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Experimental overview of BSM searches (includes resonant HH production)

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This document summarizes recent results from ATLAS and CMS collaborations in searches for physics Beyond the Standard Model (BSM) using data from LHC Runs 2 and 3. It focuses on key BSM scenarios, including extended Higgs sectors, supersymmetry, heavy fermions, and the two-Higgs-doublet model with an additional pseudoscalar. The report highlights various searches, such as those for charged and neutral Higgs bosons, dark matter interactions, and heavy fermions. Advanced analysis techniques like multivariate methods, deep neural networks, and new triggers for detecting long-lived particles are employed. Results generally show no significant deviations from Standard Model predictions, leading to the establishment of stringent upper limits on various BSM processes. The findings contribute to narrowing down the parameter space for these BSM theories, pushing the limits of current searches.

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1. Introduction

This document summarizes the most recent results in the context of searches for physics Beyond the Standard Model (BSM) from the ATLAS [1] and CMS [2] collaboration. They span over a wide range of signatures and model interpretation and consider both Run 2 and Run 3 data from the LHC. Instead of presenting them in a standard way, by grouping the results based on the model interpretation considered in each search, I decided to describe this reach list of results from a different perspective. I will highlight the results obtained in the context of the most well-known scenarios of BSM physics to start with in Sec. 2. I will then complement the description by highlighting searches exploiting beyond standard analysis strategies in Sec. 3, beyond standard signatures in Sec. 4 and beyond standard tools in Sec. 5.

2. Searches motivated by popular Beyond the Standard Model scenarios

2.1 Extended Higgs Sector

Extension of the Standard Model (SM) include, among others, the Two-Higgs-Doublet Model (2HDM) [3] which extends the SM by introducing an additional Higgs doublet, resulting in a richer Higgs sector with two charged and two neutral Higgs bosons. In this context ATLAS searches for a light charged Higgs boson ($H^{\pm}$) produced in the decay of top quarks ($t \to H^{\pm}b$), with the Higgs boson further decaying into a charm quark and a strange quark ($H^{\pm} \to cs$) [4]. To enhance the sensitivity of the search, advanced techniques such as flavor tagging, which helps to identify jets from b-quarks, and multivariate analysis (MVA) methods, which combine multiple variables to improve the distinction between signal and background, were employed. The results of the study are expressed in terms of 95% confidence level (CL) upper limits on the branching fraction $B(t \to H^{\pm}b) \times B(H^{\pm} \to cs)$ as a function of the charged Higgs boson mass as shown in Fig. 1. These findings complement a previous study from ATLAS [5] that searched for $H^{\pm}$ in the decay

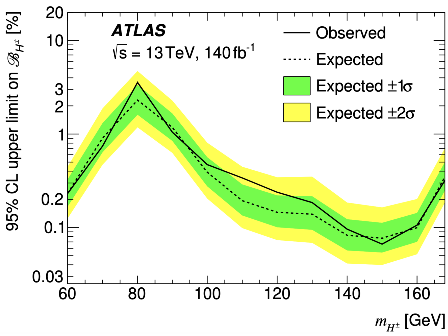

Figure 1: Observed and expected upper limits on $B(t \to H^{\pm}b) \times B(H^{\pm} \to cs)$ for charged Higgs boson with masses between 60 GeV and 168 GeV [4].

channel $H^{\pm} \to cb$ and observed an interesting excess of events around 130 GeV with a global significance of 2.5σ.

CMS experiment instead, focuses on searching for neutral Higgs bosons H or A, specifically those decaying into pairs of b quarks [6]. The study investigates final states where the Higgs bosons are produced in association with b quarks. The search explores both semi-leptonic and fully hadronic final states, by optimizing the former case in the low mass region below 700 GeV and the latter in the hogher mass region. As shown in Fig. 2 left, no significant excess over the SM background was observed, leading to stringent upper limits on the production cross-section times branching fraction for Higgs bosons in the mass range of 125 to 1800 GeV. CMS reports also on a search for a heavy CP-odd Higgs boson (A), which decays into a 125 GeV Higgs boson (h) and a Z boson [7]. The study focuses on final states where the 125 GeV Higgs boson decays into a pair of $\tau\tau$ leptons and the Z boson decays into a pair of muons or electrons. The analysis considers both gluon-gluon fusion and associated production with bottom quarks as production mechanisms for the A boson. To improve the sensitivity of the search, events are categorized based on the number of b-tagged jets and the final state of the $\tau\tau$ leptons. No significant excess above the expected background was observed. Consequently, the study sets upper limits, shown in Fig. 2 right on the production cross-section times branching fraction for the $A \to Zh$ process, with limits ranging from 0.055 pb to 1.00 pb, depending on the mass of the A boson and the production mechanism. The mass range of the A boson probed extends from 225 GeV to 800 GeV.

