Combined Measurement of the Higgs Boson Mass in $pp$ Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments

The ATLAS and CMS Collaborations

Abstract

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.

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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 $H$, 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 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 $5 \text{ fb}^{-1}$ of integrated luminosity at $\sqrt{s} = 7$ TeV, and $20 \text{ fb}^{-1}$ 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 $H \rightarrow \gamma\gamma$ 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 background, 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 \(ZZ\) continuum production. The CMS procedure is based on a three-dimensional fit, utilizing the four-lepton mass distribution, 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 parameterizations 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 parameters of interest, and \(\theta\) the nuisance parameters. There are three types of nuisance parameters: those corresponding to systematic uncertainties, the fitted parameters of the background 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 uncertainty) 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 times branching fraction with the mass. The signal strengths are defined as \(\mu = (\sigma_{\text{expt}} \times \text{BF}_{\text{expt}})/(\sigma_{\text{SM}} \times \text{BF}_{\text{SM}})\), representing the ratio of the cross section times branching fraction in the experiment to the correspond-
ing SM expectation for the different production and decay modes. Two factors, $\mu_{g\gamma}^{\gamma\gamma}$ and $\mu_{VBF+VH}^{\gamma\gamma}$, are used to scale the signal strength in the $H \rightarrow \gamma\gamma$ channel. The production processes involving Higgs boson couplings to fermions, namely gluon fusion (ggF) and associated production with a top quark-antiquark pair (t(tH)), are scaled with the $\mu_{g\gamma}^{\gamma\gamma}$ 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 $\mu_{VBF+VH}^{\gamma\gamma}$ factor. The third factor, $\mu_{4\ell}^{\gamma\gamma}$, is used to scale the signal strength in the $H \rightarrow ZZ \rightarrow 4\ell$ channel. Only a single signal-strength parameter is used for $H \rightarrow ZZ \rightarrow 4\ell$ 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 $\mu_{g\gamma}^{\gamma\gamma}$ and $\mu_{VBF+VH}^{\gamma\gamma}$ for the $H \rightarrow \gamma\gamma$ channel was previously employed by CMS [15] but not by ATLAS. Instead, ATLAS relied on a single $H \rightarrow \gamma\gamma$ 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 $H \rightarrow \gamma\gamma$ result, leading to a shift of 20 MeV in the ATLAS combined mass measurement.

The individual signal strengths $\mu_{g\gamma}^{\gamma\gamma}$, $\mu_{VBF+VH}^{\gamma\gamma}$, and $\mu_{4\ell}^{\gamma\gamma}$ 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

$$\Lambda(m_H) = \frac{L(m_H, \hat{\mu}_{g\gamma}^{\gamma\gamma}(m_H), \hat{\mu}_{VBF+VH}^{\gamma\gamma}(m_H), \hat{\mu}_{4\ell}^{\gamma\gamma}(m_H), \hat{\theta}(m_H))}{L(\hat{m}_H, \hat{\mu}_{g\gamma}^{\gamma\gamma}, \hat{\mu}_{VBF+VH}^{\gamma\gamma}, \hat{\mu}_{4\ell}^{\gamma\gamma}, \hat{\theta})}.$$  (2)

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 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ channels according to the above procedure, the mass of the Higgs boson is determined to be

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.)} \text{ GeV},$$  (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 $H \rightarrow \gamma\gamma$ 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 $\mu_{g\gamma}^{\gamma\gamma} = 1.15^{+0.28}_{-0.25}$, $\mu_{VBF+VH}^{\gamma\gamma} = 1.17^{+0.58}_{-0.54}$, and $\mu_{4\ell}^{\gamma\gamma} = 1.40^{+0.30}_{-0.25}$. The combined overall signal strength $\mu$ (with $\mu_{g\gamma}^{\gamma\gamma} = \mu_{VBF+VH}^{\gamma\gamma} = \mu_{4\ell}^{\gamma\gamma} = \mu$) 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 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ channels are

$$m_H^{\gamma\gamma} = 125.07 \pm 0.29 \text{ GeV}$$
$$= 125.07 \pm 0.25 \text{ (stat.)} \pm 0.14 \text{ (syst.)} \text{ GeV}$$  (4)
Figure 1: Scans of twice the negative log-likelihood ratio \(-2 \ln \Lambda (m_H)\) as functions of the Higgs boson mass \(m_H\) for the ATLAS and CMS combination of the \(H \rightarrow \gamma \gamma\) (red), \(H \rightarrow ZZ \rightarrow 4\ell\) (blue), and combined (black) channels. The dashed curves show the results accounting for statistical uncertainties only, with all nuisance parameters associated with systematic uncertainties fixed to their best-fit values. The 1 and 2 standard deviation limits are indicated by the intersections of the horizontal lines at 1 and 4, respectively, with the log-likelihood scan curves.

