

CMS OVERALL PERFORMANCE AND PHYSICS RESULTS IN 2010*

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The year 2010 was the first full year of operation of the Large Hadron Collider (LHC). The Compact Muon Solenoid (CMS) experiment has recorded integrated luminosity of over 43 pb^{-1} of proton–proton data at center-of-mass energy $\sqrt{s} = 7 \text{ TeV}$ and $8 \mu\text{b}^{-1}$ of lead–lead data at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$. In this paper the CMS detector is briefly introduced. Its initial readiness for data taking and status of operation in 2010 is given. The performance of CMS subsystems is shown. Selected measurements from proton–proton and lead–lead runs are described.

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1. The CMS detector and its operation in 2010

CMS [1] is a general purpose experiment for physics discoveries at the highest luminosities of the LHC. Its main component is a large (6 m diameter and 13 m long) solenoid. It delivers strong, 3.8 T magnetic field in the inner part of the CMS detector and about 1.8 T in iron return yoke. CMS is traditionally divided into barrel part (with detectors roughly parallel to beam pipe) and two endcaps. Next to beam–beam interaction region there is a tracker system, consisting of silicon Pixel and silicon Strip Detectors. The CMS tracker provides excellent reconstruction of charged particle tracks and primary- and secondary-vertices. The tracker is surrounded by an electromagnetic calorimeter. It is a homogeneous calorimeter made of lead-tungstate crystals. The energy measurement is supplemented with a sampling brass-scintillator hadron calorimeter. The above subdetectors are

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positioned in the inner part of the CMS detector, inside the coil. In the outer part, outside the coil, a muon system is placed. It is dedicated for muon reconstruction and identification. The muon system is based on gaseous detectors: Drift-Tubes in the barrel, Cathode Strip Chambers in the endcaps and Resistive Plate Chambers. The pseudorapidity ($\eta = -\ln \tan \theta/2$, where θ is a polar angle) coverage of CMS depends on a subsystem. The tracking detectors (muon system, tracker) provide reconstruction up to $|\eta| \approx 2.4$ – 2.5 . The calorimeter coverage is enlarged for the purposes of hermeticity and extends up to $|\eta| \approx 3$ in a case of the electromagnetic calorimeter and up to $|\eta| \approx 5$ in a case of the hadronic one.

After re-opening of the LHC, CMS started to collect proton–proton collisions data. The initial center-of-mass energy delivered by the LHC $\sqrt{s} = 0.9$ TeV was followed by 2.36 TeV at the end of 2009. Since March 2010, till November 2010 the LHC energy was increased up to half of its designed energy, *i.e.* to $\sqrt{s} = 7$ TeV. Although the instantaneous LHC luminosity at startup was small, during a few months of operation it was increased by 5 orders of magnitude and reached $2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$. The integrated luminosity delivered to CMS was 47pb^{-1} out of which above 43pb^{-1} was recorded by CMS. At the end of 2010, the LHC has entered into a heavy ion program, colliding lead–lead beams at nucleon–nucleon centre-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV.

During the whole year 2010 the CMS detector was performing very well. For each subdetector more than 98% channels were operational. Moreover the efficiency of taking data was very high (above 90%). The number of events passing strict CMS data-quality certification criteria correspond to integrated luminosity of about 36pb^{-1} . These events are referred as full 2010 CMS data sample.

2. Detector performance results

The CMS detector was initially commissioned with a test beams data and cosmic runs [2] before the LHC startup. Commissioning was continued with an early LHC data. At this step the key aspects were calibration and alignment of subdetectors, validation of reconstruction algorithms, comparison of detector response (reconstructed physics objects) with simulation predictions, validation and tuning of trigger algorithms and menus.

A charged particle reconstruction is one of key aspects to understand an event content. CMS has demonstrated an excellent performance and a good understanding of tracking capabilities [3, 4]. Tracker operation conditions were validated. Just after the LHC startup, timing readout windows were optimised. The early commissioning includes also measurements of Lorentz angle, energy loss (dE/dx) and detector efficiencies. The validation

of tracking reconstruction algorithms includes studies of resolution and efficiency of track and primary vertices finding, multiple interaction extraction, determination of beam line position and width.

