EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

JHEP 07 (2018) 127
DOI: DOI:10.1007/JHEP07(2018)127

CERN-EP-2017-273
12th January 2024

Search for exclusive Higgs and Z boson decays to $\phi\gamma$ and $\rho\gamma$ with the ATLAS detector

The ATLAS Collaboration

A search for the exclusive decays of the Higgs and Z bosons to a ϕ or ρ meson and a photon is performed with a pp collision data sample corresponding to an integrated luminosity of up to 35.6 fb^{-1} collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the CERN Large Hadron Collider. These decays have been suggested as a probe of the Higgs boson couplings to light quarks. No significant excess of events is observed above the background, as expected from the Standard Model. Upper limits at 95% confidence level were obtained on the branching fractions of the Higgs boson decays to $\phi\gamma$ and $\rho\gamma$ of 5.0×10^{-4} and 10.4×10^{-4}, respectively. The corresponding 95% confidence level upper limits for the Z boson decays are 0.7×10^{-6} and 4.0×10^{-6} for $\phi\gamma$ and $\rho\gamma$, respectively.

1 Introduction

Following the observation [1, 2] of a Higgs boson, H, with a mass of approximately 125 GeV [3] by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC), the properties of its interactions with the electroweak gauge bosons have been measured extensively [4–6]. The coupling of the Higgs boson to leptons has been established through the observation of the $H \to \tau^+\tau^-$ channel [4, 7, 8], while in the quark sector indirect evidence is available for the coupling of the Higgs boson to the top-quark [4] and evidence for the Higgs boson decays into $b\bar{b}$ has been recently presented [9, 10]. Despite this progress, the Higgs boson interaction with the fermions of the first and second generations is still to be confirmed experimentally. In the Standard Model (SM), Higgs boson interactions to fermions are implemented through Yukawa couplings, while a wealth of beyond-the-SM theories predict substantial modifications. Such scenarios include the Minimal Flavour Violation framework [11], the Froggatt–Nielsen mechanism [12], the Higgs-dependent Yukawa couplings model [13], the Randall–Sundrum family of models [14], and the possibility of the Higgs boson being a composite pseudo-Goldstone boson [15]. An overview of relevant models of new physics is provided in Ref. [16].

The rare decays of the Higgs boson into a heavy quarkonium state, J/ψ or $\Upsilon(nS)$ with $n = 1, 2, 3$, and a photon have been suggested for probing the charm- and bottom-quark couplings to the Higgs boson [17–20] and have already been searched for by the ATLAS Collaboration [21], resulting in 95% confidence level (CL) upper limits of 1.5×10^{-3} and $(1.3, 1.9, 1.3) \times 10^{-3}$ on the branching fractions, respectively. The $H \to J/\psi\gamma$ decay mode has also been searched for by the CMS Collaboration [22], yielding the same upper limit. The corresponding SM predictions for these branching fractions [23] are $\mathcal{B}(H \to J/\psi\gamma) = (2.95 \pm 0.17) \times 10^{-6}$ and $\mathcal{B}(H \to \Upsilon(nS)\gamma) = \left(4.6^{+1.7}_{-1.2}, 2.3^{+0.8}_{-1.0}, 2.1^{+0.8}_{-1.1}\right) \times 10^{-9}$. The prospects for observing and studying exclusive Higgs boson decays into a meson and a photon with an upgraded High Luminosity LHC [16] or a future hadron collider [24] have also been studied.

Currently, the light (u, d, s) quark couplings to the Higgs boson are loosely constrained by existing data on the total Higgs boson width, while the large multijet background at the LHC inhibits the study of such couplings with inclusive $H \to q\bar{q}$ decays. Rare exclusive decays of the Higgs boson into a light meson, M, and a photon, γ, have been suggested as a probe of the couplings of the Higgs boson to light quarks and would allow a search for potential deviations from the SM prediction [23, 25, 26]. Specifically, the observation of the Higgs boson decay to a ϕ or $\rho(770)$ (denoted as ρ in the following) meson and a photon would provide sensitivity to its couplings to the strange-quark, and the up- and down-quarks, respectively. The expected SM branching fractions are $\mathcal{B}(H \to \phi\gamma) = (2.31 \pm 0.11) \times 10^{-6}$ and $\mathcal{B}(H \to \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$ [23]. The decay amplitude receives two main contributions that interfere destructively. The first is referred to as "direct" and proceeds through the $H \to q\bar{q}$ coupling, where subsequently a photon is emitted before the $q\bar{q}$ hadronises exclusively to M. The second is referred to as "indirect" and proceeds via the $H \to \gamma\gamma$ coupling followed by the fragmentation $\gamma^* \to M$. In the SM, owing to the smallness of the light-quark Yukawa couplings, the latter amplitude dominates, despite being loop induced. As a result, the expected branching fraction predominantly arises from the "indirect" process, while the Higgs boson couplings to the light quarks are probed by searching for modifications of this branching fraction due to changes in the "direct" amplitude.

This paper describes a search for Higgs boson decays into the exclusive final states $\phi\gamma$ and $\rho\gamma$. The decay $\phi \to K^+K^-$ is used to reconstruct the ϕ meson, and the decay $\rho \to \pi^+\pi^-$ is used to reconstruct the ρ meson. The branching fractions of the respective meson decays are well known and are accounted for when calculating the expected signal yields. The presented search uses approximately 13 times more integrated luminosity than the first search for $H \rightarrow \phi\gamma$ decays [27], which led to a 95% CL upper limit of $\mathcal{B}(H \rightarrow \phi\gamma) < 1.4 \times 10^{-3}$, assuming SM production rates of the Higgs boson. Currently, no other experimental information about the $H \rightarrow \rho\gamma$ decay mode exists.

The searches for the analogous decays of the Z boson into a meson and a photon are also presented in this paper. These have been theoretically studied [28, 29] as a unique precision test of the SM and the factorisation approach in quantum chromodynamics (QCD), in an environment where the power corrections in terms of the QCD energy scale over the vector boson's mass are small [29]. The large Z boson production cross section at the LHC means that rare Z boson decays can be probed at branching fractions much smaller than for Higgs boson decays into the same final states. The SM branching fraction predictions for the decays considered in this paper are $\mathcal{B}(Z \rightarrow \phi\gamma) = (1.04 \pm 0.12) \times 10^{-8}$ [28, 29] and $\mathcal{B}(Z \rightarrow \rho\gamma) = (4.19 \pm 0.47) \times 10^{-8}$ [29]. The first search for $Z \rightarrow \phi\gamma$ decays by the ATLAS Collaboration was presented in Ref. [27] and a 95% CL upper limit of $\mathcal{B}(Z \rightarrow \phi\gamma) < 8.3 \times 10^{-6}$ was obtained. So far no direct experimental information about the decay $Z \rightarrow \rho\gamma$ exists.

2 ATLAS detector

ATLAS [30] is a multi-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer.

The inner tracking detector (ID) covers the pseudorapidity range $|\eta| < 2.5$, and is surrounded by a thin superconducting solenoid providing a 2 T magnetic field. At small radii, a high-granularity silicon pixel detector covers the vertex region and typically provides three measurements per track. A new innermost pixel-detector layer, the insertable B-layer, was added before 13 TeV data-taking began in 2015 and provides an additional measurement at a radius of about 33 mm around a new and thinner beam pipe [31]. The pixel detectors are followed by a silicon microstrip tracker, which typically provides four space-point measurements per track. The silicon detectors are complemented by a gas-filled straw-tube transition radiation tracker, which enables radially extended track reconstruction up to $|\eta| = 2.0$, with typically 35 measurements per track.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. A high-granularity lead/liquid-argon (LAr) sampling electromagnetic calorimeter covers the region $|\eta| < 3.2$, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy losses upstream. The electromagnetic calorimeter is divided into a barrel section covering $|\eta| < 1.475$ and two endcap sections covering $1.375 < |\eta| < 3.2$. For $|\eta| < 2.5$ it is divided into three layers in depth, which are finely segmented in η and ϕ. A steel/scintillator-tile calorimeter provides hadronic calorimetry in the range $|\eta| < 1.7$. LAr technology, with copper as absorber, is used for the hadronic calorimeters in the endcap region, $1.5 < |\eta| < 3.2$. The solid-angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules in $3.1 < |\eta| < 4.9$, optimised for electromagnetic and hadronic measurements, respectively.

---

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

The muon spectrometer surrounds the calorimeters and comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field provided by three air-core superconducting toroids.

A two-level trigger and data acquisition system is used to provide an online selection and record events for offline analysis [32]. The level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to 100 kHz or less from the maximum LHC collision rate of 40 MHz. It is followed by a software-based high-level trigger which filters events using the full detector information and records events for detailed offline analysis at an average rate of 1 kHz.

3 Data and Monte Carlo simulation

The search is performed with a sample of pp collision data recorded at a centre-of-mass energy $\sqrt{s} = 13$ TeV. Events are retained for further analysis only if they were collected under stable LHC beam conditions and the detector was operating normally. This results in an integrated luminosity of 35.6 and 32.3 fb^{-1} for the $\phi\gamma$ and $\rho\gamma$ final states, respectively. The integrated luminosity of the data sample has an uncertainty of 3.4% derived using the method described in Ref. [33].

The $\phi\gamma$ and $\rho\gamma$ data samples used in this analysis were each collected with a specifically designed trigger. Both triggers require an isolated photon with a transverse momentum, p_{T}, greater than 35 GeV and an isolated pair of ID tracks, one of which must have a p_{T} greater than 15 GeV, associated with a topological cluster of calorimeter cells [34] with a transverse energy greater than 25 GeV. The photon part of the trigger follows the same process as the inclusive photon trigger requiring an electromagnetic cluster in the calorimeter consistent with a photon and is described with more detail in Ref. [32], while requirements on the ID tracks are applied in the high-level trigger through an appropriately modified version of the τ-lepton trigger algorithms which are described in more detail in Ref. [35]. The trigger for the $\phi\gamma$ final state was introduced in September 2015. This trigger requires that the invariant mass of the pair of tracks, under the charged-kaon hypothesis, is in the range 987–1060 MeV, consistent with the ϕ meson mass. The trigger efficiency for both the Higgs and Z boson signals is approximately 83% with respect to the offline selection, as described in Section 4. The corresponding trigger for the $\rho\gamma$ final state was introduced in May 2016. This trigger requires the invariant mass of the pair of tracks, under the charged-pion hypothesis, to be in the range 475–1075 MeV to include the bulk of the broad ρ meson mass distribution. The trigger efficiency for the Higgs boson signal is approximately 78% and for the Z boson signal is approximately 72% with respect to the offline selection.

Higgs boson production through the gluon–gluon fusion (ggH) and vector-boson fusion (VBF) processes was modelled up to next-to-leading order (NLO) in α_{S} using the Powheg-Box v2 Monte Carlo (MC) event generator [36–40] with CT10 parton distribution functions [41]. Powheg-Box was interfaced with the Pythia 8.186 MC event generator [42, 43] to model the parton shower, hadronisation and underlying event. The corresponding parameter values were set according to the AZNLO tune [44]. Additional contributions from the associated production of a Higgs boson and a W or Z boson (denoted by WH and ZH, respectively) are modelled by the Pythia 8.186 MC event generator with NNPDF23LO parton distribution functions [45] and the A14 tune for hadronisation and the underlying event [46]. The production rates and kinematic distributions for the SM Higgs boson with $m_H = 125$ GeV are assumed throughout. These were obtained from Ref. [16] and are summarised below. The ggH production rate is normalised such that it reproduces the total cross section predicted by a next-to-next-to-next-to-leading-order QCD calculation with NLO electroweak corrections applied [47–50]. The VBF production rate is normalised to an approximate NNLO QCD cross section with NLO electroweak corrections applied [51–53]. The WH and ZH production rates are normalised to cross sections calculated at next-to-next-to-leading order (NNLO) in QCD with NLO electroweak corrections [54, 55] including the NLO QCD corrections [56] for $gg \to ZH$. The expected signal yield is corrected to include the 2% contribution from the production of a Higgs boson in association with a $t\bar{t}$ or a $b\bar{b}$ pair.

The Powheg-Box v2 MC event generator with CT10 parton distribution functions was also used to model inclusive Z boson production. Pythia 8.186 with CTEQ6L1 parton distribution functions [57] and the AZNLO parameter tune was used to simulate parton showering and hadronisation. The prediction is normalised to the total cross section obtained from the measurement in Ref. [58], which has an uncertainty of 2.9%. The Higgs and Z boson decays were simulated as a cascade of two-body decays, respecting angular momentum conservation. The meson line shapes were simulated by Pythia. The branching fraction for the decay $\phi \to K^+K^-$ is (48.9 ± 0.5)% whereas the decay $\rho \to \pi^+\pi^-$ has a branching fraction close to 100% [59]. The simulated events were passed through the detailed Geant 4 simulation of the ATLAS detector [60, 61] and processed with the same software used to reconstruct the data. Simulated pile-up events (additional pp collisions in the same or nearby bunch crossings) are also included and the distribution of these is matched to the conditions observed in the data.

4 Event selection for $\phi\gamma \to K^+K^-\gamma$ and $\rho\gamma \to \pi^+\pi^-\gamma$ final states

The $\phi\gamma$ and $\rho\gamma$ exclusive final states are very similar. Both final states consist of a pair of oppositely charged reconstructed ID tracks. The difference is that for the former the mass of the pair, under the charged-kaon hypothesis for the two tracks, is consistent with the ϕ meson mass, while for the later, under the charged-pion hypothesis for the tracks, it is consistent with the ρ meson mass. Events with a pp interaction vertex reconstructed from at least two ID tracks with $p_{\mathrm{T}} > 400\,\mathrm{MeV}$ are considered in the analysis. Within an event, the primary vertex is defined as the reconstructed vertex with the largest $\sum p_{\mathrm{T}}^2$ of associated ID tracks.

Photons are reconstructed from clusters of energy in the electromagnetic calorimeter. Clusters without matching ID tracks are classified as unconverted photon candidates while clusters matched to ID tracks consistent with the hypothesis of a photon conversion into e^+e^- are classified as converted photon candidates [62]. Reconstructed photon candidates are required to have $p_{\mathrm{T}}^{\gamma} > 35\,\mathrm{GeV}$, $|\eta^{\gamma}| < 2.37$, excluding the barrel/endcap calorimeter transition region $1.37 < |\eta^{\gamma}| < 1.52$, and to satisfy “tight” photon identification criteria [62]. An isolation requirement is imposed to further suppress contamination from jets. The sum of the transverse momenta of all tracks within $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than 5% of p_{T}^{γ}. Moreover, the sum of the transverse momenta of all calorimeter energy deposits within $\Delta R = 0.4$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than $2.45\,\mathrm{GeV} + 0.022 \times p_{\mathrm{T}}^{\gamma}$. To mitigate the effects of multiple pp interactions in the same or neighbouring bunch crossings, only ID tracks which originate from the primary vertex are considered in the photon track-based isolation. For the calorimeter-based isolation the effects of the underlying event and multiple pp interactions are also accounted for on an event by event basis using an average underlying event energy density determined from data, as described in Ref. [62].

Charged particles satisfying the requirements detailed below are assumed to be a $K^{\pm}$ meson in the $\phi\gamma$ analysis and a $\pi^{\pm}$ meson in the $\rho\gamma$ analysis. No further particle identification requirements are applied. In the following, when referring to charged particles collectively the term “charged-hadron candidates” is used, while when referring to the charged particles relevant to the $\phi\gamma$ and the $\rho\gamma$ analyses the terms “kaon candidates” and “pion candidates” are used, respectively, along with the corresponding masses. A pair of oppositely-charged charged-hadron candidates is referred to collectively as M.

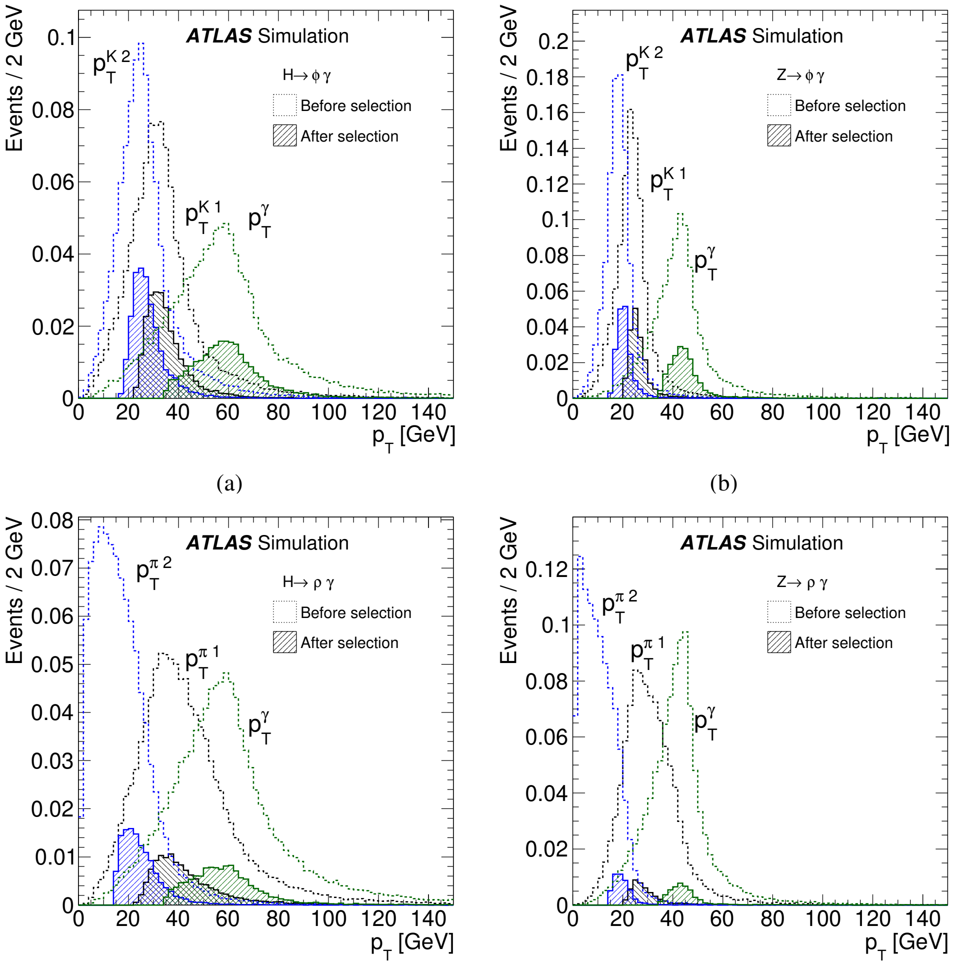
Charged-hadron candidates are reconstructed from ID tracks which are required to have $|\eta| < 2.5$, $p_{\mathrm{T}} > 15$ GeV and to satisfy basic quality criteria, including a requirement on the number of hits in the silicon detectors [63]. The $\phi \to K^+K^-$ and $\rho \to \pi^+\pi^-$ decays are reconstructed from pairs of oppositely charged-hadron candidates; the candidate with the higher p_{T}, referred to as the leading charged-hadron candidate, is required to have $p_{\mathrm{T}} > 20$ GeV.

