Searches for phenomena beyond the Standard Model at the Large Hadron Collider with the ATLAS and CMS detectors

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Abstract. The LHC has delivered several fb^{-1} of data in spring and summer 2011, opening new windows of opportunity for discovering phenomena beyond the Standard Model. A summary of the searches conducted by the ATLAS and CMS experiments based on about 1 fb^{-1} of data is presented.

1. Introduction

The Standard Model (SM) has proven to be an incredibly successful theory over the past decades. However successful, it is an effective theory that must break down above a certain energy scale, and there are strong theoretical arguments to believe that it breaks down at the electroweak scale (for a theoretical review of this subject, see [1] and the contribution in this conference from the same author). In 2011, operating at a centre-of-mass energy of 7 TeV in pp collisions, the LHC has been able to deliver several fb^{-1} of data to both ATLAS [2] and CMS [3] detectors within a few months, allowing to extend the reach of searches for phenomena beyond the Standard Model well beyond the ones carried by the Tevatron.

This article presents some of the searches carried out by ATLAS and CMS using up to 1.6 fb^{-1} of data on supersymmetry and exotic signatures. I shall start with a summary of the searches for supersymmetry, followed by an overview of some exotic searches, divided somewhat arbitrarily in three sections: search for heavy resonances, search for strong gravity at the TeV-scale, and search for long-lived particles. Unfortunately, no deviation from the SM expectation is observed, but limits on many theories beyond the SM are improved significantly.

Searches related to Higgs boson, top–antitop resonance and fourth-generation quarks are described in other contributions of this conference [4–6]. Only a selection of results is shown here; all results can be found on the ATLAS [7] and CMS [8] web pages.
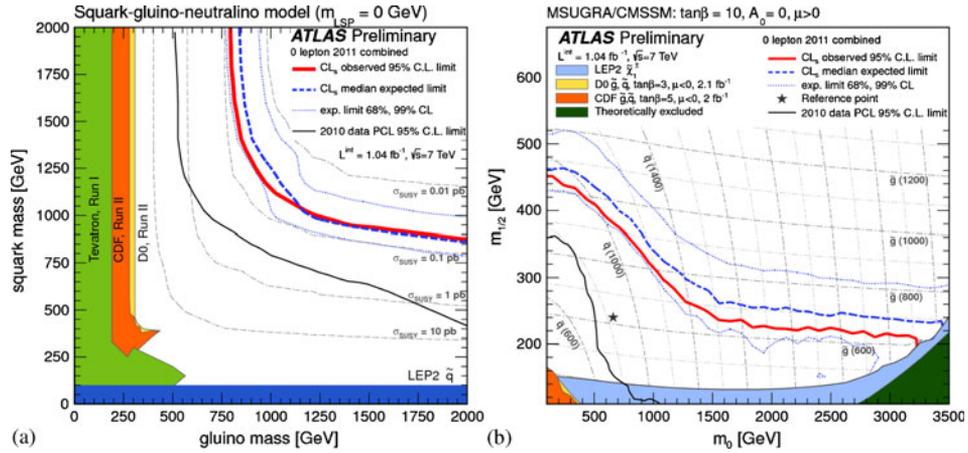
Figure 1. Limits on supersymmetric models from the 0-lepton channel at ATLAS [11]. (**a**) Simplified model assuming only squark and gluino production, and a light LSP. (**b**) CMSSM/MSUGRA model.

2. Supersymmetry

During the past decades, supersymmetry [9,10] has been considered the most promising extension of the SM. The phenomenology of supersymmetry is very diverse, which requires a search strategy following several classes of models and covering many signatures.

