

Searches for Exotica

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This contribution gives an overview of scenarios beyond the standard model and their signatures searched for at the LHC. New results presented at the EPS conference 2021 are used as examples to point out new routes explored in searches.

*** *The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****

*** *26-30 July 2021 ****

*** *Online conference, jointly organized by Universität Hamburg and the research center DESY ****

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1. Introduction

The standard model of particle physics has several unresolved problems, such as the inability to describe the nature of dark matter. An important task of the ATLAS [1], CMS [2] and LHCb [3] experiments at the Large Hadron Collider (LHC) is therefore the hunt for new physics beyond the standard model (BSM). The general philosophy of the search program is to leave no stone unturned. A broad range of BSM scenarios, detector signatures and analysis techniques is covered, including even the most exotic ones. The LHC experiments have collected proton-proton collision data corresponding to up to 139 fb^{-1} at a center of mass energy of 13 TeV in the years 2015-2018. By now, order of 100 searches for BSM signatures have been carried out with this dataset and a similar number of searches is still ongoing. At the EPS conference in 2021, 27 new search results were presented [4–30]. This contribution gives an overview of BSM scenarios and signatures searched for at the LHC, using new results as examples and pointing out new routes explored in these searches. The contribution is structured by the type of BSM scenarios aimed for by the searches, though many of them are sensitive to multiple BSM scenarios and signatures. First, searches for new fermions, i.e. new kind of matter, and searches for new bosons, i.e. new force carrying particles are presented. Then searches targeting scenarios with dark matter particles, supersymmetry (SUSY) and long-lived particles are introduced.

2. New fermions

The three most sought-after types of additional matter particles (leaving SUSY aside for now), are new quarks, new leptons and excited states of quarks and leptons. Since the discovery of the Higgs boson, a fourth generation of SM-like quarks is excluded, however, vector-like quarks, whose left- and right-handed components transform the same under the SM gauge symmetries are still allowed. At the LHC, they may be produced in pairs through the strong interaction or singly through the electro-weak interaction. Among new leptons, the most interesting candidates are heavy neutral leptons, i.e. heavy neutrinos, as they could explain the small SM neutrino mass via the seesaw mechanism. Excited states of quarks and leptons appear in scenarios where the SM particles are composite objects. Compositeness of the Higgs boson is particularly compelling as it could regulate the Higgs mass addressing the hierarchy problem. Examples of Feynman diagrams for the production and decay of new fermions are shown in Figure 1.

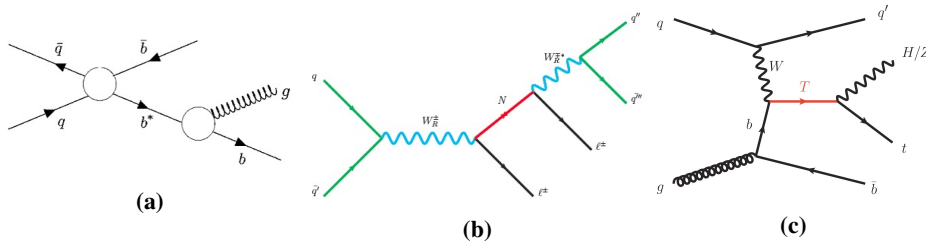


Figure 1: Feynman(-like) diagrams in BSM scenarios with new fermions [4–6].

Figure 1 (b) shows the production of a heavy neutral lepton N from the decay of a heavy right-handed charged spin-1 resonance W_R^+ and subsequent decay via a virtual W_R^0 resulting in a final

state with two leptons and two quarks. This signal is searched for in the invariant mass spectrum of the two lepton and two jet system looking for a W_R resonance as shown in Fig. 2 (left) [5]. When the W_R is significantly heavier than the N , the N is highly boosted and the lepton and the two quarks from its decay chain are collimated and reconstructed as a single jet. This jet can be decomposed into subjets and distinguished from background using a dedicated lepton subjet fraction technique. In this way, the search is for the first time sensitive to the region of high W_R mass and low N mass as shown in Fig. 2 (right).

