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Non-resonant searches at the TeV scale

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Extensions of the Standard Model are very well motivated despite the lack of new physics observations thus far. New fundamental symmetries such as supersymmetry or leptoquarks as well as extra dimensions offer elegant solutions to open questions. Such phenomena can lead to striking but often unconventional signatures that can be probed in highly energetic proton-proton collisions from the Large Hadron Collider. Recent results from the ATLAS and CMS experiments exploring a variety of such non-resonant processes using the full Run 2 dataset will be discussed here.

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1. Introduction

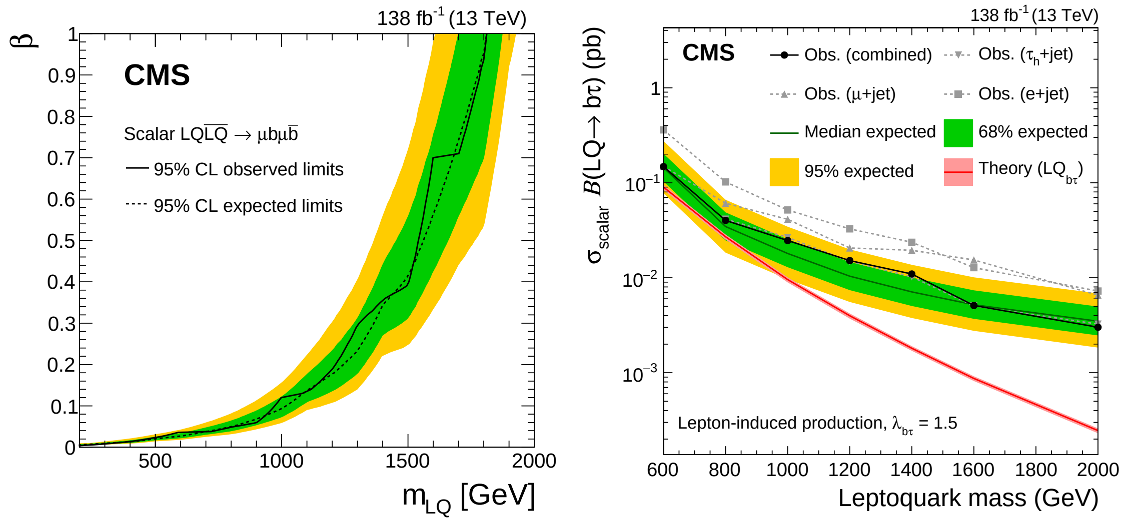
The Standard Model (SM) describes the elementary constitutes of matter and their fundamental (electroweak and strong) interactions mediated through gauge bosons. It has been proven to be correct in experiments performed during the last 50 years, and its predictive power has reached a pinnacle in 2012 with the discovery of the Higgs boson [1, 2]. Yet despite this tremendous success, there are many open questions and problems that the SM fails to explain. For example, the SM does not contain a particle candidate that could constitute dark matter, though the existence of dark matter can be confidently inferred from astrological observations such as the study of rotational velocities of galaxies. Furthermore, the observation of neutrino oscillations necessitates that neutrinos have a non-zero rest mass, yet they are massless in the SM theory. Baryogenesis cannot be sufficiently explained within the SM, in particular there is no answer as to why there is more matter than antimatter in the universe. The fact that the Higgs boson mass of about 125 GeV is much smaller than the fundamental Planck scale calls for new physics, since otherwise an incredible fine tuning to cancel out effects from quantum corrections to the observable Higgs boson mass would be required. Gravity as a fundamental force is also not part of the SM, yet it obviously exists.

Hence, the SM is apparently part of a greater theory, and new physics beyond the SM (BSM) may manifest itself through new phenomena at the TeV scale that can be probed in proton-proton collisions at the LHC operating at 13 TeV center-of-mass energy. Leptoquarks for example are the result of a fundamental symmetry between quarks and leptons, that have many striking yet unexplained similarities. Supersymmetry suggests a new underlying symmetry between fermions and bosons which can stabilize the Higgs boson mass and also predict a dark matter candidate. Extra dimensions appear in models aiming to include gravity into the framework of the SM interactions.

Such hypothesized processes can lead to somewhat unconventional signatures and are complementary to direct searches for narrow resonances and precision measurements of SM observables. With the completion of Run 2, a dataset of about 140 fb^{-1} has been collected by ATLAS and CMS each. Non-resonant searches performed with the full Run 2 dataset will be discussed in the following, focusing on new results that were presented at the LHCP conference in Boston (USA) in June 2024.