In its most hoped for incarnation, supersymmetry is expected to be discovered at the LHC through pair production of supersymmetric particles decaying in a cascade of supersymmetric and SM particles. If R-parity is conserved, the lightest supersymmetric particle
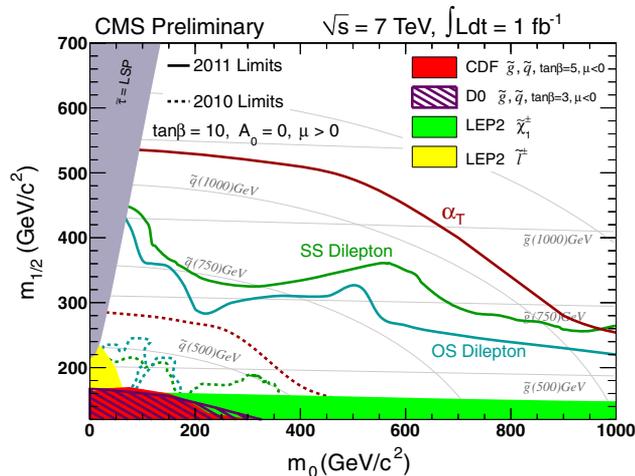

Figure 2. Summary of the searches for supersymmetry at CMS on CMSSM/MSUGRA in the 0-lepton, 1-lepton and 2-lepton channels.

(LSP) is stable and neutral, and the cascade ends with the production of LSPs, which escape the detector, producing missing transverse momentum.

In *pp* collisions, strongly coupled particles are much more likely to be produced, thus the production of squarks and gluinos is expected to dominate, leading predominantly to a final state with jets and missing transverse momentum. The 'workhorse' of supersymmetry searches at the LHC is thus the channel with large missing transverse momentum and jets of high transverse momentum. No excess above the expected SM background is observed and limits are set on supersymmetric models. Figures 1 and 2 show the limits from ATLAS [11] and CMS [12]. In addition to setting limits on the CMSSM/MSUGRA model, ATLAS also presents a limit for a simplified model assuming only squark and gluino production, and a cascade involving only quarks and gluons, and the LSP. For equal masses of squarks and gluinos, a limit of about 1 TeV is set at 95% CL.
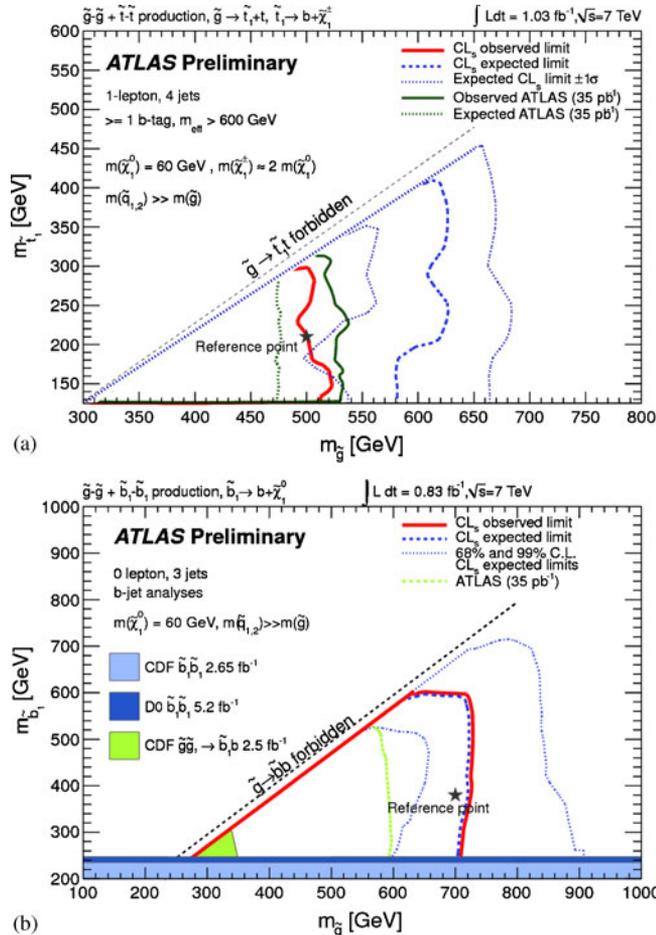

Figure 3. Search for light third-generation supersymmetric models. (**a**) 1-lepton with at least one *b*-jet [19] and (**b**) 0-lepton with *b*-jets [20].

