Combined measurement of the Higgs boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS experiments


DOI
10.1103/PhysRevLett.114.191803

Publication date
2015

Document Version
Final published version

Published in
Physical Review Letters

License
CC

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
Combined Measurement of the Higgs Boson Mass in \( pp \) Collisions at \( \sqrt{s} = 7 \) and 8 TeV with the ATLAS and CMS Experiments

G. Aad et al.\textsuperscript{*}

(Received 25 March 2015; published 14 May 2015)

A measurement of the Higgs boson mass is presented based on the combined data samples of the ATLAS and CMS experiments at the CERN LHC in the \( H \rightarrow \gamma \gamma \) and \( H \rightarrow ZZ \rightarrow 4\ell \) decay channels. The results are obtained from a simultaneous fit to the reconstructed invariant mass peaks in the two channels and for the two experiments. The measured masses from the individual channels and the two experiments are found to be consistent among themselves. The combined measured mass of the Higgs boson is \( m_H = 125.09 \pm 0.21 \) (stat) \( \pm 0.11 \) (syst) GeV.

DOI: 10.1103/PhysRevLett.114.191803

PACS numbers: 14.80.Bn, 13.85.Qk

The study of the mechanism of electroweak symmetry breaking is one of the principal goals of the CERN LHC program. In the standard model (SM), this symmetry breaking is achieved through the introduction of a complex doublet scalar field, leading to the prediction of the Higgs boson \( H \) [1–6], whose mass \( m_H \) is, however, not predicted by the theory. In 2012, the ATLAS and CMS Collaborations at the LHC announced the discovery of a particle with Higgs-boson-like properties and a mass of about 125 GeV [7–9]. The discovery was based primarily on mass peaks observed in the \( \gamma \gamma \) and \( ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^- \) (denoted \( H \rightarrow ZZ \rightarrow 4\ell \) for simplicity) decay channels, where one or both of the \( Z \) bosons can be off shell and where \( \ell \) and \( \ell' \) denote an electron or muon. With \( m_H \) known, all properties of the SM Higgs boson, such as its production cross section and partial decay widths, can be predicted. Increasingly precise measurements [10–13] have established that all observed properties of the new particle, including its spin, parity, and coupling strengths to SM particles are consistent within the uncertainties with those expected for the SM Higgs boson.

The ATLAS and CMS Collaborations have independently measured \( m_H \) using the samples of proton-proton collision data collected in 2011 and 2012, commonly referred to as LHC Run 1. The analyzed samples correspond to approximately 5 fb\(^{-1}\) of integrated luminosity at \( \sqrt{s} = 7 \) TeV, and 20 fb\(^{-1}\) at \( \sqrt{s} = 8 \) TeV, for each experiment. Combined results in the context of the separate experiments, as well as those in the individual channels, are presented in Refs. [12,14–16].

This Letter describes a combination of the Run 1 data from the two experiments, leading to improved precision for \( m_H \). Besides its intrinsic importance as a fundamental parameter, improved knowledge of \( m_H \) yields more precise predictions for the other Higgs boson properties. Furthermore, the combined mass measurement provides a first step towards combinations of other quantities, such as the couplings. In the SM, \( m_H \) is related to the values of the masses of the \( W \) boson and top quark through loop-induced effects. Taking into account other measured SM quantities, the comparison of the measurements of the Higgs boson, \( W \) boson, and top quark masses can be used to directly test the consistency of the SM [17] and thus to search for evidence of physics beyond the SM.

The combination is performed using only the \( H \rightarrow \gamma \gamma \) and \( H \rightarrow ZZ \rightarrow 4\ell \) decay channels, because these two channels offer the best mass resolution. Interference between the Higgs boson signal and the continuum background is expected to produce a downward shift of the signal peak relative to the true value of \( m_H \). The overall effect in the \( H \rightarrow \gamma \gamma \) channel [18–20] is expected to be a few tens of MeV for a Higgs boson with a width near the SM value, which is small compared to the current precision. The effect in the \( H \rightarrow ZZ \rightarrow 4\ell \) channel is expected to be much smaller [21]. The effects of the interference on the mass spectra are neglected in this Letter.

The ATLAS and CMS detectors [22,23] are designed to precisely reconstruct charged leptons, photons, hadronic jets, and the imbalance of momentum transverse to the direction of the beams. The two detectors are based on different technologies requiring different reconstruction and calibration methods. Consequently, they are subject to different sources of systematic uncertainty.

The \( H \rightarrow \gamma \gamma \) channel is characterized by a narrow resonant signal peak containing several hundred events per experiment above a large falling continuum background. The overall signal-to-background ratio is a few
percent. Both experiments divide the $H \to \gamma\gamma$ events into
different categories depending on the signal purity and mass
resolution, as a means to improve sensitivity. While CMS
uses the same analysis procedure for the measurement of
the Higgs boson mass and couplings [15], ATLAS implements
separate analyses for the couplings [24] and for the mass [14];
the latter analysis classifies events in a manner that reduces
the expected systematic uncertainties in $m_H$.

