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Large Hadron Collider and Dark Matter

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We review shortly the scenarios of Weakly Interactive Massive Particle (WIMP) and Super-Weakly Interacting Massive Particle (SuperWIMP) Dark Matter candidates and discuss the recent searches for Dark Matter candidates at the Large Hadron Collider (LHC).

1 Introduction

The simplest way to explain many cosmological observations at different length-scales, from the horizon scale to the galactic one, (see e.g. Bertone et al. 2005, for a discussion), is to introduce a new type of matter, the Dark Matter, which has different properties than any particle seen in a laboratory so far. Indeed we know that it cannot carry baryonic number, nor be electromagnetically charged, nor too light if it is a thermal relic and that it has to be sufficiently stable on cosmological timescales. Already these four simple requirements unfortunately exclude all the known particles of the Standard Model as acceptable Dark Matter candidates and oblige us to look at extensions of the model. So Dark Matter is one of the strongest hints for new physics and the identification of a Dark Matter particle an important endeavour both for particle physics and astronomy.

Even if such Dark Matter particle has not yet been seen in a laboratory or in astrophysics (various hints instead have appeared recently both in DM direct detection experiment (Aalseth et al. 2011; Angloher et al. 2012; Bernabei et al. 2008) and in indirect detection observations (Bringmann et al. 2012; Goodenough & Hooper 2009; Hooper & Linden 2011; Weniger 2012), but none is yet completely convincing or confirmed by another independent experiment or observation (Finkbeiner et al. 2013; Kelso et al. 2012; Kopp et al 2012; Schwetz & Zupan 2011)), there is still a strong hope that it may be produced and observed at the Large Hadron Collider (LHC), the collider with the highest centre-of-mass energy and recently turned operational. Indeed the LHC is finally exploring a new energy window above the electroweak scale and seems to finally have seen evidence of the Higgs boson, a first step in the exploration the electroweak sector of any extension of the Standard Model. If the Dark Matter is connected to the electroweak scale, as implied by the WIMP mechanism, there is a justified hope that the LHC should give us some information about it, if not produce it directly. On the other hand also in other type of models, where the DM is not so directly connected to the electroweak scale and could be also much lighter, e.g. the SuperWIMP type of models, still the LHC collider can provide important constraints, and in the future perhaps even find signals together with indirect searches. In this short review we will concentrate on discussing these two generic scenarios that are being probed at the LHC. We regret that we will not be able to cover in detail all possible type of DM candidates that have been proposed and point for that to the extensive literature on the subject (see, e.g., Bertone 2010 or the review Tait & Hooper 2012).

2 The Large Hadron Collider

The Large Hadron Collider (LHC) is a new proton-proton ring accelerator constructed in the LEP tunnel at CERN (Evans & Bryant 2008). It has a circumference of 27 km and it hosts 4 experiments at different interaction points along the ring. For the quest for Dark Matter the relevant experiments are the detectors ATLAS (Aad et al. 2008) and CMS (Chatrchyan et al. 2008) (in alphabetical order . . .), which are “general purpose” detectors trying to measure any possible signal of new physics.

Note that the LHC is a hadronic machine, i.e. the colliding particles are not fundamental, like electrons or photons, but are bound-states of different partons (each proton has 3 valence quarks and a sea of other quarks and gluons). In the high energy collision of two protons, only a single parton of each proton is involved in the scattering, with an initial energy that is not unique, but follows a probability distribution (the partonic distribution function). Therefore at LHC different centre-of-mass energies can be realized in the single collisions so that one can say that it is possible to “scan” energies up to the total centre-of mass energy of the collider with a single collider. On the other hand, not knowing exactly the initial energy of the two partons makes the determination of any missing energy, carried away by

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neutral stable particles like the neutrino, more difficult. In practice one has to consider the conservation of momentum in the transverse plane to the beam and then define quantities like the missing transverse momentum.

In 2011 LHC took data at 7 TeV centre-of-mass energy, while last year the energy was increased to 8 TeV. At the moment the collider is undergoing a shut-down and consolidation works, that should allow to reach the energy of 13 or 14 TeV (Heuer 2012).

