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Search for long-lived particles with the CMS detector at the LHC

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The CMS collaboration is pursuing several searches for long-lived particles produced in pp collisions at the LHC. Results from two complementary signature-based searches are presented. The explored signatures are i) a pair of jets associated to a displaced vertex and ii) a track with a high ionization energy loss and/or with a long time of flight. These signatures would, respectively, indicate the presence of a neutral long-lived particle decaying into a pair of quarks or the presence of a long-lived massive charged particle. In both cases, the data are consistent with the expected background and upper limits are set on the production cross section of such long-lived particles.

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1. Introduction

Long-lived, charged or neutral, particles are predicted by various extensions of the Standard Model (SM). A non-exhaustive list of models predicting these particles are Super Symmetry (split SUSY and MSSM), Gauge mediated Symmetry Breaking (GMSB), Hidden-Valley, Extra dimensions, and several others. If the prediction of any of these models reveals to be true, long-lived particles should be produced in quantity at the Large Hadron Collider (LHC) and observable with the Compact Muon Solenoid (CMS) detector [1]. The CMS collaboration is therefore pursuing several searches for long-lived particles.

Searches for **charged** long-lived particles generally relies on the large ionization energy loss experience by the particle travelling in the CMS detector. Two complementary analyses are exploiting this signature. The first one [2] exploits the information reccorded by CMS in a time window (O(50) ns) that is compatible with the LHC proton bunch crossing. The analysis then tries to discriminate the long-lived particle signal from the other SM particles produced in proton-proton collision. This analysis will be described in more details in the following sections. On the contrary, the other analysis [3] assume that, because of their large ionization energy loss, some of these long-lived particles may stop in the CMS detector (mostly in the calorimeters or in the iron yokes). Then, if the particles are unstable (as known from cosmological observation) but long-lived enough ($\tau > 25$ ns), they may decay while the LHC is off or no bunches were crossing in the CMS detector. These decays would be out-of-time with respect to LHC collisions and may well occur at times when there are no collisions or when there is no beam in the LHC machine. The observation of such decays, in what should be a quiet detector would be another unambiguous signature for the discovery of new physics. This analysis will not be described further in the document, but the interested reader may find all details in Ref. [3].

Searches for **neutral** long-lived particles must use different techniques. In one hand, if the life time of the particle is long compared to the detector size, it would lead to large missing transeverse energy and several dedicated searches explore this signature. On the other hand, if the life time is extremely short, $c\tau$<O(100)μm, standard searches for new physics particles decaying to prompt fermions or bosons would apply. If on the contrary, the life time of the particles is in the range O(100)μm<$c\tau$<O(10)m, the previous searches won't work: No missing energy is expected since the particle decays within the CMS detector and the second kind of searches, looking at prompt fermions and bosons will miss the decay of the long-lived particle too, since this one is not prompt. So dedicated searches looking at particles originating from a highly displaced vertex are needed. The CMS collaboration is looking for such displaced vertex in the lepton, photon and jet channels. Information about the displaced lepton and photon channel can be found in [4] and [5] respectively. The search in the jet channel [6] will be discribed further in the following sections.

2. Search for long-lived charged particles

Given their large mass and the limited energy available in LHC collisions, long-lived charged particles will be significantly slower than light ($\beta < 1$). Consequently, they will have an anomalously high ionization energy loss (dE/dx) that could be measured by the CMS Silicon Strip Tracker. A fraction of these highly penetrating particles are also expected to reach the CMS Muon System, which could therefore be used to measure the time-of-flight (TOF) of the particles. The typical signature of a long-lived charged particle is therefore a high momentum track reaching the muon system that have an anomalously high dE/dx and TOF.

The energy loss being also proportional to the square of the electric charge, this search can also be used to search for particles with non-unit electric charge ($|Q| \neq e$). Multiply (fractionnaly) charged particles would lead to dE/dx values significantly larger (lower) than what is expected from, $|Q| = e$, SM particles as shown in Fig. 1.

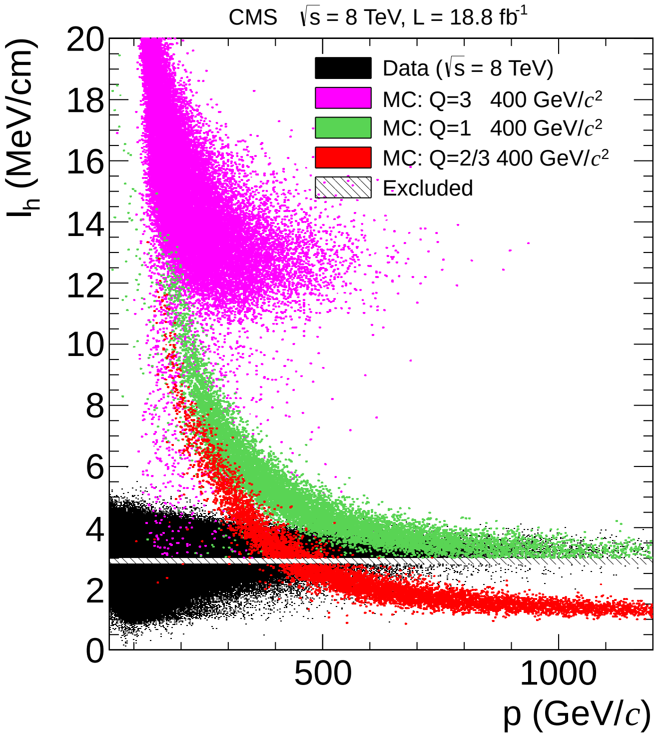

Figure 1: Distribution of a dE/dx estimator (I_h) versus particle momentum for $\sqrt{s} = 8$TeVdata (black) and also including MC simulated HSCP candidates of different charges. Tracks with $2.8 \leq I_h \leq 3.0$MeV/cm are excluded by preselection requirements.