A good illustration of an overall tracking performance are searches for well known resonances. In Fig. 1 (a) one can see invariant mass histogram of candidates for $\Xi^\pm \rightarrow \Lambda^0/\bar{\Lambda}^0 \pi^\pm$ decays. The analysis involves reconstruction of a secondary vertex (decay of Λ). It is formed by two opposite charge tracks (assumed to be pion and (anti)proton). Their transverse impact parameters should be not compatible with the beam spot. These tracks should form together a good secondary vertex with a proper invariant mass. In addition, since $\Xi^\pm$ is a long lived baryon, there should be one more charged particle (pion) not compatible with beam spot, but should form a common vertex with Λ .

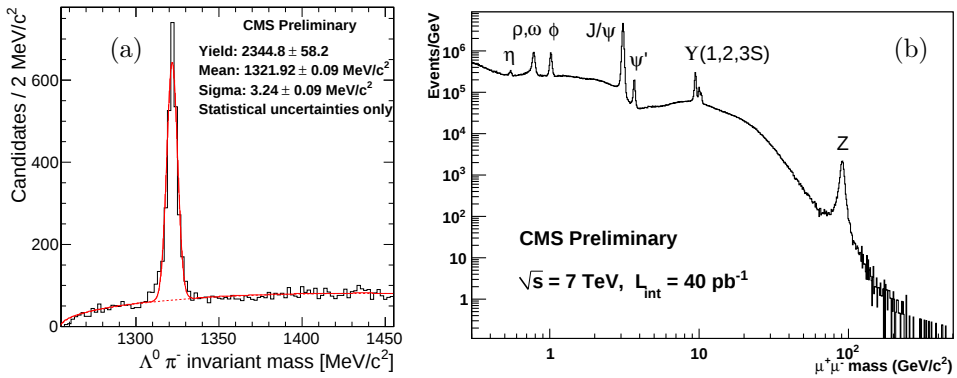


Fig. 1. (a) Illustration of low mass resonances searches: invariant mass distribution of $\Lambda^0 \pi^-$ (and $\bar{\Lambda}^0 \pi^+$) with a peak from $\Xi \rightarrow \Lambda \pi$ decays. (b) Muon reconstruction and identification: Invariant mass distributions of $\mu^+ \mu^-$ with η , (ρ, ω) , ϕ , J/Ψ , Ψ' , $\Upsilon(1, 2, 3S)$ and Z mass peaks visible.

An excellent muon reconstruction is one of design points of the CMS experiment. Muons that are supposed to come from nearby the beam spot are reconstructed in two ways. A muon track can be initially reconstructed in the muon system and updated with information from the tracker. Alternatively, a track reconstructed in the tracker can be propagated to the muon system, and identified as a muon in case of agreement with a signal found therein. Since the CMS all-silicon tracker provides very precise measurements, both ways of reconstruction lead to equivalent resolutions up to transverse momenta of $\mathcal{O}(10^2 \text{ GeV})$.

The period of an early commissioning with proton beams was dominated by validation of local reconstruction inside muon stations, alignment, calibration and data synchronisation. It has been followed by studies of muon

identification and reconstruction [5]. This includes analysis of reconstruction algorithms by comparison with generator expectations, validation of muon isolation algorithms, analysis of muon deposit in calorimeters, cosmic backgrounds, hadron decays in-flight, punch through probability and muon trigger performance. In all cases the agreement with simulation predictions was met. In order to minimise bias in muon reconstruction efficiency measurement, CMS is applying tag-and-probe technique. It relies on $J/\Psi \rightarrow \mu^+ \mu^-$ decays, with a possibility to extend to other resonances, especially Z muonic decays. It is required that one of the muons (tag) is reconstructed in the muon system and the second (probe) in the tracker. A probe track combined with a tag track must fulfil invariant mass criteria. In addition, the probe track energy deposit in calorimeter should be compatible with that of minimum ionising particle. The check of reconstruction of a probe track in the muon system allows us to determine the muon reconstruction efficiency. An illustration of a very good performance of the muon system can be a di-muon invariant mass distribution as shown in Fig. 1(b). One can note a clearly visible fine-structure of Υ family.

