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Highlights of the LHC run 1 / Résultats marquants de la première période d'exploitation du GCH

Highlights on searches for supersymmetry and exotic models

Focus sur les recherches sur la supersymétrie et les modèles exotiques

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A B S T R A C T

In this review, we present highlight results of the first three years of the LHC running on searches for new physics beyond the Standard Model. The excellent performance of the LHC machine and detectors has provided a large, high-quality dataset, mainly proton–proton interactions at a centre of mass energy of 7 TeV (collected in 2010 and 2011) and 8 TeV (collected in 2012). This allowed the experiments to test the Standard Model at the highest available energy and to search for new phenomena in a considerably enlarged phase space compared to previous colliders.

R É S U M É

Dans cette revue, nous présentons les résultats les plus marquants des trois premières années de fonctionnement du GCH sur la recherche de nouvelle physique au-delà du Modèle standard. L'excellente performance du collisionneur GCH et des détecteurs a fourni une grande quantité de données, principalement des interactions proton–proton à une énergie dans le centre de masse de 7 TeV (récoltées en 2010 et 2011) et 8 TeV (récoltées en 2012). Cela a permis aux expériences de tester le Modèle Standard aux plus hautes énergies accessibles actuellement et de rechercher des signes de nouvelle physique dans un espace de phase considérablement élargi par rapport aux collisionneurs précédents.
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1. Introduction

From its very conception, the Large Hadron Collider (LHC) was designed to be a discovery machine. Its two main goals were to elucidate the electroweak symmetry-breaking mechanism and to search for new physics beyond the Standard Model (SM). Important steps towards the first goal were achieved: in July 2012, the two general purpose experiments, ATLAS [1] and CMS [2], announced the discovery of a new particle at a mass of 125 GeV [3,4]. The measured properties of the new particle were found compatible with those of the minimal SM scalar boson proposed in 1964 by Brout, Englert and Higgs [5–7], as is presented in detail in another review of the present dossier of *Comptes rendus Physique*. In particle physics,

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the scalar boson discovery is a main achievement: it has been the missing piece of the SM for more than 40 years. Is this new particle the only elementary scalar particle in nature or are there more to be discovered? In parallel to the discovery and the study of properties of the scalar boson(s), the search for other new particles, as expected from new physics, is also crucial. Indeed, the SM cannot answer several fundamental questions and is generally considered as a low energy effective model of a more fundamental theory.

This review presents highlight results of the first three years of the LHC running on searches for new physics beyond the Standard Model (BSM), and concentrates mainly on analyses of proton–proton collisions performed by the ATLAS and CMS experiments. Results from the two other LHC experiments, LHCb and ALICE, can be found elsewhere in this dossier. The complete set of public results of the ATLAS, CMS and LHCb experiments are available on the web pages given in Refs. [8–10].

The present review is organised as follows. Section 2 gives motivations to search for new physics beyond the SM, and a brief description of the main classes of BSM theory candidates is reported in Section 3. Section 4 summarises the characteristics of the 3-year LHC dataset, called in the following the Run 1 dataset. Precise tests of the SM are reported in Section 5. The following next sections are the core of the review and present a selection of results from the ATLAS and CMS experiments on BSM searches, gathered in four parts: the search for new physics in the scalar sector in Section 6, the search for supersymmetric particles in Section 7, the search for dark matter candidates in Section 8, and a non-exhaustive list of other exotics BSM searches in Section 9. Future plans of the LHC running are reported in Section 10. Finally the conclusions are given in Section 11.

2. Why searching for new physics?

The SM describes successfully all features of electromagnetic, weak and strong interactions between matter constituents, down to distances $\sim 10^{-19}$ m and up to energies of ~ 1 TeV, as presently accessible to experiments. However, despite its incredible success, the SM is clearly not a complete theory, as it does not provide a framework to describe several important observations in the universe: it does not include gravitation; it does not provide candidates to account for the dark matter and the dark energy in the universe, as established by cosmological observations; it does not explain the matter–antimatter asymmetry observed today in the universe. This asymmetry seems inconsistent with the inflation picture of our early universe, as the present structure of the SM treats particles and antiparticles almost similarly: the SM does not include enough source of CP violation to describe the dominance of matter in our present universe, unless new interactions are introduced. Finally, in the minimal version of the SM, the neutrinos are assumed to be massless, which is incompatible with the measurement of neutrino oscillations.

The SM suffers, in addition, from several conceptual problems, in particular the so-called "fine-tuning" problem, linked to the presence of scalar (spin-0) particles in the model. Indeed, the Brout–Englert–Higgs boson candidate discovered recently is rather special in the SM: it is the only elementary spin-0 particle. In the model, a physical mass is computed as a sum of two terms: the bare mass, and contributions from radiative corrections. In the case of spin-0 particle, the radiative corrections are quadratically divergent and proportional to the cut-off scale of the model, i.e. the larger scale where the model is valid. If the cut-off scale is high (for example the Planck scale, 10^{19} GeV), corrections become unsatisfactory large in comparison to the scalar boson physical mass. This behaviour, however, does not appear in radiative corrections to fermion and gauge boson mass terms, as they are protected by chiral and gauge symmetries, respectively. A way to solve the problem is to introduce in the model new particles and new symmetries, at a certain scale, such that radiative corrections from the new particles cancel radiative corrections from the SM ones. The scale should however not be too high, typically a few (tens of) TeV or less, leading to a tuning factor much more acceptable than the ratio between the electroweak symmetry breaking scale (~ 100 GeV) and the Planck scale. Another important issue when extrapolating the SM up to high scale is to keep a stable value of the minimum of the scalar potential that breaks the electroweak symmetry. The extrapolation depends on the top and scalar boson masses, and the current mass measurements are intriguing as they favour a metastable scalar potential [11,12]. This may suggest the existence of possible additional particles coupling to the scalar sector, that could change the shape of the potential at high scale.

A last puzzling point concerns the absence of unification between interactions in the SM: when extrapolated to high energy (typically the Planck scale), the three fundamental forces (electromagnetic, weak, and strong forces) cannot be described as resulting from a unique symmetry. Adding new particles in the model can modify the evolution of the fundamental couplings and unify them at high scale.

Finally, the Brout–Englert–Higgs mechanism provides a way to introduce mass terms in the model, but it gives no explanation on the observed mass values and on the diversity of the observed mass spectrum: for example there is an unexplained large factor of $\sim 10^5$ between the electron mass and the top quark mass. The SM has 19 arbitrary free parameters and an intriguing same structure of three families for quarks and for leptons, which may point to a new symmetry.

It is now generally accepted that the SM model needs to be extended to include and explain the limitations presented above, the SM being then a low-energy approximation, or a visible part, of a larger theory at high energy.

3. New physics models

Many models have been proposed as BSM candidates, addressing some of the issues of the SM, but none of them can answer all the above questions. A rapid description of the main classes of BSM candidates is presented below.

1. Supersymmetry. It is one of the best motivated extension of the SM, see Ref. [13] for an introductory review. The theory proposes a new symmetry between bosons (integer spin) and fermions (half integer spin). Due to the cancellation among various diagrams involving SM particles and their superpartners (SUSY particles), the quadratic scalar mass sensitivity to the very high (grand unification) scale is cancelled. In addition, unification of the three fundamental gauge couplings can be achieved at high energy (10^{15}–10^{16} GeV). In $N = 1$ supersymmetry (which we consider here), for each particle of the SM, a supersymmetric partner differing by half a unit of spin is introduced, with the same other quantum numbers. The leptons (quarks) have scalar partners of two types, $\tilde{\ell}_R$ ($\tilde{q}_R$) and $\tilde{\ell}_L$ ($\tilde{q}_L$) according to their chirality. Similarly, the gauge bosons have spin one-half SUSY partners, called gauginos. In its minimal version, the minimal supersymmetric SM, the MSSM, contains two scalar doublets, giving rise to five physical scalar states after electroweak symmetry breaking: two CP-even states, h and H, one CP-odd state, A, and two charged states, H^+ and H^-. The spin 1/2 SUSY partners of the scalar bosons (called higgsinos) mix with the colourless gauginos to provide, respectively, the charginos for the charged modes ($\chi_1^\pm$, $\chi_2^\pm$) and the neutralinos for the neutral mode (χ_1^0 to χ_4^0). The mass relations between these particles depend on the MSSM parameter $\tan\beta$, the ratio of the scalar field vacuum expectation values. In the MSSM, an extra parity R is usually assumed, which takes positive values for the SM particles and negative values for the SUSY partners. As a consequence, the lightest SUSY partner (LSP) is a dark matter candidate (if it is neutral), which in the MSSM is often the lightest neutralino, χ_1^0. Supersymmetry is not an exact symmetry as no SUSY particles at the same mass as their SM partners have been observed so far. The SUSY breaking scale should, however, not be too high, as it would then fail the protection of the scalar masses against high scales. Typically, one tends to request that the radiative corrections, limited by the breaking scale, do not exceed the typical scalar masses, which (depending on the tolerance) gives an upper value around a few TeV.