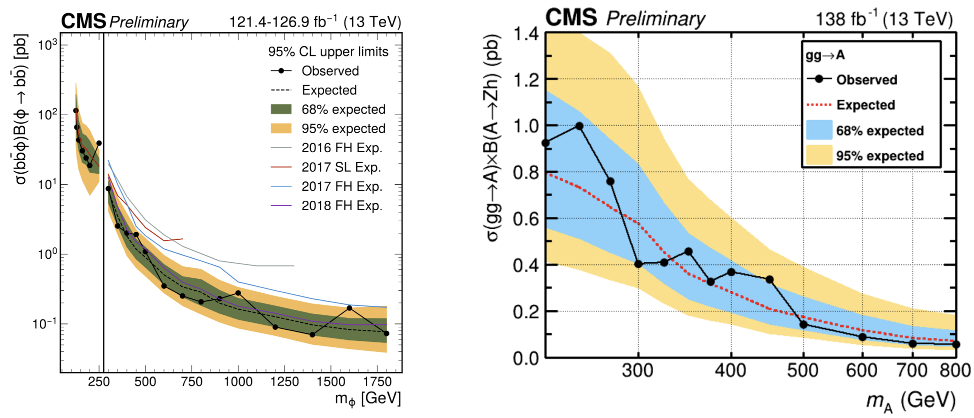

Figure 2: Left: Upper limits for the Higgs b-associated production cross-section into a b-quark pair at 95% CL as a function of the heavy Higgs boson mass [6]. Right: Upper limit at 95% CL on the production cross-section times branching ratio of the $A \to Zh$ decay for gluon fusion production process [7].

2.1.1 2HDM+a

At LHC, experiments explore also the two-Higgs-doublet model with an additional pseudoscalar (2HDM+a) [8], a theoretical extension of the SM that adds a second Higgs doublet and a pseudoscalar mediator, a, to explain dark matter (DM) interactions. In this context, CMS performed a search for DM produced in association with a Higgs boson decaying to a pair of τ leptons [9]. Since no significant excess over SM predictions is observed, for a baryonic Z' model, Z' masses up to 1050 GeV are excluded for a DM mass of 1 GeV (combining with 2016 data), while for the 2HDM+a model, heavy pseudoscalar masses between 400-700 GeV are excluded for a light pseudoscalar mass of 100 GeV as shown in Fig. 3 left. CMS performed also a search DM produced in association with bottom quark and lepton pairs [10]. The analysis explores for the first time at the LHC the associated production of a bottom quark-antiquark pair and a new neutral Higgs boson that subsequently decays into a Z boson and a pseudoscalar, where the latter acts as DM mediator in the context of the 2HDM+a model. The presence of b jets makes this search suitable to probe those scenarios in which the production of scalar in association with b-quarks is enhanced. In the context of the 2HDM+a, those scenarios are favored by cosmological observations, which could indicate a large amount of DM particles being annihilated through an s-channel process producing a substantial number of b-quarks. Exclusion regions in the 2D planes formed by four relevant 2HDM+a parameters are shown (e.g. Fig. 3 right), while at the same time, the results are compared with expectations for this model in the context of cosmological predictions.

