}^2, m_h^2, m_{A^0}^2)$, and λ is the Källen triangle function.

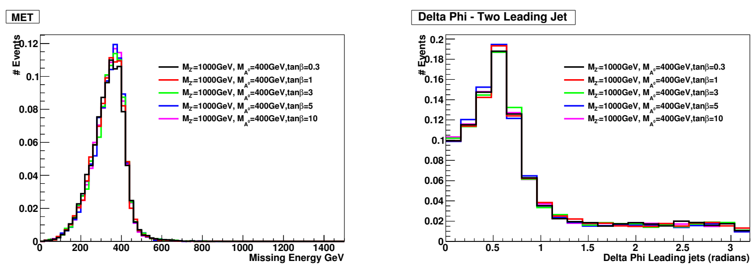
Parameter scan

The model is described by five parameters:

- the pseudoscalar mass M_{A^0},
- the DM mass m_{DM},
- the Z' mass, $M_{Z'}$,
- $\tan\beta (\equiv v_u/v_d)$,
- the Z' coupling strength g_z.

To study the signal production and kinematic dependencies on these parameters, we produced signal samples varying each of the five parameters through MadGraph for the matrix element, PYTHIA for the parton shower, and DELPHES[**?**] for a parameterized detector-level simulation.

As seen in Fig. 5.14, variations of $\tan\beta$ does not lead to any kinematic difference and the production cross section simply scales as a function of $\tan\beta$. Hence we recommend to fix $\tan\beta$ to unity in the signal generation.



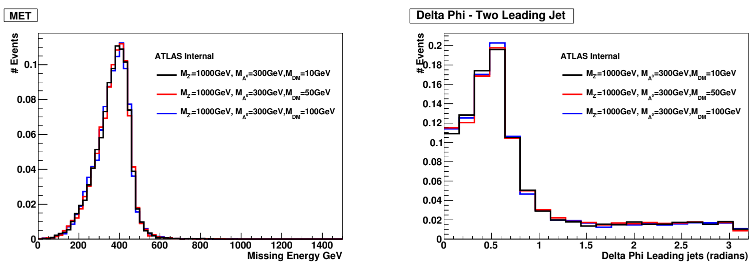
(a) MET distribution

(b) $\Delta\phi$ distance between the two $b-$ jets

Figure 5.14: Kinematic distributions of the signal process varying $\tan\beta$, in the case of a Higgs boson decaying into two b quarks, after parameterized detector simulation: no kinematic dependency is observed

Similarly, variations of g_z do not lead to any kinematic changes. The value of g_z for a given $M_{Z'}$ and $\tan\beta$ can be set according to the maximum value allowed by electroweak global fits and dijet constraints, as described in [BLW14]. Since this parameter does not influence the kinematics, we leave it up to individual analyses on whether they generate benchmark points only according to these external constraints **[TODO: add link to section as in summary. This is the same sentence we will put in for the mono-b model]**.

Since the DM pair are produced as a result of the decay of A^0, there are minimal kinematic changes when varying M_{DM} as long as $M_{DM} < M_{A^0}/2$ so that A^0 production is on-shell, as shown in Fig. 5.15 (before detector simulation). For this reason the DM mass is fixed it to 100 GeV. For two "medium" $M_{Z'}$, M_{A^0} value sets, we vary the DM mass to obtain sample cross section for rescaling results. All LO cross sections for the various parameter scan points are reported in Appendix **??** The parameter scan excludes the off-shell region, as the cross-sections are suppressed and the LHC would not have any sensitivity to these benchmark points in early data.



(a) MET distribution

(b) $\Delta\phi$ distance between the two $b-$ jets

Figure 5.15: Kinematic distributions of the signal process varying M_{DM}: minimal kinematic dependency on M_{DM} as expected when A^0 is produced on-shell. Plots shown for $M_{Z'} = 1000$ GeV, $M_{A^0} = 300$ GeV.

We recommend to produce signal events for a fixed $g_z = 0.8$, $\tan\beta = 1$ and $M_{DM} = 100$ GeV. For these values, we scan the 2-D parameter space of $M_{Z'}, M_{A^0}$ with $M_{Z'} = 600, 800, 1000, 1200, 1400$ GeV, and $M_{A^0} = 300, 400, 500, 600, 700, 800$ GeV with $M_{A^0} < M_{Z'} - m_h$, for a total of 24 points. The choice of scan is justified by the sensitivity study in **??**: the expected LHC sensitivity for Run-2 is up to $M_{Z'} \sim 1.5$ TeV.

The kinematic distributions with varying $M_{Z'}$ for fixed M_{A^0} are shown in Fig. 5.16, while the dependency on M_{A^0} is shown in Fig. 5.17. Both figures include plots before detector simulation.

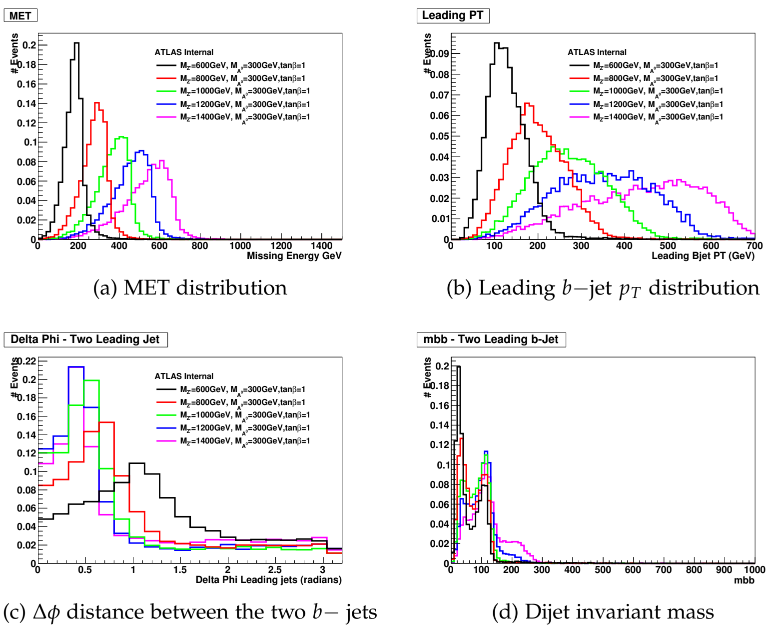
This model also allows for an additional source of Higgs plus MET signal with a similar kinematics (Fig. 5.18, shown with detector simulation samples) to the signal process from the decay of $Z' \to hZ$, where the Z decays invisibly. The partial decay width for the Z' is:

$$\Gamma_{Z' \to hZ} = (g_z \cos\alpha \sin\beta)^2 \frac{|p|}{24\pi} \left(\frac{|p|^2}{M_{Z'}^2} + 3\frac{M_Z^2}{M_{Z'}^2} \right), \tag{5.14}$$

The values for the Z' masses scanned for those samples should follow those of the previous samples, namely values of $M_{Z'} = 600, 800, 1000, 1200, 1400$ GeV.

Model implementation

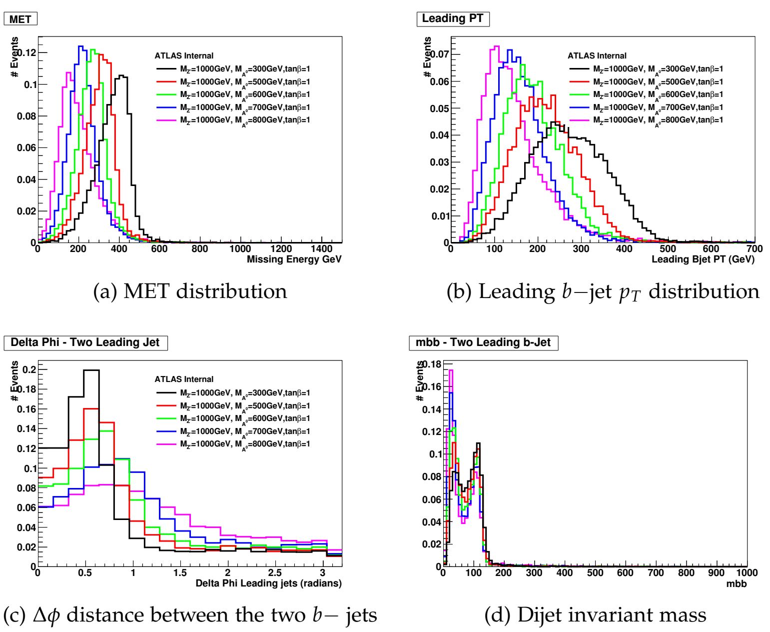
[Ask Yangyang for model / check she hasn't sent it already.]