2. Grand Unified Theories. Grand Unified Theories (GUT), see, e.g., Ref. [14], attempt at unifying the electroweak and strong interactions at high energy. They are based on larger symmetry groups, like SU(5), SO(10), E6. The full symmetry is restored at very high energies. Typical scales of 10^{16} GeV emerge from the different running (meeting point) of the strong, weak and electromagnetic couplings, and also from current limits on the rate of proton decay. Although this symmetry is broken at a scale way beyond the accessible range to the LHC, at intermediate scales a symmetry larger than the SM may remain (for instance, an extra U(1), restoration of the left–right symmetry), and be broken via several possible scenarios. These models usually predict the existence of new massive gauge bosons, called generically Z′ and W′; their couplings to SM fermions vary according to the specific model and the breaking cascade.

3. Additional spatial dimension(s). An option to attack the hierarchy problem, i.e. the huge difference in scale between the gravitational interaction ($M_{Pl} = 1.2 \times 10^{19}$ GeV) and the other fundamental interactions ($M_{ewk} \approx 100$ GeV), relies on modifying the space-time structure of our universe: the universe as we perceive would be immersed in a bulk space with $(4 + d)$ dimensions, of which the d extra spatial dimensions would be compactified [15]. In the original models, the gauge interactions would be confined to a membrane in 4 dimensions, and only gravity would spread in all dimensions. The Planck constant would then lose its fundamental character, as it would be linked to only the fraction of the gravitational interactions that spreads over the four-dimensional membrane. In these theories, the true Planck scale could thus be much closer to the electroweak scale. Several extensions of the initial idea assume that SM gauge bosons and/or scalar bosons can also propagate in the extra dimensions.

4. Dynamical symmetry breaking. Another class of theories introduce a new strong interaction that breaks the gauge symmetry of the SM. The scalar particles are bound states of fermions charged under the strong interaction, similar to pions in QCD, see Ref. [16]. In these models, there are no problems of quadratic divergences (as the form factors for the effective bosons decrease at high energy, like those of the usual mesons), but generating realistic fermion mass spectra without flavour changing neutral currents is usually difficult. Example of these type of theories are technicolour/extended technicolour/composite models.

All these models have many free parameters, and simplifying assumptions are usually introduced to study their predictions in a restricted phase space. These models are strongly constrained by precision measurements, and they have in addition to describe or at least accommodate with the existence of the new scalar particle at 125 GeV, discovered in 2012.

4. The LHC Run 1 dataset

ATLAS and CMS are multipurpose detectors described in detail in Refs. [1,2]. The results presented in this review are based on the Run 1 LHC dataset, taken during the years 2010–2011 and 2012 at a proton–proton centre of mass energy $\sqrt{s} = 7$ TeV and 8 TeV, respectively. During these three years, excellent performance was achieved by the LHC machine and the ATLAS and CMS detectors. The integrated luminosities recorded by ATLAS and CMS are more than 5 and 20 fb^{-1} at 7 and 8 TeV, respectively, with a peak instantaneous luminosity up to 7.7×10^{33} $cm^{-2} \cdot s^{-1}$. The ATLAS and CMS detectors were running with more than 95% of channels operational after the three-year period. The experiments recorded about 95% of the LHC-delivered luminosity and final results are typically based on a sample of 90 to 95% of the recorded data.

Due to the high instantaneous luminosity provided by the LHC, the number of proton–proton interactions in each beam bunch crossing was in average about 9 in 2011 and 21 in 2012, as illustrated in Fig. 1 (left). The additional (soft) interactions, called pileup events (PU), created an important challenge to experimentalists. Much effort was dedicated to PU control and correction, in particular for the 8 TeV data analyses. The particle identification and isolation criteria, and the missing transverse energy (MET) variables were designed and optimised, in order to suffer of no or little dependence on the number of pileup events. As an example, Fig. 1 (right) presents the CMS resolution on MET measurement in Drell–Yan events, as

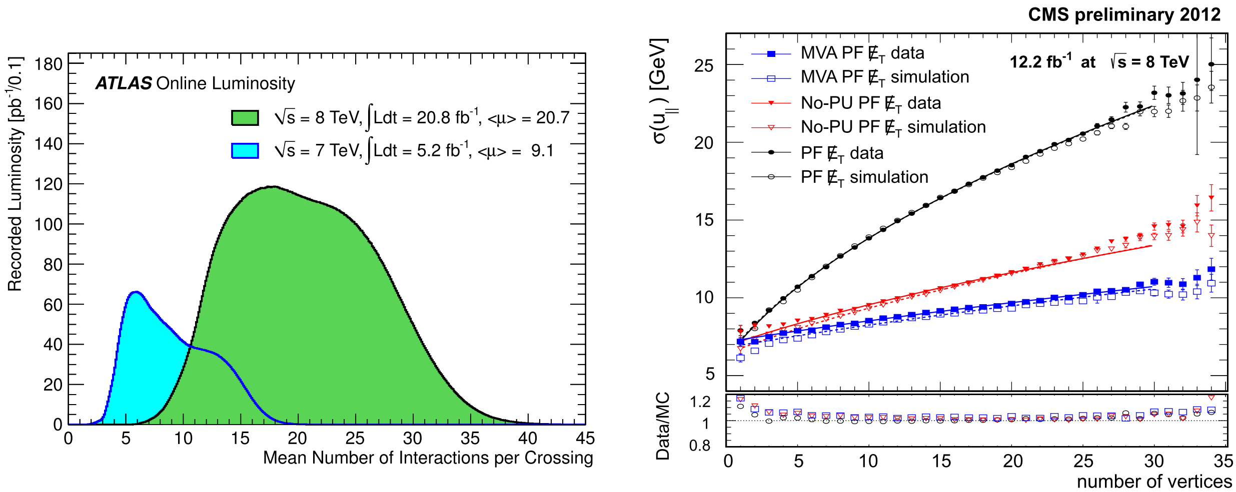

Fig. 1. (Colour online.) Distribution of the number of proton–proton interactions per beam bunch crossing recorded by ATLAS in 2011 and 2012 [8] (left). CMS MET resolution as a function of the number of reconstructed vertices for different MET algorithms using events from Drell–Yan process [17] (right).

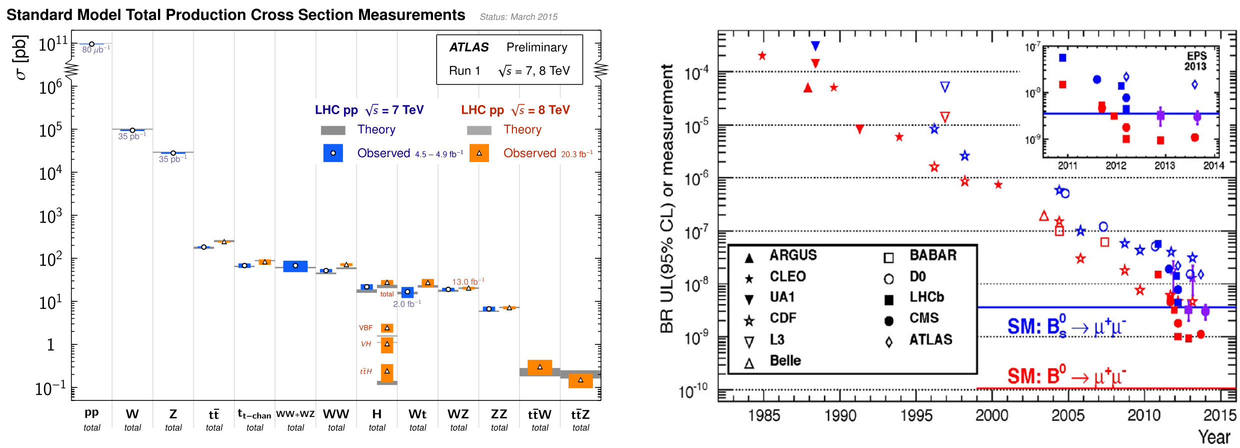

Fig. 2. (Colour online.) Summary of several SM production cross section measurements, compared to the corresponding theoretical expectations (calculated at NLO or higher order) [8] (left). Summary of the upper limits and/or measurements of the branching ratios $B_s^0 \to \mu\mu$ (in blue) and $B^0 \to \mu\mu$ (in red) [9, 18] (right); the horizontal lines show SM predictions for the two branching ratios.

a function of the number of reconstructed vertices, for several MET algorithms using particle flow techniques [17]. The algorithm without PU correction is shown with black circles, and that with PU correction in blue squares. Simulations describe impressively well the data, as it can be seen at the bottom of the figure. We will see in the following that the control of MET variables is very important for many BSM analyses, in particular for SUSY and DM searches.

5. Precise Standard Model measurements – indirect searches

ATLAS and CMS precisely measured SM process cross sections over many orders of magnitude, in particular Z and W boson production, top–antitop quark pair and single-top quark production, and di-boson production: WW, WZ and ZZ. These accurate measurements, in agreement with theory predictions computed at the Next to Leading Order (NLO) or higher order, as shown in Fig. 2 (left) (ATLAS results from [8]), demonstrate the excellent understanding of the detector, which is crucial for BSM physics as the SM processes mentioned above are usually the main backgrounds to new signal searches.

