



Letter

Search for Higgs boson exotic decays into Lorentz-boosted light bosons in the four- τ final state at $\sqrt{s} = 13$ TeV with the ATLAS detectorThe ATLAS Collaboration¹

ARTICLE INFO

Editor: Dr. M. Doser

Keywords:

Exotic Higgs decays
Low pt ditau
BSM Higgs
New scalars
New higgs bosons

ABSTRACT

A search for exotic decays of the Higgs boson into a pair of low-mass scalars that subsequently decay into τ -leptons, $H \rightarrow aa \rightarrow \tau^+ \tau^- \tau^+ \tau^-$, is presented. In models with Yukawa-like couplings, the decay to τ -leptons is favoured for light a -bosons, with mass in the range of $2m_\tau < m_a < 2m_b$. Results are presented in the range of $4 \text{ GeV} < m_a < 15 \text{ GeV}$ using the 140 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector during Run 2 of the Large Hadron Collider. This search focuses on the scenario where, for both di- τ pairs, one of the τ -leptons decays to hadrons and neutrinos, while the other decays to a muon and neutrinos. In this mass range, the $a \rightarrow \tau^+ \tau^-$ is Lorentz-boosted and a dedicated muon removal technique is used to reconstruct the di- τ pairs. No significant excess above the Standard Model background prediction is observed. Upper limits on $(\sigma(H)/\sigma_{\text{SM}}(H)) \times \mathcal{B}(H \rightarrow aa \rightarrow 4\tau)$ at 95 % confidence level are provided, ranging from 0.03 to 0.10 depending on the a -boson mass.

1. Introduction

Following the observation of the Higgs boson by the ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider (LHC) [3], both experiments are conducting an extensive programme to measure its properties and uncover its fundamental nature. Measurements of the Higgs boson couplings to other Standard Model (SM) particles can constrain the branching ratio to beyond-the-SM (BSM) particles to be less than 12 % at a 95 % confidence level (CL), assuming that the Higgs boson's coupling to vector bosons is not larger than in the SM ($\kappa_V \leq 1$) [4,5].

Exotic Higgs boson decays to BSM particles are proposed as a way to detect new physics that is weakly coupled to the SM. Due to the narrow total width of the Higgs boson in the SM, even a small coupling to a new light state could induce a significant change in BSM branching ratio [6,7]. Furthermore, new particles might preferentially couple to the Higgs boson, making it a potential *portal* for hidden-sector particles to interact with SM particles [8–10]. Exotic Higgs boson decays are possible in models of dark matter [11–13], electroweak baryogenesis [14,15], and neutral naturalness [16,17]. They are also predicted from first principles in the next-to-minimal supersymmetric SM [18,19].

In models where the SM is extended by a light scalar, a , if the a -boson can mix with the Higgs boson it will inherit its Yukawa coupling pattern to fermions. In such cases, the a -boson will decay preferentially to the heaviest kinematically allowed fermion pair. Although the a -boson is referred to as a scalar in this paper, the results presented are equally applicable to both the scalar and pseudoscalar cases. For light a -bosons, in the mass range $2m_\tau < m_a < 2m_b$, one of the pre-

ferred decays is $a \rightarrow \tau^+ \tau^-$. Due to the low mass of the a -boson, this decay is Lorentz-boosted and the two τ -leptons overlap in the detector. This search focuses on the case in which, for each a -boson, one of the τ -leptons decays to a muon $\tau \rightarrow \mu \nu_\mu \nu_\tau$ and the other decays to hadrons $\tau \rightarrow \text{hadrons} + \nu_\tau$, referred to as τ_{had} . In this decay mode, the muon can be identified close to the hadrons and, once removed from the hadron reconstruction cone, it does not impact the identification of the hadronically decaying τ -lepton. This paper presents a search for events with two di- τ pairs identified through a muon-removal technique, consistent with a decay $H \rightarrow aa \rightarrow \tau^+ \tau^- \tau^+ \tau^-$ in the mass range $4 \text{ GeV} < m_a < 15 \text{ GeV}$. When m_a is higher, the two τ -leptons do not overlap, requiring a different analysis strategy.

The CMS Collaboration has previously searched for exotic Higgs boson decays $H \rightarrow aa \rightarrow \tau^+ \tau^- \tau^+ \tau^-$ using only tracks to identify the hadronically decaying τ -leptons [20]. The ATLAS Collaboration has also searched for exotic Higgs boson decays in the $H \rightarrow aa \rightarrow \mu^+ \mu^- \tau^+ \tau^-$ decay channel using only tracks to identify the τ -lepton decays [21]. The muon-removal technique allows an improved detection of the hadronically decaying τ -leptons using both tracks and calorimeter information, as described in Ref. [22] and is used for the first time by the ATLAS Collaboration in this paper. A similar muon-removal reconstruction has also been used by the CMS Collaboration in the search for exotic Higgs boson decays in the $H \rightarrow aa \rightarrow \mu^+ \mu^- \tau^+ \tau^-$ decay channel [23].

This paper complements many previous searches for exotic Higgs boson decays $H \rightarrow aa$ conducted by the ATLAS and CMS Collaborations. In addition to the results mentioned above, searches are performed in the $\ell^+ \ell^- \ell'^+ \ell'^-$ [24,25] (where ℓ is an electron or a muon), $b\bar{b}\tau^+\tau^-$ [26,

¹ Authors are listed at the end of this paper.

27], $b\bar{b}\mu^+\mu^-$ [28,29], $b\bar{b}b\bar{b}$ [30,31], $\gamma\gamma\gamma\gamma$ [32–34], and $\gamma\gamma gg$ [35] final states.

2. ATLAS detector

The ATLAS experiment [36] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.¹ It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID-2 [37] detector, which is located close to the beam pipe. A two-level trigger system is used to select events [38]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [39] 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 simulated event samples

This search uses the full LHC Run 2 data of proton–proton (pp) collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector from 2015 to 2018, corresponding to an integrated luminosity of $140.1 \pm 1.2 \text{ fb}^{-1}$ [40]. Only data taken from stable beam collisions and that satisfy a standard set of data-quality requirements that ensure all the ATLAS subdetectors were functioning correctly are considered [41].

The data are selected from a suite of triggers requiring one or two high-transverse-momentum (p_T) muons [42]. Since the muons in the signal of interest here are produced close to hadrons, only triggers without isolation requirements are used. The lowest p_T threshold in triggers requiring a single non-isolated muon is 50 GeV. The fraction of selected signal events satisfying this trigger requirement varies from 19% to 42% for m_a from 4 GeV to 15 GeV. During the 2016–2018 (2015) data-taking period, the triggers requiring two muons have either a symmetric threshold of $p_T > 14 \text{ GeV}$ ($p_T > 10 \text{ GeV}$) for both muons or an asymmetric threshold that requires the leading muon to have $p_T > 22 \text{ GeV}$ ($p_T > 18 \text{ GeV}$) and the subleading muon to have $p_T > 8 \text{ GeV}$ ($p_T > 8 \text{ GeV}$). The efficiency of the di-muon trigger varies from 35% to 43% over the mass range from 4 GeV to 15 GeV.

Monte Carlo (MC) samples are used to perform the analysis optimisation, to estimate the signal acceptance and efficiency, and to describe

background processes with four τ -leptons in the final state. Signal samples $H \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$ are generated via gluon–gluon fusion (ggF) at next-to-leading-order (NLO) accuracy in quantum chromodynamics (QCD) using POWHEG BOX v2 [43–47] with the NNPDF3.0NNLO parton distribution function (PDF) set [48]. The signal generation achieves next-to-next-to-leading-order (NNLO) accuracy for inclusive ggF observables by reweighting the Higgs boson rapidity spectrum in Higgs plus one jet multi-scale improved NLO (HJ-MiNLO) [49,50] to that of Higgs NNLO (HNNLO) [51]. The Higgs boson decay into two scalar a -bosons and the subsequent decay of each a -boson into a pair of τ -leptons is generated with PYTHIA v8.245 [52]. Signal samples are generated with $m_a = 4, 6, 8, 10, 12, 14$, and 15 GeV. Although only the ggF production mode is explicitly generated, the difference in acceptance compared to other production modes is negligible, and the sample is used to represent inclusive Higgs boson production.

The main source of background events is processes with fewer than four τ -leptons in the final state, but in which one or two jets originating from the hadronisation of quarks or gluons are misidentified as hadronically decaying τ -leptons. These processes are collectively called *fake- τ_{had} background* hereafter and they are estimated with a data-driven technique described in Section 5.

Background events with four τ -leptons in the final state are subleading and described with simulation events. Only three processes are found to have a contribution greater than 0.1% of the total background and thus considered relevant: non-resonant $q\bar{q} \rightarrow ZZ$ and $gg \rightarrow ZZ$ production, and resonant Higgs boson $H \rightarrow ZZ^*$ production. The non-resonant $q\bar{q} \rightarrow ZZ$ process is modelled using continuum quark–antiquark annihilation from SHERPA 2.2.2 [53], which provides a matrix element calculation accurate at NLO in QCD for 0-jet and 1-jet final states and at leading-order (LO) for 2-jet and 3-jet final states. The merging with the SHERPA parton shower [54] is performed using the MEPS@NLO prescription [55]. The loop-induced non-resonant $gg \rightarrow ZZ$ process is also modelled by SHERPA 2.2.2 with 0-jet and 1-jet final states at LO in QCD. The LO-accurate matrix elements are matched to a parton shower using the MEPS@LO prescription. For all non-resonant ZZ processes modelled using SHERPA, the NNPDF3.0NNLO PDF set [48] is used, along with a dedicated AZNLO set of tuned parton-shower parameters [56].

Two different production mechanisms are generated for the resonant $H \rightarrow ZZ^*$ background. The ggF and vector-boson-fusion (VBF) production modes are generated at NLO accuracy with POWHEG BOX v2 using the CT10 PDF set [57]. Other production modes with smaller cross-sections do not contribute significantly and are not included. The Higgs boson decay, showering, and hadronisation are generated with PYTHIA v8.212 using the AZNLO parameter set.

All generated events are processed through a simulation of the ATLAS detector geometry and response using GEANT4 [58], and through the same reconstruction software as the data. The signal MC samples are processed with a fast simulation that relies on a parameterisation of the calorimeter response [59]. The effect of multiple interactions in the same and neighbouring bunch crossings (pileup) was modelled by overlaying the simulated hard-scattering event with inelastic pp events generated with PYTHIA v8.186 [60] using the NNPDF2.3LO PDF set [61] and the A3 set of tuned parameters [62].

4. Object and event selection

The signal object selected is a $\mu\tau_{\text{had}}$ object, defined as an overlapping τ_{had} and a muon with $\Delta R(\mu, \tau_{\text{had}}) < 0.4$ and opposite charges. The $\mu\tau_{\text{had}}$ object is used to reconstruct the di- τ system in the $a \rightarrow \tau^+\tau^-$ decay where one τ -lepton decays as $\tau \rightarrow \text{hadrons} + \nu_\tau$ and the other decays as $\tau \rightarrow \mu\nu_\mu\nu_\tau$ (charge-conjugated processes are implicit).

Muons are reconstructed using the information from the inner-detector system, the muon spectrometer, and the calorimeters [63]. Muon candidates are required to have $p_T > 5 \text{ GeV}$ and $|\eta| < 2.5$. Muons must also satisfy the *medium identification working point* defined in detail in Ref. [63]. Muons from τ -lepton decays can be displaced from the pri-

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 $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

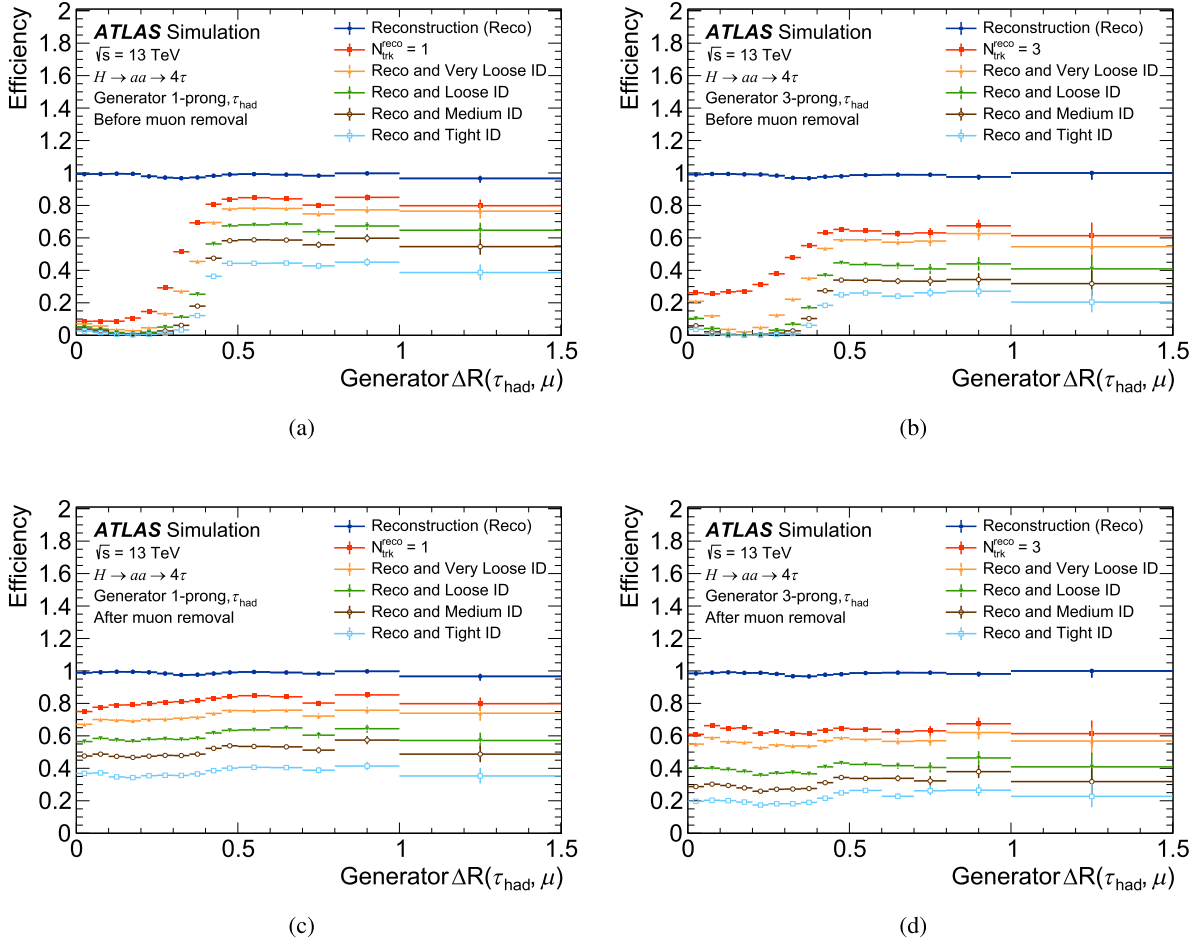


Fig. 1. Monte Carlo estimates of the τ_{had} reconstruction and RNN identification efficiency (a and b) before and (c and d) after the muon removal for generator-level (a and c) 1-prong and (b and d) 3-prong τ_{had} candidates for all working points (Very Loose, Loose, Medium, Tight) defined in Ref. [68], as a function of generator-level $\Delta R(\tau_{\text{had}}, \mu)$. The ‘Reconstruction (Reco)’ markers indicate the efficiency of a τ_{seed} jet to match a generator-level τ_{had} ; The ‘ $N_{\text{trk}}^{\text{reco}} = 1$ or 3’ markers show the efficiency of a generator-level τ_{had} reconstructed with the same number of associated charged-particle tracks as charged hadrons at generator-level. These plots are based on a mixture of $m_a = 4, 6, 8, 10, 15$ GeV samples, with equal weighting applied to each sample. The slight decrease in reconstruction efficiency for both 1-prong and 3-prong τ_{had} candidates within the range $0.2 < \Delta R(\tau_{\text{had}}, \mu) < 0.4$ is attributed to the less than 100 % generator-level matching for the signal samples with $m_a = 10$ GeV and 15 GeV. This is a result of the strict geometrical matching criteria applied between the reconstructed τ_{had} and the generator-level τ_{had} .

primary vertex due to the τ -lepton lifetime, so a loose requirement on the transverse impact parameter significance $|d_0/\sigma_{d_0}| < 7$ is imposed. The longitudinal impact parameter is required to satisfy $|z_0 \sin \theta| < 0.5$ mm relative to the position of the primary vertex.

Electrons are reconstructed by matching clusters in the electromagnetic calorimeter to tracks in the inner detector [64]. Electron candidates are required to meet the criteria of $p_T > 7$ GeV and $|\eta| < 2.47$, excluding the calorimeter transition region $1.37 < |\eta| < 1.52$. Additionally, all electrons must satisfy a *loose* likelihood identification criterion [64].

The reconstruction of the τ_{had} candidates starts from jets formed using the anti- k_t algorithm [65] as implemented in FASTJET [66] with a radius parameter $R = 0.4$. This jet is referred to as seed jet, τ_{seed} jet. The inputs to the anti- k_t algorithm are topological clusters of calorimeter cells [67]. The tracks associated with the τ_{seed} jet are used to determine the number of charged hadrons resulting from the decay of the τ -lepton. To distinguish τ_{had} candidates originating from hadronic τ -lepton decays from those originating from jets initiated by the hadronisation of quarks or gluons, a recurrent neural network (RNN) identification algorithm [68] is used. The RNN uses information from reconstructed tracks and calorimeter energy clusters associated with the τ_{had} candidates, as well as several high-level discriminating variables as input. A dedicated boosted decision tree (BDT) electron veto is also constructed to reject the backgrounds arising from electrons faking τ_{had} [69].

In $\mu\tau_{\text{had}}$ objects, the presence of the muon inside the τ_{seed} jet reduces the τ_{had} reconstruction and RNN identification efficiency, as shown in Fig. 1a and 1b for τ -lepton decaying to final states with one (1-prong) and three (3-prong) charged hadrons, respectively. To improve the reconstruction and identification efficiency of the τ_{had} and thus of the $\mu\tau_{\text{had}}$ objects, a muon-removal technique, as described in Ref. [22], is employed. In this muon-removal technique, the tracks and calorimeter energy clusters associated with the reconstructed muons within $\Delta R(\tau_{\text{had}}, \mu) < 0.4$ are removed from the inputs used for τ_{had} reconstruction and from the inputs to the RNN and BDT identification algorithms.

The muon-removal technique is able to recover τ_{had} reconstruction and RNN identification efficiencies that are similar to those of a τ_{had} without a nearby muon. Fig. 1 shows estimates of the reconstruction and RNN identification efficiency in simulation before and after applying the muon-removal technique for generator-level 1-prong and 3-prong τ_{had} candidates for all the working points defined in Ref. [68]. The efficiency is plotted as a function of merged τ_{had} candidates ($\Delta R(\tau_{\text{had}}, \mu) < 0.4$) and isolated τ_{had} candidates ($\Delta R(\tau_{\text{had}}, \mu) > 0.4$). Fig. 1a and 1b show the loss in RNN identification efficiency of the standard algorithm when the muon and the τ_{had} candidates overlap for 1-prong and 3-prong τ_{had} candidates, respectively. After applying the muon-removal technique, the efficiency values for 1-prong and 3-prong τ_{had} candidates are shown

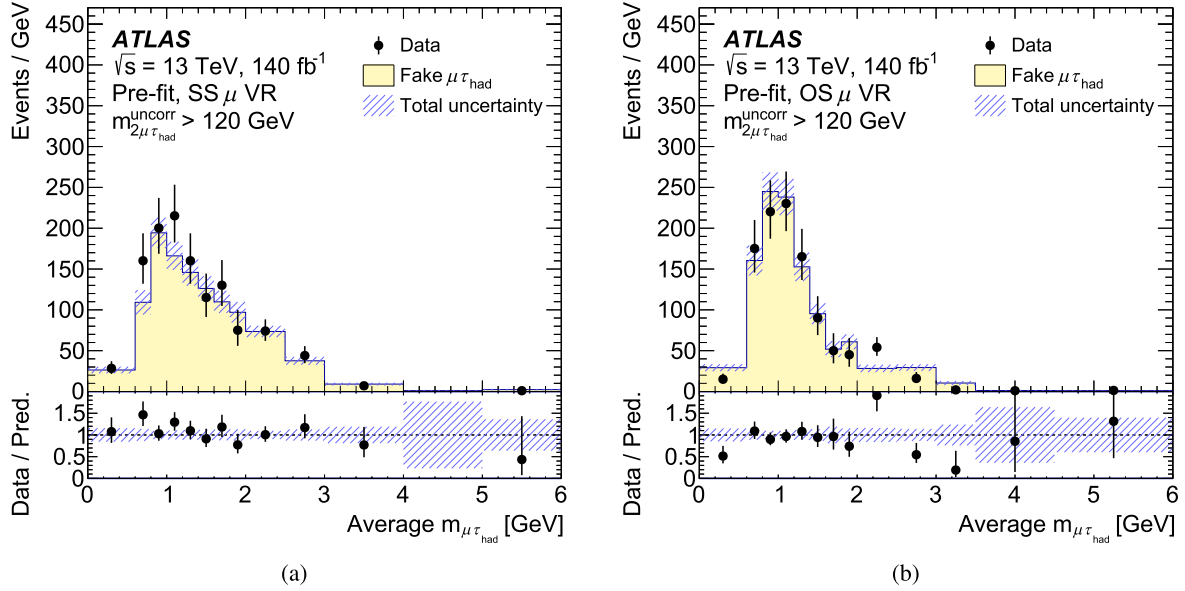


Fig. 2. Pre-fit distribution of the average mass of the two $\mu\tau_{\text{had}}$ candidates in each event for data and the expected background in (a) $\text{SS}\mu$ and (b) $\text{OS}\mu$ validation regions. The hashed area represents the total background uncertainty, including both statistical and systematic components. Overflow events up to 15 GeV are included in the last bin. The contributions from $q\bar{q}/g g \rightarrow ZZ$ and $H \rightarrow ZZ^*$ are considered, but they are not visible as they make up for less than 0.1 % in every bin.

in Fig. 1c and 1d, respectively, demonstrating that this technique effectively allows to maintain the same efficiency for the merged and isolated cases. The $N_{\text{trk}}^{\text{reco}} = 1$ or 3 lines represent the efficiency of reconstructing a generator-level τ_{had} with the same number of associated charged-particle tracks as charged hadrons at generator-level. A slight decrease in this reconstruction efficiency for $\Delta R(\tau_{\text{had}}, \mu) > 0.4$ after muon removal compared with the values before muon removal arises due to a small fraction of τ_{had} charged hadrons being misidentified as muons and subsequently removed from the τ_{seed} jet. The residual difference in τ_{had} efficiency between isolated ($\Delta R(\tau_{\text{had}}, \mu) > 0.4$) and merged ($\Delta R(\tau_{\text{had}}, \mu) < 0.4$) τ_{had} candidates is 8 % for 1-prong and 10 % for 3-prong candidates, respectively. This difference is applied as a per- τ_{had} uncertainty, as described in Section 6.

