Exotic searches by CMS

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These proceedings presents the results of new searches for various new physics phenomena in proton-proton collisions at $\sqrt{s} = 13$ TeV and 13.6 TeV delivered by the LHC and collected with the CMS detector during Run 2 (2016-2018) and Run 3 (2022-2023), respectively. In many cases these analyses set the most stringent limits on these new physics phenomena to date.

1 Introduction

These proceedings present the results of searches for various new physics phenomena beyond the standard model (SM) in proton-proton collisions delivered by the LHC and collected with the Compact Muon Solenoid (CMS)[1,2] detector. The focus will be on results from the Exotica (EXO) working group, looking for exotic new physics signatures. For the majority of these searches the full Run 2 (2016-2018) dataset has been used, corresponding to an integrated luminosity of about 140 fb^{-1} at $\sqrt{s} = 13$ TeV. Some new results with early Run 3 data collected in 2022 (with a total integrated luminosity of about 35 fb^{-1} at $\sqrt{s} = 13.6$ TeV) are also shown in Section 5. A choice was made by the author to show only recent results, most of them never presented before at a major conference, and to avoid overlaps with other reports including CMS material during the same conference. The report covers a few important aspects which are relevant nowadays in the design of EXO searches: follow up on excesses of events observed in data; explore new experimental signatures and final states; developments in trigger and analysis methods. Limits on parameters of theory models or resonance masses will be provided at 95% confidence level (CL). The updated lists of published results, preliminary results and summary plots from the EXO group are reported at Refs. [3,4,5].

2 New heavy resonances

A search for new physics in high-mass diphoton events [6] ($m_{\gamma\gamma} > 500$ GeV) was performed to look for either a bump (search for new resonances) or a broad deviation (non-resonant search) in the diphoton mass spectrum compared to what predicted by SM background processes. In the search for resonant excesses from both the spin-2 Randall-Sundrum (RS) and spin-0 heavy Higgs boson models, the diphoton mass spectrum is fit to a parameterized functional form, allowing for a description of the background shape based exclusively on data. Different resonance widths are probed (10^{-4}, 1%, 5%). In the search for non-resonant excesses that arise from the ADD extra dimension and clockwork models, a next-to-next-to-leading order (NNLO) calculation in quantum chromodynamics (QCD) is employed to estimate the SM diphoton background. The largest excess seen in the resonant search is at a resonance mass of about 1.3 TeV corresponding to a significance of 2.6 standard deviation (σ) local, and 0.8σ global after accounting for the lookelsewhere effect. No excess is observed by the corresponding ATLAS analysis. The CMS analysis excludes the existence of RS gravitons (with model parameter $\tilde{k} = 0.1$) with masses below 4850 GeV at 95% CL, compared to 4500 GeV of ATLAS. No significant deviation is observed in the non-resonant search and limits are set on the ADD model (lower limits on mass scale M_S ranging from 7.1 to 11.1 TeV depending on the specific theoretical convention) and clockwork model (with the fundamental scale M_5 excluded below 8.0 TeV for spring parameter k values between 0.2 GeV and 2.0 TeV) providing comparable sensitivity to ATLAS.

A search for new spin-0, charged resonance decaying to a W boson and a photon was performed [7], considering leptonic W decays in electron and muon final states with sizeable missing transverse energy (MET) coming from neutrinos. The analysis consists in looking for a bump in the transverse mass spectrum, built from the reconstructed charged lepton and the MET. No significant excess is observed in data under the hypothesis of either a narrow (0.01%) or a broad (5%) relative width for the new resonance. The results of the leptonic channel are combined with an existing CMS search for the same resonance in the complementary final state with hadronic W decays (jets). After the combination, the largest local excess is at 1.6 TeV mass with a local significance of 2.7σ (2.5σ) for the narrow (broad) resonance scenario. The combined analysis provides the most stringent limits to date in the 0.3-2 TeV mass range.

