The Compact Muon Solenoid Experiment
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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Dark matter searches with the CMS Experiment in 2010

Sezen Sekmen for the CMS Collaboration

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We explain the dark matter searches performed by the Compact Muon Solenoid Experiment using the 35 pb^{-1} of 7 TeV pp data collected by the CERN Large Hadron Collider in 2010. All observations so far were found to be consistent with the Standard Model predictions. The search results were used for setting exclusion limits on various new physics scenarios.

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Sezen Sekmen
on behalf of the CMS Collaboration

Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

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We explain the dark matter searches performed by the Compact Muon Solenoid Experiment using the 35 pb^{-1} of 7 TeV pp data collected by the CERN Large Hadron Collider in 2010. All observations so far were found to be consistent with the Standard Model predictions. The search results were used for setting exclusion limits on various new physics scenarios.

Keywords: Large Hadron Collider, Compact Muon Solenoid, dark matter

1. Introduction

Since its start in 2009, the CERN Large Hadron Collider (LHC) [1] has been successfully collecting data, which are used by the LHC experiments in a restless search for any hint of new physics beyond the Standard Model. These searches are quite unique, and different from the past in the sense that there is no guidance from theories or past experiments suggesting where the new physics might possibly dwell. However there exist a great variety of new physics models which attempt to provide answers for the open questions that cannot be addressed by the Standard Model (SM). One such unknown is the nature of dark matter in the Universe. Most new physics models accommodate candidates that can account for the dark matter, whose existence is suggested by astrophysics observations. This implies that, given a new physics signal at the LHC, we are also likely to extract some information on the nature of dark matter. The Compact Muon Solenoid (CMS) experiment at the LHC leads a diverse new physics program that addresses searches for a variety of dark matter candidates ranging from weakly interacting massive particles to gravitinos and axinos to TeV-scale dark matter candidates. After briefly introducing the CMS experiment, this review summarizes the dark matter searches carried on by CMS using 35 pb^{-1} of 7 TeV LHC pp data collected in 2010.

2. The CMS detector

CMS is one of the two generic-purpose detectors at the LHC. Figure 1 shows a schematic drawing of the CMS detector. The central feature of the detector is a superconducting solenoid providing an axial magnetic field of 3.8 T. The bore of this

solenoid is instrumented with several particle detection systems. Charged particle trajectories are measured within the field volume by a silicon pixel and strip tracker system, with full azimuthal (ϕ) coverage and a pseudorapidity (η) acceptance from -2.5 to $+2.5$. Here, $\eta = -\ln(\tan(\theta/2))$ and θ is the polar angle with respect to the counterclockwise beam direction. The tracking volume is surrounded by a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter that provide an η coverage from -3 to $+3$. The forward hadron calorimeter extends the calorimetric coverage symmetrically to $|\eta| < 5$. Muons are identified in gas ionization detectors embedded in the steel return yoke of the magnet. The CMS detector is nearly hermetic, which allows for momentum-balance measurements in the plane transverse to the beam axis. A more detailed description of the CMS detector can be found in [2].

Figure 1: Schematic drawing of the CMS detector

3. The CMS dark matter search

A generic-purpose detector like CMS can look for a variety of particle dark matter candidates. Currently, the most com-

Email address: ssekmen@cern.ch (Sezen Sekmen
on behalf of the CMS Collaboration)

monly explored candidates are the weakly interacting massive particles (WIMPs) such as neutralinos or sneutrinos suggested by supersymmetry (SUSY), Kaluza-Klein particles suggested by models with universal extra dimensions (UED), or the lightest T-odd parity particles suggested by little Higgs models. There also exist searches for other supersymmetric candidates such as gravitinos or axinos through indirect hints from heavy stable charged particles (HCSPs). In addition to these, other analyses look for dark photons, which may point out to TeV scale dark matter particles.