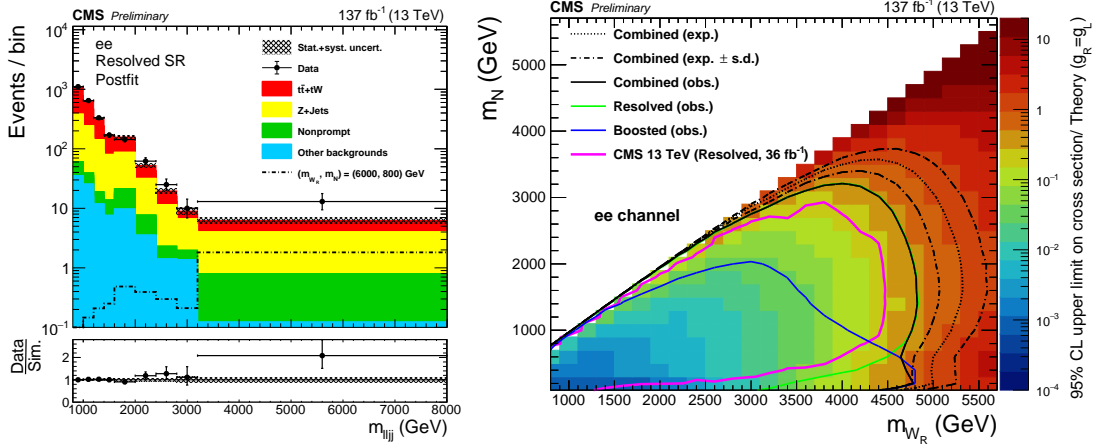


Figure 2: (left) Invariant mass distribution of two electrons and two jets. (right) Exclusion limits as a function of the W_R and N masses [5].

3. New bosons

New bosons appear in many BSM scenarios introducing new interactions among SM or BSM particles. Five popular examples of such spin-0, spin-1 and spin-2 particles which are extensively searched for at the LHC are given in the following. The most commonly thought of extension of the SM Higgs sector is the two-Higgs-doublet model (2HDM), which predicts 5 new spin-0 particles, h, H, A, H^\pm . Extensions of the SM gauge groups, including e.g. the composite Higgs scenario, typically predict new spin-1 W' or Z' particles, that can form singlets or a heavy vector triplet (HVT) with W' and Z' degenerate in mass. In scenarios introducing extra spatial dimensions in order to solve the hierarchy problem, spin-2 graviton and spin-0 radion resonances emerge. Axion-like particles (ALP) (spin-0) are candidates for dark matter, which in the special case of the QCD axion can solve the strong CP problem. BSM scenarios with Leptoquarks (spin-0/1) are popular as they provide a possible explanation of the LHCb flavour anomalies. Examples of Feynman diagrams for the production and decay of new bosons are shown in Figure 3.

Figure 3 (d) shows the production and decay of a new heavy boson X decaying into a pair of lighter new bosons a that further decay to a final state with 4 b quarks, emerging in scenarios with additional Higgs bosons. For the first time such a signature is searched for in the mass range $25 < m_a < 100$ GeV and $1 < m_X < 3$ TeV, where the a boson is highly boosted forming a single jet which contains the fragmentation of two b quarks [13]. The jets are identified using a double-b-tag requirement. Events failing this requirement are used to estimate the background.

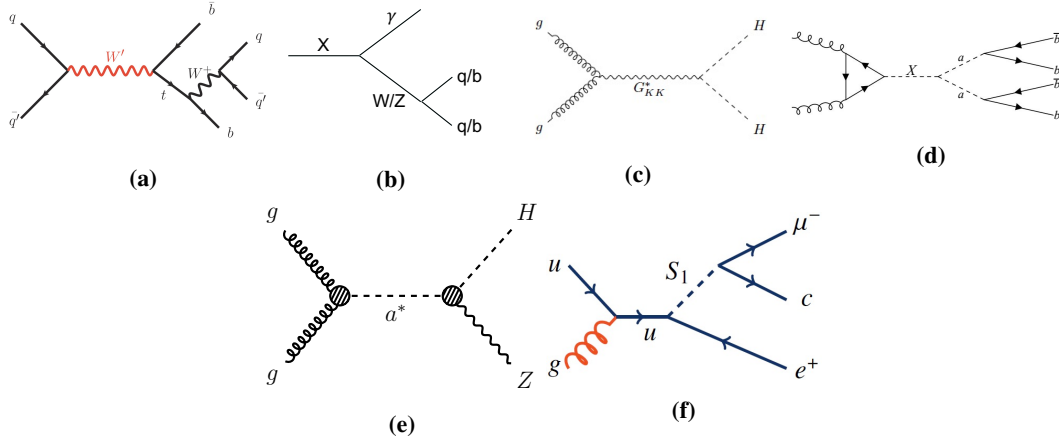


Figure 3: Feynman(-like) diagrams in BSM scenarios with new bosons [7–16].