and

\[
m_h^{\text{Prefit}} = 125.15 \pm 0.40 \text{ GeV} = 125.15 \pm 0.37 \text{ (stat.) } \pm 0.15 \text{ (syst.)} \text{ GeV.} \tag{5}
\]

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 \(m_H = 125.0\) 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 \(\mu_{\gamma\gamma}^{\text{VBF}}, \mu_{\gamma\gamma}^{\text{VH}}, \mu_{4\ell}^{\text{Syst.}}\), and all nuisance parameters are fixed to their best-fit estimates from the data. The expected uncertainties for the combined mass are

\[
\delta m_{H\text{Prefit}} = \pm 0.24 \text{ GeV} = \pm 0.22 \text{ (stat.) } \pm 0.10 \text{ (syst.)} \text{ GeV} \tag{6}
\]
Figure 2: Summary of Higgs boson mass measurements from the individual analyses of ATLAS and CMS and from the combined analysis presented here. The systematic (narrower, magenta-shaded bands), statistical (wider, yellow-shaded bands), and total (black error bars) uncertainties are indicated. The (red) vertical line and corresponding (gray) shaded column indicate the central value and the total uncertainty of the combined measurement, respectively.

for the prefit case and

$$\delta m_{H^{\text{postfit}}} = \pm 0.22 \text{ GeV} = \pm 0.19 \text{ (stat.)} \pm 0.10 \text{ (syst.) GeV}$$

(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 $H \to ZZ \to 4\ell$ measured signal strength and the increase of the $H \to ZZ$ 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 measurements [16, 30–34], leading to a significant reduction of the systematic uncertainties in the mass measurement. Nevertheless, the treatment and understanding of systematic uncertainties is an important aspect of the individual measurements and their combination. The combined analysis incorporates approximately 300 nuisance parameters. Among these, approximately 100 are fitted parameters describing the shapes and normalizations of the background models in the $H \to \gamma\gamma$ channel, including a number of discrete parameters that allow the functional form in each of the CMS $H \to \gamma\gamma$ analysis categories to be changed [35]. Of the remaining almost 200 nuisance parameters, most correspond to experimental or theoretical systematic uncertainties.

Based on the results from the individual experiments, the dominant systematic uncertainties for the combined $m_H$ result are expected to be those associated with the energy or momentum scale and its resolution: for the photons in the $H \to \gamma\gamma$ channel and for the electrons and muons in the $H \to ZZ \to 4\ell$ 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
Table 1: 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 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 evaluated using the nominal method discussed in the text, the statistical uncertainties, the total uncertainties, and the analysis weights, illustrative of the relative weight of each channel in the combined $m_H$ measurement.

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>ATLAS [GeV]: observed (expected)</th>
<th>CMS [GeV]: observed (expected)</th>
<th>Combined Result [GeV]: observed (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>0.14 (0.16)</td>
<td>0.10 (0.13)</td>
<td>0.02 (0.04)</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4\ell$</td>
<td>0.15 (0.13)</td>
<td>0.07 (0.07)</td>
<td>0.03 (0.03)</td>
</tr>
<tr>
<td>Material in front of ECAL</td>
<td>0.12 (0.13)</td>
<td>0.02 (0.01)</td>
<td>0.02 (0.03)</td>
</tr>
<tr>
<td>ECAL longitudinal response</td>
<td>0.09 (0.08)</td>
<td>0.06 (0.06)</td>
<td>0.02 (0.02)</td>
</tr>
<tr>
<td>ECAL lateral shower shape</td>
<td>0.05 (0.05)</td>
<td>0.01 (0.01)</td>
<td>0.02 (0.01)</td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>0.05 (0.01)</td>
<td>0.01 (0.01)</td>
<td>0.02 (0.01)</td>
</tr>
<tr>
<td>ATLAS $H \rightarrow \gamma\gamma$ vertex &amp; conversion reconstruction</td>
<td>0.05 (0.04)</td>
<td>0.03 (0.02)</td>
<td>0.02 (0.01)</td>
</tr>
<tr>
<td>CMS Z → ee calibration</td>
<td>0.05 (0.05)</td>
<td>0.12 (0.09)</td>
<td>0.03 (0.02)</td>
</tr>
<tr>
<td>CMS electron energy scale &amp; resolution</td>
<td>0.03 (0.04)</td>
<td>0.11 (0.10)</td>
<td>0.05 (0.02)</td>
</tr>
<tr>
<td>Muon momentum scale &amp; resolution</td>
<td>0.05 (0.03)</td>
<td>0.01 (0.01)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>ATLAS $H \rightarrow ZZ \rightarrow 4\ell$ background modeling</td>
<td>0.04 (0.03)</td>
<td>0.01 (0.01)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>0.03 (0.01)</td>
<td>0.01 (0.01)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>Additional experimental systematic uncertainties</td>
<td>0.02 (0.01)</td>
<td>0.01 (0.01)</td>
<td>0.01 (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>&lt;0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>Systematic uncertainty (sum in quadrature)</td>
<td>0.27 (0.27)</td>
<td>0.15 (0.17)</td>
<td>0.16 (0.15)</td>
</tr>
<tr>
<td>Systematic uncertainty (nominal)</td>
<td>0.27 (0.27)</td>
<td>0.15 (0.17)</td>
<td>0.17 (0.14)</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.43 (0.45)</td>
<td>0.31 (0.32)</td>
<td>0.42 (0.57)</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.51 (0.52)</td>
<td>0.34 (0.36)</td>
<td>0.45 (0.59)</td>
</tr>
<tr>
<td>Analysis weights</td>
<td>19% (22%)</td>
<td>18% (14%)</td>
<td>40% (46%)</td>
</tr>
</tbody>
</table>