The precise measurement of electromagnetic cascades is a vital aspect for the Higgs boson searches as well as many exotic channels. Thus, the early 2010 data were used to finalise calorimeter commissioning [6]. This includes validation of crystal transparency, thermal stability and timing alignment. CMS observed unphysical high deposits in single crystals. They are caused by direct ionisation of the avalanche photodiode by highly ionising particles resulting from LHC collisions. Algorithms have been developed to flag these signal based on topological and timing characteristics and reject them. The commissioning of electromagnetic calorimeter with 2010 data has been completed by analyses of reconstruction performance [7, 8], including efficiency measurement from data and calibration [9]. The CMS electromagnetic calorimeter has been pre-calibrated with laboratory measurements, test beams, cosmic rays and early LHC data. The final calibration is made in-situ using LHC collision data. The strategy to calibrate electromagnetic calorimeter in 2010 includes ϕ -symmetry inter-calibration method and π^0/η calibration. The first one is exploring the ϕ symmetry of the detector around the beam axis and can be done with minimum bias events. It allows to inter-calibrate crystals at the same pseudorapidity. The π^0 and η calibration uses the photon pairs from decays. It extends crystal inter-calibration to different values of pseudorapidities and allows to investigate calorimeter energy scale. Both methods can be combined. The invariant mass of photons from π^0 decays is a quick illustration of calorimeter performance. The one obtained with only 18 nb^{-1} collected is shown in Fig. 2(a). A good agreement with Monte Carlo generator prediction is visible. Another method of calibration uses Z and W to electron decays. The electron measurement in the tracker

can be used to correct the calorimeter energy scale. This method is expected to become the main one when integrated luminosity will reach $\sim 1 \text{ fb}^{-1}$. In addition, $Z \rightarrow e^+e^-$ and $J/\Psi \rightarrow e^+e^-$ decays can be used to monitor and correct the absolute energy scale as soon as large data sample is available.

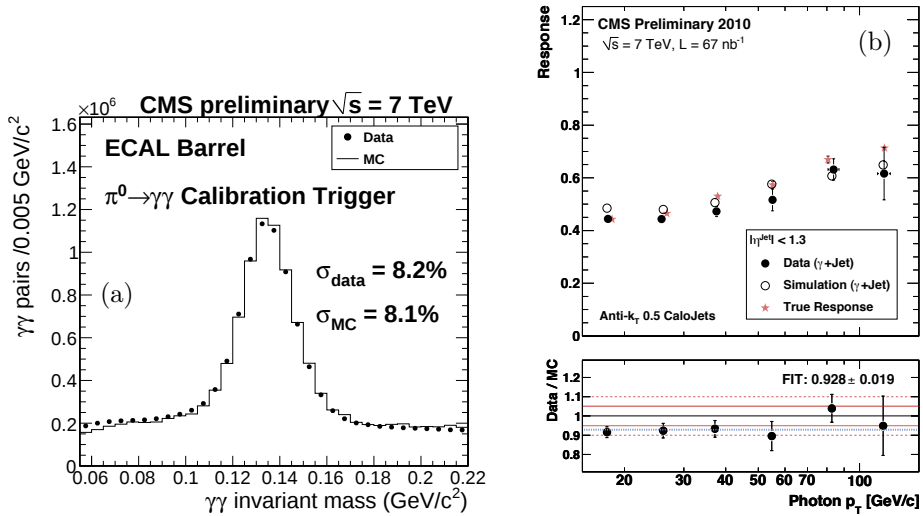


Fig. 2. (a) Result of initial calibration of electromagnetic calorimeter: Invariant mass distribution for photon pairs (barrel only). The plot was obtained after collecting only 18.7 nb^{-1} of data. The distribution expected from Monte Carlo generator, corresponding to the same number of events is also shown. (b) Initial calibration of hadronic calorimeter. For a photon plus jet sample a relative response $\langle p_T^{\text{jet}}/p_T^\gamma \rangle$ is shown as a function of p_T^γ . The data agrees well with simulation prediction. In addition simulation truth response (p_T ratio of simulated response and particle level jet) is also indicated.