The $H \to ZZ \to 4\ell$ channel yields only a few tens of
signal events per experiment, but has very little back-
ground, resulting in a signal-to-background ratio larger
than 1. The events are analyzed separately depending on the
flavor of the lepton pairs. To extract $m_H$, ATLAS employs a
two-dimensional (2D) fit to the distribution of the four-lepton
mass and a kinematic discriminant introduced to reject the main background, which arises from ZZ con-
tinuum production. The CMS procedure is based on
a three-dimensional fit, utilizing the four-lepton mass dis-
bution, a kinematic discriminant, and the estimated
event-by-event uncertainty in the four-lepton mass. Both
analyses are optimized for the mass measurement and
neither attempts to distinguish between different Higgs
boson production mechanisms.

There are only minor differences in the parametrizations
used for the present combination compared to those used
for the combination of the two channels by the individual
experiments. These differences have almost no effect on the
results.

The measurement of $m_H$, along with its uncertainty, is
based on the maximization of profile-likelihood ratios $\Lambda(\alpha)$
in the asymptotic regime [25,26]:
\[
\Lambda(\alpha) = \frac{L(\alpha, \hat{\theta}(\alpha))}{L(\hat{\alpha}, \hat{\theta})},
\]
where $L$ represents the likelihood function, $\alpha$ the par-
eters of interest, and $\theta$ the nuisance parameters. There are
three types of nuisance parameters: those corresponding to
systematic uncertainties, the fitted parameters of the back-
ground models, and any unconstrained signal model
parameters not relevant to the particular hypothesis under
test. Systematic uncertainties are discussed below. The
other two types of nuisance parameters are incorporated into
the statistical uncertainty. The $\theta$ terms are profiled, i.e.,
for each possible value of a parameter of interest (e.g., $m_H$),
all nuisance parameters are refitted to maximize $L$. The $\hat{\alpha}$
and $\hat{\theta}$ terms denote the unconditional maximum likelihood
estimates of the best-fit values for the parameters, while
$\hat{\theta}(\alpha)$ is the conditional maximum likelihood estimate for
given parameter values $\alpha$.

The likelihood functions $L$ are constructed using signal
and background probability density functions (PDFs) that
depend on the discriminating variables: for the $H \to \gamma\gamma$
channel, the diphoton mass, and, for the $H \to ZZ \to 4\ell$
channel, the four-lepton mass (for CMS, also its uncer-
tainty) and the kinematic discriminant. The signal PDFs are
derived from samples of Monte Carlo (MC) simulated
events. For the $H \to ZZ \to 4\ell$ channel, the background
PDFs are determined using a combination of simulation and
data control regions. For the $H \to \gamma\gamma$ channel, the
background PDFs are obtained directly from the fit to the
data. The profile-likelihood fits to the data are performed as
a function of $m_H$ and the signal-strength scale factors
defined below. The fitting framework is implemented
independently by ATLAS and CMS, using the ROOFIT
[27], ROOSTATS [28], and HISTFACTORY [29] data modeling
and handling packages.

Despite the current agreement between the measured
Higgs boson properties and the SM predictions, it is pertinent
to perform a mass measurement that is as independent as
possible of SM assumptions. For this purpose, three signal-
strength scale factors are introduced and profiled in the fit,
thus reducing the dependence of the results on assumptions
about the Higgs boson couplings and about the variation of
the production cross section ($\sigma$) times branching fraction
(BF) with the mass. The signal strengths are defined as
\[
\mu = \left(\sigma_{\text{expt}} \times \text{BF}_{\text{expt}}\right) / \left(\sigma_{\text{SM}} \times \text{BF}_{\text{SM}}\right),
\]
representing the ratio of the cross section times branching fraction in the experi-
tement to the corresponding SM expectation for the different
production and decay modes. Two factors, $\mu^T_{ggF+iH}$ and
$\mu^T_{VBF+VH}$, are used to scale the signal strength in the $H \to \gamma\gamma$
channel. The production processes involving Higgs boson
couplings to fermions, namely gluon fusion ($ggF$) and
associated production with a top quark-antiquark pair
(tH), are scaled with the $\mu^T_{ggF+iH}$ factor. The production
processes involving couplings to vector bosons, namely
vector boson fusion (VBF) and associated production with
a vector boson (VH), are scaled with the $\mu^T_{VBF+VH}$ factor. The third factor $\mu^{4\ell}$
is used to scale the signal strength in the $H \to ZZ \to 4\ell$
channel. Only a single signal-strength parameter is used for $H \to ZZ \to 4\ell$
events because the $m_H$ measurement in this case is found to exhibit almost no
sensitivity to the different production mechanisms.