Pairs of charged-hadron candidates are selected based on their invariant masses. Those with an invariant mass, under the charged-kaon hypothesis, $m_{K^+K^-}$ between 1012 MeV and 1028 MeV are selected as $\phi \to K^+K^-$ candidates. Pairs with an invariant mass, under the charged-pion hypothesis, $m_{\pi^+\pi^-}$ between 635 MeV and 915 MeV are selected as $\rho \to \pi^+\pi^-$ candidates. The candidates where $m_{K^+K^-}$ is consistent with the ϕ meson mass are rejected from the $\rho\gamma$ analysis. This requirement rejects a negligible fraction of the signal in the $\rho\gamma$ analysis. Selected M candidates are required to satisfy an isolation requirement: the sum of the p_{T} of the reconstructed ID tracks from the primary vertex within $\Delta R = 0.2$ of the leading charged hadron candidate (excluding the charged-hadron candidates defining the pair) is required to be less than 10% of the p_{T} of the M candidate.

The M candidates are combined with the photon candidates, to form $M\gamma$ candidates. When multiple combinations are possible, a situation that arises only in a few percent of the events, the combination of the highest-p_{T} photon and the M candidate with an invariant mass closest to the respective meson mass is selected. The event is retained for further analysis if the requirement $\Delta\phi(M, \gamma) > \pi/2$ is satisfied. The transverse momentum of the M candidates is required to be greater than a threshold that varies as a function of the invariant mass of the three-body system, $m_{M\gamma}$. Thresholds of 40 GeV and 47.2 GeV are imposed on p_{T}^{M} for the regions $m_{M\gamma} < 91$ GeV and $m_{M\gamma} \geq 140$ GeV, respectively. The threshold is varied from 40 GeV to 47.2 GeV as a linear function of $m_{M\gamma}$ in the region $91 \leq m_{M\gamma} < 140$ GeV. This approach ensures good sensitivity for both the Higgs and Z boson searches, while keeping a single kinematic selection.

For the $\phi(\to K^+K^-)\,\gamma$ final state, the total signal efficiencies (kinematic acceptance, trigger and reconstruction efficiencies) are 17% and 10% for the Higgs and Z boson decays, respectively. The corresponding efficiencies for the $\rho\gamma$ final state are 8% and 2.4%. The difference in efficiency between the Higgs and Z boson decays arises primarily from the softer p_{T} distributions of the photon and charged-hadron candidates associated with the $Z \to M\,\gamma$ production, as can be seen for the $\phi\gamma$ case by comparing Figures 1(a) and 1(b). The overall lower efficiency in the $\rho\gamma$ final state is a result of the lower efficiency of the m_M requirement due to the large ρ-meson natural width and the different kinematics of the ρ decay products, as presented in Figures 1(c) and 1(d). Meson helicity effects have a relatively small impact for the $\phi \to K^+K^-$ decays, where the kaons carry very little momentum in the ϕ rest frame. Specifically, the expected Higgs (Z) boson signal yield in the signal region is 2.4% larger (9% larger) than in the hypothetical scenario where the meson is unpolarised. For the $\rho \to \pi^+\pi^-$ decays the yields are increased by 12% (increased by 7%).

The average $m_{M\gamma}$ resolution is 1.8% for both the Higgs and Z boson decays. The Higgs boson signal $m_{M\gamma}$ distribution is modelled with a sum of two Gaussian probability density functions (pdf) with a common mean value, while the Z boson signal $m_{M\gamma}$ distribution is modelled with a double Voigtian pdf (a convolution of relativistic Breit–Wigner and Gaussian pdfs) corrected with a mass-dependent efficiency factor.

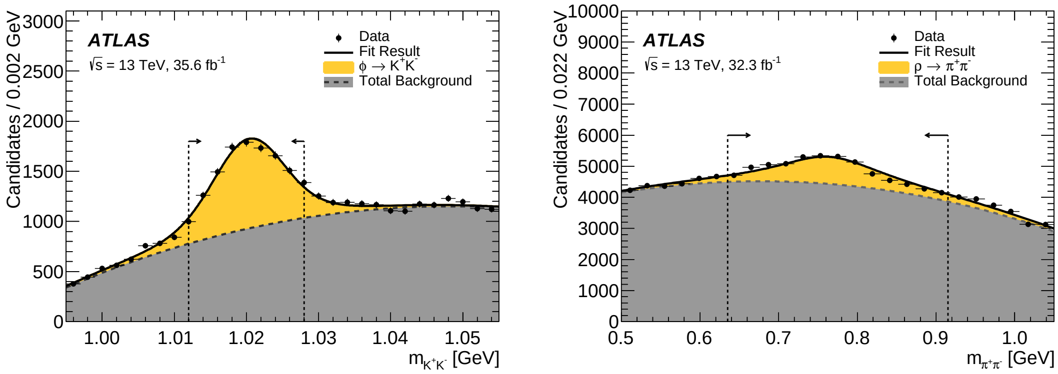


(a) (b)

(c) (d)

Figure 1: Generator-level transverse momentum (p_{T}) distributions of the photon and of the charged-hadrons, ordered in p_{T}, for (a) $H \rightarrow \phi\gamma$, (b) $Z \rightarrow \phi\gamma$, (c) $H \rightarrow \rho\gamma$ and (d) $Z \rightarrow \rho\gamma$ simulated signal events, respectively. The hatched histograms denote the full event selection while the dashed histograms show the events at generator level that fall within the analysis geometric acceptance (both charged-hadrons are required to have $|\eta| < 2.5$ while the photon is required to have $|\eta| < 2.37$, excluding the region $1.37 < |\eta| < 1.52$). The dashed histograms are normalised to unity, and the relative difference between the two sets of distributions corresponds to the effects of reconstruction, trigger, and event selection efficiencies. The leading charged-hadron candidate $h = K, \pi$ is denoted by p_{T}^{h1} and the sub-leading candidate by p_{T}^{h2}.

The $m_{K^+K^-}$ distribution for the selected $\phi\gamma$ candidates, with no $m_{K^+K^-}$ requirement applied, is shown in Figure 2(a) exhibiting a visible peak at the ϕ meson mass. The ϕ peak is fitted with a Voigtian pdf, while the background is modelled with a function typically used to describe kinematic thresholds [64]. The experimental resolution in $m_{K^+K^-}$ is approximately 4 MeV, comparable to the 4.3 MeV [59] width of the ϕ meson. In Figure 2(b), the corresponding distribution for the selected $\rho\gamma$ candidates is shown, where the ρ meson can also be observed. The ρ peak is fitted with a single Breit–Wigner pdf, modified by a mass-dependent width to match the distribution obtained from Pythia [42]. The background is fitted with the sum of a combinatoric background, estimated from events containing a same-sign di-track pair, and other backgrounds determined in the fit using a linear combination of Chebychev polynomials up to the second order. Figure 2 only qualitatively illustrates the meson selection in the studied final state, and is not used any further in this analysis.



(a)

(b)

Figure 2: The (a) $m_{K^+K^-}$ and (b) $m_{\pi^+\pi^-}$ distributions for $\phi\gamma$ and $\rho\gamma$ candidates, respectively. The candidates fulfil the complete event selection (see text), apart from requirements on $m_{K^+K^-}$ or $m_{\pi^+\pi^-}$. These requirements are marked on the figures with dashed lines topped with arrows indicating the included area. The signal and background models are discussed in the text.

5 Background

For both the $\phi\gamma$ and $\rho\gamma$ final states, the main sources of background in the searches are events involving inclusive photon + jet or multijet processes where an M candidate is reconstructed from ID tracks originating from a jet.

From the selection criteria discussed earlier, the shape of this background exhibits a turn-on structure in the $m_{M\gamma}$ distribution around 100 GeV, in the region of the Z boson signal, and a smoothly falling background in the region of the Higgs boson signal. Given the complex shape of this background, these processes are modelled in an inclusive fashion with a non-parametric data-driven approach using templates to describe the relevant distributions. The background normalisation and shape are simultaneously extracted from a fit to the data. A similar procedure was used in the earlier search for Higgs and Z boson decays into $\phi\gamma$ [27] and the search for Higgs and Z boson decays into $J/\psi\,\gamma$ and $\Upsilon(nS)\,\gamma$ described in Ref. [21].

5.1 Background modelling

The background modelling procedure for each final state exploits a sample of approximately 54 000 $K^+K^-\gamma$ and 220 000 $\pi^+\pi^-\gamma$ candidate events in data. These events pass all the kinematic selection requirements described previously, except that the photon and M candidates are not required to satisfy the nominal isolation requirements, and a looser $p_{\mathrm{T}}^{M} > 35$ GeV requirement is imposed. This selection defines the background-dominated “generation region” (GR). From these events, pdfs are constructed to describe the distributions of the relevant kinematic and isolation variables and their most important correlations. In this way, in the absence of appropriate simulations, pseudocandidate events are generated, from which the background shape in the discriminating variable is derived.

This ensemble of pseudocandidate events is produced by randomly sampling the distributions of the relevant kinematic and isolation variables, which are estimated from the data in the GR. Each pseudocandidate event is described by M and γ four-momentum vectors and the associated M and photon isolation variables. The M four-momentum vector is constructed from sampled η_M, ϕ_M, m_M and p_{T}^{M} values. For the γ four-momentum vector, the η_γ and ϕ_γ are determined from the sampled $\Delta\phi(M,\gamma)$ and $\Delta\eta(M,\gamma)$ values whereas p_{T}^{γ} is sampled directly.

The most important correlations among these kinematic and isolation variables in background events are retained in the generation of the pseudocandidates through the following sampling scheme, where the steps are performed sequentially:

i) Values for η_M, ϕ_M, m_M and p_{T}^{M} are drawn randomly and independently according to the corresponding pdfs.

ii) The distribution of p_{T}^{γ} values is parameterised in bins of p_{T}^{M}, and values are drawn from the corresponding bins given the previously generated value of p_{T}^{M}. The M isolation variable is parameterised in bins of p_{T}^{M} (p_{T}^{γ}) for the $\phi\gamma$ ($\rho\gamma$) model and sampled accordingly. The difference between the two approaches for the $\phi\gamma$ and $\rho\gamma$ accounts for the difference in the observed correlations arising in the different datasets.

iii) The distributions of the values for $\Delta\eta(M,\gamma)$, photon calorimeter isolation, normalised to p_{T}^{γ}, and their correlations are parameterised in a two-dimensional distribution. For the $\phi\gamma$ analysis, several distributions are produced corresponding to the p_{T}^{M} bins used earlier to describe the p_{T}^{γ} and M isolation variables, whereas for the $\rho\gamma$ final state the two-dimensional distribution is produced inclusively for all p_{T}^{M} values.

iv) The photon track isolation, normalised to p_{T}^{γ}, and the $\Delta\phi(M,\gamma)$ variables are sampled from pdfs generated in bins of relative photon calorimeter isolation and $\Delta\eta(M,\gamma)$, respectively, using the values drawn in step iii).

The nominal selection requirements are imposed on the ensemble, and the surviving pseudocandidates are used to construct templates for the $m_{M\gamma}$ distribution, which are then smoothed using Gaussian kernel density estimation [65]. It was verified through signal injection tests that the shape of the background model is not affected by potential signal contamination.

5.2 Background validation

To validate the background model, the $m_{M\gamma}$ distributions in several validation regions, defined by kinematic and isolation requirements looser than the nominal signal requirements, are used to compare the prediction of the background model with the data. Three validation regions are defined, each based on the GR selection and adding one of the following: the p_{T}^{M} requirement (VR1), the photon isolation requirements (VR2), or the meson isolation requirement (VR3). The $m_{M\gamma}$ distributions in these validation regions are shown in Figure 3. The background model is found to describe the data in all regions within uncertainties (see Section 6).

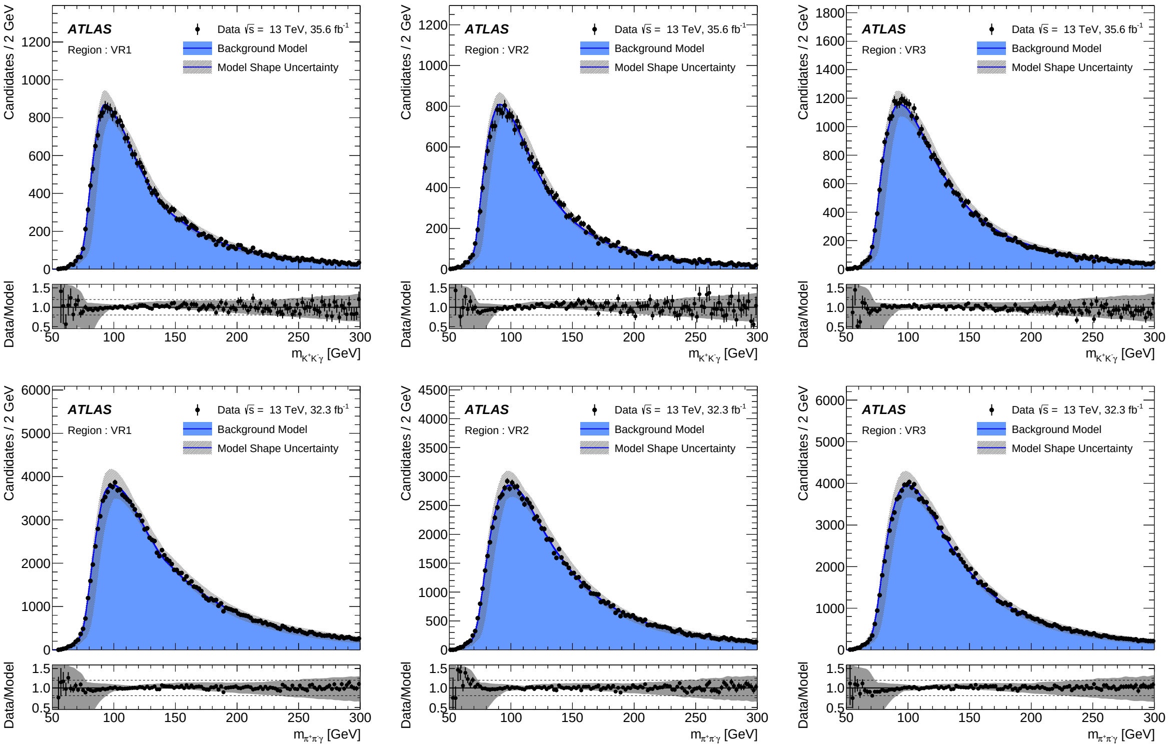
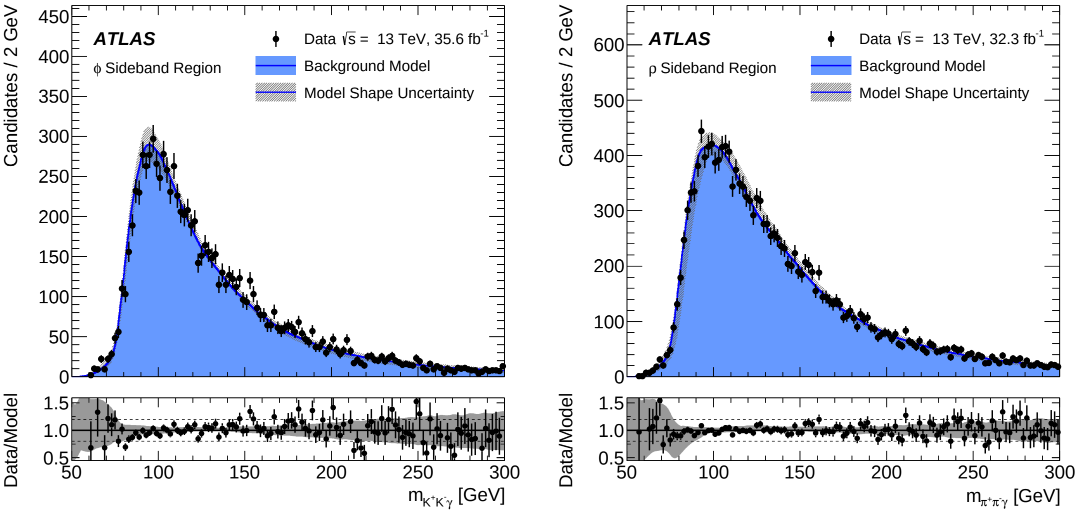


Figure 3: The distribution of $m_{K^+K^-\gamma}$ top ($m_{\pi^+\pi^-\gamma}$ bottom) in data compared to the prediction of the background model for the VR1, VR2 and VR3 validation regions. The background model is normalised to the observed number of events within the region shown. The uncertainty band corresponds to the uncertainty envelope derived from variations in the background modelling procedure. The ratio of the data to the background model is shown below the distributions.

Potential background contributions from $Z \to \ell\ell\gamma$ decays and inclusive Higgs decays were studied and found to be negligible for the selection requirements and dataset used in this analysis.

A further validation of the background modelling is performed using events within a sideband of the M mass distribution. For the $\phi\gamma$ analysis the sideband region is defined by $1.035\,\text{GeV} < m_{K^+K^-} < 1.051\,\text{GeV}$. For the $\rho\gamma$ analysis the sideband region is defined by $950\,\text{MeV} < m_{\pi^+\pi^-} < 1050\,\text{MeV}$. All other selection requirements and modelling procedures are identical to those used in the signal region. Figures 4(a) and 4(b) show the $m_{M\gamma}$ distributions for the sideband region. The background model is found to describe the data within the systematic uncertainties described in Section 6.



