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Searches for physics beyond the Standard Model at ATLAS and CMS

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1. Introduction

The main goals of the Large Hadron Collider (LHC) are to elucidate the electroweak symmetry breaking mechanism and to search for new physics beyond the Standard Model (SM). In July 2012, ATLAS and CMS announced the discovery of a new particle at a mass of 125 GeV [1, 2]. The measured properties of the new particle, as reported at the Moriond conference in March 2013 [3, 4], were found to be compatible with the ones of the minimal SM scalar boson proposed in 1964 by Brout, Englert and Higgs (H boson) [5–7]. In particle physics, the H boson discovery is a main achievement: it was indeed the missing piece of the SM for many years. Is this new particle the only elementary scalar particle of the model or more are to be discovered?

In parallel to the study of the scalar boson(s), the search for other new particles expected from new physics is also crucial. Indeed the SM cannot answer several fundamental questions (the hierarchy problem, matter-antimatter asymmetry, no dark matter candidate...). The SM is then generally considered as a low energy effective model of a more fundamental theory. A well known extension of the SM, supersymmetry (SUSY), introduces a new symmetry between bosons and fermions and allows the stabilisation of the radiative corrections to the H mass. It also generally proposes a candidate for dark matter.

This proceeding reports on searches for physics beyond the standard model (BSM), with a selection of lat-

est results from both ATLAS and CMS experiments. The complete public ATLAS and CMS results are available on the web pages given in [8, 9].

2. The LHC machine performance and the CMS and ATLAS detectors

ATLAS and CMS are multipurpose detectors described in detail in [10, 11]. Results presented in this proceeding are based on the RUN1 LHC dataset taken during the years 2011 and 2012 at the proton-proton center of mass energy $\sqrt{s} = 7$ TeV and 8 TeV, respectively. During these two years, excellent performance were achieved by the LHC machine and the ATLAS and CMS detectors. The integrated luminosities recorded by ATLAS and CMS are of more than 5 and 20 fb⁻¹ at 7 and 8 TeV respectively, as shown in Fig. 1, with a peak instantaneous luminosity up to 7.7 10³³ cm⁻²s⁻¹.

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, see Fig. 2(top). These additional (soft) interactions, called as pile-up events (PU), provide an important challenge to experimentalists. Much effort were put in the PU control and correction in particular for the 8 TeV data analyses. As an example, Fig. 2(bottom) presents the CMS resolution on the missing transverse energy (MET) measurement in Drell-Yan events, as a function of the number of reconstructed

Figure 1: The integrated luminosity recorded by CMS in 2010-12 [9].

vertex, for several MET algorithms using particle flow techniques [12].

Figure 2: Distribution of the mean number of interactions per beam bunch crossing recorded by ATLAS in 2011 and 2012 [8] (top); CMS MET resolution as a function of the number of reconstructed vertices for different MET algorithms in Drell-Yan (Zee) events [12] (bottom).

ATLAS and CMS precisely measured SM process

Figure 3: Summary of several Standard Model production cross section measured by ATLAS, compared to theoretical expectations [8].

cross sections over many orders of magnitude as the top-antitop quark pair and single-top quark production, the Z and W boson production, and the di-boson production : WW, WZ and ZZ. These accurate measurements, in agreement with the theory predictions, as shown in Fig. 3 (ATLAS results from [8]), demonstrate the excellent understanding of the detector, which is crucial for the search for BSM physics as the SM processes mentioned above are usually the main backgrounds to new signal searches.

3. Search for New Physics in the scalar sector

The search for new physics can be done indirectly, looking for deviations in the H boson coupling measurements, or directly, looking for additional scalar particles as predicted in SUSY and exotics models, also possibly as DM candidate. CMS Searches for heavy H boson in the channels : $H \rightarrow WW \rightarrow l\nu q\bar{q}'$ and $H \rightarrow ZZ \rightarrow ll\nu\nu$ have been updated [13, 14] and interpreted in BSM physics as a Higgs singlet extension of the SM, with the mass of the lighter one being around 125 GeV, see also [15]. Figure 4 presents the resulting limits on the coupling parameter as function of the heavy SM-like H mass [14].

Search for charged Higgs are also fundamental as they are predicted in 2 Higgs Doublet Models (2HDM). The main production mode is through top decays (for $m_{H^\pm}$ smaller than the top quark mass), and the branching ratio (BR) $H^\pm \rightarrow \tau\nu$ (or $H^\pm \rightarrow c\bar{s}$) is usually assumed to be 100%. No signal is observed and 95% Confidence Level (CL) limits on the BR($t \rightarrow H^\pm b$) of about 1-3% are derived as a function of the $H^\pm$ mass, in the range

Figure 4: 95% CL limit on the scale (C^2) of the coupling of the EW singlet as function of heavy H mass. The indirect limits obtained from the observation of the H(125) candidate are represented by the horizontal line, from CMS [14].

90–150 GeV [16–18]. Results are also interpreted in exclusion regions in constrained SUSY models (see next section).

