Search for the dark matter mediator with 13 TeV data

Raffaele Angelo Gerosa for the "Exotica, all searches expt SUSY", ATLAS and CMS collaborations.

Abstract

Includes low mass dijet, low mass dileptons, 3rd generation, etc.

Presented at Moriond/EW2017 52nd Rencontres de Moriond on Electroweak Interactions and Unified Theories
Search for dark matter mediators at the LHC

Raffaele Gerosa
on behalf of the ATLAS and CMS collaborations

University California San Diego (UCSD)
9500 Gilman Drive, 0354 La Jolla (CA), United States (US)

Results of searches for dark matter mediators decaying either to invisible or visible particles are presented looking at proton-proton (pp) collisions collected by the ATLAS and the CMS experiments at the LHC, focusing mostly on 13 TeV data. No significant deviations from the Standard Model (SM) predictions have been observed across several search channels, probing either spin-1 vector/axial-vector dark matter mediators or spin-0 scalar/pseudoscalar ones.

1 Introduction

Although the SM describes remarkably well everything we see in collider experiments, it is not an entirely satisfactory theory to explain all the phenomena we see in nature. Astrophysical observations have provided evidences for the existence of Dark Matter (DM) in the universe. The most current model assumes that DM candidates are weakly interactive massive particles (WIMPs). If such particles exist, direct pair production of WIMPs may occur in TeV-scale collisions at the CERN LHC.

2 Direct searches for dark matter mediators

If DM particles are produced in pp collisions, they would not generate directly observable signals in the detector. However, if they recoil against an object “X” radiated from the initial state, they may produce a large transverse momentum imbalance ($E_{\text{miss}}^{T}$) in the event. These event topologies are usually called “mono-X” signatures, where “X” might be a hadronic jet, a photon, a weak boson, etc. These signatures represent the main candles used to search for direct production of DM in particle colliders. They are sensitive to a large range of DM masses, providing complementary information to direct and indirect DM searches. The interaction between SM and DM particles is mediated by a bosonic mediator, which mass scale could be accessible by the LHC collisions. Simplified DM models are used as benchmarks, where the DM particle is assumed to be a Dirac fermion with mass $m_{\text{DM}}$, which couples to SM quarks via a spin-1 mediator, such as a $Z'$, or a spin-0 particle with unknown mass $m_{\text{med}}$. 
The channel which provides the strongest bounds on both spin-1 and spin-0 mediators is the so-called “monojet” analysis, which consists in a search for pair-produced DM particles in association with high p_T jets. Both ATLAS^8 and CMS^9 collaborations have performed this search using 2.3 fb\(^{-1}\) and 12.9 fb\(^{-1}\) of \(\sqrt{s} = 13\) TeV data, respectively\(^{10,11}\). Candidate events are accepted after requiring a high energetic jet, significant missing transverse energy and no additional leptonic activity in the detector. The main backgrounds, coming from \(Z \rightarrow \nu\nu\) and \(W \rightarrow \ell\nu+jets\), are modelled from dedicated control regions in data. No excess above the SM background prediction has been observed, thus exclusion limits at 95% CL are set on the ratio of the measured signal cross section to the predicted one.

Fig. 1 (left) shows the exclusion contours as a function of the mediator mass, \(m_{\text{med}}\), and the DM mass, \(m_{\text{DM}}\), assuming an axial-vector mediator with \(g_q = 0.25\) and \(g_{\text{DM}} = 1\). Mediator masses up to 1.95 TeV and DM masses up to 550 GeV are excluded. In contrast, Fig. 1 (right) reports the exclusion sensitivity as a function of the mediator mass for a pseudoscalar mediator with \(g_q = g_{\text{DM}} = 1\) and \(m_{\text{DM}} = 1\) GeV. In this case, the CMS monojet result is compared with alternative search channels, where a spin-0 mediator may be produced in association with a \(b\bar{b}\) or a \(t\bar{t}\) pair. Mediator masses up to 430 GeV are excluded at 95% CL.

