EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2013-037
2016/01/08

CMS-HIG-14-003

Search for a Higgs boson decaying into $\gamma^{*}\gamma \to \ell\ell\gamma$ with low dilepton mass in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

A search is described for a Higgs boson decaying into two photons, one of which has an internal conversion to a muon or an electron pair ($\ell\ell\gamma$). The analysis is performed using proton-proton collision data recorded with the CMS detector at the LHC at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$. The events selected have an opposite-sign muon or electron pair and a high transverse momentum photon. No excess above background has been found in the three-body invariant mass range $120 < m_{\ell\ell\gamma} < 150\,\mathrm{GeV}$, and limits have been derived for the Higgs boson production cross section times branching fraction for the decay $\mathrm{H} \to \gamma^{*}\gamma \to \ell\ell\gamma$, where the dilepton invariant mass is less than 20 GeV. For a Higgs boson with $m_{\mathrm{H}} = 125\,\mathrm{GeV}$, a 95% confidence level (CL) exclusion observed (expected) limit is 6.7 ($5.9^{+2.8}_{-1.8}$) times the standard model prediction. Additionally, an upper limit at 95% CL on the branching fraction of $\mathrm{H} \to (\mathrm{J}/\psi)\gamma$ for the 125 GeV Higgs boson is set at 1.5×10^{-3}.

Published in Physics Letters B as `doi:10.1016/j.physletb.2015.12.039.`

---

*See Appendix A for the list of collaboration members

1 Introduction

The rare decay into the $\ell\ell\gamma$ final state of the Higgs boson is a rich source of information that can enhance our understanding of its basic properties and probe novel couplings predicted by extensions of the standard model (SM) of particle physics. As illustrated in Fig. 1, this decay in SM has contributions from loop-induced $\mathrm{H} \to \gamma^*\gamma$ and $\mathrm{H} \to \mathrm{Z}\gamma$ diagrams (a, b, c), tree-level process $\mathrm{H} \to \ell\ell$ with final-state radiation (d), and higher-order processes, known as box diagrams (e, f, g) [1–4]. Other contributions include $\mathrm{H} \to V(q\bar{q})\gamma \to \ell\ell\gamma$, shown in Fig. 2, where V denotes a vector meson (J/ψ or Y) that decays to $\ell\ell$ [5–7]. The Higgs boson branching fraction to $\ell\ell\gamma$ is dominated by the $\mathrm{H} \to \gamma^*\gamma$ and $\mathrm{H} \to \mathrm{Z}\gamma$ modes, while the contribution from the box diagrams is negligible [1]. In the muon channel, when the dilepton invariant mass, $m_{\ell\ell}$, is greater than 100 GeV, final-state radiation in $\mathrm{H} \to \mu\mu$ starts to dominate [8]. In the three-body decay, $\mathrm{H} \to \ell\ell\gamma$, it is possible to investigate non-SM couplings by examining the angular distributions, and forward-backward asymmetry variables reconstructed from the $\ell\ell\gamma$ final state [8, 9].

The expected rates of the $\mathrm{H} \to (\mathrm{Z}/\gamma^*)\gamma \to \ell\ell\gamma$ processes compared to the rate of $\mathrm{H} \to \gamma\gamma$ decay, for a Higgs boson with mass $m_\mathrm{H} = 125\,\mathrm{GeV}$, are [10, 11]:

$$\frac{\Gamma(\mathrm{H} \to \gamma^*\gamma \to \mathrm{ee}\gamma)}{\Gamma(\mathrm{H} \to \gamma\gamma)} \sim 3.5\%, \quad \frac{\Gamma(\mathrm{H} \to \gamma^*\gamma \to \mu\mu\gamma)}{\Gamma(\mathrm{H} \to \gamma\gamma)} \sim 1.7\%, \quad \frac{\Gamma(\mathrm{H} \to \mathrm{Z}\gamma \to \ell\ell\gamma)}{\Gamma(\mathrm{H} \to \gamma\gamma)} \sim 2.3\%.$$

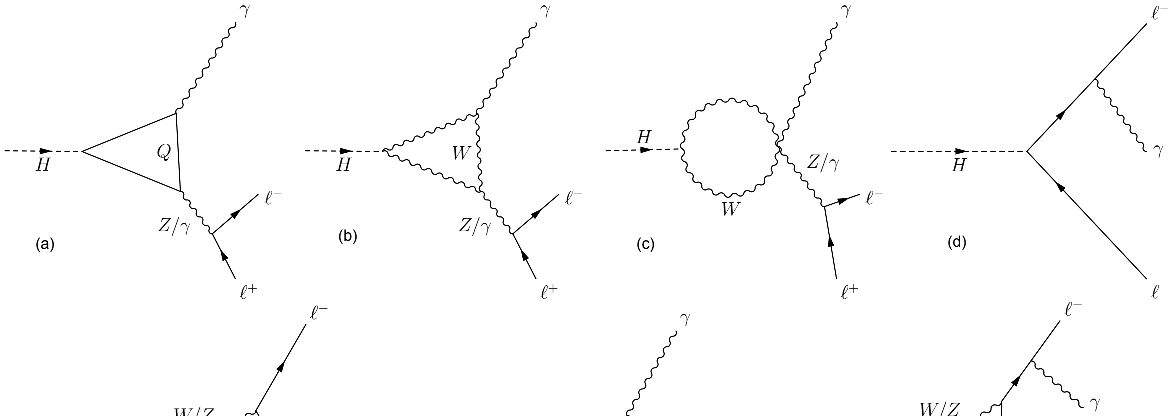

Figure 1: Diagrams contributing to $\mathrm{H} \to \ell\ell\gamma$. The contributions from diagrams (a), (b), and (c) dominate. The final-state radiation of $\mathrm{H} \to \mu\mu$ decay, shown in diagram (d), is important at high dilepton invariant mass. Higher order contributions from diagrams (e), (f) and (g) are negligible.

The $\mathrm{H} \to \gamma^*\gamma \to \mathrm{ee}\gamma$ decay is distinct from $\mathrm{H} \to \gamma\gamma$ followed by a conversion of a photon to an $\mathrm{e}^+\mathrm{e}^-$ pair in the detector, which can become a background for $\mathrm{H} \to \gamma^*\gamma$ if photon conversions are not properly identified. Experimentally, the various contributions shown in Figs. 1 and 2 can be disentangled to some extent. Requirements on $m_{\ell\ell}$ and the transverse momentum (p_T) of the photon are used to separate $\mathrm{H} \to \gamma^*\gamma$ and $\mathrm{H} \to \mathrm{Z}\gamma$. Events with final-state radiation are removed by requiring the photon to be isolated from either of the leptons. Contributions from

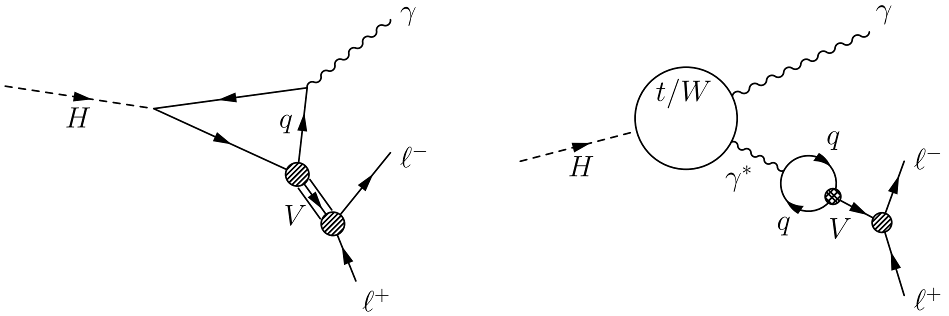

Figure 2: Diagrams contributing to H $\to V\gamma \to \ell\ell\gamma$ decay.

