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Status and perspectives of the LHC detectors

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Summary. — The paper provides an overview of the current status and main physics results of the LHC experiments. The first part describes the new measurements and major results achieved by ALICE, LHCb, LHCf and TOTEM. The most recent electroweak measurements performed by ATLAS and CMS are then discussed together with the latest searches for SUSY. The very interesting results achieved by the two general-purpose experiments in searching for the Standard Model Higgs boson are lastly discussed together with the prospects for the current 2012 running period.

PACS 12.15.-y – Electroweak interactions.
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1. – Introduction

The Large Hadron Collider and its detectors have been primarily designed to shed light on the mechanism responsible for the electroweak symmetry breaking and to detect a large variety of signals of new physics. A sizable part of the program is based on the direct search for any sort of new massive particles predicted by a wide range of models but there are also important efforts aiming at collecting indirect evidence of new physics by looking for any anomaly in well-known Standard Model processes.

Part of the program is lastly devoted to achieve a deeper understanding of the behaviour of matter exposed at the extreme conditions of high-energy heavy-ion collisions, and to produce refined measurements of the subtlest phenomena in rare decays of heavy flavoured quarks.

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 $\mathcal{L} = 2 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and delivered in total, for the full 2010, an integrated luminosity of $47\,\mathrm{pb}^{-1}$.

To have an idea of the progress achieved in 2011, this amount of integrated luminosity was typically delivered in a single day bringing the total delivered by the end of the year to an impressive value of $6\,\mathrm{fb}^{-1}$ that exceeded by far the most optimistic expectations.

Similar progress was achieved in Pb-Pb mode where an integrated luminosity in excess of $150\,\mu b^{-1}$ ($15\times$ the total amount of 2010) was delivered to experiments.

Detectors recorded typically 90–92% of the delivered luminosity and about 85–90% of it was considered good quality data for physics. The uncertainty in the luminosity determination is estimated to be 2–4%.

All this yielded an incredibly rich harvesting of physics results. Since it would be impossible to cover them in the limited amount of space available for this contribution, the following chapters will contain only some highlights of the major results.

2. – Small-angle detectors: LHCf and TOTEM

Two set of specialized detectors, LHCf and TOTEM, instrument the very forward regions of ATLAS and CMS respectively.

LHCf detectors are installed 140 m away from ATLAS in IP1 and measure particles emitted in the pseudo-rapidity range $\eta > 8.4$. They can measure energy spectra and transverse momentum distribution of gamma-rays with energies $E_\gamma > 100\,\text{GeV}$ and a resolution $\text{d}E/E < 5\%$. Neutral hadrons are measured for energies greater than a few 100 GeV with a 30% resolution while π^0's are measured up to $E > 600\,\text{GeV}$ with an excellent $< 3\%$ resolution. The measured single γ spectra are extremely important to tune models relevant for extended air shower experiments. As of today none of the current models seems to be able to describe the data over the full range of energy (100 GeV–3.5 TeV) with the largest discrepancies appearing for energies $> 2\,\text{TeV}$ [1].

The TOTEM detectors are installed around CMS at IP5. Using data taken in a short LHC special run with dedicated large β^* optics, they have measured the differential cross-section for elastic proton-proton scattering. A single exponential fit with a slope $B = 20.1 \pm 0.2(\text{stat}) \pm 0.3(\text{syst})\,\text{GeV}^{-2}$ describes the range of the squared four-momentum transfer $|t|$ from 0.02 to $0.33\,\text{GeV}^2$. After the extrapolation to $|t| = 0$, a total elastic scattering cross-section of $24.8 \pm 0.2(\text{stat}) \pm 1.2(\text{syst})\,\text{mb}$ was obtained. Applying the optical theorem and using the luminosity measurement from CMS, a total proton-proton cross-section of $98.3 \pm 0.2(\text{stat}) \pm 2.8(\text{syst})\,\text{mb}$ was deduced which is in good agreement with the expectation from the overall fit of previously measured data over a large range of center-of-mass energies (fig. 1). From the total and elastic pp cross-section measurements, an inelastic pp cross-section of $73.5 \pm 0.6(\text{stat}) + 1.8 - 1.3(\text{syst})\,\text{mb}$ was inferred [2].

