Accelerator searches for new physics in the context of dark matter

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Abstract.   A review is given of the current status of searches for dark matter at accelerators. Particular emphasis is put on generic searches for direct production of dark matter at the LHC during its first run, and on the recent developments for the interpretation of the results, where the models using an effective field theory approach are now being complemented with more generic interpretations in the context of simplified models. Furthermore, results are reported briefly for searches for dark matter at the LHC in the context of supersymmetry, as well as for non-LHC accelerator searches.

1. Introduction

The existence of an elusive form of so-called Dark Matter is since long conjectured from a wide array of evidence from gravitational effects over a large span of astronomical scales. Despite many searches over the past decades, still very little is known on this new form of matter.

Over the years, a plethora of theoretical models for dark matter have been proposed to tackle these open questions, many of which hypothesize a candidate dark-matter particle, arising in an extension of the standard model (SM) of particle physics. Also experimentally, many experiments have been and are hunting for a first confirmed observation of dark matter interacting non-gravitationally. These experiments fall in three categories: direct-detection searches, indirect-detection searches, and accelerator searches. Direct-detection searches try to observe in very sensitive underground experiments the small effects of elastic collisions of dark matter particles on nuclei, as the Earth flies through the Milky Way's dark-matter halo. The indirect searches, both ground and space-based, look for a photon, positron, neutrino, or other excess from particles arriving on earth, possibly resulting from the annihilation of dark matter particle pairs in astrophysical objects like our galaxy, the sun, the Earth, etc. Accelerator searches, finally, try to create dark-matter particles in the laboratory from collisions of standard-model particles. These three search categories are complementary, as they come with very different sensitivities to the details of the SM–dark-matter interaction, to the detection techniques used, and to the assumptions in terms of astrophysics.

[1] On behalf of the CMS and ATLAS Collaborations.

2. Dark matter searches at accelerators

Accelerator searches for dark matter are in general[2] trying to establish an experimental signal of missing momentum, originating from dark-matter particles going unhindered through the experiment and thus escaping detection. We will discuss here mostly collider searches at the Large Hadron Collider (LHC) [2], but also touch upon searches with high-intensity beam-dump experiments. In both cases, the particle mediating between standard-model particles and the dark sector may be the easier particle to discover, and some searches actually focus on that; here, however, we concentrate on searches where the dark-matter particle is explicit. It should be kept in mind, though, that, contrary to some other dark-matter search avenues, accelerator searches can establish the effect of dark-matter particles, but will not easily be able translate the hoped-for experimental deviations in the experiment into theoretical parameters. In particular, accelerators cannot prove stability of the dark-matter candidate beyond the aparratus; they may not distinguish single from multiple new invisible particles; they provide poor mass resolution on the invisible; and they may have no handle on the nature of the interaction, the particle type, its quantum numbers, etc.

Searches for dark-matter production at the LHC proceed in general to look for collisions where a momentum imbalance is created transverse to the beamline, caused by the dark-matter particles which escape detection because of their (quasi-)stability and very low interaction cross section with normal matter. Production may be categorized in two classes. In the first case, new heavy states are first produced, subsequently decaying through a cascade down to the lighter stable dark-matter particles. Supersymmetry (SUSY) with R-parity convervation, where the lightest supersymmetric particle is necessarily stable, serves as an example of this category. Another example is the on-shell production of a Higgs boson, which could decay to dark-matter particles in case a so-far undetected coupling exists, and the dark-matter candidate is sufficiently low in mass. The second production mode which can be distinguished is the direct dark-matter particle production. A typical scenario here is the pair creation of dark-matter particles through some off-shell mediator. Other particles present in the detector, like an initial state radiation (ISR) gluon or photon, are then required as a recoil to render the dark-matter candidates detectable.

