Physics results from CMS

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Abstract.

These proceedings report the results from the CMS experiment with data collected in 12 months of 7 TeV LHC collisions at CERN. With the first data collected all the major Standard Model processes have been studied: W, Z and other electroweak physics results, top and B physics. The main results are achieved with the di-leptons and di-jets reconstruction analyses. First results on searches for Higgs boson are then discussed with the prospects for the current 2011-12 running period. Search for new physics are also presented as deviations from the Standard Model distributions. First limits on new vector bosons, extra-dimensions and microscopic black holes are set depending on the theoretical models.

1. Introduction

The Compact Muon Solenoid (CMS) is one of the two “general-purpose” detectors at the Large Hadron Collider (LHC) [1]. It is located at the experimental Point 5 of the LHC near Cessy (France). The main characteristic features of CMS, shown in fig. 1, are a large superconducting solenoid magnet, which creates a strong field of 3.8 Tesla, a state-of-the-art silicon tracker, a highly granular crystal electromagnetic calorimeter, fully hermetic hadronic calorimeters and a sophisticated and redundant muon system. The detector has been built thanks to the collective effort of the CMS Collaboration consisting of more than 3000 scientists and engineers from 182 institutes distributed in 39 countries all over the world.

Prior to collecting pp collisions the detector has been accurately calibrated using cosmic muons. A large data set of cosmosics was recorded in successive campaigns of data taking from 2008 to 2009. As a result of these studies it was possible to achieve a good understanding of the initial alignment constants of the major detector components and a detailed map of the magnetic field. They led to an excellent control of the momentum resolution and absolute scale. The commissioning of the detector was then completed using the first LHC pilot runs at 0.9 and 2.36 TeV collision energies at the end of 2009. The LHC started 7 TeV operations in spring 2010, at very low luminosity, in the range of $\mathcal{L} = 10^{27}$ cm$^{-2}$s$^{-1}$, but reached quickly instantaneous luminosities exceeding $\mathcal{L} = 10^{32}$ cm$^{-2}$s$^{-1}$. In total, an integrated luminosity of 47 pb$^{-1}$ has been delivered by the LHC in 2010. With the LHC running in pp mode CMS has collected 43.2 pb$^{-1}$ of data corresponding to an overall data-taking efficiency of about 92%. The uncertainty in the luminosity determination is estimated to be 4%. The overall operational status of CMS during this data taking was excellent: for all the sub-systems more than 98% of the channels were operational. In 2011 about 1 fb$^{-1}$ has been collected so far (June 2011). These proceedings

1 On behalf of the CMS Collaboration
describe some of the most important CMS results published to date. The majority of these results are obtained with the 2010 data and will be soon updated with the 2011 luminosity.

2. QCD: Soft Physics and Jets
Taking advantage of the low luminosity phase at the beginning of the LHC running, many important measurements have been achieved by CMS. The first paper published by the collaboration using only 1 \(\mu b^{-1}\), corresponding to 2 hours of data taking, was about the transverse-momentum and pseudorapidity distributions of charged hadrons [2]. The Bose-Einstein Correlations were observed for the first time at the LHC [3] and a very interesting excess in the near-side long range (small \(\phi\) and large \(\eta\)) has been found in the charged particle distribution for high multiplicity events, with number of tracks above 110. This ridge, similar to the one observed in the ion-ion collisions, was measured for the first time in proton collisions [4]. Many analyses were also performed in the jet physics sector. Studying the inclusive jet cross-section [5] and the distributions of the di-jets events [6] it is possible to probe for new physics beyond the Standard Model. As rule of thumb, the sensitivity to a contact inetraction \(\Lambda\) is roughly 4 times the transverse energy of the most energetic jet. So far, up to jet transverse energy of about 1 TeV, all the measurements are in good agreement with the Standard Model.