2. Leptoquarks

In the SM, there are striking similarities between the quark and lepton families. Both types are fermions with half spin, they interact via the electroweak force, and they come in three generations containing each two particles with increasing mass and with discrete electric charges. These similarities may hint the presence of a deeper symmetry between both types, which is proposed in for example Grant Unified theories, compositeness or technicolor models, and superstring theory. This new symmetry leads to the postulation of leptoquarks (LQs), which are hypothetical new particles that carry both a baryon and a lepton number, have a fractional charge, and they decay to a lepton and a quark with branching fraction expressed as parameter β; this branching fraction is expressed with the parameter β. LQs can be produced resonantly in pairs via gluon-gluon fusion or singly via quark-gluon fusion or τ-lepton+quark collisions, or non-resonantly via t-channel



(a) **(b)**

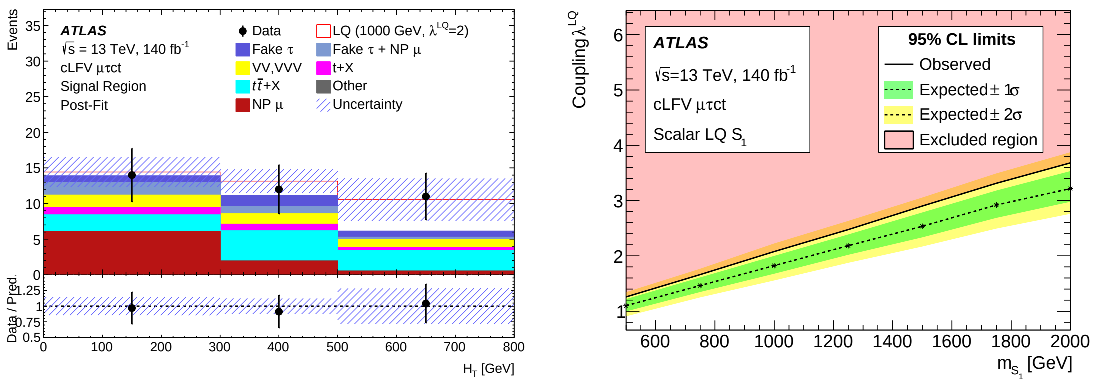
Figure 1: Expected and observed 95% CL limits as a function of the LQ mass on (a) the branching fraction of LQ to μ+b and (b) on the production cross section times branching fraction of LQ to τ-lepton+b. A specific signal model cross section for λ = 1.5 is overlayed in red. The LQs are produced either (a) in pairs or (b) via τ-lepton+quark collisions. Plots taken from Refs. [4] and [5].

exchanges. The production of scalar LQs is governed by a coupling strength parameter λ, for vector LQs there is an additional coupling parameter κ [3].

CMS searched for pair-produced LQs that decay to muons and b-quarks [4]. The event selection retains events with two muons with a large invariant mass of at least 250 GeV, and two jets of which at least one needs to be b-tagged. Boosted decision trees (BDTs) are trained on kinematic variables of the muons and jets, and a cut of the BDT score is optimized separately for each hypothesized LQ mass. The final discriminant is the number of events, i.e. a counting experiment is performed. No excess of data over predicted backgrounds is observed. Upper 95% confidence level (CL) limits on the branching fraction parameter β as a function of the LQ mass are displayed in Fig. 1a.

A novel production mode explored recently is the production of LQs via τ-lepton+quark collisions, made possible due to advancements in the lepton and photon density functions of the proton. This process was explored by CMS in the LQ decay modes to τ-lepton+quark or τ-lepton+b [5]. The τ-lepton can decay hadronically or to an electron or muon, leading to three search channels. BDTs are trained in each channel and in total 7 categories are defined by cutting on the output score of the BDT. The final discriminant is the collinear mass calculated from the visible τ-lepton decay product and the jet, which broadly peaks in the vicinity of the hypothesized LQ mass. No significant deviation from the background is observed in the data. Upper limits on the production cross section times branching fraction at 95% CL are displayed in Fig. 1b for the LQ decay to τ-lepton+b as a function of the hypothesized LQ mass. A model cross section assuming a coupling value of 1.5 is overlayed in red, but the current sensitivity is not sufficient to exclude this specific model.