The cascade can also produce leptons through the decay of sleptons, charginos, or *W/Z* bosons. Due to the smaller branching ratio, channels containing one [13,14] or more electrons or muons are less sensitive to squark and gluino strong production, but are complementary to the fully hadronic channel, as shown in figure 2 for the CMS results. In the dilepton channel, several strategies are employed: opposite-sign [15] or same-sign [16], flavour subtraction [17] to remove the flavour-correlated background, or explicit reconstruction of a *Z* produced in the cascade and decaying to a pair of muons or electrons [18].

Of particular interest are scenarios in which the third generation of supersymmetric particles is much lighter than the others. The current luminosity allows to test such scenarios only through production of gluinos decaying to stop or sbottom, leading to the final state of top and/or bottom quarks. Assuming that the stop is the only light squark, gluino pair production leads to a complex final state containing top and bottom quarks. Figure 3a shows that this scenario is excluded for gluino masses up to 500 GeV in the channel with one lepton and at least four jets, one of which is identified as a *b*-jet [19]. Alternatively, if the only light squark is an sbottom, gluino pair production leads to a final state with four *b*-jets and two LPSs; in this case, in the channel with at least three jets, at least two of which are identified as *b*-jets, gluino masses are excluded up to 700 GeV, as shown in figure 3b [20]. Additional luminosity will allow the search for direct production of third-generation quarks and gauginos.

In gauge-mediated supersymmetry breaking (GMSB) models [21], the LSP is the gravitino and the next lightest supersymmetric particle (NLSP) is a neutralino or a chargino. This leads to a cascade ending with photons and missing transverse momentum in the final state. CMS has looked for both single-photon and diphoton final states [22]. Results are shown in figure 4. In the diphoton channel, the result is also interpreted for the scenario of wino-like NLSP (neutralino and chargino nearly degenerate in mass). Universal
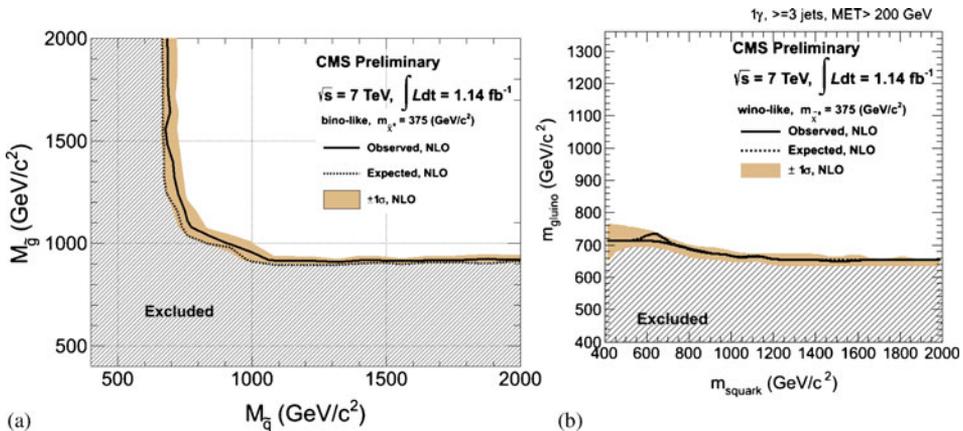

Figure 4. Search for GMSB in the single-photon plus missing transverse momentum and diphoton plus missing transverse momentum final states [22]. (**a**) Diphoton, bino-like interpretation and (**b**) single photon, wino-like interpretation.

extra-dimensions (UED) models [23] predict cascades that are very similar to supersymmetry, which allows to interpret the same analysis in both models [24].

Supersymmetric signatures involving long-lived particles are discussed in the last section.

3. Heavy resonances

Heavy resonances are predicted by many extensions of the SM. Some grand unified theories [25] predict the existence of additional gauge bosons while Randall–Sundrum models with warped extra dimensions [26,27] predict Kaluza–Klein excitations of the graviton. Both lead to a narrow resonance decaying to a pair of fermions or bosons with branching ratios varying widely depending on the model considered.

In the dilepton channel (dielectron or dimuon) [28,29], a neutral gauge boson with the same couplings as the SM Z^0 (sequential standard model Z' [30]) is excluded up to a mass of 1.9 TeV at 95% CL. A Randall–Sundrum Kaluza–Klein graviton with a coupling of $k/M_{Pl} = 0.1$ is excluded up to 1.8 TeV at 95% CL combining the dielectron and the dimuon channels, and up to 1.7 TeV in the diphoton channel alone [31]. Figures 5 and figure 6a show the dileptons and the diphoton mass spectra, respectively.