As we will see in the next sections, at high energy, heavy on-shell new particles can be produced at the LHC and discovered through their decay products, which is known as direct search for new physics. Another option is to perform very high precision measurements, searching for deviations to SM predictions coming from virtual effects of the new particles, for example in loop induced processes. Both approaches are important and complement each other. In particular, precision measurements of a number of rare decays in the bottom and charm quark sectors are studied, in view of their exceptional sensitivity to new physics beyond the SM. In this area, the golden channels are the rare branching ratio (BR) measurements of the flavour changing neutral current (FCNC) decays, for example: $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$. These BRs are precisely estimated in the SM, with small theoretical error of 6% and 9%, respectively [19]. If new physics is present, it is expected

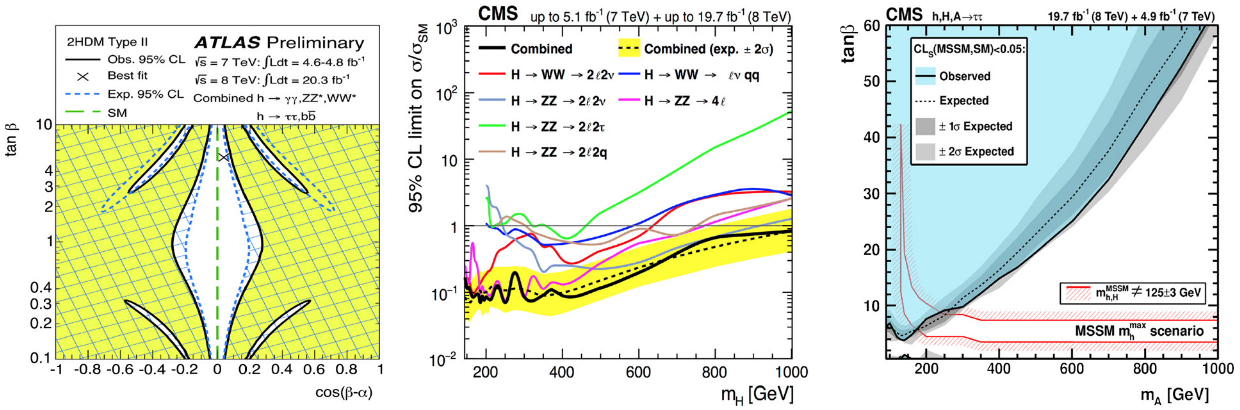

Fig. 3. (Colour online.) Regions of the $(\cos(\beta-\alpha), \tan\beta)$ plane of 2HDM type II excluded by fits to the measured rates of the h(125) scalar boson production and decays [25] (left). Upper limit on the production cross section in the search for new heavy neutral SM-like scalar bosons in the $H \to WW$ and $H \to ZZ$ channels, for each of the contributing final states separately and their combination [26] (centre). Exclusion limits in the $(M_A, \tan\beta)$ parameter space for the MSSM m_h^{max} benchmark scenario [27] (right).

to enhance these BRs by a large amount. The LHC experiments have accumulated enough data with Run 1 to start being sensitive to these impressively small BRs. The LHCb and CMS measurements were combined [18] showing the observation at the 5σ level for $BR(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$ and a 2 to 3σ measurement for $BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$, where the uncertainties include both statistical and systematic sources. These measured values are unfortunately in agreement with the SM expectations. The rapid evolution with time of the BR upper limits first and measurements then is shown in Fig. 2 (right). Another important result concerns the first observation of direct CP violation in B_s decays. Here again, no evidence was found for additional (from BSM source) large CP violation in the B_s sector [20–22].

In the present review, except mentioned explicitly, all results on cross section upper limits or particle mass lower limits are extracted at a 95% confidence level.

6. Search for new physics in the scalar sector

A detailed study of the nature of the scalar boson is extremely important in the context of BSM searches. Is the new scalar particle behaving as expected by the minimal version of the SM? or is there room for new physics? The Run 1 scalar sector analyses at the LHC are coming to their end. The scalar boson mass is measured by the ATLAS and CMS experiments with impressive precision: the combined mass result is 125.09 ± 0.21 (stat.) ± 0.11 (syst.) GeV, which corresponds to a measurement precision better than 0.2%; evidence of the scalar boson coupling with fermions has been published recently; the combined best-fit signal strength, relative to the standard model expectation, is measured to be compatible with 1.00 with a precision of 14%. Any new physics scenario, if modifying the scalar sector, should accommodate these measurements.

A natural extension of the SM scalar sector is the so-called two Higgs Doublet Model (2HDM), assuming two doublets of scalar complex fields. In the 2HDM Type I, one scalar doublet couples with vector bosons, while the other couples with fermions. The first doublet is fermiophobic in the limit of no mixing. The 2HDM Type II is a MSSM-like model, in which one scalar doublet couples with up-type quarks and the other to down-type quarks and leptons. The 2HDM can be described with six parameters: four scalar boson masses (m_h, m_H, m_A, and $m_{H^\pm}$), $\tan\beta$, and the mixing angle α of the two neutral, CP-even scalar states. Interesting results are extracted from reinterpreting the mass and couplings of the measured 125 GeV scalar boson, h(125) in extensions of the SM. A simultaneous fit to the measured rates in multiple production and decay modes is used to constrain several BSM model parameters. An example is given here for the 2HDM: Fig. 3 (left) presents regions of the $(\cos(\beta-\alpha), \tan\beta)$ plane of 2HDM type II excluded by fits to the measured rates of h(125) boson production and decays. The data are consistent with the SM limit, $\cos(\beta-\alpha) = 0$, within 1–2σ in each of the different model types considered. Another indirect way to search for new physics in the scalar sector concerns rare decays, as the search for FCNC processes in top-quark decay: $t \to cH$ [23] and $t \to qH$ [24]. These decays, strongly suppressed in the SM, are expected to be enhanced in several BSM models. The limit on the $BR(t \to cH)$ is measured to be $< 0.56\%$.

Efforts have been dedicated to direct searches for additional neutral or charged scalar particles. For example, ATLAS and CMS have performed generic searches for additional heavy neutral SM-like scalar bosons in different channels: $H \to WW$ and $H \to ZZ$ [25,26]. No new physics has been observed and upper limits on the cross-section production are presented in Fig. 3 (centre) for each of the contributing final states and their combination. The results are also interpreted in a simple benchmark model supposing an extra scalar singlet extension of the SM, with the mass of the lighter one being at 125 GeV, see also [28].

Dedicated searches for heavy neutral scalar particles $\phi = (h, A, H)$ predicted in SUSY models have been also performed, in particular in the decay channel $\phi \to \tau\tau$. This is a promising channel as the couplings of A and H to down-type fermions are enhanced at large $\tan\beta$. Several τ decay channels are considered (leptonic and hadronic decays) and combined. No new

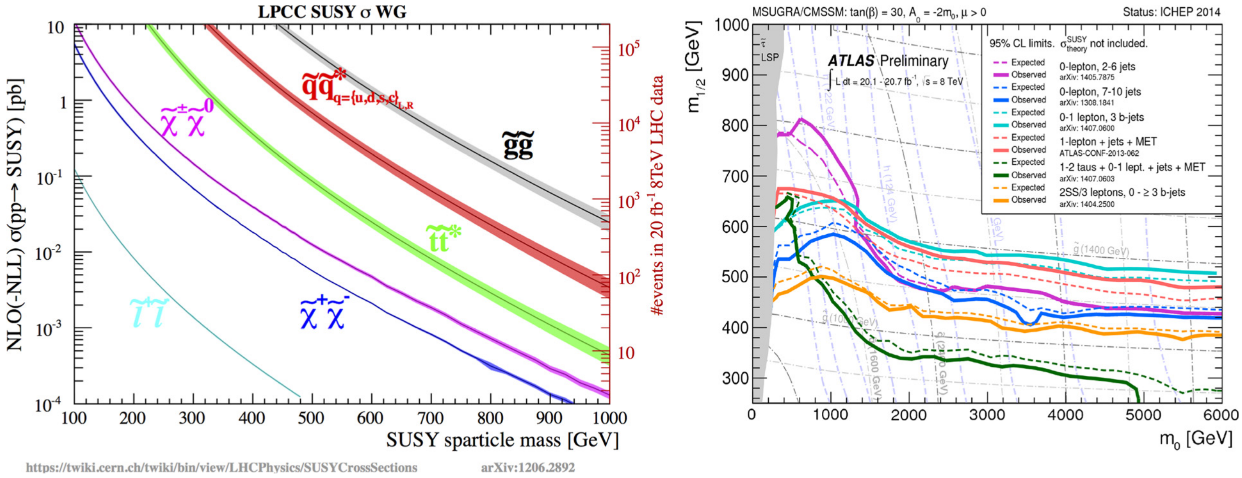

Fig. 4. (Colour online.) Theory cross sections for selected SUSY processes [36] (left). Exclusion limits in the $(m_0, m_{1/2})$ plane for the mSUGRA model, for $\tan\beta = 30$, $A_0 = -2m_0$, and $\mu > 0$; part of the model plane accommodates a lightest neutral scalar boson mass of 125 GeV (the blue dashed lines show the scalar boson mass isolines), from ATLAS [37–41] (right).

physics signal is observed and limits are extracted in various MSSM scenarios. Fig. 3 (right) presents limits in the m_h^{max} scenario, where the mass of the light CP-even scalar boson is maximised for fixed $\tan\beta$ and large M_A, the mass scale of the stop and sbottom particles being fixed to 1 TeV. The low m_A region is excluded in this particular scenario. An updated version of the m_h^{max} scenario has been proposed, the so-called modified scenario, where the light CP-even scalar boson can be interpreted as the 125 GeV LHC signal in large parts of the $(M_A, \tan\beta)$ plane [29].