Non-LHC accelerator searches for dark matter are mostly focusing on a portal to an assumed dark sector through a new dark vector boson, which couples to the standard model through kinetic mixing with the regular photon [3, 4]. This theoretically well-motivated and simple extension of the Standard Model can naturally accomodate very weakly coupled sub-GeV dark matter, still providing the right thermal relic. Also, it can explain some of the experimental anomalies, like the deviation in the muon anomalous magnetic moment $g - 2$. Because of the weak coupling, and potentially low mediator mass, the allowed parameter space goes beyond the reach of the LHC, and high intensity searches at former or future B-meson factories, at fixed-target experiments, and at beam-dump facilities, provide a complementary window to dark matter at accelerators, both through visible and invisible decay channels of the sought-for mediator.

3. Modelling dark-matter production at the LHC

The theoretical basis for modelling dark-matter production at the LHC and for search interpretations can be found among others in Refs [5, 6, 7, 8, 9, 10]. Three approaches can roughly be distinguished when modelling dark-matter production at the LHC.

Full models, where dark matter is considered as a part of a UV-complete theory, allow for coherent modelling of all interactions, decay channels, etc. The classic example here is

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[2] Also more exotic scenarios are being considered, e.g. [1].

supersymmetry in the form of the MSSM or similar. Often a huge parameter space arises, such that scans of such complete models come with reasonable assumptions to reduce the complexity. At the same time, such full models may be rather restrictive in e.g. the possible dark-matter sector, and they thus may lack coverage of possible experimental signatures.

At the other end of the spectrum of model complexity, one finds effective operators in an effective field theory (EFT) approach. In this case, the particle mediating between the standard-model and the dark matter is integrated out, describing the interaction approximatively as an effective four-point interaction. This leads to a rather model-independent approach, with a parameter space restricted to the dark-matter particle mass and the EFT scale $\Lambda = M_* = M/\sqrt{g_\chi g_q}$, with M the mass of the mediator, and g_q and g_χ respectively the couplings of the mediator to the quarks and to the dark matter. In this EFT context, assuming a single operator for the interaction, it is rather straightforward to translate from the collider context to the realm of dark matter–nucleus scattering, providing a comparison of collider search results with direct-detection experiments.

In making such interpretations in an EFT model, it is important to present the limitations of this approach. For the EFT to be a realistic model of the hard interaction, the mass of the mediator should be (much) larger than the energy transfer in each collision. The energy transfer in direct-detection experiments is very small, and the EFT is in general safely applicable. The energy scales at the LHC, however, are much higher, shrinking the range of applicability to masses of the mediator in the TeV range or higher. A second limitation is the fact that in usual presentations of EFT limits, a single operator is assumed to describe the interaction that links the standard model to the dark sector; which is not necessarily the case, e.g. for the weak interaction. A final limitation of the EFT is that in some corners of the phase space, unitarity and perturbativity should be explicitly checked.

A middle ground between full models and the EFT approach comes under the name of simplified models, restricting the new physics to only what is relevant to describe a certain experimental final-state topology under consideration. By thus considering final states in a general way, a maximal experimental coverage is aimed for. Simplified models extend the standard model with a few particles at most, explicitly specifying the mediator and interactions with the dark matter particle. In this way, parameter scans are kept manageable, while still consistently describing the physics under consideration. While not being realistic full models of new physics, simplified models have proven to be an excellent tool for interpreting the results of the LHC supersymmetry searches in the LHC runs with 7 and 8 TeV pp centre-of-mass collisions [11, 12]. For the ongoing 13 TeV run, also the searches for direct production of dark matter are making the transition to simplified models as their main tool for interpretation of the results [13, 14, 15].

4. LHC searches for direct dark matter production

In this section, the results are presented of searches for direct production of dark-matter particles with the ATLAS [16] and CMS [17] detector at the LHC. All these searches use the full LHC Run-1 dataset of about $\sim 20\,\mathrm{fb}^{-1}$ of proton–proton collisions at 8 TeV centre-of-mass energy.

The searches presented below in the monojet, mono-W/Z, and monophoton final states all have as central feature a particle being radiated from a quark line in the initial state of the hard collision, hence providing the recoil necessary to make the pair of produced dark-matter particles stand out in the detector as missing transverse momentum, $E_\mathrm{T}^\mathrm{miss}$.

