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# Searches for exotic phenomena beyond the standard model

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The 7 and 8 TeV center-of-mass energy LHC run, even though unsuccessful in finding physics beyond standard model (BSM), covered a large range of possible BSM signatures and a vast area of parameter space of many BSM models. These results, together with acquired experience and novel techniques developed in these searches form a solid base for exploring the accumulating 13 TeV data. The Run 1 legacy of non-supersymmetric BSM searches is reviewed with emphasis on most recent results and techniques.

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## 1. Introduction

The discovery of the Higgs boson brought us not only the anticipated answers about the origin of particle masses but also raised the anticipated questions related to its small mass and to the hierarchy problem. These questions, together with other open issues unsolved by the standard model (SM), strengthen the case for physics beyond the standard model (BSM). While supersymmetry remains the most popular among the extensions of the SM, many other extensions propose plausible solutions. These BSM models provide useful guidance and benchmarks for the experiments. However, the main focus of experimental searches remains on experimental signatures. The purpose of this document is to provide a selected[1] overview of where we stand in the searches for exotic phenomena after the Run 1 of LHC and what can we expect in early stages of the Run 2. It is organized by main groups of BSM experimental signatures.

## 2. Diobject searches

Many extensions of the SM predict new resonances decaying into two SM particles. These clean and simple signatures have high mass reach and hence are on top of the agenda of ATLAS [1] and CMS [2] experiments for early searches after the next energy step of the LHC. Since many new resonances would couple to quarks and gluons, the dijet signature is the most generic one. The search is performed as a classical bump hunt in a fully data-driven way, fitting a well studied function to the SM dijet invariant mass spectrum. The sensitivity depends on the width of the resonance (Fig. 1 left) with discovery potential up to widths of $20-30\%$ of the mass. Depending on the model, the Run 1 limits vary roughly between $2-5$ TeV (Fig. 1 right) [3, 4].

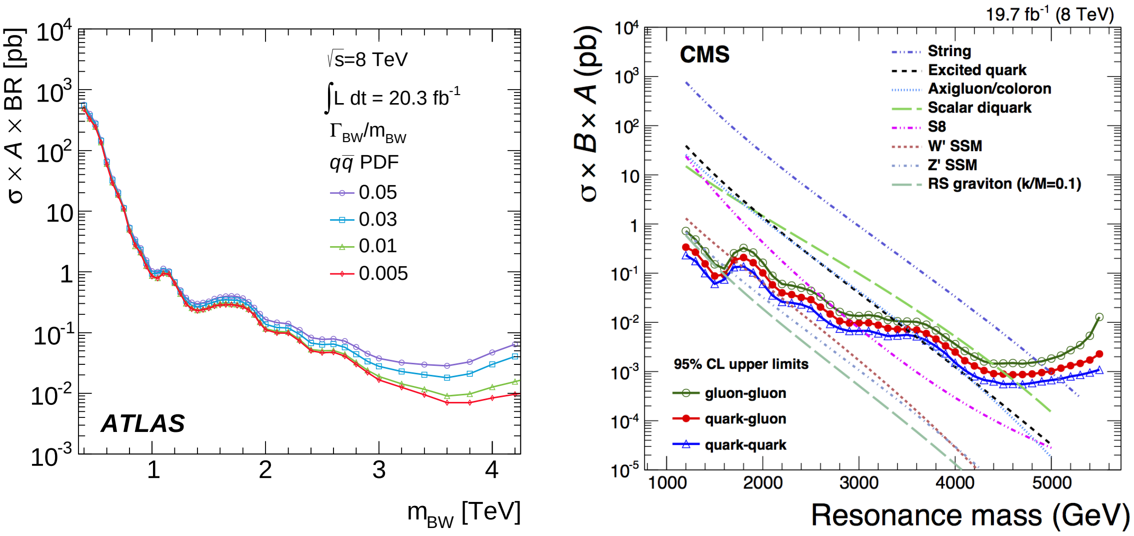

**Figure 1:** Dijet 95% CL exclusion limits for $q\bar{q}$ production mode from ATLAS as a function of resonance width (left) [3] and limits from CMS as a function of production mode for narrow (width less then 1.5%) resonances (right) [4].

