Latest results of the CMS experiment

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Abstract

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Latest results of the CMS experiment

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Abstract. The Compact Muon Solenoid (CMS) experiment at CERN’s Large Hadron Collider (LHC) has started to collect and analyze proton-proton collisions at $\sqrt{s} = 7$ TeV from the first physics run of the LHC. At the time of this conference, CMS had collected approximately 0.3 $\text{pb}^{-1}$ of collision data, including small samples at lower energies of 0.9 TeV and 2.36 TeV. These samples allowed some precise studies of QCD and heavy flavour physics, the first cross section measurements of the $W$ and $Z$ bosons at 7 TeV, the first hints of reobservation of the top quark, and even the start of the exploration of the allowed parameter space of some new physics models. The results presented here demonstrate good detector performance and illustrate well understood physics signatures that will lead in the near future to discovery physics at the LHC.

1. Introduction
At the time of this conference, the Large Hadron Collider (LHC) at CERN [1] had delivered proton-proton collisions at the record-breaking energy of 7 TeV for four months; for a fortunate coincidence, the day of this presentation coincided with the disclosure of a large wave of results for the Summer conferences with up to 280 $\text{nb}^{-1}$. This sudden flood of new results imposed some difficult choices in the selection of topics to be covered in 20 minutes; in particular, I chose to over-represent the very latest results on “hard probes” like heavy quarks and electroweak bosons, and the very first public results on searches for new physics, which were a striking novelty with respect to the results shown at any conferences since then, and first hints of a vibrant research program that will profit enormously from more statistics.

2. LHC and CMS status
The LHC restarted operations in late November 2009, colliding protons at $\sqrt{s} = 0.9$ TeV and through December accumulated 10 $\mu\text{b}^{-1}$ at this energy and 0.4 $\mu\text{b}^{-1}$ at 2.36 TeV, followed by collisions at 7 TeV at the end of March 2010. Since the initial collisions, luminosities have increased during the commissioning phase for the accelerator and experiments.

The Compact Muon Solenoid (CMS) experiment [2] is a general purpose detector designed for high-energy and high-rate hadron collisions. From the interaction point outward, CMS includes Silicon pixel and strip tracking detectors with acceptance to pseudorapidities ($\eta$) up to 2.4; a lead-tungstate crystal electromagnetic calorimeter (ECAL) for photon and electron identification; a brass-scintillator hadron calorimeter (HCAL) covering $|\eta| < 3$ and a quartz fiber forward calorimeter (HF) covering $3 < |\eta| < 5$; a superconducting solenoid operated at 3.8 Tesla; and a muon detection system consisting of drift tubes and resistive plate chambers covering $|\eta| < 1.2$ and cathode strip and resistive plate chambers covering $0.9 < |\eta| < 2.4$. 
Through 21 July 2010, the day of this presentation, CMS recorded an integrated luminosity of 303 nb$^{-1}$, out of 346 nb$^{-1}$ delivered by the LHC for an efficiency of almost 90%. The peak instantaneous luminosity achieved at the end of this period was of the order of 10$^{30}$cm$^{-2}$s$^{-1}$, and at the time of writing these proceedings the LHC commissioning is quickly progressing towards the instantaneous luminosity goal of 10$^{32}$cm$^{-2}$s$^{-1}$, which is planned to maintained through the end of 2011, with the integrated luminosity goal of 1000 pb$^{-1}$ total by the end of 2011.

3. Hadron physics with the inner tracking system
Several QCD studies with an important impact could be performed with a limited statistics and the exclusive use of the inner tracking, starting from the measurement of the charged particle multiplicity and spectrum in $pp$ collisions at 0.9, 2.36 and 7 TeV [3, 4], see Figure 1, showing that the growth with center-of-mass energy doesn’t scale as foreseen from previous fits (see also Ref. [5] for an extensive comparison of data to several generator settings for $\langle p_T \rangle$ versus track multiplicity).