Another characteristic of hadronic machines is that the colliding particles interact via the strong interaction as described by the Standard Model and therefore most of the time only "boring" SM, mostly QCD, scatterings happen in the detector. The interesting events, involving e.g. electroweakly interacting particles like the Z, W or Higgs bosons, happen at a much lower rate and have to be selected among an orders of magnitude larger background. Actually due to the limitation in the recording rate, most of the uninteresting events have to be identified immediately and are not recorded at all. How does an experiment like ATLAS and CMS "see" a particle in such a complex environment? The clearest signal is usually a peak in the invariant mass distribution of the escaping SM particles, corresponding to an intermediate unstable state. In such way, the LHC has already been able to measure known unstable particles, for example the rho, eta, J/Psi, Ypsilon mesons and the Z-boson. Unfortunately the Dark Matter particle, which is in any case neutral and stable on collider time-scales, is not visible in this way and therefore the DM searches concentrate instead on the missing momentum signature. But, as we will see below, for non-WIMP candidates also other types of signal could appear.

3 The Higgs boson and Dark Matter

The Higgs boson is the particle connected to the scalar field responsible for electroweak symmetry breaking. Such field is the main ingredient of the Brout-Englert-Higgs mechanism (Englert & Brout 1964; Higgs 1964a,b) which allows to give mass to the W/Z bosons and break the electroweak symmetry in a consistent way, retaining the renormalizability of the Standard Model. In the minimal case of one doublet Higgs field only a single physical scalar particle is added to the Standard Model degrees of freedom and such particle, called the Higgs boson, has very specific couplings to the other states, mostly proportional to those particle's masses. This is due to the fact that the vacuum expectation value of the Higgs field itself give rise to particle masses (but not to the masses of hadrons like the proton and neutrons, which is instead generated by the QCD confining scale $\Lambda_{\rm QCD}$). In this minimal case, the Standard Model is very predictive and the only free and unknown parameter is the Higgs mass (Djouadi 2012). The Higgs boson has been the missing block to complete the Standard Model of particle physics for more than 40 years. Finally it seems that the search is over: The ATLAS and CMS collaborations presented on the 4th July 2012 the first evidence of a Higgs-like boson, with a mass around 125 GeV (Aad et al. 2012; Chatrchyan et al. 2012b). After that first observation, further data on its production mechanisms and decay channels seem to confirm that it is the Standard Model Higgs, but more evidence (e.g. the experimental determination of its spin and of the couplings) is needed to have certainty that the model is just the Standard Model with a single Higgs.

It may appear that the presence of a Higgs field is completely independent from the question of Dark Matter, but it is not so. On one side, there are very popular models where the Dark Matter is part of an extended Higgs sector, like the Inert DM model (Barbieri et al. 2006; Ma 2006), recently compared to the LHC Higgs evidence in Goudelis et al. (2013); on the other side, it is important to ask if the DM couples to the Higgs field. In the last years the possibility that the DM couples to the SM only via the Higgs fields has been very thoroughly studied in the "Higgs portal" models (Chu et al. 2012; Englert et al. 2011; Kanemura et al. 2010; Lebedev et al. 2012; Lopez-Honorez et al. 2012; Mambrini 2011; McDonald 1994). In this type of scenarios, two observable signals of DM could be within reach soon: the direct detection of a WIMP Dark Matter with scattering mediated by Higgs particle itself and the invisible decay of the Higgs into Dark Matter particles (Djouadi et al. 2012a; He & Tandean 2011; Lebedev et al. 2012; Mambrini 2011). The direct detection rate through a Higgs particle is in fact close to the present experimental sensitivities for couplings of order one as required by the WIMP mechanism (Djouadi et al. 2012a). Therefore such a scenario should come to be tested very soon. Moreover, if the Dark Matter is lighter than approximately 63 GeV, an additional decay channel for the Higgs should appear, corresponding to the decay into two Dark Matter particles. Such channel is an invisible decay at the LHC and can already be constrained by present data, even if not very strongly (Djouadi et al. 2012b; Espinosa et al. 2012a,b).

