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Search for dark photons from Higgs boson decays in the gluon–gluon fusion channel in proton–proton collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS detector

The ATLAS Collaboration

This paper presents a search for semi-visible Higgs boson decays in final states with a photon (γ) and missing transverse momentum p_T^{miss} . The analysis is optimised for the gluon–gluon fusion production channel and exploits a novel trigger deployed in 2023, with reduced thresholds down to 50 GeV on the photon transverse momentum (p_T^γ) and 70 GeV on the p_T^{miss} , in combination with a selection on the transverse mass of the $p_T^{\text{miss}}-\gamma$ system (m_T) above 80 GeV. The results are interpreted in terms of Higgs boson decays into a γ and a dark photon γ_d ($H \rightarrow \gamma\gamma_d$). The analysis is performed using 135 fb^{-1} of Run 3 data collected by ATLAS in 2023 and 2024. A boosted decision tree is used to identify events with misreconstructed primary vertices, which can affect the p_T^{miss} calculation. Data-driven methods are employed to estimate the backgrounds from jets and electrons misidentified as photons, while the backgrounds with genuine photons are taken from Monte Carlo simulations, normalised to data in control regions with muons. A binned maximum-likelihood fit to the m_T distribution is performed to evaluate the compatibility of the observed data with the Standard Model expectation. No significant excess is observed over the Standard Model prediction, and an observed (expected) upper limit on the branching ratio of $H \rightarrow \gamma\gamma_d$ of 1.4% (1.2%) is obtained at 95% confidence level. Combining this result with previous Run 2 searches improves the observed (expected) upper limit to 0.9% (0.9%).

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1 Introduction

Exotic decays of the Higgs boson are well motivated by a variety of models beyond the Standard Model (BSM) [1], including supersymmetry, dark sector or extended Higgs sectors, and provide a unique opportunity to probe new physics.

This paper presents a new strategy to search for exotic Higgs boson decays into a final state with a photon (γ) and missing transverse momentum (p_T^{miss}), probing an unexplored region of the phase space with low kinematic thresholds. This semi-visible decay of the Higgs boson provides an interesting production channel for the dark photon (γ_d), which arises as the gauge boson of an additional $U(1)_D$ gauge group in dark sector models. Strong motivations for the search for this particle arise from its potential contribution to solving the small-scale structure formation problems [2, 3], as well as being a possible source of the Sommerfeld enhancement of dark matter (DM) annihilation required to explain the PAMELA–Fermi–AMS2 positron anomaly in terms of DM [4], or making asymmetric DM scenarios viable [5]. In addition, this signature can arise in several BSM models, such as those with very low-scale supersymmetry breaking where the Higgs boson can decay into a gravitino ($\tilde{G}$) and a bino ($\tilde{B}$) that subsequently decays via $\tilde{B} \rightarrow \gamma \tilde{G}$ [6], in the

Peccei–Quinn limit of next-to-minimal-supersymmetric models (NMSSM) [7], or in the decay of the Higgs boson into a pair of right-handed neutrinos (N) subsequently decaying via $N \rightarrow \nu \bar{\nu}$ and $N \rightarrow \gamma \nu$ [8].

While γ_d searches typically target the massive γ_d [9–11], which can couple directly to the Standard Model (SM) via kinetic mixing with the ordinary photon [12], this paper focuses on a massless γ_d scenario. In this case, the kinetic mixing between the γ_d and the photon can be tuned away through a rotation of the gauge fields, and the γ_d can interact with ordinary matter only through operators of dimension higher than four [12]. The Higgs boson can decay through a loop interaction involving additional scalar or pseudo-scalar BSM messenger fields, which couple both to the SM and the dark sector [13, 14], represented as an effective vertex in Figure 1. Due to the non-decoupling properties of the Higgs boson, a branching ratio of $H \rightarrow \gamma \gamma_d$ ($\mathcal{B}_{\gamma \gamma_d}$) at the sub-percent level may be allowed [15, 16], depending on the parameters of the model and taking into account constraints from searches for invisible Higgs boson decays and measurements of the branching ratio of $H \rightarrow \gamma \gamma$.

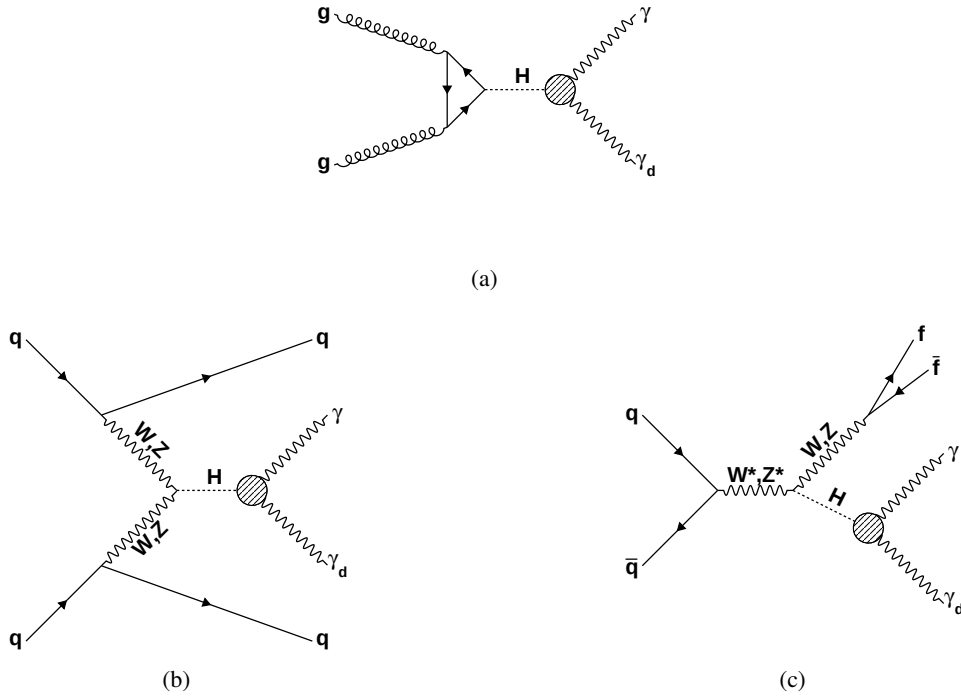


Figure 1: Feynman diagrams illustrating Higgs boson production via (a) the gluon–gluon fusion, (b) vector-boson fusion and (c) Higgsstrahlung processes, all followed by the decay into a photon and a dark photon ($H \rightarrow \gamma \gamma_d$). The hatched circle in the $H \gamma \gamma_d$ vertex represents the interaction through messenger fields.

Searches for the semi-visible decay $H \rightarrow \gamma \gamma_d$ have been conducted at the LHC by the ATLAS and CMS collaborations, in the vector boson fusion (VBF) Higgs boson production channel and in associated production with a Z boson (ZH) [17–20]. The combination of ATLAS results in the ZH and VBF channels [21] provides the best limit so far, excluding a $\mathcal{B}_{\gamma \gamma_d} > 1.3\%$ (1.5% expected) at 95% confidence level (CL) with 139 fb^{-1} of data collected during the LHC Run 2 at $\sqrt{s} = 13 \text{ TeV}$. These production modes take advantage of a richer final state in addition to the $\gamma + p_T^{\text{miss}}$ signature from the $H \rightarrow \gamma \gamma_d$ decay, with additional jets or leptons that provide powerful handles for triggering, background rejection and identification of the hard-scatter primary vertex. In contrast, the gluon–gluon fusion mode (ggF), leading to

the $\gamma + p_T^{\text{miss}}$ final state, is the dominant production mode, with a cross-section about an order of magnitude larger than that of the VBF channel. This final state has been explored by CMS [22] and ATLAS in the context of other exotic models [23] or by focusing on the decay into $\gamma\gamma_d$ of BSM Higgs bosons with masses higher than 400 GeV [24]. However, the $H \rightarrow \gamma\gamma_d$ decay of a Higgs boson with a mass of 125 GeV has not been specifically targeted, as the low thresholds on the photon transverse momentum (p_T^γ) and p_T^{miss} required for this signature constitute a challenge for the trigger. Developments in the ATLAS trigger system between Run 2 and Run 3 led to the implementation of a composite trigger that combines selections on p_T^{miss} , p_T^γ , and the transverse mass between the γ and the p_T^{miss} , $m_T = \sqrt{2p_T^\gamma p_T^{\text{miss}}(1 - \cos(\Delta\phi))}$,¹ where $\Delta\phi$ is the azimuthal separation between the photon and the p_T^{miss} . This new trigger allows to increase the acceptance of ggF events by approximately a factor of two, while keeping the trigger rate under control. By exploiting this new trigger, the analysis presented in this paper is optimised for the $H \rightarrow \gamma\gamma_d$ decay in the ggF production channel for the first time in ATLAS, while also retaining sensitivity to the VBF, ZH and WH channels.

2 ATLAS detector

The ATLAS detector [25, 26] at the LHC consists of an inner tracking detector system (ID) surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters (ECAL and HCAL), and a muon spectrometer (MS) incorporating three large superconducting air-core toroidal magnets, with an almost complete solid angle coverage around the collision point.

The ID system is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range of $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the interaction region and typically provides four measurements per track, the first hit generally being in the insertable B-layer installed before Run 2 [27, 28]. It is followed by the silicon microstrip tracker, which usually provides eight measurements per track. The outermost part of the ID is the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$. The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. The ECAL [29, 30] is a lead/liquid-argon (LAr) sampling calorimeter covering the region $|\eta| < 3.2$, divided into a barrel and two endcaps, and longitudinally segmented into three layers: the strips, the middle and the back layer. The 3-dimensional high-granularity in the fiducial acceptances $|\eta| < 1.37$ and $1.52 < |\eta| < 2.37$ allows observation of the shape of the electromagnetic showers. Before the ECAL, a thin LAr presampler covering $|\eta| < 1.8$ detects energy losses of showers starting in the material upstream. The HCAL consists of a steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadron endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic energy 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 upwards. Polar 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 $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

The MS comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$, except in the innermost layer of the endcap region, where layers of small-strip thin-gap chambers and Micromegas chambers provide precision tracking in the region $1.3 < |\eta| < 2.7$. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, thin-gap chambers in the endcap regions, and the small-strip thin-gap chambers and Micromegas chambers in the innermost layer of the endcap.

Interesting events are selected by the first-level (L1) trigger system implemented in custom hardware, followed by selections made by software-implemented algorithms in the high-level trigger (HLT) [31]. The first-level trigger selects events at a rate below 100 kHz from the 40 MHz bunch crossings; the high-level trigger further reduces that rate, in order to record events to disk at about 3 kHz. An extensive software suite [32] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and simulation

This analysis uses proton–proton (pp) collision data at a centre-of-mass energy of 13.6 TeV, collected in 2023 and 2024 by the ATLAS detector. Only data recorded during stable beam conditions and with all sub-detectors operational are considered [33], corresponding to a total integrated luminosity of 135 fb^{-1} , with an uncertainty of 1.9% [34]. Events were selected by using a dedicated trigger (‘analysis trigger’) deployed in 2023, optimised for the $\gamma + p_{\text{T}}^{\text{miss}}$ final state and described in Section 4. In addition, samples with e^+e^- , γe and $\gamma\mu$ final states, used for the modelling of the background from electrons misidentified as photons (Section 8.1) and for the efficiency studies of the analysis trigger (Section 4), were selected using dielectron, single-electron, and single-muon triggers, respectively.

Monte Carlo (MC) simulations are used to model the signal and background processes described in Section 6. In particular, the backgrounds containing genuine photons ($Z\gamma$, $W\gamma$, and processes with a direct photon, $\gamma(\text{dir})+\text{jets}$) are estimated using MC simulations. The remaining backgrounds are estimated with data-driven methods, with $W+\text{jets}$ and $Z+\text{jets}$ MC samples used as input for the data-driven estimation of the background arising from jets misidentified as photons (Section 8.2). All the samples, including processes with photons from fragmentation, $\gamma(\text{frag})+\text{jets}$, and multijets samples, are used in the training of the algorithm that identifies wrongly reconstructed hard scattering vertices (Section 7.1). Simulations of events from top-quark production are not used, as the analysis applies a veto on jets emanating from b -quarks (Section 7.1).

The simulation of the geometry and response of the ATLAS detector [35] was performed using GEANT4 [36], and all simulated events were processed through the same reconstruction chain as collision data. The effect of multiple interactions in the same and neighbouring bunch crossings, pile-up (PU), was modelled by overlaying [37] the simulated hard-scattering event with inelastic pp events generated using EPOS 2.0.1.4 [38] and PYTHIA 8.308 [39]. The EPOS events were generated with the EPOS LHC set of tuned parameters (tune) [40] and the PYTHIA events with the A3 tune [41] and the NNPDF2.3LO [42] set of parton distribution functions (PDF). PYTHIA PU events include either a high p_{T} jet, a prompt photon, or a lepton from a b -hadron decay, while events generated using EPOS were filtered to simulate all remaining PU events in the overlay sample. The individual simulations were first reweighted to ensure a smooth jet p_{T} distribution.

Table 1: Configurations used for event generation and parton shower of signal (ggF, VBF, ZH and WH) and background MC samples. The matrix element (ME) order, leading-order (LO) or next-to-leading order (NLO), refers to the order in the strong coupling constant of the perturbative calculation in the MC event generation. PDF refers to the parton density libraries used with the generator. The tune refers to the underlying-event tune of the parton shower model.

Process	Generator	ME order	PDF	Parton Shower	Tune
$H \rightarrow \gamma\gamma_d$	POWHEG v2	NLO	PDF4LHC21	PYTHIA 8.245	AZNLO
$Z\gamma, W\gamma$	SHERPA v2.2.14	0,1j@NLO + 2,3,4j@LO	NNPDF3.0 NNLO	SHERPA	SHERPA
Z +jets, W +jets	SHERPA v2.2.14	0,1,2j@NLO + 3,4,5j@LO	NNPDF3.0 NNLO	SHERPA	SHERPA
$\gamma(\text{dir})$ +jets	PYTHIA 8.186	LO	NNPDF2.3 LO	PYTHIA 8.308	A14
$\gamma(\text{frag})$ +jets	PYTHIA 8.186	LO	NNPDF2.3 LO	PYTHIA 8.308	A14
multijets	PYTHIA 8.186	LO	NNPDF2.3 LO	PYTHIA 8.308	A14

The combination was then reweighted to match the distribution of the actual number of interactions per bunch crossing measured in data.

The signal samples include multiple Higgs boson production channels. The dominant process and main target of this analysis is the ggF channel, but non-negligible contributions arise from the VBF, WH and ZH channels. One MC sample for each production mode was generated, with WH production divided into W^+H and W^-H . The matrix elements were estimated using POWHEG v2 [43, 44] at next-to-leading order (NLO), with the PDF4LHC21 set of PDFs [45]. For the ggF channel, next-to-next-to-leading (NNLO) precision was achieved through a reweighting of the events computed in bins of the p_T and rapidity of the generated Higgs boson, to match NNLOPS predictions [46]. The samples were generated with the SM Higgs boson mass set to 125 GeV. All the signal samples were normalised to state-of-the-art cross-section predictions for the centre-of-mass energy of 13 TeV [47], extrapolated to 13.6 TeV [48]. The decay into photons and dark photons, as well as the hadronisation and showering, was simulated using PYTHIA 8.245 with the CTEQ6L1 PDF set and the AZNLO tune [49]. The ‘Hidden Valley’ scenario [50] was used for modelling the $H \rightarrow \gamma\gamma_d$ decay.

The $V\gamma$ and V +jets processes were simulated using the SHERPA 2.2.14 generator [51], with up to one jet (two jets) at NLO and up to three additional jets at leading order (LO) for $Z\gamma$ and $W\gamma$ (Z +jets and W +jets). The matrix elements were matched and merged with the SHERPA parton shower [52], using the MEPS@NLO prescription [53, 54] and the NNPDF3.0 NNLO PDF set [55] with the dedicated SHERPA tune. The $\gamma(\text{dir})$ +jets, $\gamma(\text{frag})$ +jets and multijets samples were generated at LO using PYTHIA 8.186 [56, 57] with the NNPDF2.3 LO PDF set and the A14 tune [58] for the parton shower. Table 1 summarises the configurations used for the signal and background MC simulations of the analysis.

4 Analysis trigger

The ‘analysis trigger’ combines selections on the photon p_T , the p_T^{miss} and the m_T . It selects 10% of the total generated signal events, with a factor of two increase relative to previous single-photon or inclusive p_T^{miss} triggers. At L1, the trigger selected electrons or photons with p_T above 26 GeV. The HLT further required a 50 GeV photon fulfilling tight identification criteria [31]. To compute the p_T^{miss} at HLT level, a two-stage sequence of algorithms was employed, starting with the ‘cell’ p_T^{miss} computed using only the calorimeter cells as input [59]. This fast step was followed by a more sophisticated p_T^{miss} algorithm using particle flow [60] constituents, combining tracks and calorimeter clusters, with a dedicated PU

subtraction algorithm (‘pfopufit’) [31]. A minimum threshold of 40 GeV was applied for the first ‘cell’ p_T^{miss} requirement, while the second ‘pfopufit’ step had a threshold of 70 GeV. To further reduce the rate, the trigger required a minimum m_T (computed using ‘pfopufit’ p_T^{miss}) of 80 GeV. Since muons are invisible to the ‘cell’ p_T^{miss} algorithm [61], particle flow constituents consistent with muons were removed also in the ‘pfopufit’ algorithm, to preserve the same behaviour. Therefore both the ‘cell’ and the ‘pfopufit’ algorithms were insensitive to the presence of muons, which were treated as invisible in the computation of p_T^{miss} . This feature allowed samples to be selected with reconstructed muons in the final state and to treat them as invisible to mimic p_T^{miss} , without introducing a bias induced by the analysis trigger. In particular, events with muons are used to constrain the $W\gamma$ and $Z\gamma$ backgrounds in control regions with one or two muons as described in Section 8.

Events with one muon are also used to assess the accuracy of the simulation of the analysis trigger in $\gamma\mu$ final states, selected by a muon trigger used as a baseline trigger. The muon was treated as invisible in the computation of p_T^{miss} and m_T in the full (offline) reconstruction. Figure 2 shows the trigger efficiency as a function of offline p_T^γ , p_T^{miss} and m_T . The efficiency in data is compared to that of the dominant background contribution from $W\gamma$ events (75%), and that of the total background, which includes contributions from $Z\gamma$ events (2%) and from events with a jet misidentified as a photon (23%). The latter may exhibit a different trigger efficiency. The trigger efficiency measured in data is observed to be in between the one predicted by the simulations for $W\gamma$ background and for the total background. Up and down uncertainties in the trigger efficiency are therefore assigned as the differences between the efficiency measured in data and the one predicted for the total background and for the $W\gamma$ simulation, respectively. This procedure also accounts for the uncertainty in the modelling of the background from jets misidentified as photons. The m_T variable is correlated with both the p_T^γ and the p_T^{miss} . While the trigger efficiency curve rapidly reaches a plateau as a function of p_T^γ , a slower rise is observed as a function of p_T^{miss} . For this reason, uncertainties at the 2%–3% level are applied in bins of p_T^{miss} .

5 Event reconstruction

For each event, vertex candidates are required to have at least two associated tracks with $p_T > 500$ MeV. Among the reconstructed vertices, the hard-scattering (HS) primary vertex (PV) is selected as the one with the highest sum of squared transverse momenta of contributing tracks [62].

For each reconstructed physics object, looser selection criteria are first applied to define *baseline* objects, which are used for event vetos, p_T^{miss} reconstruction, and overlap removal. More stringent criteria are then required, to define *selected* objects.

Electrons are reconstructed by matching energy clusters in the ECAL to tracks in the ID [63, 64]. *Baseline* electrons are required to satisfy $p_T > 10$ GeV and $|\eta| < 2.47$, be outside the transition region between the ECAL barrel and endcaps ($1.37 < |\eta| < 1.52$), and be consistent with originating from the PV through requirements on the longitudinal and transverse impact parameters, $|z_0 \sin(\theta)| < 0.5$ mm and $|d_0/\sigma(d_0)| < 5$ where $\sigma(d_0)$ is the uncertainty in d_0 . All baseline electron candidates are required to satisfy Loose likelihood-based identification criteria [65], based on calorimeter, tracking and combined variables that provide separation between electrons and jets. *Selected* electrons are further required to satisfy Tight identification and Tight isolation requirements [65].

Muons are reconstructed by matching ID tracks to MS tracks or track segments, by associating ID tracks with calorimeter energy deposits compatible with a minimum-ionizing particle, or by identifying MS

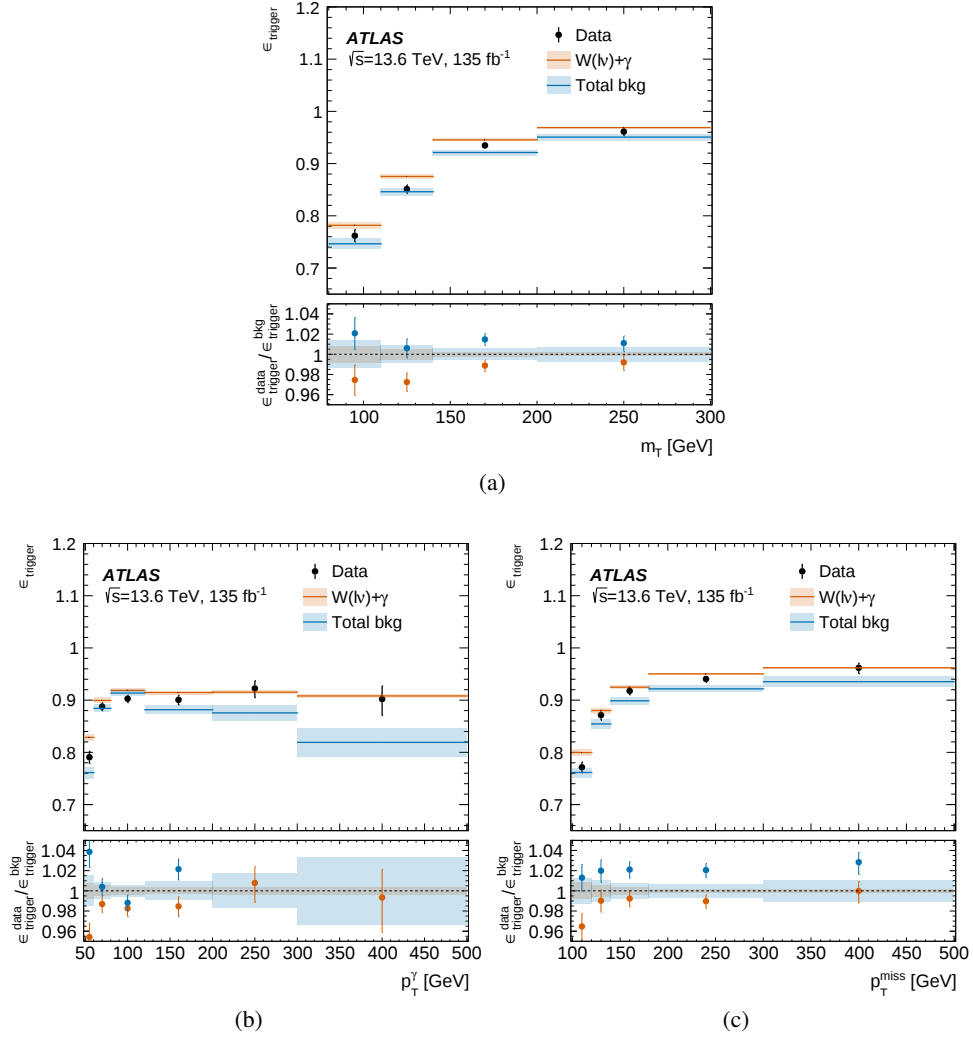


Figure 2: Analysis trigger efficiency as a function of (a) m_T (b) p_T^γ and (c) p_T^{miss} for data, simulation of the dominant background $W\gamma$ and total background. Events were selected using single-muon triggers and requiring one muon treated as invisible in the evaluation of p_T^{miss} and m_T . In addition, a subset of the selections used in the analysis is applied: $p_T^{\text{miss}} > 100$ GeV, $m_T > 80$ GeV, one photon with $p_T^\gamma > 50$ GeV and a requirement of $|\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{miss},\gamma})| > 1.25$ on the azimuthal separation between the $\vec{p}_T^{\text{miss}}$ and its photon term $\vec{p}_T^{\text{miss},\gamma}$, equivalent to $-\vec{p}_T^\gamma$. The bottom panels show the ratios of the efficiency in data to those in the $W\gamma$ MC simulation and in the total background expectation. The shaded bands and the error bars represent the statistical uncertainties associated with the MC simulation and the data, respectively.

tracks satisfying the Loose requirement and compatible with the interaction point [66, 67]. *Baseline* muon candidates must satisfy $p_T > 10$ GeV and $|\eta| < 2.7$ and Medium identification criteria. Similar selections on the impact parameter as for electrons are applied, but with $|d_0/\sigma(d_0)| < 3$. *Selected* muons are further required to satisfy Loose isolation selections [67].