LQs can also appear in models with charged lepton flavor violation (cLFV). Such processes are



(a) **(b)**

Figure 2: (a) The postfit H_T distribution for a specific LQ signal assumption indicated in the plot. A small excess of data over background is seen for high values of H_T. The ratio panel shows the data over the signal+background prediction. (b) Expected and observed 95% CL limits on the coupling strength λ as a function of the LQ mass. Plots taken from Ref. [6].

extremely rare in the SM with rates well below the experimental sensitivity, but could be enhanced in BSM models. The Scalar LQ Model S1 introduces new, multi-generational couplings between all up-type quarks and all charged leptons, where the largest coupling occurs between the top and the τ-lepton. ATLAS therefore conducts this cLFV search where the LQs decay to τ-lepton and a t-quark [6]. The t decays leptonically leading to a muon. The production mode considered here is quark-gluon fusion, making the LQ and another muon. The signal region therefore contains two same-sign muon, a hadronic τ-lepton, and at least one jet among exactly one is b-tagged. Mass reconstruction is not possible, therefore the final discriminant is H_T, the scalar sum of the lepton and the jet p_T, and a potential signal would accumulate at high values of H_T. A small excess is observed that was quantified to have a local significance of 1.6σ, displayed in Fig. 2a for the assumption of a LQ mass of 1 TeV and a coupling $\lambda = 2$. The excess is almost independent of the LQ mass and as such appears for all hypothesized values. The 95% CL limits on the coupling strength parameter λ are displayed in Fig. 2b. Coupling values larger than 1.3 to 3.7 are excluded for LQ masses between 0.5 and 2.0 TeV, where the strongest limits are obtained for low values of the LQ mass.

3. Supersymmetry

Supersymmetry (SUSY) [7] is one of the most widely recognized BSM theories, postulating a fundamental symmetry between fermions (with half-spin) and bosons (with integer-spin). Consequently, for every SM particle a SUSY partner particle with the other spin exists [1]. The lack of any experimental evidence for these SUSY partners so far implies that the SUSY mass scale is much higher than the electroweak (EW) scale, presumably in the TeV range. SUSY is popular since it can stabilize the Higgs mass (i.e. sfermion loops cancel divergent corrections terms), can preserve

[1]The SUSY partners to fermions are called sfermions (e.g. the selectron). The partners of the gauge bosons are called gauginos (gluino, wino, bino). They mix with the Higgs field partners (Higgsinos) and lead to mass eigenstates called charginos $\tilde{\chi}^{\pm}$ and neutralinos $\tilde{\chi}^{0}$.

baryon asymmetry, and the gauge couplings can unify at a high energy scale. The lightest SUSY particle (LSP) is stable in case the R-parity [2] is conserved. In this case, the LSP is a suitable dark matter candidate.

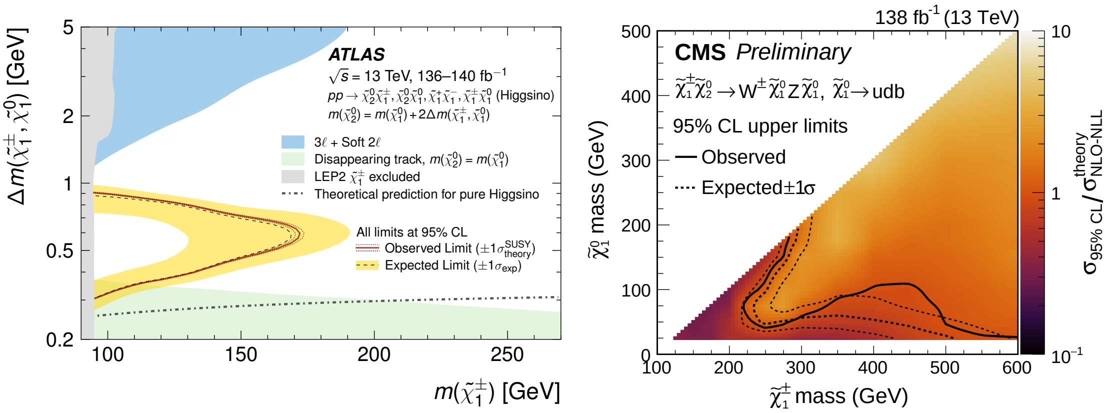
While many SUSY search results already exist, there are some less covered regions in the parameter space. One such region is when the SUSY particle spectrum is very compressed (i.e. mass differences between SUSY particles are small). ATLAS has conducted a search for compressed Higgsinos with the full Run 2 dataset [8]. The masses of the Higgsinos, that are the SUSY partners to the Higgs boson and therefore connected to the EW scale, are favored to be of O (100 GeV) even when the SUSY mass scale is much higher. In this search, the Higgsino mass eigenstates have a very small mass splitting of $\Delta m \left(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0\right) = 0.3 - 1.0$ GeV, leading to a sizable lifetime of the $\tilde{\chi}_1^{\pm}$ and a flight length of $O\,(0.1 - 1.0$ mm$)$. The strongest bounds on this phase space, up to now, came from LEP. The $\tilde{\chi}_1^{\pm}$ decays to the LSP and a charged pion with a mildly-displaced track. Events are retained with a high p_{T} jet, a large missing $E_{\mathrm{T}} > 600$ GeV and a soft track with p_{T} of $2-5$ GeV that is aligned with the missing E_{T} direction. The final discriminant is the transverse impact parameter significance, $S\,(d_0)$. A signal would accumulate at large values of $S\,(d_0)$. No excess of data over the predicted background is found, and limits are set on the mass splitting parameter Δm as a function of the chargino mass, displayed in Fig. 3a.