The 2-dimensional data spectrum as a function of the average jet mass and the dijet mass shown in Fig. 4 is searched for resonances scanning m_a and m_X .

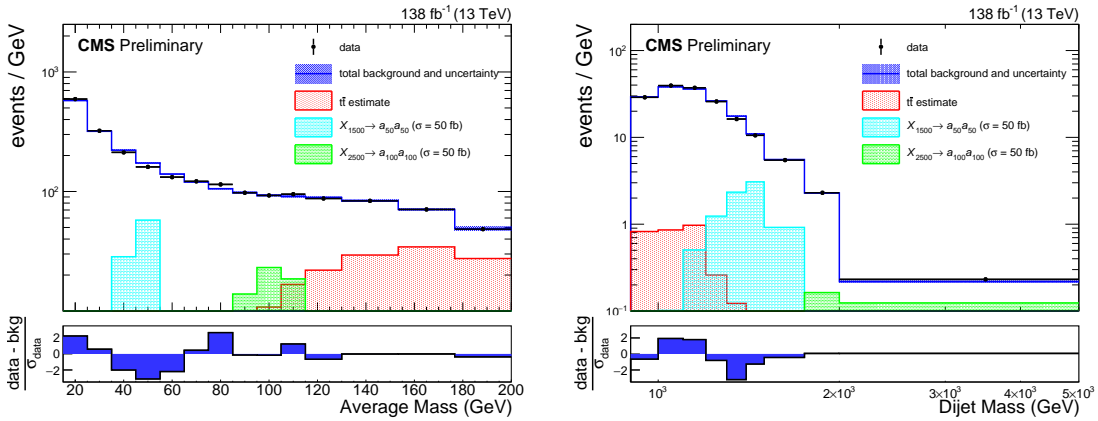


Figure 4: Average jet mass (left) and dijet mass (right) distributions [13].

Figure 3 (f) shows the production of a scalar leptoquark S_1 that couples to $u + e^-$ and $c + \mu^-$. Due to the valence quark content of the colliding protons, the production of final states with $e^+ + \mu^-$ pairs is enhanced over $e^- + \mu^+$ pairs. A measurement of the charge-flavour asymmetry $\rho = \sigma(pp \rightarrow e^+ \mu^- + X) / \sigma(pp \rightarrow e^- \mu^+ + X)$ is carried out at the LHC for the first time to search for such signatures [16]. To enhance sensitivity to various BSM scenarios, ρ is measured in multiple signal regions with requirements on missing transverse momentum and/or jets as shown in Fig. 5 (left). Fig. 5 (right) shows the resulting exclusion limit on the scalar leptoquark mass and coupling, covering phase-space that has never been explored before.

4. Dark matter and dark sector

Though there is strong evidence for its existence, the origin of dark matter is still unclear. At the LHC one may clarify this by detecting dark matter production through its weak coupling to