Colored long-lived particles, e.g. stops or gluino, are expected to form bound states, called R-hadron, in the process of hadronization. The interactions with matter experienced by these bound-states may lead to a modificaiton of their quark constituents and therefore to a change of their electric charge. Therefore a R-hadron might be produced charged (neutral) but reach the muon system with as a neutral (charged) state. Complementary analyses that does not require the particle to be charged in either the muon system or in the inner silicon tracker are therefore also used.

This search [2] for long-lived particles uses events from 7 and 8 TeV pp collisions produced by the LHC during the 2011 and 2012 Runs corresponding to an integrated luminosity of 5.0 fb^{-1} and 18.8 fb^{-1}. The events where selected using transverse missing energy (MET>150 GeV) and/or muon (muon pT>40GeV) triggers. The candidates are selected based on their pT as measured from the inner tracker or muon system, on theur tracker dE/dx and on their time-of-flight (TOF) from the interaction point to the muon system.

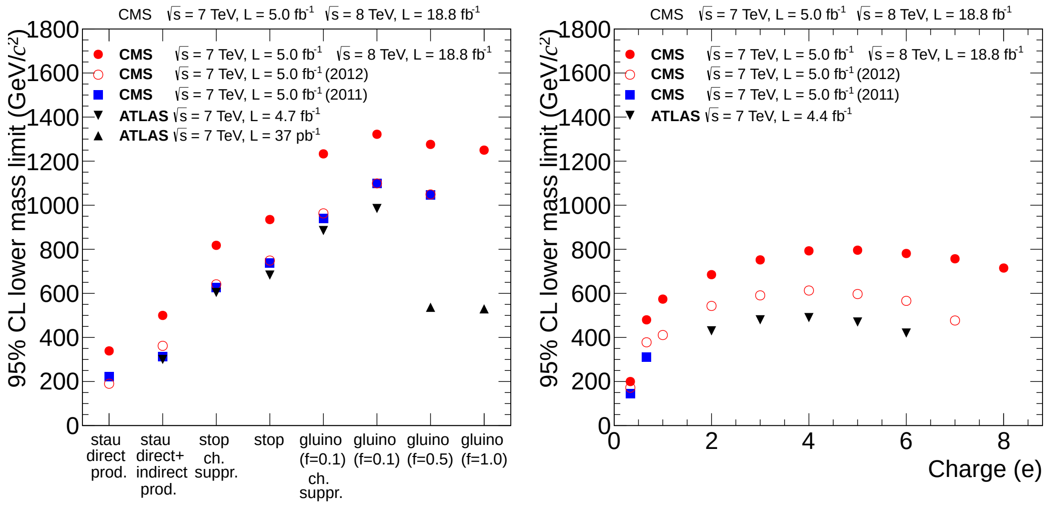

Figure 2: Lower mass limits at 95% CL for various models compared with previously published results. The model type is given on the x-axis (left). Mass limits are shown for Drell–Yan like production of fractionally, singly, and multiply charged particles (right). These particles were assumed to be neutral under $SU(3)_C$ and $SU(2)_L$.

The absence of correlation between these three variables is exploited to predict the background in the signal region (high pT, high or low dE/dx and long TOF) using a 2 or 3 dimensional ABCD technique. The mass of the candidates, reconstructed from their dE/dx and momentum, is also used to select further the candidates in $|Q| = e$ analysis. The pT being reconstructed under a $|Q| = e$ assumption, the reconstructed pT is biased by a factor $1/|Q|$ and is therefore significantly lower (higher) than the true pT for multiply (fractionnaly) charged particles. This variable is therefore not used when searching for multiply charged particles.

In all of this analyses, a good agreement between the observation and the background prediction was found. Lower limits at the 95% confidence level (C.L.) were set on production cross-section at 7 and 8 TeV and on mass of several long-lived particles, including gluinos (M < 1322 GeV/c^2), stops (M < 935 GeV/c^2), pair-produced staus (M < 339 GeV/c^2) and inclusively produced staus (M < 500 GeV/c^2). Limits were also set on the mass of long-lived leptons with $e/3 \leq |Q| \leq 8e$. Limits on colored long-lived particles are also provided in [2] for different scenarios of hadronization and interaction with matter. All mass limits obtained by this analysis and by previously published CMS and ATLAS results are shown in Fig.2.