H $\to$ (J/ψ)$\gamma \to \ell\ell\gamma$ and other resonances are identified and rejected or selected based on the value of $m_{\ell\ell}$.

The ATLAS and CMS Collaborations at the CERN LHC have both performed a search for H $\to$ Z$\gamma \to \ell\ell\gamma$ decay with $m_{\ell\ell}$ above 50 GeV [12, 13]. As a natural extension of those analyses, the current paper describes the first search for a Higgs boson Dalitz decay, H $\to \gamma^*\gamma$, where the γ^* decays into a muon or an electron pair. The search is performed for a Higgs-like particle within the mass range between 120 and 150 GeV. In order to select the contribution from the Dalitz decay, we require $m_{\ell\ell} < 20$ GeV. The $\mu\mu\gamma$ topology is a clean final state with a mass resolution of about 1.6%, as measured from the simulated signal samples. The eeγ channel is challenging due to the low $m_{\ell\ell}$ that results in a pair of merged electron showers in the electromagnetic calorimeter (ECAL). Nevertheless, when the merged showers are reconstructed in the ECAL, a mass resolution of 1.8% is achieved. Important backgrounds include the irreducible contributions from the initial- and final-state photon radiation in Drell–Yan production, and Drell–Yan events with additional jets where a jet is misidentified as a photon.

In addition, a search is performed for H $\to$ (J/ψ)$\gamma \to \mu\mu\gamma$ decay for $m_{\mathrm{H}} = 125$ GeV, which is sensitive to the Higgs boson coupling to charm quark and a promising way to access the couplings of the Higgs boson to the second generation quarks at the LHC. In the SM this decay occurs through two main processes: direct coupling of the Higgs boson to charm (Fig. 2a), and the usual t/W loop, where the radiated γ^* converts to a $c\bar{c}$ in a resonant state (Fig. 2b). The two amplitudes interfere destructively and the second one dominates [6, 7]. For the SM Higgs boson with $m_{\mathrm{H}} = 125$ GeV, the branching fraction is predicted to be 2.8×10^{-6}. A search by the ATLAS Collaboration for this decay is described in Ref. [14].

The results presented in this paper are based on proton-proton collision data recorded in 2012 with the CMS detector at a centre-of-mass energy $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1}.

2 CMS detector and trigger

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [15]. The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, the ECAL, and a hadron calorimeter (HCAL). Charged-particle trajectories are measured by silicon pixel and strip trackers, covering $0 \leq \phi \leq 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity. A lead tungstate crystal ECAL surrounds the tracking volume. It is comprised of a barrel region $|\eta| < 1.48$ and two endcaps that extend up to $|\eta| = 3$. A brass and scintillator HCAL surrounds ECAL and also covers the region $|\eta| < 3$. Iron forward calorimeters with quartz fibers, read out by photomultipliers, extend the calorimetric coverage up to $|\eta| = 5$. A lead and silicon-strip preshower detector is located in front of the ECAL endcaps. Muons are identified and measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, allowing energy balance measurements in the plane transverse to the beam direction.

A two-tier trigger system selects collision events of interest for physics analysis. Two triggers are used in the current analysis. In the muon channel, the trigger requires a single muon and a photon, both with p_{T} greater than 22 GeV. In the electron channel the $\gamma^* \to \mathrm{ee}$ process at low dielectron invariant mass mimics a photon at the trigger level. For this reason, a diphoton trigger is used in the electron channel, for $\gamma + \gamma^*$ final state. The trigger requires a leading (subleading) photon with $p_{\mathrm{T}} > 26\,(18)$ GeV. The diphoton trigger is inefficient for events with high dielectron invariant mass ($m_{\mathrm{ee}} > 2\,\mathrm{GeV}$) due to the isolation and shower shape requirements. The available dielectron triggers cannot be used to select events with $2 < m_{\mathrm{ee}} < 20\,\mathrm{GeV}$ because they also require isolation, and the p_{T} requirement made on the subleading lepton is too high.

3 Event reconstruction

The photon energy is reconstructed from a sum of signals in the ECAL crystals [16]. The ECAL signals are calibrated and corrected [17], and a multivariate regression technique, developed for the $\mathrm{H} \to \gamma\gamma$ analysis [18], is used to determine the final energy of the photon [16]. The neighboring ECAL crystals with energy deposition are combined into clusters, and the collection of clusters that contain the energy of a photon or an electron is called a supercluster. Identification criteria are applied to distinguish photons from jets and electrons. The observables used in the photon identification criteria are: the isolation variables, the ratio of the energy in the HCAL towers behind the supercluster to the electromagnetic energy in the supercluster; the transverse width in η of the electromagnetic shower; and the number of charged tracks matched to the supercluster. The efficiency of the photon identification is measured using $\mathrm{Z} \to \mathrm{ee}$ data by reconstructing the electron showers as photons, and found to be 80 (88%) at a transverse energy $> 30\,(50)$ GeV and $|\eta| < 1.44$.

Muon candidates are reconstructed in the tracker and identified by the particle-flow global event reconstruction algorithm [19, 20] using hits in the tracker and the muon systems. This approach allows us to maintain a high efficiency independent of the dimuon invariant mass and to reconstruct muons with p_{T} as low as 4 GeV. Muons from $\gamma^* \to \mu\mu$ internal conversions are expected to be isolated from other particles. A cone of size $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ is constructed around the momentum direction of each muon candidate [21]. The relative isolation of the muon is quantified by summing the p_{T} of all photons, charged and neutral hadrons within this cone, and then dividing by the muon p_{T}. The resulting quantity, corrected for additional underlying event activity due to pileup events, is required to be less than 0.4 for the leading muon. The isolation requirement rejects misidentified leptons and background arising from hadronic jets. The $\Delta R(\mu\mu)$ separation between the two muons is small due to their low invariant mass (as shown in Fig. 3) and high p_{T} of the γ^* in $\mathrm{H} \to \gamma^*\gamma$ decays. Hence, no isolation requirement is applied to the subleading muons as they are already within the isolation cone of the leading muons in most events. Dimuon identification and isolation efficiency of about 80% is obtained.

In the electron channel of the $\mathrm{H} \to \gamma^*\gamma \to \ell\ell\gamma$ decay, the two electrons produced in the $\gamma^* \to \mathrm{ee}$ process are even closer to each other than in the muon channel, since the $m_{\ell\ell}$ is smaller (Fig. 3). Therefore, their energy deposits in the ECAL are merged into one supercluster giving rise to a unique signature. To identify these merged electrons, two tracks associated to the supercluster are required. A Gaussian sum filter (GSF) algorithm is used to reconstruct the electron tracks [22]. The supercluster energy must correspond to $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and be located in the ECAL barrel ($|\eta| < 1.44$). The scalar sum $p_{\mathrm{T}}^{\mathrm{e}_1} + p_{\mathrm{T}}^{\mathrm{e}_2}$ of the corresponding two GSF tracks must exceed 44 GeV. Both GSF tracks are required to have no more than one missing hit in the pixel detector in order to reduce the background from photons converting to $\mathrm{e}^+\mathrm{e}^-$ in the detector material. A multivariate discriminator is trained to separate the $\gamma^* \to \mathrm{ee}$ objects from jets or single electrons. The input variables for the training include lateral shower shape variables, the median energy density in the event to take into account the pileup dependence, and the kinematic information from the supercluster and tracks. A combined reconstruction and selection efficiency of ∼40% is achieved for the signal. For comparison, the efficiency for a single isolated electron with similar p_{T} is ∼88% [23].