(a) (b)

Figure 4: The distribution of $m_{M\gamma}$ for the (a) $\phi\gamma$ and (b) $\rho\gamma$ selections in the sideband control region. The background model is normalised to the observed number of events within the region shown. The uncertainty band corresponds to the uncertainty envelope derived from variations in the background modelling procedure. The ratio of the data to the background model is shown below the distributions.

6 Systematic uncertainties

Trigger and identification efficiencies for photons are determined from samples enriched with $Z \rightarrow e^+e^-$ events in data [32, 62]. The systematic uncertainty in the expected signal yield associated with the trigger efficiency is estimated to be 2.0%. The photon identification and isolation uncertainties, for both the converted and unconverted photons, are estimated to be 2.4% and 2.6% for the Higgs and Z boson signals, respectively. An uncertainty of 6.0% per M candidate is assigned to the track reconstruction efficiency and accounts for effects associated with the modelling of ID material and track reconstruction algorithms if a nearby charged particle is present. This uncertainty is derived conservatively by assuming a 3% uncertainty in the reconstruction efficiency of each track [66], and further assuming the uncertainty to be fully correlated between the two tracks of the M candidate.

The systematic uncertainties in the Higgs production cross section are obtained from Ref. [16] as described in Section 3. The Z boson production cross-section uncertainty is taken from the measurement in Ref. [58].

The photon energy scale uncertainty, determined from $Z \rightarrow e^+e^-$ events and validated using $Z \rightarrow \ell\ell\gamma$ events [67], is applied to the simulated signal samples as a function of η^γ and p_{T}^{γ}. The impact of the photon energy scale uncertainty on the Higgs and Z boson mass distributions does not exceed 0.2%. The uncertainty associated with the photon energy resolution is found to have a negligible impact. Similarly, the systematic uncertainty associated with the ID track momentum measurement is found to be negligible. The systematic uncertainties in the expected signal yields are summarised in Table 1.

The shape of the background model is allowed to vary around the nominal shape, and the parameters controlling these systematic variations are treated as nuisance parameters in the maximum-likelihood fit used to extract the signal and background yields. Three such shape variations are implemented through varying p_{T}^{γ}, linear distortions of the shape of the $\Delta\phi(M,\gamma)$, and a global tilt of the three-body mass. The first two variations alter the kinematics of the pseudocandidates that are propagated to the three-body mass.

Table 1: Summary of the relative systematic uncertainties in the expected signal yields. The magnitude of the effects are the same for both the $\phi\gamma$ and $\rho\gamma$ selections.

Source of systematic uncertainty	Yield uncertainty
Total H cross section	6.3%
Total Z cross section	2.9%
Integrated luminosity	3.4%
Photon ID efficiency	2.5%
Trigger efficiency	2.0%
Tracking efficiency	6.0%

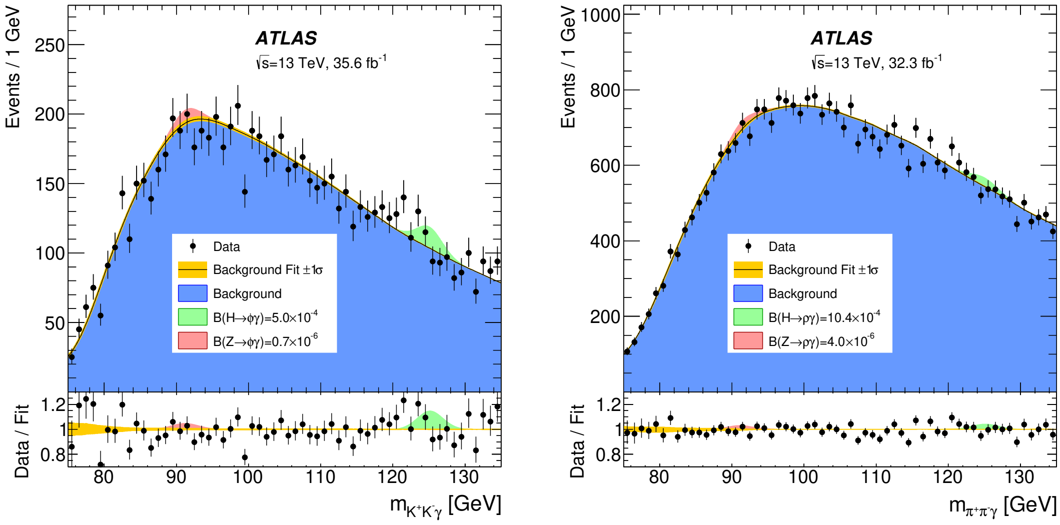
7 Results

The data are compared to background and signal predictions using an unbinned maximum-likelihood fit to the $m_{M\gamma}$ distribution. The parameters of interest are the Higgs and Z boson signal normalisations. Systematic uncertainties are modelled using additional nuisance parameters in the fit; in particular the background normalisation is a free parameter in the model. The fit uses the selected events with $m_{M\gamma} <$ 300 GeV. The expected and observed numbers of background events within the $m_{M\gamma}$ ranges relevant to the Higgs and Z boson signals are shown in Table 2. The observed yields are consistent with the number of events expected from the background-only prediction within the systematic and statistical uncertainties. The results of the background-only fits for the $\phi\gamma$ and $\rho\gamma$ analyses are shown in Figures 5(a) and 5(b), respectively.

Table 2: The number of observed events and the mean expected background, estimated from the maximum-likelihood fit and shown with the associated total uncertainty, for the $m_{M\gamma}$ ranges of interest. The expected Higgs and Z boson signal yields, along with the total systematic uncertainty, for $\phi\gamma$ and $\rho\gamma$, estimated using simulations, are also shown in parentheses.

	Observed yields (Mean expected background)					Expected signal yields	
	Mass range [GeV]					H	Z
	All	81–101		120–130		$[\mathcal{B} = 10^{-4}]$	$[\mathcal{B} = 10^{-6}]$
$\phi\gamma$	12051	3364	(3500 ± 30)	1076	(1038 ± 9)	15.1 ± 1.5	98 ± 8
$\rho\gamma$	58702	12583	(12660 ± 60)	5473	(5450 ± 30)	14.3 ± 1.4	47 ± 4

Upper limits are set on the branching fractions for the Higgs and Z boson decays into $M\gamma$ using the $\mathrm{CL_s}$ modified frequentist formalism [68] with the profile-likelihood-ratio test statistic [69]. For the upper limits on the branching fractions, the SM production cross section is assumed for the Higgs boson [16], while the ATLAS measurement of the inclusive Z boson cross section is used for the Z boson signal [58], as discussed in Section 3. The results are summarised in Table 3. The observed 95% CL upper limits on the branching fractions for $H \to \phi\gamma$ and $Z \to \phi\gamma$ decays are 208 and 87 times the expected SM branching fractions, respectively. The corresponding values for the $\rho\gamma$ decays are 52 and 597 times the expected SM branching fractions, respectively. Upper limits at 95% CL on the production cross section times branching



(a) (b)

Figure 5: The (a) $m_{K^+K^-\gamma}$ and (b) $m_{\pi^+\pi^-\gamma}$ distributions of the selected $\phi\gamma$ and $\rho\gamma$ candidates, respectively, along with the results of the maximum-likelihood fits with a background-only model. The Higgs and Z boson contributions for the branching fraction values corresponding to the observed 95% CL upper limits are also shown. Below the figures the ratio of the data to the background-only fit is shown.

fraction are also estimated for the Higgs boson decays, yielding 26.1 fb for the $H \to \phi\gamma$ decay, and 54.8 fb for the $H \to \rho\gamma$ decay.

The systematic uncertainties described in Section 6 result in a 14% deterioration of the post-fit expected 95% CL upper limit on the branching fraction in the $H \to \phi\gamma$ and $Z \to \phi\gamma$ analyses, compared to the result including only statistical uncertainties. For the $\rho\gamma$ analysis the systematic uncertainties result in a 2.3% increase in the post-fit expected upper limit for the Higgs boson decay, while for the Z boson decay the upper limit deteriorates by 29%.

Table 3: Expected and observed branching fraction upper limits at 95% CL for the $\phi\gamma$ and $\rho\gamma$ analyses. The $\pm 1\sigma$ intervals of the expected limits are also given.

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}\,(H \to \phi\gamma)$ [10^{-4}]	$4.2^{+1.8}_{-1.2}$	5.0
$\mathcal{B}\,(Z \to \phi\gamma)$ [10^{-6}]	$1.1^{+0.5}_{-0.3}$	0.7
$\mathcal{B}\,(H \to \rho\gamma)$ [10^{-4}]	$10.0^{+4.9}_{-2.8}$	10.4
$\mathcal{B}\,(Z \to \rho\gamma)$ [10^{-6}]	$5.1^{+2.1}_{-1.4}$	4.0

8 Summary

A search for the decays of Higgs and Z bosons into $\phi\gamma$ and $\rho\gamma$ has been performed with $\sqrt{s} = 13$ TeV pp collision data samples collected with the ATLAS detector at the LHC corresponding to integrated luminosities of up to 35.6 fb^{-1}. The ϕ and ρ mesons are reconstructed via their dominant decays into the K^+K^- and $\pi^+\pi^-$ final states, respectively. The background model is derived using a fully data driven approach and validated in a number of control regions including sidebands in the K^+K^- and $\pi^+\pi^-$ mass distributions.

No significant excess of events above the background expectations is observed, as expected from the SM. The obtained 95% CL upper limits are $\mathcal{B}(H \to \phi\gamma) < 5.0 \times 10^{-4}$, $\mathcal{B}(Z \to \phi\gamma) < 0.7 \times 10^{-6}$,$\mathcal{B}(H \to \rho\gamma) < 10.4 \times 10^{-4}$ and $\mathcal{B}(Z \to \rho\gamma) < 4.0 \times 10^{-6}$.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Sk lodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [70].

References

[1] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1, arXiv: `1207.7214 [hep-ex]`.

[2] CMS Collaboration,
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,
Phys. Lett. B **716** (2012) 30, arXiv: `1207.7235 [hep-ex]`.

[3] ATLAS and CMS Collaborations, *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments*,
Phys. Rev. Lett. **114** (2015) 191803, arXiv: `1503.07589 [hep-ex]`.

[4] ATLAS and CMS Collaborations,
Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV,
JHEP **08** (2016) 045, arXiv: `1606.02266 [hep-ex]`.

[5] ATLAS Collaboration, *Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at $\sqrt{s} = 7$ and 8 TeV in the ATLAS experiment*,
Eur. Phys. J. C **76** (2016) 6, arXiv: `1507.04548 [hep-ex]`.

[6] CMS Collaboration,
Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV,
Eur. Phys. J. C **75** (2015) 212, arXiv: `1412.8662 [hep-ex]`.

[7] ATLAS Collaboration,
Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector,
JHEP **04** (2015) 117, arXiv: `1501.04943 [hep-ex]`.

[8] CMS Collaboration, *Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons*,
JHEP **05** (2014) 104, arXiv: `1401.5041 [hep-ex]`.

[9] ATLAS Collaboration, *Evidence for the $H \to b\bar{b}$ decay with the ATLAS detector*,
JHEP **12** (2017) 024, arXiv: `1708.03299 [hep-ex]`.

[10] CMS Collaboration, *Evidence for the Higgs boson decay to a bottom quark–antiquark pair*,
Phys. Lett. B **780** (2018) 501, arXiv: `1709.07497 [hep-ex]`.

[11] G. D'Ambrosio, G. F. Giudice, G. Isidori and A. Strumia,
Minimal flavor violation: an effective field theory approach, Nucl. Phys. B **645** (2002) 155,
arXiv: `hep-ph/0207036`.

[12] C. D. Froggatt and H. B. Nielsen, *Hierarchy of quark masses, cabibbo angles and CP violation*,
Nucl. Phys. B **147** (1979) 277.

[13] G. F. Giudice and O. Lebedev, *Higgs-dependent Yukawa couplings*, Phys. Lett. B **665** (2008) 79,
arXiv: `0804.1753 [hep-ph]`.

[14] L. Randall and R. Sundrum, *Large Mass Hierarchy from a Small Extra Dimension*,
Phys. Rev. Lett. **83** (1999) 3370, arXiv: `hep-ph/9905221`.

[15] M. J. Dugan, H. Georgi and D. B. Kaplan, *Anatomy of a composite Higgs model*,
Nucl. Phys. B **254** (1985) 299.

[16] D. de Florian et al.,
Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector, (2016),
arXiv: `1610.07922 [hep-ph]`.

[17] M. Doroshenko, V. Kartvelishvili, E. Chikovani and S. Esakiya,
Vector quarkonium in decays of heavy Higgs particles, Yad. Fiz. **46** (1987) 864.

[18] G. Bodwin, F. Petriello, S. Stoynev and M. Velasco,
Higgs boson decays to quarkonia and the $H\bar{c}c$ coupling, Phys. Rev. D **88** (2013) 053003,
arXiv: `1306.5770 [hep-ph]`.

[19] G. T. Bodwin, H. S. Chung, J.-H. Ee, J. Lee and F. Petriello,
Relativistic corrections to Higgs-boson decays to quarkonia, Phys. Rev. D **90** (2014) 113010,
arXiv: `1407.6695 [hep-ph]`.

[20] G. T. Bodwin, H. S. Chung, J.-H. Ee and J. Lee, *New approach to the resummation of logarithms in Higgs-boson decays to a vector quarkonium plus a photon*, Phys. Rev. D **95** (2017) 054018,
arXiv: `1603.06793 [hep-ph]`.

[21] 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, arXiv: `1501.03276 [hep-ex]`.

[22] CMS Collaboration, *Search for a Higgs boson decaying into $\gamma^*\gamma \to \ell\ell\gamma$ with low dilepton mass in pp collisions at $\sqrt{s} = 8$ TeV*, Phys. Lett. B **753** (2016) 341, arXiv: `1507.03031 [hep-ex]`.

[23] M. König and M. Neubert,
Exclusive radiative Higgs decays as probes of light-quark Yukawa couplings,
JHEP **08** (2015) 012, arXiv: `1505.03870 [hep-ph]`.

[24] R. Contino et al., *Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies*, (2016), arXiv: `1606.09408 [hep-ph]`.

[25] A. L. Kagan, G. Perez, F. Petriello, Y. Soreq, S. Stoynev et al.,
An exclusive window onto Higgs Yukawa couplings, Phys. Rev. Lett. **114** (2015) 101802,
arXiv: `1406.1722 [hep-ph]`.

[26] G. Perez, Y. Soreq, E. Stamou and K. Tobioka,
Prospects for measuring the Higgs boson coupling to light quarks, Phys. Rev. **D93** (2016) 013001,
arXiv: `1505.06689 [hep-ph]`.

[27] ATLAS Collaboration, *Search for Higgs and Z Boson Decays to $\phi\gamma$ with the ATLAS Detector*,
Phys. Rev. Lett. **117** (2016) 111802, arXiv: `1607.03400 [hep-ex]`.

[28] T.-C. Huang and F. Petriello, *Rare exclusive decays of the Z boson revisited*,
Phys. Rev. D **92** (2015) 014007, arXiv: `1411.5924 [hep-ph]`.

[29] Y. Grossman, M. König and M. Neubert,
Exclusive radiative decays of W and Z bosons in QCD factorization, JHEP **04** (2015) 101,
arXiv: `1501.06569 [hep-ph]`.

[30] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*,
JINST **3** (2008) S08003.

[31] ATLAS Collaboration, *ATLAS Insertable B-Layer: Technical Design Report*,
ATLAS-TDR-19; CERN-LHCC-2010-013, 2010,
URL: `https://cds.cern.ch/record/1291633`, Addendum: ATLAS-TDR-19-ADD-1;
CERN-LHCC-2012-009, 2012, URL: `https://cds.cern.ch/record/1451888`.

[32] ATLAS Collaboration, *Performance of the ATLAS trigger system in 2015*,
Eur. Phys. J. C **77** (2017) 317, arXiv: `1611.09661 [hep-ex]`.

[33] ATLAS Collaboration,
Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC,
Eur. Phys. J. C **76** (2016) 653, arXiv: `1608.03953 [hep-ex]`.

[34] ATLAS Collaboration,
Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1,
Eur. Phys. J. C **77** (2017) 490, arXiv: `1603.02934 [hep-ex]`.

[35] ATLAS Collaboration, *The ATLAS Tau Trigger in Run 2*, ATLAS-CONF-2017-061, 2017,
URL: `https://cds.cern.ch/record/2274201`.

[36] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*,
JHEP **11** (2004) 040, arXiv: `hep-ph/0409146`.

[37] S. Frixione, P. Nason and C. Oleari,
Matching NLO QCD computations with parton shower simulations: the POWHEG method,
JHEP **11** (2007) 070, arXiv: `0709.2092 [hep-ph]`.

[38] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **06** (2010) 043,
arXiv: `1002.2581 [hep-ph]`.

[39] S. Alioli, P. Nason, C. Oleari and E. Re,
NLO Higgs boson production via gluon fusion matched with shower in POWHEG,
JHEP **04** (2009) 002, arXiv: `0812.0578 [hep-ph]`.

[40] P. Nason and C. Oleari,
NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG,
JHEP **02** (2010) 037, arXiv: `0911.5299 [hep-ph]`.

[41] H.-L. Lai et al., *New parton distributions for collider physics*, Phys. Rev. D **82** (2010) 074024,
arXiv: `1007.2241 [hep-ph]`.

[42] T. Sjöstrand, S. Mrenna and P. Z. Skands, *A brief introduction to PYTHIA 8.1*,
Comput. Phys. Commun. **178** (2008) 852, arXiv: `0710.3820 [hep-ph]`.

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

[44] ATLAS Collaboration, *Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, JHEP **09** (2014) 145,
arXiv: `1406.3660 [hep-ex]`.

[45] NNPDF Collaboration, *Parton distributions with LHC data*, Nucl. Phys. B **867** (2013) 244,
arXiv: `1207.1303 [hep-ph]`.

[46] ATLAS Collaboration, *ATLAS Pythia8 tunes to 7 TeV data*, (2014),
URL: `https://cds.cern.ch/record/1966419`.

[47] C. Anastasiou, C. Duhr, F. Dulat, F. Herzog and B. Mistlberger,
Higgs Boson Gluon-Fusion Production in QCD at Three Loops,
Phys. Rev. Lett. **114** (2015) 212001, arXiv: `1503.06056 [hep-ph]`.

[48] C. Anastasiou et al.,
High precision determination of the gluon fusion Higgs boson cross-section at the LHC,
JHEP **05** (2016) 058, arXiv: `1602.00695 [hep-ph]`.