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[1] detailed complementary talks on various subjects can be found in parallel section of these proceedings

Despite the lower branching ratio, due to low background and good mass resolution, among the most sensitive channels for new spin-1 and spin-2 resonances are various dilepton signatures. Run 1 limits for Z’ and Randall-Sundrum (RS) graviton, obtained combining the *ee* and $\mu\mu$ channels, reach $2.5-3$ TeV (Fig. 2 left) [5, 6]. The SM backgrounds, dominated by Drell-Yan process, are well understood to higher order loops and their invariant mass shape can be reliably described by simulations (Fig. 2 right). Good knowledge of the backgrounds allows also searches for non-resonant signatures like those predicted by Arkani-Hamed-Dimopoulos-Dvali (ADD) model of large extra dimensions or contact interactions [6, 7]. The W’ resonances were excluded up to masses around 3 TeV using lepton plus missing transverse energy signatures [8, 9].

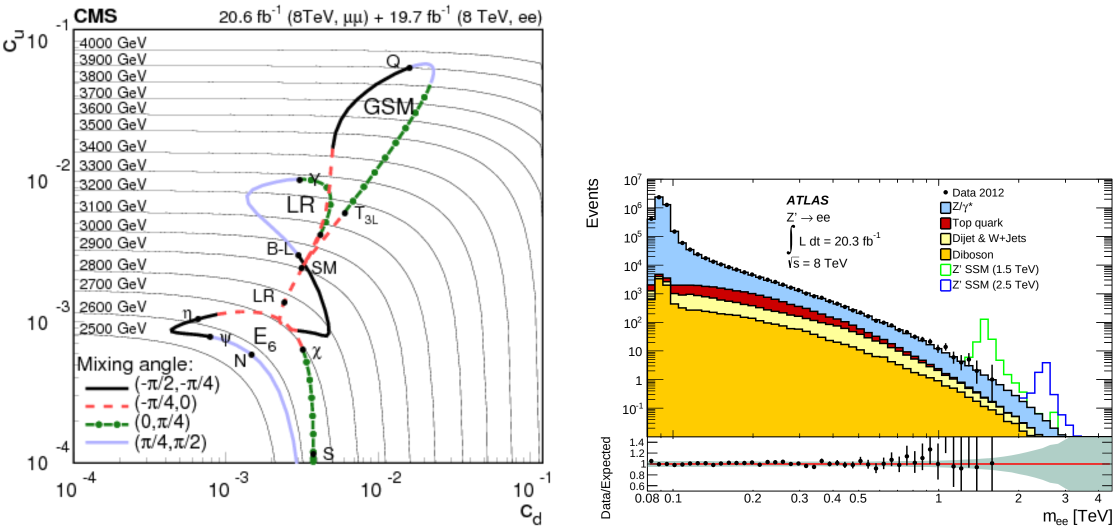

**Figure 2:** Dilepton limits for Z’ resonance represented as a function of couplings to quarks and extended gauge group mixing angle from CMS. Crossing of the mass contours and parameter orbits defines the mass limit for the given model (left) [6]. A comparison of the *ee* invariant mass spectrum in data and simulations from ATLAS (right) [5].

Another clean topology to look for spin-2, but also for spin-0, resonances is the diphoton signature. The SM diphoton invariant mass spectrum shape is well known (Fig. 3 left), awing to some extent also to the Higgs searches, and the main challenge is the photon reconstruction and identification at high energies. The sensitivity to Randall-Sundrum (RS) graviton is very similar to dilepton channel and varies, depending on the coupling parameter, between $1-2.7$ TeV (Fig. 3 right) [10, 11].