A more exotic experimental signature was considered in a new search for a massive resonance X decaying to a pair of spin-0 bosons ϕ that themselves decay to pairs of photons [8]. The analysis probes resonance masses m_X between 0.3 and 3 TeV, and is restricted to values of m_ϕ for which the ratio $\alpha = \frac{m_\phi}{m_X}$ is between 0.5% and 2.5%. For these values of α, the two photons (diphoton) from each ϕ boson are expected to be very close in space, generating energy deposits in the electromagnetic calorimeter (ECAL) detector with a significant spatial overlap. Each pair of photons from ϕ decay is reconstructed as a single cluster in ECAL (Γ) with a prominent dipolar substructure. Neural networks are designed to classify events containing such diphotons and to reconstruct the mass of the diphoton object (m_Γ) using the shapes of energy deposits in ECAL. The invariant mass spectra of $\Gamma\Gamma$ candidates are analyzed for the presence of the X resonance, in different bins of the reconstructed α^{reco} variable, defined as the ratio between the average cluster mass $< m_\Gamma >$ and the di-cluster invariant mass $m_{\Gamma\Gamma}$, in order to be sensitive to a wide range of different X and ϕ mass hypotheses. The largest excess in data compared to background predictions is observed for $m_X \sim 720$ GeV and $m_\phi \sim 6$ GeV corresponding to a local (global) significance of 3.6σ (1σ). This is currently the most sensitive search at the LHC in this final state.

3 Physics of dark sector

The so-called Hidden Valley models of new physics beyond SM consider a “dark sector” that extends the SM with a non-Abelian gauge group, similar to QCD, with new matter and gauge fields analogous to the SM quark and gluon fields. The SM particles are neutral under the new, dark interaction — “dark QCD” — and communicate with this sector only through a mediator particle that couples to both sectors. Depending on the model parameters, the formation process of jets in dark QCD showers (including fragmentation, hadronization and decays) can result in very different experimental signatures compared to the SM QCD. In this report, two different scenarios were considered.

The first search [9] considers the process $pp \to S \to \chi\chi$ were S is the mediator between SM and dark sector and χ is a quark of the dark sector (dark quark). While high momentum SM quarks produce collimated sprays of particles (jets), in this model a dark quark from the decay of an S particle produced at rest, generates a characteristic final state consisting of many low-momentum, isotropically distributed particles — described as a soft unclustered energy pattern (SUEP) — which would be very difficult to trigger. The analysis strategy employed high momentum (p_T) jet triggers to select events where the scalar mediator S is produced with