Photon candidates are reconstructed from clustered energy deposits in the ECAL [63, 64]. For photons that undergo conversions in the material upstream the ECAL, tracks in the ID are also used. *Baseline* photons are required to satisfy $p_T^\gamma > 25$ GeV, $|\eta| < 2.37$ and be outside the transition region between the ECAL barrel and endcaps ($1.37 < |\eta| < 1.52$). Photon candidates must satisfy a Tight identification criterion,

based on several requirements on the ‘shower shape’ variables [68], which can be grouped into three categories: energy leakage in the HCAL, width in the middle layer of the ECAL, and shape in the strips. *Selected* photon candidates are additionally required to be isolated. A dimensionless isolation variable is introduced:

$$\Upsilon = \frac{E_T^{\text{cone}} - 2.45 \text{ GeV}}{p_T^\gamma}, \quad (1)$$

where E_T^{cone} is the transverse energy measured by the calorimeters in a cone of size $\Delta R = 0.4$ around the photon candidate. Isolated photons are required to satisfy the `TightCaloOnly` working point, $\Upsilon < 0.022$, a typical requirement to select prompt, isolated photons in ATLAS [69]. Non-isolated photons are used in the evaluation of the background induced by jets misidentified as photons (see Sections 6 and 8.2). In this context, a *Loose* photon selection is required, with relaxed requirements on the HCAL and ECAL middle layer, and no requirements on strips. Removing *Tight* photons from the *Loose* sample provides a *Loose'* sample enriched in this background. Further photon selections *Loose''* are introduced as subsets of the *Loose'* sample, by applying the same selections as for *Tight* to the HCAL and middle layer shower shapes, but at most one requirement on one of the strips shower shapes.

Particle flow (PFlow) jets are reconstructed using the anti- k_t algorithm [70], as implemented in FastJet [71], with a radius parameter $R = 0.4$. The algorithm takes PFlow objects as inputs, combining measurements from the ID and the calorimeters [60]. *Selected* jets are required to satisfy $p_T > 20$ GeV. In addition, central jets ($|\eta| < 2.5$) are classified as originating from the HS interaction using a neural-network-based jet-vertex-tagger (NN-JVT) (an evolution of the JVT described in Ref. [72]), while a forward jet vertex tagging (fJVT) algorithm [73] is applied to forward jets ($|\eta| > 2.5$). Jets containing b -hadrons (b -jets) are identified using a graph neural network tagger with 85% b -tagging efficiency [74]. To suppress the background originating from detector noise, hardware issues, beam-induced background or cosmic-ray muons, events containing jets failing to satisfy *Loose* jet-quality criteria are rejected [75].

Hadronically decaying τ -leptons (τ_{had}) are seeded by anti- k_t jets with $R = 0.4$ and identified using a recurrent neural network algorithm that uses tracks and calorimeter energy clusters associated with τ_{had} candidates, as well as high-level discriminating variables [76]. *Baseline* τ_{had} are required to satisfy a *Medium* identification working point and have $p_T > 20$ GeV and $|\eta| < 2.5$.

The $\vec{p}_T^{\text{miss}}$, with magnitude $p_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}|$, is defined as the negative vector sum of the transverse momenta of the *baseline* reconstructed objects (‘hard term’), and of the ‘soft term’ estimated from charged PFlow objects associated with the primary vertex and not matched to any of the reconstructed hard objects [77]. In the $\vec{p}_T^{\text{miss}}$ calculation, a NN-JVT selection is applied to the jets for PU subtraction. An alternative $\vec{p}_T^{\text{miss}}$ with no PU subtraction, referred to as $\vec{p}_{T,\text{noJVT}}^{\text{miss}}$, is also exploited to help tag events with a misidentified PV, as explained in Section 7. In addition, a key quantity to identify events with fake p_T^{miss} is the p_T^{miss} significance $\mathcal{S}_{p_T^{\text{miss}}} = \frac{p_T^{\text{miss}}}{\sigma(p_T^{\text{miss}})}$, where $\sigma(p_T^{\text{miss}})$ denotes the p_T^{miss} resolution, accounting for the resolution of the reconstructed physics objects entering the p_T^{miss} computation [77, 78].

After the reconstruction of all physics objects, a sequential overlap removal procedure, as detailed in Table 2, is applied to resolve ambiguities by keeping one single object in case of overlapping objects, based on ΔR matching, shared ID tracks or calorimeter energy clusters, according to a predefined priority.

Table 2: Overview of the sequential overlap removal procedure applied to reconstructed objects and the corresponding matching criteria based on the ΔR separation and shared ID tracks. If two objects overlap based on the matching criteria described in the third column, the object in the first column is removed while the one in the second column is retained. The table is ordered according to the object priority used in the overlap removal procedure.

Remove	Keep	Matching criteria
Muon	Electron	Muon with calorimeter deposits and shared ID track
Electron	Muon	Shared ID track
Jet	Electron	$\Delta R < 0.2$
Electron	Jet	$0.2 < \Delta R < 0.4$
Electron	Electron	Shared ID track, electron with lower p_T removed
Jet	Muon	Number of tracks < 3 and $\Delta R < 0.2$
Muon	Jet	$0.2 < \Delta R < 0.4$
τ -lepton	Electron	$\Delta R < 0.2$
τ -lepton	Muon	$\Delta R < 0.2$
Jet	τ -lepton	$\Delta R < 0.2$
Photon	Electron	Shared calorimeter energy clusters
Photon	Muon	$\Delta R < 0.4$
Jet	Photon	$\Delta R < 0.4$

6 Signature and backgrounds

The $H \rightarrow \gamma\gamma_d$ signal is characterised by the presence of a single photon and p_T^{miss} . Although the z -component of the γ_d momentum cannot be reconstructed, the m_T distribution features a broad peak around the Higgs boson mass. In the ggF channel, the final state contains no leptons, while hadronic jets may originate from gluon radiation. The same final state also covers the VBF channel and VH production with hadronic decay of the vector bosons. Due to the trigger thresholds on p_T^{miss} and photon p_T^γ (Section 4), optimised as a compromise between signal acceptance and trigger rate, the selected signal events are mostly Higgs bosons recoiling against jets, resulting in a boosted topology.

The analysis is significantly affected by background from jets and electrons misidentified as photons, as well as by events reconstructed with large p_T^{miss} , due to mismeasurement or misreconstruction of physics objects (referred to as *fake* p_T^{miss}). In addition, in this signature both the photon and the p_T^{miss} have no associated tracks, therefore the reconstruction of the PV is particularly challenging, since it relies exclusively on tracks originating from the underlying event and from additional jets. When the PV is misidentified, HS jets can be incorrectly classified as PU jets and consequently removed from p_T^{miss} computation, thus enhancing the contribution from fake p_T^{miss} background. The SM background events with similar signatures can be classified in the following categories.

- **Genuine photon:** $Z(\rightarrow \nu\nu)\gamma$ (irreducible background) or $W(\rightarrow \ell\nu)\gamma$ and $Z(\rightarrow \ell\ell)\gamma$ where the lepton(s) ℓ are not reconstructed. An additional contribution arises from γ + jets processes with a direct photon, $\gamma(\text{dir})+\text{jets}$, with fake p_T^{miss} originating primarily from lost or mismeasured jets.
- **Electrons misidentified as photons ($e \rightsquigarrow \gamma$):** mostly $W(\rightarrow e\nu) + \text{jets}$ events.
- **Jets misidentified as photons ($j \rightsquigarrow \gamma$):** dominantly multijets and γ +jets with a fragmentation photon ($\gamma(\text{frag})+\text{jets}$) — in the latter, the photon is considered as $j \rightsquigarrow \gamma$, since it is embedded in a

hadronic jet and therefore not isolated. Such events pass the analysis selections when associated with fake p_T^{miss} . A smaller contribution arises from $Z(\rightarrow \nu\nu)+\text{jets}$ and $W(\rightarrow \ell\nu)+\text{jets}$ processes.

7 Event selection

Events satisfying the trigger selections described in Section 4 are further required to satisfy a set of offline requirements, designed to isolate the signal.

7.1 Baseline selection

Events are required to have exactly one selected photon with $p_T^\gamma > 50$ GeV and no additional *baseline* photons, $p_T^{\text{miss}} > 100$ GeV, a transverse mass $m_T > 80$ GeV, no *baseline* leptons nor *b*-tagged jets, and at most three central jets. The veto on the *b*-tagged jets is applied to reduce the contribution from background processes with top quarks. The requirements on p_T^γ and m_T are aligned with the trigger thresholds, exploiting the fast trigger turn-on, while a more conservative requirement is applied to p_T^{miss} as a compromise between signal acceptance and background rejection.

As discussed in Section 6, low track activity can lead to an incorrect identification of the PV. This effect has a significant impact on p_T^{miss} -related observables, particularly when HS jets are misclassified as PU jets and consequently excluded from the p_T^{miss} reconstruction. In such events, the reconstructed p_T^{miss} distribution becomes artificially harder for γ +jets and multijets backgrounds and softer for the signal, enhancing background acceptance while reducing signal efficiency. Moreover, the PV misidentification distorts the transverse mass distribution, thereby degrading the signal-to-background discrimination, since the loss of HS jets results in a final state with one photon back-to-back with p_T^{miss} , for both signal and background events. This leads to values of m_T above 140 GeV, reflecting the p_T^γ and p_T^{miss} thresholds of 50 GeV and 100 GeV, respectively. To mitigate this effect, a boosted decision tree (BDT) is trained on signal and background simulations using TMVA AdaBoost [79], to identify and reject events with a misidentified PV. This approach ensures a good control of the background modelling at the baseline selection level and, therefore, in all the analysis regions. The BDT uses information related to the reconstructed vertex properties, jet multiplicity, and the angular separation between the photon, jets, and p_T^{miss} , as summarised in Table 3. The distribution of the BDT score for events with correct and incorrect PV identification is shown in Figure 3 for signal and background processes separately, confirming a good discriminating power. As highlighted in Figure 4, a requirement on the misidentified vertex BDT score of $\text{BDT}_{\text{vertex}} > 0.1$ provides an almost complete suppression of events with a misidentified PV for both signal and background, especially when combined with the signal region selection described below. The efficiency of this selection for signal events, relative to the other baseline requirements, is approximately 55%. The $\text{BDT}_{\text{vertex}}$ distribution is validated in the main analysis regions defined below, as well as in a dedicated region with $m_T > 200$ GeV and no leptons, enriched with $W\gamma$ and $Z\gamma$ processes with a topology similar to that of the signal. In all cases, good agreement between data and the background expectation is observed for $\text{BDT}_{\text{vertex}} > 0.1$, indicating that the efficiency of this selection is well modelled both for the background and the signal processes.

Table 3: Description of the input features of the misidentified vertex BDT, in order of importance.

Variable	Description
$\log(\sum p_T^2(\text{tracks}))$	Logarithm of the sum of the squared transverse momenta of tracks associated with the vertex.
$ \Delta\phi(\vec{p}_{\text{vtx}}, \vec{p}_\gamma) $	Azimuthal separation between the momentum of the tracks associated with the vertex and the photon direction.
$ \Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{j_1}) $	Azimuthal separation between the missing transverse momentum and the leading jet.
$ \Delta\phi(j_1, j_2) $	Azimuthal separation between the two leading jets.
Δp_T^{miss}	Difference between the missing transverse momentum computed without JVT requirements and the nominal reconstruction.
$\mathcal{S}_{p_T^{\text{miss}}}$	Significance of the missing transverse momentum.
$(z_{\text{vtx}} - z_\gamma)/\sigma(z_\gamma)$	Distance along the longitudinal (z) axis between the reconstructed primary vertex and the vertex position inferred from the photon trajectory (photon pointing), normalised by the photon pointing resolution. The photon trajectory is reconstructed using its energy deposits in the first and second layer of the ECAL.
z_{skew}	Skewness of the z distribution of tracks associated with the vertex.
Number of central jets	Number of reconstructed jets in the central region ($ \eta < 2.5$).
$(p_T^{\text{miss}} + p_T^\gamma)/\sum p_T^{\text{jet}}$	Transverse momentum balance between the photon+ p_T^{miss} system and the reconstructed jets.
z_{kurt}	Kurtosis of the z distribution of tracks associated with the vertex.

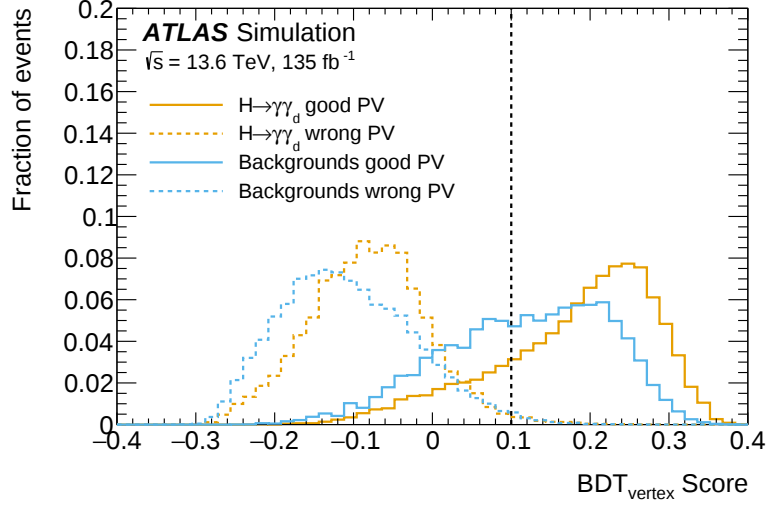


Figure 3: Normalised distributions of the $\text{BDT}_{\text{vertex}}$ score for events with correctly identified PV (solid line) and misidentified PV (dashed line). The distribution is shown for the sum of all signal channels and background processes. The vertical dashed line indicates the selection applied in the analysis.

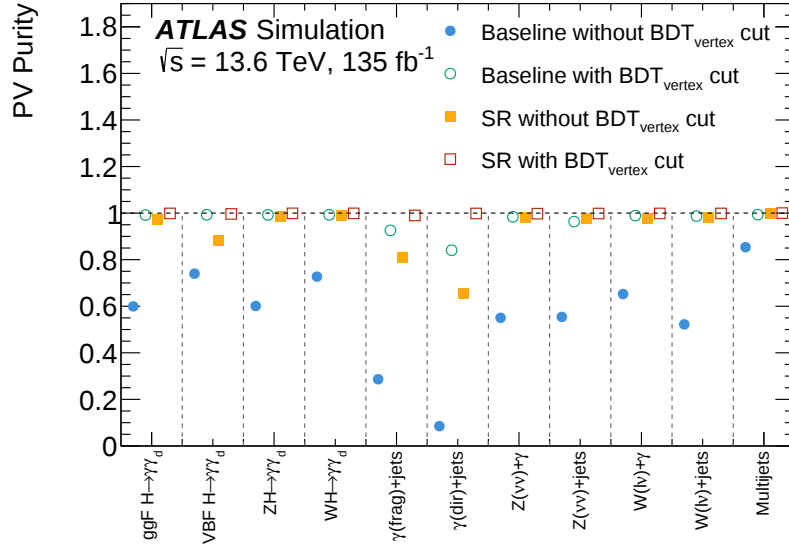


Figure 4: Fraction of events with the correct PV for the $H \rightarrow \gamma\gamma_d$ signals and for different background processes, with different selections applied: the baseline selection and the SR, with and without the $\text{BDT}_{\text{vertex}}$ requirement.

7.2 Signal region

In addition to the *baseline* selection, the signal region (SR) definition, summarised in Table 4, includes requirements on the photon kinematics, angular separations between the photon, p_T^{miss} and jets, as well as further p_T^{miss} -related variables. The latter include the $\mathcal{S}_{p_T^{\text{miss}}}$ and the difference $\Delta p_T^{\text{miss}} = p_{T,\text{noJVT}}^{\text{miss}} - p_T^{\text{miss}}$, where $p_{T,\text{noJVT}}^{\text{miss}}$ is defined in Section 5. In particular, the requirement of $\mathcal{S}_{p_T^{\text{miss}}} > 6$ further suppresses

Table 4: Summary of the selections applied in the signal (SR) and control (CR) regions. In the CRs with muons, the p_T^{miss} is recomputed treating muons as invisible particles.

Selection	SR	Low $\mathcal{S}_{p_T^{\text{miss}}}$ CR	1μ CR	2μ CR
Photon p_T^{miss} m_T $\text{BDT}_{\text{vertex}}$ $N_{e,\tau}$ $N_{b\text{-jets}}$		1 (<i>selected</i>) with $p_T > 50$ GeV > 100 GeV > 80 GeV > 0.1 0 (<i>baseline</i>) 0		
$N_{\text{jet}}^{\text{central}}$		≤ 3		—
N_μ		0 (<i>baseline</i>)	1 (<i>selected</i>)	2 (<i>selected</i>)
$\mathcal{S}_{p_T^{\text{miss}}}$	> 6	[2, 6]	> 6	—
$ \Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{miss},\gamma}) $		> 1.25		
Δp_T^{miss}		> -10 GeV		
$ \Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{miss},\text{jet}}) $		< 0.75		
$ \Delta\phi(j_1, j_2) $		< 2.5		
$ \eta^\gamma $		< 1.75		
$m_{\mu\mu\gamma}$		—		
				> 100 GeV

events with *fake* p_T^{miss} , which typically exhibit lower significance values. Moreover, events are required to satisfy $\Delta p_T^{\text{miss}} > -10$ GeV to reduce the contribution from incorrect PV identification. If a PU vertex is identified as the HS one, the standard p_T^{miss} computation rejects the HS jets while retaining PU jets. In this scenario, the $p_{T,\text{noJVT}}^{\text{miss}}$ is expected to be closer to the true p_T^{miss} than the standard reconstruction, resulting in negative Δp_T^{miss} values for events with no expected true p_T^{miss} . Additionally, restricting the photon pseudorapidity to $|\eta_\gamma| < 1.75$ reduces background contributions from $W/Z + \gamma$ processes. Further requirements $|\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{miss},\gamma})| > 1.25$ and $|\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{miss},\text{jet}})| < 0.75$ are imposed on the azimuthal separation between the $\vec{p}_T^{\text{miss}}$ and its photon or jet term, $\vec{p}_T^{\text{miss},\gamma}$ and $\vec{p}_T^{\text{miss},\text{jet}}$ (i.e. the negative vector sum of the $\vec{p}_T$ of all photons or jets in the event). The selection on $|\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{miss},\gamma})|$ is particularly effective in rejecting residual background from events with a misidentified PV while preserving the acceptance of the boosted Higgs boson signal. Finally the azimuthal separation between the two central jets with the highest p_T is required to be $|\Delta\phi(j_1, j_2)| < 2.5$.

The signal selection efficiency is 0.25% for the ggF channel, and 1.06%, 1.25% and 0.66% for the VBF, WH , and ZH channels, respectively. The trigger and p_T^{miss} requirements account for the largest efficiency loss. The dominant Higgs boson production mode is ggF (68% of the selected signal events), followed by VBF (23%), WH (6%) and ZH (3%).

8 Analysis strategy and background modelling

In addition to the SR, multiple orthogonal regions illustrated in Figure 5, are used in the analysis. Three Control Regions (CRs), enriched in $W\gamma$, $Z\gamma$ and $j \rightsquigarrow \gamma$ contributions and defined in Table 4, are used to constrain the corresponding backgrounds in a maximum-likelihood fit. Validation Regions (VRs), designed

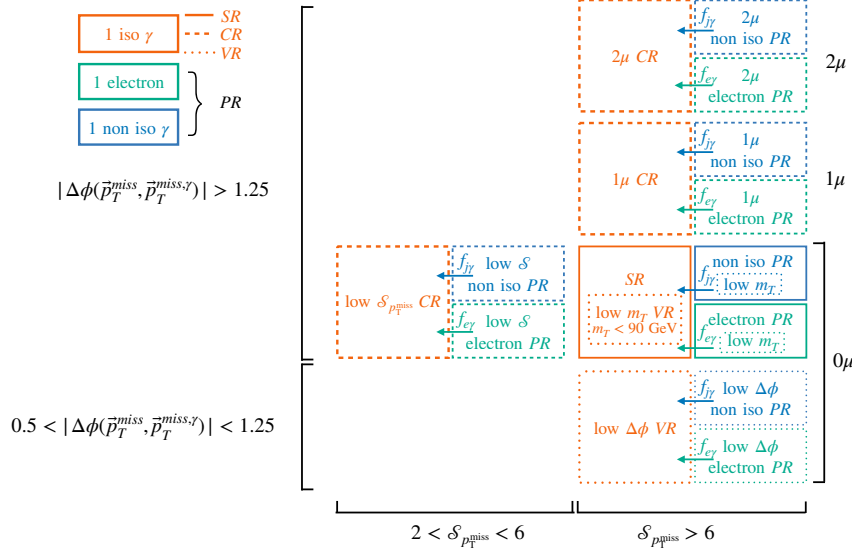


Figure 5: Schematic overview of the signal (SR), control (CR), validation (VR) and probe (PR) regions used in the analysis. Different colours correspond to different final states. Events with one isolated (iso) photon are selected in the SR (continuous lines), CRs (dashed lines) and VRs (dotted lines), while events with a single electron or non isolated photon are used for the corresponding PRs. Data in the PRs are scaled by the fake factors indicated by the arrows ($f_{e\gamma}$ and $f_{j\gamma}$) to estimate the $j \rightsquigarrow \gamma$ and $e \rightsquigarrow \gamma$ contribution in each analysis region.

to be kinematically close to the SRs, are used to validate the modelling of $j \rightsquigarrow \gamma$ and $e \rightsquigarrow \gamma$. In addition, dedicated regions, referred to as Probe Regions (PRs), are employed for the $j \rightsquigarrow \gamma$ and $e \rightsquigarrow \gamma$ data-driven estimates as detailed later.

The 1μ CR and the 2μ CR are employed to normalise the MC simulations of $W\gamma$ and $Z\gamma$ respectively to data. They are defined in a similar way to the SR, but requiring either one or two selected muons. To emulate the SR kinematics, muons are treated as invisible in the p_T^{miss} reconstruction. In the 2μ CR, some of the SR requirements, as detailed in Table 4 are loosened or removed to increase the available number of events. The contribution from the $\gamma(\text{dir})+\text{jets}$ background due to fake p_T^{miss} is estimated purely from MC, as it accounts for about 2% of the total.

The background from $e \rightsquigarrow \gamma$ or $j \rightsquigarrow \gamma$ is estimated in all the analysis regions by rescaling data in PRs, by fake factors evaluated as described in Sections 8.1 and 8.2. For the $e \rightsquigarrow \gamma$ background, electron PRs are defined for each analysis region, replacing the selected photon by a selected electron, and an electron trigger is also required, for consistency with the evaluation of the $e \rightsquigarrow \gamma$ fake factors, as explained in Section 8.1. For the $j \rightsquigarrow \gamma$ background, PRs with a non-isolated photon, $\gamma^{\text{non-isol}}$, are introduced by requiring $Y > 0.1$, in order to ensure a negligible contamination from genuine photons.

Due to the large systematic uncertainty affecting the $j \rightsquigarrow \gamma$ component, the low $\mathcal{S}_{p_T^{\text{miss}}}$ CR, defined by requiring $2 < \mathcal{S}_{p_T^{\text{miss}}} < 6$, is included in the fit to provide an additional constraint on this background. The post-fit $\mathcal{S}_{p_T^{\text{miss}}}$ distribution is shown in Figure 6(a), with the dashed line highlighting the boundary between the low $\mathcal{S}_{p_T^{\text{miss}}}$ CR and the SR. The $e \rightsquigarrow \gamma$ contribution is further constrained in the low m_T region of the SR that is dominated by $W(e\nu)+\text{jets}$ events with the electron being misidentified as a photon, yielding a

m_T value close to the W -boson mass. In particular, the low m_T VR, with $80 < m_T < 90$ GeV, has very little signal, and is also used to validate the $e \rightsquigarrow \gamma$ background before performing the fit. In addition, a low $\Delta\phi$ VR, with $0.8 < |\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{miss},\gamma})| < 1.1$, provides a sample orthogonal both to the SR and the low $S_{p_T^{\text{miss}}}$ CR to also validate the modelling of the $j \rightsquigarrow \gamma$ background at high $S_{p_T^{\text{miss}}}$ values. Figure 6(b) shows the post-fit $|\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{miss},\gamma})|$ distribution in the SR and low $\Delta\phi$ VR. This observable is particularly sensitive to PV misidentification at low values, which corresponds to events with low p_T or no jets, where the photon and the p_T^{miss} are nearly back-to-back. A mismodelling in this region is therefore expected even after applying the $\text{BDT}_{\text{vertex}}$ requirement, primarily due to events with a correct PV being misclassified by the BDT as an incorrect PV.