CMS has released a novel SUSY search that features a mass-degenerate chargino-neutralino pair that is produced through the EW process and leads to a cascade decay [9]. In the first step the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ each decay to a $\tilde{\chi}_1^0$ (which is the LSP) and a leptonically-decaying vector boson (Z, W). Then, the LSPs decay via R-parity violation into hadrons, either uds quarks or udb quarks. The final state consists of three leptons and up to 6 jets. To avoid dealing with combinatorics, the final state is not reconstructed, instead an *effective mass* variable S_{T} is calculated from the scalar p_{T} sum of charged leptons, jets and missing p_{T}. The hypothesized signal would be visible in a broad peak in S_{T}, but no significant excess of data over background is observed. Upper limits are placed on the LSP mass as a function of the chargino mass, displayed in Fig. 3b.

ATLAS has released a statistical combination of various Run 2 searches for charginos and neutralinos [10]. These searches assume pure-wino chargino pair production, pure-wino chargino-neutralino production, or Higgsino production decaying via W, Z, or Higgs bosons. The combination extends the sensitivity to SUSY production by up to 100 GeV in (N)LSP [3] masses, and the sensitivity to SUSY production cross-sections is increased by up to 40% compared to the individual searches. CMS also published a combination of EW produced SUSY with Run 2 data [11]. Improved analysis techniques such as optimized binning are employed to enhance the sensitivity in particular for compressed spectra. The results are interpreted in terms of simplified SUSY models (Wino-Bino, Gauge-mediated SUSY breaking, Higgsino-Bino, and slepton-neutralino). Limits on mass-degenerate chargino-neutralino production are displayed in Fig. 4, for ATLAS in the pure-Wino model and the WH topology, and for CMS for the Wino-Bino model with WZ decays. The combined limits of each experiment reach up to a Higgsino mass of about 1 TeV for LSP masses of less than 200 GeV. The expected limits from the CMS combination extend up to 1150 GeV but

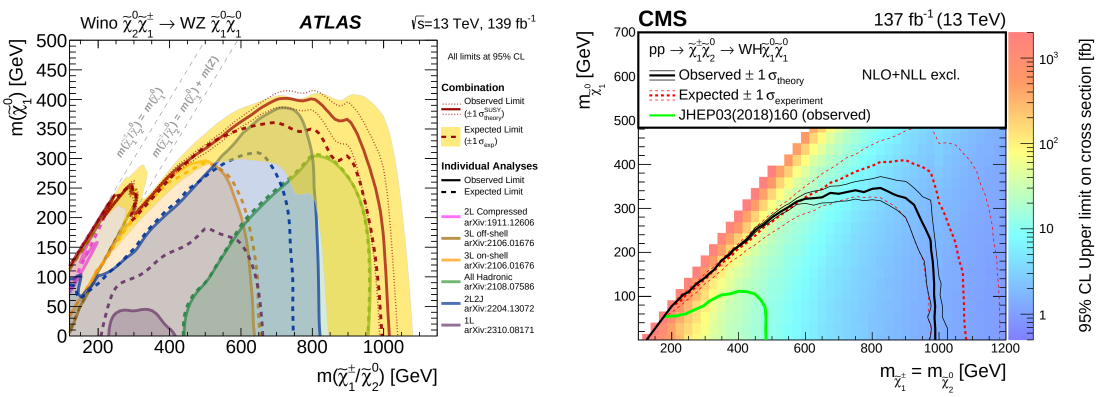
[2] The R-parity of a particle is defined as $R = (-1)^{3(B-L)+2s}$, where B is the Baryon number, L is the lepton number, and s the spin of the particle.

