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News from the LHC

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Summary. — The LHC provided more than 2 fb^{-1} to the experiments by summer 2011 and allowed a wide physics reach. ATLAS and CMS performed several measurements, testing the Standard Model with a sensitivity which already challenges the theoretical calculations and putting strong constraints on the presence of New Physics and on the Higgs mass.

PACS 14.70.-e – Gauge bosons.
PACS 14.65.Ha – Top quarks.
PACS 14.80.Ly – Supersymmetric partners of known particles.
PACS 14.80.Bn – Standard-model Higgs bosons.

1. – Introduction

The first six months of 2011 were very successful for the LHC. The peak luminosity grew up to $2 \cdot 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and the total integrated luminosity exceeded 2 fb^{-1}. The performance of ATLAS and CMS experiments has been also impressive. The efficiency in recording the events was larger than 90% and the huge amount of statistics was available for physics analysis for 2011 summer conferences. In addition, detector-wise, the quality of the reconstructed objects was already very close to the design. Not only clean objects, as electrons and muons, have been reconstructed with good resolution but also the uncertainties related to more challenging quantities as jets and missing transverse energy were under control. To give an example, the jet energy scale is already known with a 2-3% uncertainty [1, 2]. This result has been reached by the experiments after the first months of data taking. Tevatron experiments obtained a similar precision only after several years.

The fast increase of the luminosity corresponded to very different conditions during the data taking. This implied continuous rearrangements and improvements of the trigger paths. In addition, the large luminosity has been obtained via the increase of the number of protons in the bunches while keeping the number of bunches relatively small. This resulted in a large number of interactions per collisions (the average was about 6 per collision) whose impact had to be carefully evaluated and subtracted.

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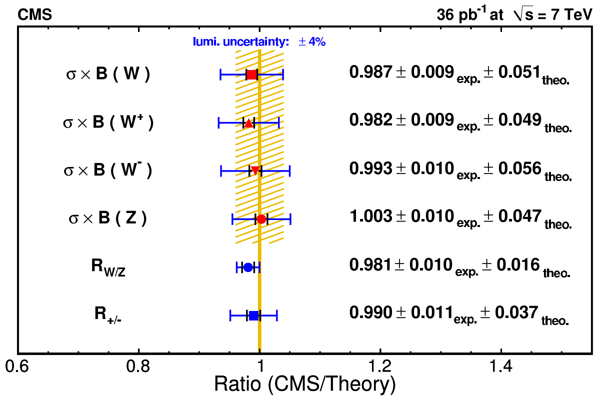

Fig. 1. – Summary of W and Z inclusive cross sections from the CMS experiment. Plotted is the ratio of the measured over the expected value from theory. In addition the W/Z and W^+/W^- ratios are also shown.

Given this great performance, the physics program was very ambitious since the start, allowing precision measurements of the Standard Model (SM) parameters and stringent limits on New Physics and on the Higgs Boson.

In this short report we review a very limited sample of results, just focusing on ATLAS and CMS experiments. We will discuss the main analyses in electroweak (EWK), top, beyond the SM, and Higgs Physics.

2. – EWK physics

EWK physics performed with the early LHC data has multiple purposes. 1) It allows for tests of perturbative QCD. 2) It helps constraining the protons PDFs. 3) Since EWK events represent the main background in the search for rare processes (*e.g.* SUSY, Higgs), their precise measurement is a crucial ingredient for discovery. 4) It is used to monitor the LHC luminosity. 5) The large cross sections and statistics of these processes and their clean signature provide candles for the detector calibration (*e.g.* $Z \to \mu\mu$ or $Z \to ee$ to tune muon and electron reconstruction). 6) Any deviation from SM expectations could be interpreted as a sign of New Physics.

Given the abundance of W and Z produced at the LHC, precise measurements of their inclusive and differential cross sections were made with the first $30\,\mathrm{pb}^{-1}$ collected, where conditions were more stable. A summary of the CMS inclusive cross section measurements is shown in fig. 1. These measurements [3], despite the small statistics used, already challenge the theory uncertainty and the present PDF sets. The measure of the differential cross section as a function of the pseudo-rapidity [4] has already the sensitivity to probe the modeling of the extra jet radiation and to select among different generators.