The procedure based on the two scale factors $\mu^T_{ggF+iH}$
and $\mu^T_{VBF+VH}$ for the $H \to \gamma\gamma$ channel was previously
employed by CMS [15] but not by ATLAS. Instead,
ATLAS relied on a single $H \to \gamma\gamma$ signal-strength scale
factor. The additional degree of freedom introduced by
ATLAS for the present study results in a shift of about
40 MeV in the ATLAS $H \to \gamma\gamma$ result, leading to a shift of
20 MeV in the ATLAS combined mass measurement.

The individual signal strengths $\mu^T_{ggF+iH}$, $\mu^T_{VBF+VH}$, and
$\mu^{4\ell}$ are assumed to be the same for ATLAS and CMS, and
are profiled in the combined fit for $m_H$. The corresponding
profile-likelihood ratio is
\[
\Lambda(m_H) = \frac{L(m_H, \hat{\mu}^T_{ggF+iH}(m_H), \hat{\mu}^T_{VBF+VH}(m_H), \mu^{4\ell}(m_H), \hat{\theta}(m_H))}{L(\hat{m}_H, \hat{\mu}^T_{ggF+iH}, \hat{\mu}^T_{VBF+VH}, \hat{\mu}^{4\ell}, \hat{\theta})},
\]
Slightly more complex fit models are used, as described below, to perform additional compatibility tests between the different decay channels and between the results from ATLAS and CMS.

Combining the ATLAS and CMS data for the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ channels according to the above procedure, the mass of the Higgs boson is determined to be

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

$$= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}, \quad (3)$$

where the total uncertainty is obtained from the width of a negative log-likelihood ratio scan with all parameters profiled. The statistical uncertainty is determined by fixing all nuisance parameters to their best-fit values, except for the three signal-strength scale factors and the $H \to \gamma\gamma$ background function parameters, which are profiled. The systematic uncertainty is determined by subtracting in quadrature the statistical uncertainty from the total uncertainty. Equation (3) shows that the uncertainties in the $m_H$ measurement are dominated by the statistical term, even when the Run 1 data sets of ATLAS and CMS are combined. Figure 1 shows the negative log-likelihood ratio scans as a function of $m_H$, with all nuisance parameters profiled (solid curves), and with the nuisance parameters fixed to their best-fit values (dashed curves).

The signal strengths at the measured value of $m_H$ are found to be $\mu_{\gamma\gamma}^{\text{postfit}} = 1.15^{+0.28}_{-0.25}$, $\mu_{\text{VBF}+\text{VH}}^{\text{postfit}} = 1.17^{+0.58}_{-0.53}$, and $\mu^{\text{eff}} = 1.40^{+0.30}_{-0.25}$. The combined overall signal strength $\mu$ (with $\mu_{\text{ggF}+\text{ttH}}^{\text{postfit}} = \mu_{\text{VBF}+\text{VH}}^{\text{postfit}} = \mu^{\text{eff}} \equiv \mu$) is $\mu = 1.24^{+0.18}_{-0.16}$. The results reported here for the signal strengths are not expected to have the same sensitivity, nor exactly the same values, as those that would be extracted from a combined analysis optimized for the coupling measurements.

The combined ATLAS and CMS results for $m_H$ in the separate $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ channels are

$$m_H^{\gamma\gamma} = 125.07 \pm 0.29 \text{ GeV}$$

$$= 125.07 \pm 0.25 \text{ (stat)} \pm 0.14 \text{ (syst) GeV} \quad (4)$$

and

$$m_H^{ZZ} = 125.15 \pm 0.40 \text{ GeV}$$

$$= 125.15 \pm 0.37 \text{ (stat)} \pm 0.15 \text{ (syst) GeV}. \quad (5)$$

The corresponding likelihood ratio scans are shown in Fig. 1. For the $H \to ZZ \to 4\ell$ channel, the systematic uncertainty is dominated by the absolute scale uncertainty in the momentum measurement for the muons and in the momentum and energy measurements for the electrons. Large samples (>10$^7$ events) of dilepton decays of the $J/\psi$, $\Upsilon(nS)$, and Z resonances are used by both experiments to evaluate the absolute scales and to correct for residual misalignments in the inner tracker systems [14,16]. The systematic uncertainty in the ATLAS $m_H$ result from $H \to ZZ \to 4\ell$ decays was conservatively set to 60 MeV in Ref. [14] to account for the limited numerical precision in its estimate. A more precise procedure, resulting in a reduced systematic uncertainty of 40 MeV, is used here. For CMS, conservative systematic uncertainties of 0.1% for the $H \to ZZ \to 4\mu$ and $2\mu 2\mu$ channels, and 0.3% for the $H \to ZZ \to 4e$ channel, were obtained in Ref. [16] and are used here.

A summary of the results from the individual analyses and their combination is presented in Fig. 2.