3. Search for displaced jet vertices

As previously introduced, long-lived neutral particles with a lifetime in the range O(100) μm < $c\tau$ < O(10) m may be completely missed by classical searches for physics beyond the standard model. While these particles could be identified thanks to their unique signature of a highly displaced vertex in the CMS detector. A pair of, same flavour but opposite charged, leptons is certainly the easiest channel to search for such displaced vertex, but this channel may also be subject to smaller rate due to unfavorable branching ratio for the lepton decay of the search. In this case, the hadronic decay channel, even if affected by larger background, turns to be a critical channel for this search.

The signature in this channel is therefore an event containing a pair of jets origninating from a common secondary vertex within the volume of the CMS tracker that is significantly transversely displaced from the event primary vertex. This topological signature has the potential to provide clear evidence for new physics and is also very powerful in suppressing backgrounds from SM processes.

While the analysis [6] inclusively search for any heavy particle that decays into a displaced pair of jets, a specific model is used as a benchmark. In this model a heavy SM-like higgs boson is produced via gluon fusion and decays into a pair of long-lived, spinless, neutral particles, named X each of them decaying into a pair of quark: $pp \rightarrow H \rightarrow XX \rightarrow (q\bar{q})(q\bar{q})$. Several H and X masses are considered as well as X lifetime. This model predicts up to two displaced dijets vertices per event, but the analysis itself only requires one of them to be reconstructed.

A dedicated trigger is used for this analysis. Two 60 GeV jets are required and each of them must contains ≤ 2 prompt tracks carrying at most 15% of the jet energy. At offline level, the trigger jet requirements are confirmed and the non-prompt ($d_{XY} > 500\mu m$) tracks contained in these jets are used to seed a vertexing algorithm. The actual selection is based on 3 sets of variables. The first (second) set is based of the number of prompt tracks and the energy fraction they carry in the first (second) jet. While the third selection variable is a likelihood discriminant built out of the secondary vertex information (chi^2, number of tracks, etc.). These 3 set of variables being uncorrelated for the backgrounds, a data-driven ABCD technique can be used to predict the yields of background in the signal region. Two selection are used depending on the expected lifetime of the X particle and therefore the dispalcement of the secondary vertex. Using the 8 TeV pp collisions produced by the LHC during the 2012 Runs and corresponding to an integrated luminosity of 18.6 fb^{-1}, the expected background rate in the signal reasion is 1.6 ± 0.6 (1.1 ± 0.5) events for the low (high) displacement selection while 2 (1) events have been observed. In the absence of significant excess, limits are therefore set on the cross section ($H \rightarrow XX$) and branching ratio ($X \rightarrow q\bar{q}$) as a function of the X lifetime and for different H and X scenarios. The figure 3 shows the limit for two representative models. In addition, reconstruction efficiency and signal acceptance are provided in Ref. [6] as a function of the displacement and of the quark flavours for a possible reinterpretation of these results in other models.

4. Conclusion

In conclusion, the CMS collaboration is searching for charged and neutral long-lived particles using several complementary techniques. No evidences of long-lived particles have yet been observed in CMS, and limits were therefore set on production cross sections, lifetime, and masses of several flavour of long-lived particles. Conducting such sophisticated searches with a detector that was not initially built for that purpose requires a true and deep understanding of the CMS detector and demonstrate the accuracy of the detector as well as the maturity of the CMS collaboration itself.

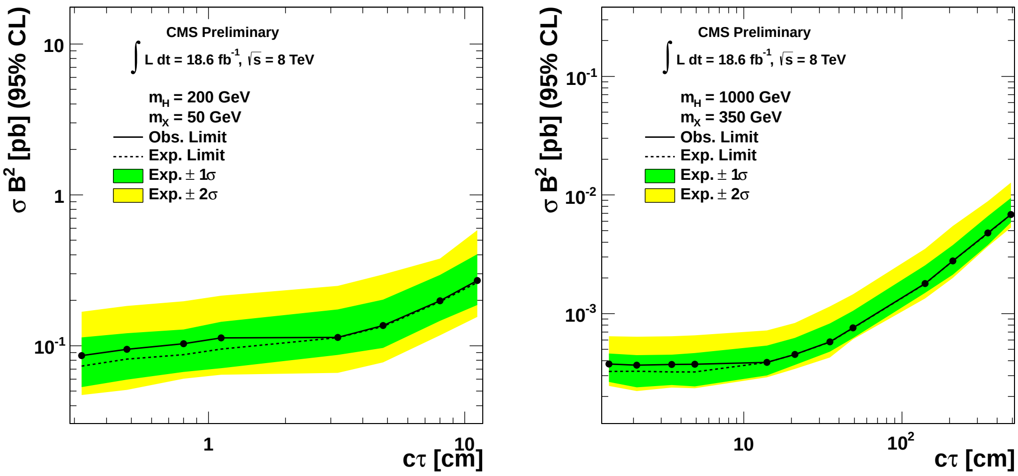

Figure 3: The 95% CL expected and observed upper limits as a function of X mean lifetime for a considered signal model considered with M(H)=200 GeV and M(X)=50 GeV on the left and with M(H)=1000 GeV and M(X)=350 GeV on the right.

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