Signatures with dibosons (boson here means W, Z or H), although more complicated than those mentioned above, provide an important complementary handle in searches for high mass spin-1 and spin-2 resonances. At resonance masses above 1 TeV, the topology of boson decays becomes boosted to such extent that common techniques are unsuitable to reconstruct the overlapping decay products. While the lepton isolation requires a special attention in case of boosted leptonic decays, the main challenge is the reconstruction of hadronic decays of such boosted bosons. For this purpose a variety of grooming techniques has been developed to clean the jet cone off the low energy components like soft radiation, pile up or noise. The jet substructure is then used to reconstruct observables suitable for boson tagging, notably the jet mass. The main difficulty remains the

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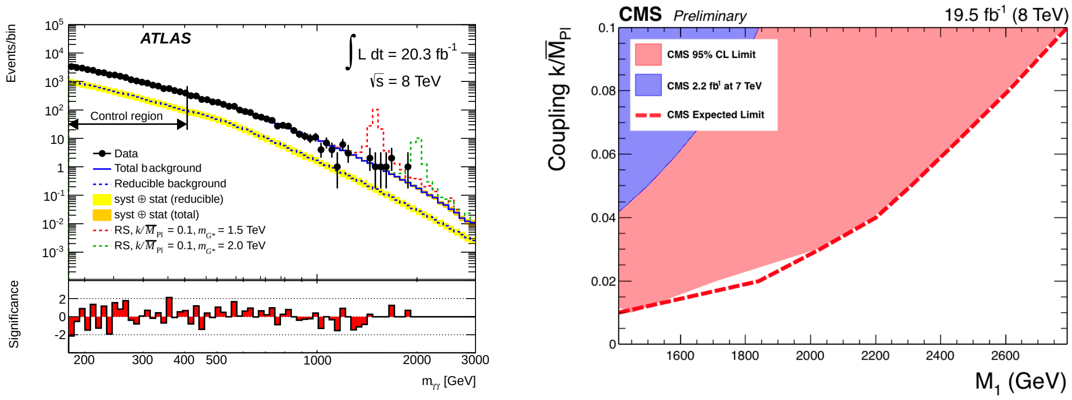

**Figure 3:** Observed diphoton invariant mass spectrum compared to background prediction by ATLAS (left) [10]. The 95% CL RS graviton limit in mass-coupling plane by CMS diphoton search (right) [11].

ambiguity between the hadronic W and Z boson decays due to their similar masses. In this respect, complementary information can be extracted by studying the whole range of final states from fully hadronic, through semi-leptonic to fully leptonic ones. Channels with Higgs bosons, making use of sub-jet b- or $\tau$-tagging, are also becoming part of the suite. Current limits for high mass resonances vary between $1.5-2$ TeV depending on the final state and model (Fig. 4) [12, 13]. Moderate excesses, with global significance of $1.5-2.5$ standard deviations, around invariant masses of $1.8-2$ TeV have been observed in some channels both by ATLAS and CMS causing substantial excitement in the community. Data collected in the 2015 run of LHC could be sufficient to provide an additional insight.

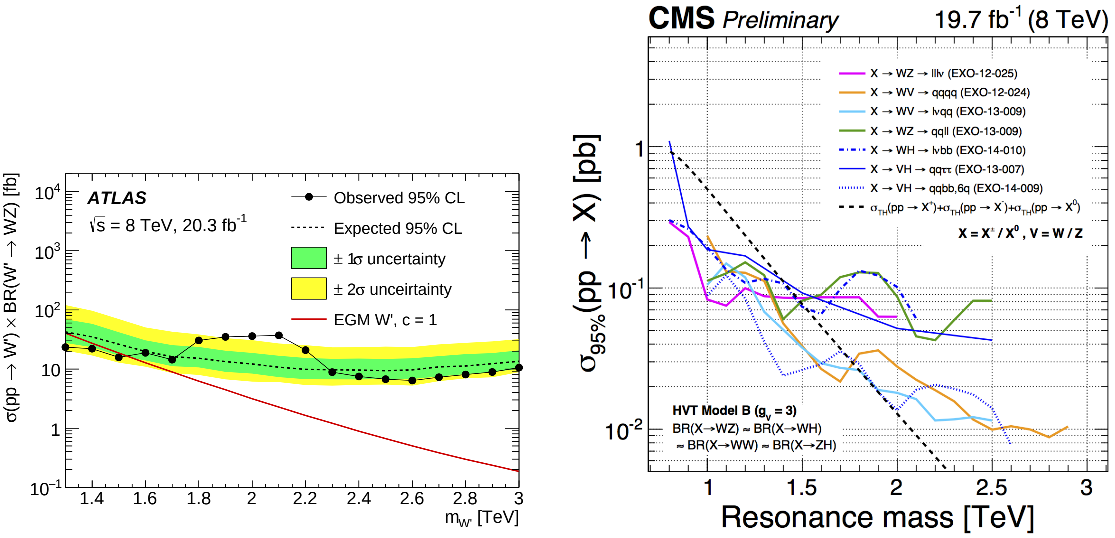

**Figure 4:** An example of the upper 95% CL limit on the cross section times BR from the ATLAS all-hadronic diboson search (here with WZ window selection) (left) [12] and a summary of CMS diboson search limits (right) [13].

