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First physics results from the CMS experiment at the LHC

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Summary. — Establishing all major SM processes and beginning the searches for new physics was the major goal of the first run of the CERN Large Hadron Collider. The paper describes the first results obtained by the CMS experiment in studying pp collisions at $\sqrt{s} = 7\,\text{TeV}$. We present first the measurements performed on W, Z and top quark. We then describe the searches for new physics performed by probing any eventual internal structure of quarks, and by looking for new massive gauge bosons, microscopic black holes and particles hinting at large extra dimensions. The first results on the searches for SUSY and Higgs particles at LHC are lastly discussed together with the prospects for the current 2011-12 running period.

PACS `12.38.-t` – Quantum chromodynamics.

1. – Introduction

The Large Hadron Collider and its detectors have been designed to discover a large range of signals of new physics: the Higgs Boson and eventual super-symmetric partners of known particles as well as a large set of new massive particles foreseen in many models for new physics including some of the recently proposed extra-dimensional models.

The Compact Muon Solenoid (CMS) is one of the two "general-purpose" detectors of LHC [1]. It is located at the experimental Point 5 of the LHC near Cessy (France). The main distinguishing features of CMS are a large superconducting solenoid magnet, which creates a strong field of 3.8 T, 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 3170 scientists and engineers from 182 Institutes distributed in 40 countries all over the world.

Prior to collecting pp collisions the detector has been thoroughly calibrated using muons produced in cosmic rays. A large data set of more than 10^9 muons was recorded in successive campaigns of cosmic ray data taking in 2008-9. 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 $\mathcal{L} = 1 \times 10^{27}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, but reached quickly instantaneous luminosities exceeding $\mathcal{L} = 2 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. In total, an integrated luminosity of $47\,\mathrm{pb}^{-1}$ has been delivered by the LHC in 2010. With the LHC running in pp mode CMS has collected $43.2\,\mathrm{pb}^{-1}$ 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: all sub-systems had a fraction of operational channels exceeding 98%.

2. – Intermediate vector bosons and top quark

The selection of W and Z bosons candidates is particularly important for CMS since their production is a benchmark process at the LHC. 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 ($E_T > 25\,\mathrm{GeV}$), isolated lepton, and significant missing transverse energy. The main backgrounds are QCD multi-jet 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 $W \to l\nu$ 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 $Z \to l^+l^-$ candidate events are required to have two opposite sign leptons satisfying the same selection criteria used for the $W \to l\nu$ sample. The inclusive cross section measurements are then extracted from the data using data-driven methods for controlling the lepton efficiency, energy and momentum scale, resolution and all major sources of background.

Figure 1 shows on the left the invariant mass distributions of the di-muon pair in logarithmic scale, to enhance the high purity of the selected sample of Z candidates, while the plot on the right shows the ratio between results and theoretical predictions. It is worth noticing the amazing 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 ratios [2].

To complete the picture, very recently, we 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 (fig. 2, left). 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 [3]. The measurement of the W polarization [4] shows that, as expected, both W^+ and W^-, are produced by LHC preferably left-handed (fig. 2, right). These complex and challenging measurements are important benchmarks to prove that precision

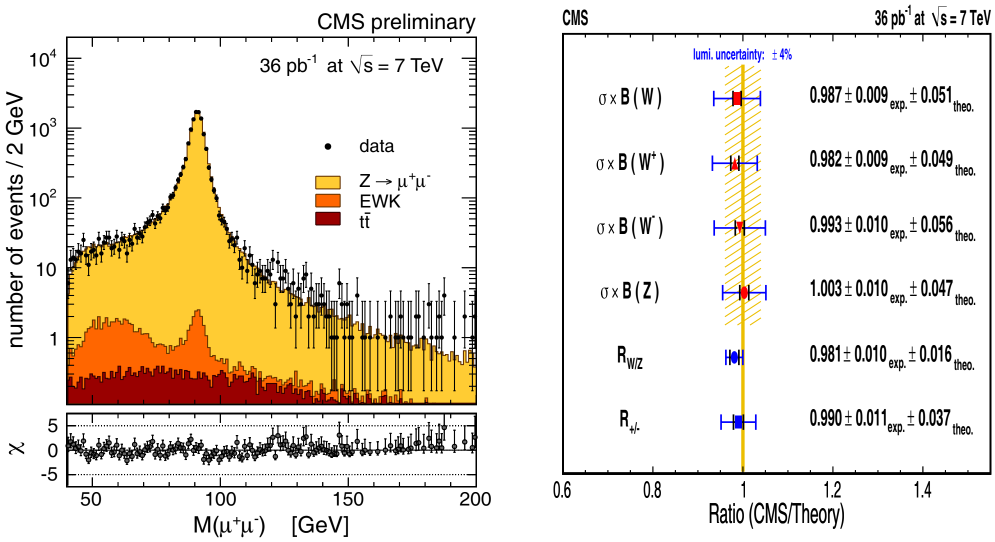

Fig. 1. – Distribution of the di-muon invariant mass of $Z \to \mu^+\mu^-$ in logarithmic scale (left) and ratio between measurements and theory (right).