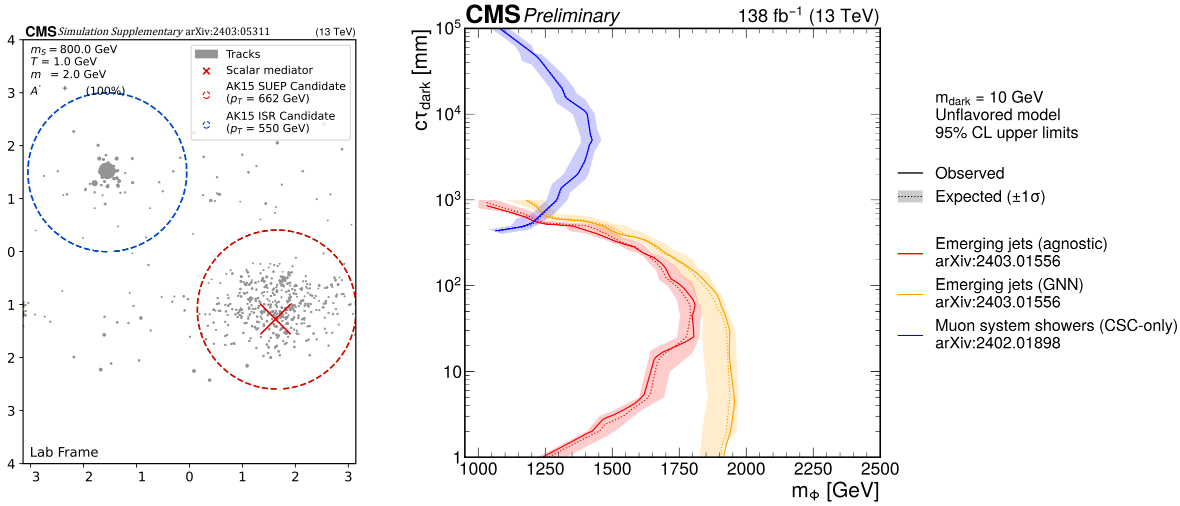

Figure 1 – An example signal event from a representative SUEP model with a resonance mass of 800 GeV, taken from Ref. [9] (left). Exclusion limits from the track-based and muon detector shower-based searches for pair production of a mediator particle ϕ that decays to a jet and an emerging jet, taken from Ref. [10] (right).

large Lorentz-boost recoiling against an initial-state radiation (ISR) jet. The S decay products are collected within a wide-cone jet (SUEP-jet) with a peculiar internal substructure. The energy pattern inside a SUEP-jet shows in fact a characteristic isotropic shape and a large multiplicity of particles, as shown in Fig. 1. The number of tracks and the associated sphericity observable in the SUEP-jet candidate are used to discriminate between the signal and the background, which is estimated from data in suitable control regions. With no observed excess of events over the SM expectation, limits are set on the model parameters. This result represents the first dedicated search for SUEPs at LHC.

The second search [10] focuses on the pair production process $pp \to \phi\phi$ where each dark sector mediator ϕ decays to a SM quark and a dark quark. In this scenario, the dark quark showers and hadronizes, it produces long-lived dark mesons (with a characteristic lifetime τ_{dark}) that subsequently decay into SM particles, resulting in a jet — known as an emerging jet (EJ) — with multiple displaced vertices. A graph neural network (GNN), which takes in input several reconstructed observables (eg. the transverse impact parameter of tracks in a jet), is used to discriminate between the signal EJ and background QCD jets. In addition, a more model agnostic search based on a traditional cut-based selection is also performed. No excess of events beyond the SM expectations is found and upper limits are set on the production cross section as a function of the mediator mass and $c\tau$, for different hypotheses on the dark meson mass. The CMS experiment covers a wide range of $c\tau_{dark}$ values for this benchmark model (from 1 mm to 10^2 m) exploiting both the EJ search and a complementary search based on muon detector showers, as shown in Fig. 1.

4 Data scouting

Theories beyond the SM often leads to the prediction of new light particles with feeble couplings. These events may not be collected in pp collisions due to high energy thresholds in standard triggers. Specialized data-taking and data-processing strategies were introduced by the CMS experiment in Run 1 (2010-2012) of the CERN LHC to enhance the sensitivity to such particles. The novel data-scouting strategy (first introduced at the end of 2011) enhances sensitivity to low-energy physics processes by significantly lowering the high-level trigger (HLT) thresholds and storing a reduced event content on disk, as shown schematically in Fig. 2. For events passing these loose trigger selections, only high-level physics objects (such as charged leptons or jets) reconstructed at the HLT are stored on disk, with no raw data from detector channels.

These dedicated data samples are then used offline to perform physics analysis. The CMS experiment has greatly expanded the sensitivity to resonances with low mass m_X thanks to data scouting, for both final states with dijets/multijets ($50 < m_X < 1500$ GeV) and dimuons ($2m_\mu < m_X < 40$ GeV). CMS has released for this conference a review paper [11] on this topic which describes the origin and evolution of data scouting in CMS, including performance studies of HLT reconstructed objects and results of physics measurements.