4 WIMPs

As discussed in the introduction, we do not know the nature of the Dark Matter particles, but a very important observation is that they could be naturally related to the electroweak scale. In fact a very well-known paradigm in cosmology is the Weakly Interacting Massive Particle (WIMP) mechanism (Bertone et al. 2005). The mechanism relies in the decoupling or *freezing out* of stable thermal massive relics and it is connected to the numerical miracle that a particle with mass of about 100 GeV with electroweak cross-sections of order $G_{\rm F}$ has a relic energy density of the order of the critical energy density. Once an explicit model for the WIMP interactions is given, the computation of the thermal decoupling can be made more precise and the parameters of the model fixed to give the correct relic density. Realization of the WIMP paradigm have been given in many different scenarios of physics beyond the Standard Model: from the case of extended Higgs sectors (Lopez Honorez et al. 2007) to supersymmetric models (Jungman et al. 1996), form models with extra dimensions (Kaluza-Klein Dark Matter) (Servant & Tait 2003) to technicolor models (Foadi et al. 2009; Nussinov 1985), etc.

In general WIMP candidates can give rise to a wealth of signals: first of all they can still annihilate at the present time where their density is large like at the centre of our galaxy or other astrophysical objects, giving rise to measurable cosmic rays and or gamma-rays (Ibarra 2012). If the annihilation produces also light charged particles also indirect radio photons can be produced by synchrotron emission (Bertone et al. 2009). This kind of signatures constitute the *indirect detection* signals for a WIMP candidate and have recently been very actively pursued (Bringmann & Weniger 2012; Ibarra 2012). Secondly the WIMP wind can scatter elastically against normal matter depositing a small amount of energy (in the keV range since DM is not relativistic in our halo) in a detector (Primack et al. 1988). This search strategy is called *direct detection* and is also very active (Baudis 2012). Finally DM can be also produced at collider from the annihilation of SM particles and this type of signatures will be discussed in more detail in the next section.

Since the direct detection and indirect detection signals can be quite similar in different WIMP models, the information of colliders can be crucial to disentangle the different possibilities. On the other hand, a DM candidate detection at a collider is not sufficient to prove that the observed particle is sufficiently stable and indeed makes up all the DM density in the Universe. It is therefore clear that only a multiple signal of the same particle in possibly all three types detection will be needed to provide a strong case for a specific WIMP DM candidate.

5 Generic WIMP searches at the LHC

A very general search for WIMP Dark Matter at the LHC is based direct production of Dark Matter particles in the annihilation of two partons. In such process we expect two DM particles to be produced, since the DM has to be stable on cosmological scales. In fact if also a single DM particle could be produced, by inverting the process this would imply also a decay of the DM within much shorter time-scales. After being produced, the DM, as a neutral stable particle, would just escape the detector leaving unfortunately no experimental signature.

Fortunately it can also happen that the initial scattering partons emit initial state radiation before annihilating, giving rise also to an additional visible particle. The emission of radiation from an accelerated charge is a universal process depending only on the initial state particle, so that the production of invisible DM plus radiation is quite general and has been suggested long time ago as a model independent signal of WIMP DM (Birkedal et al. 2004). In the case of LHC such radiation can take two different forms, i.e. that of a gluon or a photon. Both particles are visible in the detectors and provide a clear signal: a single jet or photon recoiling against nothing! This is what is called the monojet or monophoton signature.

In order to give bounds on Dark Matter models, one needs to model the interaction leading to Dark Matter production. In the last couple of years great efforts have been done in embedding such interactions in effective models for WIMP Dark Matter and in comparing them with TeVatron and LEP data (Bai et al. 2010; Fox et al. 2011; Goodman et al. 2010, 2011) setting up the theoretical tools in preparation for the LHC. Already with the very first data in fact theoretical groups were able to set the first constraints (Fox et al. 2012; Rajamaran et al. 2011).

