Searches for Physics Beyond the Standard Model with the ATLAS Detector at LHC

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Abstract—This contribution discusses in brief recent results from the search for new physics beyond the Standard Model obtained by the ATLAS experiment with the analysis of up to 80 fb⁻¹ of 13 TeV LHC data. It is organised over three main themes: the Higgs sector and new physics, searches for dark matter motivated new physics scenarios and relations between QCD and searches for new physics.

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1. THE HIGGS BOSON AND NEW PHYSICS

The discovery of the Higgs boson at a mass of 125 GeV offers an important opportunity to search for new physics through precision measurements of its properties. First, its couplings may deviate from those predicted by the Standard Model (SM) due to the effects of new particles. Then, the observed boson might be only the lightest state of a family of Higgs particles in an extended Higgs sector. The recent observation of the decay is an important step in this program. This decay is crucial to determine the nature of the H bosons because of potentially large new physics contribution to the effective coupling by direct vertex corrections, resulting into anti-correlated variations of the branching fractions into all the other decay modes. The contributions from new physics to the effective coupling, have been computed in details in the case of SUSY [1] and can be expressed as:

\[ g_{hbb} = \tan \beta (1 - \Delta_b), \]  

with the \( \Delta_b \) term in Eq. (1), arising from loop contributions with bottom or top scalar quarks and gluinos, given by:

\[ \Delta_b = \frac{2\alpha_s}{3\pi} \frac{m_{\mu} \tan \beta}{\max(m_b^2, m_{\tilde{b}}^2, m_{\tilde{t}}^2)} \]

\[ + \frac{m_t^2}{8\pi v^2 \sin^2 \beta \max(m_t^2, m_{\tilde{t}}^2, m_{\tilde{b}}^2)} \]

(2)

that highlights the \( \mu \tan \beta \) enhancement and the dependence on the SUSY particle masses.

The new ATLAS result for the search for the Higgs boson produced in association with or decaying into \( b\bar{b} \) is based on 79.8 fb⁻¹ of 13 TeV data collected by ATLAS [2] in 2015–2017 [3]. The full combination of this analysis with those from \( t\bar{t}H \), and \( VBF \) production in Run1 and Run2 data results in a 5.4 observation with a ratio of the observed yield to the SM expectation of \( \mu_{bb} = 1.01 \pm 0.12 \) (stat.) (stat.) [3]. Similar results have been reported also by CMS Collaboration [4].

Combined measurements of Higgs boson couplings from the study of the Higgs boson decays into \( \gamma\gamma \), \( ZZ \), \( WW \), \( \tau\tau \) and \( b\bar{b} \) have been obtained by ATLAS using up to ~80 fb⁻¹ of \( pp \) collision data at \( \sqrt{s} = 13 \) TeV. Results are usefully interpreted in terms of modifiers applied to the Higgs boson SM couplings to other particles, and can be used to set exclusion limits on new physics. Results are in agreement with SM predictions within measurement accuracy (see Fig. 1) [3]. However, the expected deviations for many new physics scenarios are still of the order of these accuracies and the scattering of the results in the different channels, or smaller, and sensitive tests will require the full statistics foreseen for the entire LHC program.

The study of the Higgs coupling is also effective for testing whether the observed boson is part of an extended Higgs sector, as predicted by SUSY and non-supersymmetric two Higgs doublet models (2HDM).