3. B Physics
Cross sections for heavy quark production in hard scattering interactions provide an interesting testing ground for QCD calculations. Theoretically, large uncertainties remain due to the dependence on the renormalization and factorization scales. Measurements from the LHC at the center of mass energy of 7 TeV provide new opportunities to test our understanding of the heavy quark production mechanisms.

The first heavy flavor production measurements at CMS were made by reconstructing \(J/\psi\) and \(\Upsilon\) mesons in their decays to two muon final states. Candidates are formed by fitting pairs of oppositely-signed muons to a common vertex and event yields are obtained by fitting invariant mass distributions. The fraction of \(J/\psi\) mesons produced from longlived B decays is also measured by fitting the lifetime distribution of the reconstructed \(J/\psi\) [7]. Results are shown in fig. 2. The three lowest \(\Upsilon\) states are all visible due to the excellent mass resolution.
of the CMS detector, and their cross-sections have been measured as function of rapidity and transverse-momentum [8].

Two independent techniques are used to measure inclusive beauty production. The first technique makes use of semi-muonic decays of B hadrons [9] and the second relies on the identification of displaced secondary vertices within reconstructed jets to tag them as b jets [10].

Figure 2. Fraction of J/ψ mesons produced from B decays.

A fully exclusive reconstruction technique is used to measure the cross sections for B⁺ [11], B⁰ [12], and B₅ [13] mesons and Λₜ baryon decaying into a J/ψ and K⁺, K₀, φ and Λ respectively, and to measure the relative production cross-sections. Fig. 3 shows the results for the cross-section measurements of the B mesons.

Figure 3. Cross-sections measurements for B meson production.

4. Electroweak Results: W and Z

The W and Z boson production is a benchmark process at the LHC and the selection of these boson candidates is particularly important for CMS. The Higgs boson at intermediate or high mass is expected to decay with high branching fractions to pairs of W and Z and, in general, the intermediate vector bosons are among the main sources of background to new physics processes. W candidate events are characterized by a prompt, energetic (E_T > 25 GeV), isolated lepton, and significant missing transverse energy. The main backgrounds are QCD multijet events and Drell-Yan events in which one lepton fails the selection. Simple selection cuts lead to the distributions of missing transverse energy that are used to extract the W → ℓν event yield. It is worth noticing that at the LHC, due to the quark content of the colliding protons, we expect to measure a production yield for W⁺ larger than the corresponding yield for W⁻. The Z → ℓ⁺ℓ⁻ candidate events are required to have two opposite sign leptons satisfying the same selection criteria used for the W → ℓν sample. The inclusive cross section values are then measured in the data using data-driven methods for controlling the lepton efficiency, energy and momentum scale, resolution and all major sources of background. Fig. 4 shows the invariant mass distribution of the di-muon pairs in logarithmic scale to demonstrate the high purity of the selected sample of Z candidates, while Fig. 5 shows the ratio between results and theoretical predictions. It is worth noticing the high experimental precision achieved, 1%, and the excellent agreement between data and NNLO calculations performed adopting current parton distribution functions. The largest uncertainty for the cross section measurement comes from the uncertainty in the measurement of the luminosity that, however, cancels out in the cross-section ratios of
W to Z. To complete the picture, we very recently produced the measurement of the lepton charge asymmetry in W decays and the first measurement of the W polarization at a hadron collider. The lepton charge asymmetry in W events has been measured both with electrons and with muons in a large pseudo-rapidity range and for two different thresholds on the minimum transverse momentum of the W. The values of the charge asymmetry measured with electrons and muons are in good agreement with each other and the precision of the measurement is such that it is challenging the PDF predictions [15]. The measurement of the W polarization, as performed for $P_T^W > 50\text{GeV}/c$ [16] shows that, the LHC preferentially produces left handed W$^+$ and W$^-$ as expected. The muon fit result yields the most precise measurement for the three polarization fractions, $(f_L, f_R, f_0)$ left-handed, right-handed and longitudinal: $(f_L-f_R) = 0.240 \pm 0.036\text{(stat.)} \pm 0.031\text{(syst.)}$ and $f_0 = 0.183 \pm 0.087\text{(stat.)} \pm 0.123\text{(syst.)}$ for negatively charged W bosons, and $(f_L-f_R) = 0.310 \pm 0.036\text{(stat.)} \pm 0.017\text{(syst.)}$ and $f_0 = 0.171 \pm 0.085\text{(stat.)} \pm 0.099\text{(syst.)}$ for positively charged W bosons. These complex measurements are important benchmarks to prove that precision electroweak measurements are being already performed at the LHC. The list of all the public results in Electroweak Physics obtained by CMS can be found in [17].