A charged gauge boson (W') is searched for in the $e\nu$ and $\mu\nu$ channels by reconstructing the transverse mass of the lepton transverse momentum and the event missing transverse momentum. Figure 6b shows the ATLAS transverse mass in $\mu\nu$ events. A W' with the same couplings as the SM W (sequential Standard Model W') is excluded up to a mass of 2.3 TeV at 95% CL when combining $e\nu$ and $\mu\nu$ channels [32,33]. A W' is also expected to decay to WZ, which is also a channel of interest for technicolour [34] searches; CMS has looked for a narrow resonance in the final state $WZ \rightarrow l\nu ll$ and excludes an SSM W' up a mass of 784 GeV and a techni-rho up to a mass of 436 GeV in the parameter space $m_{\rho_{TC}} < m_{\pi_{TC}} + m_W$ [35].
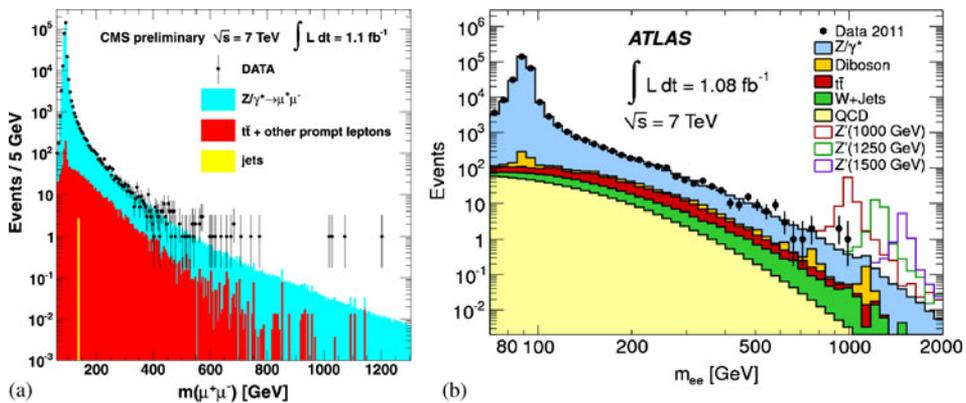

Figure 5. Search for heavy resonances in the dilepton channel. (**a**) Reconstructed dimuon mass spectrum (CMS) [29] and (**b**) reconstructed dielectron mass spectrum (ATLAS) [28].
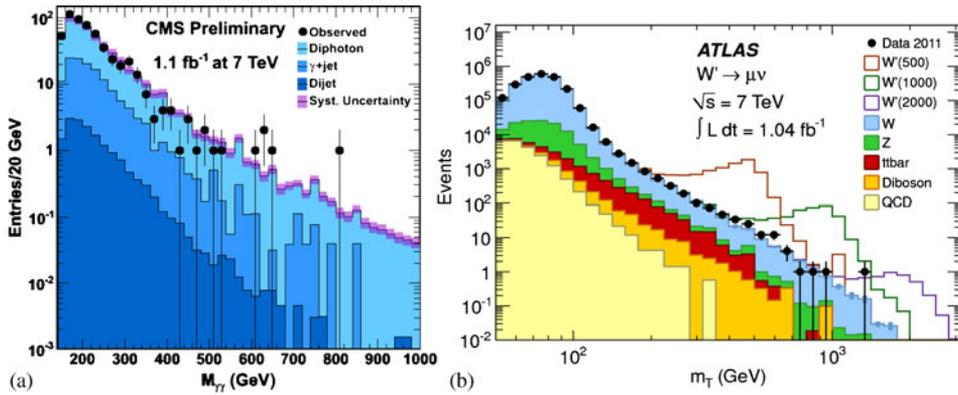
Figure 6. (**a**) Diphoton reconstructed mass spectrum (CMS) [31] and (**b**) reconstructed transverse mass in events with one muon and missing transverse momentum (ATLAS) [32].