The data scouting was significantly improved for the ongoing Run 3. A factor 4 increase in scouting HLT rate compared to Run 2 (up to a max. of 30 kHz) was reached. This improvement was made possible thanks to a new fast tracking based on pixel-detector only ("Patatrack" algorithm) and the use of graphical user interfaces (GPUs) at HLT. A single data-scouting stream is now collected with full event record of Particle Flow (PF). The PF is algorithm that aims to reconstruct and identify each individual particle (called a PF candidate) in a pp collision event, with an optimized combination of information from the various elements of the CMS detector. The event content is still reduced but rich enough to perform complex offline analyses, and it includes PF candidates, jets, muons, electrons, photons, tracks, and vertices reconstructed at HLT. The presence of PF candidates makes possible, for example, to perform offline the reclustering of jets and to study the jet substructure.

A prime example of the discovery potential with the data scouting approach is represented by the CMS search for multijet resonances. This is a comprehensive analysis that looks for pair produced resonances each decaying into two or three jets in both boosted and resolved final states. The focus of the conference report was on the resolved 6-jet final state. The corresponding benchmark signal model is the pair production of a pair of gluinos each decaying to three quarks, as foreseen in Supersymmetry models with R-parity violation (RPV SUSY). The search looks for a bump in the trijet mass spectrum after a set of selection criteria that reduce the SM QCD background and enhance the specific signal topology. The largest local excess is observed at a resonance mass of about 770 GeV with a local significance of 2.6σ. Figure 2 shows that the upper limits on signal cross section are a factor 10 to 100 times more stringent in the sub-TeV mass range than other experiments (which use instead a traditional trigger strategy) and probe resonances masses as low as 70 GeV, thanks to the data-scouting approach.

5 New Run 3 results

A new search for low-mass long-lived particles (LLPs) decaying to displaced jets [12] was presented during this conference. The benchmark signature for this search is the exotic decay of the 125 GeV Higgs boson (H) to two long-lived neutral scalars S ($H \to SS$), each of which further decays to a pair of SM fermions (bb, dd, or $\tau\tau$ hadronic final states were considered). The target signature is a pair of jets, referred to as a dijet, arising from the decay of the LLP. Displaced vertices (DVs) can be reconstructed using the displaced tracks associated with the dijet. The properties of the tracks, DVs, and dijet are used to discriminate between exotic LLP signatures and SM background processes. Major improvements compared to the previous CMS analysis were introduced: new triggers [13] (increasing the signal acceptance by a factor 10 compared to Run 2); a new reconstruction for displaced secondary and tertiary vertices (the latter coming mainly from in flight decays of B mesons to D mesons); a new LLP tagging based on GNNs. No excess was observed in data. Upper limits were set on the branching fraction of the $H \to SS$ decay as a function of the proper decay length $c\tau_0$ of the LLP. These are the best limits to date for LLPs in the 15-55 GeV mass range and with $c\tau_0 < 1$ m. The sensitivity of this CMS analysis based on Run 3 data is up to 10 times better (in terms of upper limits on branching fraction) than a similar ATLAS Run 2 search despite the 4 times smaller dataset, thanks to both trigger and analysis improvements.

