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On mono-W signatures in spin-1 simplified models ☆

Ulrich Haisch [a,b], Felix Kahlhoefer [c,*], Tim M.P. Tait [d]

[a] Rudolf Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom
[b] CERN, Theory Division, CH-1211 Geneva 23, Switzerland
[c] DESY, Notkestraße 85, D-22607 Hamburg, Germany
[d] Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

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ABSTRACT

The potential sensitivity to isospin-breaking effects makes LHC searches for mono-W signatures promising probes of the coupling structure between the Standard Model and dark matter. It has been shown, however, that the strong sensitivity of the mono-W channel to the relative magnitude and sign of the up-type and down-type quark couplings to dark matter is an artifact of unitarity violation. We provide three different solutions to this mono-W problem in the context of spin-1 simplified models and briefly discuss the impact that our findings have on the prospects of mono-W searches at future LHC runs.

1. Introduction

At least two reasons make the process $pp \to W + E_{T,\text{miss}}$ interesting in the context of dark matter (DM) searches at the LHC. First, for leptonically decaying W bosons, this process yields a distinct signature that can be searched for in dedicated analyses, which suffer from significantly less background than for instance mono-jet searches. Second, hadronic W-boson decays will instead lead to a jets + $E_{T,\text{miss}}$ final state and therefore render an electroweak (EW) contribution to the mono-jet channel.[1]

These so-called mono-W searches have received significant interest because they are potentially sensitive to the sign between the up-type and down-type quark couplings to DM [1]. The reason is that two different diagrams contribute to this process and therefore interference effects can be important. Indeed, LHC Run I analyses [2–4] based on an effective field theory (EFT) approach to parameterise the interactions of DM [5–7] found a striking difference in the predicted fiducial cross sections between same-sign (SS) and opposite-sign (OS) couplings. In the OS case, leading to constructive interference between up-type and down-type quark contributions, the mono-W results in fact turn out to set the strongest limits on the suppression scale of the unknown mediating interaction, surpassing the EFT limits that arise from mono-jet searches.[2] In direct detection experiments, on the other hand, OS couplings lead to destructive interference and correspondingly smaller event rates, making the LHC a particularly promising probe for this scenario.

Subsequently, it has however been pointed out in [10] that EFT interpretations of mono-W signals have issues with unitarity violation, if the effective higher-dimensional operators break the $SU(2)_L$ invariance of the Standard Model (SM). This is for example the case when considering pure vector DM-quark operators with OS Wilson coefficients for up-type and down-type quarks, as done in [2–4]. The enhancements of the mono-W cross section found in these analyses is thus spurious, because it is due to the emission of longitudinal W bosons. The EFT study [10] has recently been extended in [11] to the case of simplified models with t-channel exchange of a new coloured scalar. In particular, it has been shown that if these theories are formulated before EW symmetry breaking (EWSB) in an $SU(2)_L$ gauge-invariant way, effects associated with isospin breaking are generically small. This leads to the conclusion that isospin-violating DM-quark couplings are not expected to increase the sensitivity of mono-W searches in t-channel simplified models. It was also pointed out in [11] that a similar solution is expected to be present in s-channel simplified models.

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* Corresponding author.
E-mail addresses: Ulrich.Haisch@physics.ox.ac.uk (U. Haisch), felix.kahlhoefer@desy.de (F. Kahlhoefer), ttait@uci.edu (T.M.P. Tait).

[1] Note that in spite of the name, mono-jet searches do not usually veto events with two jets. Indeed, even higher jet multiplicities are included in the latest LHC searches.

[2] The ATLAS Collaboration has very recently also searched for a mono-W signal in 13 TeV data [8], upgrading their latest 8 TeV analysis [9].

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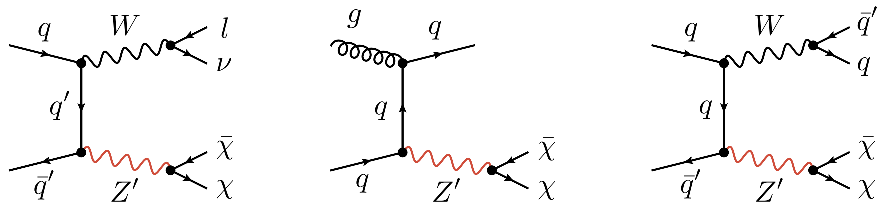

Fig. 1. Prototypes of Feynman diagrams that lead to a mono-W (left) and a mono-jet signal (middle and right). While the graph in the middle exemplifies the QCD contribution to this process, the diagram on the right-hand side represents an EW correction.