For sufficiently large \( m_{\tilde{t}} \) values, the couplings of the lightest SUSY Higgs boson to gauge bosons, \( g_{hV}, \) up-
like, $g_{h\mu\mu}$ and down-like quarks, $g_{hdd}$, can be expanded to obtain the following tree-level result:

$$g_{hVV} = \sin(\beta - \alpha) \frac{m_{m'\tau}}{m_A} \times 1 - \frac{2m_{\tau}^2}{m_A} \to 1,$$

$$g_{h\mu\mu} = \frac{m_{m'\mu}}{m_A} \times 1 + \frac{m_{\tau}^2}{2m_A} \to 1,$$

$$g_{hdh} = \frac{m_{m'\mu}}{m_A} \times \frac{m_{\tau}^2}{2m_A} \to 1,$$

$$g_{hdh} = \frac{m_{m'\mu}}{m_A} \times \frac{m_{\tau}^2}{2m_A} \to 1.$$

The couplings of the lightest $h$ boson in a generic Type II 2HDM or MSSM model approach those of the SM $H$ boson for a sufficiently heavy CP-odd $A^0$ boson and the limit is reached more quickly at large values of $\tan \beta$, again as a result of the presence of $\tan \beta$ factors in the denominators of the expansion terms in Eq. (5). The determination of the Higgs decay rates sets non-trivial constraints on the mass, $m_A$, of the heavy Higgs [6]. The ATLAS results on Higgs couplings imply that $m_A > 520$ GeV (with 400 GeV expected) at 95% C.L. [5], thus complementing the bounds set by direct searches for additional Higgs bosons in an extended Higgs sector [7, 8].
signatures, characterised by an isolated particle or jet and large missing transverse energy (MET), due to the escaping DM particles, have been applied since the time of LEP and Tevatron and their results can be interpreted in complete models, for example SUSY and Extra Dimension extensions of the SM, but also, in a more model-independent manner, using effective field theory (EFT), where new operators represent the effect of new physics whose dynamics becomes effective at an high scale \( M \), without specifying the full particle content of the model [10–13]. ATLAS has recently released new results for mono-jet [9] and mono-\( W/Z \) [14] searches. Constraints from these searches can be translated into bounds on the masses of the DM particle and their mediator (see Fig. 2). Within the range of EFT applicability, it is also possible to recast the bounds on the strengths of individual operators into bounds on DM scattering cross sections as shown in Fig. 2, thus directly connecting the LHC to searches of cosmic DM scattering in low noise experiments.

Within the searches for SUSY, those for weakly interacting particles, charginos and neutralinos, are of special importance in connection to DM. Recent ATLAS analyses have addressed the direct associated production of charginos and neutralinos with \( W \)- and \( Z \)-mediated decays [16], the direct chargino pair production with \( W \)-mediated decays [17] and the search for electro-weak SUSY production in compressed scenarios. The exclusion limits at 95% C.L. on \( \chi^+_i \chi^-_i \), \( \chi^+_i \chi^-_2 \), \( \chi^+_2 \chi^-_2 \), \( \chi^+_2 \chi^-_3 \), production with \( W \)-, \( Z \)- or \( \tilde{t} \)-mediated decays for pair production cross-sections, for pure wino and pure higgsino, are summarised in Fig. 3.

The search for electro-weak SUSY particle production in compressed scenarios, where the mass difference, \( \Delta M \), between the pair-produced particle and the lightest neutralino (generally the DM candidate of the model) is small, is a difficult program because of the low energy of the SM decay products. Two techniques have been developed to probe these scenarios. The first uses soft leptons and is sensitive to \( \Delta M \) values in the range from a few to 10 GeV [18]. The second technique is based on the search for disappearing tracks in tracklet topologies exploiting decays of charginos travelling through the layers of the ATLAS pixel detector and decaying soon afterwards, corresponding to \( \Delta M \) values from 100 to \( \sim \) 300 MeV [19]. The combination of the results of these searches constrains the compressed scenarios from the large and low ends of the \( \Delta M \) spectrum, as summarised in Fig. 3. These searches cover part of the “natural” SUSY solutions [20], where the low value of the Higgsino parameter \( \mu \) ensures a limited amount of fine tuning in the theory. These solutions are under pressure due to the negative results of direct DM searches, since the neutralino scattering cross section scales with the \( \mu \) parameter [21].