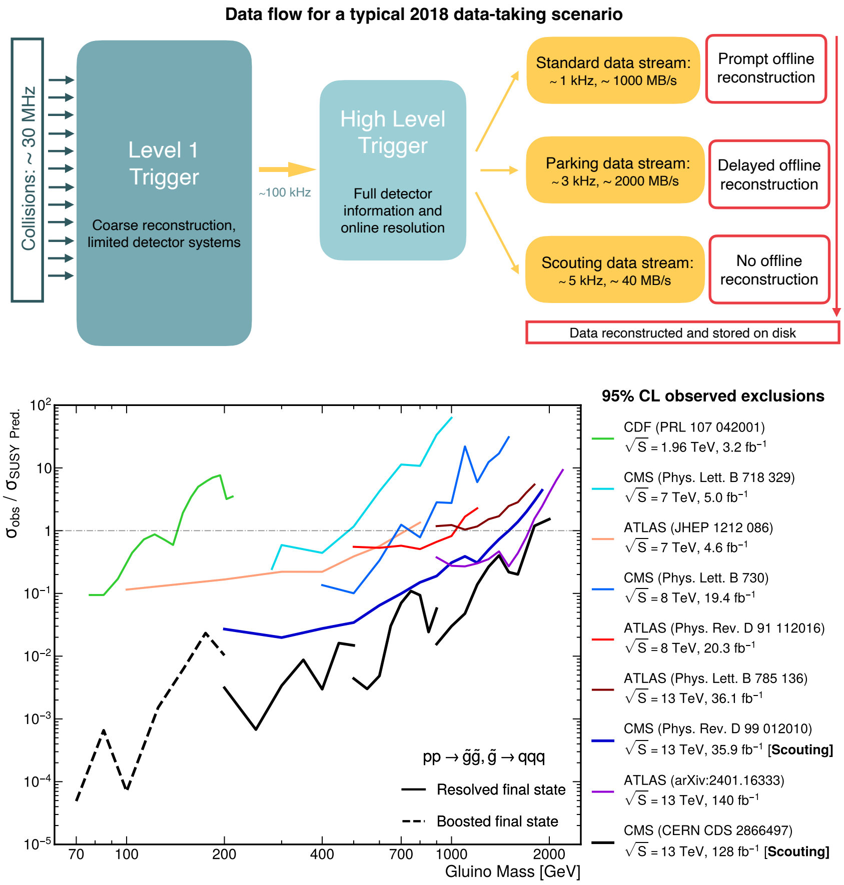

Figure 2 – A schematic view of the typical Run 2 data flow during 2018 showing the data acquisition strategy with scouting and parking data streams, along with the standard data stream (left). Comparison of limits from searches for RPV gluinos decaying to three partons (right). Plots taken from Ref. [11].

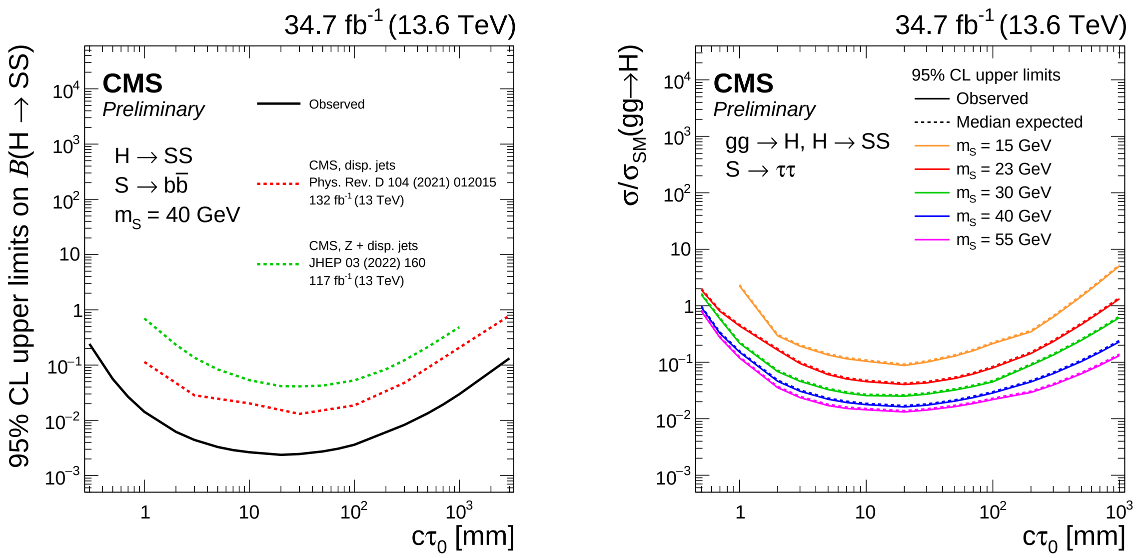

Figure 3 – Upper limits on the branching fraction of the $H \to SS$ decay for $S \to bb$ (left) and $S \to \tau\tau$ (right) for different LLP masses m_S and proper decay lengths $c\tau_0$. These are the first limits for the $S \to \tau\tau$ decay. Plots taken from Ref. [12].

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