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New Physics in di-boson resonances and long-lived particles with ATLAS and CMS: Latest Run 1 and early Run 2 results

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Summary. — This paper reports several results from the corresponding presentation given by the author at the IFAE 2016 conference in Genova. Because of the large number of studies reported there and the limited space available for these proceedings, only a small fraction of the results will be cited here. Whenever possible, results obtained by ATLAS and CMS by analysing the Run 2 collisions at $\sqrt{s} = 13\,\text{TeV}$ will be presented, mostly for di-boson searches. For long-lived particles many Run 1 studies will be reported as well, as published throughout 2015.

Introduction

The LHC Run 2 started in fall 2015, after all collaborations exploited the two years long shutdown to maintain and upgrade their detectors. Meanwhile, latest analyses of data collected in Run 1 at $\sqrt{s} = 8\,\text{TeV}$ (about 20/fb) were completed and published. ATLAS and CMS collected about 3/fb at 13 TeV until December 2015, waiting to collect more data after the technical stop (May-June 2016).

Among searches for New Physics, those looking for excesses in the invariant mass spectrum of di-boson events are particularly important: many models foresee resonant production of high-mass bosons and 3-sigma significant excesses at about 2 TeV mass were found at the end of Run 1 [1, 2]. On the other hand, exotic physics is well expected to possibly reveal itself through exotic signatures: unusually highly ionising tracks, out-of-bunch activity in the calorimeter, disappearing tracks and displaced vertices were all intensely searched for in the Run 1 dataset.

1. – Search for di-boson resonant production

As already mentioned, a number of models predict the existence of new heavy bosons X decaying to a boson pair, be it WW, WZ or ZZ(1). Perhaps the most used benchmarks by the end of 2015 were the Two Higgs Doublet Model (2HDM) for scalar bosons [3],

(1) Decays to scalar pairs are not considered in this work.

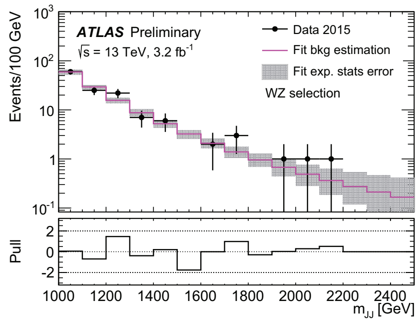

Fig. 1. – The observed invariant mass spectrum of the JJ system. Selection optimised for the WZ channel. The fitted background is also shown, along with its uncertainty.

the Heavy Vector Triplet (HVT) model foreseeing heavy vector bosons [4] and Randall-Sundrum-like models (RS) predicting spin-2 gravitons [5].

In general, searches for di-boson excesses are tuned on the products of the bosons' decays and on their kinematics: at hadron colliders signal branching fractions increase with the amount of hadronic content in the final state, as it does the background: for instance, $BR(ZZ \to 4q) \simeq 100\ BR(ZZ \to 4\ell)$, but pre-selection main backgrounds b are such that $b_{4l} \simeq 10^{-4}\, b_{4q}$. Well optimised analysis strategies may implement efficient selections, further reducing the background and maintaining good acceptance for the expected signals.

Run 1 - driven searches at high mass. – The ATLAS collaboration looked for confirmation of the weak broad excess found in Run 1 at about 2 TeV in the $2\ell 2q$ and $4q$ final states [6, 7]. Quarks are very collimated, so that q-pairs are better reconstructed as a single merged $\Delta R = 1.0$ jet (J) than two resolved 0.4 jets (jj). Figure 1 represents the invariant mass spectrum of the JJ system, together with pulls from data/background comparison. No significant excess is observed and upper limits could be derived on cross section times branching fraction for most models. As shown in fig. 2, by studying pp

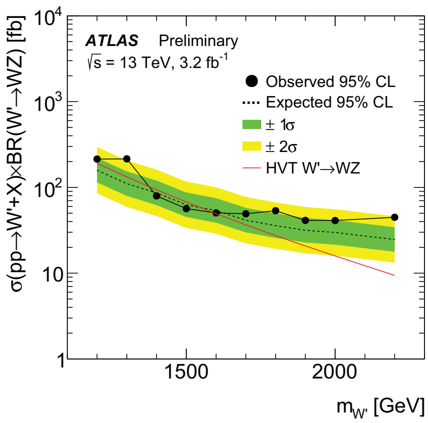

Fig. 2. – Upper limit (95% confidence level) on cross section times branching fraction for the process $W' \to WZ$ in the HVT model.