3. QCD AND NEW PHYSICS

Given the main focus of this conference, it is interesting to discuss the role of QCD in the search for new physics at the LHC. Inclusive jet and di-jet events rep-
represent a background to many of these searches. There are important QCD effects to be accounted for in the signal acceptance and background rejection. Examples can be found in many of the analyses discussed above. The extraction of the yield of \( \chi_1^0 \) is affected by a number of systematic effects related to the background from QCD processes. The \( p_T \) spectrum in \( W + \) jets, the \( m_{bb} \) spectrum in \( Z + \) jets and di-boson events and the \( VH \) acceptance due to the parton shower modelling and the QCD scales rank as the top contributions to the systematic sources of uncertainty of the measured value of \( \mu_{bb} \) [3].

In the mono-jet analysis, the uncertainties on the background at large \( p_T \), the \( m_{bb} \) spectrum in \( Z + \) jets and di-boson events and the \( VH \) acceptance due to the parton shower modelling and the QCD scales rank as the top contributions to the systematic sources of uncertainty of the measured value of \( \mu_{bb} \) [3].

Precise measurements of jet cross-sections are of great importance for LHC searches. The predictive power of fixed-order QCD calculations is therefore relevant in many searches for new physics. Jet cross sections have been measured by ATLAS double-differentially as a function of the jet \( p_T \) and absolute rapidity, \( |y| \). Di-jet production has been analysed in terms of the double-differential cross-sections as a function of the di-jet invariant mass, \( m_{jj} \), and half of the absolute rapidity separation between the two highest-\( p_T \) jets, \( y^* \) [23]. These have been compared with predictions obtained using NLO and NNLO pQCD calculations [24] using several sets of parton distribution functions (PDF) [25–29]. Overall, a good agreement for jets in individual \( y \) and \( y^* \) bins and di-jets and a tension on full phase-space for inclusive jets have been observed (see Fig. 4).

Searches for stable or metastable gluinos and R-hadrons, bound states formed by a SUSY strongly interacting particles with ordinary quarks and gluons, exploit the production of heavy stable hadrons (stable/long-lived gluinos and these hadronising into heavy bound states) identifiable in ATLAS through their specific energy loss measured in the four pixel layers [30]. This analysis brings QCD at the forefront of the ATLAS searches for new physics focusing on the possible strong interactions between SUSY and ordinary particles. The mass limits are extracted from the \( dE/dx \) in Si and the track momentum reconstructed in the tracker. Results are shown in Fig. 4.
integrated luminosities up to 80 fb$^{-1}$ have provided us at LHC. The analysis of the 13 TeV Run 2 data with represent a major part of the ATLAS physics program.

The topology and kinematics and background processes and improvements in their theoretical description and experimental bounds will benefit the sensitivity to new phenomena. QCD processes play an important role both in improving control of SM backgrounds to new physics searches. Despite the negative results of the searches performed so far, significant room for direct and direct searches. Non-perturbative and electroweak corrections are applied. (Right) 95% C.L. lower limits on the gluino mass in the gluino lifetime–mass plane (from [23]). The excluded area is to the left of the curves. The observed limit is shown by the line with the round markers and the expected limit by a solid line.

4. CONCLUSIONS

Searches for signals of new physics beyond the SM represent a major part of the ATLAS physics program at LHC. The analysis of the 13 TeV Run 2 data with integrated luminosities up to 80 fb$^{-1}$ have provided us with significant bounds on new phenomena from indirect and direct searches. Despite the negative results of the searches performed so far, significant room for testing these models further still exists, since the sensitivity to new phenomena will increase further with the full Run 2 and Run 3 data sets and the HL–LHC program. The increase in the available statistics and sensitivity makes important to ensure a constantly improving control of SM backgrounds to new physics searches. QCD processes play an important role both in defining the acceptance of signal processes and in the topology and kinematics and background processes and improvements in their theoretical description and experimental bounds will benefit the sensitivity of future new physics searches at LHC.

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