**Figure 4.** Invariant mass distribution for Z in dimuons (log scale).

**Figure 5.** Ratio of measured to theoretical predicted values for W and Z cross-sections.

5. **Top Physics**

LHC can be considered as a top-factory for the huge rate of top quarks produced at TeV collisions. Searches in CMS for top quark candidates have been made looking at channels with high $p_T$ leptons or di-leptons, jets with at least 1 jet b-tagged and missing $E_T$. Going through the full statistics collected so far corresponding to a luminosity of $36\text{ pb}^{-1}$, we have been able to measure the top pair production cross section using different techniques and various decay channels leading to a combined measurement of $\sigma_{t\bar{t}} = 158 \pm 18 \pm 6 \text{ (lum.) pb}$ [18, 19]. This value is in good agreement with the most recent NLO and approximate NNLO predictions. These methods also lead to a precise measurement of the top mass with a combined result of $m_t = 173.4 \pm 1.9\text{(stat)} \pm 2.7\text{(syst)}\text{GeV}/c^2$. 


The excellent performance of the CMS detector and the effectiveness of the reconstruction algorithms have also been proven through the first measurement of the single top production cross section [20]. The measurement is particularly challenging as a consequence of the tiny cross section expected for the process and for the presence of important sources of background mainly due to W+jets and t\bar{t} events (Fig. 6, 7). The measured cross-section for single top in the t-channel obtained using 36 pb$^{-1}$ of LHC data is $\sigma_t = 83 \pm 29.8 (\text{stat} + \text{syst}) \pm 3.3 (\text{lumi})$ pb.

Figure 6. Extraction of the single top signal in the t-channel using the angle between lepton and jet.

Figure 7. Comparison of the single top measured cross-section with the NLO theoretical predictions.

6. Higgs Physics
The search for the Higgs boson is one of the most important drivers of the LHC experiments. The amount of data collected in 2010 was not large enough to perform a complete and exhaustive search that can yield, in general, competitive results with respect to the Tevatron experiments. This has been possible, so far, only for a few analyses. One of these is the search for the SM Higgs in the W$^+W^-$ channel with the Higgs production cross section enhanced by the presence of a fourth generation, a possible extension of the SM. For large lepton and quark masses, this extension has not been excluded by existing constraints. The presence of another family of fermions would produce an enhancement of the dominant gluon fusion cross-section. The irreducible background for H$\rightarrow$W$^+W^-$ production is the SM non-resonant production of W$^+W^-$. A good understanding of this process and of its properties is needed anyway since the W$^+W^-$ channel is particularly sensitive in the intermediate mass range (114 - 200 GeV/c$^2$) and is therefore considered a candle channel for the search of the SM Higgs boson. This is why the search has been performed in conjunction with the first measurement of the W$^+W^-$ production cross section at the LHC. W$^+W^-$ candidates are selected in events with two high $p_T$ leptons (electrons or muons) and large missing $E_T$. Leptons originating from H$\rightarrow$W$^+W^-$ decays tend to have a relatively small opening angle, while those from WW backgrounds are preferentially emitted back-to-back. The opening angle between the two leptons, $\Delta \phi_{ll}$, is therefore a variable providing the best discriminating power between the Higgs boson signal and the majority of the backgrounds in the low mass range. Fig. 8 shows the distribution of $\Delta \phi_{ll}$, after applying the W$^+W^-$selections, for a SM Higgs boson signal with m(H) = 160 GeV/c$^2$, and for the major sources of backgrounds. Since no excess above the SM expectations is seen in the lower $\Delta \phi_{ll}$ region, upper limits on the Higgs boson production cross section have been derived. In the presence of a sequential fourth family of fermions with very high masses, a Higgs boson with Standard Model couplings and a mass between 144 and 207 GeV/c$^2$ has been excluded at 95% confidence level [21].
The second analysis yielding new results on Higgs is the search for minimally supersymmetric Standard Model (MSSM) Higgs decaying to $\tau$ pairs. The observed $\tau$ pair mass spectrum reveals no evidence for neutral Higgs boson production, and an upper bound on the Higgs boson production cross section is determined. These results, interpreted in the MSSM parameter space, exclude a previously unexplored region (Fig. 9) [22]. The complete set of published analyses by CMS on the Higgs search can be found in [23]. The prospects for the Higgs search at the LHC are very promising. Assuming that in 2011-12 the LHC will deliver to the experiments an integrated luminosity in a range of 5-10 fb$^{-1}$, as it appears to be possible extrapolating on last year’s performance of the machine, we are confident that we will be able to exclude the SM Higgs boson in the mass range between 114 and 600 GeV/$c^2$, or to discover it with the combination of ATLAS and CMS results.