[49] S. Actis, G. Passarino, C. Sturm and S. Uccirati,
NLO electroweak corrections to Higgs boson production at hadron colliders,
Phys. Lett. B **670** (2008) 12, arXiv: `0809.1301 [hep-ph]`.

[50] C. Anastasiou, R. Boughezal and F. Petriello,
Mixed QCD-electroweak corrections to Higgs boson production in gluon fusion,
JHEP **04** (2009) 003, arXiv: `0811.3458 [hep-ph]`.

[51] M. Ciccolini, A. Denner and S. Dittmaier, *Strong and Electroweak Corrections to the Production of a Higgs Boson + 2 Jets via Weak Interactions at the Large Hadron Collider*,
Phys. Rev. Lett. **99** (2007) 161803, arXiv: `0707.0381 [hep-ph]`.

[52] M. Ciccolini, A. Denner and S. Dittmaier,
Electroweak and QCD corrections to Higgs production via vector-boson fusion at the LHC,
Phys. Rev. D **77** (2008) 013002, arXiv: `0710.4749 [hep-ph]`.

[53] P. Bolzoni, F. Maltoni, S.-O. Moch and M. Zaro,
Higgs Boson Production via Vector-Boson Fusion at Next-to-Next-to-Leading Order in QCD,
Phys. Rev. Lett. **105** (2010) 011801, arXiv: `1003.4451 [hep-ph]`.

[54] O. Brein, A. Djouadi and R. Harlander,
NNLO QCD corrections to the Higgs-strahlung processes at hadron colliders,
Phys. Lett. B **579** (2004) 149, arXiv: `hep-ph/0307206 [hep-ph]`.

[55] A. Denner, S. Dittmaier, S. Kallweit and A. Mück, *Electroweak corrections to Higgs-strahlung off W/Z bosons at the Tevatron and the LHC with HAWK*, JHEP **03** (2012) 075,
arXiv: `1112.5142 [hep-ph]`.

[56] L. Altenkamp, S. Dittmaier, R. V. Harlander, H. Rzehak and T. J. E. Zirke,
Gluon-induced Higgs-strahlung at next-to-leading order QCD, JHEP **02** (2013) 078,
arXiv: `1211.5015 [hep-ph]`.

[57] J. Pumplin et al.,
New Generation of Parton Distributions with Uncertainties from Global QCD Analysis,
JHEP **07** (2002) 012, arXiv: `hep-ph/0201195`.

[58] ATLAS Collaboration, *Measurement of $W^{\pm}$ and Z-boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Lett. B **759** (2016) 601,
arXiv: `1603.09222 [hep-ex]`.

[59] P. Zyla et al. (Particle Data Group), *Review of Particle Physics*,
PTEP **2020** (2020) 083C01, and 2021 update.

[60] S. Agostinelli et al., *GEANT4: a simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250.

[61] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, Eur. Phys. J. C **70** (2010) 823,
arXiv: `1005.4568 [physics.ins-det]`.

[62] ATLAS Collaboration, *Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data*, Eur. Phys. J. C **76** (2016) 666, arXiv: `1606.01813 [hep-ex]`.

[63] ATLAS Collaboration,
Early Inner Detector tracking performance in the 2015 data at $\sqrt{s} = 13$ TeV,
ATL-PHYS-PUB-2015-051 (2015), URL: `http://cds.cern.ch/record/2110140`.

[64] BaBar Collaboration,
Measurement of the $D^*(2010)^+$ natural linewidth and the $D^*(2010)^+ - D^0$ mass difference,
Phys. Rev. **D88** (2013) 052003, [Erratum: Phys. Rev. **D88**, (2013) 079902],
arXiv: `1304.5009 [hep-ex]`.

[65] K. Cranmer, *Kernel estimation in high-energy physics*, Comput. Phys. Commun. **136** (2001) 198, arXiv: `hep-ex/0011057`.

[66] ATLAS Collaboration, *Performance of the ATLAS track reconstruction algorithms in dense environments in LHC Run 2*, Eur. Phys. J. C **77** (2017) 673, arXiv: `1704.07983 [hep-ex]`.

[67] ATLAS Collaboration, *Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data*, Eur. Phys. J. C **74** (2014) 3071, arXiv: `1407.5063 [hep-ex]`.

[68] A. L. Read, *Presentation of search results: the* CL_s *technique*, J. Phys. G **28** (2002) 2693.

[69] 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, arXiv: `1007.1727 [physics.data-an]`, Erratum: Eur. Phys. J. C **73** (2013) 2501.

[70] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-GEN-PUB-2016-002, URL: `https://cds.cern.ch/record/2202407`.

The ATLAS Collaboration

M. Aaboud[34d], G. Aad[99], B. Abbott[124], O. Abdinov[13,*], B. Abeloos[128], S.H. Abidi[165], O.S. AbouZeid[143], N.L. Abraham[153], H. Abramowicz[159], H. Abreu[158], R. Abreu[127], Y. Abulaiti[43a,43b], B.S. Acharya[64a,64b,o], S. Adachi[161], L. Adamczyk[81a], J. Adelman[119], M. Adersberger[112], T. Adye[141], A.A. Affolder[143], Y. Afik[158], T. Agatonovic-Jovin[16], C. Agheorghiesei[27c], J.A. Aguilar-Saavedra[136f,136a], F. Ahmadov[77,ag], G. Aielli[71a,71b], S. Akatsuka[83], H. Akerstedt[43a,43b], T.P.A. Åkesson[94], E. Akilli[52], A.V. Akimov[108], G.L. Alberghi[23b,23a], J. Albert[174], P. Albicocco[49], M.J. Alconada Verzini[86], S. Alderweireldt[117], M. Aleksa[35], I.N. Aleksandrov[77], C. Alexa[27b], G. Alexander[159], T. Alexopoulos[10], M. Alhroob[124], B. Ali[138], G. Alimonti[66a], J. Alison[36], S.P. Alkire[38], B.M.M. Allbrooke[153], B.W. Allen[127], P.P. Allport[21], A. Aloisio[67a,67b], A. Alonso[39], F. Alonso[86], C. Alpigiani[145], A.A. Alshehri[55], M.I. Alstaty[99], B. Alvarez Gonzalez[35], D. Álvarez Piqueras[172], M.G. Alviggi[67a,67b], B.T. Amadio[18], Y. Amaral Coutinho[78b], C. Amelung[26], D. Amidei[103], S.P. Amor Dos Santos[136a,136c], S. Amoroso[35], G. Amundsen[26], C. Anastopoulos[146], L.S. Ancu[52], N. Andari[21], T. Andeen[11], C.F. Anders[59b], J.K. Anders[88], K.J. Anderson[36], A. Andreazza[66a,66b], V. Andrei[59a], S. Angelidakis[37], I. Angelozzi[118], A. Angerami[38], A.V. Anisenkov[120b,120a], N. Anjos[14], A. Annovi[69a], C. Antel[59a], M. Antonelli[49], A. Antonov[110,*], D.J.A. Antrim[169], F. Anulli[70a], M. Aoki[79], L. Aperio Bella[35], G. Arabidze[104], Y. Arai[79], J.P. Araque[136a], V. Araujo Ferraz[78b], A.T.H. Arce[47], R.E. Ardell[91], F.A. Arduh[86], J-F. Arguin[107], S. Argyropoulos[75], M. Arik[12c], A.J. Armbruster[35], L.J. Armitage[90], O. Arnaez[165], H. Arnold[50], M. Arratia[31], O. Arslan[24], A. Artamonov[109,*], G. Artoni[131], S. Artz[97], S. Asai[161], N. Asbah[44], A. Ashkenazi[159], L. Asquith[153], K. Assamagan[29], R. Astalos[28a], M. Atkinson[171], N.B. Atlay[148], K. Augsten[138], G. Avolio[35], B. Axen[18], M.K. Ayoub[15a], G. Azuelos[107,av], A.E. Baas[59a], M.J. Baca[21], H. Bachacou[142], K. Bachas[65a,65b], M. Backes[131], P. Bagnaia[70a,70b], M. Bahmani[82], H. Bahrasemani[149], J.T. Baines[141], M. Bajic[39], O.K. Baker[181], P.J. Bakker[118], E.M. Baldin[120b,120a], P. Balek[178], F. Balli[142], W.K. Balunas[133], E. Banas[82], A. Bandyopadhyay[24], S. Banerjee[179,k], A.A.E. Bannoura[180], L. Barak[159], E.L. Barberio[102], D. Barberis[53b,53a], M. Barbero[99], T. Barillari[113], M-S. Barisits[35], J. Barkeloo[127], T. Barklow[150], N. Barlow[31], S.L. Barnes[58c], B.M. Barnett[141], R.M. Barnett[18], Z. Barnovska-Blenessy[58a], A. Baroncelli[72a], G. Barone[26], A.J. Barr[131], L. Barranco Navarro[172], F. Barreiro[96], J. Barreiro Guimarães da Costa[15a], R. Bartoldus[150], A.E. Barton[87], P. Bartos[28a], A. Basalaev[134], A. Bassalat[128], R.L. Bates[55], S.J. Batista[165], J.R. Batley[31], M. Battaglia[143], M. Bauce[70a,70b], F. Bauer[142], H.S. Bawa[150,m], J.B. Beacham[122], M.D. Beattie[87], T. Beau[132], P.H. Beauchemin[168], P. Bechtle[24], H.C. Beck[51], H.P. Beck[20,s], K. Becker[131], M. Becker[97], C. Becot[121], A. Beddall[12d], A.J. Beddall[12a], V.A. Bednyakov[77], M. Bedognetti[118], C.P. Bee[152], T.A. Beermann[35], M. Begalli[78b], M. Begel[29], J.K. Behr[44], A.S. Bell[92], G. Bella[159], L. Bellagamba[23b], A. Bellerive[33], M. Bellomo[158], K. Belotskiy[110], O. Beltramello[35], N.L. Belyaev[110], O. Benary[159,*], D. Benchekroun[34a], M. Bender[112], N. Benekos[10], Y. Benhammou[159], E. Benhar Noccioli[181], J. Benitez[75], D.P. Benjamin[47], M. Benoit[52], J.R. Bensinger[26], S. Bentvelsen[118], L. Beresford[131], M. Beretta[49], D. Berge[118], E. Bergeaas Kuutmann[170], N. Berger[5], L.J. Bergsten[26], J. Beringer[18], S. Berlendis[56], N.R. Bernard[100], G. Bernardi[132], C. Bernius[150], F.U. Bernlochner[24], T. Berry[91], P. Berta[97], C. Bertella[15a], G. Bertoli[43a,43b], I.A. Bertram[87], C. Bertsche[44], G.J. Besjes[39], O. Bessidskaia Bylund[43a,43b], M. Bessner[44], N. Besson[142], A. Bethani[98], S. Bethke[113], A. Betti[24], A.J. Bevan[90], J. Beyer[113], R.M.B. Bianchi[135], O. Biebel[112], D. Biedermann[19], R. Bielski[98], K. Bierwagen[97], N.V. Biesuz[69a,69b], M. Biglietti[72a], T.R.V. Billoud[107], H. Bilokon[49], M. Bindi[51], A. Bingul[12d], C. Bini[70a,70b], S. Biondi[23b,23a], T. Bisanz[51], C. Bittrich[46], D.M. Bjergaard[47], J.E. Black[150], K.M. Black[25], R.E. Blair[6], T. Blazek[28a], I. Bloch[44], C. Blocker[26], A. Blue[55], U. Blumenschein[90], Dr. Blunier[144a], G.J. Bobbink[118], V.S. Bobrovnikov[120b,120a], S.S. Bocchetta[94], A. Bocci[47], C. Bock[112], M. Boehler[50], D. Boerner[180], D. Bogavac[112], A.G. Bogdanchikov[120b,120a],

C. Bohm[43a], V. Boisvert[91], P. Bokan[170,y], T. Bold[81a], A.S. Boldyrev[111], A.E. Bolz[59b], M. Bomben[132], M. Bona[90], M. Boonekamp[142], A. Borisov[140], G. Borissov[87], J. Bortfeldt[35], D. Bortoletto[131], V. Bortolotto[61a,61b,61c], D. Boscherini[23b], M. Bosman[14], J.D. Bossio Sola[30], J. Boudreau[135], E.V. Bouhova-Thacker[87], D. Boumediene[37], C. Bourdarios[128], S.K. Boutle[55], A. Boveia[122], J. Boyd[35], I.R. Boyko[77], A.J. Bozson[91], J. Bracinik[21], A. Brandt[8], G. Brandt[51], O. Brandt[59a], F. Braren[44], U. Bratzler[162], B. Brau[100], J.E. Brau[127], W.D. Breaden Madden[55], K. Brendlinger[44], A.J. Brennan[102], L. Brenner[118], R. Brenner[170], S. Bressler[178], D.L. Briglin[21], T.M. Bristow[48], D. Britton[55], D. Britzger[44], I. Brock[24], R. Brock[104], G. Brooijmans[38], T. Brooks[91], W.K. Brooks[144b], J. Brosamer[18], E. Brost[119], J.H Broughton[21], P.A. Bruckman de Renstrom[82], D. Bruncko[28b], A. Bruni[23b], G. Bruni[23b], L.S. Bruni[118], S. Bruno[71a,71b], B.H. Brunt[31], M. Bruschi[23b], N. Bruscino[135], P. Bryant[36], L. Bryngemark[44], T. Buanes[17], Q. Buat[149], P. Buchholz[148], A.G. Buckley[55], I.A. Budagov[77], F. Buehrer[50], M.K. Bugge[130], O. Bulekov[110], D. Bullock[8], T.J. Burch[119], S. Burdin[88], C.D. Burgard[118], A.M. Burger[5], B. Burghgrave[119], K. Burka[82], S. Burke[141], I. Burmeister[45], J.T.P. Burr[131], D. Büscher[50], V. Büscher[97], P. Bussey[55], J.M. Butler[25], C.M. Buttar[55], J.M. Butterworth[92], P. Butti[35], W. Buttinger[29], A. Buzatu[155], A.R. Buzykaev[120b,120a], S. Cabrera Urbán[172], D. Caforio[138], H. Cai[171], V.M.M. Cairo[40b,40a], O. Cakir[4a], N. Calace[52], P. Calafiura[18], A. Calandri[99], G. Calderini[132], P. Calfayan[63], G. Callea[40b,40a], L.P. Caloba[78b], S. Calvente Lopez[96], D. Calvet[37], S. Calvet[37], T.P. Calvet[99], R. Camacho Toro[36], S. Camarda[35], P. Camarri[71a,71b], D. Cameron[130], R. Caminal Armadans[171], C. Camincher[56], S. Campana[35], M. Campanelli[92], A. Camplani[66a,66b], A. Campoverde[148], V. Canale[67a,67b], M. Cano Bret[58c], J. Cantero[125], T. Cao[159], M.D.M. Capeans Garrido[35], I. Caprini[27b], M. Caprini[27b], M. Capua[40b,40a], R.M. Carbone[38], R. Cardarelli[71a], F.C. Cardillo[50], I. Carli[139], T. Carli[35], G. Carlino[67a], B.T. Carlson[135], L. Carminati[66a,66b], R.M.D. Carney[43a,43b], S. Caron[117], E. Carquin[144b], S. Carrá[66a,66b], G.D. Carrillo-Montoya[35], D. Casadei[21], M.P. Casado[14,g], A.F. Casha[165], M. Casolino[14], D.W. Casper[169], R. Castelijn[118], V. Castillo Gimenez[172], N.F. Castro[136a], A. Catinaccio[35], J.R. Catmore[130], A. Cattai[35], J. Caudron[24], V. Cavaliere[171], E. Cavallaro[14], D. Cavalli[66a], M. Cavalli-Sforza[14], V. Cavasinni[69a,69b], E. Celebi[12b], F. Ceradini[72a,72b], L. Cerda Alberich[172], A.S. Cerqueira[78a], A. Cerri[153], L. Cerrito[71a,71b], F. Cerutti[18], A. Cervelli[23b,23a], S.A. Cetin[12b], A. Chafaq[34a], D Chakraborty[119], S.K. Chan[57], W.S. Chan[118], Y.L. Chan[61a], P. Chang[171], J.D. Chapman[31], D.G. Charlton[21], C.C. Chau[33], C.A. Chavez Barajas[153], S. Che[122], S. Cheatham[64a,64c], A. Chegwidden[104], S. Chekanov[6], S.V. Chekulaev[166a], G.A. Chelkov[77,au], M.A. Chelstowska[35], C. Chen[58a], C.H. Chen[76], H. Chen[29], J. Chen[58a], S. Chen[161], S.J. Chen[15c], X. Chen[15b,at], Y. Chen[80], H.C. Cheng[103], H.J. Cheng[15d], A. Cheplakov[77], E. Cheremushkina[140], R. Cherkaoui El Moursli[34e], E. Cheu[7], K. Cheung[62], L. Chevalier[142], V. Chiarella[49], G. Chiarelli[69a], G. Chiodini[65a], A.S. Chisholm[35], A. Chitan[27b], Y.H. Chiu[174], M.V. Chizhov[77], K. Choi[63], A.R. Chomont[37], S. Chouridou[160], Y.S. Chow[61a], V. Christodoulou[92], M.C. Chu[61a], J. Chudoba[137], A.J. Chuinard[101], J.J. Chwastowski[82], L. Chytka[126], A.K. Ciftci[4a], D. Cinca[45], V. Cindro[89], I.A. Cioară[24], A. Ciocio[18], F. Cirotto[67a,67b], Z.H. Citron[178], M. Citterio[66a], M. Ciubancan[27b], A. Clark[52], B.L. Clark[57], M.R. Clark[38], P.J. Clark[48], R.N. Clarke[18], C. Clement[43a,43b], Y. Coadou[99], M. Cobal[64a,64c], A. Coccaro[52], J. Cochran[76], L. Colasurdo[117], B. Cole[38], A.P. Colijn[118], J. Collot[56], T. Colombo[169], P. Conde Muiño[136a,136b], E. Coniavitis[50], S.H. Connell[32b], I.A. Connelly[98], S. Constantinescu[27b], G. Conti[35], F. Conventi[67a,aw], M. Cooke[18], A.M. Cooper-Sarkar[131], F. Cormier[173], K.J.R. Cormier[165], M. Corradi[70a,70b], F. Corriveau[101,ae], A. Cortes-Gonzalez[35], G. Costa[66a], M.J. Costa[172], D. Costanzo[146], G. Cottin[31], G. Cowan[91], B.E. Cox[98], K. Cranmer[121], S.J. Crawley[55], R.A. Creager[133], G. Cree[33], S. Crépé-Renaudin[56], F. Crescioli[132], W.A. Cribbs[43a,43b], M. Cristinziani[24], V. Croft[121], G. Crosetti[40b,40a], A. Cueto[96], T. Cuhadar Donszelmann[146], A.R. Cukierman[150], J. Cummings[181], M. Curatolo[49], J. Cúth[97], S. Czekierda[82], P. Czodrowski[35], M.J. Da Cunha Sargedas De Sousa[136a,136b], C. Da Via[98], W. Dabrowski[81a], T. Dado[28a,y], T. Dai[103], O. Dale[17], F. Dallaire[107], C. Dallapiccola[100], M. Dam[39],