The overlap of the muon with the τ_{seed} jet also impacts the τ_{had} four-momentum and the τ_{had} energy scale. A MC-based correction using signal events is derived to correct the τ_{had} four-momentum to the same energy scale as in isolated τ_{had} . The effect of the correction on the background is also checked in regions rich in fake- τ_{had} background and is found to have a negligible impact on the agreement between data and background predictions. The uncorrected kinematic quantities, before the muon removal, are used for the event selection to minimize the dependence on simulation.

After the muon-removal technique is applied, the τ_{had} candidates are required to satisfy uncorrected transverse momentum, $p_T^{\text{uncorr}} > 20$ GeV, and pseudorapidity criteria, $|\eta^{\text{uncorr}}| < 2.5$. Any candidate in the transition region between the barrel and endcap calorimeters, $1.37 < |\eta^{\text{uncorr}}| < 1.52$, is excluded. Two additional identification criteria are defined: τ_{had} candidates satisfying the *loose* identification criterion are required to have an RNN identification score above 0.01, which ensures a selection efficiency of 99 % for both 1-prong and 3-prong τ_{had} candidates; τ_{had} candidates satisfying the *tight* identification criterion are required to satisfy the RNN working point that provides a signal efficiency of 75 % (60 %) for 1-prong (3-prong) τ_{had} candidates. All τ_{had} candidates are required to satisfy the electron-veto BDT *loose* working point with a signal efficiency of 95 % for both 1-prong and 3-prong τ_{had} candidates, as defined in Ref. [69].

An overlap removal procedure is applied on all objects (except the muons and the τ_{had}) to eliminate double-counting as in Ref. [70]. The remaining objects are then used to perform the following event-level

selection. The event selection is designed to reject events from most background sources, while maintaining a high acceptance to $H \rightarrow a a \rightarrow \tau^+ \tau^- \tau^+ \tau^-$ decays. Events are required to have exactly two $\mu\tau_{\text{had}}$ objects. The leading muon among the two objects is required to satisfy $p_T > 14$ GeV. The leading (subleading) τ_{had} is required to satisfy $p_T^{\text{uncorr}} > 30$ GeV ($p_T^{\text{uncorr}} > 25$ GeV) to reduce the number of background events with fake τ -leptons. Both τ_{had} must satisfy the *tight* identification criterion.

The uncorrected τ_{had} four-momenta and the muon four-momenta are used to reconstruct an estimate of the Higgs boson mass $m_{2\mu\tau_{\text{had}}}^{\text{uncorr}}$. Events are required to satisfy $60 \text{ GeV} < m_{2\mu\tau_{\text{had}}}^{\text{uncorr}} < 120 \text{ GeV}$. The selection is below the Higgs boson mass of 125 GeV to account for the energy carried out by neutrinos. The corrected τ_{had} four-momenta are used to reconstruct an estimate of the two a -boson masses $m_{\mu\tau_{\text{had}}}$. Both $\mu\tau_{\text{had}}$ objects are required to satisfy $m_{\mu\tau_{\text{had}}} < 15$ GeV. The two mass-based selection criteria remove almost all the electroweak sources of background events while retaining approximately 90 % of the signal.

Two orthogonal signal regions (SR) are defined based on the relative charge of the two muons: a same-sign region ($\text{SS}\mu$), and an opposite-sign region ($\text{OS}\mu$). The fake- τ_{had} background in the $\text{OS}\mu$ region receives a large contribution from Z + jets events, which is absent in the $\text{SS}\mu$ region. An additional requirement $m_{\mu\mu} < 50$ GeV is imposed for events in the $\text{OS}\mu$ region to reduce this contribution and bring the background in both regions to similar levels while retaining 94 % - 98 % of the remaining signal events depending on the a -boson mass.

5. Background estimation

Background events from processes that have four τ -leptons in the final state are modelled by simulation. Only non-resonant $q\bar{q}/g g \rightarrow ZZ$ and resonant $H \rightarrow ZZ^*$ processes are explicitly included in the analysis, but they have a negligible impact on the result. After event selection, these processes contribute to less than 0.1 % of the total background.

Almost all background events come from processes in which at least one jet from the hadronisation of a quark or a gluon is mis-reconstructed and mis-identified as a τ_{had} candidate (fake τ_{had}). Simulation studies show that, in this case, the nearby muon is almost always from a non-prompt semileptonic decay of a hadron inside the jet. This background

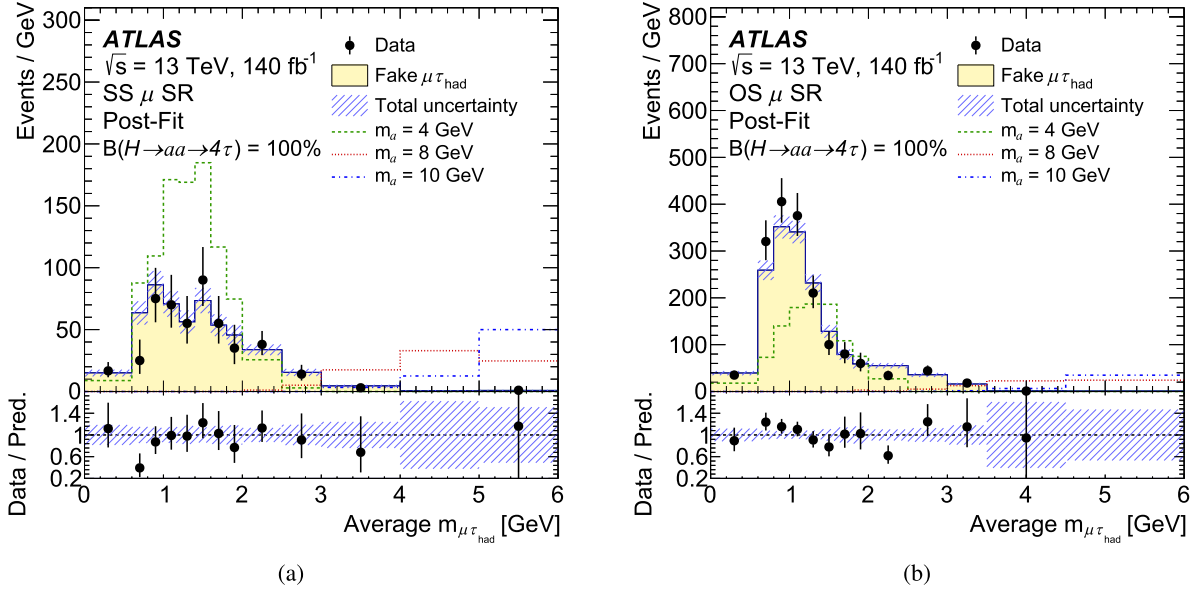


Fig. 3. Post-fit distribution of the average mass of the two $\mu\tau_{\text{had}}$ candidates in each event for data, the expected background and $m_a = 4, 8,$ and 10 GeV signals, assuming $B(H \rightarrow aa \rightarrow 4\tau) = 100\%$, in (a) SS μ and (b) OS μ signal regions. Overflow events up to 15 GeV are included in the last bin. The hashed area represents the total background uncertainty, including both statistical and systematic components. The contributions from $q\bar{q}/gg \rightarrow ZZ$ and $H \rightarrow ZZ^*$ are considered, but they are not visible as they make up for less than 0.1% in every bin.

source is estimated with a tight-to-loose data-driven method [71] as briefly described below.

As described in Section 4, each τ_{had} candidate and, therefore each $\mu\tau_{\text{had}}$ candidate, has a *loose* and a *tight* identification criterion. Events with at least one $\mu\tau_{\text{had}}$ candidate that satisfies the *loose* identification but not the *tight* one are used to estimate the fake- τ_{had} background by assigning a per- $\mu\tau_{\text{had}}$ fake-factor weight F . The sign of the overall event weight is adjusted depending on the number of $\mu\tau_{\text{had}}$ failing to meet the *tight* identification to avoid double-counting of background events [26, 71].

The fake factor F is measured using Z +jets events selected by requiring two isolated muons and one $\mu\tau_{\text{had}}$ candidate satisfying the *loose* identification requirement. The isolated muons are required to satisfy stricter impact parameter requirements $|d_0/\sigma_{d_0}| < 4$ and have an invariant mass close to the Z boson pole mass $71 \text{ GeV} < m_{\mu\mu} < 111 \text{ GeV}$. The fraction of events f in which the $\mu\tau_{\text{had}}$ also satisfies the *tight* identification criterion is used to define the fake factor $F = f/(1 - f)$, parameterised as a function of the $\mu\tau_{\text{had}}$ candidate p_T^{uncorr} and the number of associated charged-particle tracks.

The modelling of background events with fake $\mu\tau_{\text{had}}$ is verified in a validation region (VR), where events are selected in the same way as in the two signal regions, but with a high four-body invariant mass, $m_{2\mu\tau_{\text{had}}}^{\text{uncorr}} > 120 \text{ GeV}$. Negligible signal contribution is expected in this region. The modelling is verified separately for events with same-charge (SS μ VR) and opposite-charge muon pairs (OS μ VR). Fig. 2 shows the average corrected mass of the two $\mu\tau_{\text{had}}$ candidates in each event of these validation regions for data and the expected background. This variable is used as a final discriminant in the signal regions, as explained in Section 7. The residual difference between data and expected background in this distribution is used as a non-closure systematic uncertainty, as described in Section 6.

6. Systematic uncertainties

Several sources of uncertainties in the signal acceptance are considered. Experimental sources include uncertainties in the muon reconstruction and identification efficiencies, in the muon momentum scale and in the muon trigger efficiency. The methods used to derive these uncertainties are described in Refs. [42,63]. Similar systematic uncer-

tainties related to the τ_{had} reconstruction, RNN identification, and BDT electron-veto efficiencies [68,72] are considered. Uncertainties in the τ_{had} energy scale are included following the methods of Ref. [69]. An additional systematic uncertainty is included to account for the difference between identification efficiency in isolated τ_{had} candidates and $\mu\tau_{\text{had}}$ candidates after muon removal. The relative difference estimated in simulation between the two cases is 8% (10%) and applied as an uncertainty separately for each 1-prong (3-prong) τ_{had} candidate. Uncertainties in the simulation of pileup interactions are considered, but have a negligible impact on the signal acceptance. The uncertainty in the integrated luminosity is 0.83% [40], obtained using the LUCID-2 detector [37] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters.

Modelling systematic uncertainties in the signal acceptance are estimated by varying the renormalisation and factorisation scales between half and twice the nominal value used in the simulation [73]. Uncertainties related to the parton distribution function are estimated via NNPDF MC replicas and by comparing the acceptance when different PDF sets [48] are used.

The main sources of systematic uncertainty in this search are the ones related to the modelling of the fake- τ_{had} background. Uncertainties coming from the limited number of data events in the Z +jets region used to estimate the fake factor F are considered but have a negligible impact on the result. Uncertainties coming from the limited number of data events with at least one $\mu\tau_{\text{had}}$ candidate failing to meet the tight identification in the two signal regions are more important, especially for the results at higher values of m_a where they can be as large as 62% . Variations related to the fake factor parameterisation on τ_{had} p_T and η are considered, but have a negligible impact on the result.

Several uncertainties are included to account for possible differences between the fake τ_{had} composition in the Z +jets region, where the fake factors are measured, and the signal regions, where they are applied. Alternative fake factors are measured using the same set-up and Z +jets region but requiring additional light jets, b -tagged jets, or restricting $\Delta R(\tau_{\text{had}}, \mu) < 0.2$. The differences between each of these three alternative fake factors and the nominal ones are considered as independent source of systematic uncertainty. Studies in simulation show that these three variations can account for the difference between fake- τ_{had} composition in the Z +jets region, signal regions, and validation regions.

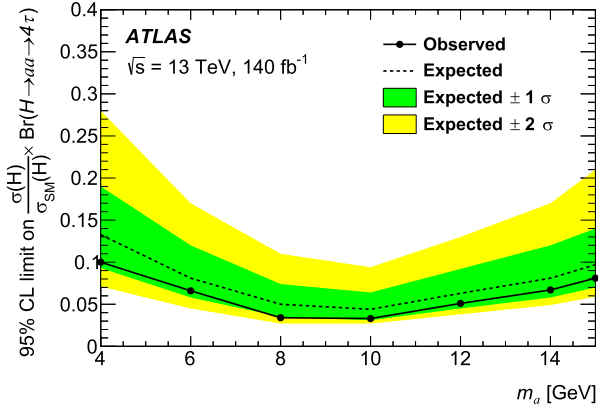


Fig. 4. Observed (solid line) and expected (dashed line) 95 % CL upper limits on $(\sigma(H)/\sigma_{\text{SM}}(H)) \times B(H \rightarrow aa \rightarrow 4\tau)$ as a function of m_a . The inner green and outer yellow shaded bands represent the ± 1 and ± 2 standard deviations around the expected limits, respectively. Limits between the mass points are interpolated linearly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Finally, a non-closure uncertainty of 8 % in the fake- τ_{had} background total yield is estimated based on the relative difference between data and expected background in the $\text{SS}\mu$ and $\text{OS}\mu$ VRs.

Systematic uncertainties in the background processes modelled with simulation were studied but they have a negligible impact on the result since these background sources account for less than 0.1 % of the total background across all signal regions.

7. Results

The average mass of the two $\mu\tau_{\text{had}}$ candidates in each event is used as a discriminating observable to test the presence of $H \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$ decays, due to its better resolution compared with the individual $\mu\tau_{\text{had}}$ masses. The binning strategy for the $\text{SS}\mu$ and $\text{OS}\mu$ signal regions was optimised to target a statistical uncertainty of approximately 20 % in the prediction of background events, as depicted in Fig. 3. The last two bins

were specifically optimised to enhance the signal significance over all mass hypotheses simultaneously while ensuring non-zero background event yields in each bin. As a result, the statistical uncertainties in these bins exceed 20 %.

The presence of a $H \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$ decay is tested with a modified profile likelihood ratio $\tilde{q}(\mu)$ [74], where $\mu = (\sigma(H)/\sigma_{\text{SM}}(H)) \times B(H \rightarrow aa \rightarrow 4\tau)$ and $\sigma_{\text{SM}}(H)$ is the inclusive Higgs boson cross-section at $\sqrt{s} = 13$ TeV. The likelihood function is built as a product of Poisson probability functions for each average $m_{\mu\tau_{\text{had}}}$ bin in the $\text{SS}\mu$ and $\text{OS}\mu$ SRs. Nuisance parameters with Gaussian constraints are introduced to model sources of systematic uncertainties and their impact on the expected signal and background yields.

The observed number of events in the two SRs is shown in Table 1 along with the predicted background. The signal yields for different m_a hypotheses are also shown assuming a $B(H \rightarrow aa \rightarrow 4\tau) = 10\%$ and the inclusive Higgs boson cross-section of 55.7 pb [75]. No significant excess is observed in the SRs when comparing the total data yield to the total background prediction in the absence of a signal. The post-fit total number of background events is 130 ± 7 for the $\text{SS}\mu$ and 368 ± 16 for the $\text{OS}\mu$ SR. Upper limits are set at the 95 % CL on $(\sigma(H)/\sigma_{\text{SM}}(H)) \times B(H \rightarrow aa \rightarrow 4\tau)$ using the CL_s method [76], and assuming a reference cross section of 55.7 pb for $\sigma_{\text{SM}}(H)$. Fig. 4 shows the observed and expected upper limits obtained using pseudo-experiments to estimate the test-statistic distribution for each value of the signal strength μ and a -boson mass hypothesis. The $\text{SS}\mu$ channel demonstrates greater sensitivity than the $\text{OS}\mu$ channel for $m_a < 6$ GeV due to less $Z/\gamma^* \rightarrow \mu^+\mu^-$ background, whereas the $\text{SS}\mu$ and $\text{OS}\mu$ channels show similar sensitivities for $m_a \geq 6$ GeV. The worse limits for $m_a < 8$ GeV are due to the poor separation between the signal and background, as the signal shapes closely resemble those of the background. Additionally, the worse limits for $m_a > 10$ GeV result from fewer merged τ -leptons, leading to lower signal efficiency. The dominant uncertainties arise from the limited number of pp collisions collected, ranging from 51 % to 70 %, depending on the mass of a -boson. The observed (expected) limit on $(\sigma(H)/\sigma_{\text{SM}}(H)) \times B(H \rightarrow aa \rightarrow 4\tau)$ ranges from 0.03 (0.04) at $m_a = 10$ GeV to 0.10 (0.13) at $m_a = 4$ GeV.

The limits presented here are comparable to other recent results in the same final state [20,23]. Once interpreted in the 2HDM+S model [77], as illustrated in Fig. 5, this final state provides strong constraints for the Type-III 2HDM+S model with $\tan\beta = 5$, offering signif-

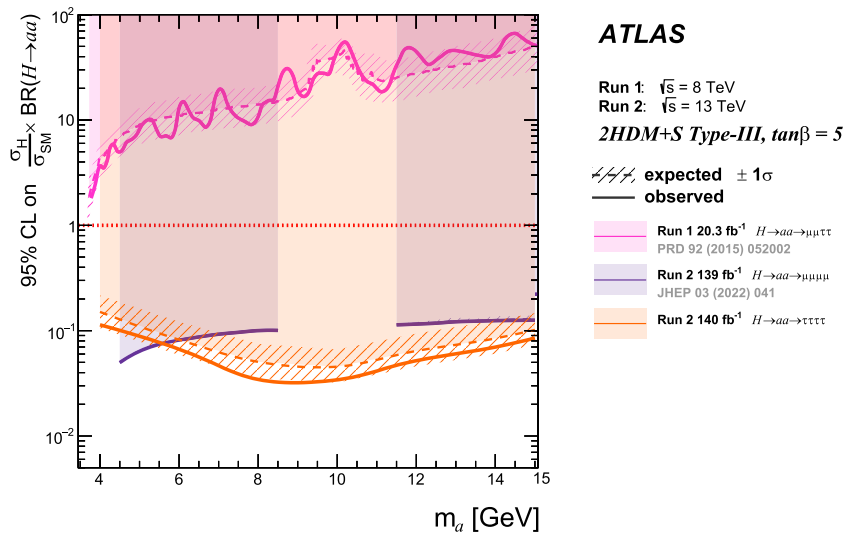


Fig. 5. The observed (solid line) and expected (dashed line) limits are interpreted within the framework of the Type-III 2HDM+S model with $\tan\beta = 5$, which maximizes the branching ratio of $a \rightarrow \tau^+\tau^-$. These limits are expressed in terms of $(\sigma(H)/\sigma_{\text{SM}}(H)) \times B(H \rightarrow aa)$ as a function of m_a . The observed limits for the $H \rightarrow aa \rightarrow \mu\mu\mu\mu$ channel are identical to the expected limits, as no events are observed in the corresponding search. The dotted red line represents the scenario where the branching ratio of the Higgs boson exotic decay $H \rightarrow aa$ equals 100 %, assuming $\sigma(H) = \sigma_{\text{SM}}(H)$. The branching ratios of $a \rightarrow \tau^+\tau^-$ are calculated based on the methodology described in Ref. [77]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

The pre-fit table showing the total number of observed and expected events in the $SS\mu$ and $OS\mu$ signal regions. The uncertainties include both statistical and systematic sources. The expected number of signal events is listed for different m_a hypotheses assuming $B(H \rightarrow aa \rightarrow 4\tau) = 10\%$ and the inclusive Higgs boson cross-section.

Process	$SS\mu$ region	$OS\mu$ region
Data	121	380
Fake- τ_{had} background	129 ± 12	350 ± 31
$q\bar{q} \rightarrow ZZ$ and $g\bar{g} \rightarrow ZZ$	< 0.01	< 0.01
$H \rightarrow ZZ^*$	< 0.01	0.09 ± 0.04
Total background	129 ± 12	350 ± 31
$H \rightarrow aa \rightarrow 4\tau$ ($m_a = 4$ GeV)	20.2 ± 3.2	21.4 ± 3.3
$H \rightarrow aa \rightarrow 4\tau$ ($m_a = 6$ GeV)	9.7 ± 1.5	10.7 ± 1.7
$H \rightarrow aa \rightarrow 4\tau$ ($m_a = 8$ GeV)	7.8 ± 1.3	6.9 ± 1.1
$H \rightarrow aa \rightarrow 4\tau$ ($m_a = 10$ GeV)	6.6 ± 1.1	6.0 ± 1.0
$H \rightarrow aa \rightarrow 4\tau$ ($m_a = 12$ GeV)	3.7 ± 0.6	3.9 ± 0.6
$H \rightarrow aa \rightarrow 4\tau$ ($m_a = 14$ GeV)	3.1 ± 0.5	2.7 ± 0.5
$H \rightarrow aa \rightarrow 4\tau$ ($m_a = 15$ GeV)	2.4 ± 0.4	2.4 ± 0.4

icant improvements over previous ATLAS results in the $\mu\mu\tau\tau$ [21] and $\mu\mu\mu\mu$ [24] final states.