4 Simulated samples

The description of the Higgs boson signal used in the search is obtained from simulated events. The samples for the Dalitz signal are produced at leading-order using the MADGRAPH 5 matrix-element generator [24] with the ANO-HEFT model [25], interfaced with PYTHIA 6.426 [26], for the gluon and vector boson fusion processes, and for associated production with a vector boson. Associated production with a $\mathrm{t\bar{t}}$ pair is ignored because of its small contribution. The sample for $\mathrm{H} \to (\mathrm{J}/\psi)\gamma$ process is produced with the PYTHIA 8.153 generator [27], and reweighted to simulate 100% polarization of the J/ψ. The parton distribution function (PDF) set used to produce these samples is given by CTEQ6L1 [28]. The SM Higgs boson production cross sections are taken from Ref. [11]. The branching fractions for $\mathrm{H} \to \gamma^*\gamma$ are estimated using MCFM 6.6 [29] and for $\mathrm{H} \to (\mathrm{J}/\psi)\gamma$ are taken from Ref. [6]. For the SM Higgs boson in the mass range of 120–150 GeV, the $\mathrm{H} \to \gamma^*\gamma \to \mu\mu\gamma\,(\mathrm{ee}\gamma)$ branching fraction is expected to be between $2.0\,(4.5) \times 10^{-5}$ and $3.3\,(7.5) \times 10^{-5}$ for $m_{\ell\ell}$ below 20 GeV. The expected branching fraction for $\mathrm{H} \to (\mathrm{J}/\psi)\gamma$ is $(2.8 \pm 0.2) \times 10^{-6}$ for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$, which is further suppressed due to the J/ψ meson decay to muons, $\mathcal{B}(\mathrm{J}/\psi \to \mu\mu) = 0.059$.

The simulation aims to include all known effects and the conditions of real data taking in CMS. Some residual differences between the data and simulation are taken into account by reweighting the simulated events with scale factors. Systematic uncertainties are assigned to cover imperfect knowledge of residual differences. Scale factors are implemented to match the distribution of primary vertices, the photon identification and isolation efficiency, and the muon isolation efficiency. No corrections are applied to the muon and electron identification and trigger efficiencies, but an uncertainty is assigned as described in Section 7.

The energy and momentum resolution of muons and photons in simulated events are corrected to match that in data. The energy scale of muons (photons) is corrected to that found in $\mathrm{Z} \to \mu\mu\,(\mathrm{ee})$ events. For the electrons, no resolution or scale corrections are applied because of their unique topology, and the absence of a data-driven method to derive those corrections. Therefore, we rely on the simulation of the $\gamma^* \to \mathrm{ee}$ process and assign uncertainties sufficient to cover any possible discrepancy in the scale and resolution between data and simulation.

5 Event selection

Events are required to pass the muon plus photon trigger in the $\mu\mu\gamma$ final state and the diphoton triggers in the $\mathrm{ee}\gamma$ final state. The trigger efficiency for signal events after the selection

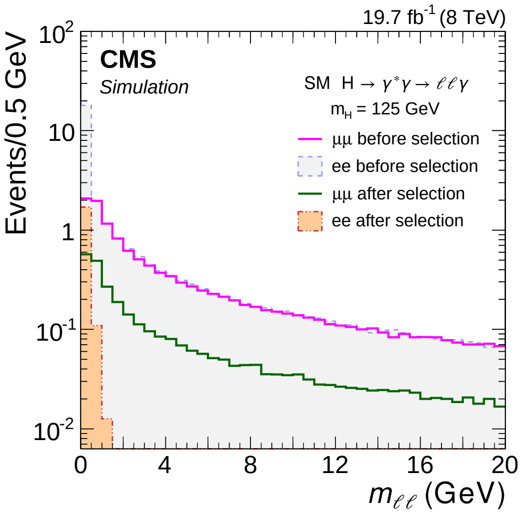

Figure 3: The invariant mass of the dilepton system in signal simulation for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$. Distributions are shown for muon and electron channels, before and after selection. The invariant mass before selection is obtained from the leptons at the generator level, while after selection the reconstructed invariant mass is used.

requirements described below is 85% (90%) in the muon (electron) channel, as measured from the simulated samples.

The muons (electrons) are required to be within $|\eta| < 2.4\,(1.44)$, while the photon is required to be within $|\eta| < 1.44$. The invariant mass of the $\ell\ell\gamma$ system, $m_{\ell\ell\gamma}$, is required to satisfy $110 < m_{\ell\ell\gamma} < 170\,\mathrm{GeV}$. The photon and dilepton momenta both must satisfy $p_{\mathrm{T}} > 0.3 \cdot m_{\ell\ell\gamma}$ requirement, which is optimized for high signal efficiency and background rejection.

On average, there are 21 pp interactions within the same bunch crossing in the 8 TeV data, which result in about 16 collision vertices reconstructed in each event. The vertex with the highest scalar sum of the p_{T}^2 of its associated tracks is taken to correspond to the primary interaction vertex. The primary vertex must have the reconstructed longitudinal position (z) within 24 cm of the geometric centre of the detector and the transverse position (x-y) within 2 cm of the beam interaction region. The lepton tracks from $\gamma^* \to \mu\mu$ (ee) are required to originate from the primary vertex, and to have transverse and longitudinal impact parameters with respect to that vertex smaller than 2.0 (0.2) mm and 5 (1) mm, respectively.

The muons must be oppositely charged, and have $p_{\mathrm{T}} > 23\,(4)\,\mathrm{GeV}$ for the leading (subleading) lepton. The p_{T} requirement on the leading muon is driven by the trigger threshold, and on the subleading muon by the minimum energy needed to reach the muon system, while maintaining high reconstruction efficiency. In the electron channel, no additional selection on p_{T} of the GSF tracks is necessary, beyond those described in Section 3. Finally, in both muon and electron channels, the separation between each lepton and the photon is required to satisfy $\Delta R > 1$ in order to suppress Drell–Yan background events with final-state radiation.

The dilepton invariant mass in the muon channel is required to be less than 20 GeV to reject contributions from pp → γZ and to suppress interference effects from the H → γZ process and the box diagrams shown in Fig. 1. Events with a dimuon mass in the ranges $2.9 < m_{\mu\mu} < 3.3\,\mathrm{GeV}$ and $9.3 < m_{\mu\mu} < 9.7\,\mathrm{GeV}$ are rejected to avoid the $\mathrm{J}/\psi \to \mu\mu$ and $\Upsilon \to \mu\mu$ contamination. In the electron channel the invariant mass, constructed from the two GSF tracks, is required to satisfy $m_{\mathrm{ee}} < 1.5\,\mathrm{GeV}$. The $m_{\ell\ell}$ distributions for simulated signal events are shown in Fig. 3 in the muon and electron channels.