[3] The NLSP is the next-to-lightest SUSY particle.



(a) (b)

Figure 3: (a) Expected (back dashed) and observed (red solid) 95% CL exclusion limits from ATLAS on the mass difference for very compressed Higgsinos as a function of the chargino mass. The limit by the LEP experiments is shown in gray, and other ATLAS results are overlayed in green and blue areas. (b) Expected (back dashed) and observed (black solid) 95% CL exclusion limits from CMS on the LSP mass as a function of the chargino mass for hadronic R-parity violating SUSY decays. Plots taken from Ref. [8] and [9].



(a) (b)

Figure 4: (a) Combined expected (dashed) and observed (solid) 95% CL exclusion limits from ATLAS on chargino–neutralino production decaying via W and Z bosons. Limits obtained by individual searches are overlaid. (b) Combined upper 95% CL cross section limits from CMS with expected and observed exclusion boundaries in the model parameter space for the WH topology assuming the Wino-Bino model. Plots taken from Ref. [8] and [9].

are weakened by a slight excess of data in the SUSY search featuring hadronic WW, WZ or WH decays [12].

4. Extra dimensions

Extra dimensions are well motivated, for example by the desire to unify all fundamental forces within one theory, and to solve cosmological problems such as the origin of dark matter and dark energy. Extra dimensions may be large, suggested by Arkani-Hamed, Dimopolous and Davli (ADD) [13], or they may be warped, as proposed by Randall and Sundrum (RS) [14]. In both concepts, gravity is weak compared to the other forces because it has its origin in the higher dimensions, where it has a much higher coupling strength, and it then *leaks* into the four-dimensional spacetime at a much reduced scale. Gravitons, as mediators of gravity, are predicted in these models and may be produced at the LHC.

The clockwork framework [15] was proposed to solve various hierarchy problems, such as the Higgs boson mass or the faint scale of gravity, by formalizing how small couplings and a number of fields can generate much larger hierarchies. In the *clockwork gravity model* with extra dimensions, massive gravitons can appear as Kaluza-Klein (KK) towers that are narrowly-spaced in mass, and thus appearing like a periodic signal in the reconstructed mass spectrum. This signal model is described by a parameter k, the mass value of the onset of the KK spectrum, and the five-dimensional reduced Planck mass M_5. If the mass resolution is worse than the wavelength, or in the continuum limit of the model, the periodic signal is not resolvable and appears as a single broad excess instead. ATLAS conducted a search for clockwork signals in the invariant mass spectra of di-photon and di-electron final states with the Run 2 dataset [16]. A continuous wavelet transform (CWT) is employed to transform the mass spectra into images (also called scalograms) of mass vs. a parameter α that dilates or compresses the periodic signal and is inversely proportional to the frequency. Convolutional neural networks or autoencoders are used to search for anomalies in the scalogram. These results are then translated into upper limits on the onset parameter k as a function of M_5. The observed di-electron scalogram and the upper limits are displayed in Fig. 5.

CMS performed a search for broad signals motivated by the ADD model or the continuum limit in the clockwork gravity model, using di-photon events of the Run 2 dataset [17]. In both models, a signal would appear as a broad, non-resonant excess in the di-photon invariant mass spectrum. Events are categorized into those where both photons are found in the barrel, and those where one photon is found in the barrel and the other one in the endcap. The background model is a hybrid of a Monte Carlo-based prediction assisted by a data-driven estimate of events where jets are misidentified as photons. No excess of data over the expected background is observed. The observed di-photon mass for the category with both photons in the barrel and the 95% CL limits in the $k - M_5$ plane are displayed in Fig. 6.

