ATLAS results and prospects with focus on beyond the Standard Model

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Abstract

A summary of results relevant for searches of phenomena beyond the Standard Model (SM) obtained by the ATLAS experiment at the LHC is presented. While all SM measurements can be considered as indirect searches, the focus will be set on direct searches and measurements interpreted as limits on phenomena beyond the SM. Prospects towards Run 3 and High Luminosity LHC are reported where available. Most results are based on an integrated luminosity of 36 fb$^{-1}$ at a centre-of-mass energy of 13 TeV.

1. Introduction

The Standard Model (SM) of particle physics is an extremely successful description of the phenomena observed so far. It leaves however several open questions, e.g. concerning the nature of Dark Matter (DM), the matter-antimatter asymmetry and the hierarchy problem. Many theories and models beyond the SM (BSM) provide answers to these questions and are therefore tested experimentally. At the LHC the high collision energy is used to search directly for heavy new particles, while the high luminosity is exploited in searches for rare processes. Results are generally presented in a model independent way leaving the possibility to recast them for new models.

During the current data taking period (Run 2) more than 100 fb$^{-1}$ of data have already been collected. In Run 3 (2021-2023) the centre-of-mass energy will be increased to 14 TeV and an integrated luminosity of 300 fb$^{-1}$ is expected, while the High Luminosity LHC (HL-LHC) will increase the total integrated luminosity by one order of magnitude at the same energy. To face the challenges of the upcoming Run 3 and at the HL-LHC, most of all in terms of trigger rate and multiple collision (pile-up) rejection, the ATLAS detector [2] needs...
to be upgraded with new muon detectors, a new inner tracker (ITk), as well as improved read-out and trigger electronics. The new hardware together with new reconstruction techniques allow to recover or improve on the Run 2 performance in spite of a much higher pile-up level. As an example, the expected \( b \)-tagging performance at the HL-LHC is shown in Figure 1. In the same range of pseudorapidity \( \eta \) the light-quark rejection at a given efficiency is significantly higher than in Run 2. The larger coverage of the ITk allows for \( b \)-tagging up to \( |\eta| < 4 \).

2. Direct BSM searches

Direct searches for BSM particles are presented in this Section, divided into dedicated searches for supersymmetric (SUSY) particles in 2.1 and signature-based and DM searches in 2.2.

2.1. SUSY searches

Several SUSY searches are dedicated to the pair production of top squarks \( \tilde{t} \). Since the decay topology depends on the masses of the intermediate SUSY particles, dedicated signal regions are chosen for each scenario, while the background estimate is performed in appropriate control regions. So far no evidence for signal is observed and model-independent limits on the number of signal events are reported, as well as their interpretation in terms of limits on the SUSY particle masses. Currently the precision of the results is limited by the available statistics in the signal regions and by background modelling uncertainties of the order of 20%. A recently published result in the almost degenerate region \( \Delta m = m_\tilde{t}_1 - m_\chi^0_1 < m_W + m_\nu \) addresses the \( \tilde{t}_1 \rightarrow c\tilde{\chi}^0_1 \) decay by using a dedicated \( c \)-tagging algorithm [4]. The result is included in the summary shown in Figure 2. Additional searches aim at \( \tilde{t}_1 \) decays to a \( \tilde{\tau}_1 \) or to jets in an R-parity violating (RPV) model [6] and exclude them at 95% confidence level up to \( m_{\tilde{t}_1} = 1.16 \text{ TeV} \) and \( m_{\tilde{\tau}_1} = 410 \text{ GeV} \), respectively. At the HL-LHC a discovery of the top squark in the decay \( \tilde{t}_1 \rightarrow c\tilde{\chi}^0_1 \) will be possible up to \( m_{\tilde{t}_1} \approx 500 \text{ GeV} \) [7].

![Figure 2: Summary of the dedicated ATLAS searches for top squark (stop) pair production based on 36 fb\(^{-1}\) of \( pp \) collision data taken at \( \sqrt{s} = 13 \text{ TeV} \). Exclusion limits at 95% CL are shown in the \( \tilde{t}_1-\tilde{\chi}^0_1 \) mass plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross section uncertainty (PDF and scale) [3].](image)

Considering the superpartners of the electroweak bosons and the production of sleptons, very different processes can lead to similar final states. Using a similar general strategy as for the squark searches, the focus of these analyses lies mostly on the background estimate techniques. Both R-parity conserving (RPC) and RPV scenarios are considered. A recent search with 2 and 3 lepton signatures uses a \( \gamma + \text{jets} \) template to estimate the dominating \( Z + \text{jets} \) background [9], while a 4 lepton analysis uses a data-driven method to estimate the background from fake or non-prompt leptons [10]. No significant excess above the SM expectation is observed in any of the signal regions considered, and the results are used to calculate exclusion limits at 95% confidence level in several simplified model scenarios. The sensitivity for discovery and exclusion at the HL-LHC has been studied in [11] and [8]. The results of the latter publication in the \( (m_{\tilde{e}_R}, m_{\tilde{\tau}_2}) \) plane are shown in Figure 3.