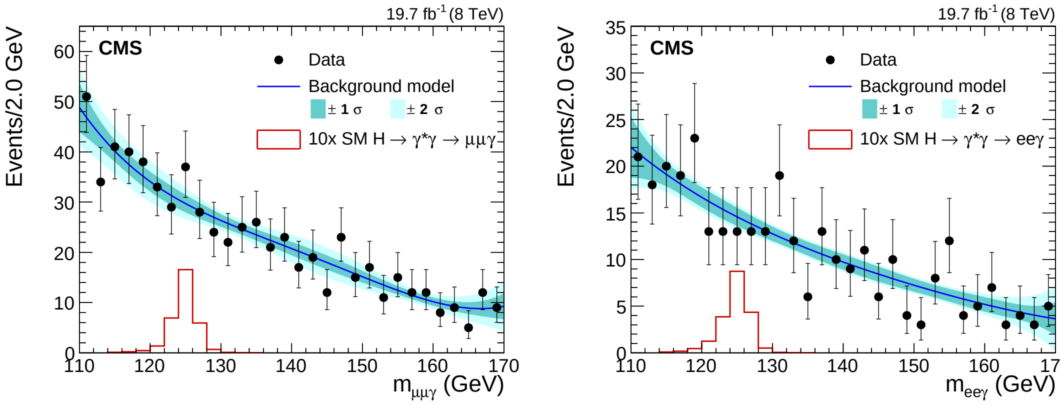

Figure 4: The $m_{\mu\mu\gamma}$ (left) and $m_{\mathrm{ee}\gamma}$ (right) spectra for 8 TeV data (points with error bars), together with the result of a background-only fit to the data. The 1σ and 2σ uncertainty bands represent the uncertainty in the parameters of the fitted function. The expected contribution from the SM Higgs boson signal with $m_{\mathrm{H}} = 125\,\mathrm{GeV}$, scaled up by a factor of 10, is shown as a histogram.

In the search for the $\mathrm{H} \to (\mathrm{J}/\psi)\gamma \to \mu\mu\gamma$, both p_{T}^{γ} and $p_{\mathrm{T}}^{\mu\mu} > 40\,\mathrm{GeV}$ are required, and the events are selected with $2.9 < m_{\mu\mu} < 3.3\,\mathrm{GeV}$.

The observed yields after the event selection described above are listed in Table 1. In the electron channel, there is also a contribution from the $\mathrm{H} \to \gamma\gamma$ process due to unidentified conversions, which is about 15% of the $\mathrm{H} \to \gamma^*\gamma$ signal (0.2 events at $m_{\mathrm{H}} = 125\,\mathrm{GeV}$). This contribution is considered as a background to $\mathrm{H} \to \gamma^*\gamma$, and negligible compared to the continuum background estimated from the fit to data described in the next section.

Table 1: The expected signal yield and the number of events in data, for an integrated luminosity of 19.7 fb^{-1}. Signal events are presented before and after applying the full selection criteria described in the text. In the $(\mathrm{J}/\psi)\gamma$ sub-category only the $\mathrm{J}/\psi \to \mu\mu$ decay is considered, and the signal yield is a sum of two contributions: $\mathrm{H} \to (\mathrm{J}/\psi)\gamma \to \mu\mu\gamma$ and $\mathrm{H} \to \gamma^*\gamma \to \mu\mu\gamma$, where the dimuon mass distribution is non-resonant.

Sample	Signal events before selection $m_{\mathrm{H}} = 125\,\mathrm{GeV}$	Signal events after selection $m_{\mathrm{H}} = 125\,\mathrm{GeV}$	Number of events in data $120 < m_{\ell\ell\gamma} < 130\,\mathrm{GeV}$
$\mu\mu\gamma$	13.9	3.3	151
$\mathrm{ee}\gamma$	25.8	1.9	65
$(\mathrm{J}/\psi \to \mu\mu)\gamma$	$0.065(\mathrm{J}/\psi) + 0.32$ (non-res.)	$0.014(\mathrm{J}/\psi) + 0.078$ (non-res.)	12

6 Background and signal modeling

The background is modeled by fitting a polynomial function to the $\ell\ell\gamma$ mass distributions in data. An unbinned maximum likelihood fit is performed over the range $110 < m_{\ell\ell\gamma} < 170\,\mathrm{GeV}$. Fig. 4 shows the $m_{\ell\ell\gamma}$ spectra, which are fitted with polynomial functions of fourth degree. The reduced χ^2 of the fits are 0.5 and 0.7 for the muon and electron channels, respectively. Even though the search is limited to $120 < m_{\mathrm{H}} < 150\,\mathrm{GeV}$, the fits to the $m_{\ell\ell\gamma}$ spectra are performed over a wider range, giving a better modeling of the background, particularly at the edges of the search range. The degree of the polynomials is chosen following a procedure similar to the one described in Ref. [30]. This procedure ensures that the potential bias due to the background modeling is at least five times smaller than statistical uncertainty.

For the $\mathrm{H} \to (\mathrm{J}/\psi)\gamma$ search, where only the single Higgs boson mass hypothesis $m_{\mathrm{H}} = 125\,\mathrm{GeV}$

is investigated, a fit to a polynomial of second degree is performed over the 110–150 GeV mass range (Fig. 5).

The signal model in all three cases is obtained from an unbinned fit to the mass distribution of the corresponding sample of simulated events to a Crystal Ball function [31] plus a Gaussian function.

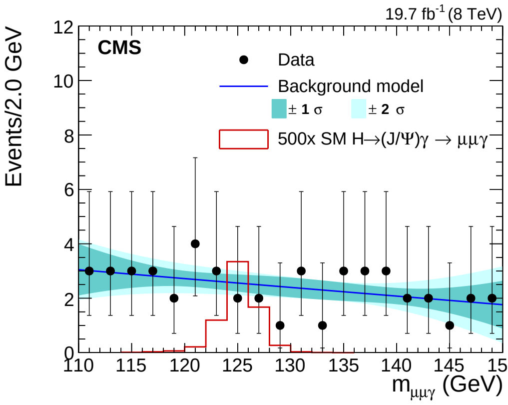

Figure 5: The $m_{\mu\mu\gamma}$ distribution for events with $2.9 < m_{\mu\mu} < 3.3$ GeV for 8 TeV data (points with error bars), together with the result of a background-only fit to the data. The 1σ and 2σ uncertainty bands represent the uncertainty in the parameters of the fitted function. The expected contribution from the $\mathrm{H} \to (\mathrm{J}/\psi)\gamma \to \mu\mu\gamma$ process of the SM H with $m_{\mathrm{H}} = 125$ GeV, scaled up by a factor of 500, is shown as a histogram.

7 Results

The data are used to derive upper limits on the Higgs boson cross section times branching fraction, $\sigma(\mathrm{pp} \to \mathrm{H})\,\mathcal{B}(\mathrm{H} \to \gamma^*\gamma \to \ell\ell\gamma)$ divided by that expected for a SM Higgs boson, for $m_{\ell\ell} < 20$ GeV. No significant excess above background is observed in the full mass range, $120 < m_{\mathrm{H}} < 150$ GeV, with a maximum excess of less than two standard deviations. In the electron channel a correction is made to account for the events that are removed by the requirement of $m_{\mathrm{ee}} < 1.5$ GeV due to the trigger and reconstruction inefficiencies described above.

The exclusion limits are calculated using the modified frequentist $\mathrm{CL_s}$ method [32–36]. An unbinned evaluation over the full mass range of data is used. The uncertainty in the limit is dominated by the size of the data sample and systematic uncertainties have a small impact.

The systematic uncertainty in the limits results only from the uncertainty in the signal description, as the background is obtained from data and biases in the fitting procedure have been found to be negligible. A summary of the systematic uncertainties is given in Table 2. The uncertainty can be separated into the uncertainty resulting from theoretical predictions and from the uncertainty in detector reconstruction and selection efficiency.

Theoretical uncertainties come from the effects of the PDF choice on signal cross section, the missing higher-order calculations (scale) [38–42], and the uncertainty in the prediction on the Higgs boson decay branching fraction [4, 11]. The uncertainty due to the muon reconstruction efficiency, 11%, is obtained from data using $\mathrm{J}/\psi \to \mu\mu$ events. It is dominated by the statistical uncertainty of the data sample. In the electron channel, the corresponding uncertainty, 3.5%, is obtained from simulation. The 11% uncertainty estimated for the muon identification efficiency is sufficiently small and it has no impact on our result, thus no simulation study was attempted, although it could greatly reduce the uncertainty.