(a) MET distribution (b) Leading $b-$jet p_T distribution

(c) $\Delta\phi$ distance between the two $b-$ jets (d) Dijet invariant mass

Figure 5.16: Kinematic distributions of the signal process varying $M_{Z'}$, for $M_{DM} = 100$ GeV, $M_{A^0} = 300$ GeV.



(a) MET distribution (b) Leading $b-$jet p_T distribution

(c) $\Delta\phi$ distance between the two $b-$ jets (d) Dijet invariant mass

Figure 5.17: Kinematic distributions of the signal process varying M_{A^0}, for $M_{DM} = 100$ GeV, $M_{Z'} = 1000$ GeV.

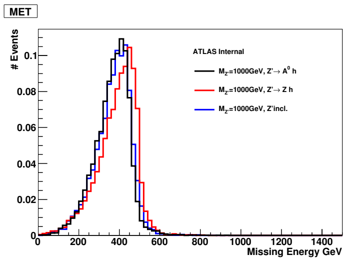
The two couplings that can be changed in the Madgraph model follow the nomenclature below:

- `Tb` - $\tan\beta$
- `gz` - g_z, gauge coupling of Z' to quarks

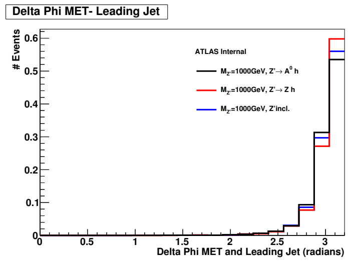
The other couplings are not changed, including `gx` (the $A\bar{\chi}\chi$ coupling) which has little impact on the signal. $\sin\alpha$ is fixed internally such that $\cos(\beta - \alpha) = 0$. The width of the Z' and A can be computed automatically within Madgraph. The couplings here don't affect the signal kinematics, so they can be fixed to default values and then the signal rates can be scaled appropriately.

The nomenclature for the masses in the Madgraph model is:

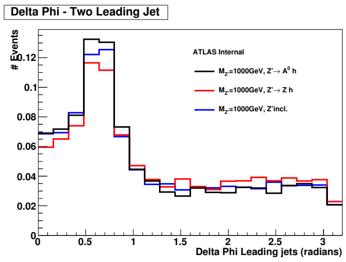
- `MZp` - PDG ID 32 - Z'



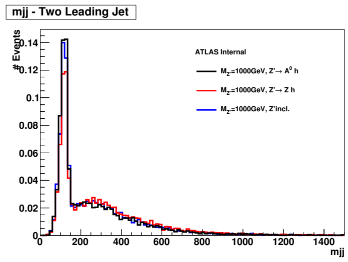
(a) MET distribution



(b) Leading $b-$jet p_T distribution



(c) $\Delta\phi$ distance between the two $b-$ jets



(d) Dijet invariant mass

Figure 5.18: Kinematic distributions of $Z' \to A^0 h$ exclusive production, $Z' \to Zh$ exclusive production and Z' inclusive production for $M_{Z'} = 1000$ GeV and $M_{A^0} = 300$ GeV

- `MA0` - PDG ID 28 - A
- `MX` - PDG ID 1000022 - dark matter particle

Both $Z' \to hZ(\bar{\nu}\nu)$ and $Z' \to hA(\bar{X}X)$ contribute to the final state. They scale differently with model parameters. It is more efficient to generate them separately, and then add together weighted by cross sections. The hZ has no M_A dependence.

In addition, it is recommended not to handle the h decay through MadGraph (which doesn't have the proper h branching ratios), or, if using MadGraph, then the resulting cross section should be rescaled to match onto the correct branching ratio.

6

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].

6.1 *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 $Q_{\rm tr}^2/M^2$, 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

$$\frac{g_{\rm DM} g_q}{Q_{\rm tr}^2 - M^2} = -\frac{g_{\rm DM} g_q}{M^2}\left(1 + \frac{Q_{\rm tr}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M^4}\right)\right) \simeq -\frac{1}{{M_*}^2}, \qquad (6.1)$$

where $Q_{\rm tr}$ is the momentum carried by the mediator, and $g_{\rm DM}$, 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 $Q_{\rm tr}^2 < M^2 = g_{\rm DM} g_q {M_*}^2$.

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

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

$$M_*^{\mathrm{rescaled}} = \left(\frac{\sigma_{\mathrm{EFT}}}{\sigma_{\mathrm{EFT}}^{\mathrm{cut}}} \right)^{1/4} M_*^{\mathrm{original}}, \tag{6.2}$$

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.

6.2 *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 $M_{\rm cut}$, 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 $E_{\rm cm}$, 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 $M_{\rm cut}$,

$$E_{\rm cm} < M_{\rm cut}\,. \tag{6.3}$$

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

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

We can use the same technique as above to restrict the signal to the events for which $E_{\rm cm} < M_{\rm cut}$, using only these events to derive the exclusion limits on M_* as a function of $(m_{\rm DM}, M_{\rm cut})$. We can also define an *effective coupling strength* $M_{\rm cut} = g_*\, M_*$, where g_* is a free parameter that substitutes the parameter $M_{\rm cut}$, and therefore derive exclusions on M_* as a function of $(m_{\rm DM}, g_*)$. 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 $\sqrt{g_{\rm DM} g_q}$. 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_*, $M_{\rm cut}$ 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 $Q_{\rm tr}$ and a specific UV completion.

6.3 *EFT validity recommendations*

6.4 *Recommendation for contact interaction theories with simplified models available*

...to be written...

6.5 *Recommendation for truncation of theories with no simplified models available*

$M_{\text{cut}}$is related to physical couplings and masses only in a UV complete theory, and so is effectively a free parameter. It makes sense to choose M_{cut}such that we identify the transition region where the EFT stops being a good description of UV complete theories. This can be done using R, which is defined as the fraction of events for which $\hat{s} > M_{\text{cut}}^2$.

For large values of M_{cut}, no events are thrown away in the truncation procedure, and R=1. As M_{cut}becomes smaller, eventually all events are thrown away in the truncation procedure, i.e. R=0, and the EFT gives no exclusion limits for the chosen acceptance.

We propose a rough scan over M_{cut}, such that we find the values of $M_{\text{cut}}$for which R ranges from, say, 0.1 to 1. We can then perform a scan over (several, your choice) values of M_{cut}, showing the truncated limit for each one.

When R=0, there is no limit. When R reaches 1, the truncated limit is identical to the original limit.

A

Appendix: Detailed studies on mono-jet signatures

A.1 CKKW parton matching implementation

The parton matching techniques are implemented in the mono-jet like MC generation in order to avoid double counting the partons from matrix elements and parton showering. The CKKW matching is better developed and preferred [A+14c] [A+08]. As the illustration sample, the EFT D5 samples are generated with `MadGraph5_aMC@NLO` version 2.2.2. The technical implementations are shown as below.

On the generator side, i.e., `MadGraph5_aMC@NLO`:

- `ickkw = 0`
- `ktdurham =` matching scale
- `dparameter = 0.4`
- `dokt = T`
- `ptj=20`
- `drjj=0`
- `mmjj=0`
- `ptj1min=0`

On the parton showering side, i.e., `Pythia 8`:

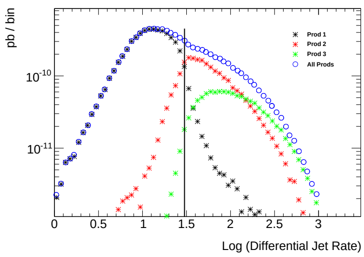
- `Merging:ktType = 1`
- `Merging:TMS =` matching scale
- `1000022:all = chi chi  2 0 0 30.0 0.0 0.0 0.0 0.0`
- `1000022:isVisible = false`
- `Merging:doKTMerging = on`
- `Merging:Process = pp>chi,1000022chi ,-1000022`
- `Merging:nJetMax = 2`

The matching scales should be the same for the generation and parton showering. In `MadGraph5_aMC@NLO`, the particle data group ID `1000022` is used for weakly interacting dark matter candidates, which should be informed to `Pythia 8`.