8. Conclusion

This letter presents the first ATLAS search for exotic Higgs boson decays in the $H \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$ final state, where a is a new light scalar with a mass range of $4\text{ GeV} < m_a < 15\text{ GeV}$. The analysis was performed using the 140 fb^{-1} of pp collision data collected between 2015 and 2018 with the ATLAS detector at the LHC. For the first time in ATLAS, a muon-removal technique is used to reconstruct merged di- τ decays. No significant excess of data over the background expectation is observed. Upper limits at 95% CL are set on $(\sigma(H)/\sigma_{\text{SM}}(H)) \times B(H \rightarrow aa \rightarrow 4\tau)$, ranging from 0.03 to 0.10 depending on m_a . This measurement significantly improved previous similar measurements.

Data availability

The release of data supporting the findings of this article follows CERN's Open Data Policy. The values of relevant plots and tables associated with this article are stored in HEPData

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [78].

We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and WFW, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia;

MEYS CR, Czech Republic; DNR and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMFT, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ICHEP and Academy of Sciences and Humanities, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MCIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, United States of America.

Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

In addition, individual members wish to acknowledge support from Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN DOCT); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1230812, FONDECYT 1240864); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700, MOST-2023YFA1609300), National Natural Science Foundation of China (NSFC - 12175119, NSFC 12275265); Czech Republic: Czech Science Foundation (GACR - 24-11373S), Ministry of Education Youth and Sports (ERC-CZ-LL2327, FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (ERC - 101002463); European Union: European Research Council (BARD No. 101116429, ERC - 948254, ERC 101089007), European Regional Development Fund (SMASH COFUND 101081355, SLO ERDF), Horizon 2020 Framework Programme (MUCCA - CHIST-ERA-19-XAI-00), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Horizon 2020 (EuroHPC - EHPC-DEV-2024D11-051), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (ANR-21-CE31-0013, ANR-21-CE31-0022, ANR-22-EDIR-0002); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG - 469666862, DFG - CR 312/5-2); China: Research Grants Council (GRF); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell'Università e della Ricerca (NextGenEU 153D23001490006 M4C2.1.1, NextGenEU I53D23000820006 M4C2.1.1, NextGenEU I53D23001490006 M4C2.1.1); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP23KK0245, JSPS KAKENHI JP24K23939); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS 2023/51/B/ST2/02507, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, UMO-2020/37/B/ST2/01043, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920, UMO-2024/53/N/ST2/00869); Portugal: Foundation for Science and Technology (FCT); Spain: Generalitat Valenciana (Artemisa, FEDER, IDIFEDER/2018/048), Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research

Council (Swedish Research Council 2023-04654, VR 2021-03651, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR 2024-05451), Knut and Alice Wallenberg Foundation (KAW 2018.0458, KAW 2022.0358, KAW 2023.0366); Switzerland: Swiss National Science Foundation (SNSF - PCEFP2.194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004), Royal Society (NIF-R1-231091); United States of America: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

The ATLAS Collaboration

G. Aad¹⁰⁴, E. Aakvaag¹⁷, B. Abbott¹²³, S. Abdelhameed^{119a}, K. Abeling⁵⁵, N.J. Abicht⁴⁹, S.H. Abidi³⁰, M. Aboelela⁴⁵, A. Aboulhorma^{36e}, H. Abramowicz¹⁵⁷, Y. Abulaiti¹²⁰, B.S. Acharya^{69a,69b,n}, A. Ackermann^{63a}, C. Adam Bourdarios⁴, L. Adamczyk^{86a}, S.V. Addepalli¹⁴⁹, M.J. Addison¹⁰³, J. Adelman¹¹⁸, A. Adiguzel^{22c}, T. Adye¹³⁷, A.A. Affolder¹³⁹, Y. Afik⁴⁰, M.N. Agaras¹³, A. Aggarwal¹⁰², C. Agheorghiesei^{28c}, F. Ahmadov^{39,ae}, S. Ahuja⁹⁷, X. Ai^{143b}, G. Aielli^{76a,76b}, A. Aikot¹⁶⁹, M. Ait Tamliah^{36e}, B. Aitbenkikh^{36a}, M. Akbiyik¹⁰², T.P.A. Åkesson¹⁰⁰, A.V. Akimov¹⁵¹, D. Akiyama¹⁷⁴, N.N. Akolkar²⁵, S. Aktas^{22a}, G.L. Alberghi^{24b}, J. Albert¹⁷¹, P. Albicocco⁵³, G.L. Albouy⁶⁰, S. Alderweireldt⁵², Z.L. Alegria¹²⁴, M. Aleksa³⁷, I.N. Aleksandrov³⁹, C. Alexa^{28b}, T. Alexopoulos¹⁰, F. Alfonsi^{24b}, M. Algren⁵⁶, M. Alhroob¹⁷³, B. Ali¹³⁵, H.M.J. Ali^{93,x}, S. Ali³², S.W. Alibocus⁹⁴, M. Aliev^{34c}, G. Alimonti^{71a}, W. Alkakh⁵⁵, C. Allaire⁶⁶, B.M.M. Allbrooke¹⁵², J.S. Allen¹⁰³, J.F. Allen⁵², P.P. Allport²¹, A. Aloisio^{72a,72b}, F. Alonso⁹², C. Alpigiani¹⁴², Z.M.K. Alsolami⁹³, A. Alvarez Fernandez¹⁰², M. Alves Cardoso⁵⁶, M.G. Alvigi^{72a,72b}, M. Aly¹⁰³, Y. Amaral Coutinho^{83b}, A. Ambler¹⁰⁶, C. Amelung³⁷, M. Amerl¹⁰³, C.G. Ames¹¹¹, T. Amezza¹³⁰, D. Amidei¹⁰⁸, B. Amini⁵⁴, K. Amirie¹⁶¹, A. Amirkhanov³⁹, S.P. Amor Dos Santos^{133a}, K.R. Amos¹⁶⁹, D. Amperiadou¹⁵⁸, S. An⁸⁴, C. Anastopoulos¹⁴⁵, T. Andeen¹¹, J.K. Anders⁹⁴, A.C. Anderson⁵⁹, A. Andreazza^{71a,71b}, S. Angelidakis⁹, A. Angerami⁴², A.V. Anisenkov³⁹, A. Annovi^{74a}, C. Antel⁵⁶, E. Antipov¹⁵¹, M. Antonelli⁵³, F. Anulli^{75a}, M. Aoki⁸⁴, T. Aoki¹⁵⁹, M.A. Aparo¹⁵², L. Aperio Bella⁴⁸, M. Apicella³¹, C. Appelt¹⁵⁷, A. Apyan²⁷, S.J. Arbiol Val⁸⁷, C. Arcaangeletti⁵³, A.T.H. Arce⁵¹, J-F. Arguin¹¹⁰, S. Argyropoulos¹⁵⁸, J.-H. Arling⁴⁸, O. Arnaez⁴, H. Arnold¹⁵¹, G. Artoni^{75a,75b}, H. Asada¹¹³, K. Asai¹²¹, S. Asai¹⁵⁹, N.A. Asbah³⁷, R.A. Ashby Pickering¹⁷³, A.M. Aslam⁹⁷, K. Assamagan³⁰, R. Astalos^{29a}, K.S.V. Astrand¹⁰⁰, S. Atashi¹⁶⁵, R.J. Atkin^{34a}, H. Atmani^{36f}, P.A. Atmasiddha¹³¹, K. Augsten¹³⁵, A.D. Aurio⁴¹, V.A. Austrup¹⁰³, G. Avolio³⁷, K. Axiotis⁵⁶, G. Azuelos^{110,ai}, D. Babal^{29b}, H. Bachacou¹³⁸, K. Bachas^{158,r}, A. Bachiu³⁵, E. Bachmann⁵⁰, M.J. Backes^{63a}, A. Badea⁴⁰, T.M. Baer¹⁰⁸, P. Bagnaia^{75a,75b}, M. Bahmani¹⁹, D. Bahner⁵⁴, K. Bai¹²⁶, J.T. Baines¹³⁷, L. Baines⁹⁶, O.K. Baker¹⁷⁸, E. Bakos¹⁶, D. Bakshi Gupta⁸, L.E. Balabram Filho^{83b}, V. Balakrishnan¹²³, R. Balasubramanian⁴, E.M. Baldin³⁸, P. Balek^{86a}, E. Balabene^{24b,24a}, F. Balli¹³⁸, L.M. Baltes^{63a}, W.K. Balunas³³, J. Balz¹⁰², I. Bamwidhi^{119b}, E. Banas⁸⁷, M. Bandieramonte¹³², A. Bandyopadhyay²⁵, S. Bansal²⁵, L. Barak¹⁵⁷, M. Barakat⁴⁸, E.L. Barberio¹⁰⁷, D. Barberis^{18b}, M. Barbero¹⁰⁴, M.Z. Barel¹¹⁷, T. Barillari¹¹², M.-S. Barisits³⁷, T. Barklow¹⁴⁹, P. Baron¹²⁵, D.A. Baron Moreno¹⁰³, A. Baroncelli⁶², A.J. Barr¹²⁹, J.D. Barr⁹⁸, F. Barreiro¹⁰¹, J. Barreiro Guimarães da Costa¹⁴, M.G. Barros Teixeira^{133a}, S. Barsov³⁸, F. Bartels^{63a}, R. Bartoldus¹⁴⁹, A.E. Barton⁹³, P. Bartos^{29a}, A. Basan¹⁰², M. Baselga⁴⁹, S. Bashiri⁸⁷, A. Bassalat^{66,b}, M.J. Basso^{162a}, S. Bataju⁴⁵, R. Bate¹⁷⁰, R.L. Bates⁵⁹, S. Batlamous¹⁰¹, M. Battaglia¹³⁹, D. Battulal¹⁹, M. Bauce^{75a,75b}, M. Bauer⁷⁹, P. Bauer²⁵, L.T. Bayer⁴⁸, L.T. Bazzano Hurrell³¹, J.B. Beacham¹¹², T. Beau¹³⁰, J.Y. Beauchemin¹⁶⁴, P. Bechtel²⁵, H.P. Beck^{20,q}, K. Becker¹⁷³, A.J. Beddall⁸², V.A. Bednyakov³⁹, C.P. Bee¹⁵¹, L.J. Beemster¹⁶, M. Begalli^{83d}, M. Begel³⁰, J.K. Behr⁴⁸, J.F. Beirer³⁷, F. Beisiegel²⁵, M. Belfkir^{119b}, G. Bella¹⁵⁷, L. Bellagamba^{24b}, A. Bellerive³⁵, C.D. Bellgraph⁶⁸, P. Bellos²¹, K. Beloborodov³⁸, D. Benchechroun^{36a}, F. Bendebe^{36a}, Y. Benhammou¹⁵⁷, K.C. Benkendorfer⁶¹, L. Beresford⁴⁸, M. Beretta⁵³, E. Bergeas Kuutmann¹⁶⁷, N. Berger⁴, B. Bergmann¹³⁵, J. Beringer^{18a}, G. Bernardi⁵, C. Bernius¹⁴⁹, F.U. Bernlochner²⁵, F. Bernon³⁷, A. Berrocal Guardia¹³, T. Berry⁹⁷, P. Berta¹³⁶, A. Berthold⁵⁰, A. Bertl^{133a}, R. Bertrand¹⁰⁴, S. Bethke¹¹², A. Betti^{75a,75b}, A.J. Bevan⁹⁶, L. Bezio⁵⁶, N.K. Bhalla⁵⁴, S. Bharthuar¹¹², S. Bhatta¹⁵¹, P. Bhattarai¹⁴⁹, Z.M. Bhatti¹²⁰, K.D. Bhide⁵⁴, V.S. Bhopatkar¹²⁴, R.M. Bianchi¹³², G. Bianco^{24b,24a}, O. Biebel¹¹¹, M. Biglietti^{77a}, C.S. Billingsley⁴⁵, Y. Bimgdi^{36f}, M. Bindl⁵⁵, A. Bingham¹⁷⁷, A. Bingul^{22b}, C. Bini^{75a,75b}, G.A. Bird³³, M. Birman¹⁷⁵, M. Biros¹³⁶, S. Biryukov¹⁵², T. Bisanz⁴⁹, E. Bisceglie^{24b,24a}, J.P. Biswal¹³⁷, D. Biswas¹⁴⁷, I. Bloch⁴⁸, A. Blue⁵⁹, U. Blumen-schein⁹⁶, J. Blumenthal¹⁰², V.S. Bobrovnikov³⁹, M. Boehler⁵⁴, B. Boehm¹⁷², D. Bogavac¹³, A.G. Bogdanchikov³⁸, L.S. Boggia¹³⁰, V. Boisvert⁹⁷, P. Bokan³⁷, T. Bold^{86a}, M. Bomben⁵, M. Bona⁹⁶, M. Boonekamp¹³⁸, A.G. Borbély⁵⁹, I.S. Bordulev³⁸, G. Borissov⁹³, D. Bortoletto¹²⁹, D. Boscherini^{24b}, M. Bosman¹³, K. Bouaouda^{36a}, N. Bouchhar¹⁶⁹, L. Boudet⁴, J. Boudreau¹³², E.V. Bouhova-Thacker⁹³, D. Boumediene⁴¹, R. Bouquet^{57b,57a}, A. Boveia¹²², J. Boyd³⁷, D. Boye³⁰, I.R. Boyko³⁹, L. Bozianu⁵⁶, J. Bracinik²¹, N. Brahimi⁴, G. Brandt¹⁷⁷, O. Brandt³³, B. Brau¹⁰⁵, J.E. Brau¹²⁶, R. Brenner¹⁷⁵, L. Brenner¹¹⁷, R. Brenner¹⁶⁷, S. Bressler¹⁷⁵, G. Brianti^{78a,78b}, D. Britton⁵⁹, D. Britzger¹¹², I. Brock²⁵, R. Brock¹⁰⁹, G. Brooijmans⁴², A.J. Brooks⁶⁸, E.M. Brooks^{162b}, E. Brost³⁰, L.M. Brown^{171,162a}, L.E. Bruce⁶¹, T.L. Bruckler¹²⁹, P.A. Bruckman de Renstrom⁸⁷, B. Brüers⁴⁸, A. Bruni^{24b}, G. Bruni^{24b}, D. Brunner^{47a,47b}, M. Bruschi^{24b}, N. Bruscino^{75a,75b}, T. Buanes¹⁷, Q. Buat¹⁴², D. Buchin¹¹², A.G. Buckley⁵⁹, O. Bulekov⁸², B.A. Bullard¹⁴⁹, S. Burdin⁹⁴, C.D. Burgard⁴⁹, A.M. Burger⁹¹, B. Burghgrave⁸, O. Burlayenko⁵⁴, J. Burleson¹⁶⁸, J.T.P. Burr³³, J.C. Burzynski¹⁴⁸, E.L. Busch⁴², V. Büscher¹⁰², P.J. Bussey⁵⁹, J.M. Butler²⁶, C.M. Buttar⁵⁹, J.M. Butterworth⁹⁸, W. Buttinger¹³⁷, C.J. Buxo Vazquez¹⁰⁹, A.R. Buzykaev³⁹, S. Cabrera Urbán¹⁶⁹, L. Cadamuro⁶⁶, D. Caforio⁵⁸, H. Cai¹³², Y. Cai^{24b,114c,24a}, Y. Cai^{114a}, V.M.M. Cairo³⁷, O. Cakir^{3a}, N. Calace³⁷, P. Calafiura^{18a}, G. Calderini¹³⁰, P. Calfayan³⁵, G. Callea⁵⁹, L.P. Caloba^{83b}, D. Calvet⁴¹, S. Calvet⁴¹, R. Camacho Toro¹³⁰, S. Camarda³⁷, D. Camarero Munoz²⁷, P. Camarri^{76a,76b}, C. Camincher¹⁷¹, M. Campanelli⁹⁸, A. Camplani⁴³, V. Canale^{72a,72b}, A.C. Canbay^{3a}, E. Canonero⁹⁷, J. Cantero¹⁶⁹, Y. Cao¹⁶⁸, F. Capocasa²⁷, M. Capua^{44b,44a}, A. Carbone^{71a,71b}, R. Cardarelli^{76a}, J.C.J. Cardenas⁸, M.P. Cardiff²⁷, G. Carducci^{44b,44a}, T. Carli³⁷, G. Carlino^{72a}, J.I. Carlotto¹³, B.T. Carlson^{132,s}, E.M. Carlson¹⁷¹, J. Carmignani⁹⁴, L. Carminati^{71a,71b}, A. Carnelli⁴, M. Carnesale³⁷, S. Caron¹¹⁶, E. Carquin^{140f}, I.B. Carr¹⁰⁷, S. Carrá^{71a}, G. Carratta^{24b,24a}, A.M. Carroll¹²⁶, M.P. Casado^{13,i}, M. Caspar⁴⁸, F.L. Castillo⁴, L. Castillo Garcia¹³, V. Castillo Gimenez¹⁶⁹, N.F. Castro^{133a,133e}, A. Catinaccio³⁷, J.R. Catmore¹²⁸, T. Cavaliere⁴, V. Cavaliere³⁰, L.J. Caviedes Betancourt^{23b}, Y.C. Cekmecelioglu⁴⁸, E. Celebi⁸², S. Cella³⁷, V. Cepaitis⁵⁶, K. Cerny¹²⁵, A.S. Cerqueira^{83a}, A. Cerri^{74a,74b,al}, L. Cerri^{76a,76b}, F. Cerutti^{18a}, B. Cervato^{71a,71b}, A. Cervelli^{24b}, G. Cesarini⁵³, S.A. Cetin⁸², P.M. Chabrilat¹³⁰, S. Chakraborty¹⁷³, J. Chan^{18a}, W.Y. Chan¹⁵⁹, J.D. Chapman³³, E. Chapon¹³⁸, B. Chargeishvili^{155b}, D.G. Charlton²¹, C. Chauhan¹³⁶, Y. Che^{114a}, S. Chekanov⁶, S.V. Chekulaev^{162a}, G.A. Chelkov^{39,a}, B. Chen¹⁵⁷, B. Chen¹⁷¹, H. Chen^{114a}, H. Chen³⁰, J. Chen^{144a}, J. Chen¹⁴⁸, M. Chen¹²⁹, S. Chen⁸⁹, S.J. Chen^{114a}, X. Chen^{144a}, X. Chen^{15,ah}, Z. Chen⁶², C.L. Cheng¹⁷⁶,

