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


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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.*

(AATLAS Collaboration)†

(CMS Collaboration)‡

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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 $H$ [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 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 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]:

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\theta}(\alpha))}{L(\hat{\alpha}, \theta)}$$

(1)

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 refit 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 ($\sigma$) times branching fraction (BF) 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 corresponding SM expectation for the different production and decay modes. Two factors, $\mu_{\gamma\gamma}^{\text{ggF}+iH}$ and $\mu_{\text{VBF}+VH}^{\text{ggF}}$, 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 ($g g F$) and associated production with a top quark-antiquark pair ($t \bar{t} H$), are scaled with the $\mu_{\gamma\gamma}^{\text{ggF}+iH}$ factor. The production processes involving couplings to vector bosons, namely vector boson fusion (VBF) and associated production with a vector boson ($V H$), are scaled with the $\mu_{\text{VBF}+VH}^{\text{ggF}}$ factor. The production process based on the two scale factors $\mu_{\gamma\gamma}^{\text{ggF}+iH}$ and $\mu_{\text{VBF}+VH}^{\text{ggF}}$ 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 $\mu_{\gamma\gamma}^{\text{ggF}+iH}^{\text{ggF}}, \mu_{\text{VBF}+VH}^{\text{ggF}}$, and $\mu_{\text{VBF}+VH}^{\text{VBF}}$ 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

$$\Lambda(m_H) = \frac{L(m_H, \mu_{\gamma\gamma}^{\text{ggF}+iH}^{\text{ggF}}, \mu_{\text{VBF}+VH}^{\text{ggF}}, \mu_{\text{VBF}+VH}^{\text{VBF}})}{L(m_H, \hat{\mu}_{\gamma\gamma}^{\text{ggF}+iH}^{\text{ggF}}, \hat{\mu}_{\text{VBF}+VH}^{\text{ggF}}, \hat{\mu}_{\text{VBF}+VH}^{\text{VBF}}, \hat{\theta}(m_H))}$$

(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

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

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

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 $\mu_{\text{ggF}+tH}^{\gamma\gamma} = 1.15^{+0.28}_{-0.25}$, $\mu_{\text{VBF}+VH}^{\gamma\gamma} = 1.17^{+0.58}_{-0.53}$, and $\mu^{4\ell} = 1.40^{+0.30}_{-0.25}$. The combined overall signal strength $\mu$ (with $\mu_{\text{ggF}+tH}^{\gamma\gamma} = \mu_{\text{VBF}+VH}^{\gamma\gamma} = \mu^{4\ell} \equiv \mu$) 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 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ channels are

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

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

and

$$m_H^{4\ell} = 125.15 \pm 0.40 \text{ GeV}$$

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

The corresponding likelihood ratio scans are shown in Fig. 1. For the $H \rightarrow ZZ \rightarrow 4\ell$ 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 $H \rightarrow ZZ \rightarrow 4\ell$ 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 $H \rightarrow ZZ \rightarrow 4\mu$ and $2\mu2\ell$ channels, and 0.3% for the $H \rightarrow ZZ \rightarrow 4\ell$ 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 $\mu_{\text{ggF}+tH}^{\gamma\gamma}$, $\mu_{\text{VBF}+VH}^{\gamma\gamma}$, and $\mu^{4\ell}$, and all nuisance parameters are fixed to their best-fit estimates from the data. The expected uncertainties for the combined mass are

$$\delta m_H^{\text{prefit}} = \pm 0.24 \text{ GeV}$$

$$= \pm 0.22 \text{ (stat)} \pm 0.10 \text{ (syst) GeV}$$

(6)
for the prefit case and
\[ \delta m_H^{\text{postfit}} = \pm 0.22 \text{ GeV} \]
\[ = \pm 0.19 \text{ (stat)} \pm 0.10 \text{ (syst) GeV} \] (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 \( H \rightarrow ZZ \rightarrow 4l \) measured signal strength and the increase of the \( H \rightarrow ZZ \rightarrow 4l \) 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 \( H \rightarrow \gamma \gamma \) channel, including a number of discrete parameters that allow the functional form in each of the CMS \( H \rightarrow \gamma \gamma \) 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 \( H \rightarrow \gamma \gamma \) channel and for the electrons and muons in the \( H \rightarrow ZZ \rightarrow 4l \) 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 uncertainties.
between the statistical 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-finier 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 \( \Delta m^{\text{exp}} \equiv m_H^{\text{ATLAS}} - m_H^{\text{CMS}} \).

