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Searches for exotic physics at CMS

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Summary. — A review of the searches for new physics at the CMS experiment is presented. The latest results exploiting all the data collected in 2012, corresponding to 19.6 fb^{-1} of luminosity, are summarized. A broad range of final states and models of new physics is investigated. No statistically significant evidence of new physics has been found.

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1. – Introduction

One of the main goals of the Compact Muon Solenoid (CMS) detector [1] at the Large Hadron Collider (LHC) is to discover evidences of physics Beyond the Standard Model (BSM). The program of BSM searches at CMS covers an extensive set of final states and models, fully exploiting the capabilities of the detector. A precise understanding of the detector performances is crucial in order to perform reliable and efficient measurements of this type. This document presents a selection of current results of searches for BSM physics carried out at CMS. The results were chosen because of the relevance of the physics models to which they are sensitive, their novelty in terms of physics models explored and experimental techniques adopted and the demonstration of the extremly high-level of control of the detector performances achieved at CMS. The highlighted results exploit the 19.6 fb^{-1} of luminosity collected in 2012 at the centre-of-mass energy of the pp collisions equal to 8 TeV.

2. – Searches for Heavy Stable Charged Particles

New particles with large masses and electric charge different from $\pm e$ are predicted by several BSM models. These particles are expected to have a long lifetime (longer than few nanoseconds) that will make them look as stable in the tracking detectors. These Heavy Stable Charged Particles (HSCP) are characterized by velocity, $\beta = v/c$, lower than 0.9 and can be identified by a study of $\mathrm{d}E/\mathrm{d}x$, the energy lost by the particle normalized by the thickness of material crossed. Depending if their interaction with the

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SM particles happens via the electromagnetic or the strong force, HSCP can be *lepton-like* or *hadron-like*, respectively. In the latter case, the HSCP would form bound states with SM quarks called R-hadrons.

An update of the search for HSCP covering a broad range of models has been performed using $19.6\,\text{fb}^{-1}$ of pp collisions with $\sqrt{s} = 8\,\text{TeV}$ [2]. Two experimental observables with good sensitivity in separating the signal from the background are $\text{d}E/\text{d}x$ (via its estimator I_h) and the time-of-flight of the HSCP candidate, δ_t (which allows to determine the velocity of the particle, $\beta^{-1} = 1 + c\delta_t/L$, where L is the flight distance). Given I_h, the mass of the HSCP candidate is reconstructed with the relation $I_h = K\,\frac{m^2}{p^2} + C$, where K and C are two empirical parameters extracted from an independent control sample of low-momentum protons. An average value of β is obtained from the combination the measurements at different muon stations, each of them weighted by its time resolution. The typical final precision on β^{-1}, $\sigma_{1/\beta}$, is 0.065. The measurement of I_h and β relies heavily on a precise calibration of the tracking devices of CMS. The final competitive results of this analysis was made possible by the excellent commissioning of the CMS detector. Events were triggered requiring either a high-p_T muon or the presence of large missing transverse energy, E_T^{miss}. The events are divided in "tracker-only", "muon-only" and "tracker+TOF", depending on the presence of a track in the inner silicon tracker, the outer muon chambers or both. The offline selections of the events ask for a high-p_T, high-quality track. A special cluster cleaning procedure is applied to remove clusters coming from overlapping tracks. A final cut $I_h > 3.0\,\text{MeV/cm}$ is applied on the HSCP candidates. For the muon-only analysis, additional cuts require the compatibility with the primary vertex and reject cosmics tracks and muons from out-of-time pile-up. The events in the muon-only and tracker+TOF categories had to pass a selection $1/\beta > 1$ and $\sigma_{1\beta} < 0.07$.

The SM background of this analysis was estimated in a data-driven way, minimizing the usage of the MC which is not able to give precise enough predictions of the number of events in the signal region. The $ABCD$ method was used: for the tracker-only analysis, the two independent variables used to define the signal and control regions were p_T and I_h, while for the muon-only p_T and $1/\beta$ were used. A simultaneous selection on p_T, I_h and $1/\beta$ defined the signal region in the tracker+TOF category. The shape of the background is taken from the MC. The prediction of the background in the tracker-only category is given in the left-hand plot of fig. 1. No significant excess over the background is observed. The right-hand plot of fig. 1 shows the mass limits for various signals and compares them with previously published results.