electroweak measurements are being already performed at LHC and many others will come as soon as additional data are available.

The selection of top quark candidates is particularly challenging since it requires a complete understanding of all major physics objects as detected by the experiment.

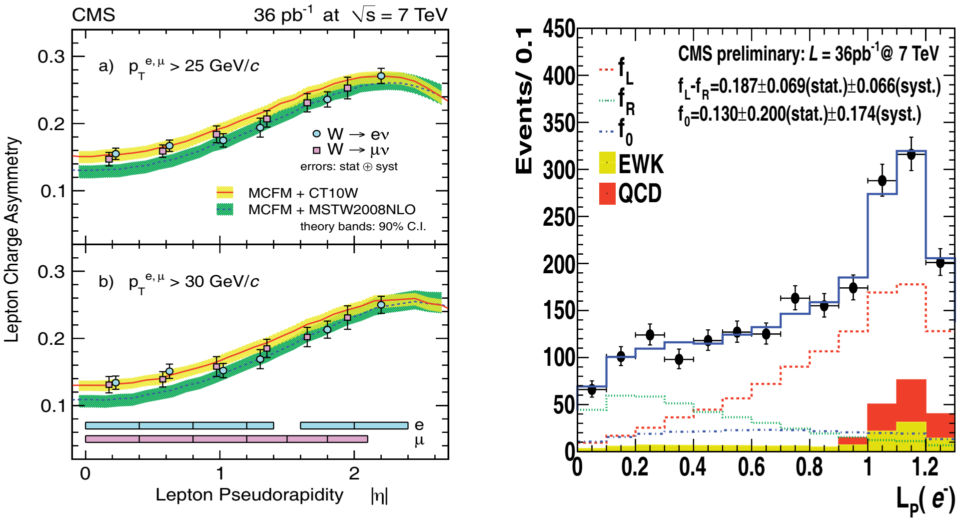

Fig. 2. – Measurement of the lepton charge asymmetry in W events (left) and of the W polarization (right).

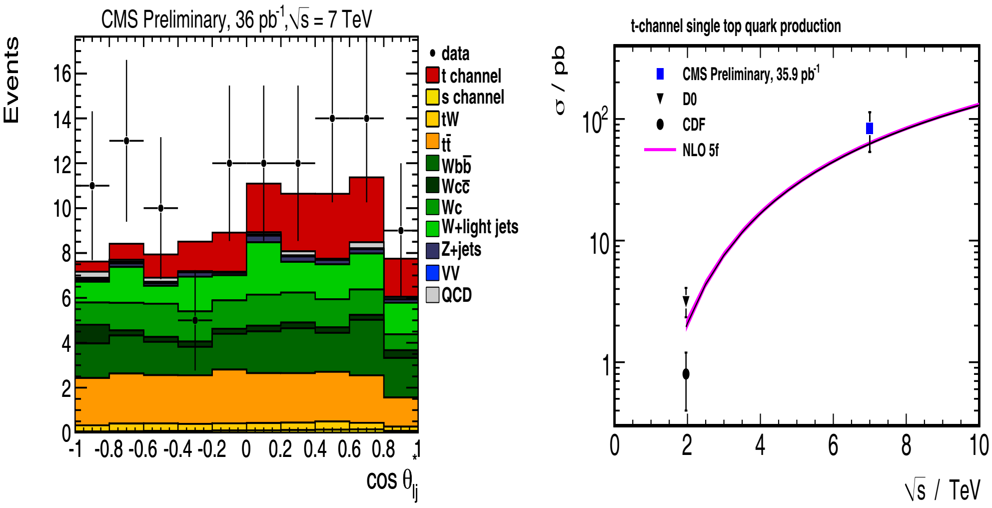

Fig. 3. – Extraction of the single top signal in the t-channel using, as discriminating variable, the angle between the lepton and the jet (left); comparison of the measured cross section at LHC with the NLO theoretical predictions (right).