A very interesting analysis in EWK Physics is the measurement of the W charge asymmetry, obtained via the reconstruction of the electron/muon produced from the W decay. This is sensitive to proton PDFs in different ranges of x since the W^+ is produced via the annihilation of a u valence quark with a d sea quark, while the W^- via the annihilation of a d valence quark with a u sea quark. The results [5, 6] are summarized

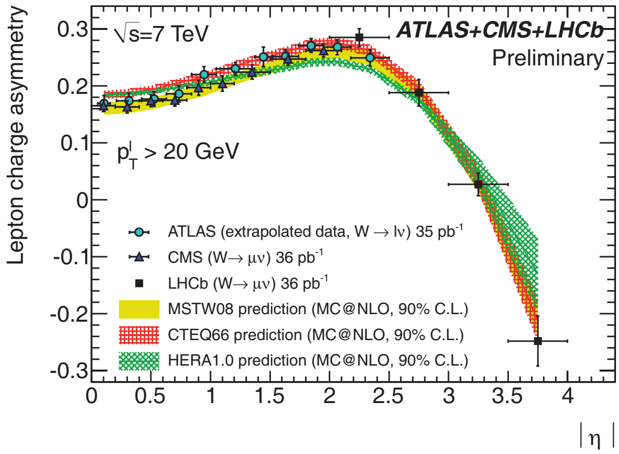

Fig. 2. – Lepton charge asymmetry from W-boson decays in bins of absolute pseudo-rapidity of the lepton for ATLAS, CMS and LHCb.

in fig. 2. The agreement among the LHC experiments in different pseudo-rapidity ranges is remarkable. With this statistics, there is already some discrimination between the various PDF sets.

Finer angular analyses of the W decay products allow for the determination of the W polarization via the study of the charged lepton and W transverse momenta. The CMS studies [7] show a nice consistency with the SM prediction.

Drell-Yan events represent the candle for the measurement of the EWK parameter $\sin^2(\theta_{eff})$ via the forward-backward asymmetry. At a pp collider this measurement is much more complicated compared to the e^+e^- colliders case. This is because the direction of the positevely charged parton is not known and there is the boost of parton-parton center of mass along the beam axis. By performing the measurement in bins of the invariant mass of the two leptons and looking at the full kinematics of the event, this SM parameter has been measured as $\sin^2(\theta_{eff}) = 0.2287 \pm 0.0020(stat.) \pm 0.0025(syst.)$ [8]. The uncertainty is still a factor 10 far from the world average but can be significantly reduced now that much more statistics is available compared to the $40\,\text{pb}^{-1}$ used in the analysis.

Another fundamental test of the SM is the measurement of the $WW/WZ/ZZ$ cross sections. The amplitude of these process is sensitive to the self interaction among EWK bosons and triple gauge couplings. In addition, these processes represent the irreducible background for the Higgs searches in the WW and ZZ channels. Both ATLAS and CMS experiments presented measurements of the cross section of these three processes [9-12], being in agreement with the expectations.

3. – Top physics

The top quark is the heaviest known elementary particle. Its mass is an important parameter of the SM and it affects predictions of SM observables via radiative corrections. Its coupling to the Higgs boson is close to unity and it could play a special role in electroweak symmetry breaking and in the generation of particle masses in alternatives to

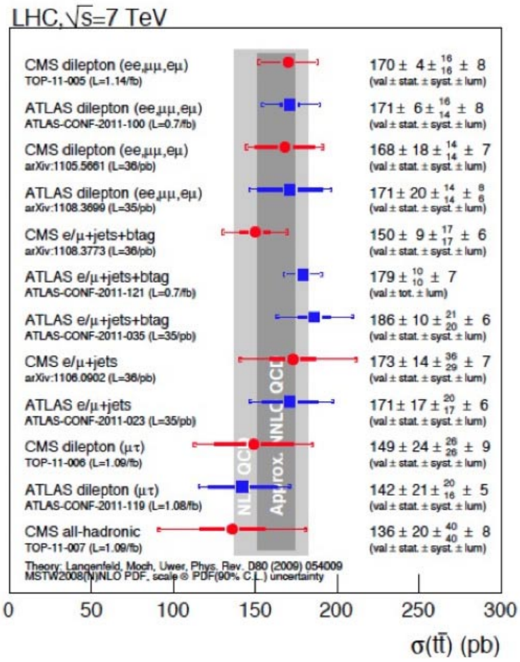

Fig. 3. – Summary of ATLAS and CMS results on $t\bar{t}$ cross section compared with NLO and NNLO calculations.

the Higgs mechanism. There are also various scenarios with direct and indirect coupling to New Physics (*e.g.* extradimensions, new strong forces). In the SM, top quark decays nearly 100% of the times to a W boson and a b quark.