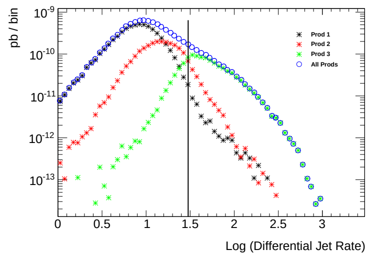
In this test we are generating the process with up to two parton emissions, so the command `Merging:nJetMax = 2` is applied to `Pythia 8`. The different parton emission cases are generated separately:

- `p p > chi chi`
- `p p > chi chi  j`
- `p p > chi chi  j j`

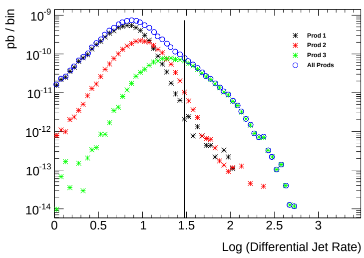
Two matching scales are tested at 30 and 80 GeV. The differential jet rates are shown in Fig. A.1 for matching scale 30 GeV and Fig. A.2 for 80 GeV. The 80 GeV matching scale gives smoother distribution, which is desired to avoid artifical effect due to parton matching. There will be a small tink around the matching scale for both cases.



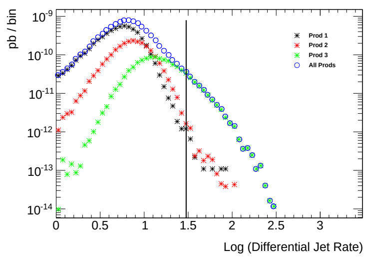
(a) 1 → 2 parton process



(b) 2 → 3 parton process



(c) 3 → 4 parton process

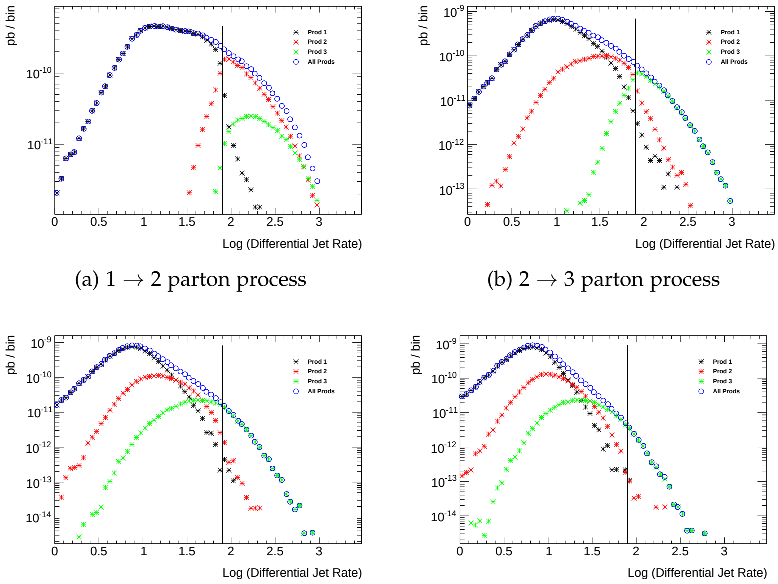


(d) 4 → 5 parton process

Figure A.1: Jet differential rates distributions for EFT D5 sample with CKKW matching scale at 30 GeV. 0-, 1- and 2-parton emission cases are generated separately. A vertical line is drawn at the matching scale.

To compare the effect in a finer step, the matching scales at 30, 50, 70, 80 and 90 GeV are plotted in FigA.3. Globally good agreement is seen among different matching scales, with some difference observed around the matching scale. A closer look in this range shows that the 80 and 90 GeV matching scales produce very close distributions, so it is safe to use 80 GeV as the baseline matching scale.

The MC distributions for the missing transverse energy and transverse momenta for the leading and subleading jets are plotted in Fig.. For the mono-jet analysis, usually a missing transverse energy cut larger than 300 GeV is applied for offline selection, which makes the contribution of the 0-parton emission case negligible in the mono-jet analysis.



(a) $1 \to 2$ parton process

(b) $2 \to 3$ parton process

(c) $3 \to 4$ parton process

(d) $4 \to 5$ parton process

Figure A.2: Jet differential rates distributions for EFT D5 sample with CKKW matching scale at 80 GeV. 0-, 1- and 2-parton emission cases are generated separately. A vertical line is drawn at the matching scale.

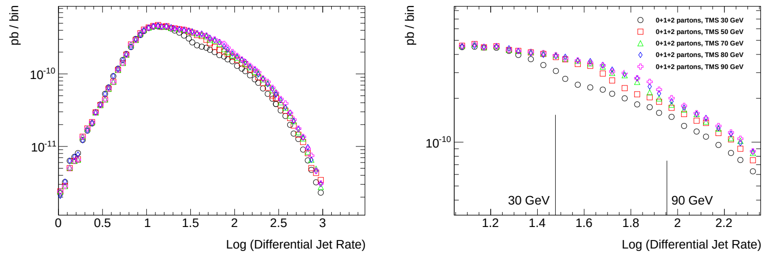
A.2 *Parton emission generation*

In order to describe the signal kinematics correctly and save time in MC generation, the parton emissions will only be generated up to a certain numbers of parton and ignore the cases with more partons. The later ones usually have cross sections small enough and limited contribution in the interested kinematic regions.

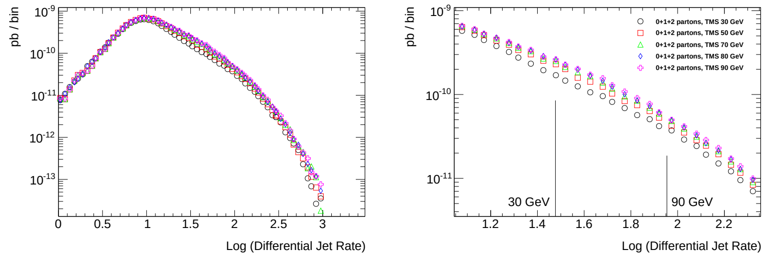
It is found that the 3- or more-parton emission cases are negligible in our intersted regions, but the 2-parton emission case has significant contributions. The 0- and 1-parton emissions are out of discussion since they give the baseline signature in this analysis. The impacts of 2- and 3-parton emissions are quantified in this section.

Here the 0-, 1-, 2- and 3-parton emissions are generated separately and requested in matching step with `Merging:nJetMax=3` and scale at 80 GeV in Pythia8for 0+1+2+3 parton emission case, while `Merging:nJetMax=2` requested for 0+1+2 case and `Merging:nJetMax=1` requested for 0+1 case. The MET distribution is plotted in Fig.A.5, while the jet multiplicity is shown in Fig.A.6.

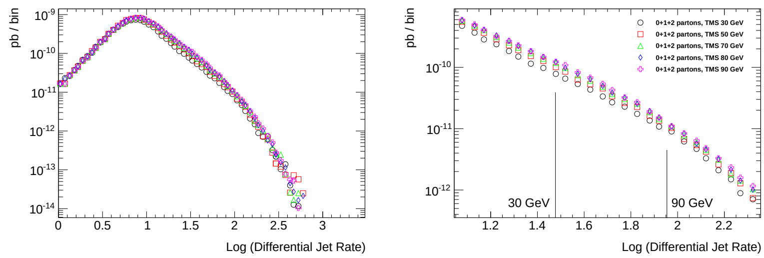
With the ATLAS run-I baseline cut (MET and leading jet p_T larger than 250 GeV, less than 4 jets), the 0+1 parton emission has 17.4% yield less compared to 0+1+2+3 parton emission, while the 0+1+2 has 2.2% less. With MET>400 GeV, 0+1 parton emission has 16.8% yield less and 0+1+2 parton emission has 2.4% less compared to 0+1+2+3 parton emission. With MET>600 GeV, 0+1 parton emission has 16.5% yield less and 0+1+2 parton emission has 2.9% less compared to 0+1+2+3 parton emission. The same numbers hold if a sysmetric cut is added on leading jet transverse momentum.



