Editors' Suggestion

Combined Measurement of the Higgs Boson Mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ Decay Channels with the ATLAS Detector Using $\sqrt{s} = 7$, 8, and 13 TeV pp Collision Data

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A measurement of the mass of the Higgs boson combining the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ decay channels is presented. The result is based on 140 fb^{-1} of proton-proton collision data collected by the ATLAS detector during LHC run 2 at a center-of-mass energy of 13 TeV combined with the run 1 ATLAS mass measurement, performed at center-of-mass energies of 7 and 8 TeV, yielding a Higgs boson mass of $125.11 \pm 0.09(\mathrm{stat}) \pm 0.06(\mathrm{syst}) = 125.11 \pm 0.11$ GeV. This corresponds to a 0.09% precision achieved on this fundamental parameter of the Standard Model of particle physics.

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The discovery of the Higgs boson in proton-proton (pp) collisions at the CERN LHC by the ATLAS and CMS Collaborations [1,2] with data collected at $\sqrt{s} = 7$ and 8 TeV (run 1) was a major step toward understanding the electroweak symmetry-breaking mechanism. Gauge theories require, in fact, that gauge bosons be massless, in apparent contradiction with observations. In this context, the seminal work of Englert and Brout [3], Higgs [4–6], and Guralnik, Hagen, and Kibble [7,8] has provided a consistent mechanism for the generation of gauge boson masses. The Glashow-Weinberg-Salam theory extended this mechanism proposing a theory of the electroweak interactions [9–11], introducing a doublet of complex scalar fields, which couples also to fermions, providing them with a mass that would otherwise be absent. This forms a major component of the Standard Model (SM) of particle physics. A salient prediction of the SM is the presence of a Higgs boson, whose mass is not predicted by the theory and needs to be estimated experimentally. Since the Higgs boson discovery, thanks to the luminosity accumulated at the LHC between 2015 and 2018 (run 2) and the increased center-of-mass energy at $\sqrt{s} = 13$ TeV, the focus has shifted to the precise measurements of Higgs boson properties [12,13]. The couplings of the Higgs boson to other elementary particles are predicted in the SM once the Higgs boson mass m_H is known. This motivates its precise measurement through decay channels that can be fully reconstructed and with the best mass resolution.

The $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decays are the most suitable processes to measure m_H at the LHC due to their excellent mass resolution, which produce a clear mass peak above a continuum background [1,2]. The Higgs boson mass m_H was measured by ATLAS and CMS in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels using the full run 1 dataset, and all measurements by the two experiments were combined resulting in a m_H value of 125.09 ± 0.24 GeV [14]. More recently, the CMS Collaboration has measured m_H in the same decay channels using 35.9 fb^{-1} of 13 TeV pp run 2 collision data. The combination of the two CMS run 2 measurements with their run 1 results yielded a m_H value of 125.38 ± 0.14 GeV [15]. This Letter presents a measurement of m_H combining the $H \to \gamma\gamma$ [16] and $H \to ZZ^* \to 4\ell$ [17] decay channels. The result is based on 140 fb^{-1} of proton-proton collision data collected by the ATLAS detector [18] during the LHC run 2 at a center-of-mass energy of 13 TeV and updates and supersedes that based on the same final states and a partial run 2 dataset corresponding to an integrated luminosity of 36.1 fb^{-1} [19]. An extensive software suite [20] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment. The combined measurements profit from the increased dataset and from significantly improved calibrations of the electron and photon energy [16,21] and of the muon momentum [17,22].

The mass measurement reported in this Letter is performed using the profile likelihood ratio [23,24] defined as $\Lambda(m_H) = \mathcal{L}(m_H, \hat{\hat{\boldsymbol{\theta}}}(m_H))/\mathcal{L}(\hat{m}_H, \hat{\boldsymbol{\theta}})$. $\hat{m}_H$ and $\hat{\boldsymbol{\theta}}$ are the values of the parameter of interest and nuisance parameters (NP), respectively, that maximize the likelihood $\mathcal{L}(m_H, \boldsymbol{\theta})$, while $\hat{\hat{\boldsymbol{\theta}}}(m_H)$ corresponds to the values of the NP that maximize the likelihood for a given value of m_H. Systematic uncertainties are modeled by constrained NP,

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while the signal and background normalizations in the various channels entering the fit are treated as free parameters. The confidence intervals are obtained assuming the asymptotic distribution of the $-2\ln\Lambda(m_H)$ test statistic [24]. The statistical uncertainty on m_H is estimated by fixing all the NP that are associated with systematic uncertainties to their best-fit values and leaving all the remaining parameters unconstrained. The total systematic uncertainty, whose squared value is evaluated as the difference between the squares of the total uncertainty and the statistical uncertainty, can be decomposed into categories representing distinct sources of uncertainty by setting all relevant subsets of NP to their best-fit values.