3. – The ALICE detector and heavy-ion physics at LHC

The ALICE Detector is highly specialized for Pb-Pb physics but it provides also pp results complementary to ATLAS, CMS and LHCb. The key features of ALICE are the capability of tracking charged particles down to very low p_t, a good particle identification in the central region up to several GeV with different techniques ($\text{d}E/\text{d}x$, TOF, TRD, Rich-HMPID), a calorimetry coverage for low p_t electrons, with gamma and π^0 identification and an excellent coverage for muons down to rapidity 4 and very low p_t.

Thanks to its excellent particle identification ALICE is able to measure the coefficient of the elliptic flow, v_2, for different species, $\pi^\pm$, $\kappa^\pm$ and $\overline{p}$. The corresponding p_t spectra are used to check for the compatibility with different models. ALICE results seem to suggest that the v_2 value for different species at LHC do not scale with the number of constituent quarks. In particular this assumption, that was used to explain RHIC data, seems not to be working for anti-protons at LHC energies.

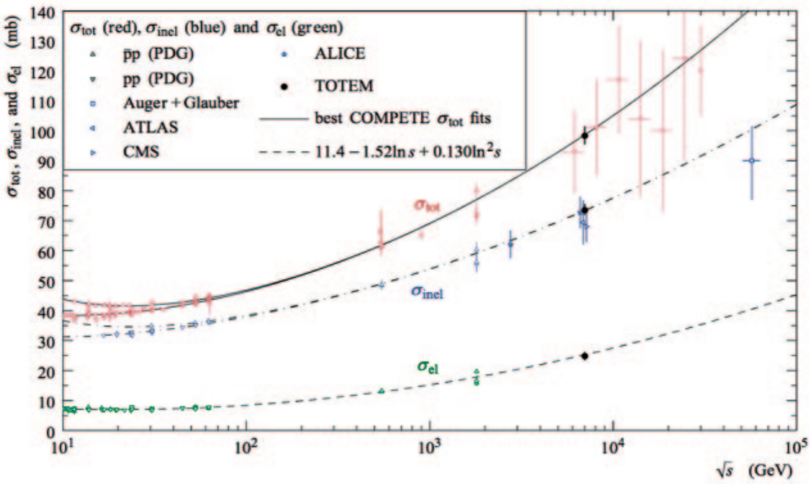

Fig. 1. – Measurement of the elastic, inelastic and total cross-section for pp collisions at $\sqrt{s} = 7\,\text{TeV}$ performed by the TOTEM detector at LHC.

Among the large set of very interesting results produced by ALICE it is worth mentioning the detailed studies on charmonium production in heavy-ion collisions. The strong energy loss of c quarks in the hot and dense QCD medium leads to a significant nuclear suppression factor for charm produced with momentum above $5\,\text{GeV}/c$ in high-centrality events (fig. 2, left). Despite this, the J/ψ suppression factor at LHC, as measured by ALICE, seems to be smaller with respect to RHIC, hinting at possible recombination mechanisms of the charm quark within the Quark Gluon Plasma (QGP)(fig. 2, right) [3].

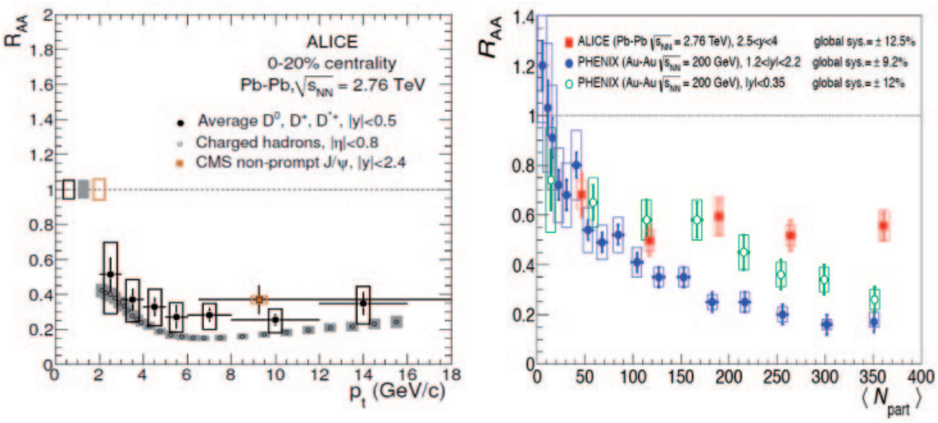

Fig. 2. – ALICE measurements of the nuclear suppression factor for charmed hadrons as a function of p_t (left). Comparison of the nuclear suppression factor for J/ψ *vs.* the number of participants in the collision as measured by ALICE at LHC and PHENIX at RHIC (right).