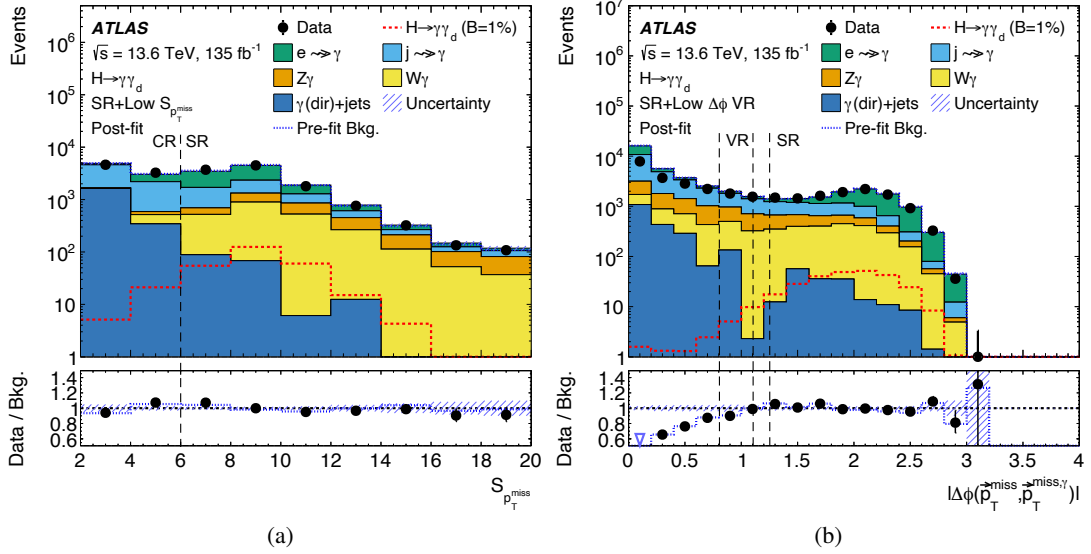


Figure 6: Post-fit distributions of (a) $S_{p_T^{\text{miss}}}$ in the signal region (SR) and low- $S_{p_T^{\text{miss}}}$ control region (CR), and of (b) $|\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{miss},\gamma})|$ in the SR and low- $\Delta\phi$ validation region (VR), for data and the expected SM background. The dashed vertical lines mark the boundaries of the SR and the CR/VR. The $H \rightarrow \gamma\gamma_d$ signal, assuming $\mathcal{B}_{\gamma\gamma_d} = 1\%$, is overlaid as a dotted line and includes the ggF, VBF, WH , and ZH production modes. The pre-fit prediction is overlaid as a dashed line. The uncertainties include both the statistical and the systematic components. The lower panels show the ratios of data to expected background yields post-fit (dots) and pre-fit (dotted line). The downward-pointing triangle marks a ratio point located below the bottom edge of the ratio plot.

8.1 Estimation of $e \rightsquigarrow \gamma$

The fake factor for $e \rightsquigarrow \gamma$ estimation is defined as:

$$f_{e\gamma} = \frac{N(e \rightsquigarrow \gamma)}{N(e \rightsquigarrow e)}, \quad (2)$$

where $N(e \rightsquigarrow \gamma)$ and $N(e \rightsquigarrow e)$ denote respectively the numbers of electrons reconstructed as photons or as electrons. The values of the $f_{e\gamma}$ are computed directly from data, exploiting the $Z \rightarrow e^+e^-$ process, where prompt isolated photons are absent. While $N(e \rightsquigarrow \gamma)$ is counted from reconstructed photons in γe events selected by a single electron trigger, $N(e \rightsquigarrow e)$ is counted from both e^+ and e^- in

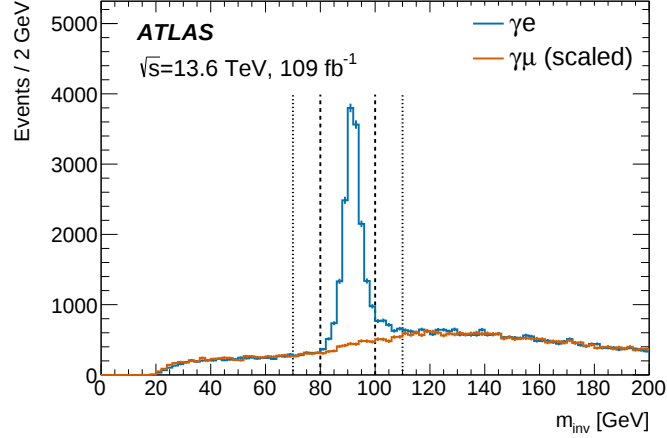


Figure 7: Invariant mass of reconstructed γe and $\gamma\mu$ pairs from data, the latter being rescaled so that its sidebands match those of the former. The vertical dashed lines show the window used to compute $f_{e\gamma}$, while the vertical dotted lines mark the sidebands used for the normalisation of the $\gamma\mu$ distribution. Plots are inclusive in p_T^γ and η^γ , and show only data taken in 2024.

e^+e^- events selected by a dielectron trigger. Both numbers are calculated in an invariant mass window $m_{\text{inv}} \in [80, 100]$ GeV around the Z peak, m_{inv} being the invariant mass of the γe or the e^+e^- pair.

While the e^+e^- events provide a rather pure sample of $Z \rightarrow e^+e^-$, the γe events contain a large number of genuine photons, mostly from the $W(\rightarrow e\nu)\gamma$ process, which must be subtracted. This is achieved by exploiting lepton universality, and selecting a sample of $\gamma\mu$ events. To account for the different reconstruction efficiency for e and μ , the invariant mass spectrum of the $\gamma\mu$ events is normalised to that of the γe in two sidebands $m_{\text{inv}} < 70$ GeV and $m_{\text{inv}} > 110$ GeV, as displayed in Figure 7. The complete definition of the fake factor is therefore:

$$f_{e\gamma} = \frac{N_{\gamma e}^{\text{peak}} - N_{\gamma\mu}^{\text{peak}} \frac{N_{\gamma e}^{\text{side}}}{N_{\gamma\mu}^{\text{side}}}}{N_{ee}^{\text{peak}}}. \quad (3)$$

The value of $f_{e\gamma}$ is computed separately for 2023 and 2024 datasets as a function of η^γ , since no significant dependence on p_T^γ is observed. The values of $f_{e\gamma}$ are weakly dependent on the choice of the peak width and on the sidebands. Each variation is treated as a systematic uncertainty, and are all combined in quadrature with the statistical uncertainty. The values of $f_{e\gamma}$ range between ~ 0.027 in the barrel and ~ 0.054 in the endcaps, with overall relative uncertainties between 3% and 8%.

The e -PR must satisfy both the analysis trigger, to guarantee the same event topology as the SR and CRs, and the electron trigger, for consistency with the $f_{e\gamma}$ evaluation. However, the $f_{e\gamma}$ evaluation does not consider the analysis trigger, therefore a further correction is necessary, to account for the efficiency of the analysis trigger on reconstructed γ and e :

$$f_{e\gamma}^{\text{corr}} = f_{e\gamma} \frac{\epsilon_\gamma^{\text{trig}}}{\epsilon_e^{\text{trig}}}. \quad (4)$$

where $\epsilon_{\gamma}^{\text{trig}}$ and ϵ_e^{trig} are the fraction of events that pass the analysis trigger, in events containing a genuine photon (SR-like) and a genuine electron (e -PR-like) respectively. The only trigger requirement affecting the evaluation of $f_{e\gamma}$ is that on the reconstructed photon, therefore the effects of the p_T^{miss} and m_T selections need to be disentangled. This is achieved by applying offline cuts on p_T^{miss} and m_T higher than the trigger-level cuts, to ensure being in the plateau of the trigger efficiency turn-on curves. To evaluate $\epsilon_{\gamma}^{\text{trig}}$, $\gamma\mu$ events were selected by a muon trigger. The muon is treated as invisible in the offline evaluation of p_T^{miss} , and $(p_T^{\text{miss}})^{\mu\text{-inv}} > 150$ GeV and $(m_T)^{\mu\text{-inv}} > 100$ GeV are required. The trigger-level evaluation of p_T^{miss} does not consider muons, therefore they are also treated as invisible by the analysis trigger. The fraction of events that satisfy the analysis trigger criteria provides the value of $\epsilon_{\gamma}^{\text{trig}}$. Similarly, ϵ_e^{trig} is evaluated on events with an electron, selected from data by an electron trigger, and fulfilling $p_T^{\text{miss}} > 200$ GeV and $m_T > 100$ GeV. The fraction of events that satisfy the analysis trigger criteria provides the value of ϵ_e^{trig} . Both $\epsilon_{\gamma}^{\text{trig}}$ and ϵ_e^{trig} are computed as a function of p_T , to better track the trigger efficiency turn-on. While $\epsilon_{\gamma}^{\text{trig}}$ reaches full efficiency for $p_T > 60$ GeV, ϵ_e^{trig} saturates at about 90%, as the photon trigger is not fully optimal for electrons. The variations of $\epsilon_{\gamma}^{\text{trig}}$ and ϵ_e^{trig} when applying different cuts on p_T^{miss} and m_T are treated as systematic uncertainties and combined in quadrature. The resulting trigger correction factor is between 1.06 and 1.26 with an overall relative uncertainty between 3% and 12%.

The validation of the $e \rightsquigarrow \gamma$ background in the low m_T VR is displayed in Figure 8, showing good agreement before the fit.

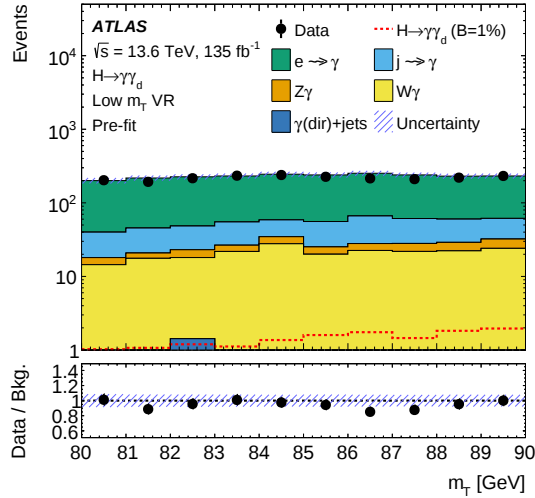


Figure 8: Pre-fit distribution of m_T for data and the expected SM background in the low- m_T VR. The $H \rightarrow \gamma\gamma_d$ signal, assuming $\mathcal{B}_{\gamma\gamma_d} = 1\%$, is overlaid as a dashed line and includes the ggF, VBF, WH , and ZH production modes. The uncertainties include both statistical and systematic components. The lower panel shows the ratio of data to expected background yields.

8.2 Estimation of $j \rightsquigarrow \gamma$

The $j \rightsquigarrow \gamma$ fake factor is defined as

$$f_{j\gamma} = \frac{N(j \rightsquigarrow \gamma)}{N(j \rightsquigarrow \gamma^{\text{non-isol}})} \quad (5)$$

where $N(j \rightsquigarrow \gamma)$ and $N(j \rightsquigarrow \gamma^{\text{non-isol}})$ denote the numbers of jets reconstructed as isolated or non-isolated photons, respectively. Isolated and non-isolated reconstructed photons are defined by requiring isolation $\Upsilon < 0.022$ and $\Upsilon > 0.1$, respectively. The evaluation of the fake factor relies on the distribution of the isolation for $j \rightsquigarrow \gamma$ satisfying the **Tight** identification, $\Phi^{\text{Tight}}(\Upsilon)$, and is calculated as:

$$f_{j\gamma} = \frac{\int_{-\infty}^{+0.022} d\Upsilon \Phi^{\text{Tight}}(\Upsilon)}{\int_{+0.1}^{+\infty} d\Upsilon \Phi^{\text{Tight}}(\Upsilon)}. \quad (6)$$

The $\Phi^{\text{Tight}}(\Upsilon)$ distribution cannot be directly extracted from data, as the **Tight** photon selection contains comparable contributions from $j \rightsquigarrow \gamma$ and genuine photons. Moreover, $\Phi^{\text{Tight}}(\Upsilon)$ is not well modelled by the MC, and depends on the MC generator used. Therefore $\Phi^{\text{Tight}}(\Upsilon)$ has to be inferred, as explained in the following. Photons satisfying the **Loose'** selection² (see Section 5) are enriched in $j \rightsquigarrow \gamma$, therefore the isolation distribution $\Phi^{\text{Loose'}}(\Upsilon)$ of $j \rightsquigarrow \gamma$ in the **Loose'** selection can be extracted from data. However, the photon selection affects the isolation, making $\Phi^{\text{Loose'}}$ broader than Φ^{Tight} . To infer Φ^{Tight} from $\Phi^{\text{Loose'}}$, an affine transform is applied to the Υ of all **Loose'** photons:

$$\Upsilon^{\text{Tight}} = m^{\text{Tight}} + \frac{w^{\text{Tight}}}{w^{\text{Loose'}}} \left(\Upsilon^{\text{Loose'}} - m^{\text{Loose'}} \right), \quad (7)$$

then all the obtained values of Υ^{Tight} are used to build Φ^{Tight} . In Eq. (7), m and w are the median and the 16%-to-84% half-width of the isolation distributions in the **Loose'** and **Tight** samples. While $m^{\text{Loose'}}$ and $w^{\text{Loose'}}$ can be computed from the observed $\Phi^{\text{Loose'}}$ in data, m^{Tight} and w^{Tight} are inferred, with the help of $j \rightsquigarrow \gamma$ from W +jets and Z +jets MC samples, assuming that

$$\left(\frac{m^{\text{Tight}} - m^{\text{Loose'}}}{w^{\text{Loose'}}} \right) = R_m \left(\frac{m_{\text{MC}}^{\text{Tight}} - m_{\text{MC}}^{\text{Loose'}}}{w_{\text{MC}}^{\text{Loose'}}} \right), \quad \left(\frac{w^{\text{Tight}}}{w^{\text{Loose'}}} \right) = R_w \left(\frac{w_{\text{MC}}^{\text{Tight}}}{w_{\text{MC}}^{\text{Loose'}}} \right), \quad (8)$$

where $m_{\text{MC}}^{\text{Tight}}$, $m_{\text{MC}}^{\text{Loose'}}$, $w_{\text{MC}}^{\text{Tight}}$, $w_{\text{MC}}^{\text{Loose'}}$ are extracted from the Z +jets and W +jets MC samples. The values of R_m and R_w are estimated by exploiting the various **Loose''** photon selections (see Section 5), which are closer to the **Tight** selection. The **Loose''** selections in data are still dominated by $j \rightsquigarrow \gamma$, therefore $m^{\text{Loose''}}$ and $w^{\text{Loose''}}$ (i.e. the median and half-width in the **Loose''** selection) can be evaluated in data from the observed $\Phi^{\text{Loose''}}$, and Eq. (8) can be used with each of the **Loose''** instead of the **Tight** selection, to derive R_m and R_w . Different choices of **Loose''** selections (labelled **Loose''**_{*a*} in the following, where *a* flags the different definitions) provide different values of R_m and R_w , and therefore different $\Phi_a^{\text{Tight}}(\Upsilon)$. Since each of the **Loose''** selections is obtained by applying at most one requirement on one of the strips shower shapes, this procedure allows the effect of one strips shower shape at a time to be probed in the **Loose' → Tight** extrapolation.

In summary, the affine transform of Eq. (7) depends on the R_m and R_w parameters. These are evaluated to achieve a **Loose' → Loose''**_{*a*} extrapolation that reproduces at best the observed **Loose''**_{*a*} sample, and are then applied to the **Loose' → Tight** extrapolation. This process is symbolised as **Loose' (→ Loose''**_{*a*}**) → Tight**, and provides an extrapolated distribution $\Phi_a^{\text{Tight}}(\Upsilon)$. The observed isolation distribution for **Loose'** photons and one of the extrapolated distributions for **Tight** photons are displayed in Figure 9. The reliability of the extrapolation is validated by comparing several extrapolated

² **Loose'** photons are selected in events satisfying the analysis trigger. This is possible, as the **Tight** selection at trigger level is looser than at analysis level. The contamination of genuine photons in the **Loose'** sample is estimated to be $\lesssim 5\%$, from simulations.

distributions $\text{Loose}'(\rightarrow \text{Loose}''_a) \rightarrow \text{Loose}''_b$ with the observed Loose''_b ones. An example is shown in Figure 9.

For each extrapolated distribution $\Phi_a^{\text{Tight}}(\Upsilon)$, a different fake factor $(f_{j\gamma})_a$ is computed. The final fake factor is computed as the arithmetic mean of all $(f_{j\gamma})_a$, and a conservative systematic uncertainty is set as half the envelope of all their values.

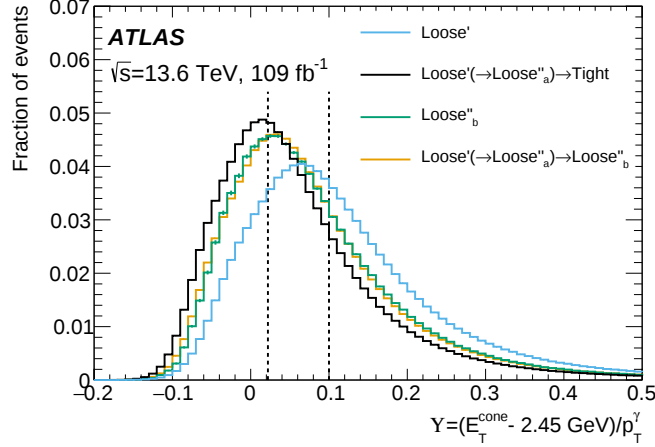


Figure 9: Distributions of the isolation $\Upsilon = (E_T^{\text{cone}} - 2.45 \text{ GeV})/p_T^\gamma$ for reconstructed photons, used for the $j \rightsquigarrow \gamma$ background estimate. The figure displays the distribution from the Loose' photon sample (enriched in $j \rightsquigarrow \gamma$), and an example of extrapolated distribution for the Tight sample ($\text{Loose}'(\rightarrow \text{Loose}''_a) \rightarrow \text{Tight}$), using a Loose''_a sample to compute R_m and R_w . The two dashed vertical lines mark the ‘isolated’ ($\Upsilon < 0.022$) and the ‘non-isolated’ ($\Upsilon > 0.1$) regions. Plots are inclusive in p_T^γ and η^γ , and show only data taken in 2024. The figure also shows the observed and extrapolated distributions for a different Loose''_b sample.

The fake factor is computed separately for 2023 and 2024 datasets as a function of η^γ . The limited number of MC events prohibits studying its dependence on p_T^γ . The values of $f_{j\gamma}$ range from ~ 1.5 in the ECAL barrel, up to ~ 2.5 in the endcaps, with relative uncertainties between 10% and 15%.

The obtained $j \rightsquigarrow \gamma$ prediction is validated, before the fit, in both the low $\mathcal{S}_{p_T^{\text{miss}}}$ CR and the low $\Delta\phi$ VR, as shown in Figure 10.

9 Systematic uncertainties

Multiple sources of systematic uncertainty are considered in the analysis. The experimental and theoretical uncertainties are applied only to the MC simulations of the signal and $V\gamma$ background, while their impact on the $\gamma(\text{dir})+\text{jets}$ simulation is expected to be negligible compared to its statistical fluctuations. Additional systematic uncertainties arise from the data-driven background estimates. The impact of the different sources of uncertainty in the fitted value of $\mathcal{B}_{\gamma\gamma_d}$ are summarised in Table 5. The contributions are evaluated using the covariance matrix decomposition method [80] and include both statistical and systematic components. The dominant contribution to the total uncertainty arises from the statistical component (88%), including contributions from both the data and the background. The dominant systematic contribution arises from experimental uncertainties (42%), primarily driven by jet-related effects. This

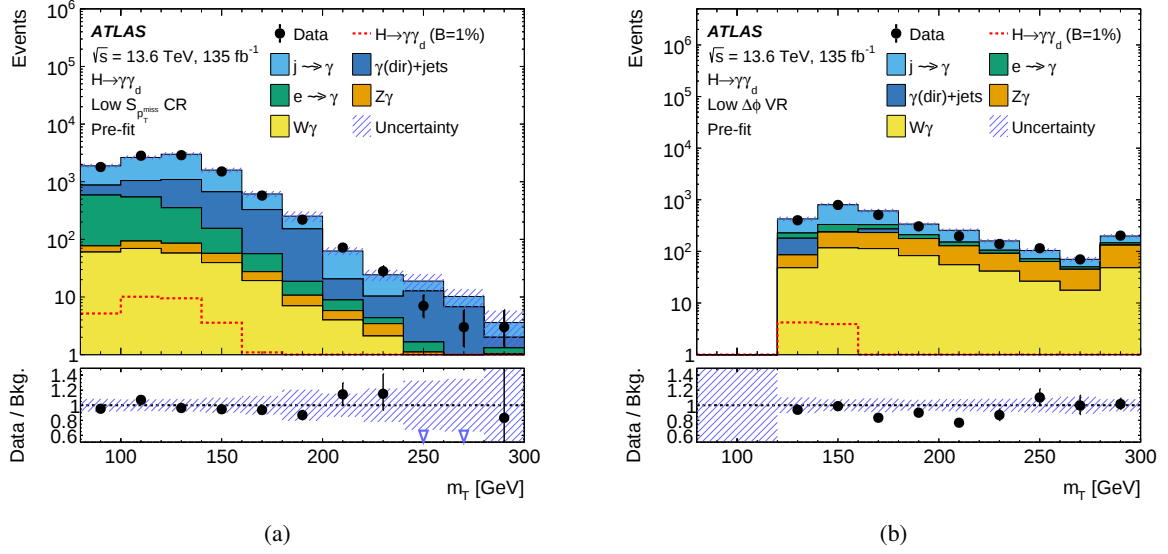


Figure 10: Pre-fit distribution of m_T for data and the expected SM background in (a) the low $S_{p_{miss}}$ CR and (b) the low $\Delta\phi$ VR, enriched in $j \rightsquigarrow \gamma$. The $H \rightarrow \gamma\gamma_d$ signal, assuming $\mathcal{B}_{\gamma\gamma_d} = 1\%$, is overlaid as a dashed line and includes the ggF, VBF, WH , and ZH production modes. The uncertainties include both statistical and systematic components. The lower panel shows the ratio of data to expected background yields. The downward-pointing triangles mark ratio points located below the bottom edge of the ratio plot.

is followed by uncertainties associated with the $e \rightsquigarrow \gamma$ and $j \rightsquigarrow \gamma$ data-driven methods (17%), and by theoretical uncertainties (17%).

Table 5: Post-fit relative impact of each source of uncertainty on the total uncertainty of the signal yields, as obtained through the covariance matrix decomposition method. The overall impacts of statistical, experimental, data-driven and theoretical systematic uncertainties are shown, followed by the individual contributions.

Category	Contribution to uncertainty in the $\mathcal{B}_{\gamma\gamma_d}$
Statistical uncertainties	88%
Data	74%
Background	48%
Experimental systematic uncertainties	42%
Luminosity	4.6%
Pile-up reweighting	7%
Pile-up corrections in jets calibration	36%
Jets	18%
Photons	3.7%
Muons	2.1%
p_T^{miss}	<1%
Trigger	<1%
Systematic on data-driven methods uncertainties	17%
$j \rightsquigarrow \gamma$	11%
$e \rightsquigarrow \gamma$	13%
Theoretical systematic uncertainties	17%

9.1 Experimental uncertainties

The uncertainty in the integrated luminosity is 1.9%, derived from the calibration of the LUCID-2 detector and complemented by information from the ID and the calorimeters [34]. This uncertainty is applied as a global normalisation uncertainty to all MC samples, including both signal and background processes. A systematic uncertainty is associated with the pileup reweighting procedure applied to simulated events to correct for mismodelling of PU interactions in simulation.

Further uncertainties are associated with the reconstruction and isolation efficiency and with the energy calibration and resolution of photons, muons and jets. Photon efficiency uncertainties are estimated by using Run 2 data and MC simulations [69], with an additional uncertainty included to account for differences between Run 2 and Run 3, as derived from simulation. The uncertainties related to photon energy calibration and resolution are evaluated following the methodology described in Ref. [81], using the Run 3 data collected between 2022 and 2024. All contributions are summed in quadrature and considered fully correlated in photon η , resulting in one systematic uncertainty associated with the energy calibration, and one with the energy resolution.

Multiple sources of uncertainties are considered for muons. The uncertainties affecting the muon momentum scale and resolution are separated into charge-dependent and charge-independent components [66]. Additional uncertainties are associated with muon reconstruction and isolation efficiencies, as well as with the track-to-vertex association efficiency, each of which is split into statistical and systematic components [67].

Jet reconstruction is affected by uncertainties related to jet vertex tagging and to the jet energy scale (JES) and resolution (JER). The uncertainty in the NN-JVT and fJVT calibrations [72, 73] is derived from $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events in 2022–2023 data and is dominated by PU modelling uncertainties, particularly at low p_T . The JES and JER uncertainties [60, 82, 83] include contributions from area subtraction, PU residual corrections, absolute energy scale, and global sequential calibration [84], and are evaluated using Run 3 MC simulations. The uncertainty in the in situ calibration is derived from Run 2 data, with an additional uncertainty included to cover differences between Run 2 and Run 3. Further uncertainties account for residual effects related to variations in the vertexing algorithm, calorimeter noise thresholds, and modelling differences in the forward calorimeter region. Among these systematic uncertainties, the dominant contribution arises from PU residual corrections, which is quoted separately in Table 5. An additional jet-related source of systematic uncertainty arises from flavour tagging [85].

The p_T^{miss} is affected by three sources of systematic uncertainty [77, 86], related to the modelling of its soft term and evaluated using Run 3 data collected in 2022–2023 and the corresponding MC simulations. One scale uncertainty is obtained by scaling up and down the parallel projection of the soft-term along the hard-term, while two resolution uncertainties are derived by smearing the parallel and perpendicular projections of the soft-term along the hard-term.

Finally, a systematic uncertainty is assigned to the trigger efficiency, as described in Section 4, to account for the observed discrepancy between data and MC simulations in the trigger efficiency curves.

9.2 Uncertainties in data-driven methods

Three additional sources of systematic uncertainty are associated with the data-driven estimates of the $e \rightsquigarrow \gamma$ and $j \rightsquigarrow \gamma$ backgrounds. As described in Section 8.1, for the $e \rightsquigarrow \gamma$ background, one systematic

uncertainty accounts for the dependence of the $f_{e\gamma}$ fake factor on the peak width and the definition of the sidebands, while the second contribution is associated with the trigger correction factors. The third data-driven systematic uncertainty is associated with the extrapolation from $\Phi^{\text{Loose}'}$ to Φ^{Tight} in the $j \rightsquigarrow \gamma$ estimation, as described in Section 8.2.