Searches in CMS for top quark candidates were made looking at channels with high p_T leptons or di-leptons, jets with at least 1 jet b-tagged and missing E_T. With a relatively small data set it was soon possible to identify good event candidates and to collect evidence for top quark production at the LHC in the lepton+jets and di-lepton channels. Going through the full statistics collected so far, 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 the top production cross section at LHC of $\sigma_{t\bar{t}} = 158 \pm 19\,\text{pb}$ [5], value that is in good agreement with the most recent NLO and approximate NNLO predictions. The complete mastering of all tools needed to reconstruct and understand top quarks at LHC has been successfully proven through the first measurement of single top production cross section. 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. 3). The fact that using only $36\,\text{pb}^{-1}$ of LHC data CMS has been able to measure the single-top production cross section in the t-channel as $\sigma_t = 83 \pm 29.8(\text{stat} + \text{syst}) \pm 3.3(\text{lumi})\,\text{pb}$ [6] is the best evidence for the readiness of the experiment to explore the completely new territory made accessible by the LHC collisions.

3. – Quark compositeness and new heavy bosons

Having fully calibrated the detector response with known SM processes we started a systematic exploration of the new energy regime. The strategy to search for signals of new physics started by looking first at distributions based on very simple, well understood physics objects, like di-jets, di-leptons and di-photons. All these can be considered discovery tools particularly suited to look for signals of quark compositeness, strongly coupling new resonances or heavy exotic particles with significant production

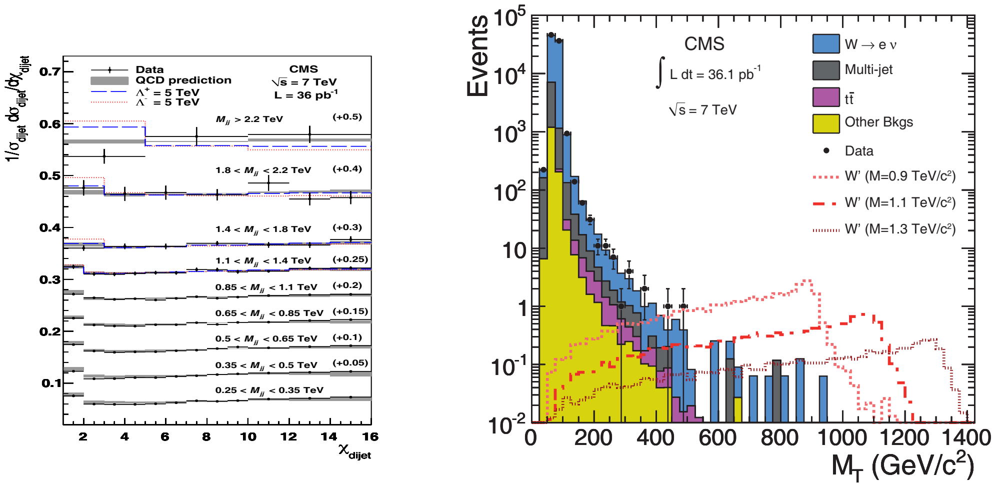

Fig. 4. – Distribution of the angular variable χ in dijet events (left); transverse mass for $W \to e + \nu$ events in logarithmic scale (right).

cross sections at the LHC. The angular distribution of di-jets is particularly sensitive to the presence of a contact interaction. If the quarks are composite objects high invariant mass di-jets will show significant deviations from the smooth angular behavior predicted by perturbative QCD. The analysis is based on the use of a variable $\chi = e^{|y_1 - y_2|}$ (with y_1 and y_2 being the rapidity of the two jets) which is constructed to be flat if quarks have no internal sub-structure, but very sensitive to any form of Rutherford scattering. Signatures of new physics that might have a more isotropic angular distribution than QCD (*e.g.* quark compositeness) would produce an excess at low values of χ (fig. 4, left). Since we do not observe any anomaly in the di-jet angular distributions it has been relatively straightforward to extract a lower limit (95% C.L.) on the contact interaction scale of $\Lambda = 5.6\,\text{TeV}$ [7]. For CMS, so far, quarks are still point-like objects.