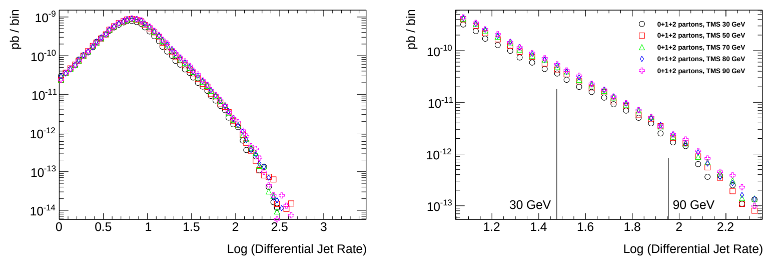
(a) $1 \rightarrow 2$ parton process



(b) $2 \rightarrow 3$ parton process



(c) $3 \rightarrow 4$ parton process



(d) $4 \rightarrow 5$ parton process

Figure A.3: Jet differential rates distributions for EFT D5 sample with CKKW matching scale at 30, 50, 70, 80 and 90 GeV. 0-, 1- and 2-parton emission cases are generated separatedly and the total merged contribution is shown. A closer look is shown around the matching scale.

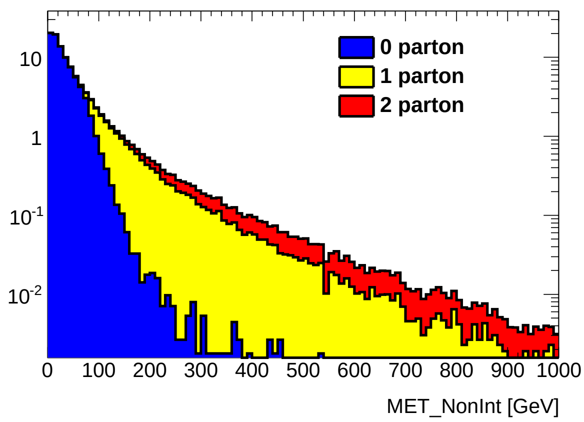


Figure A.4: Missing transverse momentum distributions for EFT D5 sample with CKKW matching scale at 80 GeV. 0-, 1- and 2-parton emission cases are generated separatedly and added together by cross sections. The 0-parton emission case has very limited contribution for missing transverse energy larger than 300 GeV region.

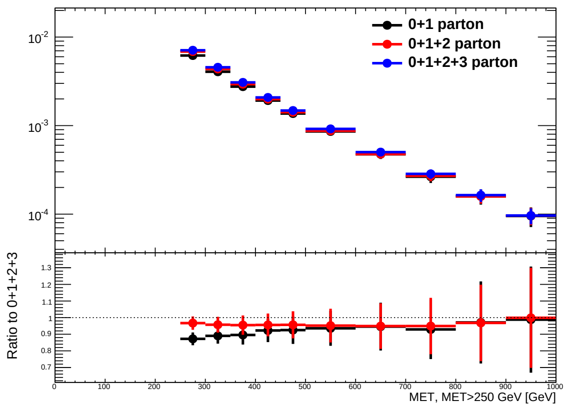


Figure A.5: Missing transverse momentum distributions for EFT D5 sample with CKKW matching scale at 80 GeV. 0-, 1-, 2- and 3-parton emission cases are generated separatedly and added together by cross sections.

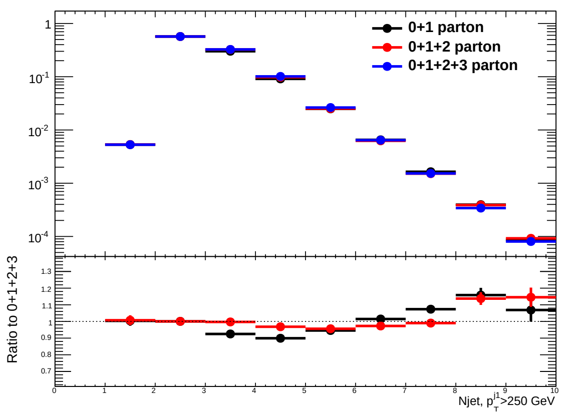


Figure A.6: Jet multiplicity distribution for EFT D5 sample with CKKW matching scale at 80 GeV. 0-, 1-, 2- and 3-parton emission cases are generated separatedly and added together by cross sections.

B

Appendix: Detailed studies for EW models

B.1 Further W+MET models with possible cross-section enhancements

As pointed out in Ref. [BCD+15], the mono-W signature can probe the iso-spin violating interactions of dark matter with quarks. The relevant operators after the electroweak symmetry breaking is

$$\frac{1}{\Lambda^2}\overline{\chi}\gamma_\mu\chi\left(\overline{u}_L\gamma^\mu u_L + \xi\bar{d}_L\gamma^\mu d_L\right) . \tag{B.1}$$

Here, we only keep the left-handed quarks because the right-handed quarks do not radiate a W-gauge boson from the weak interaction. As the LHC constraints the cutoff to higher values, it is also important to know the corresponding operators before the electroweak symmetry. At the dimension-six level, the following operator

$$\frac{c_6}{\Lambda^2}\overline{\chi}\gamma_\mu\chi\,\overline{Q}_L\gamma^\mu Q_L \tag{B.2}$$

conserves iso-spin and provides us $\xi = 1$ [**?**]. At the dimension-eight level, new operators appear to induce iso-spin violation and can be

$$\frac{c_8^d}{\Lambda^4}\overline{\chi}\gamma_\mu\chi\,(H\overline{Q}_L)\gamma^\mu(Q_L H^\dagger) + \frac{c_8^u}{\Lambda^4}\overline{\chi}\gamma_\mu\chi\,(\tilde{H}\overline{Q}_L)\gamma^\mu(Q_L\tilde{H}^\dagger)\,. \tag{B.3}$$

After inputting the vacuum expectation value of the Higgs field, we have

$$\xi = \frac{c_6\,+\,c_8^d\,v_{\rm EW}^2/2\Lambda^2}{c_6\,+\,c_8^u\,v_{\rm EW}^2/2\Lambda^2}\,. \tag{B.4}$$

For a nonzero c_6 and $v_{\rm EW} \ll \Lambda$, the iso-spin violation effects are suppressed. On the other hand, the values of c_6, c_8^d and c_8^u depend on the UV-models.

There is one possible UV-model to obtain a zero value for c_6 and non-zero values for c_8^d and c_8^u. One can have the dark matter and the SM Higgs field charged under a new $U(1)'$. There is a small mass mixing between SM Z-boson and the new Z' with a mixing angle of $\mathcal{O}(v_{\rm EW}^2/M_{Z'}^2)$. After integrating out Z', one has different effective dark matter couplings to u_L and d_L fields, which are proportional to their couplings to the Z boson. For this model, we have $c_6 = 0$ and

$$\xi = \frac{-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W}{\frac{1}{2}-\frac{2}{3}\sin^2\theta_W} \approx -2.7 \tag{B.5}$$

and order of unity.

B.2 Tabulated cross-sections

B.2.1 Higgs+MET signal from 2HDM model with a Z' and a new pseudoscalar

The leading order cross-sections from the Madgraph generator for the signal samples are listed in Tables B.1, B.2, B.3, for the various scan points recommended.

$M_{Z'}$ (GeV)	$M_{A^0}(GeV)$	σ [pb]
600	300	1.55E-01
600	400	2.18E-02
800	300	8.30E-02
800	400	2.72E-02
800	500	1.09E-02
800	600	2.98E-03
1000	300	3.74E-02
1000	400	1.53E-02
1000	500	8.91E-03
1000	600	4.89E-03
1000	700	2.21E-03
1000	800	7.05E-04
1200	300	1.70E-02
1200	400	7.65E-03
1200	500	5.14E-03
1200	600	3.52E-03
1200	700	2.25E-03
1200	800	1.27E-03
1400	300	8.00E-03
1400	400	3.79E-03
1400	500	2.75E-03
1400	600	2.09E-03
1400	700	1.58E-03
1400	800	1.06E-03

Table B.1: LO cross-sections for $Z' \to A^0 h$ samples, varying $M_{Z'}$ and M_{A^0}, keeping the DM mass fixed to 100 GeV. The columns from left to right describe $M_{Z'}$, M_{A^0} and the sample cross section in pb.