The observed results, \( \Delta m_Z = -0.1 \pm 0.5 \) GeV and \( \Delta m^{\text{exp}} = 0.4 \pm 0.5 \) GeV, are both consistent with zero within \( 1\sigma \). The difference between the mass values in
from the individual decay channels because the exhibit a greater degree of compatibility than the results evaluated using the nominal method discussed in the text, the statistical uncertainties, the total uncertainties, and the analysis weights, 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>Uncertainty in ATLAS results (GeV): observed (expected)</th>
<th>Uncertainty in CMS results (GeV): observed (expected)</th>
<th>Uncertainty in combined result (GeV): observed (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$H \rightarrow \gamma \gamma$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4 \ell$</td>
<td>$H \rightarrow ZZ \rightarrow 4 \ell$</td>
<td>$H \rightarrow ZZ \rightarrow 4 \ell$</td>
</tr>
<tr>
<td>ATLAS ECAL nonlinearity or CMS photon nonlinearity</td>
<td>0.14 (0.16)</td>
<td>0.10 (0.13)</td>
</tr>
<tr>
<td>Material in front of ECAL</td>
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<td>0.07 (0.07)</td>
</tr>
<tr>
<td>ECAL longitudinal response</td>
<td>0.12 (0.13)</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>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>0.03 (0.01)</td>
<td>0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>ATLAS $H \rightarrow \gamma \gamma$ vertex and conversion reconstruction</td>
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<td>0.01 (0.01)</td>
</tr>
<tr>
<td>CMS electron energy scale and resolution</td>
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<td>0.05 (0.05)</td>
</tr>
<tr>
<td>Muon momentum scale and resolution</td>
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<td>0.12 (0.09)</td>
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<tr>
<td>Other uncertainties:</td>
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<td>0.11 (0.10)</td>
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<tr>
<td>ATLAS $H \rightarrow \gamma \gamma$ background modeling</td>
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<td>0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>Integrated luminosity</td>
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<td>0.01 (&lt;0.01)</td>
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<tr>
<td>Additional experimental systematic uncertainties</td>
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<td>0.01 (&lt;0.01)</td>
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<tr>
<td>Theory uncertainties:</td>
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<td>&lt;0.01 (&lt;0.01)</td>
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<tr>
<td>Systematic uncertainty (sum in quadrature)</td>
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<td>0.15 (0.17)</td>
</tr>
<tr>
<td>Systematic uncertainty (nominal)</td>
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<td>0.15 (0.17)</td>
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<tr>
<td>Statistical uncertainty</td>
<td>0.43 (0.45)</td>
<td>0.31 (0.32)</td>
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<tr>
<td>Total uncertainty</td>
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<td>0.34 (0.36)</td>
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<tr>
<td>Analysis weights</td>
<td>193% (22%)</td>
<td>183% (14%)</td>
</tr>
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</table>