In the search for charged scalar bosons $H^{\pm}$, the main production mode is through top decays (for m_H^+ smaller than the top quark mass), the BR $H^+ \to \tau\nu$ (or $H^+ \to c\bar{s}$) being usually assumed to be 100%. No signal is observed and limits on the BR($t \to H^+ b$) of 0.23% and 1.3% are derived as a function of the H^+ mass, in the range 80–160 GeV [30–33]. Searches for charged scalar boson with mass larger than the top quark mass are also performed, in the associated production with a top quark, through the process $gg \to H^+ tb$ [34]. Results on the search for a charged scalar boson are interpreted in terms of exclusion regions in constrained SUSY models: in the context of the m_h^{max} scenario of the MSSM, values of $\tan\beta$ below 60 are excluded in the H^+ mass range between 80 and 140 GeV. In more exotic scalar sector models, the $H^+ \to W^+ Z$ decays are allowed, and searches for this channel have been performed via the vector–boson fusion (VBF) production mode [35].

In conclusion, no hint for a modified or extended scalar sector has been observed at the LHC Run 1. However, the scalar sector is known for providing particles difficult to detect. In addition to the scalar sector effort, direct searches for other particles predicted by new physics models have been intensively performed during the LHC Run 1, and are presented in the next sections.

7. Search for SUSY particles

The direct search for supersymmetric particles is one of the key topics at the LHC and much effort has been devoted to these activities, since SUSY is a well-motivated extension of the SM (see Section 3). In SUSY, the particle spectrum is at least two-fold, providing a rich phenomenology, with many different production mechanisms and final states. The LHC being a hadronic machine, the dominant contribution is typically that of coloured superpartners. However, electroweak processes with lower production cross sections are also considered, as they are accessible at the LHC but with reduced mass reach. Theory cross sections for selected SUSY processes are presented in Fig. 4 (left) [36], together with the number of events expected for 20 fb^{-1} of 8 TeV LHC data. R-parity is generally assumed to be conserved, in which case SUSY particles are produced in pairs at the LHC and the lightest SUSY particle (LSP) is stable. The common signature of these SUSY processes is thus the presence of large MET in different final states. These analyses are sensitive to the MET reconstruction in the event; MET variables are thus defined such as to minimise their sensitivity to misreconstruction effects and to additional pileup events. LHC experiments have also searched for SUSY signals in increasingly complicated final states from various decay chains and have combined multiple analyses in order to access more challenging SUSY scenarios or more difficult phase space.

As will be shown below, no sign for new physics is observed in the large number of final states investigated at the LHC. This negative result can be interpreted in different ways. SUSY theories have many free parameters (typically more than 100) and assumptions need to be made to extract limits in a fewer parameter phase space. A first way to interpret the data is thus to consider the so-called simplified models [42], which focus on a single production mode and a one-step (or possibly two-step) decay chain to the relevant final state, with the assumption that the BRs among this chain are 100% and that the other new particles are heavy. This provides a useful way of setting limits, which can often easily be reinterpreted in specific models. Another possibility is to set a limit in very constrained models as the constrained MSSM (CMSSM) one

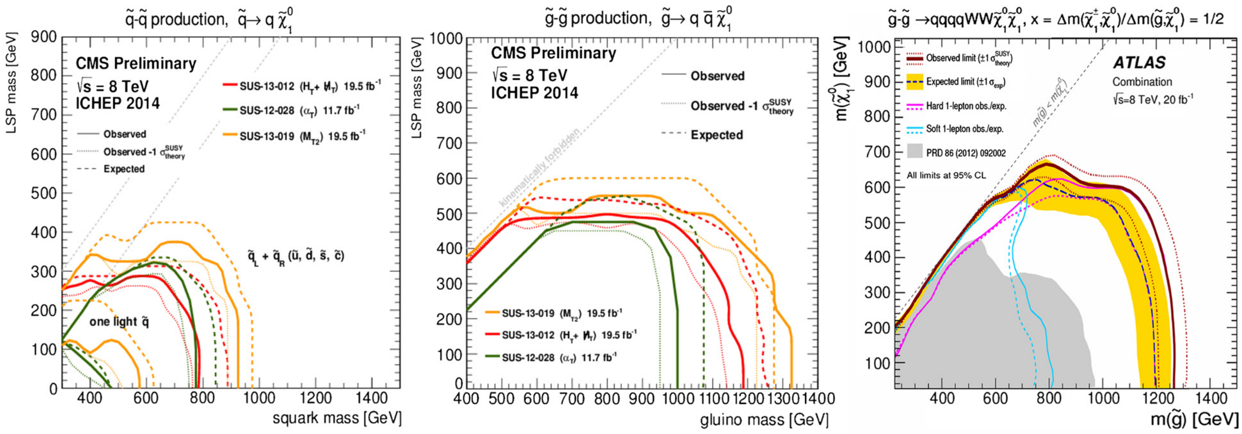

Fig. 5. (Colour online.) Exclusion limits for direct squark production with $\tilde{q} \to q\chi_1^0$ (left), with a scenario (upper set of curves) where the first two generations of squarks are degenerate and light, and another scenario (lower set of curves) corresponding to only one light flavour accessible squark. Exclusion limits for gluino pair production with $\tilde{g} \to q\bar{q}\chi_1^0$ (centre). Both plots are from CMS [45–49]. Exclusion limit from the single-lepton channels presented in the $(\tilde{g}, \chi_1^0)$ mass plane (right); the light blue and purple full (dashed) lines show the observed (expected) exclusion limits obtained by the soft and hard-lepton analyses, respectively, from ATLAS [40].

[43] or the minimal SUGRA (mSUGRA) one [44], which reduce the number of free SUSY parameters by making various assumptions on mass unification at high scale. Five parameters are needed to specify a particular MSUGRA/CMSSM model: the universal common scalar mass, m_0, the universal gaugino mass $m_{1/2}$, the universal trilinear scalar coupling, A_0, the ratio of the vacuum expectation values of the two scalar fields, $\tan\beta$, and the sign of the higgsino mass parameter, $\mathrm{sign}(\mu) = \pm 1$.

In the models above, R-parity is assumed to be conserved. Indeed, virtual exchange of SUSY particles would usually induce fast proton decay if R-Parity were violated arbitrarily. A variety of models in which R-parity is not conserved have however also been investigated at the LHC. In these models, the LSP decays to SM particles with violation of the lepton or baryon number. The final state consists of multijets and/or multileptons, with no MET.

Other SUSY models are considered as well, leading to very specific final state topologies. For example, different approaches to SUSY breaking are investigated. In Gauge-Mediated SUSY breaking (GMSB) models, the LSP is a light gravitino, $\tilde{G}$, the supersymmetric partner of the graviton. If the next to lightest SUSY particle is the neutralino χ_1^0, it decays according to $\chi_1^0 \to \tilde{G}\gamma$ and final states with photons together with MET are typical signatures of this scenario. In anomaly mediated SUSY breaking (AMSB) models, the LSP is the neutralino, but with a mass close to that of the chargino. If the mass different is very small the chargino is almost stable. This leads to a number of dedicated searches on long-lived charged particles in the final state.

The LHC SUSY results are presented below as follows. First inclusive SUSY searches are described, followed by searches for electroweak SUSY production, and by dedicated analyses on natural SUSY focusing on third generation supersymmetric particles. Finally, the last section presents searches for long-lived particles and displaced vertex analyses.

7.1. Inclusive SUSY searches

At the LHC, the gluino and squark pair production cross sections are typically large and inclusive searches for SUSY are performed looking for an excess of events in the multijet final states. An impressive number of final states has been considered by ATLAS and CMS, depending on the number of jets, ranging from 2 to 10, MET requirements, and possibly leptons and/or b-tag jets. No SUSY signal in any of these topologies has been observed and limits, extracted in the context of mSUGRA, are presented in Fig. 4 (right) [37–41]. A large part of the $(m_0, m_{1/2})$ plane is now excluded, in particular gluino (squark) masses below 1.35 (1.6) TeV. Part of the model plane accommodates a lightest neutral scalar boson mass of 125 GeV.

ATLAS and CMS have searched for first- and second-generation squarks and for gluinos in the framework of simplified models. Squark and gluino production in the channels $pp \to \tilde{q}\tilde{q}X$ with $\tilde{q} \to q\chi_1^0$ and $pp \to \tilde{g}\tilde{g}X$ with $\tilde{g} \to q\bar{q}\chi_1^0$ are searched for in final states with ≥ 2 jets and MET. Direct limits are shown in Fig. 5 (left and centre). Squark and gluino masses above 900 GeV and 1300 GeV, respectively, are excluded for low values of the neutralino mass [45–47,39]. If only one flavour of squark is accessible at the LHC, the mass limit degrades, as can be seen on the lower set of curves in Fig. 5 (left). Complementary decay chains in which the pair-produced strongly interacting sparticles decay via charginos or neutralinos are searched for in final states containing at least one isolated lepton (electron or muon), jets (with or without b-jet requirement), and large MET. Dedicated analyses are performed considering final states with soft leptons in order to increase the sensitivity to SUSY spectra at small mass splitting. The results are presented in the $(\tilde{g}, \chi_1^0)$ mass plane in Fig. 5 (right), where the exclusion limits obtained by the soft and hard-lepton analyses are presented [40].