Jets are another vital observables for CMS. They are among main tools to verify predictions of the Standard Model in the LHC energy regime. Moreover they are possible signatures of many New Physics processes. For the jet reconstruction CMS has adopted anti- k_t clustering algorithm [10]. An important part of CMS commissioning is study of jet energy response and resolution [11,12,13]. Since the energy measured in the detector differs from the particle jet energy, a factorised procedure for the jet energy calibration was developed. There are three types of corrections applied. The energy offset correction is supposed to remove contributions from calorimeter electronic noise and pile-up. The relative correction compensates non-uniform pseudorapidity response of the calorimeter. The absolute correction removes variation in jet response as a function of jet transverse momentum (p_T). In order to determine jet energy corrections CMS is using Monte Carlo truth

information and physics processes for validation and in-situ calibration (resulting currently in small additional correction). The di-jet p_T balance is used for validation of relative corrected jet energy response while photon plus jet balance method provides measurement of the absolute energy scale. An initial CMS result, illustrating not only quality of preparation of CMS for data taking but also a high quality of CMS simulation is presented in Fig. 2(b). The relative response agrees well with expectations justifying usage of 10% of jet energy uncertainties for early physics publications.

Calorimeter-only jet measurements can be improved with Particle-Flow method [14]. The CMS particle-flow event reconstruction attempts to identify and reconstruct individually all particles produced in collisions, using information from all CMS detectors. This information is used at the level of jet clusterization allowing for more precise jet reconstruction. The power of the method is well visible in Fig. 3, obtained soon after LHC startup [15]. The jet energies extend to regimes not accessible with calorimeter-only jets. The jet production cross-sections agree very well with theoretical predictions. This first-data analysis is confirmed with full 2010 CMS data sample [16]. The Particle-Flow method applied to the reconstruction of missing transverse energy and jets is used in most of physics analyses in CMS.

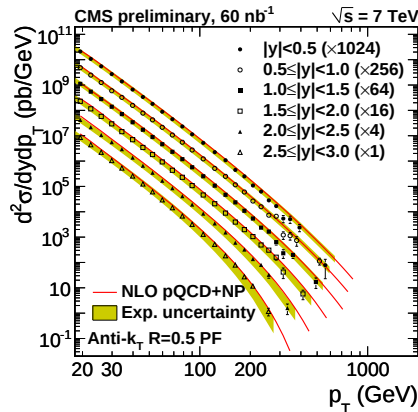


Fig. 3. The measurement of jet spectra for particle-flow jets. The theory predictions are shown. The spectra are scaled with a factor indicated in the legend.

3. Selected CMS measurements

Charged particle multiplicities and momentum spectra

The charged particle multiplicities and momentum spectra in pp collisions at energies of 0.9, 2.36 and 7 TeV were the first measurements of the CMS experiment [17]. Since majority of pp collisions does not involve hard

scattering these measurements allow us to verify predictions of soft interactions which are modelled phenomenologically only. The CMS measurements refer to non-single-diffractive (NSD) interactions provided by event selection of non-diffractive and double-diffractive events. The charged particle multiplicities were obtained using three techniques. The counting of reconstructed hits and hit pairs in the Pixel Detector grant access to tracks with transverse momenta down to 30 and 50 MeV/ c respectively. The third method relies on full track reconstruction based on at least three hits (often in the Pixel Detector) and allows not only track counting but also momentum measurements for p_T above 100 MeV/ c . These low p_T reconstruction thresholds support measurements in soft particle regime. The CMS measured the average transverse momentum of charged tracks in the early 2010 $\sqrt{s} = 7$ TeV data to be $\langle p_T \rangle = 0.545 \pm 0.005(\text{stat.}) \pm 0.015(\text{syst.})$ GeV/ c . The CMS measurements use tracks in $|\eta| < 2.4$ and accounts for very soft tracks by extrapolation of momentum distributions down to $p_T = 0$. In Fig. 4(a) the above result is compared with previous measurements taken at different beam energies. The same data were used to compute charged particle multiplicities as a function of η . CMS determined average charged multiplicity density in $|\eta| < 0.5$ to $dN_{\text{ch}}/d\eta = 5.57 \pm 0.01(\text{stat.}) \pm 0.23(\text{syst.})$. The CMS result is shown in Fig. 4(b) together with other measurements.

