Short summary of ATLAS+CMS Dark Matter Forum Recommendations For Signal MC

ATLAS+CMS Dark Matter Forum

May 4, 2015

This document outlines the choices made for the MC production and parameter scans for the simplified models recommended by the ATLAS/CMS Dark Matter Forum. This summary is aimed at defining the models and parameters for the upcoming signal Monte Carlo production by the two collaborations. Motivations for these choices, reinterpretation details, and a full bibliography will be provided in an upcoming document concluding the works of the Forum.

1 Prioritized lists of simplified models for MET+X searches

1.1 Recommended models for all MET+X analyses

For all MET+X analyses, simplified models should replace EFTs as the highest-priority dark matter interpretation. The consensus of the Forum is that all of these analyses should consider a set of simplified models involving a single, mediating particle with mass m_{med}. The two underlying choices for the model recommendations by the ATLAS/CMS DM Forum are:

1. the dark matter particle is a Dirac fermion of mass m_{DM};
2. only interactions consistent with Minimal Flavor Violation are allowed.

The highest priority models discussed within the Forum are:

a. spin-1 *s*-channel mediators with vector or axial-vector coupling to SM quarks g_q and vector or axial-vector coupling to a Dirac fermion WIMP g_{DM};

b. spin-0 *s*-channel mediators with scalar or pseudo-scalar coupling to SM quarks g_q and scalar or pseudo-scalar coupling to a Dirac fermion WIMP g_{DM};

c. and colored spin-0 *t*-channel mediators with coupling g at the vertex between quark, WIMP and mediator.

In all three cases, the coupling of the mediator to quarks g_q is identical for all three generations. In the case of the scalar and pseudo-scalar models, we assume a separate Yukawa coupling ($y_q = m_q/v$) between the quarks and the mediators multiplying g_q; the specific case of scalar mediator decaying into two top quarks is discussed in Section 1.3. The coupling between mediator and WIMP does not have any Yukawa structure.

There are thus four parameters in the first two models (m_{DM}, m_{med}, g_q, and g_{DM}) and three parameters in the last model (m_{DM}, m_{med}, g). We assume that no additional visible or invisible decays contribute to the width of the mediator. We provide formulae for calculation of the "minimal width" for any given choice of the four parameters. Early run 2 MET+X analyses are not sensitive to changes in the kinematic distributions that result from increasing the width up to $\Gamma \approx m_{med}$: their reach will not extend to narrow, off-shell mediators whose kinematics depends on the width.

All types of s-channel mediators are important, and ideally an analysis would have to include all cases. On the other hand, the vector and axial-vector models (including those with mixed couplings) produce nearly indistinguishable kinematic distributions for the MET+X analyses, and the scalar and pseudo-scalar models are also very similar. If one cannot generate all models, one could generate the full grid of mass points for only one of each type (for example, the pure axial vector and pure pseudo-scalar models).

[Open point: in this situation, do we want to mention which are preferred?]

Studies of the s-channel models include comparisons of the kinematic distributions across a scan of each of the four parameters. From these studies, we recommend generation of a set of a total of 144 ($\simeq x \times y \times z$) combinations of parameter choices in order to capture the full variety of shapes possible in the models. The grid points for the scan in m_{med}, m_{DM} are shown in Tables 2 and 3 for the vector/axial vector models and for the scalar/pseudoscalar models, respectively.

Namely the bulk of the grid scan for the s-channel models will consist of up to 25 separate samples per model, covering from 10 GeV to 3 TeV (10 GeV to 1.5 TeV) in mediator mass for the vector and axial vector (scalar and pseudoscalar) models, and from 5 GeV to 1.5 TeV in WIMP mass