3. – Searches for new physics with jets in the final state

An intense activity in searches for new phsyics with two jets in the final state is carried out at CMS. An update with the full 8 TeV statistics of the inclusive searches [3] is based on previous similar analyses [4, 5]. The online selection of the events was based on the dijet invariant mass ($m_{jj} > 750\,\text{GeV}/c^2$) and the total scalar sum of the p_T ($H_T > 650\,\text{GeV}/c$). Jets were reconstructed with the anti-k_T algorithm with distance parameter $d = 0.5$ (AK5 jets). They were required to have a reconstructed transverse momentum $p_T > 30\,\text{GeV}/c$ and to lay in the pseudorapidity range $|\eta| < 2.5$. Basic jet quality cuts are applied in order to remove jets made from noisy calorimeter cells. An algorithm for reconstructing "wide jets" is ran in order to recover QCD radiation that falls out of the jet cone up to $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 1.1$. The two highest-$p_T$ wide jets must have a ΔR separation, $\Delta R_{JJ} > 1.3$. The trigger selections together with these cuts

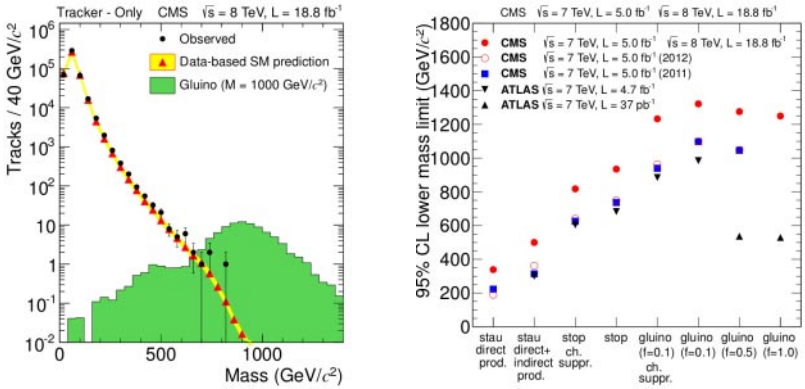

Fig. 1. – Left: comparison in the signal region of the observed events and the SM background predicted from control regions for the tracker-only category. A signal constituted by a gluino with $M = 1000\,\mathrm{GeV}/c^2$ is also shown for comparison. Right: compilation of lower limits on different models compared to previously published results, indicating the reference model on the x-axis.

define the kinematic range of the search, that starts from an invariant mass of the dijet system $m_{JJ} > 890\,\mathrm{GeV}/c^2$. The main background comes from SM QCD jets and was simulated with the `Pythia 6` MC. However, the final background estimation is taken from the data by fitting the dijet mass spectrum with an empirical function. The BSM signal models were all simulated with `Pythia 6`. The different composition of the final state, whether composed by two quarks, two gluons or one quark and one gluon affect the final resolution on the dijet mass achievable, because of the different amounts of QCD radiation. No significant excess is found in the final result and 95% CL upper limits are set. Different limits are set according on the assumption made on the SM fields composing the final state. A comparison of the limits against the many models tested in the analysis is presented in fig. 2.

A search for new physics with a single high-p_T jet and large E_T^{miss} has been updated with the full 2012 statistics [6]. Events are considered only if they have either one or two AK5 jets with $p_T > 30\,\mathrm{GeV}/c$ ($p_T > 110\,\mathrm{GeV}/c$ for the leading jet) and $|\eta| < 4.5$. The QCD dijet background was further suppressed by requiring a maximum separation in the azimuthal angle between the two jets, $\Delta\phi_{JJ} < 2.5$. A cut on $E_T^{miss} > 250\,\mathrm{GeV}/c$ was applied. Vetoes on the presence of high-p_T leptons were applied for suppressing W+jets and Z + jets SM backgorunds. The shape of the remaining backgrounds (dominated by SM $Z(\to \nu\nu)$ + jets) is taken from the MC simulation. The normalization is obtained in a data-driven way by rescaling the MC to signal-free control regions. Scenarios of dark matter direct production can be excluded interpreting the data with an effective lagrangian formalism. The upper limits obtained are presented in fig. 2 and compared to other experimental results. The CMS results are very competitive also in this case, especially in the low-mass region.