The vertexing capabilities have been demonstrated by the reconstruction of several unstable hadrons, some identified with the help of lifetime cuts (e.g., $K_S \to \pi^+\pi^-$, $\Lambda \to p\pi$, $\Xi \to \Lambda\pi$, $\Omega \to \Lambda K$, and several $D$ and $B$ mesons, see Sec. 4), and some which decay too quickly to be discerned from the primary vertex (e.g., $K^* \to K_S\pi$, $\Sigma \to \Lambda\pi$, $\Xi^0 \to \Xi^\pm\pi^\mp$, $\phi \to K^+K^-$; in the latter case the track sample has been enriched in kaons by exploiting the $dE/dx$ measurement from the microstrips, see Sec. 6) [6, 7, 8, 9].

An extensive program of Monte Carlo tuning has already started with the inclusive and exclusive measurements performed, and the comparisons between the peak positions and the known mass values of all the observed resonances are being used to validate or correct the tracker alignment, the magnetic field mapping, the material budget of the detector, and to validate particle identification (e.g., the kinematic properties of the $\Lambda \to p\pi$ decay allow to know which of the two tracks is the proton and which the pion, providing a validation of $dE/dx$-based particle-id, and the $K_S \to \pi^+\pi^-$ and $\phi \to K^+K^-$ decays allow to study the probability of pions and kaons to be identified as muons).
4. Heavy quarks (c,b,t)

The muon system of CMS allows a high-resolution measurement of di-muonic resonances ranging in mass from the \( \rho \) and \( \omega \) to the \( Z \); with 0.28 nb\(^{-1}\), well resolved peaks were observed for the \( \Upsilon \) resonances up to 3S [10], see Figure 2, and the \( J/\psi \) yield was such to allow the first differential cross sections to be meaningfully compared to the existing models [11].

The \( D \) and \( B \) mesons, copiously produced at 7 TeV pp collisions, can travel distances of the order of \FIXME{} before decaying; variables directly or indirectly related to the flight distance are thus used for the identification of \( c \) or \( b \) flavours. A direct decay length cut has been used for the identification of several \( D \) mesons [12] with the very early 7 TeV data, and for the \( B^\pm \rightarrow J/\psi K^\pm \) [13] and \( B_S \rightarrow J/\psi \phi \) [14] decays with less than 0.3 nb\(^{-1}\).

Several techniques are being used to measure the \( b\bar{b} \) cross section. For example one analysis exploits the fact that \( \approx 20\% \) of the \( b \) decay chains contain muons [15], while another public result at the time of the conference makes use of the so called \( b \) tagging algorithms [16], which take advantage of the high precision in resolving secondary vertices from \( b \) hadrons. Many algorithms have been developed in CMS, and their agreement with simulation is quite impressive for early data [17]. Figure 3 shows, as an example, a particularly complex discriminator built by combining the 3D impact parameters of all tracks in a jet, overweighting the four most displaced tracks (four being the average number of tracks from a \( b \)-hadron decay).

At the time of the conference the very first top quark candidates at 7 TeV [19] had been presented, and \( b \) tagging had given a very substantial confidence in the event interpretation of many of them. Figure 4, as an example, shows a particularly convincing di-muon candidate with two \( b \)-tagged jets.

![JetBProb Discriminator](image-url)

**Figure 3.** One of the jet \( b \)-tagging discriminators used in CMS, see definition in the text.

5. \( W \) and \( Z \) bosons

The leptonic decays of \( W \) and \( Z \) bosons provide particularly distinct signatures at hadron colliders. Such clean events play a major role in the commissioning of lepton-id in CMS and in the understanding of the first data.