H.C. Cheng^{64a}, S. Cheong¹⁴⁹, A. Cheplakov³⁹, E. Chere-mushkina⁴⁸, E. Cherepanova¹¹⁷, R. Cherkaoui El Moursli^{36e}, E. Cheu⁷, K. Cheung⁶⁵, L. Chevalier¹³⁸, V. Chiarella⁵³, G. Chiarelli^{74a}, G. Chiodini^{70a}, A.S. Chisholm²¹, A. Chitan^{28b}, M. Chitishvili¹⁶⁹, M.V. Chizhov^{39,t}, K. Choi¹¹, Y. Chou¹⁴², E.Y.S. Chow¹¹⁶, K.L. Chu¹⁷⁵, M.C. Chu^{64a}, X. Chu^{14,114c}, Z. Chu-binidze⁵³, J. Chudoba¹³⁴, J.J. Chwastowski⁸⁷, D. Cieri¹¹², K.M. Ciesla^{86a}, V. Cindro⁹⁵, A. Ciochio^{18a}, F. Ciotto^{72a,72b}, Z.H. Citron¹⁷⁵, M. Citterio^{71a}, D.A. Ciubotaru^{28b}, A. Clark⁵⁶, P.J. Clark⁵², N. Clarke Hall⁹⁸, C. Clarry¹⁶¹, S.E. Clawson⁴⁸, C. Clement^{47a,47b}, Y. Coadou¹⁰⁴, M. Cobal^{69a,69c}, A. Cocco^{57b}, R.F. Coelho Barrue^{133a}, R. Coelho Lopes De Sa¹⁰⁵, S. Coelli^{71a}, L.S. Colangeli¹⁶¹, B. Cole⁴², P. Collado Soto¹⁰¹, J. Collot⁶⁰, R. Coluccia^{70a,70b}, P. Conde Muino^{133a,133g}, M.P. Connell^{34c}, S.H. Connell^{34c}, E.I. Conroy¹²⁹, M. Contreras Cossio¹¹, F. Con-venti^{72a,aj}, H.G. Cooke²¹, A.M. Cooper-Sarkar¹²⁹, L. Corazzina^{75a,75b}, F.A. Corchia^{24b,24a}, A. Cordeiro Oudot Choi¹⁴², L.D. Corpe⁴¹, M. Corradi^{75a,75b}, F. Corrivau^{106,ac}, A. Cortes-Gonzalez¹⁹, M.J. Costa¹⁶⁹, F. Costanza⁴, D. Costanzo¹⁴⁵, B.M. Cote¹²², J. Couthures⁴, G. Cowan⁹⁷, K. Cranmer¹⁷⁶, L. Cremer⁴⁹, D. Cremonini^{24b,24a}, S. Crépé-Renaudin⁶⁰, F. Cresci-oli¹³⁰, T. Cresta^{73a,73b}, M. Cristinziani¹⁴⁷, M. Cristoforetti^{78a,78b}, V. Croft¹¹⁷, J.E. Crosby¹²⁴, G. Crosetti^{44b,44a}, A. Cueto¹⁰¹, H. Cui⁹⁸, Z. Cui⁷, W.R. Cunningham⁵⁹, F. Curcio¹⁶⁹, J.R. Cur-ran⁵², M.J. Da Cunha Sargedas De Sousa^{57b,57a}, J.V. Da Fon-seca Pinto^{83b}, C. Da Via¹⁰³, W. Dabrowski^{86a}, T. Dado³⁷, S. Dahbi¹⁵⁴, T. Dai¹⁰⁸, D. Dal Santo²⁰, C. Dallapiccola¹⁰⁵, M. Dam⁴³, G. D'amen³⁰, V. D'Amico¹¹¹, J. Damp¹⁰², J.R. Dan-doy³⁵, D. Dannheim³⁷, G. D'anniballe^{74a,74b}, M. Danninger¹⁴⁸, V. Dao¹⁵¹, G. Darbo^{57b}, S.J. Das³⁰, F. Dattola⁴⁸, S. D'Au-ria^{71a,71b}, A. D'Avanzo^{72a,72b}, T. Davidek¹³⁶, J. Davidson¹⁷³, I. Dawson⁹⁶, K. De⁸, C. De Almeida Rossi¹⁶¹, R. De As-mundis^{72a}, N. De Biase⁴⁸, S. De Castro^{24b,24a}, N. De Groot¹¹⁶, P. de Jong¹¹⁷, H. De la Torre¹¹⁸, A. De Maria^{114a}, A. De Salvo^{75a}, U. De Sanctis^{76a,76b}, F. De Santis^{70a,70b}, A. De Santo¹⁵², J.B. De Vivie De Regie⁶⁰, J. Debevc⁹⁵, D.V. Dedovich³⁹, J. De-gens⁹⁴, A.M. Deiana⁴⁵, J. Del Peso¹⁰¹, L. Delagrangé¹³⁰, F. De-liot¹³⁸, C.M. Delitzsch⁴⁹, M. Della Pietra^{72a,72b}, D. Della Volpe⁵⁶, A. Dell'Acqua³⁷, L. Dell'Asta^{71a,71b}, M. Delmastro⁴, C.C. De-logu¹⁰², P.A. Delsart⁶⁰, S. Demers¹⁷⁸, M. Demichev³⁹, S.P. Denisov³⁸, H. Denizli^{22a,m}, L. D'Eramo⁴¹, D. Derendaz⁸⁷, F. Derue¹³⁰, P. Dervan⁹⁴, K. Desch²⁵, F.A. Di Bello^{57b,57a}, A. Di Ciaccio^{76a,76b}, L. Di Ciaccio⁴, A. Di Domenico^{75a,75b}, C. Di Do-nato^{72a,72b}, A. Di Girolamo³⁷, G. Di Gregorio³⁷, A. Di Luca^{78a,78b}, B. Di Micco^{77a,77b}, R. Di Nardo^{77a,77b}, K.F. Di Petrillo⁴⁰, M. Diamantopoulou³⁵, F.A. Dias¹¹⁷, M.A. Diaz^{140a,140b}, A.R. Di-denko³⁹, M. Didenko¹⁶⁹, S.D. Diefenbacher^{18a}, E.B. Diehl¹⁰⁸, S. Díez Cornell⁴⁸, C. Diez Pardos¹⁴⁷, C. Dimitriadi¹⁵⁰, A. Dim-itrievska²¹, A. Dimri¹⁵¹, J. Dingfelder²⁵, T. Dingley¹²⁹, I-M. Dinu^{28b}, S.J. Dittmeier^{63b}, F. Dittus³⁷, M. Divisek¹³⁶, B. Dixit⁹⁴, F. Djama¹⁰⁴, T. Djobava^{155b}, C. Doglioni^{103,100}, A. Dohnalova^{29a}, Z. Dolezal¹³⁶, K. Domijan^{86a}, K.M. Dona⁴⁰, M. Donadelli^{83d}, B. Dong¹⁰⁹, J. Donini⁴¹, A. D'Onofrio^{72a,72b}, M. D'Onofrio⁹⁴, J. Dopke¹³⁷, A. Doria^{72a}, N. Dos Santos Fer-nandes^{133a}, P. Dougan¹⁰³, M.T. Dova⁹², A.T. Doyle⁵⁹, M.A. Draguet¹²⁹, M.P. Drescher⁵⁵, E. Dreyer¹⁷⁵, I. Drivas-koulouris¹⁰, M. Drnevich¹²⁰, M. Drozdova⁵⁶, D. Du⁶², T.A. du Pree¹¹⁷, Z. Duan^{114a}, F. Dubinin³⁹, M. Dubovsky^{29a}, E. Duchovni¹⁷⁵, G. Duckeck¹¹¹, P.K. Duckett⁹⁸, O.A. Ducu^{28b}, D. Duda⁵², A. Dudarev³⁷, E.R. Duden²⁷, M. D'uffizi¹⁰³, L. Du-flot⁶⁶, M. Dührssen³⁷, I. Duminica^{28g}, A.E. Dumitriu^{28b}, M. Dun-ford^{63a}, S. Dungs⁴⁹, K. Dunne^{47a,47b}, A. Duperrin¹⁰⁴, H. Du-ran Yildiz^{3a}, M. Düren⁵⁸, A. Durglishvili^{155b}, D. Duvnjak³⁵, B.L. Dwyer¹¹⁸, G.I. Dyckes^{18a}, M. Dyndal^{86a}, B.S. Dziedzic³⁷, Z.O. Earnshaw¹⁵², G.H. Eberwein¹²⁹, B. Eckerova^{29a}, S. Egge-breht⁵⁵, E. Egidio Purcino De Souza^{83c}, G. Eigen¹⁷, K. Ein-sweiler^{18a}, T. Ekelof¹⁶⁷, P.A. Ekman¹⁰⁰, S. El Farkh^{36b}, Y. El Ghazali⁶², H. El Jarrari³⁷, A. El Moussaouy^{36a}, V. El-lajosyula¹⁶⁷, M. Ellert¹⁶⁷, F. Ellinghaus¹⁷⁷, N. Ellis³⁷, J. Elmsheuser³⁰, M. Elsayy^{119a}, M. Elsing³⁷, D. Emelianov¹³⁷, Y. Enari⁸⁴, I. Ene^{18a}, S. Epari¹¹⁰, D. Ernani Martins Neto⁸⁷, F. Ernst³⁷, M. Errenst¹⁷⁷, M. Escalier⁶⁶, C. Escobar¹⁶⁹, E. Etzion¹⁵⁷, G. Evans^{133a,133b}, H. Evans⁶⁸, L.S. Evans⁹⁷, A. Ezhilov³⁸, S. Ezzarqtouni^{36a}, F. Fabbri^{24b,24a}, L. Fabbri^{24b,24a}, G. Facini⁹⁸, V. Fadeyev¹³⁹, R.M. Fakhruddinov³⁸, D. Fak-oudis¹⁰², S. Falciano^{75a}, L.F. Falda Ulhoa Coelho^{133a}, F. Fallavol-lita¹¹², G. Falsetti^{44b,44a}, J. Faltova¹³⁶, C. Fan¹⁶⁸, K.Y. Fan^{64b}, Y. Fan¹⁴, Y. Fang^{14,114c}, M. Fanti^{71a,71b}, M. Faraj^{69a,69b}, Z. Farazpay⁹⁹, A. Farbin⁸, A. Farilla^{77a}, T. Farooque¹⁰⁹, J.N. Farr¹⁷⁸, S.M. Farrington^{137,52}, F. Fassi^{36e}, D. Fassoulitis⁹, L. Fayard⁶⁶, P. Federic¹³⁶, P. Federicova¹³⁴, O.L. Fedin^{38,a}, M. Feickert¹⁷⁶, L. Feligioni¹⁰⁴, D.E. Fellers^{18a}, C. Feng^{143a}, Z. Feng¹¹⁷, M.J. Fenton¹⁶⁵, L. Ferencz⁴⁸, B. Fernandez Bar-badillo⁹³, P. Fernandez Martinez⁶⁷, M.J.V. Fernoux¹⁰⁴, J. Ferrando⁹³, A. Ferrari¹⁶⁷, P. Ferrari^{117,116}, R. Ferrari^{73a}, D. Ferrere⁵⁶, C. Ferretti¹⁰⁸, M.P. Fewell¹, D. Fiacco^{75a,75b}, F. Fiedler¹⁰², P. Fiedler¹³⁵, S. Filimonov³⁹, M.S. Filip^{28b,u}, A. Filipčić⁹⁵, E.K. Filmer^{162a}, F. Filthaut¹¹⁶, M.C.N. Fiol-hais^{133a,133c,c}, L. Fiorini¹⁶⁹, W.C. Fisher¹⁰⁹, T. Fitschen¹⁰³, P.M. Fitzhugh¹³⁸, I. Fleck¹⁴⁷, P. Fleischmann¹⁰⁸, T. Flick¹⁷⁷, M. Flores^{34d,ag}, L.R. Flores Castillo^{64a}, L. Flores Sanz De Acedo³⁷, F.M. Follega^{78a,78b}, N. Fomin³³, J.H. Foo¹⁶¹, A. Formica¹³⁸, A.C. Forti¹⁰³, E. Fortin³⁷, A.W. Fortman^{18a}, L. Foster^{18a}, L. Fountas^{9,j}, D. Fournier⁶⁶, H. Fox⁹³, P. Francavilla^{74a,74b}, S. Francescato⁶¹, S. Franchellucci⁵⁶, M. Franchini^{24b,24a}, S. Franchino^{63a}, D. Francis³⁷, L. Franco¹¹⁶, V. Franco Lima³⁷, L. Franconi⁴⁸, M. Franklin⁶¹, G. Frattari²⁷, Y.Y. Frid¹⁵⁷, J. Friend⁵⁹, N. Fritzsche³⁷, A. Froch⁵⁶, D. Froidevaux³⁷, J.A. Frost¹²⁹, Y. Fu¹⁰⁹, S. Fuenzalida Garrido^{140f}, M. Fu-jimoto¹⁰⁴, K.Y. Fung^{64a}, E. Furtado De Simas Filho^{83e}, M. Furukawa¹⁵⁹, J. Fuster¹⁶⁹, A. Gaa⁵⁵, A. Gabrielli^{24b,24a}, A. Gabrielli¹⁶¹, P. Gadow³⁷, G. Gagliardi^{57b,57a}, L.G. Gagnon^{18a}, S. Gaid^{88b}, S. Galantzan¹⁵⁷, J. Gallagher¹, E.J. Gallas¹²⁹, A.L. Gallen¹⁶⁷, B.J. Gallop¹³⁷, K.K. Gan¹²², S. Ganguly¹⁵⁹, Y. Gao⁵², A. Garabaglu¹⁴², F.M. Garay Walls^{140a,140b}, C. Gar-cía¹⁶⁹, A. Garcia Alonso¹¹⁷, A.G. Garcia Caffaro¹⁷⁸, J.E. Gar-cía Navarro¹⁶⁹, M. Garcia-Sciveres^{18a}, G.L. Gardner¹³¹, R.W. Gardner⁴⁰, N. Garelli¹⁶⁴, R.B. Garg¹⁴⁹, J.M. Gar-gan⁵², C.A. Garner¹⁶¹, C.M. Garvey^{34a}, V.K. Gassmann¹⁶⁴, G. Gaudio^{73a}, V. Gautam¹³, P. Gauzzi^{75a,75b}, J. Gavrancovic⁹⁵, I.L. Gavrilenko^{133a}, A. Gavriluk³⁸, C. Gay¹⁷⁰, G. Gaycken¹²⁶, E.N. Gazis¹⁰, A. Gekow¹²², C. Gemme^{57b}, M.H. Genest⁶⁰, A.D. Gentry¹¹⁵, S. George⁹⁷, T. Geralis⁴⁶, A.A. Gerwin¹²³, P. Gessinger-Befurt³⁷, M.E. Geyik¹⁷⁷, M. Ghani¹⁷³, K. Ghorban-ian⁹⁶, A. Ghosal¹⁴⁷, A. Ghosh¹⁶⁵, A. Ghosh⁷, B. Giacobbe^{24b}, S. Giagu^{75a,75b}, T. Giani¹¹⁷, A. Giannini⁶², S.M. Gibson⁹⁷, M. Gignac¹³⁹, D.T. Gil^{86b}, A.K. Gilbert^{86a}, B.J. Gilbert⁴², D. Gillberg³⁵, G. Gilles¹¹⁷, D.M. Gingrich^{2,ai}, M.P. Gior-dani^{69a,69c}, P.F. Giraud¹³⁸, G. Giugliarelli^{69a,69c}, D. Giugni^{71a}, F. Giuli^{76a,76b}, I. Gkialas^{9,j}, L.K. Gladilin³⁸, C. Glasman¹⁰¹, M. Glazewska²⁰, G. Glemža⁴⁸, M. Glisic¹²⁶, I. Gnesi^{44b}, Y. Go³⁰, M. Goblirsch-Kolb³⁷, B. Gocke⁴⁹, D. Godin¹¹⁰, B. Gokturk^{22a}, S. Goldfarb¹⁰⁷, T. Golling⁵⁶, M.G.D. Gololo^{34c}, D. Golubkov³⁸, J.P. Gombas¹⁰⁹, A. Gomes^{133a,133b}, G. Gomes Da Silva¹⁴⁷, A.J. Gomez Delegido¹⁶⁹, R. Gonçalves^{133a}, L. Gonella²¹, A. Gongadze^{155c}, F. Gonnella²¹, J.L. Gonski¹⁴⁹, R.Y. González An-dana⁵², S. González de la Hoz¹⁶⁹, M.V. Gonzalez Rodrigues⁴⁸, R. Gonzalez Suarez¹⁶⁷, S. Gonzalez-Sevilla⁵⁶, L. Goossens³⁷, B. Gorini³⁷, E. Gorini^{70a,70b}, A. Gorišek⁹⁵, T.C. Gosart¹³¹, A.T. Goshaw⁵¹, M.I. Gostkin³⁹, S. Goswami¹²⁴, C.A. Got-tardo³⁷, S.A. Gotz¹¹¹, M. Gouighri^{36b}, A.G. Goussiou¹⁴², N. Govender^{34c}, R.P. Grabarczyk¹²⁹, I. Grabowska-Bold^{86a},

- K. Graham³⁵, E. Gramstad¹²⁸, S. Grancagnolo^{70a,70b}, C.M. Grant¹, P.M. Gravila^{28f}, F.G. Gravili^{70a,70b}, H.M. Gray^{18a}, M. Greco¹¹², M.J. Green¹, C. Grefe²⁵, A.S. Grefsrud¹⁷, I.M. Gregor⁴⁸, K.T. Greif¹⁶⁵, P. Grenier¹⁴⁹, S.G. Grewe¹¹², A.A. Grillo¹³⁹, K. Grimm³², S. Grinstein^{13,y}, J.-F. Grivaz⁶⁶, E. Gross¹⁷⁵, J. Grosse-Knetter⁵⁵, L. Guan¹⁰⁸, G. Guerrieri³⁷, R. Guevara¹²⁸, R. Gugel¹⁰², J.A.M. Guhit¹⁰⁸, A. Guida¹⁹, E. Guillon¹⁷³, S. Guindon³⁷, F. Guo^{14,114c}, J. Guo^{144a}, L. Guo⁴⁸, L. Guo^{114b,w}, Y. Guo¹⁰⁸, A. Gupta⁴⁹, R. Gupta¹³², S. Gupta²⁷, S. Gurbuz²⁵, S.S. Gurdasani⁴⁸, G. Gustavo^{75a,75b}, P. Gutierrez¹²³, L.F. Gutierrez Zagazeta¹³¹, M. Gutsche⁵⁰, C. Gutsche⁹⁸, C. Gwenlan¹²⁹, C.B. Gwilliam⁹⁴, E.S. Haaland¹²⁸, A. Haas¹²⁰, M. Habedank⁵⁹, C. Haber^{18a}, H.K. Hadavand⁸, A. Haddad⁴¹, A. Hadeef⁵⁰, A.I. Hagan⁹³, J.J. Hahn¹⁴⁷, E.H. Haines⁹⁸, M. Haleem¹⁷², J. Haley¹²⁴, G.D. Halletwell¹⁰⁴, L. Halser²⁰, K. Hamano¹⁷¹, M. Hamer²⁵, S.E.D. Hammoud⁶⁶, E.J. Hampshire⁹⁷, J. Han^{143a}, L. Han^{114a}, L. Han⁶², S. Han^{18a}, K. Hanagaki⁸⁴, M. Hance¹³⁹, D.A. Hangal⁴², H. Hanif¹⁴⁸, M.D. Hank¹³¹, J.B. Hansen⁴³, P.H. Hansen⁴³, D. Harada⁵⁶, T. Harenberg¹⁷⁷, S. Harkusha¹⁷⁹, M.L. Harris¹⁰⁵, Y.T. Harris²⁵, J. Harrison¹³, N.M. Harrison¹²², P.F. Harrison¹⁷³, M.L.E. Hart⁹⁸, N.M. Hartman¹¹², N.M. Hartmann¹¹¹, R.Z. Hasan^{97,137}, Y. Hasegawa¹⁴⁶, F. Haslbeck¹²⁹, S. Hassan¹⁷, R. Hauser¹⁰⁹, M. Haviernik¹³⁶, C.M. Hawkes²¹, R.J. Hawkins³⁷, Y. Hayashi¹⁵⁹, D. Hayden¹⁰⁹, C. Hayes¹⁰⁸, R.L. Hayes¹¹⁷, C.P. Hays¹²⁹, J.M. Hays⁹⁶, H.S. Hayward⁹⁴, M. He^{14,114c}, Y. He⁴⁸, Y. He⁹⁸, N.B. Heatley⁹⁶, V. Hedberg¹⁰⁰, C. Heidegger⁵⁴, K.K. Heidegger⁵⁴, J. Heilmann³⁵, S. Heim⁴⁸, T. Heim^{18a}, J.G. Heinlein¹³¹, J.J. Heinrich¹²⁶, L. Heinrich¹¹², J. Hejbal¹³⁴, M. Helbig⁵⁰, A. Held¹⁷⁶, S. Hellesund¹⁷, C.M. Helling¹⁷⁰, S. Hellman^{47a,47b}, L. Henkelmann³³, A.M. Henriques Correia³⁷, H. Herde¹⁰⁰, Y. Hernández Jiménez¹⁵¹, L.M. Herrmann²⁵, T. Herrmann⁵⁰, G. Herten⁵⁴, R. Hertenberger¹¹¹, L. Hervas³⁷, M.E. Hespings¹⁰², N.P. Hessay^{162a}, J. Hessler¹¹², M. Hidaoui^{36b}, N. Hidic¹³⁶, E. Hill¹⁶¹, S.J. Hillier²¹, J.R. Hinds¹⁰⁹, F. Hinterkeuser²⁵, M. Hirose¹²⁷, S. Hirose¹⁶³, D. Hirschbuehl¹⁷⁷, T.G. Hitchings¹⁰³, B. Hiti⁹⁵, J. Hobbs¹⁵¹, R. Hobincu^{28e}, N. Hod¹⁷⁵, A.M. Hodges¹⁶⁸, M.C. Hodgkinson¹⁴⁵, B.H. Hodgkinson¹²⁹, A. Hoecker³⁷, D.D. Hofer¹⁰⁸, J. Hofer¹⁶⁹, M. Holzbock³⁷, L.B.A.H. Hommels³³, V. Homsak¹²⁹, B.P. Honan¹⁰³, J.J. Hong⁶⁸, T.M. Hong¹³², B.H. Hooberman¹⁶⁸, W.H. Hopkins⁶, M.C. Hoppesch¹⁶⁸, Y. Horii¹¹³, M.E. Horstmann¹¹², S. Hou¹⁵⁴, M.R. Housenga¹⁶⁸, A.S. Howard⁹⁵, J. Howarth⁵⁹, J. Hoya⁶, M. Hrabovsky¹²⁵, T. Hryn'ova⁴, P.J. Hsu⁶⁵, S.-C. Hsu¹⁴², T. Hsu⁶⁶, M. Hu^{18a}, Q. Hu⁶², S. Huang³³, X. Huang^{14,114c}, Y. Huang¹³⁶, Y. Huang^{114b}, Y. Huang¹⁰², Y. Huang¹⁴, Z. Huang⁶⁶, Z. Hubacek¹³⁵, M. Huebner²⁵, F. Huegging²⁵, T.B. Huffman¹²⁹, M. Hufnagel Maranha De Faria^{83a}, C.A. Hugli⁴⁸, M. Huhtinen³⁷, S.K. Huiberts¹⁷, R. Hulsken¹⁰⁶, C.E. Hultquist^{18a}, N. Huseynov^{12,g}, J. Huston¹⁰⁹, J. Huth⁶¹, R. Hyneman⁷, G. Iacobucci⁵⁶, G. Iakovidis³⁰, L. Iconomidou-Fayard⁶⁶, J.P. Iddon³⁷, P. Iengo^{72a,72b}, R. Iguchi¹⁵⁹, Y. Iiyama¹⁵⁹, T. Iizawa¹⁵⁹, Y. Ikegami⁸⁴, D. Iliadis¹⁵⁸, N. Ilie¹⁶¹, H. Imam^{36a}, G. Inacio Goncalves^{83d}, S.A. Infante Cabanas^{140c}, T. Ingebrechtsen Carlson^{47a,47b}, J.M. Inglis⁹⁶, G. Introzzi^{73a,73b}, M. Iodice^{77a}, V. Ippolito^{75a,75b}, R.K. Irwin⁹⁴, M. Ishino¹⁵⁹, W. Islam¹⁷⁶, C. Issever¹⁹, S. Istin^{22a,an}, K. Itabashi⁸⁴, H. Ito¹⁷⁴, R. Iuppa^{78a,78b}, A. Ivina¹⁷⁵, V. Izzo^{72a}, P. Jacka¹³⁴, P. Jackson¹, P. Jain⁴⁸, K. Jakobs⁵⁴, T. Jakoubek¹⁷⁵, J. Jamieson⁵⁹, W. Jang¹⁵⁹, S. Jankovych¹³⁶, M. Javurkova¹⁰⁵, P. Jawahar¹⁰³, L. Jeanty¹²⁶, J. Jelkova^{155a,af}, P. Jenni^{54,f}, C.E. Jesiman³⁵, C. Jia^{143a}, H. Jia¹⁷⁰, J. Jia¹⁵¹, X. Jia^{14,114c}, Z. Jia^{114a}, C. Jiang⁵², Q. Jiang^{64b}, S. Jiggins⁴⁸, M. Jimenez Ortega¹⁶⁹, J. Jimenez Pena¹³, S. Jin^{114a}, A. Jinaru^{28b}, O. Jinouchi¹⁴¹, P. Johansson¹⁴⁵, K.A. Johns⁷, J.W. Johnson¹³⁹, F.A. Jolly⁴⁸, D.M. Jones¹⁵², E. Jones⁴⁸, K.S. Jones⁸, P. Jones³³, R.W.L. Jones⁹³, T.J. Jones⁹⁴, H.L. Joos^{55,37}, R. Joshi¹²², J. Jovicevic¹⁶, X. Ju^{18a}, J.J. Junggeburth³⁷, T. Junkermann^{63a}, A. Juste Rozas^{13,y}, M.K. Juzek⁸⁷, S. Kabana^{140e}, A. Kaczmarska⁸⁷, M. Kado¹¹², H. Kagan¹²², M. Kagan¹⁴⁹, A. Kahn¹³¹, C. Kahra¹⁰², T. Kaji¹⁵⁹, E. Kajomovitz¹⁵⁶, N. Kakati¹⁷⁵, N. Kakoty¹³, I. Kalaitzidou⁵⁴, S. Kandel⁸, N.J. Kang¹³⁹, D. Kar^{34g}, K. Karava¹²⁹, E. Karentzos²⁵, O. Karkout¹¹⁷, S.N. Karpov³⁹, Z.M. Karpova³⁹, V. Kartvelishvili⁹³, A.N. Karyukhin³⁸, E. Kasimi¹⁵⁸, J. Katzy⁴⁸, S. Kaur³⁵, K. Kawade¹⁴⁶, M.P. Kawale¹²³, C. Kawamoto⁸⁹, T. Kawamoto⁶², E.F. Kay³⁷, F.I. Kaya¹⁶⁴, S. Kazakov¹⁰⁹, V.F. Kazanin³⁸, J.M. Keaveney^{34a}, R. Keeler¹⁷¹, G.V. Kehris⁶¹, J.S. Keller³⁵, J.J. Kempster¹⁵², O. Kepka¹³⁴, J. Kerr^{162b}, B.P. Kerridge¹³⁷, B.P. Kerševan⁹⁵, L. Keszeghova^{29a}, R.A. Khan¹³², A. Khanov¹²⁴, A.G. Kharlamov³⁸, T. Kharlamova³⁸, E.E. Khoda¹⁴², M. Kholodenko^{133a}, T.J. Khoo¹⁹, G. Khorauli¹⁷², Y. Khoulaki^{36a}, J. Khubua^{155b,*}, Y.A.R. Khwaira¹³⁰, B. Kibirige^{34g}, D. Kim⁶, D.W. Kim^{47a,47b}, Y.K. Kim⁴⁰, N. Kimura⁹⁸, M.K. Kingston⁵⁵, A. Kirchhoff⁵⁵, C. Kirfel²⁵, F. Kirfel²⁵, J. Kirk¹³⁷, A.E. Kiryunin¹¹², S. Kita¹⁶³, O. Kivernyk²⁵, M. Klassen¹⁶⁴, C. Klein³⁵, L. Klein¹⁷², M.H. Klein⁴⁵, S.B. Klein⁵⁶, U. Klein⁹⁴, A. Klimentov³⁰, T. Kliuchnikova³⁷, P. Kluit¹¹⁷, S. Kluth¹¹², E. Kneringer⁷⁹, T.M. Knight¹⁶¹, A. Knue⁴⁹, M. Kobel⁵⁰, D. Kobylanski¹⁷⁵, S.F. Koch¹²⁹, M. Kocian¹⁴⁹, P. Kodyš¹³⁶, D.M. Koeck¹²⁶, T. Koffas³⁵, O. Kolay⁵⁰, I. Koletsou⁴, T. Komarek⁸⁷, K. Köneke⁵⁵, A.X.Y. Kong¹, T. Kono¹²¹, N. Konstantinidis⁹⁸, P. Kontaxakis⁵⁶, B. Konya¹⁰⁰, R. Kopeliansky⁴², S. Koperny^{86a}, K. Korcyl⁸⁷, K. Kordas^{158,d}, A. Korn⁹⁸, S. Korn⁵⁵, I. Korolkov¹³, N. Korotkova³⁸, B. Kortman¹¹⁷, O. Kortner¹¹², S. Kortner¹¹², W.H. Kostecka¹¹⁸, M. Kostov^{29a}, V.V. Kostyukhin¹⁴⁷, A. Kotschechagia³⁷, A. Kotwal⁵¹, A. Koulouris³⁷, A. Kourkoulis-Charalampidis^{73a,73b}, C. Kourkoulis⁹, E. Kourlitis¹¹², O. Kovanda¹²⁶, R. Kowalewski¹⁷¹, W. Kozanecki¹²⁶, A.S. Kozhin³⁸, V.A. Kramarenko³⁸, G. Kramberger⁹⁵, P. Kramer²⁵, M.W. Krasny¹³⁰, A. Krasznahorkay¹⁰⁵, A.C. Kraus¹¹⁸, J.W. Kraus¹⁷⁷, J.A. Kremer⁴⁸, N.B. Krenkel¹⁴⁷, T. Kresse⁵⁰, L. Kretschmann¹⁷⁷, J. Kretschmar⁹⁴, K. Kreul¹⁹, P. Krieger¹⁶¹, K. Krizka²¹, K. Kroeninger⁴⁹, H. Kroha¹¹², J. Kroll¹³⁴, J. Kroll¹³¹, K.S. Krowpman¹⁰⁹, U. Kruchonak³⁹, H. Krüger²⁵, N. Krumnack⁸¹, M.C. Kruse⁵¹, O. Kuchinskaja³⁹, S. Kuday^{3a}, S. Kuehn³⁷, R. Kuesters⁵⁴, T. Kuhl⁴⁸, V. Kukhtin³⁹, Y. Kulchitsky³⁹, S. Kuleshov^{140d,140b}, J. Kull¹, M. Kumar^{34g}, N. Kumari⁴⁸, P. Kumari^{162b}, A. Kupco¹³⁴, T. Kupfer⁴⁹, A. Kupich³⁸, O. Kuprash⁵⁴, H. Kurashige⁸⁵, L.L. Kurchaninov^{162a}, O. Kurdysh⁴, Y.A. Kurochkin³⁸, A. Kurova³⁸, M. Kuze¹⁴¹, A.K. Kvam¹⁰⁵, J. Kvita¹²⁵, N.G. Kyriacou¹⁰⁸, C. Lacasta¹⁶⁹, F. Lacava^{75a,75b}, H. Lacker¹⁹, D. Lacour¹³⁰, N.N. Lad⁹⁸, E. Ladygin³⁹, A. Lafarge⁴¹, B. Laforge¹³⁰, T. Lagouri¹⁷⁸, F.Z. Lahbabi^{36a}, S. Lai⁵⁵, J.E. Lambert¹⁷¹, S. Lammers⁶⁸, W. Lampl⁷, C. Lampoudis^{158,d}, G. Lamprioudis¹⁰², A.N. Lancaster¹¹⁸, E. Lançon³⁰, U. Landgraf⁵⁴, M.P.J. Landon⁹⁶, V.S. Lang⁵⁴, O.K.B. Langrekken¹²⁸, A.J. Lankford¹⁶⁵, F. Lanni³⁷, K. Lantzsch²⁵, A. Lanza^{73a}, M. Lanza Berrocal¹⁶⁹, J.F. Laporte¹³⁸, T. Lari^{71a}, D. Larsen¹⁷, L. Larson¹¹, F. Lasagni Manghi^{24b}, M. Lassnig³⁷, S.D. Lawlor¹⁴⁵, R. Lazaridou¹⁷³, M. Lazzaroni^{71a,71b}, H.D.M. Le¹⁰⁹, E.M. Le Boulicaut¹⁷⁸, L.T. Le Pottier^{18a}, B. Leban^{24b,24a}, F. Ledroit-Guillon⁶⁰, T.F. Lee^{162b}, L.L. Leeuw^{34c}, M. Lefebvre¹⁷¹, C. Leggett^{18a}, G. Lehmann Miotto³⁷, M. Leigh⁵⁶, W.A. Leight¹⁰⁵, W. Leinonen¹¹⁶, A. Leisos^{158,v}, M.A.L. Leite^{83c}, C.E. Leitgeb¹⁹, R. Leitner¹³⁶, K.J.C. Leney⁴⁵, T. Lenz²⁵, S. Leone^{74a}, C. Leonidopoulos⁵², A. Leopold¹⁵⁰, J.H. Lepage Bourbonnais³⁵, R. Les¹⁰⁹, C.G. Lester³³, M. Levchenko³⁸, J. Levêque⁴, L.J. Levinson¹⁷⁵, G. Levirini^{24b,24a}, M.P. Lewicki⁸⁷, C. Lewis¹⁴², D.J. Lewis⁴, L. Lewitt¹⁴⁵, A. Li³⁰, B. Li^{143a}, C. Li¹⁰⁸, C.-Q. Li¹¹², H. Li^{143a}, H. Li¹⁰³, H. Li¹⁵, H. Li⁶², H. Li^{143a}, J. Li^{144a}, K. Li¹⁴