4. Search for SUSY particles

Supersymmetry is a well known extension of the SM. Its minimal version, the MSSM, contains two scalar doublets, giving rise to five physical states (h , H , A , H^+ , H^-). The mass relations between these particles depend in particular on the MSSM parameter $\tan\beta$, the ratio of the scalar fields vacuum expectation values. Superpartners of the SM particles are introduced: squarks, sleptons, gauginos and higgsinos. The gauginos and higgsinos mix to give charginos and neutralinos. The lightest neutralino particle (LSP) is a possible candidate for dark matter.

The charged Higgs search results of section 3 are interpreted in the context of the $m_h^{\max}$ scenario of the MSSM, and values of $\tan\beta$ above 13–26 are excluded in the mass range $90 < m_{H^\pm} < 150$ GeV [16–18].

4.1. SUSY inclusive 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 multijet + MET, or multijet + lepton(s) + MET final states. ATLAS has updated the search in six final states, and limits are extracted in the context of MSUGRA as presented in Fig. 5(top) [19–23]. The parameters m_0 and $m_{1/2}$ represent universal common mass of scalars

(squarks, sleptons, Higgs bosons) and of gauginos and higgsinos, at the GUT scale.

Figure 5: Exclusion limits at 95% CL for 8 TeV analyses in the $(m_0, m_{1/2})$ plane for the MSUGRA model (with the remaining parameters set to $\tan\beta = 30$, $A_0 = -2m_0$, and $\mu > 0$). Part of the model plane accommodates a lightest neutral scalar Higgs boson mass of 125 GeV, from ATLAS [19–23] (top); Exclusion limits at 95% CL from the single-lepton channels presented in the $m(\text{gluino})$ - $m(\text{neutralino})$ mass plane. The blue and purple lines show the exclusion obtained by the soft and hard-lepton analyses, respectively, from ATLAS [23].

Dedicated analyses are also performed considering final states with soft leptons in order to increase the sensitivity to SUSY spectra at small mass splitting, as presented in Fig. 5(bottom). Gluinos masses below 1.35 TeV are excluded for any squark mass [23].

4.2. Searches for Natural SUSY

After the hint of a new scalar boson at 125 GeV end of 2011, ATLAS and CMS focussed on phenomenology oriented approach to target the m_H hierarchy problem and several 'Natural SUSY' dedicated searches have been performed. A typical spectrum of natural SUSY is presented in [24] with $m(\text{gluino}) < 1500$

Figure 6: Summary of observed and expected limits for gluino pair production with gluino decaying via the 3-body decay (top, anti-top, neutralino) final state, from CMS [27–30] (top); Exclusion region in the plane $m(\text{stop})$ - $m(\text{gluino})$ for ATLAS dedicated searches of final states with 7 to 10 jets [22] (bottom).

GeV, $m(\text{stop}, \text{sbottom}) < 700$ GeV and $m(\text{neutralino}, \text{higgsino}) < 350$ GeV. The rest of the spectrum may be decoupled (at higher mass) without compromising naturalness.

ATLAS [20, 22, 25, 26] and CMS [27–30] presented results for the third generation SUSY searches via gluinos chains, with gluino $\rightarrow$ top stop $\rightarrow$ top top neutralino. The intermediate stop may be off-shell if $m(\text{stop}) > m(\text{gluino})$ or on-shell if $m(\text{stop}) < m(\text{gluino})$. Results of several searches depending on the number of leptons in the final state are presented in Fig. 6(top) (CMS results [27–30]). Figure 6(bottom) presents the exclusion region in the plane $m(\text{stop})$ - $m(\text{gluino})$ for ATLAS dedicated searches of final states with 7 to 10 jets [22].

Another possibility is to search directly for stop pair (or sbottom pair) production. The stop can decay directly into a top-LSP pair or via an intermedi-

ate chargino/neutralino state. Other channels are also possible if the stop is light (below the top mass), see Fig. 7(top). The final state signature is then a top-antitop pair and MET. The searches focussed on the 1-lepton channel (e/μ). At small ΔM , where $\Delta M = m(\text{stop}) - m(\text{LSP})$, the signal cross section is sizable but the analysis suffers from large $t\bar{t}$ background contamination; at large ΔM , the signal cross section is low but presents kinematical distributions different from the background.

Results from the 1-lepton channel search from CMS are presented in Fig. 7(middle) [31]. An ATLAS compilation of 9 different channel searches (0, 1, 2 leptons plus MET, with and without b-tagged jets) is shown in Fig. 7(bottom), the analyses are detailed in [32–35].

5. Dark matter search at the LHC

A search for dark matter (DM) particles in events with an energetic jet or photon and an imbalance in transverse momentum is performed in ATLAS and CMS, the unique object in the event being the jet or the photon from Initial State Radiation (ISR). The ATLAS and CMS analyses are detailed in [36, 37] and [38], respectively. The data are in good agreement with the expected contributions from SM processes. Under specific assumptions and using effective operators [39], constraints on the dark matter-nucleon scattering cross sections are determined for spin-independent model as shown in Fig. 8(top), and for spin dependent one, see Fig. 8(bottom). For the spin-independent model, these are the best limits for a dark matter particle with mass below 3.5 GeV, a region unexplored by the direct detection experiments. For the spin-dependent model, these are the most stringent constraints over the entire 1-1000 GeV mass range studied.