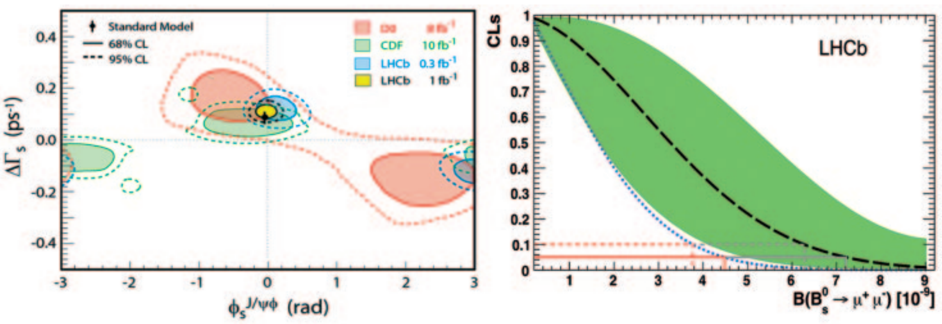

Fig. 3. – Measurement of $\Delta\Gamma_s$ and ϕ_s in B_s^0 mesons by LHCb and comparison with the measurements at the Tevatron (left). Extraction of the limit in the $BR(B_s^0 \to \mu^+\mu^-)$ using the CLs by LHCb (right).

4. – The LHCb detector and heavy-flavor physics at LHC

The LHCb detector looks for any signal of new physics that could manifest itself in the form of subtle anomalies in the rare decays of b-quarks. In particular the CP violation parameters in the B_s^0 mixing are particularly interesting since they are very sensitive to new particles or new interactions in the multi-TeV scale.

The decay time distributions of B_s^0 mesons decaying into the $J/\psi\phi$ and $J/\psi\pi\pi$ final states have been used to measure the parameters ϕ_s and $\Delta\Gamma_s$. Here ϕ_s is the CP-violating phase, equal to the phase difference between the amplitude for the direct decay and the amplitude for the decay after oscillation, and $\Delta\Gamma_s$ is the difference between the decay widths of the light and heavy B_s^0 mass eigenstates.

The results obtained by LHCb on these two variables are the most precise ones obtained so far and are fully consistent with the Standard Model expectations. Values close to zero for ϕ_s ($\phi_s = -0.002 \pm 0.083(\text{stat}) \pm 0.027(\text{syst})\,\text{rad}$) and positive for $\Delta\Gamma_s$ ($\Delta\Gamma_s = 0.116 \pm 0.018(\text{stat}) \pm 0.006(\text{syst})\,\text{ps}^{-1}$) are preferred [4, 5]. It follows that in the B_s^0 system, the mass eigenstate that is almost CP even is lighter and decays faster than the state that is almost CP odd. As it can be seen in fig. 3, left, this new result is in excellent agreement with the Standard Model expectations while previous measurements by the Tevatron experiments hinted at some tension with the SM values. It is also interesting to note that this situation is quite similar to the well known case of the neutral kaon system.

The flavor-changing neutral-current decays of the B_s^0 and B^0 mesons into di-muons are highly suppressed in the SM: they are forbidden at the tree level and can only proceed through higher-order loop diagrams where helicity is suppressed by factors of $(m_l/m_B)^2$, with m_l and m_B being the masses of the lepton and B meson, and require an internal quark annihilation within the B meson. Since the theoretical uncertainties are small these decay modes are extremely sensitive probes for Physics Beyond SM (Extended Higgs Boson sectors or SUSY in a well defined parameter space).

The LHCb Collaboration searched for $B_s^0 \to \mu^+\mu^-$ and for $B^0 \to \mu^+\mu^-$ decays using $1.0\,\text{fb}^{-1}$ of pp collision data. For both decays the number of observed events is consistent with expectation from background and Standard Model signal predictions. Upper limits on the branching fractions are determined to be $BR(B_s^0 \to \mu^+\mu^-) < 4.5(3.8) \times 10^{-9}$ (fig. 3, right) and $BR(B^0 \to \mu^+\mu^-) < 1.0(0.81) \times 10^{-9}$ at 95% (90%) confidence level [6].