9.3 Theoretical uncertainties

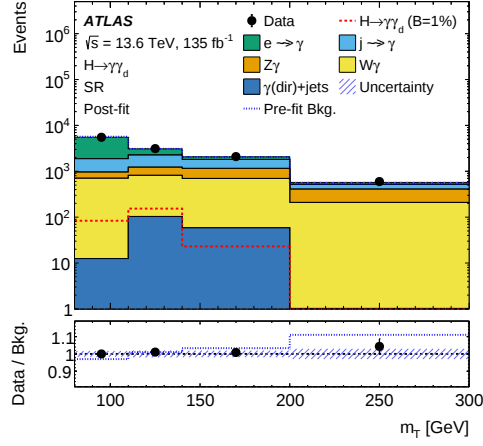
Theoretical uncertainties related to the modelling of quantum chromodynamics (QCD) effects are considered for background and signal MC samples, arising from variations of the renormalisation and factorisation scales, the value of the strong coupling constant, and the PDF uncertainties. The latter are evaluated following the PDF4LHC21 prescription [45]. The uncertainty associated with missing higher-order corrections is evaluated by independently varying the renormalisation and factorisation scales by factors of 0.5 and 2.0 relative to their nominal values and taking the envelope of the resulting variations, while the uncertainty related to the strong coupling constant α_s is obtained by varying its value by ± 0.001 .

10 Statistical treatment and results

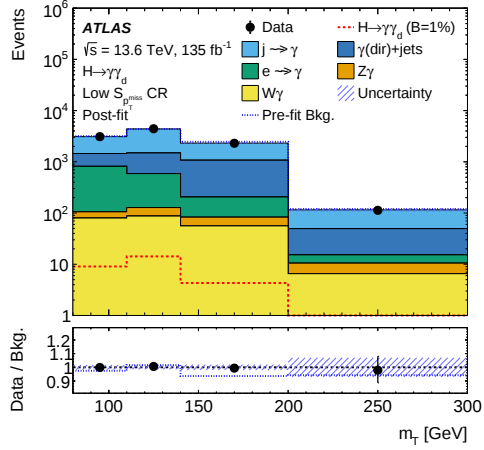
To maximise the sensitivity to the Higgs boson mass peak, the transverse mass m_T is used as the discriminating variable in the binned maximum-likelihood fit in all regions, except for the 2μ CR, which is treated as a single inclusive bin due to limited statistical precision. The m_T binning is optimised such that the bulk of the expected signal is contained in the two central bins, defined as $110 < m_T < 140$ GeV and $140 < m_T < 200$ GeV, while the lower and upper bins provide additional constraints on the background normalisation. In particular, the first bin ($80 < m_T < 110$ GeV) contains the low- m_T VR and is dominated by the $e \rightsquigarrow \gamma$ background, allowing an effective constraint on this contribution.

The likelihood function is constructed as the product of Poisson probability distribution functions describing the event counts in each m_T bin of the SR and CRs, as functions of the expected signal and background yields. The branching ratio $\mathcal{B}_{\gamma\gamma_d}$ is included in the fit as the parameter of interest (POI). In addition, two normalisation factors, $k_{W\gamma}$ and $k_{Z\gamma}$, are applied to the $W\gamma$ and $Z\gamma$ background processes respectively, and included as free parameters in the fit, primarily constrained by the corresponding 1μ and 2μ CRs. Systematic uncertainties affecting the signal and background yields are incorporated into the likelihood model as independent nuisance parameters with a Gaussian constraint centred at zero with a width corresponding to the associated uncertainty. The experimental and data-driven systematic errors are treated as fully correlated across all regions, and experimental systematic errors are also correlated amongst all MC samples. Theoretical uncertainties are treated as uncorrelated across samples. All nuisance parameters are assumed to be mutually uncorrelated. The fit model is implemented in the TRExFITTER [87] framework.

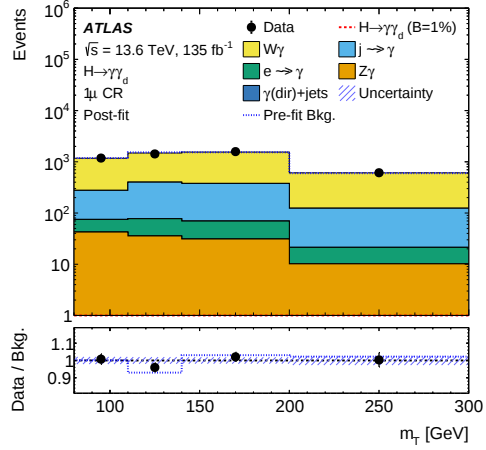
A background-only fit is first performed in the SR and CRs, with $\mathcal{B}_{\gamma\gamma_d}$ set to zero, and the $k_{W\gamma}$ and $k_{Z\gamma}$ normalisation factors left free. The fitted values are $k_{W\gamma} = 0.93^{+0.08}_{-0.08}$ and $k_{Z\gamma} = 1.03^{+0.12}_{-0.11}$. The post-fit m_T distributions for data and the expected SM background are shown in Figure 11, while the corresponding yields are reported in Table 6. The yields and background composition in each analysis region, including the VRs, are also summarised in Figure 12. Good agreement is observed between data and the SM background expectation in all the analysis regions, and the data are consistent with the background-only hypothesis with an observed p_0 -value of 0.37.



(a)



(b)



(c)

Figure 11: Distribution of m_T for data and for the expected SM background after the background-only fit, in the (a) SR and (b, c) CRs. The $H \rightarrow \gamma\gamma_d$ signal, assuming $\mathcal{B}_{\gamma\gamma_d} = 1\%$, is shown as a dashed line and includes the ggF, VBF, WH and ZH production modes. The pre-fit prediction is overlaid as a dotted line. The uncertainties include both statistical and systematic components determined by the multiple-bin fit. The lower panels show the ratios of data to expected background yields post-fit (dots) and pre-fit (dotted line).

Table 6: Data and background yields in the SR and CRs, after the background-only fit. The pre-fit expected signal yields are also shown for each Higgs boson production channel, assuming $\mathcal{B}_{\gamma\gamma_d} = 1\%$. Contributions below 10^{-5} are shown as “–”. Uncertainties include statistical and systematic components. The individual background uncertainties can be correlated and therefore do not add in quadrature to the total background uncertainty.

	SR	low $S_{E_T^{\text{miss}}}$ CR	1 μ CR	2 μ CR
Pre-fit ggF $H \rightarrow \gamma\gamma_d$	166 ± 24	18.2 ± 4.9	–	–
Pre-fit VBF $H \rightarrow \gamma\gamma_d$	56.9 ± 5.7	9.6 ± 1.6	–	–
Pre-fit WH $H \rightarrow \gamma\gamma_d$	14.7 ± 1.4	1.41 ± 0.31	0.149 ± 0.018	–
Pre-fit ZH $H \rightarrow \gamma\gamma_d$	8.19 ± 0.85	0.72 ± 0.19	0.0073 ± 0.0075	0.0249 ± 0.0097
$Z\gamma$	1332 ± 90	95 ± 21	120 ± 8.8	412 ± 25
$W\gamma$	2253 ± 68	224 ± 55	3635 ± 80	0.677 ± 0.058
$e \rightsquigarrow \gamma$	4810 ± 113	1302 ± 43	124.5 ± 3.5	11.46 ± 0.45
$j \rightsquigarrow \gamma$	2726 ± 105	5879 ± 149	941 ± 37	188 ± 10
$\gamma(\text{dir})+\text{jets}$	175.7 ± 3.6	2437 ± 62	0.0469 ± 0.0010	–
Total	11298 ± 101	9936 ± 98	4821 ± 69	612 ± 23
Data	11327	9934	4802	596

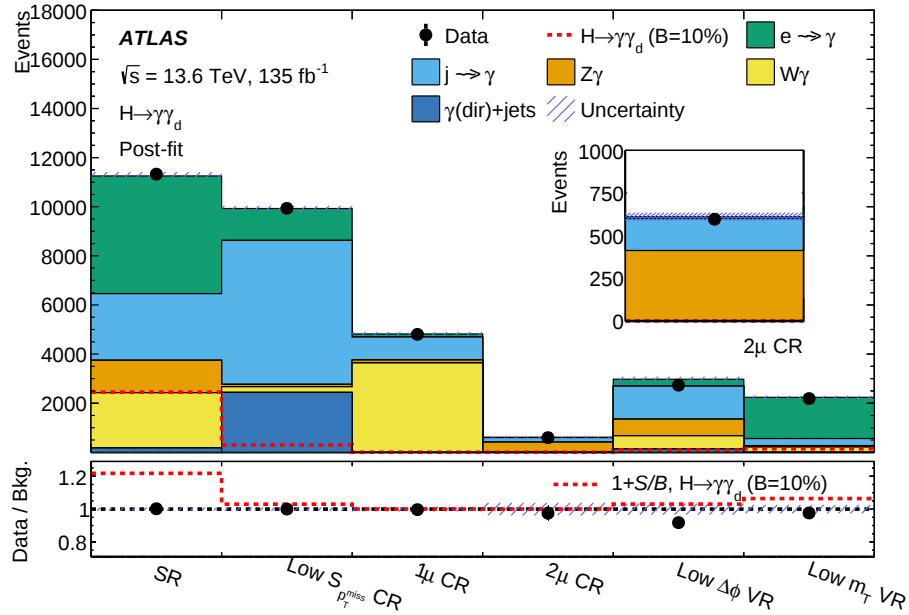


Figure 12: Observed data and post-fit background yields in the SR, CRs, and VRs after the background-only fit. The expected signal yields are overlaid, assuming $\mathcal{B}_{\gamma\gamma_d} = 10\%$ for visualisation purposes. The lower panel shows the ratio of the data to the background, together with the signal contribution defined as $1 + S/B$, where S and B denote the signal and background yields.

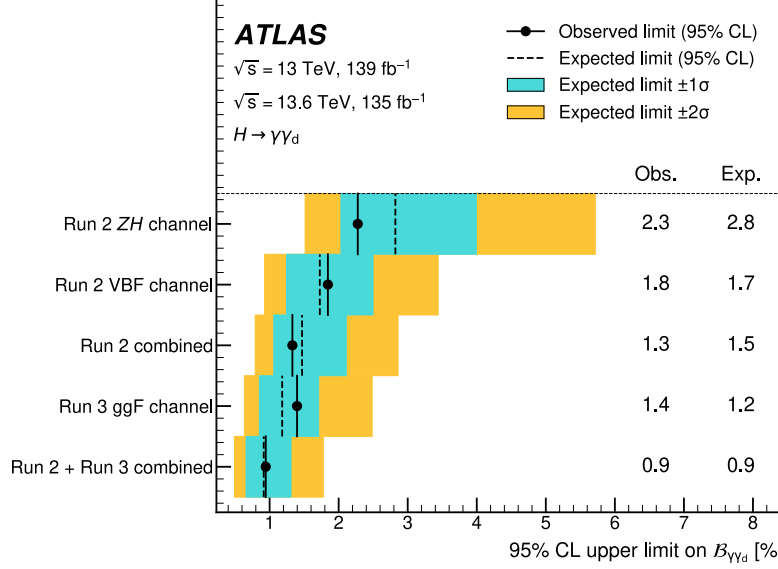


Figure 13: Summary of the 95% CL upper limits on $\mathcal{B}_{\gamma\gamma_d}$, achieved by the Run 2 searches (top three rows: ZH [17], VBF [18], and their combination [21]) and by this analysis (4th row). The overall Run 2 + Run 3 combination is displayed in the bottom row.

A second fit is then performed including the signal contribution and the branching ratio $\mathcal{B}_{\gamma\gamma_d}$ as the POI. The results are consistent with the background-only hypothesis, with the best-fit value $\mathcal{B}_{\gamma\gamma_d} = 0.002^{+0.006}_{-0.006}$. Since no significant excess over the SM prediction is observed, upper limits on the branching ratio of the exotic decay $H \rightarrow \gamma\gamma_d$ are set using the profile likelihood ratio test statistic and the CL_s approach [88], in the asymptotic approximation [89]. An observed (expected) upper limit on $\mathcal{B}_{\gamma\gamma_d}$ of 1.4% (1.2%) is obtained at 95% CL. This result can be compared with previous searches carried out on the VBF [18] and ZH [17] production channels in Run 2, as well as their combination [21], as summarised in Figure 13. The present analysis provides constraints on the $H \rightarrow \gamma\gamma_d$ decay comparable to the observed (expected) upper limits of 1.3% (1.5%) from the Run 2 combination, which are the most stringent limits from previous searches. A combination of this analysis with Run 2 results is performed, treating systematic uncertainties as uncorrelated between Run 2 and Run 3 searches, and adopting for the different Run 2 channels the same correlation scheme as in Ref. [21]. The signal modelling is treated as uncorrelated between Run 2 and Run 3 searches, as the former were not sensitive to the ggF production, which is dominant in the latter. The combination yields an observed (expected) upper limit of 0.9% (0.9%) on $\mathcal{B}_{\gamma\gamma_d}$.

11 Conclusion

A search for semi-visible decays of the SM Higgs boson into a photon and p_T^{miss} is presented. The analysis exploits a dedicated topological trigger with reduced p_T^{miss} and p_T^γ thresholds, allowing the gluon–gluon fusion production channel to be targeted for the first time in ATLAS and extending the sensitivity to a previously unexplored kinematic region. The analysis is performed using Run 3 pp collision data at $\sqrt{s} = 13.6$ TeV, collected by the ATLAS detector in 2023 and 2024, corresponding to an integrated luminosity of 135 fb^{-1} .

The impact of hard-scatter primary vertex misidentification due to low track activity is strongly mitigated using a dedicated BDT discriminant. Novel data driven techniques are employed to estimate the background arising from electrons and jets misidentified as photons, while the normalisation of the background processes with a genuine photon is obtained using MC simulations constrained by data in dedicated control regions.

No significant excess over the SM expectation is observed. The results are interpreted in terms of a $H \rightarrow \gamma\gamma_d$ decay, yielding an observed (expected) 95% CL upper limit on the branching ratio of 1.4% (1.2%) at 95% CL, comparable to the best limit from previous searches, set by the ATLAS Run 2 combination. A combination with previous ATLAS Run 2 searches improves the observed (expected) limit to 0.9% (0.9%), representing the most stringent constraint to date on this decay mode.

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The ATLAS Collaboration

G. Aad ¹⁰², E. Aakvaag ¹⁷, B. Abbott ¹²¹, S. Abdelhameed ^{83b}, K. Abeling ⁵⁴, N.J. Abicht ⁴⁸, S.H. Abidi ³⁰, M. Aboeela ⁴⁴, A. Aboulhorma ^{36e}, H. Abramowicz ¹⁵⁴, B.S. Acharya ^{68a,68b,m}, A. Ackermann ^{62a}, J. Ackerschott ⁵⁵, C. Adam Bourdarios ⁴, L. Adamczyk ^{85a}, S.V. Addepalli ¹⁴⁶, M.J. Addison ¹⁰¹, J. Adelman ¹¹⁷, A. Adiguzel ^{22c}, T. Adye ¹³⁵, A.A. Affolder ¹³⁷, Y. Afik ³⁹, M.N. Agaras ¹³, A. Aggarwal ¹⁰⁰, C. Agheorghiesei ^{28c}, A. Ahmad ^{83a}, F. Ahmadov ^{38,ad}, S. Ahuja ¹⁶⁵, X. Ai ^{113c}, G. Aielli ^{75a,75b}, A. Aikot ¹⁶⁵, M. Ait Tamlihat ^{36e}, T.P.A. Åkesson ⁹⁸, D. Akiyama ¹⁷⁰, N.N. Akolkar ²⁵, S. Aktas ¹⁶⁸, G.L. Alberghi ^{24b}, J. Albert ¹⁶⁷, U. Alberti ²⁰, P. Albicocco ⁵², S. Alderweireldt ⁵¹, Z.L. Alegria ¹²², M. Aleksa ³⁷, I.N. Aleksandrov ³⁸, C. Alexa ^{28b}, T. Alexopoulos ¹⁰, F. Alfonsi ^{24b}, M. Algren ⁵⁵, M. Alhroob ¹⁶⁹, B. Ali ¹³³, H.M.J. Ali ^{91,v}, S. Ali ³², S.W. Alibocus ⁹², M. Aliev ^{34c}, G. Alimonti ^{70a}, C. Allaire ⁶⁵, B.M.M. Allbrooke ¹⁴⁹, D.R. Allen ¹²², J.S. Allen ¹⁰¹, J.F. Allen ⁵¹, C.S. Alley ¹, E.R. Almazan ¹³⁷, A. Aloisio ^{71a,71b}, F. Alonso ⁹⁰, C. Alpigiani ¹⁴⁰, A. Alvarez Fernandez ¹⁰⁰, M. Alves Cardoso ⁵⁵, M.G. Alviggi ^{71a,71b}, Y. Amaral Coutinho ^{81b}, C. Amelung ³⁷, M. Amerl ¹⁰¹, T. Amezza ¹²⁸, B. Amini ⁵³, K. Amirie ¹⁵⁸, A. Amirkhanov ³⁸, D. Amperiadou ¹⁵⁵, C. Anastopoulos ¹⁴², T. Andeen ¹¹, J.K. Anders ⁹², A.C. Anderson ⁵⁸, A. Andreazza ^{70a,70b}, S. Angelidakis ⁹, A. Angerami ⁴¹, A.V. Anisenkov ³⁸, A. Annovi ^{73a}, C. Antel ³⁷, E. Antipov ¹⁴⁸, M. Antonelli ⁵², F. Anulli ^{74a}, M. Aoki ⁸², T. Aoki ¹⁵⁶, M.A. Aparo ¹³, L. Aperio Bella ⁴⁷, M. Apicella ³¹, C. Appelt ¹⁵⁴, A. Apyan ²⁷, M. Arampatzi ¹⁰, S.J. Arbiol Val ⁸⁶, C. Arcangeletti ⁵², A.T.H. Arce ⁵⁰, M. Arcuri ^{43b,43a}, J-F. Arguin ¹⁰⁸, S. Argyropoulos ¹⁵⁵, J.-H. Arling ⁴⁷, O. Arnaez ⁴, H. Arnold ¹⁴⁸, G. Artoni ^{74a,74b}, H. Asada ¹¹¹, S. Asatryan ¹⁷⁵, N.A. Asbah ³⁷, R.A. Ashby Pickering ¹⁶⁹, A.M. Aslam ⁹⁵, J. Assahsah ^{36d}, K. Assamagan ³⁰, R. Astalos ^{29a}, K.S.V. Astrand ⁹⁸, S. Atashi ¹⁶², R.J. Atkin ^{34a}, H. Atmani ^{36f}, P.A. Atmasiddha ¹²⁹, K. Augsten ¹³³, A.D. Auriol ⁴⁰, V.A. Austrup ¹⁰¹, A.S. Avad ⁹⁴, G. Avolio ³⁷, A. Azzam ¹³, D. Babal ^{29b}, H. Bachacou ¹³⁶, K. Bachas ^{155,p}, A. Bachiu ³⁵, E. Bachmann ⁴⁹, M.J. Backes ^{62a}, A. Badea ³⁹, T.M. Baer ¹⁰⁶, M. Bahmani ¹⁹, D. Bahner ⁵³, K. Bai ¹²⁴, L. Baines ⁹⁴, O.K. Baker ¹⁷⁴, D. Bakshi Gupta ⁸, L.E. Balabram Filho ^{81b}, V. Balakrishnan ¹²¹, R. Balasubramanian ⁴, P. Balek ^{85a}, E. Ballabene ^{24b,24a}, F. Balli ¹³⁶, L.M. Baltes ^{62a}, W.K. Balunas ¹²⁷, I. Bamwidhi ^{83c}, E. Banas ⁸⁶, M. Bandieramonte ¹³⁰, S. Bansal ²⁵, L. Barak ¹⁵⁴, M. Barakat ⁴⁷, E.L. Barberio ¹⁰⁵, D. Barberis ^{18b}, M. Barbero ¹⁰², M.Z. Barel ¹¹⁶, T. Barillari ¹¹⁰, M-S. Barisits ³⁷, T. Barklow ¹⁴⁶, P. Baron ¹³⁴, D.A. Baron Moreno ¹⁰¹, A. Baroncelli ⁶¹, A.J. Barr ^{127,g}, J.D. Barr ⁹⁶, F. Barreiro ⁹⁹, J. Barreiro Guimarães da Costa ¹⁴, M.G. Barros Teixeira ^{131a}, F. Bartels ³⁷, R. Bartoldus ¹⁴⁶, A.E. Barton ⁹¹, P. Bartos ^{29a}, M. Baselga ⁴⁸, S. Bashiri ⁸⁶, A. Bassalat ^{65,b}, M.J. Basso ^{159a}, S. Bataju ⁴⁴, R. Bate ¹⁶⁶, R.L. Bates ⁵⁸, M. Battaglia ¹³⁷, D. Battulga ¹⁹, M. Bause ^{74a,74b}, L. Bauckhage ⁴⁷, P. Bauer ²⁵, L.T. Bayer ⁴⁷, L.T. Bazzano Hurrell ³¹, T. Beau ¹²⁸, J.Y. Beaucamp ⁹⁰, S. Beauceron ¹²⁸, P.H. Beauchemin ¹⁶¹, P. Bechtel ²⁵, H.P. Beck ^{20,o}, K. Becker ¹⁶⁹, A.J. Beddall ⁸⁰, V.A. Bednyakov ³⁸, C.P. Bee ¹⁴⁸, L.J. Beemster ¹⁶, M. Begalli ^{81d}, M. Begel ³⁰, J.K. Behr ⁴⁷, J.F. Beirer ³⁷, F. Beisiegel ²⁵, I.B. Belean ^{28d}, M. Belfkir ^{83c}, G. Bella ¹⁵⁴, L. Bellagamba ^{24b}, A. Bellerive ³⁵, C.D. Bellgraph ⁶⁷, P. Bellos ²¹, I. Benaoumeur ²¹, D. Bencheikroun ^{36a}, F. Bendebeba ^{36a}, Y. Benhammou ¹⁵⁴, K.C. Benkendorfer ¹⁶⁷, L. Beresford ⁴⁷, M. Beretta ⁵², E. Bergeas Kuutmann ¹⁶³, N. Berger ⁴, B. Bergmann ¹³³, J. Beringer ^{18a}, M. Berkat ¹³⁶, G. Bernardi ⁵, C. Bernius ¹⁴⁶, F.U. Bernlochner ²⁵, A. Berrocal Guardia ¹³, T. Berry ⁹⁵, P. Berta ¹³⁴, A. Berti ^{131a},