![Figure 8](image1.png)  
**Figure 8.** Opening angle between the two leptons in WW candidate events for the Higgs search.

![Figure 9](image2.png)  
**Figure 9.** Exclusion limit in the search of MSSM neutral Higgs decaying to $\tau$ pairs.

### 7. Searches: SUSY and Exotica Physics

In this early phase of the LHC program many inclusive searches for beyond the Standard Model events have been performed. Many of these new particles have similar signature: high invariant mass of the final state, isolated high $P_T$ leptons, large missing $E_T$, very energetic photons or jets. With the first data collected in 2010, even if is difficult to disentangle between different models, many analyses are already sensitive in regions not covered so far.

Supersymmetry (SUSY) searches at CMS have been performed using many different topological signatures: di-photons and large missing $E_T$, same sign and opposite sign di-leptons, single leptons and large missing $E_T$, multi-leptons and fully hadronic final states with large missing $E_T$. None of these searches have so far produced any hints of production of SUSY particles at the LHC. All the SUSY results can be found in [24]. Using well established statistical tools [25] we have extracted limits from the experimental data producing new results exceeding significantly the best measurements performed so far by the Tevatron experiments. Fig. 10 summarizes the exclusion limits produced by these analyses for a particular choice of SUSY parameters. The highest exclusion limits are obtained using the fully hadronic final states.
Figure 10. Exclusion limits for SUSY searches

All the exotica results are summarized in [26]. Among these analyses a particular focus is put here on new heavy bosons, extra-dimensions and microscopic black holes. New heavy gauge bosons, generally indicated as $Z'$ and $W'$, are predicted in various extensions of the Standard Model. The search for these particles is usually performed in the context of the benchmark models where these bosons are considered as heavy analogues of the SM $W$ and $Z$ bosons with the same fermionic couplings. Thus the decay modes and branching fractions are similar to those of the $W$ and $Z$ bosons. In this context the search is performed looking for anomalies in the tail of the distribution of the reconstructed transverse mass of the $W$ and the invariant mass of the $Z$. $W'$ boson would imply an excess of events in the tail of the transverse mass distribution in the $W$ leptonic decay. Since no excess is visible in our data, we can extract limits on the production of heavy $W'$ vector bosons at the LHC. Assuming Standard-Model-like couplings and decay branching fractions and combining together the decay modes in electrons and in muons, it is possible to exclude a $W'$ with mass lower than 1.58 TeV/$c^2$ [27], a value that exceeds the current limits set by the Tevatron experiments. The most stringent limits to date, around 1 TeV depending on the production model, have been obtained also for the search of $Z'$, where the analysis is conceptually similar [28]. The most important source of background for both analyses are multi-jet and $t\bar{t}$ events that must be carefully understood to set limits on new phenomena.