L. Li^{144a}, R. Li¹⁷⁸, S. Li^{14,114c}, S. Li^{144b,144a}, T. Li⁵, X. Li¹⁰⁶, Z. Li¹⁵⁹, Z. Li^{14,114c}, Z. Li⁶², S. Liang^{14,114c}, Z. Liang¹⁴, M. Liberatore¹³⁸, B. Liberti^{76a}, K. Lie^{64c}, J. Lieber Marin^{83e}, H. Lien⁶⁸, H. Lin¹⁰⁸, S.F. Lin¹⁵¹, L. Linden¹¹¹, R.E. Lindley⁷, J.H. Lindon³⁷, J. Ling⁶¹, E. Lipeles¹³¹, A. Lipniacka¹⁷, A. Lister¹⁷⁰, J.D. Little⁶⁸, B. Liu¹⁴, B.X. Liu^{114b}, D. Liu^{144b,144a}, D. Liu¹³⁹, E.H.L. Liu²¹, J.K.K. Liu¹²⁰, K. Liu^{144b}, K. Liu^{144b,144a}, M. Liu⁶², M.Y. Liu⁶², P. Liu¹⁴, Q. Liu^{144b,142,144a}, X. Liu⁶², X. Liu^{143a}, Y. Liu^{114b,114c}, Y.L. Liu^{143a}, Y.W. Liu⁶², Z. Liu^{66,j}, S.L. Lloyd⁹⁶, E.M. Lobodzinska⁴⁸, P. Loch⁷, E. Lodhi¹⁶¹, T. Lohse¹⁹, K. Lohwasser¹⁴⁵, E. Loiacono⁴⁸, J.D. Lomas²¹, J.D. Long⁴², I. Longarini¹⁶⁵, R. Longo¹⁶⁸, A. Lopez Solis¹³, N.A. Lopez-canelas⁷, N. Lorenzo Martinez⁴, A.M. Lory¹¹¹, M. Losada^{119a}, G. Löschke Centeno¹⁵², X. Lou^{47a,47b}, X. Lou^{14,114c}, A. Lounis⁶⁶, P.A. Love⁹³, M. Lu⁶⁶, S. Lu¹³¹, Y.J. Lu¹⁵⁴, H.J. Lubatti¹⁴², C. Luci^{75a,75b}, F.L. Lucio Alves^{114a}, F. Luehring⁶⁸, B.S. Lunday¹³¹, O. Lundberg¹⁵⁰, J. Lunde³⁷, N.A. Luongo⁶, M.S. Lutz³⁷, A.B. Lux²⁶, D. Lynn³⁰, R. Lysak¹³⁴, V. Lysenko¹³⁵, E. Lytken¹⁰⁰, V. Lyubushkin³⁹, T. Lyubushkina³⁹, M.M. Lyukova¹⁵¹, M.Firdaus M. Soberi⁵², H. Ma³⁰, K. Ma⁶², L.L. Ma^{143a}, W. Ma⁶², Y. Ma¹²⁴, J.C. MacDonald¹⁰², P.C. Machado De Abreu Farias^{83e}, R. Madar⁴¹, T. Madula⁹⁸, J. Maeda⁸⁵, T. Maeno³⁰, P.T. Mafa^{34c,k}, H. Maguire¹⁴⁵, V. Maiboroda⁶⁶, A. Maio^{133a,133b,133d}, K. Maj^{86a}, O. Majersky⁴⁸, S. Majewski¹²⁶, R. Makhmanazarov³⁸, N. Makovec⁶⁶, V. Maksimovic¹⁶, B. Malaescu¹³⁰, J. Malamant¹²⁸, Pa. Malecki⁸⁷, V.P. Maleev³⁸, F. Malek^{60,p}, M. Mali⁹⁵, D. Malito⁹⁷, U. Mallik^{80,*}, A. Maloizel⁵, S. Maltezos¹⁰, A. Malvezzi Lopes^{83d}, S. Malyukov³⁹, J. Mamuzic¹³, G. Mancini⁵³, M.N. Mancini²⁷, G. Manco^{73a,73b}, J.P. Mandalia⁹⁶, S.S. Mandarri¹⁵², I. Mandić⁹⁵, L. Manhaes de Andrade Filho^{83a}, I.M. Maniatis¹⁷⁵, J. Manjares Ramos⁹¹, D.C. Mankad¹⁷⁵, A. Mann¹¹¹, T. Manoussos³⁷, M.N. Mantinan⁴⁰, S. Manzoni³⁷, L. Mao^{144a}, X. Mapekula^{34c}, A. Marantis¹⁵⁸, R.R. Marcelo Gregorio⁹⁶, G. Marchiori⁵, M. Marcisovsky¹³⁴, C. Marcon^{71a}, E. Maricic¹⁶, M. Marinescu⁴⁸, S. Marium⁴⁸, M. Marjanovic¹²³, A. Markhoos⁵⁴, M. Markovitch⁶⁶, M.K. Maroun¹⁰⁵, G.T. Marsden¹⁰³, E.J. Marshall⁹³, Z. Marshall^{18a}, S. Marti-Garcia¹⁶⁹, J. Martin⁹⁸, T.A. Martin¹³⁷, V.J. Martin⁵², B. Martin dit Latour¹⁷, L. Martinelli^{75a,75b}, M. Martinez^{13,y}, P. Martinez Agullo¹⁶⁹, V.I. Martinez Outschoorn¹⁰⁵, P. Martinez Suarez¹³, S. Martin-Haugh¹³⁷, G. Martinovicova¹³⁶, V.S. Martoiu^{28b}, A.C. Martyniuk⁹⁸, A. Marzin³⁷, D. Mascione^{78a,78b}, L. Masetti¹⁰², J. Masik¹⁰³, A.L. Maslennikov³⁹, S.L. Mason⁴², P. Massarotti^{72a,72b}, P. Masstrandrea^{74a,74b}, A. Mastroberardino^{44b,44a}, T. Masubuchi¹²⁷, T.T. Mathew¹²⁶, J. Matousek¹³⁶, D.M. Mattern⁴⁹, J. Maurer^{28b}, T. Maurin⁵⁹, A.J. Maury⁶⁶, B. Maček⁹⁵, C. Mavungu Tsava¹⁰⁴, D.A. Maximov³⁸, A.E. May¹⁰³, E. Mayer⁴¹, R. Mazini^{34g}, I. Maznas¹¹⁸, S.M. Mazza¹³⁹, E. Mazzeo^{71a,71b}, J.P. Mc Gowan¹⁷¹, S.P. Mc Kee¹⁰⁸, C.A. Mc Lean⁶, C.C. McCracken¹⁷⁰, E.F. McDonald¹⁰⁷, A.E. McDougall¹¹⁷, L.F. Mcelhinney⁹³, J.A. Mcfayden¹⁵², R.P. McGovern¹³¹, R.P. Mckenzie^{34g}, T.C. McLachlan⁴⁸, D.J. McLaughlin⁹⁸, S.J. McMahon¹³⁷, C.M. Mcpartland⁹⁴, R.A. McPherson^{171,ac}, S. Mehlhase¹¹¹, A. Mehta⁹⁴, D. Melini¹⁶⁹, B.R. Mellado Garcia^{34g}, A.H. Melo⁵⁵, F. Meloni⁴⁸, A.M. Mendes Jacques Da Costa¹⁰³, L. Meng⁹³, S. Menke¹¹², M. Mentink³⁷, E. Meoni^{44b,44a}, G. Mercado¹¹⁸, S. Merianos¹⁵⁸, C. Merlassino^{69a,69c}, C. Meroni^{71a,71b}, J. Metcalfe⁶, A.S. Mete⁶, E. Meuser¹⁰², C. Meyer⁶⁸, J.-P. Meyer¹³⁸, Y. Miao^{114a}, R.P. Middleton¹³⁷, M. Mihovilovic⁶⁶, L. Mijović⁵², G. Mikenberg¹⁷⁵, M. Mikestikova¹³⁴, M. Mikuž⁹⁵, H. Mildner¹⁰², A. Milic³⁷, D.W. Miller⁴⁰, E.H. Miller¹⁴⁹, L.S. Miller³⁵, A. Milov¹⁷⁵, D.A. Milstead^{47a,47b}, T. Min^{114a}, A.A. Minaenko³⁸, I.A. Minashvili^{155b}, A.I. Mincer¹²⁰, B. Mindur^{86a}, M. Mineev³⁹, Y. Mino⁸⁹, L.M. Mir¹³, M. Miralles Lopez⁵⁹, M. Mironova^{18a}, M.C. Missio¹¹⁶, A. Mitra¹⁷³, V.A. Mitsou¹⁶⁹, Y. Mitsumori¹¹³, O. Miu¹⁶¹, P.S. Miyagawa⁹⁶, T. Mkrtchyan^{63a}, M. Mlinarevic⁹⁸, T. Mlinarevic⁹⁸, M. Mlynarikova³⁷, S. Mobius²⁰, M.H. Mohamed Farook¹¹⁵, A.F. Mohammed^{14,114c}, S. Mohapatra⁴², S. Mohiuddin¹²⁴, G. Mokgatitswane^{34g}, L. Moleri¹⁷⁵, U. Molinatti¹²⁹, L.G. Mollier²⁰, B. Mondal¹³⁴, S. Mondal¹³⁵, K. Mönig⁴⁸, E. Monnier¹⁰⁴, L. Monsonis Romero¹⁶⁹, J. Montejo Berlingen¹³, A. Montella^{47a,47b}, M. Montella¹²², F. Montereali^{77a,77b}, F. Monticelli⁹², S. Monzani^{69a,69c}, A. Moranco Tarda⁴³, N. Morange⁶⁶, A.L. Moreira De Carvalho⁴⁸, M. Moreno Llacer¹⁶⁹, C. Moreno Martinez⁵⁶, J.M. Moreno Perez^{23b}, P. Morettini^{57b}, S. Morgenstern³⁷, M. Morii⁶¹, M. Morinaga¹⁵⁹, M. Moritsu⁹⁰, F. Morodei^{75a,75b}, P. Moschovakos³⁷, B. Moser⁵⁴, M. Mosidze^{155b}, T. Moskalets⁴⁵, P. Moskvitina¹¹⁶, J. Moss³², P. Moszkowicz^{86a}, A. Moussa^{36d}, Y. Moyal¹⁷⁵, H. Moyano Gomez¹³, E.J.W. Moyse¹⁰⁵, O. Mtintsilana^{34g}, S. Muanza¹⁰⁴, M. Mucha²⁵, J. Mueller¹³², R. Müller³⁷, G.A. Mullier¹⁶⁷, A.J. Mullin³³, J.J. Mullin⁵¹, A.C. Mullins⁴⁵, A.E. Mulski⁶¹, D.P. Mungo¹⁶¹, D. Munoz Perez¹⁶⁹, F.J. Munoz Sanchez¹⁰³, W.J. Murray^{173,137}, M. Muškinja⁹⁵, C. Mwewa⁴⁸, A.G. Myagkov^{38,a}, A.J. Myers⁸, G. Myers¹⁰⁸, M. Myska¹³⁵, B.P. Nachman^{18a}, K. Nagai¹²⁹, K. Nagano⁸⁴, R. Nagasaka¹⁵⁹, J.L. Nagle^{30,ak}, E. Nagy¹⁰⁴, A.M. Nairz³⁷, Y. Nakahama⁸⁴, K. Nakamura⁸⁴, K. Nakkalil⁵, H. Nanjo¹²⁷, E.A. Narayanan⁴⁵, Y. Narukawa¹⁵⁹, I. Naryshkin³⁸, L. Nasella^{71a,71b}, S. Nasri^{119b}, C. Nass²⁵, G. Navarro^{23a}, J. Navarro-Gonzalez¹⁶⁹, A. Nayaz¹⁹, P.Y. Nechaeva³⁸, S. Nechaeva^{24b,24a}, F. Nechansky¹³⁴, L. Nedic¹²⁹, T.J. Neep²¹, A. Negri^{73a,73b}, M. Negrini^{24b}, C. Nellist¹¹⁷, C. Nelson¹⁰⁶, K. Nelson¹⁰⁸, S. Nemecek¹³⁴, M. Nessi^{37,h}, M.S. Neubauer¹⁶⁸, J. Newell⁹⁴, P.R. Newman²¹, Y.W.Y. Ng¹⁶⁸, B. Ngair^{119a}, H.D.N. Nguyen¹¹⁰, J.D. Nichols¹²³, R.B. Nickerson¹²⁹, R. Nicolaidou¹³⁸, J. Nielsen¹³⁹, M. Niemeyer⁵⁵, J. Niermann³⁷, N. Nikiforou³⁷, V. Nikolaenko^{38,a}, I. Nikolic-Audit¹³⁰, P. Nilsson³⁰, I. Ninca⁴⁸, G. Ninio¹⁵⁷, A. Nisati^{75a}, N. Nishu², R. Nisius¹¹², N. Nitika^{69a,69c}, J.-E. Nitschke⁵⁰, E.K. Nkadameng^{34b}, T. Nobe¹⁵⁹, T. Nommensen¹⁵³, M.B. Norfolk¹⁴⁵, B.J. Norman³⁵, M. Noury^{36a}, J. Novak⁹⁵, T. Novak⁹⁵, R. Novotny¹³⁵, L. Nozka¹²⁵, K. Ntekas¹⁶⁵, N.M.J. Nunes De Moura Junior^{83b}, J. Ocariz¹³⁰, A. Ochi⁸⁵, I. Ochoa^{133a}, S. Oerdek^{48,z}, J.T. Offermann⁴⁰, A. Ogrodnik¹³⁶, A. Oh¹⁰³, C.C. Ohm¹⁵⁰, H. Oide⁸⁴, M.L. Ojeda³⁷, Y. Okumura¹⁵⁹, L.F. Oleiro Seabra^{133a}, I. Oleksiyuk⁵⁶, G. Oliveira Correa¹³, D. Oliveira Damazio³⁰, J.L. Oliver¹⁶⁵, Ö.O. Öncel⁵⁴, A.P. O'Neill²⁰, A. Onofre^{133a,133e,e}, P.U.E. Onyisi¹¹, M.J. Oreglia⁴⁰, D. Orestano^{77a,77b}, R. Orlandini^{77a,77b}, R.S. Orr¹⁶¹, L.M. Osojnak¹³¹, Y. Osumi¹¹³, G. Otero y Garzon³¹, H. Otono⁹⁰, G.J. Ottino^{18a}, M. Ouchrif^{36d}, F. Ould-Saada¹²⁸, T. Ovsianikova¹⁴², M. Owen⁵⁹, R.E. Owen¹³⁷, V.E. Ozcan^{22a}, F. Ozturk⁸⁷, N. Ozturk⁸, S. Ozturk⁸², H.A. Pacey¹²⁹, K. Pachal^{162a}, A. Pacheco Pages¹³, C. Padilla Aranda¹³, G. Padovano^{75a,75b}, S. Pagan Griso^{18a}, G. Palacino⁶⁸, A. Palazzo^{70a,70b}, J. Pampel²⁵, J. Pan¹⁷⁸, T. Pan^{64a}, D.K. Panchal¹¹, C.E. Pandini¹¹⁷, J.G. Panduro Vazquez¹³⁷, H.D. Pandya¹, H. Pang¹³⁸, P. Pani⁴⁸, G. Panizzo^{69a,69c}, L. Panwar¹³⁰, L. Paolozzi⁵⁶, S. Parajuli¹⁶⁸, A. Paramonov⁶, C. Paraskevopoulos⁵³, D. Paredes Hernandez^{64b}, A. Pareti^{73a,73b}, K.R. Park⁴², T.H. Park¹¹², F. Parodi^{57b,57a}, J.A. Parsons⁴², U. Parzefall⁵⁴, B. Pascual Dias⁴¹, L. Pascual Dominguez¹⁰¹, E. Pasqualucci^{75a}, S. Passaggio^{57b}, F. Pastore⁹⁷, P. Patel⁸⁷, U.M. Patel⁵¹, J.R. Pater¹⁰³, T. Pauly³⁷, F. Pauwels¹³⁶, C.I. Pazos¹⁶⁴, M. Pedersen¹²⁸, R. Pedro^{133a}, S.V. Peleganchuk³⁸, O. Penc³⁷, E.A. Pender⁵², S. Peng¹⁵, G.D. Penn¹⁷⁸, K.E. Penski¹¹¹, M. Penzin³⁸, B.S. Peralva^{83d}, A.P. Pereira Peixoto¹⁴², L. Pereira Sanchez¹⁴⁹, D.V. Perepelitsa^{30,ak}, G. Perera¹⁰⁵, E. Perez Codina^{162a}, M. Perganti¹⁰, H. Pernegger³⁷, S. Perrella^{75a,75b}, O. Perrin⁴¹, K. Peters⁴⁸, R.F.Y. Peters¹⁰³, B.A. Petersen³⁷, T.C. Petersen⁴³, E. Petit¹⁰⁴, V. Petousis¹³⁵, A.R. Petri^{71a,71b}, C. Petridou^{158,d}