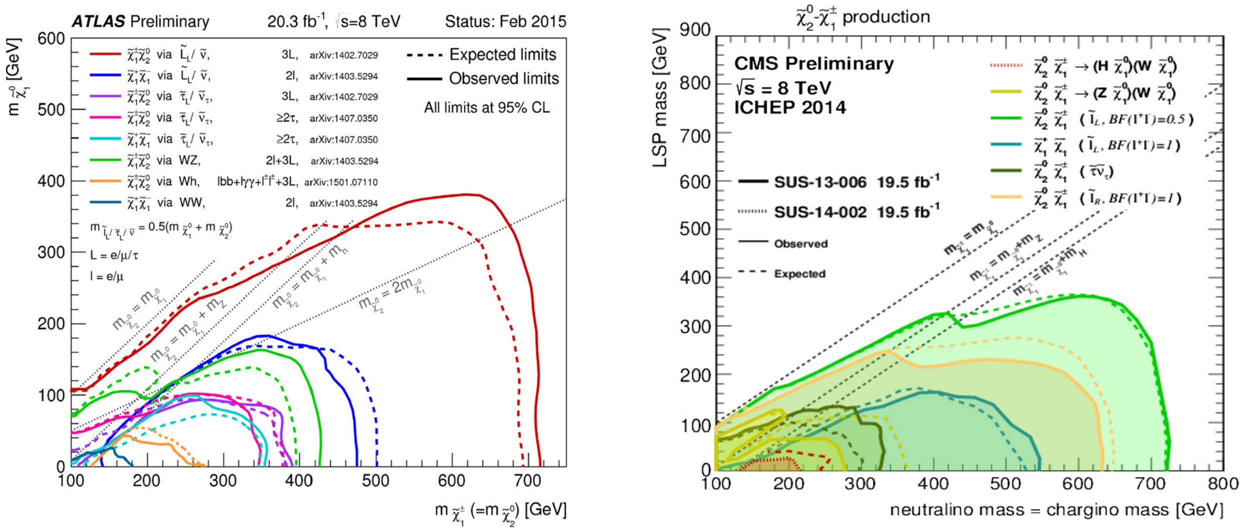

Fig. 6. (Colour online.) Summary of ATLAS [50–53] (left) and CMS [54,55] (right) searches for electroweak production of charginos and neutralinos. Exclusion regions are presented in the (χ_2^0, χ_1^0) mass plane, assuming the same mass for $\chi_1^\pm$ and χ_2^0.

7.2. Electroweak SUSY production searches

Electroweak productions of charginos, neutralinos, and sleptons have small cross sections at the LHC, but they have a discovery potential if squarks and gluinos are heavy. SUSY electroweak production searches typically include final states with one or more leptons, originating from the cascade decays of the initial sparticles, and large MET, coming from the LSP. Typical SM backgrounds to these searches are multi-jet, diboson, top–antitop pair, W + jets, Z + jets, and single top quark production. The direct production of a pair of super-partners of the electron (the selectron) or the muon (the smuon) is studied in final states containing two opposite-sign electrons or muons, low jet activity and large MET. A similar strategy is used to search for the production of chargino pairs, decaying through intermediate sleptons or through leptonically decaying W bosons. In the latter case, the analysis suffers from a large irreducible background from WW production. The associated production of $\chi_1^\pm$ and χ_2^0 leads to a variety of final states, depending on the intermediate particle being a slepton, a W, Z or the h(125) scalar boson. No signal is observed and exclusion limits in the (χ_2^0, χ_1^0) mass plane have been derived by ATLAS [50–53] and CMS [54,55] using several search channels, as shown in Fig. 6. The results are interpreted in the context of simplified models, assuming the same mass for $\chi_1^\pm$ and χ_2^0.

7.3. Natural SUSY searches

After the h(125) scalar boson discovery in 2012, ATLAS and CMS focused on phenomenology oriented approaches to target the m_h fine-tuning problem. "Natural" solutions tend to predict a relatively light spectrum of SUSY particles, while "unnatural" solution can accommodate a new physics scale much outside of the LHC reach. A spectrum for "natural SUSY" is given for example in [56] with typically $m(\tilde{\mathrm{g}}) < 1500$ GeV, $m(\tilde{\mathrm{t}}, \tilde{\mathrm{b}}) < 1000$ GeV, and the neutralino and higgsino masses below 500 GeV. The rest of the spectrum may decouple (at higher mass) without compromising naturalness. Several natural SUSY dedicated searches have been intensely performed at the LHC, focusing on the stop, sbottom and higgsino, via direct pair production, or via decays of pair-produced gluinos. These searches are summarised in the following.

ATLAS [41,57,58] and CMS [45–47,59–63] presented results for the third-generation SUSY searches via gluino chains, with $\tilde{\mathrm{g}} \to \mathrm{t}\tilde{\mathrm{t}} \to \mathrm{tt}\chi_1^0$. The intermediate $\tilde{\mathrm{t}}$ may be off-shell if $m(\tilde{\mathrm{t}}) > m(\tilde{\mathrm{g}})$, or on-shell in the opposite case. The results of several searches, depending on the number of leptons in the final state, are presented in Fig. 7 (left). Results for the corresponding searches in the case of a decay chain with a sbottom quark: $\tilde{\mathrm{g}} \to \mathrm{b}\tilde{\mathrm{b}} \to \mathrm{bb}\chi_1^0$ are presented on Fig. 7 (right) [59,63,45,47].

Another possibility is to search directly for stop (or sbottom) pair production. The stop can decay directly into a top–LSP pair or via an intermediate chargino/neutralino state. Other channels are also possible if the stop is light (below the top mass), see Fig. 8 (left). The final state signature is then a top–antitop pair and MET. The searches focused on the 1-lepton channel (e/μ). At small ΔM, where $\Delta M = m(\tilde{\mathrm{t}}) - m(\chi_1^0)$, the signal cross section is sizable but the analysis suffers from large $\mathrm{t}\bar{\mathrm{t}}$ background contamination; at large ΔM, the signal cross section is low, but presents kinematical distributions different from the background.

An ATLAS compilation of different channel searches (0, 1, 2 leptons plus MET, with and without b-tagged jets) is shown in Fig. 8 (right). Exclusion limits are shown in the $(\tilde{\mathrm{t}}, \chi_1^0)$, mass plane. Four decay modes are considered separately: $\tilde{\mathrm{t}} \to \mathrm{t}\chi_1^0$, $\tilde{\mathrm{t}} \to \mathrm{Wb}\chi_1^0$, $\tilde{\mathrm{t}} \to \mathrm{c}\chi_1^0$, and $\tilde{\mathrm{t}} \to \mathrm{ff'b}\chi_1^0$, assuming in each case a 100% BR. The analyses are detailed in [64–69].

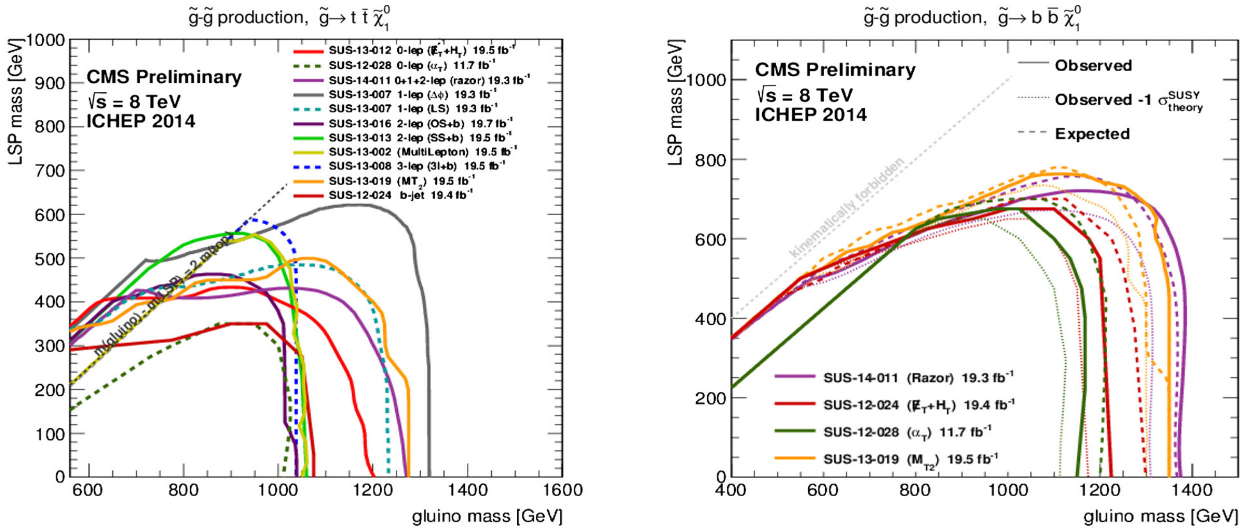

Fig. 7. (Color online) Exclusion limits for gluino pair production with gluino decaying via the 3-body decay ($t\bar{t}\chi_1^0$) final state [45–47,59–63] (left) and via the 3-body decay ($b\bar{b}\chi_1^0$) final state [59,63,45,47] (right).