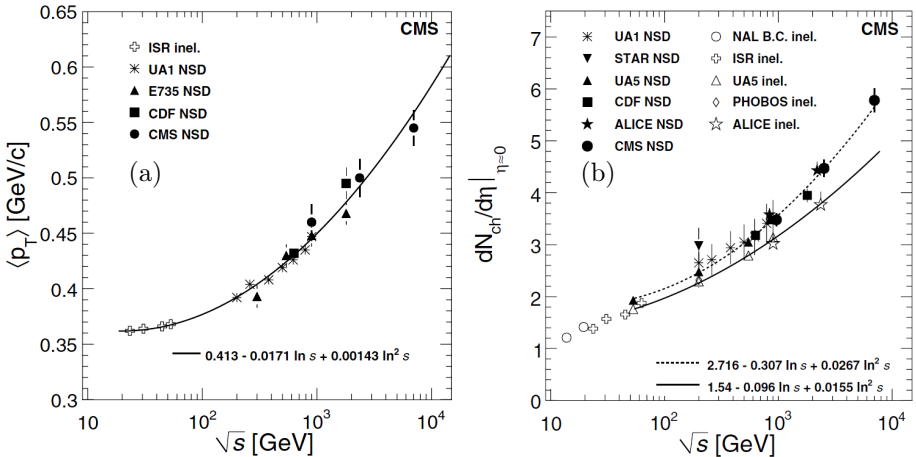


Fig. 4. (a) The average transverse momentum. (b) Charged particle multiplicity densities per unit of pseudorapidity at $\eta \simeq 0$. The CMS and other experiments measurements are presented as a function of center-of-mass energy. The second order $\ln s$ polynomial fit to data is shown on both plots.

The CMS error bars are dominated by systematic uncertainties. In order to minimise these uncertainties measurements were done in very initial period of data taking allowing to cope with a very small event pileup. The open,

Minimum Bias trigger given by any hit in Beam Scintillator Counter (BSC) in coincidence with colliding bunches was used. The presented results were corrected for contamination of disfavoured single-diffractive events, acceptance, selection and reconstruction efficiency and extrapolation accuracies. The measurements of charged particle multiplicities and momentum spectra were not well reproduced by PHOJET [18] and PYTHIA [19] Monte Carlo generators used by CMS with several tunings. It indicates need of further development of underlying models and tunings.

*The reconstruction of W and Z bosons and
production cross-section measurements*

The production of W and Z bosons with a decay to leptons is an important process for the LHC. It is a benchmark channel for lepton reconstruction. Due to accurate theoretical prediction of the cross-section it is also a test of perturbative QCD and proton parton distribution functions (PDF). Moreover it is a first electroweak process for measurement at the LHC. CMS has published results after collecting only 198 nb^{-1} and then updated them [20] with integrated luminosity of 2.9 pb^{-1} . The CMS results take into account fiducial and kinematical acceptance of the CMS detector. The selection efficiency is obtained from simulation and corrected with data as explained below.

The W events are characterised by a prompt isolated lepton and significant missing transverse energy. In the CMS analysis the W signal yields are obtained by fitting missing transverse energy ($\cancel{E}_T$) distributions in the electron channel and transverse mass¹ (M_T) distributions in muon channel. The lepton p_T threshold in the analysis is set to $20 \text{ GeV}/c$. The main backgrounds are QCD multi-jet, Drell–Yan and $t\bar{t}$ events. They are efficiently rejected by lepton isolation criteria and by single lepton required.

Similarly, the Z measurements are polluted by QCD multi-jet production which is efficiently suppressed by requirement of two isolated leptons. The additional processes with true leptons in final state from $t\bar{t}$ events, Z tauonic decays and di-bosons, result in small background level only.

The distribution of invariant and transverse mass in case of $Z \rightarrow e^+e^-$ and $W \rightarrow \mu\nu$ can be seen in Fig. 5. Almost all 2010 certified data is used. The contributions from dominant processes are shown.

Wherever possible CMS is trying to minimise uncertainties from simulation. As example, a shape of QCD background in $W \rightarrow \mu\nu$ is determined from data. It is obtained from high-purity QCD sample passing all the signal selection criteria apart of muon isolation for which inverted criteria is used.

