A search for beyond the Standard Model physics using a final state with light and boosted muon pairs at the CMS experiment

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Abstract. A search for physics beyond the Standard Model (SM) is performed using a final state with multi-muons and collision data collected by the Compact Muon Solenoid (CMS) experiment at the CERN Large Hadron Collider (LHC). The topology under study considers events with pairs of oppositely charged muons (dimuons) with a low invariant mass and a common origin. This selection offers an extremely low contribution from SM processes and fits into several beyond the SM signatures. Results are interpreted in a model-independent fashion and in the context of two scenarios: Supersymmetry including “dark” sectors (dark-SUSY) and Next-to-Minimal Supersymmetric Standard Model (NMSSM). Both scenarios postulate a non-SM decay of the Higgs boson to a pair of new light bosons which subsequently decay to a pair of muons. In the case of the dark-SUSY scenario, the hypothetical production of dark photons could give an insight on the origin of dark matter.

1. Motivation

On July 2012, the CMS and ATLAS collaborations at the CERN LHC announced the observation of a new particle with a mass of 125 GeV/c² and properties consistent with those of the predicted Higgs boson [1, 2]. This discovery constituted one of the greatest achievements made by the collaborations thus far and it marked the beginning of the LHC research program. Since then, extensive maintenance and upgrade work has been conducted on the accelerator and its different subsystems in order to reach the desired collision energy and particle rate. This effort will continue in the coming years. In the case of Higgs physics, there are two well-identified research programs at the LHC. The first one aims to collect enough data to perform precision measurements of its properties in order to determine if any of those deviate from SM expectations. The second program focuses on searches for new physics considering non-SM decays of the Higgs boson. Some of those new physics scenarios could be accessible with the available data. In this letter we explore one of the non-SM decays of the Higgs boson to a pair of new light bosons which subsequently decay to a pair of oppositely charged muons. One of the strengths of this analysis is the model-independent design; this allows for the results to be reinterpreted by other models with similar topologies. In addition, two benchmark scenarios are considered. The first one is in the context of the NMSSM that effectively extends the Higgs sector and allows for the production of new light bosons [3–5]. The second one is in the context of supersymmetric models with additional “hidden” or “dark” sectors (dark-SUSY) [6–8] which
postulate the production of dark photons ($\gamma_D$) that, unlike SM photons, are massive and could decay to SM particles via a kinetic mixing parameter ($\epsilon$). Previous searches for pair production of new light bosons that decay into dimuons have been performed at the LHC [9–13]. The two latest results, from ATLAS and CMS, consider models in which the $\gamma_D$ can be long-lived.

2. CMS detector and data acquisition

The CMS detector was designed and built with several subsystems that provide an accurate measurement of muon properties. The central feature of the CMS apparatus is a superconducting solenoid of 6m internal diameter which provides a strong magnetic field of 3.8T that is used to measure muon momentum with high precision. Muons are identified and their trajectories are reconstructed using information from three different detector technologies: Drift Tubes (DTs), Cathode Strip Chambers (CSCs), and Resistive Plate Chambers (RPCs). A more detailed description of the CMS detector and its subsystems can be found in [14]. The data was collected by the CMS experiment in 2015 using 13 TeV proton-proton collision energy and it corresponds to a total integrated luminosity of 2.8fb$^{-1}$. A dedicated tri-muon trigger running online and refined with complex algorithms offline was used to select the data for this analysis.

3. Analysis strategy and SM backgrounds

Events are selected if they contain at least four high quality reconstructed muons with a minimum transverse momentum ($p_T$) of 8 GeV/c and a pseudo-rapidity ($\eta$) range below 2.4. In addition, the leading muon is required to have a $p_T > 17$ GeV/c and to be located in the central region ($|\eta| < 0.9$) to ensure a high and flat trigger efficiency. Muons are paired based on a common vertex criteria (Kalman filter method) and low invariant mass selection of $m(\mu^+\mu^-) < 9$ GeV/$c^2$. Once all of the dimuons are formed, only events with exactly two dimuons are selected. Furthermore, each dimuon is required to have at least one hit in one of the first three pixel barrel layers or in one of the two pixel endcap layers. This constraint defines the fiducial volume used for this search. To suppress backgrounds with dimuons coming from jets, dimuons are required to be isolated from all other activity in the event. Finally, the invariant masses of the two reconstructed dimuons should be compatible with each other to within the detector resolution. This selection defines our signal region; it can be visualized as a corridor in the 2D dimuon invariant mass space, as shown in figure 1. The complete offline selection criteria can be found in [15]. Monte Carlo simulated samples for both the NMSSM and dark-SUSY scenarios were produced in order to optimize the selection criteria and quantify the sensitivity for our benchmark scenarios. Table 1 shows the total event selection efficiency $\epsilon_{MC}^{full}$ using one dark-SUSY sample with specific parameters for the dark photon. To provide a simple recipe for future reinterpretations of the results in the contexts of other models, we separately determine the geometric and kinematic acceptance of this analysis calculated using generator level information only. We denote this acceptance as $\alpha_{gen}$. The model independence of the ratio $\epsilon_{MC}^{full}/\alpha_{gen}$ (which holds for variations on NMSSM and dark-SUSY parameters) permits an estimate of the full event selection efficiency of this analysis for any arbitrary new physics model predicting the final state signature with a pair of new light bosons.