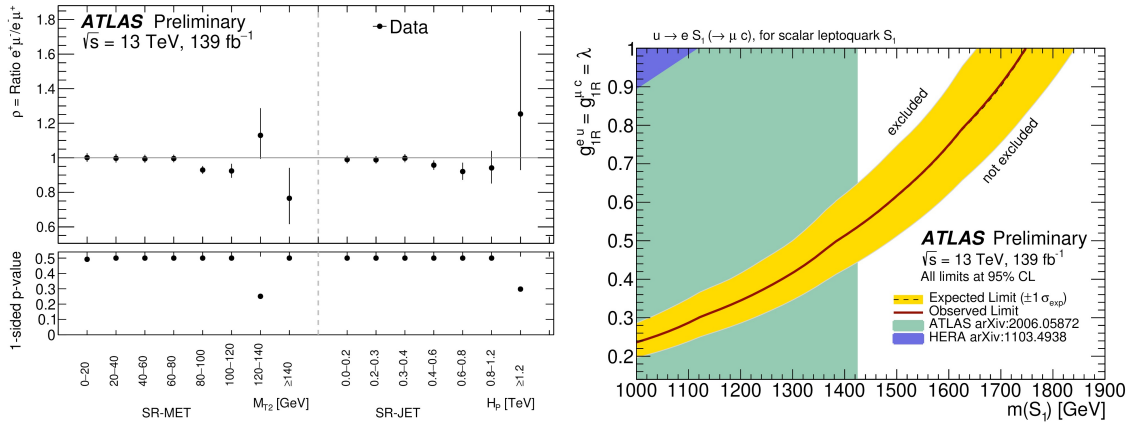


Figure 5: (left) Measured values of the charge-flavour asymmetry in various signal regions. (right) Exclusion limit on the mass and coupling of a scalar leptoquark S_1 [16].

the SM particles. The classical signature in the detector is missing transverse momentum from the undetected dark matter particles plus a SM particle ($g, \gamma, W, Z, H, t, \tau$) necessary to trigger on the event. In simplified models, where a mediator boson between SM and dark matter and corresponding coupling parameters are assumed, constraints on dark matter from the LHC can be compared to direct and indirect dark matter searches. Beyond this simple model, more complex scenarios with a dark sector, i.e. multiple fermions/bosons making up dark matter, are under study. These scenarios have mediators, called portal, between the SM and dark sector particles, which could be, e.g. a dark photon or a Higgs boson. Dark fermions may acquire their mass either through the SM Higgs boson or a dark Higgs boson. Therefore searches for exotic decays of the SM Higgs boson directly relate to dark matter searches. Examples of Feynman diagrams for the production of dark matter particles are shown in Figure 6.

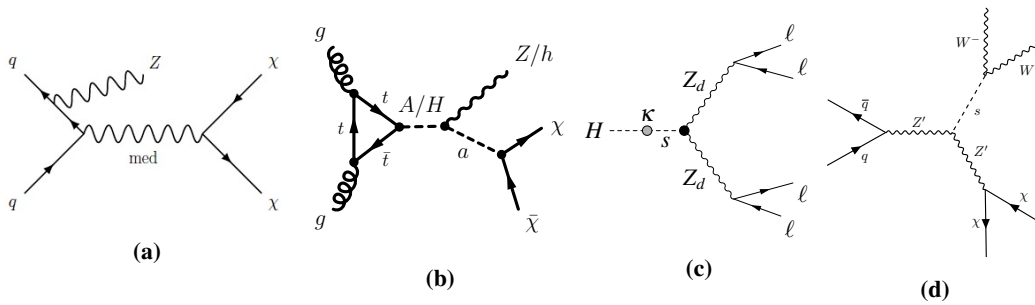


Figure 6: Feynman(-like) diagrams with dark matter particles [17–20].

Figure 6 (c) shows the production of a SM Higgs boson mixing with a dark Higgs s that decays to a pair of dark photons Z_d decaying further to a final state with 4 leptons. A search for BSM decays of the Higgs boson [19] looks for resonances in the average lepton pair invariant mass, shown in Fig. 7 (left), in events with 4 leptons with an invariant mass consistent with the SM Higgs boson mass. The search employs a dedicated reconstruction of 4 muons to reach lepton pair invariant masses down to 1 GeV. With no event observed, it sets stringent constraints on the production cross section for dark photon pair production via a SM Higgs boson shown in Fig. 7 (right).