The event selection in the monojet search [18, 19] starts from the $E_\mathrm{T}^\mathrm{miss}$ trigger used, which is fully efficient for events with $E_\mathrm{T}^\mathrm{miss}$ typically about 200 GeV. One high-momentum central jet is required, while azimuthally close to the hard jet a second softer jet is allowed. Dedicated jet-identification cuts are imposed, which were shown to efficiently suppress instrumental or other sources of anomalous $E_\mathrm{T}^\mathrm{miss}$. Electron, muon, and tau vetoes, finally, are used to reject the large

leptonically-decaying W background.

After this selection, $Z \to \nu\nu$ production dominates as the remaining background, with $W \to \ell\nu$ contributing subdominantly, from events where the lepton is not reconstructed, doesn't satisfy the identification requirements of the veto, or is invisible because it went out of detector acceptance. All other backgrounds – top, QCD multijets, diboson production – are much smaller. The two dominant background components are estimated from data using $Z \to \ell^+\ell^-$ and $W \to \ell^\pm\nu$ control event samples, accounting for the leptons as undetected particles to mimic the dark matter.

In Figure 1, the E_T^{miss} distribution is shown from the ATLAS monojet search, comparing the data with the background estimate of the individual background components. Expectations for signals from several different new-physics models are shown overlayed, one of these being a scenario with a dark-matter particle of $100\,\mathrm{GeV}$ mass produced through a vector operator with EFT scale $670\,\mathrm{GeV}$.
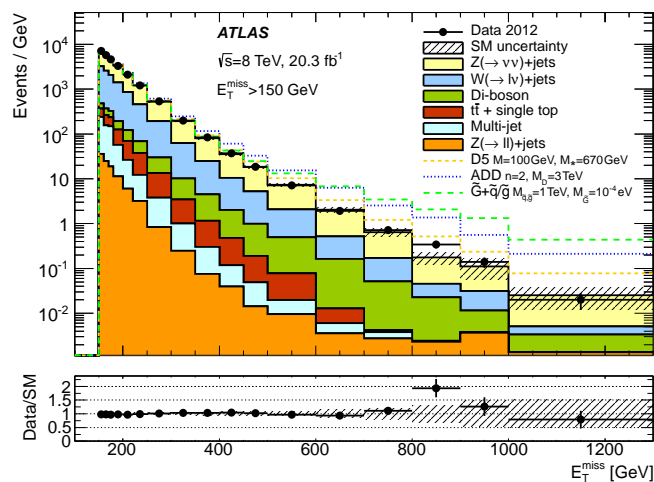

Figure 1. Distribution of E_T^{miss} after the monojet selection described in the text, showing data, background estimation, and signal expectation for several models of new physics leading to the monojet signature.

As an extension to the monojet search, the case was considered where a W or Z boson were produced recoiling off the dark matter, and decaying hadronically to two quarks [20, 21]. At sufficiently high transverse momentum, the emanating jets will be closeby, or even merge into a single jet with substructure. Using this characteristic, backgrounds can be further suppressed, since the dominant ones will not show any mass preference for the mono-jet around the W or Z boson mass.

The leptonic counterpart of this analysis is the search for dark matter recoiling against a single lepton (electron or muon) or a pair of leptons [22, 23, 24, 25]. Both these final states feature clean signatures that can be well separated from backgrounds with non-prompt leptons. This leaves these channels dominated by W and ZZ production as main backgrounds, where E_T^{miss} arises from neutrinos in the vector boson decays. Both these backgrounds are accurately predicted using simulation. In Figure 2, the key experimental variables of transverse mass and missing transverse momentum are shown respectively for the mono-W$(\to \ell\nu)$ and mono-Z$(\to \ell^+\ell^-)$ analyses.