¹ $M_T = \sqrt{2p_T \cancel{E}_T(1 - \cos \Delta\Phi)}$, where p_T — transverse momentum of muon, $\Delta\Phi$ — angle between $\vec{\cancel{E}}_T$ and $\vec{p}_T$.

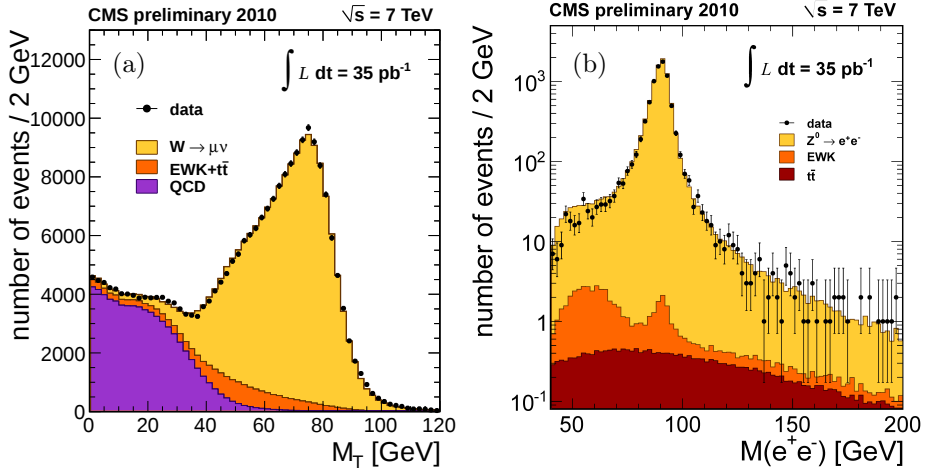


Fig. 5. (a) Distribution of M_T in $W \rightarrow \mu\nu$ analysis. (b) The di-electron invariant mass spectrum in $Z \rightarrow e^+e^-$ analysis. The points represent the data. The results of fits are superimposed in colour. Different sources of backgrounds are indicated.

The correction for isolation- E_T correlation is taken into account. This procedure results in a QCD fixed shape template used in a likelihood fit to the M_T distribution (keeping its normalisation as a free parameter). The difference between several templates used in signal yield allows us to estimate the systematic uncertainties related to QCD background shape. Among sources of systematic uncertainties other than background subtraction/modelling one can mention uncertainties in lepton reconstruction and identification, momentum and energy scale uncertainty of PDF for acceptance. The recent analysis [21] includes the full 2010 CMS data sample. The CMS measurement of production cross-section times branching fraction are combined in electron and muon decay channels to give $\sigma(pp \rightarrow WX) \times \text{BR}(W \rightarrow l\nu) = 10.31 \pm 0.02(\text{stat.}) \pm 0.09(\text{syst.}) \pm 0.10(\text{th.}) \pm 0.41(\text{lumi.}) \text{ nb}$ and $\sigma(pp \rightarrow ZX) \times \text{BR}(Z \rightarrow l^+l^-) = 0.975 \pm 0.007(\text{stat.}) \pm 0.007(\text{syst.}) \pm 0.018(\text{th.}) \pm 0.039(\text{lumi.}) \text{ nb}$.

Top-quark production

The top-quark physics is one of the key points of the LHC programme. Precise measurements of top-quark properties are necessary not only for its evidence. Many signatures in New Physics contain top quark. Top production can be also a source of significant background for many discovery processes. With only approximately 3 pb^{-1} CMS has shown evidence for top-quark pairs at the LHC and measured [22] their production cross-section to be $\sigma(pp \rightarrow t\bar{t} + X) = 194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.}) \text{ pb}$.

The top decays almost exclusively to b and W , which in turn may decay leptonically. The CMS analysis uses decay modes with di-lepton (with e , μ) and neutrinos in a final state. The lepton candidates are required to be isolated and have $p_T > 20$ GeV/ c . The lepton identification and isolation efficiency is measured from Z leptonic decays data and agrees well with simulation. Since leptonic Z decays are also considerable source of background a veto around Z mass value (± 15 GeV/ c^2) in di-lepton invariant mass is applied. Events with a small di-lepton invariant mass are also rejected. Another signature of the signal events is possible large transverse energy. It is originating from neutrinos that escape detection. The required $\cancel{E}_T$ threshold is 30 GeV, except for $e^\pm\mu^\mp$ events where much smaller background is expected from Drell–Yan events and softer, 20 GeV cut, is optimal.