[Open point: We should add to the scan the very heavy mediator mass points (5 TeV) scanned in DM mass, to use as EFT limits. 3 TeV may be borderline according to ATLAS 14 TeV studies in `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2014-007/` For S/P, no equivalent plot, but sensitivity

m_{DM} (GeV)	m_{med} (GeV)											
1	10	20	50	100	150	200	300	500	1000	**1500**	**3000**	5000
10	10	20	50	″ -	″ -						**3000**	5000
50	10		50	100	150						**3000**	5000
150	10					200	300	500			**3000**	5000
200	10					200	300	500			**3000**	5000
500	10							500	1000	*1500*	**3000**	5000
1000	*10*								*1000*	**1500**	**3000**	*5000*
1500	*10*									**1500**	**3000**	*5000*

Table 1: Simplified model benchmarks for all s-channel simplified models (spin-1 and spin-0 mediators decaying to Dirac DM fermions taking the minimum width for $g_q = g_{DM} = 1$). Points in **bold** points are only generated for the V and A cases, while points in *italics* are generated for the monojet analysis (V,A,S,P cases) but not for the search including heavy quarks.

m_{DM} (GeV)	m_{med} (GeV)
5	10, 30, 100, 300, 1000, 3000
15	10, 30, 100
50	10, 30, 100, 300
150	10, 100, 300, 1000
500	10, 300, 1000, 3000
1500	10, 1000, 3000

Table 2: Simplified model benchmark points for vector and axial vector mediators decaying to Dirac DM fermions.

m_{DM} (GeV)	m_{med} (GeV)
5	10, 30, 100, 300, 1000
15	10, 30, 100
50	10, 30, 100, 300
150	10, 100, 300, 1000
500	10, 300, 1000
1500	10, 1000

Table 3: Simplified model benchmark points for scalar and pseudoscalar mediators decaying to Dirac DM fermions.

is low.]

[The grids in Tables 2, 3 and 4 may be harmonized.]

For very heavy mediators, changing the minimal width (by changing the coupling) also affects the signal kinematic distributions. It is unclear whether the MET+jet analysis would be able to observe these signals during Run 2; therefore we recommend a more limited scan which still allows further studies. For the highest mediator mass points for the vector and axial vector models, signals should be generated with couplings in a grid of $g_{DM} = g_q = 1.0, 0.3, 0.5, 1.45$, while for the scalar and pseudoscalar signals the recommended grid is $g_{DM} = g_q = 1.0, 0.5, 1.0, 2.0, 3.0$.

Results for other choices of parameters can be related to these through simple rescalings of the total rate, using cross-section formulae that will be provided by the forum.

The parameter space of the t-channel model has not yet been studied in the same detail as the s-channel models. This model is parallel to, and partially motivated by, the squark of the MSSM, with the difference that in the MSSM the coupling of quark-squark-WIMP is small. Since the *t*-channel model can produce signatures similar to those arising from squark production in the MSSM, investigations may be needed of what ranges of g, m_{med}, and m_{DM} are already probed by other searches. The mediator can radiate a SM object, such as a jet or gauge boson, thus providing three separate MET+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, a WIMP is exchanged in the *t*-channel to produce a pair of mediators, each of which decays to a jet and a DM particle.

1.1.1 Technical implementation of the $s-$channel models

There are several matrix element implementations of the *s*-channel vector and scalar mediated DM production. They are available in POWHEG, MADGRAPH and also MCFM. We recommend the POWHEG implementation, and the associated theoretical uncertainties computed by POWHEG. POWHEG provides a set of weights in the LHE v3 format, which will be propagated through the ATLAS and CMS software to allow a determination of signal uncertainties without generating additional sets of samples. A prescription for determining these uncertainties from the weights is being provided through the forum by the POWHEG authors. For ATLAS and CMS, the necessary version of POWHEG is centrally available (V2.0 in both cases, revision 3049 for CMS and revision 3033 for ATLAS).

[Open point: The recommendations for assessing systematic uncertainties has to be approved by both collaborations. Once ready, ATLAS and CMS should discuss whether this can be harmonised.]

1.1.2 Technical implementation of the $t-$channel models

The *t*-channel model is implemented in MadGraph. The relevant parameter card can be found on the Forum SVN repository [For15f].