the two experiments is $\Delta m_{\text{exp}} = 1.3 \pm 0.6$ GeV (2.1 $\sigma$) for the $H \rightarrow \gamma \gamma$ channel and $\Delta m_{\text{exp}} = -0.9 \pm 0.7$ GeV (1.3 $\sigma$) for the $H \rightarrow ZZ \rightarrow 4 \ell$ 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 $\lambda_{\text{exp}} = \mu_{\text{ATLAS}} / \mu_{\text{CMS}}$, $\lambda_{\text{F}} = \mu_{\text{F}}^{\text{ATLAS}} / \mu_{\text{F}}^{\text{CMS}}$, and $\lambda_{\text{d/F}} = \mu_{\text{d/F}}^{\text{ATLAS}} / \mu_{\text{d/F}}^{\text{CMS}}$. 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 $\lambda_{\text{exp}} = 1.21_{-0.24}^{+0.30}$, $\lambda_{\text{F}} = 1.3_{-0.8}^{+0.8}$, and $\lambda_{\text{d/F}} = 1.3_{-0.5}^{+0.5}$, all of which are consistent with unity within 1 $\sigma$. The ratio $\lambda_{\text{V}} = \mu_{\text{VBF+VH}}^{\text{ATLAS}} / \mu_{\text{VBF+VH}}^{\text{CMS}}$ is omitted because the ATLAS mass measurement in the $H \rightarrow \gamma \gamma$ channel is not sensitive to $\mu_{\text{VBF+VH}}^{\text{ATLAS}} / \mu_{\text{VBF+VH}}^{\text{CMS}}$.

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: $\mu_{\text{ggF+iH}}^{\text{VBF+VH}} = \mu_{\text{VBF+VH}}^{\text{VBF+VH}} = \mu_{\text{tH}}^{\text{VBF+VH}} = \mu$. 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 (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 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ 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.