$M_{Z'}$ (GeV)	$M_{A^0}(GeV)$	$M_{DM}(GeV)$	σ [pb]
1000	300	10	3.76E-02
1000	300	50	3.75E-02
1200	600	10	3.64E-03
1200	600	20	3.07E-03

Table B.2: LO cross-sections for $Z' \to A^0 h$ samples, when varying M_{DM}. The columns from left to right describe $M_{Z'}$, M_{A^0}, M_{DM}, and the sample cross section in pb.

$M_{Z'}$ (GeV)	σ [pb]
600	1.15E-01
800	3.21E-02
1000	1.13E-02
1200	4.54E-03
1400	2.00E-03

Table B.3: LO cross-sections for $Z' \to Zh$ exclusive samples, varying $M_{Z'}$. The columns from left to right describe $M_{Z'}$ and the sample cross section in pb.

C

Appendix: Table of cross sections for $t\bar{t}$+MET searches

All tables need to be adjusted with right number of significant digits

Coupling (g)	m_{Phi} [GeV]	m_χ [GeV]	Γ_{min} [GeV]	σ
0.1	10	1	0.00374318	0.207 ± 0.0006846
0.1	20	1	0.00784569	0.1121 ± 0.0003285
0.1	50	1	0.01987	0.03211 ± 0.0001005
0.1	100	1	0.0398141	0.007325 ± 2.416e-05
0.1	150	1	0.0597437	0.002396 ± 7.419e-06
0.1	200	1	0.0796724	0.001018 ± 3.398e-06
0.1	300	1	0.119549	0.0003394 ± 1.234e-06
0.1	500	1	0.310863	6.802e-05 ± 2.343e-07
0.1	1000	1	0.881329	5.817e-06 ± 2.356e-08
0.1	1500	1	1.40417	8.942e-07 ± 3.832e-09
0.1	10	10	0.000100	1.007e-05 ± 3.761e-08
0.1	20	10	0.000100	3.491e-05 ± 1.012e-07
0.1	50	10	0.0153395	0.03212 ± 0.0001037
0.1	100	10	0.0374747	0.007343 ± 2.011e-05
0.1	150	10	0.0581752	0.002389 ± 7.654e-06
0.1	200	10	0.0784937	0.001018 ± 6.258e-06
0.1	300	10	0.118762	0.0003373 ± 1.448e-06
0.1	500	10	0.310391	6.773e-05 ± 2.326e-07
0.1	1000	10	0.881093	5.81e-06 ± 2.245e-08
0.1	1500	10	1.40401	8.937e-07 ± 4.013e-09
0.1	50	50	0.0000233555	2.581e-07 ± 1.214e-09
0.1	100	50	0.0000492402	1.526e-06 ± 7.038e-09
0.1	150	50	0.0247905	0.002387 ± 8.272e-06
0.1	200	50	0.051794	0.00102 ± 3.216e-06
0.1	300	50	0.100226	0.0003366 ± 1.393e-06
0.1	500	50	0.299052	6.679e-05 ± 2.406e-07
0.1	1000	50	0.875378	5.764e-06 ± 2.472e-08
0.1	1500	50	1.4002	8.866e-07 ± 3.257e-09
0.1	100	150	0.0000492402	1.246e-08 ± 5.121e-11
0.1	150	150	0.0000765167	1.393e-08 ± 6.653e-11
0.1	200	150	0.000106902	1.693e-08 ± 8.493e-11
0.1	300	150	0.000190543	7.557e-08 ± 2.171e-10

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_χ [GeV]	Γ_{min} [GeV]	σ
0.1	500	150	0.213784	5.063e-05 ± 1.724e-07
0.1	1000	150	0.828844	5.365e-06 ± 2.028e-08
0.1	1500	150	1.36872	8.603e-07 ± 3.769e-09
0.1	200	300	0.000106902	1.415e-09 ± 5.97e-12
0.1	300	300	0.000190543	1.64e-09 ± 7.878e-12
0.1	500	300	0.111924	3.078e-09 ± 1.482e-11
0.1	1000	300	0.687162	3.828e-06 ± 1.416e-08
0.1	1500	300	1.26683	7.579e-07 ± 3.041e-09
0.1	500	500	0.111924	1.784e-10 ± 1.105e-12
0.1	1000	500	0.483444	1.98e-09 ± 9.199e-12
0.1	1500	500	1.05448	4.92e-07 ± 2.14e-09
0.3	10	1	0.0336886	1.876 ± 0.006611
0.3	20	1	0.0706112	1.006 ± 0.003894
0.3	50	1	0.17883	0.2886 ± 0.0009285
0.3	100	1	0.358327	0.06598 ± 0.000182
0.3	150	1	0.537693	0.0214 ± 6.701e-05
0.3	200	1	0.717052	0.009216 ± 3.533e-05
0.3	300	1	1.07594	0.003044 ± 1.194e-05
0.3	500	1	2.79777	0.0006105 ± 2.187e-06
0.3	1000	1	7.93196	5.256e-05 ± 2.165e-07
0.3	1500	1	12.6376	8.048e-06 ± 3.473e-08
0.3	10	10	5.69808	0.0008143 ± 3.272e-06
0.3	20	10	0.0000630938	0.002836 ± 9.724e-06
0.3	50	10	0.138055	0.2869 ± 0.0008971
0.3	100	10	0.337272	0.06606 ± 0.0002407
0.3	150	10	0.523576	0.02145 ± 8.01e-05
0.3	200	10	0.706443	0.009222 ± 2.807e-05
0.3	300	10	1.06886	0.003051 ± 1.001e-05
0.3	500	10	2.79352	0.0006115 ± 2.268e-06
0.3	1000	10	7.92983	5.24e-05 ± 1.964e-07
0.3	1500	10	12.6361	8.053e-06 ± 3.203e-08
0.3	10	50	5.69808	1.704e-05 ± 7.077e-08
0.3	20	50	0.0000630938	1.746e-05 ± 7.383e-08
0.3	50	50	0.000210199	2.071e-05 ± 8.162e-08
0.3	100	50	0.000443162	0.0001245 ± 3.888e-07
0.3	150	50	0.223114	0.02138 ± 6.22e-05
0.3	200	50	0.466146	0.009186 ± 3.168e-05
0.3	300	50	0.902031	0.003039 ± 1.09e-05
0.3	500	50	2.69146	0.0005971 ± 2.181e-06
0.3	1000	50	7.8784	5.222e-05 ± 1.907e-07
0.3	1500	50	12.6018	7.947e-06 ± 2.996e-08
0.3	100	150	0.000443162	1.004e-06 ± 4.682e-09
0.3	150	150	0.00068865	1.132e-06 ± 4.644e-09
0.3	200	150	0.000962116	1.349e-06 ± 6.834e-09
0.3	300	150	0.00171489	6.08e-06 ± 2.289e-08