6. Other BSM searches

ATLAS and CMS have performed extensive searches for BSM physics in many different final states. Latest results on the search for heavy resonances and vector-like quarks are detailed below.

6.1. Search for heavy resonances

ATLAS and CMS are searching for new heavy resonances in several final states. Searches for neutral resonances decaying into a dilepton pair (ee and $\mu\mu$) are performed by ATLAS [40] and CMS [41]. Events with two isolated high p_T leptons are selected. The CMS dielectron spectrum is presented in Fig. 9(top). No excess

Figure 7: Stop quark pair production searches. The different stop decay channels depending on the stop and neutralino masses (top); CMS results of the 1-lepton channel searches [31] (middle); Compilation of ATLAS results for the 9 channels considered [32–35] (bottom).

above SM processes is observed and limits on the production cross section are derived at 95% CL, see the ATLAS results in Fig. 9(down). A SM-like coupling Z' is excluded for mass below 2.9 TeV and a superstring-inspired Z'_ψ is excluded below 2.5 TeV.

Heavy W' search are performed in the leptonic final

Figure 8: Comparison of the 90% CL upper limits on the dark matter-nucleon scattering cross section versus dark matter mass for the spin-independent (top) and spin-dependent (bottom) models, with results from various direct detection experiments. Results from ATLAS [36, 37] and CMS [38].

state ($W' \rightarrow l\nu$) and hadronic final state ($W' \rightarrow tb$). The $W' \rightarrow l\nu$ signal implies high MET in the final state, with a Jacobian peak in the falling transverse mass distribution, as shown in Fig. 10 (top) from CMS (for the electron channel) [42]. Hadronic decay search requires high p_t lepton, jets and MET in the final state. The ATLAS results based on a Boosted Decision Tree (BDT) analysis are shown in Fig. 10 (bottom) [43]. CMS results are presented in [44]. The data are compatible with the SM background estimations.

Finally, searches for a top-antitop resonance are performed by ATLAS [45] and CMS [46, 47]. Figure 11 presents the invariant mass distribution of the top-antitop quark pair (CMS data). No deviations compared to the SM expectations are observed. The top-color Z' (with narrow width) is excluded at 95% CL for mass below 2.1 TeV.

Figure 9: Dielectron spectrum, from CMS [41] (top); 95% CL limits on the production cross section, from ATLAS [40] (bottom).

Figure 10: Transverse mass distribution for the W' search in the electron decay channel, from CMS [42] (top); Distribution of the BDT output in the $W' \rightarrow t\bar{b}$ search, from ATLAS [43] (bottom).

6.2. Search for vector-like quarks

ATLAS and CMS are performing new searches on Vector-Like Quarks (VLQ) [48], defined as quarks for which both chiralities have the same transformation properties under the electroweak group $SU(2) \times U(1)$: vector-like Top ($Q=+2/3, +5/3$) or Bottom ($Q=-1/3$). VLQ appear in several extensions of the SM such as little Higgs or extra-dimensional models. A vector-like T quark has three possible decay modes, $T \rightarrow Wb$, $T \rightarrow Zt$, and $T \rightarrow Ht$, with branching ratios depending on the T quark mass and weak-isospin quantum number. The observation of a SM-like Higgs boson raises the level of interest in vector-like quark searches, as $T \rightarrow Ht$ and $B \rightarrow Hb$ decays now have completely specified final states. Figure 12(top) shows a $T(5/3)$ pair production diagram, via gluon fusion, characterized by a final state with 2 boosted jets and a same sign lepton pair. The CMS distribution of the reconstructed $T(5/3)$ mass is shown in Fig. 12(bottom). No excess is observed in the various channels and limits have been put on the

Figure 11: Top-antitop quark pair invariant mass distribution from CMS [47].

T-quark mass as function of the Wb , Zt and Ht branching ratios, as presented in Fig. 13. Detailed results from

ATLAS and CMS are presented in [49–52] and [53, 54], respectively.

Figure 12: Diagram of a $T(5/3)$ pair production via gluon fusion (top); CMS distribution of the reconstructed $T(5/3)$ mass in the ee , $e\mu$ and $\mu\mu$ channels combined [53] (bottom).

7. Conclusions

This proceeding has presented a selection of the latest results on searches for new physics at the LHC, performed by the ATLAS and CMS experiments with the RUN1 dataset collected in years 2011 and 2012. Many different signal topologies were investigated. No significant excess has been observed and limits on new physics cross section production or on new particle mass have been put. In April 2015, the LHC will restart for the high energy run (at an energy of 13 TeV) and will search for new physics in a larger phase space, with hopefully discoveries of new particles.

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