G. D'amen[23b,23a], J.R. Dandoy[133], M.F. Daneri[30], N.P. Dang[179,k], A.C. Daniells[21], N.D Dann[98],
M. Danninger[173], M. Dano Hoffmann[142], V. Dao[152], G. Darbo[53b], S. Darmora[8], J. Dassoulas[3],
A. Dattagupta[127], T. Daubney[44], S. D'Auria[55], W. Davey[24], C. David[44], T. Davidek[139], D.R. Davis[47],
P. Davison[92], E. Dawe[102], I. Dawson[146], K. De[8], R. De Asmundis[67a], A. De Benedetti[124],
S. De Castro[23b,23a], S. De Cecco[132], N. De Groot[117], P. de Jong[118], H. De la Torre[104], F. De Lorenzi[76],
A. De Maria[51,u], D. De Pedis[70a], A. De Salvo[70a], U. De Sanctis[71a,71b], A. De Santo[153],
K. De Vasconcelos Corga[99], J.B. De Vivie De Regie[128], R. Debbe[29], C. Debenedetti[143],
D.V. Dedovich[77], N. Dehghanian[3], I. Deigaard[118], M. Del Gaudio[40b,40a], J. Del Peso[96], D. Delgove[128],
F. Deliot[142], C.M. Delitzsch[7], M. Della Pietra[67a,67b], D. Della Volpe[52], A. Dell'Acqua[35], L. Dell'Asta[25],
M. Dell'Orso[69a,69b], M. Delmastro[5], C. Delporte[128], P.A. Delsart[56], D.A. DeMarco[165], S. Demers[181],
M. Demichev[77], A. Demilly[132], S.P. Denisov[140], D. Denysiuk[142], L. D'Eramo[132], D. Derendarz[82],
J.E. Derkaoui[34d], F. Derue[132], P. Dervan[88], K. Desch[24], C. Deterre[44], K. Dette[165], M.R. Devesa[30],
P.O. Deviveiros[35], A. Dewhurst[141], S. Dhaliwal[26], F.A. Di Bello[52], A. Di Ciaccio[71a,71b], L. Di Ciaccio[5],
W.K. Di Clemente[133], C. Di Donato[67a,67b], A. Di Girolamo[35], B. Di Girolamo[35], B. Di Micco[72a,72b],
R. Di Nardo[35], K.F. Di Petrillo[57], A. Di Simone[50], R. Di Sipio[165], D. Di Valentino[33], C. Diaconu[99],
M. Diamond[165], F.A. Dias[39], M.A. Diaz[144a], J. Dickinson[18], E.B. Diehl[103], J. Dietrich[19],
S. Díez Cornell[44], A. Dimitrievska[16], J. Dingfelder[24], P. Dita[27b], S. Dita[27b], F. Dittus[35], F. Djama[99],
T. Djobava[157b], J.I. Djuvsland[59a], M.A.B. Do Vale[78c], D. Dobos[35], M. Dobre[27b], D. Dodsworth[26],
C. Doglioni[94], J. Dolejsi[139], Z. Dolezal[139], M. Donadelli[78d], S. Donati[69a,69b], P. Dondero[68a,68b],
J. Donini[37], M. D'Onofrio[88], J. Dopke[141], A. Doria[67a], M.T. Dova[86], A.T. Doyle[55], E. Drechsler[51],
M. Dris[10], Y. Du[58b], J. Duarte-Campderros[159], F. Dubinin[108], A. Dubreuil[52], E. Duchovni[178],
G. Duckeck[112], A. Ducourthial[132], O.A. Ducu[107,x], D. Duda[118], A. Dudarev[35], A.C. Dudder[97],
E.M. Duffield[18], L. Duflot[128], M. Dührssen[35], C. Dülsen[180], M. Dumancic[178], A.E. Dumitriu[27b,e],
A.K. Duncan[55], M. Dunford[59a], A. Duperrin[99], H. Duran Yildiz[4a], M. Düren[54], A. Durglishvili[157b],
D. Duschinger[46], B. Dutta[44], D. Duvnjak[1], M. Dyndal[44], B.S. Dziedzic[82], C. Eckardt[44], K.M. Ecker[113],
R.C. Edgar[103], T. Eifert[35], G. Eigen[17], K. Einsweiler[18], T. Ekelof[170], M. El Kacimi[34c], R. El Kosseifi[99],
V. Ellajosyula[99], M. Ellert[170], S. Elles[5], F. Ellinghaus[180], A.A. Elliot[174], N. Ellis[35], J. Elmsheuser[29],
M. Elsing[35], D. Emeliyanov[141], Y. Enari[161], J.S. Ennis[176], M.B. Epland[47], J. Erdmann[45], A. Ereditato[20],
M. Ernst[29], S. Errede[171], M. Escalier[128], C. Escobar[172], B. Esposito[49], O. Estrada Pastor[172],
A.I. Etienvre[142], E. Etzion[159], H. Evans[63], A. Ezhilov[134], M. Ezzi[34e], F. Fabbri[23b,23a], L. Fabbri[23b,23a],
V. Fabiani[117], G. Facini[92], R.M. Fakhrutdinov[140], S. Falciano[70a], R.J. Falla[92], J. Faltova[35], Y. Fang[15a],
M. Fanti[66a,66b], A. Farbin[8], A. Farilla[72a], C. Farina[135], E.M. Farina[68a,68b], T. Farooque[104], S. Farrell[18],
S.M. Farrington[176], P. Farthouat[35], F. Fassi[34e], P. Fassnacht[35], D. Fassouliotis[9], M. Faucci Giannelli[48],
A. Favareto[53b,53a], W.J. Fawcett[131], L. Fayard[128], O.L. Fedin[134,q], W. Fedorko[173], S. Feigl[130],
L. Feligioni[99], C. Feng[58b], E.J. Feng[35], M.J. Fenton[55], A.B. Fenyuk[140], L. Feremenga[8],
P. Fernandez Martinez[172], J. Ferrando[44], A. Ferrari[170], P. Ferrari[118], R. Ferrari[68a],
D.E. Ferreira de Lima[59b], A. Ferrer[172], D. Ferrere[52], C. Ferretti[103], F. Fiedler[97], M. Filipuzzi[44],
A. Filipčič[89], F. Filthaut[117], M. Fincke-Keeler[174], K.D. Finelli[25], M.C.N. Fiolhais[136a,136c,b], L. Fiorini[172],
A. Fischer[2], C. Fischer[14], J. Fischer[180], W.C. Fisher[104], N. Flaschel[44], I. Fleck[148], P. Fleischmann[103],
R.R.M. Fletcher[133], T. Flick[180], B.M. Flierl[112], L.R. Flores Castillo[61a], M.J. Flowerdew[113],
G.T. Forcolin[98], A. Formica[142], F.A. Förster[14], A.C. Forti[98], A.G. Foster[21], D. Fournier[128], H. Fox[87],
S. Fracchia[146], P. Francavilla[69a,69b], M. Franchini[23b,23a], S. Franchino[59a], D. Francis[35], L. Franconi[130],
M. Franklin[57], M. Frate[169], M. Fraternali[68a,68b], D. Freeborn[92], S.M. Fressard-Batraneanu[35],
B. Freund[107], D. Froidevaux[35], J.A. Frost[131], C. Fukunaga[162], T. Fusayasu[114], J. Fuster[172],
O. Gabizon[158], A. Gabrielli[23b,23a], A. Gabrielli[18], G.P. Gach[81a], S. Gadatsch[35], S. Gadomski[52],
G. Gagliardi[53b,53a], L.G. Gagnon[107], C. Galea[117], B. Galhardo[136a,136c], E.J. Gallas[131], B.J. Gallop[141],
P. Gallus[138], G. Galster[39], K.K. Gan[122], S. Ganguly[37], Y. Gao[88], Y.S. Gao[150,m], C. García[172],

J.E. García Navarro[172], J.A. García Pascual[15a], M. Garcia-Sciveres[18], R.W. Gardner[36], N. Garelli[150], V. Garonne[130], A. Gascon Bravo[44], K. Gasnikova[44], C. Gatti[49], A. Gaudiello[53b,53a], G. Gaudio[68a], I.L. Gavrilenko[108], C. Gay[173], G. Gaycken[24], E.N. Gazis[10], C.N.P. Gee[141], J. Geisen[51], M. Geisen[97], M.P. Geisler[59a], K. Gellerstedt[43a,43b], C. Gemme[53b], M.H. Genest[56], C. Geng[103], S. Gentile[70a,70b], C. Gentsos[160], S. George[91], D. Gerbaudo[14], G. Gessner[45], S. Ghasemi[148], M. Ghneimat[24], B. Giacobbe[23b], S. Giagu[70a,70b], N. Giangiacomi[23b,23a], P. Giannetti[69a], S.M. Gibson[91], M. Gignac[173], M. Gilchriese[18], D. Gillberg[33], G. Gilles[180], D.M. Gingrich[3,av], M.P. Giordani[64a,64c], F.M. Giorgi[23b], P.F. Giraud[142], P. Giromini[57], G. Giugliarelli[64a,64c], D. Giugni[66a], F. Giuli[131], C. Giuliani[113], M. Giulini[59b], B.K. Gjelsten[130], S. Gkaitatzis[160], I. Gkialas[9,j], E.L. Gkougkousis[14], P. Gkountoumis[10], L.K. Gladilin[111], C. Glasman[96], J. Glatzer[14], P.C.F. Glaysher[44], A. Glazov[44], M. Goblirsch-Kolb[26], J. Godlewski[82], S. Goldfarb[102], T. Golling[52], D. Golubkov[140], A. Gomes[136a,136b,136d], R. Goncalves Gama[78b], J. Goncalves Pinto Firmino Da Costa[142], R. Gonçalo[136a], G. Gonella[50], L. Gonella[21], A. Gongadze[77], J.L. Gonski[57], S. González de la Hoz[172], S. Gonzalez-Sevilla[52], L. Goossens[35], P.A. Gorbounov[109], H.A. Gordon[29], I. Gorelov[116], B. Gorini[35], E. Gorini[65a,65b], A. Gorišek[89], A.T. Goshaw[47], C. Gössling[45], M.I. Gostkin[77], C.A. Gottardo[24], C.R. Goudet[128], D. Goujdami[34c], A.G. Goussiou[145], N. Govender[32b,c], E. Gozani[158], I. Grabowska-Bold[81a], P.O.J. Gradin[170], J. Gramling[169], E. Gramstad[130], S. Grancagnolo[19], V. Gratchev[134], P.M. Gravila[27f], C. Gray[55], H.M. Gray[18], Z.D. Greenwood[93,aj], C. Grefe[24], K. Gregersen[92], I.M. Gregor[44], P. Grenier[150], K. Grevtsov[5], J. Griffiths[8], A.A. Grillo[143], K. Grimm[87], S. Grinstein[14,z], Ph. Gris[37], J.-F. Grivaz[128], S. Groh[97], E. Gross[178], J. Grosse-Knetter[51], G.C. Grossi[93], Z.J. Grout[92], A. Grummer[116], L. Guan[103], W. Guan[179], J. Guenther[35], F. Guescini[166a], D. Guest[169], O. Gueta[159], B. Gui[122], E. Guido[53b,53a], T. Guillemin[5], S. Guindon[35], U. Gul[55], C. Gumpert[35], J. Guo[58c], W. Guo[103], Y. Guo[58a,t], R. Gupta[41], S. Gurbuz[12c], G. Gustavino[124], B.J. Gutelman[158], P. Gutierrez[124], N.G. Gutierrez Ortiz[92], C. Gutschow[92], C. Guyot[142], M.P. Guzik[81a], C. Gwenlan[131], C.B. Gwilliam[88], A. Haas[121], C. Haber[18], H.K. Hadavand[8], N. Haddad[34e], A. Hadef[99], S. Hageböck[24], M. Hagihara[167], H. Hakobyan[182,*], M. Haleem[44], J. Haley[125], G. Halladjian[104], G.D. Hallewell[99], K. Hamacher[180], P. Hamal[126], K. Hamano[174], A. Hamilton[32a], G.N. Hamity[146], P.G. Hamnett[44], L. Han[58a], S. Han[15d], K. Hanagaki[79,w], K. Hanawa[161], M. Hance[143], D.M. Handl[112], B. Haney[133], P. Hanke[59a], J.B. Hansen[39], J.D. Hansen[39], M.C. Hansen[24], P.H. Hansen[39], K. Hara[167], A.S. Hard[179], T. Harenberg[180], F. Hariri[128], S. Harkusha[105], P.F. Harrison[176], N.M. Hartmann[112], Y. Hasegawa[147], A. Hasib[48], S. Hassani[142], S. Haug[20], R. Hauser[104], L. Hauswald[46], L.B. Havener[38], M. Havranek[138], C.M. Hawkes[21], R.J. Hawkings[35], D. Hayakawa[163], D. Hayden[104], C.P. Hays[131], J.M. Hays[90], H.S. Hayward[88], S.J. Haywood[141], S.J. Head[21], T. Heck[97], V. Hedberg[94], L. Heelan[8], S. Heer[24], K.K. Heidegger[50], S. Heim[44], T. Heim[18], B. Heinemann[44,aq], J.J. Heinrich[112], L. Heinrich[121], C. Heinz[54], J. Hejbal[137], L. Helary[35], A. Held[173], S. Hellman[43a,43b], C. Helsens[35], R.C.W. Henderson[87], Y. Heng[179], S. Henkelmann[173], A.M. Henriques Correia[35], S. Henrot-Versille[128], G.H. Herbert[19], H. Herde[26], V. Herget[175], Y. Hernández Jiménez[32c], H. Herr[97], G. Herten[50], R. Hertenberger[112], L. Hervas[35], T.C. Herwig[133], G.G. Hesketh[92], N.P. Hessey[166a], J.W. Hetherly[41], S. Higashino[79], E. Higón-Rodriguez[172], K. Hildebrand[36], E. Hill[174], J.C. Hill[31], K.H. Hiller[44], S.J. Hillier[21], M. Hils[46], I. Hinchliffe[18], M. Hirose[50], D. Hirschbuehl[180], B. Hiti[89], O. Hladik[137], D.R. Hlaluku[32c], X. Hoad[48], J. Hobbs[152], N. Hod[166a], M.C. Hodgkinson[146], P. Hodgson[146], A. Hoecker[35], M.R. Hoeferkamp[116], F. Hoenig[112], D. Hohn[24], T.R. Holmes[36], M. Holzbock[112], M. Homann[45], S. Honda[167], T. Honda[79], T.M. Hong[135], B.H. Hooberman[171], W.H. Hopkins[127], Y. Horii[115], A.J. Horton[149], J-Y. Hostachy[56], A. Hostiuc[145], S. Hou[155], A. Hoummada[34a], J. Howarth[98], J. Hoya[86], M. Hrabovsky[126], J. Hrdinka[35], I. Hristova[19], J. Hrivnac[128], A. Hrynevich[106], T. Hryn'ova[5], P.J. Hsu[62], S.-C. Hsu[145], Q. Hu[29], S. Hu[58c], Y. Huang[15a], Z. Hubacek[138], F. Hubaut[99], F. Huegging[24], T.B. Huffman[131], E.W. Hughes[38], M. Huhtinen[35], R.F.H. Hunter[33], P. Huo[152], N. Huseynov[77,ag], J. Huston[104], J. Huth[57], R. Hyneman[103], G. Iacobucci[52],