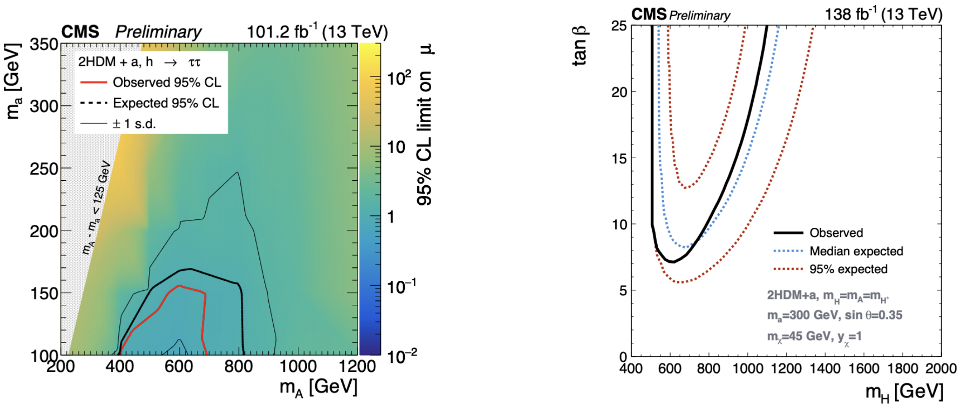

Figure 3: Left: The 95% CL upper limit on the signal strength modifier in the two masses plane [9]. Right: Excluded regions for the 2HDM+a model. Projections are presented for the m_H vs $tan\beta$ plane [10].

2.2 Supersymmetry

Supersymmetry (SUSY) is an alternative theoretical extension of the SM that predicts the existence of partner particles (sparticles) for every known particle, potentially solving key issues like the hierarchy problem and providing a candidate for dark matter. In this context, CMS presented a general search for supersymmetric particles [11]. The study targets scenarios with compressed mass spectra, where the mass difference between the parent sparticle and the lightest supersymmetric particle (LSP) is small, making the detection of sparticles challenging. Events are categorized based on lepton and jet multiplicity, b-tags, and other kinematic variables. The results set lower mass limits at 95% CL for the production of electroweakinos, sleptons, and top squarks ($\tilde{t}$). The limits reach up to 760 GeV for top squarks (see Fig. 4), 300 GeV for electroweakinos, and 275 GeV for sleptons in the most favorable scenarios. This study pushes the boundaries of current SUSY searches, particularly in regions with compressed mass spectra.

2.3 Heavy Fermions

Heavy fermions, which are hypothetical particles predicted by theories beyond the SM, could provide insights into the nature of mass generation and the hierarchy problem. In this context, ATLAS presented a search for the electroweak production of vector-like leptons (VLLs) using Run 2 of the LHC [12]. The VLLs are hypothesized to decay into third-generation quarks and leptons via a vector leptoquark, U_1, as predicted by the '4321' model [13], a BSM theory designed to

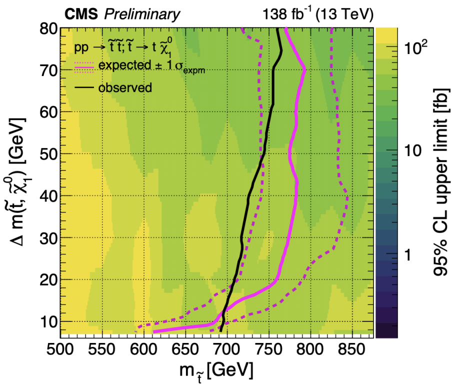

Figure 4: Observed upper limits at 95% CL on top squarks pair production are shown using the color scale where the $\tilde{t}$ mass is on the x-axis and the mass difference between the $\tilde{t}$ and the LSP is on the y-axis [11].

explain flavor anomalies in B-meson decays. No significant excess over the SM prediction was observed, leading to the setting of 95% CL limits on the cross-section as a function of the VLL mass, shown in Fig. 5 left. The observed lower limit on the VLL mass was set at 910 GeV, while the expected limit was 970 GeV. CMS instead presented a Run 2 search for the pair production of new heavy resonances, specifically excited top quarks (denoted as t^*), which decay into a top quark and a gluon [14]. A deep neural network was employed to enhance the signal-like event sample, and the scalar sum of the transverse momenta of all reconstructed objects was analyzed to detect any signal. The analysis found no significant deviations from the SM predictions. As a result, upper limits at the 95% CL were set on the product of cross-section and branching fraction squared for the pair production of t^*. As shown in Fig. 5 right, these limits range from 0.12 pb to 0.8 fb for spin-1/2 t^* and from 0.015 pb to 1.0 fb for spin-3/2 t^*, corresponding to mass exclusion limits up to 1050 GeV and 1700 GeV, respectively.