Table 2: Systematic uncertainties affecting the signal

Source	Uncertainty
Integrated luminosity (ref. [37])	2.6%
Theoretical uncertainties:	
PDF	2.6–7.5%
Scale	0.2–7.9%
$H \to \gamma^* \gamma \to \ell\ell\gamma$ branching fraction	10%
Experimental uncertainties:	
Pileup reweighting	0.8%
Trigger efficiency, μ (e) channel	4 (2)%
Muon reconstruction efficiency	11%
Electron reconstruction efficiency	3.5%
Photon reconstruction efficiency	0.6%
$m_{\ell\ell\gamma}$ scale, μ (e) channel	0.1 (0.5)%
$m_{\ell\ell\gamma}$ resolution, μ (e) channel	10 (10)%

The expected and observed individual and combined $\mu\mu\gamma$ and eeγ limits are shown in Fig. 6. The limits are calculated at 1 GeV intervals in the 120–150 GeV mass range. The median expected exclusion limits at 95% confidence level (CL) are between 6 and 10 times the SM prediction and the observed limit ranges between about 5 and 11 times the SM. The observed (expected) limit for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ is 6.7 ($5.9^{+2.8}_{-1.8}$) times the SM prediction.

The 95% CL exclusion limits on $\sigma(\mathrm{pp} \to \mathrm{H})\,\mathcal{B}(\mathrm{H} \to \mu\mu\gamma)$ for a narrow scalar particle without assuming the decay kinematics of a SM Higgs boson, in the muon channel, are shown in Fig. 7. The observed (expected) limit for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ is 7.3 ($5.2^{+2.4}_{-1.6}$) fb. The total signal efficiency is 24% and almost independent of the dimuon invariant mass. In the electron channel, however, this efficiency depends on the dielectron mass, since it is strongly shaped by the selection. For this reason the corresponding limit in the electron channel is not evaluated.

Additionally, for the SM Higgs boson with $m_{\mathrm{H}} = 125\,\mathrm{GeV}$, we place an upper limit for a $2.9 < m_{\ell\ell} < 3.3\,\mathrm{GeV}$ region in the muon channel: $\sigma(\mathrm{pp} \to \mathrm{H})\,\mathcal{B}(\mathrm{H} \to \mu\mu\gamma) < 1.80\,\mathrm{fb}$, while the expected limit is $1.90 \pm 0.97\,\mathrm{fb}$. One can interpret this result as an upper limit on $\sigma(\mathrm{pp} \to \mathrm{H})\,\mathcal{B}(\mathrm{H} \to (\mathrm{J}/\psi)\gamma \to \mu\mu\gamma)$ and obtain for the branching fraction, $\mathcal{B}(\mathrm{H} \to (\mathrm{J}/\psi)\gamma) < 1.5 \times 10^{-3}$ at 95% CL, which is about 540 times the prediction in Ref. [6]. The limit on the branching fraction at 90% CL is $\mathcal{B}(\mathrm{H} \to (\mathrm{J}/\psi)\gamma) < 1.2 \times 10^{-3}$. The number of events present in this $m_{\mu\mu}$ mass window coming from the $\mathrm{H} \to \gamma^*\gamma \to \mu\mu\gamma$ is large compared to the $\mathrm{H} \to (\mathrm{J}/\psi)\gamma \to \mu\mu\gamma$ (as shown in Table 1). On the other hand it is small compared to the total background, hence it is considered as a part of the background when extracting the limit on $\mathcal{B}(\mathrm{H} \to (\mathrm{J}/\psi)\gamma)$.

8 Summary

A search for a Higgs boson decay $\mathrm{H} \to \gamma^*\gamma \to \ell\ell\gamma$ is presented. No excess above the background predictions has been found in the three-body invariant mass range $120 < m_{\ell\ell\gamma} < 150\,\mathrm{GeV}$. Limits on the Higgs boson production cross section times the $\mathrm{H} \to \gamma^*\gamma \to \ell\ell\gamma$ branching fraction divided by the SM values have been derived. The observed limit for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ is about 6.7 times the SM prediction. Limits at 95% CL on $\sigma(\mathrm{pp} \to \mathrm{H})\,\mathcal{B}(\mathrm{H} \to \mu\mu\gamma)$ for a narrow resonance are also obtained in the muon channel. The observed limit for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ is 7.3 fb. Events consistent with the J/ψ in dimuon invariant mass are used to set a 95% CL limit on the branching fraction $\mathcal{B}(\mathrm{H} \to (\mathrm{J}/\psi)\gamma) < 1.5 \times 10^{-3}$, that is, 540 times the SM prediction for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$.