The full description of the run 2 mass measurement in the $H \to \gamma\gamma$ channel is given in Ref. [16]. A description of the key aspects of this measurement is summarized here. The $H \to \gamma\gamma$ decay is reconstructed by requiring two energetic photons fulfilling strict identification and isolation criteria. The invariant mass $m_{\gamma\gamma}$ distribution of the selected photon pairs exhibits a peak near m_H, arising from resonant Higgs boson decays, over a smoothly falling distribution from background processes mainly due to nonresonant diphoton production. The value of m_H is determined from the position of the peak in data through a profile-likelihood fit to the $m_{\gamma\gamma}$ distribution. Simulated signal and background event samples are used to optimize the analysis criteria, to choose the signal and background $m_{\gamma\gamma}$ models used in the fit, and to estimate some of the systematic uncertainties on m_H. To increase the sensitivity of the measurement, the selected events are classified into 14 mutually exclusive categories with different diphoton invariant mass resolutions and signal-to-background ratios, which are analyzed simultaneously. The normalization factor for each category is independent and fitted to the data. The $m_{\gamma\gamma}$ resolution ranges from about 1.1 to 2.0 GeV, depending on the category. The signal model consists of a double-sided Crystal Ball probability density function [25], with the mean and standard deviation of its Gaussian core parametrized as a function of m_H in each category using simulated signal events generated at different m_H hypotheses. Compared with the mass result reported in Ref. [19], the $H \to \gamma\gamma$ mass measurement used in this combination and reported in Ref. [16] profits from an increased data sample, a new photon reconstruction algorithm with better energy resolution [26], an improved estimation of the photon energy scale with significantly reduced uncertainties [21], and an optimized event classification strategy. Uncertainties for photons converting into electron-positron pairs before reaching the electromagnetic calorimeter, which are experimentally similar to electrons, are only moderately improved by the updated calibrations at energies typically observed in the $H \to \gamma\gamma$ decay (e.g., $E_T \sim 60$ GeV). For unconverted photons, the energy calibration is improved by typically 30% in the central part of the calorimeter ($|\eta| < 1.37$) and up to a factor 2 in the end cap region ($1.51 \leq |\eta| < 2.37$). The reduction of the uncertainties on the photon energy scale arises from an improved understanding of the difference in data and simulation of the inputs to the photon energy scale regression and of the introduction of transverse energy (E_T) dependent *in situ* scales derived from $Z \to e^+e^-$ events, that reduce the calibration extrapolation uncertainties from the Z boson mass to the Higgs mass and from electrons to photons [21]. The measured mass of the Higgs boson in the $H \to \gamma\gamma$ final state using the full run 2 dataset is $m_H = 125.17 \pm 0.11(\text{stat}) \pm 0.09(\text{syst}) = 125.17 \pm 0.14$ GeV [16]. The dominant sources of systematic uncertainties on the measurement are associated to the $Z \to e^+e^-$ *in situ* scale (59 MeV), the residual E_T-dependent electron energy scale calibration (44 MeV), and the calibration extrapolation from electrons to photons (30 MeV) [16]. The effect of the interference between the $H \to \gamma\gamma$ signal and the $\gamma\gamma$ continuous background [27] is evaluated to have an impact on the determination of m_H of approximately 26 MeV. The full effect is accounted as a systematic uncertainty on the quoted result, and no shift of the mass value is applied. A combination with the measurement of m_H using the run 1 dataset [14], $m_H = 126.02 \pm 0.43(\text{stat}) \pm 0.27(\text{syst}) = 126.02 \pm 0.51$ GeV, is performed. In this combination, only the E_T-independent component of the uncertainty associated to the *in situ* scale derived from $Z \to e^+e^-$ events, the resolution uncertainties, and the theoretical uncertainties related to the various Higgs production modes are considered as correlated between run 1 and run 2. The combined measurement of m_H using run 1 and run 2 datasets in the $H \to \gamma\gamma$ channels is $m_H = 125.22 \pm 0.11(\text{stat}) \pm 0.09(\text{syst}) = 125.22 \pm 0.14$ GeV.

