Latest results of the CMS experiment

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Latest results from 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. At the time of this conference, CMS had collected ≈ 300 nb^{-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 may 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; the CMS experiment has collected an integrated luminosity of 300 nb^{-1}.

We have analysed the data for validating Standard Model physics at a higher center-of-mass energy than ever before and have searched for physics beyond the Standard Model. This sudden flood of new results imposed on us 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 search for heavy quarks and electroweak bosons, and the very first public results on searches for new physics.

2. LHC and CMS Status

The LHC restarted operation in late November 2009, colliding protons at $\sqrt{s} = 0.9$ TeV and through December accumulated 10 μb^{-1} at this energy and 0.4 μb^{-1} at 2.36 TeV, followed by collisions at 7 TeV at the end of March 2010. Since the initial collision, luminosity has 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 and heavy-ion collision. From the interaction point outward, CMS includes silicon pixel and strip tracking detectors with acceptance in $|\eta| < 2.4$; a lead-tungstate crystal electromagnetic calorimeter (ECAL) covering $|\eta| < 3$ 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 this proceeding the LHC commissioning is quickly progressing towards an instantaneous luminosity goal of 10^{32}cm^{-2}s^{-1}, which the experiment plans to maintain through the end of 2011, hoping to achieve an integrated luminosity goal of 1000 pb^{-1} by the end of 2011.

3. Hadron Physics with the Inner Tracking System

Several important QCD studies could be performed with the limited data set and the exclusive use of the inner tracking system. Figure 1 shows the measurement of the charged particle multiplicity and spectrum in pp collisions at 0.9, 2.36 and 7 TeV [3, 4]. It is observed 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).
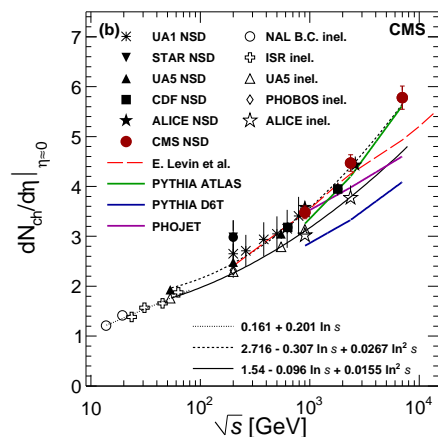
Figure 1. Growth of particle multiplicity with center-of-mass energy in pp and $p\bar{p}$ collisions.
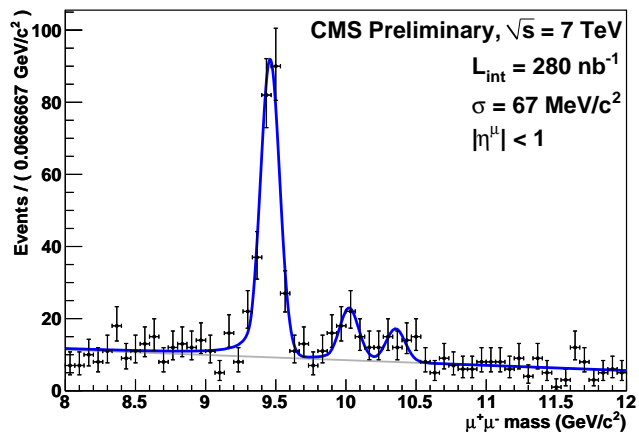
Figure 2. Reconstruction of the Υ resonances decaying into muons, with both muons within $|\eta| < 1$.

The vertex reconstruction capability has 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 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. For example, the kinematic properties of the $\Lambda \to p\pi$ decay allow to know which of the two tracks is the proton track and which one is the pion track, 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 the CMS detector allows for a high-resolution measurement of the di-muonic resonances ranging in mass from the ρ and ω to the Z. With 280 nb^{-1} of data, well resolved peaks were observed for the Υ resonances up to 3S [10], see Figure 2, and the J/ψ yield was such as to allow for 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 the millimeter 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 identification of several D mesons [12] with very early data at $\sqrt{s} = 7$ TeV, and for the $B^{\pm} \to J/\psi K^{\pm}$ [13] and $B_S \to J/\psi\phi$ [14] decays with less than 300 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 takes 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 even for very limited early data [17]. As an example, figure 3 shows a particularly complex discriminator built by combining the likelihoods of the measured 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).

Figure 4 shows a particularly convincing di-muon candidate event with two b-tagged jets at $\sqrt{s} = 7$ TeV data presented at this conference. The confidence in the event as a golden top quark candidate arises from very good understanding of b-tagging using our silicon system.
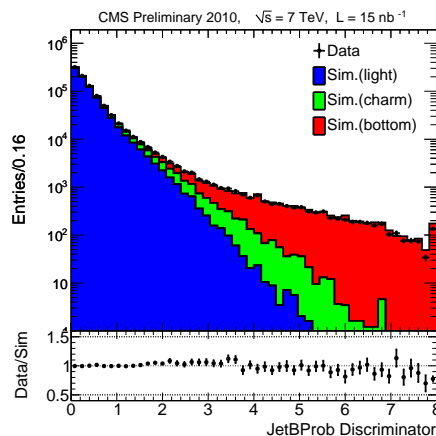
**Figure 3.** One of the jet b-tagging discriminators used in CMS, see definition in the text.
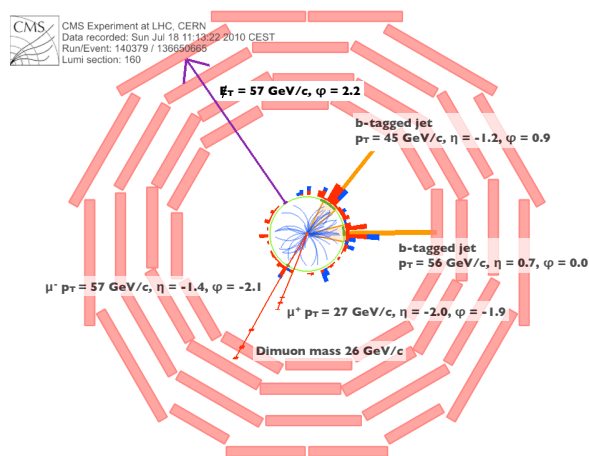
Figure 4. A "golden" top quark candidate, interpreted as $t\bar{t} \to \mu^+\mu^-\nu\bar{\nu}b\bar{b}$.