R. Bertrand ¹⁰², S. Bethke ¹¹⁰, A. Betti ^{74a,74b}, T.F. Beumker ¹⁷³, A.J. Bevan ⁹⁴, L. Bezio ⁵⁵, N.K. Bhalla ⁵³, S. Bharthuar ¹¹⁰, S. Bhatta ¹⁴⁸, P. Bhattarai ¹⁴⁶, Z.M. Bhatti ¹¹⁸, K.D. Bhide ¹⁶⁴, V.S. Bhopatkar ¹²², R.M. Bianchi ¹³⁰, G. Bianco ^{24b,24a}, O. Biebel ¹⁰⁹, M. Biglietti ^{76a}, P. Bijl ⁵³, C.S. Billingsley ⁴⁴, Y. Bimgdi ^{36f}, M. Bindi ⁵⁴, A. Bingham ¹⁷³, A. Bingul ^{22b}, C. Bini ^{74a,74b}, M. Biros ¹³⁴, S. Biryukov ¹⁴⁹, T. Bisanz ⁴⁸, E. Bisceglie ^{24b,24a}, J.P. Biswal ¹³⁵, D. Biswas ¹⁴⁴, M. Biyabi ¹⁴, I. Bloch ⁴⁷, A. Blue ⁵⁸, U. Blumenschein ⁹⁴, V.S. Bobrovnikov ³⁸, L. Boccardo ^{56b,56a}, M. Boehler ⁵³, D. Bogavac ¹³, L.S. Boggia ¹²⁸, V. Boisvert ⁹⁵, P. Bokan ¹⁶³, T. Bold ^{85a}, M. Bomben ⁵, M. Bona ⁹⁴, M. Boonekamp ¹³⁶, A.G. Borbély ⁵⁸, G. Borissov ⁹¹, A. Borkar ¹⁶⁸, D. Bortoletto ¹²⁷, M. Borysova ¹⁷¹, D. Boscherini ^{24b}, M. Bosman ¹³, K. Bouaouda ^{36a}, L. Boudet ¹³⁶, J. Boudreau ¹³⁰, E.V. Bouhova-Thacker ⁹¹, D. Boumediene ⁴⁰, R. Bouquet ^{56b,56a}, A. Boveia ¹²⁰, D. Boye ³⁰, I.R. Boyko ³⁸, L. Bozianu ⁵⁵, J. Bracinik ²¹, N. Brahimi ⁴, G. Brandt ¹⁷³, O. Brandt ³³, B. Brau ¹⁰³, R. Brenner ¹⁷¹, L. Brenner ¹¹⁶, R. Brenner ¹⁶³, S. Bressler ¹⁷¹, M. Brettell ⁹⁶, G. Brianti ¹¹⁶, D. Britton ⁵⁸, D. Britzger ¹¹⁰, I. Brock ²⁵, R. Brock ¹⁰⁷, H. Bronson ¹²⁹, G. Brooijmans ⁴¹, A.J. Brooks ⁶⁷, E.M. Brooks ^{159b}, E. Brost ³⁰, L.M. Brown ^{167,159a}, L.E. Bruce ⁶⁰, T.L. Bruckler ¹²⁷, P.A. Bruckman de Renstrom ⁸⁶, B. Brüers ⁴⁷, A. Bruni ^{24b}, G. Bruni ^{24b}, D. Brunner ^{46a,46b}, M. Bruschi ^{24b}, N. Bruscino ^{74a,74b}, T. Buanes ¹⁷, Q. Buat ¹⁴⁰, D. Buchin ¹¹⁰, A.G. Buckley ⁵⁸, J. Bucko ¹³⁴, M. Buhring ⁴⁹, O. Bulekov ⁸⁰, B.A. Bullard ¹⁴⁶, T.O. Buratovich ⁹⁰, S. Burdin ⁹², C.D. Burgard ⁴⁸, A.M. Burger ⁸⁹, B. Burghgrave ⁸, O. Burlayenko ⁵³, J. Burleson ¹⁶⁴, J.C. Burzynski ¹²¹, V. Büscher ¹⁰⁰, P.J. Bussey ⁵⁸, O. But ²⁵, J.M. Butler ²⁶, C.M. Buttar ⁵⁸, J.M. Butterworth ⁹⁶, P. Butti ³⁷, W. Buttinger ¹³⁵, C.J. Buxo Vazquez ¹⁰⁷, A.R. Buzykaev ³⁸, S. Cabrera Urbán ¹⁶⁵, L. Cadamuro ⁶⁵, H. Cai ³⁷, Y. Cai ^{24b,112c,24a}, Y. Cai ^{112a}, M.A. Cairo ¹²⁹, V.M.M. Cairo ³⁷, O. Cakir ^{3a}, N. Calace ³⁷, P. Calafiura ^{18a}, G. Calderini ¹²⁸, P. Calfayan ³⁵, L. Calic ⁹⁸, G. Callea ⁵⁸, L.P. Caloba ^{81b}, D. Calvet ⁴⁰, S. Calvet ⁴⁰, R. Camacho Toro ¹²⁸, S. Camarda ³⁷, D. Camarero Munoz ²⁷, P. Camarri ^{75a,75b}, G. Camia ⁴⁷, C. Camincher ³⁷, M. Campanelli ⁹⁶, A. Camplani ⁴², V. Canale ^{71a,71b}, A.C. Canbay ^{3a}, E. Canonero ⁹⁵, J. Cantero ¹⁶⁵, F. Capocasa ²⁷, P. Cappelli ²⁷, M. Capua ^{43b,43a}, A. Carbone ^{70a,70b}, R. Cardarelli ^{75a}, J.C.J. Cardenas ⁸, M.P. Cardiff ²⁷, G. Carducci ^{43b,43a}, T. Carli ³⁷, G. Carlino ^{71a}, J.I. Carlotto ¹³, B.T. Carlson ^{130,q}, E.M. Carlson ¹⁶⁷, L. Carminati ^{70a,70b}, A. Carnelli ⁴, M. Carnesale ³⁷, S. Caron ¹¹⁵, E. Carquin ^{138g}, I.B. Carr ¹⁰⁵, S. Carrá ^{72a,72b}, G. Carratta ^{24b,24a}, C. Carrion Martinez ¹⁶⁵, A.M. Carroll ¹²⁴, N. Cartalade ⁴⁰, M.P. Casado ^{13,h}, P. Casolaro ^{71a,71b}, M. Caspar ⁴⁷, F. Cassinese ⁹⁰, F. Castiglioni ^{73a,73b}, W.R. Castiglioni ³⁹, F.L. Castillo ⁴, V. Castillo Gimenez ¹⁶⁵, N.F. Castro ^{131a,131e}, A. Catinaccio ³⁷, J.R. Catmore ¹²⁶, T. Cavaliere ⁴, V. Cavaliere ³⁰, E. Celebi ⁸⁰, S. Cella ³⁰, V. Cepaitis ⁵⁵, K. Cerny ¹²³, A.S. Cerqueira ^{81a}, A. Cerri ^{73a,ap}, L. Cerrito ^{75a,75b}, F. Cerutti ^{18a}, B. Cervato ^{70a,70b}, A. Cervelli ^{24b}, G. Cesarini ⁵², S.A. Cetin ⁸⁰, V.C. Chabalala ^{34j}, P.M. Chabrilat ¹²⁸, R. Chakkappai ⁶⁵, S. Chakraborty ¹⁶⁹, A. Chambers ⁶⁰, J. Chan ^{18a}, J.D. Chapman ³³, E. Chapon ¹³⁶, D.G. Charlton ²¹, C. Chauhan ¹³², Y. Che ^{112a}, S. Chekanov ⁶, G.A. Chelkov ^{38,a}, H. Chen ³⁰, J. Chen ^{141a}, J. Chen ¹⁴⁵, M. Chen ⁵⁹, S. Chen ⁸⁷, S.J. Chen ^{112a}, X. Chen ^{141a}, X. Chen ^{15,ai}, Z. Chen ⁶¹, C.L. Cheng ¹⁴⁶, H.C. Cheng ^{63a}, S. Cheong ¹⁴⁶, A. Cheplakov ³⁸, E. Cherepanova ¹¹⁶, E. Cheu ⁷, K. Cheung ⁶⁴, L. Chevalier ¹³⁶, G. Chiarelli ^{73a}, G. Chiodini ^{69a}, A.S. Chisholm ²¹, J.L. Chisholm ¹⁶⁶, A. Chitan ^{28b}, M. Chitishvili ¹⁶⁵, M.V. Chizhov ^{38,r}, K. Chmiel ^{76a,76b}, K. Choi ¹¹, Y. Chou ¹⁴⁰, E.Y.S. Chow ¹¹⁵, G. Christou ⁵¹, K.L. Chu ¹⁷¹, M.C. Chu ^{63a}, Z. Chubinidze ⁵², J. Chudoba ¹³², J.J. Chwastowski ⁸⁶, D. Cieri ¹¹⁰, K.M. Ciesla ^{85a}, V. Cindro ⁹³, A. Ciocio ^{18a}, F. Ciotto ^{71a,71b}, Z.H. Citron ¹⁷¹, M. Citterio ^{70a}, D.A. Ciubotaru ^{28b}, A. Clark ⁵⁵, P.J. Clark ⁵¹, N. Clarke Hall ³⁷, C. Clarry ¹⁵⁸, S.E. Clawson ³⁷, C. Clement ^{46a,46b}, L. Clissa ^{24b,24a}, Y. Coadou ¹⁰²,

M. Cobal ^{68a,68c}, A. Coccaro ^{56b}, M.G. Cochran Branson ¹⁴⁰, R.F. Coelho Barrue ^{131a},
R. Coelho Lopes De Sa ¹⁰³, S. Coelli ^{70a}, M.M. Cohen ¹²⁹, L.S. Colangeli ¹⁵⁸, B. Cole ⁴¹,
P. Collado Soto ⁹⁹, J. Collot ⁵⁹, M.R. Coluccia ^{69a}, I. Combes ⁶⁵, P. Conde Muño ^{131a,131g},
L.H.J. Condren ¹⁶², M.P. Connell ^{34c}, S.H. Connell ^{34c}, E.I. Conroy ¹⁶¹, M. Contreras Cossio ¹¹,
F. Conventi ^{71a,ak}, A.M. Cooper-Sarkar ¹²⁷, L. Corazzina ^{74a,74b}, F.A. Corchia ^{24b,24a},
A. Cordeiro Oudot Choi ¹⁴⁰, L.D. Corpe ⁴⁰, M. Corradi ^{74a,74b}, F. Corriveau ^{104,ab},
A. Cortes-Gonzalez ¹⁵⁶, M.J. Costa ¹⁶⁵, F. Costanza ⁴, D. Costanzo ¹⁴², J. Couthures ⁴,
G. Cowan ⁹⁵, K. Cranmer ¹⁷², L. Cremer ⁴⁸, D. Cremonini ^{24b,24a}, S. Crépe-Renaudin ⁵⁹,
F. Crescioli ¹²⁸, T. Cresta ^{72a,72b}, M. Cristinziani ¹⁴⁴, M. Cristoforetti ^{77a,77b}, T.M. Critchley ⁵⁵,
E. Critelli ⁹⁶, A. Cueto ⁹⁹, H. Cui ⁹⁶, Z. Cui ⁷, B.M. Cunnett ¹⁴⁹, W.R. Cunningham ⁵⁸,
E. Cuppini ¹¹⁰, F. Curcio ¹⁶⁵, J.R. Curran ⁵¹, M.J. Da Cunha Sargedas De Sousa ^{56b,56a},
J.V. Da Fonseca Pinto ^{81b}, C. Da Via ¹⁰¹, W. Dabrowski ^{85a}, T. Dado ³⁷, S. Dahbi ¹⁵¹,
T. Dai ¹⁰⁶, D. Dal Santo ²⁰, C. Dallapiccola ¹⁰³, M. Dam ⁴², G. D'amen ³⁰, V. D'Amico ¹⁰⁹,
J.R. Dandoy ³⁵, M. D'Andrea ^{56b,56a}, D. Dannheim ³⁷, G. D'anniballe ^{73a,73b}, M. Danninger ¹⁴⁵,
V. Dao ¹⁴⁸, G. Darbo ^{56b}, F. Dattola ⁴⁷, S. D'Auria ^{70a,70b}, A. D'Avanzo ^{71a,71b}, T. Davidek ¹³⁴,
J. Davidson ¹⁶⁹, I. Dawson ⁹⁴, K. De ⁸, C. De Almeida Rossi ¹⁵⁸, N. De Biase ⁴⁷,
S. De Castro ^{24b,24a}, N. De Groot ¹¹⁵, P. de Jong ¹¹⁶, H. De la Torre ¹¹⁷, A. De Maria ^{112a},
S. De Miranda Rimes ^{81d}, A. De Salvo ^{74a}, U. De Sanctis ^{75a,75b}, F. De Santis ^{69a,69b},
A. De Santo ¹⁴⁹, J.B. De Vivie De Regie ⁵⁹, K.G. De Vries ¹¹⁶, J. Debevc ⁹³, D.V. Dedovich ³⁸,
J. Degens ⁹², A.M. Deiana ⁴⁴, J. Del Peso ⁹⁹, L. Delagrangé ²⁷, F. Deliot ¹³⁶, C.M. Delitzsch ⁴⁸,
M. Della Pietra ^{71a,71b}, D. Della Volpe ⁵⁵, A. Dell'Acqua ³⁷, L. Dell'Asta ^{70a,70b}, M. Delmastro ⁴,
C.C. Delogu ^{56b,56a}, P.A. Delsart ⁵⁹, S. Demers ¹⁷⁴, M. Demichev ³⁸, H. Denizli ^{22a,1},
M.G. Depala ⁹², L. D'Eramo ⁴⁰, D. Derendarz ⁸⁶, L. Derin ^{56b,56a}, F. Derue ¹²⁸, P. Dervan ^{92,*},
A.M. Desai ¹, K. Desch ²⁵, F.A. Di Bello ^{73a,73b}, A. Di Ciaccio ^{75a,75b}, L. Di Ciaccio ⁴,
D. Di Croce ³⁷, C. Di Donato ^{71a,71b}, A. Di Girolamo ³⁷, G. Di Gregorio ⁶⁵, A. Di Luca ^{77a,77b},
B. Di Micco ^{76a,76b}, R. Di Nardo ^{76a,76b}, K.F. Di Petrillo ³⁹, M. Diamantopoulou ¹⁵⁴,
F.A. Dias ¹¹⁶, M.A. Diaz ^{138a,138b}, A.R. Didenko ³⁸, M. Didenko ¹⁶⁵, S.D. Diefenbacher ^{18a},
E.B. Diehl ¹⁰⁶, S. Díez Cornell ⁴⁷, C. Díez Pardos ¹⁴⁴, C. Dimitriadi ¹⁴⁷, A. Dimitrievska ²¹,
A. Dimri ¹⁴⁸, Y. Ding ⁶¹, J. Dingfelder ²⁵, T. Dingley ¹²⁷, I-M. Dinu ^{28b}, S.J. Dittmeier ^{62b},
F. Dittus ³⁷, M. Divisek ¹³⁴, B. Dixit ⁹², F. Djama ¹⁰², T. Djobava ^{152b}, C. Doglioni ^{101,98},
A. Dohnalova ^{29a}, Z. Dolezal ¹³⁴, K. Domijan ^{85a}, K.M. Dona ³⁹, M. Donadelli ^{81d},
B. Dong ¹⁰⁷, J. Donini ⁴⁰, A. D'Onofrio ^{71a,71b}, M. D'Onofrio ⁹², J. Dopke ¹³⁵, A. Doria ^{71a},
N. Dos Santos Fernandes ^{131a}, I.A. Dos Santos Luz ^{81e}, P. Dougan ⁴⁴, M.T. Dova ⁹⁰,
A.T. Doyle ⁵⁸, M.P. Drescher ⁵⁴, E. Dreyer ¹⁷¹, I. Drivas-koulouris ¹⁰, M. Drnevich ¹¹⁸,
D. Du ⁶¹, T. Du ³⁹, T.A. du Pree ¹¹⁶, Z. Duan ^{112a}, M. Dubau ⁴, F. Dubinin ³⁸, M. Dubovsky ^{29a},
E. Duchovni ¹⁷¹, G. Duckeck ¹⁰⁹, P.K. Duckett ⁹⁶, O.A. Ducu ^{28b}, D. Duda ⁵¹, A. Dudarev ³⁷,
M.M. Dudek ⁸⁶, E.R. Duden ²⁷, M. D'uffizi ¹⁰¹, L. Duflo ⁶⁵, M. Dührssen ³⁷, I. Duminica ^{28g},
A.E. Dumitriu ^{28b}, M. Dunford ^{62a}, T. Duong ⁴, A. Duperrin ¹⁰², A.F. Duque Bran ⁴⁰,
H. Duran Yildiz ^{3a}, A. Durglishvili ^{152b}, G.I. Dyckes ^{18a}, M. Dyndal ^{85a}, B.S. Dziedzic ³⁷,
G.H. Eberwein ¹²⁷, B. Eckerova ^{29a}, J.C. Egan ⁹⁶, S. Eggebrecht ⁵⁴,
E. Egidio Purcino De Souza ^{81e}, G. Eigen ¹⁷, K. Einsweiler ^{18a}, T. Ekelof ¹⁶³, P.A. Ekman ⁹⁸,
S. El Farkh ^{36b}, Y. El Ghazali ⁶¹, H. El Jarrari ¹⁰⁴, A. El Moussaouy ^{36a}, I. Elbaz ¹⁵⁴,
D. Elitez ³⁷, M. Ellert ¹⁶³, F. Ellinghaus ¹⁷³, T.A. Elliot ⁹⁵, J. Elmsheuser ³⁰, M. Elsayy ^{83b},
M. Elsing ³⁷, D. Emeliyanov ¹³⁵, Y. Enari ⁸², S. Epari ¹⁰⁸, D. Ernani Martins Neto ⁸⁶, F. Ernst ³⁷,
M. Escalier ⁶⁵, C. Escobar ¹⁶⁵, R. Estevam De Paula ^{81c}, E. Etzion ¹⁵⁴, G. Evans ^{131a,131b},
H. Evans ⁶⁷, L.S. Evans ⁴⁷, S. Ezzarqtouni ^{36a}, F. Fabbri ^{24b,24a}, L. Fabbri ^{24b,24a}, G. Facini ⁹⁶,
V. Fadeyev ¹³⁷, D. Fakoudis ¹⁰⁰, S. Falciano ^{74a}, L.F. Falda Ulhoa Coelho ²⁷, F. Fallavollita ¹¹⁰,

G. Falsetti ^{43b,43a}, J. Faltova ¹³⁴, C. Fan ¹⁶⁴, K.Y. Fan ^{63b}, Y. Fan ¹⁴, Y. Fang ^{14,112c}, M. Fanti ^{70a,70b}, M. Faraj ^{68a,68c}, Z. Farazpay ⁹⁷, A. Farbin ⁸, A. Farilla ^{76a}, K. Farman ¹⁵¹, J.N. Farr ¹⁷⁴, M.S. Farrington ⁶⁰, S.M. Farrington ^{135,51}, F. Fassi ^{36e}, D. Fassouliotis ⁹, L. Fayard ⁶⁵, G. Fazzino ^{62b}, P. Federic ¹³⁴, P. Federicova ¹³², M. Feickert ¹⁷², L. Feligioni ¹⁰², D.E. Fellers ^{18a}, C. Feng ^{113b}, Y. Feng ¹⁴, Z. Feng ⁶⁵, B. Fernandez Barbadillo ⁹¹, P. Fernandez Martinez ⁶⁶, C. Fernandez Ruiz ³³, J. Ferrando ⁹¹, A. Ferrari ¹⁶³, P. Ferrari ^{116,115}, R. Ferrari ^{72a}, D. Ferrere ⁵⁵, C. Ferretti ¹⁰⁶, M.P. Fewell ¹, D. Fiacco ^{74a,74b}, F. Fiedler ¹⁰⁰, P. Fiedler ¹³³, S. Filimonov ³⁸, M.S. Filip ^{28b,s}, M. Filipig ^{68a,68c}, A. Filipčič ⁹³, E.K. Filmer ^{159a}, F. Filthaut ¹¹⁵, M.C.N. Fiolhais ^{131a,131c,c}, L. Fiorini ¹⁶⁵, W.C. Fisher ¹⁰⁷, T. Fitschen ¹⁰¹, I. Fleck ¹⁴⁴, P. Fleischmann ¹⁰⁶, T. Flick ¹⁷³, M. Flores ^{34d,ag}, L.R. Flores Castillo ^{63a}, M. Foll ¹²⁶, F.M. Follega ^{77a,77b}, N. Fomin ³³, A. Formica ¹³⁶, M. Fornasiero ¹⁴⁹, A.C. Forti ¹⁰¹, N. Forti ^{24b,24a}, E. Fortin ¹⁰², A.W. Fortman ^{18a}, L. Foster ^{18a}, L. Fountas ⁹, H. Fox ⁹¹, P. Francavilla ^{73a,73b}, S. Francescato ⁶⁰, S. Franchellucci ²⁰, M. Franchini ^{24b,24a}, S. Franchino ^{62a}, D. Francis ³⁷, L. Franco ⁴⁷, L. Franconi ⁴⁷, M. Franklin ⁶⁰, G. Frattari ³⁷, Y.Y. Frid ¹⁵⁴, N. Fritzsche ³⁷, A. Froch ⁵⁵, D. Froidevaux ³⁷, J.A. Frost ¹³⁵, Y. Fu ¹⁰⁷, S. Fuenzalida Garrido ^{138g}, Y.C. Fujikake ¹³⁷, M. Fujimoto ¹⁴⁸, K.Y. Fung ^{63a}, E. Furtado De Simas Filho ^{81e}, M. Furukawa ¹⁵⁶, M. Fuste Costa ⁴⁷, P. Fuste Martin ¹³, J. Fuster ¹⁶⁵, A. Gaa ⁵⁴, A. Gabrielli ^{24b,24a}, A. Gabrielli ¹⁵⁸, G. Gagliardi ^{56b,56a}, L.G. Gagnon ¹⁴⁶, S. Galantzan ¹⁵⁴, J. Gallagher ¹, E.J. Gallas ¹²⁷, A.L. Gallen ¹⁶³, B.J. Gallop ¹³⁵, K.K. Gan ¹²⁰, Y. Gao ⁵¹, Z. Gao ^{112a}, A. Garabaglu ¹⁴⁰, F.M. Garay Walls ^{138a,138b}, C. García ¹⁶⁵, A. Garcia Alonso ¹¹⁶, A.G. Garcia Caffaro ¹⁷⁴, J.E. García Navarro ¹⁶⁵, M.A. Garcia Ruiz ^{23b}, M. Garcia-Sciveres ^{18a}, G.L. Gardner ¹²⁹, R.W. Gardner ³⁹, N. Garelli ¹⁶¹, R.B. Garg ¹⁴⁶, J.M. Gargan ³³, C.A. Garner ¹⁵⁸, C.M. Garvey ^{34a}, V.K. Gassmann ¹⁶¹, G. Gaudio ^{72a}, A.J. Gavin ⁹⁴, J. Gavranovic ⁹³, I.L. Gavrilenko ^{131a}, C. Gay ¹⁶⁶, G. Gaycken ¹²⁴, A. Gekow ¹²⁰, C. Gemme ^{56b}, M.H. Genest ⁵⁹, A.D. Gentry ¹¹⁴, S. George ⁹⁵, T. Geralis ⁴⁵, A.A. Gerwin ¹²¹, P. Gessinger-Befurt ³⁷, M. Ghani ¹⁶⁹, K. Ghorbanian ⁹⁴, A. Ghosal ¹⁴⁴, A. Ghosh ¹⁶², A. Ghosh ⁷, B. Giacobbe ^{24b}, S. Giagu ^{74a,74b}, A. Giannini ⁶¹, S.M. Gibson ⁹⁵, D.T. Gil ^{85b}, B.J. Gilbert ⁴¹, D. Gillberg ³⁵, G. Gilles ¹¹⁶, D.M. Gingrich ^{2,aj}, M.P. Giordani ^{68a,68c}, P.F. Giraud ¹³⁶, G. Giugliarelli ^{68a,68c}, D. Giugni ^{70a}, F. Giuli ^{75a,75b,al}, I. Gkialas ^{9,i}, B.C. Gladwyn ¹²⁷, C. Glasman ⁹⁹, M. Glazewska ²⁰, R.M. Gleason ¹⁶², G. Glemža ⁴⁷, I. Gnesi ^{24b,24a,am}, Y. Go ³⁰, M. Goblirsch-Kolb ³⁷, B. Gocke ⁴⁸, D. Godin ¹⁰⁸, B. Gokturk ^{22a}, S. Goldfarb ¹⁰⁵, T. Golling ⁵⁵, M.G.D. Gololo ^{34c}, A. Golub ¹⁴⁰, J.P. Gombas ¹⁰⁷, A. Gomes ^{131a,131b}, G. Gomes Da Silva ¹⁴⁴, A.J. Gomez Delegido ³⁷, R. Gonçalves ^{131a}, A. Gongadze ^{152c}, F. Gonnella ²¹, J.L. Gonski ¹⁴⁶, R.Y. González Andana ⁵¹, S. González de la Hoz ¹⁶⁵, M.V. Gonzalez Rodrigues ⁴⁷, R. Gonzalez Suarez ¹⁶³, S. Gonzalez-Sevilla ⁵⁵, L. Goossens ³⁷, B. Gorini ³⁷, E. Gorini ^{69a,69b}, A. Gorišek ⁹³, T.C. Gosart ¹²⁹, A.T. Goshaw ⁵⁰, M.I. Gostkin ³⁸, S. Goswami ¹²², C.A. Gottardo ³⁷, S.A. Gotz ¹⁰⁹, M. Goughri ^{36b}, A.G. Goussiou ¹⁴⁰, N. Govender ^{34c}, R.P. Grabarczyk ¹²⁷, I. Grabowska-Bold ^{85a}, K. Graham ³⁵, E. Gramstad ¹²⁶, S. Grancagnolo ^{69a,69b}, C.M. Grant ¹, P.M. Gravila ^{28f}, F.G. Gravili ^{69a,69b}, H.M. Gray ^{18a}, M. Greco ¹¹⁰, M.J. Green ¹, C. Grefe ²⁵, A.S. Grefsrud ³⁷, I.M. Gregor ⁴⁷, K.T. Greif ¹⁶², P. Grenier ¹⁴⁶, S.G. Grewe ¹¹⁰, K. Grimm ³², S. Grinstein ^{13,x}, E. Gross ¹⁷¹, J. Grosse-Knetter ⁵⁴, L.H. Grossman ^{18b}, L. Guan ¹⁰⁶, G. Guerrieri ³⁷, R. Guevara ¹²⁶, R. Gugel ¹⁰⁰, J.A.M. Guhit ¹⁰⁶, A. Guida ¹⁹, E. Guilloton ¹⁶⁹, S. Guindon ³⁷, F. Guo ^{14,112c}, J. Guo ^{141a}, L. Guo ⁴⁷, L. Guo ^{112b,u}, Y. Guo ¹⁰⁶, Y. Guo ⁴¹, A. Gupta ⁴⁸, R. Gupta ¹³⁰, S. Gupta ²⁷, S. Gurbuz ²⁵, S.S. Gurdasani ⁴⁷, G. Gustavino ^{74a,74b}, P. Gutierrez ¹²¹, L.F. Gutierrez Zagazeta ¹²⁹, M. Gutsche ⁴⁹, C. Gutschow ⁹⁶, W. Guérin ⁸⁹, C. Gwenlan ¹²⁷,