A narrow resonance decaying to a pair of jets is also predicted by numerous models. Considering the excited quark model (q^*) [36] as a benchmark, no narrow resonance in the dijet system is observed up to 2.9 TeV at 95% CL [37,38]. Figure 7 shows the ATLAS model-independent limit on the cross-section for several hypotheses of the resonance width, and the CMS limits on several models depending on the nature of the jet (quark jet or gluon jet).

A heavy particle decaying to a pair of charged leptons of same-sign, such as a doubly-charged Higgs, would be a striking signature of physics beyond the SM. More generally, final states including a pair of charged leptons of same-sign are predicted by many BSM models (including supersymmetry, same-sign top production, fourth-generation b', heavy
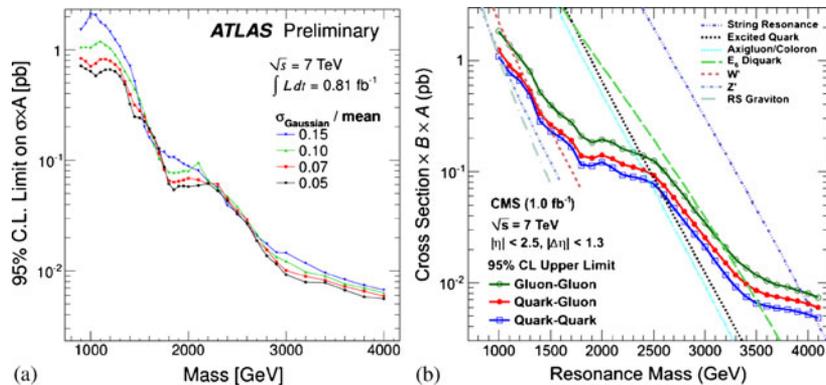

Figure 7. 95% CL upper limits on the production cross-section times the acceptance of resonances decaying to a pair of jets. (**a**) The limit is presented in a model-independent way as a function of the full width (both physical and experimental) of the resonance (ATLAS) [37] and (**b**) limits on narrow resonances of types gluon–gluon, gluon–quark and quark–quark are compared with various theoretical predictions (CMS) [38].
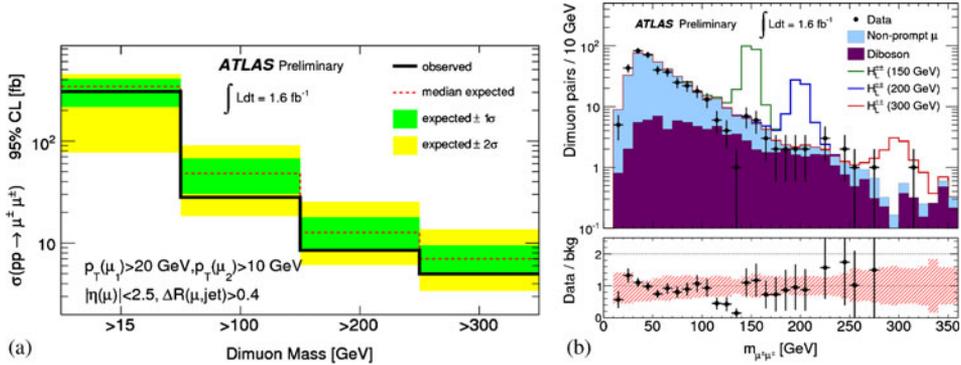
Figure 8. (**a**) Model-independent fiducial cross-section limit on the production of same-sign dimuon pairs [39] and (**b**) reconstructed mass of the same-sign muon pairs in ATLAS and expected doubly-charged Higgs signal of various masses [40].

Majorana neutrino, etc.) and enjoy a very small SM background. Thus, an inclusive search for same-sign dilepton pair is very sensitive to a wide range of models, and thanks to the small background is almost as sensitive as a search optimized for a particular model. With 1.6 fb^{-1} of integrated luminosity, ATLAS sets a model-independent limit on the fiducial cross-section of isolated pairs of same-sign muons as a function of the dilepton pair mass [39] as shown on figure 8. The same mass spectrum is used to search for a narrow resonance, allowing to exclude doubly-charged Higgs pair production up to a mass of 375 GeV in the left-handed coupling triplet model [40].

