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# Combination of all searches and extraction of properties of the Higgs boson (ATLAS and CMS)

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The ATLAS and CMS Collaborations observed a new resonance decaying into two photons, into four leptons via $Z$-boson pair production, and into two $W$ bosons decaying leptonically. With all the LHC run-1 data, amounting to about 25 fb$^{-1}$ collected at $\sqrt{s} = 7$ TeV and 8 TeV, it is now possible to probe the fundamental properties of this particle: mass, spin, couplings, testing its compatibility with a Standard Model Higgs boson. This document contains a review of the results from the ATLAS and CMS Collaborations.

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## 1. Introduction

The Standard Model (SM) of particle physics describes all fundamental interactions by means of gauge symmetries, where a local symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ generates vector-boson-mediated interactions with color, weak isospin and weak hypercharge. In gauge theories, the intermediate vector bosons must be massless: this is the case for photons ($\gamma$) and (to our knowledge) gluons ($g$), but clearly this is not the case for the weak vector bosons $Z, W^{\pm}$. Moreover, due to the chirality of the weak interactions, fermions should also be massless. In the SM, the masses of vector bosons and fermions are introduced through a spontaneous symmetry breaking of the vacuum state — the "Higgs mechanism" — in which a scalar field acquires a non-vanishing vacuum expectation value $\upsilon$.In this model, all particles interacting with the scalar field acquire mass dynamically, according to the relations:

$$m_W = \frac{g}{2}\upsilon \quad ; \quad m_Z = \frac{g}{2\cos\theta_W}\upsilon = \frac{m_W}{\cos\theta_W} \quad ; \quad m_F = \frac{g_F}{\sqrt{2}}\upsilon \tag{1.1}$$

Moreover, an observable particle $H$ is predicted, with zero charge, spin zero, even parity and unknown mass $m_H$, interacting with all massive particles through couplings

$$g_V = 2\frac{m_V^2}{\upsilon} \quad ; \quad g_F = \frac{m_F}{\upsilon} \tag{1.2}$$

for vector bosons $V = W, Z$ and fermions $F$, respectively.

During the search for the SM Higgs boson, both the ATLAS [1] and CMS [2] Collaborations have reported evidence of a new resonance $H$ [3], that can decay into two photons, two $Z$-bosons, or two $W^{\pm}$-bosons. If this resonance is indeed the SM Higgs boson, it should have two typical "fingerprints": a spin-parity state $J^P = 0^+$ and couplings related to the masses, as described. Moreover, through the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decays its mass can be measured with high accuracy, thus providing the last missing parameter of the SM. All the observable properties of the Higgs boson (production cross-sections, decay width, branching ratios) would therefore be calculable.

This document summarizes the study of the properties of the new resonance, obtained by the ATLAS and CMS Collaborations[1].

## 2. Statistical treatment

When performing measurements, a model with a likelihood function $\mathscr{L}$ is needed in order to establish confidence intervals.

For each event $e$ there is a set of observables $\vec{x}_e$ distributed according to a probability density function (PDF) $f_s(\vec{x}_e)$ for the signal, and $f_b(\vec{x}_e)$ for the background. Calling $n_s$, $n_b$ the signal and background yields, the negative logarithm of the extended likelihood function reads:

$$\begin{aligned} -\ln\mathscr{L}(\vec{\alpha};\vec{\nu}) \;=\; & (n_s+n_b) - \sum_e \ln\left[n_s \cdot f_s\left(\vec{x}_e|\vec{\alpha},\vec{\nu}_s\right) + n_b \cdot f_b\left(\vec{x}_e|\vec{\nu}_b\right)\right] \\ & - \sum_k \ln\pi_k(\nu_k) \end{aligned} \tag{2.1}$$

[1]This document refers to the results available at the time of the conference. Since then, updated results have been published [4].

The PDF's $f_s$, $f_b$ depend on several parameters, that are classified as *parameters of interest* (POI) $\vec{\alpha}$ and *nuisance parameters* (NP) $\vec{\nu}$. Many NP's are further constrained by ancillary PDF's $\pi_k$, driven by auxiliary measurements. Such PDF's are usually Gaussian or log-normal, but in some cases they may be chosen as rectangular, when the NP is known to lie in a given interval but there are no hints about its prior distribution.

