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Recent exotics search results from CMS

C. Henderson on behalf of the CMS Collaboration
Department of Physics & Astronomy, University of Alabama - Tuscaloosa, AL, USA

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Summary. — A survey is presented of results from some recent searches for exotic physics such as heavy resonances, dark matter, and long-lived particles by the CMS experiment at the LHC.

PACS `12.60.-i` – Models beyond the standard model.

1. – Introduction

The Standard Model (SM) of particle physics has been very successful, yet it is widely believed that the SM is incomplete, and that there needs to be some new beyond-SM (BSM) physics at the TeV-scale, which — if it exists — should manifest itself in collisions at the LHC. We present a selection of recent results from searches for BSM physics such heavy resonances, dark matter, and long-lived particles, performed by the CMS experiment [1] at the LHC. All results presented here use the complete $\sim 20\,\mathrm{fb}^{-1}$ dataset collected by CMS from pp collisions at 8 TeV.

2. – Searches for heavy resonances

A heavy (that is, TeV-scale) resonance would be an unambiguous signal of new physics beyond the Standard Model. We present results from several recent searches by the CMS collaboration for heavy resonances, in a variety of different channels.

2˙1. *Dijet resonance search.* – The most basic final state in a proton-proton collision is the dijet final state; however, this final state could also provide evidence for new phenomena, as many BSM theories predict new heavy resonances that could decay to dijets. CMS has performed a search for dijet resonances in LHC collisions at 8 TeV [2]. Jets with $p_T > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$ are reconstructed with the CMS Particle Flow algorithm and clustered using the anti-k_T jet algorithm. To be less sensitive to gluon radiation, geometrically close jets are combined into "wide jets", by taking the two highest p_T jets in the event as seeds, and then adding the Lorentz vectors of all other jets to the closest leading jet, providing they are within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$.

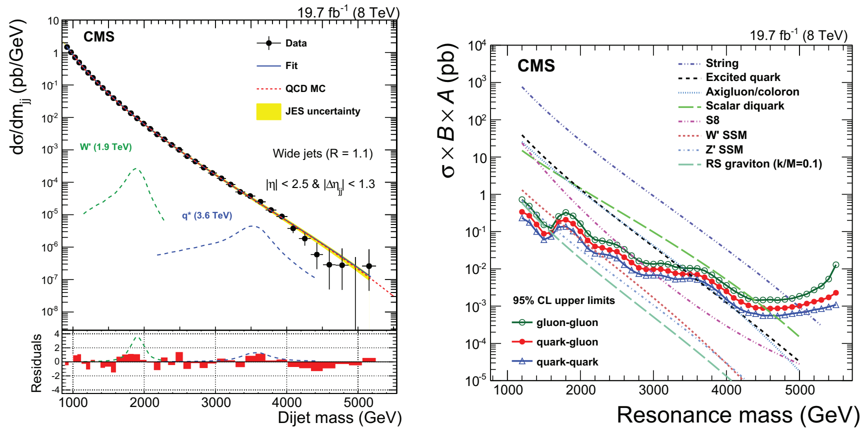

Fig. 1. – Left: Inclusive dijet invariant mass spectrum; Right: 95% confidence level limits on cross-section × branching ratio × acceptance ($\sigma \times B \times A$) for potential new physics as a function of the dijet resonance mass, compared to predictions from various BSM theories.

This procedure leaves two wide jets, which define the dijet system for this analysis. Events are further required to have dijet mass $M_{jj} > 890\,\text{GeV}$, where the trigger used for online selection of these events is observed to be virtually 100% efficient.

The inclusive dijet mass spectrum is shown in fig. 1 (left). Spectra are also studied for events categorized by the presence of 0, 1 or 2 b-tagged jets, to be more sensitive to BSM scenarios which may preferentially produce b-quarks. The dijet mass spectra are well described by a smooth function, and no evidence is observed for any resonance indicating new phenomena. Limits are obtained on the cross-section × branching ratio × acceptance for potential new physics as a function of the dijet resonance mass. These cross-section limits can then be compared to the theoretically predicted cross-sections for specific new physics models which may produce quark-quark, quark-gluon or gluon-gluon resonances, and then limits can be set on the theory model parameters. This is illustrated in fig. 1 (right).