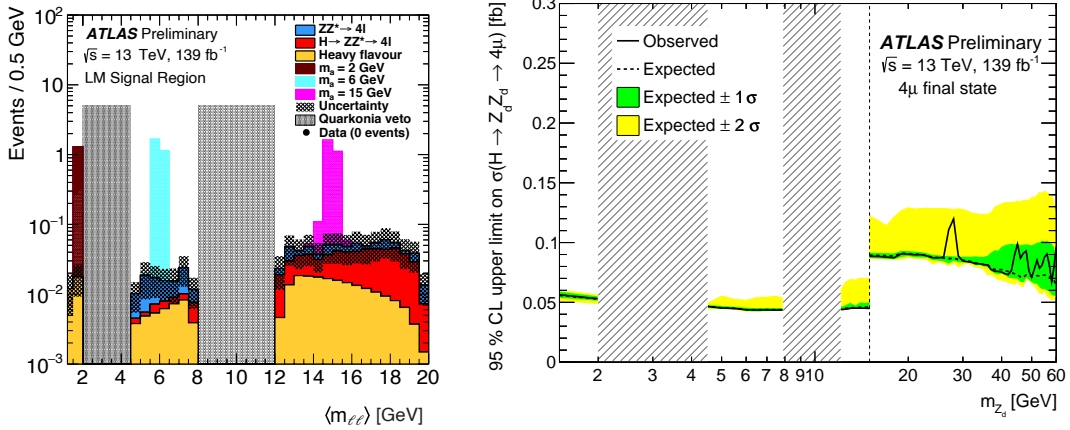


Figure 7: (left) Lepton pair invariant mass distribution. (right) Exclusion limit on dark photon pair production via a Higgs boson [19].

5. Supersymmetry

Introducing a new supersymmetry (SUSY) among the fermion and boson particle content of the SM can potentially address multiple unresolved problems in particle physics. A whole search program for such supersymmetric partner particles is therefore carried out at the LHC. The most typical signature at the LHC (in R-parity-conserving scenarios) is pair production of SUSY particles that decay via a (long) chain to SM particles and the lightest SUSY particle (LSP) which escapes undetected, resulting in a final state with SM particles and missing transverse momentum. The LSP is a potential dark matter candidate. Examples of Feynman diagrams for the production of SUSY particles are shown in Figure 8.

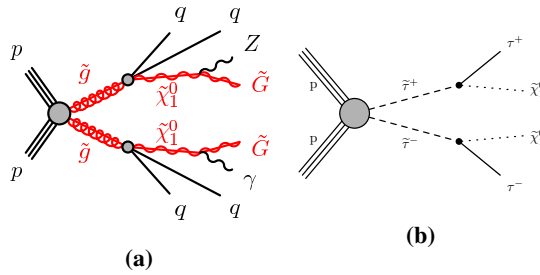


Figure 8: Feynman(-like) diagrams with supersymmetric particles [21, 22].

Figure 8 (b) shows the pair production of SUSY partners of τ leptons (staus) which decay into SM τ s and undetected neutralinos (neutral partners of SM bosons). To maximize sensitivity to this particular and similar decay chains, events are categorized according to the transverse momenta of the τ s and how the missing transverse momentum is aligned w.r.t. the τ s (with the variables $\sum m_T, m_{T2}$) as shown in Fig 9 (left) [22]. Dedicated search regions identifying taus with displaced production vertices are introduced to cover scenarios where the staus have a lifetime corresponding to up to $c\tau < 2.5\text{mm}$ which appear in scenarios of gauge-mediated SUSY breaking (GMSB). This search excludes staus with masses up to 400 GeV as shown in Fig 9 (right).

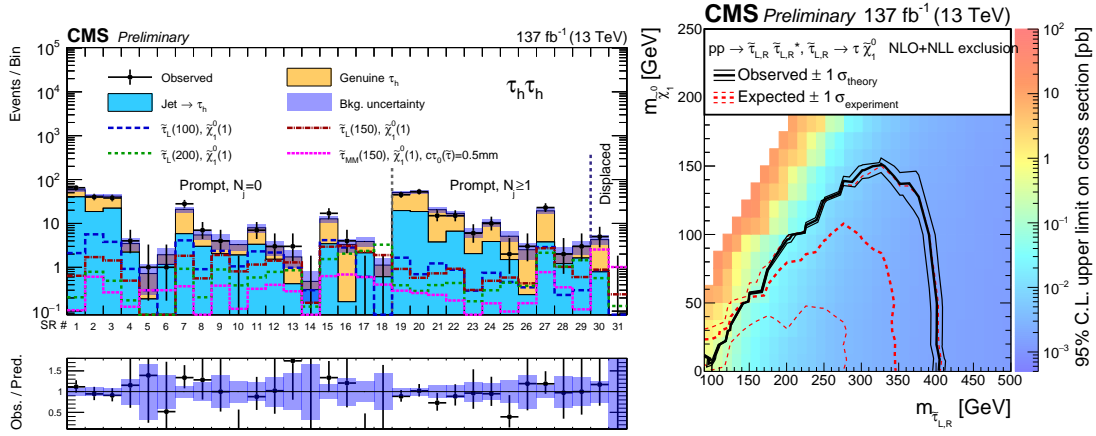


Figure 9: (left) Distribution of event counts in the search regions. (right) Exclusion limit for degenerate stau production as a function of the stau and neutralino masses. [22].