4. Strong gravity

Theories of extra dimension are a possible answer to the hierarchy problem. In the large extra-dimension ADD model [41], gravity is allowed to propagate into extra dimensions, thus appearing weak at (spatial) scales much larger than the scale of the extra dimensions, but possibly becoming strong at a scale of 1/TeV. The fundamental mass scale M_D at which gravity becomes strong is related to the Planck scale via $m_{Pl}^2 = m_D^{2+n} R^n$ where n is the number of extra dimensions and R is the size of the extra dimension, and can indeed be close to the TeV scale for well-chosen values of n and R.

A promising signature at colliders is the production of a single graviton escaping the detector and recoiling against a jet or a photon, leading to monojet [42,43] or monophoton [44] final states with large missing transverse momentum. Figure 9 shows the missing transverse momentum spectrum in the ATLAS monojet (a) and CMS monophoton (b) analyses. Thanks to a larger cross-section, the monojet channel gives the most stringent limits, excluding M_D up to 3.7 TeV for $n = 2$ and 2.3 TeV for $n = 6$ (conservatively assuming LO cross-sections).

Another signature of ADD extra dimensions is a non-resonant enhancement of the expected dilepton and diphoton events at high invariant mass through virtual graviton exchange. CMS has searched for deviations in the dimuon [45] and diphoton [46] spectra, with a sensitivity similar to the monojet channel.
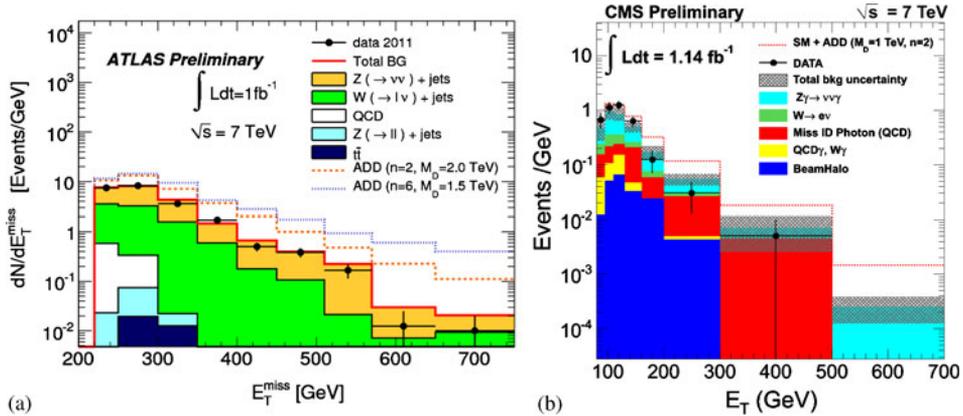
Figure 9. Missing transverse momentum in (**a**) ATLAS monojet and (**b**) CMS monophoton analyses [42,43].

Finally, if gravity becomes strong at the TeV scale, microscopic black holes may be produced at the LHC. Due to our lack of understanding of quantum gravity, it is impossible to make precise predictions of such phenomena. However, one can expect such objects to decay democratically and isotropically, leading to a final state with a large multiplicity of high-momentum particles, and a high content of leptons. Several channels have been considered: multijet [47], same-sign dimuon with a high track multiplicity [48], and multiobject [49] (where an object refers to an electron, a muon, a photon, or a jet, and a large number of objects is required in the event). In the latter case, CMS sets limits on black hole masses up to 4–5 TeV for some classes of models. Figure 10 shows the S_T
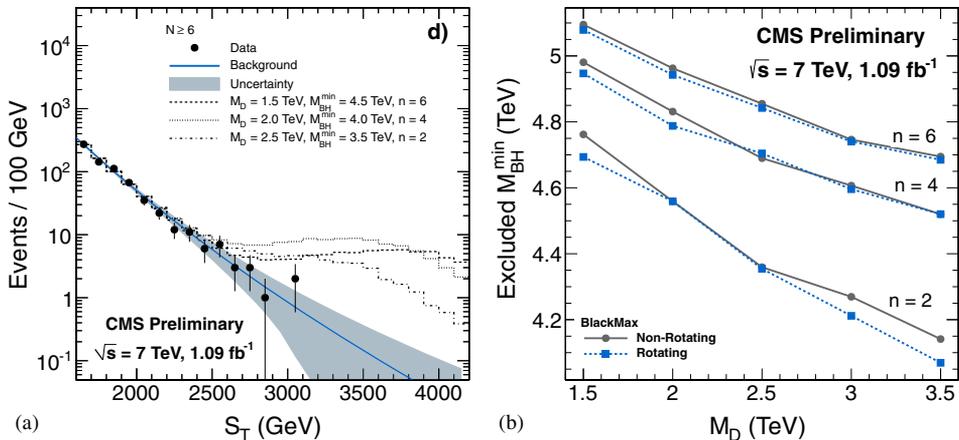