This search has excluded, at 95% confidence level (CL), string resonances with masses below 5.0 TeV, scalar diquarks below 4.7 TeV, excited quarks below 3.5 TeV, and excited b-quarks below 1.2–1.6 TeV (depending on their decay properties), among other models. All of the above models produce resonances whose intrinsic width is narrow compared to the experimental dijet mass resolution. The same CMS dijet spectra have also been used to search for wide resonances, with a width up to 30% of the central mass value. This wide resonance search has excluded axigluons and colorons with mass below 3.6 TeV, and color-octet scalar particles with mass below 2.5 TeV.

2·2. *Search for new physics in dilepton events.* – CMS has recently published results from a search for BSM physics in the dielectron and dimuon invariant mass spectra [3]. Muons are selected with $p_T > 45\,\text{GeV}$ and $|\eta| < 2.4$ (the trigger muon must be within $|\eta| < 2.1$) and electrons are selected with $E_T > 35\,\text{GeV}$ and $|\eta| < 2.5$, excluding the barrel-endcap transition region $1.442 < |\eta| < 1.560$. SM Drell-Yan production of dileptons is an irreducible background for this search; this process is simulated at next-to-leading order (NLO) by the POWHEG event generator. There are also contributions from other SM processes which produce two real same-flavour dileptons, such as $t\bar{t}$ and diboson

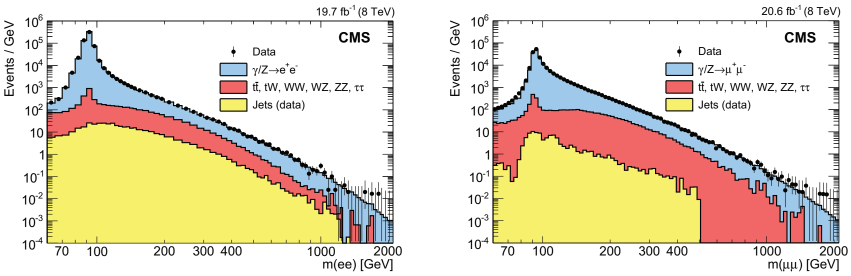

Fig. 2. – Invariant mass spectra for dielectron (left) and dimuon (right) events recorded by CMS in 8 TeV pp collisions at the LHC.

production, and also from multijet and W/Z+jet events where a jet is misidentified as a lepton in the detector. The dilepton mass spectra are shown compared to the background predictions in fig. 2. There is no evidence of any excess indicating the presence of BSM physics.

Many BSM theories involve an extension of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group of the Standard Model, and when the enlarged BSM gauge group is broken down to the SM group at low energy, there often remains at least one new $U(1)$ group, whose physical manifestation is a new gauge boson known generically as a Z'. Two convenient benchmark models for this type of scenario are a Sequential Standard Model Z'_{SSM}, whose couplings to SM particles is identical to those of the SM Z boson, and a Z'_{ψ}, arising from grand unified theories with an E_6 gauge group. The dilepton decay channel is typically the most sensitive in which to search for a Z', and this CMS analysis has excluded, at 95% CL, a Z'_{SSM} with mass less than 2.90 TeV and a Z'_{ψ} with mass below 2.57 TeV. This search is also sensitive to excited Kaluza-Klein graviton states in the Randall-Sundrum (RS) scenario with a warped extra dimension; masses below 1.27–2.73 TeV are excluded at 95% CL by this search, for a range of values of the coupling parameter $0.01 \leq \tilde{k} \leq 0.10$ in the RS model. The search results can also be interpreted in terms of BSM scenarios which would produce a broad non-resonant excess in the dilepton mass spectra, such as the ADD model of large extra dimensions. A 95% CL limit on the energy scale Λ_T of the extra dimensions in the GRW convention is set at 4.14 TeV (results are also reported for other conventions).