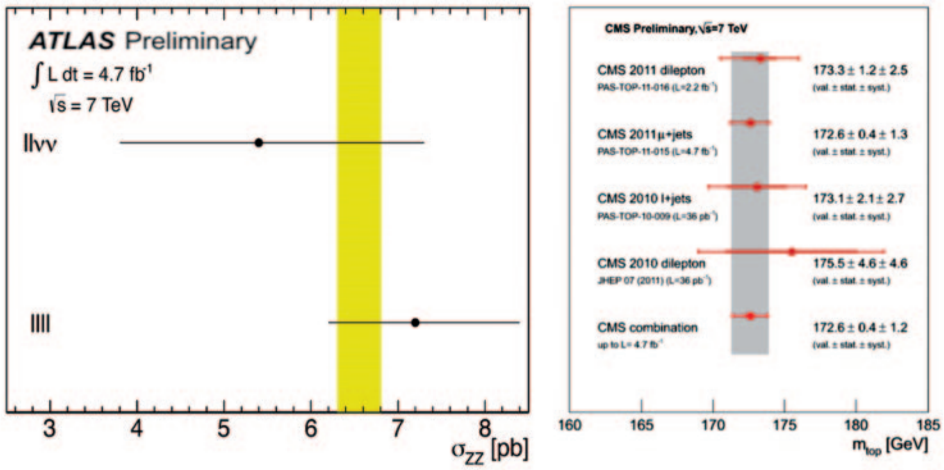

Fig. 4. – ATLAS measurement of the production cross-section of ZZ decaying into four leptons or two leptons and two neutrinos (left). CMS measurement of the top quark mass in the dilepton and lepton+jets channels and combined result (right).

As of today these are the world best limits and they are currently used to produce further indirect constraints on SUSY and other models for new physics.

5. – The general-purpose detectors: ATLAS and CMS

The main goals of the two general-purpose detectors, ATLAS and CMS, is to discover the SM Higgs boson or alternative mechanisms for the electroweak symmetry breaking and to look for direct evidence of new physics. To address properly these issues it is mandatory to master extremely well all known Standard Model processes that appear as typical background processes for any new discovery.

For example the di-boson (WW and ZZ) cross-sections are very important test of the SM and irreducible background for SM Higgs searches. Both experiments produced updated results with full 2011 statistics. As an example we quote ATLAS result on the measurement of the WW production cross-section $\sigma_{WW} = 53.4 \pm 2.1(\text{stat}) \pm 4.5(\text{sys}) \pm 2.1(\text{lumi})\,\text{pb}$ in reasonable agreement with the NLO prediction $45.1 \pm 2.8\,\text{pb}$ [7]. The equivalent results on the ZZ, shown in fig. 4, left, are also compatible with the SM predictions [8]. It is worth to notice that the production cross-section for this process falls in the same ball park of the typical cross-sections for the production of a low mass SM Higgs boson at 7 TeV, therefore, this kind of measurements can be seen as important test bench for the readiness of the experiments in hunting the Higgs.

The selection of top quark candidates requires a complete understanding of all major physics objects. Going through the full statistics collected so far, both ATLAS and CMS experiments have been able to measure the top pair production cross section using different techniques and various decay channels. The top cross-section measurements are important test of perturbative QCD and key background for many searches. A new combination has been produced by ATLAS using the decay modes in di-leptons, single-lepton + jets and the all-hadronic channels. The combined measurement of the top production cross-section at LHC yields a value $\sigma_{t\bar{t}} = 177 \pm 3 \pm 7\,\text{pb}$ that is in good agreement with the most recent NLO and approximate NNLO predictions [9]. It

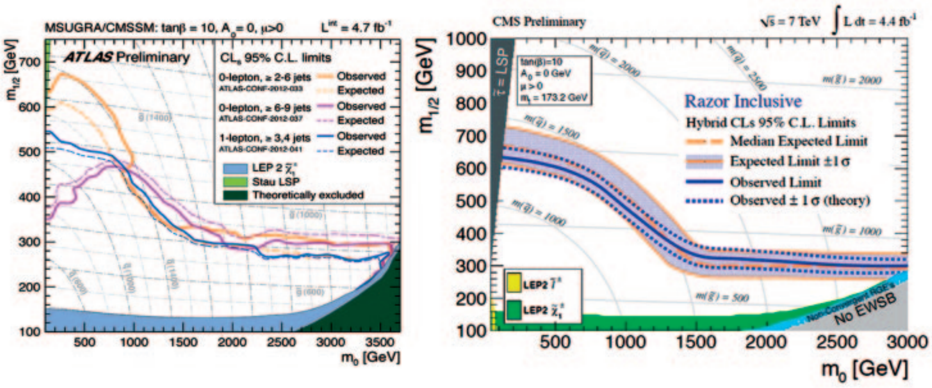

Fig. 5. – Summary of the exclusion limits for squarks and gluinos for a particular choice of SUSY parameters in ATLAS (left) and CMS (right).

is worth noticing that the current experimental precision, 6%, is already smaller than the uncertainty of the approximate NNLO theoretical predictions. That means that the measurements at LHC are already systematic-limited: any improvement will require better understanding of detector performance, signal modeling and backgrounds.