When performing measurements on a (set of) continuous POI(s) — e.g. mass, cross-section — a "profiled likelihood ratio" (PLR) is built:

$$q_{\vec{\alpha}} = -2\ln\Lambda(\vec{\alpha}) = -2\ln\frac{\mathscr{L}(\alpha,\hat{\hat{\nu}}(\alpha))}{\mathscr{L}(\hat{\alpha},\hat{\nu})} \tag{2.2}$$

where in the denominator the values $\hat{\alpha},\hat{\nu}$ are set to maximize $\mathscr{L}$, whereas in the numerator the value of $\alpha$ is set to the value under test and $\hat{\hat{\nu}}$ is chosen to maximize $\mathscr{L}$ under this constraint. The Wilks theorem [5] guarantees that the test statistic $q_\alpha$, for a large enough data set, is distributed according to a $\chi^2_D$ distribution with degree-of-freedom $D$ given by the dimensionality of the POI $\alpha$, if the value of $\alpha$ under test is the right one. This allows to set confidence regions: when measuring only one POI the 68% and 95% confidence intervals are defined by $q<1$ and $q<4$ respectively, whereas for a simultaneous measurement of two POI's the same confidence levels are defined by $q<2.3$ and $q<6.0$.

When comparing two hypotheses $\mathscr{H}_0$ and $\mathscr{H}_{\rm alt}$ on a discrete parameter — e.g. spin, parity — a "ratio of profiled likelihoods" is used:

$$q = \ln\frac{\mathscr{L}(\mathscr{H}_0,\hat{\hat{\nu}}(\mathscr{H}_0))}{\mathscr{L}(\mathscr{H}_{\rm alt},\hat{\hat{\nu}}(\mathscr{H}_{\rm alt}))} \tag{2.3}$$

where the NP's $\hat{\hat{\nu}}(\mathscr{H}_{0,\rm alt})$ are chosen to maximize $\mathscr{L}$ for either of the hypotheses $\mathscr{H}_{0,\rm alt}$ under test.

## 3. Mass measurement

The mass measurement is performed combining the $\gamma\gamma$ and $ZZ^*\to 4\ell$ decay channels [6, 7]. The two channels individually give:

$$m_H^{\gamma\gamma} = 126.8\pm0.2(stat)\pm0.7(syst)\ \text{GeV} \quad ; \quad m_H^{4\ell} = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)\ \text{GeV} \qquad (ATLAS)$$

and

$$m_H^{\gamma\gamma} = 125.4\pm0.5(stat)\pm0.6(syst)\ \text{GeV} \quad ; \quad m_H^{4\ell} = 125.8\pm0.5(stat)\pm0.2(syst)\ \text{GeV} \qquad (CMS)$$

The main source of systematic uncertainty is the energy scale. In the $4\ell$ channel, this is dominated by the $4\mu$ decays: the muon energy scale is calibrated using $J/\psi,\Upsilon,Z\to\mu^+\mu^-$ decays, yielding a systematic uncertainty on the $4\mu$ invariant mass of $\sim0.2\%$ at ATLAS and $\sim0.1\%$ at CMS. The photon energy scale in the $\gamma\gamma$ channel relies on several assumptions (electron energy scale from $Z\to e^+e^-$ decays, $e\to\gamma$ extrapolation and knowledge of the material budget in front of the calorimeter, intercalibration of the calorimeters' layers), which overall bring a relative uncertainty on the $\gamma\gamma$ invariant mass of $\sim0.55\%$ at ATLAS and 0.47% at CMS.