The full description of the run 2 mass measurement in the $H \to ZZ^* \to 4\ell$ channel is given in Ref. [17]. A description of the key aspects of this measurement is summarized here. The $H \to ZZ^* \to 4\ell$ decay is reconstructed by requiring two pairs of same-flavor opposite-sign isolated leptons ($\ell = e,\mu$) in the final state. The pair with the invariant mass closer to that of the Z boson mass is defined as the leading dilepton pair, while the remaining one is referred to as the subleading dilepton pair. The selected quadruplets are separated into four subchannels according to the flavor of the leading and subleading dilepton pairs (4μ, $2e2\mu$, $2\mu2e$, $4e$). A neural-network-based classifier is employed to discriminate between the Higgs boson signal and the dominant $ZZ^* \to 4\ell$ background. The m_H measurement is performed with a simultaneous unbinned maximum likelihood fit of the reconstructed invariant mass of the four-lepton system, $m_{4\ell}$, in the four subchannels. The $m_{4\ell}$ resolution ranges from about 1.5 GeV (4μ and $2e2\mu$ subchannels) to about 2.1 GeV ($2\mu2e$ and $4e$ subchannels). The signal model consists of a double-sided Crystal Ball probability density function, with the mean of its Gaussian core parametrized as a function of m_H and the standard deviation expressed as a function of the predicted event-level resolution. The signal and background normalization for each of the four subchannels are free parameters in the fit. Compared with the measurement reported in Ref. [19], the $H \rightarrow ZZ^* \rightarrow 4\ell$ used in this combination and reported in Ref. [17] profits from an increased data sample, a new high-precision muon momentum calibration [22], the neural-network-based classifier for the signal versus background discrimination, and the inclusion of the event-by-event invariant mass resolution in the analytical model used to fit the collision data. The measured mass of the Higgs boson in the $H \rightarrow ZZ^* \rightarrow 4\ell$ final state using the full run 2 dataset is $m_H = 124.99 \pm 0.18(\mathrm{stat}) \pm 0.04(\mathrm{syst}) = 124.99 \pm 0.19$ GeV. The dominant sources of systematic uncertainty on the measurement are the uncertainties in the muon momentum scale, resolution and sagitta bias correction (28 MeV), and the electron energy scale [26] (19 MeV). A combination with the measurement of m_H using the run 1 dataset [14], $m_H = 124.51 \pm 0.52(\mathrm{stat}) \pm 0.04(\mathrm{syst}) = 124.51 \pm 0.52$ GeV, has been performed. In this combination, only the uncertainties on the electron calibration were considered correlated, while the muon calibration systematic uncertainty is uncorrelated between the two measurements due to improved and independent techniques in the muon momentum scale calibration. The combined measurement of m_H performed with run 1 and run 2 datasets in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel is $m_H = 124.94 \pm 0.17(\mathrm{stat}) \pm 0.03(\mathrm{syst}) = 124.94 \pm 0.18$ GeV.

The combined mass measurement in the $H \rightarrow \gamma\gamma$ channel [16] is similarly affected by the statistical uncertainty (110 MeV) and the systematic uncertainty (90 MeV), mainly associated to the photon energy scale calibration. In contrast, the combined mass measurement in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel [17] is primarily dominated by the statistical uncertainty (170 MeV), while the systematic uncertainty, mainly related the muon momentum scale calibration, has a minor impact (30 MeV) on the measurement. The differences between the two channels can be traced to the distinct decay branching ratios, final state reconstruction efficiencies, background levels, and the resulting signal-to-background ratios in the two channels. A detailed comparison of the two channels, qualitatively similar to those presented here, is given in Ref. [28].

In the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels combination, the correlations between systematic uncertainties in the two measurements are accounted for in the profile likelihood function by using the same constraint for each of the correlated NP. All potential correlations between measurements and data-taking periods are thoroughly examined. Because of substantial variations in the calibration of electrons, photons, and muons, most correlations are small. If applicable, these correlations are incorporated following the approach that yields the most conservative result. In the combinations of the run 1 and run 2 measurements of the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ individual channels, the correlation of the experimental systematic uncertainties follows what was done in Refs. [16,17], respectively. The correlation scheme between the run 1 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ measurements is unchanged relative to the published run 1 combination [14]. The choice of correlation model between the run 2 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ measurements reflects the improvements in the photon calibration adopted by the $H \rightarrow \gamma\gamma$ analysis not being mirrored in the calibration of the electrons used in the $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis;