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_χ [GeV]	Γ_{min} [GeV]	σ
0.3	500	150	1.92405	0.000456 ± 2.064e-06
0.3	1000	150	7.45959	4.818e-05 ± 1.84e-07
0.3	1500	150	12.3185	7.796e-06 ± 2.802e-08
0.3	200	300	0.000962116	1.144e-07 ± 4.635e-10
0.3	300	300	0.00171489	1.324e-07 ± 6.534e-10
0.3	500	300	1.00732	2.5e-07 ± 1.113e-09
0.3	1000	300	6.18446	3.439e-05 ± 1.376e-07
0.3	1500	300	11.4014	6.834e-06 ± 2.623e-08
0.3	500	500	1.00732	1.449e-08 ± 5.536e-11
0.3	1000	500	4.35099	1.487e-07 ± 6.617e-10
0.3	1500	500	9.49035	4.374e-06 ± 1.739e-08
0.7	10	1	0.183416	10.2 ± 0.03649
0.7	20	1	0.384439	5.462 ± 0.02022
0.7	50	1	0.97363	1.558 ± 0.004491
0.7	100	1	1.95089	0.3568 ± 0.001143
0.7	150	1	2.92744	0.1161 ± 0.0003685
0.7	200	1	3.90395	0.04995 ± 0.0001494
0.7	300	1	5.85789	0.01649 ± 5.579e-05
0.7	500	1	15.2323	0.003313 ± 1.464e-05
0.7	1000	1	43.1851	0.0002823 ± 1.233e-06
0.7	1500	1	68.8045	4.481e-05 ± 1.885e-07
0.7	10	10	0.0000310229	0.02403 ± 0.0001038
0.7	20	10	0.000343511	0.08347 ± 0.0004742
0.7	50	10	0.751635	1.553 ± 0.004764
0.7	100	10	1.83626	0.3569 ± 0.0009501
0.7	150	10	2.85058	0.1165 ± 0.0004139
0.7	200	10	3.84619	0.04984 ± 0.0001855
0.7	300	10	5.81933	0.01649 ± 6.843e-05
0.7	500	10	15.2092	0.003301 ± 1.289e-05
0.7	1000	10	43.1735	0.0002815 ± 1.129e-06
0.7	1500	10	68.7967	4.491e-05 ± 2.108e-07
0.7	10	50	0.0000310229	0.000511 ± 1.977e-06
0.7	20	50	0.000343511	0.0005184 ± 2.146e-06
0.7	50	50	0.00114442	0.0006176 ± 3.053e-06
0.7	100	50	0.00241277	0.003681 ± 1.333e-05
0.7	150	50	1.21473	0.1156 ± 0.0003755
0.7	200	50	2.53791	0.04988 ± 0.0001824
0.7	300	50	4.91106	0.01651 ± 6.317e-05
0.7	500	50	14.6535	0.003218 ± 1.523e-05
0.7	1000	50	42.8935	0.0002794 ± 1.049e-06
0.7	1500	50	68.6098	4.46e-05 ± 1.989e-07
0.7	100	150	0.00241277	2.968e-05 ± 1.364e-07
0.7	150	150	0.00374932	3.327e-05 ± 1.594e-07
0.7	200	150	0.00523819	4.04e-05 ± 1.861e-07
0.7	300	150	0.00933663	0.0001787 ± 7.694e-07

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_χ [GeV]	Γ_{min} [GeV]	σ
0.7	500	150	10.4754	0.00243 ± 1.128e-05
0.7	1000	150	40.6133	0.0002573 ± 1.014e-06
0.7	1500	150	67.0675	4.239e-05 ± 1.707e-07
0.7	100	300	0.00241277	3.132e-06 ± 1.547e-08
0.7	150	300	0.00374932	3.227e-06 ± 1.433e-08
0.7	200	300	0.00523819	3.393e-06 ± 1.437e-08
0.7	300	300	0.00933663	3.918e-06 ± 1.628e-08
0.7	500	300	5.4843	7.383e-06 ± 2.87e-08
0.7	1000	300	33.6709	0.0001801 ± 7.992e-07
0.7	1500	300	62.0745	3.644e-05 ± 1.473e-07
0.7	500	500	5.4843	4.301e-07 ± 1.836e-09
0.7	1000	500	23.6887	3.684e-06 ± 2.358e-08
0.7	1500	500	51.6697	2.291e-05 ± 9.843e-08
1.	10	1	0.374318	20.79 ± 0.08102
1.	20	1	0.784569	11.08 ± 0.0396
1.	50	1	1.987	3.146 ± 0.01331
1.	100	1	3.98141	0.7199 ± 0.002775
1.	150	1	5.97437	0.2354 ± 0.0008189
1.	200	1	7.96724	0.1009 ± 0.0003854
1.	300	1	11.9549	0.03369 ± 0.0001155
1.	500	1	31.0863	0.006652 ± 2.898e-05
1.	1000	1	88.1329	0.0005705 ± 2.817e-06
1.	1500	1	140.417	9.244e-05 ± 4.273e-07
1.	10	10	0.000063312	0.1009 ± 0.00035
1.	20	10	0.000701043	0.3475 ± 0.002265
1.	50	10	1.53395	3.139 ± 0.01028
1.	100	10	3.74747	0.7158 ± 0.002486
1.	150	10	5.81752	0.236 ± 0.0007591
1.	200	10	7.84937	0.1013 ± 0.0003668
1.	300	10	11.8762	0.03374 ± 0.0001403
1.	500	10	31.0391	0.006631 ± 2.585e-05
1.	1000	10	88.1093	0.0005663 ± 2.515e-06
1.	1500	10	140.401	9.408e-05 ± 4.698e-07
1.	10	50	0.000063312	0.00212 ± 8.815e-06
1.	20	50	0.000701043	0.002149 ± 9.604e-06
1.	50	50	0.00233555	0.002568 ± 1.017e-05
1.	100	50	0.00492402	0.01523 ± 5.043e-05
1.	150	50	2.47905	0.2351 ± 0.0008404
1.	200	50	5.1794	0.09993 ± 0.0003164
1.	300	50	10.0226	0.03349 ± 0.0001351
1.	500	50	29.9052	0.006402 ± 2.604e-05
1.	1000	50	87.5378	0.0005634 ± 2.601e-06
1.	1500	50	140.02	9.211e-05 ± 4.909e-07
1.	100	150	0.00492402	0.0001247 ± 5.899e-07
1.	150	150	0.00765167	0.0001387 ± 5.889e-07

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_{χ} [GeV]	Γ_{min} [GeV]	σ
1.	200	150	0.0106902	0.000168 ± 7.656e-07
1.	300	150	0.0190543	0.0007464 ± 2.977e-06
1.	500	150	21.3784	0.004856 ± 1.95e-05
1.	1000	150	82.8844	0.0005122 ± 1.98e-06
1.	1500	150	136.872	8.662e-05 ± 3.821e-07
1.	200	300	0.0106902	1.422e-05 ± 6.147e-08
1.	300	300	0.0190543	1.626e-05 ± 6.865e-08
1.	500	300	11.1924	3.081e-05 ± 1.244e-07
1.	1000	300	68.7162	0.0003534 ± 1.392e-06
1.	1500	300	126.683	7.258e-05 ± 3.651e-07
1.	500	500	11.1924	1.777e-06 ± 9.67e-09
1.	1000	500	48.3444	1.331e-05 ± 6.551e-08
1.	1500	500	105.448	4.443e-05 ± 1.988e-07
1.5	10	1	0.842215	46.59 ± 0.1797
1.5	20	1	1.76528	24.52 ± 0.08387
1.5	50	1	4.47075	6.903 ± 0.02244
1.5	100	1	8.95817	1.577 ± 0.005493
1.5	150	1	13.4423	0.5224 ± 0.002309
1.5	200	1	17.9263	0.2259 ± 0.0008625
1.5	300	1	26.8985	0.07529 ± 0.0003407
1.5	500	1	69.9442	0.01445 ± 6.469e-05
1.5	1000	1	198.299	0.001234 ± 5.694e-06
1.5	1500	1	315.939	0.0002179 ± 1.024e-06
1.5	10	10	0.000142452	0.5117 ± 0.002037
1.5	20	10	0.00157735	1.763 ± 0.01031
1.5	50	10	3.45138	6.906 ± 0.02283
1.5	100	10	8.4318	1.568 ± 0.006489
1.5	150	10	13.0894	0.5162 ± 0.001934
1.5	200	10	17.6611	0.2249 ± 0.0008153
1.5	300	10	26.7214	0.07541 ± 0.0002941
1.5	500	10	69.8379	0.01447 ± 6.923e-05
1.5	1000	10	198.246	0.001242 ± 6.739e-06
1.5	1500	10	315.903	0.0002157 ± 8.805e-07
1.5	10	50	0.000142452	0.01068 ± 4.527e-05
1.5	20	50	0.00157735	0.01093 ± 6.079e-05
1.5	50	50	0.00525498	0.01302 ± 6.649e-05
1.5	100	50	0.011079	0.07677 ± 0.0002445
1.5	150	50	5.57786	0.5195 ± 0.001577
1.5	200	50	11.6536	0.2195 ± 0.0006711
1.5	300	50	22.5508	0.07353 ± 0.0003291
1.5	500	50	67.2866	0.0139 ± 6.13e-05
1.5	1000	50	196.96	0.001209 ± 7.038e-06
1.5	1500	50	315.045	0.0002109 ± 8.631e-07
1.5	100	150	0.011079	0.0006295 ± 3.008e-06
1.5	150	150	0.0172162	0.000706 ± 3.661e-06