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:

- uncertainties in the energy or momentum scale and resolution for photons, electrons, and muons (“scale”),
- theoretical uncertainties, e.g., uncertainties in the Higgs boson cross section and branching fractions, and in the normalization of SM background processes (“theory”),
- 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

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

from which it is seen that the systematic uncertainty is indeed dominated by the energy and momentum scale terms.

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 \( H \to \gamma\gamma \) channel. To model this background, ATLAS uses specific analytic functions in each category \[14\] while CMS simultaneously considers different background parameterizations \[35\]. 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 re-evaluating 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 1. 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 1 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 1. 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\% (\( H \to \gamma\gamma \)) and 18\% (\( H \to ZZ \to 4\ell \)) for ATLAS, and 40\% (\( H \to \gamma\gamma \)) and 23\% (\( H \to ZZ \to 4\ell \)) for CMS. These weights are reported in the last row of Table 1 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 1 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 1.

The results in Table 1 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.

Figure 3: The impacts $\delta m_H$ (see text) of the nuisance parameter groups in Table 1 on the ATLAS (left), CMS (center), and combined (right) mass measurement uncertainty. The observed (expected) results are shown by the solid (empty) bars.

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 $\Delta m_{\gamma\gamma} \equiv m_{\gamma\gamma}^H - m_{\gamma\gamma}^H$ as the parameter of interest, with all other parameters, includ-
ing $m_H$, 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 $\Delta m^\text{expt} = m_H^\text{ATLAS} - m_H^\text{CMS}$. The observed results, $\Delta m_{\gamma Z} = -0.1 \pm 0.5$ GeV and $\Delta m^\text{expt} = 0.4 \pm 0.5$ GeV, are both consistent with zero within 1$\sigma$. The difference between the mass values in the two experiments is $\Delta m^\text{expt} = 1.3 \pm 0.6$ GeV (2.1$\sigma$) for the $H \to \gamma\gamma$ channel and $\Delta m^\text{expt} = -0.9 \pm 0.7$ GeV (1.3$\sigma$) 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 $\Delta m^\text{expt}$ value has opposite signs in the two channels.

The compatibility of the signal strengths from ATLAS and CMS is evaluated through the ratios $\lambda_f^\text{expt} = \mu_\gamma^\text{ATLAS} / \mu_\gamma^\text{CMS}$, $\lambda_F^\text{expt} = \mu_\gamma^\text{ATLAS} / \mu_\gamma^\text{CMS}$, and $\lambda_{4\ell}^\text{expt} = \mu_{4\ell}^\text{ATLAS} / \mu_{4\ell}^\text{CMS}$. 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 $\lambda_f^\text{expt} = 1.21^{+0.30}_{-0.24}$, $\lambda_F^\text{expt} = 1.3^{+0.8}_{-0.5}$, and $\lambda_{4\ell}^\text{expt} = 1.3^{+0.5}_{-0.4}$, all of which are consistent with unity within 1$\sigma$. The ratio $\lambda_V^\text{expt} = \mu_\gamma^\text{VBF+VH} / \mu_\gamma^\text{CMS}$ is omitted because the ATLAS mass measurement in the $H \to \gamma\gamma$ channel is not sensitive to $\mu_\gamma^\text{VBF+VH}$.