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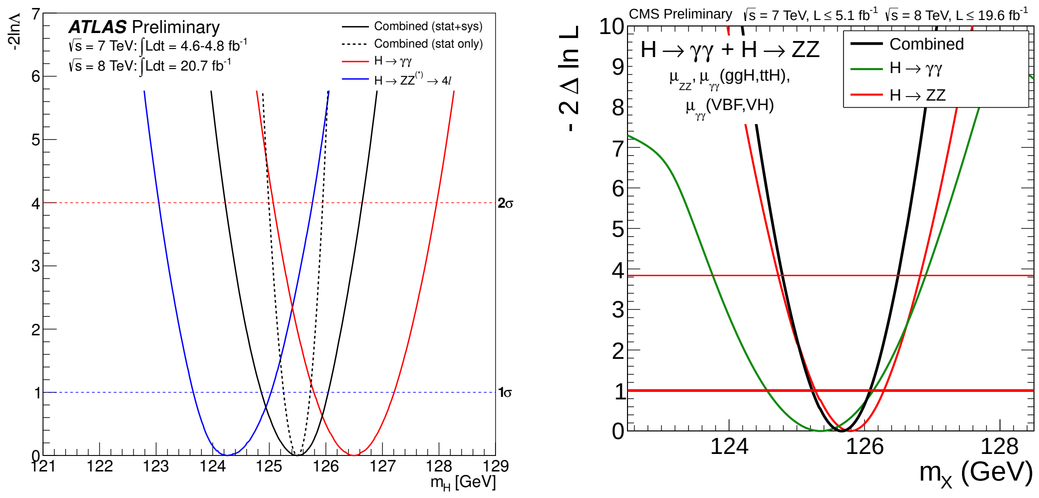


**Figure 1:** Likelihood scans of $m_H$, for the $\gamma\gamma$ and the $4\ell$ decay channels, and for their combination, from ATLAS (*left*, [6]) and CMS (*right*, [7]). The horizontal lines show the 68% and 95% confidence intervals.

The results from the individual channels and the combined result are shown by the PLR scans in Fig. 1, for both ATLAS and CMS. The $m_H$ measurement in ATLAS exhibits a tension between measurements in the $\gamma\gamma$ and $4\ell$ channels. However this discrepancy is not alarming, as the curves relative to the individual measurements cross below the $2\sigma$ level.

The combined mass measurements are:

$$m_H^{ATLAS} = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)\ \text{GeV} \quad ; \quad m_H^{CMS} = 125.7 \pm 0.3(stat) \pm 0.3(syst)\ \text{GeV} \tag{3.1}$$

## 4. Couplings measurements

At the LHC, the Higgs boson can be produced through four processes:the dominant one is the gluon fusion (ggF), mediated by a top-quark loop; the second is the vector-boson fusion (VBF) where the valence quarks of the colliding protons emit weak bosons that form a Higgs boson. Associated production ($VH$, with $V$ being $Z$ or $W$, and $t\bar{t}H$) may also occur, in processes like $V^* \to VH$, or when two gluons split to $t\bar{t}$ pairs, and a $t$ and a $\bar{t}$ produce the Higgs boson.

For each search channel, the events are divided in categories that are sensitive to the production mechanism [8, 7]. In this way, the sensitivity to the signal is improved, and it becomes possible to probe the relative proportion of different productions. The following "production tags" are introduced:

- events with two hard jets at large rapidity are typical of VBF;
- events with two jets with smaller di-jet invariant mass are typical of $VH$ production, where the weak boson undergoes hadronic decay;
- events with an additional identified lepton ($e$ or $\mu$) are typical of $VH$ production, where the weak boson undergoes leptonic decay;

- events with a large missing transverse momentum $\vec{\not{p}}_T$ are typical of $ZH$ production, where the $Z$-boson decays in neutrinos.

All the remaining events are mostly from ggF. Each category is enhanced by a production mode, but large contaminations exist among the categories, and must be accounted for.

### 4.1 Signal strengths

A first test of SM predictions is performed by measuring the "signal strength" $\mu = \sigma^{\rm obs}/\sigma^{\rm SM}$, i.e. the ratio between the observed signal yield and that expected for a SM Higgs boson. This can be done for all sought decay channels $\gamma\gamma$, $ZZ^*, WW^*, b\bar{b}$, $\tau^+\tau^-$ individually — see Fig. 2 (left,centre) — and for different "production tags" — see Fig. 2 (right). The measurements obtained by ATLAS and CMS do not deviate significantly from unity, and do not exhibit a common trend.The combined measurements of the signal strength by ATLAS and CMS are:

$$\mu^{ATLAS} = 1.30 \pm 0.13(stat) \pm 0.14(syst) \quad ; \quad \mu^{CMS} = 0.80 \pm 0.14$$