Certain models predict resonances, like leptophobic Z', RS gluon or pseudoscalar Higgs boson

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with enhanced couplings to top quarks. The ditop searches have to deal with even more complex boosted topologies. Nevertheless, the quality of boosted top-tagging techniques allowed to exclude already in Run 1 the searched types of resonances with masses up to $2.5-3$ TeV [14, 15]. The field of boosted topologies continues to develop. As the exclusion mass scales continue to grow, these techniques are becoming an integral part in many search areas, some mentioned also in next sections, and will further gain importance in Run 2 of the LHC.

## 3. Searches with "mono"-object and missing energy

The monojet [16, 17] and monophoton [18, 19] signatures, besides having potential to probe large extra dimension models, supersymmetric models with compressed spectra and unparticles are considered the key channels for collider Dark Matter (DM) search. DM particles produced in particle collisions would remain invisible to the detectors. Such events can be triggered and reconstructed by making use of the initial state radiation recoiling against the DM particles which generate a large transverse energy imbalance.

Along with direct (nucleus recoil) and indirect (annihilation) DM searches, the DM searches at colliders provide an important and complementary window of opportunity to find DM. Early collider DM searches were interpreted in terms of effective field theories (EFT) as a contact interaction. Such interpretation assumes large mediator mass which restricts significantly the validity range of the results. In recent years a need was recognized to extend the collider DM interpretations into a larger parameter space involving not only the parameters of the DM particles but also the parameters of the mediator particle, like its mass and couplings to SM and DM particles. In this effort, the ATLAS-CMS Dark Matter Forum, formed beginning of the year 2015, formulated a new concept of collider DM search interpretations in terms of simplified models and determined a common parameter scan strategy [20]. It is interesting to note that the mediator particle from these simplified models may well be identical to the subject of diobject resonance searches.

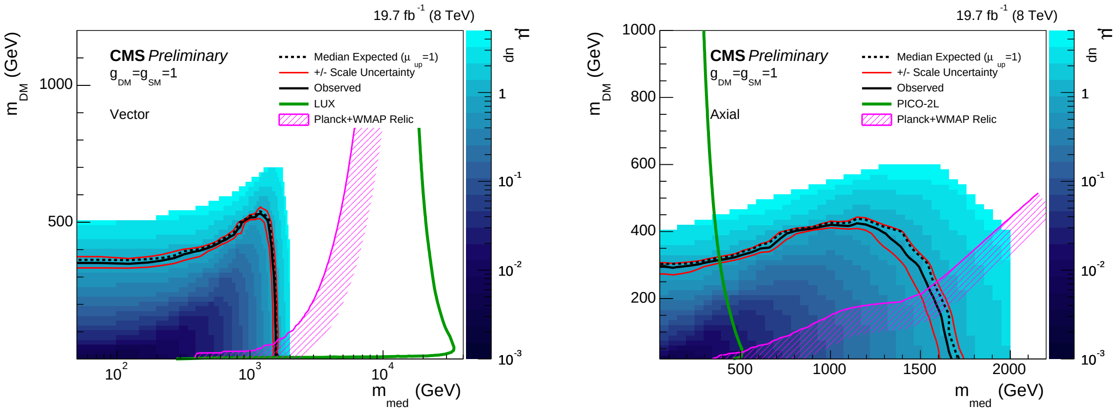

**Figure 5:** 90% CL DM exclusion contours in the mediator mass - DM mass plane assuming vector (left) and axial-vector (right) mediator in the CMS combine monojet and monoV search [21]. The blue scale shows the 90% CL upper limit on the signal strength assuming the mediator only couples to fermions. The excluded region is to the bottom-left of the contours shown in all cases except for that from the relic density as indicated by the shading.