In hadron colliders, top-quark production is dominated by the production of $t\bar{t}$ pairs. At the Tevatron, they are mainly produced via quark-antiquark annihilation while at the LHC the gluon fusion process dominates. Measurements of the $t\bar{t}$ cross section can provide important tests of our understanding of the top-quark production mechanism and can also be used in searches for New Physics. The $t\bar{t}$ analysis is categorized depending on the decay of the W bosons produced by the pair. Thus, three different channels exist: the channel in which both W bosons decay to leptons is referred to as the di-lepton channel, the channel in which one W decays to leptons and the other to quark jets is the lepton + jets channel, and the channel in which both W bosons decay to jets is called the all-hadronic channel. A further ingredient in the analyses with jets is represented by the tagging of the jet originated by a b quark. In fig. 3 all results from both experiments are reported. As shown, there is agreement between theory and experimental measurements which now challenge the NNLO calculations.

The SM predicts three mechanisms for single-top quark production in pp collisions: t-channel, s-channel, and tW production. The t-channel has the largest cross section and the cleanest final-state topology, because of the presence of a light jet recoiling against the single-top quark. These are very complicated analyses where many ingredients enters: lepton and jet reconstruction, b-tagging and multivariate analysis techniques (*e.g.* boosted decision tree, BDT [13]), which probes the overall compatibility of the signal event candidates with the event topology of electroweak top-quark production.

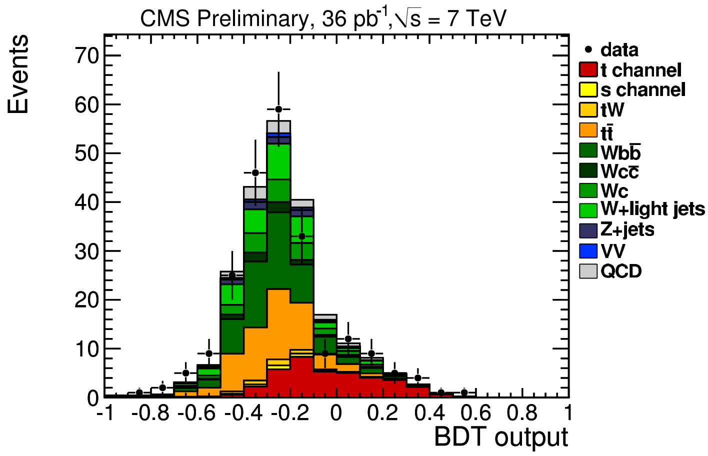

Fig. 4. – Boosted decision tree (BDT) output in the t-channel single top analysis from CMS.

An example of the BDT output for the t-channel search is shown in fig. 4 for the CMS experiment. The t-channel has been seen by both ATLAS and CMS experiments [14-16], while there is not yet enough sensitivity for the s-channel and tW production.

Two very important analyses which at the moment do not have enough sensitivity are the measurement of the top charge asymmetry and the top mass. At LHC a small charge asymmetry in the rapidity distributions of top and antitop quark is predicted. Top quarks have a slightly broader rapidity distribution, while antitop quarks are produced more centrally and therefore possess a narrower rapidity distribution. For many beyond the SM scenarios top-antitop pairs can be created via the exchange of new heavy particles (like axigluons, Z' bosons, or colored Kaluza Klein excitations of gluons [17]) in the t or u channel but not in the s channel. Then, the $t\bar{t}$ invariant mass cannot be used to discover them while the top charge asymmetry is sensitive to their presence. Both ATLAS and CMS presented results [18, 19] where the asymmetry is still compatible with 0 and more statistics is needed to measure the small SM prediction which is of the order of 1%. As far as the measurement of the top mass is concerned, LHC results are comparable to the Tevatron ones in terms of statistical uncertainty [20, 21]. The limiting factor at the moment is represented by the uncertainty related to the jet energy scale. This uncertainty is going to be reduced in future once more data will be processed. When this uncertainty will be pushed down to 1% level, the top mass measurement will become competitive with the present world average.