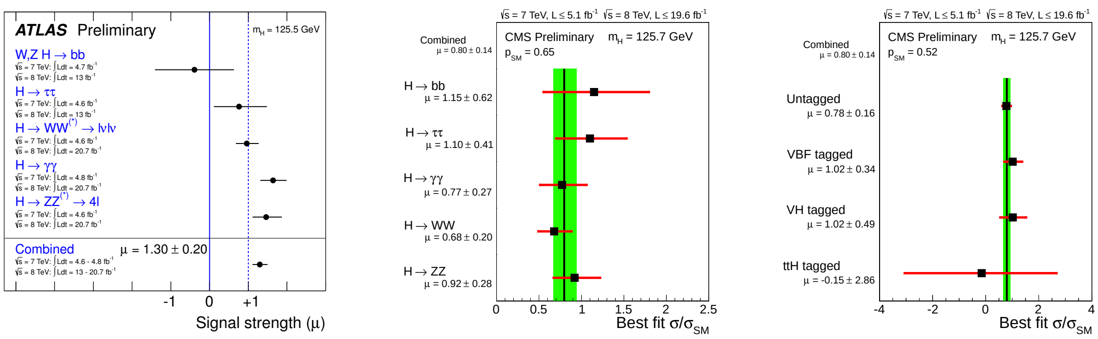


**Figure 2:** Measurements of the signal strength $\mu = \sigma^{\rm obs}/\sigma^{\rm SM}$, for several decay channels (*left*: ATLAS [8] and *centre*: CMS [7]), and for different "production tags" (*right*: CMS).

To probe the couplings to fermions and vector bosons separately, two signal strengths are introduced, one involving $ttH$ coupling (ggF+$t\bar{t}H$) and one involving $WWH$ and $ZZH$ couplings (VBF and $VH$). The result of the measurements is displayed in Fig. 3, showing evidence for coupling to both weak bosons and fermions (the latter mainly through the $t$-loop in ggF production).

### 4.2 Effective couplings

The SM Higgs boson, for a mass $m_H \simeq 125$ GeV, is expected to have a decay width $\Gamma_H \simeq$ 4 MeV. In a zero-width approximation, the cross-section for a process $ii \to H$ is proportional to the partial width for the decay $H \to ii$: $\sigma_{ii\to H} \propto \Gamma_{H\to ii}$. Therefore, the cross-section for a process $ii \to H \to oo$ can be written as:

$$\sigma_{ii\to H\to oo} = \sigma_{ii\to H} \cdot BR(H \to oo) \propto \frac{\Gamma_{H\to ii}\Gamma_{H\to oo}}{\Gamma_H} \tag{4.1}$$

Each interaction vertex $HXX$ is parametrized by means of effective couplings $g_X$, which for the SM are given by Eq. (1.2). To probe the real couplings, the "modifiers" $\kappa_X = g_X/g_X^{\rm SM}$ are introduced.

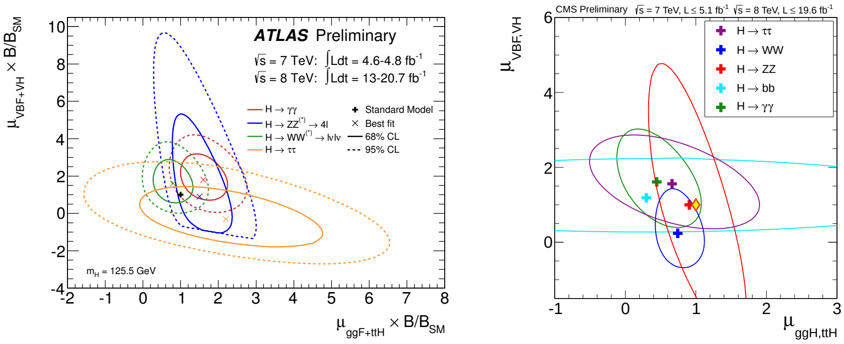


**Figure 3:** Confidence contours for signal strengths measured for ggF+$t\bar{t}H$ production (horizontal axis) and VBF+$VH$ production (vertical axis): ATLAS measurements [8] on the left, CMS measurements [7] on the right. The expected SM value is $(1,1)$.