The observed uncertainties in the combined measurement can be compared with expectations. The latter are evaluated by generating two Asimov data sets [26], where an Asimov data set is a representative event sample that provides both the median expectation for an experimental result and its expected statistical variation, in the asymptotic approximation, without the need for an extensive MC-based calculation. The first Asimov data set is a “prefit” sample, generated using $m_H = 125.0 \text{ GeV}$ and the SM predictions for the couplings, with all nuisance parameters fixed to their nominal values. The second Asimov data set is a “postfit” sample, in which $m_H$, the three signal strengths $\mu_{\gamma\gamma}^{\text{postfit}}$, $\mu_{\text{VBF}+\text{VH}}^{\text{postfit}}$, and $\mu^{\text{eff}}$, and all nuisance parameters are fixed to their best-fit estimates from the data. The expected uncertainties for the combined mass are

$$\delta m_{H\text{prefit}} = \pm 0.24 \text{ GeV}$$

$$= \pm 0.22 \text{ (stat)} \pm 0.10 \text{ (syst) GeV} \quad (6)$$
for the prefit case and

$$\delta m_H^{\text{postfit}} = \pm 0.22 \text{ GeV}$$

$$= \pm 0.19 \text{ (stat)} \pm 0.10 \text{ (syst) GeV} \quad (7)$$

for the postfit case, which are both very similar to the observed uncertainties reported in Eq. (3).

Constraining all signal yields to their SM predictions results in an $m_H$ value that is about 70 MeV larger than the nominal result with a comparable uncertainty. The increase in the central value reflects the combined effect of the higher-than-expected $H \rightarrow ZZ \rightarrow 4\ell$ measured signal strength and the increase of the $H \rightarrow ZZ$ branching fraction with $m_H$. Thus, the fit assuming SM couplings forces the mass to a higher value in order to accommodate the value $\mu = 1$ expected in the SM.

Since the discovery, both experiments have improved their understanding of the electron, photon, and muon momenta ($E_T$) and its resolution: for the photons in the $H \rightarrow \gamma\gamma$ channel and for the electrons and muons in the $H \rightarrow ZZ \rightarrow 4\ell$ channel [14–16]. These uncertainties are assumed to be uncorrelated between the two experiments since they are related to the specific characteristics of the detectors as well as to the calibration procedures, which are fully independent except for negligible effects due to the use of the common Z boson mass [36] to specify the absolute energy and momentum scales. Other experimental systematic uncertainties [14–16] are similarly assumed to be uncorrelated between the two experiments. Uncertainties in the theoretical predictions and in the measured integrated luminosities are treated as fully and partially correlated, respectively.

To evaluate the relative importance of the different sources of systematic uncertainty, the nuisance parameters are grouped according to their correspondence to three broad classes of systematic uncertainty: (1) uncertainties in the energy or momentum scale and resolution for photons, electrons, and muons (“scale”), (2) theoretical uncertainties, e.g., uncertainties in the Higgs boson cross section and branching fractions, and in the normalization of SM background processes (“theory”), (3) other experimental uncertainties (“other”).

First, the total uncertainty is obtained from the full profile-likelihood scan, as explained above. Next, parameters associated with the scale terms are fixed and a new scan is performed. Then, in addition to the scale terms, the parameters associated with the theory terms are fixed and a scan performed. Finally, in addition, the other parameters are fixed and a scan performed. Thus the fits are performed iteratively, with the different classes of nuisance parameters cumulatively held fixed to their best-fit values. The uncertainties associated with the different classes of nuisance parameters are defined by the difference in quadrature.
between the uncertainties resulting from consecutive scans. The statistical uncertainty is determined from the final scan, with all nuisance parameters associated with systematic terms held fixed, as explained above. The result is

\[ m_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (scale)} \pm 0.02 \text{ (other)} \pm 0.01 \text{ (theory)} \text{ GeV}, \tag{8} \]

from which it is seen that the systematic uncertainty is indeed dominated by the energy and momentum scale terms. The result in Eq. (8) is consistent with the values of \( m_H \) derived from the less precise WW and \( \tau \tau \) Higgs boson decay modes [37–40].

The relative importance of the various sources of systematic uncertainty is further investigated by dividing the nuisance parameters into yet-finer groups, with each group associated with a specific underlying effect, and evaluating the impact of each group on the overall mass uncertainty. The matching of nuisance parameters to an effect is not strictly rigorous because nuisance parameters in the two experiments do not always represent exactly the same effect and in some cases multiple effects are related to the same nuisance parameter. Nevertheless, the relative impact of the different effects can be explored. A few experiment-specific groups of nuisance parameters are defined. For example, ATLAS includes a group of nuisance parameters to account for the inaccuracy of the background modeling for the \( H \rightarrow \gamma\gamma \) channel. To model this background, ATLAS uses specific analytic functions in each category [14] while CMS simultaneously considers different background parametrizations [35]. The systematic uncertainty in \( m_H \) related to the background modeling in CMS is estimated to be negligible [15].