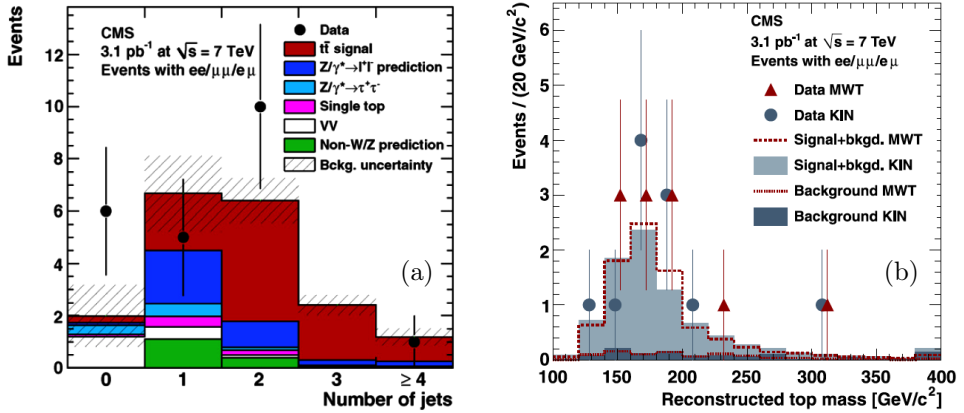


Fig. 6. (a) Number of jets in events passing selection criteria. The data points are superimposed on signal and background predictions. The main contributions to background are Drell–Yan events escaping Z -veto, single top, di-bosons and leptons from other sources than W or Z . The hatched area represents uncertainties in background estimation. (b) Distribution of reconstructed top-quark mass. The Kinematical method (KIN) [23] and Matrix Weighting Technique (MWT) [24] are applied to data and to simulated signal-plus-background and background hypothesis. The predictions assume top-quark mass of 172.5 GeV/ c^2 .

The distribution of number of jets with $p_T > 30$ GeV/ c and all other cuts applied is shown in Fig. 6(a). Only events with at least two jets contribute to measurements. The initial CMS evidence for a top quark at the LHC is based on eleven events passing all criteria. It agrees well with expected 7.7 ± 1.5 signal and 2.1 ± 1.0 background events. It can be further constrained by superimposing b -jet identification criteria. In Fig. 6(b) the distribution of reconstructed top-quark mass is shown. Results of the two top-quark mass reconstruction methods are consistent with Tevatron measurements.

Several sources of systematics errors were evaluated. Among them there are uncertainties on the simulation of signal selection, di-lepton selection efficiency measured from data and the jet energy scale. The background sources were assumed to have 50% systematic uncertainties except for those measured with data, where uncertainty is obtained by comparing data and simulation.

Topological correlations in two-particle distributions

One of the most interesting CMS results is an observation of long-range ($2 < |\Delta\eta| < 4.8$) two-particle correlations [25]. The study of particle correlations at the LHC energy frontier provides important information helping to understand and model mechanism of hadronisation and possible collective effects due to high energy densities in collisions.

A typical long-range correlations in particle distributions arise from momentum conservation and away-side jet fragmentation. It has been demonstrated [26] at RHIC that hot and dense matter in heavy ion collisions modify that simple picture. Significant particle densities in highest multiplicity proton–proton events at the LHC are motivation to study possible correlations.

The data were collected in two ways: using CMS minimum bias trigger and dedicated high-multiplicity path. The latter one required energy deposit at calorimeters above 60 GeV at Level-1 and large number of pixel-tracks reconstructed at High-Level Trigger. The pixel-tracks are based on simplified track reconstruction inside Pixel Detector only. The online threshold for minimal number of pixel-tracks was 70–85, depending on the luminosity.