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Apart from interpretation aspects, significant development went also into the experimental techniques. New results involving monoboson signatures lead to improved sensitivity. For example a recent CMS analysis combined the classical monojet search with hadronically decaying monoboson (W and Z) signatures making use of boosted topology techniques [21] (Fig. 5). Significant improvements were achieved also by using multiple control data samples to mimic the irreducible Z($\nu\nu$)+Jets background and performing a missing transverse energy shape analysis. Another examples extending the reach of simple monojet searches are the leptonic monoZ [22] signature or multijet plus missing energy searches using techniques developed in the context of supersymmetry searches [23].

A new probe of collider DM searches is the mono-Higgs signature. In this case, the Higgs boson is produced not as part of the initial state radiation but couples directly to the mediator. Hence, this very clean signature opens new possibilities to explore additional models with different kinematics [24] (Fig. 6). Another interesting signatures, particularly suited for searches for DM with scalar effective coupling to SM particles, are heavy quarks with missing energy, providing the most stringent limits for this type of DM [25, 26].

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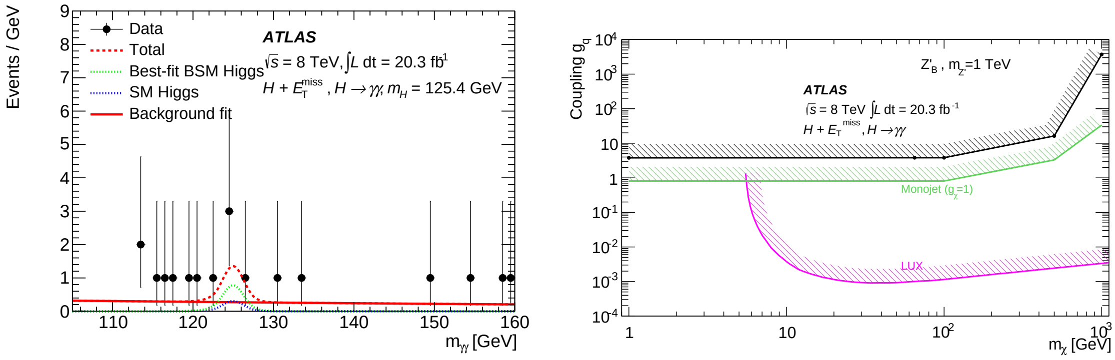

**Figure 6:** Distribution of the diphoton invariant mass with maximum-likelihood fit (left) and limits on coupling parameters for DM simplified models with a heavy mediator with mass of 1 TeV from ATLAS mono-Higgs search (right) [24].

## 4. Multiobject searches

The relatively simple signatures described in previous sections, of course, do not cover the whole spectrum of possible New Physics manifestations. One prominent example of searches with multiobject signatures involves final states with a combination of boosted heavy quarks and bososns (W, Z, H) which would arise from decays of vector-like quarks (VLQ) predicted by BSM models such as little Higgs or composite Higgs. These spin-1/2 color-triplets are the simplest extension to three quark generations allowed by experimental constraints. Based on naturalness, the top and bottom quark partners (T, B) are predicted with masses at TeV scale. At Run 1 energies, the VLQs would be produced predominantly in pairs, each decaying to a heavy quark and boson. This requires advanced experimental boosted topology techniques including top-tagging and Higgs-tagging (e.g. Fig. 7 left [27]) and exploration of various final states from all-hadronic, through semi-leptonic to multi-leptonic ones. Since each type of VLQ decays into three different final states, the search limits are typically presented in triangular plots (e.g. Fig. 7 right [28]) and reach currently 600 – 900 GeV by both, ATLAS and CMS, experiments. In Run 2, also the single T, B production will become important and will enrich the experimental possibilities.