Quantum black holes (QBHs) appear in extra dimensional models with a low scale of quantum gravity (also called threshold mass), typically of $O(1-10)$ TeV. They are produced in 2-to-2 scattering such as quark-quark reactions. They decay with a large branching fraction to two particle final states such as two leptons with different flavor or a lepton and a quark. These decays appear since global symmetries such as the baryon or lepton number may not be conserved in strong-gravity interactions at extremely small distances. ATLAS has performed a search for QBHs in two channels, electron+jet or muon+jet channels, that are then statistically combined, with the full Run 2 dataset [18]. The invariant mass of both final state objects is the final discriminant, and a QBH signal would accumulate at very large mass values. Upper limits on the production cross section times the branching ratio are displayed in Fig. 7a. ATLAS excludes QBH with threshold masses of up to 6.8 TeV in the RS model with one extra dimension. CMS has searched for QBHs separately in the channels of electron+muon, electron+τ-lepton, or muon+τ-lepton [19]. The highest sensitivity is achieved with the electron+muon channel, for which QBHs with threshold masses of up to 5.6

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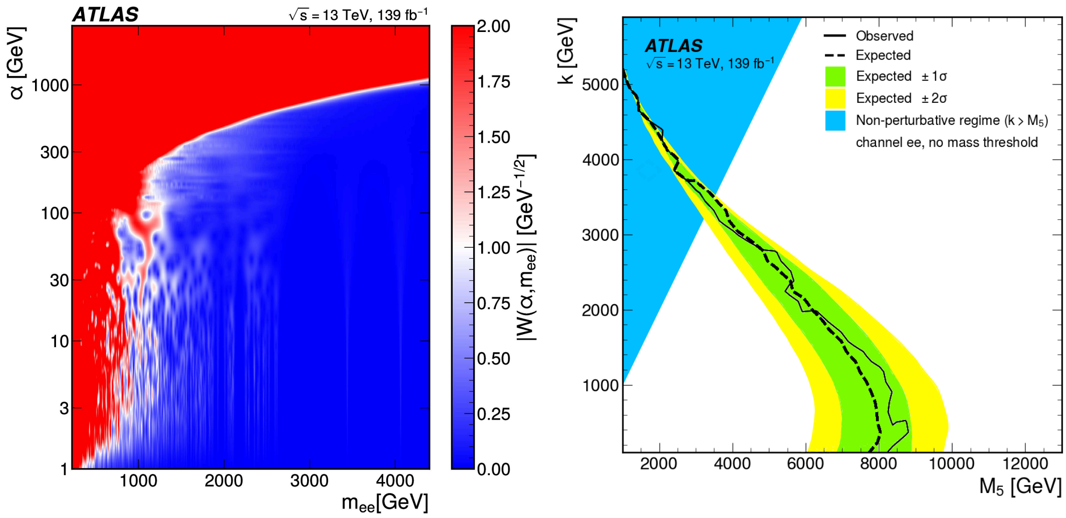


(a) (b)

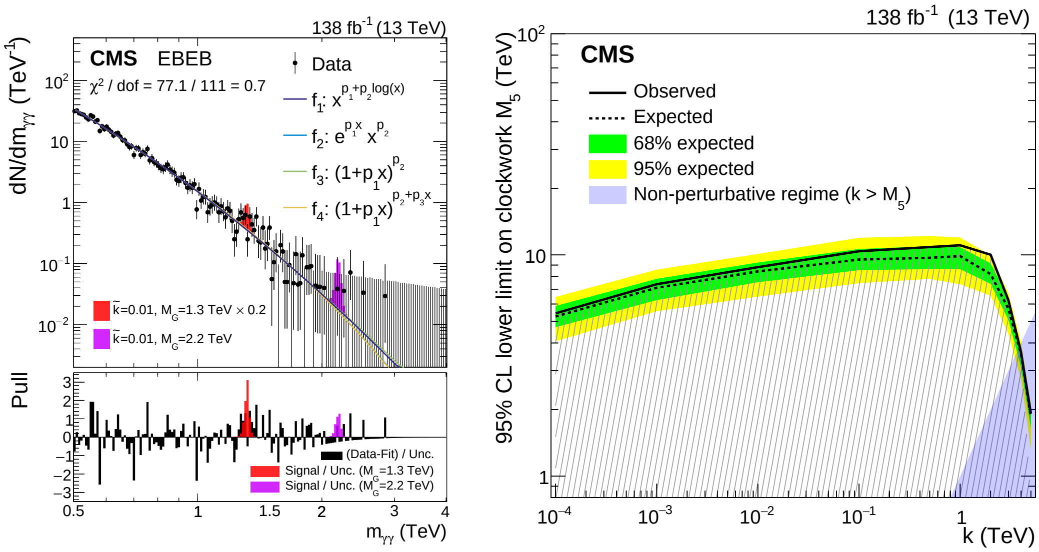
Figure 5: (a) The scalogram output of the CWT for the di-electron channel for the observed signal region data. Red colors indicate a better agreement of the data with the tested parameters. A signal would appear as a red *island* in the blue area. The sharp transition between red and blue areas are an expected feature of the CWT. (b) The expected and observed exclusion limits at 95% CL for the clockwork gravity model projected in the $k - M_5$ parameter space for the di-electron channel. Plots taken from Ref. [16].