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G. Aad, 85,† B. Abbott, 113,† J. Abdallah, 151,‡ O. Abidinov, 11,‡ R. Aben, 107,‡ M. Abolins, 90,‡ O. S. AbouZeid, 15,§ H. Abramowicz, 153,§ H. Abreu, 152,§ R. Abreu, 30,‡ Y. Abulaiti, 146a,146b,‡ B. S. Acharya, 164a,164b,‡ L. Adamczyk, 38a,‡ D. L. Adams, 25,‡ J. Adelman, 108,‡ S. Adomeit, 103,‡ T. Adye, 131,‡ A. A. Affolder, 74,‡ T. Agatonovic-Jovin, 13,‡ J. A. Aguilar-Saavedra, 124a,124b,‡ S. Ahlen, 22,‡ F. Ahmadov, 65,¢,‡ G. Aielli, 133a,133b,‡ H. Akerstedt, 146a,146b,‡ T. P. A. Åkesson, 81,‡ G. Akimoto, 155,‡ A. V. Akimov, 96,‡ G. L. Alberghi, 20a,20b,‡ J. Albert, 169,‡ S. Albrand, 55,‡ M. J. Alconada Verzini, 71,‡ M. Aleksa, 30,‡ I. N. Aleksandrov, 65,¢,‡ C. Alexa, 26a,‡ G. Alexander, 153,‡ T. Alexopoulos, 10,‡ M. Alhroob, 113,‡ G. Alimonti, 91a,‡ L. Alio, 85,‡ J. Alison, 31,‡ S. P. Alkire, 35,‡ B. M. M. Allbrooke, 18,‡ P. P. Allport, 74,‡ A. Aloisio, 104a,104b,‡ A. Alonso, 36,‡ F. Alonso, 71,‡ C. Alpigiani, 76,‡ A. Altherme, 35,‡ B. Alvarez Gonzalez, 10,‡ D. Álvarez Piquerás, 167,‡ M. G. Alviggi, 104a,104b,‡ B. T. Amadio, 15,‡ K. Amako, 66,‡ Y. Amaral Coutinho, 24a,‡ C. Amelung, 23,‡ D. Amidei, 89,‡ S. P. Amor Dos Santos, 126a,126c,‡ A. Amorim, 126a,126b,‡ S. Amoroso, 48,‡ N. Amram, 153,‡ G. Amundsen, 23,‡ C. Anastopoulos, 139,‡ L. S. Ancu, 49,‡ N. Andari, 30,‡ T. Andeen, 35,‡ C. F. Anders, 58b,‡ G. Anders, 30,‡ J. K. Anders, 74,‡ K. J. Anderson, 31,‡ A. Andreazzu, 91a,91b,‡ V. Andrei, 58a,‡ S. Angelidakis, 9,‡ I. Angelozzi, 107,‡ P. Anger, 44,‡ A. Angerami, 35,‡ F. Anghinolfi, 30,‡ A. V. Anisenkov, 109,d,‡ N. Anjos, 12,‡ A. Annovi, 44,‡ F. Anulli, 132a,‡ M. Aoki, 66,‡ L. Aperio Bella, 18,‡ G. Arabidze, 90,‡ Y. Arai, 66,‡ J. P. Araque, 126a,‡ A. T. H. Arce, 45,‡ F. A. Ardu, 71,‡ J-F. Arguin, 95,‡ S. Argyropoulos, 42,‡ M. Arik, 19a,‡ A. J. Armbruster, 30,‡ O. Arnaez, 51,‡ V. Arnaud, 82,‡ H. Arnold, 48,‡ M. Arratia, 28,‡ O. Arslan, 21,‡ A. Artamonov, 97,‡ G. Artoni, 23,‡ S. Asai, 155,‡ N. Asbach, 12,‡ A. Askkenazi, 153,‡ B. Åsman, 146a,146b,‡ L. Asquith, 249,‡ K. Assamaj, 249,‡ R. Astalos, 144a,‡ M. Atkinson, 165,‡ N. B. Atlay, 141,‡ B. Auverbach, 6,‡ K. Augsten, 128,‡ M. Aurousseau, 145b,‡ G. Avolio, 30,‡ B. Axen, 15,‡ M. K. Ayoub, 117,‡ G. Azuelos, 95,‡ M. A. Baak, 30,‡ A. E. Baas, 58a,‡ C. Bacci, 134a,134b,‡ H. Bachacou, 136,‡ K. Bachas, 154,‡ M. Backes, 30,‡ M. Backhaus, 30,‡ E. Badescu, 26a,‡ P. Bagiacchi, 132a,132b,‡ P. Bagnaia, 132a,132b,‡ Y. Bai, 33a,‡ T. Bain, 35,‡ J. T. Baines, 131,‡ O. K. Baker, 176,‡ P. Balek, 129,‡ T. Balestre, 148,‡ F. Bally, 84,‡ E. Banas, 39,‡ S. Banerjee, 173,‡ A. A. E. Bannoura, 175,‡ H. S. Bansil, 18,‡ L. Barak, 30,‡ S. P. Baranov, 96,‡ E. L. Barbero, 88,‡ D. Barberis, 50a,50b,‡ M. Barbero, 85,‡ T. Barillari, 101,‡ M. Barisonzi, 164a,164b,‡ T. Barklow, 143,‡ N. Barlow, 28,‡ S. L. Barnes, 84,‡ B. M. Barnett, 15,‡ Z. Barnovska, 5,‡ A. Baroncelli, 134a,‡ G. Barone, 49,‡ A. J. Barr, 120,‡ F. Barreiro, 82,‡ J. Barreiro Guimarães da Costa, 57,‡ R. Bartoldus, 143,‡ A. E. Barton, 72,‡
37 INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy
38 Dipartimento di Fisica, Università della Calabria, Rende, Italy
39 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
40 Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
41 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
42 Physics Department, Southern Methodist University, Dallas, Texas, USA
43 Physics Department, University of Texas at Dallas, Richardson, Texas, USA
44 DESY, Hamburg and Zeuthen, Germany
45 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
46 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
47 Department of Physics, Duke University, Durham, North Carolina, USA
48 SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
49 INFN Laboratori Nazionali di Frascati, Frascati, Italy
50 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
51 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
52 Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
53 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
54 Physics Department, Southern Methodist University, Dallas, Texas, USA
55 INFN Laboratori Nazionali di Frascati, Frascati, Italy
56 Department of Physics, Hampton University, Hampton, Virginia, USA
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
58 Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
59 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
60 ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
61 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
62 Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
63 Department of Physics, The University of Hong Kong, Hong Kong, China
64 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
65 Physics Department, Indiana University, Bloomington, Indiana, USA
66 Physics Department, Indiana University, Bloomington, Indiana, USA