New heavy gauge bosons, generally indicated as Z' and W', are predicted in various extensions of the Standard Model (SM). The search for a W' is usually performed in the context of the benchmark models where the W' boson is considered a heavy analogue of the SM W boson with the same left-handed fermionic couplings. Thus the W' decay modes and branching fractions are similar to those of the W boson. In this context the search is performed looking for anomalies in the tail of the distribution of the reconstructed transverse mass of the W. An example of this distribution for W decaying to electrons and neutrinos is shown in fig. 4, right, where one can note that events with transverse mass exceeding $400\,\text{GeV}/c^2$ have been collected by CMS. The production of a W' boson would imply an excess of events in the tail of the distribution. 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, we can exclude a W' with mass lower than $1.58\,\text{TeV}/c^2$, a value that exceeds the current limits set by the Tevatron experiments [8]. The most stringent limits to date have been obtained also for the search of Z' where the analysis is conceptually similar [9]. The challenge is to study in detail the high mass part of the Z resonance tail looking for any excess that could hint

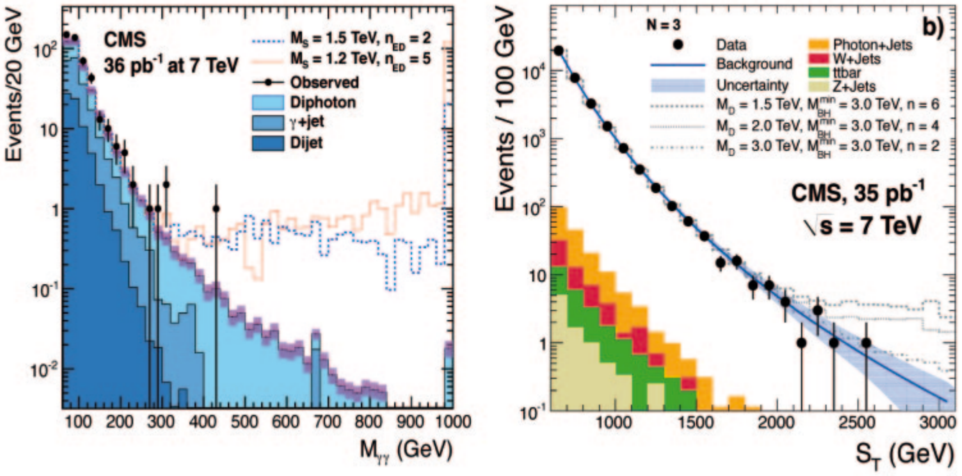

Fig. 5. – Invariant mass distribution of di-photon events with simulation of the excess foreseen in a couple of extra-dimensional models (left). Distribution of the variable S_T and simulation of the excess due to the production of microscopic black holes in different models (right).

at the production of new massive bosons. 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.

Many new limits have been published by CMS in the search for exotic particles, however there is not enough space in this paper to cover all of them. I want to mention briefly only the direct search for large spatial extra-dimensions and the first direct search for signature of microscopic black holes at a particle collider.

4. – Extra-dimensions and microscopic black holes

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, $M_{Pl} = 10^{19}\,\mathrm{GeV}/c^2$, is so much higher than the electroweak scale $M_{\mathrm{EWSB}} = 10^3\,\mathrm{GeV}/c^2$. 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. 5, left). The new limits, obtained in the range of 1.6–2.3 TeV/c^2, 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 the most restrictive limits on the existence of large extra-dimensions to date for their number greater than two [10].

Another possible manifestation of the fact that the effective Planck scale, M_D, could be brought to the TeV scale for the presence of compactified extra dimensions could be the production of microscopic black holes. Partons colliding in LHC, once they approach each other to a distance comparable to the size of extra dimensions, could start feeling 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 $1\,\mathrm{TeV}/c^2$. 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. 5, right). 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 minimum masses between 3.5 and $4.5\,\mathrm{TeV}/c^2$, for the values of M_D in the range of 1.5–$3.5\,\mathrm{TeV}/c^2$ and various other model parameters [11]. 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.

5. – Supersymmetry

Supersymmetry is widely considered an attractive theory that is able to solve the hierarchy problem of the Standard Model at the expense of introducing a large number of supersymmetric particles with the same quantum numbers as the SM particles, but differing by half a unit of spin. If R-parity conservation is assumed, supersymmetric particles are produced in pairs and decay to the lightest supersymmetric particle (neutralino or LSP), leading to a characteristic signature of events with large missing transverse energy. The dominant production channels of heavy coloured sparticles at the LHC are squark-squark, squark-gluino and gluino-gluino pair production. Heavy squarks and gluinos decay into quarks, gluons and other SM particles, as well as neutralinos which escape undetected, leading to final states with several hadronic jets and large missing transverse energy.