The effective field theory description is based on writing down all the possible non-renormalizable operators between two Dark Matter fields and the Standard Model particles up to dimension six and classifying them according to the DM particle type. In particular for a scalar DM field one has

$$\mathcal{L} = \sum_i \mathcal{O}_i^{2+n}(\mathrm{SM}) \frac{|\chi|^2}{\Lambda^{\mathrm{n}}}, \tag{1}$$

where $\mathcal{O}_i^{2+n}(\mathrm{SM})$ are operators of mass dimension $2+n$ in the SM fields. We see here clearly that the lowest dimension operators can only involve the Higgs field, justifying for example the study of scenario like the Higgs portal one. Assuming that a single of these operators dominates, the absence of a signal at the LHC can be translated into a lower bound on the scale of the operator Λ. Moreover if the same operator is also giving the main contribution to the WIMP-nucleon elastic scattering, the LHC results can be directly compared to the direct detection experiments (Bai et al. 2010; Fox et al. 2011; Goodman et al. 2010, 2011).

The LHC collaborations have also searched for this kind of signals, until now without evidence of any excess above the background (Aad et al. 2013a,b; Chatrchyan et al. 2012c). At the moment such exclusion regions are comparable to the ones from direct detection and are usually stronger in the low DM mass region, which lies mostly below the threshold of the direct detection experiments, and for the case of spin-dependent interaction. It must nevertheless be mentioned that these constraints still contain a model dependence in the specific non-renormalizable operator considered and not all the operators are bounded at the same level. As it is to be expected, the LHC is mostly sensitive to operators that couple DM to the colored sector of the SM, in particular gluons and first generation quarks. Nevertheless weaker bound on the leptonic operators have been obtained also from LEP (Fox et al. 2011).

6 Supersymmetric WIMP: the neutralino

Supersymmetry is one of the best theoretically motivated symmetries for enlarging the Standard Model. It is a symmetry between bosons and fermions and requires to double the SM spectrum adding for every particle a superpartner with the same quantum numbers but different spin (Nilles 1984). In the minimal supersymmetric extension, the MSSM, a second Higgs field is needed as well, enlarging also the Higgs sector of the theory and an additional discrete symmetry R-parity, which forbids baryon and lepton violating interactions keeping the proton stable. Within the MSSM the lightest neutralino, one of the fermionic superpartners of the neutral gauge and Higgs bosons, is a natural WIMP candidate as it was realized long ago (Jungman et al. 1996). In general the MSSM tends to point to a Higgs mass value lower than the one observed at the LHC and therefore probably more extended models are nowadays preferred (Hall et al. 2012).

In the case of a supersymmetric model (or also any other explicit WIMP model with colored states!), we expect at the LHC much stronger production rates for colored superparticles than for the neutralino. The searches have therefore mostly concentrated on gluinos (the superpartners of the gluons, which are present in the proton) and first two generation squarks (the scalar superpartners of the quarks), without success so far, pushing the bounds on these superparticle masses above the TeV (see Aad et al. 2013b; Chatrchyan et al. 2012d) for published results on the 7 TeV data of 2011, but more recent ones have been presented in conference notes or preprints, e.g. in ATLAS (2012) and in Chatrchyan et al. (2013). Nevertheless, there are more general supersymmetric models which allow to accommodate a heavier spectrum and still a neutralino WIMP and DM (Arbey et al. 2012a,b; Cahill-Rowley et al. 2012a,b), so supersymmetry is not yet excluded. In fact only recently the LHC collaborations have started probing directly electroweakly charged states like the charginos, superpartners of the charged Higgs and W-bosons or supersymmetric models with R-parity violation, where instead the gravitino, the superpartner of the graviton, could be DM instead.

Moreover there are regions of the parameter space, where the signals of colored superparticles are less evident, for example in case of compressed mass spectrum: in fact if the mass difference between the superpartners is very small, the SM particles arising from the chain decays into neutralino may have such a low energy and momentum to be effectively invisible.[1]

In those scenarios, though, the monojet or monophoton channels can again become useful. For example monojet/monophoton bounds on the case of graviton production in extra-dimensional scenarios and for Dark Matter production at colliders given in (Aad et al. 2013c; Chatrchyan et al. 2012c) have recently been reinterpreted for the case of a degenerate gaugino spectrum, excluding gluino masses up to 450–500 GeV (Dreiner & Tattersall 2012).

[1] One has to recall that in order to reduce the SM backgrounds, the LHC collaborations require a minimal energy/momentum threshold for the particles in the final state.