4. – Physics beyond the standard model

There are many open issues in the SM like the hierarchy problem and the origin of the Dark Matter. Many solutions to those have been proposed. One of the possible extensions of the SM is Supersymmetry (SUSY) which introduces a new symmetry between fermions and bosons. A large number of new particles then appear with the same quantum numbers as their SM partners, but differing by half a unit of spin. If R-parity conservation is assumed, supersymmetric particles, such as squarks and gluinos, are produced in pairs and decay to the lightest, stable supersymmetric particle (LSP). If the LSP is neutral and weakly interacting, a typical signature is a final state accompanied by significant

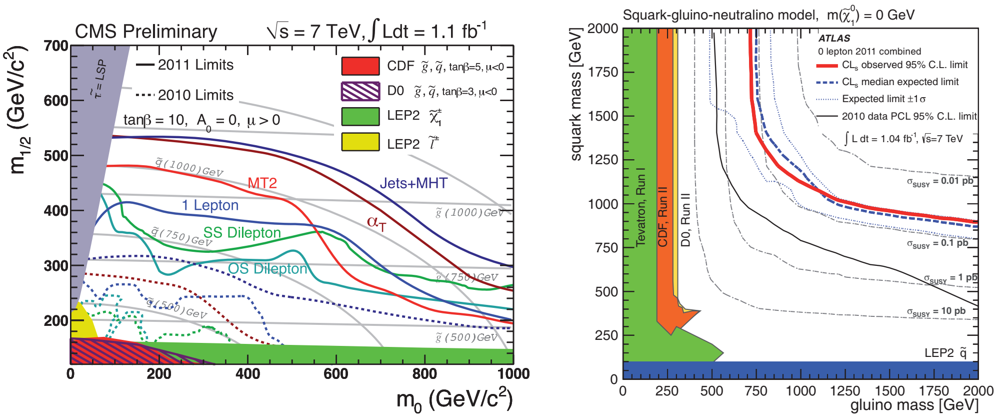

Fig. 5. – (Color online) Left: observed 95% CL limits from several 2011 CMS SUSY searches plotted in the CMSSM $(m_0, m_{1/2})$ plane. Right: ATLAS combined exclusion limit for the simplified models with mLSP = 0. The red bold line shows the observed limit at 95% CL, and the blue dashed line corresponds to the median expected 95% CL limit. The dotted blue lines show the expected 68% and 99% CL expected limits.

missing transverse energy (MET). In addition, the decay of the supersymmetric particles produced from the parton interaction implies the presence of few jets with large transverse momentum (p_T) and, if there are sgauginos and sleptons, their decay produces leptons with large p_T.

The signature of a SUSY events then consists of large MET, few high p_T jets and, possibly, high p_T leptons. There are many analyses for the SUSY search, each selecting the different possible final states. There is no indication of SUSY so far, and a summary of the current limits on SUSY parameters (in the so called Constrained Minimal Supersymmetric Standard Model, CMSSM) for the CMS experiment is reported in fig. 5. As shown, the limits are now much more stringent than the Tevatron ones. Those limits, in the specific case where $m(\text{squark}) = m(\text{gluino})$, would correspond to a $m(\text{squark}) < 1\,\text{TeV}$ exclusion. The most sensitive channels at the moment are the fully hadronic ones where there are requirements on MET and high p_T jets only [22-24]. The leptonic channels are less sensitive but they still offer a complementary approach. The current limits can be also converted into limits in simplified models which allow a systematic scan through the phase space in the sparticle mass plane and in the corresponding final state kinematics. This approach reduces the dimensionality of the theoretical parameter space to two up to four sparticle mass parameters and relevant branching ratios. An example is shown in fig. 5 where the results for hadronic channels from ATLAS are reported for the simplified models with mLSP = 0.