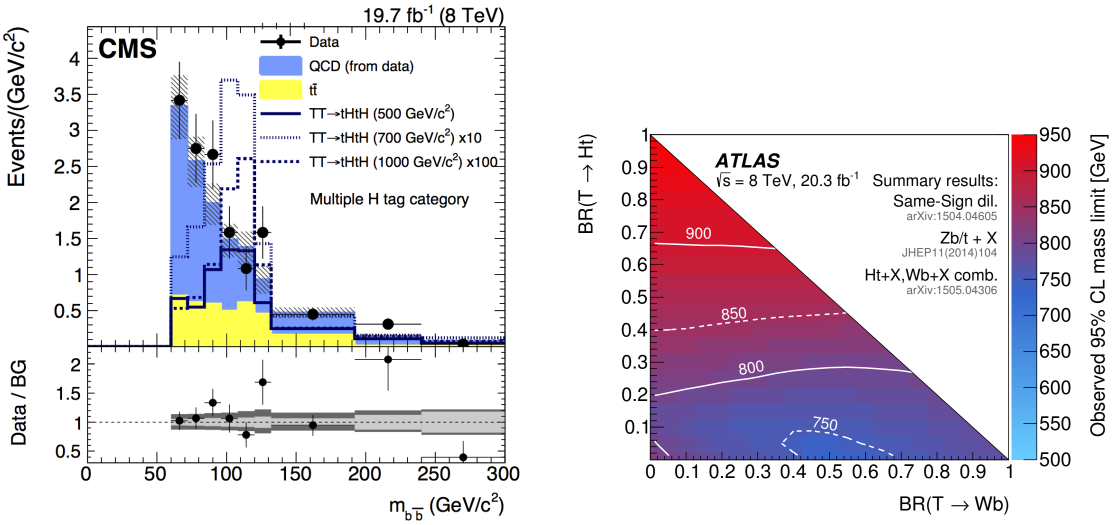

**Figure 7:** An example of Higgs boson candidate mass distribution arising from the Higgs-tagging technique (left) [27]. A summary of the most restrictive observed 95% CL limits on the mass of the T quark in the BR plane from all ATLAS searches for TT production (right) [28].

Another example of multiobject final states combines two leptons with a photon or a Z boson. These final states are sensitive to excited leptons predicted by various compositeness BSM models. Excited leptons are assumed to be produced in contact interactions together with a SM lepton and subsequently decay to another lepton and SM vector boson. Searches in photon and Z boson final states probe different couplings of excited leptons to SM bosons. Again, final states with Z boson require boosted topology techniques (Fig. 8) [29, 30]. The Run 1 excited lepton mass limits vary around 2 – 2.5 TeV for typical configurations of parameters of the model. For reference, the strongest limits on excited quark masses, obtained from dijet and photon+jet topologies are around 3.5 – 4 TeV (e.g. [3, 4]).

The multitude of multiobject final states is difficult to exhaust. An example of up to recently unstudied final state, consisting of three or more photons, was shown for the first time at this conference by ATLAS [31].

## 5. Displaced or delayed object searches

A special class of experimental signatures probing exotic phenomena are signatures involving displaced or delayed objects. Such signatures emerge when particles are long-lived as predicted by a variety of BSM models with weak couplings (Hidden Valley, gauge-mediated supersymmetry breaking), small mass gaps (Stealth supersymmetry, anomaly-mediated supersymmetry breaking), weakly broken symmetries (R-parity violating supersymmetry) or with high mass mediator (Split supersymmetry). In this type of searches, besides ATLAS and CMS, other experiments such as

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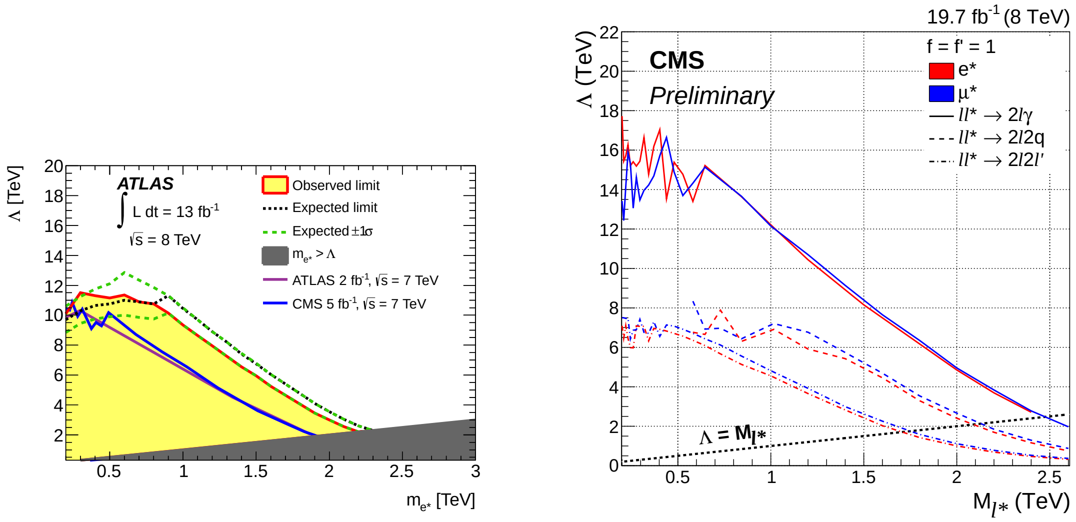