1.2 Specific models for analyses of MET+b quark(s)

1.2.1 Single b+MET

We consider a simplified model for single-*b*-jet signatures, with a colored scalar mediator coupling to Dark Matter and a $b-$quark. This model is described in Ref. [ABHL14]. Preliminary studies show that generation of a grid of roughly 10 points in DM mass, 15 points in mediator mass and two coupling values is sufficient to cover the parameter space probed by the LHC with early searches.

This model is available in MADGRAPH, and the relevant card files are available in the Forum SVN repository [For15e].

1.2.2 $b\bar{b}$+MET

[Open point: Do we plan for a specific implementation of the scalar/pseudoscalar with $b-$jets in the final state instead of ttbar?]

1.3 Specific models for analyses of MET+top(s)

1.3.1 $t\bar{t}$+MET

As mentioned in Sec. 1.1, we assume mass dependent Yukawa couplings to quarks for spin-0 scalar and pseudoscalar mediators. Couplings to top quarks will dominate, producing a tree-level signature of a $t\bar{t}$ pair in association with missing transverse momentum from the two DM particles. The parameter scan for this model is based on three different kinematic regimes: the case of a very heavy mediator with $m_{med} > 2m_{top}$, the case of an on-shell mediator below the $t\bar{t}$ threshold ($m_{med} > m_{DM}, m_{med} < 2m_{top}$) and the case of an off-shell mediator below the $t\bar{t}$ threshold ($m_{med} < 2m_{DM}$, $m_{med} < 2m_{top}$). Large kinematic differences are found between on-shell and off-shell mediator regimes, while the total width changes slope depending on whether one is above or below the ttbar threshold. Scalar and pseudoscalar models shows kinematic differences as the mediator mass is reduced, due to the difference in coupling of the top pair to the mediator. These considerations lead to the choice of the grid scan shown in Table 4.

The effect of varying the couplings (and therefore the mediator width) is small in the on-shell regime, but is significant in the case of very small or very large couplings and large mediator masses, with the latter effect due to parton distribution function suppression. LHC searches will be sensitive to those masses after roughly 30 fb^{-1} of data. A table of cross-sections will be provided, for several values of coupling strengths, to aid reinterpretation and validate the suggested scaling of the cross-sections that substitutes the scan in couplings for early searches.

m_{DM} (GeV)	m_{med} (GeV)
1	10, 20, 50, 100, 150, 200, 300, 500, 1000, 1500
10	10, 20, 50, 100, 150, 200, 300, 500, 1000, 1500
50	50, 100, 150, 200, 300, 500, 1000, 1500
150	150, 200, 300, 500, 1000, 1500
500	500, 1000, 1500

Table 4: Simplified model benchmarks for $t\bar{t}$+DM production via spin-0 mediators decaying to Dirac DM fermions taking the minimum width presciption for $g_v = g_{DM} = 1$.

The implementation of this model is available in POWHEG, MADGRAPH and MCFM. In the case of searches with heavy quarks in the final state that are sensitive only to the tree-level mediator decays into DM particles in association with two top quarks, the MADGRAPH implementation is suggested for Run-2 searches. The relevant parameter cards are available in the Forum SVN repository [For15b].

1.3.2 *single top+MET*

Two simplified models, described in Refs. [AFM11, BCDF15], are recommended for the signature of a single top quark+MET [1]:

- *s*-channel production of a colored scalar resonance, decaying into a top quark and a fermion that can decay in two DM candidates;
- *s*- and *t*- channel non-resonant production of a top quark and a color singlet, vector mediator which then decays invisibly.

The parameters for the *s*-channel resonant production are:

- the couplings of the scalar mediator to down-type quarks, all considered equal and denoted with a^{q}_{res};
- the couplings of the DM particle to up-type quarks and to the mediator, denoted with $a^{1/2}_{res}$;

The mediator width is computed according to the couplings, assuming no other decays in addition to those in DM and quarks. Fixing the branching fraction to DM particles to 100% would lead to a single value for the coupling of the mediator to DM particles. $a^{1/2}_{res}$ may however become a parameter to be scanned, after further studies on whether changing the mediator width leads to significant changes in the kinematics of the model. This point will be settled after further studies.