In case of mass-degenerate spectra, small couplings or highly virtual intermediate states, the new particles can be long-lived and their search requires dedicated reconstruction techniques. Additionally to the limited statistics, the background estimate is therefore particu-
Figure 4: Constraints on the gluino mass-vs-lifetime plane for a split-supersymmetry model with the gluino R-hadron decaying into a gluon or light quarks and a neutralino with a mass of 100 GeV. The solid lines indicate the observed limits, while the dashed lines indicate the expected limits. The area below the curves is excluded. For the displaced vertices result the expected and observed limits are identical. For the stopped gluino result the limit extends to larger lifetimes (not quoted here, see reference). The dots represent results for which the particle is assumed to be prompt or stable (escaping the detector) [3].

Figure 5: Observed and expected 95% CL exclusion regions in the $(m_A, m_H)$ plane for various $\tan \beta$ values for Type II 2HDM, obtained from the search for a heavy Higgs boson ($A$) decaying into a $Z$ boson and another heavy Higgs boson ($H$) [16].

2.2. Signature-based and DM searches

The most typical signature-based searches for BSM particles look for resonances in the form of a peak over a smooth background in the spectrum of a sensitive kinematic variable, e.g. the invariant mass of the decay products. Results compatible with the SM expectation are presented as (almost) model independent limits in cross-section times branching fraction ($\sigma \cdot BR$), as well as model dependent limits in the mass of the new particle. At low invariant masses the limiting factor is the uncertainty on the background estimate, at high invariant masses the results are mostly statistically limited. Recent results include diboson searches for a resonance decaying to a $W$, $Z$ or Higgs boson ($h$) together with a photon with a highly collimated (boosted) decay of the $W$, $Z$ or $h$ [15] and in the decay of a heavy neutral Higgs boson, $A$, decaying into a $Z$ boson and another heavy Higgs boson, $H$, in the context of the two-Higgs-doublet model (2HDM) [16]. Di-jet resonance searches were also recently published, for which either special trigger requirements are implemented to cover the low-mass region in the $bb$ or $bg$ decay channel [17], or the whole analysis is performed in the fast electronic of the first trigger level [18]. In none of the analyses an excess with respect to the SM expectation is observed and 95% confidence level limits on $\sigma \cdot BR$ as low as a fraction of a picobarn for resonance masses up to 6 TeV are set and in some cases translated into model dependent mass limits. The results of the search for $A \rightarrow ZH$ in the $(m_H, m_A)$ plane for the 2HDM Type II model are shown in Figure 5. The expected sensitivity of a search for a $Z'$ boson decaying to $\ell \ell$ at the HL-LHC is presented in [19]. If no excess is found, the limit at 95% confidence level is expected to be at a $Z'$ mass of 4 TeV.

Additionally to the RPC SUSY searches, that can be interpreted as DM searches, some dedicated analyses exploit a high $E_T^{miss}$ signature when looking for DM candidates, while resonance searches can be reinterpreted to set model dependent limits on mediator masses. A search for a single $b$ or $t$ quark with high $E_T^{miss}$ uses a very similar strategy to SUSY searches with low-background signal regions [20], while a search for a DM candidate accompanied by a vector boson has a large irreducible background and is limited by systematic uncertainties [21]. No evidence for an excess with
Figure 6: A comparison of the inferred limits to the constraints from direct detection experiments on the spin-independent WIMP-nucleon scattering cross section in the context of the $Z'$-like simplified model with vector couplings. The results from this analysis, excluding the region to the left of the contour, are compared with limits from the LUX, PandaX, Xenon1T and CRESST II experiments. LHC limits are shown at 95% CL and direct detection limits at 90% CL. The comparison is valid solely in the context of this model, assuming a mediator width fixed by the dark matter mass and coupling values $g_q = 0.25$ and $g_{DM} = 1$. LHC searches and direct detection experiments exclude the shaded areas. Exclusions of smaller scattering cross-sections do not imply that larger scattering cross-sections are also excluded. The single dijet and $E_T^{miss}+X$ exclusion region represents the union of exclusions from all analyses of that type [3].