The impact of groups of nuisance parameters is evaluated starting from the contribution of each individual nuisance parameter to the total uncertainty. This contribution is defined as the mass shift \( \delta m_H \) observed when reevaluating the profile-likelihood ratio after fixing the nuisance parameter in question to its best-fit value increased or decreased by 1 standard deviation (\( \sigma \)) in its distribution. For a nuisance parameter whose PDF is a Gaussian distribution, this shift corresponds to the contribution of that particular nuisance parameter to the final uncertainty. The impact of a group of nuisance parameters is estimated by summing in quadrature the contributions from the individual parameters.

The impacts \( \delta m_H \) due to each of the considered effects are listed in Table I. The results are reported for the four individual channels, both for the data and (in parentheses) the prefit Asimov data set. The row labeled “Systematic uncertainty (sum in quadrature)” shows the total sums in quadrature of the individual terms in the table. The row labeled “Systematic uncertainty (nominal)” shows the corresponding total systematic uncertainties derived using the subtraction in quadrature method discussed in connection with Eq. (3). The two methods to evaluate the total systematic uncertainty are seen to agree within 10 MeV, which is comparable with the precision of the estimates. The two rightmost columns of Table I list the contribution of each group of nuisance parameters to the uncertainties in the combined mass measurement, for ATLAS and CMS separately.

The statistical and total uncertainties are summarized in the bottom section of Table I. Since the weight of a channel in the final combination is determined by the inverse of the squared uncertainty, the approximate relative weights for the combined result are 19% (\( H \rightarrow \gamma\gamma \)) and 18% (\( H \rightarrow ZZ \rightarrow 4\ell \)) for ATLAS, and 40% (\( H \rightarrow \gamma\gamma \)) and 23% (\( H \rightarrow ZZ \rightarrow 4\ell \)) for CMS. These weights are reported in the last row of Table I, along with the expected values. Figure 3 presents the impact of each group of nuisance parameters on the total systematic uncertainty in the mass measurement of ATLAS, CMS, and the combination. For the individual ATLAS and CMS measurements, the results in Fig. 3 are approximately equivalent to the sum in quadrature of the respective \( \delta m_H \) terms in Table I multiplied by their analysis weights, after normalizing these weights to correspond to either ATLAS only or CMS only. The ATLAS and CMS combined results in Fig. 3 are the sum in quadrature of the combined results in Table I.

The results in Table I and Fig. 3 establish that the largest systematic effects for the mass uncertainty are those related to the determination of the energy scale of the photons, followed by those associated with the determination of the electron and muon momentum scales. Since the CMS \( H \rightarrow \gamma\gamma \) channel has the largest weight in the combination, its impact on the systematic uncertainty of the combined result is largest.

The mutual compatibility of the \( m_H \) results from the four individual channels is tested using a likelihood ratio with four masses in the numerator and a common mass in the denominator, and thus three degrees of freedom. The three signal strengths are profiled in both the numerator and denominator as in Eq. (1). The resulting compatibility, defined as the asymptotic \( p \) value of the fit, is 10%. Allowing the ATLAS and CMS signal strengths to vary independently yields a compatibility of 7%. This latter fit results in an \( m_H \) value that is 40 MeV larger than the nominal result.

The compatibility of the combined ATLAS and CMS mass measurement in the \( H \rightarrow \gamma\gamma \) channel with the combined measurement in the \( H \rightarrow ZZ \rightarrow 4\ell \) channel is evaluated using the variable \( \Delta m_Z \equiv m_{H^{\gamma\gamma}} - m_{H^{4\ell}} \) as the parameter of interest, with all other parameters, including \( m_H \), profiled. Similarly, the compatibility of the ATLAS combined mass measurement in the two channels with the CMS combined measurement in the two channels is evaluated using the variable \( \Delta m^{\text{ext}} = m_{H^{\gamma\gamma}}^{\text{ATLAS}} - m_{H^{4\ell}}^{\text{CMS}} \). The observed results, \( \Delta m_Z = -0.1 \pm 0.5 \text{ GeV} \) and \( \Delta m^{\text{ext}} = 0.4 \pm 0.5 \text{ GeV} \), are both consistent with zero within 1\( \sigma \). The difference between the mass values in
the two experiments is \( \Delta m^\text{exp} = 1.3 \pm 0.6 \text{ GeV (2.1σ)} \) for the \( H \to \gamma\gamma \) channel and \( \Delta m^\text{exp} = -0.9 \pm 0.7 \text{ GeV (1.3σ)} \) for the \( H \to ZZ \to 4\ell \) channel. The combined results exhibit a greater degree of compatibility than the results from the individual decay channels because the \( \Delta m^\text{exp} \) value has opposite signs in the two channels.