The only relevant parameters considered for the $s-$ and $t-$channel non-resonant production are the coupling of the vector mediator to up-type quarks, all considered equal and denoted with $a_{non-res}$. The width of the non-resonant mediator does not affect the model kinematics. A proposal for the scan in the parameters of these models will be prepared after further study from the ATLAS and CMS analysers.

Card files for MadGraph are provided on the Forum SVN repository [For15d].

[1] The non-resonant production contributes to both both MET+t and MET+tt final states.

1.4 *Specific models for MET+EW boson searches*

Searches with an electroweak boson (photon, Z, Higgs or W) in the final state should include the general models recommended in Section 1.1. In addition to these, we recommend models where an electroweak boson participates in the dark matter interaction itself, rather than appearing as final state radition.

Though the requisite set simplified models have not yet been fully developed by the theoretical community, it is here especially that searches in MET+photon, W, Z, or H may play a more important role than in the general models considered above. Until all necessary simplified models are developed, we must recommend use of EFT contact operators in some cases, provided the region of validity is carefully studied following the relevant recommendations in Section 2.

1.4.1 MET+photon,Z,W

These searches should consider an effective $VV\chi\chi$ vertex, with two electroweak bosons and two WIMPs, via an EFT contact operator. Such operators are available for scalar and fermion WIMPs and $VV = ZZ, Z\gamma, WW, \gamma\gamma$ (so-called dimension 4, 5, and 7 operators [CNS+13, CHH15]). We prioritize the Dirac fermion WIMP (dimension 7) operators, as those have been studied more widely and yield kinematic distributions that are distinct from any of the simplified models described above. Correlations between the different MET+photon, Z and W signatures are accounted for by the use of two model parameters encapsulating the various couplings (k_1 and k_2). Since only the cross section, and not the kinematic distributions, depend on the value of those parameters, we recommend the generation of these benchmarks using only a single value of these parameters. No difference in the kinematics is seen between the scalar and pseudoscalar models considered. This leads to the parameter scan for this benchmark to correspond to 8 different DM masses: 1, 10, 50, 100, 200, 400, 800 and 1300 GeV. The scale of the EFT for the generation is fixed at 3 TeV, and the couplings are set to $k_1 = k_2 = 1$.

These models are generated at leading order with MadGraph 2.2.2, using Pythia8 for the parton shower. Parameter cards can be found on the Forum SVN repository [For15a].

MET+W enhancements The *s*-channel model mentioned in Subsection 1.1 has previously been simulated using different coupling parameters between the mediator and the up and down quarks, leading to an increase in cross-section for W boson production. It has recently been shown [BCD+15] that this is due to a violation of gauge invariance. For this reason, we do not recommend this practice anymore, and restrict the grid scan to equal couplings between the quarks. Simplified models overcoming this issue are under development, beyond the timescale of the Forum. Meanwhile, the *t*-channel model of the previous subsection may be used to obtain different couplings and interference, but those studies are left for a longer timescale.

1.4.2 *MET+Higgs*

[Open point: we will add EFT models with direct boson-DM production for mono-Higgs. The parameter scan is being discussed, and it may initially follow the mono-$Z/W/\gamma$ parameters.]

Two benchmark simplified models [CDM+14] are recommended for MET+Higgs searches:

- A model where a vector mediator (Z') 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 couples to the SM only through the SM Higgs and decays to two DM particles.