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: $\mu_\gamma^\text{ATLAS} = \mu_\gamma^\text{CMS}$, $\mu_\gamma^\text{VBF+VH}$, and $\mu_{4\ell}$, and thus the ratios of the production cross sections times branching fractions are constrained to the SM 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 (CL) 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 $H \to ZZ \to 4\ell$ 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

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

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.

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Figure 4: 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% CL 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.

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A The ATLAS Collaboration

The ATLAS Collaboration

4 (a) Department of Physics, Ankara University, Ankara; (c) Istanbul Aydin University, Istanbul;
(b) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics
and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
Tre, Roma, Italy

135 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Énergie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier et LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco

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

137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

138 Department of Physics, University of Washington, Seattle WA, United States of America

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

140 Department of Physics, Shinshu University, Nagano, Japan

141 Fachbereich Physik, Universität Siegen, Siegen, Germany

142 Department of Physics, Simon Fraser University, Burnaby BC, Canada

143 SLAC National Accelerator Laboratory, Stanford CA, United States of America

144 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

145 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

147 Physics Department, Royal Institute of Technology, Stockholm, Sweden

148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

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

150 School of Physics, University of Sydney, Sydney, Australia

151 Institute of Physics, Academia Sinica, Taipei, Taiwan

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

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

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

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

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

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

158 Department of Physics, University of Toronto, Toronto ON, Canada

159 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada

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

161 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

164 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
A The ATLAS Collaboration

Department of Physics, University of Illinois, Urbana IL, United States of America
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 BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, 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 WI, United States of America
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 CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

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, United States of America
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
Also at Departamento de Fisica e Astronomia, 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, United States of America
Also at Institucio 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, United States of America
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, United States of America
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, United States of America
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, United States of America
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, United States of America
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
* Deceased
B The CMS Collaboration

1 Yerevan Physics Institute, Yerevan, Armenia
2 Institut für Hochenergiephysik der OeAW, Wien, Austria
3 National Centre for Particle and High Energy Physics, Minsk, Belarus
4 Universiteit Antwerpen, Antwerpen, Belgium
5 Vrije Universiteit Brussel, Brussel, Belgium
6 Université Libre de Bruxelles, Bruxelles, Belgium
7 Ghent University, Ghent, Belgium
8 Université Catholique de Louvain, Louvain-la-Neuve, Belgium
9 Université de Mons, Mons, Belgium
10 Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
11 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
12 Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
13 Universidade Estadual Paulista
14 Universidade Federal do ABC
15 Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
16 University of Sofia, Sofia, Bulgaria
17 Institute of High Energy Physics, Beijing, China
18 State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
19 Universidad de los Andes, Bogota, Colombia
20 University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
21 University of Split, Faculty of Science, Split, Croatia
22 Institute Rudjer Boskovic, Zagreb, Croatia
23 University of Cyprus, Nicosia, Cyprus
24 Charles University, Prague, Czech Republic
25 Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
26 National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
27 Department of Physics, University of Helsinki, Helsinki, Finland
28 Helsinki Institute of Physics, Helsinki, Finland
29 Lappeenranta University of Technology, Lappeenranta, Finland
30 DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
31 Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
32 Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
33 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
34 Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
35 Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
36 RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
37 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
38 RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
39 Deutsches Elektronen-Synchrotron, Hamburg, Germany
40 University of Hamburg, Hamburg, Germany
41 University of Hamburg, Hamburg, Germany
42 RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
43 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
44 Deutsches Elektronen-Synchrotron, Hamburg, Germany
45 University of Hamburg, Hamburg, Germany
46 Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
47 Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
41 University of Athens, Athens, Greece
42 University of Ioánnina, Ioánnina, Greece
43 Wigner Research Centre for Physics, Budapest, Hungary
44 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
45 University of Debrecen, Debrecen, Hungary
46 National Institute of Science Education and Research, Bhubaneswar, India
47 Panjab University, Chandigarh, India
48 University of Delhi, Delhi, India
49 Saha Institute of Nuclear Physics, Kolkata, India
50 Bhabha Atomic Research Centre, Mumbai, India
51 Tata Institute of Fundamental Research, Mumbai, India
52 Indian Institute of Science Education and Research (IISER), Pune, India
53 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
54 University College Dublin, Dublin, Ireland
55 INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
55a INFN Sezione di Bari
55b Università di Bari
55c Politecnico di Bari
56 INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
56a INFN Sezione di Bologna
56b Università di Bologna
57 INFN Sezione di Catania, Università di Catania, CSFNSM, Catania, Italy
57a INFN Sezione di Catania
57b Università di Catania
57c CSFNSM
58 INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
58a INFN Sezione di Firenze
58b Università di Firenze
59 INFN Laboratori Nazionali di Frascati, Frascati, Italy
60 INFN Sezione di Genova, Università di Genova, Genova, Italy
60a INFN Sezione di Genova
60b Università di Genova
61 INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
61a INFN Sezione di Milano-Bicocca
61b Università di Milano-Bicocca
62 INFN Sezione di Napoli, Università di Napoli ‘Federico II’, Napoli, Italy, Università della Basilicata, Potenza, Italy, Università G. Marconi, Roma, Italy
62a INFN Sezione di Napoli
62b Università di Napoli ‘Federico II’
62c Università della Basilicata
62d Università G. Marconi
63 INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy
63a INFN Sezione di Padova
63b Università di Padova
63c Università di Trento
64 INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
64a INFN Sezione di Pavia
64b Università di Pavia
INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
INFN Sezione di Roma, Università di Roma, Roma, Italy
INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy
INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
Infrastrutture Istituzionali, Università di Firenze, Firenze, Italy
Kangwon National University, Chunchon, Korea
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