In this way, the cross-sections can be expressed as:

$$\sigma_{ii\to H\to oo} = \sigma^{\rm SM}_{ii\to H\to oo} \times \frac{\kappa_i^2\,\kappa_o^2}{\kappa_H^2} \qquad \left( \kappa_H^2 = \sum_X \kappa_X^2 \cdot BR^{\rm SM}(H\to XX) \right) \tag{4.2}$$

In principle, there is a $\kappa$-factor for any possible initial and final state. Therefore, some assumptions are made, e.g.:

- universality of weak boson couplings: $\kappa_W = \kappa_Z = \kappa_V$;
- universality of fermion couplings: $\kappa_t = \kappa_b = \kappa_\tau = \kappa_F$
- the $ggH$ interaction is mediated by a top-quark loop (as in SM), therefore $\kappa_g = \kappa_t = \kappa_F$;
- the $H\gamma\gamma$ interaction is mediated by a $W$-loop and a top-quark loop, as in the SM: for $m_H \simeq$ 125 GeV this means that $\kappa_\gamma^2 = (1.26\cdot\kappa_W - 0.26\cdot\kappa_t)^2$;
- using the SM branching ratios, $\kappa_H^2 = 0.75\cdot\kappa_F^2 + 0.25\cdot\kappa_V^2$ for $m_H \simeq 125$ GeV.

This model is sensitive only to the relative sign of $\kappa_V, \kappa_F$ through the $\kappa_\gamma$ effective coupling modifier. The sign of $\kappa_V$ is assumed positive by convention.

With such assumptions, the confidence contours obtained by ATLAS and CMS in the $(\kappa_F, \kappa_V)$ plane are shown in Fig. 4. In both cases, the fit to data prefers the positive sign for $\kappa_F$, although for ATLAS a negative region is also allowed, as an effect of the large observed $H\to\gamma\gamma$ yield. The ATLAS measurement is compatible with the SM at 8% confidence level, that from CMS is completely compatible with SM.

More refined tests are then carried out, leaving the couplings modifiers $\kappa_W, \kappa_Z$ independent and testing their ratio $\lambda_{WZ} = \kappa_W/\kappa_Z$: the results are shown in Fig. 5 (top). Some extended Higgs models, such as the "two-Higgs-doublet Model" (2HDM) introduce different couplings for fermions with up/down weak isospin, or different couplingsfor quarks and leptons. For this reason, the ratios $\lambda_{du} = \kappa_d/\kappa_u$ and $\lambda_{\ell q} = \kappa_\ell/\kappa_q$ are also probed, as displayed in Fig. 5 (bottom).

Since the $ggH$ and $H\gamma\gamma$ interactions are entirely loop-mediated, probing directly $\kappa_g, \kappa_\gamma$ could provide sensitivity to the existence of new particles beyond the SM that could enter these loops. Therefore, all $\kappa$-parameters are set to 1 except $\kappa_g, \kappa_\gamma$ that are left free: the result is shown in Fig. 6.

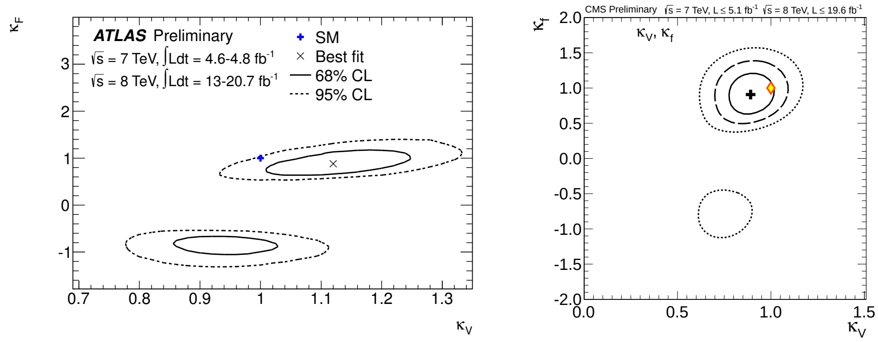


**Figure 4:** Confidence contours for the fermionic and vector-boson effective couplig modifiers $\kappa_F, \kappa_V$: ATLAS measurements [8] on the left, CMS measurements [7] on the right. The expected SM value is $(1,1)$.

