PROCEEDINGS OF SCIENCE

Searches in CMS for long-lived particles and other non-conventional signatures

Celia Fernández Madrazo[a,1,*]

[a] *Instituto de Física de Cantabria, (CSIC - Universidad de Cantabria), Edificio Juan Jordá, Avenida de los Castros s/n, Santander, Spain*

E-mail: celia.fernandez.madrazo@cern.ch

Many models beyond the standard model predict new particles with long lifetimes, such that the position of their decay is measurably displaced from their production vertex, and particles giving rise to other non-conventional signatures. We present recent results of searches for long-lived particles and other non-conventional signatures obtained using data recorded by the CMS experiment at Run 2 of the LHC.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

[1]on behalf of the CMS Collaboration
[*]Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

https://pos.sissa.it/

PoS(ICHEP2022)152

1. Introduction

The fundamental particles and their interactions are described by the Standard Model (SM) of particle physics. The SM, despite of being an accurate theory which has been verified by the experimental results, fails to describe some of the existing phenomena in the universe such as dark matter or gravity. For this reason, multiple extensions of the SM have been proposed and the high energy experiments were correspondingly developed and optimized for their detection and study. These extensions are often expected to manifest as prompt new mass resonances, missing energy measured in the detector or deviations of the measured quantities from their expected values, among others. The detectors, data processing and the analyses studying such physics models are therefore optimized to target these topologies. However, several theories beyond the Standard Model (BSM) also predict the existence of particles that may appear as atypical topologies in the detectors, referred as non-conventional signatures.

Non-conventional signatures are challenging to both detect and analyse as neither the trigger, data acquisition or most common analysis techniques were optimized for them. For this reason, analyses targeting non-conventional signatures often have to deal with the estimation of non-standard backgrounds which are not usually well reproduced by simulation, loss of efficiency in the particle reconstruction or reduced trigger performance. Despite these difficulties, there is an increasing effort to improve the analysis infrastructure in many fronts. In this sense, non-conventional signatures have pushed to improve and develop dedicated triggers, algorithms and analysis strategies whenever possible. They have provided a deeper understanding of both known physics and our experiments.

2. Recent searches in CMS for non-conventional signatures

The CMS Collaboration has performed many searches targeting non-conventional signatures over the last years studying pp collisions collected with the Compact Muon Solenoid (CMS) detector [1]. Every search is intended to be inclusive i.e. provide sensitivity to different BSM scenarios that may be compatible with the topology. The analysis strategies also try to be sensitive to low masses and low momentum and, in the case of long-lived particles, improve the efficiency at high displacement to cover as wide lifetime range as possible. Despite the fact that all these searches are very specific and were designed to target very different topologies they can be classified according to the experimental signature that was studied in each case. The analyses presented in this proceedings are classified within three distinct topologies: three analysis targeting displaced leptons, one analysis studying displaced jets and an analysis which searches for fractionally charged particles that appear as low ionizing particles in the detector. The latest is a new release for ICHEP 2022. Table 1 shows a summary of these searches with their signature and the displacement and mass to which they are sensitive.

The first leptonic analysis is a search for long-lived particles decaying into displaced leptons with large impact parameters [2]. The considered topology consists of pairs of displaced leptons that are not required to originate from a common vertex, which makes this search sensitive to

PoS(ICHEP2022)152

Analysis	Signature	Displacement	Mass
CMS-EXO-18-003	Displaced (di)leptons	Within pixel tracker	> 30 GeV
CMS-EXO-20-014	Displaced dimuon vertex	Within pixel tracker	> 200 MeV
CMS-EXO-21-006	Displaced dimuon vertex	Tracker and muon system	> 10 GeV
CMS-EXO-20-003	Displaced jets + Z	Within tracker	> 15 GeV
CMS-EXO-19-006	Low ionizing particles	Outside of CMS	> 100 GeV

Table 1: Summary of recent analyses targeting non-conventional signatures and long-lived particles.

PoS(ICHEP2022)152

displaced leptons produced in the decay of two distinct LLPs. LLP decays are limited to occur within the pixel tracker volume. Both displaced electrons and muons are studied and different channels are defined according to the possible lepton type combinations, namely $\mu\mu$, ee and $e\mu$. The events were triggered by using dedicated displaced dimuon streams for muons and diphoton streams for electrons. The optimization of the event selection is based exclusively on displaced lepton information, being the main discriminant of this search the transverse impact parameter $|d_0|$, which covers values from 0.01 to 10 cm. Several background sources are identified and among all of them the most important ones are leptonic tau decays, leptons with mismeasured d_0, and decays of heavy flavor mesons. Their contribution at high $|d_0|$ is estimated from data with an ABCD method where the control regions are defined with the measured $|d_0|$ of the two selected leptons. As these values may be correlated for some of these processes, dedicated corrections are derived, being this effect found significant for leptonic tau decays. Other sources, like cosmic muons, interactions with the detector material and long-lived SM resonances, are efficiently rejected by the lepton selection, leaving their contribution in the signal region to be negligible.