C.B. Gwilliam ⁹², E.S. Haaland ¹²⁶, A. Haas ¹¹⁸, M. Habedank ⁵⁸, C. Haber ^{18a}, R.J. Haberle ¹⁷¹, H.K. Hadavand ⁸, A. Haddad ⁴⁰, A. Hadeef ⁴⁹, A.I. Hagan ⁹¹, J.J. Hahn ¹⁴⁴, M. Haleem ¹⁶⁸, J. Haley ¹²², G.D. Hallowell ¹⁰², J.A. Hallford ⁴⁷, H. Hamdaoui ¹⁶³, M. Hamer ²⁵, S.E.D. Hammoud ⁶⁵, E.J. Hampshire ⁹⁵, L. Han ^{112a}, L. Han ⁶¹, S. Han ¹⁴, K. Hanagaki ⁸², M. Hance ¹³⁷, D.A. Hangal ⁴¹, H. Hanif ¹⁴⁵, M.D. Hank ¹²⁹, J.B. Hansen ⁴², P.H. Hansen ⁴², T. Harenberg ¹⁷³, S. Harkusha ¹⁷⁵, M.L. Harris ¹⁰³, Y.T. Harris ²⁵, J. Harrison ¹³, P.F. Harrison ¹⁶⁹, M.L.E. Hart ⁹⁶, N.M. Hartman ¹¹⁰, N.M. Hartmann ¹⁰⁹, R.Z. Hasan ^{95,135}, Y. Hasegawa ¹⁴³, D. Hashimoto ¹¹¹, F. Haslbeck ³⁷, S. Hassan ¹²⁶, R. Hauser ¹⁰⁷, M. Haviernik ¹³⁴, C.M. Hawkes ²¹, R.J. Hawkins ³⁷, Y. Hayashi ¹⁵⁶, D. Hayden ¹⁰⁷, R.L. Hayes ¹¹⁶, C.P. Hays ¹²⁷, J.M. Hays ⁹⁴, H.S. Hayward ⁹², M. He ^{14,112c}, Y. He ⁴⁷, Y. He ⁹⁶, V. Hedberg ⁹⁸, J. Heilman ³⁵, S. Heim ⁴⁷, T. Heim ^{18a}, J.J. Heinrich ¹²⁴, L. Heinrich ¹¹⁰, J. Hejbal ¹³², M. Helbig ⁴⁹, A. Held ¹⁷², S. Hellesund ¹⁷, C.M. Helling ¹⁶⁶, F.N.E. Henry ⁵⁸, H. Herde ⁹⁸, Y. Hernández Jiménez ¹⁴⁸, G. Herten ⁵³, R. Hertenberger ¹⁰⁹, L. Hervas ³⁷, M.E. Hespings ¹⁰⁰, N.P. Hessey ^{159a}, J. Hessler ¹¹⁰, R. Hicks ¹²⁹, M. Hidaoui ^{36b}, N. Hidic ¹³⁴, E. Hill ¹⁵⁸, T.S. Hillersoy ¹⁷, S.J. Hillier ²¹, J.R. Hinds ¹⁰⁷, F. Hinterkeuser ²⁵, M. Hirose ¹²⁵, S. Hirose ¹⁷⁰, D. Hirschbuehl ¹⁷³, B. Hiti ⁹³, J. Hobbs ¹⁴⁸, R. Hobincu ^{28e}, N. Hod ¹⁷¹, A.M. Hodges ¹⁶⁴, M.C. Hodgkinson ¹⁴², B.H. Hodgkinson ¹²⁷, A. Hoecker ³⁷, D.D. Hofer ¹⁰⁶, J. Hofer ¹⁶⁵, J. Hofner ¹⁰⁰, M. Holzbock ³⁷, L.B.A.H. Hommels ³³, V. Homsak ¹²⁷, J.J. Hong ⁶⁷, T.M. Hong ¹³⁰, R. Honscheid ¹²⁷, B.H. Hooberman ¹⁶⁴, W.H. Hopkins ⁶, M.C. Hoppesch ¹⁶⁴, Y. Horii ¹¹¹, M.E. Horstmann ¹¹⁰, M.M. Horzela ⁵⁴, S. Hou ¹⁵¹, M.R. Housenga ¹⁶⁴, J. Howarth ⁵⁸, J. Hoya ⁶, M. Hrabovsky ¹²³, T. Hryn'ova ⁴, P.J. Hsu ⁶⁴, S.-C. Hsu ¹⁴⁰, T. Hsu ⁶⁵, M. Hu ^{18a}, P. Hu ^{63b}, Q. Hu ⁶¹, S. Huang ³³, X. Huang ^{14,112c}, Y. Huang ¹³⁴, Y. Huang ^{112b}, Y. Huang ¹⁴, Z. Huang ⁶⁵, Z. Hubacek ¹³³, F. Huegging ²⁵, T.B. Huffman ¹²⁷, M. Hufnagel Maranha De Faria ^{81a}, C.A. Hugli ⁴⁷, M. Huhtinen ³⁷, S.K. Huiberts ¹⁷, R. Hulsken ¹⁰⁴, C.E. Hultquist ^{18a}, D.L. Humphreys ¹⁰³, N. Huseynov ¹², J. Huston ¹⁰⁷, B. Huth ³⁷, J. Huth ⁶⁰, L. Huth ⁴⁷, R. Hyneman ⁷, G. Iacobucci ⁵⁵, G. Iakovidis ³⁰, L. Iconomidou-Fayard ⁶⁵, J.P. Iddon ³⁷, P. Iengo ^{71a,71b}, Y. Iiyama ¹⁵⁶, T. Iizawa ¹⁵⁶, Y. Ikegami ⁸², D. Iliadis ¹⁵⁵, N. Ilic ¹⁵⁸, H. Imam ^{36a}, G. Inacio Goncalves ^{81d}, S.A. Infante Cabanas ^{138c}, T. Ingebretsen Carlson ^{46a,46b}, J.M. Inglis ⁹⁴, G. Introzzi ^{72a,72b}, M. Iodice ^{76a}, V. Ippolito ^{74a,74b}, R.K. Irwin ⁹², M. Ishino ¹⁵⁶, W. Islam ¹⁷², C. Issever ¹⁹, O.N. Istitia ^{65,b}, S. Istin ^{22a,ar}, K. Itabashi ¹²⁵, H. Ito ¹⁷⁰, R. Iuppa ^{77a,77b}, A. Ivina ¹⁷¹, F. Ivone ³⁷, S. Izumiyama ¹¹¹, V. Izzo ^{71a}, P. Jacka ¹³³, P. Jackson ¹, P.R. Jacobson ⁵⁰, P. Jain ⁴⁷, K. Jakobs ⁵³, J. Jamieson ⁵⁸, W. Jang ¹⁵⁶, S. Jankovych ¹¹⁶, B.K. Jashal ¹³⁵, M. Javurkova ¹⁰³, P. Jawahar ¹⁰¹, L. Jeanty ¹²⁴, J. Jejelava ^{152a,ae}, P. Jenni ^{53,f}, L. Jerala ⁹³, C.E. Jessiman ³⁵, H. Jia ¹⁶⁶, J. Jia ¹⁴⁸, K. Jia ¹⁴⁶, X. Jia ^{110,112c}, C. Jiang ⁵¹, Q. Jiang ^{63b}, S. Jiggins ⁴⁷, M. Jimenez Ortega ¹⁶⁵, J. Jimenez Pena ¹³, S. Jin ^{112a}, A. Jinaru ^{28b}, O. Jinnouchi ¹³⁹, P. Johansson ¹⁴², K.A. Johns ⁷, J.W. Johnson ¹³⁷, F.A. Jolly ⁴⁷, D.M. Jones ¹⁴⁹, E. Jones ⁴⁷, P. Jones ³³, R.W.L. Jones ⁹¹, T.J. Jones ⁹², H.L. Joos ³⁷, R. Joshi ¹²⁰, J. Jovicevic ¹⁶, X. Ju ^{18a}, J.J. Junggeburth ³⁷, T. Junkermann ^{62a}, A. Juste Rozas ^{13,x}, M.K. Juzek ⁸⁶, S. Kabana ^{138f}, A. Kaczmarska ⁸⁶, S.A. Kadir ¹⁴⁶, M. Kado ¹¹⁰, H. Kagan ¹²⁰, M. Kagan ¹⁴⁶, A. Kahn ¹²⁹, C. Kahra ¹⁰⁰, T. Kaji ¹⁵⁶, E. Kajomovitz ¹⁵³, N. Kakati ¹⁷¹, N. Kakoty ¹³, S. Kandel ⁸, E. Kanellaki ⁴⁵, N. Kanellos ¹⁰, S. Kang ⁵⁰, D. Kar ^{34j,*}, E. Karentzos ²⁵, K. Karki ⁸, O. Karkout ¹¹⁶, S.N. Karpov ³⁸, Z.M. Karpova ³⁸, V. Kartvelishvili ^{91,152b}, E. Kasimi ¹⁵⁵, J. Katzy ⁴⁷, S. Kaur ³⁵, R. Kavak ³⁷, K. Kawade ¹⁴³, M.P. Kawale ¹²¹, C. Kawamoto ⁸⁷, E.F. Kay ³⁷, S. Kazakos ¹⁰⁷, K. Kazakova ¹⁰², J.M. Keaveney ^{34a}, R. Keeler ¹⁶⁷, G.V. Kehris ⁶⁰, J.S. Keller ³⁵, J.M. Kelly ¹⁶⁷, J.I. Kelsey ¹⁶⁴, J.J. Kempster ¹⁴⁹, O. Kepka ¹³², J. Kerr ^{159b}, B.P. Kerridge ¹³⁵,

B.P. Kerševan ⁹³, L. Keszeghova ^{29a}, R.A. Khan ¹³⁰, A. Khanov ¹²², M. Kholodenko ^{131a},
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 Y.K. Kim ³⁹, N. Kimura ⁹⁶, M.K. Kingston ⁵⁴, F. Kirfel ²⁵, J. Kirk ¹³⁵, A.E. Kiryunin ¹¹⁰,
 S. Kita ¹⁵⁶, O. Kivernyk ²⁵, M. Klassen ³⁷, C. Klein ³⁵, L. Klein ¹⁶⁸, M.H. Klein ⁴⁴,
 U. Klein ⁹², A. Klimentov ³⁰, P. Kluit ¹¹⁶, S. Kluth ¹¹⁰, E. Kneringer ⁷⁸, T.M. Knight ¹⁵⁸,
 A. Knue ⁴⁸, M. Kobel ⁴⁹, D. Kobylanskii ¹⁷¹, S.F. Koch ³⁷, M. Kocian ¹⁴⁶, P. Kodyš ¹³⁴,
 D.M. Koeck ¹²⁴, T. Koffas ³⁵, K. Kojima ⁸², O. Kolay ⁴⁹, I. Koletsou ⁴, T. Komarek ⁸⁶,
 S. Kondo ¹⁵⁶, K. Köneke ⁵⁴, A.X.Y. Kong ¹, T. Kono ¹¹⁹, N. Konstantinidis ⁹⁶,
 P. Kontaxakis ⁵⁵, B. Konya ⁹⁸, R. Kopeliansky ⁴¹, S. Koperny ^{85a}, R. Koppenhofer ⁵³,
 I. Kopsalis ¹⁰, K. Korcyl ⁸⁶, K. Kordas ^{155,d}, A. Korn ⁹⁶, S. Korn ⁵⁴, I. Korolkov ¹³,
 O. Kortner ¹¹⁰, S. Kortner ¹¹⁰, W.H. Kostecka ¹¹⁷, M. Kostov ^{29a}, V.V. Kostyukhin ¹⁴⁴,
 A. Kotsokechagia ³⁷, A. Kotwal ⁵⁰, A. Koulouris ³⁷, A. Kourkouveli-Charalampidi ^{72a,72b},
 O. Kovanda ¹²⁴, R. Kowalewski ¹⁶⁷, W. Kozanecki ¹²⁴, G. Kramberger ⁹³, P. Kramer ²⁵,
 A. Krasznahorkay ¹⁰³, A.C. Kraus ¹¹⁷, J.W. Kraus ¹⁷³, J.A. Kremer ⁴⁷, N.B. Krengel ¹⁴⁴,
 T. Kresse ¹⁵⁸, L. Kretschmann ¹⁷³, J. Kretschmar ⁹², P. Krieger ¹⁵⁸, K. Krizka ²¹,
 K. Kroeninger ⁴⁸, H. Kroha ¹¹⁰, J. Kroll ¹³², J. Kroll ¹²⁹, K.S. Krowpman ¹⁰⁷, U. Kruchonak ³⁸,
 H. Krüger ²⁵, N. Krumnack ⁷⁹, J. Krupa ¹⁴⁶, M.C. Kruse ⁵⁰, O. Kuchinskaia ³⁸, S. Kuday ^{3a},
 S. Kuehn ³⁷, R. Kuesters ⁵³, T. Kuhl ⁴⁷, V. Kukhtin ³⁸, Y. Kulchitsky ³⁸, S. Kuleshov ^{138d,138b},
 J. Kull ¹, E.V. Kumar ¹⁰⁹, M. Kumar ^{34j}, N. Kumari ⁴⁷, P. Kumari ^{159b}, A. Kupco ¹³²,
 O. Kuprash ⁵³, H. Kurashige ⁸⁴, L.L. Kurchaninov ^{159a}, O. Kurdysh ⁴, M. Kuze ¹³⁹,
 A.K. Kvam ¹⁰³, J. Kvita ¹²³, N.G. Kyriacou ¹⁴⁰, M. Laassiri ³⁰, C. Lacasta ¹⁶⁵, H. Lacker ¹⁹,
 D. Lacour ¹²⁸, E. Ladygin ³⁸, A. Lafarge ⁴⁰, B. Laforge ¹²⁸, T. Lagouri ¹⁷⁴, F.Z. Lahbabi ^{36a},
 J. Lai ¹²⁴, S. Lai ⁵⁴, W.S. Lai ⁹⁶, I.K. Lakomic ⁵⁴, J.E. Lambert ¹⁶⁷, S. Lammers ⁶⁷,
 W. Lampl ⁷, C. Lampoudis ¹⁵⁵, G. Lamprinoudis ¹⁶⁸, A.N. Lancaster ¹¹⁷, U. Landgraf ⁵³,
 M.P.J. Landon ⁹⁴, V.S. Lang ⁵³, A.J. Lankford ¹⁶², F. Lanni ³⁷, C.S. Lantz ¹⁶⁴, K. Lantzs ²⁵,
 A. Lanza ^{72a}, M. Lanzac Berrocal ¹⁶⁵, T. Lari ^{70a}, D. Larsen ¹⁷, L. Larson ¹¹,
 F. Lasagni Manghi ^{24b}, M. Lassnig ³⁷, H.C. Lau ¹⁶⁷, S.D. Lawlor ¹⁴², R. Lazaridou ¹⁶²,
 M. Lazzaroni ^{70a,70b}, E.T.T. Le ¹⁶², H.D.M. Le ¹⁰⁷, E.M. Le Boulicaut ¹⁷⁴, D.O. Le Guennec ¹³⁶,
 L.T. Le Pottier ^{18a}, B. Leban ^{24b,24a}, F. Ledroit-Guillon ⁵⁹, T.F. Lee ^{159b}, L.L. Leeuw ^{34h},
 M. Lefebvre ¹⁶⁷, C. Leggett ^{18a}, L.M. Lehmann ¹¹⁶, W.A. Leight ¹⁰³, W. Leinonen ¹¹⁵,
 A. Leisos ^{155,t}, M.A.L. Leite ^{81c}, C.E. Leitgeb ¹⁹, R. Leitner ¹³⁴, E. Lelak ¹³⁴, K.J.C. Leney ⁴⁴,
 T. Lenz ²⁵, S. Leone ^{73a}, C. Leonidopoulos ⁵¹, A. Leopold ¹⁴⁷, J. LePage-Bourbonnais ³⁵,
 R. Les ⁶⁵, C.G. Lester ³³, J. Levêque ⁴, L.J. Levinson ¹⁷¹, G. Levrini ^{24b,24a}, M.P. Lewicki ⁸⁶,
 C. Lewis ¹⁴⁰, D.J. Lewis ⁴, L. Lewitt ¹⁴², A. Li ³⁰, B. Li ^{113b}, C. Li ¹⁰⁶, C-Q. Li ¹¹⁰, H. Li ^{113b},
 H. Li ¹⁰¹, H. Li ¹⁵, H. Li ⁶¹, H. Li ^{113b}, J. Li ^{141a}, L. Li ^{141a}, R. Li ¹⁷⁴, S. Li ^{141b,141a}, Y. Li ¹⁴,
 Z. Li ^{14,112c}, Z. Li ⁶¹, S. Liang ^{14,112c}, Z. Liang ¹⁴, M. Liberatore ¹³⁶, B. Liberti ^{75a},
 G.B. Libotte ^{81d}, M. Licchelli ^{70b}, K. Lie ^{63c}, J. Lieber Marin ^{81e}, H. Lien ⁶⁷, H. Lin ¹⁰⁶,
 S.F. Lin ¹⁴⁸, L. Linden ¹⁰⁹, R.E. Lindley ⁷, J.H. Lindon ³⁷, J. Ling ⁶⁰, E. Lipeles ¹²⁹,
 A. Lipniacka ¹⁷, A. Lister ¹⁶⁶, J.D. Little ⁶⁷, B. Liu ^{113a}, B.X. Liu ^{112b}, D. Liu ¹⁵³, D. Liu ¹³⁷,
 E.H.L. Liu ²¹, H. Liu ^{112b}, J.K.K. Liu ¹¹⁸, K. Liu ^{141b}, K. Liu ^{141b}, M. Liu ⁶¹, M.Y. Liu ⁶¹,
 P. Liu ^{113b}, Q. Liu ¹⁴⁶, S. Liu ¹⁴⁸, X. Liu ^{113b}, Y. Liu ^{112b,112c}, Y. Liu ¹⁶⁴, Y.L. Liu ^{113b},
 Y.W. Liu ⁶¹, Z. Liu ^{65j}, S.L. Lloyd ⁹⁴, E.M. Lobodzinska ⁴⁷, P. Loch ⁷, E. Lodhi ¹⁵⁸,
 K. Lohwasser ¹⁴², E. Loiacono ¹²², J.D. Lomas ²¹, I. Longarini ¹⁶², R. Longo ^{24b,24a,am},
 A. Lopez Solis ¹³, N.A. Lopez-canelas ⁷, N. Lorenzo Martinez ⁴, A.M. Lory ¹⁰⁹, M. Losada ^{83b},
 G. Löschke Centeno ⁴, X. Lou ^{14,112c}, P.A. Love ⁹¹, H. Lu ¹⁴, M. Lu ⁶⁵, S. Lu ¹²⁹,
 Y.J. Lu ¹⁵¹, H.J. Lubatti ¹⁴⁰, C. Luci ^{74a,74b}, F.L. Lucio Alves ^{112a}, J.A. Lue ¹²⁴, F. Luehring ⁶⁷,
 B.S. Lunday ¹²⁹, O. Lundberg ¹⁴⁷, J. Lunde ³⁷, N.A. Luongo ⁶, M.S. Lutz ¹⁵⁸, A.B. Lux ²⁶,