**Figure 8:** Excited lepton 95% CL exclusion limits in compositeness scale (Λ) and excited lepton mass plane in ATLAS $ee\gamma$ channel (left) [29] and in all channels studied by CMS (right) [30].

LHCb or BaBar and Belle, provide competitive and complementary results. A future facility, complementary to collider searches, aiming at study of very weak couplings at low energy scale, called SHiP, has been recently proposed at CERN [32].

Neutral long-lived particles would manifest themselves by delayed signals in detectors, displaced jets, leptons, photons or vertices or as lepton jets. In a typical benchmark scenario a pair of neutral spinless long-lived Hidden Sector particles is produced from a decay of a scalar boson (SM or non-SM) and decays into displaced pairs of e.g. muons or jets. In the effort to extend the probed lifetime range, experiments recently developed new techniques to reconstruct displaced objects exclusively in the outermost muon systems, such as stand-alone (non-tracker) muons in CMS (Fig. 9 left) [33] or Muon Spectrometer jets in ATLAS (Fig. 9 right) [34].

Heavy charged long-lived particles produced at LHC are expected to be highly non-relativistic. Therefore, typical detector signatures include a large ionization energy loss (dE/dx) or a large time-of-flight (TOF). A unique detector signature is available to LHCb which recently published results using the absence of signals in the ring-imaging Cherenkov detector [35]. Typical benchmark objects are meta-stable or stable R-hadrons, colorless states combining SM quarks or gluons with squarks or gluinos (Fig. 10 left [36]). Such searches can be reinterpreted to constrain significant sub-spaces of phenomenological minimal supersymmetric SM (pMSSM) or anomaly-mediated supersymmetry breaking (AMSB) models, as shown by CMS (Fig. 10 right) [37].

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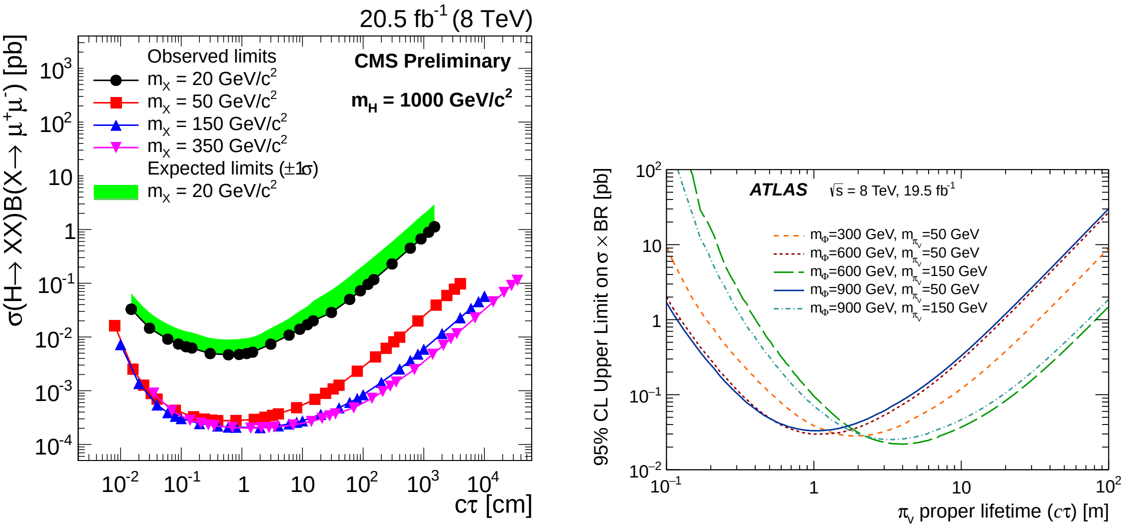

**Figure 9:** Example of observed 95% CL upper limits on the production of neutral long-lived spinless particle pairs obtained using a combination of results from muons reconstructed in tracker and muon system only by CMS (left) [33]. Similar limits by ATLAS from a combination of results with displaced jet-pair vertices in Inner Detector and Muon System (right) [34].