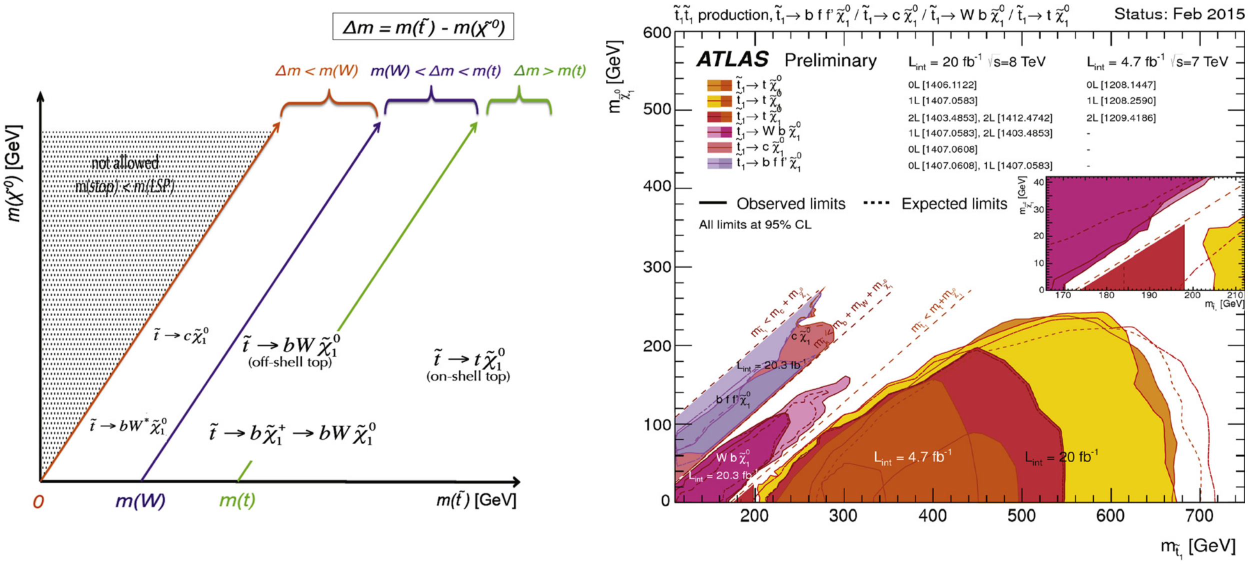

Fig. 8. (Colour online.) Stop quark pair production searches: the different stop decay channels depending on the stop and neutralino masses (left). Compilation of ATLAS results for the different channels considered [64–69] (right).

Natural scenarios with a compressed particle mass spectrum are experimentally very challenging: the event acceptance is typically low due to the presence of the soft decay products. In order to be sensitive as much as possible to this parameter phase space, CMS and ATLAS developed various strategies relying on events from vector boson fusion production or events with initial state radiation. An example of this is the use of the monojet and monophoton analyses [70–72] developed originally for the dark matter search (see Section 8), or use of the measurement of the spin correlation in top–antitop quark events [69].

7.4. Search for long-lived particles

A series of models of new physics predict the existence of new, long-lived particles (LLP), which would be characterised by very specific and distinctive experimental signatures. Scenarios in which these new particles are predicted include supersymmetric scenarios such as GSMB, AMSB, SUSY with R-parity violation, or split SUSY, hidden valley models. These new states include long-lived super-partners of the leptons, quarks and gluons, as well as the charginos and neutralinos. The LLP searches are characterised by final state topologies with non-standard reconstruction techniques and are often challenging at triggering the events.

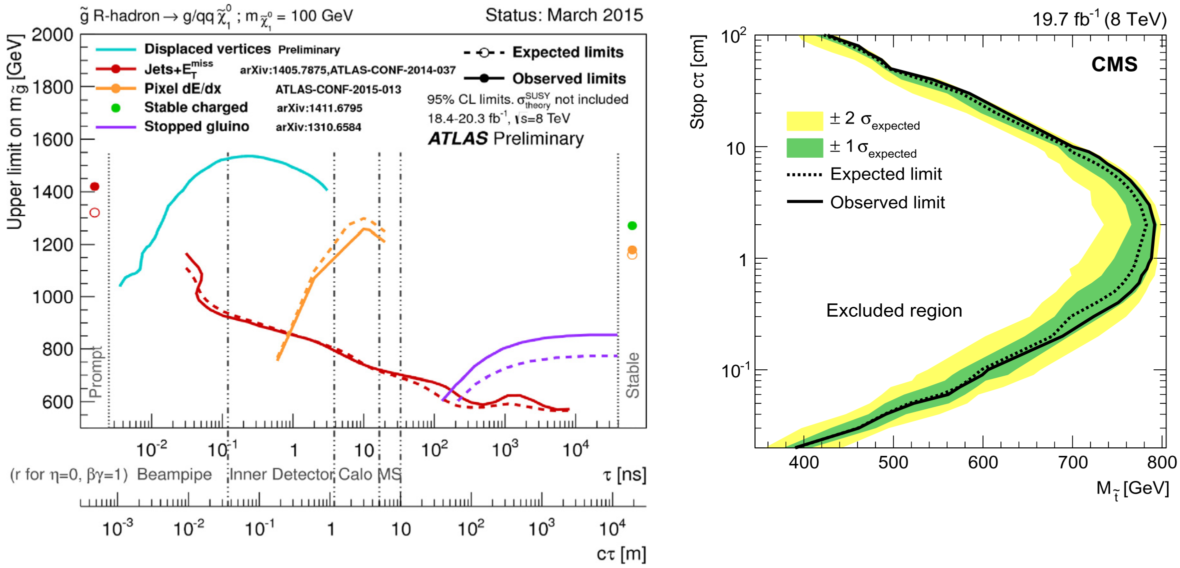

Fig. 9. (Color online) Compilation of ATLAS results on constraints in the gluino mass versus lifetime plane for a split-supersymmetry model with the gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV, from Refs. [39,76–78] (left). Cross-section exclusion contours on the displaced supersymmetry model for stop pair production in the plane of stop lifetime ($c\tau$) and mass (a 100% BR through the RPV vertex $\tilde{t} \to$ bl is assumed) [84] (right).

ATLAS and CMS have performed searches for neutral LLPs with a lifetime such that they decay within the detector, but at a significant displacement from the primary event vertex. The decay products of these particles include a pair of electrons or muons (displaced leptons) [73] or a pair of jets (displaced jets) [74], as well as topologies with non-pointing photons [75].

Charged LLP searches typically rely on the large ionisation energy loss by the particles travelling across the detector. They can be of two types: lepton-like (as stau) and hadron-like (as gluino and squark) LLPs. Coloured LLPs would hadronise forming bound states composed of the LLP and light standard model quarks or gluons, called R-hadrons. They may emerge as charged or neutral states from the proton–proton collision and be converted into states with a different charge by interactions with the detector material, and thus arrive as neutral, charged or doubly charged particles in the muon detectors of the LHC experiment. Searches for charged LLPs, considering various lifetime parameters, have been performed by ATLAS [39,76–78] and CMS [79–81]. A combination of the ATLAS results is presented in Fig. 9 (left) as constraints in the gluino mass versus lifetime plane for a split-supersymmetry model with the gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV. The area below the curves is excluded.

Long-lived charged particles that decay within the detector are also searched for in signatures as "disappearing tracks", identified as those with little or no associated calorimeter energy deposits and with missing hits in the outer layers of the tracker [82,83]. The results of the search are interpreted in the context of the AMSB model (small mass splitting between the lightest chargino and the lightest neutralino). The long-lived chargino decay: $\chi_1^+ \to \chi_1^0 \pi^+$ can occur, producing a very soft pion in the final state, with a p_t of about 100 MeV, typically too low to be reconstructed. For charginos that decay inside the tracker volume, this results in a disappearing track topology.

Searches for non-prompt electron–muon final states have been performed [84] and limits are set on the displaced supersymmetry model [85], with pair production of stops decaying into an $e\mu$ final state via R-parity-violating interactions. Fig. 9 (right) presents the cross section exclusion contours for stop pair production in the plane of the stop lifetime versus mass. The region to the left of the contours is excluded. For a lifetime hypothesis of $c\tau = 2$ cm, stop masses up to 790 GeV are excluded in this model.

8. Search for dark matter candidates

A strong motivation for new physics is that the SM does not provide candidates for the dark matter (DM), which accounts for about 27% of the total energy in our universe. The understanding of the nature of DM is undoubtedly one of the most important and challenging issues in physics today. Much efforts are presently deployed in astrophysics and particle physics to the search for DM candidates.