4. – Searches for heavy gauge bosons and excited tops

The presence of additional massive vector bosons, W' and Z', is predicted by many BSM models that extend the gauge symmetry of the SM. In the Sequential Standard

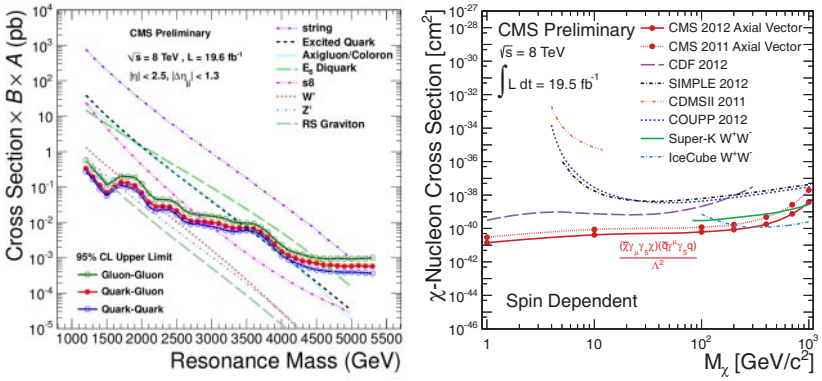

Fig. 2. – Left: observed 95% CL upper limits on $\sigma \times B \times A$ for several signal models of dijet resonances. Different assumptions on the partons originating the dijet resonance are presented (gluon-gluon, gluon-quark, quark-quark). Right: limits on dark matter cross section as a function of the mass of the dark matter particle, under the assumption of spin-dependent axial-vector terms in the effective lagrangian.

Model (SSM), the additional vector bosons W' and Z' are assumed to have properties similar to those of the SM W and Z. Differences can show up in the branching ratios of the decays, in case the mass of the new boson is higher than the top mass, and the helicity of the new gauge boson. Different admixtures of right-handed (RH) and left-handed (LH) W' can be considered, taking special care in treating the interference with the SM W in the LH case. CMS has a well established program of searches targeted for this type of BSM. The most "classic" approach is in the leptonic final state, studying the processes $W' \to \ell\nu$ or $Z' \to \ell^+\ell^-$, where $\ell = \mu$ or e. The experimental signature of the W' is the presence in the event of one high-p_T lepton, large E_T^{miss} and large values of the transverse mass $M_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{miss} \cdot (1 - \cos\Delta\Phi_{\ell,\nu})}$, where $\Delta\Phi_{\ell,\nu}$ is the angle in the $x-y$ plane between the lepton and the E_T^{miss}. For the Z', the analysis looks for two high-p_T leptons creating a bump on the spectrum of the dilepton invariant mass, $M_{\ell\ell}$. In both cases, it is crucial to measure precisely the momentum scale of the lepton and the E_T^{miss}. This sets very high requirements on the alignment of the tracking devices and the calibration of the calorimeters, and on the precision of the simulation of the SM and of the instrumental backgrounds. The search for W' in the leptonic channel has been updated with the full statistics at $\sqrt{s} = 8\,\text{TeV}$ [7]. Only one well-reconstructed and isolated high-p_T muon (electron) had to be identified in the event and reconstructed with $p_T > 45\,\text{GeV}/c$ ($p_T > 100\,\text{GeV}/c$). It was required a sufficient balancing between the E_T^{miss} and the lepton. The signal is seeked in the form of an excess in the high end tail of the M_T distribution. No significant excess of this type was found and the limits shown in the left-hand plot of fig. 3 were set. The Z' analysis [8] selects leptons in a similar way, with the exception that no large E_T^{miss} is required and the p_T thresholds are lowered thanks to the usage of double-lepton triggers with softer thresholds. Also in this case, no excess over the smoothly falling distribution of the dilepton mass is found and the limits over several BSM scenarios are presented in the right-hand plot of fig. 3.

A search for a heavy W' in the tb final state has been carried out with the full 2012 statistics of $19.6\,\text{fb}^{-1}$ [9]. The top quark was identified via its leptonic decay $t \to \ell\nu b$.

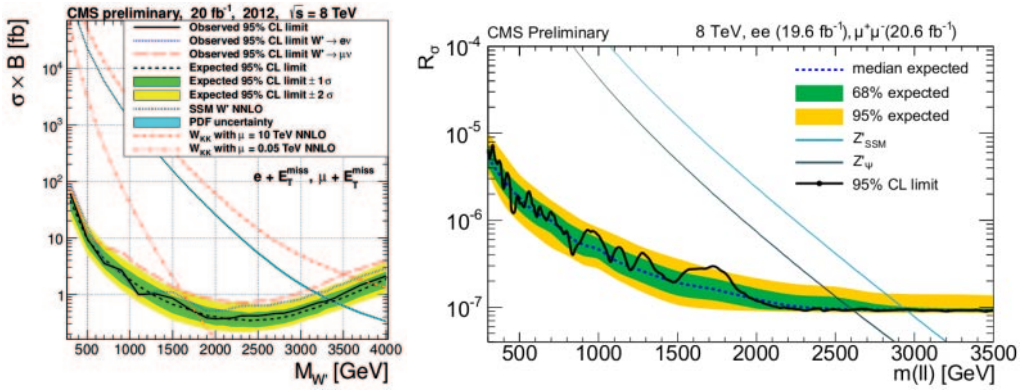

Fig. 3. – Upper limit at 95% CL for the searches of new massive vector bosons in the $W' \to \ell\nu$ (left) and $Z' \to \ell^+\ell^-$ channels (right).