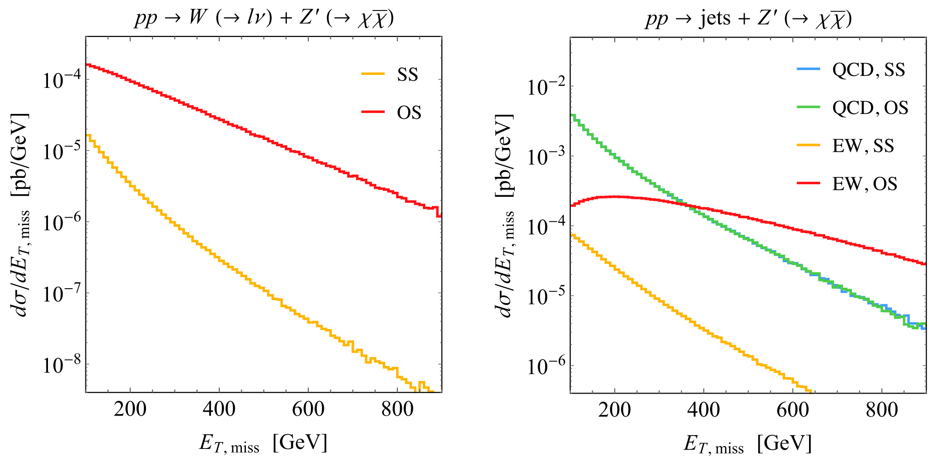

Fig. 2. Example of a $E_{T,\text{miss}}$ spectrum of a mono-W (left panel) and mono-jet (right panel) signal arising in the spin-1 simplified model. See text for additional explanations. (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

The goal of this note is to fully develop the reasoning presented in [10,11] for s-channel DM models with vector or axial-vector mediator exchange. In Section 2 we demonstrate that a naive calculation of mono-W signatures in spin-1 simplified models leads to unphysical predictions, in particular the violation of unitarity at large energies. We point out that this issue also affects mono-jet searches once EW corrections are included in the signal prediction. In Section 3, we propose a simple solution to this problem based on imposing certain requirements on the coupling structure of the simplified model. A different solution is derived in Section 4 by considering mono-W signatures in the SM, where the potentially dangerous terms are cancelled via interference with a diagram involving a triple gauge boson interaction. We discuss how this solution can be extended to simplified DM models. In Section 5 it is then shown that this second solution is indeed the one naturally incorporated in Z' models that obtain non-universal couplings to quarks from mixing with the SM gauge bosons. In Section 6, we briefly discuss how unitarity violation can be parameterised by non-renormalisable interactions. The main findings of this note are summarised in Section 7, while the impact of EW corrections in an existing mono-jet search are studied in Appendix A.

2. The mono-W problem in simplified models

In order to illustrate the issues that can appear in the calculation of mono-W signals in simplified DM models, we consider a spin-1 mediator Z'_μ with mass $M_{Z'}$ and a Dirac DM particle χ with mass m_{DM}. We write the relevant interaction terms in the Lagrangian as

$$[b]\mathcal{L} = - Z'_\mu\, \bar\chi \left[g^V_{\text{DM}} \gamma^\mu + g^A_{\text{DM}} \gamma^\mu \gamma_5 \right] \chi - \sum_{f=q,l,\nu} Z'_\mu\, \bar f \left[g^V_f \gamma^\mu + g^A_f \gamma^\mu \gamma_5 \right] f \,. \qquad (1)$$

In the context of such a simplified model, the mono-W signature arises at the LHC from the process $pp \to W + Z'$, followed by the decay of the Z' into DM particles. A possible Feynman diagram leading to a $l + E_{T,\text{miss}}$ final state is shown on the left-hand side of Fig. 1. Notice that the interactions (1) also give rise to mono-jet signatures. There are in fact both QCD and EW corrections to jets + $E_{T,\text{miss}}$, which are exemplified by the middle and right diagram in Fig. 1, respectively.

The fundamental problem discussed in this paper is illustrated in Fig. 2, which shows the predicted $E_{T,\text{miss}}$ spectrum for leptonically (left panel) and hadronically (right panel) decaying W produced in association with an invisibly decaying Z'. Our event generation has been performed at leading order with `MadGraph5_aMCNLO` [12] starting from the implementation of the spin-1 simplified model presented in [13] and utilises `NNPDF2.3` parton distribution functions (PDFs) [14]. We consider pp collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV, employ $M_{Z'} = 1$ TeV, $\Gamma_{Z'} = 56.5$ GeV, $m_{\text{DM}} = 10$ GeV, $g^V_{\text{DM}} = 1$ and set all axial-vector and leptonic couplings to zero. The yellow curves in both panels correspond to SS couplings $g^V_u = g^V_d = 0.25$, while the red curves represent the OS coupling choice $g^V_u = -g^V_d = -0.25$. It is evident from the left plot in Fig. 2 that the mono-W predictions for the two coupling choices do not simply differ by a rescaling factor, but that the predicted differential cross sections are fundamentally different. Most notably the $E_{T,\text{miss}}$ spectrum in the OS case is significantly harder than that for the SS choice.

The suspicious high-energy behaviour of the $pp \to W + Z'$ amplitudes in the OS case becomes particularly obvious in the right panel of Fig. 2, where we compare the $E_{T,\text{miss}}$ spectrum for hadronically decaying W to the $E_{T,\text{miss}}$ spectrum for a conventional mono-jet analysis, where the jets arise from QCD interactions (see middle and right diagram in Fig. 1). In the SS case, one observes that the $E_{T,\text{miss}}$ spectra for both processes are similar, but that the overall cross section for the QCD process (blue curve) is