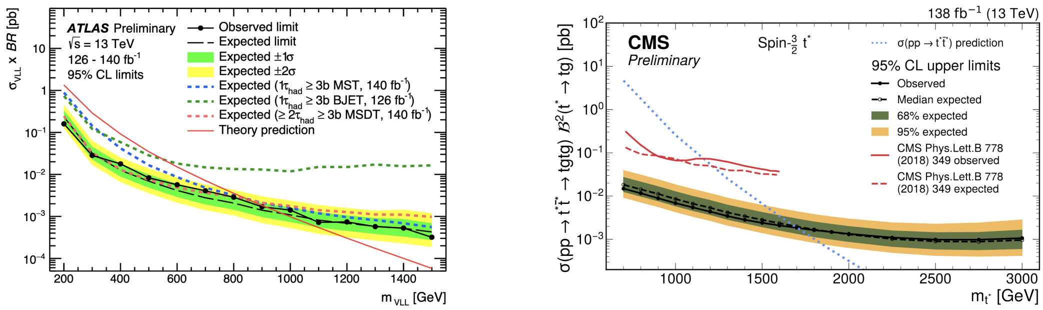

Figure 5: Left: Observed and expected 95% CL upper limits for the VLL pair production as a function of the VLL mass [12]. Right: Expected and observed 95% CL upper limits on the t^*t^* production cross section for a spin-3/2 t^* vs t^* mass [14].

3. Searches exploiting beyond standard analysis strategies

3.1 Identifying merged objects

ATLAS presented a search for light neutral particles, known as dark photons, that decay into collimated pairs of electrons or muons using Run 2 data [15]. The search strategy involves identifying events with collimated pairs of leptons, termed Lepton-Jets (LJs), which are characteristic of dark photon decays. The study sets upper limits (shown in Fig. 6 left) on the branching ratio of Higgs boson decays into dark photons at 95% confidence level, ranging from 0.001% to 5%, depending on the dark photon mass and the specific signal model considered. ATLAS presented also a search for exotic decays of the Higgs boson into a pair of pseudoscalar particles (denoted as a), where one pseudoscalar decays into a b-quark pair and the other into a $\tau\tau$-lepton pair [16]. The analysis builds on previous studies by refining techniques, especially for detecting low-mass, merged "double b-quark" jets, which are challenging due to their low transverse momentum. This work provides tighter constraints on new physics scenarios involving light pseudoscalar particles in Higgs boson decays and sets upper limits at a 95% CL on the branching ratio of Higgs bosons decaying via this exotic process, shown in Fig. 6 right.

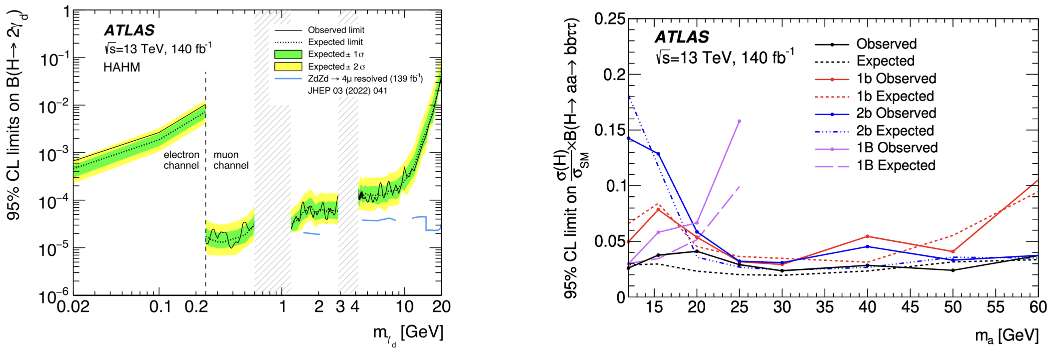

Figure 6: Left: 95% CL exclusion limits on the branching ratio of the Higgs boson to dark photons as a function of the dark photon mass [15]. Right: 95% CL upper limits on production cross section times branching fraction as a function of the a is when considering different heavy-flavor categories [16].

3.2 Accessing low energies

CMS presented a search for low mass vector and scalar resonances that decay into quark-antiquark pairs [17]. The analysis focuses on resonances with masses between 50 and 300 GeV, which are produced alongside significant initial-state radiation (ISR). The search considers two scenarios: resonances coupling equally to all quark flavors or preferentially to bottom quarks. The resonances are identified as large-radius jets with specific two-pronged substructures, analyzed using the ParticleNet algorithm [18]. The paper sets the most stringent limits to date on the coupling strengths of new scalar and vector resonances to quarks in the mass range considered, shown in Fig. 7 compared to previous dijet searches at CMS that complement the results at higher masses.