7 SuperWIMPs and decaying Dark Matter

Let us now consider another type of dark matter candidates, i.e. particles that interact much more weakly than the electroweak interaction. An example of this category is the gravitino, the superpartner of the graviton, which has spin 3/2 and interactions suppressed by the Planck scale (Wess & Bagger 1992). To be a Cold Dark Matter (CDM) candidate, the gravitinos must be heavier than 100 keV or so and remain out of thermal equilibrium.[2] Scattering processes in the primordial plasma can nevertheless produce a sufficiently large gravitino population, in particular those mediated by dimension 5 operators involving the QCD gauge interactions (Bolz et al. 2001; Pradler & Steffen 2007; Rychkov & Strumia 2007).

Another population of gravitinos is also generated by the decay of the Next-to-lightest Superparticle (NLSP), after it has frozen out, in the SuperWIMP mechanism (Feng et al. 2003a,b), as

$$\Omega_{3/2}\, h^2 = \frac{m_{3/2}}{m_{\rm WIMP}} \Omega_{\rm WIMP}\, h^2, \qquad (2)$$

where we are assuming the NLSP to be a WIMP particle. But if such decay happens during or after nucleosynthesis, the energy density of the NLSP is very strongly constrained (Jedamzik & Pospelov 2009). An easy option to avoid this problem is to allow for a small R-parity violation, so that the NLSP decays only to SM particles (long) before nucleosynthesis (Buchmüller et al. 2007). In that case also the gravitino is unstable, but it can have a lifetime much longer than the age of the Universe and remain a good DM candidate. The requirement that the NLSP decays early enough and for the lepton- or baryon-violating processes connected to R-parity violation not to be in equilibrium at the same time as the sphaleron processes (Dreiner & Ross 1993; Endo et al. 2010), singles out a particular window in the range of these couplings, 10^{-7}–10^{-12}. Of course once R-parity is broken, the danger of too fast proton decay reappears in the MSSM, but it can be avoided if e.g. only the lepton number violating couplings or only the baryon number violating ones are switched on.

If the R-parity breaking couplings are large enough, DM decay could be observable today in different channels of indirect DM detection observations (Bertone et al. 2007; Bobrovskyi et al. 2010; Bomark et al. 2010; Buchmüller et al. 2009; Choi et al. 2010; Covi et al. 2009; Ishiwata et al. 2008). At the moment the FERMI data set a lower bound on the DM lifetime in photons of the order of 5×10^{28} s (Abdo et al. 2010; Vertongen & Weniger 2011), already excluding part of the R-parity breaking parameter space. For particular gaugino masses and light gravitino, the DM decay in gamma and neutrino can be suppressed (Restrepo et al. 2012), allowing for larger R-parity breaking couplings, able to accommodate also the neutrino masses.

[2] If they reach thermal equilibrium, contrary to WIMPs, they decouple as a relativistic species and therefore with a too large number density.

8 Supersymmetric SuperWIMP: the gravitino at the LHC

Supersymmetric models with gravitino Dark Matter (or in general with SuperWIMPs DM ...) can give at the LHC quite different signals than the neutralino WIMP scenarios. In that case in fact, the role of the lightest supersymmetric particle at the collider is effectively played by the Next-to-lightest particle, that can be also a charged state and decays into gravitinos only far away from the detector. Then the charged tracks of such metastable particle would cross the whole detector and be difficult to miss. The long lifetime of a charged particle would then be the signal that a *super-weakly* coupled particle is involved. In fact strong bounds exist on charged relics and they do imply that any such charged particle cannot be stable on cosmological scales. The LHC collaborations have already performed searches for exotic metastable particles, setting strong constraints on metastable stop and gluino NLSP, reaching lower limits of the order of about 800 and 1200 GeV respectively (Chatrchyan et al. 2012a). Weaker constraints apply on the other hand to the s-tau NLSP as well as the other non-colored particles.

If the lifetime of the NLSP is shorter, then also the possibility of displaced vertices within the detector arises and even a neutral NLSP could be visible. For the R-parity violating models discussed above, the LHC can then probe the scenario of neutralino NLSP also beyond the parameter space already excluded by FERMI (Bobrovskyi et al. 2011). On the other hand, if the NLSP is neutral, it may become difficult to disentangle the gravitino DM from a neutralino WIMP only relying on collider data. In that case the presence or absence of detection in direct detection experiments may be needed to distinguish the two models.