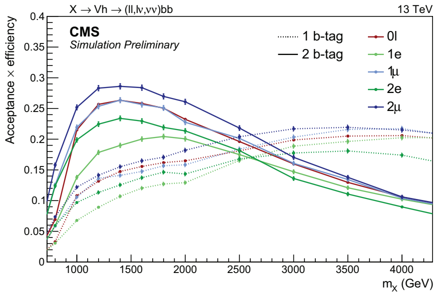

Fig. 3. – Signal efficiencies for different final states (color code) and b-tagging multiplicity (dashed/solid line).

interactions at $\sqrt{s} = 13\,\text{TeV}$ the mass interval $M_{W'} \simeq (1.4\text{–}1.6)\,\text{TeV}$ is excluded at 95% confidence level. Similar results were obtained by CMS in the $\ell\nu qq$ and $4q$ channels [8]: no evidence of significant excesses was found. Remarkably, these results were obtained by CMS by categorising the W/Z-induced jets according to their "subjettiness": high- and low-purity samples both contributed to the final upper limits.

Other searches at high mass. – Other channels were studied by ATLAS in view of future combination of results, namely $\ell\nu 2q$ and $2\nu 2q$ [9,10]: in spite of the low statistics, the existence of a resonant W' was excluded for masses up to $m_{W'} = 1.5\,\text{TeV}$ and $m_{W'} = 1.7\,\text{TeV}$, respectively (HVT model). Within the spin-2 interpretation of results, both the analyses report a $+2\sigma$ deviation from expectation in the 1.3–1.6 TeV mass range. The importance of exploiting b-tagging whenever possible was well shown by the CMS collaboration: acceptance $\times$ efficiency of 2-tag events is twice as large than of 0/1-tag ones, up to masses of 1.5 TeV [11]. Figure 3 clearly shows gain up to 2.5 TeV.

Searches at low mass. – ATLAS and CMS performed searches for di-boson excesses also in the sub-TeV mass region, where the V-jets are resolved; in this regime final states with two leptons are the most sensitive: assuming maximum coupling, the $2\ell 2q$ analysis from ATLAS excluded gravitons as heavy as 0.8 TeV or less [12] and the $2\ell 2\nu$ results from ATLAS and CMS attributed masses higher than 1 TeV to heavy Higgs bosons in the 2HDM model: see for instance fig. 4, taken from [13].

2. – Search for exotic long-lived particles

Unknown particles, often named "exotic", could be long-lived enough to leave detectable signatures in the ATLAS and CMS detectors. Models like split-Supersymmetry (split-SUSY) [14], Anomaly-mediated Supersymmetry Breaking (AMSB) [15] or generic Hidden Valley scenarios [16] are quite predictive on this side. Because of the rarity of these events, high statistics is needed to significantly compare data with predictions, as well as to suitably tune data-driven background estimates. Most results presented here are about Run 1 data.

Highly ionising particles. – Silicon trackers in magnetic field allow for particle identification because of the combined measurement of the momentum p and the energy loss $\mathrm{d}E/\mathrm{d}x$. The large amount of tracks collected already with few fb^{-1} of integrated luminosity makes it possible to look for anomalies in the $\mathrm{d}E/\mathrm{d}x$-p plane. Figure 5 shows

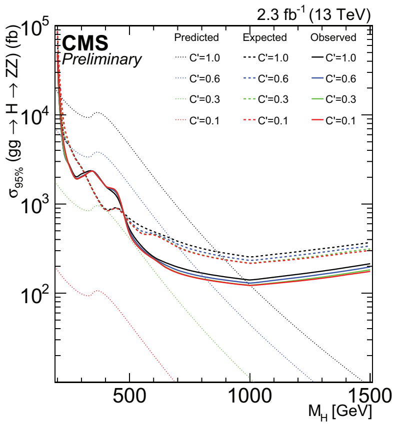

Fig. 4. – Upper limits at 95% CL set on the gluon-fusion production cross section of a heavy scalar H as function of its mass. It is assumed that the branching fraction of H to non-SM decay modes is 0. Various values of the mixing parameter C' are considered.