The compatibility of the signal strengths from ATLAS and CMS is evaluated through the ratios \( \lambda^\text{exp} = \mu^\text{ATLAS} / \mu^\text{CMS} \), \( \lambda_F^\text{exp} = \mu_{F+\tau+\tau+H}^\text{ATLAS} / \mu_{F+\tau+\tau+H}^\text{CMS} \), and \( \lambda_{\delta\ell}^\text{exp} = \mu_{\delta\ell}^\text{ATLAS} / \mu_{\delta\ell}^\text{CMS} \). For this purpose, each ratio is individually taken to be the parameter of interest, with all other nuisance parameters profiled, including the remaining two ratios for the first two tests. We find \( \lambda^\text{exp} = 1.21^{+0.30}_{-0.24} \), \( \lambda_F^\text{exp} = 1.3^{+0.8}_{-0.5} \), and \( \lambda_{\delta\ell}^\text{exp} = 1.3^{+0.5}_{-0.4} \), all of which are consistent with unity within 1σ. The ratio \( \lambda_V^\text{exp} = \mu_V^\text{ATLAS} / \mu_V^\text{CMS} \) is omitted because the ATLAS mass measurement in the \( H \to \gamma\gamma \) channel is not sensitive to \( \mu_V^\text{ATLAS} / \mu_V^\text{CMS} \).

The correlation between the signal strength and the measured mass is explored with 2D likelihood scans as functions of \( \mu \) and \( m_H \). The three signal strengths are assumed to be the same: \( \mu_{F+\tau+\tau+H} = \mu_{V+B+VH} = \mu^\text{exp} = \mu \), and thus the ratios of the production cross sections times branching fractions are constrained to the SM

\[ \lambda_i = \frac{\Delta m_i^\text{obs}}{\Delta m_i^\text{exp}} \]

The table divides the sources of systematic uncertainty into three classes, which are discussed in the text. The bottom section of the table shows the total systematic uncertainties estimated by adding the individual contributions in quadrature, the total systematic uncertainties, and the analysis weights, illustrative of the relative weight of each channel in the combined \( m_H \) measurement.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ATLAS (GeV)</th>
<th>CMS (GeV)</th>
<th>Combined (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale uncertainties:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS ECAL nonlinearity</td>
<td>0.14 (0.16)</td>
<td>0.10 (0.13)</td>
<td>0.02 (0.04)</td>
</tr>
<tr>
<td>CMS photon nonlinearity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material in front of ECAL</td>
<td>0.15 (0.13)</td>
<td>0.07 (0.07)</td>
<td>0.03 (0.03)</td>
</tr>
<tr>
<td>ECAL longitudinal response</td>
<td>0.12 (0.13)</td>
<td>0.02 (0.01)</td>
<td>0.02 (0.01)</td>
</tr>
<tr>
<td>ECAL lateral shower shape</td>
<td>0.09 (0.08)</td>
<td>0.06 (0.06)</td>
<td>0.02 (0.02)</td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>0.03 (0.01)</td>
<td>0.01 (&lt;0.01)</td>
<td>0.02 (&lt;0.01)</td>
</tr>
<tr>
<td>ATLAS ( H \to \gamma\gamma ) vertex and conversion reconstruction</td>
<td>0.05 (0.05)</td>
<td></td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>CMS electron energy scale and resolution</td>
<td>0.05 (0.04)</td>
<td>0.03 (0.02)</td>
<td>0.02 (0.02)</td>
</tr>
<tr>
<td>Muon momentum scale and resolution</td>
<td></td>
<td></td>
<td>0.03 (0.02)</td>
</tr>
<tr>
<td>Other uncertainties:</td>
<td>0.04 (0.03)</td>
<td></td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>ATLAS ( H \to \gamma\gamma ) background modeling</td>
<td>0.01 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>0.03 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>Additional experimental systematic uncertainties</td>
<td>0.01 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>Theory uncertainties:</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>Systematic uncertainty (sum in quadrature)</td>
<td>0.27 (0.27)</td>
<td>0.04 (0.04)</td>
<td>0.15 (0.17)</td>
</tr>
<tr>
<td>Systematic uncertainty (nominal)</td>
<td>0.27 (0.27)</td>
<td>0.04 (0.05)</td>
<td>0.15 (0.17)</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.43 (0.45)</td>
<td>0.52 (0.66)</td>
<td>0.31 (0.32)</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.51 (0.52)</td>
<td>0.52 (0.66)</td>
<td>0.34 (0.36)</td>
</tr>
<tr>
<td>Analysis weights</td>
<td>19% (22%)</td>
<td>18% (14%)</td>
<td>40% (46%)</td>
</tr>
</tbody>
</table>