9 Conclusions

The search for a DM particle is gaining momentum and continues on all fronts: at the LHC collider, in direct detection experiments and in indirect detection observations! We do not have convincing signals so far, but it is still early days.

The recent observation of a Higgs-like particle with mass around 125 GeV is the first measurement on the Higgs sector of our theory and already poses a few challenges for the simplest supersymmetric models. But if the Dark Matter is a WIMP that couples preferentially to the Higgs, a signal should come very soon from direct detection.

Regarding general WIMPs, the monojet/monophoton searches are providing independent tests of this paradigm, complementary to the direct and indirect detection searches. Such channels are actually also able to constrain other difficult scenarios like the case of small mass differences in the new particle spectrum. Supersymmetric searches for colored superpartners have reached the TeV scale and beyond in the simpler cases, but the constraints on non-colored particles or third generation squarks are not yet as strong. There is still room both for a neutralino WIMP or for a gravitino SuperWIMP, let us hope that another signal, apart for the Higgs boson, will appear soon!

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References

Aad, G., Abat, E., Abdallah, J., et al. (ATLAS Collaboration) 2008, Journal of Instrumentation, 3, S08003
Aad, G., Abajyan, T., Abbott, B., et al. (ATLAS Collaboration) 2012, Phys. Lett. B, 716, 1
Aad, G., et al. (ATLAS Collaboration) 2013a, Journal of High Energy Physics, 1304, 075
Aad, G., Abajyan, T., Abbott, B., et al. (ATLAS Collaboration) 2013b, The European Physical Journal C, 73, 2362
Aad, G., Abajyan, T., Abbott, B., et al. (ATLAS Collaboration) 2013c, Phys. Rev. Lett., 110, 011802
Aalseth, C.E., Barbeau, P.S., Bowden, N.S., et al. (CoGeNT collaboration) 2011, Phys. Rev. Lett., 106, 131301
Abdo, A., Ackermann, M., Ajello, M., et al. 2010, Phys. Rev. Lett., 104, 091302
Angloher, G., Bauer, M., Bavykina, I., et al. 2012, The European Physical Journal C, 72, 1971
Arbey, A., Battaglia, M., & Mahmoudi, F. 2012a, The European Physical Journal C, 72, 2169
Arbey, A., Battaglia, M., Djouadi, A., & Mahmoudi, F. 2012b, Journal of High Energy Physics, 1209, 107
ATLAS Collaboration 2012, Search for squarks and gluinos with the atlas detector using final states with jets and missing transverse momentum and 5.8 fb^{-1} of $\sqrt{s}$=8 tev proton-proton collision data, Tech. Rep. ATLAS-CONF-2012-109 CERN Geneva
Bai, Y., Fox, P.J., & Harnik, R. 2010, Journal of High Energy Physics, 1012, 048
Barbieri, R., Hall, L. J., & Rychkov, V. S. 2006, Phys. Rev. D, 74, 015007
Baudis, L. 2012, Physics of the Dark Universe, 1, 94
Bernabei, R., Belli, P., Cappella, F., et al. (DAMA Collaboration) 2008, The European Physical Journal C, 56, 333
Bertone, G., Hooper, D., & Silk, J. 2005, Physics Reports, 405, 279
Bertone, G., Buchmüller, W., Covi, L., & Ibarra, A. 2007, Journal of Cosmology and Astroparticle Physics, 0711, 003
Bertone, G., Cirelli, M., Strumia, A., & Taoso, M. 2009, Journal of Cosmology and Astroparticle Physics, 0903, 009
Bertone, G. 2010, Particle Dark Matter: Observations, Models and Searches (Cambridge University Press, UK)
Birkedal, A., Matchev, K., & Perelstein, M. 2004, Phys. Rev. D, 70, 077701
Bobrovskyi, S., Buchmüller, W., Hajer, J., & Schmidt, J. 2010, Journal of High Energy Physics, 1010, 061
Bobrovskyi, S., Buchmüller, W., Hajer, J., & Schmidt, J. 2011, Journal of High Energy Physics, 1109, 119
Bolz, M., Brandenburg, A., & Buchmüller, W. 2001, Nuclear Physics B, 606, 518
Bomark, N. E., Lola, S., Osland, P., & Raklev, A. 2010, Phys. Lett. B, 686, 152