Three main SM processes contribute to the background in the signal region. The dominant contribution comes from events with two b-quarks ($b\bar{b}$), in which each b-quark decays to a pair of muons via double semi-leptonic decay; this background is estimated directly from the data by examining a control region where this process is enhanced and then extrapolating the contribution to the signal region. The second contribution is the prompt production of two $J/\psi$ particles coming from two different mechanisms (double and single parton scattering) and is estimated with a combination of data and Monte Carlo simulation. The third (and smallest) contribution comes from electroweak production of four muons where the dominant process is the production of two Z bosons that further decay into muons; this background is estimated purely
Table 1. Event selection efficiencies $\epsilon^MC(m_h, m_{\gamma_D})$ and kinematic acceptances $\alpha_{gen}(m_h, m_{\gamma_D})$ for a dark SUSY benchmark model with a dark photon lifetime of 2 mm.

| $m_h$ [GeV] | 0.25 | 0.7  | 1.5  | 8.5  |
|-------------|------|------|------|------|
| $m_{\gamma_D}$ [GeV] | 125  | 125  | 125  | 125  |
| $\epsilon^MC$         | 0.00631 ± 0.00021 | 0.01733 ± 0.00042 | 0.03325 ± 0.00056 | 0.13099 ± 0.00137 |
| $\alpha_{gen}$        | 0.00982 ± 0.00026 | 0.02710 ± 0.00053 | 0.05096 ± 0.00070 | 0.20032 ± 0.00175 |
| $\epsilon^MC/\alpha_{gen}$ | 0.64232 ± 0.01258 | 0.63956 ± 0.00919 | 0.65242 ± 0.00637 | 0.65393 ± 0.00380 |

from Monte Carlo simulation. The total contribution to the background from SM processes into the signal region is estimated to be $0.74^{+0.54}_{-0.32}$ (stat.) ± 0.15 (syst.) events.

4. Results and interpretation

The full event selection criteria is applied in data; it results in one observed event inside the signal region. This observation is consistent with the expectation from SM, therefore results are interpreted as exclusion limits. The model independent limit on $\sigma(pp \rightarrow 2a + X) \times B^2(a \rightarrow 2\mu) \times \alpha_{gen}$ is 1.7fb and it is constant in the entire $m_a$ range as a consequence of having a constant $\epsilon^MC/\alpha_{gen}$ for each signal mass. For the NMSSM scenario, the 95% CL upper limit is derived for $\sigma(pp \rightarrow h_{1, 2} \rightarrow 2a_1) \times B^2(a_1 \rightarrow 2\mu)$ as a function of $m_{h_1}$ for three choices of $m_{a_1}$ (where $a_1$ is the new light boson), as shown in figure 2. In the case of the dark-SUSY scenario, a 95% CL limit on the product of the Higgs boson production cross section and the branching fractions of the Higgs boson decay to a pair of dark photons is determined. The limit is set in the $(m_{\gamma_D}, \epsilon)$ plane and it is shown in figure 3, along with limits from other experimental searches. The lifetime is directly related to the kinetic mixing parameter $\epsilon$ and the mass of the dark photon $m_{\gamma_D}$ via $\tau_{\gamma_D}(\epsilon, m_{\gamma_D}) = \epsilon^{-2} f(m_{\gamma_D})$, where $f(m_{\gamma_D})$ is a function that depends only on the mass of the dark photon [16].

5. Conclusions and future perspectives

A search for physics beyond the SM is proposed. The models under study postulate the production of new light bosons from a non-SM decay of the Higgs boson. After a detailed study of analysis selection criteria and estimation of background contributions, there is no
Figure 2. The 95% CL upper limits on the production of new light bosons ($a_1$) as a function of $m_{h_1}$, for the NMSSM scenario.

Figure 3. 95% CL upper limits on the production of dark photons (black solid curves) in the $(m_{\gamma_D}, \varepsilon)$ plane.

evidence for deviations from SM expectations. Results are interpreted as exclusion limits in a model-independent fashion and as a function of NMSSM and dark-SUSY parameters. An updated analysis is in preparation in which the data collected by the CMS experiment in 2016 will be analyzed. This data corresponds to about ten times the luminosity used here; it can potentially increase the probability of observing new physics phenomena and also improve the current analysis methods.

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