TABLE I. Systematic uncertainties \( \delta m_H \) (see text) associated with the indicated effects for each of the four input channels, and the corresponding contributions of ATLAS and CMS to the systematic uncertainties of the combined result. “ECAL” refers to the electromagnetic calorimeters. The numbers in parentheses indicate expected values obtained from the prefit Asimov data set discussed in the text. The uncertainties for the combined result are related to the values of the individual channels through the relative weight of the individual channel in the combination, which is proportional to the inverse of the respective uncertainty squared. The top section of the table shows the total systematic uncertainties estimated by adding the individual contributions in quadrature, the total systematic uncertainties, and the analysis weights, illustrative of the relative weight of each channel in the combined \( m_H \) measurement.
predictions. Assuming that the negative log-likelihood ratio
\(-2 \ln \Lambda(\mu, m_H)\) is distributed as a \(\chi^2\) variable with two
degrees of freedom, the 68% confidence level (C.L.)
confidence regions are shown in Fig. 4 for each individual
measurement, as well as for the combined result.

In summary, a combined measurement of the Higgs
boson mass is performed in the \(H \to \gamma\gamma\) and \(H \to ZZ \to 4l\)
channels using the LHC Run 1 data sets of the ATLAS
and CMS experiments, with minimal reliance on the
assumption that the Higgs boson behaves as predicted
by the SM.

The result is
\[
m_H = 125.09 \pm 0.24 \text{ GeV}
\]
\[
= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV},
\]
where the total uncertainty is dominated by the statistical
term, with the systematic uncertainty dominated by effects
related to the photon, electron, and muon energy or
momentum scales and resolutions. Compatibility tests are
performed to ascertain whether the measurements are
consistent with each other, both between the different decay
channels and between the two experiments. All tests on
the combined results indicate consistency of the different
measurements within 1\(\sigma\), while the four Higgs boson mass
measurements in the two channels of the two experiments
agree within 2\(\sigma\). The combined measurement of the Higgs
boson mass improves upon the results from the individual
experiments and is the most precise measurement to date of
this fundamental parameter of the newly discovered particle.

We thank CERN for the very successful operation of the
LHC, as well as the support staff from our institutions
without whom ATLAS and CMS could not be operated
efficiently. We acknowledge the support of ANPCyT
(Argentina); YerPhI (Armenia); ARC (Australia);
BMWFV and FWF (Austria); ANAS (Azerbaijan);
SSTC (Belarus); FNRS and FWO (Belgium); CNPq,
CAPES, FAPERJ, and FAPESP (Brazil); MES

![FIG. 3](color online). The impacts \(\delta m_H\) (see text) of the nuisance parameter groups in Table I on the ATLAS (left), CMS (center), and combined (right) mass measurement uncertainty. The observed (expected) results are shown by the solid (empty) bars.

![FIG. 4](color online). Summary of likelihood scans in the 2D plane of signal strength \(\mu\) versus Higgs boson mass \(m_H\) for the ATLAS and CMS experiments. The 68% C.L. confidence regions of the individual measurements are shown by the dashed curves and of the overall combination by the solid curve. The markers indicate the respective best-fit values. The SM signal strength is indicated by the horizontal line at \(\mu = 1\).
and MIZ, MSTD and MESTD (Serbia); MSSR (Slovakia); ARRS
MON, RosAtom, RAS, and RFBR (Russian Federation);
CONACYT, SEP, and UASLP-FAI (Mexico); CNRST,
JINR; MSIP, and NRF (Republic of Korea); LAS
(Ireland); ISF, MINERV A, GIF, I-CORE, and Benoziyo
NSRF (Greece); RGC (Hong Kong SAR, China); OTKA
HGF, MPG, and AvH Foundation (Germany); GSRT and
CNRS/IN2P3 (France); GNSF (Georgia); BMBF, DFG,
Academy of Finland, MEC, and HIP (Finland); CEA,
EPLANET, ERC, and NSRF (European Union);
RPF (Cyprus); MSMT CR, MPO CR, and VSC CR (Czech
COLCIENCIAS (Colombia); MSES and CSF (Croatia);
CONICYT (Chile); CAS, MoST, and NSFC (China);
ARRS, SNSF, UniZH, and Cantons of Bern, Genève, and
SEIDI, and CPAN (Spain); SRC and Wallenberg
TUBITAK and TAEK (Turkey); NASU and SFFR
ThEPCenter, IPST, STAR, and NSTDA (Thailand);
Zurich (Switzerland); NSC (Taipei); MST (Taiwan);
SER, SNSF, UniZH, and Cantons of Bern, Genève, and
Leaverhulme Trust (U.K.); DOE and NSF (U.S.). In addition,
we gratefully acknowledge the crucial computing support from
all WLCG partners, in particular from CERN and the Tier-1 and
Tier-2 facilities worldwide.