There exist other possible extensions of the SM, like the sequential SM, GUT-inspired theories, Technicolor, Kaluza-Klein Extra Dimensions, where heavy resonances are expected. When these states decay into di-fermion mode, they offer a striking experimental signature. Given the unprecedented center-of-mass energies accessible at the LHC, ATLAS and CMS can extend the searches for these resonances to much higher masses compared to Tevatron. The searches are performed in several final states. Two examples for the di-jet and di-lepton final states are in [25, 26]. Currently, there is no excess and the SM prediction is confirmed. In models where the heavy resonance has a large production cross sections, like the sequential SM, the 95% CL limits corresponds to excluding resonances with $\text{M} \lesssim 2\,\text{TeV}$.

5. – Higgs physics

One of the key questions of the SM is the origin of the masses of elementary particles. In the SM it is attributed to the spontaneous breaking of the electroweak symmetry. The existence of the associated field quantum, the Higgs boson, has still to be experimentally confirmed. ATLAS and CMS has been built to be able to discover the Higgs in the whole mass range from 100 GeV to 600 GeV. The branching ratio of the Higgs depends strongly on the Higgs mass. While for low masses (below the WW threshold) the decay in fermions, gluons, and photons dominates, at high masses WW and ZZ decays are the most relevant channels. We can then identify three different mass regions depending on the sensitivity to the decay modes: low mass $m_H < 130\,\mathrm{GeV}$, intermediate mass $130\,\mathrm{GeV} < m_H < 200\,\mathrm{GeV}$, and large mass $m_H > 200\,\mathrm{GeV}$.

At low masses the most relevant channel for the Higgs search is $H \to \gamma\gamma$. This channel as a clear signature given by the presence of two photons whose invariant mass peaks at the Higgs mass. Nevertheless, the irreducible SM $pp \to \gamma\gamma$ backgrounds and the low branching ratio make this analysis very tough, with a signal over background ratio of the order of 10% or less. The key ingredient of this search is the quality of photon identification and the resolution in the momentum reconstruction of photons. With the present statistics, this channel is not sensitive enough to either discover or exclude the Higgs.

At intermediate masses $H \to WW \to l\nu l\nu$ is the most important decay channel. Here the signature consists of two charged leptons and large MET due to the undetected neutrinos. Background is made of $t\bar{t}$, Drell-Yan, and EWK WW events. There is no invariant mass peak but the signal over background ratio is about one. The most relevant issues in this analysis are the MET resolution and the description of the Drell-Yan background. Through this search, ATLAS and CMS were able to exclude the Higgs in the region which corresponds to about $140\,\mathrm{GeV} < m_H < 200\,\mathrm{GeV}$.

Finally, for large masses, $H \to ZZ$ is the most sensitive channel. In particular, $H \to ZZ \to 4l$ is the golden channel for discovery because of the clean signature (four charged lepton whose invariant mass corresponds to the Higgs mass) and the very small backgrounds. With $2\,\mathrm{fb}^{-1}$ and in combination with the other final states like $H \to ZZ \to ll\nu\nu$ and $H \to ZZ \to lljetjet$, there is enough sensitivity to exclude a Higgs with $m_H > 200\,\mathrm{GeV}$.

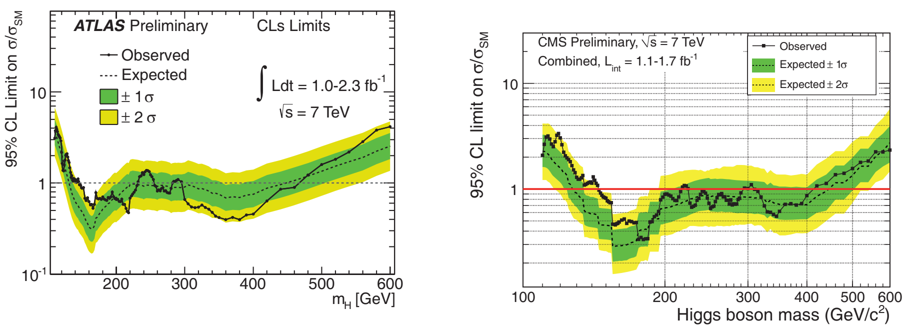

Fig. 6. – (Color online) The combined ATLAS and CMS 95% CL upper limits on the ratio σ/σ_{SM}, as a function of the SM Higgs boson mass in the range 110–600 GeV. The observed limits are shown by the solid symbols and the black line. The dashed line indicates the median σ/σ_{SM} expected limit for the background-only hypothesis, while the green/yellow bands indicate the ranges that are expected to contain 68%/95% of all observed limit excursions from the median. When σ/σ_{SM} goes below unity, the SM Higgs boson is excluded at 95% CL.