6. Long-lived particles

Long-lived particles (LLP) decaying on a time scale detectable with the LHC experiments appear in the SM and are equally plausible in BSM scenarios. They can appear in processes involving small couplings, phase-space suppression, heavy intermediate states or (almost) conserved symmetries. A whole search program therefore aims at identifying signatures with LLPs. Signatures at the LHC include timing, ionisation and displacement which are reconstructed with dedicated techniques. Benchmark models include SUSY scenarios (as in the example given above), heavy neutral leptons and dark sectors. Examples of Feynman diagrams with long-lived particles are shown in Figure 10.

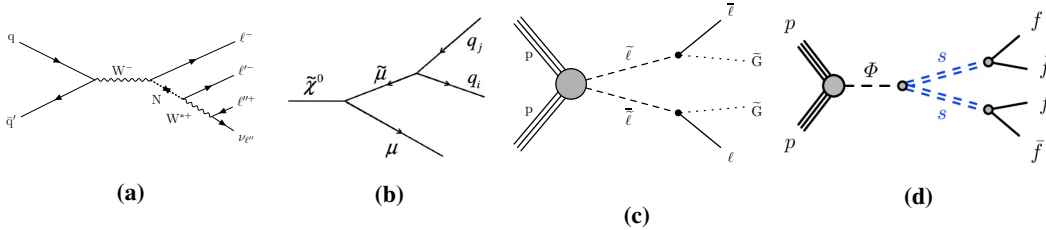


Figure 10: Feynman diagrams with long-lived particles [23–26].

Figure 10 (b) shows the decay of a LLP to a muon and a pair of quarks. This and related signatures are targeted by a search [24] for massive long-lived particles in a muon plus jets final state. A displaced ($0.5 < c\tau < 20\text{mm}$) high-multiplicity vertex with one associated isolated muon with large transverse momentum is reconstructed. After a multivariate kinematic selection, the invariant mass spectrum of this LLP vertex shown in Fig. 11 (left) is examined for both non-resonant and resonant pair production of LLPs. Fig. 11 (right) show the resulting exclusion limit on the production cross section for resonant LLP production via a Higgs boson.

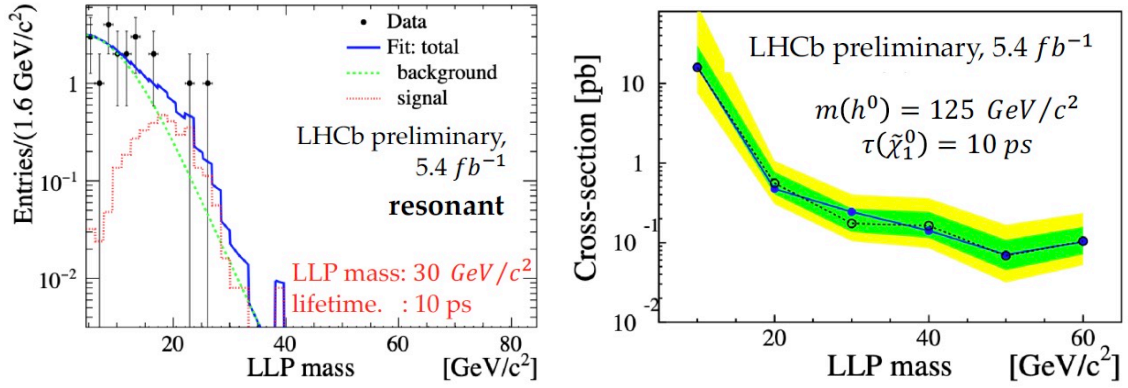


Figure 11: (left) Distribution of the reconstructed LLP invariant mass. (right) Upper exclusion limit on the production cross section as a function of LLP mass. [24].

7. Conclusions

In summary, a large number of BSM models and signatures has already been explored with the LHC Run2 data. Besides the amount of data, sensitivity is significantly enhanced over previous early Run2 searchers with new reconstruction and analysis techniques. Several new models and signatures have been explored for the first time. No new evidence for BSM was reported at EPS. However, the range of excluded model phase-space has been significantly extended. There are still many more exotic models, detector signatures and analysis techniques to explore. The LHC Run3 will offer new detector and trigger capabilities for the BSM search.

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