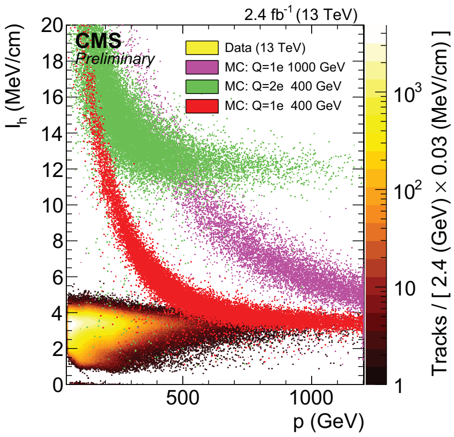

Fig. 5. – Distribution of the dE/dx estimator, I_h, *vs.* particle momentum for 13 TeV data, and for singly or multiply charged heavy stable charged particle simulation.

the signature expected for some mass-charge combination, whereas fig. 6 provides an interpretation of null findings within SUSY scenarios (from [17]).

This signature is so clean to be capable to provide results even with the poor statistics of Run 2. For instance, in the Split-SUSY model, the gluino $\tilde{g}$ is the only supersymmetric particle possibly produced at the LHC, *i.e.* with mass lower than 1 TeV and strongly coupled to the Standard Model (SM) sector(^{2}). It would be contained in bound states called R-hadrons, then decaying to a neutralino and a quark pair $\tilde{\chi}_0 q\bar{q}$. The null observation in 3.2/fb already allowed to exclude a portion of the phase space in the τ-$m_{\tilde{g}}$ plane, as visible in fig. 7, taken from [17].

(^{2}) The lightest squark is predicted to have mass of 10^3–10^5 TeV.

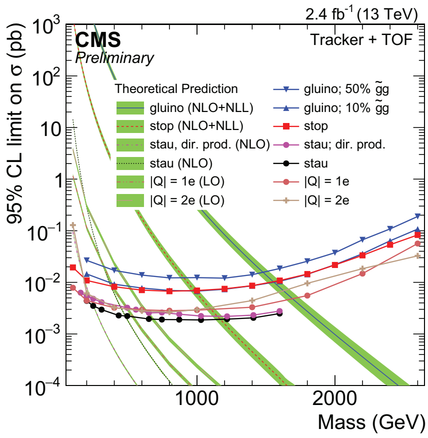

Fig. 6. – Cross section upper limits at 95% CL on various signal models for the tracker + TOF CMS analysis.

Stopped R-hadrons. – In case the R-hadron is made of gluino, top squark, or bottom squark that come to rest within the detector, and decay later to hadronic jets and a neutralino, one may expect to have events in selected empty bunch crossings of the LHC: this approach completely removes pp collision backgrounds [19, 20]. The sensitivity is typically flat in the interval $\tau = 10^{-6}$–10^{8} seconds, *i.e.* from the minimum acceptable separation between bunches (one tenth of the protons' circulation time in the LHC) to the uptime of experiments (a few years). The lower limits obtained on the masses are visible for instance in fig. 8.

Disappearance of tracks. – Several models, like the AMSB, foresee small mass difference between the chargino and the neutralino. The chargino may be long-lived enough to pass through the inner detectors before decaying to a neutralino plus a charged pion: $\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}_0\, \pi^{\pm}$. The low momentum transferred to the pion would produce little or no

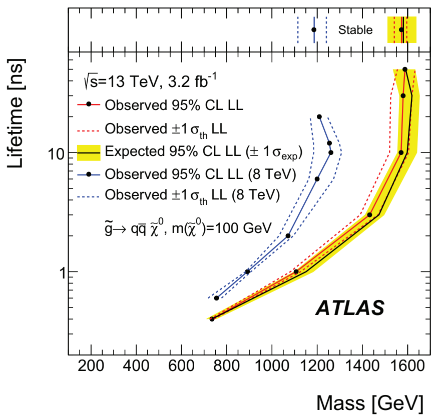

Fig. 7. – Excluded range of lifetimes as a function of gluino R-hadron mass. The expected lower limit is given with respect to the nominal theoretical cross section. The limit observed at $\sqrt{8}$ TeV is also shown for comparison.