One lepton with $p_T > 50\,\mathrm{GeV}/c$ and two jets (of which at least one b-tagged) with $p_T > 40\,\mathrm{GeV}/c$ ($p_T > 120\,\mathrm{GeV}/c$ for the leading jet) were required in order to select the events. By imposing the constraint that the $\ell\nu$ invariant mass must match the nominal mass of the W boson, the full kinematics of the process could be reconstructed. Limits on M_{tb} are set for a generic parametrization of the helicity of the W', where the parameter a_L (a_R) are related to the LH (RH) coupling of the vector boson.

A novel search for pair production of excited top quarks, t^*, decaying to a top and a gluon was performed with the full statistics collected at $\sqrt{s} = 8\,\mathrm{TeV}$ [10]. The analysis focused on a spin 3/2 particle because of its larger production cross section. Large multiplicity of high-p_T jets (≥ 6 AK5 jets with $p_T > 30\,\mathrm{GeV}/c$ and $|\eta| < 2.5$) and two identified tops (one decaying semileptonically and hte other fully hadronically) would be the signature of such events. To meet trigger requirements, the leading three jets were required to have transverse momenta of $p_T > 45\,\mathrm{GeV}/c$ in the early data taking period and $p_T > 55\,\mathrm{GeV}/c$, $p_T > 45\,\mathrm{GeV}/c$, and $p_T > 35\,\mathrm{GeV}/c$, respectively, at later

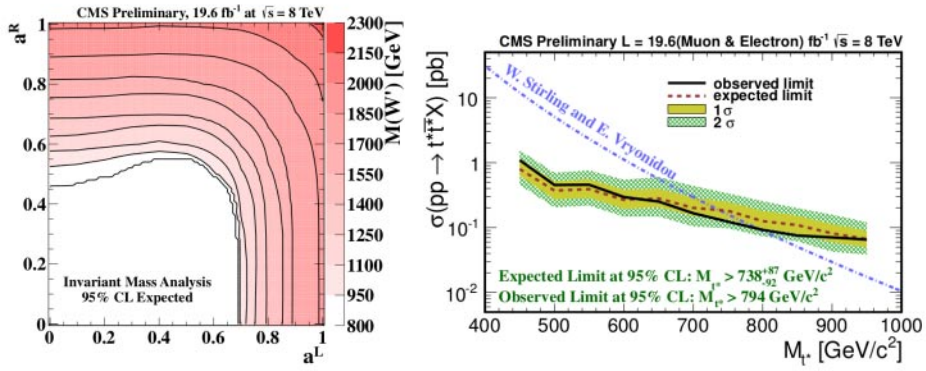

Fig. 4. – Left: 95% CL upper limits on the mass of t^* combining the results from the muon and electron channels. Right: 95% C.L. upper limits on the mass of the W' for the process $W' \to tb$, as a function of a_L and a_R, which parametrize the fraction of LH and RH components of the W' field.

times. At least one jet had to be b-tagged. Ambiguities in the association of the jets to the t^* candidate were solved by choosing the configuration that maximized the χ^2 of a kinematic fit which included constraints on the W and t masses and the condition that the two t^* must have the same mass. The search was carried out by looking for resonances on the smoothly falling background function, estimated directly from data with a procedure similar to the one of the dijet analysis. No excess is found and the first limits set on excited spin 3/2 top quarks are presented in fig. 4. Excited tops with masses below $794\,\mathrm{GeV}/c^2$ are excluded at 95% CL.

5. – Conclusion

CMS keeps carrying out an ambitious program of BSM searches covering a very large spectrum of models and final states. As the statistics accumulated increases, the energy frontier explored by the searches is pushed further high. Excellent detector performances and commissioning are crucial in this task and the most recent alignments and calibrations, together with a careful detector simulation, allowed CMS to establish a firm control over the reconstruction and identification of high-p_T objects, thus further increasing the sensitivity at high masses. No significant excesses have been found and limits, in most of the cases the most stringent to date, have been set.

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