2˙3. *Search for ditau resonances in the eμ decay channel.* – CMS has also searched for new phenomena in the final state consisting of two tau leptons, where one tau decays in the electron channel and the other decays in the muon channel [4]. Such a search could be particularly sensitive to new physics which decays preferentially to third-generation fermions. Events are required to contain an isolated electron and muon with $p_T > 20$ GeV. To form a ditau pair, the two leptons must have opposite charge, and must not overlap ($\Delta R > 0.3$). The ditau pair has large invariant mass, so the electron and muon decay products are expected to be back-to-back — the lepton pair are therefore required to satisfy $\cos \Delta\phi(\mu, e) < -0.95$. Events are also required to have missing transverse energy $MET > 20$ GeV, consistent with the presence of neutrinos from the tau decays, and the direction of the missing transverse momentum is also required to be consistent with that expected for tau decays.

A mass variable for ditau events $M(\mu, e, MET)$ is constructed from the energy and momentum values of the muon and electron candidates and the MET. At low mass, the dominant background to this search comes from SM Drell-Yan production of $\tau^+\tau^-$

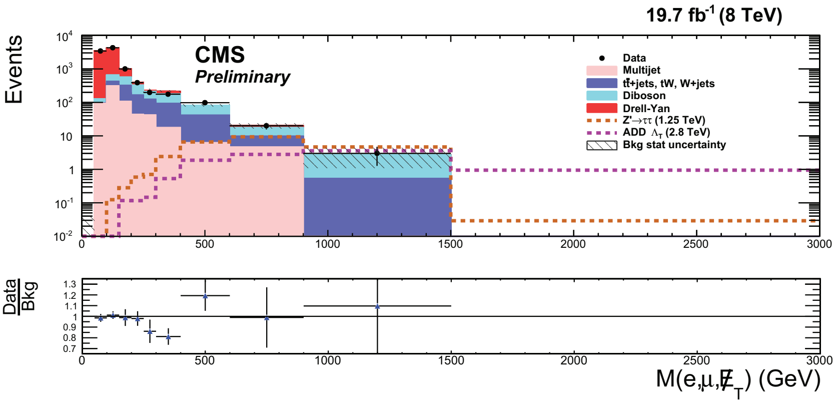

Fig. 3. – Distribution of the ditau mass $M(\mu, e, MET)$ in data compared to expected background. The lower plot shows the ratio of the data to the total background expectation.

pairs, while at high mass (where a potential BSM signal would be expected to appear) the main backgrounds are actually from SM WW and $t\bar{t}$ processes, in the decay channels with opposite lepton flavours. The distribution of the ditau mass variable in the observed data compared to the expected background is shown in fig. 3. The agreement is good, and no excess is seen in the data which might indicate the presence of new physics. This agreement is translated into limits on potential new physics models. Using the benchmark Z' scenarios described in sect. **2**˙2, this search for ditau resonances in the $e-\mu$ decay channel has excluded a Z'_{SSM} with mass less than 1300 GeV and a Z'_{ψ} with mass below 810 GeV, at 95% CL.

2˙4. *Search for top-antitop resonances in dilepton final states.* – The top quark, as the heaviest fermion and with a mass very close to the electroweak scale, may be a particularly sensitive probe of new physics beyond the Standard Model. CMS has searched for new physics producing a signature in $t\bar{t}$ events, in the decay channel $t\bar{t} \rightarrow W^+bW^-\bar{b}$, with both W bosons decaying to leptons (electron or muon) [5].

Event selection requires two opposite-charged leptons, with different p_T thresholds depending on the decay channel (ee, $\mu\mu$ or $e\mu$). To reduce contributions from low-mass resonances and from Z boson production, the invariant mass of the lepton candidates in the ee and $\mu\mu$ channels are required to be $M_{\ell\ell} > 12\,\text{GeV}$ and not in the window $76 < M_{\ell\ell} < 106\,\text{GeV}$. At least two jets with $p_T > 100\,\text{GeV}$ are required, and missing transverse energy $MET > 30\,\text{GeV}$ is required in ee and $\mu\mu$ channels. Events are considered in two categories, depending on whether one or two jets are identified as arising from b quarks based on a displaced secondary vertex tagger. Because the BSM $t\bar{t}$ resonance signal is expected to have high mass, the decay products will be highly boosted, and this can be used to further separate signal from SM background. The spatial separation between each lepton and its closest jet, $\Delta R_{min}(\ell, jet)$, is smaller in simulated signal events than in SM $t\bar{t}$ production, and requiring $\Delta R_{min}(\ell_1, jet) < 1.2$ for the leading lepton and $\Delta R_{min}(\ell_2, jet) < 1.5$ for the sub-leading lepton reduces the SM $t\bar{t}$ background by more than a factor of two, while only reducing the efficiency for a high-mass signal by $\sim 10\%$.