Bringmann, T., & Weniger, C. 2012, Physics of the Dark Universe, 1, 194
Bringmann, T., Huang, X., Ibarra, A., Vogl, S., & Weniger, C. 2012, Journal of Cosmology and Astroparticle Physics, 1207, 054
Buchmüller, W., Covi, L., Hamaguchi, K., Ibarra, A., & Yanagida, T. 2007, Journal of High Energy Physics, 0703, 037
Buchmüller, W., Ibarra, A., Shindou, T., Takayama, F., & Tran, D. 2009, Journal of Cosmology and Astroparticle Physics, 0909, 021
Cahill-Rowley, M. W., Hewett, J. L., Hoeche, S., Ismail, A., & Rizzo, T. G. 2012a, The European Physical Journal C, 72, 2156
Cahill-Rowley, M. W., Hewett, J. L., Ismail, A., & Rizzo, T. G. 2012b, hep-ph/1211.1981
Chatrchyan, S., Hmayakyan, G., Khachatryan, V., et al. (CMS Collaboration) 2008, Journal of Instrumentation, 3, S08004
Chatrchyan, S., et al. (CMS Collaboration) 2012a, Phys. Lett. B, 713, 408
Chatrchyan, S., et al. (CMS Collaboration) 2012b, Phys. Lett. B, 716, 30
Chatrchyan, S. et al. (CMS Collaboration) 2012c, hep-ex/1206.5663
Chatrchyan, S., et al. (CMS Collaboration) 2012d, hep-ex/1212.6961
Chatrchyan, S., et al. (CMS Collaboration) 2013, hep-ex/1303.2985
Choi, K. Y., Lopez-Fogliani, D. E., Munoz, C., & de Austri, R. R. 2010, Journal of Cosmology and Astroparticle Physics, 1003, 028
Chu, X., Hambye, T., & Tytgat, M. H. 2012, Journal of Cosmology and Astroparticle Physics, 1205, 034
Covi, L., Grefe, M., Ibarra, A., & Tran, D. 2009, Journal of Cosmology and Astroparticle Physics, 0901, 029
Djouadi, A. 2012, The Higgs Mechanism and the Origin of Mass, in Progress in Theoretical Physics (ICPTP 2011), ed. N. Mebarki, J. Mimouni, N. Belaloui, & K. Ait Moussa, AIPC 1444 (AIP, Melville), 45
Djouadi, A., Lebedev, O., Mambrini, Y., & Quevillon, J. 2012a, Phys. Lett. B, 709, 65
Djouadi, A., Falkowski, A., Mambrini, Y., & Quevillon, J. 2012b, hep-ph/1205.3169
Dreiner, H. K., & Ross, G. G. 1993, Nuclear Physics B, 410, 188
Dreiner, H. K., & Tattersall, M. K. J. 2012, hep-ph/1207.1613
Endo, M., Hamaguchi, K., & Iwamoto, S. 2010, Journal of Cosmology and Astroparticle Physics, 1002, 032
Englert, F., & Brout, R. 1964, Phys. Rev. Lett., 13, 321
Englert, C., Plehn, T., Zerwas, D., & Zerwas, P. M. 2011, Phys. Lett. B, 703, 298
Espinosa, J. R., Mühlleitner, M., Grojean, C., & Trott, M. 2012a, Journal of High Energy Physics, 1209, 126
Espinosa, J. R., Grojean, C., Mühlleitner, M., & Trott, M. 2012b, Journal of High Energy Physics, 1212, 045
Evans, L., & Bryant, P. 2008, Journal of Instrumentation, 3, S08001
Feng, J. L., Rajaraman, A., & Takayama, F. 2003a, Phys. Rev. Lett., 91, 011302
Feng, J. L., Rajaraman, A., & Takayama, F. 2003b, Phys. Rev. D, 68, 063504
Finkbeiner, D. P., Su, M., & Weniger, C. 2013, Journal of Cosmology and Astroparticle Physics, 1301, 029