Several other searches for direct dark matter production have been performed by the ATLAS and CMS collaborations. The monophoton searches [26, 27] look for a single photon from
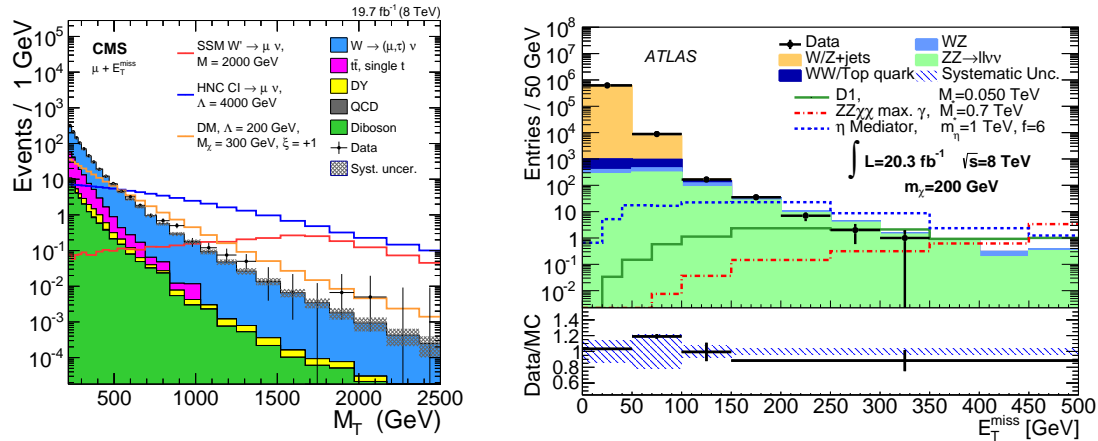
Figure 2. Distribution of transverse mass (left) and missing transverse momentum (right) for the mono-W($\to \ell\nu$) and mono-Z($\to \ell^+\ell^-$) analyses respectively, showing data, estimated background contributions, and signal expectation for an example model of dark matter production.

QED initial-state radiation to recoil against E_T^{miss} from dark matter. Since QCD gluon radiation is always more prevalent at a hadron collider like the LHC, the monojet analysis is expected to dominate the sensitivity with respect to the monophoton search, but photons, being cleaner experimental probes, allow for an important cross-check, and additionally give access to somewhat lower values of E_T^{miss}.

For scalar or pseudoscalar interactions, to avoid flavour constraints, Yukawa-like couplings of the mediator to the fermions are usually assumed, making the dark matter coupling to quarkjs stronger for the heavy bottom and top quarks. As a result, such interactions are to be searched in events with E_T^{miss} production in association with heavy quarks, e.g. with a $t\bar{t}$ or $b\bar{b}$ pair. Although such searches can profit from higher energy and luminosity, first results start to probe also such production modes [28, 29].

A related, but at the same time rather distinct channel searched for, contains a single top quark recoiling against missing momentum. Models considered so far to interpret this experimental signature assume a specific flavour-changing simplified model, with either resonant or non-resonant production [30, 31]. Another specialized case is the search for mono-Higgs production, where several models beyond the negligible initial-state radiation were considered. Here, the H $\to \gamma\gamma$ decay comes with low rates but boasts a very clean experimental signature [32].

5. Interpretation of the LHC dark-matter searches

All searches discussed above find the data to be compatible with the background expectations. The analyses have thus set limits on the possible presence of dark-matter signals in the data. Limits on the visible cross section of a potential new physics signal are complemented with limits on the interaction scale of the EFT approach as a function of the mass of the dark-matter particle, for each considered EFT interaction operator, or with cross-section limits on specific simplified models as a function of the dark-matter and the mediator masses. These limits can then in a next step be translated to the plane of the dark-matter–nucleon elastic scattering cross section versus the mass of the dark-matter particle, in which results from direct-detection experiments are usually shown.

In Figure 3, the 90%CL upper limits on the dark-matter–nucleon scattering cross section are shown from the monojet, monophoton, and mono-Z($\to \ell^+\ell^-$) searches as a function of the dark-