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_χ [GeV]	Γ_{min} [GeV]	σ
1.5	200	150	0.0240529	0.00086 ± 3.608e-06
1.5	300	150	0.0428723	0.003751 ± 1.304e-05
1.5	500	150	48.1013	0.01046 ± 4.013e-05
1.5	1000	150	186.49	0.001072 ± 4.469e-06
1.5	1500	150	307.963	0.0001931 ± 1.022e-06
1.5	200	300	0.0240529	7.176e-05 ± 3.641e-07
1.5	300	300	0.0428723	8.3e-05 ± 3.627e-07
1.5	500	300	25.183	0.000155 ± 6.658e-07
1.5	1000	300	154.611	0.0007234 ± 2.773e-06
1.5	1500	300	285.036	0.0001529 ± 7.694e-07
1.5	500	500	25.183	9.099e-06 ± 4.301e-08
1.5	1000	500	108.775	5.335e-05 ± 2.699e-07
1.5	1500	500	237.259	8.736e-05 ± 4.268e-07
2.	10	1	1.49727	82.65 ± 0.3408
2.	20	1	3.13828	43.1 ± 0.1487
2.	50	1	7.948	11.84 ± 0.04278
2.	100	1	15.9256	2.712 ± 0.01209
2.	150	1	23.8975	0.9056 ± 0.004237
2.	200	1	31.869	0.3952 ± 0.001653
2.	300	1	47.8195	0.132 ± 0.0004713
2.	500	1	124.345	0.02461 ± 0.0001101
2.	1000	1	352.532	0.002071 ± 1.061e-05
2.	1500	1	561.669	0.0003815 ± 1.4e-06
2.	10	10	0.000253248	1.627 ± 0.005672
2.	20	10	0.00280417	5.528 ± 0.03152
2.	50	10	6.13579	11.98 ± 0.04005
2.	100	10	14.9899	2.696 ± 0.01091
2.	150	10	23.2701	0.8981 ± 0.004067
2.	200	10	31.3975	0.3921 ± 0.001675
2.	300	10	47.5047	0.1312 ± 0.0005524
2.	500	10	124.156	0.02454 ± 0.0001302
2.	1000	10	352.437	0.002051 ± 9.73e-06
2.	1500	10	561.606	0.0003797 ± 1.522e-06
2.	10	50	0.000253248	0.03397 ± 0.0001354
2.	20	50	0.00280417	0.03452 ± 0.0001623
2.	50	50	0.00934219	0.04088 ± 0.0001623
2.	100	50	0.0196961	0.24 ± 0.0008579
2.	150	50	9.9162	0.8991 ± 0.002903
2.	200	50	20.7176	0.382 ± 0.001411
2.	300	50	40.0903	0.1287 ± 0.0005596
2.	500	50	119.621	0.02328 ± 0.0001255
2.	1000	50	350.151	0.001995 ± 1.184e-05
2.	1500	50	560.08	0.0003671 ± 1.741e-06
2.	10	150	0.000253248	0.001822 ± 7.946e-06
2.	20	150	0.00280417	0.001842 ± 8.453e-06

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_χ [GeV]	Γ_{min} [GeV]	σ
2.	50	150	0.00934219	0.00187 ± 8.818e-06
2.	100	150	0.0196961	0.001985 ± 8.101e-06
2.	150	150	0.0306067	0.002231 ± 1.131e-05
2.	200	150	0.0427607	0.002694 ± 1.215e-05
2.	300	150	0.0762174	0.01186 ± 4.862e-05
2.	500	150	85.5134	0.01769 ± 8.02e-05
2.	1000	150	331.538	0.001716 ± 7.617e-06
2.	1500	150	547.49	0.0003242 ± 1.537e-06
2.	100	300	0.0196961	0.0002092 ± 8.197e-07
2.	150	300	0.0306067	0.0002152 ± 8.37e-07
2.	200	300	0.0427607	0.0002275 ± 8.607e-07
2.	300	300	0.0762174	0.0002609 ± 1.05e-06
2.	500	300	44.7698	0.0004931 ± 2.01e-06
2.	1000	300	274.865	0.001119 ± 5.167e-06
2.	1500	300	506.731	0.0002432 ± 1.053e-06
2.	300	500	0.0762174	2.367e-05 ± 1.206e-07
2.	500	500	44.7698	2.871e-05 ± 1.09e-07
2.	1000	500	193.378	0.000131 ± 5.569e-07
2.	1500	500	421.793	0.0001323 ± 5.222e-07
2.5	10	1	2.33949	128.4 ± 0.4393
2.5	20	1	4.90356	65.92 ± 0.2248
2.5	50	1	12.4187	17.77 ± 0.0663
2.5	100	1	24.8838	4.051 ± 0.01562
2.5	150	1	37.3398	1.364 ± 0.004927
2.5	200	1	49.7953	0.6008 ± 0.002928
2.5	300	1	74.718	0.2036 ± 0.0008994
2.5	500	1	194.29	0.03629 ± 0.0001865
2.5	1000	1	550.831	0.002918 ± 1.235e-05
2.5	1500	1	877.608	0.0005639 ± 2.327e-06
2.5	10	10	0.0003957	3.918 ± 0.0159
2.5	20	10	0.00438152	13.54 ± 0.05349
2.5	50	10	9.58718	18.03 ± 0.06068
2.5	100	10	23.4217	4.025 ± 0.01458
2.5	150	10	36.3595	1.36 ± 0.00698
2.5	200	10	49.0586	0.5979 ± 0.002445
2.5	300	10	74.2262	0.2016 ± 0.0006995
2.5	500	10	193.994	0.03579 ± 0.0001738
2.5	1000	10	550.683	0.002902 ± 1.515e-05
2.5	1500	10	877.509	0.0005651 ± 2.275e-06
2.5	10	50	0.0003957	0.08298 ± 0.000365
2.5	20	50	0.00438152	0.08474 ± 0.0003631
2.5	50	50	0.0145972	0.09986 ± 0.000455
2.5	100	50	0.0307751	0.5855 ± 0.001667
2.5	150	50	15.4941	1.359 ± 0.005802
2.5	200	50	32.3712	0.5728 ± 0.002188

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_χ [GeV]	Γ_{min} [GeV]	σ
2.5	300	50	62.6411	0.1938 ± 0.0008665
2.5	500	50	186.907	0.03384 ± 0.0001589
2.5	1000	50	547.111	0.002773 ± 1.645e-05
2.5	1500	50	875.125	0.0005349 ± 3.534e-06
2.5	10	150	0.0003957	0.004461 ± 1.951e-05
2.5	20	150	0.00438152	0.004473 ± 2.159e-05
2.5	50	150	0.0145972	0.00451 ± 1.808e-05
2.5	100	150	0.0307751	0.00486 ± 1.984e-05
2.5	150	150	0.0478229	0.00548 ± 2.35e-05
2.5	200	150	0.0668136	0.006545 ± 2.81e-05
2.5	300	150	0.11909	0.02878 ± 0.0001168
2.5	500	150	133.615	0.02572 ± 0.00011
2.5	1000	150	518.027	0.002339 ± 1.101e-05
2.5	1500	150	855.453	0.0004622 ± 2.297e-06
2.5	100	300	0.0307751	0.0005104 ± 2.62e-06
2.5	150	300	0.0478229	0.000526 ± 2.091e-06
2.5	200	300	0.0668136	0.0005503 ± 2.402e-06
2.5	300	300	0.11909	0.0006368 ± 2.911e-06
2.5	500	300	69.9528	0.001197 ± 4.697e-06
2.5	1000	300	429.476	0.001499 ± 6.445e-06
2.5	1500	300	791.767	0.0003277 ± 1.439e-06
2.5	300	500	0.11909	5.773e-05 ± 2.645e-07
2.5	500	500	69.9528	6.973e-05 ± 3.037e-07
2.5	1000	500	302.152	0.0002498 ± 1.042e-06
2.5	1500	500	659.052	0.000172 ± 8.531e-07
3.	10	1	3.36886	185.9 ± 0.8608
3.	20	1	7.06112	92.49 ± 0.3581
3.	50	1	17.883	24.38 ± 0.08507
3.	100	1	35.8327	5.551 ± 0.02275
3.	150	1	53.7693	1.878 ± 0.008801
3.	200	1	71.7052	0.8398 ± 0.004651
3.	300	1	107.594	0.2856 ± 0.001301
3.	500	1	279.777	0.04861 ± 0.0002143
3.	1000	1	793.196	0.003716 ± 1.874e-05
3.	1500	1	1263.76	0.0007294 ± 3.217e-06
3.	10	10	0.000569808	8.181 ± 0.03184
3.	20	10	0.00630938	28.05 ± 0.09412
3.	50	10	13.8055	24.97 ± 0.07128
3.	100	10	33.7272	5.485 ± 0.01916
3.	150	10	52.3576	1.858 ± 0.007406
3.	200	10	70.6443	0.8336 ± 0.003435
3.	300	10	106.886	0.2832 ± 0.001293
3.	500	10	279.352	0.04802 ± 0.0003129
3.	1000	10	792.983	0.003669 ± 1.542e-05
3.	1500	10	1263.61	0.0007221 ± 3.036e-06