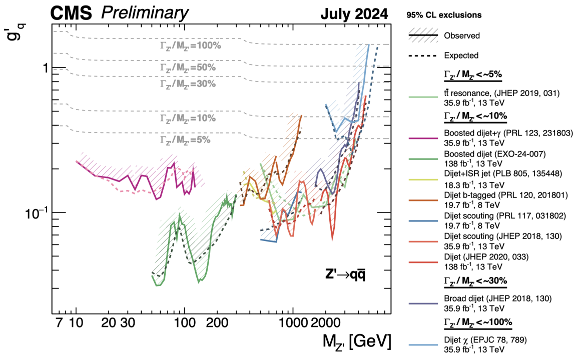

Figure 7: Limits on the universal coupling g'_q between a leptophobic Z boson and quarks [arXiv:1611.03568] from various CMS dijet analyses [17].

4. Searches exploring beyond standard signatures

4.1 Probing the multi-TeV scale

The LHC experiments have recently explored the existence of new particles at very high energies focusing on simple final states like di-lepton or di-jet production. Since no hints of new physics has been found so far, experiments started to develop more elaborated searches where additional objects are present in the final states, for example b-quarks. In this context CMS presented a search for a new neutral gauge boson Z that could violate lepton flavor universality by preferentially coupling to the third generation of quarks, specifically decaying into two muons with one or two b-jets [19]. This analysis is significant because previous searches, which mostly considered Z production via light quark fusion, provided weaker constraints on models where Z is produced in association with b-jets. The study found no significant deviation from the SM predictions, leading to the establishment of upper limits on the cross-section times branching fraction for the Z boson, shown in Fig. 8 left. CMS performed also a search for nonresonant new physics in high-mass di-lepton events associated with b-tagged jets with Run 2 data [20]. The study also investigates potential violations of lepton flavor universality by comparing the di-electron and di-muon mass spectra across different b-jet multiplicities, as shown in Fig. 8 right.

4.2 Signatures with Long Lived particles

LHC experiments have also a rich program of searches for long-lived particles (LLPs), particles that do not originate from the primary proton-proton collision point. ATLAS presented its first search for LLPs that includes data from Run 2 (13 TeV) and partial Run 3 (13.6 TeV) LHC datasets, with an emphasis on new triggers and reconstruction techniques that improve sensitivity to low-momentum displaced leptons and highly displaced electrons [21]. The results show no significant deviation from SM predictions, allowing to set exclusion limits on several theoretical models, including gauge-mediated supersymmetry breaking (GMSB) (see Fig. 9 left for the case of displaced electrons). The paper reports that selectrons, smuons, and staus are excluded at 95% confidence level up to masses of 740 GeV, 840 GeV, and 380 GeV, respectively, for specific lifetime ranges. These findings extend previous limits and demonstrate enhanced detection capabilities due to the technological advancements introduced in Run 3. ATLAS searched also for neutral LLPs that

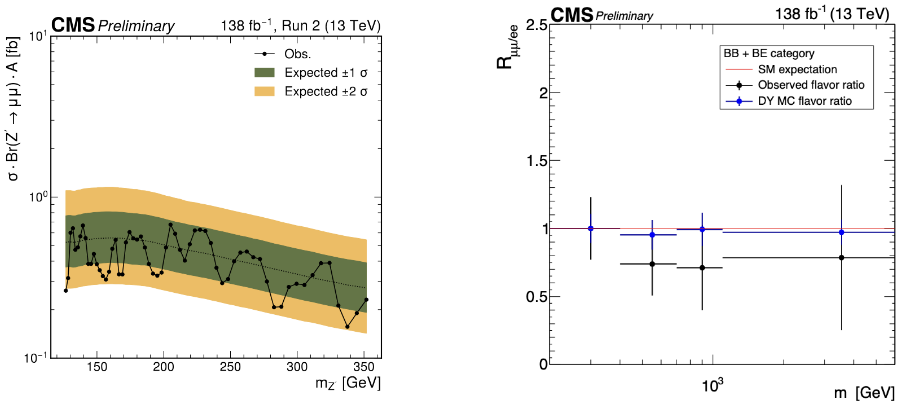

Figure 8: Left: 95% CL limits on acceptance times cross section times branching fraction to di-muon decays produced in association with at least one b-jet [19]. Right: Ratio of the differential di-lepton production cross section in the di-muon and di-electron channels as a function of di-lepton mass in final states with at least one b-jet [20].