Moreover, the SM Higgs boson might play the role of a scalar dark matter mediator\(^{13,14,15,16}\) since it couples to every particles with mass. Both ATLAS and CMS collaborations have performed direct searches for invisible decays of the Higgs boson, exploring different production mechanisms: gluon fusion (monojet search), vector boson fusion, associated production with weak bosons (mono-V searches) or with \(t\bar{t}\) pairs. Eventually, a combination of these searches at \(\sqrt{s} = 7, 8\) TeV performed by the ATLAS collaboration yields an upper limit of 25% on the Higgs boson invisible branching fraction \(B(h \rightarrow \text{inv})\)\(^{17}\). Similarly, the CMS collaboration performed a combination using data collected at \(\sqrt{s} = 7, 8, 13\) TeV, which sets an upper bound on \(B(h \rightarrow \text{inv})\) of 24%\(^{18}\).

Fig. 2 (left) shows the CMS profile likelihood ratios as a function of \(B(h \rightarrow \text{inv})\) for both partial combinations of individual channels and the full combination. Upper limits on \(B(h \rightarrow \text{inv})\) are interpreted in the context of the Higgs portal model of DM interactions, where a hidden sector provides a stable DM candidate with tree-level couplings to the SM Higgs boson. Direct detection experiments are sensitive to the elastic scattering between DM particles and nuclei through Higgs boson exchange, producing nuclear recoil signatures which can be interpreted in terms of DM-nucleon interaction cross section. When the DM candidate is lighter than \(m_h/2\), the limit on invisible Higgs decay width (\(\Gamma_{\text{inv}}\)) can be translated into a spin-independent DM-nucleon interaction cross section. 

![Figure 1](image1.png)  
![Figure 2](image2.png)
cross section bound. Fig. 2 (right) shows the 90% CL upper limit on the spin-independent DM-nucleon cross section from the ATLAS collaboration, assuming \( m_h = 125 \) GeV, for the scalar, majorana and vector DM particle scenarios.

Figure 2 – Left: CMS profile likelihood ratios as a function of \( B(h \rightarrow \text{inv}) \) assuming SM production cross sections of the Higgs boson, where the solid curves represent the observation in data, while the dashed ones are the expectation from the background only hypothesis. The likelihood scans are shown for the full combination as well as for the individual channels targeting different Higgs production modes. Right: ATLAS upper limit at 90% CL on the spin-independent DM-nucleon cross section in the context of the Higgs portal model vs the dijet mass spectrum, \( m_{jj} \). One of the most popular benchmark for the dijet search is \( \kappa_Z^2 \) of 1 TeV, which predicts a spin-1 resonance coupled to SM quarks via a universal coupling constant, \( g_q \). If the \( Z' \) is allowed to decay also to invisible particles, i.e. \( g_{\text{DM}} \neq 0 \), this benchmark becomes equivalent to the simplified DM model for spin-1 DM mediators. Therefore, dijet measurements may allow to further constrain the existence of DM particles.

Both ATLAS and CMS collaboration have recently released measurements of the dijet spectrum based on 2016 data \( ^{21,22} \), corresponding to 37 fb\(^{-1} \) and 35.9 fb\(^{-1} \), respectively. Due to a limited amount of bandwidth available at the trigger level, these searches can only explore the dijet spectrum for \( m_{jj} > 1.25 \) TeV. No excess over the predicted background has been observed. Fig. 3 (left) shows the ATLAS 95% CL exclusion limit on the quark coupling \( g_q \) as a function of the resonance mass, \( m_{Z'} \), for the leptophobic \( Z' \) model. In addition, both collaborations have also performed a trigger object based analysis to search for resonances with mass in the range between 0.6 and 1.1 TeV \( ^{22,23} \). Eventually, to test the existence of resonances lighter than 600 GeV, ATLAS looked at events where the mediator is boosted in the transverse plane, recoiling against a high-\( p_T \) ISR photon or jet \( ^{24} \). This allows to probe resonances with mass between 0.25 and 1 TeV for the \( X + \gamma \) search and between 300 and 600 GeV for the \( X + j \) case. Finally, another limitation occurs while going even lower in mass: for boosted resonances lighter than \( \approx 300 \) GeV, the jets arising from the decay overlap in the detector so that jet substructure techniques are necessary to reconstruct signal events. CMS performed a search for boosted low mass \( Z' \) resonances probing, for the first time at hadron colliders, the mass region between 100 and 300 GeV, using 2.7 fb\(^{-1} \) of 13 TeV data \( ^{25} \). Results are shown in Fig. 3 (right).