The road from pp collisions to any inference on the nature and properties of dark matter is long and arduous. First, CMS has to discover a deviation from the SM in one or more final states. Then, investigations will be made to see if the discovered signal is due to new physics that predicts a dark matter candidate. This may also bring along a rough estimate of the dark matter particle's mass. Subsequently, the masses of all other particles related to new physics will be measured based on the kinematics of the high branching ratio decays. This will be followed by precision measurements involving cross sections, branching ratios, angular distributions and rare decays that seemingly need 14 TeV of center of mass energy and at least $O(10 \text{ fb}^{-1})$ of integrated luminosity. All these will eventually lead to model-independent calculations of quantities such as the dark matter relic density and various interaction cross sections involving the dark matter particles.

However, as noted earlier, CMS has not yet seen any deviation from the SM predictions. Therefore, the current CMS activity is mainly focused on mapping this consistency with the SM into exclusions on candidate new physics models. So far, all such new physics interpretations that can be related to dark matter are done within the framework of supersymmetry (SUSY). In the following, we will summarize the results of searches for new physics related to dark matter, and the interpretation of these results. Current searches can be classified as follows: *i*) searches with missing energy final states; *ii*) searches for heavy stable charged particles and *iii*) searches for lepton jets.

3.1. Searches with missing energy final states

Missing energy is a well-known signature of many classical SUSY scenarios with WIMP dark matter candidates like neutralinos or sneutrinos. Such scenarios are typically characterized by dominant direct production of squarks and gluinos, and occasionally of charginos and neutralinos at the LHC, followed by cascade decays involving leptons and jets into a pair of heavy, neutral, stable particles. All these lead to a diverse set of final states with missing energy, which are systematically explored by the CMS SUSY searches. Using the 35 pb^{-1} of 7 TeV 2010 pp LHC data, CMS has performed searches in various missing energy final states which are listed in Table 1.

Figure 2, which shows distributions for data and various SM and SUSY Monte Carlo simulations is an example that illustrates the consistency of the LHC data with the SM¹. Though

Table 1: CMS 2010 SUSY searches using missing energy final states

Final state	Ref
jets + E_T^{miss} (using the α_T variable [5])	[3]
jets + b -jets + E_T^{miss} (using the α_T variable [5])	[4]
jets + E_T^{miss} (using the razor variable [7])	[6]
jets + missing transverse momentum	[8]
diphotons + E_T^{miss} + jets	[9]
photon + lepton + jets + E_T^{miss}	[10]
single lepton + jets + transverse momentum	[11]
same-sign dileptons + jets + E_T^{miss}	[12]
opposite-sign dileptons + jets + E_T^{miss}	[13]
Z + E_T^{miss} + jets	[14]
multipiletons + E_T^{miss}	[15]

there is no significant excess, there are some events at the high missing transverse momentum tail.

Figure 2: Missing momentum distributions for data and various Monte Carlo simulation samples after all baseline selection cuts except that on missing momentum (from the jets + missing transverse momentum analysis [8]).

An event display for the rightmost data event with highest missing transverse momentum is shown in Figure 3. The high missing transverse momentum in this striking event was checked to be not due to any detector effect. Furthermore, none of the jets were identified to originate from a heavy flavour jet, and none of the jet invariant mass combinations matches the W or top masses.

The most popular model that has been used for interpreting new physics searches with missing energy is the constrained MSSM (CMSSM) which is defined by four free parameters and a sign (m_0 , $m_{1/2}$, A_0 , $\tan\beta$ and $\text{sgn}(\mu)$) at the GUT scale. Figure 4 shows the 95%CL exclusion curves obtained by various analyses on the $m_0 - m_{1/2}$ plane with fixed $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. We see that, assuming neutralino dark matter, the low $m_0 - m_{1/2}$ bulk region and some parts of the stau coannihilation region (that give relic densities consistent with the WMAP measurements) are disfavored. A large part of the favored regions predict relic densities higher than the observed WMAP

¹Note however that this figure is only an illustration, and that CMS analyses generally quantify SM background yields based on data-driven estimation methods.

Figure 3: Event 70626194, in luminosity section 49 of run 148953. (r, ϕ) view of the highest missing transverse momentum event passing the search selections [8].

upper limit, which might indicate viability of non-WIMP candidates such as axions/axinos or gravitinos.

Figure 4: 95%CL exclusion curves obtained by various analyses on the $m_0 - m_{1/2}$ plane with fixed $A_0 = 0$, $\tan \beta = 10$ and $\mu > 0$.