- T. Petru¹³⁶, A. Petrukhin¹⁴⁷, M. Pettee^{18a}, A. Petukhov⁸², K. Petukhova³⁷, R. Pezoa^{140f}, L. Pezzotti^{24b,24a}, G. Pezzullo¹⁷⁸, L. Pfaffenbichler³⁷, A.J. Pflieger³⁷, T.M. Pham¹⁷⁶, T. Pham¹⁰⁷, P.W. Phillips¹³⁷, G. Piacquadio¹⁵¹, E. Pianori^{18a}, F. Piazza¹²⁶, R. Piegai³¹, D. Pietreanu^{28b}, A.D. Pilkington¹⁰³, M. Pinamonti^{69a,69c}, J.L. Pinfold², B.C. Pinheiro Pereira^{133a}, J. Pinol Bel¹³, A.E. Pinto Pinoargote¹³⁰, L. Pintucci^{69a,69c}, K.M. Piper¹⁵², A. Pirttikoski⁵⁶, D.A. Pizzi³⁵, L. Pizzimento^{64b}, A. Plebani³³, M.-A. Pleier³⁰, V. Pleskot¹³⁶, E. Plotnikova³⁹, G. Poddar⁹⁶, R. Poettgen¹⁰⁰, L. Poggioli¹³⁰, S. Polacek¹³⁶, G. Polese^{73a}, A. Poley¹⁴⁸, A. Polini^{24b}, C.S. Pollard¹⁷³, Z.B. Pollock¹²², E. Pompa Pacchi¹²³, N.I. Pond⁹⁸, D. Ponomarenko⁶⁸, L. Pontecorvo³⁷, S. Popa^{28a}, G.A. Popeneciu^{28d}, A. Poreba³⁷, D.M. Portillo Quintero^{162a}, S. Pospisil¹³⁵, M.A. Postill¹⁴⁵, P. Postolache^{28c}, K. Potamianos¹⁷³, P.A. Potepa^{86a}, I.N. Potrap³⁹, C.J. Potter³³, H. Potti¹⁵³, J. Poveda¹⁶⁹, M.E. Pozo Astigarraga³⁷, R. Pozzi³⁷, A. Prades Ibanez^{76a,76b}, J. Pretel¹⁷¹, D. Price¹⁰³, M. Primavera^{70a}, L. Primomo^{69a,69c}, M.A. Principe Martin¹⁰¹, R. Privara¹²⁵, T. Procter^{86b}, M.L. Proffitt¹⁴², N. Proklova¹³¹, K. Prokofiev^{64c}, G. Proto¹¹², J. Proudfoot⁶, M. Przybicien^{86a}, W.W. Przygoda^{86b}, A. Psallidas⁴⁶, J.E. Puddefoot¹⁴⁵, D. Pudzha⁵³, D. Pyatizbyantseva¹¹⁶, J. Qian¹⁰⁸, R. Qian¹⁰⁹, D. Qichen¹⁰³, Y. Qin¹³, T. Qiu⁵², A. Quadt⁵⁵, M. Queitsch-Maitland¹⁰³, G. Quetant⁵⁶, R.P. Quinn¹⁷⁰, G. Rabanal Bolanos⁶¹, D. Rafanoharana⁵⁴, F. Raffaeli^{76a,76b}, F. Ragusa^{71a,71b}, J.L. Rainbolt⁴⁰, J.A. Raine⁵⁶, S. Rajagopalan³⁰, E. Ramakoti³⁹, L. Rambelli^{57b,57a}, I.A. Ramirez-Berend³⁵, K. Ran^{48,114c}, D.S. Rankin¹³¹, N.P. Rapheeha^{34g}, H. Rasheed^{28b}, D.F. Rassloff^{63a}, A. Rastogi^{18a}, S. Rave¹⁰², S. Ravera^{57b,57a}, B. Ravina³⁷, I. Ravinovich¹⁷⁵, M. Raymond³⁷, A.L. Read¹²⁸, N.P. Readioff¹⁴⁵, D.M. Rebuzzi^{73a,73b}, A.S. Reed¹¹², K. Reeves²⁷, J.A. Reidelsturz¹⁷⁷, D. Reikher¹²⁶, A. Rej⁴⁹, C. Rembser³⁷, H. Ren⁶², M. Renda^{28b}, F. Renner⁴⁸, A.G. Rennie⁵⁹, A.L. Rescia⁴⁸, S. Resconi^{71a}, M. Ressegotti^{57b,57a}, S. Rettie³⁷, W.F. Rettie³⁵, E. Reynolds^{18a}, O.L. Rezanova³⁹, P. Reznicek¹³⁶, H. Riani^{36d}, N. Ribaric⁵¹, E. Ricci^{78a,78b}, R. Richter¹¹², S. Richter^{47a,47b}, E. Richter-Was^{86b}, M. Ridel¹³⁰, S. Ridouani^{36d}, P. Rieck¹²⁰, P. Riedler³⁷, E.M. Riefel^{47a,47b}, J.O. Rieger¹¹⁷, M. Rijssenbeek¹⁵¹, M. Rimoldi³⁷, L. Rinaldi^{24b,24a}, P. Rincke¹⁶⁷, G. Ripellino¹⁶⁷, I. Riu¹³, J.C. Rivera Vergara¹⁷¹, F. Rizatdinova¹²⁴, E. Rizvi⁹⁶, B.R. Roberts^{18a}, S.S. Roberts¹³⁹, D. Robinson³³, M. Robles Manzano¹⁰², A. Robson⁵⁹, A. Rochi^{76a,76b}, C. Roda^{74a,74b}, S. Rodriguez Bosca³⁷, Y. Rodriguez Garcia^{23a}, A.M. Rodríguez Vera¹¹⁸, S. Roe³⁷, J.T. Roemer³⁷, O. Røhne¹²⁸, R.A. Rojas³⁷, C.P.A. Roland¹³⁰, A. Romaniouk⁷⁹, E. Romano^{73a,73b}, M. Romano^{24b}, A.C. Romero Hernandez¹⁶⁸, N. Rompotis⁹⁴, L. Roos¹³⁰, S. Rosati^{75a}, B.J. Rosser⁴⁰, E. Rossi¹²⁹, E. Rossi^{72a,72b}, L.P. Rossi⁶¹, L. Rossini⁵⁴, R. Rosten¹²², M. Rotaru^{28b}, B. Rottler⁵⁴, D. Rousseau⁶⁶, D. Rousso⁴⁸, S. Roy-Garand¹⁶¹, A. Rozanov¹⁰⁴, Z.M.A. Rozario⁵⁹, Y. Rozen¹⁵⁶, A. Rubio Jimenez¹⁶⁹, V.H. Ruelas Rivera¹⁹, T.A. Ruggeri¹, A. Ruggiero¹²⁹, A. Ruiz-Martinez¹⁶⁹, A. Rummeler³⁷, Z. Rurikova⁵⁴, N.A. Rusakovich³⁹, H.L. Russell¹⁷¹, G. Russo^{75a,75b}, J.P. Rutherford⁷, S. Rutherford Colmenares³³, M. Rybar¹³⁶, P. Rybczynski^{86a}, A. Ryzhov⁴⁵, J.A. Sabater Iglesias⁵⁶, H.F.-W. Sadrozinski¹³⁹, F. Safai Tehrani^{75a}, S. Saha¹, M. Sahinsoy⁸², B. Sahoo¹⁷⁵, A. Saibel¹⁶⁹, B.T. Saifuddin¹²³, M. Saimpert¹³⁸, G.T. Saito^{83c}, M. Saito¹⁵⁹, T. Saito¹⁵⁹, A. Sala^{71a,71b}, A. Salnikov¹⁴⁹, J. Salt¹⁶⁹, A. Salvador Salas¹⁵⁷, F. Salvatore¹⁵², A. Salzburger³⁷, D. Sammel⁵⁴, E. Sampson⁹³, D. Sampsonidis^{158d}, D. Sampsonidou¹²⁶, J. Sánchez¹⁶⁹, V. Sanchez Sebastian¹⁶⁹, H. Sandaker¹²⁸, C.O. Sander⁴⁸, J.A. Sandesara¹⁷⁶, M. Sandhoff¹⁷⁷, C. Sandoval^{23b}, L. Sanfilippo^{63a}, D.P.C. Sankey¹³⁷, T. Sano⁸⁹, A. Sansoni⁵³, L. Santi³⁷, C. Santoni⁴¹, H. Santos^{133a,133b}, A. Santra¹⁷⁵, E. Sanzani^{24b,24a}, K.A. Saoucha^{88b}, J.G. Saraiva^{133a,133d}, J. Sardain⁷, O. Sasaki⁸⁴, K. Sato¹⁶³, C. Sauer³⁷, E. Sauvan⁴, P. Savard^{161ai}, R. Sawada¹⁵⁹, C. Sawyer¹³⁷, L. Sawyer⁹⁹, C. Sbarra^{24b}, A. Sbrizzi^{24b,24a}, T. Scanlon⁹⁸, J. Schaarschmidt¹⁴², U. Schäfer¹⁰², A.C. Schaffer^{66,45}, D. Schaile¹¹¹, R.D. Schamberger¹⁵¹, C. Scharf¹⁹, M.M. Schefer²⁰, V.A. Schegelsky³⁸, D. Scheirich¹³⁶, M. Schernau^{140e}, C. Scheulen⁵⁶, C. Schiavi^{57b,57a}, M. Schioppa^{44b,44a}, B. Schlag¹⁴⁹, S. Schlenker³⁷, J. Schmeing¹⁷⁷, E. Schmidt¹¹², M.A. Schmidt¹⁷⁷, K. Schmieden¹⁰², C. Schmitt¹⁰², N. Schmitt¹⁰², S. Schmitt⁴⁸, L. Schoeffel¹³⁸, A. Schoening^{63b}, P.G. Scholer³⁵, E. Schopf¹⁴⁷, M. Schott²⁵, S. Schramm⁵⁶, T. Schroer⁵⁶, H.-C. Schultz-Coulon^{63a}, M. Schumacher⁵⁴, B.A. Schumm¹³⁹, Ph. Schune¹³⁸, H.R. Schwartz¹³⁹, A. Schwartzman¹⁴⁹, T.A. Schwarz¹⁰⁸, Ph. Schwemling¹³⁸, R. Schwienhorst¹⁰⁹, F.G. Sciacca²⁰, A. Sciandra³⁰, G. Sciolla²⁷, F. Scuri^{74a}, C.D. Sebastiani³⁷, K. Sedlaczek¹¹⁸, S.C. Seidel¹¹⁵, A. Seiden¹³⁹, B.D. Seidlitz⁴², C. Seitz⁴⁸, J.M. Seixas^{83b}, G. Sekhniaidze^{72a}, L. Selem⁶⁰, N. Semprini-Cesari^{24b,24a}, A. Semushin¹⁷⁹, D. Sengupta⁵⁶, V. Senthilkumar¹⁶⁹, L. Serin⁶⁶, M. Sessa^{76a,76b}, H. Severini¹²³, F. Sforza^{57b,57a}, A. Sfyrila⁵⁶, Q. Sha¹⁴, E. Shabalina⁵⁵, H. Shaddix¹¹⁸, A.H. Shah³³, R. Shaheen¹⁵⁰, J.D. Shahinian¹³¹, M. Shamim³⁷, L.Y. Shan¹⁴, M. Shapiro^{18a}, A. Sharma³⁷, A.S. Sharma¹⁷⁰, P. Sharma³⁰, P.B. Shatalov³⁸, K. Shaw¹⁵², S.M. Shaw¹⁰³, Q. Shen^{144a}, D.J. Sheppard¹⁴⁸, P. Sherwood⁹⁸, L. Shi⁹⁸, X. Shi¹⁴, S. Shimizu⁸⁴, C.O. Shimmin¹⁷⁸, I.P.J. Shipsey^{129,*}, S. Shirabe⁹⁰, M. Shiyakova^{39,aa}, M.J. Shochet⁴⁰, D.R. Shope¹²⁸, B. Shrestha¹²³, S. Shrestha^{122,am}, I. Shreyber³⁹, M.J. Shroff¹⁷¹, P. Sicho¹³⁴, A.M. Sickles¹⁶⁸, E. Sideras Haddad^{34g,166}, A.C. Sidley¹¹⁷, A. Sidoti^{24b}, F. Siegert⁵⁰, Dj. Sijacki¹⁶, F. Sili⁹², J.M. Silva⁵², I. Silva Ferreira^{83b}, M.V. Silva Oliveira³⁰, S.B. Silverstein^{47a}, S. Simion⁶⁶, R. Simoniello³⁷, E.L. Simpson¹⁰³, H. Simpson¹⁵², L.R. Simpson⁶, S. Simsek⁸², S. Sindhu⁵⁵, P. Sinervo¹⁶¹, S.N. Singh²⁷, S. Singh³⁰, S. Sinha⁴⁸, S. Sinha¹⁰³, M. Sioli^{24b,24a}, K. Sioulas⁹, I. Siral³⁷, E. Sitnikova⁴⁸, J. Sjölin^{47a,47b}, A. Skaf⁵⁵, E. Skorda²¹, P. Skubic¹²³, M. Slawinska⁸⁷, I. Slazyk¹⁷, V. Smakhtin¹⁷⁵, B.H. Smart¹³⁷, S.Yu. Smirnov^{140b}, Y. Smirnov⁸², L.N. Smirnova^{38a}, O. Smirnova¹⁰⁰, A.C. Smith⁴², D.R. Smith¹⁶⁵, J.L. Smith¹⁰³, M.B. Smith³⁵, R. Smith¹⁴⁹, H. Smitmanns¹⁰², M. Smizanska⁹³, K. Smolek¹³⁵, P. Smolyanskiy¹³⁵, A.A. Snezarev³⁹, H.L. Snoek¹¹⁷, S. Snyder³⁰, R. Sobie^{171,ac}, A. Soffer¹⁵⁷, C.A. Solans Sanchez³⁷, E.Yu. Soldatov³⁹, U. Soldevila¹⁶⁹, A.A. Solodkov^{34g}, S. Solomon²⁷, A. Soloshenko³⁹, K. Solovieva⁵⁴, O.V. Solovyanov⁴¹, P. Sommer⁵⁰, A. Sonay¹³, A. Sopczak¹³⁵, A.L. Sopio⁵², F. Sopkova^{29b}, J.D. Sorenson¹¹⁵, I.R. Sotarriva Alvarez¹⁴¹, V. Sothilingam^{63a}, O.J. Soto Sandoval^{140c,140b}, S. Sottocornola¹⁶⁸, R. Soualah^{88a}, Z. Soumami^{36e}, D. South⁴⁸, N. Soybelman¹⁷⁵, S. Spagnolo^{70a,70b}, M. Spalla¹¹², D. Sperlich⁵⁴, B. Spisso^{72a,72b}, D.P. Spiteri⁵⁹, L. Splendori¹⁰⁴, M. Spouta¹³⁶, E.J. Staats³⁵, R. Stamen^{63a}, E. Stanecka⁸⁷, W. Stanek-Maslouska⁴⁸, M.V. Stange⁵⁰, B. Stanislaus^{18a}, M.M. Stanitzki⁴⁸, B. Stapf⁴⁸, E.A. Starchenko³⁸, G.H. Stark¹³⁹, J. Stark⁹¹, P. Staroba¹³⁴, P. Starovoitov^{88b}, R. Staszewski⁸⁷, G. Stavropoulos⁴⁶, A. Stefl³⁷, P. Steinberg³⁰, B. Stelzer^{148,162a}, H.J. Stelzer¹³², O. Stelzer^{162a}, H. Stenzel⁵⁸, T.J. Stevenson¹⁵², G.A. Stewart³⁷, J.R. Stewart¹²⁴, M.C. Stockton³⁷, G. Stoica^{28b}, M. Stolarski^{133a}, S. Stonjek¹¹², A. Straessner⁵⁰, J. Strandberg¹⁵⁰, S. Strandberg^{47a,47b}, M. Stratmann¹⁷⁷, M. Strauss¹²³, T. Streblor¹⁰⁴, P. Strizenec^{29b}, R. Ströhmer¹⁷², D.M. Strom¹²⁶, R. Stroynowski⁴⁵, A. Strubig^{47a,47b}, S.A. Stucci³⁰, B. Stugu¹⁷, J. Stupak¹²³, N.A. Styles⁴⁸, D. Su¹⁴⁹, S. Su⁶², X. Su⁶², D. Suchy^{29a}, K. Sugizaki¹³¹, V.V. Sulin³⁸, M.J. Sullivan⁹⁴, D.M.S. Sultan¹²⁹, L. Sultanaliyeva³⁸, S. Sultansoy^{3b}, S. Sun¹⁷⁶, W. Sun¹⁴, O. Sunneborn Gudnadottir¹⁶⁷, N. Sur¹⁰⁰, M.R. Sutton¹⁵², H. Suzuki¹⁶³, M. Svatos¹³⁴, P.N. Swallow³³, M. Swiatkowski^{162a}, T. Swirski¹⁷², I. Sykora^{29a}, M. Sykora¹³⁶, T. Sykora¹³⁶, D. Ta¹⁰², K. Tackmann^{48,z}, A. Taffard¹⁶⁵