TeV are excluded in ADD models with 4 dimensions. The upper limits on the QBH production cross section times branching fraction are displayed in Fig. 7b. Both experiments report no significant excess.

5. Conclusions

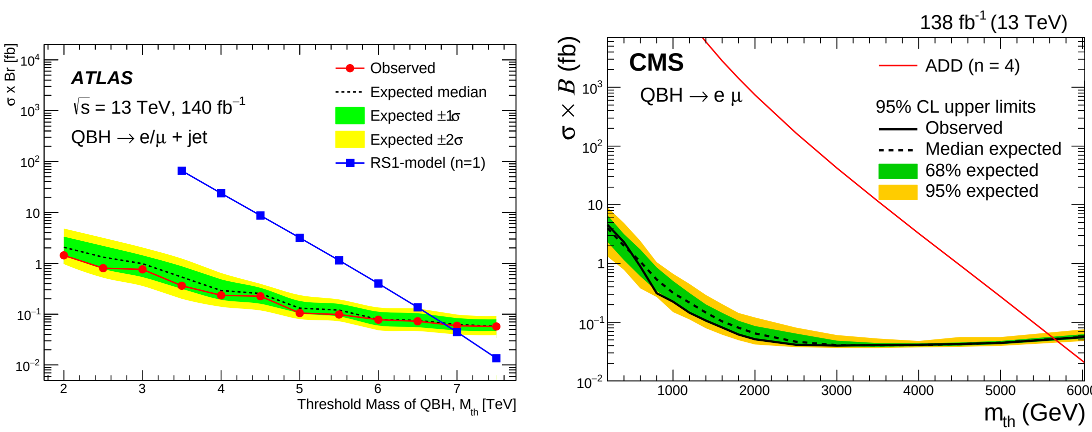
The Run 2 dataset presents an extraordinary opportunity to search for signs of new physics at the TeV scale. Non-resonant searches often feature unconventional signatures, such as periodic signals, broad excesses in mass or enhancements at high p_T, and those searches complement those for narrow resonances or precision measurements of SM observables. A small subset of these non-resonant searches from ATLAS and CMS has been discussed here. No significant excess is found, but stringent limits are placed on parameters in a variety of models that introduce new fundamental symmetries or extra dimensions that lead to the prediction of new particles.

The Run 3 data taking is ongoing and a strong search program from both ATLAS and CMS is well in progress. Improvements of the sensitivities are expected not only from the increased dataset, but also from refined analysis techniques and advances for object reconstruction and identification algorithms. The larger center-of-mass energy of 13.6 TeV in Run 3 increases the production cross section for TeV processes, which will boost the sensitivities to, for example, strong SUSY searches or heavy objects such as QBHs (for example, the cross section for a 9 TeV QBH will double in Run 3).



(a) **(b)**

Figure 6: (a) Observed diphoton invariant mass when both photons are reconstructed in the barrel. Also shown are the results of a likelihood fit to the background-only hypothesis using four different fit functions. The lower panel displays the difference between the data and the fit using function f1, divided by the statistical uncertainty in the data points. (b) The 95% CL exclusion limit for the clockwork framework over the $k - M_5$ parameter space. The region below the solid line is excluded. Plots taken from Ref. [17].



(a) **(b)**

Figure 7: (a) The combined 95% CL upper limits from ATLAS on the production times decay as a function of the threshold mass for QBH production with decay into lepton+jet for the RS1 model (RS with one extra dimension). Circles along the solid red line indicate the threshold mass of the signal where the observed limit is computed. (b) CMS 95% CL upper limits on the product of the cross section and the branching fraction for QBH production in an ADD model with 4 extra dimensions, in the electron+muon channel, as a function of the threshold mass. Plots taken from Ref. [18] and [19].

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