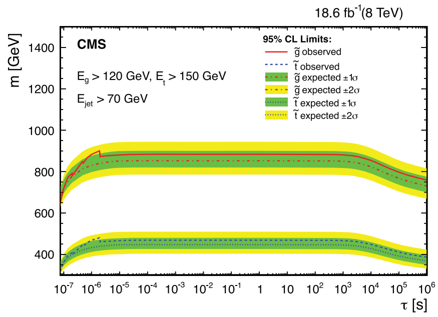

Fig. 8. – Lower limits at 95% CL on gluino and top squark mass as a function of particle lifetime. See [20] for more details.

signal and the resulting signature would be the chargino inner detector track without matching signal in calorimeters and muon chambers. ATLAS and CMS looked for such "disappearing" tracks in Run 1 and excluded a large portion of the τ-$m_{\tilde{\chi}^{\pm}}$ plane. An example is represented in fig. 9, from [21]. Similar results can be found in [22].

Displaced vertices. – Long-lived neutral particles may be the decay products of the mediator of a new interaction, from a Hidden Valley scenario. The mediator is strongly coupled with the SM particles or mixed with the SM mediators. The products themselves possibly decay to SM pions, producing jets from a single displaced vertex. The analysis is sensitive to lifetimes in the range 1 cm/10 m, *i.e.* the orders of minimum and maximum distances of the instrumentation from the interaction point. These analyses usually apply data-driven background estimation techniques, so that high statistics is needed to complete them. Figure 10 is an example of the exclusion power of these searches for the Hidden Valley Z' case. Other models were benchmarked in [23, 24]. The case of purely leptonic decays ("lepton jets") is extensively studied in [25, 26].

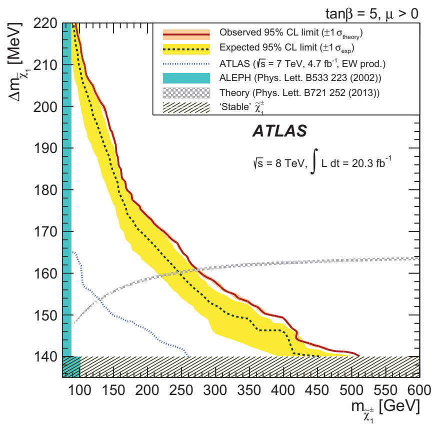

Fig. 9. – The constraint on the $\Delta m_{\tilde{\chi}^{\pm}}$ space of the AMSB model for $\tan\beta = 5$ and $\mu > 0$. The dashed line shows the expected limits at 95% CL. Observed limits are indicated by the solid bold contour representing the nominal limit. The limit observed at $\sqrt{8}$ TeV is also shown for comparison.

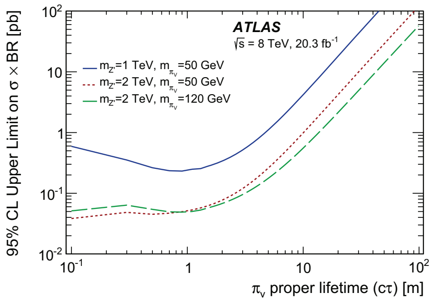

Fig. 10. – Observed 95% CL limits on $\sigma \times BR$ for the Z' boson predicted in a Hidden Valley model. Various mass values are reported.

3. – Conclusion

This paper reports results from the ATLAS and the CMS experiments at LHC, which looked for New Physics in pp collisions at $\sqrt{s} = 8$ and 13 TeV. Quests for di-boson resonances not predicted by the Standard Model allowed to exclude the existence of exotic particles with mass up to 2 TeV, depending on the model under consideration. Signatures sensitive to long-lived particles were also used to interpret data within SUSY and Hidden Valley scenarios, narrowing the space of parameters available to coherently build the theory.

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