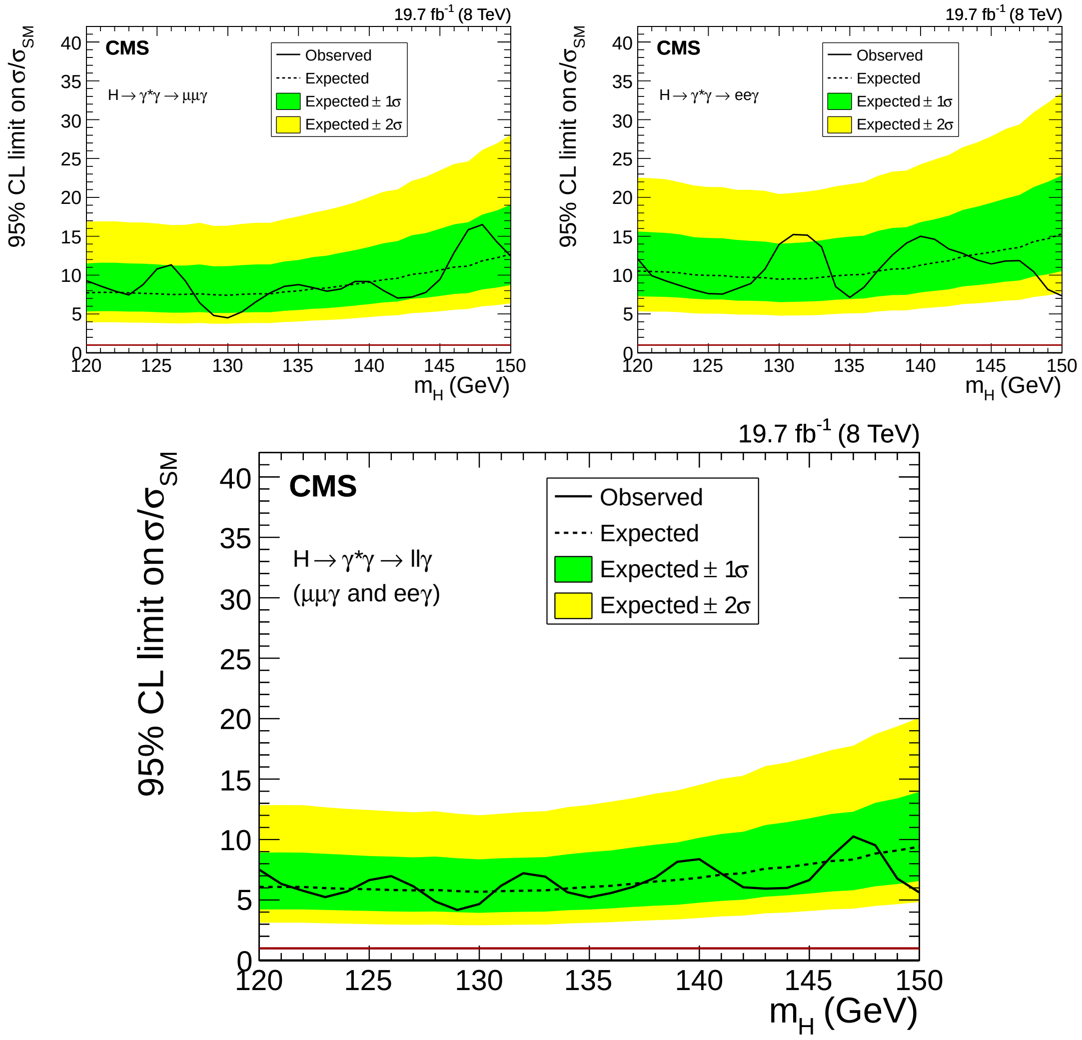

Figure 6: The 95% CL exclusion limit, as a function of the mass hypothesis, m_{H}, on σ/σ_{SM}, the cross section times the branching fraction of a Higgs boson decaying into a photon and a lepton pair with $m_{\ell\ell} < 20\,\mathrm{GeV}$, divided by the SM value. (Upper left) muon, (upper right) electron channels, (bottom) statistical combination of the results in the two channels

.

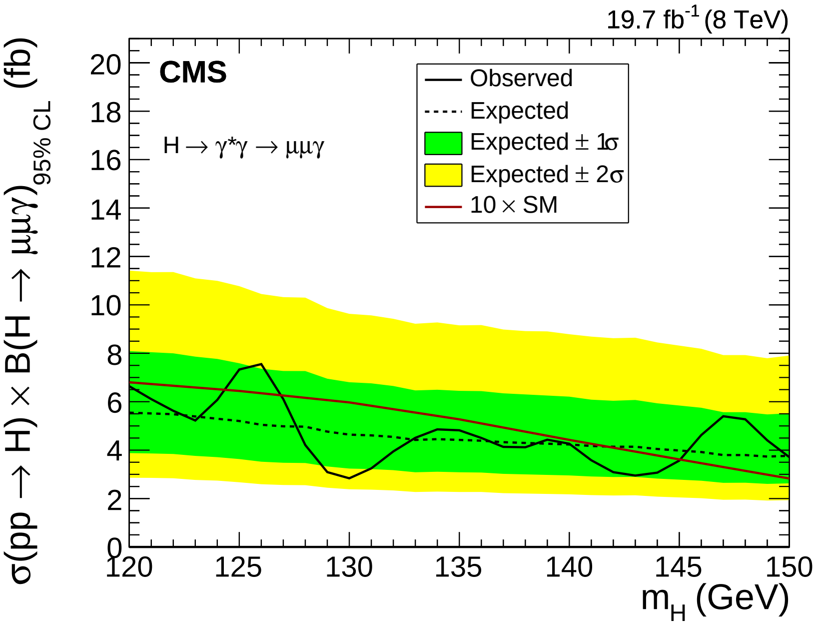

Figure 7: The 95% CL exclusion limit on $\sigma(\mathrm{pp} \to \mathrm{H})\,\mathcal{B}(\mathrm{H} \to \mu\mu\gamma)$, with $m_{\mu\mu} < 20\,\mathrm{GeV}$, for a Higgs-like particle, as a function of the mass hypothesis, m_{H}.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di

San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Programme by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); and the Welch Foundation.

References

[1] A. Abbasabadi, D. Bowser-Chao, D. A. Dicus, and W. W. Repko, "Radiative Higgs boson decays $\mathrm{H} \to f f \gamma$", *Phys. Rev. D* **55** (1997) 5647, `doi:10.1103/PhysRevD.55.5647`, `arXiv:hep-ph/9611209`.

[2] L. B. Chen, C. F. Qiao, and R. L. Zhu, "Reconstructing the 125 GeV SM Higgs boson through $\ell\bar{\ell}\gamma$", *Phys. Lett. B* **726** (2013) 306, `doi:10.1016/j.physletb.2013.08.050`, `arXiv:1211.6058`.

[3] D. A. Dicus and W. W. Repko, "Calculation of the decay $\mathrm{H} \to \mathrm{e}\bar{\mathrm{e}}\gamma$", *Phys. Rev. D* **87** (2013) 077301, `doi:10.1103/PhysRevD.87.077301`, `arXiv:1302.2159`.

[4] G. Passarino, "Higgs boson production and decay: Dalitz sector", *Phys. Lett. B* **727** (2013) 424, `doi:10.1016/j.physletb.2013.10.052`, `arXiv:1308.0422`.

[5] G. T. Bodwin, F. Petriello, S. Stoynev, and M. Velasco, "Higgs boson decays to quarkonia and the $\mathrm{H}\bar{c}c$ coupling", *Phys. Rev. D* **88** (2013) 053003, `doi:10.1103/PhysRevD.88.053003`, `arXiv:1306.5770`.

[6] G. T. Bodwin et al., "Relativistic corrections to Higgs boson decays to quarkonia", *Phys. Rev. D* **90** (2014) 1130, `doi:10.1103/PhysRevD.90.113010`, `arXiv:1407.6695`.

[7] M. König and M. Neubert, "Exclusive radiative Higgs decays as probes of light-quark Yukawa couplings", *JHEP* **08** (2015) 012, `doi:10.1007/JHEP08(2015)012`, `arXiv:1505.03870`.

[8] Y. Sun, H. Chang, and D. Gao, "Higgs decays to $\gamma\ell^{+}\ell^{-}$ in the standard model", *JHEP* **05** (2013) 061, `doi:10.1007/JHEP05(2013)061`, `arXiv:1303.2230`.

[9] A. Korchin and V. Kovalchuk, "Angular distribution and forward-backward asymmetry of the Higgs-boson decay to photon and lepton pair", *Eur. Phys. J. C* **74** (2014) `doi:10.1140/epjc/s10052-014-3141-7`, `arXiv:1408.0342`.

[10] A. Firan and R. Stroynowski, "Internal conversions in Higgs decays to two photons", *Phys. Rev. D* **76** (2007) 057301, `doi:10.1103/PhysRevD.76.057301`, `arXiv:0704.3987`.

[11] S. Heinemeyer et al., "Handbook of LHC Higgs cross sections: 3. Higgs properties", CERN Report CERN-2013-004, 2013. `doi:10.5170/CERN-2013-004`, `arXiv:1307.1347`.

[12] ATLAS Collaboration, "Search for Higgs boson decays to a photon and a Z boson in pp collisions at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS detector", *Phys. Lett. B* **732** (2014) 8, `doi:10.1016/j.physletb.2014.03.015`, `arXiv:1402.3051`.

[13] CMS Collaboration, "Search for a Higgs boson decaying into a Z and a photon in pp collisions at $\sqrt{s} = 7$ and 8 TeV", *Phys. Lett. B* **726** (2013) 587, `doi:10.1016/j.physletb.2013.09.057`, `arXiv:1307.5515`.

[14] ATLAS Collaboration, "Search for Higgs and Z boson decays to J/$\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS detector", *Phys. Rev. Lett.* **114** (2015) 121801, `doi:10.1103/PhysRevLett.114.121801`, `arXiv:1501.03276`.

[15] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, `doi:10.1088/1748-0221/3/08/S08004`.

[16] CMS Collaboration, "Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$", *JINST* **10** (2015) P08010, `doi:10.1088/1748-0221/10/08/P08010`, `arXiv:1502.02702`.

[17] CMS Collaboration, "Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s} = 7\,\text{TeV}$", *JINST* **8** (2013) P09009, `doi:10.1088/1748-0221/8/09/P09009`, `arXiv:1306.2016`.