67 University of Iowa, Iowa City, Iowa, USA
68 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
69 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
70 Graduate School of Science, Kobe University, Kobe, Japan
71 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
72 Department of Physics, Royal Holloway University of London, Egham, United Kingdom
73 Physics Department, Lancaster University, Lancaster, United Kingdom
74 Department of Physics, University of Lecce, Lecce, Italy
75 Dipartimento di Matematica e Fisica, Università di Salento, Lecce, Italy
76 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
77 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
78 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
79 Department of Physics and Astronomy, University College London, London, United Kingdom
80 Louisiana Tech University, Ruston, Louisiana, USA
81 Laboratoire de Physique Nucléaire et de Hautes Énergies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
82 Fysiska institutionen, Lunds universitet, Lund, Sweden
83 Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
84 Institut für Physik, Universität Mainz, Mainz, Germany
85 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
86 CPPM, Aix-Marseille Université et CNRS/IN2P3, Marseille, France
87 Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
88 Department of Physics, McGill University, Montreal, Quebec, Canada
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco
Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPEHA-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 Energies 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
Institut de Physique de l’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 OeAW, Wien, Austria
181 National Centre for Particle and High Energy Physics, Minsk, Belarus
182 Universiteit Antwerpen, Antwerpen, Belgium
183 Vrije Universiteit Brussel, Brussel, Belgium
184 Université Libre de Bruxelles, Bruxelles, Belgium
185 Ghent University, Ghent, Belgium
186 Université Catholique de Louvain, Louvain-la-Neuve, Belgium
187 Université de Mons, Mons, Belgium
188 Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
189 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
190 Universidade Estadual Paulista, São Paulo, Brazil
191 Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
192 University of Sofia, Sofia, Bulgaria
193 Institute of High Energy Physics, Beijing, China
194 State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
195 Universidad de Los Andes, Bogota, Colombia
196 University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
197 University of Split, Faculty of Science, Split, Croatia
198 Institute Rudjer Boskovic, Zagreb, Croatia
199 University of Cyprus, Nicosia, Cyprus
200 Charles University, Prague, Czech Republic
201 Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
202 National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
203 Department of Physics, University of Helsinki, Helsinki, Finland
204 Helsinki Institute of Physics, Helsinki, Finland
205 Lappeenranta University of Technology, Lappeenranta, Finland
206 DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
207 Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
208 Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
209 Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
210 Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
211 Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
212 RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
213 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
214 RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
215 Deutsches Elektronen-Synchrotron, Hamburg, Germany
216 University of Hamburg, Hamburg, Germany
217 Institut für Experimentelle Kernphysik, Karlsruhe, Germany
218 Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
219 University of Athens, Athens, Greece
220 University of Ioannina, Ioannina, Greece
221 Wigner Research Centre for Physics, Budapest, Hungary
222 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
223 University of Debrecen, Debrecen, Hungary
224 National Institute of Science Education and Research, Bhubaneswar, India
225 Panjab University, Chandigarh, India
226 University of Delhi, Delhi, India
227 Saha Institute of Nuclear Physics, Kolkata, India
228 Bhabha Atomic Research Centre, Mumbai, India
229 Tata Institute of Fundamental Research, Mumbai, India
230 Indian Institute of Science Education and Research (IISER), Pune, India
231 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
232 University College Dublin, Dublin, Ireland
233 INFN Sezione di Bari, Bari, Italy
234 INFN Sezione di Bologna, Bologna, Italy
235 INFN Sezione di Bologna, Bologna, Italy
236 INFN Sezione di Bologna, Bologna, Italy
INFN Sezione di Catania, Catania, Italy
Università di Catania, Catania, Italy
CSFNSM, Catania, Italy