Respect to the SM expectation is observed and 95% confidence limits are set in the DM particle vs. mediator mass plane. For a specific choice of model and couplings, these limits can be compared to the results from direct DM detection experiments, see Figure 6. While the direct detection experiments cover in particular very low cross sections at moderate DM candidate masses, the LHC sensitivity extends to much lower DM candidate masses for moderate cross sections. The expected sensitivity at the HL-LHC for the jet+$E_T^{miss}$ signature is investigated in [22], where a strong dependence is found on the systematic uncertainty of the SM background estimate.

3. Indirect BSM searches

An alternative approach to direct searches is to look for deviations from SM expectations either via enhancement of very rare processes (see Section 3.1) or via anomalous couplings (see Section 3.2).

3.1. Very rare processes

For some processes expected to occur with very low probability in the SM, a strong enhancement is predicted in BSM models. Therefore experimental searches are well motivated even long before the sensitivity to the SM cross section can be reached. These searches are statistically limited and they often make use of multivariate techniques to separate signal from background and of data-driven background estimates.

Flavour-changing neutral current (FCNC) decays of the top quark into a Higgs boson and a quark are excluded at 95% confidence level above 0.19% [23] with an expected improvement at the HL-LHC by more than an order of magnitude [24]. Figure 7 shows a summary of the limits on FCNC top quark decays set by the ATLAS and CMS collaborations. The cross section of the four top quark production is excluded at 95% confidence level above 60 fb, corresponding to 6.5 times the SM cross section [25]. Limits on the production cross section of two Higgs bosons decaying to a pair of $b$ quarks and a pair of photons are used to constrain the Higgs boson self-coupling ($\kappa_{\lambda} = \lambda_{HHH}/\lambda_{SM_{HHH}}$) at 95% confidence level to $-8.2 < \kappa_{\lambda} < 13.2$ [26]. At the end of the HL-LHC running this limit is expected to improve to $-0.7 < \kappa_{\lambda} < 7.7$ [27] under the assumption that no significant deviation from the SM expectation is observed.

3.2. Higgs boson and top quark couplings

For a long time cross section measurements of several production and decay channels of the SM Higgs boson have been interpreted in terms of effective couplings within the so-called $\kappa$ framework, which is strongly model dependent [30, 31]. Recently both inclusive and differential cross section measurements have been interpreted in terms of anomalous couplings within the context of effective field theories (EFT) [28]. As an exam-
ple of the latter interpretation, the 68% and 95% confidence level regions for the Wilson coefficients specifying the strength of the new CP-even and CP-odd interactions to vector bosons from the measurement of the $H \rightarrow \gamma\gamma$ decay are shown in Figure 8. So far all couplings have been found to be compatible with the SM prediction within uncertainty. The expected improvement in the coupling determination with the integrated luminosity accumulated at the end of Run 3 and at the end of the HL-LHC running is estimated within the $\kappa$ framework in [32]. Most ratios of couplings can reach the precision of a few to about 10%.

Precise measurements of top quark properties, like the single top quark production in the $t$-channel [29] and the $W$ boson polarisation in top pair production [33] are used to constrain BSM contributions to the $Wtb$ vertex within EFT. While in the SM at LO only the left-handed vector coupling is non-vanishing, an effective Lagrangian can be built to include left- and right-handed vector ($V_L, V_R$) and tensor ($g_L, g_R$) couplings and limits are set on ratios of these complex coupling constants. Without any assumptions on the values of the other parameters, the most stringent constraints are obtained in [29] with the following 95% confidence level intervals: $-0.12 < \text{Re}[g_R/V_L] < 0.17$ and $-0.07 < \text{Im}[g_R/V_L] < 0.06$. These interpretations are currently based on results obtained from data at $\sqrt{s} = 8$ TeV.

4. Conclusion

An extensive programme of direct BSM searches is carried out at ATLAS employing a large variety of strategies and many ingenious analysis methods. So far no deviations from the SM expectations have been observed and limits have been set on production cross section times branching fraction of several BSM particles as well as on their mass in the context of specific models. Additionally, more and more SM measurements are being interpreted as limits on anomalous couplings. Very rare processes are being searched for long before sensitivity at SM level is reached and Higgs boson and top quark cross section and property measurements are interpreted in the context of EFT.

With the high luminosity upgrade of the LHC a slightly higher energy, 3 ab$^{-1}$ of integrated luminosity and a strongly improved detector will be of great advantage for all statistically limited searches. At the same time the background estimate can profit from more populated control regions, as well as more precise measurements and calculations. On the other hand the much higher pile-up requires improved analysis techniques. Fortunately, already many very promising ideas have been developed in collaboration between experimentalists and theorists.

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