decay into displaced jets within the hadronic calorimeter [22]. The analysis employs the "CalRatio" variable to distinguish between displaced jets from LLP decays and SM jets. Despite thorough investigation across different kinematic regimes, no significant deviations from SM predictions were observed. Exclusion of Higgs boson branching fractions into hadronically decaying neutral LLPs greater than 1% for decay lengths between 30 cm and 4.5 m are set (see Fig. 9 center). Exclusion of long-lived dark photons produced with a Z boson with cross-sections above 0.1 pb for decay lengths from 20 cm to 50 m are also provided. First-time probing of photo-phobic axion-like particles by ATLAS is finally performed, by excluding production cross-sections above 0.1 pb in the 0.1 mm to 10 m range. Finally CMS presented a study for VLL with LLPs decays in the CMS muon system [23]. Specifically, the research focuses on VLLs that decay into a long-lived pseudoscalar particle and a SM τ lepton. The pseudoscalar, with a mass of 2 GeV, decays into a pair of photons, which are detected through a muon detector shower signature. The study selects events featuring at least one reconstructed muon detector hit cluster and one hadronic τ lepton. No significant excess of events was observed compared to the expected background, leading to the derivation of 95% CL limits on the VLL production cross section. These limits, shown in Fig. 9 right, exclude VLL masses up to around 690 GeV, depending on the lifetime of the pseudoscalar particle. The results add new constraints on BSM models involving VLLs and LLPs.

5. Searches using beyond standard tools

5.1 Dedicated data streams

The CMS experiment developed an innovative data acquisition strategy, called data scouting [24], to efficiently handle the enormous amount of data generated during high-energy proton-proton collisions. The main goals of the so called scouting are to increase the sensitivity to certain types of new physics phenomena, particularly those that might manifest as subtle or low-mass signals, and to allow for real-time analysis of a much larger volume of collision data. This method

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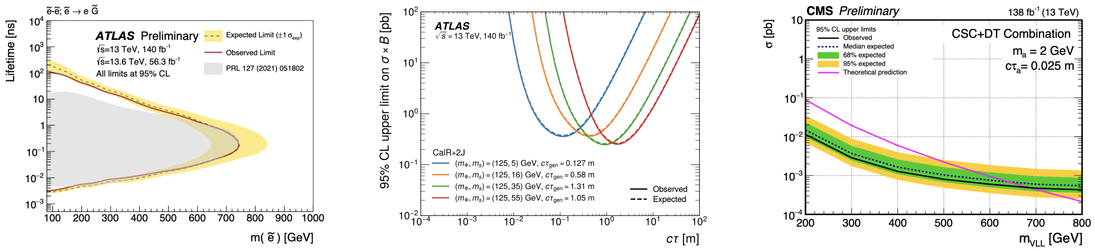

Figure 9: Left: Expected and observed 95% CL exclusion contours for the selectron model [21]. Center: 95% CL upper limits for a pair-produced LLPs models with mediator masses of 125 GeV [22]. Right: 95% CL upper limits on VLL production cross section vs the VLL mass for a pseudoscalar lifetime of 0.025 m [23].

is particularly useful in searches for new particles, such as low-mass resonances, and other rare or unexpected phenomena that could indicate physics BSM. During Run 2, scouting at CMS was performed exploiting standard objects like muons [25] and jets [26]. In Run 3 CMS did a step forward by reconstructing also low-energy hadronically decaying τ leptons in the scouting dataset [27]. This new tool will help extend the searches with τ leptons in the final state to low masses and lower transverse momenta, opening up a previously inaccessible region of phase space (transverse τ momentum down up to 5 GeV). This can potentially reveal signals of new particles or interactions that might be elusive at higher mass scales or higher τ momenta. Extensive validation checks have been performed to verify the reliability and effectiveness of the Scouting τ reconstruction. Among these checks, CMS observes the $Z \to \tau\tau$ process with the expected cross section, for the first time using Scouting data as shown in Fig. 10.