Figure 5 shows the transverse invariant mass built from a high-\( p_T \) muon candidate and the missing transverse energy; the distinctive evidence for \( W \) decays is the “Jacobian peak” at the known \( W \) mass. Figure 6 shows the invariant mass of pairs of high-\( p_T \) electrons passing tight quality selections combining the tracking and calorimetric informations.
The first cross sections at 7 TeV have been presented with 0.2 pb$^{-1}$ [18], yielding values in agreement with expectations, see Figure 7. An extensive program of measurements of events with $W$ and $Z$ bosons is already ongoing: $W$ asymmetry versus $\eta$, $Z$ forward-backward asymmetry, associated jet multiplicity. These will be important to constrain the Parton Distribution Function (e.g., in the first two examples) and to characterize one of the main backgrounds to top quark measurements and some SUSY searches.

Figure 5. Transverse invariant mass distribution for $W \rightarrow \mu\nu$ candidates.

Figure 6. Invariant mass distribution for $Z \rightarrow e^+e^-$ candidates.

6. The first CMS searches
The LHC is, first of all, a machine for discoveries. Nevertheless, it could come as a surprise that so early a few analyses reached a sensitivity comparable with previous experiments. This happened, in particular, for the searches of new particles with striking signatures and that can have coupling to gluons: at the LHC energy, gluon-gluon fusion has a huge role in massive particle production, as in the top quark case.

Figure 8 shows the reach of a search for resonances in the di-jet final state [20]. From the smoothness of the di-jet mass distribution generic cross section limits have been derived, which in turn have been used to constrain models of new physics. The first 120 nb$^{-1}$ were sufficient to exclude at 95% C.L. string resonances with mass less than 1.67 TeV, excited quarks with mass less than 0.59 TeV and axigluons and colorons with mass less than 0.52 TeV. Remarkably, these limit on string resonances were already more stringent than previously published limits.

A signature-based search is performed for heavy stable charged particles (HSCPs) [21] by combining momentum and ionization energy loss measurements, exploiting the property of slowly moving particles to release much more energy by ionization than ultra-relativistic ones. Two selections are applied, one where candidate inner tracks are matched to muon-like tracks, which gives a very high signal-to-background ratio for models where the HSCP is lepton-like (e.g., stable staus or charginos), and one entirely based on the inner tracking system, which is thus sensitive to the so called R-hadrons, i.e., bound states of colored heavy particles (e.g., stable stops or gluinos) which have a very high probability of interacting in the calorimeters. Figure 9 shows the distribution of reconstructed masses (from the inversion of the $dE/dx$ versus $P$ relation) for selected tracks passing also the muon identification requirements. With only 198 nb$^{-1}$, lower limits at 95% C.L. on the mass of stable gluinos were set at 284 GeV with the analysis that uses muon identification and 271 GeV with no muon identification.

Complementary to this analysis, CMS is also searching for long-lived gluinos which have stopped in the calorimeters and decay during no-beams periods [22], using a dedicated
calorimeter trigger. In a dataset with a peak instantaneous luminosity of $1.3 \times 10^{30} cm^{-2} s^{-1}$, an integrated luminosity of $203 - 232 nb^{-1}$ depending on the gluino lifetime, and a search interval corresponding to 115 hours of LHC operation, no significant excess above background was observed, allowing to set stringent limits on gluino pair production over 14 orders of magnitude of gluino lifetime, extending existing limits from the Tevatron.

Figure 8. Distribution of di-jet invariant mass, and predictions for some new physics models.

Figure 9. Distribution of reconstructed masses for the muon-matched HSCP search.

7. Outlook and conclusion

The CMS detector is performing well, already demonstrating excellent reconstruction of the many ingredients expected in many searches for new physics: missing transverse energy, b-tagging, leptons, and jets. All the known particles have been reobserved, and many “known unknowns” are being measured; some searches based on simple topologies or unusual signatures have already started, in some cases already improving over the existing limits, thanks to the steep dependence of the cross sections on the collision energy. Some of the success can be credited to the long commissioning campaign with cosmic rays, and the overall quality of the first results is impressive and bodes well for the future.

References
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