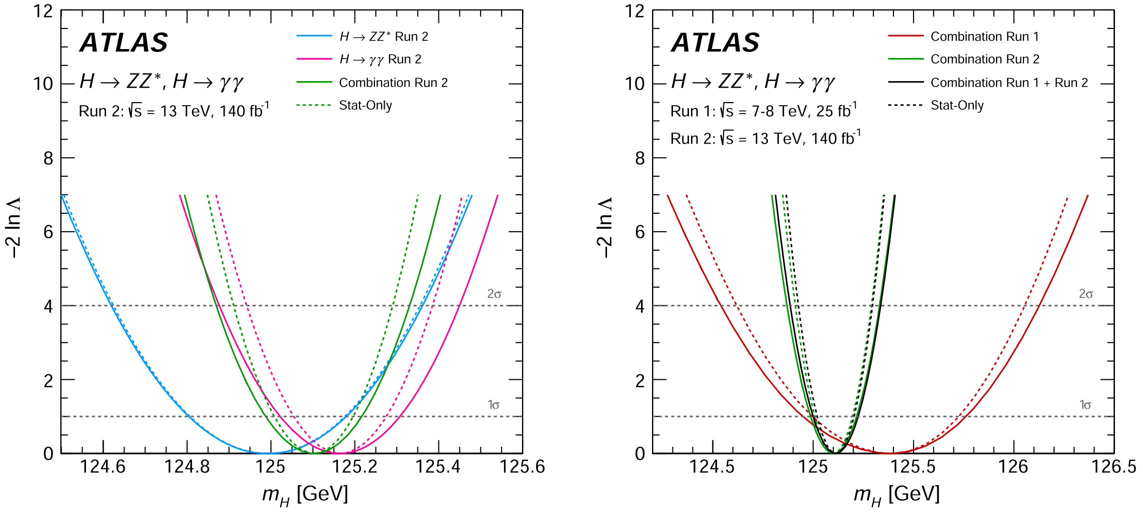

FIG. 1. Value of $-2 \ln \Lambda$ as a function of m_H for (left) $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels and their combination (magenta, cyan, and green, respectively) using run 2 data only and for (right) run 1, run 2, and their combination (red, green, and black, respectively). The dashed lines show the statistical component of the uncertainty. The 1σ (2σ) confidence interval is indicated by the intersections of the horizontal line at 1 (4) with the log-likelihood curves.

TABLE I. Impact of the main sources of systematic uncertainty on the m_H measurement from the combination of the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ final states using run 2 data. The systematic uncertainties associated with the combination of run 1 and run 2 data are nearly identical. The sum in quadrature of the individual contributions is not expected to reproduce the total systematic uncertainty due to the different methodologies employed to derive them.

Source	Systematic uncertainty on m_H (MeV)
e/γ E_T-independent $Z \to ee$ calibration	44
e/γ E_T-dependent electron energy scale	28
$H \to \gamma\gamma$ interference bias	17
e/γ photon lateral shower shape	16
e/γ photon conversion reconstruction	15
e/γ energy resolution	11
$H \to \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7

only the electron and photon resolution systematic uncertainties and those associated with the E_T-independent component of the electron and photon *in situ* energy scale are considered as correlated. Other sources of systematic uncertainties correlated between the two channels are the theory uncertainties on the prediction of the various Higgs production modes, the modeling of additional (*pileup*) pp collisions, and the uncertainty on the integrated luminosity. The choice of correlation model is also tested by using different approaches (e.g., correlating the muon calibration systematic uncertainties in run 1 and run 2, correlating all sources of photon and electron calibration systematic uncertainties between the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels) and is shown to have negligible impact on the result. Signal yield normalizations are treated as independent free parameters in the fit to minimize model-dependent assumptions in the measurement of m_H.

The combined value measured using run 2 data is $m_H = 125.10 \pm 0.11$ GeV. The uncertainty is compatible with the expected error assuming a SM Higgs boson mass of 125 GeV. The statistical component of the uncertainty is ± 0.09 GeV. The corresponding profile likelihood, for the two channels and for their combination, is shown in Fig. 1 (left) as a function of m_H. If the small interference predicted by the SM between the Higgs boson and the nonresonant diphoton background was considered for the $H \to \gamma\gamma$ signal parametrization, the m_H value measured by the combination would increase by 15 MeV. This result is in good agreement with the ATLAS + CMS run 1 measurement [19], $m_H = 125.09 \pm 0.24$ GeV. The contributions of the main sources of systematic uncertainty to the combined measurement, using ATLAS run 2 data, are summarized in Table I. The values differ from those reported in Refs. [16,17] because of the relative impact of the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ results in the combination. The E_T-independent component of the electron and photon *in situ* energy scale ("$e/\gamma E_T$-independent $Z \to ee$ calibration" in Table I) is among the few uncertainties correlated between the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ measurements and impacts the former measurement by 59 MeV [16] and the latter by 19 MeV [17]. The combined measurement