D. Lynn ³⁰, R. Lysak ¹³², V. Lysenko ¹³³, E. Lytken ⁹⁸, V. Lyubushkin ³⁸, T. Lyubushkina ³⁸,
 M.M. Lyukova ¹⁴⁸, H. Ma ³⁰, K. Ma ⁶¹, L.L. Ma ^{113b}, W. Ma ⁶¹, Y. Ma ^{113b},
 P.C. Machado De Abreu Farias ^{81e}, D. Macina ³⁷, R. Madar ⁴⁰, T. Madula ⁹⁶, J. Maeda ⁸⁴,
 T. Maeno ³⁰, P.T. Mafa ^{34f}, G. Magni ⁶⁵, H. Maguire ¹⁴², M. Maheshwari ³³, V. Maiboroda ⁶⁵,
 G. Maineri ^{70a,70b}, A. Maio ^{131a,131b,131d}, K. Maj ^{85a}, O. Majersky ⁴⁷, S. Majewski ¹²⁴,
 A. Makita ¹⁵⁶, N. Makovec ⁶⁵, V. Maksimovic ¹⁶, B. Malaescu ¹²⁸, J. Malamant ¹²⁶,
 Pa. Malecki ⁸⁶, F. Malek ^{59,n}, M. Mali ⁹³, D. Malito ⁹⁵, A. Maloizel ⁵, A. Malvezzi Lopes ^{81d},
 S. Malyukov ³⁸, J. Mamuzic ⁹³, G. Mancini ⁵², M.N. Mancini ²⁷, G. Manco ^{72a,72b},
 S.S. Mandarray ¹⁴⁹, I. Mandić ⁹³, L. Manhaes de Andrade Filho ^{81a}, I.M. Maniatis ¹⁷¹,
 J. Manjarres Ramos ⁸⁹, D.C. Mankad ¹⁷¹, A. Mann ¹⁰⁹, T. Manoussos ¹⁰⁰, M.N. Mantinan ³⁹,
 S. Manzoni ³⁷, L. Mao ^{141a}, X. Mapekula ^{34c}, A. Marantis ¹⁵⁵, R.R. Marcelo Gregorio ¹,
 G. Marchiori ⁵, C. Marcon ^{70a}, E. Maricic ¹⁶, M. Marinescu ⁴⁷, S. Marium ⁴⁷,
 M. Marjanovic ¹²¹, A. Markhoos ⁵³, M. Markovitch ⁶⁵, M.K. Maroun ¹⁰³, M.C. Marr ¹⁴⁵,
 T.L. Marsault ¹³⁶, G.T. Marsden ¹⁰¹, Z. Marshall ^{18a}, S. Marti-Garcia ¹⁶⁵, J. Martin ⁹⁶,
 T.A. Martin ¹³⁵, V.J. Martin ⁵¹, B. Martin dit Latour ¹⁷, L. Martinelli ^{74a,74b},
 V.I. Martinez Outschoorn ¹⁰³, P. Martinez Suarez ³⁷, S. Martin-Haugh ¹³⁵, G. Martinovicova ¹³⁴,
 V.S. Martoiu ^{28b}, A. Martone ⁸⁹, A.C. Martyniuk ⁹⁶, A. Marzin ³⁷, D. Mascione ^{77a,77b},
 L. Masetti ¹⁰⁰, J. Masik ¹⁰¹, A.L. Maslennikov ³⁸, S.L. Mason ⁴¹, P. Massarotti ^{71a,71b},
 P. Mastrandrea ^{73a,73b}, A. Mastroberardino ^{43b,43a}, R. Mastrofrancesco ^{72a,72b}, T. Masubuchi ¹²⁵,
 T.T. Mathew ¹²⁴, J. Matousek ¹³⁴, D.M. Mattern ⁴⁸, K. Mauer ⁴⁷, J. Maurer ^{28b}, T. Maurin ⁵⁸,
 B. Maček ⁹³, C. Mavungu Tsava ¹⁰², A.E. May ¹⁰¹, E. Mayer ⁴⁰, R. Mazini ^{34j}, S.M. Mazza ¹³⁷,
 E. Mazzeo ³⁷, J.P. Mc Gowan ¹⁶⁷, S.P. Mc Kee ¹⁰⁶, C.C. McCracken ¹⁶⁶, E.F. McDonald ¹⁰⁵,
 L.F. Mcelhinney ⁹¹, J.A. Mcfayden ¹⁴⁹, R.P. McGovern ¹⁶⁷, R.P. Mckenzie ^{34j},
 D.J. McLaughlin ⁹⁶, S.J. McMahon ¹³⁵, C.M. Mcpartland ⁹², R.A. McPherson ^{167,ab},
 S. Mehlhase ¹⁰⁹, A. Mehta ⁹², D. Melini ¹⁶⁵, B.R. Mellado Garcia ^{14,ah}, A.H. Melo ⁵⁴,
 F. Meloni ⁴⁷, A.M. Mendes Jacques Da Costa ¹⁰¹, L. Meng ⁹¹, S. Menke ¹¹⁰, M. Mentink ³⁷,
 E. Meoni ^{43b,43a}, G. Mercado ¹¹⁷, S. Merianos ¹⁵⁵, C. Merlassino ^{68a,68c}, C. Meroni ^{70a,70b},
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 Y. Miao ^{112a}, R.P. Middleton ¹³⁵, M. Mihovilovic ⁶⁵, L. Mijović ⁵¹, G. Mikenberg ¹⁷¹,
 M. Mikestikova ¹³², M. Mikuž ⁹³, H. Mildner ¹⁰⁰, A. Milic ³⁷, D.W. Miller ³⁹, E.H. Miller ¹⁴⁶,
 A. Milov ¹⁷¹, D.A. Milstead ^{46a,46b}, T. Min ^{112a}, I.A. Minashvili ^{152b}, A.I. Mincer ¹¹⁸, B. Mindur ^{85a},
 M. Mineev ³⁸, L.M. Mir ¹³, M. Miralles Lopez ⁵⁸, M. Mironova ^{18a}, M. Missio ⁴⁰, A. Mitra ¹⁶⁹,
 V.A. Mitsou ¹⁶⁵, P.S. Miyagawa ⁹⁴, R. Mizuhiki ⁸⁴, T. Mkrtchyan ³⁷, M. Mlinarevic ⁹⁶,
 T. Mlinarevic ⁹⁶, M. Mlynarikova ¹³⁴, L. Mlynarska ^{85a}, C. Mo ^{141a}, H. Mobius ⁴⁷,
 S. Mobius ²⁰, M.H. Mohamed Farook ¹¹⁴, S. Mohapatra ⁴¹, M.F. Mohd Soberi ⁵¹,
 S. Mohiuddin ¹²², G. Mokgatitswane ^{34j}, R. Mole ²¹, L. Moleri ¹⁷¹, U. Molinatti ¹²⁷,
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 F. Montekali ^{76a,76b}, F. Monticelli ⁹⁰, S. Monzani ^{68a,68c}, M.E.E. Moors ²⁵,
 A. Morancho Tarda ⁴², N. Morange ⁶⁵, M. Moreno Llácer ¹⁶⁵, C. Moreno Martinez ⁵⁵,
 J.M. Moreno Perez ^{23b}, P. Morettini ^{56b}, S. Morgenstern ^{62a}, M. Morii ⁶⁰, M. Morinaga ¹⁵⁶,
 F. Morodei ^{74a,74b}, P. Moschovakos ³⁷, B. Moser ⁵³, M. Mosidze ^{152b}, T. Moskalets ⁴⁴,
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 Y. Moyal ^{171,k}, H. Moyano Gomez ¹³, E.J.W. Moyse ¹⁰³, T.G. Mroz ⁸⁶, S. Muanza ¹⁰²,
 M. Mucha ²⁵, J. Mueller ¹³⁰, D. Muller ¹⁴⁴, G.A. Mullier ¹⁶³, A.J. Mullin ³³, J.J. Mullin ⁵⁰,
 A.C. Mullins ⁴⁴, A.E. Mulski ⁶⁰, D.P. Mungo ¹⁵⁸, D. Munoz Perez ¹²², F.J. Munoz Sanchez ¹⁰¹,
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M. Myska ¹³³, B.P. Nachman ¹⁴⁶, I.A. Nadas ^{28d}, K. Nagai ¹²⁷, K. Nagano ⁸², R. Nagasaka ¹⁵⁶,
J.L. Nagle ^{30,ao}, E. Nagy ¹⁰², A.M. Nairz ³⁷, T. Nakagawa ⁸⁷, Y. Nakahama ⁸², K. Nakamura ⁸²,
A. Nandi ^{62b}, H. Nanjo ¹²⁵, E.A. Narayanan ⁴⁴, Y. Narukawa ¹⁵⁶, L. Nasella ^{70a,70b}, S. Nasri ^{83c},
C. Nass ²⁵, G. Navarro ^{23a}, A. Nayaz ¹⁹, S. Nechaeva ^{24b,24a}, F. Nechansky ¹³², L. Nedic ¹²⁷,
A. Negri ^{72a,72b}, M. Negrini ^{24b}, C. Nellist ¹¹⁶, C. Nelson ¹⁰⁴, K. Nelson ¹⁰⁶, S. Nemecek ¹³²,
M. Nessi ^{37,g}, M.S. Neubauer ¹⁶⁴, J. Newell ⁹², P.R. Newman ²¹, Y.W.Y. Ng ¹⁶⁴, B. Ngair ^{83b},
H.D.N. Nguyen ¹⁰⁸, J.D. Nichols ¹²¹, R. Nicolaidou ¹³⁶, J. Nielsen ¹³⁷, M. Niemeyer ⁵⁴,
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D. Nishimura ¹⁵⁶, R. Nisius ¹¹⁰, N. Nitika ¹⁷¹, E.K. Nkadimeng ^{34b}, T. Nobe ¹⁵⁶, D. Noll ¹⁴⁶,
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T. Novak ⁹³, P. Novotny ¹⁷¹, R. Novotny ¹³³, L. Nozka ¹²³, K. Ntekas ³⁷, D. Ntounis ¹⁴⁶,
N.M.J. Nunes De Moura Junior ^{81b}, J. Ocariz ¹²⁸, I. Ochoa ^{131a}, A. Odella Rodriguez ¹³,
S. Oerdek ⁴⁷, J.T. Offermann ³⁹, A. Ogrodnik ⁸⁶, A. Oh ¹⁰¹, C.C. Ohm ¹⁴⁷, H. Oide ⁸²,
M.L. Ojeda ³⁷, Y. Okumura ¹⁵⁶, L.F. Oleiro Seabra ^{131a}, I. Oleksiyuk ⁵⁵, G. Oliveira Correa ¹³,
D. Oliveira Damazio ³⁰, J.L. Oliver ¹, R. Omar ⁶⁷, A.P. O'Neill ²⁰, Y. Onoda ¹³⁹,
A. Onofre ^{131a,131e,e}, P.U.E. Onyisi ¹¹, M.J. Oreglia ³⁹, D. Orestano ^{76a,76b}, R. Orlandini ^{76a,76b},
R.S. Orr ¹⁵⁸, L.M. Osojnak ⁴¹, Y. Osumi ¹¹¹, G. Otero y Garzón ³¹, H. Otono ⁸⁸,
M. Ouchrif ^{36d}, F. Ould-Saada ¹²⁶, T. Ovsianikova ¹⁴⁰, M. Owen ⁵⁸, R.E. Owen ¹³⁵,
S.A. Oyeniran ¹¹⁴, V.E. Ozcan ^{22a}, F. Ozturk ⁸⁶, N. Ozturk ⁸, S. Ozturk ⁸⁰, H.A. Pacey ¹²⁷,
K. Pachal ^{159a}, A. Pacheco Pages ¹³, C. Padilla Aranda ¹³, G. Padovano ^{74a,74b},
S. Pagan Griso ^{18a}, L. Pagani ^{75a,75b}, J. Pampel ²⁵, D.K. Panchal ¹¹, C.E. Pandini ⁵⁹,
J.G. Panduro Vazquez ¹³⁵, H.D. Pandya ¹, H. Pang ¹³⁶, P. Pani ⁴⁷, G. Panizzo ^{68a,68c},
L. Panwar ^{128,w}, L. Paolozzi ²¹, S. Parajuli ¹⁶⁴, A. Paramonov ⁶, C. Paraskevopoulos ⁵²,
D. Paredes Hernandez ^{63b}, S.R. Paredes Saenz ⁵¹, A. Pareti ^{72a,72b}, K.R. Park ⁴¹, T.H. Park ¹¹⁰,
F. Parodi ^{56b,56a}, J.A. Parsons ⁴¹, J.A. Partridge ¹³⁷, U. Parzefall ⁵³, B.A. Paschen ^{18a},
B. Pascual Dias ⁴⁰, L. Pascual Dominguez ⁹⁹, E. Pasqualucci ^{74a}, S. Passaggio ^{56b}, F. Pastore ⁹⁵,
P. Patel ⁸⁶, U.M. Patel ⁵⁰, J.R. Pater ¹⁰¹, T. Pauly ³⁷, A. Paunovic ¹⁶, F. Pauwels ¹³⁴,
C.I. Pazos ¹⁶¹, M. Pedersen ¹²⁶, R. Pedro ^{131a}, O. Penc ¹³², C.C. Penelaud ¹²⁸, S. Peng ¹⁵,
G.D. Penn ¹⁷⁴, B.S. Peralva ^{81d}, A.P. Pereira Peixoto ¹⁴⁰, L. Pereira Sanchez ¹⁴⁶,
D.V. Perepelitsa ^{30,ao}, G. Perera ¹⁰³, E. Perez Codina ³⁷, M. Perganti ¹⁰, H. Pernegger ³⁷,
S. Perrella ^{74a,74b}, K. Peters ⁴⁷, R.F.Y. Peters ¹⁰¹, B.A. Petersen ³⁷, T.C. Petersen ⁴², E. Petit ¹⁰²,
V. Petousis ¹³³, A.R. Petri ^{70a,70b}, V.A. Petrovic ⁹⁶, T. Petru ¹³⁴, M. Pettee ^{18a}, A. Petukhov ⁸⁰,
K. Petukhova ³⁷, R. Pezoa ^{138g}, L. Pezzotti ^{24b,24a}, G. Pezzullo ¹⁷⁴, L. Pfaffenbichler ³⁷,
A.J. Pflieger ⁷⁸, T.M. Pham ¹⁷², T. Pham ¹⁰⁵, P.W. Phillips ¹³⁵, G. Piacquadio ¹⁴⁸, E. Pianori ^{18a},
F. Piazza ¹²⁴, R. Piegai ³¹, D. Pietreanu ^{28b}, A.D. Pilkington ¹⁰¹, T. Pilusa ^{34j},
M. Pinamonti ^{68a,68c}, J.L. Pinfeld ², G. Pinheiro Matos ⁴¹, B.C. Pinheiro Pereira ^{131a},
J. Pinol Bel ¹³, A.E. Pinto Pinoargote ¹²⁸, L. Pintucci ^{68a,68c}, K.M. Piper ¹⁴⁹, A. Pirttikoski ⁵⁵,
D.A. Pizzi ³⁵, L. Pizzimento ^{63b}, A. Plebani ³³, M.-A. Pleier ³⁰, V. Pleskot ¹³⁴, E. Plotnikova ³⁸,
G. Poddar ⁹⁴, R. Poettgen ⁹⁸, L. Poggioli ¹²⁸, S. Polacek ¹³⁴, G. Polesello ^{72a}, A. Poley ¹⁴⁵,
A. Polini ^{24b}, C.S. Pollard ¹⁶⁹, Z.B. Pollock ¹²⁰, E. Pompa Pacchi ¹²¹, N.I. Pond ⁹⁶,
D. Ponomarenko ⁶⁷, L. Pontecorvo ³⁷, S. Popa ^{28a}, G.A. Popeneciu ^{28d}, A. Poreba ³⁷,
A. Portentoso ^{70b}, D.M. Portillo Quintero ^{159a}, S. Pospisil ¹³³, M.A. Postill ¹⁴², P. Postolache ^{28c},
K. Potamianos ¹⁶⁹, P.A. Potepa ^{85a}, I.N. Potrap ³⁸, C.J. Potter ³³, H. Potti ¹⁵⁰, J. Poveda ¹⁶⁵,
M.E. Pozo Astigarraga ³⁷, R. Pozzi ³⁷, A. Prades Ibanez ^{75a,75b}, S.R. Pradhan ¹⁴², J. Preston ⁹⁵,
J. Pretel ¹⁶⁷, D. Price ¹⁰¹, M. Primavera ^{69a}, L. Primomo ^{68a,68c}, M.A. Principe Martin ⁹⁹,
R. Privara ¹²³, T. Procter ^{85b}, M.L. Proffitt ¹⁴⁰, N. Proklova ¹²⁹, K. Prokofiev ^{63c}, G. Proto ¹¹⁰,
J. Proudfoot ⁶, M. Przybycien ^{85a}, W.W. Przygoda ^{85b}, A. Psallidas ⁴⁵, D. Pudzha ⁵², P. Puhl ⁵⁷,

H.I. Purnell ¹, D. Pyatiizbyantseva ¹¹⁵, J. Qian ¹⁰⁶, R. Qian ¹⁰⁷, D. Qichen ¹²⁷, Y. Qin ¹³,
 T. Qiu ⁵¹, A. Quadt ⁵⁴, M. Queitsch-Maitland ¹⁰¹, G. Quetant ⁵⁵, R.P. Quinn ¹⁶⁶,
 D. Rafanoharana ¹¹⁰, J.L. Rainbolt ³⁹, S. Rajagopalan ³⁰, E. Ramakoti ³⁸, L. Rambelli ^{56b,56a},
 I.A. Ramirez-Berend ³⁵, K. Ran ^{106,112c}, S.D. Randles ⁹², D.S. Rankin ¹²⁹, N.P. Rapheeha ^{34j},
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 M. Raymond ³⁷, A.L. Read ¹²⁶, N.P. Readioff ¹⁴², D.M. Rebuzzi ^{72a,72b}, A.S. Reed ⁵⁸,
 K. Reeves ²⁷, D. Reikher ³⁷, T. Reisch ⁵⁵, A. Rej ⁴⁸, H. Ren ⁶¹, M. Renda ^{28b}, F. Renner ⁴⁷,
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 S. Rettie ¹¹⁶, W.F. Rettie ³⁵, M.M. Revering ³³, O.L. Rezanova ³⁸, P. Reznicek ¹³⁴, H. Riani ^{36d},
 N. Ribaric ³⁷, B. Ricci ^{68a,68c}, E. Ricci ^{77a,77b}, R. Richter ¹¹⁰, E. Richter-Was ^{85b}, M. Ridel ¹²⁸,
 S. Ridouani ^{36d}, P. Riedler ³⁷, E.M. Riefel ^{46a,46b}, J.O. Rieger ¹¹⁶, M. Rimoldi ^{34c},
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 Y. Rodriguez Garcia ^{23a}, A.M. Rodríguez Vera ¹¹⁷, S. Roe ³⁷, J.T. Roemer ³⁷, O. Røhne ¹²⁶,
 R.A. Rojas ³⁷, Z. Rokavec ⁹³, C.P.A. Roland ¹²⁸, A. Romaniouk ⁷⁸, E. Romano ^{72a,72b},
 M. Romano ^{24b}, N. Rompotis ⁹², L. Roos ¹²⁸, S. Rosati ^{74a}, L. Roscher ⁴⁷, B.J. Rosser ³⁹,
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 R. Roth ³⁷, F.A. Rothen ⁵⁵, D. Rousseau ⁶⁵, D. Rousso ⁴⁷, S. Roy-Garand ⁵⁵, A. Rozanov ¹⁰²,
 Z.M.A. Rozario ⁵⁸, Y. Rozen ¹⁵³, A. Rubio Jimenez ¹⁶⁵, V.H. Ruelas Rivera ¹⁹, T.A. Ruggeri ¹,
 A. Ruggiero ¹²⁷, A. Ruiz-Martinez ¹⁶⁵, A. Rummler ³⁷, G.B. Rupnik Boero ³⁷,
 N.A. Rusakovich ³⁸, S. Ruscelli ⁴⁸, H.L. Russell ¹⁶⁷, G. Russo ¹³⁷, J.P. Rutherford ⁷,
 S. Rutherford Colmenares ¹¹⁸, M. Rybar ¹³⁴, P. Rybczynski ^{85a}, A. Ryzhov ⁴⁴, M.A.E. Saadawy ⁴⁴,
 F. Safai Tehrani ^{74a}, S. Saha ¹, B. Sahoo ¹⁷¹, B.T. Saifuddin ¹²¹, M. Saimpert ¹³⁶,
 I. Sainz Saenz Diez ^{62a}, G.T. Saito ^{81c}, M. Saito ¹⁵⁶, T. Saito ¹⁵⁶, A. Sala ^{70a,70b}, O.T. Salin ⁶⁵,
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 D. Sammel ⁵³, E. Sampson ⁹¹, D. Sampsonidis ^{155,d}, D. Sampsonidou ¹²⁴, M.A.A. Samy ⁵⁸,
 J. Sánchez ¹⁶⁵, H. Sandaker ¹²⁶, C.O. Sander ⁴⁷, J.A. Sandesara ¹⁷², M. Sandhoff ¹⁷³,
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 M. Santana Queiroz ^{18b}, L. Santi ³⁷, C. Santoni ⁴⁰, G. Santoro ^{43b,43a}, H. Santos ^{131a,131b},
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 M.A. Schmidt ¹⁷³, K. Schmieden ²⁵, C. Schmitt ¹⁰⁰, N. Schmitt ¹⁰⁰, S. Schmitt ⁴⁷,
 N.A. Schneider ¹⁰⁹, L. Schoeffel ¹³⁶, A. Schoening ^{62b}, P.G. Scholer ³⁵, E. Schopf ¹⁴⁴,
 M. Schott ²⁵, S. Schramm ⁵⁵, T. Schroer ⁵⁵, H-C. Schultz-Coulon ^{62a}, M. Schumacher ⁵³,
 B.A. Schumm ¹³⁷, Ph. Schune ¹³⁶, H.R. Schwartz ⁷, A. Schwartzman ¹⁴⁶, T.A. Schwarz ¹⁰⁶,
 Ph. Schwemling ¹³⁶, R. Schwienhorst ¹⁰⁷, F.G. Sclacca ²⁰, A. Sciandra ³⁰, G. Sciolla ²⁷,
 S.A. Scoville ¹³⁰, F. Scuri ^{73a}, C.D. Sebastiani ³⁷, K. Sedlaczek ¹¹⁷, S. Seguni ^{70b},
 A. Sehwat ^{138b}, S.C. Seidel ¹¹⁴, B.D. Seidlitz ⁴¹, C. Seitz ⁴⁷, J.M. Seixas ^{81b},
 G. Sekhniaidze ^{71a}, L. Selem ¹²⁸, N. Semprini-Cesari ^{24b,24a}, A. Semushin ¹⁷⁵,
 V. Senthilkumar ¹¹⁶, L. Serin ⁶⁵, M. Sessa ^{71a,71b}, H. Severini ¹²¹, F. Sforza ^{56b,56a}, A. Sfyrla ⁵⁵,
 Q. Sha ¹⁴, H. Shaddix ¹¹⁷, A.H. Shah ³³, R. Shaheen ¹⁴⁷, J.D. Shahinian ¹²⁹, M. Shamim ³⁷,

L.Y. Shan ¹⁴, M. Shapiro ^{18a}, A. Sharma ³⁷, A.S. Sharma ¹⁶⁶, P. Sharma ³⁰, K. Shaw ¹⁴⁹,
 S.M. Shaw ¹⁰¹, D. Shemyakin ¹⁷¹, Q. Shen ¹⁴, D.J. Sheppard ¹⁴⁵, P. Sherwood ⁹⁶, L. Shi ^{112b},
 X. Shi ¹⁴, E.B. Shields ¹⁷¹, S. Shimizu ⁸², S. Shirabe ⁸⁸, M. Shiyakova ^{38,z}, M.J. Shochet ³⁹,
 D.R. Shope ¹²⁶, S. Shrestha ^{120,aq}, I. Shreyber ³⁸, M.J. Shroff ¹⁰⁴, P. Sicho ¹³², A.M. Sickles ¹⁶⁴,
 E. Sideras Haddad ^{34j}, A.C. Sidley ¹¹⁶, A. Sidoti ^{24b}, F. Siegert ⁴⁹, Dj. Sijacki ¹⁶, F. Sili ⁶¹,
 J.M. Silva ⁵¹, I. Silva Ferreira ^{81b}, M.V. Silva Oliveira ³⁰, S.B. Silverstein ^{46a}, S. Simion ⁶⁵,
 R. Simoniello ³⁷, E.L. Simpson ¹⁰¹, H. Simpson ¹⁴⁹, L.R. Simpson ⁶, S. Simsek ⁸⁰,
 S.N. Singh ²⁷, S. Singh ³⁰, S. Sinha ⁴⁷, S. Sinha ¹⁰¹, M. Sioli ^{24b,24a}, K. Sioulas ⁹,
 E. Sitnikova ⁴⁷, J. Sjölin ^{46a,46b}, A. Skaf ⁵⁴, E. Skorda ²¹, P. Skubic ¹²¹, M. Slawinska ⁸⁶,
 I. Slazyk ¹⁷, I. Sliusar ¹²⁶, V. Smakhtin ¹⁷¹, B.H. Smart ¹³⁵, S.Yu. Smirnov ^{138b}, Y. Smirnov ^{34c},
 O. Smirnova ⁹⁸, J.L. Smith ¹⁰¹, M.B. Smith ³⁵, R. Smith ¹⁴⁶, H. Smitmanns ¹⁰⁰, M. Smizanska ⁹¹,
 K. Smolek ¹³³, P. Smolyanskiy ¹³³, A.A. Snesarev ³⁸, H.L. Snoek ¹¹⁶, R.M. Snyder ⁵⁰,
 S. Snyder ³⁰, R. Sobie ^{167,ab}, A. Soffer ¹⁵⁴, C.A. Solans Sanchez ³⁷, E.Yu. Soldatov ³⁸,
 U. Soldevila ¹⁶⁵, A.A. Solodkov ^{34j}, S. Solomon ²⁷, A. Soloshenko ³⁸, O.V. Solovyanov ⁴⁰,
 P. Sommer ⁴⁹, A. Sopczak ¹³³, A.L. Sopio ⁵¹, F. Sopkova ^{29b}, J.D. Sorenson ¹¹⁴,
 I.R. Sotarriva Alvarez ¹³⁹, V. Sothilingam ^{62a}, O.J. Soto Sandoval ^{138c,138b}, S. Sottocornola ⁶⁷,
 R. Soualah ^{83a}, D. South ⁴⁷, N. Soybelman ¹⁷¹, S. Spagnolo ^{69a,69b}, A.S. Spellman ¹²⁴,
 D. Sperlich ⁵³, B. Spisso ^{71a,71b}, L. Splendori ¹⁰², M. Spousta ¹³⁴, E.J. Staats ³⁵, R. Stamen ^{62a},
 E. Stanecka ⁸⁶, W. Stanek-Maslouska ⁴⁷, M.V. Stange ⁴⁹, B. Stanislaus ^{18a}, M.M. Stanitzki ⁴⁷,
 G.H. Stark ¹³⁷, J. Stark ⁸⁹, P. Staroba ¹³², P. Starovoitov ^{83d}, R. Staszewski ⁸⁶, C. Stauch ¹⁰⁹,
 G. Stavropoulos ⁴⁵, A. Stefl ³⁷, A. Stein ¹⁰⁰, P. Steinberg ³⁰, B. Stelzer ^{145,159a}, H.J. Stelzer ¹³⁰,
 O. Stelzer ^{159a}, H. Stenzel ⁵⁷, T.J. Stevenson ¹⁴⁹, G.A. Stewart ⁴⁷, G. Stoicea ^{28b},
 M. Stolarski ^{131a}, S. Stonjek ¹¹⁰, A. Straessner ⁴⁹, J. Strandberg ¹⁴⁷, S. Strandberg ^{46a,46b},
 M. Stratmann ¹⁷³, M. Strauss ¹²¹, T. Strebler ¹⁰², P. Strizenec ^{29b}, R. Ströhmer ¹⁶⁸,
 D.M. Strom ¹²⁴, R. Stroynowski ⁴⁴, A. Strubig ^{46a,46b}, S.A. Stucci ³⁰, B. Stugu ¹⁷, J. Stupak ¹²¹,
 N.A. Styles ⁴⁷, D. Su ¹⁴⁶, S. Su ⁶¹, X. Su ⁶¹, D. Suchy ^{29a}, A.D. Sudhakar Ponnu ⁵⁴,
 L. Sudit ¹⁷¹, Y. Sue ⁸², K. Sugizaki ¹²⁹, D.M.S. Sultan ¹²⁷, L. Sultanaliyeva ²⁵, S. Sultansoy ^{3b},
 S. Sun ¹⁷², W. Sun ¹⁴, S. Sundar Raman ¹⁶⁶, N. Sur ⁹⁸, J.P. Surdutovich ¹²⁰, N. Suri Jr ¹⁷⁴,
 M.R. Sutton ¹⁴⁹, M. Svatos ¹³², P.N. Swallow ³³, S.N. Swatman ³⁷, M. Swiatlowski ^{159a},
 A. Swoboda ³⁷, I. Sykora ^{29a}, M. Sykora ¹³⁴, T. Sykora ¹³⁴, D. Ta ¹⁰⁰, K. Tackmann ^{47,y},
 A. Taffard ¹⁶², R. Tafirot ^{159a}, Y. Takubo ⁸², M. Talby ¹⁰², N.M. Tamir ¹⁵⁴, A. Tanaka ¹⁵⁶,
 J. Tanaka ¹⁵⁶, R. Tanaka ⁶⁵, M. Tanasini ¹⁴⁸, Z. Tao ¹⁶⁶, S. Tapia Araya ^{138g}, S. Tapprogge ¹⁰⁰,
 A. Tarek Abouelfadl Mohamed ³⁷, S. Tarem ¹⁵³, K. Tariq ¹⁴, G. Tarna ³⁷, G.F. Tartarelli ^{70a},
 M.J. Tartarin ^{141b}, P. Tas ¹³⁴, M. Tasevsky ¹³², E. Tassi ^{43b,43a}, A.C. Tate ¹⁶⁴, Y. Tayalati ^{36e,aa},
 G.N. Taylor ¹⁰⁵, W. Taylor ^{159b}, R.J. Taylor Vara ¹⁶⁵, A.S. Tegetmeier ⁸⁹, P. Teixeira-Dias ⁹⁵,
 J.J. Teoh ¹⁵⁸, K. Terashi ¹⁵⁶, J. Terron ⁹⁹, S. Terzo ¹³, M. Testa ⁵², R.J. Teuscher ^{158,ab},
 A. Thaler ⁷⁸, T. Thevenaux-Pelzer ¹⁰², J.P. Thomas ²¹, E.A. Thompson ^{18a}, P.D. Thompson ²¹,
 E. Thomson ¹²⁹, R.E. Thornberry ³⁰, T.M. Thory-Rao ²¹, C.N. Thotamuna Wijewardhana ¹⁴⁸,
 C. Tian ⁶¹, Y. Tian ⁵⁵, V. Tikhomirov ⁸⁰, Yu.A. Tikhonov ³⁸, D. Timoshyn ¹³⁴, E.X.L. Ting ¹,
 P. Tipton ¹⁷⁴, A. Tishelman-Charny ³⁰, K. Todome ¹³⁹, S. Todorova-Nova ¹³⁴, L. Toffolin ^{68a,68c},
 M. Togawa ⁸², J. Tojo ⁸⁸, S. Tokár ^{29a}, O. Toldaiev ⁶⁷, A.J. Toler ¹⁰³, G. Tolkachev ¹⁰²,
 M. Tomoto ⁸², L. Tompkins ¹⁴⁶, E. Torrence ¹²⁴, H. Torres ⁸⁹, D.I. Torres Arza ^{138g},
 E. Torres Reoyo ¹⁶⁵, E. Torró Pastor ¹⁶⁵, M. Toscani ³¹, C. Tosciri ³⁹, M. Tost ¹¹, D.R. Tovey ¹⁴²,
 T. Trefzger ¹⁶⁸, P.M. Tricarico ¹³, A. Tricoli ³⁰, I.M. Trigger ^{159a}, S. Trincaz-Duvold ¹²⁸,
 D.A. Trischuk ¹⁶⁷, A. Tropina ³⁸, D. Truncali ^{75a,75b}, L. Truong ^{34c}, M. Trzebinski ⁸⁶,
 A. Trzupek ⁸⁶, F. Tsai ¹⁴⁸, A. Tsiamis ¹⁵⁵, P.V. Tsiareshka ³⁸, S. Tsigaridas ^{159a}, A. Tsirigotis ^{155,t},
 V. Tsiskaridze ^{152a}, E.G. Tskhadadze ^{152a}, H.F. Tsoi ¹²⁹, Y. Tsujikawa ⁸⁷, V. Tsulaia ^{18a},