[1] F. Englert and R. Brout, Broken Symmetry and the Mass of
[2] P. W. Higgs, Broken symmetries, massless particles and
13, 585 (1964).
[7] ATLAS Collaboration, Observation of a new particle in the
search for the Standard Model Higgs boson with the ATLAS
[8] CMS Collaboration, Observation of a new boson at a mass
of 125 GeV with the CMS experiment at the LHC, Phys.
[9] CMS Collaboration, Observation of a new boson with mass
near 125 GeV in pp collisions at √s = 7 and 8 TeV, J. High
production and couplings in diboson final states with the
Higgs boson using ATLAS data, Phys. Lett. B 726, 120
(2013).
[12] CMS Collaboration, Precise determination of the mass of the
Higgs boson and tests of compatibility of its couplings with the
standard model predictions using proton collisions at 7 and 8 TeV,
[13] CMS Collaboration, Constraints on the spin-parity and
anomalous HVV couplings of the Higgs boson in proton
(to be published)].
mass from the H → γγ and H → ZZ → 4ℓ channels in pp
collisions at center-of-mass energies of 7 and 8 TeV with the
[15] CMS Collaboration, Observation of the diphoton decay of the
125 GeV Higgs boson and measurement of its properties,
[16] CMS Collaboration, Measurement of the properties of a
Higgs boson in the four-lepton final state, Phys. Rev. D 89,
092007 (2014).
[17] M. Baak et al. (Gfitter Group), The global electroweak fit at
NNLO and prospects for the LHC and ILC, Eur. Phys. J. C
74, 3046 (2014).
[18] L. J. Dixon and M. S. Siu, Resonance-Continuum Interfer-
tence in the Diphoton Higgs Signal at the LHC, Phys. Rev.
Lett. 90, 252001 (2003).
from interference with background, Phys. Rev. D 86,
073016 (2012).
[20] L. J. Dixon and Y. Li, Bounding the Higgs Boson Width
anomalous HVV couplings of the Higgs boson in proton
(to be published)].
[22] ATLAS Collaboration, The ATLAS experiment at the
CERN Large Hadron Collider, J. Instrum. 3, S08003
(2008).
[23] CMS Collaboration, The CMS experiment at the CERN
production in the diphoton decay channel in pp collisions at
center-of-mass energies of 7 and 8 TeV with the ATLAS
Rep. CMS NOTE 2011/005, ATL-PHYS-PUB 2011-11,
[26] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymp-
totic formulae for likelihood-based tests of new physics,
[27] W. Verkerke and D. P. Kirkby, The rootft toolkit for
data modeling, in Proceedings of the 13th International


[34] CMS Collaboration, Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, arXiv:1502.02702.


Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco

Centre National de l’Énergie des Sciences Techniques Nucleaires, Rabat, Morocco

Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco

Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco

Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco

DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Énergies Alternatives), Gif-sur-Yvette, France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA

Department of Physics, University of Washington, Seattle, Washington, USA

Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Department of Physics, Shinshu University, Nagano, Japan

Fachbereich Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada

SLAC National Accelerator Laboratory, Stanford, California, USA

Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic

Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

Department of Physics, University of Cape Town, Cape Town, South Africa

Department of Physics, University of Johannesburg, Johannesburg, South Africa

School of Physics, University of the Witwatersrand, Johannesburg, South Africa

Department of Physics, Stockholm University, Sweden

The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Department of Physics, University of Toronto, Toronto, Ontario, Canada

TRIUMF, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy

ICTP, Trieste, Italy

Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

Department of Physics, University of Illinois, Urbana, Illinois, USA

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, Connecticut, USA

Yerevan Physics Institute, Yerevan, Armenia

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

Yerevan Physics Institute, Yerevan, Armenia

Institut für Hochenergiephysik der ÖeAW, Wien, Austria
Deceased.
Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at TRIUMF, Vancouver, BC, Canada.
Also at Department of Physics, California State University, Fresno, CA, USA.
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
Also at Departamento de Física e Astronomía, Faculdade de Ciencias, Universidade do Porto, Portugal.
Also at Tomsk State University, Tomsk, Russia.
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
Also at Università di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Louisiana Tech University, Ruston, LA, USA.
Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, National Tsing Hua University, Taiwan.
Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
Also at CERN, Geneva, Switzerland.
Also at Georgian Technical University (GTU), Tbilisi, Georgia.
Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
Also at Manhattan College, New York, NY, USA.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at School of Physics, Shandong University, Shandong, China.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at International School for Advanced Studies (SISSA), Trieste, Italy.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
Also at National Research Nuclear University MEPhI, Moscow, Russia.
Also at Department of Physics, Stanford University, Stanford, CA, USA.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
Also at Vienna University of Technology, Vienna, Austria.
Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
Also at Universidade Estadual de Campinas, Campinas, Brazil.
Also at Centre National de la Recherche Scientifique (CNRS)–IN2P3, Paris, France.
Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
Also at Joint Institute for Nuclear Research, Dubna, Russia.
Also at Ain Shams University, Cairo, Egypt.