matter mass, for spin-independent and spin-dependent interactions, for several assumptions on the interaction and dark-matter particle types. Further interpretations for these and the other analyses discussed above can be found in the respective references.
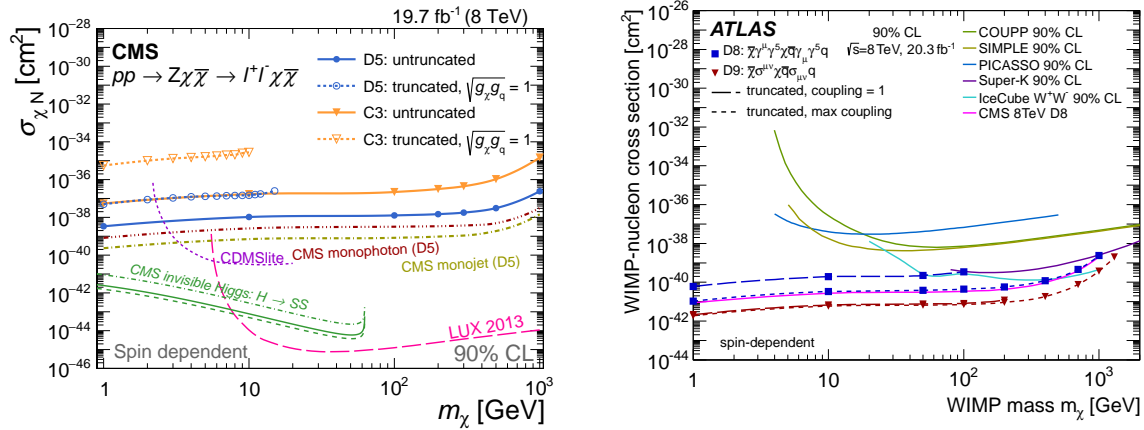

Figure 3. 90%CL upper limits on the dark-matter–nucleon scattering cross section, from the monojet, monophoton, and mono-Z($\to \ell^+\ell^-$) searches, as a function of the dark-matter mass, for spin-independent (left) [25] and spin-dependent (right) [19] interactions. Several interaction types and dark-matter particle natures are considered.

In Figure 3, the LHC results are further compared to the limits from several direct- and indirect-detection experiments. While one should keep the aforementioned caveats in mind on the interpretation of the EFT results, some robust conclusions can be drawn regarding the complementarity between the collider and direct searches. The first striking feature is the importance of the collider searches for low-mass dark matter. Indeed, where at low mass the energy deposits in the direct searches become too low for efficient detection, the collider setting yields a maximized missing momentum, and thus sensitivity, at zero mass. Another complementarity follows from the comparison of the two plots: direct-detection experiments typically exhibit little sensitivity to spin-dependent interactions, allowing the collider searches to have complementary coverage also at intermediate masses for e.g. scalar mediators. At higher mass, the collider searches see the cross sections being kinematically suppressed – here indirect searches with e.g. neutrino telescopes probe complementary ground.

With the advent of simplified models, it becomes now possible to reliably map out the area of low mediator masses. Here we consider so far s-channel models. At high mass, the simpified model interpretation coincides with the corresponding EFT limits. At intermediate mass, the mediator goes on-shell, and the production cross section is resonantly enhanced, showing the EFT limit to be too conservative. At even lower masses, the mediator will at some point need to be produced off-shell, and limits are subsequently suppressed, making EFT results too aggressive. In Figure 4 (left), these three regimes can be distinguished from the scale up to which the signal can be excluded, for various assumptions on the dark-matter mass and the mediator width. In Figure 4 (right), the search interpretation is performed in the natural collider phase space, namely the dark-matter mass versus mediator mass plane. The resonant enhancement near the diagonal, as well as the off-shell regime towards the left can be discerned.