INFN Sezione di Firenze, Firenze, Italy
Università di Firenze, Firenze, Italy

INFN Laboratori Nazionali di Frascati, Frascati, Italy

INFN Sezione di Genova, Genova, Italy
Università di Genova, Genova, Italy

INFN Sezione di Milano-Bicocca, Milano, Italy
Università di Milano-Bicocca, Milano, Italy

INFN Sezione di Napoli, Napoli, Italy
Università di Napoli “Federico II,” Napoli, Italy
Università della Basilicata, Roma, Italy
Università G. Marconi, Roma, Italy

INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
Università di Trento, Trento, Italy
INFN Sezione di Pavia, Pavia, Italy
Università di Pavia, Pavia, Italy

INFN Sezione di Perugia, Perugia, Italy
Università di Perugia, Perugia, Italy
INFN Sezione di Pisa, Pisa, Italy
Università di Pisa, Pisa, Italy

Scuola Normale Superiore di Pisa, Pisa, Italy
INFN Sezione di Roma, Roma, Italy
Università di Roma, Roma, Italy
INFN Sezione di Torino, Novara, Italy
Università di Torino, Novara, Italy

Università del Piemonte Orientale, Novara, Italy
INFN Sezione di Trieste, Trieste, Italy
Università di Trieste, Trieste, Italy

Kangwon National University, Chunchon, Korea
Kyungpook National University, Daegu, Korea
Chonbuk National University, Jeonju, Korea

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

Korea University, Seoul, Korea
Seoul National University, Seoul, Korea
University of Seoul, Seoul, Korea
Sungkyunkwan University, Suwon, 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
Universidad Iberoamericana, Mexico City, Mexico
Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
Universidad Autónoma de San Luis Potosí, San Luis Potosí, 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
aDeceased.
bAlso at Department of Physics, King’s College London, London, United Kingdom.
cAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
dAlso at Novosibirsk State University, Novosibirsk, Russia.
eAlso at TRIUMF, Vancouver, BC, Canada.
fAlso at Department of Physics, California State University, Fresno, CA, USA.
gAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.
hAlso at Departamento de Física e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
iAlso at Tomsk State University, Tomsk, Russia.
jAlso at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
kAlso at Università di Napoli Parthenope, Napoli, Italy.
lAlso at Institute of Particle Physics (IPP), Canada.
mAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
nAlso at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
oAlso at Louisiana Tech University, Ruston, LA, USA.
pAlso at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
qAlso at Department of Physics, National Tsing Hua University, Taiwan.
rAlso at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
sAlso at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
tAlso at CERN, Geneva, Switzerland.
uAlso at Georgian Technical University (GTU), Tbilisi, Georgia.
vAlso at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
wAlso at Manhattan College, New York, NY, USA.
xAlso at Institute of Physics, Academia Sinica, Taipei, Taiwan.
yAlso at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
zAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
aaAlso at School of Physics, Shandong University, Shandong, China.
abAlso at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
cAlso at Section de Physique, Université de Genève, Geneva, Switzerland.
daAlso at International School for Advanced Studies (SISSA), Trieste, Italy.
bAlso at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
eAlso at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
fAlso at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
gAlso at National Research Nuclear University MEPhI, Moscow, Russia.
hAlso at Department of Physics, Stanford University, Stanford, CA, USA.
iAlso at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
jAlso at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
kAlso at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
mAlso at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
nAlso at Vienna University of Technology, Vienna, Austria.
oAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
pAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
qAlso at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
rAlso at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
sAlso at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
tAlso at Universidade Estadual de Campinas, Campinas, Brazil.
uAlso at Centre National de la Recherche Scientifique (CNRS)–IN2P3, Paris, France.
vAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
wAlso at Joint Institute for Nuclear Research, Dubna, Russia.
xAlso at Ain Shams University, Cairo, Egypt.