CMS results from the analyses involving photons were interpreted within the context of general gauge mediation (GGM) models. Here, the lightest supersymmetric particle (LSP) and hence, the dark matter candidate is a light, $O(\sim \text{MeV})$ gravitino, and the next-to-lightest supersymmetric particle (NLSP) is a neutralino, which decays promptly to the gravitino plus a photon. Interpretations were made for two cases:

- for gluino or squark NNLSP (next-to-next-to-lightest supersymmetric particle) that decays to quarks + NLSP, using the photons + jets + E_T^{miss} results,
- for chargino NNLSP that decays to a lepton + NLSP, using the lepton + photon + jets + E_T^{miss} results.

Figure 5 shows the lower 95% CL exclusion limits on the squark and gluino masses in the GGM benchmark models for

50, 150 and 500 GeV neutralino masses. The non-observation of a signal in the photon channels is consistent with the constraints from Big Bang Nucleosynthesis (BBN) that disfavor SUSY models with gravitino LSP and neutralino NLSP.

Figure 5: Lower 95% CL exclusion limits on the squark ($\tilde{q}$) and gluino ($\tilde{g}$) masses in the GGM benchmark models for 50, 150, and 500 GeV neutralino ($\tilde{\chi}_1^0$) masses. The areas below and to the left of the lines are excluded. The expected exclusion limit for 150 GeV neutralino mass is shown by the dashed line. The shaded band represents the ± 1 standard deviation of theoretical uncertainty on the GGM cross section [9].

3.2. Searches for heavy stable charged particles

CMS also performed other more exotic searches that looked for heavy stable charged particles (HSCPs). HSCPs are, as the name suggests, heavy and charged particles that can traverse the whole detector before they decay. Thus, HSCPs would look like "non-relativistic" muons in the detector, where the slowness is due to their non-negligible mass. Discovering HSCPs would hint non-WIMP dark matter such as gravitinos and axinos, which have relatively weak couplings to the rest of the sparticles. In cases where the gravitino or axino is the LSP and a charged slepton or squark is the NLSP, the weak gravitino coupling implies that the charged NLSP will have a long enough lifetime to traverse the detector before it decays. HSCP searches were conducted by identifying tracks compatible with heavy, slow-moving particles through momentum and ionization-energy-loss measurements in the inner tracker detector, and additionally, by analyzing tracks passing muon identification requirements [16]. In the end, lower limits were set on the masses of various HSCP candidates. Figure 6 shows predicted theoretical cross sections and observed 95% CL upper limits on the cross section for gluinos and stops, for various nuclear interaction models.

3.3. Searches for lepton jets

Recent astrophysics observations showing an excess of high energy positrons in the cosmic ray spectrum [17] gave rise to various new models [18] that associate this excess with annihilation of TeV-scale dark matter particles in the galactic halo. Such models may also account for the observed discrepancies in

Figure 6: Predicted theoretical cross sections and observed 95% CL upper limits on the cross sections for different combinations of models and scenarios considered in the analysis. The bands represent the theoretical uncertainties on the cross section values [16].

Figure 7: Dimuon invariant mass distribution for events with a single dimuon of $p_T > 80$ GeV compared with the expected background. If new physics had been discovered in this channel, it would appear as a narrow peak above the background curve (with resolution similar to that of the J/ψ , which is the detector resolution) [19].

tion of collider and astrophysics results in order to reveal the true nature of dark matter.

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4. Conclusions

We have presented a summary of new physics searches with the Compact Muon Solenoid experiment based on the 35 pb⁻¹ of 7 TeV LHC pp data collected in 2010, whose results can guide our understanding of dark matter. Neither the searches explained here, nor the searches performed so far in 2011, have observed any traces of new physics, and hence found any clues of dark matter yet. The observed consistency with the SM has been used for setting exclusion limits on various new physics models. However, the LHC is still young - it has much more data to collect, and higher collision energies to attain - thus, the quest for new physics is only in its beginning. In case a discovery is made, a long series of rigorous interpretation studies would await us, which would necessarily involve the combina-

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