Just a couple of months after the end of the 2010 data taking CMS performed the first search for SUSY particles at the LHC in events with two or more energetic jets and significant missing transverse energy. Since we were looking for massive objects, events were pre-selected requiring high values of the scalar sum of the transverse energy of jets, $H_T > 350\,\mathrm{GeV}$, thus ensuring large hadronic activity in the event. The analysis is then based on the use of a very simple variable $\alpha_T = E_{Tj2}/M_T$, where E_{Tj2} is the transverse energy of the less energetic of the two jets in the event and M_T is the transverse mass of the di-jet system. For a perfectly measured di-jet event, with $E_{Tj1} = E_{Tj2}$ and jets back to back in ϕ, and in the limit where the jet momenta are large compared to their masses, the value of α_T is 0.5. In the case of an imbalance in the measured transverse energies of back to back jets, α_T takes on values smaller than 0.5, while for jets that are not back to back, α_T can be greater than 0.5. Values of α_T above 0.5 can occur for QCD multi-jet events, either with multiple jets failing the $E_T > 50\,\mathrm{GeV}$

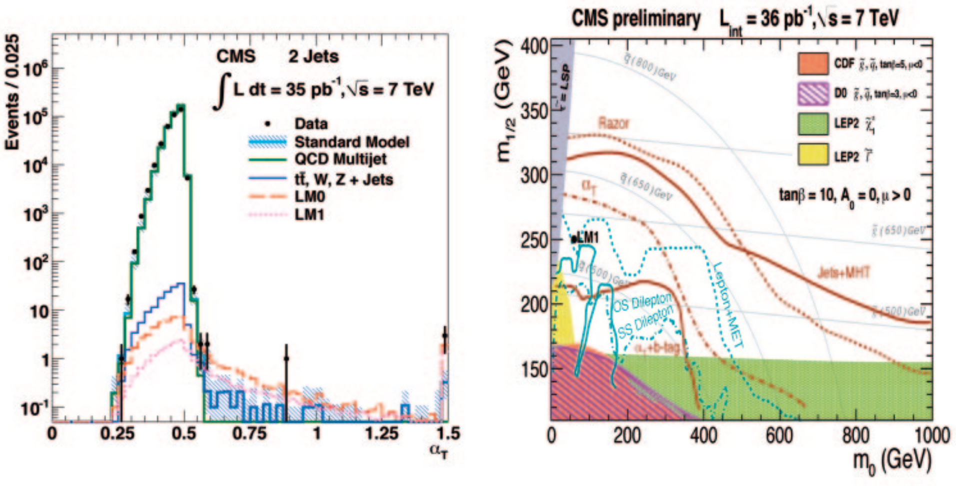

Fig. 6. – Distribution of α_T for di-jet events (left). Exclusion limits on SUSY produced by several different analyses (right).

requirement, or with missing transverse energy arising from jet energy resolution or severe jet energy under-measurements due to detector inefficiencies. On the other hand, events with genuine missing E_T often have much larger values of α_T, resulting in a good separation of signal events from the QCD multi-jet background. As anticipated, these distributions peak at $\alpha_T = 0.5$ for QCD multi-jet events and then fall sharply in the range 0.5 to 0.55, reaching a level 4 to 5 orders of magnitude lower than the peak value (fig. 6, left). Multi-jet events from QCD background are therefore efficiently rejected by requiring α_T to exceed 0.55. A simple generalization of the variable α_T can be used to include final states with more than two jets. A small tail of $t\bar{t}$ and W+jets and Z invisible+jets events survive as a possible contamination to the signal region. Data-driven methods are used to understand all major sources of background. The search for SUSY signals involves looking for an excess of events in the high α_T region. Since no excess has been observed in the full 2010 data set, we have published limits constraining significantly the simplest minimal supersymmetric extensions of the SM [12].

A complex set of additional searches has then been performed using many different topological signatures of SUSY: 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 produced so far hints of production of SUSY particles at the LHC. Using conservative statistical tools we have extracted limits from the experimental data producing new results exceeding significantly the best measurements performed so far by the Tevatron experiments. Figure 6, right, 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. Based on the results obtained from the analysis of the 2010 data, we can extrapolate that, if supersymmetry is really a symmetry of nature, it will be definitely possible to detect SUSY signals in the 2011-12 LHC data, supposed to be 50-100 times larger with respect to the amount of data so far analyzed.