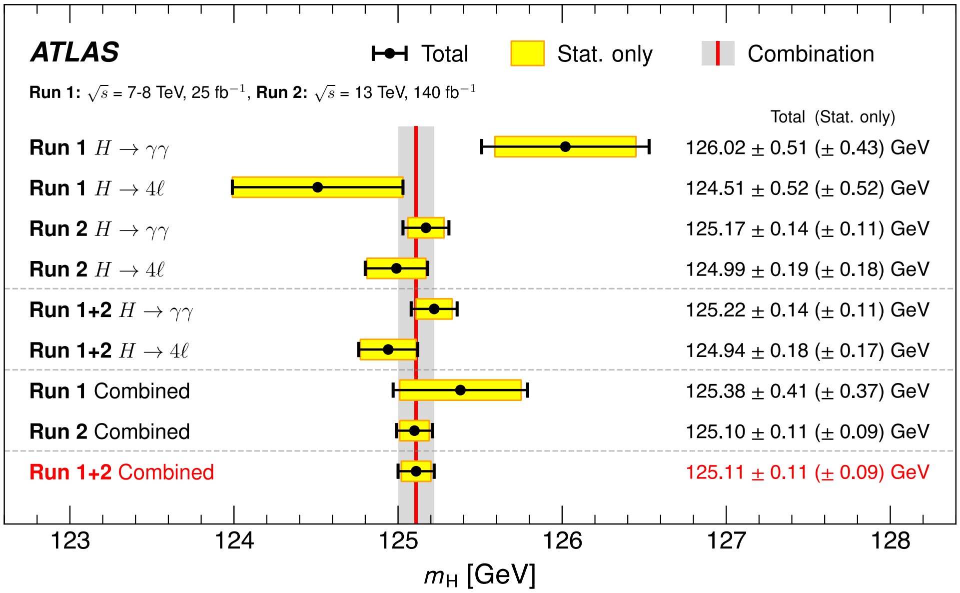

FIG. 2. Summary of m_H measurements from the individual $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels and their combination presented in this Letter. The uncertainty bar on each point corresponds to the total uncertainty; the horizontal shaded bands represent the statistical component of the uncertainties; the vertical red line and gray band represent the combined result presented in this Letter with its total uncertainty.

from the ATLAS run 1 and run 2 results is $m_H = 125.11 \pm 0.11$ GeV. The statistical component of the uncertainty is ± 0.09 GeV. The four combined measurements are compatible with a p value of 18%. Figure 1 (right) shows the corresponding profile likelihoods, separately for the ATLAS run 1 and run 2 datasets, as well as for their combination, as a function of m_H. The contributions of the main sources of systematic uncertainty to the combination of run 1 and run 2 data are nearly identical to those presented in Table I. Figure 2 presents a summary of the m_H measurements from the individual $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels and their combinations discussed in this Letter.

In conclusion, the Higgs boson mass m_H is measured using run 2 collision data at 13 TeV yielding

$$\begin{aligned} m_H &= 125.10 \pm 0.09(\mathrm{stat}) \pm 0.07(\mathrm{syst}) \\ &= 125.10 \pm 0.11\ \mathrm{GeV}, \end{aligned}$$

which is a significant improvement with respect to that reported in Ref. [19]. The systematic uncertainty affecting the $H \to \gamma\gamma$ measurement is reduced by a factor of about 3 thanks to a novel and improved approach to the photon energy calibration. This is comparable with the factor of about 2 associated with the increase in the data statistics. The systematic uncertainty on the muon momentum calibration decreases by about 50% relative to Ref. [19]. Combining the run 2 result with the m_H measurements performed in run 1 at 7 and 8 TeV, the combined result is

$$\begin{aligned} m_H &= 125.11 \pm 0.09(\mathrm{stat}) \pm 0.06(\mathrm{syst}) \\ &= 125.11 \pm 0.11\ \mathrm{GeV}. \end{aligned}$$

This result currently represents the most precise measurement of the Higgs boson mass, reaching a 0.09% precision on this fundamental quantity.

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