G. Iakovidis[29], I. Ibragimov[148], L. Iconomidou-Fayard[128], Z. Idrissi[34e], P. Iengo[35], O. Igonkina[118,ac], T. Iizawa[177], Y. Ikegami[79], M. Ikeno[79], Y. Ilchenko[11], D. Iliadis[160], N. Ilic[150], F. Iltzsche[46], G. Introzzi[68a,68b], P. Ioannou[9,*], M. Iodice[72a], K. Iordanidou[38], V. Ippolito[57], M.F. Isacson[170], N. Ishijima[129], M. Ishino[161], M. Ishitsuka[163], C. Issever[131], S. Istin[12c,an], F. Ito[167], J.M. Iturbe Ponce[61a], R. Iuppa[73a,73b], H. Iwasaki[79], J.M. Izen[42], V. Izzo[67a], S. Jabbar[3], P. Jackson[1], R.M. Jacobs[24], V. Jain[2], G. Jäkel[180], K.B. Jakobi[97], K. Jakobs[50], S. Jakobsen[74], T. Jakoubek[137], D.O. Jamin[125], D.K. Jana[93], R. Jansky[52], J. Janssen[24], M. Janus[51], P.A. Janus[81a], G. Jarlskog[94], N. Javadov[77,ag], T. Javůrek[50], M. Javurkova[50], F. Jeanneau[142], L. Jeanty[18], J. Jejelava[157a,ah], A. Jelinskas[176], P. Jenni[50,d], C. Jeske[176], S. Jézéquel[5], H. Ji[179], J. Jia[152], H. Jiang[76], Y. Jiang[58a], Z. Jiang[150], S. Jiggins[92], J. Jimenez Pena[172], S. Jin[15c], A. Jinaru[27b], O. Jinnouchi[163], H. Jivan[32c], P. Johansson[146], K.A. Johns[7], C.A. Johnson[63], W.J. Johnson[145], K. Jon-And[43a,43b], R.W.L. Jones[87], S.D. Jones[153], S. Jones[7], T.J. Jones[88], J. Jongmanns[59a], P.M. Jorge[136a,136b], J. Jovicevic[166a], X. Ju[179], A. Juste Rozas[14,z], A. Kaczmarska[82], M. Kado[128], H. Kagan[122], M. Kagan[150], S.J. Kahn[99], T. Kaji[177], E. Kajomovitz[158], C.W. Kalderon[94], A. Kaluza[97], S. Kama[41], A. Kamenshchikov[140], N. Kanaya[161], L. Kanjir[89], V.A. Kantserov[110], J. Kanzaki[79], B. Kaplan[121], L.S. Kaplan[179], D. Kar[32c], K. Karakostas[10], N. Karastathis[10], M.J. Kareem[166b], E. Karentzos[10], S.N. Karpov[77], Z.M. Karpova[77], K. Karthik[121], V. Kartvelishvili[87], A.N. Karyukhin[140], K. Kasahara[167], L. Kashif[179], R.D. Kass[122], A. Kastanas[151], Y. Kataoka[161], C. Kato[161], A. Katre[52], J. Katzy[44], K. Kawade[80], K. Kawagoe[85], T. Kawamoto[161], G. Kawamura[51], E.F. Kay[88], V.F. Kazanin[120b,120a], R. Keeler[174], R. Kehoe[41], J.S. Keller[33], E. Kellermann[94], J.J. Kempster[91], J. Kendrick[21], H. Keoshkerian[165], O. Kepka[137], S. Kersten[180], B.P. Kerševan[89], R.A. Keyes[101], M. Khader[171], F. Khalil-Zada[13], A. Khanov[125], A.G. Kharlamov[120b,120a], T. Kharlamova[120b,120a], A. Khodinov[164], T.J. Khoo[52], V. Khovanskiy[109,*], E. Khramov[77], J. Khubua[157b], S. Kido[80], C.R. Kilby[91], H.Y. Kim[8], S.H. Kim[167], Y.K. Kim[36], N. Kimura[160], O.M. Kind[19], B.T. King[88], D. Kirchmeier[46], J. Kirk[141], A.E. Kiryunin[113], T. Kishimoto[161], D. Kisielewska[81a], V. Kitali[44], O. Kivernyk[5], E. Kladiva[28b], T. Klapdor-Kleingrothaus[50], M.H. Klein[103], M. Klein[88], U. Klein[88], K. Kleinknecht[97], P. Klimek[119], A. Klimentov[29], R. Klingenberg[45,*], T. Klingl[24], T. Klioutchnikova[35], F.F. Klitzner[112], P. Kluit[118], S. Kluth[113], E. Kneringer[74], E.B.F.G. Knoops[99], A. Knue[113], A. Kobayashi[161], D. Kobayashi[85], T. Kobayashi[161], M. Kobel[46], M. Kocian[150], P. Kodys[139], T. Koffas[33], E. Koffeman[118], M.K. Köhler[178], N.M. Köhler[113], T. Koi[150], M. Kolb[59b], I. Koletsou[5], A.A. Komar[108,*], T. Kondo[79], N. Kondrashova[58c], K. Köneke[50], A.C. König[117], T. Kono[79,ap], R. Konoplich[121,ak], N. Konstantinidis[92], B. Konya[94], R. Kopeliansky[63], S. Koperny[81a], A.K. Kopp[50], K. Korcyl[82], K. Kordas[160], A. Korn[92], A.A. Korol[120b,120a,ao], I. Korolkov[14], E.V. Korolkova[146], O. Kortner[113], S. Kortner[113], T. Kosek[139], V.V. Kostyukhin[24], A. Kotwal[47], A. Koulouris[10], A. Kourkoumeli-Charalampidi[68a,68b], C. Kourkoumelis[9], E. Kourlitis[146], V. Kouskoura[29], A.B. Kowalewska[82], R. Kowalewski[174], T.Z. Kowalski[81a], C. Kozakai[161], W. Kozanecki[142], A.S. Kozhin[140], V.A. Kramarenko[111], G. Kramberger[89], D. Krasnopevtsev[110], M.W. Krasny[132], A. Krasznahorkay[35], D. Krauss[113], J.A. Kremer[81a], J. Kretzschmar[88], K. Kreutzfeldt[54], P. Krieger[165], K. Krizka[18], K. Kroeninger[45], H. Kroha[113], J. Kroll[137], J. Kroll[133], J. Kroseberg[24], J. Krstic[16], U. Kruchonak[77], H. Krüger[24], N. Krumnack[76], M.C. Kruse[47], T. Kubota[102], H. Kucuk[92], S. Kuday[4b], J.T. Kuechler[180], S. Kuehn[35], A. Kugel[59a], F. Kuger[175], T. Kuhl[44], V. Kukhtin[77], R. Kukla[99], Y. Kulchitsky[105], S. Kuleshov[144b], Y.P. Kulinich[171], M. Kuna[70a,70b], T. Kunigo[83], A. Kupco[137], T. Kupfer[45], O. Kuprash[159], H. Kurashige[80], L.L. Kurchaninov[166a], Y.A. Kurochkin[105], M.G. Kurth[15d], E.S. Kuwertz[174], M. Kuze[163], J. Kvita[126], T. Kwan[174], D. Kyriazopoulos[146], A. La Rosa[113], J.L. La Rosa Navarro[78d], L. La Rotonda[40b,40a], F. La Ruffa[40b,40a], C. Lacasta[172], F. Lacava[70a,70b], J. Lacey[44], D.P.J. Lack[98], H. Lacker[19], D. Lacour[132], E. Ladygin[77], R. Lafaye[5], B. Laforge[132], S. Lai[51], S. Lammers[63], W. Lampl[7], E. Lançon[29], U. Landgraf[50], M.P.J. Landon[90], M.C. Lanfermann[52], V.S. Lang[44], J.C. Lange[14], R.J. Langenberg[35], A.J. Lankford[169], F. Lanni[29], K. Lantzsch[24], A. Lanza[68a],

A. Lapertosa[53b,53a], S. Laplace[132], J.F. Laporte[142], T. Lari[66a], F. Lasagni Manghi[23b,23a], M. Lassnig[35], T.S. Lau[61a], P. Laurelli[49], W. Lavrijsen[18], A.T. Law[143], P. Laycock[88], T. Lazovich[57], M. Lazzaroni[66a,66b], B. Le[102], O. Le Dortz[132], E. Le Guirriec[99], E.P. Le Quilleuc[142], M. LeBlanc[174], T. LeCompte[6], F. Ledroit-Guillon[56], C.A. Lee[29], G.R. Lee[144a], L. Lee[57], S.C. Lee[155], B. Lefebvre[101], G. Lefebvre[132], M. Lefebvre[174], F. Legger[112], C. Leggett[18], G. Lehmann Miotto[35], X. Lei[7], W.A. Leight[44], M.A.L. Leite[78d], R. Leitner[139], D. Lellouch[178], B. Lemmer[51], K.J.C. Leney[92], T. Lenz[24], B. Lenzi[35], R. Leone[7], S. Leone[69a], C. Leonidopoulos[48], G. Lerner[153], C. Leroy[107], R. Les[165], A.A.J. Lesage[142], C.G. Lester[31], M. Levchenko[134], J. Levêque[5], D. Levin[103], L.J. Levinson[178], M. Levy[21], D. Lewis[90], B. Li[58a,t], C-Q. Li[58a], H. Li[152], L. Li[58c], Q. Li[15d], Q.Y. Li[58a], S. Li[47], X. Li[58c], Y. Li[148], Z. Liang[15a], B. Liberti[71a], A. Liblong[165], K. Lie[61c], J. Liebal[24], W. Liebig[17], A. Limosani[154], C.Y. Lin[31], K. Lin[104], S.C. Lin[156], T.H. Lin[97], R.A. Linck[63], B.E. Lindquist[152], A.L. Lionti[52], E. Lipeles[133], A. Lipniacka[17], M. Lisovyi[59b], T.M. Liss[171,as], A. Lister[173], A.M. Litke[143], B. Liu[76], H.B. Liu[29], H. Liu[103], J.B. Liu[58a], J.K.K. Liu[131], J. Liu[58b], K. Liu[99], L. Liu[171], M. Liu[58a], Y.L. Liu[58a], Y.W. Liu[58a], M. Livan[68a,68b], A. Lleres[56], J. Llorente Merino[15a], S.L. Lloyd[90], C.Y. Lo[61b], F. Lo Sterzo[41], E.M. Lobodzinska[44], P. Loch[7], F.K. Loebinger[98], A. Loesle[50], K.M. Loew[26], T. Lohse[19], K. Lohwasser[146], M. Lokajicek[137], B.A. Long[25], J.D. Long[171], R.E. Long[87], L. Longo[65a,65b], K.A. Looper[122], J.A. Lopez[144b], I. Lopez Paz[14], A. Lopez Solis[132], J. Lorenz[112], N. Lorenzo Martinez[5], M. Losada[22], P.J. Lösel[112], X. Lou[15a], A. Lounis[128], J. Love[6], P.A. Love[87], H. Lu[61a], N. Lu[103], Y.J. Lu[62], H.J. Lubatti[145], C. Luci[70a,70b], A. Lucotte[56], C. Luedtke[50], F. Luehring[63], W. Lukas[74], L. Luminari[70a], O. Lundberg[43a,43b], B. Lund-Jensen[151], M.S. Lutz[100], P.M. Luzi[132], D. Lynn[29], R. Lysak[137], E. Lytken[94], F. Lyu[15a], V. Lyubushkin[77], H. Ma[29], L.L. Ma[58b], Y. Ma[58b], G. Maccarrone[49], A. Macchiolo[113], C.M. Macdonald[146], J. Machado Miguens[133,136b], D. Madaffari[172], R. Madar[37], W.F. Mader[46], A. Madsen[44], N. Madysa[46], J. Maeda[80], S. Maeland[17], T. Maeno[29], A.S. Maevskiy[111], V. Magerl[50], C. Maiani[128], C. Maidantchik[78b], T. Maier[112], A. Maio[136a,136b,136d], O. Majersky[28a], S. Majewski[127], Y. Makida[79], N. Makovec[128], B. Malaescu[132], Pa. Malecki[82], V.P. Maleev[134], F. Malek[56], U. Mallik[75], D. Malon[6], C. Malone[31], S. Maltezos[10], S. Malyukov[35], J. Mamuzic[172], G. Mancini[49], I. Mandić[89], J. Maneira[136a,136b], L. Manhaes de Andrade Filho[78a], J. Manjarres Ramos[46], K.H. Mankinen[94], A. Mann[112], A. Manousos[35], B. Mansoulie[142], J.D. Mansour[15a], R. Mantifel[101], M. Mantoani[51], S. Manzoni[66a,66b], L. Mapelli[35], G. Marceca[30], L. March[52], L. Marchese[131], G. Marchiori[132], M. Marcisovsky[137], C.A. Marin Tobon[35], M. Marjanovic[37], D.E. Marley[103], F. Marroquim[78b], S.P. Marsden[98], Z. Marshall[18], M.U.F Martensson[170], S. Marti-Garcia[172], C.B. Martin[122], T.A. Martin[176], V.J. Martin[48], B. Martin dit Latour[17], M. Martinez[14,z], V.I. Martinez Outschoorn[171], S. Martin-Haugh[141], V.S. Martoiu[27b], A.C. Martyniuk[92], A. Marzin[35], L. Masetti[97], T. Mashimo[161], R. Mashinistov[108], J. Masik[98], A.L. Maslennikov[120b,120a], L.H. Mason[102], L. Massa[71a,71b], P. Mastrandrea[5], A. Mastroberardino[40b,40a], T. Masubuchi[161], P. Mättig[180], J. Maurer[27b], B. Maček[89], S.J. Maxfield[88], D.A. Maximov[120b,120a], R. Mazini[155], I. Maznas[160], S.M. Mazza[66a,66b], N.C. Mc Fadden[116], G. Mc Goldrick[165], S.P. Mc Kee[103], A. McCarn[103], R.L. McCarthy[152], T.G. McCarthy[113], L.I. McClymont[92], E.F. McDonald[102], J.A. Mcfayden[35], G. Mchedlidze[51], S.J. McMahon[141], P.C. McNamara[102], C.J. McNicol[176], R.A. McPherson[174,ae], S. Meehan[145], T. Megy[50], S. Mehlhase[112], A. Mehta[88], T. Meideck[56], B. Meirose[42], D. Melini[172,h], B.R. Mellado Garcia[32c], J.D. Mellenthin[51], M. Melo[28a], F. Meloni[20], A. Melzer[24], S.B. Menary[98], L. Meng[88], X.T. Meng[103], A. Mengarelli[23b,23a], S. Menke[113], E. Meoni[40b,40a], S. Mergelmeyer[19], C. Merlassino[20], P. Mermod[52], L. Merola[67a,67b], C. Meroni[66a], F.S. Merritt[36], A. Messina[70a,70b], J. Metcalfe[6], A.S. Mete[169], C. Meyer[133], J. Meyer[118], J-P. Meyer[142], H. Meyer Zu Theenhausen[59a], F. Miano[153], R.P. Middleton[141], S. Miglioranzi[53b,53a], L. Mijović[48], G. Mikenberg[178], M. Mikestikova[137], M. Mikuž[89], M. Milesi[102], A. Milic[165], D.A. Millar[90], D.W. Miller[36], C. Mills[48], A. Milov[178], D.A. Milstead[43a,43b], A.A. Minaenko[140], Y. Minami[161], I.A. Minashvili[157b], A.I. Mincer[121], B. Mindur[81a], M. Mineev[77],