The dominant (and irreducible) background to this search is SM $t\bar{t}$ production, which is simulated by POWHEG. A mass variable is constructed from the 4-momenta of the two leading leptons, the two leading jets and the missing transverse momentum;

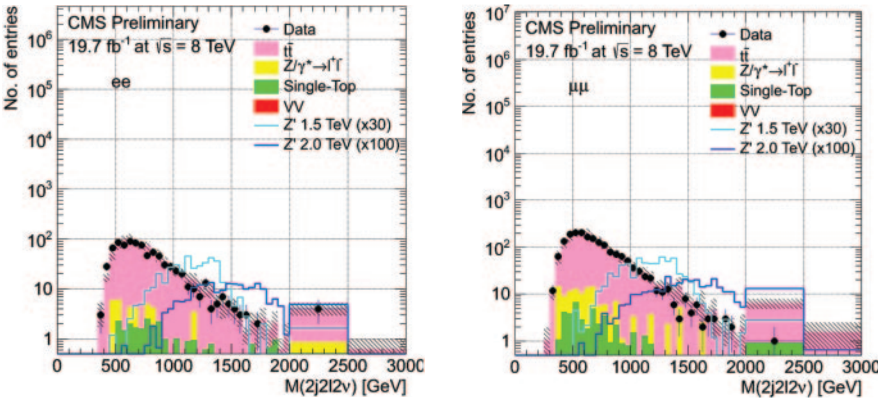

Fig. 4. – Distribution of the mass variable in $t\bar{t}$ events in the ee (left) and $\mu\mu$ channels (right), for data, expected background, and some potential Z' signals.

the distribution of this mass variable in the ee and $\mu\mu$ channels is shown in fig. 4. The mass distributions agree well with the expected background from SM sources, and no evidence for new physics is seen. With this agreement, a leptophobic Z' decaying to $t\bar{t}$ is excluded at 95% CL for masses below 1.5 TeV assuming a narrow width (1%) and below 2.0 TeV for a broad width (10%).

2˙5. *Search for narrow resonances decaying to Z and Higgs bosons.* – A search for narrow high-mass resonances decaying into Z and Higgs (H) bosons has recently been performed by CMS [6]. Final states are considered where the Z boson has decayed to $q\bar{q}$ and the Higgs boson to $\tau^+\tau^-$. For a high-mass resonance, the Z and H decay products are highly boosted. This results in the hadronic Z decay being reconstructed as a single jet; jet pruning and subjet-searching algorithms are then used to discriminate between such a "Z-jet" and normal QCD jets, based on the expected jet substructure. For the tau pair, all decay channels are considered: leptonic, semileptonic and all-hadronic, with different selection criteria in each case. The backgrounds to this search from SM sources also depend on the particular decay channel: for leptonic channels, the primary background is Z+jets; W+jets and $t\bar{t}$ are also significant contributions to the semileptonic and all-hadronic decay channels; and in addition, multijet background must also be considered for the all-hadronic channel. Figure 5 (left) shows the mass M_{ZH} of the Z-H pair in the all-hadronic channel, for illustration. The M_{ZH} distributions in all channels are found to agree well with SM predictions. As shown in fig. 5 (right), production cross sections in the range 0.9–27.8 fb are excluded at 95% CL by this search for BSM physics resulting in a ZH resonance, depending on the resonance mass.

3. – Searches for dark matter at the LHC

Dark matter (DM), whose existence is inferred from astronomical observations such as gravitational lensing and galaxy rotation curves, is believed to comprise 23% of the universe, yet it cannot be explained within the Standard Model. Many BSM theories produce a natural DM candidate, and it is possible that DM particles could be produced in pp collisions at the LHC. CMS has performed several searches for DM particles at the LHC; here we present results from a recent search in the monophoton final state.