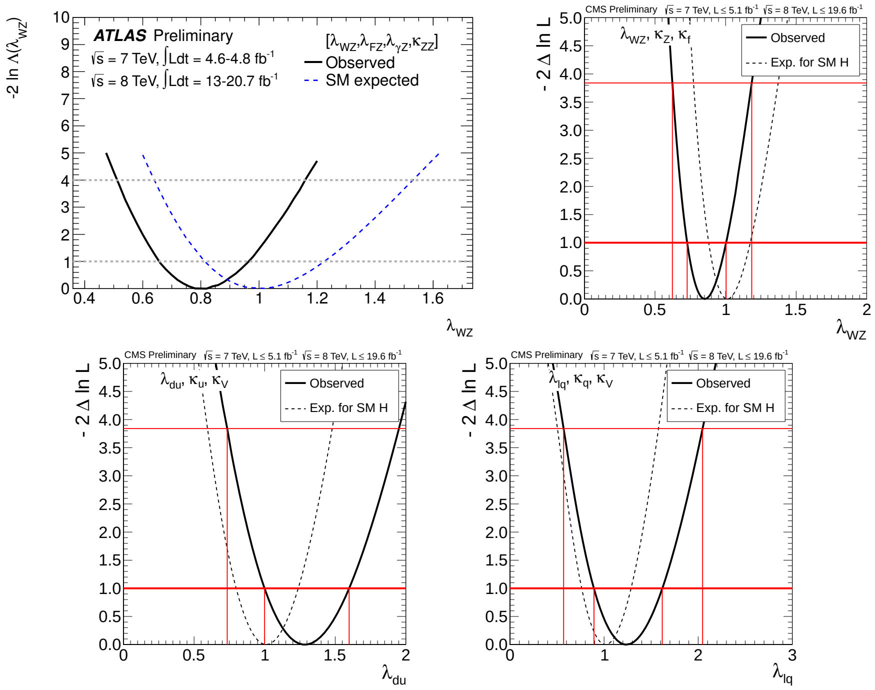


**Figure 5:** Likelihood scans to probe possible deviations from the universality of couplings modifiers: $\lambda_{WZ} = \kappa_W/\kappa_Z$ (top figures: *left* for ATLAS [8] and *right* for CMS [7]); $\lambda_{du} = \kappa_d/\kappa_u$ (bottom left); $\lambda_{\ell q} = \kappa_\ell/\kappa_q$ (bottom right).

## 5. Spin and parity measurements

The observed decay channels imply integer spin. The $\gamma\gamma$ decay, in particular, forbids the spin-1 state (Landau-Yang theorem [9]), however as a cross-check this state is anyway investigated in the $ZZ^*$ decays. Exploiting the angular distributions of the decay products, and the di-lepton invariant masses in the $ZZ^*, WW^*$ decays, the spin-parity hypothesis $J^P = 0^+$ characteristic of a Higgs boson is compared with alternative hypotheses $J^P_{\rm alt} = 0^-, 2^+, 1^\pm$.

For the $J^P = 2^+$ hypothesis, a graviton-inspired tensor with minimal couplings to SM particles has been adopted [10]. This state can be produced via gluon-gluon fusion or quark-antiquark

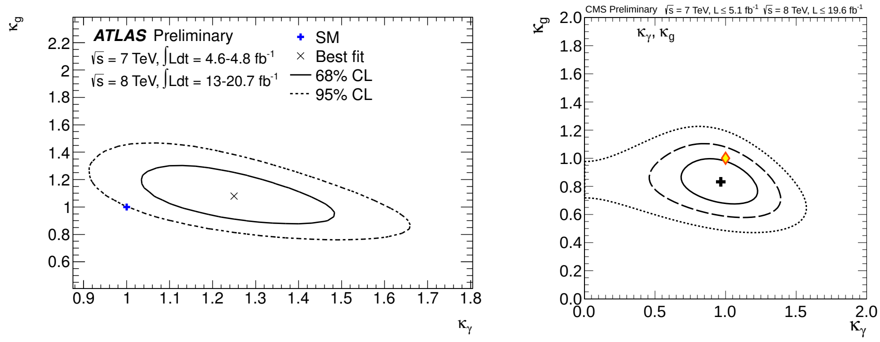


**Figure 6:** Confidence contours for the $\kappa_\gamma$, $\kappa_g$ effective couplings modifiers, for ATLAS [8] (left) and CMS [7] (right). The expected SM value is $(1,1)$.