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 commissioning the lepton-id in CMS and in the understanding of the first data.

Figure 5 shows the distinctive "Jacobian peak" in transverse mass distribution of W reconstructed from its decay into a muon and missing transverse energy. Figure 6 shows the invariant mass of Z decaying into pairs of high-p_T electrons passing tight quality selections

combining the tracking and calorimetric informations. Figure 7 shows the first cross sections at 7 TeV with 198 nb^{-1} [18], yielding values in agreement with expectations. An extensive program of understanding physics with W and Z bosons is already ongoing; for example, W asymmetry study, Z forward-backward asymmetry, and studies of vector bosons associated with jets. The first two of these studies will be important to constrain the parton distribution functions and the last one to characterize one of the main backgrounds to top quark measurements and various SUSY searches.
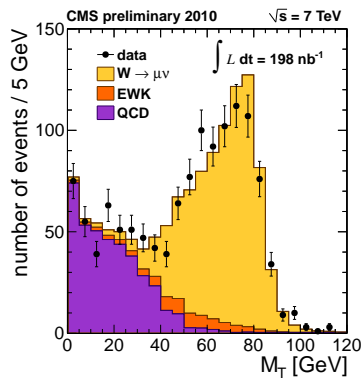
Figure 5. Transverse mass distribution for $W \rightarrow \mu\nu$ candidates.
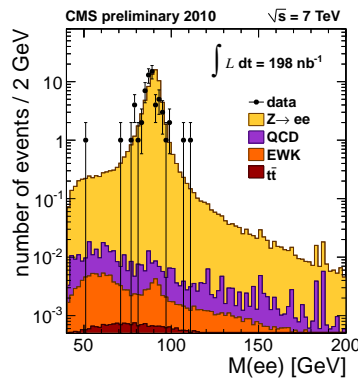
Figure 6. Invariant mass distribution for $Z \rightarrow e^+e^-$ candidates.
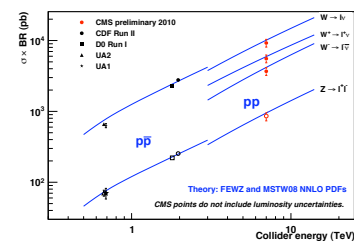
Figure 7. W and Z cross sections times branching ratio for their decay into electon and muon channels, versus center-of-mass energy.

6. The First CMS Searches

The LHC is, first of all, a machine meant to discover new physics. Nevertheless, it came as a surprise that so early a few analyses reached a sensitivity comparable with previous experiments. Searches for new particles with striking signatures could reach a very good sensitivity even with an incomplete understanding of all the detector subsystems; moreover, several new physics models predict massive particles with direct coupling to gluons, which implies the possibility to produce them by gluon-gluon fusion and therefore a big advantage of LHC over previous accelerators, in analogy with top quark production.

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} of data 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.

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} of data, lower limits at 95% C.L. on the mass of stable gluinos were set at 284 GeV (271 GeV) from analysis with (without) muon identification.

Complementary to this analysis, using dedicated calorimeter triggers, CMS is also searching for long-lived gluinos which may stop in the calorimeters and decay during no-beams periods [22]. 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 [23].
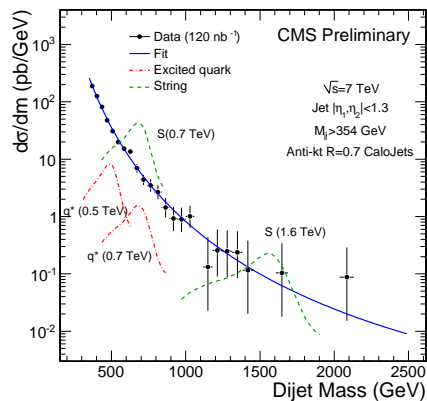
Figure 8. Distribution of di-jet invariant mass, and predictions for some new physics models.
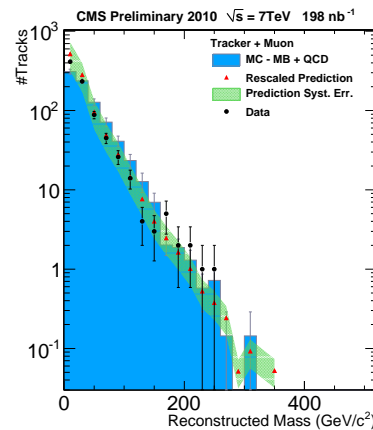
Figure 9. Distribution of reconstructed masses for the muon-matched HSCP search.

7. Outlook and Conclusion

The CMS detector is performing well. It has already demonstrated 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.

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