[18] CMS Collaboration, "Observation of the diphoton decay of the Higgs boson and measurement of its properties", *Eur. Phys. J. C* **74** (2014) 3076, `doi:10.1140/epjc/s10052-014-3076-z`, `arXiv:1407.0558`.

[19] CMS Collaboration, "Particle–flow event reconstruction in CMS and performance for jets, taus, and $E_{\mathrm{T}}^{\text{miss}}$", CMS Physics Analysis Summary CMS-PAS-PFT-09-001, CERN, 2009.

[20] CMS Collaboration, "Commissioning of the particle–flow event reconstruction with the first LHC collisions recorded in the CMS detector", CMS Physics Analysis Summary CMS-PAS-PFT-10-001, CERN, 2010.

[21] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7\,\text{TeV}$", *JINST* **7** (2012) P10002, `doi:10.1088/1748-0221/7/10/P10002`, `arXiv:1206.4071`.

[22] W. Adam, R. Frühwirth, A. Strandlie, and T. Todor, "Reconstruction of electrons with the Gaussian-Sum Filter in the CMS Tracker at the LHC", Technical Report CMS-NOTE-2005-001, CERN, 2005.

[23] CMS Collaboration, "Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$", *JINST* **10** (2015) P06005, `doi:10.1088/1748-0221/10/06/P06005`, `arXiv:1502.02701`.

[24] J. Alwall et al., "MadGraph 5: going beyond", *JHEP* **06** (2011) 128, `doi:10.1007/JHEP06(2011)128`, `arXiv:1106.0522`.

[25] T. Corbett, O. J. P. Éboli, J. Gonzalez-Fraile, and M. C. Gonzalez-Garcia, "Constraining anomalous Higgs boson interactions", *Phys. Rev. D* **86** (2012) 075013, `doi:10.1103/PhysRevD.86.075013`, `arXiv:1207.1344`.

[26] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 physics and manual", *JHEP* **05** (2006) 026, `doi:10.1088/1126-6708/2006/05/026`, `arXiv:hep-ph/0603175`.

[27] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "A brief introduction to PYTHIA 8.1", *Comput. Phys. Commun.* **178** (2008) 852, `doi:10.1016/j.cpc.2008.01.036`, `arXiv:0710.3820`.

[28] J. Pumplin et al., "New generation of parton distributions with uncertainties from global QCD analysis", *JHEP* **07** (2002) 012, `doi:10.1088/1126-6708/2002/07/012`, `arXiv:hep-ph/0201195`.

[29] J. M. Campbell and R. Ellis, "MCFM for the Tevatron and the LHC", *Nucl. Phys. Proc. Suppl.* **205-206** (2010) 10, `doi:10.1016/j.nuclphysbps.2010.08.011`, `arXiv:1007.3492`.

[30] CMS Collaboration, "Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV", *JHEP* **06** (2013) 081, `doi:10.1007/JHEP06(2013)081`, `arXiv:1303.4571`.

[31] M. J. Oreglia, "A study of the reactions $\psi' \to \gamma\gamma\psi$". PhD thesis, Stanford University, 1980. SLAC Report SLAC-R-236, see Appendix D.

[32] A. L. Read, "Presentation of search results: the $\mathrm{CL_s}$ technique", *J. Phys. G* **28** (2002) 2693, `doi:10.1088/0954-3899/28/10/313`.

[33] T. Junk, "Confidence level computation for combining searches with small statistics", *Nucl. Instrum. Meth. A* **434** (1999) 435, `doi:10.1016/S0168-9002(99)00498-2`, `arXiv:hep-ex/9902006`.

[34] ATLAS and CMS Collaborations, "Procedure for the LHC Higgs boson search combination in summer 2011", Technical Report ATL-PHYS-PUB-2011-011, CMS-NOTE-2011/005, CERN, 2011.

[35] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, `doi:10.1140/epjc/s10052-011-1554-0`, `arXiv:1007.1727`.

[36] L. Moneta et al., "The RooStats Project", in *13th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT2010)*. SISSA, 2010. `arXiv:1009.1003`.

[37] CMS Collaboration, "CMS luminosity based on pixel cluster counting - Summer 2013 update", CMS Physics Analysis Summary CMS-PAS-LUM-13-001, CERN, 2013.

[38] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, "Parton distributions for the LHC", *Eur. Phys. J. C* **63** (2009) 189, `doi:10.1140/epjc/s10052-009-1072-5`, `arXiv:0901.0002`.

[39] H. Lai et al., "New parton distributions for collider physics", *Phys. Rev. D* **82** (2010) 74024, `doi:10.1103/PhysRevD.82.074024`, `arXiv:1007.2241`.

[40] S. Alekhin et al., "The PDF4LHC Working Group Interim Report", (2011). `arXiv:1101.0536`.

[41] M. Botje et al., "The PDF4LHC Working Group Interim Recommendations", (2011). `arXiv:1101.0538`.

[42] NNPDF Collaboration, "Impact of heavy quark masses on parton distributions and LHC phenomenology", *Nucl. Phys. B* **849** (2011) 296, `doi:10.1016/j.nuclphysb.2011.03.021`, `arXiv:1101.1300`.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth[1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler[1], V. Knünz, A. König, M. Krammer[1], I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady[2], B. Rahbaran, H. Rohringer, J. Schieck[1], R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz[1]

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
P. Barria, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, D. Dobur, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang[3]

Ghent University, Ghent, Belgium
K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi[4], O. Bondu, S. Brochet, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco[5], J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov[6], L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium
N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, C. Hensel, C. Mora Herrera, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[7], A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[7], A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[b], A. De Souza Santos[b], S. Dogra[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], C.S. Moon[a,8], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, V. Genchev[†], R. Hadjiiska, P. Iaydjiev, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina[9], F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, D. Polic, I. Puljak

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger[10], M. Finger Jr.[10]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
R. Aly[11], S. Aly[11], E. El-khateeb[12], A. Lotfy[13], A. Mohamed[14], A. Radi[15,12], E. Salama[12,15], A. Sayed[12,15]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[16], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[16], X. Coubez, J.-C. Fontaine[16], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin[2], K. Skovpen, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[17]

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[10]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov[6]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann[2], A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras,

A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel[18], H. Jung, A. Kalogeropoulos, O. Karacheban[18], M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann[18], R. Mankel, I. Marfin[18], I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, D. Nowatschin, J. Ott, F. Pantaleo[2], T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann[2], U. Husemann, F. Kassel[2], I. Katkov[6], A. Kornmayer[2], P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Psallidas, I. Topsis-Giotis

University of Athens, Athens, Greece
A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece
I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath[19], F. Sikler, V. Veszpremi, G. Vesztergombi[20], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[21], J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary
M. Bartók[22], A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
P. Mal, K. Mandal, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U.Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, N. Nishu, J.B. Singh, G. Walia

University of Delhi, Delhi, India
Ashok Kumar, Arun Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, Sh. Jain, R. Khurana, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[2], L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India
T. Aziz, S. Banerjee, S. Bhowmik[23], R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu[24], G. Kole, S. Kumar, B. Mahakud, M. Maity[23], G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar[23], K. Sudhakar, N. Sur, B. Sutar, N. Wickramage[25]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami[26], A. Fahim[27], R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh[28], M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], C. Caputo[a,b], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,c], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a,2], R. Venditti[a,b], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[2], A.C. Benvenuti[a], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a,b], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], CSFNSM [c], Catania, Italy
G. Cappello[a], M. Chiorboli[a,b], S. Costa[a,b], F. Giordano[a], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Gonzi[a,b], V. Gori[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,b], L. Viliani[a,b]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
V. Calvelli[a,b], F. Ferro[a], M. Lo Vetere[a,b], M.R. Monge[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
L. Brianza, M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], B. Marzocchi[a,b,2], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], S. Di Guida[a,d,2], M. Esposito[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], G. Lanza[a], L. Lista[a], S. Meola[a,d,2], M. Merola[a], P. Paolucci[a,2], C. Sciacca[a,b], F. Thyssen