Vilnius University, Vilnius, Lithuania
National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
University of Auckland, Auckland, New Zealand
University of Canterbury, Christchurch, New Zealand
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
National Centre for Nuclear Research, Swierk, Poland
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
Joint Institute for Nuclear Research, Dubna, Russia
Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Institute for Nuclear Research, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
P.N. Lebedev Physical Institute, Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade,
Serbia

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

Universidad Autónoma de Madrid, Madrid, Spain

Universidad de Oviedo, Oviedo, Spain

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

CERN, European Organization for Nuclear Research, Geneva, Switzerland

Paul Scherrer Institut, Villigen, Switzerland

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

Universität Zürich, Zurich, Switzerland

National Central University, Chung-Li, Taiwan

National Taiwan University (NTU), Taipei, Taiwan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

Cukurova University, Adana, Turkey

Middle East Technical University, Physics Department, Ankara, Turkey

Bogazici University, Istanbul, Turkey

Istanbul Technical University, Istanbul, Turkey

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

Brunel University, Uxbridge, United Kingdom

Baylor University, Waco, USA

The University of Alabama, Tuscaloosa, USA

Boston University, Boston, USA

Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA

University of California, Santa Barbara, Santa Barbara, USA

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA

University of Colorado at Boulder, Boulder, USA

Cornell University, Ithaca, USA

Fermi National Accelerator Laboratory, Batavia, USA

University of Florida, Gainesville, USA

Florida International University, Miami, USA

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA

University of Illinois at Chicago (UIC), Chicago, USA

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA

Lawrence Livermore National Laboratory, Livermore, USA

University of Maryland, College Park, USA
Massachusetts Institute of Technology, Cambridge, USA
University of Minnesota, Minneapolis, USA
University of Mississippi, Oxford, USA
University of Nebraska-Lincoln, Lincoln, USA
State University of New York at Buffalo, Buffalo, USA
Northeastern University, Boston, USA
Northwestern University, Evanston, USA
University of Notre Dame, Notre Dame, USA
The Ohio State University, Columbus, USA
Princeton University, Princeton, USA
Purdue University, West Lafayette, USA
Purdue University Calumet, Hammond, USA
Rice University, Houston, USA
University of Rochester, Rochester, USA
The Rockefeller University, New York, USA
Rutgers, The State University of New Jersey, Piscataway, USA
University of Tennessee, Knoxville, USA
Texas A&M University, College Station, USA
Texas Tech University, Lubbock, USA
Vanderbilt University, Nashville, USA
University of Virginia, Charlottesville, USA
Wayne State University, Detroit, USA
University of Wisconsin, Madison, USA

a Deceased
b Also at Vienna University of Technology, Vienna, Austria
c Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
d Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
e Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
f Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
g Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
h Also at Universidade Estadual de Campinas, Campinas, Brazil
i Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
j Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
k Also at Joint Institute for Nuclear Research, Dubna, Russia
m Now at British University in Egypt, Cairo, Egypt
n Now at Helwan University, Cairo, Egypt
o Also at Suez University, Suez, Egypt
p Also at Cairo University, Cairo, Egypt
q Now at Fayoum University, El-Fayoum, Egypt
s Now at Ain Shams University, Cairo, Egypt
u Also at Université de Haute Alsace, Mulhouse, France
v Also at Brandenburg University of Technology, Cottbus, Germany
w Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
x Also at Eötvös Loránd University, Budapest, Hungary
y Also at University of Debrecen, Debrecen, Hungary
z Also at Wigner Research Centre for Physics, Budapest, Hungary
aa Also at University of Visva-Bharati, Santiniketan, India