6. Beyond LHC direct dark-matter production
Many LHC searches beyond the ones discussed above use some form of missing momentum as a key observable to search for new physics. If considering dark-matter production through a
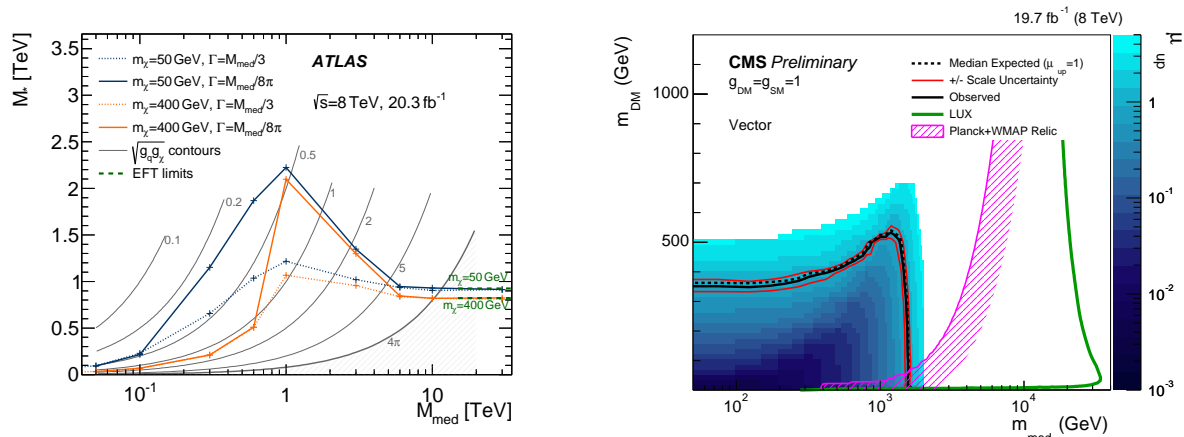
Figure 4. Left: limits at 90% CL on the interaction scale M_*, as a function of the mediator mass in a simplified model with an s-channel vector mediator [19]. Several mass and width assumptions are considered. Right: limits at 95% CL on the signal strength with respect to the considered simplified model, as a function of the dark-matter and mediator mass [21].

standard-model Higgs portal, then a substantial fraction of Higgs bosons may decay invisibly, provided the dark-matter mass is below half the Higgs-boson mass. Several searches have been performed [20, 33, 34], limiting the still-allowed invisible branching fraction.

Also some searches for supersymmetry are ideally suited for interpretation as a dark-matter search. Examples include dijet searches originally conceived for squark pair production [35, 36] and searches for compressed SUSY spectra in a weak-boson fusion topology [37].

In general, almost all searches for R-parity conserving supersymmetry are looking for missing momentum recoiling off the observable final state. The missing momentum arises here from the lightest supersymmetric particle, which necessarily remains stable at the end of a decay chain of any other SUSY particle. These SUSY dark-matter searches at the LHC are in general also interpreted in a rich set of simplified models, typically more restrictive than generic dark-matter production since SUSY cross sections and couplings are assumed. Overall, this is a very rich search program; summaries of the many searches being conducted can be found in Refs. [38, 39].

In the context of supsersymmetry, also full model interpretations have been performed by the experiments [40, 41]. A pMSSM model – a 19-parameter reduction of the minimal supersymmetric standard model – is employed, applying constraints of many LHC SUSY searches as well as several other LHC and non-LHC constraints, to a broad scan of model points. Such an exercise is very valuable in reveiling in particular model topologies and regions of parameter space that are particularly hard to discover at the LHC.

What concerns non-LHC accelerator searches for dark matter, finally, several experimental efforts are underway or are being planned. These will most notably probe low-mass – up to $\sim 1\,\mathrm{GeV}$ vector boson mediators, coupling to the standard model through kinetic mixing with the usual photon. In particular, searches are proposed at a new experimental facility SHiP at the CERN SPS [42].

7. Conclusions and outlook
The LHC comes with a vast program of dark matter searches through analyses looking for missing momentum signatures beyond the standard-model expectations. This program brings strong complementarity with the fields of direct and indirect searches for dark matter. We reviewed this search program, with particular emphasis on the transition of the interpretations

of the results from approximative but simple EFT models to the more complex but richer simplified models. We concentrated on the results for direct production of dark matter at the LHC, but also touched upon dark matter in the context of supersymmetry or non-LHC searches at accelerators. With LHC gearing up in its second run at higher energy and higher luminosity, and many non-LHC accelerator proposals on the table, the next few vibrant years are bound to further intensify the interplay and complementarity between direct detection, indirect detection, and accelerator searches for dark matter.