Figure 10. Multiobject search for microscopic black-holes at CMS [49]. (**a**) Scalar sum of the transverse momentum of all objects in events with at least six objects and (**b**) limit on black-hole mass as a function of M_D, number of extra dimensions, for two black-hole models.
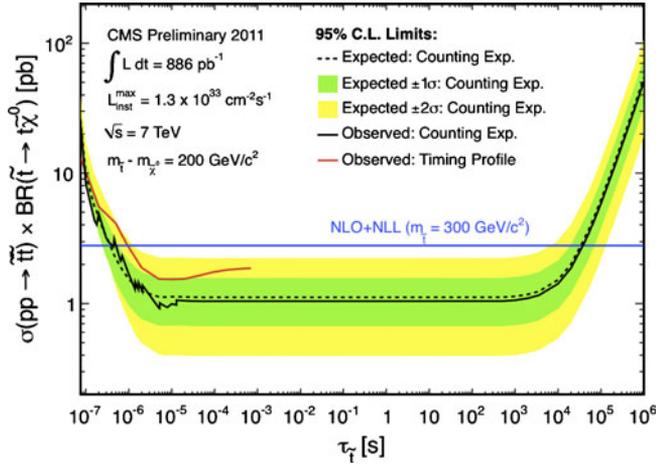
Figure 11. Search for out-of-time decay of heavy long-lived particles stopped in the detector: limit on the cross-section times branching ratio as a function of the stop life-time [54].

variable, defined as the scalar sum of the transverse momentum of all objects in the event, for events with at least six objects (a), and the limits achieved on the black-hole mass (b).

5. Long-lived particles

Several extensions of the SM, including hidden valley models [50], and supersymmetry in some scenarios [51], predict the existence of long-lived heavy particles. In the case of supersymmetry, a long-lived gluino or squark hadronizes into hadronic states called *R*-hadrons. The experimental signature depends strongly on the property of the particle, and in particular its lifetime. If the lifetime is short (between 1 ps and several ns), the particle decays within the detector in time with the collision that produced it; in this case it is possible to identify the decay thanks to dedicated vertexing [52].

If the lifetime is much longer than 1 ns, there is no hope to see it decay in the detector. If the particle is charged, it is possible to take advantage of the properties of a slow heavy particle and identify it thanks to high-energy loss in the tracking detectors and long time-of-flight [53]. Alternatively, for a lifetime up to about 1 month, if the particle is stopped within the detector, it is possible to observe its decay long after the collision that produced it occurred [54]. Figure 11 shows the limit on the production of long-lived scalar top stopping in the detector and decaying out-of-time; the analysis is sensitive over 13 orders of magnitudes, from 100 ns to 1 month.

6. Conclusion

The LHC has performed exceptionally well and has provided ATLAS and CMS with more luminosity than expected. Many searches for physics beyond the SM have been

conducted up to 1.6 fb^{-1}, covering a wide range of signatures. Unfortunately, no deviation from the SM has been observed so far. Supersymmetry in its most hoped-for incarnation is starting to be pushed to the border of fine-tuning: in the framework of the CMSSM, supersymmetry is excluded up to a mass of 1 TeV in the (optimistic) scenario of equal squark-gluino mass. This opens the field to variations of supersymmetry that require more luminosity or new search strategies. Heavy gauge bosons are excluded up to masses of about 2 TeV, while quark compositeness is tested up to 3 TeV.

Acknowledgements

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