Preliminary studies of these models show that the parameter scan for these models (on DM mass, mediator mass, mediator couplings and width, mixing of the mediator with the Z boson) can be reduced to a scan in DM mass and mediator mass that follows Table 2 while keeping the other model parameters fixed to the following values:

- coupling between mediator and SM Higgs boson $g_{hZ'Z'}/m_{med}$ = 1
- mediator-DM coupling g_{DM} = 1
- mediator-quark g_q = 0.333
- mixing angle between the new baryonic Higgs in this model and the SM Higgs $sin(\theta)$ = 0.3

for the vector mediator model, and the following values:

- Yukawa coupling to DM y_{DM} = 1
- new physics coupling between scalar and SM Higgs b = 3
- mixing angle $sin(\theta)$ = 0.3

for the scalar model.

[Open point: Update after wider discussion within the Forum, maybe mention correlations with diagrams yielding a MET+jet signature.]

The MADGRAPH implementations of those models can be found on the Forum SVN repository [For15c].

1.5 *Prioritization of parameter scans and external constraints*

The prioritization of parameter scans according to existing constraints has been widely discussed. It is generally difficult to map collider results to results of other searches for dark matter, such as direct detection cross-section. This mapping is highly model-dependent, and in order to do this with certainty one must have a fully specified theory of dark matter interactions. At present, using a single benchmark at a time leads to many unwarranted guesses and does not arrive at such a theory. More than one flavor of dark matter may exist, multiple or different interactions may be relevant, etc.

The problems that arise when mapping collider results on to the results of other experiments, such as the direct detection scattering cross-section, arise with equal difficult in the reverse direction, when attempting to apply results from non-collider searches to collider models. One should consider non-collider and relic density constraints only with a complete theory in mind; for this reason the experiments should provide information on the widest sensible range of parameters so that others who are interested in specific models can apply the constraints within their model of choice.

Another type of constraint 'external' to the MET+X analyses comes from the LHC experiments themselves. Resonant signals of dark matter mediators are a key difference between simplified models and the EFT scenario. Direct searches for these mediators, for example in dijet, ttbar, and dilepton final states, are thus a crucial part of the LHC search program. These are discussed in the forum report but specific recommendations for them are beyond the scope of the document. It is tempting to apply the constraints from these mediator searches to reduce the parameter space studied in the MET+X searches, but one should remember that the proposed simplified models are intended as representative benchmarks. There is a wide consensus amongst the participants of the forum that these constraints cannot be applied to the parameter scans in any rigorous quantitative way, without a more complete theory of dark matter.

2 *Recommendation for contact operator interpretation*

Except in the cases explicitly mentioned above, EFT contact operators should no longer be a target for optimization: in general there is a poor relationship between the kinematic distributions predicted by the EFTs and the types of signals to which Run 2 analyses will be sensitive. On the other hand, many theorists participating in the forum insist that the information conveyed by EFT limits is valuable. For the V/A and S/P simplified models, the highest mediator mass has been chosen to provide an equivalent of the D5/D8 and D1 [2] EFT interpretations, which are the limiting-cases of these models. We recommend to cross-check the kinematics of the highest-mass simplified model point with the corresponding contact interaction benchmark limit, after having ensured the robustness of the contact interaction benchmark point tested (e.g. with the ratio of valid events R defined in [Col15]).

[2] Following the notation of Ref. [GIR+10]

In case limits on other EFT operators are requested by theorists, and they cannot be obtained by suitable combinations of simplified models, the forum proposes two truncation procedures to ensure the EFT prediction is defensible:

- for cut and count analyses (all of the searches done so far), a very conservative truncation for EFT limits from Ref. [RWZ15] is proposed as a modification of the approach ATLAS has used for 8 TeV papers [Col15]
- for shape-based analyses, the references above may be used to obtain the criteria that have to be applied to discard generated events, rather than rescaling the limit as done for cut and count analyses.

[Open point: when the completion involves loops, the kinematics may vary significantly depending on the scale of the particles in the loops, applying a truncation may not be as straight-forward as when we do have a simpler completion.]

With Run 1 analyses, both experiments are very familiar with simulation of the EFT contact operators. The forum has focused on validity procedures that may be applied at analysis-level after sample generation. Thus, so long as samples of contact operators are actually produced where required, the forum recommendations here have no direct bearing on MC requests.

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