Dedicated direct detection experiments are measuring the nuclear recoil in the possible interaction of a DM particle (χ) scattering off a nucleus in the detector: $\chi \mathrm{q} \to \chi \mathrm{q}$. These experiments are sensitive to DM mass above few GeV. For lower DM mass, the nucleus recoil energy is below present detector sensitivity. If the interaction is spin-independent, the scattering is coherent off the whole nucleus and the sensitivity is enhanced compared to the spin-dependent interaction case. Another class of experiments search for DM indirectly via its annihilation into SM particles. At the LHC, complementary DM searches are performed by looking for production of pairs of DM particles via the channel: $\mathrm{q}\bar{\mathrm{q}} \to \chi \bar{\chi}$. As this process leads

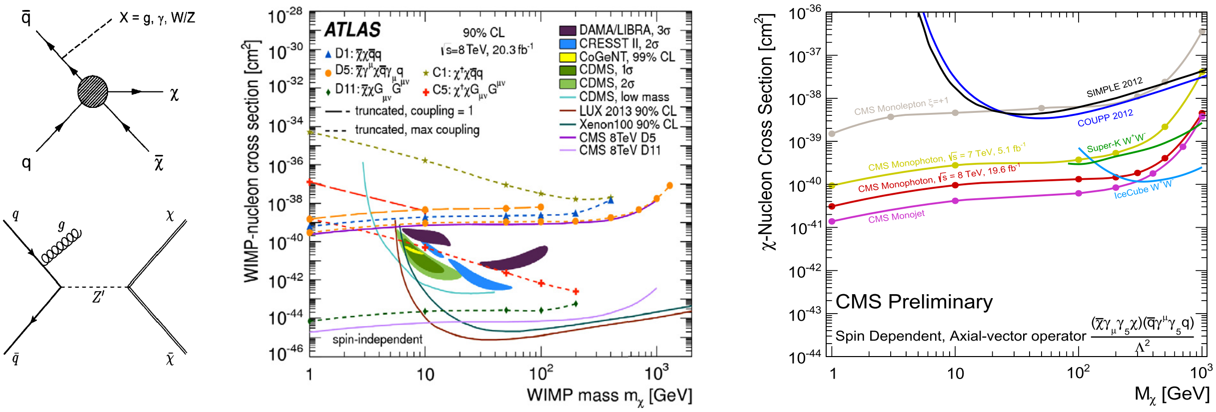

Fig. 10. (Color online) Diagrams of dark matter production at the LHC (left) via a contact interaction described with effective operators, or via a simplified model with a Z′ boson exchange. The 90% confidence level upper limits on the χ-nucleon cross section as a function of dark-matter mass for different operators in the case of spin-independent (centre) and spin-dependent (right) scattering [86,91]. Limits from selected experiments are also shown.

to an invisible final state in the LHC detectors, searches are performed using events with Initial State Radiation (ISR) of a gluon, a photon or an electroweak boson (W or Z), see Fig. 10 (left). The signal events are then characterised by final states with an energetic jet, photon or W/Z boson (recoiling again the DM system) and a large imbalance in transverse momentum, leading to spectacular events. The main SM background comes from $Z \to \nu\bar{\nu}$ boson production with ISR. The ATLAS and CMS analyses are detailed in [86–89] and [90–93], respectively. The data are in good agreement with the expected contributions from SM processes.

To compare these LHC results with the ones from direct detection experiments, an effective theory (EFT) is used, describing the SM-DM interaction in an effective 4-point operator, the hypothesis being made that the exchanged unknown particle must be very heavy compared to the energy scale of the collision. Under specific assumptions and using effective operators [94], the LHC results set constraints on the DM-nucleon scattering cross sections for spin-independent and for spin-dependent models, as shown in Fig. 10. For the spin-independent case, these are the best limits for a DM particle with mass below 3 GeV, a region unexplored by direct detection experiments. For the spin-dependent case, they are the most stringent constraints over the 1–300 GeV DM mass range. The validity of the EFT has been studied. For a given operator, one possible validity criterion is that the momentum transferred in the hard interaction is below the mediator particle mass. According to this criterion, truncated analysis is defined, in which events where the interaction energy scale exceeds the mediator particle mass are not considered. This approach is also compared to simplified models, with the mediator and the interaction explicitly specified, for example the exchange of a Z′ boson.

9. Other BSM searches

The LHC experiments have performed extensive searches for BSM physics in many different final states, and summary plots can be found in Refs. [8–10]. The final results of Run 1 for a selection of ATLAS and CMS searches are presented in the following subsections.

9.1. Search for heavy resonances

In particle physics, the easiest way to discover a new narrow resonance is to search for a localised excess of events in the invariant mass distribution of its decay product. New heavy bosons (Z'/γ', W′, graviton, heavy gluons) are expected from a large range of models (from GUT to models with extra spatial dimensions). ATLAS and CMS are searching for new heavy resonances in many different topologies, such as dilepton, diboson, and dijet final states. Only some of these results are presented below.

The search for neutral resonances decaying into a dilepton pair (ee and $\mu\mu$) profits from a simple final state with a good dilepton invariant mass resolution and suffers from little SM background, coming mainly from the Drell–Yan process. Events with two isolated high p_t leptons are selected, see Refs. [95,96]. Fig. 11 (left) presents the ATLAS dielectron invariant mass distribution. No excess above SM processes is observed and limits on the production cross section times BR are derived. A SM-like coupling Z′ is excluded for a mass below 2.9 TeV and a superstring-inspired Z'_ψ is excluded below 2.5 TeV. Heavy Z bosons often arise in grand unified theories and typically follow lepton universality. However, some models predict that such bosons could rather preferentially couple with third-generation fermions. Search for Z′ decaying in di-tau final states have been performed. The lower mass limits in the case of SM-like coupling Z′ is 2.0 TeV [97,98].

Heavy W′ searches are performed in the leptonic ($W' \to \ell\nu$) and hadronic ($W' \to$ tb) final states. The $W' \to \ell\nu$ signal implies high MET in the final state, with a Jacobian peak in the falling transverse mass distribution, as shown in Fig. 11 (centre) from CMS (for the electron channel). No signal is observed, and a SM-like coupling W′ is excluded for a mass

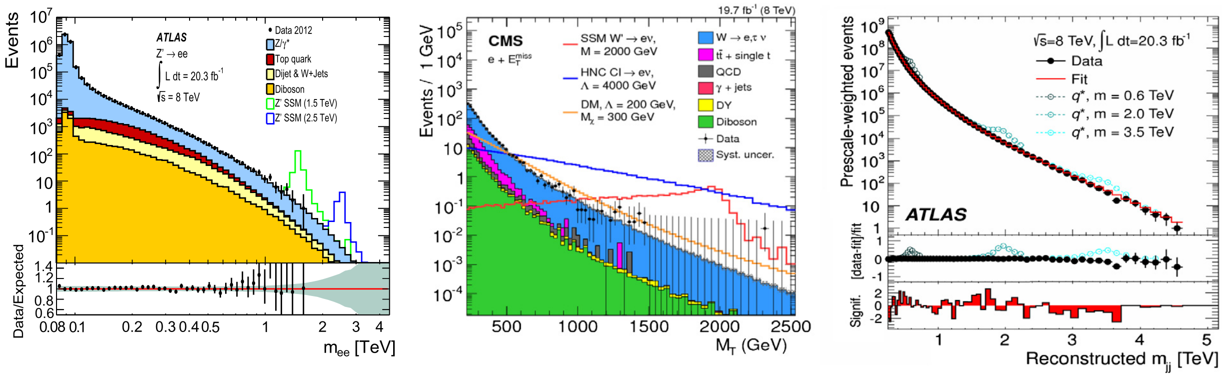

Fig. 11. (Colour online.) Dielectron mass spectrum, from ATLAS [95] (left). Transverse mass distribution for the W′ search in the electron decay channel, from CMS [92] (centre). Dijet mass spectrum from ATLAS [103] (right).

below 3.28 TeV [92]. ATLAS results are given in Ref. [99]. The search for a W′ boson decaying to a top quark and a b quark is sensitive to models inaccessible to leptonic decay searches. In the right-handed sector, for example, the W′ boson cannot decay to a lepton and a right-handed neutrino if the latter has a mass greater than the W′ boson mass, and only hadronic decays are allowed. The W′ hadronic decay search requires a high p_t lepton, jets and MET in the final state. The ATLAS and CMS results are presented in Refs. [100–102]. For W′ bosons with purely right-handed couplings, the limit on the W′ mass is about 2 TeV.

Many extensions of the SM predict the existence of new massive objects that couple with quarks or antiquarks and gluons, resulting in resonances in the dijet mass spectrum. Dijet masses up to about 4.5 TeV are probed by ATLAS and CMS, see Fig. 11 (right), and no resonance-like features are observed [103,104]. Limits on the cross section times acceptance are set for various new physics models. These analyses exclude excited quarks with mass below 4.09 TeV, colour-octet scalars below 2.79 TeV, heavy Z and graviton below 1.68 and 1.58 TeV, heavy W′ bosons below 2.45 TeV, chiral W bosons below 1.75 TeV. Dedicated analyses to search for a top–antitop quark resonance are performed by ATLAS [105] and CMS [106]. No deviation compared to the SM expectations is observed in the top–antitop invariant mass distribution. The top-colour Z′ (with narrow width) is excluded for mass below 2.1 TeV.

9.2. Search for excited fermions

In the SM, fermions are the building blocks of matter and are supposed to have no internal structure. However, if present, sub-structures can lead to the observation of excited fermionic states. ATLAS and CMS are searching for excited quarks and excited leptons through the channels $q^* \to q\gamma$ and $\ell^* \to \ell\gamma$. Model-independent searches for s-channel γ+jet production are performed by selecting events with photons and jets with high transverse momenta. The $\gamma +$ jet mass distribution is compared to a background model fit from data. No significant deviation from the background-only hypothesis is found and q^* masses below 3.5 TeV are excluded for unit couplings with their SM partners [107,108]. Excited leptons ℓ^* are assumed to be produced via contact interactions in conjunction with a SM lepton and to decay via $\ell^* \to \ell\gamma$, yielding a final state with two energetic leptons and a photon. The number of events observed in data is consistent with that expected from the SM and excited leptons with masses below 2.2 TeV are excluded [109,110].