Acknowledgments

References

[1] Daci N, De Bruyn I, Lowette S, Tytgat M H G and Zaldivar B 2015 *JHEP* **11** 108
[2] Evans L (ed.) and Bryant P (ed.) 2008 *JINST* **3** S08001
[3] Essig R *et al* 2013 *Preprint arXiv:1311.0029 [hep-ph]*
[4] Izaguirre E, Krnjaic G, Schuster P and Toro N 2015 *Phys. Rev. Lett.* **115** 25 251301
[5] Beltran M, Hooper D, Kolb E W, Krusberg Z A C and Tait T M P 2010 *JHEP* **09** 037
[6] Goodman J, Ibe M, Rajaraman A, Shepherd W, Tait T M P and Yu H B 2011 *Phys. Lett.* B **695** 185
[7] Bai Y, Fox P J and Harnik R 2010 *JHEP* **12** 048
[8] Goodman J, Ibe M, Rajaraman A, Shepherd W, Tait T M P and Yu H B 2010 *Phys. Rev. D* **82** 116010
[9] Rajaraman A, Shepherd W, Tait T M P and Wijangco A M 2011 *Phys. Rev. D* **84** 095013
[10] Fox P J, Harnik R, Kopp J and Tsai Y 2012 *Phys. Rev. D* **85** 056011
[11] Alwall J, Schuster P and Toro N 2009 *Phys. Rev. D* **79** 075020
[12] Alves D *et al* [LHC New Physics Working Group] 2012 *J. Phys. G* **39** 105005
[13] Abdallah J *et al* 2015 *Phys. Dark Univ.* **9-10** 8
[14] Abercrombie D *et al* 2015 arXiv:1507.00966 [hep-ex]
[15] Abdallah J *et al* 2014 arXiv:1409.2893 [hep-ph]
[16] ATLAS Collaboration 2008 *JINST* **3** S08003
[17] CMS Collaboration 2008 *JINST* **3** S08004
[18] CMS Collaboration 2015 *Eur. Phys. J.* C **75** 5 235
[19] ATLAS Collaboration 2015 *Eur. Phys. J.* C **75** 7 299 Erratum: [2015 *Eur. Phys. J.* C **75** 9 408]
[20] ATLAS Collaboration 2014 *Phys. Rev. Lett.* **112** 4 041802
[21] CMS Collaboration 2012 *Preprint* CMS-PAS-EXO-12-055
[22] ATLAS Collaboration 2014 *JHEP* **09** 037
[23] CMS Collaboration 2015 *Phys. Rev. D* **91** 9 092005
[24] ATLAS Collaboration 2014 *Phys. Rev. D* **90** 1 012004
[25] CMS Collaboration 2016 *Phys. Rev. D* **93** 5 052011
[26] CMS Collaboration 2016 *Phys. Lett.* B **755** 102
[27] ATLAS Collaboration 2015 *Phys. Rev. D* **91** 1 012008 Erratum: [2015 *Phys. Rev. D* **92** 5 059903]
[28] ATLAS Collaboration 2015 *Eur. Phys. J.* C **75** 2 92
[29] CMS Collaboration 2015 *JHEP* **06** 121
[30] CMS Collaboration 2015 *Phys. Rev. Lett.* **114** 10 101801
[31] ATLAS Collaboration 2015 *Eur. Phys. J.* C **75** 2 79
[32] ATLAS Collaboration 2015 *Phys. Rev. Lett.* **115** 13 131801
[33] CMS Collaboration 2014 *Eur. Phys. J.* C **74** 2980
[34] ATLAS Collaboration 2016 *JHEP* **01** 172
[35] CMS Collaboration 2016 *Preprint* arXiv:1603.08914 [hep-ex]
[36] Buchmueller O, Malik S A, McCabe C and Penning B 2015 *Phys. Rev. Lett.* **115** 18 181802
[37] CMS Collaboration 2014 *Preprint* CMS-PAS-SUS-14-019
[38] `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS`
[39] `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults`
[40] ATLAS Collaboration 2015 *JHEP* **10** 134
[41] CMS Collaboration 2013 *Preprint* CMS-PAS-SUS-13-020
[42] Alekhin S *et al* 2015 *Preprint* arXiv:1504.04855 [hep-ph]