annihilation: the proportion of the two mechanisms can be computed at leading-order, but receives large corrections when more real parton emission is allowed in the model. For this reason, several admixtures of the two processes are tested, by scanning the fraction of $q\bar{q}$-annihilation $f_{q\bar{q}}$ from 0% to 100% in steps of 25%. All $\gamma\gamma$, $WW^* \to e\nu\mu\nu$ and $ZZ^* \to 4\ell$ decays are exploited and combined. In the $\gamma\gamma$ channel [11], the photon production angle in the Collins-Soper centre-of-mass frame [12] is used. In the $WW^*$ channel [13, 14], the spin of the resonance and the $V-A$ decay of the weak bosons induce a correlation between the decay angles of the charged leptons: closer together for a spin-0 resonance, more apart for spin-2. In the $ZZ^*$ channel [15, 16], the final state can be fully reconstructed, thus providing several kinematic variables (angles and invariant masses) that allow to probe the polarization of both the resonance and the $Z$-bosons. In this channel all the alternative hypotheses $J^P_{\rm alt} = 0^-, 2^+, 1^\pm$ can be probed.

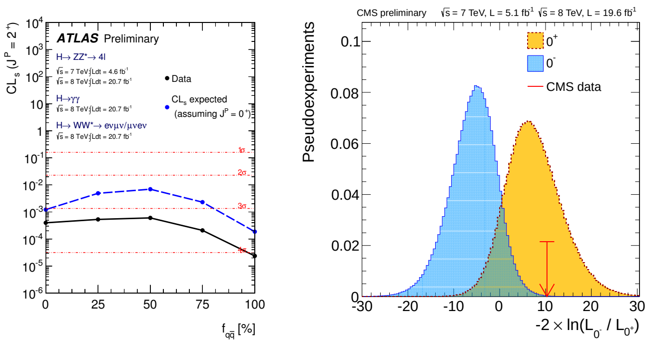


**Figure 7:** *Left*: expected (blue dashed line) and observed (black solid line) probability that observed data come from a $J^P = 2^+$ state, as a function of the fraction $f_{q\bar{q}}$ (see text) (ATLAS [17]). *Right*: distributions of the likelihood ratio for the $J^P = 0^+$ and $J^P = 0^-$ hypotheses, expected for $J^P = 0^+$ (blue/solid line distribution) and $0^-$ (red/dashed line distribution) signals. The observed value is indicated by the vertical solid line and the expected medians by the dashed lines. The coloured areas are used to compute the confidence levels for the rejection of each hypothesis (CMS [16]).

For each decay channel individually, and for each value of $f_{q\bar{q}}$, data always favour the $0^+$ hypothesis. With a statistical combination of all the channels [17], the $2^+$ state can be excluded at a confidence level (CL) higher than 99.9%, as displayed in Fig. 7 (left).

The $ZZ^* \to 4\ell$ decays are also sensitive to $0^-$ and $1^\pm$ states. The $0^-$ state is excluded at a CL higher than 99%, as displayed in Fig. 7 (right).

## 6. Conclusions

The new resonance discovered by ATLAS and CMS Collaborations has been studied in detail to see whether it is compatible to the Standard Model Higgs boson. The measurement of its mass is $m_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)$ GeV at ATLAS, and $m_H^{CMS} = 125.7 \pm 0.3(stat) \pm 0.3(syst)$ GeV, in remarkable agreement. Its spin-parity state is compatible with that of a Higgs boson: $J^P = 0^+$. An alternative hypothesis $J^P = 2^+$ is excluded with a confidence level higher than 99.9%. The $0^-$ and $1^\pm$ states are excluded at confidence levels higher than 99%.

None of the couplings measurements shows significant deviations from the Standard Model expectations. This conveys confidence that the new particle is indeed involved in symmetry breaking and mass generation. However, the statistical and systematic uncertainties are still sizable ($\sim 20\%$ in the best cases), therefore it is not possible at present to conclude whether this particle is the Higgs boson of the Standard Model, nor if new physics is present in the Higgs sector.

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