Compact large extra-dimensions are an intriguing proposed solution to the hierarchy problem of the Standard Model, which refers to the puzzling fact that the fundamental scale of gravity, $M_P = 10^{19}$ GeV/$c^2$, is so much higher than the electroweak scale $M_{EW} = 10^3$ GeV/$c^2$. With such a difference in scales, it is difficult to protect the Higgs mass from radiative corrections without a very high degree of fine-tuning. The original proposal to use extra dimensions to solve the hierarchy problem assumed a scenario where the SM is constrained to the common 3+1 space-time dimensions, while gravity is free to propagate through the entire multidimensional space. Because of this, the gravitational force is effectively diluted, having undergone a Gauss-
Law reduction in the flux. Phenomenologically, this scenario results in s-channel production of massive Kaluza-Klein (KK) graviton states, which decay into a di-photon final state that can be detected in modern, hermetic detectors like CMS. A search for large extra-dimensions via virtual graviton exchange in the di-photon channel has been performed by CMS looking for an excess of events in the high mass tail of the distribution of the di-photon invariant mass (Fig. 11). The new limits, obtained in the range of 1.6 - 2.3 TeV/c², depending on the number of extra-dimensions, can be interpreted as the lower limits on the effective Planck scale, $M_D$, in these models, and are to date the most restrictive limits on the existence of two or more large extra-dimensions [29].

Another possible manifestation of the fact that the effective Planck scale, $M_D$, could be brought to the TeV scale by the presence of compactified extra dimensions could be the production of microscopic black holes. Partons colliding in the LHC, once they approach each other to a distance comparable to the size of extra dimensions, could be sensitive to the full strength of gravity and may collapse into a microscopic black hole. The production cross section can be as high as 100 pb for $M_D$ of 1 TeV/c². Once produced, the microscopic black holes evaporate almost instantaneously by emitting energetic particles. About three quarters of the emitted particles are expected to be quark and gluons; the rest is accounted for by leptons, photons, W/Z bosons, and possibly Higgs particles. We look therefore for events with high multiplicity of energetic objects. Since the main background comes from copious production of multi-jets that are not well described in QCD predictions, we must use data-driven methods. We have found that a variable, $S_T$, which is defined as the scalar sum of transverse momenta of all the energetic objects in the event (reconstructed hadronic jets, leptons, photons and missing transverse energy) can be used to describe the multi-jet QCD background (Fig. 12). The resulting background predictions for the inclusive multiplicities of 3, 4, and 5 or more objects in the final state agree with the observed spectra in the data. As a result, we have been able to exclude black holes with the masses up to between 3.5 and 4.5 TeV/c², for the values of $M_D$ in the range of 1.5-3.5 TeV/c² and various other model parameters [30]. These limits are the first direct limits on black hole production at particle colliders and go well beyond potential reach of the Tevatron or cosmic-ray experiments.

8. Conclusions
In these proceedings the first physics results obtained using pp collisions at $\sqrt{s} = 7$ TeV are presented. After a few months of data taking a good understanding of the detector performance has been achieved and the Standard Model properties of the pp collisions studied. Soon afterwards started the systematic exploration of the new energy regime in the quest for signals of new physics. New limits have been produced in many searches: supersymmetry, new vector bosons, extra dimensions. The first studies of the Higgs boson in the LHC data have been presented together with the prospects for the current 2011-12 running period.

Acknowledgments
I would like to thank the LHC accelerator team for achieving an impressive performance of the machine in its first year of running. I am grateful to all colleagues of the CMS Collaboration for their huge collective effort in constructing and running the experiment and analyzing quickly and efficiently data collected recently.
Figure 11. Invariant mass distribution for di-photon events with superimposed the expected results for two different extradimensional models.

Figure 12. $S_T$ distribution in the data compared with the simulation of the effect in case of microscopic black-holes production.

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