Another example of the progress achieved in the top sector by the LHC experiments is the updated measurement of the top mass performed by CMS. Using the full 2011 data-set CMS performed a careful study of the top mass in the di-lepton and lepton+jets channels. Likelihood methods have been used to simultaneously fit the top mass and the Jet Energy Scale. The result yielded the best mass determination in the di-lepton channel as of today and a combined result for the top mass $m_t = 172.6 \pm 0.4 \pm 1.2\,\text{GeV}$ which is already competitive with the Tevatron combination (fig. 4, right) [10]. Many more new results on the top have been produced by the LHC experiments: single top measurements, spin correlations in $t\bar{t}$ events, ISR/FSR measurement, top charge asymmetry, search for FCNC in top decays, etc. but they cannot be reported here do the limited amount of space available for this contribution.

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 new 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.

A complex set of 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. Therefore, using conservative statistical tools, ATLAS and CMS have extracted new limits exceeding significantly the best measurements performed so far by the Tevatron experiments. Figure 5 summarizes the exclusion limits produced

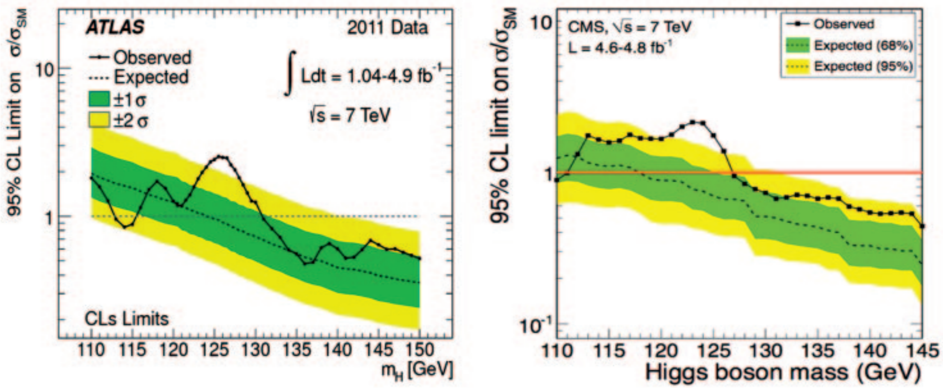

Fig. 6. – Search for the Standard Model Higgs boson at LHC: excess of events in the low-mass region reported by ATLAS (left) and CMS (right) in December 2011.

by these analyses for a particular choice of SUSY parameters in ATLAS and CMS [11,12]. The highest exclusion limits are obtained using the fully hadronic final states. Just as an example in MSUGRA models ($e.g.$, $\tan\beta = 10, A_0 = 0, \mu > 0$) the current exclusion limits for $m_{gluino} = m_{squark}$ are pushed up to 1.4 TeV.

The search for the Higgs boson is one of the most ambitious goals of the LHC experiments. The amount of data collected in 2011 was large enough to perform a complete and exhaustive search whose results have been presented in a special seminar held at CERN on December 13, 2011.

Both experiments performed a complex set of studies using all major decay modes (WW, ZZ, $b\bar{b}$, $\tau^+\tau^-$ and $\gamma\gamma$), foreseen for the SM Higgs boson and new exclusion limits at 95% CL were reported between 600 and about 129 GeV/c^2. Both experiments were not able to exclude the presence of the SM Higgs boson in the low mass region due to the presence of an excess of events around 125 GeV/c^2 (fig. 6).

ATLAS observed an excess of events around $m_H = 126\,\text{GeV}/c^2$ with a local significance of 3.6σ to be compared with a median expected value, in presence of a SM Higgs boson in data, of 2.4σ. The observed excess was compatible with the expected signal strength within 1σ. The global significance of the excess, taking into account the Look-Elsewhere-Effect, was 2.3σ [13].

CMS observed an excess of events which is most compatible with a SM Higgs hypothesis in the vicinity of $m_H = 124\,\text{GeV}/c^2$ with local statistical significance 2.6σ (1.9σ global) [13].