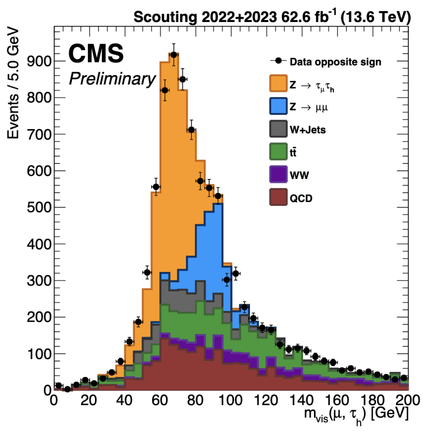

Figure 10: $Z \to \tau\tau$ visible invariant mass boson peak shown using the Scouting τ object in 2022 and 2023 data [27].

5.2 Ad-hoc triggers for non conventional signatures at Run 3

Finally standard triggers are usually inadequate for LLPs searches at LHC, because they are designed for promptly decaying particles, and custom techniques are often needed to collect and reconstruct the data. Many improvements and extensions for triggering on LLPs with the CMS and

ATLAS experiments were made for and during Run 3 of the LHC, which started in 2022. A couple of examples from the experiments LLP trigger program are presented here and the performance of these custom triggers provided. ATLAS developped a dedicated trigger path to tag new heavy, charged particles, which may leave large energy deposits in the ID silicon layers compared to what is expected from a minimally ionizing particle [28]. The measurement of these large ionisation energy losses per unit path length in the Pixel detector is a handle to identify tracks as signal candidates. Fig. 11 left shows the correlation of the online dE/dx measurement to the offline measurement. Conversely CMS exploited the excellent tracking capabilities of the HLT system to implement a dedicated displaced-jets triggers, where the displaced jets can be identified as jets with small number of prompt tracks and/or with presence of displaced tracks [29]. The ratio between the Run 3 displaced-jets trigger efficiency and the Run 2 displaced-jets trigger efficiency for a 125 GeV $H \rightarrow SS$, with $S \rightarrow bb$ signal model is shown in Fig. 11 right. In this case Run 3 trigger efficiencies are higher than the Run 2 trigger efficiencies by a factor of 4 to 11 for m S between 10 and 60 GeV, and lifetimes 0 between 1 and 1000 mm, bringing a tremendous improvement in the analysis sensitivity and allowing the Run 3 search to have the same sensitivity of the Run 2 one with roughly 1/3 of the data available.

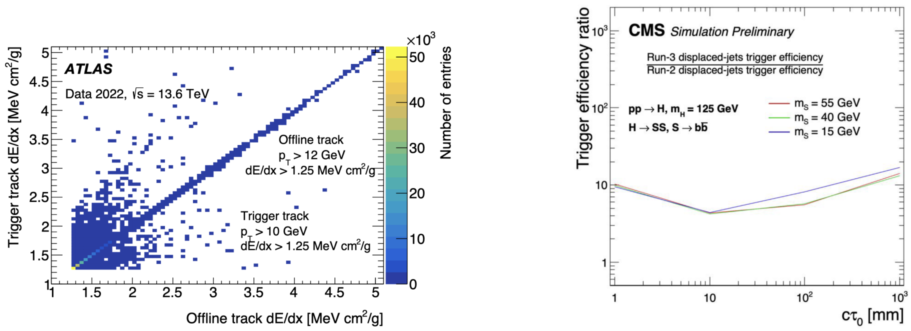

Figure 11: Left: Correlation of online vs offline dE/dx for offline tracks with transverse momentum above 12 GeV [28]. Right: Run 3 vs Run 2 efficiencies ratio of the displaced-jets trigger at CMS as a function of the LLP lifetime [29].

6. Conclusions

Now that ICHEP 2024 conference has passed, what should we envision in our light-cone in terms of BSM searches at LHC in the next few years? Primary Run 3 still has to provide a plethora of new results, including chasing those cases where an intriguing excess has been observed during Run 2 by either ATLAS or CMS. For example the case of low-mass di-photon resonances [30] of very high mass di-jet events [31, 32]. Eventually High-Luminosity LHC, expected to begin in 2029 will significantly increase physics reach by providing gains from high luminosity and new detector capabilities. The latter case is particularly interesting since new timing detectors, expected to be operative at that time, will provide a novel and unique handle to probe signatures with characteristic time structures like LLPs with a completely new approach at colliders. The next few years at LHC will provide us with a massive amount of new knowledge and we are expecting to exceed expectations.

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