Y. Minegishi[161], Y. Ming[179], L.M. Mir[14], A. Mirto[65a,65b], K.P. Mistry[133], T. Mitani[177], J. Mitrevski[112], V.A. Mitsou[172], A. Miucci[20], P.S. Miyagawa[146], A. Mizukami[79], J.U. Mjörnmark[94], T. Mkrtchyan[182], M. Mlynarikova[139], T. Moa[43a,43b], K. Mochizuki[107], P. Mogg[50], S. Mohapatra[38], S. Molander[43a,43b], R. Moles-Valls[24], M.C. Mondragon[104], K. Mönig[44], J. Monk[39], E. Monnier[99], A. Montalbano[152], J. Montejo Berlingen[35], F. Monticelli[86], S. Monzani[66a], R.W. Moore[3], N. Morange[128], D. Moreno[22], M. Moreno Llácer[35], P. Morettini[53b], S. Morgenstern[35], D. Mori[149], T. Mori[161], M. Morii[57], M. Morinaga[177], V. Morisbak[130], A.K. Morley[35], G. Mornacchi[35], J.D. Morris[90], L. Morvaj[152], P. Moschovakos[10], M. Mosidze[157b], H.J. Moss[146], J. Moss[150,n], K. Motohashi[163], R. Mount[150], E. Mountricha[29], E.J.W. Moyse[100], S. Muanza[99], F. Mueller[113], J. Mueller[135], R.S.P. Mueller[112], D. Muenstermann[87], P. Mullen[55], G.A. Mullier[20], F.J. Munoz Sanchez[98], W.J. Murray[176,141], H. Musheghyan[35], M. Muškinja[89], A.G. Myagkov[140,al], M. Myska[138], B.P. Nachman[18], O. Nackenhorst[52], K. Nagai[131], R. Nagai[79,ap], K. Nagano[79], Y. Nagasaka[60], K. Nagata[167], M. Nagel[50], E. Nagy[99], A.M. Nairz[35], Y. Nakahama[115], K. Nakamura[79], T. Nakamura[161], I. Nakano[123], R.F. Naranjo Garcia[44], R. Narayan[11], D.I. Narrias Villar[59a], I. Naryshkin[134], T. Naumann[44], G. Navarro[22], R. Nayyar[7], H.A. Neal[103], P.Y. Nechaeva[108], T.J. Neep[142], A. Negri[68a,68b], M. Negrini[23b], S. Nektarijevic[117], C. Nellist[51], A. Nelson[169], M.E. Nelson[131], S. Nemecek[137], P. Nemethy[121], M. Nessi[35,f], M.S. Neubauer[171], M. Neumann[180], P.R. Newman[21], T.Y. Ng[61c], Y.S. Ng[19], T. Nguyen Manh[107], R.B. Nickerson[131], R. Nicolaidou[142], J. Nielsen[143], N. Nikiforou[11], V. Nikolaenko[140,al], I. Nikolic-Audit[132], K. Nikolopoulos[21], P. Nilsson[29], Y. Ninomiya[79], A. Nisati[70a], N. Nishu[58c], R. Nisius[113], I. Nitsche[45], T. Nitta[177], T. Nobe[161], Y. Noguchi[83], M. Nomachi[129], I. Nomidis[33], M.A. Nomura[29], T. Nooney[90], M. Nordberg[35], N. Norjoharuddeen[131], O. Novgorodova[46], M. Nozaki[79], L. Nozka[126], K. Ntekas[169], E. Nurse[92], F. Nuti[102], F.G. Oakham[33,av], H. Oberlack[113], T. Obermann[24], J. Ocariz[132], A. Ochi[80], I. Ochoa[38], J.P. Ochoa-Ricoux[144a], K. O'Connor[26], S. Oda[85], S. Odaka[79], A. Oh[98], S.H. Oh[47], C.C. Ohm[151], H. Ohman[170], H. Oide[53b,53a], H. Okawa[167], Y. Okumura[161], T. Okuyama[79], A. Olariu[27b], L.F. Oleiro Seabra[136a], S.A. Olivares Pino[144a], D. Oliveira Damazio[29], M.J.R. Olsson[36], A. Olszewski[82], J. Olszowska[82], D.C. O'Neil[149], A. Onofre[136a,136e], K. Onogi[115], P.U.E. Onyisi[11], H. Oppen[130], M.J. Oreglia[36], Y. Oren[159], D. Orestano[72a,72b], N. Orlando[61b], A.A. O'Rourke[44], R.S. Orr[165], B. Osculati[53b,53a,*], V. O'Shea[55], R. Ospanov[58a], G. Otero y Garzon[30], H. Otono[85], M. Ouchrif[34d], F. Ould-Saada[130], A. Ouraou[142], K.P. Oussoren[118], Q. Ouyang[15a], M. Owen[55], R.E. Owen[21], V.E. Ozcan[12c], N. Ozturk[8], K. Pachal[149], A. Pacheco Pages[14], L. Pacheco Rodriguez[142], C. Padilla Aranda[14], S. Pagan Griso[18], M. Paganini[181], F. Paige[29], G. Palacino[63], S. Palazzo[40b,40a], S. Palestini[35], M. Palka[81b], D. Pallin[37], E.St. Panagiotopoulou[10], I. Panagoulias[10], C.E. Pandini[52], J.G. Panduro Vazquez[91], P. Pani[35], S. Panitkin[29], D. Pantea[27b], L. Paolozzi[52], T.D. Papadopoulou[10], K. Papageorgiou[9,j], A. Paramonov[6], D. Paredes Hernandez[181], A.J. Parker[87], K.A. Parker[44], M.A. Parker[31], F. Parodi[53b,53a], J.A. Parsons[38], U. Parzefall[50], V.R. Pascuzzi[165], J.M.P. Pasner[143], E. Pasqualucci[70a], S. Passaggio[53b], F. Pastore[91], S. Pataraia[97], J.R. Pater[98], T. Pauly[35], B. Pearson[113], S. Pedraza Lopez[172], R. Pedro[136a,136b], S.V. Peleganchuk[120b,120a], O. Penc[137], C. Peng[15d], H. Peng[58a], J. Penwell[63], B.S. Peralva[78a], M.M. Perego[142], D.V. Perepelitsa[29], F. Peri[19], L. Perini[66a,66b], H. Pernegger[35], S. Perrella[67a,67b], R. Peschke[44], V.D. Peshekhonov[77,*], K. Peters[44], R.F.Y. Peters[98], B.A. Petersen[35], T.C. Petersen[39], E. Petit[56], A. Petridis[1], C. Petridou[160], P. Petroff[128], E. Petrolo[70a], M. Petrov[131], F. Petrucci[72a,72b], N.E. Pettersson[100], A. Peyaud[142], R. Pezoa[144b], F.H. Phillips[104], P.W. Phillips[141], G. Piacquadio[152], E. Pianori[176], A. Picazio[100], M.A. Pickering[131], R. Piegaia[30], J.E. Pilcher[36], A.D. Pilkington[98], M. Pinamonti[71a,71b], J.L. Pinfold[3], H. Pirumov[44], M. Pitt[178], L. Plazak[28a], M-A. Pleier[29], V. Pleskot[97], E. Plotnikova[77], D. Pluth[76], P. Podberezko[120b,120a], R. Poettgen[94], R. Poggi[68a,68b], L. Poggioli[128], I. Pogrebnyak[104], D. Pohl[24], I. Pokharel[51], G. Polesello[68a], A. Poley[44], A. Policicchio[40b,40a], R. Polifka[35], A. Polini[23b], C.S. Pollard[55], V. Polychronakos[29], K. Pommès[35], D. Ponomarenko[110], L. Pontecorvo[70a], G.A. Popeneciu[27d], D.M. Portillo Quintero[132], S. Pospisil[138], K. Potamianos[44], I.N. Potrap[77], C.J. Potter[31], H. Potti[11], T. Poulsen[94], J. Poveda[35], M.E. Pozo Astigarraga[35], P. Pralavorio[99], A. Pranko[18], S. Prell[76], D. Price[98], M. Primavera[65a], S. Prince[101], N. Proklova[110], K. Prokofiev[61c], F. Prokoshin[144b], S. Protopopescu[29], J. Proudfoot[6], M. Przybycien[81a], A. Puri[171], P. Puzo[128], J. Qian[103], G. Qin[55], Y. Qin[98], A. Quadt[51], M. Queitsch-Maitland[44], D. Quilty[55], S. Raddum[130], V. Radeka[29], V. Radescu[131], S.K. Radhakrishnan[152], P. Radloff[127], P. Rados[102], F. Ragusa[66a,66b], G. Rahal[95], J.A. Raine[98], S. Rajagopalan[29], C. Rangel-Smith[170], T. Rashid[128], S. Raspopov[5], M.G. Ratti[66a,66b], D.M. Rauch[44], F. Rauscher[112], S. Rave[97], I. Ravinovich[178], J.H. Rawling[98], M. Raymond[35], A.L. Read[130], N.P. Readioff[56], M. Reale[65a,65b], D.M. Rebuzzi[68a,68b], A. Redelbach[175], G. Redlinger[29], R. Reece[143], R.G. Reed[32c], K. Reeves[42], L. Rehnisch[19], J. Reichert[133], A. Reiss[97], C. Rembser[35], H. Ren[15d], M. Rescigno[70a], S. Resconi[66a], E.D. Resseguie[133], S. Rettie[173], E. Reynolds[21], O.L. Rezanova[120b,120a], P. Reznicek[139], R. Rezvani[107], R. Richter[113], S. Richter[92], E. Richter-Was[81b], O. Ricken[24], M. Ridel[132], P. Rieck[113], C.J. Riegel[180], J. Rieger[51], O. Rifki[124], M. Rijssenbeek[152], A. Rimoldi[68a,68b], M. Rimoldi[20], L. Rinaldi[23b], G. Ripellino[151], B. Ristić[35], E. Ritsch[35], I. Riu[14], F. Rizatdinova[125], E. Rizvi[90], C. Rizzi[14], R.T. Roberts[98], S.H. Robertson[101,ae], A. Robichaud-Veronneau[101], D. Robinson[31], J.E.M. Robinson[44], A. Robson[55], E. Rocco[97], C. Roda[69a,69b], Y. Rodina[99,aa], S. Rodriguez Bosca[172], A. Rodriguez Perez[14], D. Rodriguez Rodriguez[172], S. Roe[35], C.S. Rogan[57], O. Røhne[130], J. Roloff[57], A. Romaniouk[110], M. Romano[23b,23a], S.M. Romano Saez[37], E. Romero Adam[172], N. Rompotis[88], M. Ronzani[50], L. Roos[132], S. Rosati[70a], K. Rosbach[50], P. Rose[143], N-A. Rosien[51], E. Rossi[67a,67b], L.P. Rossi[53b], J.H.N. Rosten[31], R. Rosten[145], M. Rotaru[27b], J. Rothberg[145], D. Rousseau[128], D. Roy[32c], A. Rozanov[99], Y. Rozen[158], X. Ruan[32c], F. Rubbo[150], F. Rühr[50], A. Ruiz-Martinez[33], Z. Rurikova[50], N.A. Rusakovich[77], H.L. Russell[101], J.P. Rutherfoord[7], N. Ruthmann[35], E.M. Rüttinger[44,l], Y.F. Ryabov[134], M. Rybar[171], G. Rybkin[128], S. Ryu[6], A. Ryzhov[140], G.F. Rzehorz[51], A.F. Saavedra[154], G. Sabato[118], S. Sacerdoti[30], H.F-W. Sadrozinski[143], R. Sadykov[77], F. Safai Tehrani[70a], P. Saha[119], M. Sahinsoy[59a], M. Saimpert[44], M. Saito[161], T. Saito[161], H. Sakamoto[161], Y. Sakurai[177], G. Salamanna[72a,72b], J.E. Salazar Loyola[144b], D. Salek[118], P.H. Sales De Bruin[170], D. Salihagic[113], A. Salnikov[150], J. Salt[172], D. Salvatore[40b,40a], F. Salvatore[153], A. Salvucci[61a,61b,61c], A. Salzburger[35], D. Sammel[50], D. Sampsonidis[160], D. Sampsonidou[160], J. Sánchez[172], V. Sanchez Martinez[172], A. Sanchez Pineda[64a,64c], H. Sandaker[130], R.L. Sandbach[90], C.O. Sander[44], M. Sandhoff[180], C. Sandoval[22], D.P.C. Sankey[141], M. Sannino[53b,53a], Y. Sano[115], A. Sansoni[49], C. Santoni[37], H. Santos[136a], I. Santoyo Castillo[153], A. Sapronov[77], J.G. Saraiva[136a,136d], B. Sarrazin[24], O. Sasaki[79], K. Sato[167], E. Sauvan[5], G. Savage[91], P. Savard[165,av], N. Savic[113], C. Sawyer[141], L. Sawyer[93,aj], J. Saxon[36], C. Sbarra[23b], A. Sbrizzi[23b,23a], T. Scanlon[92], D.A. Scannicchio[169], J. Schaarschmidt[145], P. Schacht[113], B.M. Schachtner[112], D. Schaefer[36], L. Schaefer[133], R. Schaefer[44], J. Schaeffer[97], S. Schaepe[35], S. Schaetzel[59b], U. Schäfer[97], A.C. Schaffer[128], D. Schaile[112], R.D. Schamberger[152], V.A. Schegelsky[134], D. Scheirich[139], F. Schenck[19], M. Schernau[169], C. Schiavi[53b,53a], S. Schier[143], L.K. Schildgen[24], C. Schillo[50], M. Schioppa[40b,40a], S. Schlenker[35], K.R. Schmidt-Sommerfeld[113], K. Schmieden[35], C. Schmitt[97], S. Schmitt[44], S. Schmitz[97], U. Schnoor[50], L. Schoeffel[142], A. Schoening[59b], B.D. Schoenrock[104], E. Schopf[24], M. Schott[97], J.F.P. Schouwenberg[117], J. Schovancova[35], S. Schramm[52], N. Schuh[97], A. Schulte[97], M.J. Schultens[24], H-C. Schultz-Coulon[59a], H. Schulz[19], M. Schumacher[50], B.A. Schumm[143], Ph. Schune[142], A. Schwartzman[150], T.A. Schwarz[103], H. Schweiger[98], Ph. Schwemling[142], R. Schwienhorst[104], A. Sciandra[24], G. Sciolla[26], M. Scornajenghi[40b,40a], F. Scuri[69a], F. Scutti[102], J. Searcy[103], P. Seema[24], S.C. Seidel[116], A. Seiden[143], J.M. Seixas[78b], G. Sekhniaidze[67a], K. Sekhon[103], S.J. Sekula[41], N. Semprini-Cesari[23b,23a], S. Senkin[37], C. Serfon[130], L. Serin[128], L. Serkin[64a,64b], M. Sessa[72a,72b], R. Seuster[174], H. Severini[124], F. Sforza[168], A. Sfyrla[52], E. Shabalina[51], N.W. Shaikh[43a,43b], L.Y. Shan[15a], R. Shang[171], J.T. Shank[25], M. Shapiro[18], P.B. Shatalov[109], K. Shaw[64a,64b], S.M. Shaw[98], A. Shcherbakova[43a,43b], C.Y. Shehu[153], Y. Shen[124], N. Sherafati[33], A.D. Sherman[25], P. Sherwood[92], L. Shi[155,ar], S. Shimizu[80], C.O. Shimmin[181], M. Shimojima[114], I.P.J. Shipsey[131], S. Shirabe[85], M. Shiyakova[77], J. Shlomi[178], A. Shmeleva[108], D. Shoaleh Saadi[107], M.J. Shochet[36], S. Shojaii[102], D.R. Shope[124], S. Shrestha[122], E. Shulga[110], M.A. Shupe[7], P. Sicho[137], A.M. Sickles[171], P.E. Sidebo[151], E. Sideras Haddad[32c], O. Sidiropoulou[175], A. Sidoti[23b,23a], F. Siegert[46], Dj. Sijacki[16], J. Silva[136a,136d], S.B. Silverstein[43a], V. Simak[138], L. Simic[77], S. Simion[128], E. Simioni[97], B. Simmons[92], M. Simon[97], P. Sinervo[165], N.B. Sinev[127], M. Sioli[23b,23a], G. Siragusa[175], I. Siral[103], S.Yu. Sivoklokov[111], J. Sjölin[43a,43b], M.B. Skinner[87], P. Skubic[124], M. Slater[21], T. Slavicek[138], M. Slawinska[82], K. Sliwa[168], R. Slovak[139], V. Smakhtin[178], B.H. Smart[5], J. Smiesko[28a], N. Smirnov[110], S.Yu. Smirnov[110], Y. Smirnov[110], L.N. Smirnova[111], O. Smirnova[94], J.W. Smith[51], M.N.K. Smith[38], R.W. Smith[38], M. Smizanska[87], K. Smolek[138], A.A. Snesarev[108], I.M. Snyder[127], S. Snyder[29], R. Sobie[174,ae], F. Socher[46], A. Soffer[159], A. Søgaard[48], D.A. Soh[155], G. Sokhrannyi[89], C.A. Solans Sanchez[35], M. Solar[138], E.Yu. Soldatov[110], U. Soldevila[172], A.A. Solodkov[140], A. Soloshenko[77], O.V. Solovyanov[140], V. Solovyev[134], P. Sommer[146], H. Son[168], A. Sopczak[138], D. Sosa[59b], C.L. Sotiropoulou[69a,69b], S. Sottocornola[68a,68b], R. Soualah[64a,64c,i], A.M. Soukharev[120b,120a], D. South[44], B.C. Sowden[91], S. Spagnolo[65a,65b], M. Spalla[69a,69b], M. Spangenberg[176], F. Spanò[91], D. Sperlich[19], F. Spettel[113], T.M. Spieker[59a], R. Spighi[23b], G. Spigo[35], L.A. Spiller[102], M. Spousta[139], R.D. St. Denis[55,*], A. Stabile[66a,66b], R. Stamen[59a], S. Stamm[19], E. Stanecka[82], R.W. Stanek[6], C. Stanescu[72a], M.M. Stanitzki[44], B. Stapf[118], S. Stapnes[130], E.A. Starchenko[140], G.H. Stark[36], J. Stark[56], S.H Stark[39], P. Staroba[137], P. Starovoitov[59a], S. Stärz[35], R. Staszewski[82], M. Stegler[44], P. Steinberg[29], B. Stelzer[149], H.J. Stelzer[35], O. Stelzer-Chilton[166a], H. Stenzel[54], T.J. Stevenson[90], G.A. Stewart[55], M.C. Stockton[127], M. Stoebe[101], G. Stoicea[27b], P. Stolte[51], S. Stonjek[113], A.R. Stradling[8], A. Straessner[46], M.E. Stramaglia[20], J. Strandberg[151], S. Strandberg[43a,43b], M. Strauss[124], P. Strizenec[28b], R. Ströhmer[175], D.M. Strom[127], R. Stroynowski[41], A. Strubig[48], S.A. Stucci[29], B. Stugu[17], N.A. Styles[44], D. Su[150], J. Su[135], S. Suchek[59a], Y. Sugaya[129], M. Suk[138], V.V. Sulin[108], D.M.S. Sultan[73a,73b], S. Sultansoy[4c], T. Sumida[83], S. Sun[57], X. Sun[3], K. Suruliz[153], C.J.E. Suster[154], M.R. Sutton[153], S. Suzuki[79], M. Svatos[137], M. Swiatlowski[36], S.P. Swift[2], I. Sykora[28a], T. Sykora[139], D. Ta[50], K. Tackmann[44,ab], J. Taenzer[159], A. Taffard[169], R. Tafirout[166a], E. Tahirovic[90], N. Taiblum[159], H. Takai[29], R. Takashima[84], E.H. Takasugi[113], K. Takeda[80], T. Takeshita[147], Y. Takubo[79], M. Talby[99], A.A. Talyshev[120b,120a], J. Tanaka[161], M. Tanaka[163], R. Tanaka[128], S. Tanaka[79], R. Tanioka[80], B.B. Tannenwald[122], S. Tapia Araya[144b], S. Tapprogge[97], S. Tarem[158], G.F. Tartarelli[66a], P. Tas[139], M. Tasevsky[137], T. Tashiro[83], E. Tassi[40b,40a], A. Tavares Delgado[136a,136b], Y. Tayalati[34e], A.C. Taylor[116], A.J. Taylor[48], G.N. Taylor[102], P.T.E. Taylor[102], W. Taylor[166b], P. Teixeira-Dias[91], D. Temple[149], H. Ten Kate[35], P.K. Teng[155], J.J. Teoh[129], F. Tepel[180], S. Terada[79], K. Terashi[161], J. Terron[96], S. Terzo[14], M. Testa[49], R.J. Teuscher[165,ae], S.J. Thais[181], T. Theveneaux-Pelzer[99], F. Thiele[39], J.P. Thomas[21], J. Thomas-Wilsker[91], A.S. Thompson[55], P.D. Thompson[21], L.A. Thomsen[181], E. Thomson[133], Y. Tian[38], M.J. Tibbetts[18], R.E. Ticse Torres[51], V.O. Tikhomirov[108,am], Yu.A. Tikhonov[120b,120a], S. Timoshenko[110], P. Tipton[181], S. Tisserant[99], K. Todome[163], S. Todorova-Nova[5], S. Todt[46], J. Tojo[85], S. Tokár[28a], K. Tokushuku[79], E. Tolley[122], L. Tomlinson[98], M. Tomoto[115], L. Tompkins[150,r], K. Toms[116], B. Tong[57], P. Tornambe[50], E. Torrence[127], H. Torres[46], E. Torró Pastor[145], J. Toth[99,ad], F. Touchard[99], D.R. Tovey[146], C.J. Treado[121], T. Trefzger[175], F. Tresoldi[153], A. Tricoli[29], I.M. Trigger[166a], S. Trincaz-Duvoid[132], M.F. Tripiana[14], W. Trischuk[165], B. Trocmé[56], A. Trofymov[44], C. Troncon[66a], M. Trottier-McDonald[18], M. Trovatelli[174], L. Truong[32b], M. Trzebinski[82], A. Trzupek[82], K.W. Tsang[61a], J.C-L. Tseng[131], P.V. Tsiareshka[105], G. Tsipolitis[10], N. Tsirintanis[9], S. Tsiskaridze[14], V. Tsiskaridze[50], E.G. Tskhadadze[157a], I.I. Tsukerman[109], V. Tsulaia[18], S. Tsuno[79], D. Tsybychev[152], Y. Tu[61b], A. Tudorache[27b], V. Tudorache[27b], T.T. Tulbure[27a], A.N. Tuna[57], S. Turchikhin[77], D. Turgeman[178], I. Turk Cakir[4b,v], R. Turra[66a], P.M. Tuts[38], G. Ucchielli[23b,23a], I. Ueda[79], M. Ughetto[43a,43b], F. Ukegawa[167], G. Unal[35], A. Undrus[29], G. Unel[169], F.C. Ungaro[102], Y. Unno[79], K. Uno[161],