The results in the different decay modes can be combined to put a global constraint on the Higgs mass [27, 28]. This is shown in fig. 6 for both ATLAS and CMS. It can be noted that the two experiment reported very similar results and sensitivities. Even if an ATLAS-CMS combination has not been performed yet, we expect that the Higgs boson can be excluded in the range $140\,\text{GeV} < m_H < 450\,\text{GeV}$.

6. – Conclusions

The first six months of 2011 have been very successful for the LHC. The collider integrated more than $2\,\text{fb}^{-1}$. ATLAS and CMS recorded events with high efficiency ($> 90\%$) and with excellent performance of the trigger and of the reconstruction of physics objects. With this statistics, precise measurements of electroweak and top physics processes have been done. Many direct searches of New Physics processes have been performed. No deviation from the Standard Model was observed. The search of the Higgs boson resulted in the world-best exclusion, corresponding to the range $140\,\text{GeV} < m_H < 450\,\text{GeV}$.

REFERENCES

[1] CMS Collaboration, CMS-PAS-JME-10-011, arXiv:1107.4277 [hep-ex] (2011).
[2] ATLAS Collaboration, ATLAS-CONF-2011-067 (2011).
[3] CMS Collaboration, CMS-PAS-EWK-10-005, arXiv:1107.4789 [hep-ex] (2011).
[4] ATLAS Collaboration, CERN-PH-EP-2011-134, arXiv:1108.6308 [hep-ex] (2011).
[5] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **04** (2011) 050.
[6] Aad G. *et al.* (ATLAS Collaboration), *Phys. Lett. B*, **701** (2011) 31.
[7] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Rev. Lett.*, **107** (2011) 021802.
[8] CMS Collaboration, CMS-PAS-EWK-10-011(2011).
[9] CMS Collaboration, CMS-PAS-EWK-11-010 (2011).
[10] ATLAS Collaboration, ATLAS-CONF-2011-110 (2011).
[11] ATLAS Collaboration, ATLAS-CONF-2011-107 (2011).
[12] ATLAS Collaboration, ATLAS-CONF-2011-099 (2011).
[13] Breiman L. *et al.*, *Classification and Regression Trees* (Wadsworth and Brooks, Monterey, CA) 1984; Freund Y. and Schapire E., *Proceedings of the Thirteenth International Conference on Machine Learning* (Morgan Kaufmann Publishers, San Francisco, CA) 1996, p. 148.
[14] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Rev. Lett.*, **107** (2011) 091802.
[15] ATLAS Collaboration, ATLAS-CONF-2011-101 (2011).
[16] ATLAS Collaboration, ATLAS-CONF-2011-118 (2011).
[17] Ferrario P. and Rodrigo G., *JHEP*, **02** (2010) 051.
[18] CMS Collaboration, CMS-PAS-TOP-11-014 (2011).
[19] ATLAS Collaboration, ATLAS-CONF-2011-106 (2011).
[20] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **07** (2011) 049.
[21] ATLAS Collaboration, ATLAS-CONF-2011-120 (2011).
[22] CMS Collaboration, CMS-PAS-SUS-11-004 (2011).
[23] ATLAS Collaboration, CERN-PH-EP-2011-145, arXiv:1109.6572 [hep-ex] (2011).
[24] ATLAS Collaboration, CERN-PH-EP-2011-155, arXiv:1110.2291 [hep-ex] (2011).
[25] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Lett. B*, **704** (2011) 123.
[26] ATLAS Collaboration, CERN-PH-EP-2011-123, arXiv:1108.1582 [hep-ex] (2011).
[27] CMS Collaboration, CMS-PAS-HIG-11-022 (2011).
[28] ATLAS Collaboration, ATLAS-CONF-2011-135 (2011).