9.3. Search for leptoquarks

As mentioned above, a striking feature of the SM is the similar structure for quarks and leptons, suggesting a possible new symmetry between them. Some extensions of the SM predict the existence of leptoquarks (LQ), having both lepton and baryon numbers. In view of the strong constraint from experimental results on flavour-changing neutral currents, lepton-number violation and proton decay, it is usually assumed that LQs do not couple with particles from different generations, leading to three generations of LQs. At hadron colliders, LQs are produced in pairs via gluon–gluon fusion and quark–antiquark annihilation, and singly via quark–gluon fusion. The pair-production of LQs at the LHC has a large cross section and could be detected via their decay into a lepton (charged or neutral) and a quark. This leads to topologies with a resonant peak in the lepton–jet invariant mass (in the case of charged leptons) or a significant excess in missing transverse energy (in the case of neutrinos). The first- and second-generation LQs are reconstructed at the LHC, requesting electrons or muons in the final state, in addition to two jets. The final-state event signatures from the decay of singly produced LQs can be classified as either dilepton and jet (the LQ decays to a charged lepton and a quark), or lepton, missing transverse energy, and jet (the LQ decays into a neutrino and a quark). In the search for third-generation leptoquarks, events with tau leptons and bottom or top quarks in the final state are selected. No sign of new physics is observed and LQ production is excluded for masses below 1005 (1070) GeV for the first (second) generation of scalar LQ [111–113], see Fig. 12 (left). Third-generation

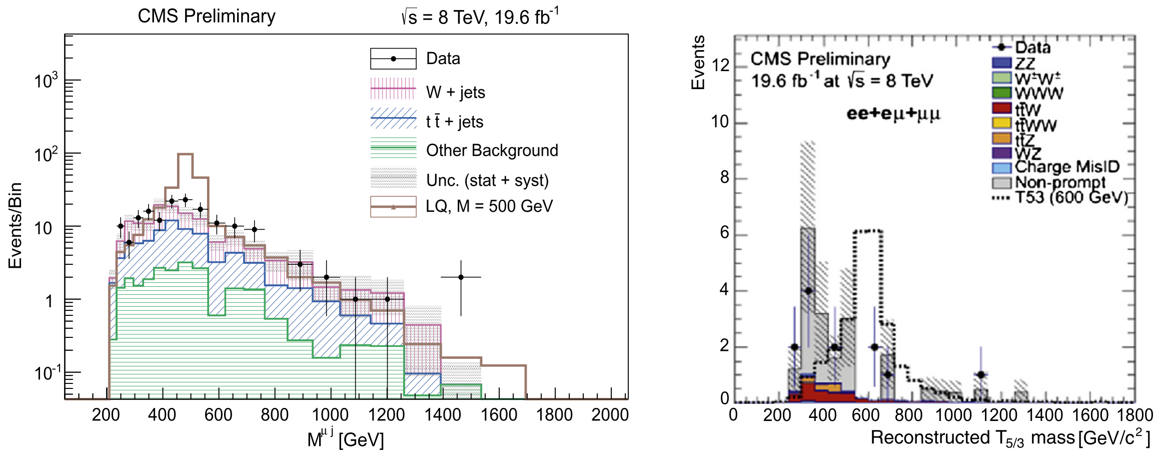

Fig. 12. (Colour online.) Search for second-generation of leptoquarks: the μ + jet invariant mass distribution [112] (left); Search for vector-like quarks: distribution of the reconstructed T(5/3) mass in the ee, eμ and $\mu\mu$ channels combined [122] (right).

leptoquarks are excluded for masses less than 740 GeV [114–116]. These limits assume a BR of a leptoquark to a charged lepton and a quark to be 100%.

9.4. Search for vector-like quarks

Vector-like quarks (VLQ) [117] are motivated by the fact that they can naturally solve the fine tuning problem, similar to what a stop squark does in SUSY. The vector-like Tops ($Q = +2/3$ or $+5/3$) and Bottom ($Q = -1/3$) are defined as heavy quarks for which both chiralities have the same transformation properties under the electroweak group, in order not to significantly modify the scalar boson SM production cross section and BR. VLQ appear in several extensions of the SM such as extra-dimensional models, composite Higgs, or non-minimal SUSY. ATLAS and CMS are performing searches for VLQ. A vector-like T quark has three possible decay modes, T → Wb, T → Zt, and T → Ht, with branching ratios depending on the T quark mass and the weak-isospin quantum number. The observation of the SM-like scalar boson has enhanced the level of interest in VLQ searches, since the T → Ht and B → Hb decays have now completely specified final states. The CMS distribution of the reconstructed T(5/3) mass is shown in Fig. 12 (right). No excess is observed in the various channels and limits have been put on the T-quark mass as a function of the Wb, Zt and Ht branching ratios. Detailed results from ATLAS and CMS are presented in Refs. [118–121] and [122–125], respectively. The vector-like T and B quarks are typically excluded for masses below 700–800 GeV, for the various decay channels considered.

9.5. Generic searches

As seen in the previous sections, many searches on new physics have been performed at the LHC. However, it is possible that new physics signals are still hidden in the Run 1 dataset, in topologies not yet investigated because, e.g., they are not motivated by theory. The strategy is then to perform model-independent analyses, that systematically scan the ATLAS and CMS data and search for deviations from the SM predictions, accounting for systematic uncertainties, see Refs. [126–128]. The data are divided into exclusive classes according to the number and type of reconstructed objects in the event: electrons, muons, photons, jets, b-tagged jets and missing transverse energy. In each class, a broad scan is performed in the distributions of various variables, as the scalar p_T sum and the invariant mass of all visible objects, and the missing transverse energy in the event. The data are compared to the SM predictions, and no significant signal for new physics is observed. The treatment of the probabilities of statistical fluctuations is important in these analyses that deal with many classes; they are modelled using pseudo-experiments. From the full Run-1 dataset analysis, no event class is found with a local p-value below 10^{-4} [126]. The observed deviations follow the SM expectations obtained from simulations.

10. Future of the LHC

After Run 1, the accelerator complex and the LHC detectors were being upgraded (in 2013–2014) to scope with high-energy runs. The LHC Run-2 data taking is expected to start in June 2015 at an energy of 13 TeV in the proton–proton centre of mass, and will run for a 3-year period until 2017. An integrated luminosity of about 10 to 15 fb^{-1} is expected to be accumulated in 2015 and about 40 fb^{-1} per year in 2016–2017, leading to a total Run-2 dataset luminosity of ∼ 100 fb^{-1}. Compared to Run 1, the Run 2 data are thus characterised by an increase of a factor 1.6 in energy and a factor 4 in luminosity. The increase in luminosity will be mainly achieved by operating at 25 ns between proton bunch crossings (compared to 50 ns for Run 1).

The increase in energy is crucial for the search for new physics, enlarging considerably the model parameter phase space for discoveries. For example, a factor 15 increase in partonic ($q\bar{q}$) luminosity at $M = 2.5$ TeV is achieved for 13-TeV pp collisions compared to 8-TeV collisions. The LHC Run 3 is planned in 2020–2022, with a total integrated luminosity of about ~ 300 fb^{-1} at 13- or 14-TeV centre of mass energy.

The possibility for the LHC to run beyond 2022, the so-called High-Luminosity LHC (HL–LHC) upgrade, is being studied. The expected peak luminosity of HL–LHC is 10^{35} cm^{-2}·s^{-1}. The target is to deliver a total of about 3000 fb^{-1} to the experiments by 2035. The ATLAS and CMS detectors are planning major upgrades to stand the HL–LHC running conditions. The main physics goal for this upgrade is the measurement to a few percent level of the scalar boson couplings with various particles (photons, gluons, W and Z bosons, top and bottom quarks and charged leptons), and the observation of possible deviations from the minimal SM predictions. LHC experiments are presently working on a Technical Proposal (TP) document that should be ready in 2015, followed by a Technical Design Report (TDR), presenting in detail the physics motivations of the project and its technical challenges and solutions.

11. Conclusions

The LHC machine is the most powerful particle accelerator ever built. Its first 3-year period of data taking and analysis is now over. The ATLAS and CMS experiments provided reference results in particle physics in the so-called "Run-1 legacy papers". The most spectacular result was the scalar boson discovery, and a vast program of precision measurements and searches has been performed. In this review, highlights on searches for new physics at the LHC were presented. No significant excess has been observed in the many channels considered. Strong limits on new physics cross-section production and on new particle masses have been derived.

How far is the scale of new physics? Which kind of new physics? Is there a symmetry that stabilises the scalar mass? What is the nature of dark matter in the universe? If the LHC Run 1 could not answer these questions, much hope is placed on the new high-energy run to shed light on these crucial issues. In June 2015, the LHC will start the high-energy run (at a centre of mass energy of 13 TeV) and will search for new physics in a much larger phase space, with hopefully discoveries of new particles. Running beyond 2022, with ten times higher integrated luminosity, the High-Luminosity LHC will be needed for more detailed studies of the scalar sector and of any new physics that hopefully could be discovered meanwhile. Many important results are thus expected to come from the LHC in the future.

Acknowledgement

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