Foadi, R., Frandsen, M. T., & Sannino, F. 2009, Phys. Rev. D, 80, 037702
Fox, P. J., Harnik, R., Kopp, J., & Tsai, Y. 2011, Phys. Rev. D, 84, 014028
Fox, P. J., Harnik, R., Kopp, J., & Tsai, Y. 2012, Phys. Rev. D, 85, 056011
Goodenough, L., & Hooper, D. 2009, astro-ph/0910.2998
Goodman, J., Ibe, M., Rajaraman, A., et al. 2010, Phys. Rev. D, 82, 116010
Goodman, J., Ibe, M., Rajaraman, A., et al. 2011 Phys. Lett. B, 695, 185
Goudelis, A., Herrmann, B., & Stål, O. 2013, hep-ph/1303.3010
Hall, L. J., Pinner, D., & Ruderman, J. T. 2012, Journal of High Energy Physics, 1204, 131
He, X. G., & Tandean, J. 2011, Phys. Rev. D, 84, 075018
Heuer, R.-D. 2012 physics.acc-ph/1202.5860
Higgs, P. W. 1964a, Phys. Lett., 12, 132
Higgs, P. W. 1964b, Phys. Rev.Lett., 13, 508
Hooper, D., & Linden, T. 2011, Phys. Rev. D, 83, 083517
Ibarra, A. 2012, Acta Physica Polonica B, 43, 2199
Ishiwata, K., Matsumoto, S., & Moroi, T. 2008, Phys. Rev. D, 78, 063505
Jedamzik, K., & Pospelov, M. 2009, New J. Phys., 11, 105028
Jungman, G., Kamionkowski, M., & Griest, K. 1996, Physics Reports, 267, 195
Kanemura, S., Matsumoto, S., Nabeshima, T., & Okada, N. 2010, Phys. Rev. D, 82, 055026
Kelso, C., Hooper, D., & Buckley, M. R. 2012, Phys. Rev. D, 85, 043515
Kopp, J., Schwetz, T., & Zupan, J. 2012 Journal of Cosmology and Astroparticle Physics, 1203, 001
Lebedev, O., Lee, H. M., & Mambrini, Y. 2012, Phys. Lett. B, 707, 570
Lopez Honorez, L., Nezri, E., Oliver, J. F., & Tytgat, M. H. 2007, Journal of Cosmology and Astroparticle Physics, 0702, 028
Lopez-Honorez, L., Schwetz, T., & Zupan, J. 2012, Phys. Lett. B, 716, 179
Ma, E. 2006, Phys. Rev. D, 73, 077301
Mambrini, Y. 2011, Phys. Rev. D, 84, 115017
McDonald, J. 1994, Phys. Rev. D, 50, 3637
Nilles, H. P. 1984, Physics Reports, 110, 1
Nussinov, S. 1985, Phys. Lett. B, 165, 55
Pradler, J., & Steffen, F. D. 2007, Phys. Rev. D, 75, 023509
Primack, J. R., Seckel, D., & Sadoulet, B. 1988, Annual Review of Nuclear and Particle Sciences, 38, 751
Rajaraman, A., Shepherd, W., Tait, T. M., & Wijangco, A. M. 2011, Phys. Rev. D, D84, 095013
Restrepo, D., Taoso, M., Valle, J., & Zapata, O. 2012, Phys. Rev. D, 85, 023523
Rychkov, V. S., & Strumia, A. 2007, Phys. Rev. D, 75, 075011
Schwetz, T., & Zupan, J. 2011, Journal of Cosmology and Astroparticle Physics, 1108, 008
Servant, G., & Tait, T. M. 2003, Nuclear Physics B, 650, 391
Tait, T. M., & Hooper, D. 2012, Comptes Rendus Physique, 13, 719
Vertongen, G., & Weniger, C. 2011, Journal of Cosmology and Astroparticle Physics, 1105, 027
Weniger, C. 2012, Journal of Cosmology and Astroparticle Physics, 1208, 007
Wess, J., & Bagger, J. 1992, Supersymmetry and Supergravity (Princeton University Press)