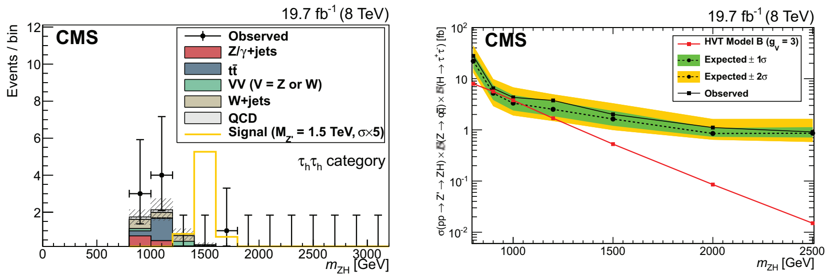

Fig. 5. – Left: Distribution of the mass variable for the all-hadronic tau decay channel, in the search for $ZH(\rightarrow \tau\tau)$ resonances. Right: Expected and observed limits on a possible ZH resonance cross-section.

3˙1. *Search for new phenomena in the monophoton final state.* – DM particles (χ) could be pair-produced in LHC collisions via $q\bar{q}$ annihilation ($q\bar{q} \rightarrow \chi\bar{\chi}$). The DM particles will not interact with the detector and will therefore be invisible; however, such an event can be identified if one of the initial state quarks radiates a photon, leading to a signature of photon + missing transverse energy, known as a "monophoton" final state. CMS has searched for new physics in this final state [7]. Events are selected with photons reconstructed in the barrel ($|\eta| < 1.44$) of the CMS Electromagnetic Calorimeter (ECAL) with $E_T > 145\,\text{GeV}$, and with missing transverse energy (MET) >140 GeV.

The primary, irreducible, background to this exotic signature comes from SM $Z\gamma$ production, where the MET arises when the Z decays to neutrinos. This SM process is modelled by the MADGRAPH event generator, with production cross-sections corrected to NLO using the MCFM program. The next largest background is from SM $W\gamma$ production, where the W decays to lepton+neutrino. This background is reduced by vetoing events which contain a reconstructed isolated lepton with $p_T > 10\,\text{GeV}$; the contribution which still remains is estimated from Monte Carlo (MC) in the same manner as the $Z\gamma$ background. Other sources of background include: $W \rightarrow e\nu$, where the electron is misidentified as a photon in the CMS detector; photon+jet events, where the MET signature arises from jet energy mismeasurement in the calorimeter; and non-collision sources such as beam halo (see sect. **4**˙1 for a description of this).

The total number of events in the signal region, and the distributions of the photon E_T and MET variables are studied and compared to the background expectation. No excess is seen in the data that might indicate the presence of BSM physics, and this agreement can be translated into limits on the production cross-section for DM particles. The interaction between SM and DM particles is assumed to be mediated by a virtual particle of mass much larger than the DM particle mass (M_χ), such that it is effectively a contact interaction, and can be described by an effective field theory (EFT). The DM pair-production process at LHC can then be related to the process of DM-nucleon scattering in direct DM searches. Within this EFT framework, CMS has calculated limits on the DM-nucleon cross-section, as a function of M_χ, for both pure vector and pure axial vector effective operators. These results are shown in fig. 6, and are compared to results from several direct DM detection experiments. One can see that DM searches at the LHC such as this can be sensitive to small M_χ values beyond the reach of current direct detection experiments, and indeed are competitive with direct searches across the entire M_χ range for the case of axial vector (*i.e.* spin-dependent) couplings.