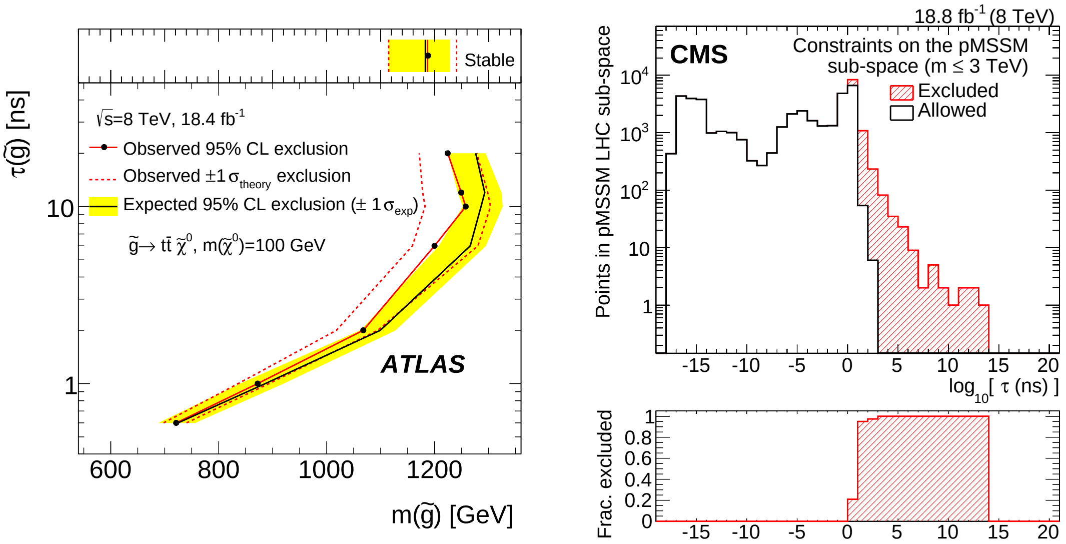

**Figure 10:** An example of exclusion limits for R-hadrons in lifetime - gluino-mass plane by ATLAS (left) [36] and the sub-space of pMSSM excluded by CMS projected on the chargino lifetime (right) [37].

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## 6. Conclusions

The legacy of searches for exotic phenomena in the LHC Run 1 does not consist only in the large range of limits on various BSM models, of which just a small part could be presented in this overview. The experimental tools have made a huge step forward with tuned reconstruction and triggering tools, improved interaction pileup handling, advanced techniques to explore boosted objects and statistical tools for combination of different samples and final states (owing to Higgs boson searches). In addition, the collaboration between the experiments in difficult subjects improved as shown by the example of ATLAS-CMS Dark Matter Forum. Moreover, the intensive collaboration with theorists brought improvements in signal and background generators (higher order corrections, PDF uncertainties, radiative effects, additional processes), construction of signature oriented simplified models and tools to bridge them to full models (e.g. SModelS), agreement on data presentation and tools for simplified detector simulation.

Such rich legacy promises a good readiness and efficient exploration of the early Run 2 data. In this conference, already a few weeks after the first data were collected, ATLAS and CMS collaborations were able to present first distributions and event displays with key observables well under control. This is important, since the data being collected will allow us to break into new territory already this year. With the center of mass energy step from 8 TeV to 13 TeV, the increased parton luminosities provide access to high mass scales with much less integrated luminosity. ATLAS and CMS collected at least 3 fb$^{-1}$ in the 2015 LHC run. This will allow to surpass the Run 1 reach in final states sensitive to objects with masses above $1.5-2$ TeV depending on the production mechanism. This concerns most of the searches mentioned in this document. We have all reasons to have high expectations and to be excited.

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