Since then all papers have been submitted and new results with refined analyses have been presented in the Winter Conferences. A new analysis for the Higgs decaying into two photons was produced by CMS. The new analysis used sophisticated Multi-Variate techniques for the photon identification and for the assignment of the vertex ID. In addition a new category was added to the baseline search requesting di-photon events to be tagged by two energetic jets in the forward region. The new category has an excellent sensitivity for a SM Higgs boson produced through Vector Boson fusion mechanisms. As a result of the increased sensitivity the local significance of the excess in the di-photon signal around 125 GeV/c^2 increased to 2.9σ bringing the overall significance of the global CMS combination to 2.8σ [14]. The signal strength compatibility of the various channels

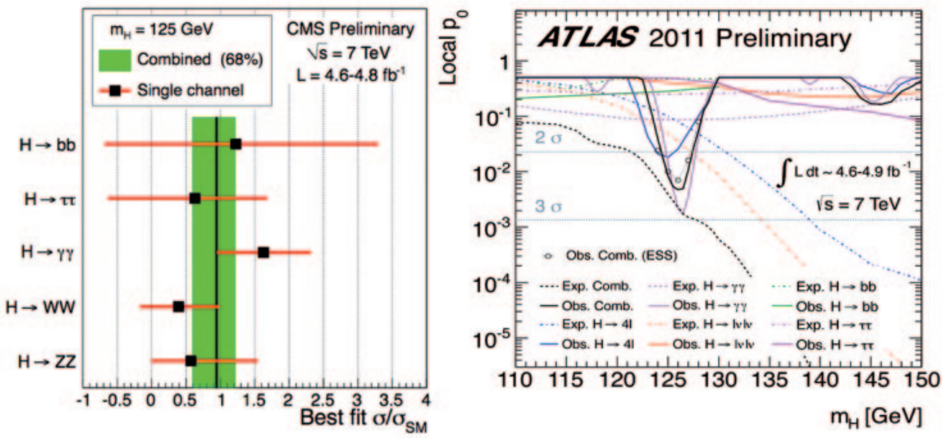

Fig. 7. – The signal strength compatibility of the various channels studied by CMS with respect to the hypothesis of the presence of the SM Higgs boson in data at a mass of $125\,\mathrm{GeV}/c^2$ (left). The p-value with respect to the background only hypothesis of the new ATLAS combination as presented in the winter conferences (right).

studied by CMS with respect to the hypothesis of the presence of the SM Higgs boson in data is shown in fig. 7, left.

With respect to the preliminary results presented in the December seminar ATLAS updated the results with the full 2011 statistics on all channels that play a relevant role in the low-mass region: WW, ZZ, $\gamma\gamma$, $b\bar{b}$, $\tau^+\tau^-$. The p-value with respect to the background only hypothesis of the new ATLAS combination as presented in the winter conferences is shown in fig. 7, right where an excess at $126\,\mathrm{GeV}/c^2$ of mass is clearly visible. Still the excess is dominated by the two channels presented in December: $\gamma\gamma$ with a 2.8σ local significance and $ZZ \to llll$ with 2.1σ local significance, but some lack of an excess in the WW channel brings the global significance sligthly down 2.5σ with respect to the very preliminary results but still fully compatible with the expectations (2.9σ) in presence of a SM Higgs boson signal [15].

In conclusion the intriguing excess of events detected by both experiments around a mass of $125\,\mathrm{GeV}/c^2$ is definitely there but only the additional data we are going to collect in the current year at 8 TeV center-of-mass energy will be able to ascertain the origin of this excess and make conclusive statements.

6. – Conclusion

Thanks to the fantastic performance of the LHC and of its detectors in 2011, an incredible amount of new physics results have been produced: a new and deeper understanding of the behaviour of matter exposed at the extreme conditions of high-energy heavy-ion collisions; refined measurements of the subtlest phenomena in rare decays in the b-quark sector; new QCD, Top and Electroweak measurements highly competitive with results coming from the Tevatron experiments. The exploration of the 7 TeV energy regime did not bring us, so far, convincing evidence of new physics while the phase space for SUSY starts being seriously constrained.

Intriguing hints of the possible presence of the SM Higgs boson in the LHC data around a mass of $125\,\mathrm{GeV}/c^2$ have been reported independently by ATLAS and CMS.

We expect conclusive statements (confirmation at the observation level or exclusion at least at 95% CL) on this subject using the 2012 run at 8 TeV that has just started with expectations for an integrated luminosity $> 15\,\text{fb}^{-1}$.

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