C. Unverdorben[112], J. Urban[28b], P. Urquijo[102], P. Urrejola[97], G. Usai[8], J. Usui[79], L. Vacavant[99],
V. Vacek[138], B. Vachon[101], K.O.H. Vadla[130], A. Vaidya[92], C. Valderanis[112], E. Valdes Santurio[43a,43b],
M. Valente[52], S. Valentinetti[23b,23a], A. Valero[172], L. Valéry[14], S. Valkar[139], A. Vallier[5],
J.A. Valls Ferrer[172], W. Van Den Wollenberg[118], H. Van der Graaf[118], P. Van Gemmeren[6],
J. Van Nieuwkoop[149], I. Van Vulpen[118], M.C. van Woerden[118], M. Vanadia[71a,71b], W. Vandelli[35],
A. Vaniachine[164], P. Vankov[118], G. Vardanyan[182], R. Vari[70a], E.W. Varnes[7], C. Varni[53b,53a], T. Varol[41],
D. Varouchas[128], A. Vartapetian[8], K.E. Varvell[154], G.A. Vasquez[144b], J.G. Vasquez[181], F. Vazeille[37],
D. Vazquez Furelos[14], T. Vazquez Schroeder[101], J. Veatch[51], V. Veeraraghavan[7], L.M. Veloce[165],
F. Veloso[136a,136c], S. Veneziano[70a], A. Ventura[65a,65b], M. Venturi[174], N. Venturi[35], A. Venturini[26],
V. Vercesi[68a], M. Verducci[72a,72b], W. Verkerke[118], A.T. Vermeulen[118], J.C. Vermeulen[118],
M.C. Vetterli[149,av], N. Viaux Maira[144b], O. Viazlo[94], I. Vichou[171,*], T. Vickey[146], O.E. Vickey Boeriu[146],
G.H.A. Viehhauser[131], S. Viel[18], L. Vigani[131], M. Villa[23b,23a], M. Villaplana Perez[66a,66b], E. Vilucchi[49],
M.G. Vincter[33], V.B. Vinogradov[77], A. Vishwakarma[44], C. Vittori[23b,23a], I. Vivarelli[153], S. Vlachos[10],
M. Vogel[180], P. Vokac[138], G. Volpi[14], H. von der Schmitt[113], E. Von Toerne[24], V. Vorobel[139],
K. Vorobev[110], M. Vos[172], R. Voss[35], J.H. Vossebeld[88], N. Vranjes[16], M. Vranjes Milosavljevic[16],
V. Vrba[138], M. Vreeswijk[118], T. Šfiligoj[89], R. Vuillermet[35], I. Vukotic[36], T. Ženiš[28a], L. Živković[16],
P. Wagner[24], W. Wagner[180], J. Wagner-Kuhr[112], H. Wahlberg[86], S. Wahrmund[46], K. Wakamiya[80],
J. Walder[87], R. Walker[112], W. Walkowiak[148], V. Wallangen[43a,43b], C. Wang[15c], C. Wang[58b,e], F. Wang[179],
H. Wang[18], H. Wang[3], J. Wang[154], J. Wang[44], Q. Wang[124], R.-J. Wang[132], R. Wang[6], S.M. Wang[155],
T. Wang[38], W. Wang[155,p], W.X. Wang[58a,af], Z. Wang[58c], C. Wanotayaroj[44], A. Warburton[101],
C.P. Ward[31], D.R. Wardrope[92], A. Washbrook[48], P.M. Watkins[21], A.T. Watson[21], M.F. Watson[21],
G. Watts[145], S. Watts[98], B.M. Waugh[92], A.F. Webb[11], S. Webb[97], M.S. Weber[20], S.A. Weber[33],
S.M. Weber[59a], S.W. Weber[175], J.S. Webster[6], A.R. Weidberg[131], B. Weinert[63], J. Weingarten[51],
M. Weirich[97], C. Weiser[50], H. Weits[118], P.S. Wells[35], T. Wenaus[29], T. Wengler[35], S. Wenig[35],
N. Wermes[24], M.D. Werner[76], P. Werner[35], M. Wessels[59a], T.D. Weston[20], K. Whalen[127],
N.L. Whallon[145], A.M. Wharton[87], A.S. White[103], A. White[8], M.J. White[1], R. White[144b],
D. Whiteson[169], B.W. Whitmore[87], F.J. Wickens[141], W. Wiedenmann[179], M. Wielers[141],
C. Wiglesworth[39], L.A.M. Wiik-Fuchs[50], A. Wildauer[113], F. Wilk[98], H.G. Wilkens[35], H.H. Williams[133],
S. Williams[31], C. Willis[104], S. Willocq[100], J.A. Wilson[21], I. Wingerter-Seez[5], E. Winkels[153],
F. Winklmeier[127], O.J. Winston[153], B.T. Winter[24], M. Wittgen[150], M. Wobisch[93], A. Wolf[97],
T.M.H. Wolf[118], R. Wolff[99], M.W. Wolter[82], H. Wolters[136a,136c], V.W.S. Wong[173], N.L. Woods[143],
S.D. Worm[21], B.K. Wosiek[82], J. Wotschack[35], K.W. Woźniak[82], M. Wu[36], S.L. Wu[179], X. Wu[52],
Y. Wu[103], T.R. Wyatt[98], B.M. Wynne[48], S. Xella[39], Z. Xi[103], L. Xia[15b], D. Xu[15a], L. Xu[29], T. Xu[142],
W. Xu[103], B. Yabsley[154], S. Yacoob[32a], D. Yamaguchi[163], Y. Yamaguchi[163], A. Yamamoto[79],
S. Yamamoto[161], T. Yamanaka[161], F. Yamane[80], M. Yamatani[161], T. Yamazaki[161], Y. Yamazaki[80],
Z. Yan[25], H.J. Yang[58c,58d], H.T. Yang[18], Y. Yang[155], Z. Yang[17], W-M. Yao[18], Y.C. Yap[44], Y. Yasu[79],
E. Yatsenko[5], K.H. Yau Wong[24], J. Ye[41], S. Ye[29], I. Yeletskikh[77], E. Yigitbasi[25], E. Yildirim[97],
K. Yorita[177], K. Yoshihara[133], C.J.S. Young[35], C. Young[150], J. Yu[8], J. Yu[76], S.P.Y. Yuen[24], I. Yusuff[31,a],
B. Zabinski[82], G. Zacharis[10], R. Zaidan[14], A.M. Zaitsev[140,al], N. Zakharchuk[44], J. Zalieckas[17],
A. Zaman[152], S. Zambito[57], D. Zanzi[102], C. Zeitnitz[180], G. Zemaityte[131], A. Zemla[81a], J.C. Zeng[171],
Q. Zeng[150], O. Zenin[140], D. Zerwas[128], D.F. Zhang[58b], D. Zhang[103], F. Zhang[179], G. Zhang[58a,af],
H. Zhang[128], J. Zhang[6], L. Zhang[50], L. Zhang[58a], M. Zhang[171], P. Zhang[15c], R. Zhang[58a,e], R. Zhang[24],
X. Zhang[58b], Y. Zhang[15d], Z. Zhang[128], X. Zhao[41], Y. Zhao[58b,128,ai], Z. Zhao[58a], A. Zhemchugov[77],
B. Zhou[103], C. Zhou[179], L. Zhou[41], M.S. Zhou[15d], M. Zhou[152], N. Zhou[58c], Y. Zhou[7], C.G. Zhu[58b],
H. Zhu[15a], J. Zhu[103], Y. Zhu[58a], X. Zhuang[15a], K. Zhukov[108], A. Zibell[175], D. Zieminska[63],
N.I. Zimine[77], C. Zimmermann[97], S. Zimmermann[50], Z. Zinonos[113], M. Zinser[97], M. Ziolkowski[148],
G. Zobernig[179], A. Zoccoli[23b,23a], R. Zou[36], M. Zur Nedden[19], L. Zwalinski[35].

[1]Department of Physics, University of Adelaide, Adelaide; Australia.
[2]Physics Department, SUNY Albany, Albany NY; United States of America.
[3]Department of Physics, University of Alberta, Edmonton AB; Canada.
[4](a)Department of Physics, Ankara University, Ankara;(b)Istanbul Aydin University, Istanbul;(c)Division of Physics, TOBB University of Economics and Technology, Ankara; Turkey.
[5]LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
[6]High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
[7]Department of Physics, University of Arizona, Tucson AZ; United States of America.
[8]Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
[9]Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
[10]Physics Department, National Technical University of Athens, Zografou; Greece.
[11]Department of Physics, University of Texas at Austin, Austin TX; United States of America.
[12](a)Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul;(b)Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul;(c)Department of Physics, Bogazici University, Istanbul;(d)Department of Physics Engineering, Gaziantep University, Gaziantep; Turkey.
[13]Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[14]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
[15](a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;(b)Physics Department, Tsinghua University, Beijing;(c)Department of Physics, Nanjing University, Nanjing;(d)University of Chinese Academy of Science (UCAS), Beijing; China.
[16]Institute of Physics, University of Belgrade, Belgrade; Serbia.
[17]Department for Physics and Technology, University of Bergen, Bergen; Norway.
[18]Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America.
[19]Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
[21]School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
[22]Centro de Investigaciónes, Universidad Antonio Nariño, Bogota; Colombia.
[23](a)Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna;(b)INFN Sezione di Bologna; Italy.
[24]Physikalisches Institut, Universität Bonn, Bonn; Germany.
[25]Department of Physics, Boston University, Boston MA; United States of America.
[26]Department of Physics, Brandeis University, Waltham MA; United States of America.
[27](a)Transilvania University of Brasov, Brasov;(b)Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;(c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;(d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;(e)University Politehnica Bucharest, Bucharest;(f)West University in Timisoara, Timisoara; Romania.
[28](a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
[29]Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
[30]Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina.
[31]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
[32](a)Department of Physics, University of Cape Town, Cape Town;(b)Department of Mechanical

Engineering Science, University of Johannesburg, Johannesburg;(c)School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
[33]Department of Physics, Carleton University, Ottawa ON; Canada.
[34](a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;(b)Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat;(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;(d)Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;(e)Faculté des sciences, Université Mohammed V, Rabat; Morocco.
[35]CERN, Geneva; Switzerland.
[36]Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
[37]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
[38]Nevis Laboratory, Columbia University, Irvington NY; United States of America.
[39]Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
[40](a)Dipartimento di Fisica, Università della Calabria, Rende;(b)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
[41]Physics Department, Southern Methodist University, Dallas TX; United States of America.
[42]Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
[43](a)Department of Physics, Stockholm University;(b)Oskar Klein Centre, Stockholm; Sweden.
[44]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
[45]Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund; Germany.
[46]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
[47]Department of Physics, Duke University, Durham NC; United States of America.
[48]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
[49]INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
[50]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[51]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
[52]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[53](a)Dipartimento di Fisica, Università di Genova, Genova;(b)INFN Sezione di Genova; Italy.
[54]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
[55]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
[56]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
[57]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
[58](a)Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;(b)Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;(c)School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai;(d)Tsung-Dao Lee Institute, Shanghai; China.
[59](a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;(b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
[60]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima; Japan.
[61](a)Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;(b)Department of Physics, University of Hong Kong, Hong Kong;(c)Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
[62]Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
[63]Department of Physics, Indiana University, Bloomington IN; United States of America.

[64](a)INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;(b)ICTP, Trieste;(c)Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine; Italy.
[65](a)INFN Sezione di Lecce;(b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
[66](a)INFN Sezione di Milano;(b)Dipartimento di Fisica, Università di Milano, Milano; Italy.
[67](a)INFN Sezione di Napoli;(b)Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
[68](a)INFN Sezione di Pavia;(b)Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
[69](a)INFN Sezione di Pisa;(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
[70](a)INFN Sezione di Roma;(b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
[71](a)INFN Sezione di Roma Tor Vergata;(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
[72](a)INFN Sezione di Roma Tre;(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
[73](a)INFN-TIFPA;(b)Università degli Studi di Trento, Trento; Italy.
[74]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria.
[75]University of Iowa, Iowa City IA; United States of America.
[76]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
[77]Joint Institute for Nuclear Research, Dubna; Russia.
[78](a)Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;(c)Universidade Federal de São João del Rei (UFSJ), São João del Rei;(d)Instituto de Física, Universidade de São Paulo, São Paulo; Brazil.
[79]KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
[80]Graduate School of Science, Kobe University, Kobe; Japan.
[81](a)AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow;(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
[82]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
[83]Faculty of Science, Kyoto University, Kyoto; Japan.
[84]Kyoto University of Education, Kyoto; Japan.
[85]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
[86]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
[87]Physics Department, Lancaster University, Lancaster; United Kingdom.
[88]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
[89]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
[90]School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
[91]Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[92]Department of Physics and Astronomy, University College London, London; United Kingdom.
[93]Louisiana Tech University, Ruston LA; United States of America.
[94]Fysiska institutionen, Lunds universitet, Lund; Sweden.
[95]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France.
[96]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
[97]Institut für Physik, Universität Mainz, Mainz; Germany.
[98]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
[99]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[100]Department of Physics, University of Massachusetts, Amherst MA; United States of America.

[101]Department of Physics, McGill University, Montreal QC; Canada.
[102]School of Physics, University of Melbourne, Victoria; Australia.
[103]Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
[104]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[105]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus.
[106]Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus.
[107]Group of Particle Physics, University of Montreal, Montreal QC; Canada.
[108]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia.
[109]Institute for Theoretical and Experimental Physics (ITEP), Moscow; Russia.
[110]National Research Nuclear University MEPhI, Moscow; Russia.
[111]D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
[112]Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
[113]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
[114]Nagasaki Institute of Applied Science, Nagasaki; Japan.
[115]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
[116]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
[117]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
[118]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
[119]Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
[120](a)Budker Institute of Nuclear Physics, SB RAS, Novosibirsk;(b)Novosibirsk State University Novosibirsk; Russia.
[121]Department of Physics, New York University, New York NY; United States of America.
[122]Ohio State University, Columbus OH; United States of America.
[123]Faculty of Science, Okayama University, Okayama; Japan.
[124]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
[125]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
[126]Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic.
[127]Center for High Energy Physics, University of Oregon, Eugene OR; United States of America.
[128]LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
[129]Graduate School of Science, Osaka University, Osaka; Japan.
[130]Department of Physics, University of Oslo, Oslo; Norway.
[131]Department of Physics, Oxford University, Oxford; United Kingdom.
[132]LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
[133]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
[134]Konstantinov Nuclear Physics Institute of National Research Centre ”Kurchatov Institute”, PNPI, St. Petersburg; Russia.
[135]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
[136](a)Laboratório de Instrumentação e Física Experimental de Partículas - LIP;(b)Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;(c)Departamento de Física, Universidade de Coimbra, Coimbra;(d)Centro de Física Nuclear da Universidade de Lisboa, Lisboa;(e)Departamento

de Física, Universidade do Minho, Braga;(f)Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain);(g)Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica; Portugal.
[137]Institute of Physics, Academy of Sciences of the Czech Republic, Prague; Czech Republic.
[138]Czech Technical University in Prague, Prague; Czech Republic.
[139]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
[140]State Research Center Institute for High Energy Physics, NRC KI, Protvino; Russia.
[141]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
[142]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
[143]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
[144](a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;(b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
[145]Department of Physics, University of Washington, Seattle WA; United States of America.
[146]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[147]Department of Physics, Shinshu University, Nagano; Japan.
[148]Department Physik, Universität Siegen, Siegen; Germany.
[149]Department of Physics, Simon Fraser University, Burnaby BC; Canada.
[150]SLAC National Accelerator Laboratory, Stanford CA; United States of America.
[151]Physics Department, Royal Institute of Technology, Stockholm; Sweden.
[152]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
[153]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
[154]School of Physics, University of Sydney, Sydney; Australia.
[155]Institute of Physics, Academia Sinica, Taipei; Taiwan.
[156]Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei; Taiwan.
[157](a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;(b)High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia.
[158]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
[159]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
[160]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
[161]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
[162]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.
[163]Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.
[164]Tomsk State University, Tomsk; Russia.
[165]Department of Physics, University of Toronto, Toronto ON; Canada.
[166](a)TRIUMF, Vancouver BC;(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.
[167]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
[168]Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
[169]Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
[170]Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
[171]Department of Physics, University of Illinois, Urbana IL; United States of America.
[172]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

[173]Department of Physics, University of British Columbia, Vancouver BC; Canada.
[174]Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
[175]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
[176]Department of Physics, University of Warwick, Coventry; United Kingdom.
[177]Waseda University, Tokyo; Japan.
[178]Department of Particle Physics, Weizmann Institute of Science, Rehovot; Israel.
[179]Department of Physics, University of Wisconsin, Madison WI; United States of America.
[180]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[181]Department of Physics, Yale University, New Haven CT; United States of America.
[182]Yerevan Physics Institute, Yerevan; Armenia.
[a] Also at Department of Physics, University of Malaya, Kuala Lumpur; Malaysia.
[b] Also at Borough of Manhattan Community College, City University of New York, NY; United States of America.
[c] Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa.
[d] Also at CERN, Geneva; Switzerland.
[e] Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[f] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[g] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[h] Also at Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain); Spain.
[i] Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.
[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[k] Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
[l] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[m] Also at Department of Physics, California State University, Fresno CA; United States of America.
[n] Also at Department of Physics, California State University, Sacramento CA; United States of America.
[o] Also at Department of Physics, King's College London, London; United Kingdom.
[p] Also at Department of Physics, Nanjing University, Nanjing; China.
[q] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.
[r] Also at Department of Physics, Stanford University; United States of America.
[s] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[t] Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
[u] Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
[v] Also at Giresun University, Faculty of Engineering, Giresun; Turkey.
[w] Also at Graduate School of Science, Osaka University, Osaka; Japan.
[x] Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; Romania.
[y] Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
[z] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[aa] Also at Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
[ab] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[ac] Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University

Nijmegen/Nikhef, Nijmegen; Netherlands.
[ad] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.
[ae] Also at Institute of Particle Physics (IPP); Canada.
[af] Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.
[ag] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[ah] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[ai] Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
[aj] Also at Louisiana Tech University, Ruston LA; United States of America.
[ak] Also at Manhattan College, New York NY; United States of America.
[al] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
[am] Also at National Research Nuclear University MEPhI, Moscow; Russia.
[an] Also at Near East University, Nicosia, North Cyprus, Mersin; Turkey.
[ao] Also at Novosibirsk State University, Novosibirsk; Russia.
[ap] Also at Ochadai Academic Production, Ochanomizu University, Tokyo; Japan.
[aq] Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[ar] Also at School of Physics, Sun Yat-sen University, Guangzhou; China.
[as] Also at The City College of New York, New York NY; United States of America.
[at] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[au] Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
[av] Also at TRIUMF, Vancouver BC; Canada.
[aw] Also at Universita di Napoli Parthenope, Napoli; Italy.
[*] Deceased