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_{χ} [GeV]	Γ_{min} [GeV]	σ
3.	10	50	0.000569808	0.1714 ± 0.0007653
3.	20	50	0.00630938	0.1751 ± 0.000689
3.	50	50	0.0210199	0.2073 ± 0.001019
3.	100	50	0.0443162	1.21 ± 0.003153
3.	150	50	22.3114	1.896 ± 0.007571
3.	200	50	46.6146	0.787 ± 0.002939
3.	300	50	90.2031	0.2685 ± 0.001344
3.	500	50	269.146	0.04468 ± 0.0002221
3.	1000	50	787.84	0.003505 ± 1.861e-05
3.	1500	50	1260.18	0.0006823 ± 3.857e-06
3.	10	150	0.000569808	0.009285 ± 4.234e-05
3.	20	150	0.00630938	0.00924 ± 4.234e-05
3.	50	150	0.0210199	0.009462 ± 3.85e-05
3.	100	150	0.0443162	0.01017 ± 4.443e-05
3.	150	150	0.068865	0.01124 ± 5.221e-05
3.	200	150	0.0962116	0.01366 ± 6.834e-05
3.	300	150	0.171489	0.05937 ± 0.0002495
3.	500	150	192.405	0.03448 ± 0.0001467
3.	1000	150	745.959	0.00288 ± 1.359e-05
3.	1500	150	1231.85	0.0005735 ± 3.925e-06
3.	50	300	0.0210199	0.001039 ± 3.982e-06
3.	100	300	0.0443162	0.001056 ± 4.834e-06
3.	150	300	0.068865	0.001096 ± 4.922e-06
3.	200	300	0.0962116	0.001147 ± 5.869e-06
3.	300	300	0.171489	0.001327 ± 6.728e-06
3.	500	300	100.732	0.00245 ± 9.636e-06
3.	1000	300	618.446	0.001853 ± 7.863e-06
3.	1500	300	1140.14	0.0003934 ± 2.083e-06
3.	150	500	0.068865	0.0001123 ± 4.327e-07
3.	200	500	0.0962116	0.000114 ± 5.127e-07
3.	300	500	0.171489	0.0001206 ± 5.124e-07
3.	500	500	100.732	0.0001447 ± 6.102e-07
3.	1000	500	435.099	0.0004016 ± 1.656e-06
3.	1500	500	949.035	0.0002061 ± 8.548e-07
3.5	10	1	4.58539	257.5 ± 0.9241
3.5	20	1	9.61097	123.8 ± 0.4645
3.5	50	1	24.3407	31.59 ± 0.09614
3.5	100	1	48.7723	7.04 ± 0.02954
3.5	150	1	73.186	2.417 ± 0.01038
3.5	200	1	97.5987	1.089 ± 0.004308
3.5	300	1	146.447	0.3709 ± 0.001616
3.5	500	1	380.808	0.06035 ± 0.0003762
3.5	1000	1	1079.63	0.004345 ± 2.711e-05
3.5	1500	1	1720.11	0.0008581 ± 3.653e-06
3.5	10	10	0.000775572	15.08 ± 0.0569

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_{χ} [GeV]	Γ_{min} [GeV]	σ
3.5	20	10	0.00858777	51.42 ± 0.1478
3.5	50	10	18.7909	32.56 ± 0.1113
3.5	100	10	45.9065	6.963 ± 0.03199
3.5	150	10	71.2646	2.38 ± 0.009493
3.5	200	10	96.1548	1.079 ± 0.004244
3.5	300	10	145.483	0.369 ± 0.001602
3.5	500	10	380.229	0.05978 ± 0.0003017
3.5	1000	10	1079.34	0.004302 ± 2.412e-05
3.5	1500	10	1719.92	0.0008525 ± 3.878e-06
3.5	10	50	0.000775572	0.3176 ± 0.001314
3.5	20	50	0.00858777	0.3229 ± 0.001215
3.5	50	50	0.0286105	0.3857 ± 0.001618
3.5	100	50	0.0603192	2.228 ± 0.00751
3.5	150	50	30.3684	2.477 ± 0.008787
3.5	200	50	63.4476	1.025 ± 0.003864
3.5	300	50	122.776	0.3483 ± 0.001614
3.5	500	50	366.338	0.05534 ± 0.0003035
3.5	1000	50	1072.34	0.004076 ± 2.371e-05
3.5	1500	50	1715.24	0.0008077 ± 4.889e-06
3.5	10	150	0.000775572	0.01719 ± 9.115e-05
3.5	20	150	0.00858777	0.01719 ± 8.334e-05
3.5	50	150	0.0286105	0.01754 ± 8.239e-05
3.5	100	150	0.0603192	0.01855 ± 8.371e-05
3.5	150	150	0.0937329	0.02099 ± 0.0001038
3.5	200	150	0.130955	0.0252 ± 0.0001138
3.5	300	150	0.233416	0.1096 ± 0.0006465
3.5	500	150	261.885	0.04374 ± 0.0002091
3.5	1000	150	1015.33	0.00334 ± 1.751e-05
3.5	1500	150	1676.69	0.0006583 ± 3.614e-06
3.5	10	300	0.000775572	0.001925 ± 9.279e-06
3.5	20	300	0.00858777	0.001916 ± 1.026e-05
3.5	50	300	0.0286105	0.001918 ± 8.166e-06
3.5	100	300	0.0603192	0.001958 ± 7.426e-06
3.5	150	300	0.0937329	0.002036 ± 8.81e-06
3.5	200	300	0.130955	0.002123 ± 8.379e-06
3.5	300	300	0.233416	0.002448 ± 9.259e-06
3.5	500	300	137.107	0.004413 ± 2.588e-05
3.5	1000	300	841.774	0.002184 ± 1.014e-05
3.5	1500	300	1551.86	0.0004471 ± 2.349e-06
3.5	10	500	0.000775572	0.0002016 ± 7.906e-07
3.5	20	500	0.00858777	0.0002011 ± 9.138e-07
3.5	50	500	0.0286105	0.0002018 ± 9.929e-07
3.5	100	500	0.0603192	0.0002033 ± 8.104e-07
3.5	150	500	0.0937329	0.0002067 ± 8.026e-07
3.5	200	500	0.130955	0.0002106 ± 8.439e-07

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Table C.1 – continued from previous page

Coupling (g)	m_{Phi} [GeV]	m_{χ} [GeV]	Γ_{min} [GeV]	σ
3.5	300	500	0.233416	0.0002225 ± 9.256e-07
3.5	500	500	137.107	0.0002686 ± 1.162e-06
3.5	1000	500	592.219	0.0005877 ± 2.823e-06
3.5	1500	500	1291.74	0.0002318 ± 1.11e-06

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