This analysis sets exclusion limits on a RPV SUSY model with long-lived stops where the maximum sensitivity is reached at $m_{\tilde{t}}$ = 1500 GeV and $c\tau_{\tilde{t}}$ = 2 cm; on GMSB SUSY excluding long-lived sleptons of $m_{\tilde{\ell}}$ = 680 GeV and $c\tau_{\tilde{\ell}}$ = 2 cm; and also on Higgs boson decays into long-lived scalars where the stringent constraints are found around $c\tau_{\text{S}}$ = 1 cm.

There is a second search for displaced muons [3] which extends the displaced dimuon sensitivity to higher displacement and LLP lifetimes by exploiting the use of the tracker and the muon system alone to reconstruct the muons. Unlike the previous search, the two muons are required to be fitted to a common vertex. The muons are reconstructed with the muon chambers but also in the tracker whenever possible so the analysis is splitted into three categories according to which CMS subsystems succeeded to reconstruct the muons of the pair. These categories are equivalent to three distinct analyses where the muon selection is optimized separately: one targeting pairs of muons reconstructed only in the muon chambers, other with the two muons reconstructed in both muon chambers and tracker, and a third hybrid category that comprises events where one muon of the pair was reconstructed only in the muon system and the other muon also in the tracker. Each category provides coverture in a different range of displacement, being the tracker reconstruction dominant at low LLP decay length values up to 30 cm, the hybrid pairs contributing in the medium range, from 30 to 60 cm, and the reconstruction in the muon system recovering the efficiency when the dimuon vertices are reconstructed more displaced, over 60 cm. The events were collected with dedicated streams that reconstruct the muons by using only the muon system and removing the algorithm constraints to the pp interaction point. While some background sources, such as cosmic muons, multijets and low mass resonances, are heavily suppressed with the optimized muon selection, two main contributions are estimated from data measured in control regions. The first one comes from missreconstruction of muons produced in prompt processes where Drell-Yan is the main background. This contribution is estimated from a control region defined by means of the difference in azimuthal angle between the dimuon momentum $\vec{p}_T^{\mu\mu}$ and the vector $\vec{L}_{xy}$ that joins the interaction point with the reconstructed vertex. The other consists of dimuon vertices produced in nonprompt processes, mainly QCD, and it is estimated from a control region with same-sign charged dimuon vertices as this contribution is expected to be charged-symmetric.

Limits are set on a Hidden Abelian Higgs Model (HAHM) with long-lived dark photons Z_D, where a branching fraction of the Higgs boson to dark photons of 1% is excluded for m_{Z_D} masses between 20 to 60 GeV and lifetimes from a few tens of μm to 100 m. The results of this analysis are complemented at lower mass and lifetime values by the next leptonic analysis. Constraints are also set in a model with BSM heavy scalar bosons decaying to long-lived scalars.

The third leptonic analysis is a search for LLPs decaying to muons with high rate triggers [4]. It studies the same topology as the previous one but the events were collected with scouting triggers, which are special streams with looser requirements than the usual triggers i.e. lower muon p_T and invariant mass thresholds, but using simplified reconstruction algorithms. Thanks to these loosen restrictions on the physical objects, the sensitivity to low mass LLPs is strongly increased with respect to other analyses. To compensate the huge event rate recorded by these streams, the information saved in the events is limited. The muon pairs reconstructed at trigger level are filtered and only the opposited-sign charged ones found within the pixel tracker are kept. Therefore, the sensitivity of this search is limited to LLP decays occurring within its volume. The dimuon vertices are selected to reject the background, composed of cosmic muons, vertices made from PU tracks, QCD, missreconstruction, interactions with detector material and specially B hadron decays. The events are also categorized as a function of the transverse distance of the vertices L_{xy}, the dimuon $p_T^{\mu\mu}$ and whether the muons are isolated or not. The bins resulting from this categorization provide coverture to different LLP lifetimes and masses. To extract the final results and set limits to the considered theoretical models, a simultaneous signal + background fit is done to the data in separate invariant mass windows. Invariant mass regions around low mass SM resonances are masked. Both signal and background contributions are parameterized by analytical functions.

This search sets upper limits on the same HAHM model as the previous one. In this case, constraints on long-lived Z_D are set for masses down to 700 MeV and highly improve over 5 GeV, where there is no background contribution from b hadron decays. Limits are also extracted for long-lived resonances arising from b hadron decays, $h_b \rightarrow \phi X$, down to m_ϕ = 200 MeV.