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], R. Carlin[a,b], A. Carvalho Antunes De Oliveira[a,b], P. Checchia[a], M. Dall'Osso[a,b,2], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], F. Gonella[a], A. Gozzelino[a], K. Kanishchev[a,c], M. Margoni[a,b], G. Maron[a,29], A.T. Meneguzzo[a,b], F. Montecassiano[a], M. Passaseo[a], J. Pazzini[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], M. Zanetti, P. Zotto[a,b], A. Zucchetta[a,b,2], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
L. Alunni Solestizi[a,b], M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b,2], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a,30], P. Azzurri[a], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], M.A. Ciocci[a,30], R. Dell'Orso[a], S. Donato[a,c,2], G. Fedi, L. Foà[a,c†], A. Giassi[a], M.T. Grippo[a,30], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,b], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A. Savoy-Navarro[a,31], A.T. Serban[a], P. Spagnolo[a], P. Squillacioti[a,30], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], G. D'imperio[a,b,2], D. Del Re[a,b], M. Diemoz[a], S. Gelli[a,b], C. Jorda[a], E. Longo[a,b], F. Margaroli[a,b], P. Meridiani[a], F. Micheli[a,b], G. Organtini[a,b], R. Paramatti[a], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], P. Traczyk[a,b,2]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c,2], S. Argiro[a,b], M. Arneodo[a,c], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], G. Dughera[a], L. Finco[a,b,2], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Musich[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], F. Ravera[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a], U. Tamponi[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b,2], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], C. La Licata[a,b], M. Marone[a,b], A. Schizzi[a,b], T. Umer[a,b], A. Zanetti[a]

Kangwon National University, Chunchon, Korea
S. Chang, A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea
J.A. Brochero Cifuentes, H. Kim, T.J. Kim, M.S. Ryu

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

Korea University, Seoul, Korea
S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea
H.D. Yoo

University of Seoul, Seoul, Korea
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali[32], F. Mohamad Idris[33], W.A.T. Wan Abdullah

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz[34], A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler, S. Reucroft

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev[35], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[36], E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
A. Bylinkin

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[37], I. Dremin[37], M. Kirakosyan, A. Leonidov[37], G. Mesyats, S.V. Rusakov, A. Vinogradov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, M. Dubinin[38], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[39], M. Ekmedzic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez,

J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain
H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi[40], M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, T. du Pree, N. Dupont, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli[41], L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi[42], M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas[43], D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres[20], N. Wardle, H.K. Wöhri, A. Zagozdzinska[44], W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, M. Rossini, A. Starodumov[45], M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[46], L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, S. Taroni, Y. Yang

National Central University, Chung-Li, Taiwan
M. Cardaci, C.P. Chang, K.H. Chen, T.H. Doan, C. Ferro, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
R. Bartek, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.F. Tsai, Y.M. Tzeng

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, S. Cerci[47], C. Dozen, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal[48], A. Kayis Topaksu, G. Onengut[49], K. Ozdemir[50], S. Ozturk[51], B. Tali[47], H. Topakli[51], M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, B. Bilin, S. Bilmis, B. Isildak[52], G. Karapinar[53], U.E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E.A. Albayrak[54], E. Gülmez, M. Kaya[55], O. Kaya[56], T. Yetkin[57]

Istanbul Technical University, Istanbul, Turkey
K. Cankocak, S. Sen[58], F.I. Vardarlı

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold[59], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[60], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, L. Thomas, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom
M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas[59], L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko[45], J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta[61], T. Virdee, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA
A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

Brown University, Providence, USA
J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA
R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny

University of California, San Diego, La Jolla, USA
J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[62], C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, I. Suarez, W. To, C. West, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan[†], S. Lammel, J. Linacre, D. Lincoln, R. Lipton,

T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, A. Whitbeck, F. Yang, H. Yin

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic[63], G. Mitselmakher, L. Muniz, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA
V. Bhopatkar, M. Hohlmann, H. Kalakhety, D. Mareskas-palcek, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

The University of Iowa, Iowa City, USA
B. Bilki[64], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[65], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[54], A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, K. Nash, M. Osherson, M. Swartz, M. Xiao, Y. Xin

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, R. Stringer, Q. Wang, J.S. Wood

Kansas State University, Manhattan, USA
I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, I. Svintradze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA
C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, K. Pedro, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, G.M. Innocenti, M. Klute, D. Kovalskyi,

Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. Mcginn, C. Mironov, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA
B. Dahmes, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, J. George, A. Godshalk, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northwestern University, Evanston, USA
K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA
A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[35], T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Purdue University, West Lafayette, USA
V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

Purdue University Calumet, Hammond, USA
N. Parashar, J. Stupak

Rice University, Houston, USA
A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti

The Rockefeller University, New York, USA
L. Demortier

Rutgers, The State University of New Jersey, Piscataway, USA
S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA
O. Bouhali[66], A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon[67], V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer[2]

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin, Madison, USA
D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Now at Helwan University, Cairo, Egypt
12: Now at Ain Shams University, Cairo, Egypt
13: Now at Fayoum University, El-Fayoum, Egypt
14: Also at Zewail City of Science and Technology, Zewail, Egypt
15: Also at British University in Egypt, Cairo, Egypt
16: Also at Université de Haute Alsace, Mulhouse, France
17: Also at Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Eötvös Loránd University, Budapest, Hungary
21: Also at University of Debrecen, Debrecen, Hungary
22: Also at Wigner Research Centre for Physics, Budapest, Hungary
23: Also at University of Visva-Bharati, Santiniketan, India
24: Now at King Abdulaziz University, Jeddah, Saudi Arabia
25: Also at University of Ruhuna, Matara, Sri Lanka
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
30: Also at Università degli Studi di Siena, Siena, Italy
31: Also at Purdue University, West Lafayette, USA
32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
34: Also at CONSEJO NATIONAL DE CIENCIA Y TECNOLOGIA, MEXICO, Mexico
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
37: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
38: Also at California Institute of Technology, Pasadena, USA
39: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
40: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
41: Also at National Technical University of Athens, Athens, Greece
42: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
43: Also at University of Athens, Athens, Greece
44: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
45: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
46: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
47: Also at Adiyaman University, Adiyaman, Turkey
48: Also at Mersin University, Mersin, Turkey
49: Also at Cag University, Mersin, Turkey
50: Also at Piri Reis University, Istanbul, Turkey
51: Also at Gaziosmanpasa University, Tokat, Turkey
52: Also at Ozyegin University, Istanbul, Turkey

53: Also at Izmir Institute of Technology, Izmir, Turkey
54: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
55: Also at Marmara University, Istanbul, Turkey
56: Also at Kafkas University, Kars, Turkey
57: Also at Yildiz Technical University, Istanbul, Turkey
58: Also at Hacettepe University, Ankara, Turkey
59: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
60: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
61: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
62: Also at Utah Valley University, Orem, USA
63: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
64: Also at Argonne National Laboratory, Argonne, USA
65: Also at Erzincan University, Erzincan, Turkey
66: Also at Texas A&M University at Qatar, Doha, Qatar
67: Also at Kyungpook National University, Daegu, Korea