3 **Indirect searches for dark matter mediators**

A large variety of BSM models predict new narrow resonances which can be observed along the dijet mass spectrum, \( m_{jj} \). One of the most popular benchmark for the dijet search is represented by the \( Z' \) leptophobic model \( ^{19,20} \), which predicts a spin-1 resonance coupled to SM quarks via a universal coupling constant, \( g_q \). If the \( Z' \) is allowed to decay also to invisible particles, i.e. \( g_{\text{DM}} \neq 0 \), this benchmark becomes equivalent to the simplified DM model for spin-1 DM mediators. Therefore, dijet measurements may allow to further constrain the existence of DM particles.

Limits are reported separately for a scalar, majorana or vector WIMP and they are determined from the 90% CL bound of 22% on \( B(h \rightarrow \text{inv}) \). ATLAS results are compared to several exclusion contours from direct detection experiments.
This set of complementary approaches allow to search for new physics in dijet events over a broad mass range, from 100 GeV up to 4 TeV. Dijet limits are used to constrain DM simplified models with a leptophobic vector and axial-vector mediators that couples to quarks and DM particles. Fig. 4 left (right) shows the exclusion contours in the plane defined by the mediator mass, \( m_{\text{med}} \) and the DM one, \( m_{\text{DM}} \), for a vector (axial-vector) mediator assuming \( g_q = 0.25 \) and \( g_{\text{DM}} = 1 \). For this particular choice of couplings, the dijet analysis shows stronger sensitivity than direct DM searches, excluding mediator masses between 0.5 and 2.5 TeV independently of \( m_{\text{DM}} \). The exclusion power of the dijet search on \( m_{\text{med}} \) increases with \( m_{\text{DM}} \) because the branching fraction in \( q g \) increases with \( m_{\text{DM}} \). When \( 2 \cdot m_{\text{DM}} > m_{\text{med}} \), the mediator cannot decay to DM particles, thus DM limits becomes equivalent to the leptophobic Z’ ones with \( g_q = 0.25 \). In addition, when \( m_{\text{DM}} = 0 \), dijet DM bounds corresponds the ones on the Z’ mass at \( g_q / \sqrt{1 + 16/3 \cdot N_f} \approx 0.18 \). In contrast, direct searches have better sensitivity only for light mediators, which cannot be probed by the dijet analysis.

It should also be noted that the excluded region strongly depends on the chosen coupling and model scenario. For small values of \( g_q \), the Z’ production cross section decreases while the branching ratio into DM increases, thus the dijet exclusion sensitivity decreases more rapidly then the one from direct searches.
4 Comparison with direct and indirect detection experiments

The limits from ATLAS and CMS experiments, obtained using the simplified DM models, may be compared to the ones from direct and indirect DM detection experiments, which are usually expressed as bounds on the DM-nucleon scattering cross section. The approach outlined in Ref. 26 is used to translate the exclusion contours in the $m_{\text{med}} - m_{\text{DM}}$ plane into limits on the spin-dependent/spin-independent DM-nucleon cross section as a function of $m_{\text{DM}}$. Results from CMS and ATLAS collaborations are shown in Fig. 5 for the vector (left) and axial-vector (right) mediators. When compared to direct detection experiments, limits from the LHC are the strongest one for DM masses smaller than 5 GeV for the vector case. For an axial-vector mediator, LHC limits are the strongest one over the whole $m_{\text{DM}}$ range.

![Graph showing excluded regions at 90% CL on the spin-independent and spin-dependent DM-nucleon cross section as a function of $m_{\text{DM}}$.]

Figure 5 – Excluded regions at 90% CL on the spin-independent (left) and spin-dependent (right) DM-nucleon cross section as a function of $m_{\text{DM}}$ as obtained from the latest CMS\textsuperscript{22} and ATLAS\textsuperscript{27} direct (mono-X) and indirect (dijet) searches. The exclusion contours from LHC measurements are compared with limits from CDMSlite, Cresst, PandaX and LUX for the spin-independent case, while only LUX is shown in the spin-dependent one.

References

6. P. Harris, V. V. Khoze, M. Spannowsky and C. Williams, “Closing up on Dark Sectors at Colliders: from 14 to 100 TeV”, Phys. Rev. D 93, no. 5, 054030 (2016).
10. ATLAS Collaboration, “Search for new phenomena in final states with an energetic jet..."