The next analysis is a search for Higgs boson decays into long-lived particles in associated Z boson production [5]. The studied long-lived particles are assumed to decay hadronically and appear as jets reconstructed displaced from the interaction point. This topology is used to discriminate the signal from the background e.g. SM displaced decays, interactions with detector material,

PoS(ICHEP2022)152

photon conversion and jet miss-identification. Jets are reconstructed with standard CMS clustering algorithms but tagged with track level information variables as done in a previous CMS search [6] where this technique was developed and optimized. The signal region of this search comprises the events where at least two displaced jets were tagged with this criteria. The Z bosons are key objects of the search, as they are assumed to decay into prompt leptons that are used to trigger the events without loosing efficiency regardless of how displaced the jets are. The main background contributions, which are Drell-Yan, $t\bar{t}$ and single top decays, are estimated from control regions defined from these prompt lepton kinematics. Estimation of other minoritary background sources is provided by Monte Carlo simulation. The whole estimated background yields are validated in seven separate validation regions defined by inverting the displaced jet tagging cuts.

This analysis sets upper limits on the Higgs boson branching fraction to a pair of long-lived scalars S to d (b) quarks, which is constrained to 3-4 (4-5)% for masses $m_S = 40, 55$ GeV and lifetimes in the range 10-100 mm. Constraints to lower masses, at $m_S = 15$ GeV are found to be 14 (13)% in the 20-35 mm range.

The last analysis presented in these proceedings is a search for fractionally charged particles (FCP) [7] and a new release in 2022. The FCPs considered in this search are stable enough to decay outside of the CMS detector and they are identified as high p_T inner tracker tracks matched to muon tracks reconstructed in the muon spectrometer. This signature is very similar to the one left by muons arising from W or Z decays, which comprise the majority background of this search. The energy that ionizing particles deposit per unit length dE/dx in the detector is described by the Bethe Block function and strongly depends on their charge. As fractionally charged particles have $Q < 1$ the dE/dx spectrum would be expected to be shifted towards lower values with respect to SM particles that are measured in the CMS detector. The number of hits with low measured dE/dx, referred as $N_{\text{hits}}^{\text{low}dE/dx}$, is therefore higher for FCPs, and this variable is used as the main discriminant of the analysis. Background appear at high $N_{\text{hits}}^{\text{low}dE/dx}$ values thanks to radiation damage in the detector, pixel inefficiencies, hits in the edge of modules and other effects that are mitigated with an optimized track hit selection. Its contribution is modeled with a binomial distribution fitted to data to extract the background yield estimation.

Upper limits on the FCP production cross section are computed for given charge and mass scenarios. FCPs of charges $2/3e$ are excluded for cross sections above 0.283 fb at masses of $m_{\text{FCP}} = 636$ GeV. Exclusion limits cover charge values from $0.9e$ down to $1/2e$.

3. Conclusions

Non-conventional signatures offer the possibility to perform new appealing searches while looking at unexplored regions of the phase space. Due to their atypical characteristics, they may provide a powerful handle to reduce the background and gain sensitivity, but at the same time are challenging to detect and analyse. Five of the latest Run 2 CMS searches studying non-conventional signatures were presented, three analyses targeting displaced leptons, one studying displaced jets

PoS(ICHEP2022)152

and a new release in 2022 searching for fractionally charged particles. No evidence of any excess over background has been observed and upper limits have been set in different BSM models

References

[1] The CMS Collaboration *et all*, The CMS experiment at the CERN LHC. 2008 *JINST* **3**, S08004

[2] The CMS Collaboration, Search for long-lived particles decaying to leptons with large impact parameter in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$. *Eur. Phys. J. C* **82**, 152 (2022)

[3] The CMS Collaboration, Search for long-lived particles decaying to a pair of muons in proton-proton collisions at $\sqrt{s}$ = 13 TeV. Submitted to the *Journal of High Energy Physics*. arXiv:2205.08582

[4] The CMS Collaboration, Search for long-lived particles decaying into muon pairs in proton-proton collisions at $\sqrt{s}$ = 13 TeV collected with a dedicated high-rate data stream. *J. High Energ. Phys.* **2022**, 62 (2022)

[5] The CMS Collaboration, Search for long-lived particles produced in association with a Z boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV. *J. High Energ. Phys.* **2022**, 160 (2022)

[6] The CMS Collaboration, Search for new long-lived particles at $\sqrt{s}$ = 13 TeV. *Physics Letters B*, Volume 780, (2018)

[7] The CMS Collaboration, Physics Analysis Summary EXO-19-006, in preparation.

PoS(ICHEP2022)152