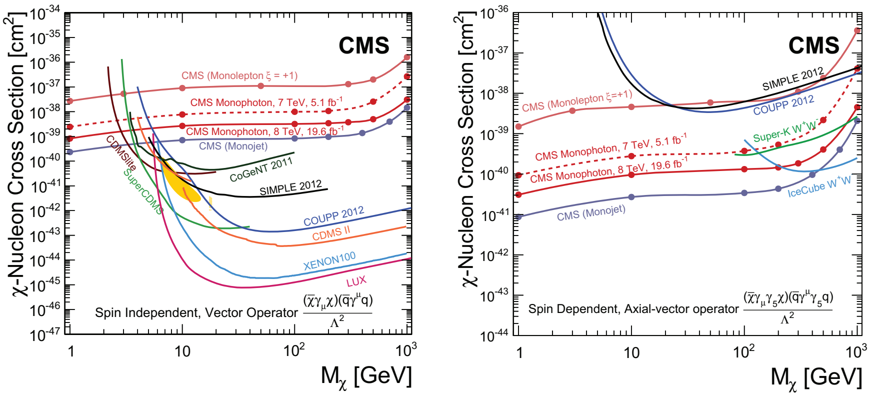

Fig. 6. – Limits on the DM-nucleon interaction cross-section as a function of the DM particle mass M_χ, from the CMS monophoton analysis, compared to other CMS DM searches and also to direct DM detection experiments. Left: limits assuming a pure vector effective operator; Right: pure axial vector effective operator.

4. – Searches for long-lived particles

Physics beyond the SM could also result in new particles that are long-lived on the scale of a particle physics detector – these could produce novel experimental signatures, that may require new triggering and event reconstruction techniques in the detector. CMS has released several results on searches for long-lived particles. Here we discuss a recent search for particles which stop and later decay in the CMS calorimeter.

4˙1. *Search for stopped long-lived particles.* – New long-lived heavy particles, such as a gluino or a top squark, could be produced in pairs in LHC collisions. These new colored particles can combine with SM particles, forming semi-stable "R-hadrons", which would interact with the detector material, and if slowed below a critical velocity, may lose enough energy to come to rest within the detector. The stopped particles will later decay, potentially a long time after the collision in which they were produced — if such a decay were observed to happen at a time when there were no collisions in the detector, this would be a striking signature of new physics. CMS has performed a search for such stopped particles [8].

An "out-of-time" trigger was developed which uses the two beam position and timing monitors (BPTX) located along the beam-line at either end of the CMS detector. These are electrostatic "pick-up" devices which can detect the presence of protons passing through the beam-line; it is then possible to trigger on "empty" bunch crossings by requiring that neither BPTX indicates a signal. To identify a possible stopped particle decay, a calorimeter jet trigger is additionally required, with a trigger threshold of 50 GeV, in coincidence with an empty bunch crossing. This trigger was active for 281 hours during 8 TeV *pp* collisions in 2012, corresponding to an integrated luminosity of 18.6 fb^{-1}.

The leading background to this exotic signature arises from non-collision muons undergoing a large bremsstrahlung in the CMS calorimeter. Such high-energy muons could come from cosmic rays, or from so-called "beam halo" processes, where LHC beam protons strike some material upstream of the CMS detector, and the resulting particle shower produces muons that are then long-lived enough to reach the CMS calorimeter.

The background from cosmic ray muons is reduced by vetoing events with hit patterns in the muon chambers that are consistent with a cosmic ray muon track passing through the calorimeter. Similarly, beam halo background is reduced by vetoing events with hits in the forward muon chambers at both ends of the CMS detector, consistent with the trajectory of a muon passing through CMS parallel to the LHC beam. The residual background which remains after these selections is estimated to be $13.2^{+3.6}_{-2.5}$ events for the entire running period (this includes also a small contribution expected from possible instrumental noise in the calorimeter). There were 10 events observed in the data. The absence of any significant excess of data over expected background can be translated into limits on model parameters for new physics scenarios which could produce long-lived colored particles that would decay with this signature. Assuming a particular model for R-hadron interactions, a gluino with mass $\lesssim 1000\,\text{GeV}$ and a top squark with mass $\lesssim 525\,\text{GeV}$ are excluded, for lifetimes between $1\,\mu\text{s}$ and $1000\,\text{s}$. These results are the most stringent constraints to date on stopped particles.

5. – Conclusion

In conclusion, we have presented several recent results for BSM searches by the CMS experiment, spanning many final states and a range of new physics scenarios, including heavy resonances, dark matter and long-lived particles. Although no clear evidence for BSM physics has been seen yet in 8 TeV *pp* collisions, the search for new physics will continue with enthusiasm when the LHC restarts with 13 TeV collisions later in 2015.

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