R. Tafirout^{162a}, Y. Takubo⁸⁴, M. Talby¹⁰⁴, A.A. Talyshv³⁸, K.C. Tam^{64b}, N.M. Tamir¹⁵⁷, A. Tanaka¹⁵⁹, J. Tanaka¹⁵⁹, R. Tanaka⁶⁶, M. Tanasini¹⁵¹, Z. Tao¹⁷⁰, S. Tapia Araya^{140f}, S. Tapprogge¹⁰², A. Tarek Abouelfadl Mohamed¹⁰⁹, S. Tarem¹⁵⁶, K. Tariq¹⁴, G. Tarna^{28b}, G.F. Tartarelli^{71a}, M.J. Tartarin⁹¹, P. Tas¹³⁶, M. Tasevsky¹³⁴, E. Tassi^{44b,44a}, A.C. Tate¹⁶⁸, G. Tateno¹⁵⁹, Y. Tayalati^{36e,ab}, G.N. Taylor¹⁰⁷, W. Taylor^{162b}, A.S. Tegetmeier⁹¹, P. Teixeira-Dias⁹⁷, J.J. Teoh¹⁶¹, K. Terashi¹⁵⁹, J. Terron¹⁰¹, S. Terzo¹³, M. Testa⁵³, R.J. Teuscher^{161,ac}, A. Thaler⁷⁹, O. Theiner⁵⁶, T. Theveniaux-Pelzer¹⁰⁴, D.W. Thomas⁹⁷, J.P. Thomas²¹, E.A. Thompson^{18a}, P.D. Thompson²¹, E. Thomson¹³¹, R.E. Thornberry⁴⁵, C. Tian⁶², Y. Tian⁵⁶, V. Tikhomirov⁸², Yu.A. Tikhonov³⁹, S. Timoshenko³⁸, D. Timoshyn¹³⁶, E.X.L. Ting¹, P. Tipton¹⁷⁸, A. Tishelman-Charny³⁰, K. Todome¹⁴¹, S. Todorova-Nova¹³⁶, S. Todt⁵⁰, L. Toffolin^{69a,69c}, M. Togawa⁸⁴, J. Tojo⁹⁰, S. Tokár^{29a}, O. Toldaiev⁶⁸, G. Tolkachev¹⁰⁴, M. Tomoto^{84,113}, L. Tompkins^{149,o}, E. Torrence¹²⁶, H. Torres⁹¹, E. Torró Pastor¹⁶⁹, M. Toscani³¹, C. Toscirt⁴⁰, M. Tost¹¹, D.R. Tovey¹⁴⁵, T. Trefzger¹⁷², P.M. Tricarico¹³, A. Tricoli³⁰, I.M. Trigger^{162a}, S. Trincas-Duvold¹³⁰, D.A. Trischuk²⁷, A. Tropina³⁹, L. Truong^{34c}, M. Trzebinski⁸⁷, A. Trzupek⁸⁷, F. Tsai¹⁵¹, M. Tsai¹⁰⁸, A. Tsiamis¹⁵⁸, P.V. Tsiarshka³⁹, S. Tsigaridas^{162a}, A. Tsigaridis^{158,v}, V. Tsiskaridze¹⁶¹, E.G. Tskhadadze^{155a}, M. Tsopoulou¹⁵⁸, Y. Tsujikawa⁸⁹, I.I. Tsukerman³⁸, V. Tsulaia^{18a}, S. Tsuno⁸⁴, K. Tsuru¹²¹, D. Tsybychev¹⁵¹, Y. Tu^{64b}, A. Tudorache^{28b}, V. Tudorache^{28b}, S. Turchikhin^{57b,57a}, I. Turk Cakir^{3a}, R. Turra^{71a}, T. Turtuvshin^{39,ad}, P.M. Tuts⁴², S. Tzamarias^{158,d}, E. Tzovara¹⁰², Y. Uematsu⁸⁴, F. Ukegawa¹⁶³, P.A. Ulloa Poblete^{140c,140b}, E.N. Umaka³⁰, G. Unal³⁷, A. Undrus³⁰, G. Unel¹⁶⁵, J. Urban^{29b}, P. Urrejola^{140a}, G. Usai⁸, R. Ushioda¹⁶⁰, M. Usman¹¹⁰, F. Ustuner⁵², Z. Uysal⁸², V. Vacek¹³⁵, B. Vachon¹⁰⁶, T. Vafeiadis³⁷, A. Vaitkus⁹⁸, C. Valderanis¹¹¹, E. Valdes Santurio^{47a,47b}, M. Valente³⁷, S. Valentini^{24b,24a}, A. Valero¹⁶⁹, E. Valiente Moreno¹⁶⁹, A. Vallier⁹¹, J.A. Valls Ferrer¹⁶⁹, D.R. Van Arneeman¹¹⁷, T.R. Van Daalen¹⁴², A. Van Der Graaf⁴⁹, H.Z. Van Der Schyf^{34g}, P. Van Gemmeren⁶, M. Van Rijnbach³⁷, S. Van Stroud⁹⁸, I. Van Vulpen¹¹⁷, P. Vana¹³⁶, M. Vanadia^{76a,76b}, U.M. Vande Vorde¹⁵⁰, W. Vandelli³⁷, E.R. Vandewall¹²⁴, D. Vannicola¹⁵⁷, L. Vannoli⁵³, R. Vari^{75a}, E.W. Varnes⁷, C. Varni^{18b}, D. Varouchas⁶⁶, L. Varriale¹⁶⁹, K.E. Varvell¹⁵³, M.E. Vasile^{28b}, L. Vaslin⁸⁴, M.D. Vassilev¹⁴⁹, A. Vasyukov³⁹, L.M. Vaughan¹²⁴, R. Vavricka¹³⁶, T. Vazquez Schroeder¹³, J. Veatch³², V. Vecchio¹⁰³, M.J. Veen¹⁰⁵, I. Veliscek³⁰, I. Velkovska⁹⁵, L.M. Veloce¹⁶¹, F. Veloso^{133a,133c}, S. Veneziano^{75a}, A. Ventura^{70a,70b}, S. Ventura Gonzalez¹³⁸, A. Verbytskyi¹¹², M. Verducci^{74a,74b}, C. Vergis⁹⁶, M. Verissimo De Araujo^{83b}, W. Verkerke¹¹⁷, J.C. Vermeulen¹¹⁷, K.E. Vernieri¹⁴⁹, M. Vessella¹⁶⁵, M.C. Vetterli^{148,ai}, A. Vgenopoulos¹⁰², N. Viaux Maira^{140f}, T. Vickey¹⁴⁵, O.E. Vickey Boeriu¹⁴⁵, G.H.A. Viehhauser¹²⁹, L. Vignani^{63b}, M. Vigl¹¹², M. Villa^{24b,24a}, M. Villaplana Perez¹⁶⁹, E.M. Villhauer⁵², E. Vilucchi⁵³, M.G. Vincker³⁵, A. Visibile¹¹⁷, C. Vittori³⁷, I. Vivarelli^{24b,24a}, E. Voevodina¹¹², F. Vogel¹¹¹, J.C. Voigt⁵⁰, P. Vokac¹³⁵, Yu. Volkotrub^{86b}, E. Von Toerne²⁵, B. Vormwald³⁷, K. Vorobev⁵¹, M. Vos¹⁶⁹, K. Voss¹⁴⁷, M. Vozak³⁷, L. Vozdecky¹²³, N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, M. Vreeswijk¹¹⁷, N.K. Vu^{144b,144a}, R. Vuillermet³⁷, O. Vujanovic¹⁰², I. Vukotic⁴⁰, I.K. Vyas³⁵, J.F. Wack³³, S. Wada¹⁶³, C. Wagner¹⁴⁹, J.M. Wagner^{18a}, W. Wagner¹⁷⁷, S. Wahdan¹⁷⁷, H. Wahlberg⁹², C.H. Waits¹²³, J. Walder¹³⁷, R. Walker¹¹¹, W. Walkowiak¹⁴⁷, A. Wall¹³¹, E.J. Wallin¹⁰⁰, T. Wamorkar^{18a}, A.Z. Wang¹³⁹, C. Wang¹⁰², C. Wang¹¹, H. Wang^{18a}, J. Wang^{64c}, P. Wang¹⁰³, P. Wang⁹⁸, R. Wang⁶¹, R. Wang⁶, S.M. Wang¹⁵⁴, S. Wang¹⁴, T. Wang⁶², T. Wang⁶², W.T. Wang⁸⁰, W. Wang¹⁴, X. Wang¹⁶⁸, X. Wang^{144a},

X. Wang⁴⁸, Y. Wang^{114a}, Y. Wang⁶², Z. Wang¹⁰⁸, Z. Wang^{144b}, Z. Wang¹⁰⁸, C. Wanotayaroj⁸⁴, A. Warburton¹⁰⁶, A.L. Warner-bring¹⁴⁷, N. Warrack⁵⁹, S. Waterhouse⁹⁷, A.T. Watson²¹, H. Watson⁵², M.F. Watson²¹, E. Watton⁵⁹, G. Watts¹⁴², B.M. Waugh⁹⁸, J.M. Webb⁵⁴, C. Weber³⁰, H.A. Weber¹⁹, M.S. Weber²⁰, S.M. Weber^{63a}, C. Wei⁶², Y. Wei⁵⁴, A.R. Weidberg¹²⁹, E.J. Weik¹²⁰, J. Weingarten⁴⁹, C. Weiser⁵⁴, C.J. Wells⁴⁸, T. Wenaus³⁰, B. Wendland⁴⁹, T. Wengler³⁷, N.S. Wenke¹¹², N. Wermes²⁵, M. Wessels^{63a}, A.M. Wharton⁹³, A.S. White⁶¹, A. White⁸, M.J. White¹, D. Whiteson¹⁶⁵, L. Wickremasinghe¹²⁷, W. Wiedenmann¹⁷⁶, M. Wielers¹³⁷, R. Wierda¹⁵⁰, C. Wiglesworth⁴³, H.G. Wilkens³⁷, J.J.H. Wilkinson³³, D.M. Williams⁴², H.H. Williams¹³¹, S. Williams³³, S. Willocq¹⁰⁵, B.J. Wilson¹⁰³, D.J. Wilson¹⁰³, P.J. Windischhofer⁴⁰, F.I. Winkel³¹, F. Winklmeier¹²⁶, B.T. Winter⁵⁴, M. Wittgen¹⁴⁹, M. Wobisch⁹⁹, T. Wojtkowski⁶⁰, Z. Wolffs¹¹⁷, J. Wollrath³⁷, M.W. Wolter⁸⁷, H. Wolters^{133a,133c}, M.C. Wong¹³⁹, E.L. Woodward⁴², S.D. Worm⁴⁸, B.K. Wosiek⁸⁷, K.W. Woźniak⁸⁷, S. Wozniowski⁵⁵, K. Wraight⁵⁹, C. Wu¹⁶¹, C. Wu²¹, J. Wu¹⁵⁹, M. Wu^{114b}, M. Wu¹¹⁶, S.L. Wu¹⁷⁶, S. Wu¹⁴, X. Wu⁶², Y. Wu⁶², Z. Wu⁴, J. Wuerzinger¹¹², T.R. Wyatt¹⁰³, B.M. Wynne⁵², S. Xella⁴³, L. Xia^{114a}, M. Xia¹⁵, M. Xie⁶², A. Xiong¹²⁶, J. Xiong^{18a}, D. Xu¹⁴, H. Xu⁶², L. Xu⁶², R. Xu¹³¹, T. Xu¹⁰⁸, Y. Xu¹⁴², Z. Xu⁵², Z. Xu^{114a}, B. Yabsley¹⁵³, S. Yacoub^{34a}, Y. Yamaguchi⁸⁴, E. Yamashita¹⁵⁹, H. Yamauchi¹⁶³, T. Yamazaki^{18a}, Y. Yamazaki⁸⁵, S. Yan⁵⁹, Z. Yan¹⁰⁵, H.J. Yang^{144a,144b}, H.T. Yang⁶², S. Yang⁶², T. Yang^{64c}, X. Yang³⁷, X. Yang¹⁴, Y. Yang¹⁵⁹, Y. Yang⁶², W.-M. Yao^{18a}, C.L. Yardley¹⁵², J. Ye¹⁴, S. Ye³⁰, X. Ye⁶², Y. Yeh⁹⁸, I. Yeletsikh³⁹, B. Yeo^{18b}, M.R. Yexley⁹⁸, T.P. Yildirim¹²⁹, P. Yin⁴², K. Yorita¹⁷⁴, C.J.S. Young³⁷, C. Young¹⁴⁹, N.D. Young¹²⁶, Y. Yu⁶², J. Yuan^{14,114c}, M. Yuan¹⁰⁸, R. Yuan^{144b,144a}, L. Yue⁹⁸, M. Zaazoua⁶², B. Zabinski⁸⁷, I. Zahir^{36a}, A. Zaio^{57b,57a}, Z.K. Zak⁸⁷, T. Zakareishvili¹⁶⁹, S. Zambito⁵⁶, J.A. Zamora Saa^{140d}, J. Zang¹⁵⁹, D. Zanzi⁵⁴, R. Zanzottera^{71a,71b}, O. Zaplatilek¹³⁵, C. Zeitnitz¹⁷⁷, H. Zeng¹⁴, J.C. Zeng¹⁶⁸, D.T. Zenger Jr²⁷, O. Zenin³⁸, T. Ženiš^{29a}, S. Zenz⁹⁶, D. Zerwas⁶⁶, M. Zhai^{14,114c}, D.F. Zhang¹⁴⁵, G. Zhang¹⁴, J. Zhang^{143a}, J. Zhang⁶, K. Zhang^{14,114c}, L. Zhang⁶², L. Zhang^{114a}, P. Zhang^{14,114c}, R. Zhang¹⁷⁶, S. Zhang⁹¹, T. Zhang¹⁵⁹, X. Zhang^{144a}, Y. Zhang¹⁴², Y. Zhang⁹⁸, Y. Zhang⁶², Y. Zhang^{114a}, Z. Zhang^{18a}, Z. Zhang^{143a}, Z. Zhang⁶⁶, H. Zhao¹⁴², T. Zhao^{143a}, Y. Zhao³⁵, Z. Zhao⁶², Z. Zhao⁶², A. Zhemchugov³⁹, J. Zheng^{114a}, K. Zheng¹⁶⁸, X. Zheng⁶², Z. Zheng¹⁴⁹, D. Zhong¹⁶⁸, B. Zhou¹⁰⁸, H. Zhou⁷, N. Zhou^{144a}, Y. Zhou¹⁵, Y. Zhou^{114a}, Y. Zhou⁷, C.G. Zhu^{143a}, J. Zhu¹⁰⁸, X. Zhu^{144b}, Y. Zhu^{144a}, Y. Zhu⁶², X. Zhuang¹⁴, K. Zhukov⁶⁸, N.I. Zimine³⁹, J. Zinsser^{63b}, M. Ziolkowski¹⁴⁷, L. Živković¹⁶, A. Zoccoli^{24b,24a}, K. Zoch⁶¹, T.G. Zorbas¹⁴⁵, O. Zormpa⁴⁶, L. Zwalinski³⁷.

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 d'Annecy 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) University of South Africa, Department of Physics, Pretoria; (f) University of Zululand, KwaDlangezwa; (g) 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 institute formerly covered by a cooperation agreement with CERN.
- ³⁹Affiliated with an international laboratory covered by a cooperation agreement with CERN.
- ⁴⁰Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
- ⁴¹LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- ⁴²Nevis Laboratory, Columbia University, Irvington NY; United States of America.
- ⁴³Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
- ⁴⁴(a) Dipartimento di Fisica, Università della Calabria, Rende; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
- ⁴⁵Physics Department, Southern Methodist University, Dallas TX; United States of America.
- ⁴⁶National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
- ⁴⁷(a) Department of Physics, Stockholm University; (b) Oskar Klein Centre, Stockholm; Sweden.
- ⁴⁸Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- ⁴⁹Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany.
- ⁵⁰Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
- ⁵¹Department of Physics, Duke University, Durham NC; United States of America.
- ⁵²SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
- ⁵³INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
- ⁵⁴Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ⁵⁵II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- ⁵⁶Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ⁵⁷(a) Dipartimento di Fisica, Università di Genova, Genova; (b) INFN Sezione di Genova; Italy.
- ⁵⁸II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
- ⁵⁹SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- ⁶⁰LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
- ⁶¹Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
- ⁶²Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; China.
- ⁶³(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
- ⁶⁴(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.
- ⁶⁵Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.

- ⁶⁶IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
- ⁶⁷Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
- ⁶⁸Department of Physics, Indiana University, Bloomington IN; United States of America.
- ^{69(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.
- ^{70(a)}INFN Sezione di Lecce; ^(b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
- ^{71(a)}INFN Sezione di Milano; ^(b)Dipartimento di Fisica, Università di Milano, Milano; Italy.
- ^{72(a)}INFN Sezione di Napoli; ^(b)Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
- ^{73(a)}INFN Sezione di Pavia; ^(b)Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
- ^{74(a)}INFN Sezione di Pisa; ^(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- ^{75(a)}INFN Sezione di Roma; ^(b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
- ^{76(a)}INFN Sezione di Roma Tor Vergata; ^(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
- ^{77(a)}INFN Sezione di Roma Tre; ^(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
- ^{78(a)}INFN-TIFPA; ^(b)Università degli Studi di Trento, Trento; Italy.
- ⁷⁹Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
- ⁸⁰University of Iowa, Iowa City IA; United States of America.
- ⁸¹Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
- ⁸²Istinye University, Sariyer, Istanbul; Türkiye.
- ^{83(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.
- ⁸⁴KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
- ⁸⁵Graduate School of Science, Kobe University, Kobe; Japan.
- ^{86(a)}AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; ^(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
- ⁸⁷Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
- ^{88(a)}Khalifa University of Science and Technology, Abu Dhabi; ^(b)University of Sharjah, Sharjah; United Arab Emirates.
- ⁸⁹Faculty of Science, Kyoto University, Kyoto; Japan.
- ⁹⁰Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan.
- ⁹¹L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
- ⁹²Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
- ⁹³Physics Department, Lancaster University, Lancaster; United Kingdom.
- ⁹⁴Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
- ⁹⁵Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
- ⁹⁶Department of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
- ⁹⁷Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
- ⁹⁸Department of Physics and Astronomy, University College London, London; United Kingdom.
- ⁹⁹Louisiana Tech University, Ruston LA; United States of America.
- ¹⁰⁰Fysiska institutionen, Lunds universitet, Lund; Sweden.
- ¹⁰¹Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
- ¹⁰²Institut für Physik, Universität Mainz, Mainz; Germany.
- ¹⁰³School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
- ¹⁰⁴CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- ¹⁰⁵Department of Physics, University of Massachusetts, Amherst MA; United States of America.
- ¹⁰⁶Department of Physics, McGill University, Montreal QC; Canada.
- ¹⁰⁷School of Physics, University of Melbourne, Victoria; Australia.
- ¹⁰⁸Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- ¹⁰⁹Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- ¹¹⁰Group of Particle Physics, University of Montreal, Montreal QC; Canada.
- ¹¹¹Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
- ¹¹²Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
- ¹¹³Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
- ^{114(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.
- ¹¹⁵Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
- ¹¹⁶Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
- ¹¹⁷Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
- ¹¹⁸Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
- ^{119(a)}New York University Abu Dhabi, Abu Dhabi; ^(b)United Arab Emirates University, Al Ain; United Arab Emirates.
- ¹²⁰Department of Physics, New York University, New York NY; United States of America.
- ¹²¹Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
- ¹²²Ohio State University, Columbus OH; United States of America.
- ¹²³Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
- ¹²⁴Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
- ¹²⁵Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.
- ¹²⁶Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
- ¹²⁷Graduate School of Science, University of Osaka, Osaka; Japan.
- ¹²⁸Department of Physics, University of Oslo, Oslo; Norway.
- ¹²⁹Department of Physics, Oxford University, Oxford; United Kingdom.
- ¹³⁰LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.
- ¹³¹Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
- ¹³²Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
- ^{133(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.

¹³⁴Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.

¹³⁵Czech Technical University in Prague, Prague; Czech Republic.

¹³⁶Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.

¹³⁷Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

¹³⁸IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.

¹³⁹Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.

^{140(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)Instituto de Alta Investigación, Universidad de Tarapacá, Arica;^(f)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

¹⁴¹Department of Physics, Institute of Science, Tokyo; Japan.

¹⁴²Department of Physics, University of Washington, Seattle WA; United States of America.

^{143(a)}Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;^(b)School of Physics, Zhengzhou University; China.

^{144(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.

¹⁴⁵Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

¹⁴⁶Department of Physics, Shinshu University, Nagano; Japan.

¹⁴⁷Department Physik, Universität Siegen, Siegen; Germany.

¹⁴⁸Department of Physics, Simon Fraser University, Burnaby BC; Canada.

¹⁴⁹SLAC National Accelerator Laboratory, Stanford CA; United States of America.

¹⁵⁰Department of Physics, Royal Institute of Technology, Stockholm; Sweden.

¹⁵¹Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

¹⁵²Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.

¹⁵³School of Physics, University of Sydney, Sydney; Australia.

¹⁵⁴Institute of Physics, Academia Sinica, Taipei; Taiwan.

^{155(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.

¹⁵⁶Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.

¹⁵⁷Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.

¹⁵⁸Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.

¹⁵⁹International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.

¹⁶⁰Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.

¹⁶¹Department of Physics, University of Toronto, Toronto ON; Canada.

^{162(a)}TRIUMF, Vancouver BC;^(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.

¹⁶³Division of Physics and Tomonaga Center for the History of the

Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

¹⁶⁴Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

¹⁶⁵Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

¹⁶⁶University of West Attica, Athens; Greece.

¹⁶⁷Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

¹⁶⁸Department of Physics, University of Illinois, Urbana IL; United States of America.

¹⁶⁹Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

¹⁷⁰Department of Physics, University of British Columbia, Vancouver BC; Canada.

¹⁷¹Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

¹⁷²Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.

¹⁷³Department of Physics, University of Warwick, Coventry; United Kingdom.

¹⁷⁴Waseda University, Tokyo; Japan.

¹⁷⁵Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.

¹⁷⁶Department of Physics, University of Wisconsin, Madison WI; United States of America.

¹⁷⁷Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.

¹⁷⁸Department of Physics, Yale University, New Haven CT; United States of America.

¹⁷⁹Yerevan 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 CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC); Azerbaijan.

^h Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

ⁱ Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.

^j Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.

^k Also at Department of Mathematical Sciences, University of South Africa, Johannesburg; South Africa.

^l Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; China.

^m Also at Department of Physics, Bolu Abant İzzet Baysal University, Bolu; Türkiye.

ⁿ Also at Department of Physics, King's College London, London; United Kingdom.

^o Also at Department of Physics, Stanford University, Stanford CA; United States of America.

^p Also at Department of Physics, Stellenbosch University; South Africa.

^q Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.