K. Tsuru ¹¹⁹, D. Tsybychev ¹⁴⁸, Y. Tu ^{63b}, A. Tudorache ^{28b}, V. Tudorache ^{28b}, S.B. Tuncay ¹²⁷, S. Turchikhin ^{56b,56a}, I. Turk Cakir ^{3a}, R. Turra ^{70a}, T. Turtuvshin ^{38,ac}, P.M. Tuts ⁴¹, M. Ubaldi ¹⁴⁹, Y. Uematsu ⁸², F. Ukegawa ¹⁶⁰, P.A. Ulloa Poblete ^{138c,138b}, G. Unal ³⁷, A. Undrus ³⁰, J. Urban ^{29b}, P. Urrejola ^{138e}, G. Usai ⁸, R. Ushioda ¹⁵⁷, M. Usman ¹⁰⁸, F. Ustuner ⁵¹, Z. Uysal ⁸⁰, V. Vacek ¹³³, B. Vachon ¹⁰⁴, A. Vaitkus ⁹⁶, C. Valderanis ¹⁰⁹, E. Valdes Santurio ^{46a,46b}, M. Valente ³⁷, S. Valentinetti ^{24b,24a}, A. Valero ¹⁶⁵, E. Valiente Moreno ¹⁶⁵, A. Vallier ⁸⁹, J.A. Valls Ferrer ¹⁶⁵, D.R. Van Arneman ¹¹⁶, R. Van Den Broucke ¹²⁸, A. Van Der Graaf ⁴⁸, H.Z. Van Der Schyf ^{34j}, P. Van Gemmeren ⁶, M. Van Rijnbach ³⁷, S. Van Stroud ⁹⁶, I. Van Vulpen ¹¹⁶, P. Vana ¹³⁴, M. Vanadia ^{75a,75b}, U.M. Vande Voorde ¹⁴⁷, W. Vandelli ³⁷, E.R. Vandewall ¹⁴⁶, D. Vannicola ¹⁵⁴, R. Vari ^{74a}, M. Varma ¹⁷⁴, E.W. Varnes ⁷, C. Varni ^{85a}, D. Varouchas ⁶⁵, L. Varriale ¹⁶⁵, K.E. Varvell ¹⁵⁰, M.E. Vasile ^{28b}, A. Vasileiadou ⁹, L. Vaslin ⁸², M.D. Vassilev ¹⁴⁶, A. Vasyukov ³⁸, L.M. Vaughan ¹²², R. Vavricka ¹³⁴, T. Vazquez Schroeder ¹³, J. Veatch ³², V. Vecchio ¹⁰¹, M.J. Veen ¹⁰³, I. Veliscek ³⁰, I. Velkovska ⁹³, L.M. Veloce ¹⁵⁸, F. Veloso ^{131a,131c}, A.G. Veltman ⁵¹, S.H. Venetianer ¹⁶¹, S. Veneziano ^{74a}, A. Ventura ^{69a,69b}, A. Verbytskyi ¹¹⁰, M. Verducci ^{73a,73b}, C. Vergis ⁹⁴, M. Verissimo De Araujo ^{81b}, W. Verkerke ¹¹⁶, J.C. Vermeulen ¹¹⁶, C. Vernieri ¹⁴⁶, M. Vessella ¹⁶², M.C. Vetterli ^{145,aj}, A. Vgenopoulos ¹⁰⁰, N. Viaux Maira ^{138g,af}, L. Vicenik ¹³³, T. Vickey ¹⁴², O.E. Vickey Boeriu ¹⁴², G.H.A. Viehhauser ¹²⁷, L. Vigani ^{62b}, M. Vigi ¹¹⁰, M. Villa ^{24b,24a}, M. Villaplana Perez ¹⁶⁵, E.M. Villhauer ³⁹, E. Vilucchi ⁵², M. Vincent ¹⁶⁵, M.G. Vincter ³⁵, A. Visibile ¹¹⁶, A. Visive ¹¹⁶, C. Vittori ^{24b,24a}, I. Vivarelli ^{24b,24a}, M.I. Vivas Alborno ⁴⁷, E. Voevodina ¹¹⁰, F. Vogel ¹⁰⁹, J.C. Voigt ⁴⁹, P. Vokac ¹³³, Yu. Volkotrub ^{85b}, L. Vomberg ²⁵, E. Von Toerne ²⁵, B. Vormwald ³⁷, K. Vorobev ⁵⁰, M. Vos ¹⁶⁵, K. Voss ¹⁴⁴, M. Vozak ³⁷, L. Vozdecky ¹²¹, N. Vranjes ¹⁶, M. Vranjes Milosavljevic ¹⁶, M. Vreeswijk ¹¹⁶, N.K. Vu ^{112a}, R. Vuillermet ³⁷, I. Vukotic ³⁹, I.K. Vyas ³⁵, J.F. Wack ³³, A. Wada ¹¹¹, S. Wada ¹⁶⁰, C. Wagner ¹⁴⁶, J.M. Wagner ^{18a}, W. Wagner ¹⁷³, S. Wahdan ¹⁷³, H. Wahlberg ⁹⁰, C.H. Waits ¹²¹, J. Walder ¹³⁵, R. Walker ¹⁰⁹, K. Walkingshaw Pass ⁵⁸, W. Walkowiak ¹⁴⁴, A. Wall ¹²⁹, E.J. Wallin ⁹⁸, T. Wamorkar ¹⁴⁶, K. Wandall-Christensen ¹⁶⁵, A. Wang ⁶¹, A.Z. Wang ¹³⁷, C. Wang ⁴⁷, C. Wang ¹¹, H. Wang ^{18a}, J. Wang ^{63c}, P. Wang ¹⁰¹, P. Wang ⁹⁶, R. Wang ⁶⁰, R. Wang ¹⁰⁶, R. Wang ⁶, S.M. Wang ¹⁵¹, S. Wang ^{14,an}, T. Wang ¹¹⁵, T. Wang ⁶¹, W.T. Wang ¹²⁷, W. Wang ^{113c}, X. Wang ¹⁶⁴, X. Wang ^{141a}, X. Wang ⁴⁷, Y. Wang ¹⁴⁸, Y. Wang ¹¹⁴, Z. Wang ¹⁴, Z. Wang ^{63b}, C. Wanotayaroj ⁸², A. Warburton ¹⁰⁴, A.L. Warnerbring ¹⁴⁴, S. Waterhouse ⁹⁶, A.T. Watson ²¹, H. Watson ⁵¹, M.F. Watson ²¹, E. Watton ³⁷, G. Watts ¹⁴⁰, B.M. Waugh ⁹⁶, J.M. Webb ⁵³, C. Weber ³⁰, M.S. Weber ²⁰, C. Wei ⁶¹, Y. Wei ⁵³, A.R. Weidberg ¹²⁷, E.J. Weik ¹¹⁸, J. Weingarten ⁴⁸, C. Weiser ⁵³, C.J. Wells ⁴⁷, P.S. Wells ³⁷, T. Wenaus ³⁰, T. Wengler ³⁷, N.S. Wenke ¹¹⁰, N. Wermes ²⁵, D. Werner ⁴⁷, M. Wessels ^{62a}, A.M. Wharton ⁹¹, A.S. White ³⁷, A. White ⁸, M.J. White ¹, D. Whiteson ¹⁶², W. Wiedenmann ¹⁷², M. Wielers ¹³⁵, R. Wierda ¹⁴⁷, C. Wiglesworth ⁴², H.G. Wilkens ³⁷, J.J.H. Wilkinson ³³, S. Williams ³³, S. Willocq ¹⁰³, D.J. Wilson ¹⁰¹, P.J. Windischhofer ³⁹, F.I. Winkel ³¹, F. Winklmeier ¹²⁴, B.T. Winter ⁵³, M. Wittgen ¹⁴⁶, M. Wobisch ⁹⁷, T. Wojtkowski ⁵⁹, Z. Wolfs ¹¹⁶, J. Wollrath ³⁷, M.W. Wolter ⁸⁶, H. Wolters ^{131a,131c}, M.C. Wong ¹³⁷, E.L. Woodward ⁴¹, S.D. Worm ⁴⁷, B.K. Wosiek ⁸⁶, K.A. Wozniak ⁵⁵, K.W. Woźniak ⁸⁶, S. Wozniowski ⁵⁴, K. Wraight ⁵⁸, C. Wu ¹⁵⁸, J. Wu ¹⁵⁶, M. Wu ^{112b}, M. Wu ¹¹⁵, S.L. Wu ¹⁷², S. Wu ^{14,an}, X. Wu ⁶¹, Y.Q. Wu ¹⁵⁸, Y. Wu ⁶¹, Z. Wu ¹⁰², Z. Wu ^{112a}, J. Wuerzinger ¹¹⁰, T.R. Wyatt ¹⁰¹, B.M. Wynne ⁵¹, S. Xella ⁴², L. Xia ^{112a}, M. Xie ⁶¹, A. Xiong ¹²⁴, I. Xioidis ³⁷, D. Xu ¹⁴, H. Xu ⁶¹, L. Xu ⁶¹, R. Xu ¹²⁹, T. Xu ¹⁰⁶, W. Xu ^{112a}, Y. Xu ¹⁴⁰, Z. Xu ⁵¹, R. Xue ¹³⁰, B. Yabsley ¹⁵⁰, S. Yacoob ¹¹, Y. Yamaguchi ⁸², E. Yamashita ¹⁵⁶, H. Yamauchi ¹⁶⁰,

T. Yamazaki ^{18a}, Y. Yamazaki ⁸⁴, F. Yan ², S. Yan ⁵⁸, Z. Yan ¹⁰³, Z. Yan ^{141b}, C. Yang ^{18a}, H.J. Yang ^{141a}, H.T. Yang ⁶¹, S. Yang ⁶¹, X. Yang ³⁷, X. Yang ¹⁴, Y. Yang ¹⁵⁶, Y. Yang ⁶¹, W-M. Yao ^{18a}, C.L. Yardley ¹⁴⁹, J. Ye ¹⁴, S. Ye ³⁰, X. Ye ¹⁰⁶, I. Yeletsikh ³⁸, B. Yeo ^{18b}, M.R. Yexley ⁹⁶, T.P. Yildirim ¹²⁷, K. Yorita ¹⁵⁶, C.J.S. Young ³⁷, C. Young ¹⁴⁶, I.N.L. Young ⁵⁸, N.D. Young ¹²⁴, D. Yu ^{141b,5}, Y. Yu ⁶¹, J. Yuan ^{14,112c,an}, M. Yuan ¹⁰⁶, R. Yuan ^{141b}, L. Yue ⁹⁶, M. Zaazoua ⁶¹, B. Zabinski ⁸⁶, I. Zahir ^{36a}, Q.U.A. Zahoor ⁵¹, A. Zaio ^{56b,56a}, Z.K. Zak ⁸⁶, T. Zakareishvili ¹⁶⁵, S. Zambito ⁵⁵, J. Zang ¹⁵⁶, R. Zanzottera ^{70a,70b}, O. Zaplatilek ¹³³, I. Zatocilova ⁵³, E. Zaya ¹⁴⁷, C. Zeitnitz ¹⁷³, H. Zeng ¹⁴, D.T. Zenger Jr ²⁷, T. Ženiš ^{29a}, S. Zenz ⁹⁴, W. Zhan ⁶¹, B. Zhang ¹⁶⁹, D.F. Zhang ¹⁴², G. Zhang ^{14,an}, J. Zhang ^{113b}, J. Zhang ⁶, L. Zhang ⁶¹, L. Zhang ^{112a}, P. Zhang ^{14,112c}, R. Zhang ^{112a}, S. Zhang ¹⁴, Y. Zhang ¹⁴⁰, Y. Zhang ⁹⁶, Y. Zhang ⁶¹, Y. Zhang ^{112a}, Z. Zhang ¹⁴⁹, Z. Zhang ¹⁰¹, Z. Zhang ^{18a}, Z. Zhang ^{113b}, Z. Zhang ⁶⁵, H. Zhao ¹⁴⁰, T. Zhao ^{113b}, Y. Zhao ³⁵, Z. Zhao ⁶¹, Z. Zhao ⁶¹, A. Zhemchugov ³⁸, J. Zheng ^{112a}, K. Zheng ¹⁶⁴, L. Zheng ^{113b}, X. Zheng ⁶¹, Z. Zheng ¹⁴⁶, D. Zhong ¹⁶⁴, B. Zhou ¹⁰⁶, B. Zhou ^{141b,141a}, N. Zhou ^{141a}, Y. Zhou ¹⁵, Y. Zhou ^{112a}, Y. Zhou ⁷, Z. Zhou ⁶¹, J. Zhu ¹⁰⁶, X. Zhu ^{141b}, Y. Zhu ^{141a}, X. Zhuang ¹⁴, K. Zhukov ⁶⁷, P. Ziakas ⁴, N.I. Zimine ³⁸, J. Zinsser ^{62b}, M. Ziolkowski ¹⁴⁴, L. Živković ¹⁶, A. Zoccoli ^{24b,24a}, K. Zoch ³⁷, A. Zografos ³⁷, T.G. Zorbas ¹⁴², L. Zwalinski ³⁷.

¹Department of Physics, University of Adelaide, Adelaide; Australia.

²Department of Physics, University of Alberta, Edmonton AB; Canada.

^{3(a)}Department of Physics, Ankara University, Ankara; ^(b)Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.

⁴LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

⁵APC, Université Paris Cité, CNRS/IN2P3, Paris; France.

⁶High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.

⁷Department of Physics, University of Arizona, Tucson AZ; United States of America.

⁸Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.

⁹Physics Department, National and Kapodistrian University of Athens, Athens; Greece.

¹⁰Physics Department, National Technical University of Athens, Zografou; Greece.

¹¹Department of Physics, University of Texas at Austin, Austin TX; United States of America.

¹²Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

¹³Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.

¹⁴Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; China.

¹⁵Physics Department, Tsinghua University, Beijing; China.

¹⁶Institute of Physics, University of Belgrade, Belgrade; Serbia.

¹⁷Department for Physics and Technology, University of Bergen, Bergen; Norway.

^{18(a)}Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; ^(b)University of California, Berkeley CA; United States of America.

¹⁹Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.

²⁰Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.

²¹School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.

^{22(a)}Department of Physics, Bogazici University, Istanbul; ^(b)Department of Physics Engineering, Gaziantep University, Gaziantep; ^(c)Department of Physics, Istanbul University, Istanbul; Türkiye.

^{23(a)}Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; ^(b)Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.

- ^{24(a)}Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;^(b)INFN Sezione di Bologna; Italy.
- ²⁵Physikalisches Institut, Universität Bonn, Bonn; Germany.
- ²⁶Department of Physics, Boston University, Boston MA; United States of America.
- ²⁷Department of Physics, Brandeis University, Waltham MA; United States of America.
- ^{28(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)National University of Science and Technology Politehnica, Bucharest;^(f)West University in Timisoara, Timisoara;^(g)Faculty of Physics, University of Bucharest, Bucharest; Romania.
- ^{29(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.
- ³⁰Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
- ³¹Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.
- ³²California State University, CA; United States of America.
- ³³Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
- ^{34(a)}Department of Physics, University of Cape Town, Cape Town;^(b)iThemba Labs, Western Cape;^(c)Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;^(d)National Institute of Physics, University of the Philippines Diliman (Philippines);^(e)Department of Physics, Stellenbosch University, Matieland;^(f)University of KwaZulu-Natal, School of Agriculture and Science, Mathematics, Westville;^(g)University of South Africa, Department of Physics, Pretoria;^(h)University of Pretoria, Department of Mechanical and Aeronautical Engineering, Pretoria;⁽ⁱ⁾University of Zululand, KwaDlangezwa;^(j)School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
- ³⁵Department of Physics, Carleton University, Ottawa ON; Canada.
- ^{36(a)}Faculté des Sciences Ain Chock, Université Hassan II de Casablanca;^(b)Faculté des Sciences, Université Ibn-Tofail, Kénitra;^(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;^(d)LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda;^(e)Faculté des sciences, Université Mohammed V, Rabat;^(f)Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- ³⁷CERN, Geneva; Switzerland.
- ³⁸Affiliated with an international laboratory covered by a cooperation agreement with CERN.
- ³⁹Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
- ⁴⁰LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- ⁴¹Nevis Laboratory, Columbia University, Irvington NY; United States of America.
- ⁴²Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
- ^{43(a)}Dipartimento di Fisica, Università della Calabria, Rende;^(b)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
- ⁴⁴Physics Department, Southern Methodist University, Dallas TX; United States of America.
- ⁴⁵National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
- ^{46(a)}Department of Physics, Stockholm University;^(b)Oskar Klein Centre, Stockholm; Sweden.
- ⁴⁷Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- ⁴⁸Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany.
- ⁴⁹Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
- ⁵⁰Department of Physics, Duke University, Durham NC; United States of America.

- ⁵¹SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
- ⁵²INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
- ⁵³Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ⁵⁴II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- ⁵⁵Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ⁵⁶(^a) Dipartimento di Fisica, Università di Genova, Genova; (^b) INFN Sezione di Genova; Italy.
- ⁵⁷II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
- ⁵⁸SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- ⁵⁹LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
- ⁶⁰Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
- ⁶¹Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; China.
- ⁶²(^a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (^b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
- ⁶³(^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.
- ⁶⁴Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
- ⁶⁵IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
- ⁶⁶Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
- ⁶⁷Department of Physics, Indiana University, Bloomington IN; United States of America.
- ⁶⁸(^a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (^b) ICTP, Trieste; (^c) Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
- ⁶⁹(^a) INFN Sezione di Lecce; (^b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
- ⁷⁰(^a) INFN Sezione di Milano; (^b) Dipartimento di Fisica, Università di Milano, Milano; Italy.
- ⁷¹(^a) INFN Sezione di Napoli; (^b) Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
- ⁷²(^a) INFN Sezione di Pavia; (^b) Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
- ⁷³(^a) INFN Sezione di Pisa; (^b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- ⁷⁴(^a) INFN Sezione di Roma; (^b) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
- ⁷⁵(^a) INFN Sezione di Roma Tor Vergata; (^b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
- ⁷⁶(^a) INFN Sezione di Roma Tre; (^b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
- ⁷⁷(^a) INFN-TIFPA; (^b) Università degli Studi di Trento, Trento; Italy.
- ⁷⁸Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
- ⁷⁹Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
- ⁸⁰Istinye University, Sariyer, Istanbul; Türkiye.
- ⁸¹(^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) Instituto de Física, Universidade de São Paulo, São Paulo; (^d) Rio de Janeiro State University, Rio de Janeiro; (^e) Federal University of Bahia, Bahia; Brazil.
- ⁸²KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
- ⁸³(^a) Khalifa University of Science and Technology, Abu Dhabi; (^b) New York University Abu Dhabi, Abu Dhabi; (^c) United Arab Emirates University, Al Ain; (^d) University of Sharjah, Sharjah; United Arab Emirates.
- ⁸⁴Graduate School of Science, Kobe University, Kobe; Japan.

- ⁸⁵(^a) AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; (^b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
- ⁸⁶Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
- ⁸⁷Faculty of Science, Kyoto University, Kyoto; Japan.
- ⁸⁸Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
- ⁸⁹L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
- ⁹⁰Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
- ⁹¹Physics Department, Lancaster University, Lancaster; United Kingdom.
- ⁹²Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
- ⁹³Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
- ⁹⁴Department of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
- ⁹⁵Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
- ⁹⁶Department of Physics and Astronomy, University College London, London; United Kingdom.
- ⁹⁷Louisiana Tech University, Ruston LA; United States of America.
- ⁹⁸Fysiska institutionen, Lunds universitet, Lund; Sweden.
- ⁹⁹Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
- ¹⁰⁰Institut für Physik, Universität Mainz, Mainz; Germany.
- ¹⁰¹School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
- ¹⁰²CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- ¹⁰³Department of Physics, University of Massachusetts, Amherst MA; United States of America.
- ¹⁰⁴Department of Physics, McGill University, Montreal QC; Canada.
- ¹⁰⁵School of Physics, University of Melbourne, Victoria; Australia.
- ¹⁰⁶Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- ¹⁰⁷Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- ¹⁰⁸Group of Particle Physics, University of Montreal, Montreal QC; Canada.
- ¹⁰⁹Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
- ¹¹⁰Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
- ¹¹¹Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
- ¹¹²(^a) Department of Physics, Nanjing University, Nanjing; (^b) School of Science, Shenzhen Campus of Sun Yat-sen University; (^c) University of Chinese Academy of Science (UCAS), Beijing; China.
- ¹¹³(^a) School of Physics, Nankai University, Tianjin; (^b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; (^c) School of Physics, Zhengzhou University; China.
- ¹¹⁴Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
- ¹¹⁵Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
- ¹¹⁶Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
- ¹¹⁷Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
- ¹¹⁸Department of Physics, New York University, New York NY; United States of America.
- ¹¹⁹Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
- ¹²⁰Ohio State University, Columbus OH; United States of America.
- ¹²¹Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United

States of America.

¹²²Department of Physics, Oklahoma State University, Stillwater OK; United States of America.

¹²³Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.

¹²⁴Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.

¹²⁵Graduate School of Science, University of Osaka, Osaka; Japan.

¹²⁶Department of Physics, University of Oslo, Oslo; Norway.

¹²⁷Department of Physics, Oxford University, Oxford; United Kingdom.

¹²⁸LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.

¹²⁹Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.

¹³⁰Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.

¹³¹(^a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (^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, Escola de Ciências, Universidade do Minho, Braga; (^f) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); (^g) Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.

¹³²Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.

¹³³Czech Technical University in Prague, Prague; Czech Republic.

¹³⁴Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.

¹³⁵Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

¹³⁶IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.

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

¹³⁸(^a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (^b) Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; (^c) Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; (^d) Universidad Andres Bello, Department of Physics, Santiago; (^e) Universidad San Sebastian, Recoleta; (^f) Instituto de Alta Investigación, Universidad de Tarapacá, Arica; (^g) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

¹³⁹Department of Physics, Institute of Science, Tokyo; Japan.

¹⁴⁰Department of Physics, University of Washington, Seattle WA; United States of America.

¹⁴¹(^a) State Key Laboratory of Dark Matter Physics, School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; (^b) State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai; China.

¹⁴²Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

¹⁴³Department of Physics, Shinshu University, Nagano; Japan.

¹⁴⁴Department Physik, Universität Siegen, Siegen; Germany.

¹⁴⁵Department of Physics, Simon Fraser University, Burnaby BC; Canada.

¹⁴⁶SLAC National Accelerator Laboratory, Stanford CA; United States of America.

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

¹⁴⁸Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

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

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

¹⁵¹Institute of Physics, Academia Sinica, Taipei; Taiwan.

- ^{152(a)}E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;^(b)High Energy Physics Institute, Tbilisi State University, Tbilisi;^(c)University of Georgia, Tbilisi; Georgia.
- ¹⁵³Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
- ¹⁵⁴Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
- ¹⁵⁵Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
- ¹⁵⁶International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
- ¹⁵⁷Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.
- ¹⁵⁸Department of Physics, University of Toronto, Toronto ON; Canada.
- ^{159(a)}TRIUMF, Vancouver BC;^(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.
- ¹⁶⁰Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
- ¹⁶¹Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
- ¹⁶²Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
- ¹⁶³Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
- ¹⁶⁴Department of Physics, University of Illinois, Urbana IL; United States of America.
- ¹⁶⁵Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
- ¹⁶⁶Department of Physics, University of British Columbia, Vancouver BC; Canada.
- ¹⁶⁷Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
- ¹⁶⁸Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
- ¹⁶⁹Department of Physics, University of Warwick, Coventry; United Kingdom.
- ¹⁷⁰Waseda University, Tokyo; Japan.
- ¹⁷¹Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.
- ¹⁷²Department of Physics, University of Wisconsin, Madison WI; United States of America.
- ¹⁷³Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
- ¹⁷⁴Department of Physics, Yale University, New Haven CT; United States of America.
- ¹⁷⁵Yerevan Physics Institute, Yerevan; Armenia.
- ^a Also at Affiliated with an institute formerly covered by a cooperation agreement with CERN.
- ^b Also at An-Najah National University, Nablus; Palestine.
- ^c Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
- ^d Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
- ^e Also at Centre of Physics of the Universities of Minho and Porto (CF-UM-UP); Portugal.
- ^f Also at CERN, Geneva; Switzerland.
- ^g Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ^h Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
- ⁱ Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
- ^j Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; China.
- ^k Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
- ^l Also at Department of Physics, Bolu Abant İzzet Baysal University, Bolu; Türkiye.
- ^m Also at Department of Physics, King's College London, London; United Kingdom.
- ⁿ Also at Department of Physics, Stellenbosch University; South Africa.

- ^o Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- ^p Also at Department of Physics, University of Thessaly; Greece.
- ^q Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
- ^r Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria.
- ^s Also at Faculty of Physics, University of Bucharest; Romania.
- ^t Also at Hellenic Open University, Patras; Greece.
- ^u Also at Henan University; China.
- ^v Also at Imam Mohammad Ibn Saud Islamic University; Saudi Arabia.
- ^w Also at Indian Institute of Technology (IIT), Jodhpur; India.
- ^x Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- ^y Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^z Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
- ^{aa} Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- ^{ab} Also at Institute of Particle Physics (IPP); Canada.
- ^{ac} Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
- ^{ad} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^{ae} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- ^{af} Also at Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; Chile.
- ^{ag} Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
- ^{ah} Also at School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
- ^{ai} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{aj} Also at TRIUMF, Vancouver BC; Canada.
- ^{ak} Also at Università di Napoli Parthenope, Napoli; Italy.
- ^{al} Also at Università degli Studi Link; Italy.
- ^{am} Also at University and INFN Torino, Torino; Italy.
- ^{an} Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
- ^{ao} Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
- ^{ap} Also at University of Siena; Italy.
- ^{aq} Also at Washington College, Chestertown, MD; United States of America.
- ^{ar} Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
- * Deceased