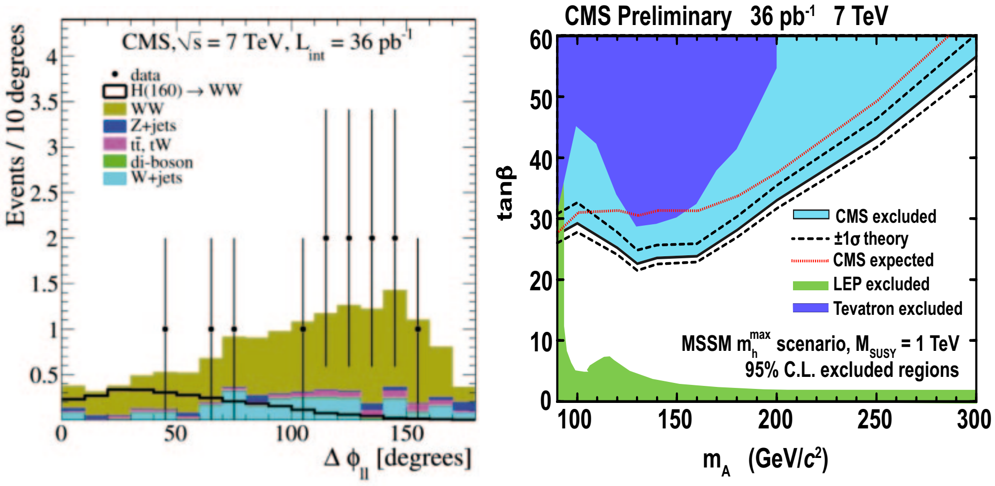

Fig. 7. – Distribution of the opening angle between the two leptons, $\Delta\phi_{ll}$, in WW event candidates (left). Exclusion limits on MSSM neutral Higgs decaying to τ pairs (right).

6. – Higgs boson

The search for the Higgs boson is one of the most ambitious goals 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 Collider. This has been possible, so far, only for a couple of analyses. One analysis 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 is the addition of a fourth family of fermions. 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 $H \to W^+W^-$ 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 (120–200 GeV/c^2) and is therefore considered a sort of work-horse for the search of the SM Higgs boson. This is why the search was performed in conjunction with the first measurement of the W^+W^- production cross section at 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 $H \to W^+W^-$ 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. Figure 7, left, shows the distribution of $\Delta\phi_{ll}$, after applying the W^+W^- selections, for a SM Higgs boson signal with $m_H = 160\,\mathrm{GeV}/c^2$, and for the major sources of backgrounds. Since no excess above the SM expectations was found 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% condence level [13].

The second analysis yielding new results on Higgs is the search for MSSM Higgs decaying to τ pairs. The minimal supersymmetric extension to the standard model (MSSM) requires the presence of two Higgs doublets. This leads to a more complicated Higgs boson sector, with five massive Higgs bosons: a light neutral scalar (h), two charged scalars ($H^{\pm}$), a heavy neutral CP-even state (H) and a neutral CP-odd state (A). The τ pair decays of the neutral Higgs bosons, having a branching ratio of about 10%, serve as the best experimental signature for this search. The b mode, though it has a much larger branching ratio, suffers from an overwhelming background from QCD processes. Three final states where the τ decays leptonically or hadronically are used in our analysis: $e+\tau_h$, $\mu + \tau_h$, and $e\mu$, where we use the symbol τ_h to indicate a reconstructed hadronic decay of a τ. The ee and $\mu\mu$ final states suffer too much background from $Z \to e^+e^-(\mu^+\mu^-)$ events to be usable. The observed τ pair mass spectrum reveals no evidence for neutral Higgs boson production, and we determine an upper bound on the product of the Higgs boson cross section and τ pair branching ratio. These results, interpreted in the MSSM parameter space, exclude a previously unexplored region reaching as low as $\tan\beta = 23$ at $m_A = 130\,\mathrm{GeV}/c^2$ (fig. 7,right) [14]. The results obtained in the searches for the Higgs boson using the 2010 data set bodes well for the current LHC data taking. 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 to be able to exclude the SM Higgs boson in the mass range between 120 and 600 GeV/c^2, or to discover it with the combination of ATLAS and CMS results.

7. – Conclusion

We have presented the first physics results obtained using pp collisions at 7 TeV. After a few months of data taking we have achieved a good understanding of the detector performance and of the Standard Model properties at 7 TeV. Soon afterwards we have 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: quark compositeness, new vector bosons, extra dimensions. Lastly, the first studies on the searches for SUSY particles and the Higgs boson in LHC data have been presented together with the prospects for the current 2011-12 running period.

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I would like to thank first 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 so quickly and so efficiently data collected so recently.

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