- ^r Also at Department of Physics, University of Thessaly; Greece.
- ^s Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
- ^t Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria.
- ^u Also at Faculty of Physics, University of Bucharest; Romania.
- ^v Also at Hellenic Open University, Patras; Greece.
- ^w Also at Henan University; China.
- ^x Also at Imam Mohammad Ibn Saud Islamic University; Saudi Arabia.
- ^y Also at Institutio Catalana de Recerca i Estudis Avançats, ICREA, Barcelona; Spain.
- ^z Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^{aa} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
- ^{ab} Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- ^{ac} Also at Institute of Particle Physics (IPP); Canada.
- ^{ad} Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
- ^{ae} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^{af} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- ^{ag} Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
- ^{ah} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{ai} Also at TRIUMF, Vancouver BC; Canada.
- ^{aj} Also at Università di Napoli Parthenope, Napoli; Italy.
- ^{ak} Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
- ^{al} Also at University of Sienna; Italy.
- ^{am} Also at Washington College, Chestertown, MD; United States of America.
- ^{an} Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
- * Deceased

References

- [1] ATLAS Collaboration, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B* 716 (2012) 1. [arXiv:1207.7214](https://doi.org/10.1016/j.physletb.2012.08.020). <https://doi.org/10.1016/j.physletb.2012.08.020>
- [2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Phys. Lett. B* 716 (2012) 30. [arXiv:1207.7235](https://arxiv.org/abs/1207.7235). <https://doi.org/10.1016/j.physletb.2012.08.021>
- [3] L. Evans, P. Bryant, LHC machine, *JINST* 3 (2008) S08001. <https://doi.org/10.1088/1748-0221/3/08/S08001>
- [4] ATLAS Collaboration, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery, *Nature* 607 (2022) 52–59. [arXiv:2207.00092](https://arxiv.org/abs/2207.00092) <https://doi.org/10.1038/s41586-022-04893-w>
- [5] CMS Collaboration, A portrait of the Higgs boson by the CMS experiment ten years after the discovery, *Nature* 607 (2022) 60–68. [arXiv:2207.00043](https://arxiv.org/abs/2207.00043) <https://doi.org/10.1038/s41586-022-04892-x>
- [6] D. Curtin, R. Essig, S. Gori, P. Jaiswal, A. Katz, et al., Exotic decays of the 125 GeV Higgs boson, *Phys. Rev. D* 90 (2014) 075004. [arXiv:1312.4992](https://arxiv.org/abs/1312.4992) <https://doi.org/10.1103/PhysRevD.90.075004>
- [7] M. Cepeda, S. Gori, V. Martinez Outschoorn, J. Shelton, Exotic Higgs Decays (2021). [arXiv:2111.12751](https://arxiv.org/abs/2111.12751) <https://doi.org/10.1146/annurev-nucl-102319-024147>
- [8] M.J. Strassler, K.M. Zurek, Echoes of a hidden valley at hadron colliders, *Phys. Lett. B* 651 (2007) 374–379. [arXiv:hep-ph/0604261](https://arxiv.org/abs/hep-ph/0604261) <https://doi.org/10.1016/j.physletb.2007.06.055>
- [9] R.M. Schabinger, J.D. Wells, A Minimal spontaneously broken hidden sector and its impact on Higgs boson physics at the large hadron collider, *Phys. Rev. D* 72 (2005) 093007. [arXiv:hep-ph/0509209](https://arxiv.org/abs/hep-ph/0509209) <https://doi.org/10.1103/PhysRevD.72.093007>
- [10] B. Patt, F. Wilczek, Higgs-field portal into hidden sectors (2006). [arXiv:hep-ph/0605188](https://arxiv.org/abs/hep-ph/0605188)
- [11] V. Silveira, A. Zee, Scalar phantoms, *Phys. Lett. B* 161 (1985) 136. [https://doi.org/10.1016/0370-2693\(85\)90624-0](https://doi.org/10.1016/0370-2693(85)90624-0)
- [12] M. Pospelov, A. Ritz, M. Voloshin, Secluded WIMP dark matter, *Phys. Lett. B* 662 (1) (2008) 53–61. <https://www.sciencedirect.com/science/article/pii/S0370269308002402>. <https://doi.org/10.1016/j.physletb.2008.02.052>
- [13] P. Draper, T. Liu, C.E.M. Wagner, L.-T. Wang, H. Zhang, Dark light-Higgs bosons, *Phys. Rev. Lett.* 106 (2011) 121805. [arXiv:1009.3963](https://arxiv.org/abs/1009.3963) <https://doi.org/10.1103/PhysRevLett.106.121805>
- [14] M. Carena, Y.-Y. Li, T. Ou, Y. Wang, Anatomy of the electroweak phase transition for dark sector induced baryogenesis, *JHEP* 02 (2023) 139. [arXiv:2210.14352](https://arxiv.org/abs/2210.14352) [https://doi.org/10.1007/JHEP02\(2023\)139](https://doi.org/10.1007/JHEP02(2023)139)
- [15] J. Kozaczuk, M.J. Ramsey-Musolf, J. Shelton, Exotic Higgs boson decays and the electroweak phase transition, *Phys. Rev. D* 101 (11) (2020) 115035. [arXiv:1911.10210](https://arxiv.org/abs/1911.10210) <https://doi.org/10.1103/PhysRevD.101.115035>
- [16] N. Craig, A. Katz, M. Strassler, R. Sundrum, Naturalness in the Dark at the LHC, *JHEP* 07 (2015) 105. [arXiv:1501.05310](https://arxiv.org/abs/1501.05310) [https://doi.org/10.1007/JHEP07\(2015\)105](https://doi.org/10.1007/JHEP07(2015)105)
- [17] D. Curtin, C.B. Verhaaren, Discovering uncolored naturalness in exotic Higgs decays, *JHEP* 12 (2015) 072. [arXiv:1506.06141](https://arxiv.org/abs/1506.06141) [https://doi.org/10.1007/JHEP12\(2015\)072](https://doi.org/10.1007/JHEP12(2015)072)
- [18] B.A. Dobrescu, K.T. Matchev, Light axion within the next-to-minimal supersymmetric standard model, *JHEP* 09 (2000) 031. [arXiv:hep-ph/0008192](https://arxiv.org/abs/hep-ph/0008192) <https://doi.org/10.1088/1126-6708/2000/09/031>
- [19] U. Ellwanger, J.F. Gunion, C. Hugonie, S. Moretti, Towards a No-lose Theorem for NMSSM Higgs Discovery at the LHC (2003). [arXiv:hep-ph/0305109](https://arxiv.org/abs/hep-ph/0305109)
- [20] CMS Collaboration, Search for light pseudoscalar boson pairs produced from decays of the 125 GeV Higgs boson in final states with two muons and two nearby tracks in pp collisions at $\sqrt{s} = 13$ TeV, *Phys. Lett. B* 800 (2020) 135087. [arXiv:1907.07235](https://arxiv.org/abs/1907.07235) <https://doi.org/10.1016/j.physletb.2019.135087>
- [21] ATLAS Collaboration, Search for Higgs bosons decaying to aa in the $\mu\mu\tau\tau$ final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS experiment, *Phys. Rev. D* 92 (2015) 052002. [arXiv:1505.01609](https://arxiv.org/abs/1505.01609) <https://doi.org/10.1103/PhysRevD.92.052002>
- [22] ATLAS Collaboration, Improved reconstruction of highly boosted τ -lepton pairs in the $\tau\tau \rightarrow (\mu\nu_\mu\nu_\tau)(\text{hadrons} + \nu_\tau)$ decay channels with the ATLAS detector (2024). [arXiv:2412.14937](https://arxiv.org/abs/2412.14937)
- [23] CMS Collaboration, Search for a light pseudoscalar Higgs boson in the boosted $\mu\mu\tau\tau$ final state in proton–proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 08 (2020) 139. [arXiv:2005.08694](https://arxiv.org/abs/2005.08694) [https://doi.org/10.1007/JHEP08\(2020\)139](https://doi.org/10.1007/JHEP08(2020)139)
- [24] ATLAS Collaboration, Search for Higgs bosons decaying into new spin-0 or spin-1 particles in four-lepton final states with the ATLAS detector with 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV, *JHEP* 03 (2022) 041. [arXiv:2110.13673](https://arxiv.org/abs/2110.13673) [https://doi.org/10.1007/JHEP03\(2022\)041](https://doi.org/10.1007/JHEP03(2022)041)
- [25] CMS Collaboration, Search for low-mass dilepton resonances in Higgs boson decays to four-lepton final states in proton–proton collisions at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* 82 (2022) 290. [arXiv:2111.01299](https://arxiv.org/abs/2111.01299) <https://doi.org/10.1140/epjc/s10052-022-10127-0>
- [26] ATLAS Collaboration, Search for decays of the Higgs boson into a pair of pseudoscalar particles decaying into $b\bar{b}\tau^+\tau^-$ using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Rev. D* 110 (2024) 052013. [arXiv:2407.01335](https://arxiv.org/abs/2407.01335) <https://doi.org/10.1103/PhysRevD.110.052013>
- [27] CMS Collaboration, Search for exotic decays of the Higgs boson to a pair of pseudoscalars in the $\mu\mu b\bar{b}$ and $\tau\tau b\bar{b}$ final states, *Eur. Phys. J. C* 84 (2024) 493. [arXiv:2402.13358](https://arxiv.org/abs/2402.13358) <https://doi.org/10.1140/epjc/s10052-024-12727-4>
- [28] ATLAS Collaboration, Search for Higgs boson decays into a pair of pseudoscalar particles in the $b\bar{b}\mu\mu$ final state with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* 105 (2022) 012006. [arXiv:2110.00313](https://arxiv.org/abs/2110.00313) <https://doi.org/10.1103/PhysRevD.105.012006>
- [29] CMS Collaboration, Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two muons and two b quarks in pp collisions at 13 TeV, *Phys. Lett. B* 795 (2019) 398. [arXiv:1812.06359](https://arxiv.org/abs/1812.06359) <https://doi.org/10.1016/j.physletb.2019.06.021>
- [30] ATLAS Collaboration, Search for Higgs boson decays into two new low-mass spin-0 particles in the $4b$ channel with the ATLAS detector using pp collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* 102 (2020) 112006. [arXiv:2005.12236](https://arxiv.org/abs/2005.12236) <https://doi.org/10.1103/PhysRevD.102.112006>
- [31] CMS Collaboration, Search for the decay of the Higgs boson to a pair of light pseudoscalar bosons in the final state with four bottom quarks in proton–proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 06 (2024) 097. [arXiv:2403.10341](https://arxiv.org/abs/2403.10341) [https://doi.org/10.1007/JHEP06\(2024\)097](https://doi.org/10.1007/JHEP06(2024)097)
- [32] ATLAS Collaboration, Search for short- and long-lived axion-like particles in $H \rightarrow aa \rightarrow 4\gamma$ decays with the ATLAS experiment at the LHC, *Eur. Phys. J. C* 84 (2024) 742. [arXiv:2312.03306](https://arxiv.org/abs/2312.03306) <https://doi.org/10.1140/epjc/s10052-024-12979-0>
- [33] CMS Collaboration, Search for exotic Higgs boson decays $H \rightarrow AA \rightarrow 4\gamma$ with events containing two merged diphotons in proton–proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* 131 (2023) 101801. [arXiv:2209.06197](https://arxiv.org/abs/2209.06197) <https://doi.org/10.1103/PhysRevLett.131.101801>
- [34] CMS Collaboration, Search for the exotic decay of the Higgs boson into two light pseudoscalars with four photons in the final state in proton–proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 07 (2023) 148. [arXiv:2208.01469](https://arxiv.org/abs/2208.01469) [https://doi.org/10.1007/JHEP07\(2023\)148](https://doi.org/10.1007/JHEP07(2023)148)
- [35] ATLAS Collaboration, Search for Higgs boson decays into pairs of light (pseudo)scalar particles in the $\gamma\gamma jj$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 782 (2018) 750. [arXiv:1803.11145](https://arxiv.org/abs/1803.11145) <https://doi.org/10.1016/j.physletb.2018.06.011>
- [36] ATLAS Collaboration, The ATLAS experiment at the CERN large hadron collider, *JINST* 3 (2008) S08003. <https://doi.org/10.1088/1748-0221/3/08/S08003>
- [37] G. Avoni, et al., The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS, *JINST* 13 (2018) P07017. <https://doi.org/10.1088/1748-0221/13/07/P07017>
- [38] ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, *Eur. Phys. J. C* 77 (2017) 317. [arXiv:1611.09661](https://arxiv.org/abs/1611.09661) <https://doi.org/10.1140/epjc/s10052-017-4852-3>

- [39] ATLAS Collaboration, Software and computing for Run 3 of the ATLAS experiment at the LHC (2024). [arXiv:2404.06335](https://arxiv.org/abs/2404.06335)
- [40] ATLAS Collaboration, Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC, *Eur. Phys. J. C* 83 (2023) 982. [arXiv:2212.09379](https://arxiv.org/abs/2212.09379) <https://doi.org/10.1140/epjc/s10052-023-11747-w>
- [41] ATLAS Collaboration, ATLAS data quality operations and performance for 2015–2018 data-taking, *JINST* 15 (2020) P04003. [arXiv:1911.04632](https://arxiv.org/abs/1911.04632) <https://doi.org/10.1088/1748-0221/15/04/P04003>
- [42] ATLAS Collaboration, Performance of the ATLAS muon triggers in Run 2, *JINST* 15 (2020) P09015. [arXiv:2004.13447](https://arxiv.org/abs/2004.13447) <https://doi.org/10.1088/1748-0221/15/09/P09015>
- [43] K. Hamilton, P. Nason, E. Re, G. Zanderighi, NNLOPS simulation of Higgs boson production, *JHEP* 10 (2013) 222. [arXiv:1309.0017](https://arxiv.org/abs/1309.0017) [https://doi.org/10.1007/JHEP10\(2013\)222](https://doi.org/10.1007/JHEP10(2013)222)
- [44] K. Hamilton, P. Nason, G. Zanderighi, Finite quark-mass effects in the NNLOPS POWHEG + MinLO Higgs generator, *JHEP* 05 (2015) 140. [arXiv:1501.04637](https://arxiv.org/abs/1501.04637) [https://doi.org/10.1007/JHEP05\(2015\)140](https://doi.org/10.1007/JHEP05(2015)140)
- [45] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, *JHEP* 06 (2010) 043. [arXiv:1002.2581](https://arxiv.org/abs/1002.2581) [https://doi.org/10.1007/JHEP06\(2010\)043](https://doi.org/10.1007/JHEP06(2010)043)
- [46] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *JHEP* 11 (2004) 040. [arXiv:hep-ph/0409146](https://arxiv.org/abs/hep-ph/0409146) <https://doi.org/10.1088/1126-6708/2004/11/040>
- [47] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, *JHEP* 11 (2007) 070. [arXiv:0709.2092](https://arxiv.org/abs/0709.2092) <https://doi.org/10.1088/1126-6708/2007/11/070>
- [48] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, *J. Phys. G* 43 (2016) 023001. [arXiv:1510.03865](https://arxiv.org/abs/1510.03865) <https://doi.org/10.1088/0954-3899/43/2/023001>
- [49] K. Hamilton, P. Nason, G. Zanderighi, MINLO: multi-scale improved NLO, *JHEP* 10 (2012) 155. [arXiv:1206.3572](https://arxiv.org/abs/1206.3572) [https://doi.org/10.1007/JHEP10\(2012\)155](https://doi.org/10.1007/JHEP10(2012)155)
- [50] K. Hamilton, P. Nason, C. Oleari, G. Zanderighi, Merging H/W/Z + 0 and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching, *JHEP* 05 (2013) 082. [arXiv:1212.4504](https://arxiv.org/abs/1212.4504) [https://doi.org/10.1007/JHEP05\(2013\)082](https://doi.org/10.1007/JHEP05(2013)082)
- [51] G. Bozzi, S. Catani, D. de Florian, M. Grazzini, Transverse-momentum resummation and the spectrum of the Higgs boson at the LHC, *Nucl. Phys. B* 737 (2006) 73–120. [arXiv:hep-ph/0508068](https://arxiv.org/abs/hep-ph/0508068) <https://doi.org/10.1016/j.nuclphysb.2005.12.022>
- [52] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* 191 (2015) 159. [arXiv:1410.3012](https://arxiv.org/abs/1410.3012) <https://doi.org/10.1016/j.cpc.2015.01.024>
- [53] E. Bothmann, et al., Event generation with Sherpa 2.2, *SciPost Phys.* 7 (3) (2019) 034. [arXiv:1905.09127](https://arxiv.org/abs/1905.09127) <https://doi.org/10.21468/SciPostPhys.7.3.034>
- [54] S. Schumann, F. Krauss, A parton shower algorithm based on Catani–Seymour dipole factorisation, *JHEP* 03 (2008) 038. [arXiv:0709.1027](https://arxiv.org/abs/0709.1027) <https://doi.org/10.1088/1126-6708/2008/03/038>
- [55] S. Höche, F. Krauss, M. Schönherr, F. Siegert, QCD matrix elements + parton showers. The NLO case, *JHEP* 04 (2013) 027. [arXiv:1207.5030](https://arxiv.org/abs/1207.5030) [https://doi.org/10.1007/JHEP04\(2013\)027](https://doi.org/10.1007/JHEP04(2013)027)
- [56] ATLAS Collaboration, Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, *JHEP* 09 (2014) 145. [arXiv:1406.3660](https://arxiv.org/abs/1406.3660) [https://doi.org/10.1007/JHEP09\(2014\)145](https://doi.org/10.1007/JHEP09(2014)145)
- [57] H.-L. Lai, et al., New parton distributions for collider physics, *Phys. Rev. D* 82 (2010) 074024. [arXiv:1007.2241](https://arxiv.org/abs/1007.2241) <https://doi.org/10.1103/PhysRevD.82.074024>
- [58] S. Agostinelli, et al., GEANT4 – a simulation toolkit, *Nucl. Instrum. Meth. A* 506 (2003) 250. [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
- [59] ATLAS Collaboration, The ATLAS Simulation Infrastructure, *Eur. Phys. J. C* 70 (2010) 823. [arXiv:1005.4568](https://arxiv.org/abs/1005.4568) <https://doi.org/10.1140/epjc/s10052-010-1429-9>
- [60] T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* 178 (2008) 852–867. [arXiv:0710.3820](https://arxiv.org/abs/0710.3820) <https://doi.org/10.1016/j.cpc.2008.01.036>
- [61] NNPDF Collaboration, R.D. Ball, et al., Parton distributions with LHC data, *Nucl. Phys. B* 867 (2013) 244. [arXiv:1207.1303](https://arxiv.org/abs/1207.1303) <https://doi.org/10.1016/j.nuclphysb.2012.10.003>
- [62] ATLAS Collaboration, The pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model, *ATL-PHYS-PUB-2016-017*, 2016. <https://cds.cern.ch/record/2206965>
- [63] ATLAS Collaboration, Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* 81 (2021) 578. [arXiv:2012.00578](https://arxiv.org/abs/2012.00578) <https://doi.org/10.1140/epjc/s10052-021-09233-2>
- [64] ATLAS Collaboration, Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data, *JINST* 14 (2019) P12006. [arXiv:1908.00005](https://arxiv.org/abs/1908.00005) <https://doi.org/10.1088/1748-0221/14/12/P12006>
- [65] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_t jet clustering algorithm, *JHEP* 04 (2008) 063. [arXiv:0802.1189](https://arxiv.org/abs/0802.1189) <https://doi.org/10.1088/1126-6708/2008/04/063>
- [66] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, *Eur. Phys. J. C* 72 (2012) 1896. [arXiv:1111.6097](https://arxiv.org/abs/1111.6097) <https://doi.org/10.1140/epjc/s10052-012-1896-2>
- [67] ATLAS Collaboration, Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1, *Eur. Phys. J. C* 77 (2017) 490. [arXiv:1603.02934](https://arxiv.org/abs/1603.02934) <https://doi.org/10.1140/epjc/s10052-017-5004-5>
- [68] ATLAS Collaboration, Identification of hadronic tau lepton decays using neural networks in the ATLAS experiment, *ATL-PHYS-PUB-2019-033*, 2019. <https://cds.cern.ch/record/2688062>
- [69] ATLAS Collaboration, Reconstruction, energy calibration, and identification of hadronically decaying tau leptons in the ATLAS experiment for run-2 of the LHC, *ATL-PHYS-PUB-2015-045*, 2015. <https://cds.cern.ch/record/2064383>
- [70] ATLAS Collaboration, Measurements of Higgs boson production cross-sections in the $H \rightarrow \tau^+\tau^-$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *JHEP* 08 (2022) 175. [arXiv:2201.08269](https://arxiv.org/abs/2201.08269) [https://doi.org/10.1007/JHEP08\(2022\)175](https://doi.org/10.1007/JHEP08(2022)175)
- [71] ATLAS Collaboration, Estimation of backgrounds from jets misidentified as τ -leptons using the Universal Fake Factor method with the ATLAS detector (2025). [arXiv:2502.04156](https://arxiv.org/abs/2502.04156)
- [72] ATLAS Collaboration, Measurement of the tau lepton reconstruction and identification performance in the ATLAS experiment using pp collisions at $\sqrt{s} = 13$ TeV, *ATLAS-CONF-2017-029*, 2017. <https://cds.cern.ch/record/2261772>
- [73] E. Bothmann, M. Schönherr, S. Schumann, Reweighting QCD matrix-element and parton-shower calculations, *Eur. Phys. J. C* 76 (11) (2016) 590. [arXiv:1606.08753](https://arxiv.org/abs/1606.08753) <https://doi.org/10.1140/epjc/s10052-016-4430-0>
- [74] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* 71 (2011) 1554. [arXiv:1007.1727](https://arxiv.org/abs/1007.1727) <https://doi.org/10.1140/epjc/s10052-011-1554-0>
- [75] D. de Florian, et al., LHC Higgs Cross Section Working Group, Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector (2017). [arXiv:1610.07922](https://arxiv.org/abs/1610.07922) <https://doi.org/10.23731/CYRM-2017-002>
- [76] A.L. Read, Presentation of search results: the CL_s technique, *J. Phys. G* 28 (2002) 2693. <https://doi.org/10.1088/0954-3899/28/10/313>
- [77] U. Haisch, J.F. Kamenik, A. Malinauskas, M. Spira, Collider constraints on light pseudoscalars, *JHEP* 03 (2018) 178. [arXiv:1802.02156](https://arxiv.org/abs/1802.02156) [https://doi.org/10.1007/JHEP03\(2018\)178](https://doi.org/10.1007/JHEP03(2018)178)
- [78] ATLAS Collaboration, ATLAS Computing acknowledgements, *ATL-SOFT-PUB-2025-001*, 2025. <https://cds.cern.ch/record/2922210>