The two-particle correlations were analysed as a functions of their distance in azimuthal angle $\Delta\Phi$ and pseudorapidity $\Delta\eta$. The correlation function $R(\Delta\eta, \Delta\Phi)$ is expressed in terms of normalised signal $S_N(\Delta\eta, \Delta\Phi)$ and background $B_N(\Delta\eta, \Delta\Phi)$ distributions ratio. The S_N distribution counts a $(\Delta\eta, \Delta\Phi)$ distance for all track pairs in an event. The B_N denotes uncorrelated track pairs distributions by combining tracks from randomly selected different events. Both S_N and B_N are independently normalised to unit integral taking into account combinatorial factor. The CMS measurement of two-particle correlations is shown in Fig. 7. The intermediate p_T range ($1 < p_T < 3$ GeV/c) where the effect is most pronounced is chosen.

The peak at $(\Delta\eta, \Delta\Phi) \approx (0, 0)$ corresponds to particles inside the same jet, the away-side $\Delta\Phi \approx \pi$ ridge results from the fragmentation of back-to-back jets. In the subsample of events with high multiplicity the additional ridge appears at $\Delta\phi \approx 0$ extending in several units of $\Delta\eta$. This is the novel feature, not observed before in pp or $p\bar{p}$ collisions. It was also not predicted by any Monte Carlo generators used by CMS (PYTHIA [19, 27], HERWIG++ [28], MADGRAPH [29]).

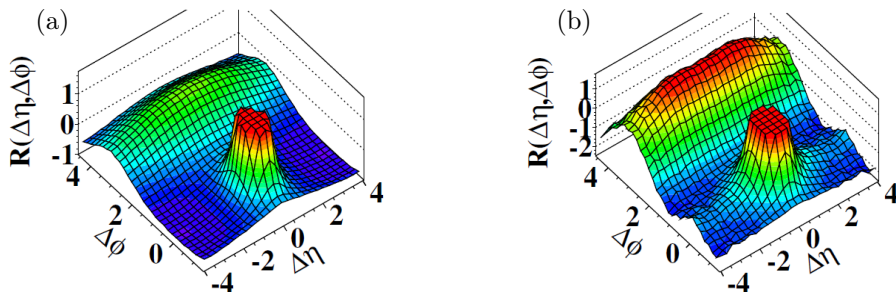
CMS MinBias, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$ CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$ 

Fig. 7. Two-dimensional particle correlation functions for intermediate transverse momentum range $1 < p_T < 3 \text{ GeV}/c$. (a) Minimum bias events. (b) Large multiplicity ($N \geq 110$) subsample. The sharp peak around $(\Delta\eta, \Delta\phi) \approx (0, 0)$ is truncated to better illustrate overall structure. Since particle order in computation of correlation is arbitrary, the plot is symmetries along $\Delta\eta = 0$ and $\Delta\phi = 0$.

Other CMS measurements

CMS has already performed over 25 measurement analyses resulting in publications. The CMS proton-physics measurements can be subdivided to results on soft QCD physics, particle correlations, perturbative QCD, bosons and heavy flavour. Among not described analyses the measurements of direct and in-direct J/ψ production [30], isolated prompt photon production [31], and reach b -physics program appear. Another class of analyses was opened when the LHC entered heavy ion program. Just after a few days of lead-lead collisions CMS has found first Z candidate. CMS has also observed [32] and studied the jet quenching phenomena which was one of proposed [33] signatures of quark gluon plasma. It manifests as imbalance of jet energy resulting from parton energy loss in dense plasma. CMS has analysed momentum balance in di-jet events as a function of centrality. The imbalance is well visible for central events with leading jet $p_T > 120 \text{ GeV}/c$. The imbalanced momentum can be recovered by looking at low p_T tracks.

4. Summary

The performance of the LHC machine in 2010 was excellent. It allowed the CMS experiment to collect interesting data which are still under analysis. The early data were used to finalise commissioning and verify calibration and initial performance. This very early period was followed by measurement of already know or expected processes. The CMS measurement agrees well with pQCD and EWK predictions. The long-range near-side two-particle correlations were observed in pp collisions. The jet-quenching phenomena

was observe in lead–lead collisions. The exciting era of CMS searches has already started. More details about CMS searches are given in other contributions in these proceedings.

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